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Tracking the invisible. A search for supersymmetric higgsinos with the ATLAS detector

COORDINATOR

Prof. Aniello Mennella

SUPERVISOR

Dr. Tommaso Lari

PH.D THESIS OF

Alessandro Sala - R13824

 0000-0003-0824-7326

Academic Year 2025-2026

Commission of the final examination

Prof. Monica D'Onofrio

Dr. Andreas Hoecker

Prof. Marco Paganoni

Referees

Prof. Monica D'Onofrio

Prof. Marco Paganoni

Final examination

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Cover illustration

Sketch of an event display shown in the transverse plane consistent with a SUSY signature featuring an energetic jet recoiling against large missing transverse momentum and a soft, “mildly-displaced track”.

Abstract

This thesis presents two complementary searches for supersymmetric particles with compressed mass spectra using proton-proton collision data collected by the ATLAS detector during the LHC Run 2 and Run 3. The analyses target the production of charginos and neutralinos near the electroweak scale and with mass splittings in the range $0.3 - 1.5$ GeV. Owing to the small mass differences, the heavier neutralino and chargino are relatively long-lived and decay into low-momentum charged pions, which are reconstructed as soft tracks displaced by a few millimeters from the proton-proton interaction point and characterised by unusually large impact parameters. The resulting final-state signature is defined by the presence of an energetic jet, missing transverse momentum, and one or more than one soft, mildly displaced tracks. The first search uses data collected at a center-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to a total integrated luminosity of 140 fb^{-1} . Dedicated event-level and track-level selections are applied to define two Signal Regions maximising the overall signal-to-background ratio. No significant data excess above the Standard Model expectations is observed, and 95% confidence level exclusion limits are set on the chargino and neutralino masses as a function of their mass splitting. In the mass splitting range $0.35 - 1$ GeV, chargino masses are excluded up to about 170 GeV, significantly extending the reach beyond the legacy LEP results for the first time. The second search uses data collected at center-of-mass energies of $\sqrt{s} = 13$ and $\sqrt{s} = 13.6$ TeV, corresponding to a total integrated luminosity of 299 fb^{-1} . In this second analysis, an event-level binary neural network and a track-level parameterised multi-class neural network are developed and employed in place of the cut-based approach used in the first analysis. The enhanced discriminating power provided by the machine learning techniques, combined with the increased statistics of the Run 3 data set, is expected to further extend the LHC sensitivity into regions of parameter space that are anticipated to remain inaccessible to future direct detection Dark Matter experiments.

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Introduction

The discovery of the Higgs boson, announced by the ATLAS [1] and CMS [2] collaborations in July 2012, marked a major milestone in particle physics: the final missing piece of the Standard Model (SM) [3–11] had been observed at last. The SM provides a comprehensive and self-consistent framework for describing both the electroweak and strong interactions. Its predictions have been rigorously tested across a wide range of energies and have consistently demonstrated remarkable agreement with experimental results. Despite its success, the Standard Model has several well-known limitations. Notably, it does not address the hierarchy problem [12–15], nor does it offer a viable candidate for Dark Matter (DM) [16–21]. Numerous extensions of the SM have been proposed to address these shortcomings, among which Supersymmetry (SUSY) [22–26] remains one of the most compelling. SUSY not only has the potential to address multiple deficiencies of the Standard Model simultaneously, but also introduces new particles as viable DM candidates and provides a framework for the unification of fundamental interactions at high energy scales.

Supersymmetry is based on a simple yet powerful principle: for every Standard Model fermion (boson), there exists a corresponding superpartner with bosonic (fermionic) properties, and the superpartners are related to their SM counterparts through a fundamental symmetry of nature. This principle introduces a new spectrum of particles that differ from their SM counterparts by half a unit of spin and offer potential solutions to several of the Standard Model’s unresolved issues. For instance, due to the opposite sign of their loop contributions, supersymmetric particles cancel the quadratic divergences in the radiative corrections to the Higgs boson mass, thereby resolving the hierarchy problem without a too unnatural fine-tuning. A consistent supersymmetric extension of the Standard Model requires the inclusion of two Higgs doublets. After the electroweak symmetry breaking, the fermionic superpartners of these Higgs fields, the *higgsinos*, mix with the *gauginos*, the superpartners of the SM gauge bosons. The mixing gives rise to four electrically neutral mass eigenstates called *neutralinos*, and four charged ones called *charginos*. If *R*-parity [27] is conserved, the lightest neutralino is stable. Being massive, electrically neutral, and weakly interacting, the lightest neutralino naturally emerges as a compelling candidate for the DM. Thus, in addition to solving the hierarchy problem, SUSY also offers a viable framework for explaining the nature of Dark Matter.

The masses of the higgsinos and the electroweak gauginos prior to mixing determine the mass spectrum of the resulting charginos and neutralinos [28]. In the regime where the

higgsinos are significantly lighter than the gauginos, the spectrum becomes compressed and features a nearly degenerate triplet of states, composed of the lightest chargino and the two lightest neutralinos. Since this triplet is predominantly higgsino-like, while the heavier chargino and neutralinos are mainly bino- and wino-like, throughout this document the term “higgsinos” is used generically to also denote the mass eigenstates forming the triplet. If the gaugino masses are heavy — on the order of $\mathcal{O}(10)$ TeV — the mass splitting between the two lightest neutralinos, $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, becomes negligible. However, the mass difference between the lightest chargino and the lightest neutralino, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, remains finite, typically in the range of 250 – 400 MeV due to electroweak radiative corrections. In contrast, when the gaugino masses are lighter — around $\mathcal{O}(1)$ TeV — the mass difference $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ can increase up to $\mathcal{O}(1)$ GeV. The higgsino phenomenology at colliders like the LHC is highly sensitive to the mass splittings between the individual states. When $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \approx 250 - 400$ MeV, the chargino becomes long-lived due to the compressed phase space. As a result, it can traverse part of the tracking systems before decaying into soft pions that evade reconstruction, producing a distinctive “disappearing track” signature [29]. Both ATLAS [30] and CMS [31] have utilised this signature to search for higgsinos with lifetimes on the order of $\mathcal{O}(0.1 - 10)$ ns. When the mass splitting is larger, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \gtrsim 2$ GeV, higgsinos searches rely on identifying pairs of prompt soft leptons produced in the decay of the second-lightest neutralino via an off-shell Z boson [32–34]. A challenging intermediate regions where $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \approx 0.3 - 1$ GeV remained unexplored before the results presented in this thesis. In this regime, a chargino decays too promptly to leave a disappearing track, while the decay products of the second-lightest neutralino are too soft to be reliably reconstructed. Consequently, the most stringent limits still originate from legacy LEP searches [35], as even direct detection experiments face difficulties probing such a compressed mass spectrum.

The primary objective of this thesis is to investigate the sensitivity gap in the higgsino phase space between the existing “disappearing track” and “soft leptons” searches, by developing and applying a novel analysis approach first proposed in Ref. [36]. The SUSY models of interest feature mass splittings in the range $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \in [0.3, 1.5]$ GeV, which result in the lightest chargino and the second-lightest neutralino acquiring relatively long lifetimes on the order of $\mathcal{O}(1 - 10)$ ps and decaying predominantly into low-momentum pions at distances of approximately $\mathcal{O}(0.1 - 10)$ mm from the proton-proton interaction point. Such decays give rise to pion tracks with measurable displacements from the primary vertex. The ATLAS detector is capable of precisely reconstructing these displacements using the transverse impact parameter of tracks, with a typical resolution ranging from 10 to 100 μm . While SM processes produce numerous low-momentum prompt tracks in pp collisions, pion tracks originating from higgsino decays can be discriminated by requiring significant impact parameters. At the same time, nonetheless, developing robust strategies to suppress and estimate the background contributions is essential for extending the experimental sensitivity in this challenging region of parameter space.

Summary of the thesis and personal contributions

This manuscript is organised in seven chapters as follows. Chapter 1 provides a brief introduction to the Standard Model and its limitations. Supersymmetry is introduced as a theoretical extension that addresses several of these shortcomings. The phenomenology of the Minimal Supersymmetric Standard Model is discussed, with a particular focus on compressed mass spectra, the search area that constitutes the main subject of this thesis. In addition, existing experimental constraints from collider experiments are briefly reviewed, motivating the use of the “mildly-displaced track” signature as a promising strategy to the search for SUSY higgsinos. Chapter 2 and Chapter 3 describe the LHC accelerator complex and the ATLAS detector, respectively. Chapter 4 details the reconstruction, identification, and calibration of physics objects used in the analyses presented in this work. Special emphasis is placed on the smearing of the track impact parameter, a method used to incorporate resolution effects as a source of systematic uncertainty in the analyses. During Run 3, I was the primary person responsible for producing the recommendations adopted by the ATLAS Collaboration to smear the track impact parameter. This work also involved updating and maintaining the associated software framework. As documented in Section 4.2 of Chapter 4, I identified a shift in the impact parameter bias during the Run 3 data taking. This observation initiated an internal discussion within the Collaboration on how to treat this effect as an additional source of systematic uncertainty to be consistently included across all affected analyses. A dedicated software solution is currently being deployed by ATLAS to address this issue. Chapter 5 presents a first attempt to explore the sensitivity gap in the compressed higgsino parameter space using a “cut-based” approach with the full LHC Run 2 dataset. With this method, a set of carefully chosen kinematic selections is applied to discriminate the SUSY signal from Standard Model backgrounds. The chapter also discusses the primary background components and the strategies employed to reduce and estimate them. Different estimation methods are used for different backgrounds, and all are validated to ensure accurate modeling of the SM predictions in the relevant kinematic regions. The analysis results are presented along with a statistical interpretation in terms of exclusion limits on simplified SUSY models and upper limits on the production cross section of generic signals beyond the SM. In the context of this first analysis, my contributions included the optimisation of the event and track selection, the modelling of signal and background processes, the design and validation of the background estimation strategy, the evaluation of both experimental and theoretical systematic uncertainties, and the statistical interpretation of the final results. Chapter 6 introduces a new approach to the same search, employing machine learning techniques and leveraging the additional statistics provided by the (partial) Run 3 dataset. In particular, improved versions of an event-level neural network and a track-level neural network [37] are used as discriminants in place of traditional cut-based selections. This results in improved expected sensitivity to the considered simplified SUSY models. Within this second analysis, I was responsible for the development and training of both the event-level and track-level neural networks, the definition of the signal regions, the design of the background estimation and validation strategies, and the evaluation of the impact of experimental and theoretical systematic uncertainties. In

addition, I served as the main developer of the analysis software and as editor of the internal supporting documentation, providing a comprehensive and coherent description of the analysis. Finally, Chapter 7 summarises the results obtained from both analysis strategies and provides concluding remarks.

Beyond the Standard Model: Supersymmetry



How come you only want tomorrow / With its promise
of something hard to do / A real life adventure worth
more than pieces of gold / Blue skies above and sun on
your arms strength in your stride / And hope in those
squeaky clean eyes...

— DAVID BOWIE, *Teenage Wildlife*

The **Standard Model** (SM) [3–11] of particle physics is a gauge quantum field theory that provides a unified framework to describe the fundamental particles of nature and their interactions via the strong and electroweak forces. Developed between the 1950s and 1970s, the theory is based on the Lie symmetry group

$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y, \quad (1.1)$$

where $\mathrm{SU}(3)_C$ describes quantum chromodynamics, and $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ governs the electroweak interaction. The SM incorporates twelve spin-1/2 fermionic fields representing the fundamental constituents of matter: *quarks* and *leptons*. Quarks participate in both strong and electroweak interactions, whereas leptons are charged only under the electroweak sector. These fermions are arranged into three generations, which possess identical quantum numbers but differ in mass, with each successive generation being heavier than the previous one. For every fermionic field, the theory predicts a corresponding anti-particle with identical mass and opposite quantum numbers. In a gauge theory, invariance under local symmetry transformations requires the introduction of spin-1 gauge fields, whose excitation modes are identified with *gauge bosons*, the mediators of the fundamental interactions. The $\mathrm{SU}(3)_C$ gauge symmetry gives rise to eight gauge bosons corresponding to the gluons responsible for mediating the strong interaction. The electroweak sector introduces four gauge fields: a neutral field B_μ associated with $\mathrm{U}(1)_Y$, and three fields corresponding to the $\mathrm{SU}(2)_L$ internal symmetries and denoted as W_μ^1 , W_μ^2 , and W_μ^3 . The charged weak bosons mediating charged-current weak interactions emerge

as linear combinations of W_μ^1 and W_μ^2 :

$$W_\mu^\pm = \frac{1}{\sqrt{2}} \left(W_\mu^1 \mp W_\mu^2 \right). \quad (1.2)$$

The remaining neutral gauge fields, W_μ^3 and B_μ , mix through the Weinberg angle θ_W according to

$$\begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}. \quad (1.3)$$

This rotation yields two physical neutral bosons: the photon, identified with the gauge field A_μ and responsible for mediating the electromagnetic interaction, and the Z boson, which mediates weak neutral-current interactions between quarks and leptons of the same flavor. Local gauge invariance prohibits explicit mass terms for gauge bosons in the SM Lagrangian, in contrast with the experimental observations which show that, of the four electroweak bosons, only the photon is massless, whereas the $W^\pm$ and Z bosons are massive [38]. This apparent contradiction is resolved through the Higgs mechanism [9–11]. In close analogy with the Meißner-Ochsenfeld [39] effect in superconductivity — where the presence of a scalar field causes the photon to appear massive — the SM introduces an additional scalar field that combined with the spontaneous electroweak symmetry breaking, a condition in which the ground state of a system does not share the symmetry of the underlying Lagrangian, generates masses for the gauge bosons while preserving local gauge invariance. The Higgs mechanism is incorporated in the electroweak sector of the SM by introducing a weak-isospin doublet of complex scalar fields,

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad (1.4)$$

whose self-interaction is described by the scalar potential

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2. \quad (1.5)$$

The scalar field Φ enters the SM Lagrangian through the term

$$\mathcal{L}_\Phi = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi), \quad (1.6)$$

which is manifestly gauge-invariant under $SU(2)_L \otimes U(1)_Y$ due to the presence of the covariant derivative D_μ . The shape of the scalar potential $V(\Phi)$ is central to the Higgs mechanism. The condition $\lambda > 0$ ensures the existence of global minima, while the sign of μ^2 discriminates between a unique minimum at $\Phi = 0$ ($\mu^2 > 0$) and a continuous set of degenerate minima ($\mu^2 < 0$). In the latter case, there are infinite configurations of Φ that minimise the potential, and the scalar field acquires one such configuration as its vacuum expectation value while the Lagrangian of Eq. 1.6 remains invariant under $U(1)_Y$ transformations. The original electroweak symmetry is therefore said to be *hidden* or *spontaneously broken*. After electroweak symmetry breaking, mass terms for the weak gauge bosons emerge as

$$m_W = \frac{g^v}{2} \quad \text{and} \quad m_Z = \frac{g^v}{2 \cos \theta_W} = \frac{m_W}{\cos \theta_W}, \quad (1.7)$$

where g denotes the weak coupling constant and $v = \sqrt{\frac{-\mu^2}{\lambda}}$ is the vacuum expectation value of the real scalar field commonly referred to as the Higgs field. The excitation mode of the Higgs field corresponds to the massive physical Higgs boson.

The Standard Model has demonstrated extraordinary predictive power and consistency with experimental results across a vast range of energy scales. The discovery of the Higgs boson by the ATLAS and CMS collaborations in 2012 [1, 2] marked a milestone in particle physics, confirming the Higgs mechanism by which electroweak gauge invariance $SU(2)_L \otimes U(1)_Y$ is spontaneously broken [10, 11] to $U(1)_{EM}$ of the electromagnetic interaction, and particles that couple to the Higgs field acquire mass. Although the SM does not include a quantum description of gravity, this omission is not critical at the energy scales probed by current collider experiments and can be safely neglected, being many orders of magnitude weaker than the other fundamental forces at subatomic distances. A schematic representation of the Standard Model and its constituent particles is visible in Figure 1.1.

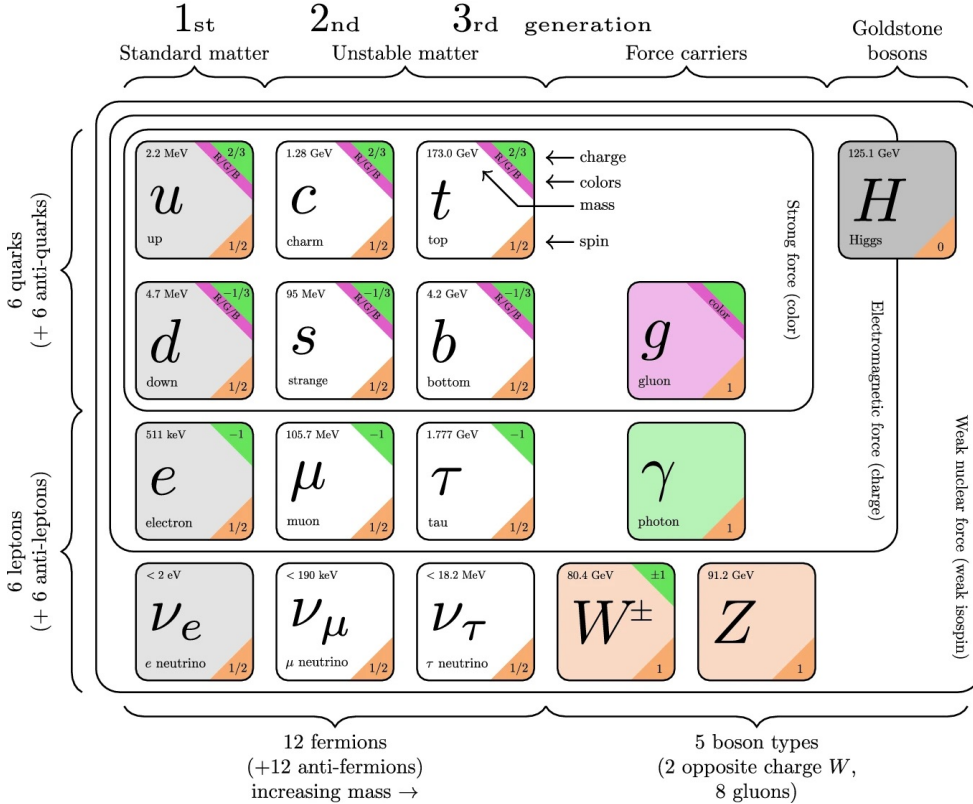


Figure 1.1 – Elementary particles described by the Standard Model.

1.1 Shortcomings of the Standard Model

Despite its remarkable empirical success, the Standard Model is widely regarded as a mere low-energy approximation of a more fundamental theory. In other words, the SM cannot be the ultimate theory of everything, as it faces significant experimental and theoretical challenges. This section briefly highlights some of these key issues.

1.1.1 Hierarchy problem

One of the most profound theoretical shortcomings of the SM is its inability to explain the vast disparity between the electroweak scale and the Planck scale, where quantum gravitational effects become relevant and the SM must be inevitably modified. This discrepancy is known as the **hierarchy problem** [12–15], and one of its prominent manifestations is the extreme *fine-tuning* required to stabilise the Higgs boson mass. After the electroweak symmetry breaking, the Higgs field couples to the SM fermions (excluding neutrinos) and vector bosons, allowing them to acquire finite masses. The Higgs boson itself obtains a mass equal to

$$m_H^2 = -2\lambda v^2, \quad (1.8)$$

where λ is the Higgs self-coupling constant and v is the vacuum expectation value of the Higgs potential. However, at higher orders in perturbation theory, loop corrections to the Higgs mass arise from every particle the Higgs field couples to — directly or indirectly — with fermions providing the dominant contributions [28]. These corrections take the form

$$\Delta m_H^2 = -\frac{|\lambda_f^2|}{8\pi^2} \Lambda_{UV}^2 + \dots, \quad (1.9)$$

where λ_f is the coupling constant between the Higgs and a generic fermion f , while Λ_{UV} is an ultraviolet momentum cutoff used to regulate the loop corrections and should be interpreted as the energy scale at which new physics enters to alter the high-energy behavior of the SM. If Λ_{UV} is assumed to be of the order of the Planck scale, then Δm_H^2 becomes approximately 34 orders of magnitude larger than the experimentally observed Higgs boson mass [40]. To reconcile this discrepancy, correction terms must cancel almost exactly, something that can happen only if the SM parameters are unnaturally “fine-tuned”. The situation becomes even more problematic with the introduction of hypothetical heavy particles beyond the SM that couple to the Higgs field and provide additional corrections terms [28]. For example, a heavy complex scalar S with mass m_S would give rise to corrections of the form

$$\Delta m_H^2 = -\frac{\lambda_S}{16\pi^2} \left[\Lambda_{UV}^2 - 2m_S^2 \ln(\Lambda_{UV}/m_S) + \dots \right], \quad (1.10)$$

where both the cutoff and the mass of the new scalar contribute significantly. Again, avoiding such large corrections would require an unnatural fine-tuning of the SM parameters. A plausible resolution that systematic cancels out these dangerous contributions to Δm_H^2 is the introduction of a new symmetry, as it will be made clear in the following sections.

1.1.2 Dark Matter

A wide range of precise cosmological and astrophysical observations has demonstrated that ordinary baryonic matter accounts for only a small fraction of the total mass in the Universe. Current evidence suggests that there is approximately 5-6 times more mass in a form of non-relativistic “invisible” matter that does not interact electromagnetically, the **Dark Matter** (DM). One of the earliest indications of DM comes from the observations of galactic rotation curves [16, 17]. An illustrative example is shown in Figure 1.2, which displays the rotation curve of the galaxy NGC 6503. The velocity profile in the galaxy’s outer arms remains flat rather than declining, as would be expected based on visible matter alone. This discrepancy implies the presence of an extended halo of unseen non-luminous, gravitationally interacting matter. Additional, independent evidence supporting the existence of DM comes from gravitational lensing [18, 42, 43] and the anisotropies of the Cosmic Microwave Background (CMB) [19, 20], both of which imply a substantial non-baryonic mass component in the Universe. Moreover, numerical simulations of large-scale structure formation not only reinforce the existence of DM in the present-day Universe but also indicate its non-relativistic nature [44–46], essential to allow the formation of cosmic structure from smaller to larger scales, effectively ruling out the possibility that DM consists solely of neutrinos or any other light non-baryonic relativistic particles with masses below approximately 100 eV [47].

Several candidates for the DM have been proposed. These range from elementary particles beyond the SM — such as Weakly Interacting Massive Particles (WIMPs) and axions [48–51] — to macroscopic objects like primordial black holes [52–54]. WIMPs are particularly compelling because they can arise naturally as thermal relics from the early Universe. As the Universe cooled below the WIMP mass scale, their number density would have decreased exponentially, eventually “freezing-out” once their interactions with SM particles became negligible. This process, known as *thermal freeze-out* [55, 56], predicts a relic abundance of WIMPs in the present-day Universe equal to

$$\Omega_{\text{WIMP}} h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right), \quad (1.11)$$

with $\langle \sigma v \rangle$ being the thermally averaged self-annihilation cross section multiplied by the relative velocity v of the WIMP [57]. If a new particle with mass near the electroweak scale ($\mathcal{O}(100 - 1000)$ GeV) and weak-scale interactions exists, its annihilation cross section

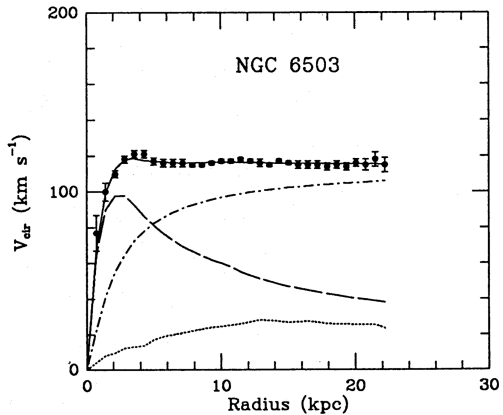


Figure 1.2 – Rotation curve observed in galaxy NGC 6503 [41]. The data points represent measured rotation velocities at various distances from the galactic center. The solid line shows the best-fit including a DM component. Dotted, dashed, and dash-dot lines represent the contributions from gas, stellar disk, and DM halo, respectively.

can be estimated to be $\langle\sigma v\rangle \sim 1 \text{ pb} \sim 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ [21, 28]. Since current observations indicate a DM density of approximately $\Omega_{\text{WIMP}}/h^2 \simeq 0.12$ [20], such a WIMP could account for nearly the entire DM content of the Universe. This striking coincidence, often referred to as the “WIMP miracle”, suggests that if a stable particle associated with new physics at the electroweak scale exists, it is by matter of facts the Dark Matter. Consequently, this idea has driven an enormous experimental effort to detect WIMPs, especially at high-energy colliders such as the LHC where the electroweak-scale phenomena are readily accessible.

1.1.3 Unification of forces

As previously discussed, the SM is a gauge theory based on the $\text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y$ symmetry group. Within this framework, the Gell-Mann–Nishijima relation

$$Q = T^3 + \frac{Y}{2} \quad (1.12)$$

connects the electric charge Q to the third component of the weak isospin T^3 and the weak hypercharge Y . The electric charges of charged leptons Q_ℓ and down-type quarks Q_d are related by $|Q_\ell| = 3|Q_d|$. However, because weak hypercharges are not constrained to take fixed values *a priori*, there is no intrinsic reason within the SM for this quantised relationship to hold. Moreover, internal consistency of the theory requires the cancellation of $\text{U}(1)_Y$ gauge anomalies. This cancellation is ensured in the SM only if the sum of the weak hypercharges across all fermions vanishes — a condition that is indeed satisfied in the SM. The quantised nature of charges and the anomaly cancellation conditions were among the earliest hints pointing toward the existence of a Grand Unified Theory (GUT), where the SM gauge group is embedded in a larger one unifying the strong and electroweak interactions as manifestations of a single fundamental force. In such GUT framework, the SM would then emerge as a low-energy effective field theory, valid only below a certain unification scale. If such unification exists, the three gauge couplings of the SM should converge to a common value at some high energy scale. This can be explored by extrapolating the experimentally measured values of the gauge couplings at the electroweak scale to higher energies using renormalization group equations. The result of this extrapolation within the SM is illustrated in Figure 1.3. Notably, the running couplings fail to unify. This deviation strongly motivates the search for a GUT framework in which the couplings do indeed converge, possibly requiring the inclusion of new physics that is able to alter the running behavior and achieve true unification.

1.2 Supersymmetry

Supersymmetry (SUSY) [22–26, 28] is one of the most compelling theoretical frameworks proposed to extend the Standard Model. At its core, SUSY is built on a simple yet powerful assumption: the existence of a fundamental symmetry that relates every SM fermion (boson) to a new bosonic (fermionic) partner. This symmetry is encoded in the action of a

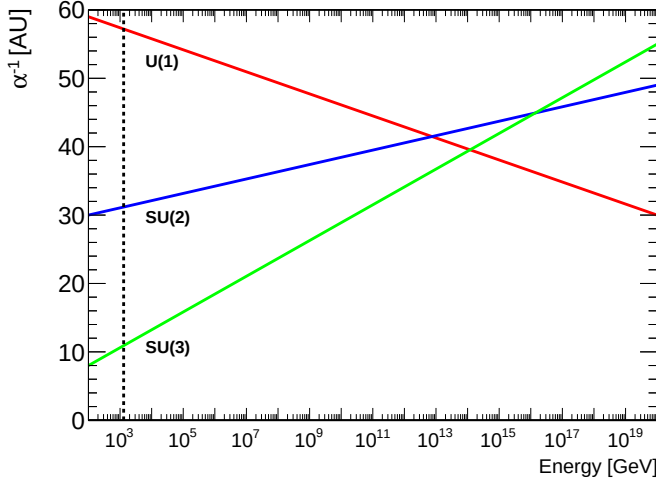


Figure 1.3 – Two-loop renormalization group evolution of the inverse gauge couplings α^{-1} in the SM. The red, blue, and green lines correspond to the electromagnetic, weak, and strong couplings, respectively. The vertical dashed black line marks the highest energy currently accessible at the LHC. Adapted from Ref. [28].

fermionic operator Q , which transform fermionic states $|f\rangle$ into bosonic states $|b\rangle$ and *vice versa*:

$$Q|f\rangle = |b\rangle, \quad Q|b\rangle = |f\rangle. \quad (1.13)$$

The operator Q , along its hermitian conjugate $Q^\dagger$, forms the basis of the supersymmetric algebra when combined with the four-momentum generator P^μ of spacetime translations:

$$\begin{aligned} \{Q_\alpha, Q_{\dot{\beta}}^\dagger\} &= 2\sigma_{\alpha\dot{\beta}}^\mu P_\mu, \\ \{Q_\alpha, Q_\beta\} &= \{Q_{\dot{\alpha}}^\dagger, Q_{\dot{\beta}}^\dagger\} = 0, \\ [P_\mu, Q_\alpha] &= [P_\mu, Q_{\dot{\alpha}}^\dagger] = 0. \end{aligned} \quad (1.14)$$

Here, α and β , and their dotted counterparts are the spinor indices of Q and $Q^\dagger$, respectively, while $\sigma^\mu = (\mathbb{1}, \sigma_i)$ denotes the set of Pauli matrices extended to four-vector notation. The irreducible representations of this algebra are called supermultiplets, single-particle states made of both fermions and bosons related to each other by Eq. 1.13. Since supersymmetric generators commute with the generators of gauge transformations, all members of a given supermultiplet share identical quantum numbers, including color, weak isospin, and electric charge. It can be further proved that a key property of supermultiplets is the equality between the number of fermionic and bosonic degrees of freedom [28]. Accordingly, two main types of supermultiplets partake in supersymmetric extensions of the SM:

- **Chiral supermultiplets**, consisting of a two-component Weyl fermion (i.e., a Weyl spinor with two helicity states) and a complex scalar field, and

- **Gauge or vector supermultiplets**, consisting of a vector boson and a two-component Weyl fermion.

Considering renormalizability and gauge invariance, SUSY assigns SM fermions to Weyl fermions in chiral supermultiplets, and SM vector bosons to vector bosons in gauge supermultiplets. This leads to the prediction that each SM fermion has a scalar superpartner (called a “sfermion”), and each SM gauge boson has a fermionic superpartner (a “gaugino”). The SM Higgs boson, being a scalar, must belong to a chiral supermultiplet and thus requires a fermionic superpartner (a “higgsino”). Moreover, since the squared-mass operator $-P_\mu P^\mu$ commutes with both Q and $Q^\dagger$, all particles belonging to the same supermultiplet are expected to have the same mass. Therefore, if SUSY was an exact symmetry, SUSY particles would be produced at the same rate and with the same mass as their SM counterparts in high-energy colliders such as the LHC. However, no SUSY particles have been observed to date. This lack of experimental evidence suggests that supersymmetry must be a broken symmetry, much like electroweak symmetry in the SM, such that superpartners acquire masses significantly larger than those of the SM, placing them potentially beyond the current reach of collider experiments.

1.2.1 SUSY as a solution to the problems of the Standard Model

Historically, SUSY was introduced in the context of quantum field theory for its elegant mathematical properties. With the experimental establishment of the SM between the 1950s and 1970s, SUSY gained renewed interest for its ability to address several of the SM’s outstanding issues.

Hierarchy problem

It has already been noted that any new heavy complex scalar S with mass m_S introduces radiative corrections to the Higgs boson mass, as described by Eq. 1.10 and illustrated in Figure 1.4. If, for simplicity, one assumes a relation between the scalar and fermion Yukawa couplings of the form $\lambda_S = |\lambda_f|^2$, then the one-loop quadratic divergences to the Higgs mass cancel exactly within SUSY. The cancellation occurs because each SM fermion is associated with two complex scalar superpartners, ensuring that bosonic and fermionic loop contributions offset each other. As a result, the fine-tuning required in the Standard Model to stabilise the Higgs mass becomes unnecessary, and the hierarchy problem appears to be resolved. However, a more careful examination reveals that this cancellation does not persist at higher orders. Specifically, second-order correction terms take the form

$$\Delta m_H^2 = \frac{\lambda}{16\pi^2} \left[m_f^2 \ln \left(\frac{\Lambda_{UV}}{m_f} \right) - m_S^2 \ln \left(\frac{\Lambda_{UV}}{m_S} \right) \right], \quad (1.15)$$

where λ stands for a generic Yukawa coupling. Since SUSY must be spontaneously broken and the masses of fermions and scalar superpartners are no longer equal ($m_f \neq m_S$), an incomplete cancellation of the higher order terms occur, reintroducing a degree of fine-tuning. Nonetheless, the re-emergence of the hierarchy problem is significantly

mitigated provided that SUSY breaking occurs near the TeV scale. If SUSY particles have masses on the order of at most $\mathcal{O}(1)$ TeV, the remaining radiative corrections to the Higgs mass remain under control. Conversely, if superpartner masses lie significantly above the TeV scale, the corrections grow large, and the fine-tuning problem surfaces once again. Therefore, the hierarchy problem not only motivates SUSY but also naturally sets the energy scale at which new physics — specifically in the form of SUSY particles — is expected to appear. This scale lies within the reach of current experiments, such as those conducted at the LHC.



Figure 1.4 – One-loop radiative corrections contributing to the Higgs boson mass calculation from SM fermions (left) and SUSY scalars (right).

Dark Matter

SUSY predicts the existence of an entirely new spectrum of particles. As it will be discussed in the Section 1.3, the lightest supersymmetric particle (LSP) is stable under the assumption of R -parity conservation. If the LSP is also electrically neutral, it interacts with ordinary matter only via the weak force, making it a compelling candidate for DM. Among the possible LSPs, two are often considered as viable DM candidates: the lightest neutralino and the gravitino. After SUSY-breaking, the electrically neutral components of bino, wino, and higgsino — the supersymmetric partner of the Standard Model B , W^0 , and Higgs bosons, respectively — mix to form four mass eigenstates known as neutralinos. The lightest neutralino is widely regarded as the leading candidate of WIMP Dark Matter. The composition of the lightest neutralino — the mixing ratio between bino, wino, and higgsino states — largely depends on the choice of parameters in the framework of the Minimal Supersymmetric Standard Model. For a detailed discussion, see Section 1.3.3. Here, it suffices to note that bino-like neutralinos tend to have very small annihilation cross sections, resulting in early thermal freeze-out and an overabundance of relics in the present-day Universe. Most bino-like DM models are thereby excluded by relic density constraints. However, viable cases still exist, such as the bino-stau coannihilation scenario, where the bino LSP and a slightly heavier stau (the SUSY partner of the tau lepton) coannihilate, enhancing the overall annihilation rate and reducing the relic abundance to acceptable levels [58, 59]. Wino-like and pure higgsino-like neutralinos are allowed by relic density constraints to have masses up to 3 TeV and 1.1 TeV, respectively. At lower masses, the neutralino LSP contributes only partially to the total DM abundance, requiring either additional DM components or non-thermal production mechanisms to account for the full observed relic density [60–62]. Alternatively, if the gravitino, the

supersymmetric partner of the hypothetical graviton, is the LSP, as is often the case in gauge-mediated SUSY breaking scenarios, its viability as a DM candidate is highly constrained by cosmological considerations. In particular, to avoid the so-called “gravitino problem”, the gravitino mass must typically be less than $\lesssim \mathcal{O}(10)$ eV [63–65].

Unification of forces

As previously discussed, the gauge coupling constants in the SM do not unify when extrapolated to high energies using the renormalisation group equations. SUSY introduces additional contributions to the two-loop renormalisation group equations, particularly when its spontaneous breaking occurs near the TeV scale. These corrections significantly alter the running of the couplings, as can be seen in Figure 1.5: in contrast to the SM case, the three gauge couplings in the Minimal Supersymmetric Standard Model evolve to meet at a common scale around $\Lambda_{\text{GUT}} \sim 10^{16}$ GeV, suggesting the possible existence of a supersymmetric GUT. It is important to note nevertheless that, while the convergence is significantly improved compared to the SM, the unification is still not exact. This slight mismatch could potentially be resolved by postulating the existence of additional particles beyond the Minimal Supersymmetric Standard Model, which may appear near the GUT scale and affect the running of the couplings in the final stages of unification.

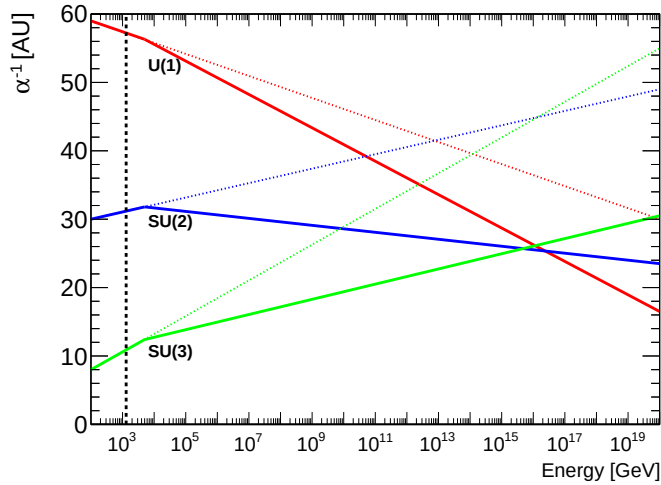


Figure 1.5 – Two-loop renormalization group evolution of the inverse gauge couplings α^{-1} in the Standard Model (dotted lines) and the Minimal Supersymmetric Standard Model (solid lines). The red, blue, and green lines correspond the electromagnetic, weak, and strong couplings, respectively. The vertical dashed black line marks the highest energy currently accessible at the LHC. Adapted from Ref. [28].

1.3 The Minimal Supersymmetric Standard Model

The **Minimal Supersymmetric Standard Model** (MSSM) [27, 66, 67] is the simplest supersymmetric extension of the SM and has been the primary focus of numerous studies searching for evidence of SUSY. The MSSM introduces only the minimal set of new particles required to build a consistent supersymmetric theory: one superpartner for each SM particle and two Higgs doublets.

In the MSSM, Standard Model fermions are incorporated into chiral supermultiplets. Since both the left- and right-handed quarks and leptons are distinct two-component Weyl fermions with different gauge transformation properties, each of them requires its own complex scalar partner. For instance, the SM left-handed doublet (u_L, d_L) corresponds to a supermultiplet containing both the fermions (u_L, d_L) and their scalar partners $(\tilde{u}_L, \tilde{d}_L)$. Similarly, the right-handed singlet u_R is accompanied by its superpartner $\tilde{u}_R$. The tilde ($\sim$) notation is conventionally added to the SM particles to denote the corresponding SUSY partners. The scalar superpartners of SM fermions are collectively referred to as *sfermions*, and their names are derived by prepending an s (for scalar) to the name of the SM counterparts. Sfermions include *squarks* and *sleptons*, the superpartners of quarks and leptons, respectively.

Names		Spin-0	Spin-1/2
Squarks, quarks ($\times 3$ generations)	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)
	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$
Sleptons, leptons ($\times 3$ generations)	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)
	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$
Higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$

Table 1.1 – Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, while the spin-1/2 fields are left-handed two-component Weyl fermions.

In the Higgs sector, the SM Higgs boson is already a spin-0 particle, which suggests it must belong to a chiral supermultiplet as a spin-1/2 Weyl fermion. However, a single chiral supermultiplet is not enough, for two main reasons. First, a consistent quantum field theory requires gauge anomalies to cancel. Part of this translates to demanding the sum of hypercharges for all fermions to be exactly zero. The fermionic partners of the Higgs bosons contribute to gauge anomalies, necessitating a second Higgs supermultiplet to ensure the cancellation. Secondly, two Higgs doublets are needed to generate appropriate Yukawa couplings for both up-type and down-type fermions, without introducing

large flavor-changing neutral currents. As a result, the MSSM introduces two Higgs supermultiplets: H_u and H_d , with hypercharges $Y = 1/2$ and $Y = -1/2$, respectively. The H_u multiplet gives mass to up-type quarks, whereas H_d is responsible for giving mass to down-type quarks and charged leptons. The isospin components of H_u have electric charges $+1$ and 0 and are denoted as (H_u^+, H_u^0) , while those of H_d have charges 0 and -1 and are labelled as (H_d^0, H_d^-) . Their fermionic superpartners, the *higgsinos*, are indicated as $(\tilde{H}_u^+, \tilde{H}_u^0)$ and $(\tilde{H}_d^0, \tilde{H}_d^-)$, respectively. A summary of the MSSM chiral supermultiplets is presented in Table 1.1.

The vector bosons of the SM belong to gauge supermultiplets in the MSSM. Their fermionic superpartners are known as *gauginos*, named by appending the suffix “-ino” to the name of their SM counterparts. The $SU(3)_C$ color gauge interactions of QCD are mediated by the gluon g , whose spin-1/2 color-octet supersymmetric partner is the *gluino* $\tilde{g}$. The electroweak symmetry $SU(2)_L \otimes U(1)_Y$ is associated with the spin-1 gauge bosons $W^\pm$, W^0 and B^0 , with spin-1/2 superpartners $\tilde{W}^\pm$, $\tilde{W}^0$ and $\tilde{B}^0$ called *winos* and *bino*. After the electroweak symmetry breaking, W^0 and B^0 mix to form the physical mass eigenstates Z^0 and γ , with their corresponding gaugino mixtures called *zino* ($\tilde{Z}^0$) and *photino* ($\tilde{\gamma}$). Table 1.2 summarizes the gauge supermultiplets of a minimal supersymmetric extension of the Standard Model.

Names	Spin-1/2	Spin-1
Gluino, gluon	$\tilde{g}$	g
Wino, W bosons	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$
Bino, B boson	$\tilde{B}^0$	B^0

Table 1.2 – Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

1.3.1 The MSSM Lagrangian and soft-supersymmetry breaking

SUSY must be broken at least at the electroweak scale. Otherwise, SM particles and their SUSY partners would have identical masses, which is experimentally excluded. For this to occur, the MSSM must possess a Lagrangian that is invariant under supersymmetric transformations, but with a vacuum state that is not. In other words, supersymmetry must be a hidden symmetry at low energies, much like the electroweak symmetry in the Standard Model. To naturally preserve the hierarchy between the electroweak scale and any much larger mass scale, SUSY-breaking must occur through *soft* terms in the Lagrangian. These soft terms are designed to break supersymmetry without reintroducing the hierarchy problem, and they consist solely of mass terms and couplings with positive mass dimensions, excluding any dimensionless couplings. Accordingly, the effective MSSM Lagrangian can be written as

$$\mathcal{L}^{\text{MSSM}} = \mathcal{L}_{\text{SUSY}}^{\text{MSSM}} + \mathcal{L}_{\text{soft}}^{\text{MSSM}}, \quad (1.16)$$

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where $\mathcal{L}_{\text{SUSY}}^{\text{MSSM}}$ includes all supersymmetry-preserving gauge and Yukawa interactions, while $\mathcal{L}_{\text{soft}}^{\text{MSSM}}$ introduces SUSY-breaking terms through soft parameters. The soft-breaking Lagrangian is given by:

$$\begin{aligned} \mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2} \left(M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.} \right) \\ & - \left(\tilde{u} \mathbf{A}_u \tilde{Q} H_u - \tilde{d} \mathbf{A}_d \tilde{Q} H_d - \tilde{e} \mathbf{A}_e \tilde{L} H_d + \text{c.c.} \right) \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_u^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_d^2 \tilde{d}^\dagger - \tilde{e} \mathbf{m}_e^2 \tilde{e}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - \left(b H_u H_d + \text{c.c.} \right). \end{aligned} \quad (1.17)$$

The first line contains mass terms for the gluino, wino, and bino, with M_3 , M_2 , and M_1 denoting their respective masses. The second line contains the trilinear scalar interactions for squarks and sleptons, with the coupling matrices $\mathbf{A}_u$, $\mathbf{A}_d$, and $\mathbf{A}_e$. The third line contains mass terms for the SUSY scalar fields with $\mathbf{m}_Q^2$, $\mathbf{m}_L^2$, $\mathbf{m}_u^2$, $\mathbf{m}_d^2$, and $\mathbf{m}_e^2$ being 3×3 complex hermitian mass matrices in the generation space. The final line of Eq. 1.17 gives the soft supersymmetry-breaking terms of the Higgs potential, with $m_{H_u}^2$, $m_{H_d}^2$, and b denoting mass-squared parameters. To solve the hierarchy problem naturally, all soft SUSY-breaking parameters are expected to lie near a common mass scale m_{soft} , typically not far above the TeV scale:

$$\begin{aligned} M_1, M_2, M_3, \mathbf{A}_u, \mathbf{A}_d, \mathbf{A}_e & \sim m_{\text{soft}}, \\ \mathbf{m}_Q^2, \mathbf{m}_L^2, \mathbf{m}_u^2, \mathbf{m}_d^2, \mathbf{m}_e^2 & \sim m_{\text{soft}}^2. \end{aligned} \quad (1.18)$$

One of the main challenges of SUSY-breaking in the MSSM is that it introduces a large number of new parameters — 105 in total [68] — including masses, phases, and mixing angles that have no counterparts in the Standard Model. This apparent tremendous arbitrariness is a drawback of the theory. However, by imposing a set of well-motivated phenomenological constraints, the number of independent parameters can be reduced to just 19. This simplification is not merely artificial. It can be justified by postulating that SUSY is spontaneously broken in a “hidden sector” of particles that couple only weakly to the “visible sector” of the MSSM. The effects of SUSY-breaking are then mediated from the hidden sector to the MSSM through a specific mechanism, giving rise to the soft terms described above. Crucially, SUSY breaking must occur outside the MSSM itself; otherwise, it would imply the existence of a SUSY scalar lighter than its SM fermion counterpart, which is excluded by experiments. Several viable mediation mechanisms for SUSY-breaking exist. One widely studied scenario is gravity-mediated supersymmetry-breaking, which involves the effects of supergravity (SUGRA) [69–76]. In this framework, supersymmetry is promoted from a global to a local symmetry, incorporating gravity via the spin-2 graviton and its fermionic superpartner, the spin-3/2 *gravitino*. Alternative mechanisms include gauge-mediated [77–80] and anomaly-mediated [81, 82] supersymmetry-breaking.

1.3.2 R-parity

The most general form of a gauge-invariant SUSY Lagrangian can include terms that violate both baryon number (B) and lepton number (L) conservation. The potential presence of such terms is concerning, as no B - and L -violating processes have never been observed experimentally to date. Figure 1.6 illustrates a Feynman diagram for such a process: the

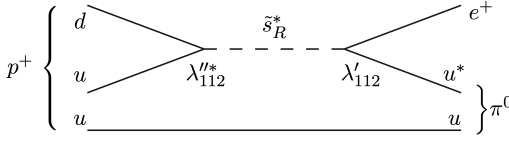


Figure 1.6 – Feynman diagram of a proton decay mediated by a strange squark [28].

decay of a proton into a positron and a neutral pion, mediated by a strange squark. If the squark mediator had a mass of the order of $\mathcal{O}(\text{TeV})$, the predicted proton mean lifetime would be extremely short - on the order of a fraction of a second. This sharply contrasts with the experimental lower bound on the proton lifetime, which exceeds $2.4 \cdot 10^{34}$ years [38]. The natural way the MSSM addresses this problem is by introducing a new symmetry, the **R-parity** [27], a multiplicatively conserved quantum number defined as

$$R = (-1)^{3(B-L)+2s}, \quad (1.19)$$

where s is the particle's spin. As a result, all SM particles have $R = +1$, while all SUSY partners have $R = -1$. Conservation of R-parity has three crucial phenomenological implications.

- SUSY particles must be produced in pairs in collider experiments involving only SM particles, such as those conducted at the LHC.
- The lightest supersymmetric particle (LSP) must be absolutely stable, since any decay into SM particles would violate the R-parity conservation. If the LSP is electrically neutral and interacts only via the weak force with ordinary matter, it becomes a natural candidate for non-baryonic DM.
- All other sparticles beside the LSP must eventually decay into a state containing an odd number of LSPs, ensuring that R-parity is preserved throughout their decay chains.

One might question whether it is reasonable to assume that R-parity is exactly conserved in the MSSM, especially since all known discrete symmetries in the SM are violated to some extent. Fortunately, several theoretical extensions of the MSSM — particularly supersymmetric GUTs — naturally incorporate R-parity conservation. In these models, R-parity emerges as a consequence of deeper symmetries and remains conserved even down to the electroweak scale, making its conservation in the MSSM appear well-motivated rather than arbitrary. If, however, R-parity conservation is still considered theoretically unconvincing, R-parity violating models [83–86] offer viable alternatives. To prevent rapid proton decay, these models typically assume that either B or L is conserved. Consequently, sparticles can decay entirely into non-supersymmetric particles, leading to novel experimental signatures and unusual decay processes. It should be noted, however, that R-parity violation comes at the cost of losing stable Dark Matter candidates.

1.3.3 Mass spectra in the MSSM

Following the electroweak supersymmetry-breaking, the interaction eigenstates of sparticles in the MSSM do not necessarily coincide with their mass eigenstates, due to possible mixing between fields with identical quantum numbers. This section provides a concise overview of the MSSM mass spectrum, essential for understanding its phenomenological implications and the constraints imposed by experimental data.

Electroweak symmetry breaking and the Higgs sector

The MSSM Higgs sector consists of two Higgs doublets: $H_u = (H_u^+, H_u^0)$ and $H_d = (H_d^0, H_d^-)$. Extracting the terms in the Lagrangian relevant for the electroweak symmetry breaking, the scalar Higgs potential takes the form [28]

$$\begin{aligned}
 V = & \left(|\mu|^2 + m_{H_u}^2 \right) \left(|H_u^0|^2 + |H_u^+|^2 \right) + \left(|\mu|^2 + m_{H_d}^2 \right) \left(|H_d^0|^2 + |H_d^-|^2 \right) \\
 & + \left[b \left(H_u^+ H_d^- - H_u^0 H_d^0 \right) + \text{c.c.} \right] \\
 & + \frac{1}{8} \left(g_2^2 + g_Y^2 \right) \left(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2 \right)^2 \\
 & + \frac{1}{2} g_2^2 \left| H_u^+ H_d^{0*} + H_u^0 H_d^{-*} \right|^2 .
 \end{aligned} \tag{1.20}$$

Here, g_2 and g_Y are the $SU(2)_L$ and the $U(1)_Y$ gauge coupling constants, respectively, while μ is the supersymmetric version of the Higgs boson mass in the SM. For the electroweak symmetry breaking to occur, both neutral Higgs components H_u^0 and H_d^0 must acquire non-zero vacuum expectation values (VEVs), i.e.

$$v_{\text{SM}}^2 = v_u^2 + v_d^2 = \langle H_u^0 \rangle^2 + \langle H_d^0 \rangle^2 = \frac{2m_Z^2}{g_2^2 + g_Y^2} , \tag{1.21}$$

where m_Z is the mass of the Z boson. By defining

$$\tan \beta = \frac{v_u}{v_d} \tag{1.22}$$

and requiring that the Higgs potential is minimized with respect to the neutral components ($H_u^+ = H_d^- = 0$ and $\partial V / \partial H_u^0 = \partial V / \partial H_d^0 = 0$), the following relationships are obtained:

$$\begin{aligned}
 \sin 2\beta &= \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2} , \\
 m_Z^2 &= \frac{|m_{H_u}^2 - m_{H_d}^2|}{\sqrt{1 - \sin^2 2\beta}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2 .
 \end{aligned} \tag{1.23}$$

As a result, after the electroweak symmetry breaking, three of the eight real scalar degrees of freedom in the two Higgs doublets become the longitudinal modes of the $SU(2)_L$ massive $W^\pm$ and Z bosons. The remaining five degrees of freedom, on the other hand,

manifest as five physical Higgs bosons: two CP-even neutral scalars h^0 and H^0 , one CP-odd neutral scalar A^0 , and two charged scalars $H^\pm$. Assuming that v_u and v_d minimize the tree-level potential in Eq. 1.20, the tree-level Higgs boson masses are given by

$$\begin{aligned} m_{A^0}^2 &= \frac{2b}{\sin(2\beta)} = 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2, \\ m_{h^0, H^0}^2 &= \frac{1}{2} \left(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 - m_Z^2)^2 + 4m_Z^2 m_{A^0}^2 \sin^2 2\beta} \right), \\ m_{H^\pm}^2 &= m_{A^0}^2 + m_W^2, \end{aligned} \quad (1.24)$$

where m_W is the mass of the SM $W^\pm$ bosons. Well before the discovery of the Higgs boson by the ATLAS and CMS collaborations [1, 2], it had been shown that the CP-even neutral scalar h^0 exhibits properties closely resembling those of the Standard Model Higgs [87]. Furthermore, it was found that in the MSSM

$$m_{h^0} \lesssim 135 \text{ GeV}, \quad (1.25)$$

provided that all the sparticles coupling to h^0 contributing to loop corrections have masses below approximately 1 TeV. Consequently, h^0 is typically identified with the Higgs boson observed at the LHC, with its mass generated through the electroweak symmetry breaking in the MSSM.

Neutralinos and charginos

The electroweak symmetry breaking induces mixing among the neutral and charged gauginos and higgsinos. Specifically, the two neutral higgsinos, $\tilde{H}_u^0$ and $\tilde{H}_d^0$, and the two neutral gauginos, $\tilde{B}^0$ and $\tilde{W}^0$, combine to form four neutral mass eigenstates known as **neutralinos** and denoted by $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4$). Similarly, the charged higgsinos $\tilde{H}_u^\pm$, $\tilde{H}_d^\pm$, and the charged winos $\tilde{W}^\pm$ mix to form two charged mass eigenstates called **charginos**, denoted by $\tilde{\chi}_i^\pm$ ($i = 1, 2$). By convention, the eigenstates are ordered by increasing mass:

$$m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_3^0} < m_{\tilde{\chi}_4^0}, \quad m_{\tilde{\chi}_1^\pm} < m_{\tilde{\chi}_2^\pm}. \quad (1.26)$$

Neutralinos and charginos are collectively referred to as *electroweakinos*. The lightest neutralino, $\tilde{\chi}_1^0$, is usually assumed to be the LSP and, if R -parity is conserved, a compelling candidate for non-baryonic DM.

The neutralino mass terms in the MSSM Lagrangian can be expressed as

$$\mathcal{L}_{\tilde{\chi}^0} = -\frac{1}{2} (\psi^0)^T \mathbf{M}_{\tilde{\chi}^0} \psi^0 + \text{c.c.} \quad (1.27)$$

using the gauge-eigenstate basis $\psi^0 = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$. The corresponding symmetric mass matrix is then:

$$\mathbf{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}. \quad (1.28)$$

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Here, $s_\beta = \sin \beta$, $c_\beta = \cos \beta$, $s_W = \sin \theta_W$, and $c_W = \cos \theta_W$, with θ_W being the Weinberg mixing angle defined via $\tan \theta_W = g_Y/g_2$. Diagonalising $\mathbf{M}_{\tilde{\chi}^0}$ yields the physical masses of the four neutralinos. With a similar approach, the chargino mass terms in the Lagrangian can be written as

$$\mathcal{L}_{\tilde{\chi}^\pm} = -\frac{1}{2}(\psi^\pm)^T \mathbf{M}_{\tilde{\chi}^\pm} \psi^\pm + \text{c.c.} \quad (1.29)$$

using the gauge-eigenstate basis $\psi^\pm = (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$. The resulting mass matrix is:

$$\mathbf{M}_{\tilde{\chi}^\pm} = \begin{pmatrix} 0 & 0 & M_2 & \sqrt{2}c_\beta m_W \\ 0 & 0 & \sqrt{2}s_\beta m_W & \mu \\ M_2 & \sqrt{2}s_\beta m_W & 0 & 0 \\ \sqrt{2}c_\beta m_W & \mu & 0 & 0 \end{pmatrix}. \quad (1.30)$$

Even at tree level, the physical chargino and neutralino masses result from non-trivial mixing between gaugino and higgsino states, and the resulting eigenvalues are generally cumbersome to write explicitly. However, it is important to note that these mass terms depend on four key parameters which must be determined experimentally: μ , M_2 , M_1 , and $\tan \beta$. These parameters play a central role in shaping the phenomenology of the MSSM at colliders and in cosmological observations.

Electroweakinos in compressed mass scenarios

One of the key motivations for SUSY, as previously discussed, is its ability to address the hierarchy problem. This motivation is reflected in the context of Section 1.2, where the second relation in Eq. 1.23 can be rewritten as [88]

$$-\frac{m_Z^2}{2} = |\mu|^2 - \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1}. \quad (1.31)$$

This new expression highlights the requirement that the higgsino mass parameter μ must not be too large compared to the electroweak scale, i.e. $|\mu|^2 \sim -m_{H_u}^2 \sim m_Z^2$. Otherwise, an excessive fine-tuning of the SM parameters would be needed to recover the experimentally measured Z boson mass. This condition is known as “electroweak naturalness” [88, 90–92]. Electroweak naturalness sets a preferred energy scale where higgsinos are expected to be produced, implying at the same time a hierarchy

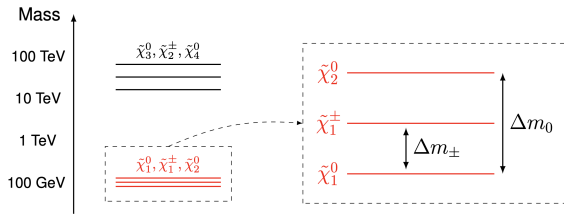


Figure 1.7 – Electroweakinos mass spectrum in the higgsino LSP limit, assuming decoupled gauginos masses. The lightest chargino and the two lightest neutralinos form a nearly degenerate mass triplet. Δm_0 is the mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$, while $\Delta m_\pm$ is the mass splitting between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$. The remaining electroweakinos are bino- and wino-like states with masses around M_1 and M_2 . From Ref. [89].

where higgsinos are significantly lighter than the gauginos:

$$|\mu| \ll M_1, M_2. \quad (1.32)$$

In this limit, after the electroweak symmetry breaking, the higgsino sector forms a nearly degenerate higgsino-like triplet consisting of the lightest chargino and the two lightest neutralinos, $(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_2^0)$, with the two remaining wino-like neutralinos and the second-lightest bino-like chargino at mass scales close to M_2 and M_1 , respectively. This mass hierarchy is illustrated in Figure 1.7. The mass splitting between the two light neutralinos, $\Delta m_0 = m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$, is induced via mixing with bino and wino states [36, 93, 94], and can be approximated by

$$\Delta m_0 \simeq m_Z^2 \left| \frac{c_W^2}{M_2} + \frac{s_W^2}{M_1} \right|. \quad (1.33)$$

The mass difference between the lightest chargino and neutralino, $\Delta m_\pm = m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)$ receives contributions at both tree-level and through radiative corrections. These contributions are expressed as [36, 93, 94]

$$\begin{aligned} \Delta m_\pm^{\text{tree}} &\simeq \frac{\Delta m_0}{2} - \frac{1}{2} m_Z^2 \sin 2\beta \left(\frac{c_W^2}{M_2} - \frac{s_W^2}{M_1} \right), \\ \Delta m_\pm^{\text{rad}} &\simeq \frac{\alpha_2 s_W^2 \mu}{2\pi} \int_0^1 (1+t) \ln \left[1 + \frac{m_Z^2 (1-t)}{\mu^2 t^2} \right] dt, \end{aligned} \quad (1.34)$$

where α_2 is the fine-structure constant for the $\text{SU}(2)_L$ gauge group. In the limit where $\mu \gg m_Z$, the radiative correction term simplifies to [36]:

$$\Delta m_\pm^{\text{rad}} \simeq \frac{\alpha_2 m_Z}{2} \sin^2 \theta_W \simeq 354 \text{ MeV}. \quad (1.35)$$

Within the MSSM, mass splittings increase with stronger higgsino-gaugino mixing, and $\Delta m_\pm$ typically remains larger than $\mathcal{O}(200 - 300)$ MeV due to radiative corrections [95]. The mixing also enhances the DM-nucleon scattering cross section, creating a strong correlation between the mass splittings and observables directly accessible by DM direct detection experiments [29]. Current limits from DM direct detection experiments [96] require $\Delta m_\pm^{\text{tree}} \gtrsim \mathcal{O}(1)$ GeV. In other words, the limits indicate that direct detection experiments are capable of finding higgsinos provided that the mass difference exceeds a few GeV, approximately [97]. Consequently, phase space regions where $\Delta m_\pm^{\text{tree}} \lesssim \mathcal{O}(1)$ GeV remain largely unexplored, being primarily within reach of collider experiments only. The higgsino phenomenology at colliders is highly sensitive to the mass splittings. In the regime $m_{\pi^\pm} < \Delta m_\pm \lesssim 1$ GeV, with $m_{\pi^\pm}$ denoting the charged pion mass, the dominant decay mode of the lightest chargino becomes $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ [98]. The decay length of this process is given by

$$\Gamma_{\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm}^{-1} \simeq \frac{14 \text{ mm}}{\hbar c} \cdot \left[\left(\frac{\Delta m_\pm}{340 \text{ MeV}} \right)^3 \sqrt{1 - \frac{m_{\pi^\pm}^2}{\Delta m_\pm^2}} \right]^{-1}. \quad (1.36)$$

From this expression, it is possible to extract the chargino mean lifetime as a function of the mass splitting, as shown in Figure 1.8. In the relevant parameter space, the chargino lifetime is typically $c\tau \approx \mathcal{O}(0.1 - 10)$ mm, which is sufficiently long for the resulting pion to be spatially separated from other particles produced promptly in the interaction point. Similar considerations apply to the second-lightest neutralino. Motivated by the electroweak naturalness and DM considerations, this thesis focuses precisely on the scenario described above: a higgsino-like nearly degenerate mass triplet $(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_2^0)$, with masses near the electroweak scale, and a measurable higgsino lifetime resulting in *displaced decay* signatures.

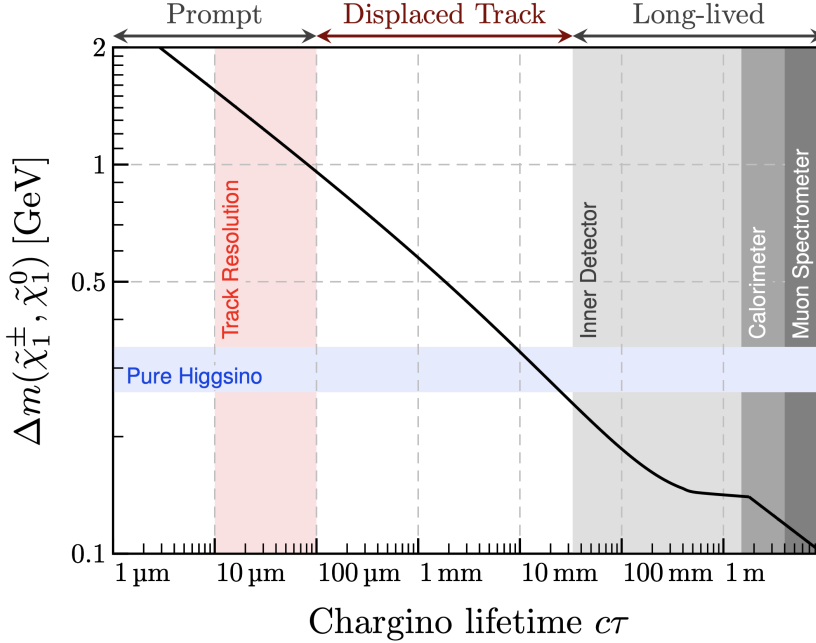


Figure 1.8 – Chargino lifetime $c\tau$ as a function of the mass difference between the lightest chargino and the lightest neutralino $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$. The gray band shows the spatial coverage of the various ATLAS detector subsystems. The blue region corresponds to the range of mass splittings where the gaugino mass is sufficiently decoupled from the higgsino mass parameter. The red band represents the impact parameter resolution of tracks reconstructed by ATLAS. Charginos with lifetimes exceeding this resolution may produce detectable displaced pion tracks. From Ref. [89].

Gluino

Unlike neutralinos and charginos, the gluino is a colored octet fermion and does not mix with any other particles in the MSSM, even in the presence of R -parity violation. Assuming gauge coupling unification at a sufficiently high-energy scale, the gluino mass parameter M_3 is related to the bino and wino masses M_1 and M_2 , as introduced in Eq.

1.17. Up to second-order corrections, M_3 is given by

$$M_3 = \frac{\alpha_s}{\alpha} \sin^2 \theta_W M_2 = \frac{3}{5} \frac{\alpha_s}{\alpha} \cos^2 \theta_W M_1, \quad (1.37)$$

where α_s and α are the strong coupling and the electromagnetic fine-structure constants, respectively. This relation leads to the following approximate mass hierarchy near the TeV scale

$$M_3 : M_2 : M_1 \approx 6 : 2 : 1, \quad (1.38)$$

implying that the gluino is naturally expected to be significantly heavier than the lighter neutralinos and charginos, and potentially beyond the reach of current collider experiments. Nonetheless, it should be noted that gluino searches at the LHC are still conducted, typically treating the gluino mass as a free parameter within simplified SUSY models rather strictly adhering to the above relation.

Squarks and sleptons

Although scalars with identical quantum numbers can, in general, mix to form mass eigenstates, squarks and sleptons in the MSSM are expected to exhibit less intricate mixing patterns compared to the Higgs-sector particles. This is primarily due to stringent experimental constraints on flavor-changing and CP-violating processes. To calculate squark and slepton mass terms, it is common to adopt an idealised scenario where the sfermion mass matrices in Eq. 1.17 are assumed to be proportional to the 3×3 identity matrix:

$$\mathbf{m}_Q^2 = m_Q^2 \times \mathbb{1}, \quad \mathbf{m}_L^2 = m_L^2 \times \mathbb{1}, \quad \mathbf{m}_u^2 = m_u^2 \times \mathbb{1}, \quad \mathbf{m}_d^2 = m_d^2 \times \mathbb{1}, \quad \mathbf{m}_e^2 = m_e^2 \times \mathbb{1}. \quad (1.39)$$

Suppression of flavor-changing neutral current processes can be achieved by assuming that the trilinear coupling matrices $\mathbf{A}_{u,d,e}$ in Eq. 1.17 are proportional to the corresponding Yukawa coupling matrices $\mathbf{y}_{u,d,e}$, which in turn can be approximated to receive contributions only from third-generation components. Under these assumptions, all matrices of Eq. 1.39 can be treated as diagonal, between the first- and second-generation sfermions. For example, the mass matrix of left-handed squarks takes the approximate form

$$\mathbf{m}_Q^2 \approx \begin{pmatrix} m_{Q_{1,2}}^2 & 0 & 0 \\ 0 & m_{Q_{1,2}}^2 & 0 \\ 0 & 0 & m_{Q_{1,2}}^2 \end{pmatrix}, \quad (1.40)$$

with analogous expressions holding for $\mathbf{m}_L^2$, $\mathbf{m}_u^2$, $\mathbf{m}_d^2$, and $\mathbf{m}_e^2$. Due to large third-generation Yukawa couplings and trilinear couplings, the third generation sfermions generally have different masses from their first- and second-generation counterparts. Significant left-right mixing may occur for the third-generation sfermions, resulting in the following multiplets: $(\tilde{t}_L, \tilde{t}_R)$, $(\tilde{b}_L, \tilde{b}_R)$, and $(\tilde{\tau}_L, \tilde{\tau}_R)$. Considering top squarks (*stops*), the Lagrangian mass term in the gauge-eigenstate basis $(\tilde{t}_L, \tilde{t}_R)$ is given by

$$\mathcal{L}_{\text{stop}} = -(\tilde{t}_L^* \tilde{t}_R^*) \mathbf{m}_{\tilde{t}}^2 \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}, \quad (1.41)$$

where the mass matrix is

$$\mathbf{m}_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & v (A_t^* \sin \beta - \mu y_t \cos \beta) \\ v (A_t \sin \beta - \mu^* y_t \cos \beta) & m_{\tilde{u}_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix}. \quad (1.42)$$

This mass matrix is diagonalised to obtain the mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{t}} & -\sin \theta_{\tilde{t}} \\ \sin \theta_{\tilde{t}} & \cos^* \theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}. \quad (1.43)$$

Here, $\theta_{\tilde{t}}$ denotes the stop mixing angle. Due to the sizable off-diagonal elements in the mass matrix, strong mixing is induced, and the values of $m_{Q_3}^2$ and $m_{\tilde{u}_3}^2$ are significantly smaller than their corresponding parameters of first- and second-generation squarks. Overall, this causes a reduction in the lighter stop mass eigenvalue, making $\tilde{t}_1$ — predominantly composed of $\tilde{t}_R$ — the lightest squark in the MSSM. Similar considerations apply to bottom squarks and tau sleptons, with mass matrices given by:

$$\begin{aligned} \mathbf{m}_{\tilde{b}}^2 &= \begin{pmatrix} m_{Q_3}^2 + \Delta_{\tilde{d}_L} & v (A_b^* \cos \beta - \mu y_b \sin \beta) \\ v (A_b \cos \beta - \mu^* y_b \sin \beta) & m_{\tilde{d}_3}^2 + \Delta_{\tilde{d}_R} \end{pmatrix}, \\ \mathbf{m}_{\tilde{\tau}}^2 &= \begin{pmatrix} m_{L_3}^2 + \Delta_{\tilde{e}_L} & v (A_{\tau}^* \cos \beta - \mu y_{\tau} \sin \beta) \\ v (A_{\tau} \cos \beta - \mu^* y_{\tau} \sin \beta) & m_{\tilde{e}_3}^2 + \Delta_{\tilde{e}_R} \end{pmatrix}. \end{aligned} \quad (1.44)$$

The extent of left-right mixing for sbottoms and staus is highly sensitive to the value of $\tan \beta$. For moderate values ($\tan \beta \lesssim 10$), the mixing effect remains small due to the relatively weak bottom and tau Yukawa couplings, leading to near mass degeneracy between $\tilde{b}_R$, $\tilde{\tau}_L$, $\tilde{\tau}_R$, $\tilde{\nu}_{\tau}$, and their first- and second-generation counterparts. In contrast, for large $\tan \beta$, the enhanced mixing causes the third-generation mass eigenstates $\tilde{b}_1$ and $\tilde{\tau}_1$ to become significantly lighter than their first- and second-generation counterparts, while $\tilde{\nu}_{\tau}$ remains nearly mass degenerate with $\tilde{\nu}_e$ and $\tilde{\nu}_{\mu}$.

On the other hand, the first- and second-generation sfermions have negligible Yukawa couplings and therefore exhibit minimal mixing. Their mass eigenstates are essentially degenerate doublets: $(\tilde{u}_L, \tilde{c}_L)$, $(\tilde{d}_L, \tilde{s}_L)$, $(\tilde{u}_R, \tilde{c}_R)$, $(\tilde{d}_R, \tilde{s}_R)$, $(\tilde{e}_L, \tilde{\mu}_L)$, $(\tilde{e}_R, \tilde{\mu}_R)$, and $(\tilde{\nu}_e, \tilde{\nu}_{\mu})$. Assuming universal sfermion masses at the GUT scale with a common mass parameter m_0 , the first- and second-generation sfermion masses at low energies can be written as

$$\begin{aligned} m_{Q_1}^2 &= m_{Q_2}^2 = m_0^2 + K_3 + K_2 + \frac{1}{36}K_1 + \Delta_Q, \\ m_{\tilde{u}_1}^2 &= m_{\tilde{u}_2}^2 = m_0^2 + K_3 + \frac{4}{9}K_1 + \Delta_u, \\ m_{\tilde{d}_1}^2 &= m_{\tilde{d}_2}^2 = m_0^2 + K_3 + \frac{1}{9}K_1 + \Delta_{\tilde{d}}, \\ m_{L_1}^2 &= m_{L_2}^2 = m_0^2 + K_2 + \frac{1}{4}K_1 + \Delta_L, \\ m_{\tilde{e}_1}^2 &= m_{\tilde{e}_2}^2 = m_0^2 + K_1 + \Delta_{\tilde{e}}, \end{aligned} \quad (1.45)$$

where the K_i ($i = 1, 2, 3$) terms represent the effects of renormalization group running proportional to the gaugino masses. The K_i parameters can be numerically determined

once the energy scale is specified. The Δ_ϕ terms denote electroweak symmetry breaking corrections, responsible for hyperfine splittings that differentiate the components of the slepton and squark $SU(2)_L$ doublets.

From theory to simplified models

As discussed in Section 1.3, SUSY-breaking within the MSSM introduces a large number of free parameters, which is one of its main drawbacks. In particular, the masses of all MSSM particles are free parameters, significantly affecting the predicted signatures in particle detectors and the corresponding cross sections. To manage this complexity, many searches for SUSY particles at the LHC employ **simplified models** [99]. These models are often constructed by applying reasonable approximations, such as assumptions about the structure of trilinear coupling matrices and sfermion mass matrices. One commonly used reduction is the *phenomenological* MSSM (pMSSM), which captures the essential features of the MSSM while limiting the number of free parameters as summarised in Table 1.3. A further simplification involves assuming 100% branching ratios in the decay chains of SUSY particles, and all particles not involved in the process under consideration as effectively decoupled. This reduces the parameter space to quantities directly accessible at collider experiments, such as particle masses and production cross sections. Simplified models serve several important purposes: they help define the sensitivity limits of searches, guide the study of new physics signatures, and provide a framework to interpret results within broader theoretical contexts. When interpreting search results, understanding the boundaries of detector sensitivity, such as reconstruction efficiencies, allows experimentalists and theorists to identify blind spots and unexplored signatures. This also provides a reference point for models with similar decay topologies. In the event of a potential signal of new physics, simplified models are valuable for characterizing properties such as particle masses of such new signal, which can help the development of more complete theories. Moreover, results from simplified model searches can be reinterpreted in the context of more general models by comparing upper limits on observable signal events with theoretical predictions. The ATLAS Collaboration has a comprehensive program of SUSY searches based on simplified models, as will be discussed in Section 1.4.

1.3. THE MINIMAL SUPERSYMMETRIC STANDARD MODEL

Parameter	Description
μ	Higgs/higgsino mass
$\tan \beta$	Ratio of the Higgs vacuum expectation values
m_{A^0}	Mass of the CP-odd neutral Higgs boson
M_1	Bino mass parameter
M_2	Wino mass parameter
M_3	Gluino mass parameter
$m_{Q_{1,2}}$	First- and second-generation left-handed squark mass
m_{Q_3}	Third-generation left-handed squark mass
$m_{u_{1,2}}$	First- and second-generation right-handed up-type squark mass
m_{u_3}	Third-generation right-handed up-type squark mass
$m_{d_{1,2}}$	First- and second-generation right-handed down-type squark mass
m_{d_3}	Third-generation right-handed down-type squark mass
$m_{L_{1,2}}$	First- and second-generation left-handed slepton mass
m_{L_3}	Third-generation left-handed slepton mass
$m_{e_{1,2}}$	First- and second-generation right-handed slepton mass
m_{e_3}	Third-generation right-handed slepton mass
A_t	Top quark trilinear coupling
A_b	Bottom quark trilinear coupling
A_τ	τ lepton trilinear coupling

Table 1.3 – Phenomenological Minimal Supersymmetric Standard Model free parameters.

1.4 Constraints on Supersymmetry from LHC experiments

Supersymmetry has been the focus of extensive search efforts by the ATLAS experiment at the Large Hadron Collider, across a wide range of scenarios [100]. These include the strong production of squark and gluinos - with a particular emphasis on third generation squarks - as well as electroweak production of higgsinos and sleptons, searches involving R -parity violating models, and long-lived particles (LLPs). All these searches interpret their results using simplified models, as described in Section 1.3. A summary of ATLAS's combined sensitivity across various supersymmetric scenarios is shown in Figure 1.9 [101]. The CMS Collaboration has also conducted similar analyses, obtaining comparable results [102].

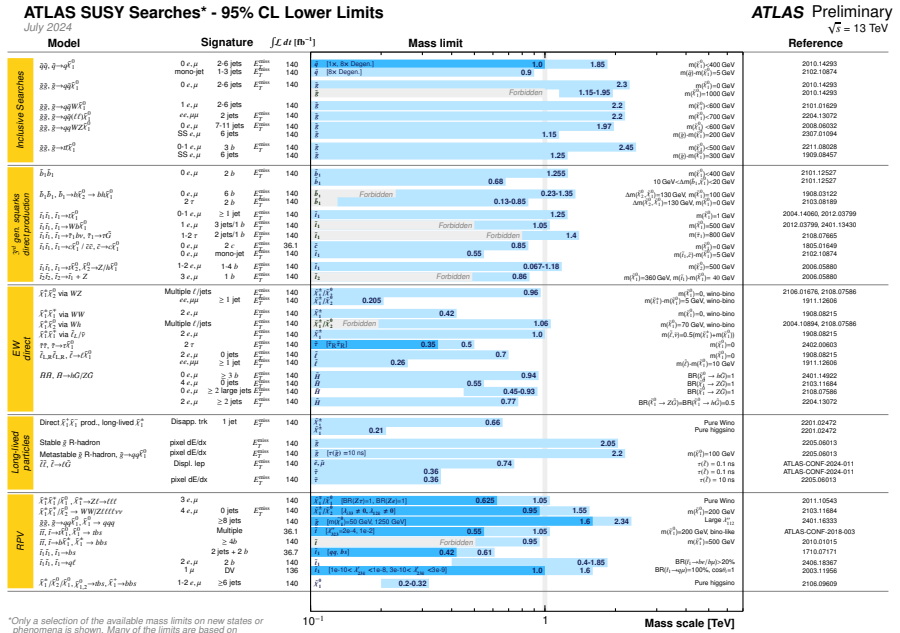


Figure 1.9 – Mass reach of the ATLAS searches for SUSY, with a representative selection of the available search results. From Ref. [101].

1.4.1 Constraints on higgsinos in compressed mass spectra

Focusing on higgsinos in compressed mass spectra, the subject of this thesis, the search faces unique challenges. Due to the soft visible decay products of the SUSY states, the primary signature suitable for triggering is the missing transverse energy (E_T^{miss}) originating from the undetected neutralinos. To achieve sufficiently large E_T^{miss} above the trigger threshold, searches exploit an initial-state radiation (ISR) topology, where the SUSY system recoils against hadronic or leptonic activity. This results in a distinctive “ E_T^{miss} + objects” signature, which provides sensitivity to higgsino production regardless of the decay mode. This strategy was first implemented by the four experiments operating

at the Large Electron-Positron Collider (LEP): ALEPH, DELPHI, L3, and OPAL [35]. In regions with sufficiently large mass splittings ($\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) > 3$ GeV), the resulting E_T^{miss} combined with jet or lepton topologies enabled the four experiments to set exclusion limits on the higgsino mass up to about 100 GeV. In the small mass difference region ($\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) < 3$ GeV), ISR photons were used to boost the SUSY system and suppress the SM backgrounds, extending the exclusion reach to approximately 90 GeV in the higgsino mass. More recently, both ATLAS and CMS have adopted the “ $E_T^{\text{miss}} + \text{jet}$ ” (monojet) topology in their searches [103, 104]. However, such searches suffer from relatively low signal-to-background ratios due to the small SUSY production cross sections and significant irreducible backgrounds. As a result, the sensitivity to direct higgsino production remains limited. To overcome this challenge, additional search strategies have been developed. These include requiring specific decay signatures in addition to the monojet topology — most notably, soft leptons and disappearing tracks — which provide enhanced discrimination power and improve sensitivity in the compressed higgsino mass spectrum. A summary of the results from these analyses is presented in Figure 1.10.

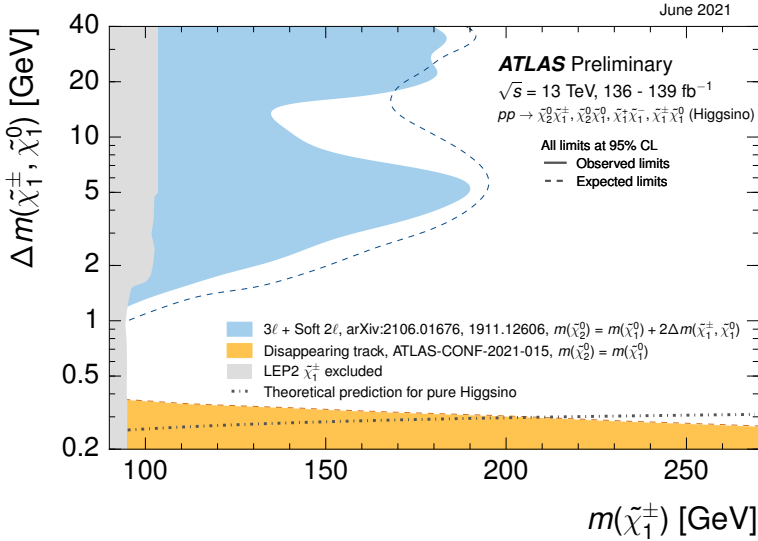


Figure 1.10 – Experimental constraints compressed higgsino states, set by the ATLAS experiment (as of June 2021). The dashed grey line represents the evolution of the mass splitting as a function of the chargino mass due to radiative corrections in the case of a pure higgsino. The soft lepton analysis (blue) excludes mass differences larger than 1.5 GeV, while the disappearing track analysis (orange) probes the region with mass splittings below 400 MeV. A sensitivity gap remains between these two analyses, which has only been explored up to about 90 GeV in the chargino mass by the LEP experiments. From Ref. [105].

Limits from the soft leptons searches

For higgsino mass differences $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \gtrsim 1.5$ GeV, the final-state leptons produced in higgsino decays acquire sufficiently large transverse momentum (p_T) to be reconstructed

with reasonable efficiency in the ATLAS detector. In the ATLAS soft 2-leptons search [32], a pair of soft leptons — originating from the decay of the second-lightest neutralino via an off-shell Z boson — is required, in addition to the monojet signature. The selection accepts leptons with p_T as low as 3 GeV for muons and 4.5 GeV for electrons, and requires a small dilepton invariant mass. The ATLAS soft 3-leptons search [33] further targets scenarios where the lightest chargino decays leptonically via an off-shell W boson, resulting in a final state with three soft leptons. The statistical combination of these two analyses, shown in Figure 1.10, extends the sensitivity to higgsino masses up to 180 GeV and probes mass differences between the lightest chargino and the lightest neutralino down to 1.5 GeV. The CMS Collaboration has performed a similar analysis, achieving comparable results [34].

Limits from the disappearing track search

When the mass splitting between higgsino states is of only a few hundred MeV, the lightest chargino becomes long-lived enough to traverse the innermost layers of the tracking detector before decaying into a charged pion with very low transverse momentum, typically $p_T \sim \mathcal{O}(100)$ MeV. Due to the intrinsic p_T threshold of the track reconstruction algorithms, such low- p_T pions are not reconstructed. As a result, this decay leads to a characteristic signature known as a “disappearing track”: the chargino leaves a visible track in the tracking system, which suddenly vanishes when the chargino decays, leaving no corresponding hits in the outer layers. This disappearing track provides an additional handle on top of the traditional “ $E_T^{\text{miss}} + \text{jet}$ ” signature. The latest results from this analysis, reported in Ref. [30], are illustrated in Figure 1.10. The analysis is sensitive to higgsino mass splittings up to approximately 400 MeV and can probe pure higgsino states with masses around 200 GeV. Again, the CMS Collaboration has performed a similar study, reaching comparable conclusions [31].

The “higgsino gap”

It is worth noting that both the soft leptons and disappearing track searches exhibit a sharp drop in sensitivity within the $0.3 \lesssim \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 1.25$ GeV region, the so-called “higgsino gap”, where the most stringent constraints still stem from legacy LEP experiments. The primary goal of this thesis is to probe this previously unexplored phase space at the LHC by introducing a novel analysis strategy that targets mildly-displaced pion tracks arising from the higgsino decays.

The Large Hadron Collider



The **Large Hadron Collider** (LHC) [106] is the world's largest and highest-energy circular collider. Located approximately 100 meters underground at CERN near Geneva, it consists of a 27 kilometer ring designed to accelerate and collide protons or heavy ions. The LHC was designed to reach a center-of-mass energy $\sqrt{s} = 14$ TeV for pp collisions, with a peak instantaneous luminosity of $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This thesis is based on data collected from pp collisions delivered by the LHC during the second and (part of the) third operational periods, Run 2 and Run 3, when the collider operated at center-of-mass energies between $\sqrt{s} = 13$ TeV and $\sqrt{s} = 13.6$ TeV. Over a span of seven years (2015-2018 and 2022-2024), these runs delivered a cumulative integrated luminosity of $\mathcal{L}_{\text{int}} = 349 \text{ fb}^{-1}$, of which 328 fb^{-1} were recorded by ATLAS.

2.1 Proton-proton interactions at hadron colliders

The LHC was conceived as a hadron accelerator and collider to overcome a fundamental limitation associated with circular electron-positron collider accelerators: significant energy loss due to the emission of synchrotron radiation. The radiative energy loss for a charged particles following a curved trajectory is given by [107]

$$\frac{dE}{dt} \propto \frac{E^4}{m^4 R^2}, \quad (2.1)$$

where E , m , and R denote the particle's energy, mass, and the radius of the circular trajectory, respectively. Owing to the m^{-4} dependence, energy losses for electrons are significantly higher than for protons ($m_p^4/m_e^4 \sim 10^{12}$). This makes it extremely challenging to achieve high center-of-mass energies in circular electron-positron colliders, thus motivating the choice of protons and heavy ions for the LHC.

It is necessary to note that hadron colliders like the LHC face a set of challenges too. Since protons are composite particles — bound states of quarks and gluons (collectively known as partons) — two distinct types of interactions can occur during collisions.

- **Soft collisions** are low momentum-transfer, long-distance interactions between two protons within the colliding beams. These produce final-state particles with low transverse momentum, typically scattering at small angles.
- **Hard collisions** represent, instead, high momentum-transfer interactions between individual partons within protons. Though rarer, these events can yield particles in the final state with large transverse momentum and/or mass.

From a physics standpoint, hard collisions are the most valuable as they probe high-energy parton-level interactions. However, the composite structure of protons introduce additional complexities. First, it is necessary to take into account the inability to directly measure the cross section of the underlying partonic interaction, happening at an unknown center-of-mass energy, with the hadronic cross section only being experimentally accessible. While it is true partonic cross sections can be calculated using perturbative QCD, ideally to arbitrary precision, computing the hadronic cross section requires incorporating parton distribution functions (PDFs) in the calculations, and in turn this introduces additional uncertainties into the theoretical predictions. Moreover, partons not involved in the primary hard-scattering interaction undergo hadronisation or secondary interactions, generating a dense environment populated by a substantial irreducible QCD background, the *underlying event*, which adds another layer of complexity to the event reconstruction and analysis. Lastly, hard and soft collisions occur simultaneously within the same bunch crossing, resulting in additional background noise: the pileup.

2.2 The accelerator complex

The entire CERN accelerator complex is illustrated in Figure 2.1. Proton-proton or heavy-ion collisions occur at four interaction points along the LHC ring, where the four main experiments are located: ATLAS, CMS, LHCb, and ALICE. ATLAS (A Toroidal LHC Apparatus) [108] and CMS (Compact Muon Solenoid) [109] are general-purpose detectors designed to observe a wide range of signals, whether they originate from Standard Model processes or from potential new physics beyond it. In contrast, LHCb [110] and ALICE (A Large Ion Collider Experiments) [111] are specialised experiments. LHCb is dedicated to studying bottom quark physics and performing precision measurements of CP-violating processes, while ALICE focuses on heavy-ion collisions and aims to characterise the properties of quark-gluon plasma.

The two proton beams circulating in the LHC ring travel in opposite directions within adjacent beam pipes. They are kept on a circular trajectory by 1,232 niobium-titanium superconducting dipole magnets (Figure 2.2a), which generate magnetic fields of up to 8.4 T while operating at a temperature of 1.9 K. Because dipole magnets inherently disperse beams travelling through them, focusing in the horizontal and vertical planes is achieved using 392 superconducting quadrupole magnets, whose cross section is shown in Figure 2.2b. Additional higher-order magnets — sextupoles, octupoles, and decapoles — are used to correct for non-uniformities in the magnetic field geometry and to maintain the beam stability. As the proton beams approach the interaction points, they are squeezed to increase the likelihood of collisions between particles in the two opposing bunches.

2.2. THE ACCELERATOR COMPLEX

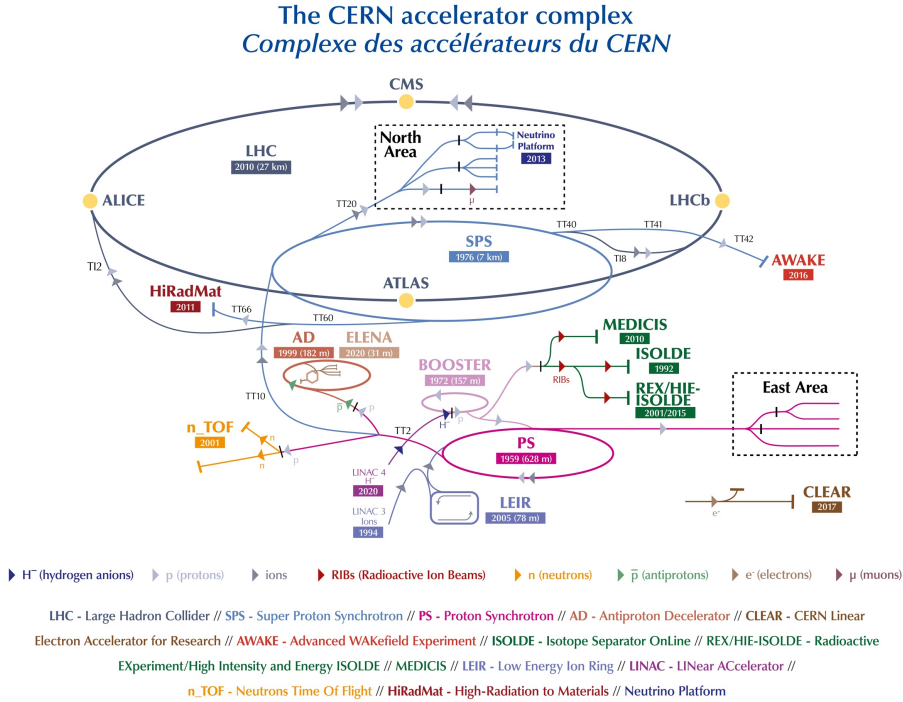


Figure 2.1 – The CERN accelerator complex [112]. Protons are extracted from a hydrogen gas bottle and accelerated through a series of smaller accelerators before being injected into the LHC.

This beam squeezing is accomplished using eight sets of quadrupole magnet triplets, the inner triplets, which are positioned in pairs around the ring near each of the four main experiments. Each proton beam is accelerated by eight superconducting radio-frequency cavities, which provide a combined maximum accelerating voltage of 16 MV for each proton beam and oscillate at a frequency of 400 MHz. Depending on their exact energy, protons receive slightly different accelerating kicks. A proton that reaches the nominal energy of $\sqrt{s}/2$ will not be accelerated further when passing through the cavities. In contrast, protons with lower or higher energy arriving later or earlier than the ideal time are accelerated or decelerated, bringing their energy closer to the nominal value. This mechanism helps to sort the proton beams into well separated bunches.

Protons injected into the LHC start with an energy of 450 GeV, having been pre-accelerated by a series of smaller accelerators. The process begins with a hydrogen gas bottle, from which protons are extracted using an electric field that strips away the electrons from the hydrogen atoms. These protons are first accelerated to 50 MeV by the linear accelerator LINAC 4. They are then passed through the Proton Synchrotron Booster (PSB) and the Proton Synchrotron (PS), where their energy is increased to 1.4 GeV and 25 GeV, respectively. The final stage before injection into the LHC is the Super Proton Synchrotron (SPS), which boosts the proton energy to 450 GeV. During the Run 2, protons

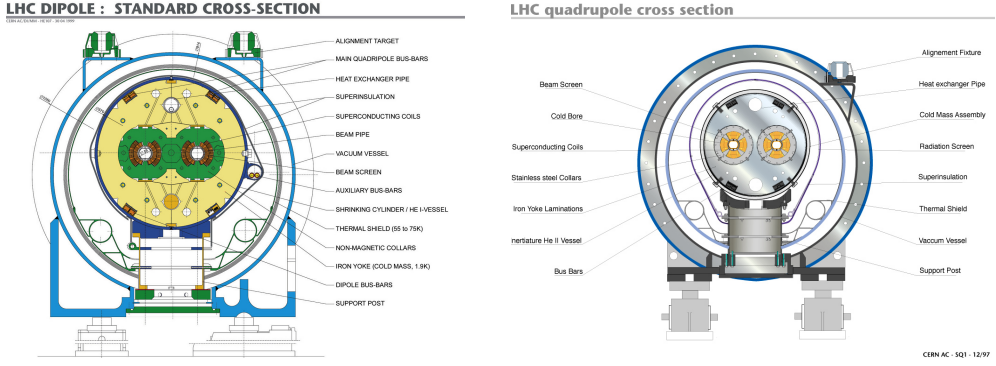


Figure 2.2 – Schematic diagram of an LHC dipole magnet [113] (left) and quadrupole magnet [114] (right). Proton beams travel in the two adjacent beampipes visible at the center of the magnet’s cross sections.

circulating in the LHC reached a maximum energy of 6.5 TeV, resulting in a center-of-mass energy of $\sqrt{s} = 13$ TeV for pp collisions. In Run 3, this energy was increased to 6.8 TeV per beam, corresponding to a center-of-mass energy of $\sqrt{s} = 13.6$ TeV.

2.3 Luminosity and pileup

In a particle collider, the rate at which a specific physics process occurs is related to its cross section σ by

$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma, \quad (2.2)$$

where $\mathcal{L}$ is the *instantaneous luminosity*, measured in $\text{cm}^{-2} \text{s}^{-1}$. The instantaneous luminosity can be expressed in terms of beam parameters as

$$\mathcal{L} = \frac{n_b N_b^2 \nu_{\text{rev}} \gamma}{4\pi \epsilon_n \beta^*} F, \quad (2.3)$$

where

- N_b is the number of particles per bunch,
- n_b the number of bunches per beam,
- ν_{rev} is the revolution frequency,
- γ is the relativistic Lorentz factor,
- ϵ_n is the normalized transverse beam emittance, representing the spread of the particle’s positions and momenta in the two planes orthogonal to the beam trajectory,
- β^* is the beta function at the collision point, relating beam emittance to the transverse beam size,

2.3. LUMINOSITY AND PILEUP

- F is the geometric luminosity reduction factor, which accounts for the reduction in effective luminosity due to the crossing angle between the colliding bunches.

During 2017 and 2018, and again in Run 3, the LHC consistently operated at more than twice its nominal instantaneous luminosity, reaching a peak of $\mathcal{L} = 2.4 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in 2025, as visible in Figure 2.3.

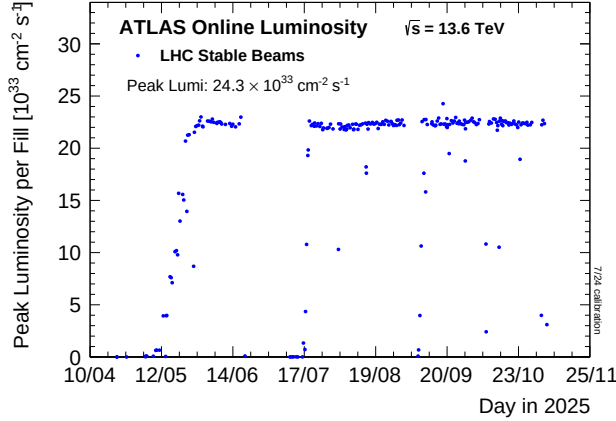


Figure 2.3 – Peak instantaneous luminosity delivered to ATLAS during stable beams for pp collisions at 13.6 TeV center-of-mass energy for each LHC fill as a function of time in 2025 [115].

The *integrated luminosity* $\mathcal{L}_{\text{int}}$ is obtained by integrating the instantaneous luminosity of Equation 2.3, over the accelerator’s operational time:

$$\mathcal{L}_{\text{int}} = \int \mathcal{L}(t) dt . \quad (2.4)$$

It is usually expressed in inverse femtobarns (fb^{-1}) and is used to relate the total number of observed events of a given physics process to its cross section:

$$N_{\text{evt}} = \mathcal{L}_{\text{int}} \cdot \sigma . \quad (2.5)$$

Figure 2.4 shows the integrated luminosity delivered by the LHC and recorded by ATLAS over time during Run 2 and the first three data-taking years of Run 3. Because individual detector components can occasionally experience issues, such as electronic noise spikes or high-voltage trips, data quality must be closely monitored to ensure suitability for physics analyses. Each detector subsystem is continuously monitored, and any data-taking periods affected by such issues are flagged for exclusion from subsequent analyses. As a result, the total integrated luminosity certified as good-quality data is slightly less than the full amount recorded by ATLAS during the Run 2. The certified luminosity that meets all data-quality requirements corresponds to $140.1 \pm 1.2 \text{ fb}^{-1}$ [116]. For the first three years of the Run 3, the corresponding value is $160.9 \pm 3.1 \text{ fb}^{-1}$ [117].

The LHC delivers such high instantaneous luminosity that multiple pp interactions typically occur simultaneously at each bunch crossing near the interaction points. This

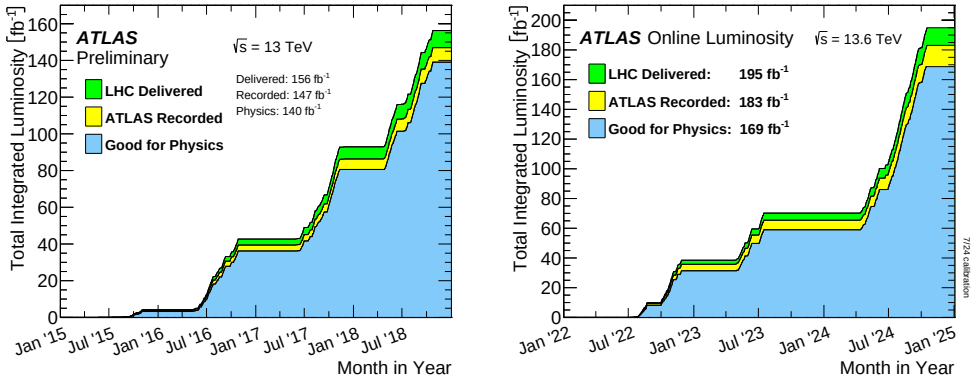


Figure 2.4 – Cumulative luminosity versus time delivered to (green), recorded by ATLAS (yellow), and classified as good for physics (blue) during stable beams for pp collisions in Run 2 [118] (left) and the first three data-taking years of the Run 3 [115] (right).

condition is quantified by the average number of inelastic interactions per bunch crossing, denoted by μ , and commonly referred to as *pileup*. Pileup events, which predominantly arise from soft collisions, overlap with the hard interactions of interest and are generally treated as background in physics analyses. Pileup adversely affects the reconstruction of the event of interest by degrading the energy resolution of physics objects such as jets, leptons, photons, and missing transverse momentum. It also complicates the reconstruction of tracks and vertices by creating dense environments within the detector's tracking system. Pileup is directly proportional to the instantaneous luminosity and can be expressed as

$$\mu = \frac{\mathcal{L}}{\sigma_{pp}} \cdot \frac{1}{n_b \nu_{\text{rev}}} , \quad (2.6)$$

where σ_{pp} is the inelastic pp cross section, while n_b and ν_{rev} are the same terms described above. As shown in Figure 2.5, the average number of interactions per bunch crossing was approximately 33.7 during Run 2 and increased to about 54 during the first three years of Run 3. This trend closely follows the rise in instantaneous luminosity delivered by the LHC year over year. It is therefore crucial to strike a balance between achieving higher luminosities, which increase data statistics, and managing pileup levels, which can degrade the quality of the recorded data. Additionally, it is crucial to consider the limitations of the current trigger and data acquisition systems, which were not designed to operate under conditions more challenging than those presently experienced by the LHC experiments. For this reason, the LHC is expected to continue operating with a maximum $\mu \approx 65$ until all the major experiments complete their upgrades in preparation for the High-Luminosity LHC (HL-LHC) era.

2.3. LUMINOSITY AND PILEUP

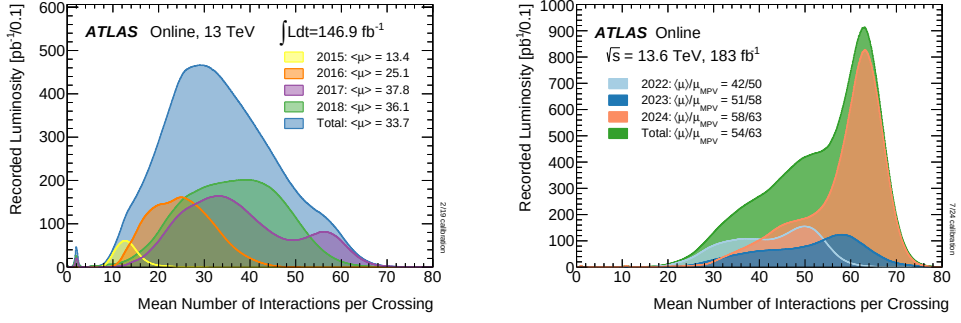


Figure 2.5 – Luminosity-weighted distribution of the mean number of interactions per bunch crossing (μ) in pp collisions recorded by ATLAS in the four data-taking years of Run 2 [118] (left) and in the first three data-taking years of Run 3 [115] (right).

The ATLAS detector



So you train by shadow boxing, search for the truth / But it's all but it's all used up / You break open your million dollar weapon / And push your luck still you push still you push your luck...

— DAVID BOWIE, *Teenage Wildlife*

ATLAS (A Toroidal LHC ApparatuS) [108, 119] is the largest particle detector ever built for a collider and one of the two general-purpose experiments at the LHC. It is designed to explore a wide range of physics phenomena arising from pp collisions, taking full advantage of the unprecedented energy levels achieved at the LHC. The detector has a cylindrical structure with a diameter of 25 meters, a length of 46 meters, and a total weight of approximately 7,000 tonnes. It is located nearly 100 meters underground at Interaction Point 1 of the LHC.

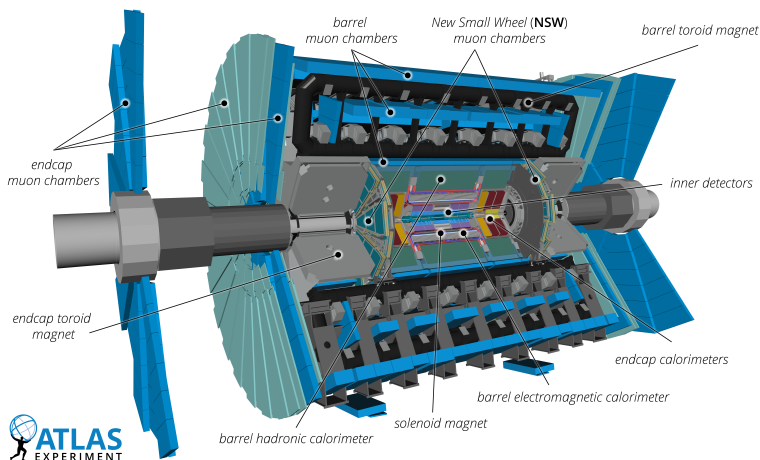


Figure 3.1 – A schematic view of the ATLAS detector configuration in Run 3 [119].

As illustrated in Figure 3.1, the ATLAS detector is composed of three major subsystems: the **Inner Detector**, the **calorimeter system**, and the **Muon Spectrometer**. These sub-detectors are arranged concentrically around the interaction point, and they complement one another. The Inner Detector tracks charged particles with high precision, the calorimeters measure the energy of photons, electrons, and charged and neutral hadrons, and the Muon Spectrometer is responsible for tracking and momentum measurements of highly penetrating muons. Each subsystem is optimised to detect specific types of particles and to measure particular physical properties, while the full reconstruction of collision events relies on the integration of the information provided by all of them. To measure the momentum of charged particles, ATLAS employs two separate **magnet systems**. A solenoid magnet surrounds the Inner Detector, providing a 2 T magnetic field necessary to bend the trajectories of charged particles. For the Muon Spectrometer, an 8-coil toroidal magnet system generates a strong magnetic field tailored to muon tracking and momentum measurements.

ATLAS uses a right-handed Cartesian coordinate system with its origin at the center of the detector, where the pp or heavy-ion collisions occur. In this system, the x -axis points towards the center of the LHC ring, the y -axis points vertically upward, and the z -axis is aligned with the beamline. Several key physical quantities are commonly defined on the (x, y) plane — referred to as the transverse plane — using modified polar coordinates rather than Cartesian ones. In particular, the azimuthal angle ϕ , measured around the beam direction relative to the x -axis, and the *pseudorapidity* η are used. The latter is defined as

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right), \quad (3.1)$$

where θ is the polar angle measured from the z -axis. Positive and negative values of η correspond to the positive and negative directions along the z -axis, with $\eta = 0$ representing the transverse plane at the interaction point, as shown in Figure 3.2. The use of pseudorapidity offers a significant advantage over the polar angle: differences in η are invariant under Lorentz boosts along the z -axis. This property is particularly beneficial in the analysis of pp collision events, where parton-level interactions often produced final states that are highly boosted along the beam direction due to the asymmetric momentum distribution of the colliding partons.

As a natural consequence of the choice of such coordinate system, distances in the (ϕ, η) plane are computed as

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}, \quad (3.2)$$

a quantity which is itself invariant under longitudinal boosts. ΔR also provides a useful measure of angular separation between objects in the detector.

3.1 The Inner Detector

The ATLAS Inner Detector (ID) [120, 121] is the innermost subsystem of the ATLAS detector. It consists of a central barrel section and two end-caps, providing tracking

3.1. THE INNER DETECTOR

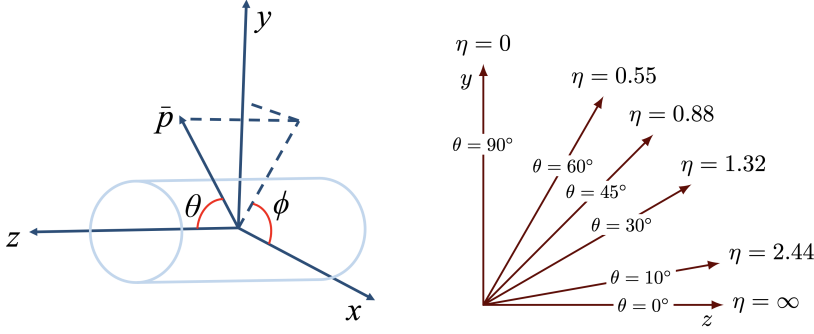


Figure 3.2 – Polar coordinates system used by the ATLAS detector (left), and relation between the pseudorapidity η and the standard polar angle θ (right).

coverage up to $|\eta| < 2.5$. Its primary functions are to deliver high-precision tracking and accurate momentum measurements for charged particles, as well as to reconstruct both primary and secondary vertices with high spatial resolution. To meet these objectives, the ID is designed with minimal material budget to reduce multiple scattering and energy loss effects, while maintaining strong radiation resistance to withstand the high radiation environment near the interaction point. The combined performance of the high-granularity pixel and silicon strip detectors, located closer to the beamline where track density is the highest, and the Transition Radiation Tracker at larger radii ensures that these requirements are fulfilled. The complete layout of the ID, with its three main components — the **Pixel detector**, the **Semi-Conductor Tracker (SCT)**, and the **Transition Radiation Tracker (TRT)** — is illustrated in Figure 3.3.

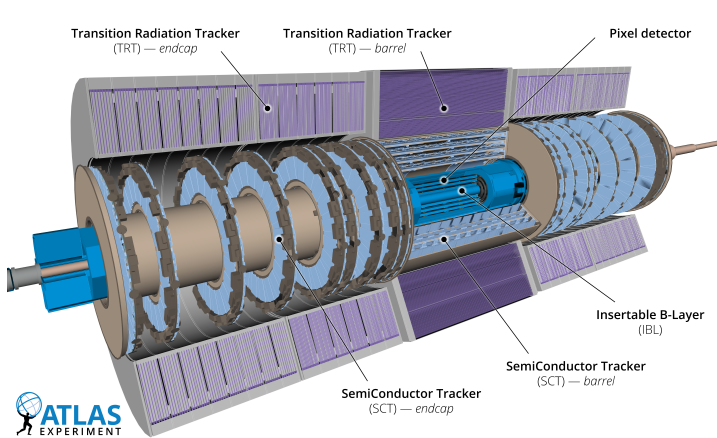


Figure 3.3 – Cut-away view of the ATLAS Inner Detector configuration in Run 3 [119]. The ID is designed to provide a high-precision reconstruction of charged-particle trajectories in the pseudorapidity range $|\eta| < 2.5$ and has full coverage in ϕ .

3.1.1 Pixel Detector

The Pixel Detector [122, 123] is the first subsystem of the ID encountered by particles produced in pp or heavy-ion collisions. In the barrel region, it comprises 1,744 silicon pixel modules arranged in four concentric layers at radii of 3.3 cm, 5.1 cm, 8.9 cm, and 12.3 cm from the beampipe. The first and innermost of these layers, the Insertable B-Layer (IBL) [124, 125], was installed between Run 1 and the Run 2 of the LHC to enhance the tracking performance by reducing the distance between the interaction point and the detector, and to cope with the higher instantaneous luminosity delivered in Run 2. The addition of the IBL significantly improved the resolution of both the longitudinal and transverse impact parameters of tracks by up to a factor two from Run 1 to Run 2 [126]. In each of the two end-cap regions, the Pixel Detector contains 288 modules arranged in three disks. Pixel modules are segmented both in the $R - \phi$ plane and along the z -axis, with a minimum pixel size of $50 \times 250 \mu\text{m}^2$ in the IBL and $50 \times 400 \mu\text{m}^2$ in the outer layers. Overall, the detector achieves an intrinsic spatial resolution of $8 \mu\text{m}$ within the IBL in the $R - \phi$ plane, slightly degrading to $10 \mu\text{m}$ in the outer barrel and end-cap regions. Typically, the Pixel Detector provides between three and four precise measurement points (hits) used for track reconstruction.

3.1.2 Semiconductor Tracker

Following the Pixel Detector, the Semiconductor Tracker (SCT) [127] provides four to nine additional hit measurements per track at radii between 30 cm and 51 cm over the fiducial coverage of the Inner Detector. The SCT tiles four coaxial cylindrical layers in the barrel region and two end-caps each containing nine disk layers, covering a maximum pseudorapidity range of $|\eta| < 2.5$. In total, the SCT contains 4,088 modules for a total active surface of 63 m^2 . The barrel modules are rectangular with a strip pitch of $80 \mu\text{m}$, whereas the end-cap modules are trapezoidal with strip pitches ranging from $56.9 \mu\text{m}$ to $94.2 \mu\text{m}$. The silicon microstrips provide single-hit spatial resolutions of $17 \mu\text{m}$ in the $R - \phi$ plane and $580 \mu\text{m}$ along the z -axis.

3.1.3 Transition Radiation Tracker

The Transition Radiation Tracker (TRT) [128, 129] is the outermost component of the Inner Detector and provides a large number of hits per track, albeit with a lower spatial resolution of $130 \mu\text{m}$ in the $R - \phi$ plane. The TRT serves both as a drift chamber and as a transition radiation detector, allowing it to contribute to tracking and particle identification. In the barrel region, it consists of 52,544 kapton and carbon-fiber drift tubes, each 144 cm long and aligned parallel to the beampipe, while the end-cap regions contain an additional 250,000 shorter straws, each 39 cm long, arranged radially. This configuration covers a pseudorapidity range of $|\eta| < 2$. Originally, each TRT straw was filled with a Xenon-based gas mixture, optimised for particle identification through transition radiation detection. However, by the end of Run 1, several leaks had developed in the exhaust pipes, often located in inaccessible areas where repairs were not possible. As the

number of leaks was expected to increase with higher luminosity, it was decided to continue operating leaking modules with a less expensive Argon-based gas mixture, while maintaining the original Xenon-based mixture in the rest. This hybrid approach allowed the TRT to preserve its overall tracking performance [130]. Regardless of the exact gas mixture used, each TRT straw is operated at a fixed high voltage. When a charged particle passes through a straw and ionises the gas, the resulting ions and electrons drift toward the outer wall and central anode wire, respectively, producing a detectable signal. The hit position is then inferred by converting the electron drift time to the anode into a radial distance from the wire. In addition to tracking, the TRT aids in particle identification by detecting transition radiation, produced when a particle crosses boundaries between materials with different dielectric constants — polymer fibers in the barrel and foils in the end-caps. The emitted radiation is proportional to the particle’s relativistic Lorentz factor, $\gamma = E/m$, allowing effective discrimination between particles of similar energies but different masses, such as electrons and pions, over a momentum range of approximately 1 to 200 GeV. It should be noted however that the switch to an Argon-based mixture in some modules at the end of Run 1 led to a reduction in transition radiation performance [130].

3.2 The calorimeter system

The ATLAS calorimeters are designed to measure the energy of all charged and neutral particles produced in pp or heavy-ion interactions, with the exception of highly penetrating muons and weakly-interacting neutrinos. Surrounding the Inner Detector, the ATLAS calorimeter system consists of three distinct sub-detectors, as illustrated in Figure 3.4, each optimised for specific purposes and employing different technologies. The **Electromagnetic Calorimeter** (EMCalo) is optimized for measuring the energy of electrons and photons. The **Hadronic Calorimeter** (HCal) is dedicated to detecting and measuring hadrons. Finally, the **Forward Calorimeter** (FCal) is designed to measure both electromagnetic and hadronic showers in the forward regions of the detector.

Energy measurement in calorimeters is inherently destructive. When a particle interacts with the detector material via electromagnetic or strong forces, it initiates a cascade of secondary particles, known as *shower*, each carrying progressively lower energy. These secondary particles are fully absorbed, and the energy they deposit is converted into a measurable quantity, such as scintillation light, which is then used to determine the energy of the particle that initiated the shower. Specifically, ATLAS calorimeters are sampling calorimeters, constructed by alternating layers of absorber material, typically high-density materials such as lead or copper, and active layers that collect the deposited energy and produce a measurable signal.

3.2.1 Electromagnetic Calorimeter

The Electromagnetic Calorimeter (EMCalo) [131–133] is the first calorimeter traversed by particles emerging from the ID. It is arranged in a cylindrical geometry, with an outer radius of 2.25 m and an overall length of 6.8 m. The EMCalo is divided into a central

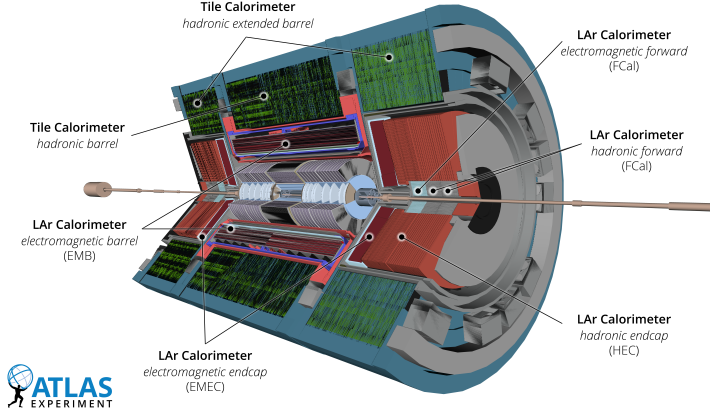


Figure 3.4 – Schematic layout of the ATLAS calorimeter system configuration in Run 3 [119]. The calorimeters measure the energies and positions of charged and neutral particles out to $|\eta| < 4.9$.

barrel section, covering the region with $|\eta| < 1.475$, and two end-cap sections, which extend the coverage up to $|\eta| < 3.2$. The transition region between the barrel and the end-caps, defined as $1.37 < |\eta| < 1.52$, is commonly referred to as the *crack* region. The EMCalo is a sampling calorimeter that employs 4-mm thick layers of Liquid Argon (LAr) as the active medium. Ionization charges, produced by the electromagnetic shower of secondary particles initiated by the primary incident electrons or photons, are collected by copper electrodes immersed in the LAr. Lead plates serve as absorber material, with thicknesses varying from 1.1 mm to 1.5 mm in the barrel, and from 1.7 mm to 2.2 mm in the end-caps. To ensure full azimuthal ϕ coverage and eliminate gaps caused by the readout system, the copper electrodes and lead absorbers are arranged in an accordion geometry, as illustrated in Figure 3.5. This design achieves an effective radiation length X_0^1 of approximately $22 X_0$ in the barrel and $24 X_0$ in the end-caps. Located in front of the EMCalo is the *presampler*, an additional instrumented LAr layer. It covers the region $|\eta| < 1.52$ in the barrel and $1.5 < |\eta| < 1.8$ in the end-caps. The presampler corrects for energy lost by particles before they enter the main calorimeter volume. The nominal energy resolution of the EMCalo [131] is

$$\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E [\text{GeV}]}} \oplus 0.7\% , \quad (3.3)$$

consistent with the typical performance of sampling electromagnetic calorimeters.

¹ The radiation length is defined as the average distance x that an electron needs to travel in a material to reduce its energy to $1/e$ of its original energy E_0 , and governs the rate at which electrons lose energy by *bremsstrahlung* radiation [134]:

$$\langle E(x) \rangle = E_0 e^{-x/X_0} .$$

3.2. THE CALORIMETER SYSTEM

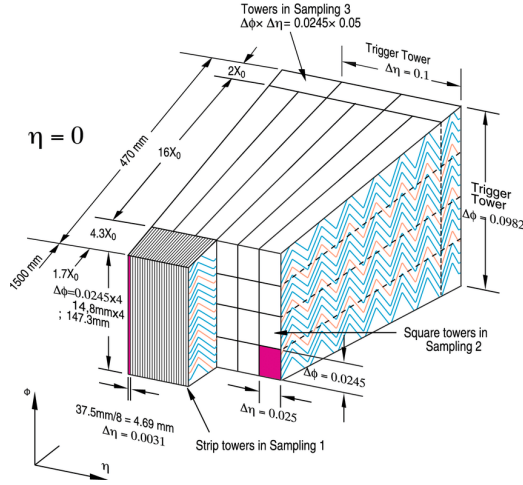


Figure 3.5 – Visualisation of an EMCalo barrel slice at $\eta = 0$ with its peculiar accordion-like shape.

3.2.2 Hadronic Calorimeter

The Hadronic Calorimeter (HCal) is an 11.5 m-long cylinder with an outer radius of 4.25 m, covering a pseudorapidity range of $|\eta| < 4.9$. Positioned directly after the EMCalo, the HCal is designed to fully contain and measure hadronic showers. In the central barrel region, spanning $|\eta| < 1.7$, the Tile Calorimeter [135, 136] is employed. This is a sampling calorimeter that uses scintillating tiles as the active medium and steel as the absorber, playing a crucial role in measuring the energy of hadrons produced in the central region. For higher pseudorapidity regions, the Hadronic End-Cap Calorimeter (HEC) [137, 138] extends the coverage up to $1.5 < |\eta| < 3.2$. The HEC is also a sampling calorimeter, but it uses copper or tungsten plates as absorbers, with LAr interleaves as the active medium. The HEC consists of two separate disks, located behind the EMCalo end-caps and enclosed in the same cryostat. The EMCalo and the HCal combined performance results in a global energy resolution of

$$\frac{\sigma(E)}{E} \approx \frac{50\%}{\sqrt{E [\text{GeV}]}} \oplus 3\% \quad (3.4)$$

for jet energy measurements [131].

3.2.3 Forward Calorimeter

The Forward Calorimeter (FCal) [139] is designed to measure the energy of both electromagnetic and hadronic showers in the forward regions of the detector, extending the overall pseudorapidity coverage of the ATLAS calorimeter system to the range $3.1 < |\eta| < 4.9$. Radiation hardness is a critical design requirements for detectors operating in this region. Therefore, the FCal uses LAr as active medium, combined with copper or tungsten rods

as absorber materials. The FCal achieves energy resolutions for pions as high as

$$\frac{\sigma(E)}{E} \approx \frac{(94.2 \pm 1.6)\%}{\sqrt{E} [\text{GeV}]} \oplus (7.5 \pm 0.4)\% , \quad (3.5)$$

while, for electrons, the resolution can be quantified as

$$\frac{\sigma(E)}{E} \approx \frac{(28.5 \pm 1.0)\%}{\sqrt{E} [\text{GeV}]} \oplus (3.5 \pm 0.1)\% . \quad (3.6)$$

3.3 The Muon Spectrometer

Along with weakly-interacting neutrinos, muons are the only particles capable of traversing the ATLAS calorimeter system without being fully thermalised. Due to their substantially larger mass compared to electrons, muons undergo significantly reduced energy loss through *bremstrahlung*, making them unlikely to initiate electromagnetic showers in the calorimeters. Moreover, muons do not interact via the strong force with the detector material, further reducing the probability of being stopped by the detector material. As a result, muons typically pass through the Inner Detector and the calorimeters with minimal disturbance, losing at most a few GeV of energy. This characteristic allows muon reconstruction down to transverse momenta as low as 3 GeV. To accurately track their trajectories and measure their momenta, the Muon Spectrometer (MS) [140, 141], the outermost component of the ATLAS detector, is employed.

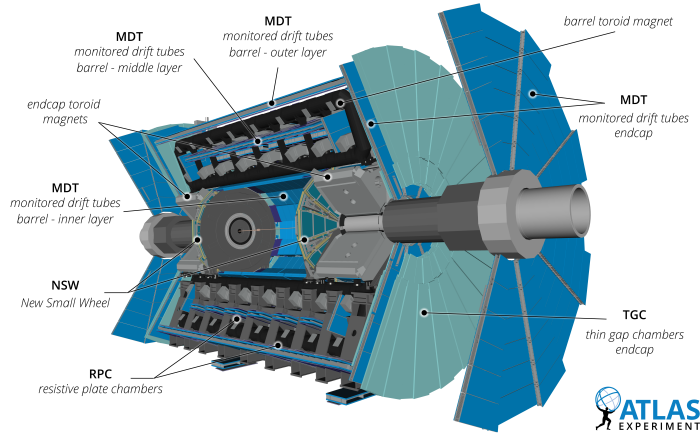


Figure 3.6 – Cut-away view of the ATLAS muon system. It detects charged particles exiting the barrel and end-cap calorimeters and measures their momentum in the pseudorapidity range $|\eta| < 2.7$.

The design of the MS, illustrated in Figure 3.6, is largely determined by the geometry of the toroidal magnet system, which divides the spectrometer into eight azimuthal sectors (octants). Muon trajectories, projected onto the bending plane, are reconstructed primarily using **Monitored Drift Tubes** (MDTs), which cover most of the pseudorapidity range up

to $|\eta| < 2.7$. Each MDT consists of 3 to 8 layers of aluminum drift tubes, filled with a high-pressure gas mixture of Ar/CO₂, and containing a central 50 μm wire, achieving a spatial resolution of 35 μm in the bending plane. During Run 1 and 2, the MDTs in the forward region ($2 < |\eta| < 2.7$) were complemented by **Cathode Strip Chambers** (CSCs), multiwire proportional chambers capable of providing three-dimensional measurements of the muon positions with a resolution of 40 μm in the bending plane and 5 mm in the azimuthal direction. To handle the harsher conditions of the Run 3 and the upcoming HL-LHC era, the CSCs were replaced between Run 2 and Run 3 by the **New Small Wheels** (NSWs) [141]. The NSWs incorporate two advanced detector technologies: **small-strip Thin Gap Chambers** (sTGCs) [142] and **Micromegas** detectors [143]. Compared to the CSCs, these systems offer improved tracking precision in the bending plane and enhanced momentum resolution in the azimuthal direction, while maintaining the Level-1 trigger rate at acceptable levels without requiring pre-scaling or increasing the p_{T} threshold. For trigger purposes and additional tracking capability within the range $|\eta| < 2.4$, the MS includes **Resistive Plate Chambers** (RPCs) in the barrel region and **Thin Gap Chambers** (TGCs) in the end-caps.

3.4 The magnet system

A charged particle moving through a magnetic field follows a curved trajectory, whose curvature radius R depends on the particle's momentum p and the strength of the magnetic field B . For a uniform magnetic field, the transverse component of the momentum p_{T} , is given by

$$p_{\text{T}} [\text{GeV}] \approx 0.3 \cdot |q| \cdot B [\text{T}] \cdot R [\text{m}] , \quad (3.7)$$

where q is the charge of the particle. ATLAS exploits this relationship to measure the momenta of charged particles by reconstructing the curvature of their tracks. This is made possible by immersing both the Inner Detector and the Muon Spectrometer in strong magnetic fields generated by the magnet system. This system comprises a superconducting solenoid magnet [144] and a toroidal one [145, 146]. The **solenoid magnet** surrounds the Inner Detector and provides a magnetic field of 2 T aligned with the beam axis. It operates with a current of 8 kA and is maintained at a cryogenic temperature of 4.5 K, with its cooling being achieved by immersing the solenoid coil in the same cryostat used for the ATLAS calorimeters. The solenoid is 5.8 m long, with an inner radius of 1.23 m and an outer radius of 1.28 m, corresponding to only 0.66 radiation lengths, minimising its impact on the energy resolution of the EMCalo. The **toroid magnet** system, illustrated in Figure 3.6, lies outside the calorimeter volume and is composed of three large superconducting magnets: one barrel toroid and two end-cap toroids. The barrel toroid generates a magnetic field ranging from 0.2 to 2.5 T and consists of eight superconducting coils symmetrically arranged around the beam axis. Each coil operates with a 20.5 kA current and is housed in its standalone cryostat. The barrel toroid spans 25.3 m in length, with an inner diameter of 9.4 m and an outer diameter of 20.1 m. The end-cap toroids extend the magnetic field coverage into the forward regions, ensuring nearly complete tracking performance for muons up to $|\eta| < 2.7$. Each end-cap toroid

consists of eight superconducting coils, 5 m in length, spanning a radial range from 1.65 m to 10.7 m. These toroids provide magnetic field strengths of up to 3.5 T.

3.5 Trigger and data acquisition

The LHC beams collide at the interaction point at the center of the ATLAS detector at a frequency of 40 MHz, corresponding to one bunch crossing every 25 ns. A typical bunch crossing produces, on average, between 30 to 65 simultaneous pp collisions, collectively referred to as an event. The average size of each event is around 1.5 MB [147], which, at a collision rate of 40 MHz, would result in a raw data rate of 60 TB/s. Such an immense data volume far exceeds the storage and processing capabilities of any computing system. Therefore, a rapid online selection process must determine whether each event is of sufficient interest to be recorded for offline analysis. This task is handled by the ATLAS Trigger and Data Acquisition (TDAQ) system, a critical component of the experiment responsible for online event selection and data readout. The trigger system reduces the incoming data rate from 40 MHz to 1 kHz, by exploiting two subsystems: the **Level-1 (L1) Trigger** [148] and the **High-Level Trigger (HLT)** [147].

The L1 trigger uses low granularity information from the calorimeters and muon subsystems to rapidly evaluate event-level quantities (*e.g.*, total energy deposited in the calorimeter, missing transverse momentum), or the number of physics objects passing a predefined p_T threshold, or, finally, selection on topological quantities including invariant masses and angular distances. This evaluation is performed by custom hardware directly integrated into the detector, enabling real-time processing. The L1 trigger reduces the event rate from 40 MHz to 100 kHz, making its decision within a latency of 2.5 μ s. When an L1-accept signal is issued, full-granularity data from the various sub-detectors is sent to ReadOut Drivers (RODs) for initial processing and formatting, and then to ReadOut Systems (ROSeS) for buffering. The L1 trigger also identifies Regions of Interest (RoIs) — localised detector regions with potentially interesting activity — defined in terms of (η, ϕ) coordinates. These RoIs guide the next stage of event processing by the HLT. The HLT uses the full-granularity data associated with the L1-selected RoIs to perform partial event reconstruction using more complex algorithms, also exploiting the information from the ID, allowing for much finer object identification and kinematic reconstruction. Operating in this way, the HLT reduces the event rate from 100 kHz to approximately 1 kHz, issuing the final trigger decision on whether the event should be recorded for offline analysis. Once an event is accepted by the HLT, the complete event data is transmitted from the ROSeS to CERN's Tier-0 data processing center at a rate of 1.2 GB/s. There, events undergo initial reconstruction before being distributed to computing centers worldwide for offline processing and analysis.

Both the L1 and HLT systems operate based on trigger menus [149, 150], which define the types of event that are considered valuable for physics analyses. These menus include criteria for selecting specific event topologies (*e.g.*, high- p_T jets, leptons, missing energy) and assign predefined output rates for each trigger path to ensure a balanced and manageable data stream for downstream analysis.

Objects Reconstruction

4

Each event recorded by the ATLAS detector, or generated through Monte Carlo (MC) simulations, undergoes offline reconstruction, a process in which detector-level information is translated into physics-level “objects” using dedicated reconstruction and identification algorithms. For example, hits recorded in the various layers of the Inner Detector or the Muon Spectrometer — caused by charged particles traversing their active layers — are combined to form tracks. Similarly, energy deposits in the calorimeters, resulting from electromagnetic and hadronic showers, are grouped into calorimetric clusters. These low-level objects serve as building blocks for reconstructing high-level physics objects that reflect the activity observed across the ATLAS sub-detectors. A simplified illustration of how data from different detector components are combined to identify particles emerging from the pp collisions is shown in Figure 4.1. This Chapter describes the reconstruction algorithms and identification techniques employed during the Run 2 and the Run 3, focusing on the physics objects relevant to the search presented in this thesis.

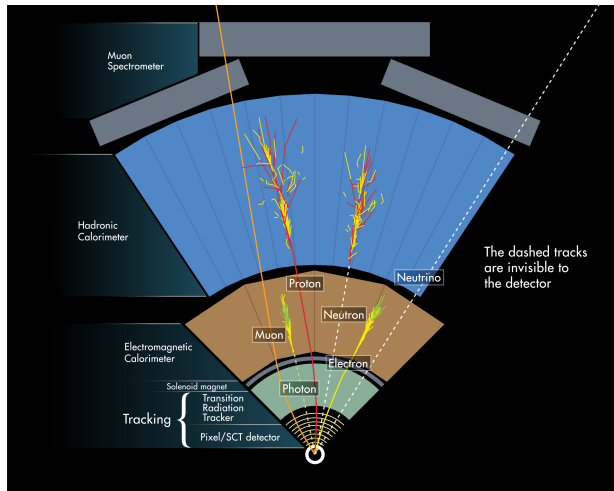


Figure 4.1 – Cross-sectional view of the ATLAS detector, illustrating the various sub-detectors and the corresponding physics objects reconstructed by each of them [151].

4.1 Tracks and Vertices reconstruction

Charged particles traversing the ATLAS Inner Detector lose a small fraction of their energy through ionisation and radiative processes. When the energy deposited in a measurement layer exceeds a predefined threshold, the resulting electrical signal is recorded as a *hit*. The hits serve as the foundation for reconstructing the trajectories of charged particles, the **tracks**, which follow helical paths with radii inversely proportional to their momentum (see Eq. 3.7), and any spatial point where two or more tracks intersect, the **vertices**, which typically correspond to primary interaction points or secondary decay locations. This Section outlines the methods used by the ATLAS detector to reconstruct track and vertices, while Section 4.2 focuses specifically on the calibration of the impact parameter of tracks in Monte Carlo simulation relative to the observed data.

4.1.1 Tracks

Tracks from charged particles with transverse momentum $p_T > 0.5$ GeV, pseudorapidity $|\eta| < 2.5$, and lifetimes sufficient to reach the SCT detector are reconstructed using the primary “inside-out” tracking algorithm [152], designed for high-efficiency reconstruction of primary charged particles with minimal rate of fakes.

Reconstruction

Track reconstruction begins by clustering raw data from the Pixel and SCT detectors: neighboring pixels or strips with recorded hits are grouped together in clusters and assigned spatial positions, called *space-points*. Track seeds are then formed by identifying sets of three or four space-points across different layers that are likely to originate from the same charged particle trajectory. Seeds meeting a set of quality criteria are extended by adding compatible clusters from other ID layers using a Kalman filter [153], creating initial track candidates. A dedicated ambiguity resolution procedure is applied to select the most promising track candidates, resolve overlaps, and eliminate spurious combinations of space-points not originating from a single particle (i.e. fake tracks). All candidates are fit using a global χ^2 minimisation algorithm that compares predicted trajectories to measured positions to provide the best estimate of track parameters. The ambiguity solver ranks track candidates by a quality score constructed from the number of *unique* and *shared* clusters¹, the number of *holes* (missing expected hits between two consecutive measurements), and the track p_T , and processes them in descending score order until all candidates are either accepted or rejected. Surviving track candidates are then refit with the same global χ^2 minimisation algorithm to determine the final track parameters. Once silicon-based track reconstruction is complete, an extension to the TRT is attempted to improve the momentum resolution

¹Clusters appearing on multiple tracks are often the result of incorrect assignment. However, in *dense environments* [154], where particle separations approach sensor dimensions, multiple particles can contribute to a single cluster, which may then be shared among different candidate tracks. Clusters are marked as *shared* in such cases; otherwise, they are considered *unique*.

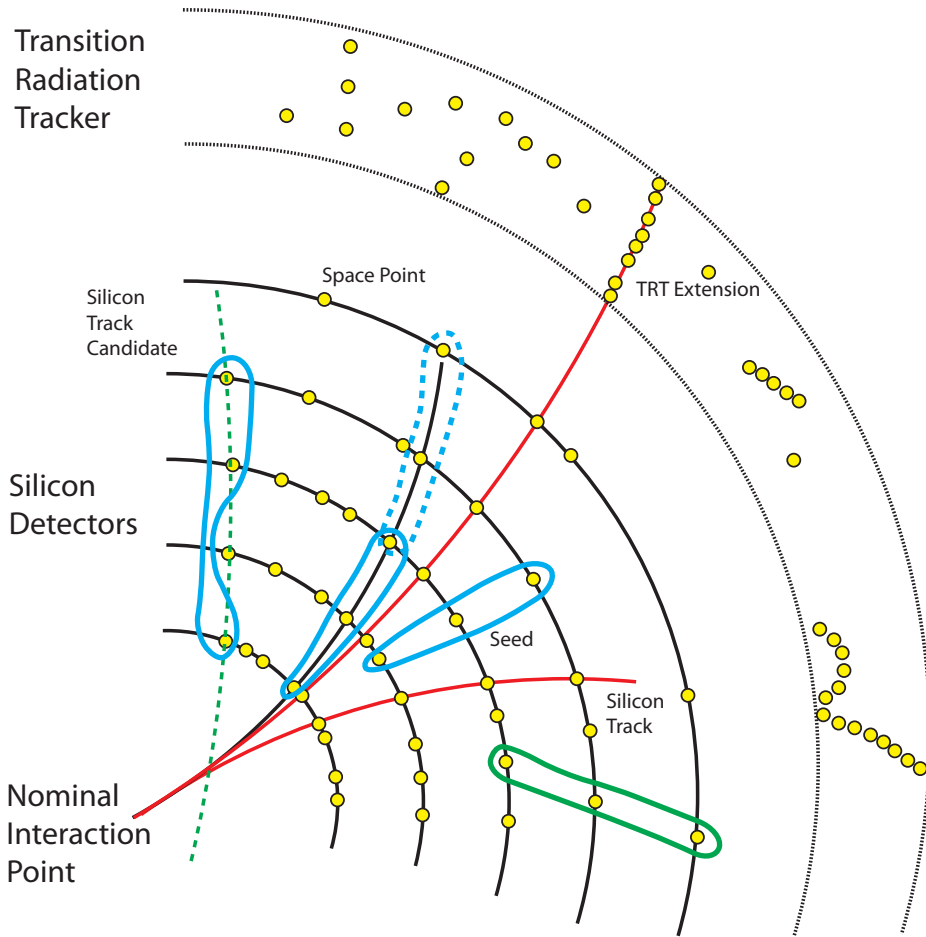


Figure 4.2 – Illustration of the stages of “inside-out” track reconstruction in a simplified representation of the Inner Detector. Space points are shown in yellow. Seeds reconstructed from combinations of space points are indicated in blue. The dashed blue seed highlights a case where two seeds correspond to the trajectory of the same charged particle. The green seed is rejected for being inconsistent with a particle’s trajectory from the nominal interaction point. Track candidates are shown with lines. The green dashed track candidate is rejected because it is inconsistent with the nominal interaction point. Red track candidates are fully reconstructed silicon tracks, potentially extendable into the TRT.

of tracks. The extension is performed by associating at least nine TRT measurements compatible with the extrapolated track trajectory, and tracks are refit and retained only if the fit quality remains acceptable. Figure 4.2 schematically illustrates the different stages of the inside-out tracking algorithm described above. Each resulting track object is described by five parameters in the perigee representation: the transverse impact parameter d_0 , the longitudinal impact parameter z_0 , the azimuthal and polar angles, ϕ and θ , respectively, and charge-to-momentum ratio q/p determined from the curvature of the track in the solenoidal magnetic field.

To further refine the selection of reconstructed tracks, specific track quality working points (WPs) are defined [155], balancing reconstruction efficiency against the rate of mis-reconstructed tracks. Two standard WPs are defined as follows.

- The **Loose** WP closely matches the quality requirements used in the primary reconstruction algorithm and prioritises high efficiency, tolerating a moderate level of fake tracks. It was optimised based on studies of physics performance and computational cost under Run 3 pileup conditions [156].
- The **Tight Primary** WP imposes stricter quality criteria, reducing the rate of fakes at the cost of lower reconstruction efficiency for primary charged particles.

Selection criteria	Loose	Tight Primary
p_T	$> 500 \text{ MeV}$	$> 500 \text{ MeV}$
$ \eta $	< 2.5	< 2.5
N_{Si}	≥ 8	≥ 9 if $ \eta \leq 1.65$, ≥ 11 elsewhere
$N_{\text{mod}}^{\text{shared}}$	≤ 1	≤ 1
$N_{\text{Pix}}^{\text{hole}}$	≤ 1	$= 0$
$N_{\text{Si}}^{\text{hole}}$	≤ 2	≤ 2
$N_{\text{L0}} + N_{\text{L1}}$	-	> 0 (if hits on both layers are expected)

Table 4.1 – Definition of the Loose and Tight Primary working points. N_{Si} is the number of silicon (Pixel + SCT) hits, $N_{\text{mod}}^{\text{shared}}$ is the number of shared silicon modules, $N_{\text{Pix}}^{\text{hole}}$ is the number of pixel holes, $N_{\text{Si}}^{\text{hole}}$ is the number of silicon (Pixel + SCT) holes, and N_{L0} and N_{L1} are the number of innermost and next-to-innermost layer measurements, respectively.

The selection criteria used to define the two working points, based on the number of hits, holes, and shared clusters, are summarised in Table 4.1.

It is worth noting that, in addition to the primary inside-out tracking, ATLAS employs specialised tracking algorithms to target signatures that evade common assumptions. For example, the “Large-Radius Tracking” algorithm [157] reconstructs tracks from decays of long-lived particles that travel macroscopic distances in the detector before decaying.

Performance

The efficiency with which tracks are reconstructed for subsequent analysis is a key factor in determining the overall performance of the ATLAS experiment. Maximising this

4.1. TRACKS AND VERTICES RECONSTRUCTION

efficiency must be balanced against maintaining an acceptable level of misreconstructed tracks, depending on the intended use. The two track quality working points presented above offer various trade-offs for this selection. Track reconstruction efficiency quantifies the fraction of generated charged particles that are successfully reconstructed as tracks. It is defined as the number of reconstructed tracks that are matched to a simulated truth-level particle, $N_{\text{rec}}^{\text{matched}}$, divided by the total number of generated charged particles in simulation, N_{gen} :

$$\epsilon_{\text{trk}}(p_T, \eta) = \frac{N_{\text{rec}}^{\text{matched}}(p_T, \eta)}{N_{\text{gen}}(p_T, \eta)}. \quad (4.1)$$

Here, p_T and η denote the transverse momentum and pseudorapidity of the truth-level particle, respectively. The efficiency can therefore be studied as a function of both p_T and η . Figure 4.3 shows a comparison of the tracking efficiency for the Loose and Tight Primary quality working points. In general, the Tight Primary working point exhibits an

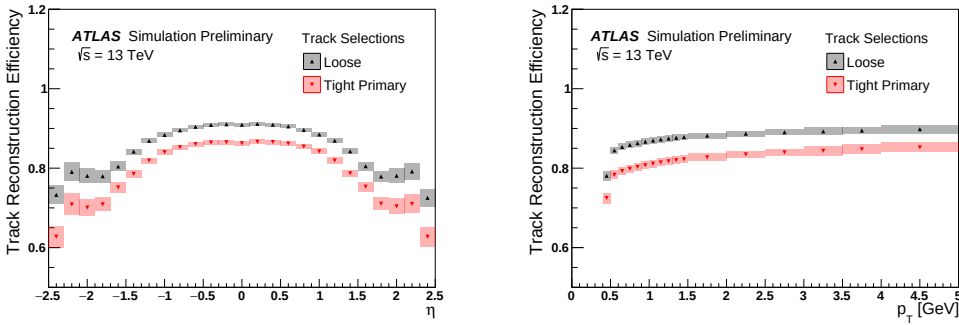


Figure 4.3 – Track reconstruction efficiency as a function of the truth particle η (left) and p_T (right) for a minimum bias MC sample. The error bands represent the total systematic uncertainty on the tracking efficiency computation. From Ref. [155].

efficiency that is 5-10% lower than Loose, with the difference increasing at higher η . In the central region, $|\eta| < 1.5$, where there is less detector material, the efficiency is relatively flat, around 85% for Loose tracks and 80% for the Tight Primary working point. The small rise in efficiency around $|\eta| = 2.0$ is attributed to the detector geometry, which increases the number of active layers traversed by particles in this region. As a function of p_T , both working points follow the same trend, reaching a plateau around 1.5 GeV. The Loose working point consistently achieves about 5% higher efficiency than Tight Primary, with only percent-level variations across the p_T spectrum.

Misreconstructed (fake) tracks primarily result from incorrect combinations of detector measurements originating from multiple particles. Their occurrence is highly dependent on the the local measurement density, which increases with the average pileup $\langle \mu \rangle$. Since the efficiency for reconstructing genuine tracks remains relatively stable as a function of $\langle \mu \rangle$, the contribution from misreconstructed tracks can be estimated by analysing how the average number of reconstructed tracks per event scales with $\langle \mu \rangle$ itself. To this end, a

linear fit is performed to the average number of reconstructed tracks per event at low $\langle\mu\rangle$, where the contribution from misreconstructed tracks is assumed to be negligible. Any observed deviation from linearity at higher $\langle\mu\rangle$ is then attributed to an increasing presence of fake tracks. Figure 4.4 shows the results of such fit for both the Loose and Tight Primary working points, with fractions of fake tracks up to 0.04 and 0.14, respectively.

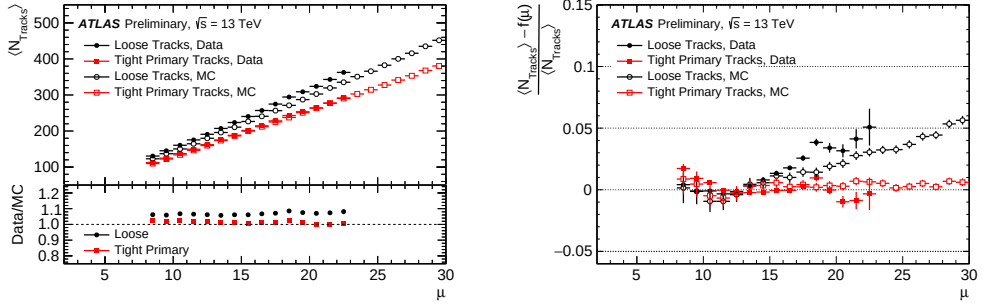


Figure 4.4 – Loose and Tight Primary average number of total reconstructed tracks per event (left) and fake track fraction (right) as a function of $\langle\mu\rangle$ in a 2018 zero-bias data sample. Linear fits are performed in the $10 < \langle\mu\rangle < 20$ region. From Ref. [155].

4.1.2 Vertices

Primary vertices represent the reconstructed position of pp interactions within the ATLAS detector. Accurate and efficient reconstruction of these vertices is essential, as they serve as the reference point for the reconstruction of all other physics objects and for the determination of the event kinematics.

Primary vertex reconstruction is performed using dedicated vertex finding and fitting algorithms that rely on the information from reconstructed tracks [158]. These algorithms are implemented via the open-source, experiment-independent ACTS toolkit [159] and operate following a “finding-through-fitting” approach, where new vertices are seeded from tracks not yet compatible with an existing vertex. Vertex reconstruction begins by forming an initial vertex seed, typically based on the maximum in the distribution of the track z positions. This seed, along with its nearby tracks, is then used as input to the adaptive vertex fitting algorithm [160], which iteratively refines the vertex position. During each iteration, tracks that are poorly compatible with the current vertex estimate are down-weighted, and the vertex position is recomputed. This continues until a stable and satisfactory estimate of the vertex position is achieved. Tracks that are found to be incompatible with the current vertex are used to seed additional vertices, and the procedure is repeated until all tracks are associated with a vertex, each required to have at least two associated tracks. Among the multiple vertices reconstructed in an event, the one with the highest sum of the squared transverse momenta of associated tracks is identified as the primary hard-scatter vertex. This vertex is used as the reference point for object calibration and kinematic reconstruction. The remaining vertices are

typically associated with pileup interactions (additional pp collisions in the same bunch crossing) or, in some cases, may originate from the decays of long-lived particles, forming secondary vertices.

4.2 Track impact parameter

The track reconstruction algorithm provides track objects characterised by five parameters, including the transverse and longitudinal impact parameters (IPs). The **transverse impact parameter** d_0 is defined as the distance in the transverse plane between the point of closest approach of the reconstructed track to the beam line. The beam line is a line parallel to the z -axis and passing through the average position of pp collisions (reference point). The **longitudinal impact parameter** z_0 corresponds to the distance along the z -axis between the point on the track at closest approach to the beamline and the reference point. A schematic illustration of the definitions of d_0 and z_0 is shown in Figure 4.5. The transverse and longitudinal impact parameters of tracks are essential quantities for identifying particles originating from a specific pp interaction point. A prominent example involves particles from decays occurring at macroscopic distances from the pp interaction point: these typically exhibit a non-zero transverse impact parameter, making this quantity a powerful discriminator for identifying processes such as heavy-flavor decays. Similarly, particles produced in pileup interactions tend to have non-zero longitudinal impact parameters, allowing them to be distinguished from those produced in the hard-scattering collision. The resolution of the measured impact parameters plays therefore a critical role in the performance of higher-level reconstruction algorithms. This is especially true for the identification of the flavour of high- p_T jets, where tracks are tightly clustered in *dense environments* and precise impact parameter measurements are essential [154]. Two main effects limit the resolution: multiple scattering and the finite single-point resolution of the detector.

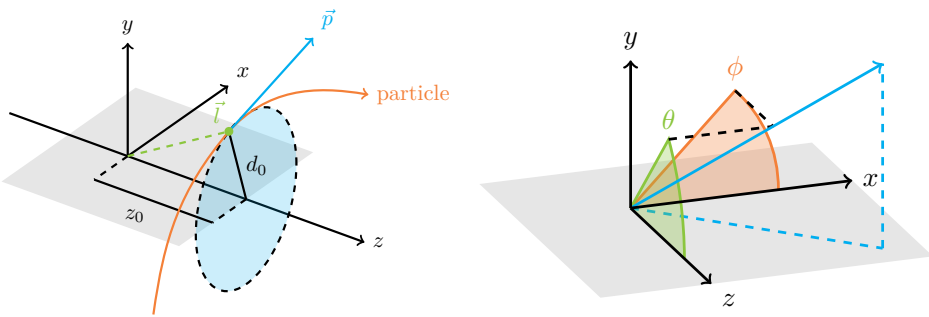


Figure 4.5 – Schematic of the track parameters evaluated at the point of closest approach to the beam axis in the $x - y$ plane, known as the perigee point [161], including (left) the transverse and longitudinal impact parameters and (right) the azimuthal and polar angles. The vector $\vec{p}$ represents the particle's momentum, while the vector from the reference point to the point of closest approach is denoted by $\vec{l}$. From Ref. [159].

- When a charged particle traverses the detector elements of the tracking system, it undergoes Coulomb interactions with the atomic nuclei of the detector material. These interactions cause the particle to deviate from its original path, a phenomenon known as *multiple scattering*. For small deflection angles, the distribution of the angular deviations can be approximated by a Gaussian distribution. However, at larger angles, the behavior transitions to that of Rutherford scattering, which features broader tails than a Gaussian distribution [38]. Considering the scenario illustrated in Figure 4.6, where a particle with momentum p enters the detector material perpendicularly at a radial position r_1 and is deflected by an angle, the contribution of multiple scattering to the impact parameter is given by [38]

$$\sigma_{d_0}^{\text{MS}} = r_1 \tan \omega \approx \frac{r_1}{p} \cdot 13.6 \text{ MeV} \sqrt{\frac{x_1}{X_0}} \left[1 + 0.038 \ln \left(\frac{x_1}{X_0} \right) \right], \quad (4.2)$$

where x_1/X_0 represents the thickness of the material traversed by the particle, expressed in units of radiation length. In a more general case where the particle enters the detector at an angle θ relative to the normal, the expression becomes

$$\sigma_{d_0}^{\text{MS}} \approx \frac{r}{p \sin \theta \sqrt{\sin \theta}} \cdot 13.6 \text{ MeV} \sqrt{\frac{x_1}{X_0}} \left[1 + 0.038 \ln \left(\frac{x}{X_0 \sin \theta} \right) \right], \quad (4.3)$$

where the substitutions $r_1 = r / \sin \theta$ and $x_1 = x / \sin \theta$ have been applied. Noting that $p_T = p \sin \theta$, Eq. 4.3 can be approximated as

$$\sigma_{d_0}^{\text{MS}} \approx \frac{b}{p_T}, \quad (4.4)$$

where b is a constant term. This expression highlights that the effect of multiple scattering on the IP resolution is inversely proportional to the transverse momentum of the particle, and, consequently, it becomes the dominant contributor to the resolution at low track p_T .

4.2. TRACK IMPACT PARAMETER

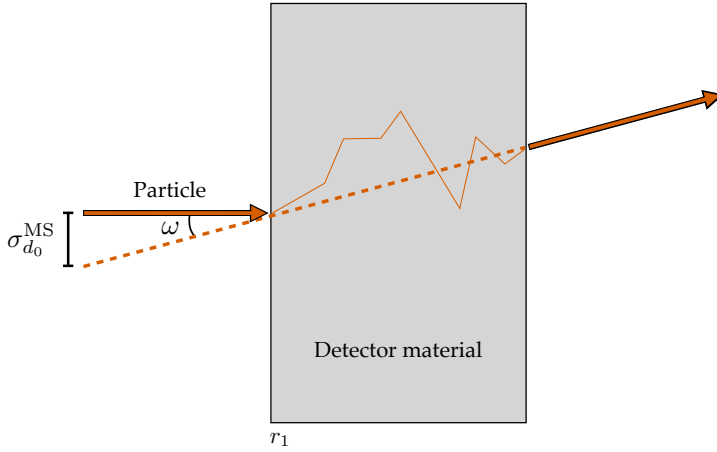


Figure 4.6 – Effect of multiple scattering due to Coulomb interactions between the incident particle and atomic nuclei in the detector material. The particle, striking the detector layer at position r_1 , is deflected from its original trajectory by an angle ω .

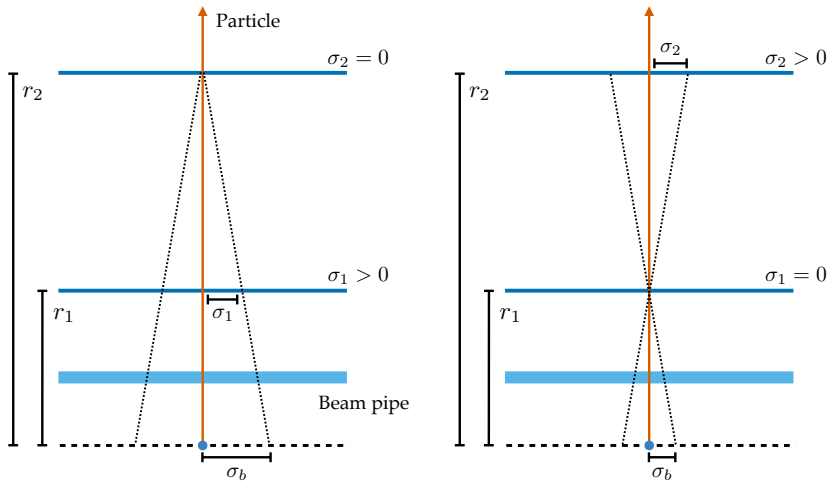


Figure 4.7 – Schematic representation of the two cases contributing to the single-point resolution. On the left, the single-hit resolution at the second layer of the tracking system is zero, whereas, on the right, it is zero in correspondence to the first layer.

- Finite single-point resolution reflects the intrinsic resolution of the detector as well as potential misalignments. A two-layers approximation, using a tracking system composed of only two layers, can be used to illustrate this effect. The two layers are located at positions r_1 and r_2 , respectively, with corresponding single-hit resolutions σ_1 and σ_2 . Two possible scenarios may occur, as shown in Figure 4.7: $\sigma_1 > 0, \sigma_2 = 0$, and $\sigma_1 = 0, \sigma_2 > 0$. In these scenarios, the contribution to the resolution σ_b from the two layers can be calculated as

$$\frac{\sigma_b}{\sigma_1} = \frac{r_2}{r_2 - r_1}, \quad \frac{\sigma_b}{\sigma_2} = \frac{r_1}{r_2 - r_1}, \quad (4.5)$$

and, therefore, the intrinsic resolution term becomes

$$\sigma_{\text{intrinsic}} = \sqrt{\left(\frac{r_1}{r_2 - r_1}\sigma_2\right)^2 + \left(\frac{r_2}{r_2 - r_1}\sigma_1\right)^2} = \sqrt{\frac{r_1^2\sigma_2^2 + r_2^2\sigma_1^2}{(r_2 - r_1)^2}} \approx a, \quad (4.6)$$

where a is a constant that depends on the detector geometry and the space-point measurement's accuracy. Hence, if the radii of the detector layers and their corresponding intrinsic resolutions remain constant, the contribution to the IP resolution also remains constant and becomes the dominant one at high p_T .

Since the single-point measurement error and the multiple scattering effects are independent, the total impact parameter resolution is obtained by summing in quadrature the two contributions:

$$\sigma_{d_0} = \sigma_{\text{intrinsic}} \oplus \sigma_{\text{MS}} \approx \sqrt{a^2 + \frac{b^2}{p_T}}. \quad (4.7)$$

As a result, the resolution of the transverse impact parameter primarily depends on the track momentum. In contrast, the track pseudorapidity affects the resolution of the longitudinal impact parameter, which is also sensitive to variations in the material budget and the increased extrapolation distances from the first measured point to the interaction point at higher $|\eta|$. More complex parameterisations that extend beyond the two-layers approximation are possible; for an in-depth discussion, see Ref. [162].

The impact parameter resolution of the ATLAS detector was first measured in Ref. [155] using data collected in 2015, the first year of the Run 2. In that work, primary vertices served as the reference point for the distance of closest approach, and the intrinsic resolutions of the track impact parameters were extracted from data and simulation by deconvolving the primary vertex uncertainty using an iterative deconvolution procedure [163]. In this thesis, a new approach is adopted where the beamspot is used as the reference point for all calculations, eliminating the need for deconvolution. This simplifies the workflow for deriving the impact parameter resolutions. The resolution is measured using central tracks ($|\eta| < 0.8$), selected with an inclusive working point (encompassing both Loose and Tight Primary tracks) in jets with $p_T > 300$ GeV. The transverse width of the beam spot — approximately $7 - 8 \mu\text{m}$ [164] — is subtracted in quadrature from the measured transverse impact parameter to obtain the intrinsic resolution. Distributions of d_0 and z_0 are analysed in bins of track p_T and track η . The core of the d_0 distribution,

dominated by prompt particles, is fit within a 1.5σ window with a single Gaussian function

$$f(d_0) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[-\frac{(d_0 - \mu)^2}{2\sigma^2} \right], \quad (4.8)$$

where μ and σ represent the bias and the resolution of the transverse impact parameter, respectively. An example of such a fit is shown in Figure 4.8 for tracks with $5 < p_T < 6$ GeV and $0.3 < |\eta| < 0.4$ reconstructed from data collected in 2024. A similar procedure is adopted for the longitudinal impact parameter z_0 . Data collected in 2022, 2023, and 2024 are compared with simulated multi-jet events, as shown in Figure 4.9. At low track p_T (below ~ 10 GeV), the resolution is broader in data than in simulation — especially below 2 GeV — highlighting the impact of multiple scattering and potential mismodelling of the detector material [165]. Above 10 GeV, the resolution plateaus, with a mild degradation occurring above 20 GeV due to an increased fraction of lower-quality tracks. This behaviour is consistent across both transverse and longitudinal components of the IP. Data from 2022, 2023, and 2024 are also compared with simulated multi-jet events to assess the bias in the transverse impact parameter d_0 . The results are shown in Figure 4.10. In 2022 and 2023 data, the bias remains generally within $-2 \mu\text{m}$, whereas in 2024 it increases and shifts toward positive values. This trend suggests that misalignments in the Inner Detector may have occurred between 2023 and 2024, which were not accounted for during the initial processing of the 2024 dataset. A future reprocessing of the data may correct this issue. In contrast, MC simulations remain nearly unbiased and show consistent behavior across all three data-taking years.

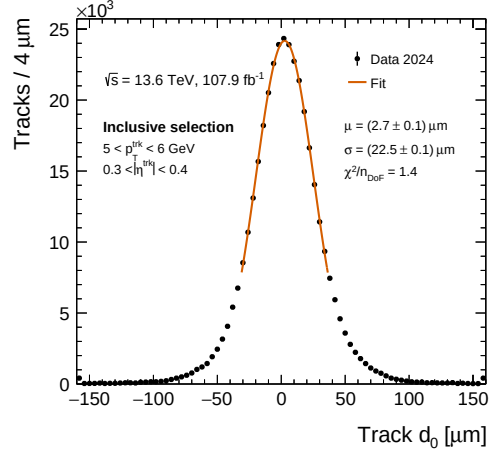


Figure 4.8 – Distribution of the transverse impact parameter for tracks with $5 < p_T < 6$ GeV and $0.3 < |\eta| < 0.4$ reconstructed from 2024 data. A single Gaussian function, fit to the core of the distribution to estimate the impact parameter bias and resolution, is superimposed. The first and last bins of the distribution include the underflow and overflow entries, respectively.

The precision of impact parameter measurements may depend on whether a given track is isolated or surrounded by other nearby tracks, since in densely populated environments, such as the core of jets, overlapping tracks may hinder the ability to resolve them individually. To investigate this effect, the transverse impact parameter resolution σ_{d_0} is studied as a function of the angular separation ΔR between two selected tracks, across various track p_T ranges and for the different data-taking periods of Run 3. The results, shown in Figure 4.11, generally indicate that the IP resolution remains constant at large ΔR and degrades sharply only when $\Delta R < 0.02$ is reached, corresponding to the dense core region of the selected jets the tracks are associated to. In this core region,

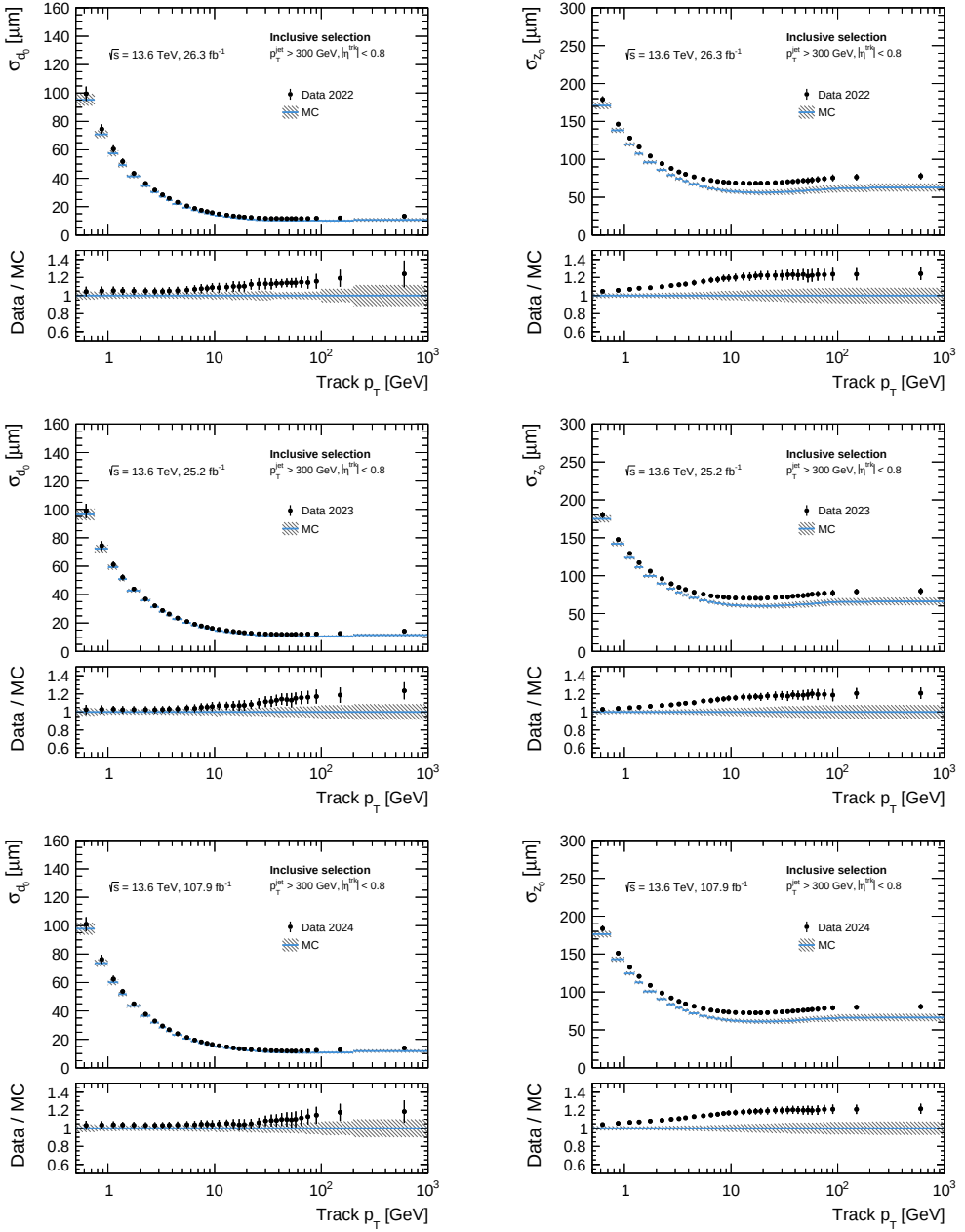


Figure 4.9 – Impact parameter resolution for data and simulation on (left) the transverse plane, σ_{d_0} , and (right) along the longitudinal axis, σ_{z_0} . The distributions compare the data collected during 2022 (top), 2023 (middle), and 2024 (bottom) with multi-jet Monte Carlo simulated events. When visible, the hatched band and the error bars on the data points represent the quadratic sum of the statistical uncertainty derived from the fit procedure and a systematic uncertainty estimated by fitting the same impact parameter distribution with a single Gaussian function within a 2σ window.

4.2. TRACK IMPACT PARAMETER

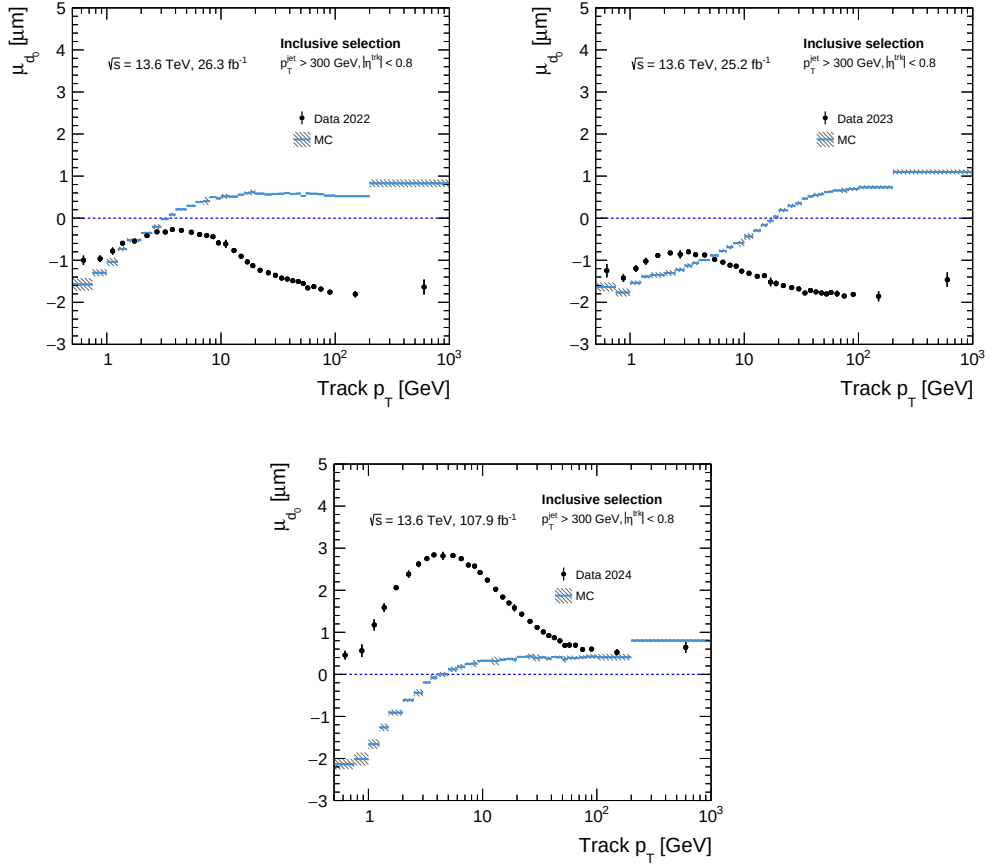


Figure 4.10 – Transverse impact parameter bias μ_{d_0} for data and simulation. The distributions compare data collected during 2022 (top-left), 2023 (top-right), and 2024 (bottom) with multi-jet Monte Carlo simulated events. When visible, the hatched band and the error bars on the data points represent the quadratic sum of the statistical uncertainty derived from the fit procedure and a systematic uncertainty estimated by fitting the same impact parameter distribution with a single Gaussian function within a 2σ window.

the high particle density can lead to merged pixel clusters in the ATLAS Pixel Detector, causing energy deposits to become virtually indistinguishable. This effect, in turn, degrades both track reconstruction performance and the precision of the impact parameter measurements. The transverse impact parameter resolution is also studied as a function of the average number of interactions per bunch crossing, μ . The plots of Figure 4.12 show the results for 2022, 2023, and 2024 data, compared to multi-jet Monte Carlo simulations. Overall, the resolution shows no significant variation across the three data-taking years, with only a slight degradation observed at high pileup conditions, particularly for $\mu \sim 65$.

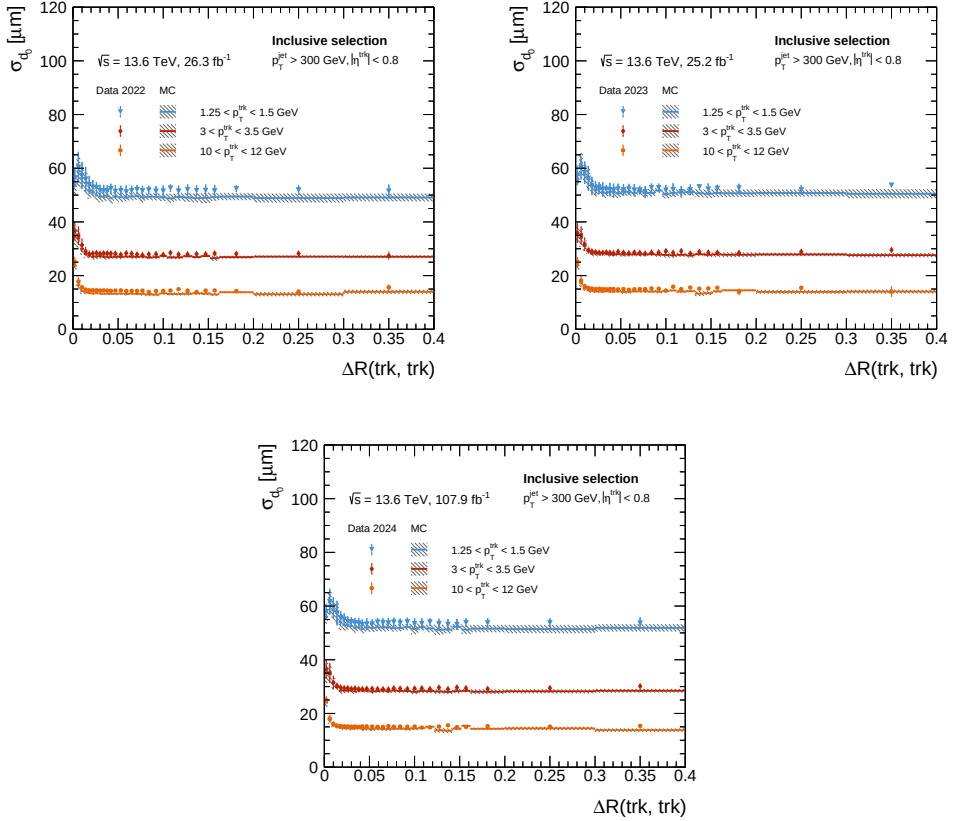


Figure 4.11 – Transverse impact parameter resolution σ_{d_0} as a function of the angular distance ΔR between two tracks across different track p_T ranges. The distributions compare data collected during 2022 (top), 2023 (middle), and 2024 (bottom) with multi-jet Monte Carlo simulated events. When visible, the hatched band and the error bars on the data points represent the quadratic sum of the statistical uncertainty derived from the fit procedure and a systematic uncertainty estimated by fitting the same impact parameter distribution with a single Gaussian function within a 2σ window.

4.2. TRACK IMPACT PARAMETER

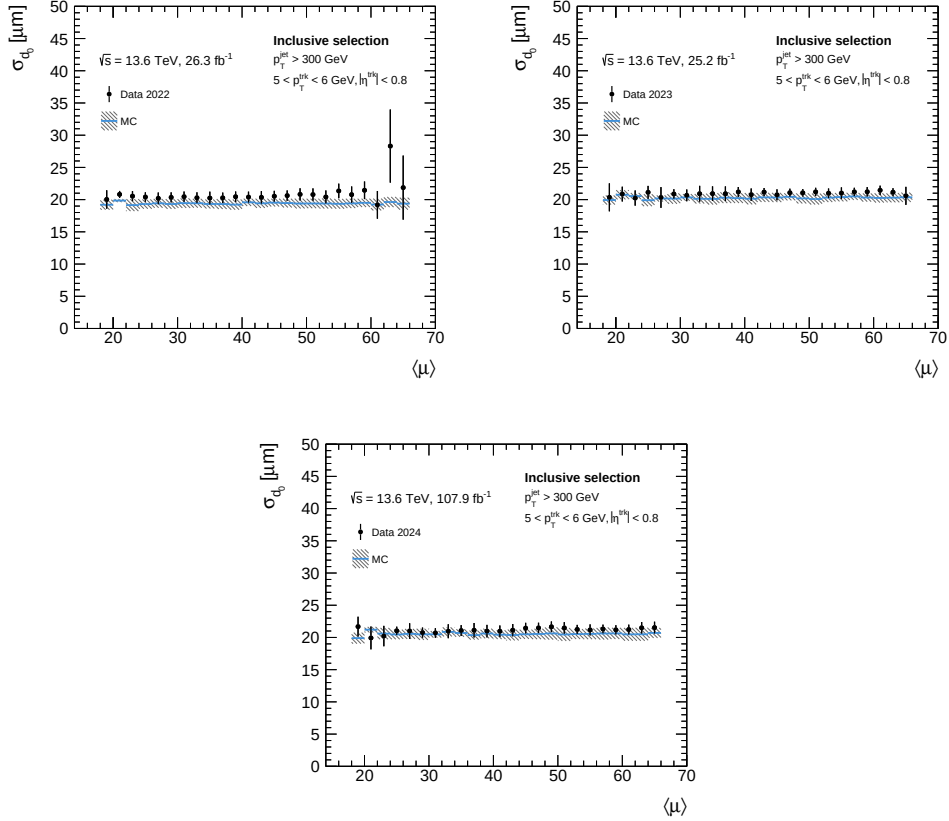


Figure 4.12 – Transverse impact parameter resolution σ_{d_0} as a function of the average number of interactions per bunch crossing μ (right). The distributions compare data collected during 2022 (top), 2023 (middle), and 2024 (bottom) with multi-jet Monte Carlo simulated events. When visible, the hatched band and the error bars on the data points represent the quadratic sum of the statistical uncertainty derived from the fit procedure and a systematic uncertainty estimated by fitting the same impact parameter distribution with a single Gaussian function within a 2σ window.

Monte Carlo simulations can be then corrected to match the IP resolution observed in data for offline analyses. This is done by defining a bin-by-bin correction term, $\sigma_{d_0, z_0}^{\text{corr}}$, calculated as the quadrature difference between the IP resolution measured in data and that obtained from simulations. Figure 4.13 illustrates two examples of these bin-by-bin correction terms for the transverse and longitudinal impact parameters, which are used to adjust the simulated resolution to match the one observed on data collected during 2024. The correction is applied through a smearing procedure: a random value is drawn from a Gaussian distribution with zero mean and a standard deviation equal to $\sigma_{d_0, z_0}^{\text{corr}}$, and is then added to the transverse or longitudinal impact parameter of each simulated track.

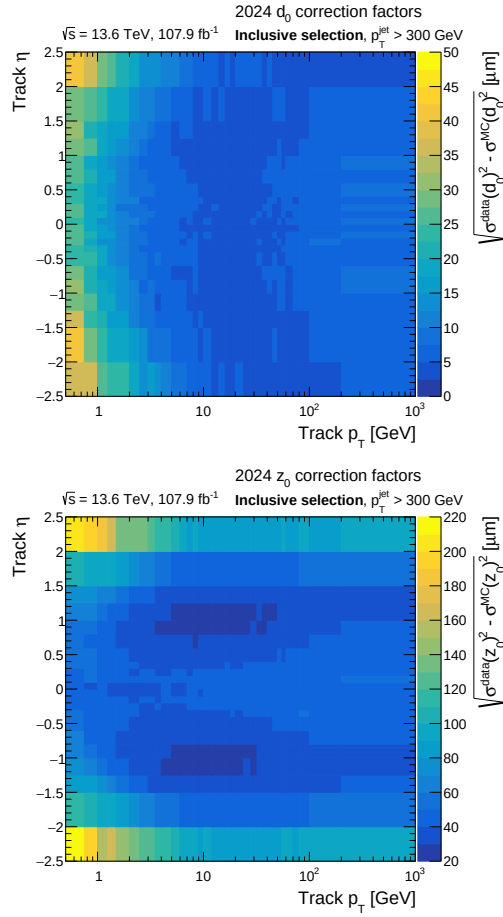


Figure 4.13 – Correction terms for the transverse (top) and longitudinal (bottom) impact parameters, derived in (p_T, η) bins. These correction terms are used to adjust the impact parameter resolution in Monte Carlo simulations to match that observed in 2024 data.

4.3 Jets reconstruction

Quarks and gluons are produced abundantly in pp collisions at the LHC, either as part of the underlying event or directly from the hard-scattering process. However, due to color confinement, these colored partons cannot be observed individually in the final state. Instead, when they carry momenta above 10-20 GeV, their fragmentation and subsequent hadronisation result in the formation of collimated “streams” of hadrons, travelling in the direction of the original parton. These observable objects are known as **jets** [166].

Particle-flow jets

The hadronic spray forming a jet includes both charged and neutral particles. Charged hadrons with $|\eta| < 2.4$ leave tracks in the Inner Detector, while both charged and neutral hadrons deposit energy in the calorimeters by producing hadronic showers. Jet reconstruction in the ATLAS detector follows the *particle-flow* (PFlow) strategy [167, 168]. Unlike traditional approaches that rely solely on calorimetric energy deposits [169] the PFlow method adopts a “holistic reconstruction”, by combining information from both the ID and the calorimeters to reconstruct all stable particles in the event. These particle-flow objects, ideally originating from the hadronisation of a single parton, are then clustered to form jets. The primary advantage of the PFlow approach lies in its ability to exploit the complementary strengths of the ID and the calorimeters while mitigating their respective limitations.

- For low-energy charged particles, the ID provides significantly better momentum resolution than the calorimeters. Conversely, the calorimeters offer superior energy resolution at higher energies, broader pseudorapidity coverage compared to the tracker, and the ability to detect neutral particles.
- The ID also provides excellent angular resolution for charged tracks, enables identification of low- p_T charged particles that may be deflected out of the jet cone by the magnetic field before reaching the calorimeter, and allows association of tracks with the primary vertex — a critical feature for pileup mitigation during jet reconstruction.

On the other hand, the PFlow strategy introduces a significant challenge. For any particle with a reconstructed track, its corresponding calorimeter signal must be correctly identified and subtracted to prevent double-counting of its energy during jet reconstruction. This necessitates a binary decision: whether to use the calorimetric or tracking information for a given particle. The central difficulty of the PFlow algorithm is to perform this subtraction with high precision, ensuring complete removal of the relevant energy contribution from a given particle without affecting energy deposits from other nearby particles.

Jet reconstruction begins with the identification of energy clusters from calorimeter cells that are topologically connected, the *topoclusters*. The key variable governing the

formation of these clusters is the significance of each calorimeter cell, defined as

$$\zeta_{\text{cell}}^{\text{EM}} = \left| \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise}}^{\text{EM}}} \right|, \quad (4.9)$$

where $E_{\text{cell}}^{\text{EM}}$ is the energy deposited in a given cell, and $\sigma_{\text{noise}}^{\text{EM}}$ is the expected noise, accounting for contributions from both the read-out electronics and an estimate of the pileup conditions, calibrated to the average instantaneous luminosity. The clustering algorithm scans the calorimeter map, selects seed cells, and grows clusters around them following the so-called “4-2-0” scheme.

1. Seed cells are identified as those with $\zeta_{\text{cell}}^{\text{EM}} > 4$, excluding cells in the Presampler and the first layer of the EMCalo.
2. Neighbouring cells with $\zeta_{\text{cell}}^{\text{EM}} > 2$ are added around seed cells to form topoclusters. If a cell is shared between two clusters, they are merged into one.
3. A surrounding crown of nearest-neighbour cells with $\zeta_{\text{cell}}^{\text{EM}} > 0$ is then added to complete the topocluster.
4. Topoclusters containing multiple local energy maxima — defined as cells with $E_{\text{cell}}^{\text{EM}} > 500$ MeV and at least four neighbours, none of which having higher energy — are split into separate clusters.

After topoclusters are formed, tracks reconstructed in the ID are matched to clusters in the EMCalo. For a reconstructed track with charge q to be considered matched to a topocluster, the following criteria must be satisfied: $|\eta_{\text{cluster}} - \eta_{\text{track}}| < 0.05$ and $-0.20 < q \cdot (\phi^{\text{track}} - \phi^{\text{cluster}}) < 0.05$, if the track momentum is used for extrapolation from the last ID hit, or $-0.10 < q \cdot (\phi^{\text{track}} - \phi^{\text{cluster}}) < 0.05$, if the cluster energy is used for extrapolation from the track perigee. Additionally, the ratio of cluster energy to the track momentum is required to satisfy $E^{\text{cluster}}/p^{\text{track}} > 0.1$. All matched tracks are ranked based on the angular distance $\Delta R'$ between the barycenter of the topocluster and the extrapolated track position to the second layer of the electromagnetic calorimeter. $\Delta R'$ is defined as

$$\Delta R' = \sqrt{\left(\frac{\Delta\eta}{\sigma_\eta}\right)^2 + \left(\frac{\Delta\phi}{\sigma_\phi}\right)^2}, \quad (4.10)$$

where σ_η and σ_ϕ represent the angular widths of the topocluster in η and ϕ , respectively, computed as the standard deviation of the calorimeter cell positions with respect to the topocluster barycenter. If multiple tracks are matched to the same topocluster, the one with the smallest $\Delta R'$ is selected as the best match. Once a track with momentum p^{track} is matched to a topocluster, the expected energy deposited in the calorimeters, $\langle E_{\text{dep}} \rangle$, from the particle associated with the track is estimated as

$$\langle E_{\text{dep}} \rangle = p^{\text{track}} \cdot \langle E_{\text{ref}}^{\text{cluster}}/p_{\text{ref}}^{\text{track}} \rangle, \quad (4.11)$$

where $\langle E_{\text{ref}}^{\text{cluster}}/p_{\text{ref}}^{\text{track}} \rangle$ is the average energy-to-momentum ratio, derived from simulated single-pion samples without pileup, for topoclusters within a cone of radius $\Delta R = 0.4$

around the track. The spread of the expected energy deposit, $\sigma(E_{\text{dep}})$, is also determined from the standard deviation of the $E_{\text{ref}}^{\text{cluster}}/p_{\text{ref}}^{\text{track}}$ distribution. The estimated energy $\langle E_{\text{dep}} \rangle$ is then compared with the measured energy of the matched topocluster, E^{cluster} . If the difference $\langle E_{\text{dep}} \rangle - E^{\text{cluster}}$ is positive and exceeds the spread $\sigma(E_{\text{dep}})$, it is assumed that the particle has deposited energy in multiple topoclusters. In this case, additional nearby topoclusters within a cone of radius $\Delta R = 0.2$ are considered for association with the track. Once the full set of topoclusters matched to the track has been identified, the expected deposited energy is subtracted to avoid double-counting the particle's energy in both the tracker and the calorimeters. This subtraction is applied only if

$$\frac{E^{\text{cluster}} - \langle E_{\text{dep}} \rangle}{\sigma(E_{\text{dep}})} < 33.2 \cdot \log_{10} \left(\frac{40 \text{ GeV}}{p_{\text{T}}^{\text{track}}} \right). \quad (4.12)$$

This condition ensures energy subtraction is applied for tracks with $p_{\text{T}} < 40 \text{ GeV}$, except in cases with unusually large calorimeter activity, such as in dense environments, where subtraction becomes less reliable. After energy subtraction, particle-flow objects are formed and subsequently used in jet reconstruction. ATLAS employs the *anti- k_t* algorithm [170] for jet clustering. This algorithm is favored to alternative methods for its stability against soft radiation, and the tendency to produce geometrically regular, conical jets. The *anti- k_t* algorithm defines two distance metrics: one, d_i , between particle i and the beam, the other, d_{ij} , between two PFlow objects i and j . d_i and d_{ij} are given by

$$d_i = \frac{1}{p_{\text{T}i}^2}, \quad d_{ij} = \min \left(\frac{1}{p_{\text{T}i}^2}, \frac{1}{p_{\text{T}j}^2} \right) \frac{\Delta_{ij}^2}{R^2}, \quad (4.13)$$

where $\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$ is the squared angular separation between i and j , and R is a fixed radius parameter, typically set to $R = 0.4$. The algorithm proceeds iteratively. It computes the distances d_{ij} between all pairs of particles. If $d_{ij} < d_i$, i and j are merged into a new single object which replaces them in the initial set, and their momenta are summed. If $d_{ij} > d_i$, object i is removed from the input list and declared a jet. This process repeats until all PFlow objects are clustered into jets and no further combinations are possible.

Calibration

During reconstruction, jets are initially calibrated at the electromagnetic scale, which ensures that the deposited energy of electrons and photons matches their true energy. However, this calibration underestimates the energy of hadrons by approximately 15% to 55%, due to the differing interactions of electromagnetic and hadronic particles with the detector material. To correct for this discrepancy, a recalibration is required to align the reconstructed jet energy with that of truth-level jets — jets built at particle level from stable final-state particles in Monte Carlo simulations, excluding detector effects. The complete jet energy scale (JES) calibration procedure [168], illustrated in Figure 4.14, consists of several correction steps that modify the jet four-momentum, including adjustments to transverse momentum, energy, and mass.

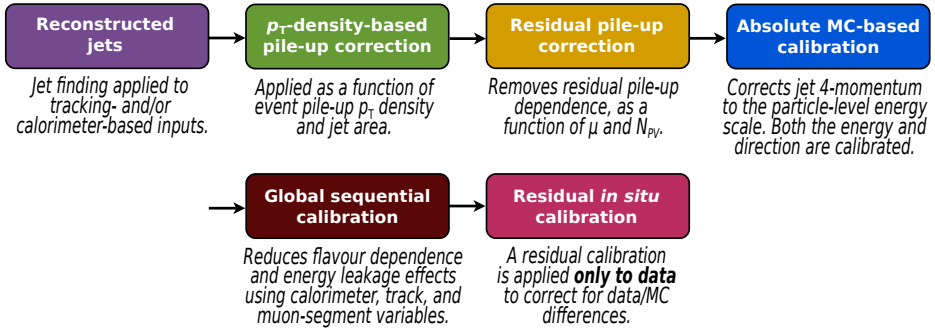


Figure 4.14 – Flowchart of the jet energy scale calibration procedure used in ATLAS [168].

1. The JES calibration begins with the *pileup corrections*, by removing the excess energy from pileup activity. An initial correction is applied based on the jet area and the median transverse momentum density, evaluated across (η, ϕ) regions of the detector. This estimates how much pileup contributes to a given jet. A residual correction, parameterised using MC simulations, is then applied to mitigate remaining dependencies of jet p_T on the average number of interactions per bunch crossing and the number of primary vertices in the event.
2. In the second step, the *absolute JES calibration* aligns the reconstructed jet energy and direction with truth jets from di-jet MC events. It corrects for effects such as the non-compensating response of the calorimeters, energy losses in passive material, energy deposited outside of the cone of radius R used during jet clustering, and biases in jet η reconstruction arising due to transitions between different calorimeter regions and varying granularity.
3. Even after the absolute JES calibration, residual variations in the energy response may remain within the same kinematic region. These result from differences in jet flavor composition, energy distribution of constituent particles, transverse spread, and fluctuations in the hadronic shower development. The *global sequential calibration* applies a third sequence of multiplicative corrections to the jet four-momentum, aiming to reduce these fluctuations and improve the resolution without altering the average energy response. Corrections are based on observables from the tracking system, calorimeter, and muon spectrometer.
4. After correcting PFlow jets to particle level, the η -intercalibration and *in-situ calibration* are applied to account for differences between data and simulations. The η -intercalibration accounts for response variations across detector regions. The in-situ calibration compares jets in data to well-measured reference objects from $Z + \text{jets}$, $\gamma + \text{jets}$, and multi-jet processes. The data-to-MC ratio response is measured across overlapping p_T regions and used to derive a final correction applied to data, aligning the JES with the simulation.

The full JES calibration introduces 125 systematic uncertainty components originating

4.3. JETS RECONSTRUCTION

from the various calibration stages. These uncertainties stem from event selection choices during in-situ analyses, event topology, MC modeling assumptions, and statistical limitations. Figure 4.15 illustrates how these uncertainties vary with jet p_T and η , with the most significant contributions coming from pileup corrections (especially at low p_T) and jet flavor response. In addition to JES, differences in jet energy resolution (JER) between data and simulation must also be addressed. These arise from mismodelling of both detector effects and physics processes in simulations. The JER is measured directly in data using di-jet events, where the two jets are expected to be balanced in momentum. Furthermore, random trigger events (unbiased by physics selection) are used to measure fluctuations in the calorimeter caused by pileup, helping to estimate the noise component of the energy resolution. These measurements are combined to derive the final JER corrections, which are then applied to analysis-level jets.

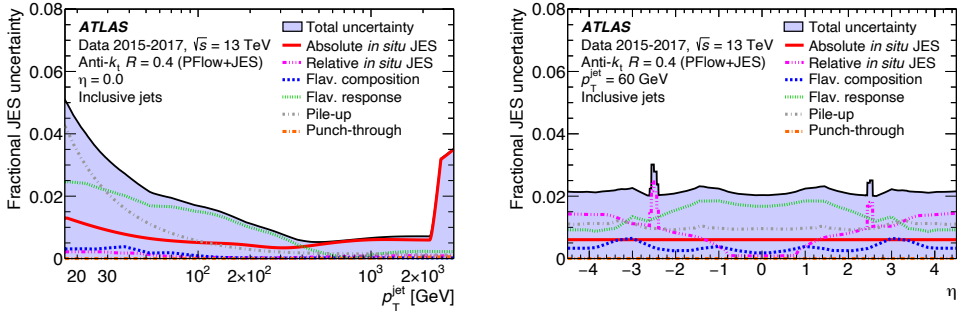


Figure 4.15 – Relative impact of systematic uncertainties on the jet energy scale for anti- k_t jets with $R = 0.4$ jets, as a function of jet p_T at $\eta = 0$ (left) and of jet η at $p_T = 60$ GeV (right), using jets reconstructed from particle-flow objects [168]. The total uncertainty, computed as the quadrature sum of all individual components, is shown as a filled region topped by a solid black line. Major contributions to the total uncertainty are indicated by the colored lines.

Jet vertex tagging

Jets can originate not only from the primary vertex but also from pileup interactions. Since the analyses presented in this thesis rely exclusively on jets originating from the hard-scattering vertex, a pileup mitigation techniques is required. To this end, the Jet Vertex Tagger (JVT) [171] is employed. JVT is implemented as a two-dimensional likelihood discriminant constructed in the plane defined by the corrected jet vertex fraction (corrJVF) and R_{p_T} . The corrJVF variable is defined as the ratio of the scalar sum of the transverse momenta of tracks associated with the jet and originating from the primary vertex ($\sum_m p_{T,m}^{\text{track}}(\text{PV}_0) = p_T^{\text{PU}}$) to the sum of the transverse momenta of all associated tracks that originate from any of the pileup interactions ($\sum_{n \geq 1} \sum_l p_{T,l}^{\text{track}}(\text{PV}_n)$):

$$\text{corrJVF} = \frac{\sum_m p_{T,m}^{\text{track}}(\text{PV}_0)}{\sum_l p_{T,l}^{\text{track}}(\text{PV}_0) + \frac{1}{\kappa \cdot n_{\text{track}}^{\text{PU}}} \sum_{n \geq 1} \sum_l p_{T,l}^{\text{track}}(\text{PV}_n)} . \quad (4.14)$$

Here, the denominator includes a correction for the linear dependence of p_T^{PU} on the total number of pileup tracks per event. This is achieved by dividing p_T^{PU} by $\kappa \cdot n_{\text{track}}^{\text{PU}}$, where $\kappa = 0.01$ and $n_{\text{track}}^{\text{PU}}$ is the number of pileup tracks. The second variable, R_{p_T} , is defined as

$$R_{p_T} = \frac{\sum_k p_{T,k}^{\text{track}}(\text{PV}_0)}{p_T^{\text{jet}}}, \quad (4.15)$$

where p_T^{jet} is the fully calibrated transverse momentum of the jet. For the analyses presented in the following chapters, the Tight working point of the JVT is applied to jets with $p_T < 60$ GeV and within the acceptance of the ATLAS ID ($|\eta| < 2.4$).

4.4 Electrons and Photons reconstruction

Electron reconstruction in the ATLAS detector is performed in parallel with photon reconstruction [172–175]. Both procedures rely on collections of energy deposits primarily contained within the Electromagnetic Calorimeter, complemented by tracks and secondary vertices reconstructed in the Inner Detector. The reconstruction sequence begins with the identification of topoclusters, following the procedure outlined in Section 4.3. Subsequently, photon conversion reconstruction and supercluster formation are carried out.

Reconstruction of photon conversion vertices

Tracks that are loosely matched to fixed-size topoclusters are used as input for reconstructing photon conversion vertices in the ID. Two types of photon conversions are considered.

- Double-track conversions occur when two oppositely charged tracks originate from a common spacial point. Geometric criteria, such as the angle between the tracks, their separation at the point of closest approach, and their distance in correspondence of the reconstructed vertex, are applied to ensure consistency of the reconstructed vertex with the one originating from a massless particle.
- Single-track conversion vertices account for asymmetric photon conversions, where one electron carries the majority of the photon energy, or for highly energetic photons, where the electron-positron tracks are highly collimated. These vertices are reconstructed only if there are no hits in the innermost ID layer, thereby suppressing misidentification of prompt electrons as single-track conversion.

Once conversion vertices are reconstructed, they are matched to topoclusters by extrapolating the associated tracks to the second EMCalo layer and computing their distance to the topocluster barycenter in the $\eta - \phi$ plane. If multiple conversion vertices are matched to a single topocluster, preference is given to double-track conversions.

Supercluster formation

Matched topoclusters and tracks serve as inputs to the superclustering algorithm [176], which operates in two distinct stages, as illustrated in Figure 4.16. In the first stage, the

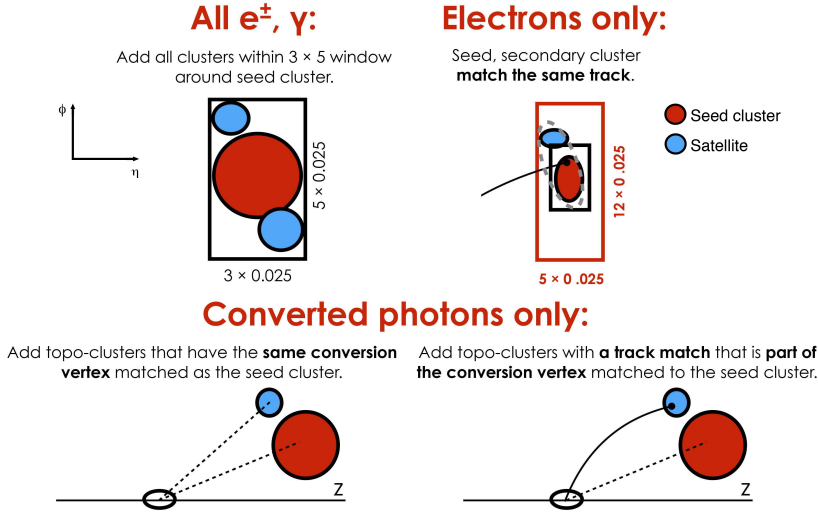


Figure 4.16 – Schematic diagram of the superclustering algorithm for electrons and photons [176]. Seed clusters are shown in red, satellite clusters in blue.

algorithm scans topoclusters to identify suitable seeds for supercluster formation. For electrons, topoclusters with transverse energy $E_T > 1$ GeV that are matched to a track with at least four silicon hits are selected. For photons, seed topoclusters are required to have $E_T > 1.5$ GeV, due to the absence of a matching track. In the second stage, the algorithm searches for satellite topoclusters within a window of $\Delta\eta \times \Delta\phi = 0.075 \times 0.125$ centered on the seed topocluster's barycenter. Only topoclusters with lower E_T than the seed are considered as satellite clusters. For electrons superclusters, additional satellite clusters may also be included from a larger window of $\Delta\eta \times \Delta\phi = 0.125 \times 0.3$ around the seed barycenter, provided they are matched to a track with silicon hits and share the same best-matched track as the seed. For the specific case of converted photons, satellite clusters are accepted if they are matched to the same conversion vertex as the seed, or to any of the tracks associated with that vertex. The final electron and photon superclusters are constructed by merging all calorimeter cells from the seed topocluster and its associated satellite clusters.

After the supercluster formation, tracks and conversion vertices are matched to the resulting electron and photon superclusters using the same procedures as for individual topoclusters. Since electron and photon superclusters are constructed independently, it is possible for a single topocluster to seed both an electron and a photon candidate supercluster. To resolve such ambiguities, a dedicated ambiguity resolution algorithm is applied to assign each candidate definitively as an electron, photon, or both, depending on the full reconstruction context.

Calibration and creation of analysis objects

As with jets, once electrons and photons are correctly reconstructed, their energies must be calibrated to account for various detector effects [175]. These include energy losses in passive materials, electromagnetic shower leakage, and fluctuations in the deposited energy. Calibration is performed through a sequence of correction steps, resulting in final physics objects that are suitable for use in offline analyses. The applied corrections address several key factors, such as the intercalibration of the different calorimeter layers, pileup-induced energy shifts, and non-uniformities in the calorimeter energy response. Overall, these corrections account for residual differences between data and simulation, ensuring consistent energy measurements across the detector. Following the calibration, the results are validated using well-understood Standard Model processes, specifically the $J/\Psi \rightarrow ee$ and $Z \rightarrow ee\gamma$ decays. The former is used to probe the energy response for low-energy electrons, while radiative Z boson decays test the photon energy scale in events where photons are emitted. In both cases, the performance of the calibration is evaluated by fitting the invariant mass distribution of the e^+e^- pair, allowing for a precise comparison between data and simulation.

Identification and isolation

Once an electron or photon candidate has been reconstructed, it must be unambiguously identified. This is achieved using a likelihood-based (LH) discrimination method, which relies on input variables such as calorimetric shower shapes and track properties for electrons, and shower shape variables only for photons. Three identification working points — *Loose*, *Medium*, and *Tight* — are defined for both object classes. These offer progressively stronger background rejection at the cost of decreasing identification efficiency [172–174]. For electrons with $E_T > 40$ GeV, the Loose, Medium, and Tight WPs are designed to achieve minimum efficiencies of 93%, 88%, and 80%, respectively. For photons, the Loose WP is optimised to achieve 99% efficiency for $E_T > 40$ GeV. The Tight selection, on the other hand, achieves an efficiency of approximately 85% at the same transverse energy, increasing to about 92% for unconverted photons and 95% for converted photons when $E_T > 100$ GeV. Figure 4.17 and Figure 4.18 present the identification efficiencies of the three WPs for electrons and photons, respectively, as functions of transverse energy and pseudorapidity. In the case of photons, only the $|\eta| < 0.6$ slice is shown, as the efficiency varies with the longitudinal position within the ATLAS detector.

Prompt electrons and photons are typically expected to be isolated from significant hadronic activity. To suppress backgrounds from fake candidates, a set of isolation requirements is defined. A comprehensive overview of them can be found in Ref. [173]. Isolation is quantified using nearby energy deposits in the calorimeters or close-by tracks reconstructed in the ID. This is done by measuring the activity within a fixed distance from the candidate electron or photon and requiring it to remain a small fraction of the candidate's own energy. For instance, calorimetric isolation, E_T^{cone20} , is computed as the scalar sum of transverse energies of topoclusters with barycenters within a cone of radius $\Delta R = 0.2$ around the electron or photon supercluster barycenter. Similarly, track-based

4.4. ELECTRONS AND PHOTONS RECONSTRUCTION

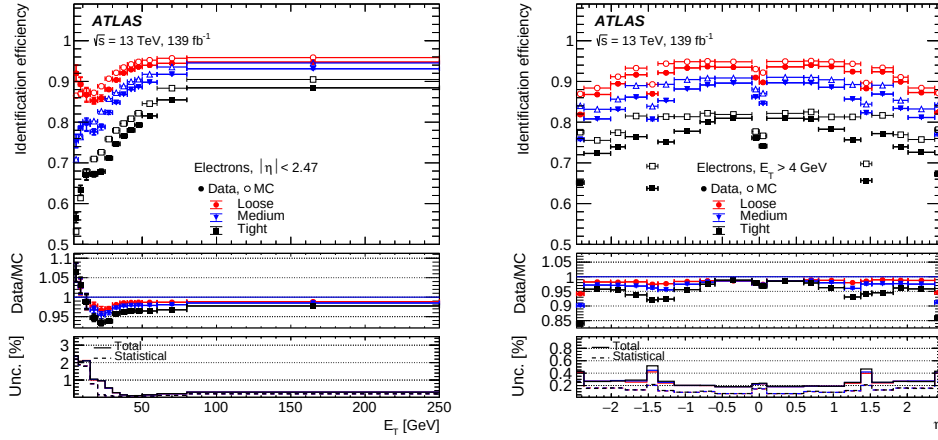


Figure 4.17 – Electron identification efficiency as a function of E_T (left) and η (right) for the Loose, Medium and Tight working points in data and simulation [174].

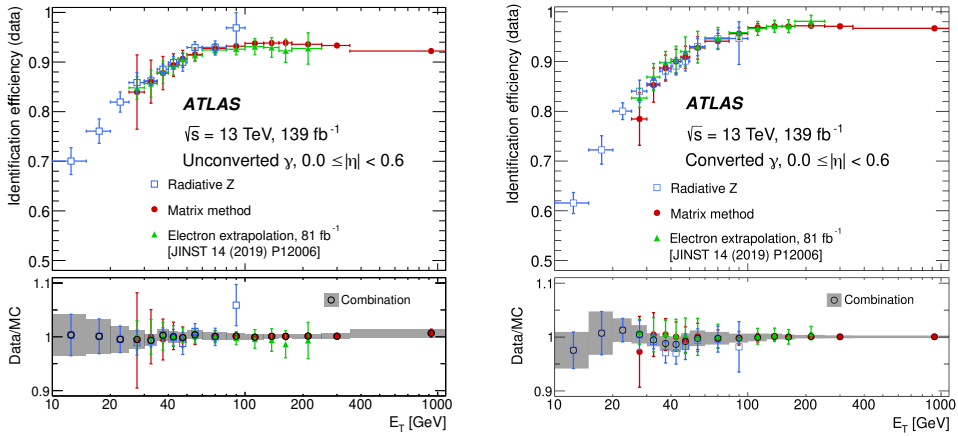


Figure 4.18 – Tight photon identification efficiency for unconverted (left) and converted (right) photons, along with the data-to-MC efficiency ratio, as a function of E_T in the $|\eta| < 0.6$ slice [174].

isolation, p_T^{cone20} , is calculated as the scalar sum of the transverse momenta of all the selected track particles within the same cone. Additional isolation variables are defined using larger cones, typically with $\Delta R = 0.3 - 0.4$.

4.5 Muons reconstruction

Muons are reconstructed independently in the Inner Detector, the Muon Spectrometer, and the calorimeters [177, 178]. The information from each sub-detector is combined using a track fitting procedure which integrates hits from both the ID and the MS and also accounts for energy loss in the calorimeters, resulting in a complete muon track object. Based on the primary sub-detector contributing to the reconstruction, five types of muon candidates are defined.

- *Combined* muons are formed by matching independently reconstructed MS tracks to ID tracks, with hits from both subsystems refit into a single muon track.
- *Inside-out combined* muons are reconstructed by extrapolating high-quality ID tracks to the MS and matching them to at least three loosely aligned MS hits. The resulting muon track is obtained by refitting the ID track, calorimeter energy losses, and MS hits.
- *Segmented-tagged* muons are identified by extrapolating ID tracks to local track segments in the MS.
- *Calorimeter-tagged* muons are identified from energy deposits in the calorimeters consistent with minimum ionising particles. This category extends reconstruction acceptance to the $|\eta| < 0.1$ region, where the MS is only partially instrumented.
- *Extrapolated* muons are reconstructed using only MS hits, with a loose association to the primary vertex.

Following reconstruction, identification criteria are applied to suppress muons originating from hadron decays, ensuring selection of prompt muons from the hard-scatter vertex. These criteria are based on variables assessing track fit quality, as muons from secondary decays typically exhibit poorer quality than prompt muons. Three standard identification working points are defined — *Loose*, *Medium*, and *Tight* — offering increasing background rejection at the expense of efficiency. Figure 4.19 illustrates the efficiency of the three WPs as a function of muon p_T and η for both prompt muons and muons from hadron decays. Additionally, two specialised WPs are provided: *Low- p_T* and *High- p_T* , designed to improve efficiency for low- p_T ($3 < p_T < 5\text{GeV}$) and high- p_T ($p_T > 1\text{TeV}$) muons, respectively. Both WPs meet the Medium selection requirements.

To further distinguish signal muons from background, isolation requirements are imposed to ensure muons are well separated from nearby hadronic activity. Muon isolation can be evaluated similarly to electrons and photons, by using track-based, calorimetric variables, or combined variables incorporating particle-flow information [167]. Track-based isolation is defined as the scalar sum of the transverse momenta of ID tracks associated with the primary vertex within a cone of size ΔR around the muon,

4.6. MISSING TRANSVERSE MOMENTUM

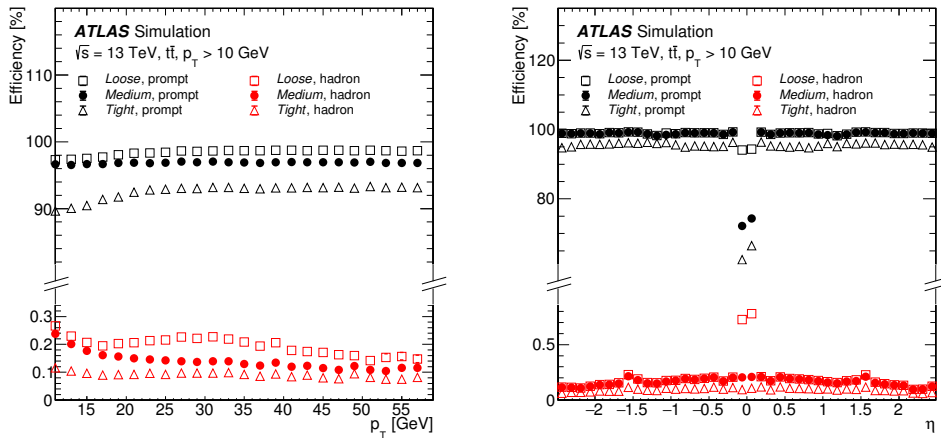


Figure 4.19 – Identification efficiency as a function of p_T (left) and η (right) for the Loose, Medium and Tight WP requirements in simulated $t\bar{t}$ events, shown separately for prompt muons and muons from hadron decays [178].

excluding the muon track itself. Depending on the specific criterion, ΔR is either fixed at 0.2 (p_T^{cone20}) or set to $\min(10 \text{ GeV}/p_T(\mu), 0.3)$ ($p_T^{\text{varcone30}}$), the latter optimised for topologies with nearby jets or leptons. Calorimeter-based isolation, denoted $E_T^{\text{topoetcone20}}$, is computed as the sum of the transverse energy of calorimeter cell clusters in a cone of size $\Delta R = 0.2$ around the muon, after subtracting the muon’s own energy deposit. Finally, combined isolation uses the track-based isolation and adds the transverse energy of neutral particle-flow objects within a cone of size $\Delta R = 0.2$, with corrections for the muon’s energy deposit and pileup contributions, resulting in the variable E_T^{neflow20} . Further details on muon isolation WP definitions and performance can be found in Ref. [178].

4.6 Missing transverse momentum

Particles that do not interact via the strong or electromagnetic forces pass through the ATLAS detector without leaving any trace. These include neutrinos, as well as potential BSM particles like neutralinos. However, since the transverse momentum of the initial pp collision system at the LHC is zero, the presence of such invisible particles can be inferred from an imbalance in the transverse momentum plane, denoted as $\mathbf{p}_T^{\text{miss}}$, with its magnitude referred to as E_T^{miss} [179]. The missing transverse momentum, $\mathbf{p}_T^{\text{miss}}$, is reconstructed as the negative vector sum of all visible *hard* and *soft* physics objects in the event. The hard objects include electrons (e), photons (γ), hadronically decaying tau leptons (τ), muons (μ), and jets (j). The soft term accounts for additional contributions from charged tracks with $p_T > 0.5$ GeV and $|\eta| < 2.5$ that originate from the primary

vertex but are not matched to any reconstructed object. Thus, $\mathbf{p}_T^{\text{miss}}$ is an event-level quantity defined as

$$\mathbf{p}_T^{\text{miss}} = - \sum_{\text{electrons}} \mathbf{p}_T^e - \sum_{\text{photons}} \mathbf{p}_T^\gamma - \sum_{\text{taus}} \mathbf{p}_T^\tau - \sum_{\text{muons}} \mathbf{p}_T^\mu - \sum_{\text{jets}} \mathbf{p}_T^j - \mathbf{p}_T^{\text{soft term}}, \quad (4.16)$$

with the magnitude and azimuthal angle given by

$$E_T^{\text{miss}} = \sqrt{(p_x^{\text{miss}})^2 + (p_y^{\text{miss}})^2}, \quad \phi^{\text{miss}} = \arctan\left(\frac{p_y^{\text{miss}}}{p_x^{\text{miss}}}\right). \quad (4.17)$$

To accommodate the needs of different offline analyses, three $\mathbf{p}_T^{\text{miss}}$ working points are provided.

- The *Loose* $\mathbf{p}_T^{\text{miss}}$ includes all jets with $p_T > 20$ GeV that also pass the JVT criteria² when the jet has $|\eta| < 2.4$ and $p_T < 60$ GeV.
- The *Tight* working point is optimised to reduce the pileup dependence by excluding forward jets with $|\eta| > 2.4$ and $20 < p_T < 30$ GeV from the calculation.
- The *forward-JVT* (fJVT) $\mathbf{p}_T^{\text{miss}}$, aimed to suppress tails in the $\mathbf{p}_T^{\text{miss}}$ distribution, uses the same jet selection as the Loose working point but removes any forward jet with $|\eta| > 2.5$, $20 < p_T < 50$ GeV, and that fails the Loose fJVT requirement as defined in Ref. [180].

Search for SUSY higgsinos using soft mildly-displaced tracks and a cut-based approach with Run 2 data



As an extension of the Standard Model, Supersymmetry introduces an entirely new set of particles. Among these are the superpartners of the Higgs boson: the *higgsinos*. If R -parity is conserved [27], following the electroweak symmetry breaking, the higgsinos mix with the superpartners of the SM gauge bosons, the *gauginos*, to form four neutral mass eigenstates, called **neutralinos** and denoted by $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4$), and two charged mass eigenstates, known as **charginos** and denoted by $\tilde{\chi}_i^\pm$ ($i = 1, 2$). The mass of the higgsinos and the gauginos prior to mixing determine the resulting mass spectrum of the charginos and neutralinos [28]. As discussed in Section 1.3, when the gaugino mass parameters are sufficiently large, $M_1, M_2 > \mathcal{O}(100)$ TeV, radiative corrections can lead to a small mass difference between the lightest chargino and neutralino, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, typically in the range of 250-400 MeV. Conversely, when $M_1, M_2 \sim \mathcal{O}(10)$ TeV or lower, the mass splitting can increase up to $\sim \mathcal{O}(1)$ GeV. The value of $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ strongly influences the topology of the final state: a larger $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ corresponds to a shorter higgsino lifetime (Eq. 1.36). This has motivated different experimental strategies for searching for higgsinos with compressed mass spectra. For example, the disappearing track signature has been used to probe small mass splittings ($\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 250 - 400$ MeV) [30, 31], while soft lepton searches target larger differences ($\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \gtrsim 1.5$ GeV) [32–34]. However, the intermediate mass region of $0.3 \lesssim \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 1.25$ GeV, the “higgsino gap”, remains largely unprobed since the LEP era [35]. This gap persists due to limitations in existing techniques: for such $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ values, the chargino lifetime is typically too short to produce a disappearing track signature, while decay products in the form of leptons are too soft to be efficiently reconstructed. The primary goal of this thesis is to explore this unprobed region, where a measurable higgsino lifetime is expected, leading to characteristic *soft displaced signatures* that offer a novel experimental handle.

5.1 Target scenario

In the aforementioned “higgsino gap”, defined by $0.3 \lesssim \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 1.25$ GeV, the second-lightest neutralino and the lightest chargino acquire relatively long lifetimes, on the order of $\mathcal{O}(1 - 10)$ ps, and predominantly decay into charged pions [181]. These decays occur at transverse distances of approximately $\mathcal{O}(0.1 - 10)$ mm from the primary proton-proton interaction point. The resulting soft pions, with average transverse momenta around 1 GeV, can be reconstructed as tracks exhibiting a distinct feature: a finite transverse displacement from the hard-scattering vertex [36]. Throughout the rest of this thesis, such tracks, originating from soft pions with significant displacement due to SUSY higgsino decays, are referred to as (soft) “mildly-displaced tracks”. Figure 5.1 schematically illustrates this signature. On the left, the lightest neutralino and a charged pion are shown traversing the ATLAS Inner Detector, depicted in gray. The neutralino, which interacts only via the weak force, escapes detection, while the charged pion is reconstructed as a displaced track. The right-hand panel zooms in on the innermost tracking layers, highlighting the pion track’s measurable displacement, a direct consequence of the chargino’s finite lifetime. Crucially, the ATLAS Inner Detector provides excellent spatial resolution allowing precise reconstruction of such displacements (see Section 4.2, particularly Figure 4.9). Although low-momentum tracks from prompt decays in the underlying event or pileup are abundant, mildly-displaced tracks from compressed higgsino decays can be effectively distinguished by requiring significant non-zero impact parameters.

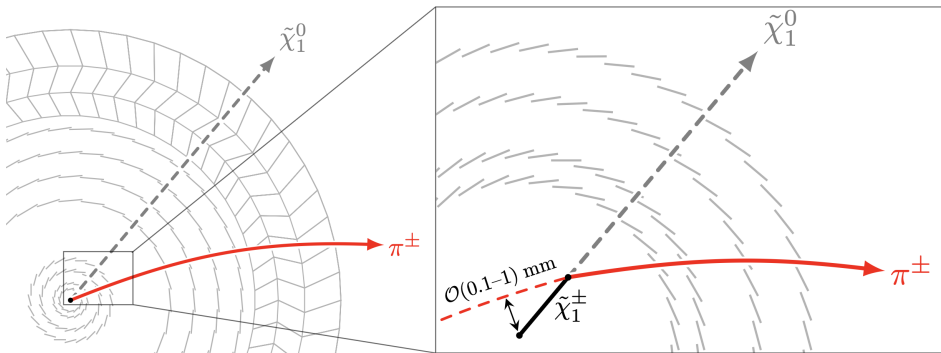


Figure 5.1 – Schematic illustration of the mildly-displaced track signature targeted in this thesis. The left-hand panel shows the lightest neutralino and a charged pion traversing the ATLAS Inner Detector, depicted in gray. The neutralino, represented by a dotted gray line, interacts only via the weak force and escapes detection. The right-hand panel provides a magnified view of the central tracking region, illustrating the reconstruction of the pion as a track with significant transverse displacement arising from the relatively long lifetime of the lightest chargino. From Ref. [89].

5.2 Signal features

The analysis presented here, and published in Ref. [182], extends sensitivity to scenarios with small mass splittings by building upon the strategy adopted in previous compressed higgsino searches [30–34]. It targets events characterised by a distinctive “ $E_T^{\text{miss}} + \text{jets}$ ” signature, with an additional requirement of soft, mildly-displaced tracks in the final state, as originally proposed in the phenomenological study of Ref. [36].

- Due to the small mass splitting, the decay products of higgsinos in the form of charged pions or leptons are very soft, with momenta on the order of a few GeV. As a result, signal events can only be efficiently triggered only by requiring significant missing transverse energy E_T^{miss} in the final state. To achieve high E_T^{miss} — ensuring operation within the plateau region of the E_T^{miss} trigger efficiency curve [183] — and to suppress Standard Model background contributions, the presence of a high-energy initial-state radiation (ISR) jet is required. This jet boosts the SUSY system, causing the two lightest neutralinos to recoil and align in the same azimuthal direction ϕ . To exploit this topology, events must exhibit a minimum azimuthal separation between the $\mathbf{p}_T^{\text{miss}}$ and any jets, quantified via the variables $\min \Delta\phi \left(p_T^{\text{jet}}, \mathbf{p}_T^{\text{miss}} \right)$.
- High-energy pp collisions produce an enormous amount of low- p_T tracks originating from prompt SM particles. In contrast, the small mass splitting between the lightest chargino and the lightest neutralino results in mean lifetimes long enough for these particles to travel measurable distances in the detector before decaying into visible pions. These decay lengths are typically shorter than the distance to the innermost layer of the ATLAS Pixel Detector, the IBL. The resulting pions are usually sufficiently energetic to be reconstructed as tracks ($p_T > 0.5$ GeV) and are characterised by a transverse impact parameter d_0 in the range of $\mathcal{O}(0.1 - 10)$ mm. The ATLAS ID provides excellent d_0 resolution, on the order of $\mathcal{O}(0.01 - 0.1)$ mm [184]. Therefore, these mildly-displaced tracks can be distinguished from most SM tracks by requiring a large impact parameter significance, defined as $S(d_0) = |d_0|/\sigma(d_0)$, which allows the identification of signal tracks even near the p_T reconstruction threshold. Tracks from pileup interactions, being displaced along the longitudinal z direction relative to the primary vertex, can be suppressed by exploiting the longitudinal impact parameter z_0 and the track polar angle θ . A requirement on the quantity $|\Delta z_0 \sin \theta|$ effectively removes such pileup tracks, since the typical separation between pileup vertices exceeds the longitudinal decay length of the higgsinos under consideration. Additionally, reconstructing secondary vertices helps reducing background tracks from long-lived hadron and heavy-flavour meson decays. Finally, due to the boost from the ISR jet, the soft mildly-displaced tracks from higgsino decays tend to lie in the same azimuthal hemisphere as the E_T^{miss} . A selection on the absolute value of the azimuthal separation between such tracks and the E_T^{miss} direction, $\left| \Delta\phi \left(p_T^{\text{track}}, \mathbf{p}_T^{\text{miss}} \right) \right|$, enhances the signal-to-background ratio and significantly reduces background tracks which exhibit no such alignment.

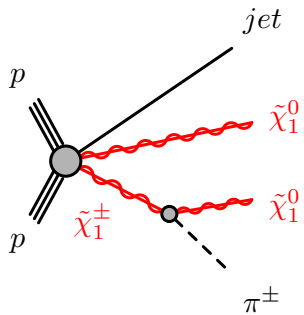


Figure 5.2 – Example signal diagram for the targeted signature featuring a jet from initial-state radiation. For illustration, the $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ process is shown only. The chargino decays via an off-shell W boson to the LSP and a charged pion which is reconstructed as low- p_T mildly-displaced track. The two final-state neutralinos are aligned in the ϕ direction due to the boost received by the ISR jet, leading to large E_T^{miss} .

Figure 5.2 shows a representative diagram for the targeted $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production process. Other production channels — $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$, and $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ — which similarly result in final states with one or more mildly-displaced tracks, are considered in the analysis as well.

5.3 Data and simulated samples

This thesis is based on data collected by the ATLAS detector from proton-proton collisions delivered by the LHC. In addition, Monte Carlo (MC) simulation samples are used to model (part of) the Standard Model backgrounds and the SUSY signal processes.

5.3.1 Dataset

The analysis uses the full Run 2 dataset recorded by the ATLAS detector between 2015 and 2018, corresponding to pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV. During this period, the LHC delivered a total integrated luminosity of 156 fb^{-1} , of which 147 fb^{-1} were recorded by ATLAS. After applying standard data quality criteria [185], the final dataset used in this analysis corresponds to an integrated luminosity of $140.1 \pm 1.2 \text{ fb}^{-1}$ [116], with a total uncertainty of 0.83%, as determined by the LUCID-2 (LUminosity CHerenkov Integrating Detector) detector [186]. The integrated luminosity collected during each year of Run 2 is 3.24, 33.40, 44.63, and 58.79 fb^{-1} , respectively for 2015, 2016, 2017, and 2018 [116]. Pileup conditions varied significantly across these years [118], impacting in different ways event reconstruction and background composition.

5.3.2 Monte Carlo simulated samples

Monte Carlo samples are essential for evaluating selection efficiencies, modelling the distributions of discriminating observables in background and signal processes, and constructing the statistical models used for hypothesis testing under both the background-only and signal-plus-background scenarios. Additionally, MC simulations are used to assess the impact of systematic uncertainties, both experimental and theoretical.

The generation of MC samples begins with simulating the hard-scattering process, using matrix elements computed to a fixed order in perturbation theory via dedicated event generators. Following this, parton showering [187–190] — the emission of quarks

and gluons from the partons involved in the primary interaction — is simulated, along with the hadronisation process [191, 192], where colored partons transition into color-neutral hadrons. These processes are typically handled by the same or complementary event generators that also simulate the decays of unstable particles produced in the hard scattering. The simulation also includes modelling the underlying event and pileup interactions. The next step of MC sample generation involves simulating the interactions of stable final-state particles in the ATLAS detector. This is achieved by the ATLAS simulation framework [193], either through full simulation of the detector’s response via GEANT4 [194], or through fast simulation with ATLFastII (AFII) [195, 196] or its successor ATLFast3 (AF3) [197]. AFII uses GEANT4 to simulate the interactions in the ID and muon spectrometer, and a parameterised simulation, FastCaloSim [195], for the electromagnetic and hadronic calorimeters. AF3 improves upon this by combining FastCaloSim V2 [197] for low- and high-energy showers, with FastCaloGAN [198], a Generative Adversarial Network [199] approach, to more accurately model medium-energy hadrons and calorimeter energy fluctuations. Both AFII and AF3 effectively reduce computational time by avoiding the full simulation of complex shower development in the calorimeters, thus saving substantial CPU resources. Finally, after simulation, both SM background events and BSM signal are processed through the same reconstruction algorithms used for data reconstruction to ensure consistency in object definition and event selection.

In this analysis, MC samples are generated for all relevant signal and background processes. While SM samples employ the full detector simulation, SUSY signals are processed using ATLFastII. A summary of the Monte Carlo event generators and their corresponding configurations is provided in Table 5.1.

Process	Matrix element	Parton shower	Tune	PDF set	Cross section
$V + \text{jets}$	SHERPA 2.2.11/2.2.2		SHERPA standard	NNPDF3.0 _{NNLO}	NNLO
VV	SHERPA 2.2.1/2.2.2		SHERPA standard	NNPDF3.0 _{NNLO}	Generator NLO
$t\bar{t}$	POWHEG-BOX	PYTHIA 8.230	A14	NNPDF3.0 _{NNLO}	NNLO+NNLL
Single top	POWHEG-BOX	PYTHIA 8.230	A14	NNPDF3.0 _{NNLO}	NNLO+NNLL
Multi-jet		PYTHIA 8.235	A14	NNPDF2.3 _{LO}	Generator LO
SUSY signals	MADGRAPH5 2.9.5	PYTHIA 8.306	A14	NNPDF2.3 _{LO}	NLO+NNL

Table 5.1 – Summary of Monte Carlo generators setup for SM backgrounds and SUSY signal samples.

Vector boson production

At the hadron colliders like the LHC, single boson and di-boson production processes have relatively large cross sections. Representative Feynman diagrams for these processes are shown in Figure 5.3. Among all SM background processes considered in this analysis, single boson production provides by far the largest contribution. Within this category, the dominant production mechanism is the t -channel process mediated by the strong interaction, which significantly outweighs the s -channel process that proceeds purely via

electroweak interactions. In t -channel production, additional jets are produced through QCD interactions. Di-boson production is typically initiated by quark-antiquark annihilation, but it can also occur via triple and quartic gauge boson couplings, as well as through loop-induced gluon-gluon fusion processes.

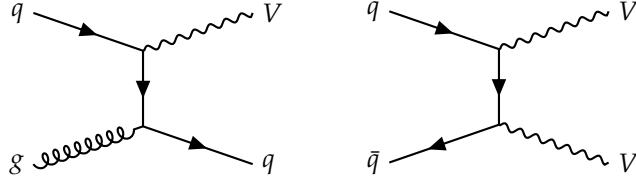


Figure 5.3 – Tree-level Feynman diagrams for single boson production (left) and quark-initiated di-boson production (right).

Event generation for single boson and di-boson production, including matrix element calculation, parton showering, and hadronisation, is performed using SHERPA 2.2.11/2.2.2 (for single boson samples) and SHERPA 2.2.1/2.2.2 (for di-boson samples) [200]. The NNPDF3.0_{NNLO} parton distribution functions are used [201]. Since single boson cross sections are computed at next-to-next-to leading order (NNLO) accuracy, the total cross section predicted by SHERPA is normalised to NNLO using scale factors provided in Ref. [202].

Top production

Due to its high center-of-mass energy, which leads to large production cross sections, the LHC effectively functions as a top quark factory. Approximately 90% of the top quark production is initiated by gluon-gluon fusion, while the remaining 10% arises from quark-antiquark interactions. Single top production occurs via three distinct processes: the dominant t -channel production, the associated tW -channel, and the s -channel. Feynman diagrams illustrating top-quark pair and single top production are shown in Figure 5.4.

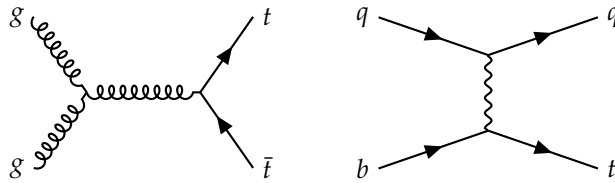


Figure 5.4 – Tree-level Feynman diagrams for gluon-initiated top-quark pair production (left) and t -channel single top production (right).

The matrix element calculation is performed using POWHEG-BOX [203–206], at next-to-leading order (NLO) accuracy, with NNPDF3.0_{NNLO} parton distribution functions [201]. The POWHEG-BOX output is interfaced with PYTHIA 8.230 [207] for parton showering and

hadronisation, using the A14 tune [208]. The A14 tune is a set of parameters optimised to match observables sensitive to the underlying event, jet structure, and additional jet radiation, based on ATLAS data collected during the LHC Run 1. Heavy-flavour particle decays are simulated using EVTGEN 1.6.0 [209]. As the theoretical cross section is calculated at next-to-next-to-leading order plus next-to-next-to-leading logarithmic (NNLO+NNLL) accuracy, the total cross section from POWHEG-BOX is normalised to NNLO+NNLL by applying the scale factors provided in Ref. [210].

Multi-jet production

Fully hadronic multi-jet production has the highest production cross section [211] among all SM background processes considered in this thesis. However, despite its large production rate, multi-jet background becomes negligible after applying the event-level and track-level selections described below in Section 5.4.1, and is only relevant for the background validation strategy. Tree-level Feynman diagrams illustrating QCD multi-jet production are shown in Figure 5.5. Event generation, including the matrix element calculation, parton showering, and hadronisation, is performed using PYTHIA 8.235 [207] with NNPDF2.3LO parton distribution functions [201]. The matrix element is calculated at leading-order (LO) accuracy. The A14 tune [208] is applied to model parton showering and the underlying event. Heavy-flavour particle decays are simulated using EVTGEN 1.6.0 [209].

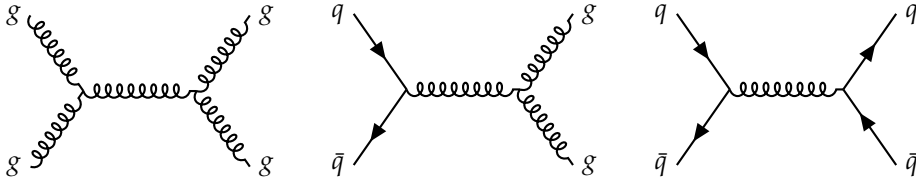


Figure 5.5 – Tree-level Feynman diagrams for multi-jet production.

SUSY signals production

Simplified SUSY models [99] of chargino and neutralino direct pair production, with subsequent decays mediated by off-shell W and Z bosons, are considered in this thesis. As the wino and bino mass parameters are assumed to be decoupled relative to the higgsino mass term μ , the heaviest chargino $\tilde{\chi}_2^\pm$ and the heavier neutralinos $\tilde{\chi}_{3,4}^0$ have masses well above the electroweak energy scale, resulting in negligible production cross sections. Consequently, only the following electroweakino production modes are considered:

$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \tilde{\chi}_2^0, \tilde{\chi}_2^0 \tilde{\chi}_1^0. \quad (5.1)$$

The properties of the electroweakinos — including mass values and decay modes — are determined by several parameters in the MSSM. In the simplified models considered here, all SUSY particles other than $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$ are set to a mass of 45 TeV. The mass hierarchy assumed is $m(\tilde{\chi}_1^0) < m(\tilde{\chi}_1^\pm) < m(\tilde{\chi}_2^0)$, with equally spaced mass splittings:

$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm) = \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$. Thus, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ and the mass of the lightest neutralino $\tilde{\chi}_1^0$ are the only free parameters in the models. The branching ratios of the second-lightest neutralino and the lightest chargino are calculated following Ref. [181]. Figure 5.6 shows that the branching ratios depend primarily on the mass splitting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$. Since the final-state topology targeted in this analysis depends only on the higgsino mass difference, fixing the model parameters as described above does not result in a loss of generality.

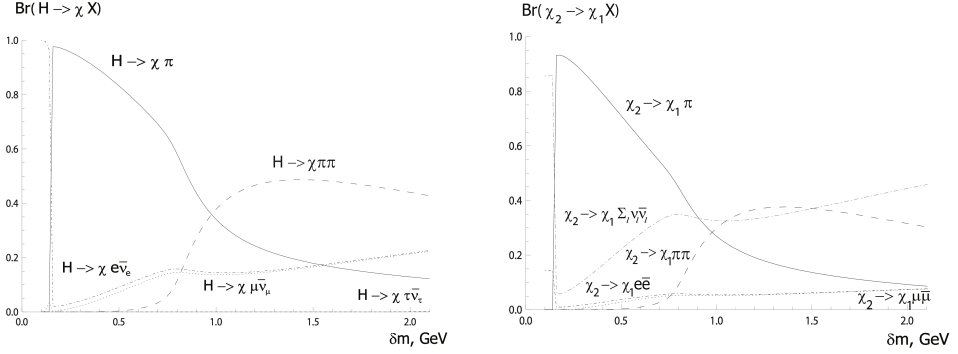


Figure 5.6 – Branching ratios for the lightest chargino (left) and the second-lightest neutralino (right) as functions of the mass splitting [181].

Tree-level Feynman diagrams for the pair production of the considered electroweakinos are shown in Figure 5.7. Signal simulated samples are generated for each production mode using pure higgsino-like states. The mass difference $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ and the mass of the neutralino LSP vary in the intervals [0.25, 1.5] GeV and [85, 225] GeV, respectively. Signal samples are generated using MADGRAPH5_AMC@NLO 2.9.5 [212] for the matrix element, and PYTHIA 8.306 [207] for parton showering and hadronisation. Cross sections and their uncertainties are computed at NLO+NLL accuracy using RESUMMINO [213, 214]. Since electroweakino decays are handled by PYTHIA, spin correlations and polarisation effects of the W and Z bosons produced from $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decays are not included. A cross-check using MADSPIN [215, 216], which takes into account spin effects, showed no significant impact on the kinematic distributions of final-state particles. Therefore, neglecting W and Z boson polarisation effects does not affect the accuracy of the signal modelling for this analysis.

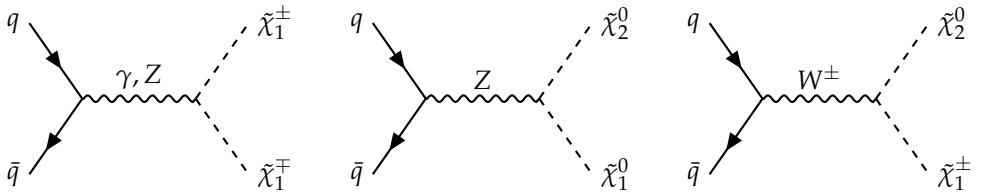


Figure 5.7 – Tree-level Feynman diagrams for electroweakinos pair production.

Figure 5.8 shows the production cross sections for the relevant electroweakino production modes as a function of the higgsino mass, calculated with RESUMMINO at NLO+NLL accuracy, assuming a center-of-mass-energy of $\sqrt{s} = 13$ TeV. The calculation is performed in the limit where the masses of $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$ are degenerate, while all the other supersymmetric particles are assumed to be heavy and decoupled. Within the mass range relevant to this analysis, the typical production cross sections vary between $\approx 10^{-2}$ pb and ≈ 1 pb.

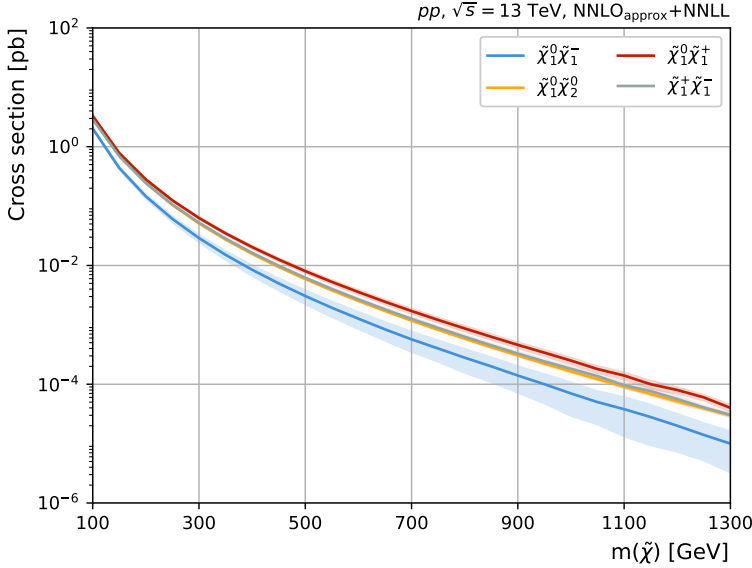


Figure 5.8 – Higgsino-like pair production cross sections computed at a center-of-mass-energy $\sqrt{s} = 13$ TeV using RESUMMINO [213, 214]. The cross sections are computed at NLO plus NLL precision in a limit of mass-degenerate $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$ with all the other supersymmetric particles assumed to be heavy and decoupled.

5.4 Event and track selection

A baseline set of selection criteria is applied to the physics objects reconstructed as described in Chapter 4. These selections are summarised in Table 5.2 and collectively define two classes of objects: *baseline* and *signal*. Baseline electrons, muons, and photons are reconstructed with the lowest p_T thresholds for which ATLAS calibrations are available and are used to define the so-called “0 ℓ ” category, by applying a veto on them. Baseline jets, on the other hand, are primarily used in the computation of the missing transverse momentum and in the overlap removal procedure. To prevent the reconstruction of a single particle as multiple objects, an overlap removal procedure is applied to all baseline objects as detailed in Ref. [217]. Following this, signal objects are defined with tighter criteria and used for auxiliary categorisation in background estimation and validation.

To further reduce contributions from Standard Model background processes and select events consistent with the “ E_T^{miss} + jets” signature containing at least one displaced track

— as emphasised in Section 5.2 — additional requirements are imposed. They include both event-level selections (Section 5.4.1) and track-level selections (Section 5.4.2), which together define the Signal Regions (SRs). Throughout this analysis, SRs belong exclusively to the 0ℓ category.

	Baseline	Signal
Jets		
Kinematic	$p_T > 20 \text{ GeV}, \eta < 4.5$	$p_T > 20 \text{ GeV}, \eta < 2.8$
Pileup mitigation	JVT Tight ¹ for $p_T < 60 \text{ GeV}, \eta < 2.4$	
Muons		
Kinematic	$p_T > 3 \text{ GeV}, \eta < 2.7$	$p_T > 3 \text{ GeV}, \eta < 2.5$
Identification	Medium	Medium
Isolation	-	PflowLoose_VarRad
Impact parameter	$ z_0 < 0.5 \text{ mm}$	$ d_0/\sigma(d_0) < 3, z_0 < 0.5 \text{ mm}$
Electrons		
Kinematic	$p_T > 4.5 \text{ GeV}, \eta < 2.47$	
Identification	LooseAndBLayerLLH	MediumLLH
Isolation	-	Loose_VarRad
Impact parameter	$ z_0 < 0.5 \text{ mm}$	$ d_0/\sigma(d_0) < 5, z_0 < 0.5 \text{ mm}$
Photons		
Kinematic	$p_T > 25 \text{ GeV}, \eta < 2.37$	$p_T > 130 \text{ GeV}, \eta < 2.37$
Identification	Tight	Tight
Isolation	-	FixedCutTight
Missing Transverse Momentum		
Working Point		Tight

Table 5.2 – Summary of Run 2 baseline and signal object definitions used in this analysis.

5.4.1 Event selection

As detailed in Section 5.3, events are first required to pass standard data quality criteria to ensure that they were recorded during periods when the ATLAS detector was operating under stable conditions [185]. After event cleaning, each event must contain at least one reconstructed interaction vertex with a minimum of two associated tracks with $p_T > 500 \text{ MeV}$. Additional selection requirements are then applied as follows.

- Neutralinos in the final state recoling against the ISR leading jet produce large E_T^{miss} , which serves as a trigger requirement for the events. The E_T^{miss} trigger efficiency

¹ The tight working point of the JVT is employed. Further details on the JVT definition can be found in Ref. [171].

varies across data-taking periods due to different pileup conditions, and achieves full efficiency for $E_T^{\text{miss}} > 200$ GeV [183]. Accordingly, this analysis requires events to satisfy the E_T^{miss} trigger and have $E_T^{\text{miss}} > 300$ GeV. This threshold also helps to suppress multi-jet events, which typically generate fake E_T^{miss} due to jet energy mismeasurement.

- To effectively boost the SUSY system and generate sufficient E_T^{miss} for triggering, the ISR leading jet - the reconstructed jet with the largest momentum - is required to have $p_T > 250$ GeV. Furthermore, no more than four signal jets with transverse momenta above 30 GeV and pseudorapidity $|\eta| < 2.8$ are allowed. This restriction reduces contributions from multi-jet and $t\bar{t}$ processes without compromising the signal acceptance, as signal events generally exhibit lower hadronic activity.
- Inaccurate jet energy reconstruction can lead to mismeasured E_T^{miss} , often aligned with one of the reconstructed jets, as illustrated in Figure 5.9. To mitigate this effect, the analysis requires the minimum azimuthal separation between any reconstructed jet and the $\mathbf{p}_T^{\text{miss}}$, denoted as $\min \Delta\phi(\mathbf{p}_T^{\text{jet}}, \mathbf{p}_T^{\text{miss}})$, to be greater than 0.4.

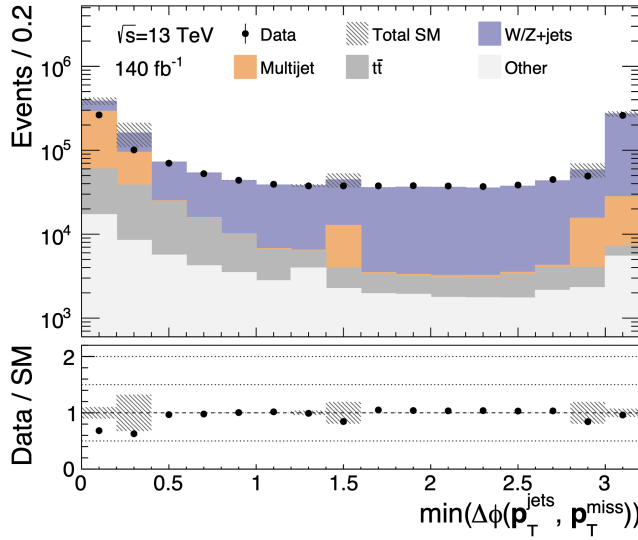


Figure 5.9 – Distribution of $\min \Delta\phi(\mathbf{p}_T^{\text{jet}}, \mathbf{p}_T^{\text{miss}})$ after requiring jet $p_T > 250$ GeV and $E_T^{\text{miss}} > 300$ GeV. Multi-jet events often exhibit jet energy mismeasurements, resulting in $\min \Delta\phi(\mathbf{p}_T^{\text{jet}}, \mathbf{p}_T^{\text{miss}})$ values close to zero. From Ref. [89].

- Several SM processes produce neutrinos in the final state, including $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$, $W(\rightarrow \ell\nu) + \text{jets}$, di-boson, $t\bar{t}$, and single top production. Since neutrinos pass undetected through the ATLAS detector, these processes result in significant E_T^{miss} . Among them, the only processes that contribute significantly to the SRs and yield final states without visible electrons or muons are $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ and $W(\rightarrow \tau\nu) + \text{jets}$ with hadronically decaying τ leptons. In contrast, the presence of reconstructed

electrons or muons in the other processes can be exploited to suppress their contributions to the SRs. To achieve this, the variable $N(\ell_{\text{base}})$ is defined as the number of leptons that satisfy the baseline selection criteria outlined in Table 5.2. Events containing reconstructed leptons are vetoed by requiring $N(\ell_{\text{base}}) = 0$. Although the lightest chargino predominantly decays into a charged pion, a non-negligible fraction of decays to leptons occurs nonetheless, especially in scenarios with large mass splittings, as shown in Figure 5.6. For the mass differences relevant to this analysis, the resulting leptons are typically very soft and therefore often fail to pass the baseline lepton selection, avoiding exclusion by the lepton veto.

Despite the selections described above, the dataset can still contain events with significant *non-collision* background (NCB) contributions. This background arises from large energy depositions in the calorimeters caused by beam-induced particles produced by proton interactions with the LHC collimators or residual gas in the beam pipe, as well as by cosmic ray muons. A defining characteristic of non-collision background is that it does not conserve transverse momentum, resulting in large “fake” $E_{\text{T}}^{\text{miss}}$ oriented opposite to the particles interacting with the ATLAS detector, and jets exhibiting anomalous features. Jets originating from NCB can be identified by examining their shower shape and direction relative to the interaction point, or by the absence of associated tracks. The latter can be quantified by the ratio of the total p_{T} of associated tracks to the total energy of the jet. To mitigate NCB contamination, ATLAS analyses typically impose a set of *loose* jet quality criteria, which involve variables such as the pulse shape of the energy deposits in calorimeter cells, the electromagnetic energy fraction, the maximum fraction of the jet energy collected by a single calorimeter layer, and the charged-particle fraction. Because the analysis presented here is particularly sensitive to residual NCB contributions, an additional cleaning strategy — based on the approach of Ref. [218], where a search for “mono-jet” event topologies is performed — is adopted. Specifically, in addition to the *loose* cleaning, the leading jet is required to meet the *tight* working point criteria defined in Ref. [219]: the ratio of the jet charged-particle fraction to the maximum fraction of the jet energy collected by a single calorimeter layer is required to be larger than 0.1. Figure 5.10 shows the distribution of the azimuthal angle ϕ of the missing transverse momentum before and after applying this requirement. Non-collision is evident as two pronounced peaks in data near $|\phi| = 0$ and $|\phi| = \pi$, corresponding to azimuthal directions where most cosmic muons enter the ATLAS detector. The peaks disappear once the tight WP criteria are applied to the leading jet, resulting in good agreement between data and MC simulations across the entire ϕ spectrum.

5.4.2 Track selection

For each event satisfying the selections outlined in Section 5.4.1, additional, more stringent requirements are applied to identify tracks originating from chargino and neutralino decays, while suppressing SM backgrounds.

- In pp collisions recorded by the ATLAS detector, numerous interactions can occur simultaneously, leading to a high density of hits in the Inner Detector. This can

5.4. EVENT AND TRACK SELECTION

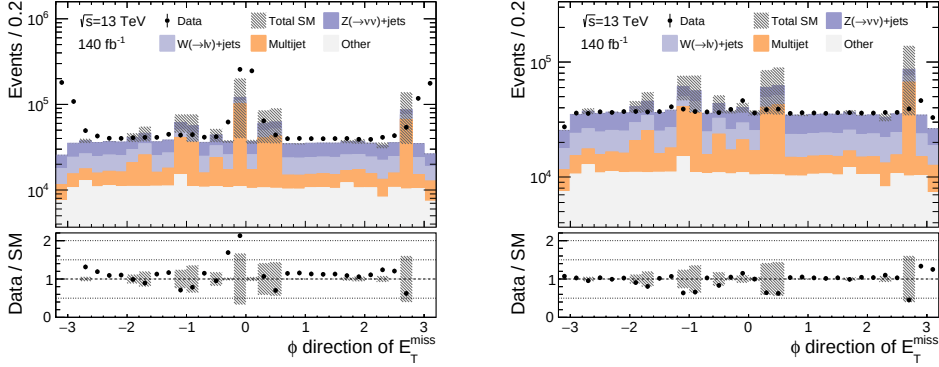


Figure 5.10 – Distribution of the azimuthal angle ϕ of the missing transverse momentum before (left) and after (right) enforcing the tight working point criteria on the leading jet [89]. Prior to the cleaning, two peaks appear in data near $|\phi| = 0$ and $|\phi| = \pi$, due to non-collision background effects. These peaks vanish after applying the tight jet cleaning. Residual contributions localised at $|\phi| = \pi$ are suppressed once the cut on $\min \Delta\phi(\mathbf{p}_T^{\text{jet}}, \mathbf{p}_T^{\text{miss}})$ is imposed.

result in the reconstruction of “fake” tracks from random combination of hits, which are typically characterised by large impact parameters. To suppress them, signal candidate tracks are required to satisfy the Tight Primary working point criteria, as defined in Table 4.1. The Tight Primary requirement significantly reduces the fake rate while maintaining a high tracking efficiency (Section 4.1.1). Additionally, because the expected higgsino lifetime is short enough for its decays to occur well within the beam pipe, tracks are required to exhibit at least one hit on the IBL detector [124], the ID innermost layer.

- Tracks originating from low- p_T particles produced in pileup interactions or by QCD processes represent a major background for the analysis. These tracks emerge from vertices distributed randomly along the beam axis, and are more likely to be emitted in the forward region. To suppress them, three selection criteria are applied. First, tracks are required to be within central regions of the detector, with pseudorapidity $|\eta| < 1.5$. Second, they must satisfy $|\Delta z_0 \sin \theta| < 1.5$ mm, ensuring proximity to the primary vertex along the beam axis. Here, z_0 is the longitudinal impact parameter, while θ represents the track polar angle. Lastly, given the average higgsino lifetime of the order of $\mathcal{O}(0.1 - 10)$ mm, the transverse impact parameter is required to be less than 10 millimeters, $|d_0| < 10$ mm. Depending on the mass splitting hypothesis under consideration, the resulting combined signal selection efficiency of these criteria ranges from approximately 80% to nearly 100%.
- Due to the boost imparted by the ISR leading jet, pion tracks originating from higgsino decays are expected to be aligned with the missing transverse momentum. Therefore, an upper bound on their azimuthal separation, $|\Delta\phi(\mathbf{p}_T^{\text{track}}, \mathbf{p}_T^{\text{miss}})| < 0.4$,

is imposed.

- Among the metastable particles produced by Standard Model processes, τ leptons, strange hadrons, and B/D mesons have lifetimes comparable to those of the higgsinos, allowing them to leave tracks similar to those belonging to the signal of interest. Figure 5.11 illustrates the decay topology of such particles. Notably, 1-prong τ tracks constitute an irreducible background for this analysis. The strategy to estimate their rate in the SRs is discussed in Section 5.5. On the other hand, 3-prong τ decay tracks and tracks from strange hadrons or B/D mesons can be efficiently reduced by measuring the hadronic activity surrounding the candidate signal track. To this end, a track-based isolation criterion is applied. It requires that no other Tight Primary track with $p_T > 1.5$ GeV, $|\Delta z_0 \sin \theta| < 1.5$ mm, and $|d_0| < 1.5$ mm is found within a cone of radius $\Delta R = 0.4$ centered on the candidate signal track. Furthermore, in cases of tracks originating from decays of neutral strange hadrons like K_S^0 or Λ^0 , secondary decay vertices are reconstructed using mass-constrained fits [157, 220, 221]. Tracks associated to secondary vertices consistent with the decays $\Lambda^0 \rightarrow p\pi^-$, $\bar{\Lambda}^0 \rightarrow \bar{p}\pi^+$, or $K_S^0 \rightarrow \pi^+\pi^-$, are subsequently vetoed to suppress any remaining contribution that survives the track-based isolation.
- Despite the above selections, an overwhelming number of QCD tracks still survives at very low transverse momentum. Applying a simple lower p_T threshold of 1 GeV significantly reduces this background. Further optimisation of the track p_T selection toward to SR definition is performed in the next Section.
- If an event contains multiple tracks passing all the above selections, only the track with the largest transverse impact parameter significance $S(d_0)$ is retained, while all the others are discarded.

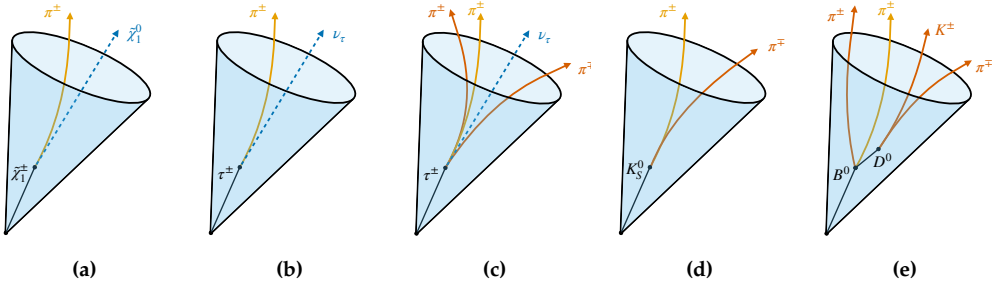


Figure 5.11 – Track-level topology of (a) chargino decay, (b) 1-prong τ decay, (c) 3-prong τ decay, (d) neutral kaon K_S^0 decay, and (e) neutral meson B^0 decay. The orange arrow indicates the signal candidate track. Red arrows represent other particle within a cone of radius $\Delta R = 0.4$ centered around the signal candidate track, and that may cause the track-based isolation requirement to fail. Invisible particle inside the cone are shown as dashed blue lines.

5.4.3 Signal Region definition

Since achieving a background-free condition is neither possible nor desirable, a potential signal is always sought by testing whether the observed data within a specific phase space region is compatible with a statistical fluctuation of the SM backgrounds. Signal Regions (SRs) are therefore defined as regions enriched in signal events relative to SM background expectations. To identify the optimal selections that define the SRs and maximise the discrimination between signal and background, an optimisation procedure is performed. This involves a multidimensional scan over all possible selections on the various analysis variables of interest. For each candidate selection, it is assumed that the number of observed events equals the sum of all SM background events plus the SUSY signal events, allowing the evaluation of their statistical compatibility under the background-only hypothesis. Because this optimisation is performed prior to the actual background estimation, the expected background rates are taken directly from MC simulations without any data-driven corrections, and a total uncertainty of 10% is assigned to the predicted yields. The statistical significance (Z) of a BSM signal is defined as [222]

$$Z = \begin{cases} +\sqrt{2 \left(n \ln \left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2} \right] - \frac{b^2}{\sigma^2} \ln \left[1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)} \right] \right)} & \text{if } n \geq b \\ -\sqrt{2 \left(n \ln \left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2} \right] - \frac{b^2}{\sigma^2} \ln \left[1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)} \right] \right)} & \text{if } n < b \end{cases}, \quad (5.2)$$

where b is the expected number of background events with uncertainty σ , and n is the total number of observed events (signal plus background). SRs are defined by identifying the set of selections that maximise Z . Among the variables considered in the analysis, the missing transverse energy E_T^{miss} , the significance of the track impact parameter $S(d_0)$, and the track transverse momentum p_T provide the strongest discrimination between signal and backgrounds. These variables are therefore included in the multidimensional optimisation scan, as shown in Figure 5.12. Consequently, SRs are designed with the requirements $E_T^{\text{miss}} > 600$ GeV, $S(d_0) > 8$, and $p_T \in [2, 5]$ GeV. The upper threshold on the track p_T helps reducing contributions from τ decay tracks, which tend to have higher transverse momenta compared to both QCD and signal tracks (see Section 5.5 for a more in-depth discussion about the classification of the background sources). To further enhance the sensitivity to signals with different mass splitting hypotheses, the SR is subdivided into two $S(d_0)$ bins. For scenarios with a small mass difference between the lightest chargino and neutralino, where the higgsino lifetime is relatively long, a larger $S(d_0)$ value is expected. This motivates the definition of **SR-High** with a stricter requirement of $S(d_0) > 20$. Conversely, for large mass splittings leading to shorter higgsino lifetimes and consequently smaller $S(d_0)$ values, **SR-Low** is defined with a looser selection, $8 < S(d_0) < 20$.

5.5 Background Estimation

By construction, Signal Regions (SRs) are enriched in potential signal events. At the same time, they must contain enough statistics to avoid being biased toward phase

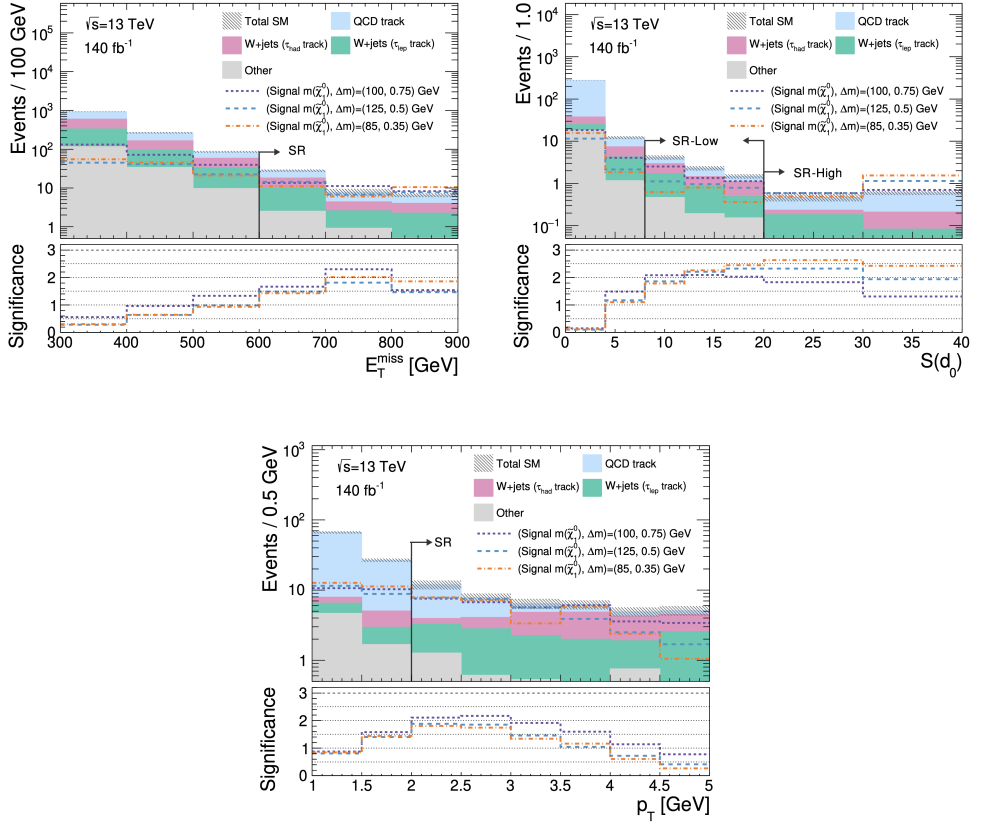


Figure 5.12 – E_T^{miss} (top-left), track $S(d_0)$ (top-right), and track p_T (bottom) distributions after applying $S(d_0) > 8$ and $p_T \in [2, 5]$ GeV, $E_T^{\text{miss}} > 600$ GeV and $p_T \in [2, 5]$ GeV, and $S(d_0) > 8$ and $E_T^{\text{miss}} > 600$ GeV, respectively. The stacked filled histograms represent SM backgrounds, while SUSY signals are shown as dashed lines. The hatched area indicates MC statistical uncertainties. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, di-boson, $t\bar{t}$, single top, and multi-jet production. The bottom panel shows the statistical significance Z calculated by accumulating the yields of bins to the right, assuming a total 10% background uncertainty. From Ref. [89].

space regions with zero or near-zero background events, which could simply be statistical fluctuations in the MC simulations. As a result, SRs always have some contamination from SM background processes, which must be accurately estimated before any claim of excess in data can be made. To prevent bias in the definition of the SRs and in the test statistic used for hypothesis testing, the SRs are initially *blinded*: their data content is not examined until the background is well constrained. To estimate the background contributions, a set of **Control Regions** (CRs) is defined. CRs are regions of phase space kinematically close to the SRs but with negligible signal contamination. They are employed in one of two ways. In a partially data-driven approach, MC background predictions are normalised to the observed data in the CRs, deriving normalisation factors that are subsequently applied to the SRs to adjust the nominal MC predicted yields. In a fully data-driven approach, no MC simulations are used instead and background estimates in the SR are derived by extrapolating a background template constructed directly from the data events in the CRs. To validate the accuracy of the normalisation procedure or the template-based extrapolation, a set of **Validation Regions** (VRs) is also defined. VRs are kinematic regions closer to the SRs than the CRs and are chosen to have the lowest signal contamination as possible. Once the background modelling is confirmed through the VRs, the SRs can be unblinded, allowing examination of their data content to check for any potential excess.

5.5.1 Background components

The main backgrounds in this analysis arise from soft displaced tracks in $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ and $W(\rightarrow \ell\nu) + \text{jets}$ events. Although the background composition within the Signal Regions (SRs) varies with the exact $S(d_0)$ selection, two major categories can be identified.

- Tracks originating from soft initial- or final-state radiation, interactions between partons other than those involved in the hard scatter, or from pileup vertices form the main source of low- p_T mildly-displaced tracks in both $Z + \text{jets}$ and $W + \text{jets}$ processes. In the following, these tracks will be always referred to as “QCD tracks”. Characterised by large impact parameters and low p_T , QCD tracks tend to dominate SR-High but become less relevant at lower $S(d_0)$ values. Since accurately modelling particles generated by QCD interactions is challenging, MC simulations alone are not reliable for estimating their contribution. Therefore, a fully data-driven approach is employed to estimate the rate of QCD tracks in the SRs.
- Produced in $W(\rightarrow \tau\nu) + \text{jets}$ decays, tracks originating from hadronic or leptonic τ decays represent the second background process that contaminates the SRs. Due to their relatively long lifetime, τ leptons produce displaced pions and leptons when decaying (Figure 5.11). Such particles are fully reconstructed as tracks and, since τ leptons are emitted mostly opposite the W boson’s direction, they tend to have relatively low momentum. Consequently, the lepton veto adopted to define the SRs is not fully efficient at suppressing this background source, mainly because of the p_T threshold and the reduced lepton reconstruction efficiency at low p_T . The τ background is estimated using a semi data-driven approach. MC simulations, which accurately model τ decays via the electroweak interaction, provide the expected

yields in dedicated CRs. The MC nominal predictions are then normalised to data to correct for potential mismodelling, and the derived normalisation factors are extrapolated to the SRs.

Tracks in other SM processes, such as $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson, have minor impact on both SR-Low and SR-High and are therefore estimated directly from simulation samples.

5.5.2 Fully data-driven estimation of QCD tracks

The contribution of QCD tracks in the $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ and $W(\rightarrow \ell\nu) + \text{jets}$ processes — collectively referred to as “ $V + \text{jets}$ ” processes — to the SRs is estimated using a fully data-driven approach, based on the “ABCD” method [223, 224]. This approach relies on the assumption that QCD tracks originating from the underlying event or pileup vertices are independent of the weak boson decays. Consequently, because tracking information is uncorrelated to the topology of the event, equivalent track variable distributions can be extracted from regions dominated by $V + \text{jets}$ processes with different decays. In particular, the shape of the $S(d_0)$ distribution can be extracted from an inclusive- $S(d_0)$ region where $Z(\rightarrow \ell\ell) + \text{jets}$ or $W(\rightarrow \ell\nu) + \text{jets}$ decays occur ($N(\ell_{\text{base}}) \neq 0$), and then normalised to the data in a low- $S(d_0)$ CR, defined by $S(d_0) < 8$ and vetoing leptons, to obtain the QCD track estimate in the SRs. For this approach to work, leptons from weak boson decays must be treated as invisible to mimic the “ $E_T^{\text{miss}} + \text{jets}$ ” signature required in the SRs. This is achieved by defining the variable $\mathbf{p}_T^{\text{recoil}}$, which approximates the missing transverse momentum by adding the transverse momentum vectors of the leptons in the event to the $\mathbf{p}_T^{\text{miss}}$. In the SRs, where no leptons are present, the magnitude of $\mathbf{p}_T^{\text{recoil}}$, indicated as p_T^{recoil} , is effectively equivalent to the E_T^{miss} . Applying selections on $\mathbf{p}_T^{\text{recoil}}$ ensures consistent final-state topologies between the 0ℓ category and other categories containing leptons. For each category used in this analysis, the $V + \text{jets}$ final-state decay topology is illustrated in Figure 5.13 alongside the definition of $\mathbf{p}_T^{\text{recoil}}$.

The $Z(\rightarrow \ell\ell) + \text{jets}$ process closely resembles the $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ one, except for the final-state decay mode involving two charged leptons instead of neutrinos. Both processes share similar weak boson kinematics, allowing the $Z(\rightarrow \ell\ell) + \text{jets}$ process to be potentially used for extrapolating the $S(d_0)$ template for QCD tracks in the SRs. However, the branching ratio for $Z(\rightarrow \ell\ell) + \text{jets}$ is approximately five times smaller than that for $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ [38], resulting in limited statistics and significant uncertainties on the $S(d_0)$ template computation. To improve statistical precision and obtain reliable estimates, regions dominated by the $W(\rightarrow \mu\nu) + \text{jets}$ process are used instead. A “ 1μ ” category is defined by selecting events passing the E_T^{miss} trigger, containing exactly one muon satisfying signal criteria from Table 5.2 with $p_T(\mu) > 10$ GeV, and having transverse mass $m_T \in [56, 106]$ GeV, consistent with W boson decays. The transverse mass is defined as $m_T = \sqrt{2p_T(\ell)E_T^{\text{miss}}(1 - \cos \Delta\phi(\ell, \mathbf{p}_T^{\text{miss}}))}$, where $p_T(\ell)$ is the lepton’s transverse momentum. The $\mathbf{p}_T^{\text{recoil}}$ for the 1μ category is calculated as the vector sum of $\mathbf{p}_T^{\text{miss}}$ and the muon’s transverse momentum: $\mathbf{p}_T^{\text{recoil}} = \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T(\mu)$. To further increase statistics, the p_T^{recoil} selection is relaxed to 300 GeV. Additionally, all track-level selections from Section

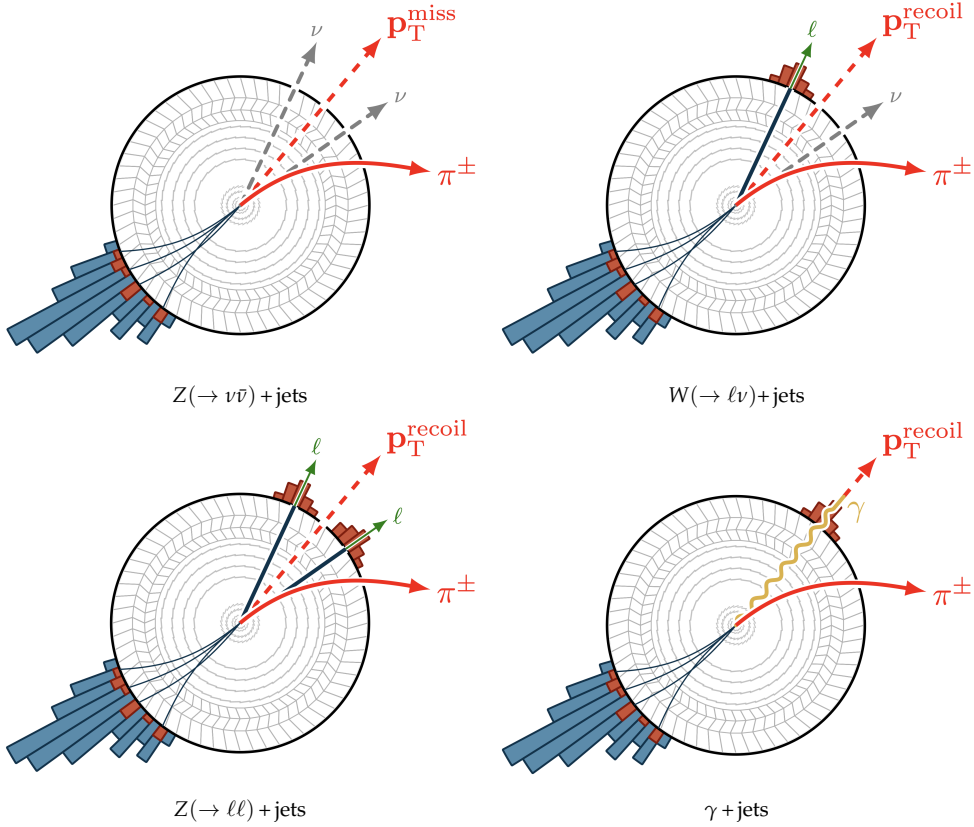


Figure 5.13 – Schematic of the event topology for different $V + \text{jets}$ processes in the ATLAS detector [89]. The outer part of the circle shows the calorimeter system, while the inner part displays the Inner Detector. The red and blue bars represent the energy measured by the hadronic and electromagnetic calorimeters, respectively. Thick blue lines indicate tracks from leptons, which must be removed from the event to ensure consistent event topology across different $V + \text{jets}$ processes. Although leptons and photons also deposit energy in the calorimeter, the energy deposits do not need to be removed since signal tracks are defined without using calorimeter information.

5.4.2 are applied, and tracks associated with the reconstructed muons are removed to mimic the 0ℓ topology. To prevent photon conversion tracks with large impact parameter to populate the 1μ category and bias the extrapolation of the $S(d_0)$ template, a minimum separation ΔR of 0.04 between tracks and muons is required, achieving almost 98% reduction of the undesired tracks. The $S(d_0)$ template is extracted from the 1μ category for each SR bin by computing two **Transfer Factors** (TFs) as the ratio of QCD track yields between CRs with $S(d_0) < 8$ and corresponding CRs with higher $S(d_0)$ values. Specifically, the TF for SR-High is calculated as

$$\text{TF}_{\text{SR-High}} = \frac{N_{\text{CR-1}\mu\text{-High}}^{\text{data}} - N_{\text{CR-1}\mu\text{-High}}^{\text{non-QCD-track}}}{N_{\text{CR-1}\mu}^{\text{data}} - N_{\text{CR-1}\mu}^{\text{non-QCD-track}}}, \quad (5.3)$$

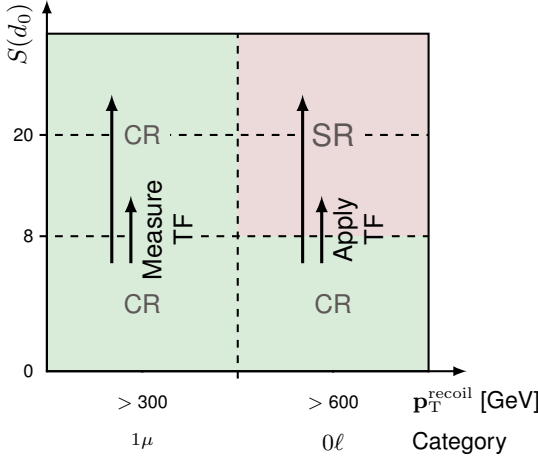


Figure 5.14 – Schematic illustration of the region definitions in the 0ℓ and 1μ categories. Regions with $S(d_0) > 8$ are further divided into two bins separated by a boundary at $S(d_0) = 20$. The green (red) area represents the CRs (SRs) used to estimate the contribution from QCD tracks. The TF for each $S(d_0)$ bin is calculated as the ratio between the CR yields in the 1μ category, as indicated by the arrow on the left. These TFs are then multiplied by the CR yields in the 0ℓ category to estimate the QCD track background in the SRs.

while the TF for SR-Low is given by

$$\text{TF}_{\text{SR-Low}} = \frac{N_{\text{CR-}1\mu\text{-Low}}^{\text{data}} - N_{\text{CR-}1\mu\text{-Low}}^{\text{non-QCD-track}}}{N_{\text{CR-}1\mu}^{\text{data}} - N_{\text{CR-}1\mu}^{\text{non-QCD-track}}} . \quad (5.4)$$

Here, $N_{\text{CR-}1\mu\text{-High}}^{\text{data}}$ ($N_{\text{CR-}1\mu\text{-Low}}^{\text{data}}$) represents the observed data yields in the one-muon category CR- 1μ -High (CR- 1μ -Low), defined by requiring $S(d_0) > 20$ ($8 < S(d_0) < 20$). The quantity $N_{\text{CR-}1\mu}^{\text{data}}$ corresponds instead to the observed data in the CR- 1μ with $S(d_0) < 8$. Similar $S(d_0)$ selections are applied to define the expected yields of non-QCD tracks, indicated by the superscript “non-QCD-track”, and which are taken from Monte Carlo simulations. Figure 5.14 schematically illustrates the TFs computation from the 1μ regions and the extrapolation of the $S(d_0)$ shape used to estimate the QCD tracks in the SRs. QCD track yields in the SRs are obtained by multiplying the TFs by the data yields, subtracted of the expected non-QCD track from MC simulations, in the adjacent CR- 0ℓ , defined by $E_T^{\text{miss}} > 600$ GeV and $S(d_0) < 8$:

$$\begin{aligned} N_{\text{SR-High}}^{\text{QCD tracks}} &= \text{TF}_{\text{SR-High}} \times (N_{\text{CR-}0\ell}^{\text{data}} - N_{\text{CR-}0\ell}^{\text{non-QCD-track}}) , \\ N_{\text{SR-Low}}^{\text{QCD tracks}} &= \text{TF}_{\text{SR-Low}} \times (N_{\text{CR-}0\ell}^{\text{data}} - N_{\text{CR-}0\ell}^{\text{non-QCD-track}}) . \end{aligned} \quad (5.5)$$

Validation Regions

As with the background estimation, the TFs validation strategy relies on the assumption that tracking information is uncorrelated with both the energy scale and the hard-scatter process. Validation of the $S(d_0)$ template is therefore performed using $W(\rightarrow e\nu) + \text{jets}$ and $Z(\rightarrow \ell\ell) + \text{jets}$ events, which define the “ $1e$ ” and “ 2ℓ ” categories, respectively. The $1e$ category requires events to pass a single-electron trigger [225], and to have exactly one electron satisfying the signal selection criteria in Table 5.2 with $p_T > 30$ GeV and transverse mass $m_T \in [56, 106]$ GeV. The 2ℓ category targets events with two signal

leptons - either electrons (single-electron trigger) or muons (E_T^{miss} trigger) - from the decay of a Z boson, with and invariant mass in the range $m_{\ell\ell} \in [66.2, 116.2]$ GeV. In both cases, $\mathbf{p}_T^{\text{recoil}}$ is defined as the vector sum of the missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ and the transverse momenta of the reconstructed leptons. Due to relatively low production cross sections, both categories are expected to suffer from limited statistics. To mitigate this, the p_T^{recoil} selection is again relaxed to 300 GeV. Additional validation is performed using γ + jets events in a “1 γ ” category, which is defined by requiring exactly one signal photon with $p_T > 200$ GeV passing a single-photon trigger [225] selection. Approximately 70% of the events in this category originate from γ + jets, with the remaining 30% from multi-jet production. Owing to the significantly higher cross section of γ + jets compared to weak boson production, the 1 γ category offers high-statistics regions that are predominantly populated by QCD tracks. As such, it allows validation of the TFs in the high- p_T^{recoil} regime ($p_T^{\text{recoil}} > 600$ GeV). In all three categories - 1e, 2 ℓ , and 1 γ - track selections described in Section 5.4.2 are applied. Additionally, tracks associated with the reconstructed leptons or photon are removed, and a minimum angular separation $\Delta R > 0.04$ between tracks and leptons/photons is enforced to remove contributions from photon conversion tracks. Following the same procedure used in the background estimation, TFs derived from the 1 μ CRs are applied to data in the $S(d_0) < 8$ regions of the 1e, 2 ℓ , and 1 γ categories - referred to as CR-1e, CR-2 ℓ , and CR-1 γ , respectively. The extrapolated yields are used to estimate the contribution from QCD tracks in the validation region bins with $S(d_0) > 20$ ($8 < S(d_0) < 20$), denoted as VR-1e-High (-Low), VR-2 ℓ -High (-Low), and VR-1 γ -High (-Low) for the respective categories. In all CRs and VRs for the estimation of the QCD tracks, the contribution of the τ decay tracks is sufficiently small to be reliably estimated directly from MC simulations, while signal contamination is found to be below 5%. Table 5.3 summarises the selection criteria adopted to define all CRs and VRs for the validation of the QCD track transfer factors.

The background estimation and validation strategy for QCD tracks, as discussed in this Section, is summarised below.

1. The $S(d_0)$ template is extracted from data in the 1 μ category regions, enriched in $W(\rightarrow \mu\nu)$ + jets events, to calculate the TFs for each SR bin.
2. The TFs are validated in the 1e and 2 ℓ categories, enriched in $W(\rightarrow e\nu)$ + jets and $Z(\rightarrow \ell\ell)$ + jets processes, respectively. Due to the low production cross sections of these processes, validation is performed in the low- p_T^{recoil} regime only to achieve sufficient statistical precision.
3. To validate the TFs in the high- p_T^{recoil} regime, the 1 γ category, comprising approximately 70% of events from γ + jets process, is used.

Figure 5.15 provides a schematic overview of all the CRs and VRs used to extrapolate and validate the $S(d_0)$ template across the various categories.

Variable	0ℓ	1μ	$1e$	2ℓ	1γ
Trigger	E_T^{miss}	E_T^{miss}	Single- e	E_T^{miss} or Single- e	Single- γ
$N(\ell_{\text{base}})$	$= 0$	$= 1$	$= 1$	$= 2$	-
$N(\ell_{\text{sig}})$	$= 0$	$= 1$	$= 1$	$= 2$	-
$N(\gamma)$	-	-	-	-	$= 1$
$p_T(\ell_1)$ [GeV]	-	> 10	> 30	$p_T(\mu) > 10, p_T(e) > 30$	-
$p_T(\ell_2)$ [GeV]	-	-	-	> 10	-
$p_T(\gamma)$ [GeV]	-	-	-	-	> 200
m_T [GeV]	-	[56, 106]	[56, 106]	-	-
$m_{\ell\ell}$ [GeV]	-	-	-	[66.2, 116.2]	-
	SR(CR- 0ℓ)	CR- 1μ	VR(CR)- $1e$	VR(CR)- 2ℓ	VR(CR)- 1γ
p_T^{recoil} [GeV]	> 600	> 300	> 300	> 300	> 600
Track $S(d_0)$	$> 8 (< 8)$	Inclusive	$> 8 (< 8)$	$> 8 (< 8)$	$> 8 (< 8)$

Table 5.3 – Selection criteria applied across the different categories to define SRs, CRs, and VRs for the calculation and validation of QCD track transfer factors. Only selections orthogonal to the SRs are listed. The track-level selection is omitted as it is identical across all categories.

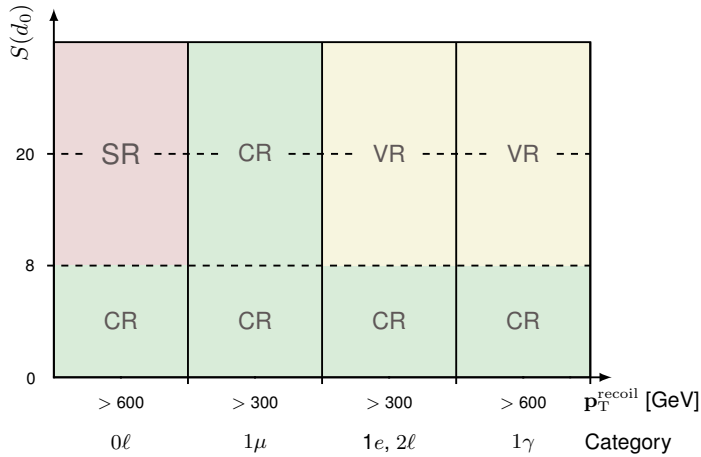


Figure 5.15 – Schematic illustration of the region definitions used to validate the measured transfer factors (TFs). Regions with $S(d_0) > 8$ are further divided into two bins, separated by a boundary at $S(d_0) = 20$. The yellow area highlights the VRs employed to validate the QCD tracks estimation in different $V + \text{jets}$ topologies. Adapted from Ref. [182].

Results in Validation Regions

The yields in the VRs are estimated via a background-only fit that includes the VRs. Table 5.4 and Table 5.5 present the post-fit yields for the $S(d_0) > 8$ and $8 < S(d_0) < 20$ VR bins, respectively. Post-fit distributions are available in Ref. [89]. In all cases, post-fit SM predictions agree with the observed data within 1.5σ , indicating a good modelling of the QCD track background and supporting the assumption of no correlation between tracking variables and event-level features.

	VR-1e-High	VR-2 ℓ -High	VR-1 γ -High
Observed data	79	39	33
SM prediction	80 ± 10	49 ± 7	28 ± 4
QCD track	64 ± 10	46 ± 7	28 ± 4
$W(\rightarrow \tau_h \nu) + \text{jets}$	0.16 ± 0.12	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	< 0.1	-	-
Other	16.4 ± 3.0	2.7 ± 1.0	-

Table 5.4 – Number of expected and observed data events in the high- $S(d_0)$ VRs. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

	VR-1e-Low	VR-2 ℓ -Low	VR-1 γ -Low
Observed data	106	58	40
SM prediction	121 ± 11	69 ± 7	39 ± 5
QCD track	89 ± 11	65 ± 8	39 ± 5
$W(\rightarrow \tau_h \nu) + \text{jets}$	< 1	-	< 0.1
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	< 1	-	< 0.1
Other	30.9 ± 6.2	4.4 ± 1.2	< 0.1

Table 5.5 – Number of expected and observed data events in the low- $S(d_0)$ VRs. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due the limited statistics of the CRs.

5.5.3 Semi data-driven estimation of τ decay tracks

The $W(\rightarrow \tau\nu) + \text{jets}$ process constitutes the most significant SM background in SR-Low and provides non-negligible contribution to SR-High. Two types of signal-like tracks may originate from it: τ decay tracks and QCD tracks, with the latter estimated as described in

the previous Section. Hadronic and leptonic τ decay tracks are estimated using a partially data-driven method that relies on dedicated CRs adjacent to the SRs to normalise the nominal MC predictions to the observed data, thereby deriving a **Normalisation Factor** (NF).

As outlined in Section 5.4.3, SR bins in the 0ℓ category require track transverse momentum to lie within $2 < p_T < 5$ GeV. By raising this requirement to $8 < p_T < 20$ GeV, while keeping all the other track selection fixed, a region enriched in hadronic τ decay tracks (CR- τ_h) is obtained, as illustrated in Figure 5.16. The lower track p_T threshold of 8 GeV is chosen to reduce contamination from signal models with large mass splittings, which typically produce high- p_T tracks. Requiring the presence of final-state signal

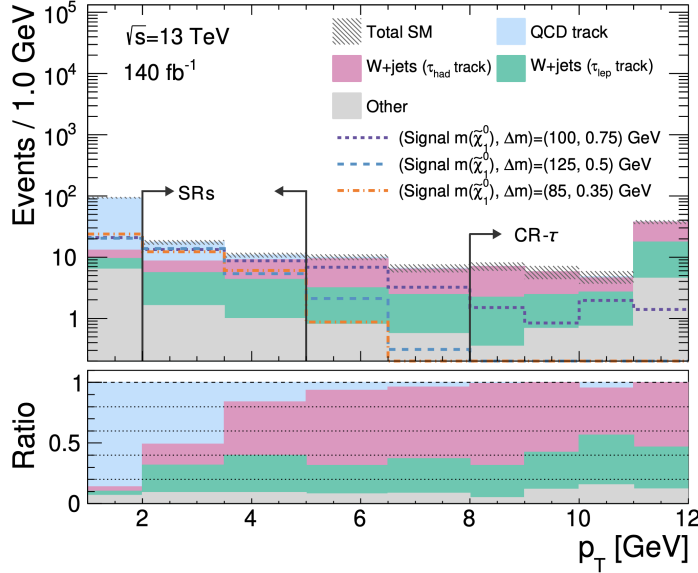


Figure 5.16 – Pre-fit track p_T distribution after applying all the SR selection criteria except the track p_T one. SM backgrounds are shown as filled stacked histograms, while dashed lines represent SUSY signals simulated for various mass and mass-splitting scenarios. The hatched band indicates the combined systematic and MC statistical uncertainties. The lower panel shows the relative background composition in each track p_T bin. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, di-boson processes, and multi-jet processes. From Ref. [89].

muons results in a selection dominated by $W(\rightarrow \mu\nu) + \text{jets}$ events, similar to the QCD track estimation. Alternatively, if exactly one baseline muon track is required — without imposing any selections on its transverse impact parameter — muons originating from leptonic τ decays can be selected, since they generally have $S(d_0) > 3$ (see Table 5.2). This defines a “ $1\mu_{\text{base}}$ ” category, a phase space predominantly populated by $W(\rightarrow \tau\nu) + \text{jets}$ events with leptonic τ decays, allowing better modelling of these decays compared to using CR- τ_h alone. Both CR- τ_h and CR- τ_ℓ are therefore used simultaneously to estimate

hadronic and leptonic τ decay tracks in the SRs by deriving a single NF², defined as

$$\text{NF} = \frac{N_{\text{data}} - N_{\text{non-}\tau\text{-tracks}}}{N_{\tau\text{-tracks}}} , \quad (5.6)$$

where N_{data} is the observed data yield, $N_{\tau\text{-tracks}}$ denotes the expected τ decay tracks from the MC simulation, and $N_{\text{non-}\tau\text{-tracks}}$ represents the total expected yield from tracks not originating from τ decays. This NF is then applied to the MC-predicted τ decay track yields in the SRs to correct the background estimates. To ensure robust background modelling, both CR- τ_h and CR- τ_ℓ require events to pass the E_T^{miss} trigger and satisfy the track selections outlined in Section 5.4.2. As previously mentioned, the track p_T selection is shifted to $8 < p_T < 20$ GeV in both CRs. To improve the statistical precision, a looser selection on the track impact parameter significance is applied: $S(d_0) > 3$, compared to $S(d_0) > 8$ used in the SR definition. In CR- τ_h , p_T^{recoil} corresponds to the missing transverse momentum, whereas in CR- τ_ℓ p_T^{recoil} is defined as the vector sum of the $\mathbf{p}_T^{\text{miss}}$ and the transverse momentum of the baseline muon. To suppress contributions from $W(\rightarrow \mu\nu) + \text{jets}$ decays and avoid contamination from other SUSY signals beyond those considered in this thesis, CR- τ_ℓ further requires the muon transverse mass to be less than 50 GeV. Table 5.6 summarises the selections applied to define the CRs for estimating the τ decay tracks. It also includes the definitions of the VRs and additional CRs used to validate the normalisation factor.

Variable	0ℓ			$1\mu_{\text{base}}$	
$N(\ell_{\text{base}})$	$= 0$			$= 1$	
$N(\mu_{\text{base}})$	$= 0$			$= 1$	
m_T [GeV]	-			< 50	
	SR-Low (-High)	CR- τ_h	CR2(VR)- τ_h	CR- τ_ℓ	CR2(VR)- τ_ℓ
p_T^{recoil} [GeV]	> 600	> 600	$[300, 400]$	> 600	$[300, 400]$
Track p_T [GeV]	$[2, 5]$	$[8, 20]$	$[8, 20] ([5, 8])$	$[8, 20]$	$[8, 20] ([5, 8])$
Track $S(d_0)$	$[8, 20] (> 20)$	> 3	> 3	> 3	> 3

Table 5.6 – Selection criteria applied across the 0ℓ and $1\mu_{\text{base}}$ categories to define SRs, CRs, and VRs for the calculation and validation of hadronic and leptonic τ decay track normalisation factor. Only selections orthogonal to the SRs are listed. The track-level selection is omitted as it is identical across all categories.

Validation Regions

In the low track p_T regime ($2 < p_T < 5$ GeV), QCD tracks and tracks from pions produced in the decays of SUSY higgsinos dominate. Therefore, the accuracy of extrapolating the

² Historically, separate NFs were applied separately to the hadronic and leptonic τ decays. However, as the individual NFs were found to be fully compatible within the uncertainties, a single combined NF was ultimately adopted to improve the stability of the statistical fit. Both CR- τ_h and CR- τ_ℓ were retained to take advantage of the increased statistical power, rather than relying solely on CR- τ_h .

NF measured in the high- p_T regime to the lower one is verified by applying it to the MC-predicted yields at intermediate track p_T values, $5 < p_T < 8$ GeV. However, for $p_T^{\text{recoil}} > 600$ GeV, signal contamination becomes too large in both the 0ℓ and $1\mu_{\text{base}}$ categories, preventing a reliable validation there. To address this, the NF validation is performed in the low- p_T^{recoil} regime by defining two additional control regions, denoted as $\text{CR}2\text{-}\tau_h$ and $\text{CR}2\text{-}\tau_\ell$ targeting the hadronic and leptonic τ decays, respectively. These CRs share the same definitions of $\text{CR}\text{-}\tau_h$ and $\text{CR}\text{-}\tau_\ell$ except for the p_T^{recoil} selection. A second NF is extracted from $\text{CR}2\text{-}\tau_h$ and $\text{CR}2\text{-}\tau_\ell$ and validated in two validation regions, $\text{VR}\text{-}\tau_h$ and $\text{VR}\text{-}\tau_\ell$, which are defined at intermediate track p_T ($5 < p_T < 8$ GeV) and with $300 < p_T^{\text{recoil}} < 400$ GeV. The key assumption here is that the τ decay track NF is independent from the p_T^{recoil} selection. If the validation the low- p_T^{recoil} regime is satisfactory, this provides confidence in extrapolating the NF from the high- p_T^{recoil} CRs to the SRs. Figure 5.17 presents a schematic overview of the estimation and validation strategy for the τ decay track NF.

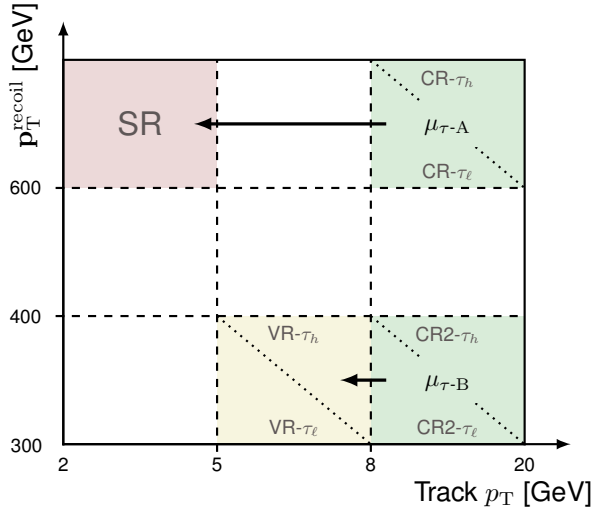


Figure 5.17 – Schematic illustration of the region definitions used for the estimation and validation of τ decay tracks. The red, green, and yellow areas indicate the SRs, CRs, and VRs, respectively. A single normalisation factor is constrained using two CRs in the high- p_T regime of the 0ℓ and $1\mu_{\text{base}}$ categories. This NF is extrapolated to the low- p_T regime and applied to the τ decay track yields in the SRs, as indicated by the arrow at the top. VRs are defined in the medium track p_T and low- p_T^{recoil} ranges of the 0ℓ and $1\mu_{\text{base}}$ categories to avoid potentially large signal contamination. A second NF is derived in the low- p_T^{recoil} regime and applied to the VR yields, as indicated by the arrow at the bottom of the figure. Adapted from Ref. [182].

The background estimation and validation strategies described in this Section are summarised below.

1. A single NF is defined to estimate both the hadronic and leptonic τ decay tracks in the SRs. This NF is measured in the high track p_T regime of the 0ℓ and $1\mu_{\text{base}}$

categories, where the 0ℓ CR is enriched in hadronic decays and the $1\mu_{\text{base}}$ CR is enriched in tracks from leptonic decays.

2. To validate the extrapolation of the NF from the high track p_T range ($8 < p_T < 20$ GeV) to the low track p_T range ($2 < p_T < 5$ GeV), a VR with $300 < p_T^{\text{recoil}} < 400$ GeV and intermediate track p_T ($5 < p_T < 8$ GeV) is defined. These selections minimise signal contamination. An additional NF, derived from the corresponding $\text{CR2-}\tau_h$ and $\text{CR2-}\tau_\ell$, is applied for this validation under the assumption that if the NF extrapolation is validated in this low- p_T^{recoil} regime, the same extrapolation from high- p_T^{recoil} CRs to the SRs is justified.

Results in Validation Regions

The yields in the VRs are estimated via the same background-only fit that also includes the CRs and VRs used for the QCD background estimation and validation. Table 5.7 shows the post-fit yields for $\text{VR-}\tau_h$ and $\text{VR-}\tau_\ell$. Post-fit distributions can be found in Ref. [89]. In all cases, the post-fit SM predictions agree with the observed data within 1σ , indicating a good modelling of both hadronic and leptonic τ decay track backgrounds.

	$\text{VR-}\tau_h$	$\text{VR-}\tau_\ell$
Observed data	839	304
SM prediction	848 ± 24	308 ± 18
QCD track	75 ± 12	14 ± 14
$W(\rightarrow \tau_h \nu) + \text{jets}$	449 ± 15	2.0 ± 1.0
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	209 ± 7	244 ± 10
Other	116 ± 13	47.7 ± 5.8

Table 5.7 – Number of expected and observed data events in the τ decay VRs. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

5.5.4 Simultaneous validation of QCD and τ decay tracks

Sections 5.5.2 and 5.5.3 presented the individual background estimation and validation for QCD and τ decay tracks, respectively. As a final step, a simultaneous validation of both background components is performed in a new set of VRs, designed to closely match the kinematics of the SRs, except for a relaxed E_T^{miss} requirement of $300 < E_T^{\text{miss}} < 400$ GeV. To this end, $\text{VR-}0\ell\text{-Low}$ and $\text{VR-}0\ell\text{-High}$ are defined using the same event-level and track-level selections as the SRs, but without the strict E_T^{miss} requirement. The estimation of the QCD track background in these VRs is carried out by applying the TFs derived from the 1μ CRs to data yields observed in a 0ℓ CR, defined with $S(d_0) < 8$ and $300 < E_T^{\text{miss}} < 400$ GeV. Concurrently, the NF obtained from $\text{CR2-}\tau_h$ and $\text{CR2-}\tau_\ell$ is applied to the τ

decay tracks to correct the nominal MC predictions. Figure 5.18 provides a schematic overview of the new VRs, along with the corresponding TFs and NF used for validating both background components in VR-0 ℓ -Low and VR-0 ℓ -High. Signal contamination is found to be as high as 12% in VR-0 ℓ -Low and 16% in VR-0 ℓ -High; however, these levels are considered acceptable for the purposes of validation. The post-fit yields in these regions are summarised in Table 5.8. The strong agreement between the observed data and the SM predictions reinforces confidence in the overall background modelling and supports the validity of the TFs and NF used to obtain the correct background estimates in the SRs.

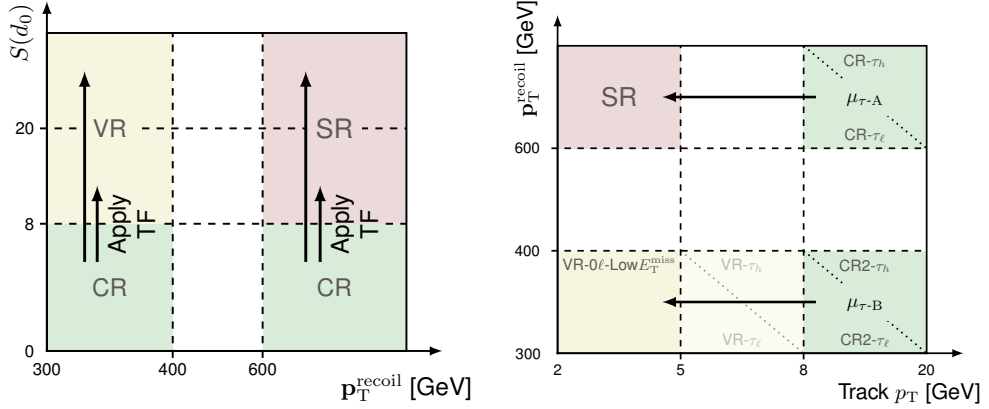


Figure 5.18 – Schematic illustration of the region definitions used for the simultaneous validation of the QCD track (left) and τ decay track (right) backgrounds. The red, green, and yellow areas indicate the SRs, CRs, and VRs, respectively. To reduce signal contamination, an upper bound of 400 GeV is applied to the p_T^{recoil} range. Regions with $S(d_0) > 8$ are divided into two bins, with a boundary at $S(d_0) = 20$. TFs for QCD tracks are derived from CR yields in the low- p_T^{recoil} range and used to estimate the yields in the VRs. Similarly, the NF for τ decay tracks is obtained in the low- p_T^{recoil} region and applied to the corresponding VR yields.

	VR-0 ℓ -Low	VR-0 ℓ -High
Observed data	736	343
SM prediction	740 ± 40	351 ± 33
QCD track	298 ± 35	213 ± 32
$W(\rightarrow \tau_h \nu) + \text{jets}$	194 ± 10	59 ± 5
$W(\rightarrow \tau_l \nu) + \text{jets}$	165 ± 8	44.1 ± 3.4
Other	82 ± 9	35 ± 4.2

Table 5.8 – Number of expected and observed data events in VR-0 ℓ -Low and VR-0 ℓ -High. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

5.5.5 Summary of the Validation Regions

A comprehensive summary of all the VRs described in the previous sections is shown in Figure 5.19. The statistical significance S , used to quantify the difference between the observed data n_{obs} and the expected post-fit SM backgrounds, n_{exp} is defined as

$$S = \frac{n_{\text{obs}} - n_{\text{exp}}}{\sigma_{\text{total}}} , \quad (5.7)$$

where σ_{total} is the total uncertainty on the SM background expectation, including both statistical and systematic contributions. Across all VRs, the observed discrepancies are less or equal to 1σ , indicating the excellent modelling of both the QCD tracks and the hadronic and leptonic τ decay track backgrounds.

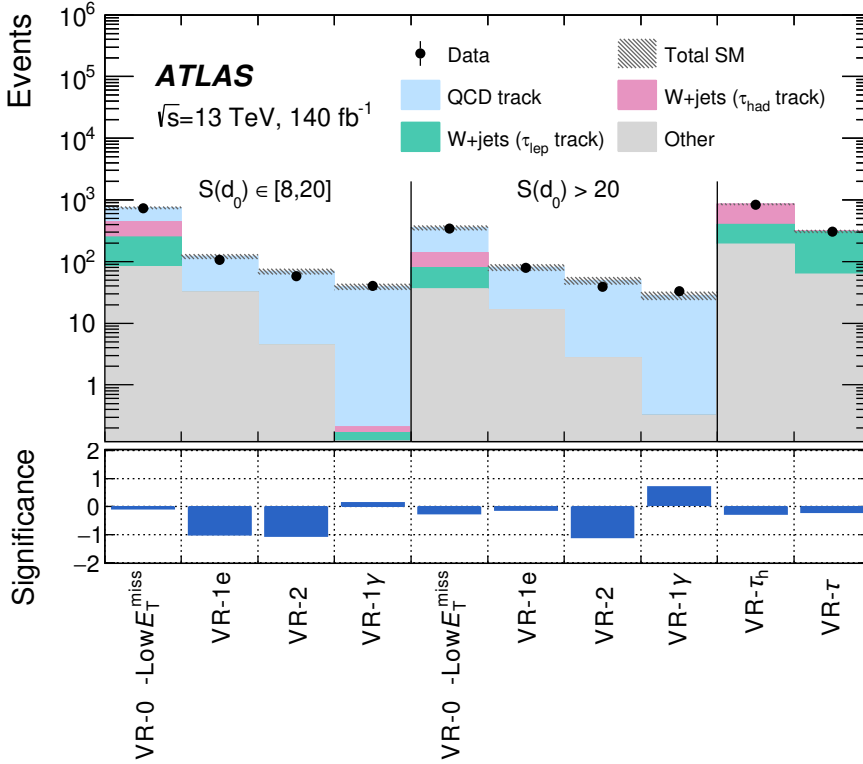


Figure 5.19 – Comparisons of the observed data and the expected post-fit SM backgrounds in the VRs. The hatched band indicates the total uncertainty on the SM background expectation, including both statistical and systematic uncertainties. The bottom panel shows the statistical significances of the discrepancy between the expected and the observed event yields. From Ref. [182].

5.6 Systematic Uncertainties

The sensitivity of the analysis presented here is primarily limited by statistics, due to the limited data collected by the ATLAS detector during Run 2 and the stringent selections applied to both events and tracks. Systematic uncertainties can still contribute non-negligibly and affect the final results in the SRs. These systematic uncertainties stem from various sources and can be grouped into three main categories: experimental, theoretical, and analysis-specific uncertainties.

5.6.1 Experimental uncertainties

Experimental uncertainties are evaluated for all Monte Carlo samples to account for potential mismodelling of the detector response, imperfections in the calibration of physics objects, as well as uncertainties in luminosity measurements and pileup. Since QCD tracks in V + jets events are estimated via a fully data-driven approach, they are not subject to these uncertainties. The dominant experimental systematic uncertainties arise from the jet calibration procedure, where the energy of reconstructed jets is scaled to recover the full energy scale and the resolution of the simulated samples is calibrated to match data, as well as from the smearing of track impact parameters, performed as described in Section 4.2. Specifically, uncertainties from the jet energy scale (JES) [168] and the impact parameter smearing contribute to the final estimates in the SRs more than 2% and 1%, respectively. Other experimental effects — such as jet energy resolution (JER) [168], jet vertex tagging (JVT) [171], pileup modelling [226], electron [172] and muon [178] identification and calibration, E_T^{miss} reconstruction [183], trigger efficiencies [172, 178, 225], and luminosity measurements [116] — have all negligible impact (less than 1%) on the SRs.

5.6.2 Theoretical uncertainties

Systematic uncertainties arising from missing higher-order corrections in theoretical calculations — commonly referred to as renormalisation and factorisation scale uncertainties [227] — along with uncertainties propagated from the PDFs [228] and the strong coupling constant α_S impact the theoretical predictions of the simulated samples. In this analysis, scale uncertainties are estimated by varying the renormalisation (μ_F) and factorisation (μ_R) scale parameters of the simulated samples by a factor of 2.0, resulting in 7-point variations ($\{\mu_R, \mu_F\} = \{0.5, 0.5\}, \{1.0, 0.5\}, \{0.5, 1.0\}, \{1.0, 1.0\}, \{2.0, 1.0\}, \{1.0, 2.0\}, \{2.0, 2.0\}$). The envelope of these variations is taken as the overall scale uncertainty. PDF and α_S uncertainties are instead obtained by extrapolating dedicated PDF sets at different energy scales in the MC generator using the DGLAP [187, 190] and renormalisation group equations, respectively. For the $W(\rightarrow \tau\nu)$ + jets sample, simulated at NNLO QCD precision, the contribution of NLO electroweak corrections becomes increasingly significant at higher transverse momentum of the weak boson. Therefore, approximate NLO electroweak corrections are included for $W(\rightarrow \tau\nu)$ + jets simulations and are evaluated using the electroweak virtual approximation [229]. Finally, for SUSY signal samples, PYTHIA is tuned

to match distributions observed in data, which are particularly sensitive to the underlying event, the jet structure, and additional jets emission. As a result, additional systematic uncertainties are considered for the signal samples to account for this tuning, as well as the uncertainties related to the cross section computation. Overall, the combined impact of all background theoretical uncertainties in the SRs is approximately 4%.

5.6.3 Analysis-specific uncertainties

As discussed in Section 5.5.2, a key assumption of the QCD track background estimation strategy is that the track $S(d_0)$ variable is independent from the specific hard-scattering process, and therefore its distribution is equivalent across the different 0ℓ , 1μ , $1e$, 2ℓ , and 1γ categories used in this analysis. To verify this assumption, $S(d_0)$ distributions in the different categories have been compared using MC simulated samples. The results, shown in Figure 5.20, indicate that all distributions are consistent with one another within the MC statistical uncertainties.

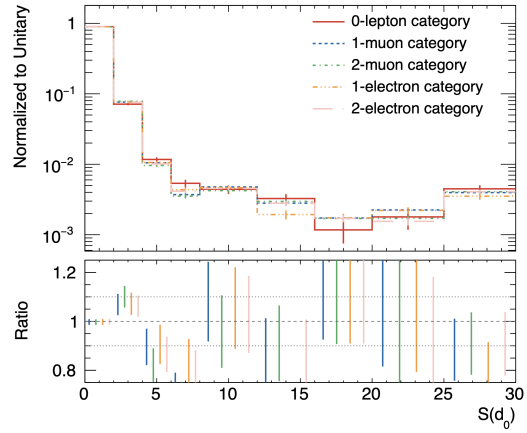


Figure 5.20 – Comparison of the track $S(d_0)$ distributions in the 0ℓ , 1μ , $1e$, and 2ℓ categories. Error bars indicate MC statistical uncertainties. From Ref. [89].

a conservative systematic uncertainty of 5% (10%) is assigned to the fully data-driven QCD track background estimates of SR-Low (SR-High). This uncertainty is treated as uncorrelated between the two $S(d_0)$ SR bins.

5.6.4 Summary

A visual summary of all the systematic uncertainties considered in this analysis across the various SRs and VRs is presented in Figure 5.21. The figure also presents two additional systematic effects: the limited data statistics in the CRs used to estimate the QCD track and the τ decay track backgrounds (labelled as the “CR data statistics”), and the limited number of events available in Monte Carlo simulated samples (indicated as the “MC statistics”). Among all sources of systematic uncertainties, the former emerges as the dominant one in the two SRs considered in the analysis.

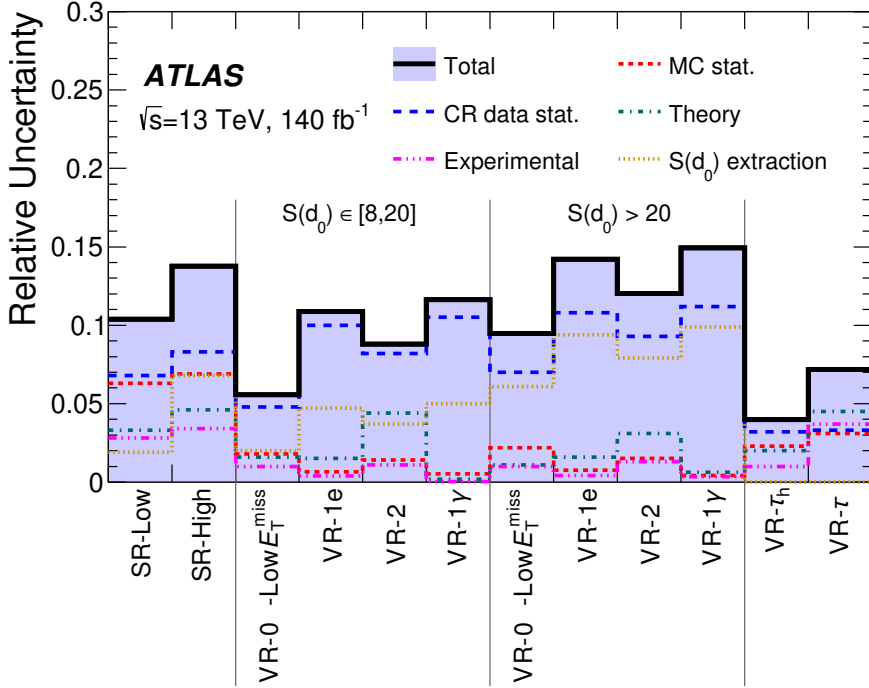


Figure 5.21 – Relative systematic uncertainties on the fitted SM background for the SR bins (left), low- $S(d_0)$ VRs (middle-left), high- $S(d_0)$ VRs (middle-right), and $W(\rightarrow \tau\nu)$ +jets VRs (right). The uncertainty in the CR data statistics category corresponds to the statistical uncertainties arising from the size of the data samples in the $W(\rightarrow \tau\nu)$ +jets CRs and in the regions used to estimate the QCD track background. The MC statistics uncertainty category reflects the limited size of the MC samples used to model the non-QCD track background, while the Theory category encompasses various sources of theoretical modelling uncertainties. Uncertainties related to the $S(d_0)$ template, extracted in the 1μ CRs, are included in the $S(d_0)$ extraction category. The uncertainties arising from the reconstruction and selection of leptons, jets, E_T^{miss} , and the track impact parameters are grouped under the Experimental category. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. From Ref. [182].

5.7 Statistical analysis

The results of this analysis, as well as the statistical compatibility of the SM expectations with the observed data under different hypotheses, are obtained via a *maximum likelihood* approach using the HISTFITTER tool [230]. This method involves constructing a likelihood function and identifying the model parameters that maximise it over the parameter space, i.e. those parameter values that make the observed data most probable given the model. In this analysis, the likelihood function is built from the observed data and Monte Carlo yields in the SRs and CRs, along with additional terms to model systematic uncertainties. It can be expressed as

$$\begin{aligned}
 L(\mathbf{n}|\mu_{\text{sig}}, \mathbf{s}, \mathbf{b}, \boldsymbol{\theta}) &= \prod_{i \in \text{SR}} P_i \times \prod_{j \in \text{CR}} P_j \times C_{\text{syst}} \\
 &= \prod_{i \in \text{SR}} P(n_i | \lambda_i(\mu_{\text{sig}}, s_i, \mathbf{b}, \boldsymbol{\theta})) \times \prod_{j \in \text{CR}} P(n_j | \lambda_j(\mu_{\text{sig}}, s_j, \mathbf{b}, \boldsymbol{\theta})) \times \prod_{s \in \text{syst}} G_{\theta_s},
 \end{aligned} \tag{5.8}$$

where P_i (P_j) denotes the Poisson probability of observing n_i (n_j) events in SR i (CR j) while expecting λ_i (λ_j) events. The term C_{syst} represents the product of Gaussian constraints G_{θ_s} on the nuisance parameters θ_s , each with zero mean and unit standard deviation, modelling the systematic uncertainties of the analysis. The Poisson probability distribution for a generic kinematic region k is given by

$$P(n_k | \lambda_k(\mu_{\text{sig}}, s_k, \mathbf{b}, \boldsymbol{\theta})) = \frac{\lambda_k^{n_k}}{n_k!} e^{-\lambda_k}, \tag{5.9}$$

where the expected number of events λ_k is defined as:

$$\lambda_k(\mu_{\text{sig}}, s_k, \mathbf{b}, \boldsymbol{\theta}) = \mu_{\text{sig}} \cdot s_k(\boldsymbol{\theta}) + \sum_{\alpha \in \text{bkg}} b_{k,\alpha}(\boldsymbol{\theta}). \tag{5.10}$$

Therefore, the likelihood function depends on several components, notably:

- μ_{sig} is the signal strength, representing the normalisation factor of the signal process under consideration;
- $s_k(\boldsymbol{\theta})$ represents the expected number of signal events from MC simulations in the kinematic region k , potentially affected by the nuisance parameters $\boldsymbol{\theta}$;
- $b_{k,\alpha}(\boldsymbol{\theta})$ gives the expected number of background events of type α in region k , where α can be QCD, τ decay, or other background sources as described in Section 5.5;
- $\boldsymbol{\theta}$ models the full set of nuisance parameters, including systematic uncertainties as well as normalisation and transfer factors.

From Equation 5.8, the *profile likelihood ratio* [231] is defined as:

$$\Lambda(\mu_{\text{sig}}) = \frac{L(\mu_{\text{sig}}, \hat{\boldsymbol{\theta}})}{L(\hat{\mu}_{\text{sig}}, \hat{\boldsymbol{\theta}})}. \tag{5.11}$$

In the numerator, the nuisance parameters θ are fixed to their maximum likelihood estimates $\hat{\theta}$, obtained by maximising the likelihood function for a given value of the signal strength. In the denominator, both the signal strength and the nuisance parameters are set to their global best-fit values $\hat{\mu}$ and $\hat{\theta}$, respectively, which jointly maximise the likelihood function. The best-fit $\hat{\mu}$ represents the central value of the signal strength measurements. Its uncertainty is determined from the 68% confidence interval, assuming the validity of the asymptotic approximation [231], under which the profile likelihood ratio is distributed according to a χ^2 function with a number of degrees of freedom equal to the number of parameters of interest. The profile likelihood ratio provides a more robust measure of the agreement between the hypothesised value of μ_{sig} and the observed data than the likelihood function alone. Since by definition $0 \leq \Lambda(\mu_{\text{sig}}) \leq 1$, values of $\Lambda(\mu_{\text{sig}})$ close to 1 indicate strong agreement between the model and the data.

In the absence of a signal, the statistical interpretation focuses on setting upper limits on the signal strength of the considered SUSY model. The relevant test statistic for limit setting is defined as the natural logarithm of the profile likelihood ratio:

$$q_{\mu_{\text{sig}}} = -2 \ln (\Lambda(\mu_{\text{sig}})) = \begin{cases} -2 \ln \frac{L(\mu_{\text{sig}}, \hat{\theta})}{L(\hat{\mu}_{\text{sig}}, \hat{\theta})} & \text{if } \mu_{\text{sig}} \geq \hat{\mu}_{\text{sig}} \\ 0 & \text{if } 0 \leq \mu_{\text{sig}} < \hat{\mu}_{\text{sig}} \end{cases}. \quad (5.12)$$

For a given value of μ_{sig} , the level of agreement with the observed data is quantified by the p -value

$$p_{\mu_{\text{sig}}} = \int_{q_{\mu_{\text{sig}}, \text{obs}}}^{\infty} f(q_{\mu_{\text{sig}}} | \mu_{\text{sig}}) dq_{\mu_{\text{sig}}}, \quad (5.13)$$

where $q_{\mu_{\text{sig}}, \text{obs}}$ is the test statistic evaluated on the observed data, and $f(q_{\mu_{\text{sig}}} | \mu_{\text{sig}})$ is its probability density function under the assumption of signal strength μ_{sig} . In practice, this function is evaluated both for the signal-plus-background hypothesis ($\mu_{\text{sig}} = 1$) and the background-only hypothesis ($\mu_{\text{sig}} = 0$). In this analysis, the background-only hypothesis is first used to predict the expected number of background tracks in the SRs and VRs. Then, if is no significant excess of data over the SM prediction is observed in the SRs, both model-dependent and model-independent fits are performed to set upper limits on the signal strength. The limits are derived using the CL_s method [232], where the exclusion confidence level is defined as:

$$\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b} = \frac{\int_{q_{\mu_{\text{sig}}, \text{obs}}}^{\infty} f(q_{\mu_{\text{sig}}} | \mu_{\text{sig}} = 1) dq_{\mu_{\text{sig}}}}{\int_{q_{\mu_{\text{sig}}, \text{obs}}}^{\infty} f(q_{\mu_{\text{sig}}} | \mu_{\text{sig}} = 0) dq_{\mu_{\text{sig}}}}. \quad (5.14)$$

If $\text{CL}_s < 0.05$, the signal-plus-background hypothesis, and thus the signal model under test, is considered excluded at 95% of confidence level by the model-dependent fit. By scanning over possible values of μ_{sig} and calculating the corresponding p -values via Eq. 5.13 in a model-independent fit, one can determine the values of the signal yields corresponding to a p -value of 0.05. These are denoted as S_{exp}^{95} and S_{obs}^{95} , representing the expected and observed upper limits on the number of signal events, respectively, for a generic Beyond the Standard Model signal. Finally, by taking the ratio between S_{obs}^{95} and

the total integrated luminosity $\mathcal{L}_{\text{int}}$, the observed upper limit on the visible cross section of such a BSM signal is defined:

$$\langle \epsilon \sigma_{\text{obs}}^{95} \rangle = \frac{S_{\text{obs}}^{95}}{\mathcal{L}_{\text{int}}} . \quad (5.15)$$

5.8 Results

As discussed in the previous Section, statistical results are derived using a maximum likelihood fit that includes the Signal Regions (SRs), Control Regions (CRs), and Validation Regions (VRs). To assess the robustness of the background estimation strategy outlined in Section 5.5, a background-only fit is first performed using the CRs and VRs, excluding any SUSY contribution from Monte Carlo simulations. From this fit, a Normalisation Factor (NF) and two Transfer Factors (TFs) — used to estimate background contributions from τ decay and QCD tracks, respectively — are determined and then extrapolated to the SRs. Since no significant excess is observed in the data relative to the post-fit SM predictions, both model-dependent and model-independent interpretations of the results in the SRs are carried out. As a result, new exclusion limits are set on the simplified SUSY models considered in this thesis, along with upper limits on the cross section of generic BSM signals.

5.8.1 Background only fit

The observed data and the post-fit SM predictions in the CRs are summarised in Table 5.9. The NF, derived from the simultaneous fit in CR- τ_h and CR- τ_ℓ , is found to be equal to 1.07 ± 0.11 . The TFs, obtained from the 1μ category control regions, are $(1.10 \pm 0.12) \times 10^{-2}$ and $(7.9 \pm 0.9) \times 10^{-3}$, respectively for the “Low” and “High” SR bins.

	CR- τ_ℓ	CR- τ_h	CR- 0ℓ	CR- 1μ -Low	CR- 1μ -High	CR- 1μ
Observed data	68	126	1461	183	120	14450
SM prediction	68 ± 6	126 ± 10	1460 ± 40	183 ± 14	120 ± 11	14450 ± 120
QCD track	0.3 ± 0.2	4.6 ± 1.3	1270 ± 40	140 ± 15	100 ± 11	12660 ± 230
$W(\rightarrow \tau_h \nu) + \text{jets}$	0.2 ± 0.1	67 ± 6	69 ± 9	< 1	< 1	< 100
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	59 ± 7	42 ± 5	42 ± 5	< 1	< 1	< 100
Other	7.8 ± 3.1	13 ± 2	77 ± 11	43 ± 6	20 ± 3	1780 ± 200

Table 5.9 – Number of expected and observed data events from the background-only fit in the CRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

As discussed in Section 5.5, the difference between the observed data and predicted yields across the VRs is found to be within at most 1.5σ . This confirms the robustness of

the background estimation strategy. Consequently, no additional systematic uncertainty is assigned due to the adopted estimation method, and the NF and the TFs obtained from the CRs are extrapolated to the SRs. The final results in the SRs are summarised in Table 5.10. Figure 5.22 shows the post-fit distribution of the track $S(d_0)$ variable for the observed data and the SM background predictions, overlaid to several benchmark SUSY signal models. Overall, no significant discrepancy is observed between data and the SM prediction. Additional post-fit distributions for SR-High and SR-Low are visible in Figure 5.23 and Figure 5.24, respectively.

	SR-Low	SR-High
Observed data	35	15
SM prediction	37 ± 4	14.8 ± 2.0
QCD track	14.0 ± 1.7	10.0 ± 1.6
$W(\rightarrow \tau_h \nu) + \text{jets}$	9.6 ± 1.6	2.0 ± 0.6
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	10.6 ± 2.0	1.9 ± 0.8
Other	3.2 ± 0.7	0.8 ± 0.4

Table 5.10 – Expected and observed data events in the two SR bins. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties. Adapted from Ref. [182].

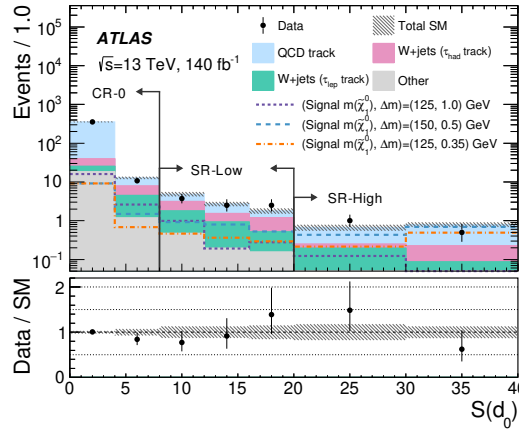


Figure 5.22 – Post-fit $S(d_0)$ distribution in the SR bins and the adjacent CR-0 ℓ , with the selection on the $S(d_0)$ variable removed. The arrows indicate the cut value to define the individual regions. The SM background expectation is shown as a histogram stack, and representative SUSY signal models are overlaid. The last bin includes the overflow. The hatched band indicates the uncertainty on the SM background expectation, while the error bars on the black dots represent the Poisson error associated with the event yields. From Ref. [182].

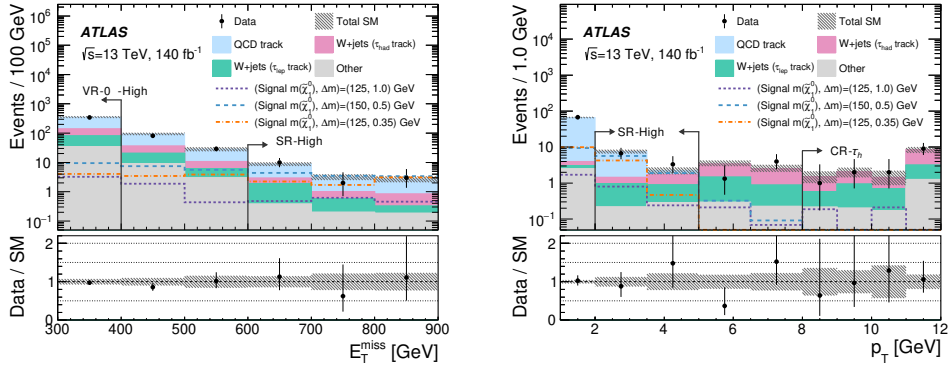


Figure 5.23 – Post-fit distributions of E_T^{miss} (left) and track p_T (right) in, and near, SR-High. The selection criterion on the variable shown by each plot is removed, while the arrow indicates the selection used to define the region. The SM background expectation is shown as a histogram stack, and a selection of representative SUSY signal models is overlaid. The last bin includes the overflow. The hatched band indicates the uncertainty on the mean value of the SM background expectation, while the error bars on the black dots represent the Poisson error associated with the event yields. From Ref. [182].

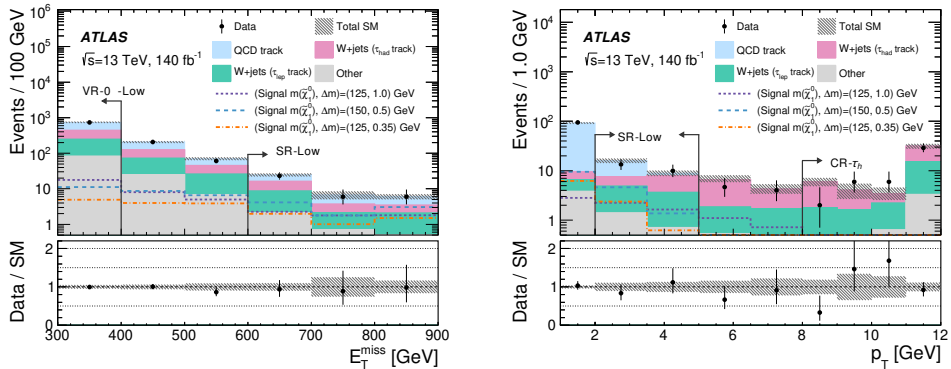


Figure 5.24 – Post-fit distributions of E_T^{miss} (left) and track p_T (right) in, and near, SR-Low. The selection criterion on the variable shown by each plot is removed, while the arrow indicates the selection used to define the region. The SM background expectation is shown as a histogram stack, and a selection of representative SUSY signal models is overlaid. The last bin includes the overflow. The hatched band indicates the uncertainty on the mean value of the SM background expectation, while the error bars on the black dots represent the Poisson error associated with the event yields. From Ref. [182].

5.8.2 Model-dependent exclusion limits

Exclusion limits on simplified SUSY models are determined by performing a signal-plus-background hypothesis test under the assumption $\mu_{\text{sig}} = 1$. This test incorporates signal yields, estimated from simulation samples, into the likelihood fit using both SR-Low and SR-High. Control Regions are also included to constrain the background normalisations, while validation regions are excluded from this procedure. For each signal point in the $(m(\tilde{\chi}_1^0), \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0))$ plane, the test statistic is used to compute the CL_s value. These values are then smoothly interpolated across the plane, and the exclusion contour is defined by connecting points with $\text{CL}_s = 0.05$. The resulting exclusion limits are shown in Figure 5.25, and compared with previous constraints from LEP [35] and earlier ATLAS searches [30, 32, 33]. The analysis shows that the sensitivity in the compressed higgsino region is predominantly driven by SR-High, while SR-Low contributes more effectively at larger mass splittings. Higgsino mass up to approximately 170 GeV is excluded for mass splittings around 0.6 GeV, and, remarkably, for the first time since the LEP era, an LHC analysis is able to probe the challenging $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.3 - 1.0$ GeV region.

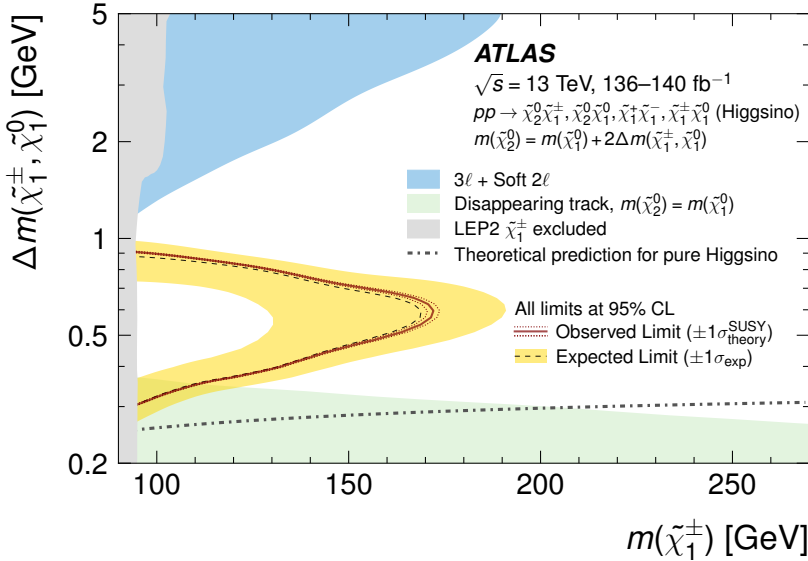


Figure 5.25 – Expected (dashed black line) and observed (solid red line) 95% CL exclusion limits on the higgsino simplified model considered in this analysis. The limits are shown with $\pm 1\sigma_{\text{exp}}$ (yellow band) from experimental systematic and statistical uncertainties, and with $\pm 1\sigma_{\text{theory}}^{\text{SUSY}}$ (red dotted lines) from signal cross section uncertainties, respectively. The limits set by the ATLAS searches using the soft lepton [32, 33] and disappearing track [30] signatures are illustrated by the blue and green regions, respectively, while the limit imposed by the LEP experiments [35] is shown in gray. The dot-dashed gray line indicates the predicted mass splitting for the pure higgsino scenario. From Ref. [182].

5.8.3 Model-independent exclusion limits

Model-independent fits are performed to set upper limits on both the number of events and the visible cross section for a generic BSM signal producing a final-state “ $E_{\text{T}}^{\text{miss}} + \text{jets}$ ” topology, accompanied by a single soft track mildly-displaced from the primary vertex. SR-Low and SR-High are again used to derive these limits. The results are summarised in Table 5.11. The upper limits on the visible cross section are found to be 0.10 fb and 0.07 fb for SR-Low and SR-High, respectively.

Signal Region	$\langle \epsilon \sigma_{\text{obs}}^{95} \rangle$ [fb]	S_{obs}^{95}	S_{exp}^{95}	CL_b	$p(s = 0)$ (Z)
SR-Low	0.10	13.5	$15.1^{+6.3}_{-4.2}$	0.37	0.50 (0.00)
SR-High	0.07	9.9	$9.6^{+4.4}_{-2.8}$	0.52	0.50 (0.01)

Table 5.11 – 95% CL upper limits on the visible cross section ($\langle \epsilon \sigma_{\text{obs}}^{95} \rangle$), the number of observed signal events (S_{obs}^{95}), and the expected number of signal events assuming the background-only hypothesis (S_{exp}^{95}). The last two columns display the CL_b value and the discovery p -value. When the observed yield is lower than the expected one, the p -value is capped at 0.5.

Search for SUSY higgsinos using soft mildly-displaced tracks and machine learning with Run 2 and Run 3 data



Same old thing in brand new drag
comes sweeping into view...

— DAVID BOWIE, *Teenage Wildlife*

The analysis presented in Chapter 5 and published in Ref. [182] constituted the first attempt by an LHC experiment to probe the so-called “higgsino gap”. No significant excess above the Standard Model predictions was observed, and exclusion limits were set on simplified SUSY models (Figure 5.25), with comparable results obtained by the CMS Collaboration [233]. Nevertheless, as discussed in Ref. [97], regions of the parameter space with $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim \mathcal{O}(1)$ GeV are expected to remain beyond the reach of current and future direct detection DM experiments, since their sensitivity to compressed higgsinos will be severely limited once the neutrino floor is reached. The ATLAS and CMS experiments are therefore uniquely positioned to continue exploring these challenging scenarios as the LHC delivers increasing data statistics. In this context, the present Chapter describes a renewed effort to investigate the $0.3 \lesssim \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 1.25$ GeV region, by building upon the experience gained during the Run 2 analysis and employing advanced machine learning techniques to enhance the separation between SUSY signals and SM backgrounds. The analysis uses data collected by the ATLAS detector during Run 2 and the first three years of Run 3 (2022-2024) of the LHC, accounting for a total integrated luminosity of 299 fb^{-1} .

6.1 Analysis strategy

The strategy adopted for the full Run 2 analysis is based on the identification of independent, sequential selections on event- and track-level kinematic variables to construct the Signal Regions (SRs), Control Regions (CRs), and Validation Regions (VRs). This tradi-

tional “cut-based” approach implicitly assumes the existence of a threshold or boundary in the distributions of kinematic variables that separates signal-like events and tracks from background processes. Consequently, each individual selection applied in the SR definition requires a careful optimisation procedure aimed at maximising the signal selection efficiency while simultaneously minimising contamination from SM processes.

An alternative strategy can be developed by using machine learning algorithms, in the form of multi-layer feed-forward neural networks (NNs) [234, 235], to construct functions that provide a continuous measure - the *output scores* - indicating how signal-like or background-like each analysis object is. To this end, in this new analysis two dedicated neural network classifiers are developed: one exploiting the kinematic information of individual tracks (referred to as the “track-level” neural network) and another exploiting global event observables (referred to as the “event-level” neural network). These models are designed to enhance the separation between SUSY signal and SM backgrounds beyond what is achievable with traditional cut-based selections. Since the assumed mass splitting hypothesis affects the kinematic of the soft, mildly displaced pion tracks produced in higgsino decays (as discussed in Sections 5.2 and 5.4), the track-level neural network is *parameterised* (pNN) to produce an output score that varies continuously with the mass splitting [236]. Furthermore, because three distinct track categories can be identified, the track-level pNN is implemented as a multi-class classifier, providing three output scores (each a continuous function of the mass splitting) corresponding to the probabilities for a track to originate from higgsino decays, QCD processes, or hadronic or leptonic τ decays. In contrast, the event-level NN is constructed as a binary classifier, as the higgsino mass difference has negligible impact on the global event observables.

The output scores of the two classifiers serve then as final discriminants for the SR definition, under the assumption that by combining multiple input observables the output scores can perform better than a cut-based method using the same inputs. Selections on these NN output scores replace therefore the event- and track-level selection criteria described in Section 5.4. Since the tracking information used as input to the track-level pNN is uncorrelated to the event topology, the three pNN output scores are statistically independent of the event-level NN score. This independence allows to exploit the same background estimation strategy outlined in Section 5.5:

- a fully data-driven estimation of QCD track via an ABCD method, where regions are defined by selections on the output scores, and
- a semi data-driven estimation of the τ -decay tracks using dedicated CRs dominated by high- p_T tracks.

While the previous cut-based SR employed a requirement of $E_T^{\text{miss}} > 600$ GeV along with two $S(d_0)$ bins to target generic scenarios with small (SR-High, $S(d_0) > 20$) and large (SR-Low, $8 < S(d_0) < 20$) mass splittings, the improved discrimination power of the NN classifiers, particularly the pNN output tailored to each mass splitting hypothesis, allows the definition of SRs specifically optimised for a corresponding signal model. In addition, the larger statistics afforded by the NN-based approach allows the introduction of multiple bins within each SR, thereby making it possible to perform a shape fit. Sensi-

tivity is further enhanced by including in the analysis dedicated SR bins targeting events that contain more than one displaced track, such as those expected from the production of $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ or $\tilde{\chi}_1^+ \tilde{\chi}_1^-$, as illustrated in Figure 6.1. The statistical combination of these two orthogonal sets of SR bins extends the exclusion reach for SUSY simplified models beyond that achieved by the previous analysis effort based solely on the full Run 2 dataset.

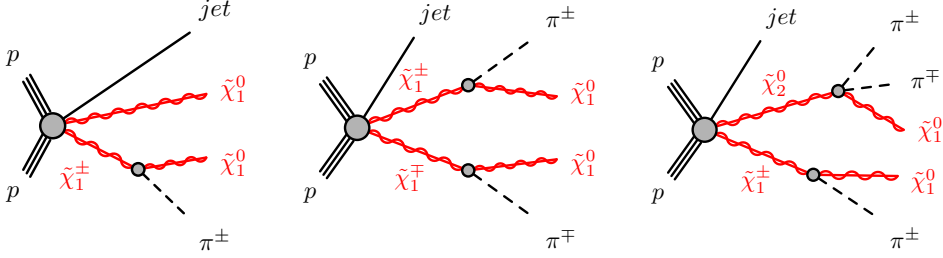


Figure 6.1 – Example signal diagrams for the targeted signature featuring a jet from initial-state radiation. The lightest chargino and the next-to-lightest lightest neutralino decay via off-shell W and Z bosons, respectively, into the LSP and one or two charged pions, which are reconstructed as low- p_T mildly-displaced track. The two final-state neutralinos are aligned in the ϕ direction due to the boost imparted by the ISR jet, resulting to large E_T^{miss} .

6.2 Data and simulated samples

As in the analysis presented in Chapter 5, the search presented here is based on data collected by the ATLAS detector from proton-proton collisions delivered by the LHC and Monte Carlo (MC) simulation samples used to model (part of) the Standard Model backgrounds and the SUSY signal processes.

6.2.1 Dataset

The analysis uses the full Run 2 (2015-2018) dataset and the partial Run 3 (2022-2024) dataset recorded by the ATLAS detector from pp collisions at center-of-mass energies of $\sqrt{s} = 13$ TeV and $\sqrt{s} = 13.6$ TeV, respectively. During these periods, the LHC delivered a total integrated luminosity of 349 fb^{-1} , of which 328 fb^{-1} were recorded by ATLAS. After applying standard data quality criteria [185], the final dataset used in this analysis corresponds to an integrated luminosity of $140.1 \pm 1.2 \text{ fb}^{-1}$ [116] for Run 2, with a total uncertainty of 0.83%, and of $159.4 \pm 3.0 \text{ fb}^{-1}$ for Run 3 [117], with a total uncertainty of 1.9%, as determined by the LUCID-2 detector [186]. The integrated luminosity collected during each year of Run 2 is 3.24, 33.40, 44.63, and 58.79 fb^{-1} , for 2015, 2016, 2017, and 2018, respectively [116]. For Run 3, the corresponding values are 26.3, 25.2, and 107.9 fb^{-1} , for 2022, 2023, and 2024 [117]. Pileup conditions varied significantly across these years [118], impacting in different ways event reconstruction and background composition.

6.2.2 Monte Carlo simulated samples

Monte Carlo simulated samples are produced for all relevant signal and background processes, following the same setup described in Section 5.3. Standard Model samples employ the full detector simulation, while SUSY signals are processed with the ATLFAST3 [197] fast simulation framework. Compared to ATLFASTII, ATLFAST3 provides improved performance by combining the updated FastCaloSim V2 parameterisation [197] for low- and high-energy showers with FastCaloGAN [198], a Generative Adversarial Network [199], used to more accurately model medium-energy hadrons and calorimeter energy fluctuations. A summary of the Monte Carlo event generators and their corresponding configurations is provided in Table 5.1. Updated generator versions - SHERPA 2.2.14, MADGRAPH5 3.4.2, and PYTHIA 8.308/8.309 - are employed for both SM and SUSY signal samples. For SUSY signals, the mass difference $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ and the mass of the neutralino LSP vary in the intervals [0.25, 1.25] GeV and [100, 250] GeV, respectively.

Process	$\sqrt{s}$ [TeV]	Matrix element	Parton shower	Tune	PDF set	Cross section
$V + \text{jets}$	13	SHERPA 2.2.11/2.2.2		SHERPA standard	NNPDF3.0 _{NNLO}	NNLO
	13.6	SHERPA 2.2.14		SHERPA standard	NNPDF3.0 _{NNLO}	NNLO
VV	13	SHERPA 2.2.1/2.2.2		SHERPA standard	NNPDF3.0 _{NNLO}	Generator NLO
	13.6	SHERPA 2.2.2/2.2.14		SHERPA standard	NNPDF3.0 _{NNLO}	Generator NLO
$t\bar{t}$	13/13.6	POWHEG-BOX	PYTHIA 8.308	A14	NNPDF3.0 _{NLO}	NNLO+NNLL
Single top	13/13.6	POWHEG-BOX	PYTHIA 8.308	A14	NNPDF3.0 _{NLO}	NNLO+NNLL
Multi-jet	13/13.6		PYTHIA 8.308	A14	NNPDF2.3 _{LO}	Generator LO
SUSY signals	13/13.6	MADGRAPH5 3.4.2	PYTHIA 8.309	A14	NNPDF2.3 _{LO}	NLO+NNLL

Table 6.1 – Summary of Monte Carlo generators setup for Run 2 and Run 3 simulated SM backgrounds and SUSY signal samples.

6.3 Event and track selection

A baseline set of selection criteria is applied to the reconstructed physics objects described in Chapter 4. These selections, summarised in Table 6.2, define two classes of objects: *baseline* and *signal*. Baseline electrons, muons, and photons are reconstructed with the lowest p_T thresholds for which ATLAS calibrations are available and are used to define the so-called “0 ℓ ” category, by applying a veto on their presence. Baseline jets, on the other hand, are primarily used in the computation of the missing transverse momentum and in the overlap removal procedure. To prevent the reconstruction of a single particle as multiple objects, an overlap removal procedure is applied to all baseline objects as detailed in Ref. [217]. Following this, signal objects are defined with tighter criteria and used for auxiliary categorisation in background estimation and validation. The most notable difference in the object definitions with respect to those used in the analysis presented in Chapter 5 is the adoption of a lower p_T threshold and a looser identification working point for baseline photons. This choice ensures the possibility of statistically combining the present analysis with future searches targeting “radiative” decays of wino-like neutralinos into the lightest neutralino and a photon, accompanied by a hard initial

state radiation jet [237, 238]. The impact of the new baseline photon definition on the present analysis is minimal, amounting to a loss of $\approx 1\%$ of the expected signal yield. Moreover, signal electrons are defined using tighter identification and isolation working points, following the ATLAS recommendations available at the time of writing this thesis.

To further reduce contributions from Standard Model background processes and select events consistent with the “ $E_T^{\text{miss}} + \text{jets}$ ” signature containing at least one displaced track additional requirements are imposed. They include both event-level selections (Section 6.3.1) and track-level selections (Section 6.3.2). All events and tracks satisfying these criteria are used as inputs for the training of the neural networks, whose outputs provide the final discriminant used in the definition of the Signal Regions (SRs). Throughout this analysis, SRs belong exclusively to the 0ℓ category.

	Baseline	Signal
Jets		
Kinematic	$p_T > 20 \text{ GeV}, \eta < 4.5$	$p_T > 30 \text{ GeV}, \eta < 2.8$
Pileup mitigation	JVT FixedEffPt ¹ for $p_T < 60 \text{ GeV}, \eta < 2.4$	
Muons		
Kinematic	$p_T > 3 \text{ GeV}, \eta < 2.7$	$p_T > 3 \text{ GeV}, \eta < 2.5$
Identification	Medium	Medium
Isolation	-	PflowLoose_VarRad
Impact parameter	$ z_0 < 0.5 \text{ mm}$	$ d_0/\sigma(d_0) < 3, z_0 < 0.5 \text{ mm}$
Electrons		
Kinematic	$p_T > 4.5 \text{ GeV}, \eta < 2.47$	
Identification	LooseAndBLayerLLH	TightLLH
Isolation	-	Tight_VarRad
Impact parameter	$ z_0 < 0.5 \text{ mm}$	$ d_0/\sigma(d_0) < 5, z_0 < 0.5 \text{ mm}$
Photons		
Kinematic	$p_T > 7 \text{ GeV}, \eta < 2.37$	$p_T > 130 \text{ GeV}, \eta < 2.37$
Identification	Loose	Tight
Isolation	-	FixedCutTight
Missing Transverse Momentum		
Working Point		Tight

Table 6.2 – Summary of Run 2 and Run 3 baseline and signal object definitions used in this analysis.

² The FixedEffPt working point of the JVT is an updated version of those presented in Ref. [171], obtained using neural-network-based algorithms.

6.3.1 Event selection

As detailed in Section 5.3, events are first required to pass standard data quality criteria to ensure that they were recorded during periods when the ATLAS detector was operating under stable conditions [185]. After event cleaning, each event must contain at least one reconstructed interaction vertex with a minimum of two associated tracks with $p_T > 500$ MeV. Additional selection requirements are then applied as follows.

- Neutralinos in the final state recoling against the ISR leading jet produce large E_T^{miss} , which serves as the trigger requirement for the events. The E_T^{miss} trigger efficiency varies across data-taking periods due to different pileup conditions, and plateaus around $E_T^{\text{miss}} > 200$ GeV [183]. Accordingly, events are required to satisfy the E_T^{miss} trigger and have $E_T^{\text{miss}} > 250$ GeV. This threshold effectively suppresses multi-jet events, which typically generate fake E_T^{miss} due to jet energy mismeasurement, while retaining sufficient statistics for training the event-level NN.
- To effectively boost the SUSY system and generate sufficient E_T^{miss} for triggering, the ISR leading jet is required to have $p_T > 250$ GeV. In addition, events are required to contain no more than four signal jets with $p_T > 30$ GeV and $|\eta| < 2.8$. This requirement reduces contributions from multi-jet and $t\bar{t}$ processes without compromising the signal acceptance, as signal events generally exhibit lower hadronic activity.
- Mismeasured jet energies can result in spurious E_T^{miss} , often aligned with one of the reconstructed jets, as illustrated in Figure 5.9. To mitigate this effect, the analysis requires $\min \Delta\phi(p_T^{\text{jet}}, p_T^{\text{miss}})$ to be greater than 0.4.
- Several SM processes produce neutrinos, including $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$, $W(\rightarrow \ell\nu) + \text{jets}$, di-boson, $t\bar{t}$, and single top production, which result in significant E_T^{miss} in the final state. Among them, the only processes that contribute significantly to the SRs and yield final states without visible electrons or muons are $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ and $W(\rightarrow \tau\nu) + \text{jets}$ with hadronically decaying τ leptons. In the remaining processes, the presence of reconstructed electrons or muons can be exploited to suppress their contributions to the SRs. The variable $N(\ell_{\text{base}})$ is defined as the number of leptons that satisfy the baseline selection criteria outlined in Table 6.2. Events containing reconstructed baseline leptons are vetoed by requiring $N(\ell_{\text{base}}) = 0$.

After applying all selections described above, the dataset may still contain contributions from *non-collision* background. To suppress these, the same strategy described in Section 5.4.1 is employed here: the leading jet is required to meet the *tight* working point criteria as defined in Ref. [219]. Events fulfilling all the selection requirements described so far are subsequently used for training the event-level neural network.

6.3.2 Track selection

For each event satisfying the selections outlined in Section 6.3.1, additional requirements are applied on tracks. These criteria are a looser version of those presented in Section 5.4.2, designed to identify tracks originating from chargino and neutralino decays while

suppressing the dominant SM backgrounds and retaining at the same time enough statistics for training the track-level pNN.

- “Fake” tracks, arising from random combination of hits and characterised by large impact parameters, are suppressed by requiring signal candidate tracks to satisfy the Tight Primary working point, as defined in Table 4.1. The Tight Primary requirement significantly reduces the fake rate while maintaining high tracking efficiency (Section 4.1.1). Furthermore, since the expected higgsino lifetime is short enough that its decay occurs well within the beam pipe, tracks are required to include at least one hit in the IBL detector [124].
- To reduce tracks originating from low- p_T particles produced in pileup interactions or soft QCD processes, candidate tracks are required to originate from the central detector region ($|\eta| < 1.5$), have a longitudinal impact parameter satisfying $|\Delta z_0 \sin \theta| < 3$ mm, and a transverse impact $|d_0| < 5$ mm (applied at reconstruction level) with a significance of $S(d_0) < 100$. Depending on the mass splitting hypothesis under consideration, the combined signal selection efficiency of these criteria ranges from approximately 80% to nearly 100%.
- Tracks consistent with secondary vertices reconstructed from the decays of long-lived neutral hadrons, such as K_S^0 or Λ^0 , are rejected. Specifically, track candidates originating from secondary vertices whose mass, reconstructed using mass-constrained fits [157, 220, 221], is found to be consistent with the $\Lambda^0 \rightarrow p\pi^-$, $\bar{\Lambda}^0 \rightarrow \bar{p}\pi^+$, or $K_S^0 \rightarrow \pi^+\pi^-$ decays, are vetoed.
- If an event contains multiple tracks passing all the above selections, only the two tracks with the largest transverse impact parameter significance $S(d_0)$ are retained; all others are discarded. Since the performance of the track-level pNN is primarily driven by $S(d_0)$, this requirement effectively selects the two tracks with the highest signal score in approximately 95% of cases, without significantly degrading the expected sensitivity.

6.4 Event-level NN and track-level pNN discriminants

The final discriminants used in this analysis to determine whether events and tracks originate from signal or background processes are constructed from the outputs of two neural network models: a binary event-level *deep* neural network and a multi-class parameterised *deep* neural network (pNN). Both models are implemented in KERAS [239], with TENSORFLOW [240] as the backend framework. The optimisation of the networks’ hyperparameters is performed using KERASTUNER [241], and the optimal values are summarised in Table 6.3. The set of input variables used for the training of the two neural network models is listed in Table 6.4.

6.4.1 Event-level NN

To exploit the available information from global event observables and maximise the sensitivity to signal events, an event-level neural network is employed for event selec-

	Layers	Nodes	Activation function	Optimiser	Learning rate	Batch size	Loss function
Event-level NN	4	[40, 60, 50, 1]	ReLU / Sigmoid	Adam [242]	$1.5 \cdot 10^{-4}$	256	Binary cross-entropy
Track-level pNN	4	[35, 70, 45, 3]	ReLU / Softmax	Adam [242]	$5 \cdot 10^{-5}$	256	Categorical cross-entropy

Table 6.3 – Summary of hyperparameters of (top) event-level NN and (bottom) track-level pNN.

	Input variable	Description
Event-level NN	E_T^{miss}	Magnitude of missing transverse momentum
	$E_T^{\text{miss}} / p_T^{\text{lead. jet}}$	Ratio of missing transverse momentum and leading jet p_T
	H_T	Scalar sum of p_T of all jets $p_T > 30$ GeV
	$\min \Delta\phi \left(p_T^{\text{jet}}, \mathbf{p}_T^{\text{miss}} \right)$	Minimum azimuthal angular difference between $\mathbf{p}_T^{\text{miss}}$ and all jets in the event
Track-level pNN	p_T	Kinematics of tracks
	η	
	d_0	Transverse impact parameter
	$S(d_0)$	Transverse impact parameter significance $ d_0 / \sigma(d_0) $
	z_0	Longitudinal impact parameter
	$z_0 \sin \theta$	
	χ^2 / n_{DoF}	Ratio of chi square and number of degrees of freedom from track fitting
	p_T^{cone20}	Scalar sum of p_T of tracks within $\Delta R < [0.2, 0.3, 0.4]$ (excluding itself, and the second $S(d_0)$ -selected track if it lies within the same cone)
	p_T^{cone30}	
	p_T^{cone40}	
	$\Delta m \left(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)$	Mass difference between the lightest chargino and neutralino (parameter θ)

Table 6.4 – Summary of input variables of (top) event-level NN and (bottom) track-level pNN. Events may not contain more than four jets, and only the leading and second-to-leading Sd0 tracks are considered, as discussed in Section 6.3.

tion. Figure 6.2 schematically illustrates the overall structure of the model. Given the input values of four kinematic variables, the algorithm outputs a single score ranging from 0 to 1, where values closer to 1 indicate a higher likelihood that the input event originates from a SUSY signal process. All input variables are standardised to a Gaussian distribution using the STANDARDSCALER class from SCIKIT-LEARN [243]. The optimised event-level NN architecture consists of three hidden layers with 40, 60, and 50 nodes, respectively, using rectified linear unit (ReLU) activation functions. The output layer contains a single node with sigmoid activation, providing a probabilistic interpretation of the network output. Other optimised hyperparameters are summarised in Table 6.3. The four kinematic variables used as input are E_T^{miss} , $E_T^{\text{miss}} / p_T^{\text{lead. jet}}$, H_T , and $\min \Delta\phi \left(p_T^{\text{jet}}, \mathbf{p}_T^{\text{miss}} \right)$, which are collectively described in Table 6.4. These variables are selected among those presented in Ref. [37] and providing the highest discriminating power between signal and background while exhibiting the lowest mutual correlaton. The network is trained using simulated higgsino production, $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$, and $W(\rightarrow \tau\nu) + \text{jets}$ MC samples. The higgsino samples are grouped into a single signal category, regardless of the assumed mass or mass splitting hypothesis, as these variations have only a minor impact on the global event observables. The $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ and $W(\rightarrow \tau\nu) + \text{jets}$ samples are grouped

into a common background category as well, together accounting for more than 90% of the expected Standard Model contribution to the SRs. Monte Carlo event weights are applied during training to account for the correct process cross sections and to ensure proper normalisation of the kinematic input distributions. The resulting training dataset contains approximately $2 \cdot 10^6$ events, of which roughly $1.5 \cdot 10^6$ arise from SM background processes and the remaining $5 \cdot 10^5$ from SUSY signal events. To further enhance generalisation and reduce overfitting, the training is performed using a two-fold cross-validation setup with early stopping.

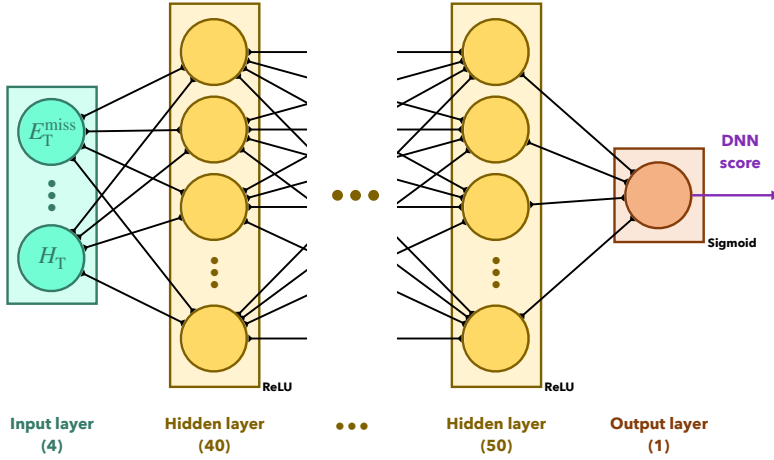


Figure 6.2 – Schematic overview of the overall structure of the event-level NN model used for event selection. The model takes four kinematic variables as input and includes three fully connected hidden layers with 40, 60, and 50 nodes, respectively. The network produces a single output score ranging from 0 to 1, where higher values indicate a greater likelihood that the input event originates from SUSY signal processes.

Figure 6.3 shows the receiver operating characteristic (ROC) curves obtained from the network output as well as from the individual input variables. Since the event-level topology closely resembles that of typical mono-jet searches [218], the E_T^{miss} is the variable that primarily drives the performance of the event-level neural network. Nonetheless, the remaining input variables still provide non-negligible discriminating power, as indicated by the improved signal efficiency achieved by the event-level NN ROC curve compared to the ROC curves of the individual inputs. Figure 6.4 shows the SHAP (SHapley Additive exPlanations) values [244, 245] for the same neural network, illustrating the marginal contribution of each input variable to the overall output score. The E_T^{miss} is again confirmed to be the dominant discriminant between signal and background events, closely followed by H_T . The latter, which includes the contribution of the p_T of the ISR leading jet recoling against the missing transverse momentum, further helps in differentiating mono-jet event topologies from others backgrounds.

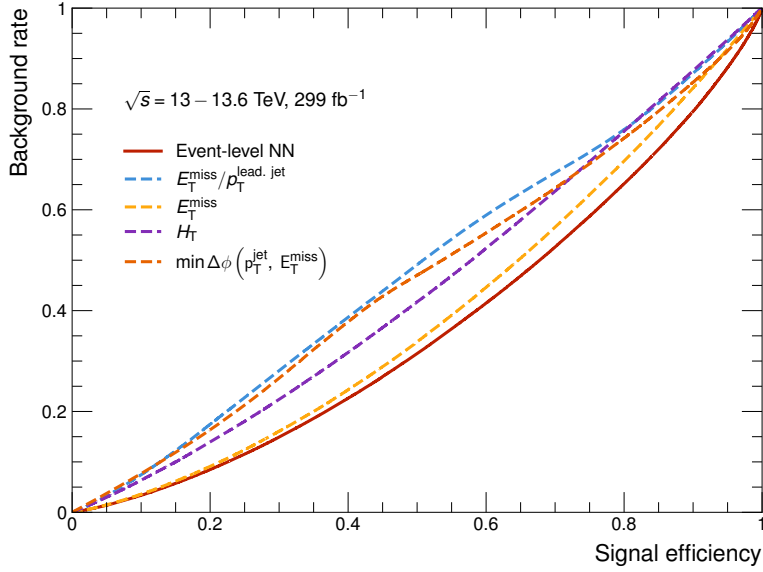


Figure 6.3 – ROC curves for the event-level neural network and for each of the input variables used in its training. Although the overall performance is driven almost entirely by E_T^{miss} , the neural network still outperforms any selection based solely on orthogonal cuts applied to the individual input variables.

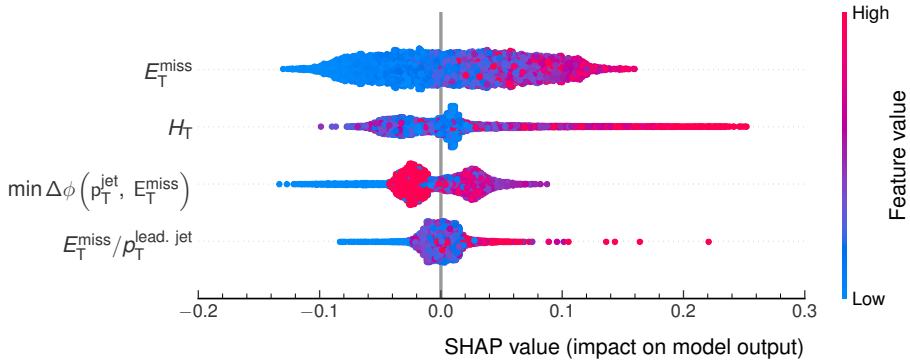


Figure 6.4 – SHAP values for the event-level neural network trained on higgsino production, $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$, and $W(\rightarrow \tau\nu) + \text{jets}$ Monte Carlo samples. Points to the right correspond to more signal-like predictions, while points to the left correspond to more background-like ones. The colour of each point indicates the magnitude of the corresponding input variable.

6.4.2 Track-level pNN

As the topology of signal higgsino tracks strongly depends on the mass splitting between the lightest chargino and neutralino, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, the main track selection is performed using a parameterised multi-class deep neural network (pNN) [236]. A conventional neural network, as the one described in the previous Section, takes as input a vector of features $\bar{\mathbf{x}} = (x_1, x_2, \dots, x_N)$, where each x_i represents a physical quantity or a kinematic variable of a reconstructed object. After training, the network output is a function of these features: $f(\bar{\mathbf{x}})$. In contrast, a pNN operates on an extended input space that includes one or more parameters $\bar{\boldsymbol{\theta}} = (\theta_1, \theta_2, \dots, \theta_N)$, producing an output that explicitly depends on these parameters $\bar{\boldsymbol{\theta}}$: $f(\bar{\mathbf{x}}, \bar{\boldsymbol{\theta}})$ (Figure 6.5). Thus, for a fixed set of input features, the pNN output varies with different choices of $\bar{\boldsymbol{\theta}}$. As illustrated in Figure 1.8, for small values of $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, higgsinos can travel several millimeters before decaying into very low- p_T pions. In this regime, signal candidate tracks typically exhibit large d_0 and $S(d_0)$ values but small transverse momenta. Conversely, for large $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, the higgsino lifetime becomes so short that the mean decay length is of the order of $\mathcal{O}(0.1)$ mm, with resulting pions exhibiting higher momenta. In this case, tracks feature small d_0 and $S(d_0)$, but larger transverse momenta. The pNN is introduced to precisely capture these dependencies and to perform the signal-background discrimination in a dynamic $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ -dependent manner. By choosing the physics parameter θ to represent the mass splitting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, a single network can provide a continuous, parameterised track selection across different $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ values. This approach simplifies the training procedure, as the pNN can smoothly interpolate between different mass splitting hypotheses, thus also giving the possibility to potentially explore various $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ scenarios beyond those explicitly simulated in the Monte Carlo samples used for the neural network training.

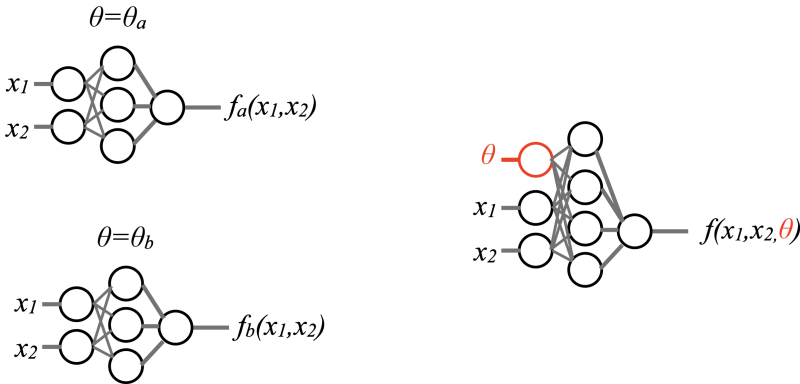


Figure 6.5 – When the input features x_1 and x_2 of a neural network depend on a physical parameter θ , the conventional approach in machine learning typically requires training separate network configurations for each fixed value of θ to achieve optimised performance (left). In contrast, the parameterised neural network approach trains a single model that includes both x_1 and x_2 , and the parameter θ as inputs, allowing the network to generalise its predictions across different values of the parameter θ itself (right). From Ref. [236].

Figure 6.6 schematically illustrates the overall structure of the pNN model developed for track selection. Given the input values of Δm ($\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$) and ten kinematic variables, the algorithm outputs three “class- i -likeness” scores, each ranging from 0 to 1 and collectively summing to unity. A score of 1 indicates that the input track is most consistent with one of three categories: signal-like, QCD-like, or τ -decay-like. In the following, the three outputs are referred to as signal track score, QCD track score, and τ track score, respectively. All of the input variables beside Δm ($\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$) are standardised to a Gaussian distribution using the STANDARDSCALER class provided by SCIKIT-LEARN [243]. The pNN architecture consists of three hidden layers with 35, 70, and 45 nodes, respectively, using rectified linear unit (ReLU) activation functions. The output layer comprises three nodes with a softmax activation function, ensuring a probabilistic interpretation of the outputs. Other optimised hyperparameters are summarised in Table 6.3. The eleven kinematic variables used for training are listed in Table 6.4. Among these, track p_T , d_0 , $S(d_0)$, z_0 , and $z_0 \sin \theta$ exhibit strong Δm ($\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$) dependence and thus play a key role in the final discrimination performance. The variable χ^2/n_{Dof} is included to allow the pNN to distinguish good-quality tracks from those that are poorly reconstructed, while p_T^{cone20} , p_T^{cone30} , and p_T^{cone40} are used to characterise the level of isolation across different cone radii. The pNN is trained using simulated higgsino production and $W(\rightarrow \tau\nu) + \text{jets}$ MC samples.

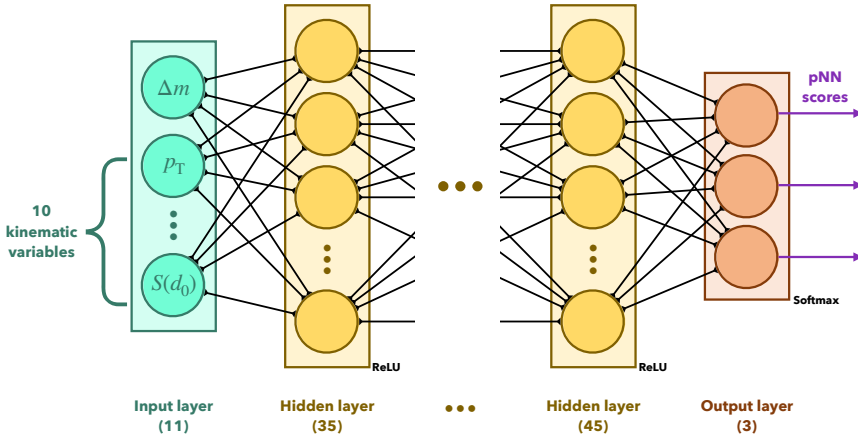


Figure 6.6 – Schematic overview of the overall structure of the pNN model used for track selection. The model takes as input the Δm ($\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$) parameter along with ten kinematic variables. It consists of three fully connected hidden layers containing 35, 70, and 45 nodes, respectively. The network outputs three pNN scores, each ranging from 0 to 1 and collectively summing to 1. A score of 1 indicates that the input track is most consistent with one of the three categories: signal-like, QCD-like, or tau-decay-like.

The higgsino samples contain tracks from both SUSY and soft QCD processes, whereas $W(\rightarrow \tau\nu) + \text{jets}$ samples provide tracks from soft QCD and τ -lepton decays. Since the characteristics of QCD tracks are independent of the specific hard-scattering process - an observation confirmed in Chapter 5 - training on higgsino production and $W(\rightarrow \tau\nu) + \text{jets}$

samples allows the pNN to effectively identify QCD-like tracks in other background processes, such as $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$, $t\bar{t}$, or di-boson production. Since the dataset used for training is highly unbalanced - with approximately $1.7 \cdot 10^6$ signal tracks, $15 \cdot 10^6$ QCD tracks, and $7 \cdot 10^5$ tracks originating from τ decays - class weights are applied during training to tracks originating from SUSY, soft QCD or τ -decay processes. The weights are defined as

$$W_i = \frac{N_{\text{tot}}^{\text{trk}}}{3 \cdot N_i^{\text{trk}}} , \quad (6.1)$$

where $N_{\text{tot}}^{\text{trk}}$ denotes the total number of tracks in the training dataset, and N_i^{trk} is the number of tracks belonging to class i . This weighting ensures that each class contributes equally to the overall loss function during training, mitigating biases due to class imbalance. To further improve generalisation and minimise overfitting, the training is performed using a two-fold cross-validation setup with early stopping enabled. The pNN is trained with six $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ values: 0.25, 0.35, 0.5, 0.75, 1 and 1.25 GeV. Of these, four values - 0.35, 0.5, 0.75, and 1 GeV - are used to define non-orthogonal search regions.

Figure 6.7 and Figure 6.8 show the ROC curves and SHAP values for each $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ hypothesis, respectively. Since the pNN provides a multi-class output, both the ROC curves and the SHAP values are computed under a “signal-vs-rest” assumption, in which tracks originating from QCD processes and τ decays are grouped into a common background category. Because the topology differences between signal and background tracks are most pronounced for intermediate mass splittings ($\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35 -$

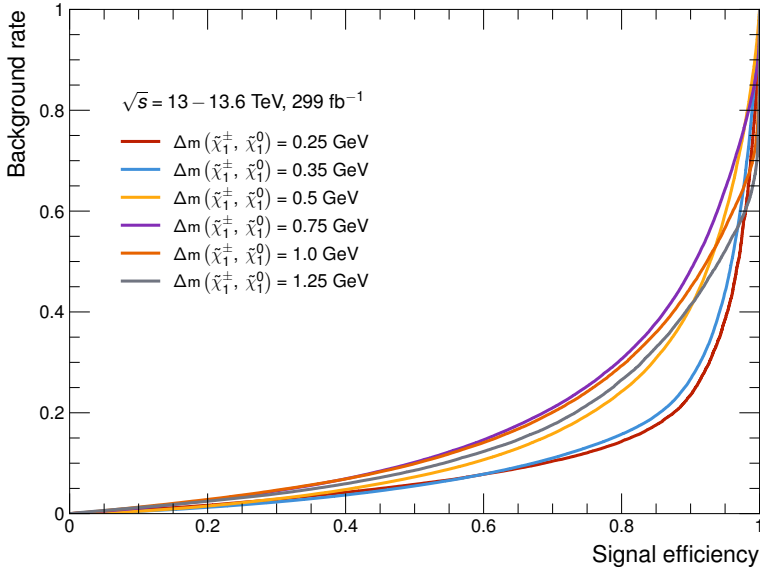


Figure 6.7 – ROC curves for the track-level parametric neural network under the different mass splitting hypotheses. Since the pNN provides a multi-class output, the ROC curves are computed under a “signal-vs-rest” assumption, in which tracks originating from QCD processes and τ decays are grouped into a common background category.

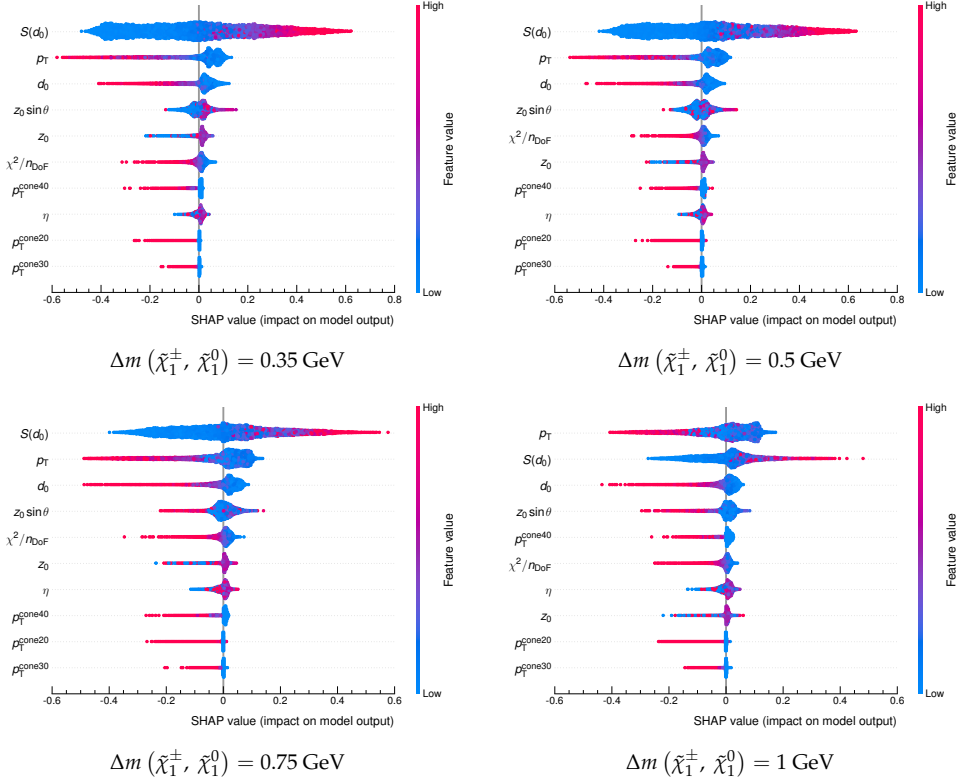


Figure 6.8 – SHAP values for the track-level parametric neural network trained on higgsino production and $W(\rightarrow \tau\nu) + \text{jets}$ Monte Carlo samples. The values are shown for mass splitting hypothesis of $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35, 0.5, 0.75$, and 1 GeV. Points to the right correspond to more signal-like predictions, while points to the left correspond to more background-like ones. The colour of each point indicates the magnitude of the corresponding input variable.

0.75 GeV), the best signal-background separation is achieved for these intermediate values. Nevertheless, the pNN still shows good performance for the $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.25$ GeV and $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1.25$ GeV hypotheses, as indicated by their respective ROC curves. This behaviour suggests that the reduced sensitivity to the extreme mass splitting scenarios does not stem from a lack of discriminating power in the pNN, but rather from the extremely low track reconstruction efficiency at $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.25$ GeV² and from the limited signal selection efficiency of the track-level criteria described in Section 6.3.2 for the $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1.25$ GeV hypothesis. For these reasons, the pNN outputs for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.25$ GeV and $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1.25$ GeV are not used to define dedicated search regions in the subsequent analysis. The SHAP values also clearly illustrate the dependence of the input variables on the mass splitting hypothesis. For instance, the

² Most signal tracks from higgsino decays at $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.25$ GeV have $p_T < 500$ MeV. Since 500 MeV is the lowest threshold applied during track reconstruction, the analysis rapidly loses sensitivity in this regime when relying solely on the standard tracking algorithm. Future searches may benefit from specialised tracking techniques capable of reconstructing tracks with p_T as low as 100 MeV [246].

track p_T is the second most important discriminant for low to intermediate mass splitting hypotheses, but becomes the dominant one at $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1$ GeV, where tracks are expected to have significantly harder momenta. An opposite trend is observed for $S(d_0)$, instead.

6.5 Signal Region definition

As discussed above, the event-level NN score and the track-level pNN scores are used as the final discriminants to define the Signal Regions of the analysis. To determine the optimal selections that maximise the separation between signal and background, an optimisation procedure is performed via a multidimensional scan over all possible choices of NN score thresholds. For each candidate selection, the number of observed events is assumed to be equal to the sum of all SM background events and the SUSY signal events, allowing the evaluation of the statistical compatibility under the background-only hypothesis. Since this optimisation is carried out prior to the actual background estimation, the expected background rates are taken directly from MC simulations without any data-driven corrections, and a conservative total uncertainty of 15% is assigned to the predicted yields. The statistical significance is computed according to Eq. 5.2. Because the event-level NN score is independent of the specific mass splitting hypothesis, a common requirement is applied across all SRs: event-level NN score > 0.48 . Moreover, because tracks with $p_T > 10$ GeV are expected to arise from SM processes only, all SRs inclusively require track $p_T < 10$ GeV. In contrast, the track-level pNN scores explicitly depend on the mass splitting choice. Four non-orthogonal SRs are defined by applying selections on two of the three pNN output scores³, as described below.

- QCD track score < 0.14 , signal track score > 0.6 for the SR targeting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35$ GeV;
- QCD track score < 0.04 , signal track score > 0.6 for the SR targeting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.5$ GeV;
- QCD track score < 0.04 , signal track score > 0.4 for the SR targeting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.75$ GeV; and
- QCD track score < 0.06 , signal track score > 0.2 for the SR targeting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1$ GeV.

An additional set of SRs is defined to target events with two displaced tracks. These regions apply selection criteria on the same event-level NN and track-level pNN scores, but always require the presence of two opposite charge tracks in the final state. To ensure orthogonality between the “one-track” (1T) and “two-tracks” (2T) SRs, the 1T SRs require the second track (if present) to have pNN signal score < 0.2 . A summary of the selection criteria defining both the 1T and 2T SRs is provided in Table 6.5. Figures 6.9, 6.10, and 6.11 illustrate the results of the optimisation procedure for the 1T SRs. The distributions

³ The three pNN output scores collectively sum to unity; therefore, applying selections on two of them automatically constrains the third one.

Variable	Event selection							
$N(\ell_{\text{base}})$	= 0							
$N(\gamma_{\text{base}})$	= 0							
N_{jets}	[1, 4]							
Leading jet p_{T} [GeV]	> 250							
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 300							
$\min \Delta\phi\left(p_{\text{T}}^{\text{jet}}, \mathbf{p}_{\text{T}}^{\text{miss}}\right)$	> 0.4							
Event NN Score	> 0.48							
	Track selection							
Working point	Tight Primary							
Hit on IBL	Required							
p_{T} [GeV]	[0.5, 10]							
$ \eta $	< 1.5							
$ \Delta z_0 \sin \theta $ [mm]	< 1.5							
Secondary vertex veto	Required							
	1T SR				2T SR			
Target $\Delta m\left(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0\right)$ [GeV]	0.35	0.5	0.75	1.0	0.35	0.5	0.75	1.0
$\left \Delta\phi\left(p_{\text{T}}^{\text{track}}, \mathbf{p}_{\text{T}}^{\text{miss}}\right)\right $	< 0.4				< 0.6			
Opposite charge	-				Required			
Leading track QCD score	< 0.14	< 0.04	< 0.04	< 0.06	< 0.2	< 0.1	< 0.1	< 0.1
Leading track signal score	> 0.6	> 0.6	> 0.4	> 0.2	> 0.2	> 0.2	> 0.2	> 0.2
Second-to-leading track signal score (if present)	< 0.2	< 0.2	< 0.2	< 0.2	> 0.2	> 0.2	> 0.2	> 0.2

Table 6.5 – Summary of the event-level and track-level selections defining the 1T and 2T SRs.

shown in Figure 6.9 demonstrate that the optimal threshold on the event-level NN score is independent of the assumed mass splitting, motivating the use of a common selection across all SRs. In contrast, the distributions presented in Figures 6.10 and 6.11 show that the optimal selections on the pNN QCD and signal track scores depend on the mass splitting hypothesis under consideration. An analogous optimisation is applied to determine the selections for the 2T SR definitions, and the results are presented in Appendix A.

To further enhance sensitivity to the different signal scenarios, both the 1T and 2T SRs will be binned in one the following three variables: the event-level NN score, the track-level pNN signal score, or $|\Delta\phi(p_T^{\text{track}}, \mathbf{p}_T^{\text{miss}})|$, as these provide the strongest discrimination between signal and background. The final choice of variable and the number of bins will be determined based on the results of the model-dependent exclusion limits, including the contributions of all sources of systematic uncertainty.

6.5. SIGNAL REGION DEFINITION

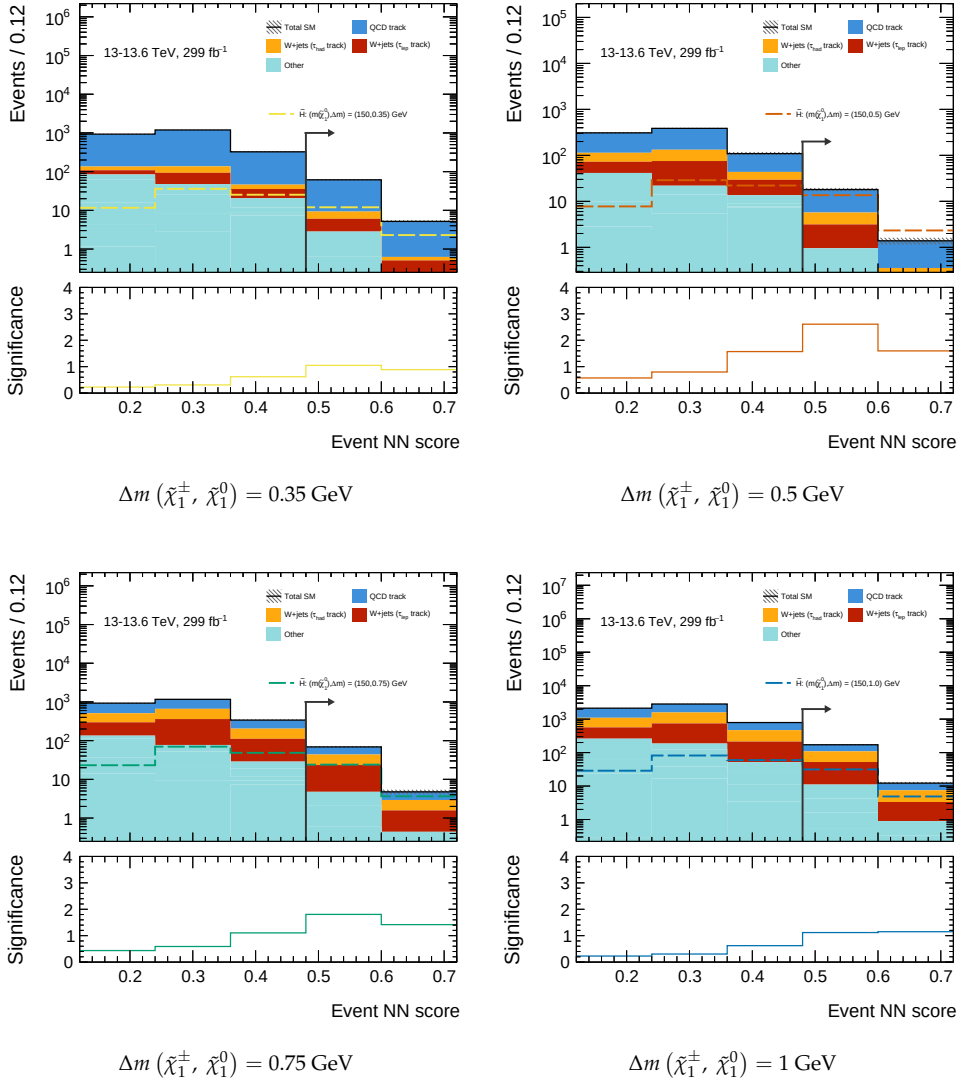


Figure 6.9 – Event-level NN score distributions for the one-track SRs, obtained by applying selections on all analysis variables except the one shown. The stacked filled histograms represent SM backgrounds, while SUSY signals are shown as dashed lines. The hatched area indicates MC statistical uncertainties. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, di-boson, $t\bar{t}$, single top, and multi-jet production. The bottom panel shows the statistical significance calculated by accumulating the yields of bins to the right, assuming a total 15% background uncertainty.

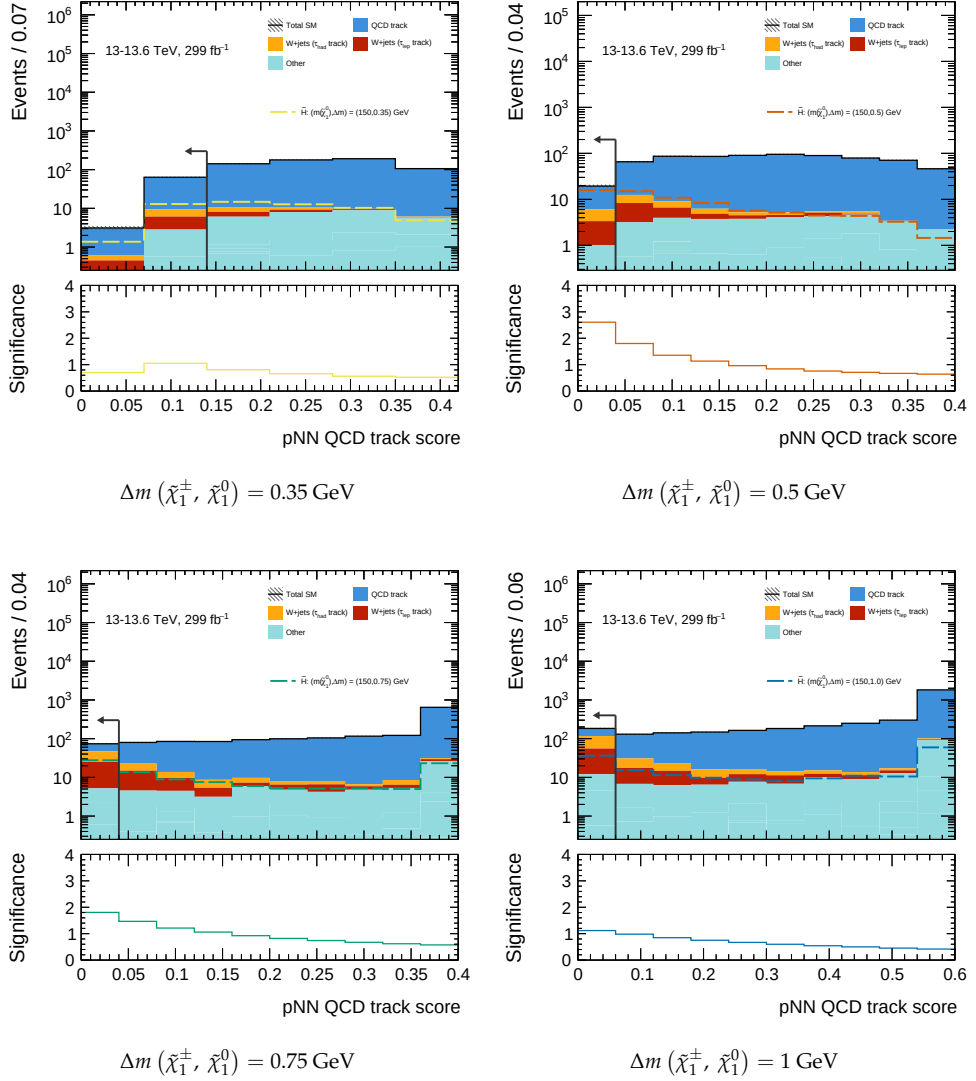


Figure 6.10 – pNN QCD track score distributions for the one-track SRs, obtained by applying selections on all analysis variables except the one shown. The stacked filled histograms represent SM backgrounds, while SUSY signals are shown as dashed lines. The hatched area indicates MC statistical uncertainties. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, di-boson, $t\bar{t}$, single top, and multi-jet production. The bottom panel shows the statistical significance calculated by accumulating the yields of bins to the left, assuming a total 15% background uncertainty.

6.5. SIGNAL REGION DEFINITION

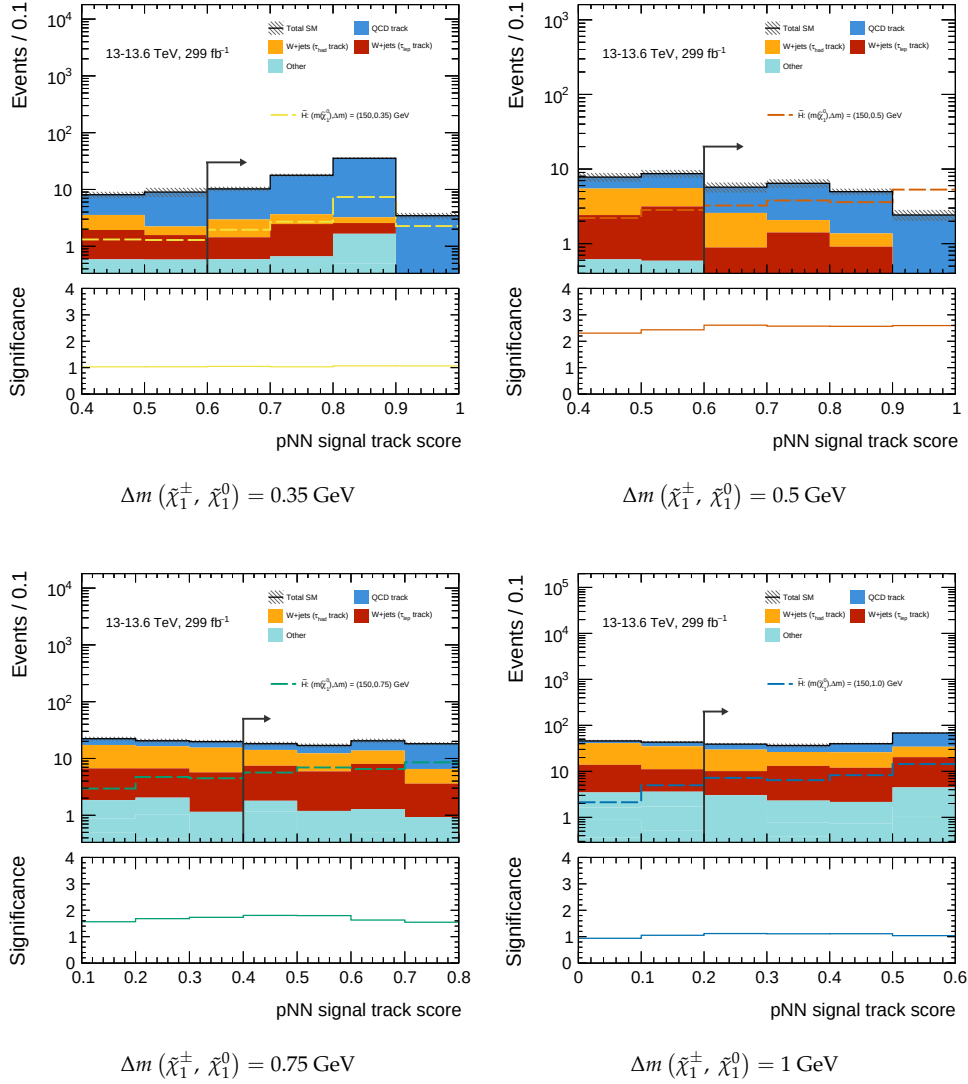


Figure 6.11 – pNN signal track score distributions for the one-track SRs, obtained by applying selections on all analysis variables except the one shown. The stacked filled histograms represent SM backgrounds, while SUSY signals are shown as dashed lines. The hatched area indicates MC statistical uncertainties. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, di-boson, $t\bar{t}$, single top, and multi-jet production. The bottom panel shows the statistical significance calculated by accumulating the yields of bins to the right, assuming a total 15% background uncertainty.

6.6 Background Estimation

The background estimation strategy adopted to estimate the two dominant background components in the SRs follows the approach presented in Chapter 5.

- QCD tracks originating from soft initial- or final-state radiation, interactions between partons other than those involved in the hard scatter, or from pileup vertices in $Z + \text{jets}$ and $W + \text{jets}$ processes tend to dominate the low- Δm ($\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$) SR bins and become progressively less relevant for higher mass splitting hypotheses. Since accurately modelling particles generated by QCD interactions is challenging, MC simulations alone are not reliable for estimating their contribution. Therefore, a fully data-driven method is employed to estimate the rate of QCD tracks in the SRs.
- Produced in $W(\rightarrow \tau\nu) + \text{jets}$ decays, tracks originating from hadronic or leptonic τ decays closely resemble those arising from SUSY signal processes. They constitute the second major background component and tend to dominate the SR bins associated to high- Δm ($\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$) hypotheses. τ -decay background tracks are estimated using a semi data-driven approach. MC simulations, which accurately model τ decays via the electroweak interaction, are used to predict the nominal yields in dedicated CRs. These predictions are then normalised to data to correct for potential mismodelling, and the resulting normalisation factors are extrapolated to the SRs.

Tracks in other SM processes, such as $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and diboson, have minor impact on both categories of SR bins and are therefore estimated directly from simulation samples. In the following, the background estimation strategy for the Δm ($\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$) = 0.5 GeV 1T and 2T SRs is described. An analogous approach is adopted for the SRs targeting other mass splitting hypotheses, with the QCD and signal track score selections in the CRs adjusted to match those used in each corresponding SR. Additional details are provided in Appendix B.

6.6.1 Data-driven estimation of QCD tracks

The contribution of QCD tracks in $V + \text{jets}$ processes to the SRs is estimated using a fully data-driven approach based on the ABCD method [223, 224]. This approach relies on the assumption that QCD tracks originating from the underlying event or pileup interactions are independent of the weak boson decays. The assumption is validated through a closure test performed on MC simulations; further details are provided in Section 6.7. Since tracking information is uncorrelated to the topology of the event, equivalent track variable distributions can be extracted from regions dominated by $V + \text{jets}$ processes with different decay modes, and the number of QCD tracks in the SRs can be estimated from the number of tracks originating from the same process in regions dominated by $W(\rightarrow \mu\nu) + \text{jets}$ decays. A 1μ category is therefore defined by selecting events passing the E_T^{miss} trigger, containing exactly one muon satisfying signal criteria from Table 6.2 with $p_T(\mu) > 10$ GeV, and having transverse mass $m_T \in [56, 106]$ GeV, consistent with W boson decays. Leptons from weak bosons are treated as invisible to reproduce the E_T^{miss} + jets signature required in the SRs. To ensure operating on the E_T^{miss} trigger efficiency

plateau, the magnitude of $\mathbf{p}_T^{\text{recoil}}$ (p_T^{recoil}) — defined identically to that in Chapter 5 — is required to exceed 300 GeV. All quantities derived from the E_T^{miss} , including the E_T^{miss} itself, are replaced by their p_T^{recoil} -based counterparts. The statistical precision on the computation of the QCD tracks estimate is improved by removing the event-level NN score requirement used in the SR definitions. Track-level selections described in Section 6.3.2 are applied, and tracks associated with the reconstructed muons are removed to mimic the 0ℓ topology. To prevent photon conversion tracks with large signal track score to populate the 1μ category and biasing the computation of QCD tracks, a minimum separation ΔR of 0.04 between tracks and muons is required, achieving almost 98% reduction of the undesired tracks. The number of QCD tracks is extracted from the 1μ category for each 1T and 2T SR bin by computing a set of **Trasfer Factors** (TFs) as the ratio of QCD track yields between CRs with low- and high-QCD score. Specifically, the TF for each SR bin i is given by

$$\text{TF}_{\text{SR}_i} = \frac{N_{\text{CR-}1\mu\text{-Low}_i}^{\text{data}} - N_{\text{CR-}1\mu\text{-Low}_i}^{\text{non-QCD-track}}}{N_{\text{CR-}1\mu\text{-High}}^{\text{data}} - N_{\text{CR-}1\mu\text{-High}}^{\text{non-QCD-track}}} . \quad (6.2)$$

Here, $N_{\text{CR-}1\mu\text{-Low}_i}^{\text{data}}$ represents the observed data in bin i of CR- 1μ -Low, defined by requiring the same QCD track score selection as the target SR bin. The quantity $N_{\text{CR-}1\mu\text{-High}}^{\text{data}}$ corresponds instead to the observed data in the CR- 1μ defined by requiring a high QCD track score. A gap is left between the QCD score selections of CR- 1μ -Low and CR- 1μ -High to be potentially used as a region to validate the background estimates. Similar selections on the QCD track score are applied to define the expected yields of non-QCD tracks, indicated by the superscript “non-QCD-track”, and which are taken from MC simulations. QCD track yields in the SR bins are obtained by multiplying the TFs to the data yields in the adjacent CR- 0ℓ (event-level NN score > 0.48 and high QCD track score), after subtracting the expected non-QCD-track contribution from MC simulation:

$$N_{\text{SR}_i}^{\text{QCD tracks}} = \text{TF}_{\text{SR}_i} \times (N_{\text{CR-}0\ell}^{\text{data}} - N_{\text{CR-}0\ell}^{\text{non-QCD-track}}) , \quad (6.3)$$

Figure 6.12 schematically illustrates the TFs computation and the subsequent extrapolation to the bins of the 1T SR, with a similar strategy adopted for the 2T one.

Validation Regions

Following the approach adopted in the cut-based analysis presented in Chapter 5, the extrapolation of the TFs for the QCD background estimation is primarily validated using data in regions belonging to the 1γ category. To this end, the VR- 1γ is defined for both the 1T and 2T categories by applying the same selections as in the SRs, with the exception of replacing the lepton veto with the requirement of exactly one final-state photon. The photon must have $p_T > 200$ GeV, fulfil the signal selection criteria listed in Table 6.2, and pass a single-photon trigger [225] selection. The selected photon is treated as invisible in calculating the missing transverse momentum ($\mathbf{p}_T^{\text{recoil}} = \mathbf{p}_T^{\text{miss}} + \mathbf{p}_T(\gamma)$). All variables that depend on the missing transverse momentum are recalculated using $\mathbf{p}_T^{\text{recoil}}$ and are

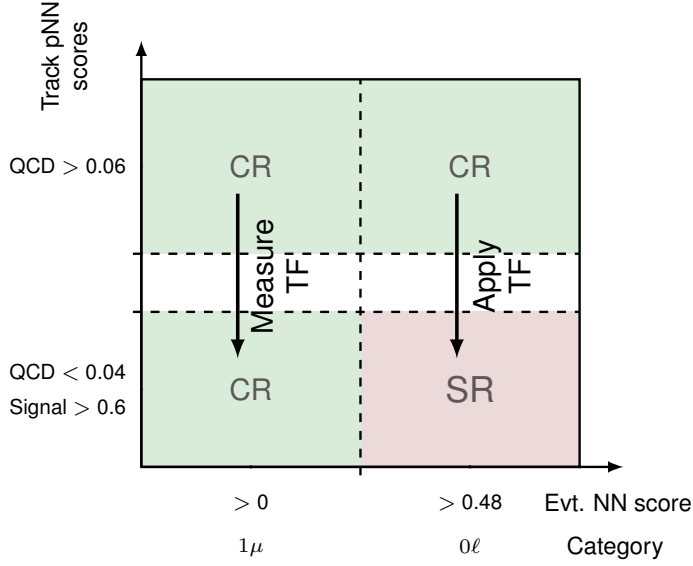


Figure 6.12 – Schematic illustration of the region definitions in the 0ℓ and 1μ categories for the QCD track estimation in the 1T SR targeting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.5$ GeV signals. Regions with pNN QCD track score < 0.04 will be further binned in one of the following three variables: the event-level NN score, the track-level pNN signal score, or $|\Delta\phi(p_T^{\text{track}}, \mathbf{p}_T^{\text{miss}})|$. The green (red) area represents the CRs (SRs) used to estimate the contribution from QCD tracks. The TF (for each bin that will be defined) is calculated as the ratio between the CR yields in the 1μ category, as indicated by the arrow on the left. The TF is then multiplied by the CR yields in the 0ℓ category to estimate the QCD track background in the SR bins.

subsequently used for event selection and for the computation of the event-level NN score. In all 1γ regions, the track selections described in Section 6.3.2 are applied, and a minimum angular separation of $\Delta R > 0.04$ between tracks and photons is required in order to suppress contributions from photon conversion tracks. Consistent with the background estimation procedure, TFs derived from the 1μ CRs are applied to data in the 1γ CRs that replace their corresponding 0ℓ counterparts (defined by a QCD track score greater than 0.06 and 0.15 for the 1T and 2T selections, respectively), to obtain the final background estimates in the VRs. Since the statistical precision of the VR- 1γ region is comparable to that of the SR for both the 1T and 2T categories, an additional region with enhanced statistics is defined — VR- 1γ -Extended — by relaxing the selection on the event-level NN signal score to 0.30. The full set of selection criteria defining all CRs and VRs used for the validation of the QCD track TFs is summarised in Table 6.6.

The QCD track background estimation and validation strategy described in this Section is summarised as follows.

1. The number of QCD tracks in the SRs is estimated from data in the 1μ category regions, enriched in $W(\rightarrow \mu\nu) + \text{jets}$ events, through the computation of the TFs for each SR bin in both the 1T and 2T categories.

2. The derived TFs are validated in the 1γ category, enriched γ + jets process.
3. Due to the limited statistics in the nominal 1γ regions, additional validation is performed in 1γ -Extended VRs, obtained by relaxing the selection on the event-level NN score to 0.30.

Variable	0ℓ	1μ	1γ	
Trigger	E_T^{miss}	E_T^{miss}	Single- γ	
$N(\ell_{\text{base}})$	= 0	= 1	-	
$N(\ell_{\text{signal}})$	-	= 1	-	
$N(\gamma_{\text{base}})$	= 0	-	= 1	
$N(\gamma_{\text{signal}})$	-	-	= 1	
$p_T(\ell)$ [GeV]	-	> 10	-	
$p_T(\gamma)$ [GeV]	-	-	> 200	
m_T [GeV]	-	[56, 106]	-	
One-track	SR(CR- 0ℓ)	CR- 1μ -Low(-High)	VR(CR)- 1γ	VR(CR)- 1γ -Extended
Event-level NN score	> 0.48	-	> 0.48	> 0.30
Leading track QCD score	< 0.04 (> 0.06)		< 0.04 (> 0.06)	
Leading track signal score	> 0.6 (-)		> 0.6 (-)	
Second-to-leading track signal score (if present)	< 0.2		< 0.2	
Two-tracks	SR(CR- 0ℓ)	CR- 1μ -Low(-High)	VR(CR)- 1γ	VR(CR)- 1γ -Extended
Event-level NN score	> 0.48	-	> 0.48	> 0.30
Leading track QCD score	< 0.1 (> 0.15)		< 0.1 (> 0.15)	
Leading track signal score	> 0.2 (-)		> 0.2 (-)	
Second-to-leading track signal score	> 0.2 (-)		> 0.2 (-)	

Table 6.6 – Selection criteria applied across the different categories to define SRs, CRs, and VRs employed in the calculation and validation of QCD track transfer factors. Only selections orthogonal to the SRs are listed. The event-level and track-level preselections are omitted as they are identical across all categories, as presented in Section 6.3.

Results in Validation Regions

The yields in the VRs are estimated via a background-only fit that simultaneously includes the CRs and the VRs. Table 6.7 reports the post-fit yields for Run 2 and Run 3 in the 1γ VRs both for the 1T and 2T selections. Results for VRs corresponding to mass splitting hypotheses other than $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.5$ GeV are provided in Appendix C. Across all VRs, post-fit SM predictions are consistent with the observed data within 1.5σ , indicating a good modelling of the QCD track background and supporting the assumption of uncorrelation between event-level features and tracking variables, and consequently between the event-level and track-level neural network scores that form the basis of the background estimation strategy.

	VR-1 γ -1T	VR-1 γ -Extended-1T	VR-1 γ -2T	VR-1 γ -Extended-2T
Observed data	25	241	55	797
SM prediction	21 ± 3	243 ± 35	61 ± 8	728 ± 84
QCD track	21 ± 3	243 ± 35	61 ± 8	728 ± 84
$W(\rightarrow \tau_h \nu) + \text{jets}$	-	-	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	-	-	-	-
Other	-	-	-	-

	VR-1 γ -1T	VR-1 γ -Extended-1T	VR-1 γ -2T	VR-1 γ -Extended-2T
Observed data	25	293	112	1324
SM prediction	25 ± 3	268 ± 30	116 ± 9	1197 ± 80
QCD track	25 ± 3	268 ± 30	116 ± 9	1197 ± 80
$W(\rightarrow \tau_h \nu) + \text{jets}$	-	-	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	-	-	-	-
Other	-	-	-	-

Table 6.7 – Number of expected and observed data events in Run 2 (top) and Run 3 (bottom) 1 γ VRs for both the 1T and 2T selections. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

6.6.2 Semi data-driven estimation of τ decay tracks

The $W(\rightarrow \tau\nu) + \text{jets}$ process constitutes the other significant SM background in the defined SR bins. It can produce two types of signal-like tracks: τ decay tracks and QCD tracks, with the latter estimated as described in the previous Section. Hadronic and leptonic τ decay tracks are estimated using a partially data-driven method based on dedicated CRs adjacent to the SR bins to normalise the nominal MC predictions to the observed data, thereby deriving a common **Normalisation Factor** (NF) applied to both the 1T and 2T SRs. To avoid double counting the QCD track component of the $W(\rightarrow \tau\nu) + \text{jets}$ background in these regions, selected tracks are required to be matched to hadronic or leptonic tau decays. In the 2T selection, at least one of the two selected tracks in MC simulations must satisfy this matching requirement.

Two CRs are defined to normalise the $W(\rightarrow \tau\nu) + \text{jets}$ background. CR- τ_h , dominated by events with hadronic τ decays, requires tracks with $10 < p_T < 20$ GeV, a pNN QCD track score below 0.04, and no requirement on the signal track score. For the events where multiple tracks satisfy all selection criteria, the track with the lowest pNN signal track score is chosen. All other selections are identical to those of the 1T SR definition. The p_T

requirement ensures orthogonality with all the SRs and negligible signal contamination, while also suppressing contributions from high- p_T QCD tracks. The $\text{CR-}\tau_\ell$ region is defined analogously to $\text{CR-}\tau_h$, except that the lepton veto is replaced by the requirement of a baseline muon and the selected track to be matched to it. As a result, this CR is primarily populated by dominated by events with leptonic τ decays. While the SRs are defined using $\mathbf{p}_T^{\text{miss}}$ -based quantities, $\text{CR-}\tau_\ell$ instead employs $\mathbf{p}_T^{\text{recoil}}$, defined as the vector sum of the missing transverse momentum and the transverse momentum of the baseline muon. To suppress contributions from $W(\rightarrow \mu\nu)$ +jets decays and avoid contamination from SUSY signals beyond those considered in the analysis, $\text{CR-}\tau_\ell$ further requires the muon transverse mass to be less than 50 GeV.

$\text{CR-}\tau_h$ and $\text{CR-}\tau_\ell$ are used simultaneously to estimate hadronic and leptonic τ decay tracks in the SR bins by deriving a single inclusive NF^4 , defined as

$$\text{NF} = \frac{N_{\text{data}} - N_{\text{non-}\tau\text{-tracks}}}{N_{\tau\text{-tracks}}}, \quad (6.4)$$

where N_{data} is the observed data yield, $N_{\tau\text{-tracks}}$ denotes the expected τ decay tracks from MC simulations, and $N_{\text{non-}\tau\text{-tracks}}$ represents the total expected yield from tracks not originating from τ decays. This NF is applied to the MC-predicted τ decay track yields in the SRs to correct the background estimates. The same NF is used for the 1T and 2T SRs.

A schematic overview of the CR definitions used to extract the τ -decay track NF is shown in Figure 6.13.

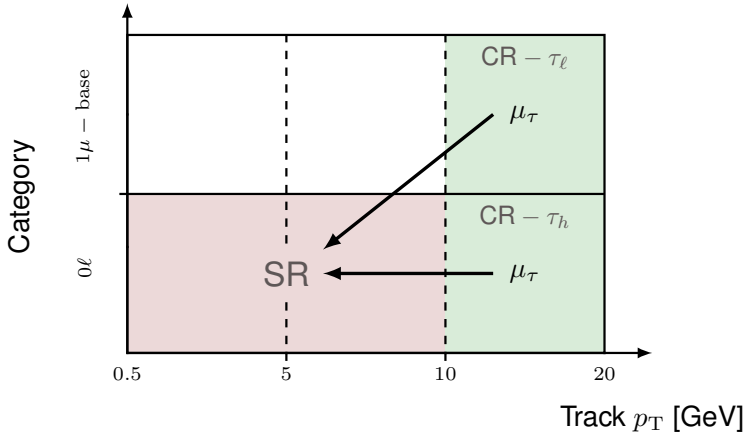


Figure 6.13 – Schematic illustration of the region definitions used for the estimation of τ decay tracks. The red and green areas indicate the SR and the CRs, respectively. A single normalisation factor is constrained using the two CRs in the high- p_T regime of the 0ℓ and $1\mu_{\text{base}}$ categories. This NF is extrapolated to the low- p_T regime and applied to the τ decay track yields in the SRs, as indicated by the two arrows.

⁴ As in the analysis presented in Chapter 5, two normalisation factors were initially considered to separately estimate hadronic and leptonic τ decay tracks. However, since individual NFs were found to be fully compatible within statistical uncertainties, a single combined NF was ultimately adopted to improve the stability of the statistical fit.

Validation Regions

The validity of extrapolating the NF from the high track p_T control regions ($[10, 20]$ GeV) is assessed by defining a dedicated VR populated by low- p_T tracks ($p_T < 10$ GeV). VR- τ is defined by inclusively selecting events belonging to either the 0ℓ or the $1\mu_{\text{base}}$ categories; that is, events are required to either satisfy the lepton veto or contain exactly one final-state baseline muon with transverse mass below 50 GeV matched to the selected track. The tracking selections are kept aligned with those of the 1T SR, with the exception that an upper threshold is imposed on the pNN signal track score is adopted (< 0.2) to avoid any overlap between the defined VR and the SRs and to suppress potential signal contamination. The combination of these selection criteria defines a kinematic region close to the SRs and populated by hadronic and leptonic tau decay tracks in more than 70% of events. Table 6.8 summarises the selections applied to define the CRs for estimating the τ decay track background, and also includes the definitions of the VR used to validate the normalisation factor.

Variable	0ℓ		$1\mu_{\text{base}}$	$0\ell + 1\mu_{\text{base}}$
$N(\ell_{\text{base}})$	$= 0$		$= 1$	$= 0$ OR $= 1$
$N(\mu_{\text{base}})$	$= 0$		$= 1$	$= 0$ OR $= 1$
m_T [GeV]	-		< 50	< 50 (if muon is selected)
	SR-1T (SR-2T)	CR- τ_h	CR- τ_ℓ	VR- τ
Track p_T [GeV]	< 10	$[10, 20]$	$[10, 20]$	< 10
Leading track signal score	> 0.6 (> 0.2)	-	-	< 0.2

Table 6.8 – Selection criteria applied across the 0ℓ and $1\mu_{\text{base}}$ categories to define SRs, CRs, and VRs for the calculation and validation of hadronic and leptonic τ decay track normalisation factor. Only selections orthogonal to the SRs are listed. The track-level selection is omitted as it is identical across all categories.

The background estimation and validation strategy for the τ decay tracks described in this Section is summarised below.

1. A single NF is defined to estimate both the hadronic and leptonic τ decay tracks simultaneously in the 1T and 2T SRs. This NF is measured in the high track p_T regime of the 0ℓ and $1\mu_{\text{base}}$ categories, where the 0ℓ CR is enriched in hadronic decays and the $1\mu_{\text{base}}$ CR is enriched in tracks from leptonic decays.
2. The extrapolation of the NF from the high track p_T range ($10 < p_T < 20$ GeV) to the low track p_T range ($0.5 < p_T < 10$) is validated using a dedicated validation regions. VR- τ follows the same selection criteria as the 1T SR, but imposes an upper threshold on the pNN signal track score (< 0.2) and requires events to either satisfy the lepton veto or contain exactly one final-state baseline matched to the selected track. Overall, these requirements are designed to minimise signal contamination while retaining sufficient statistical power for validation.

Results in Validation Regions

The yields in the VRs are estimated via the same background-only fit that also includes the CRs and VRs used for the QCD background estimation and validation. Table 6.9 shows the post-fit yields for VR- τ for both Run 2 and Run 3. Results for VRs corresponding to mass splitting hypotheses other than $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.5$ GeV are provided in Appendix C. In all cases, the post-fit SM predictions agree with the observed data within 1σ , indicating a good modelling of both hadronic and leptonic τ decay track backgrounds.

	Run 2 VR- τ	Run 3 VR- τ
Observed data	33	28
SM prediction	33 ± 6	37 ± 6
QCD track	4.3 ± 1.8	4.6 ± 2.6
$W(\rightarrow \tau_h \nu) + \text{jets}$	14.9 ± 4.2	16 ± 3
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	10.7 ± 2.1	12.8 ± 2.9
Other	3.0 ± 0.5	3.2 ± 1.2

Table 6.9 – Number of expected and observed data events in Run 2 and Run 3 τ decay VR. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

6.6.3 Simultaneous validation of QCD and τ decay tracks

Sections 6.6.1 and 6.6.2 presented the individual background estimation and validation for QCD and τ decay tracks, respectively. A simultaneous validation of both background components is additionally performed in a dedicated set of VRs, designed to closely reproduce the kinematics and the background composition of the SRs. To this end, VR- 0ℓ is defined for both the 1T and 2T categories by applying the same event-level and track-level selections as the SRs, while relaxing the requirement on the event-level NN score to range $[0.1, 0.2]$. As shown in Figure 6.9 and in Appendix A, this selection yields a region with significantly higher statistics than the SRs, thus minimising statistical uncertainties, and with negligible signal contamination. The validation of the QCD track background in these VRs is carried out by applying the TFs derived from the 1μ CRs to data yields observed in 0ℓ CRs, which are defined using the same selection criteria as the CR- 0ℓ regions listed in Table 6.6 but with the relaxed requirement on the event-level NN score. In parallel, and following the same strategy adopted in the cut-based analysis, a NF obtained from low event-level NN score, τ -enriched CRs (CR2- τ_h and CR2- τ_ℓ) is applied to the τ decay tracks to correct the nominal MC predictions. The resulting post-fit yields in the two $\Delta m = 0.5$ GeV VRs for Run 2 and Run 3 are summarised in Table 6.10. Results for VRs corresponding to the other mass splitting hypotheses are provided in Appendix C. Overall, the difference between the observed data and SM predicted yields across

the VRs is found to be within at most 1σ , indicating the robustness of the background estimation strategy.

	VR-0 ℓ -1T	VR-0 ℓ -2T
Observed data	87	292
SM prediction	102 ± 13	270 ± 28
QCD track	68 ± 10	238 ± 28
$W(\rightarrow \tau_h \nu) + \text{jets}$	12 ± 6	6.1 ± 3.2
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	8.0 ± 2.5	5.5 ± 2.5
Other	14 ± 2	20 ± 3

	VR-0 ℓ -1T	VR-0 ℓ -2T
Observed data	131	481
SM prediction	119 ± 12	500 ± 31
QCD track	84 ± 11	438 ± 30
$W(\rightarrow \tau_h \nu) + \text{jets}$	10.7 ± 2.8	14.5 ± 5.3
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	5.9 ± 2.8	13.6 ± 5.5
Other	19 ± 4	34 ± 11

Table 6.10 – Number of expected and observed data events in Run 2 (top) and Run 3 (bottom) VR-0 ℓ -1T and VR-0 ℓ -2T. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

6.6.4 Summary of the Validation Regions

A comprehensive summary of all the $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.5$ GeV VRs described in the previous sections is shown in Figure 6.14. The statistical significance is computed according to Eq. 5.7. Across all VRs, the observed discrepancies are less than 1.5σ , indicating the good modelling of both the QCD tracks and the hadronic and leptonic τ decay track backgrounds, both for Run 2 and Run 3. A similar level of agreement is observed for the other mass splitting hypotheses (Appendix C), with the sole exception of $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35$ GeV. In this case, the 1γ VRs consistently exhibit an excess of data with respect to the SM predictions, ranging from 10% to 25% both in Run 2 and Run 3. At the time of writing this thesis, investigations are ongoing to understand the origin of such behaviour.

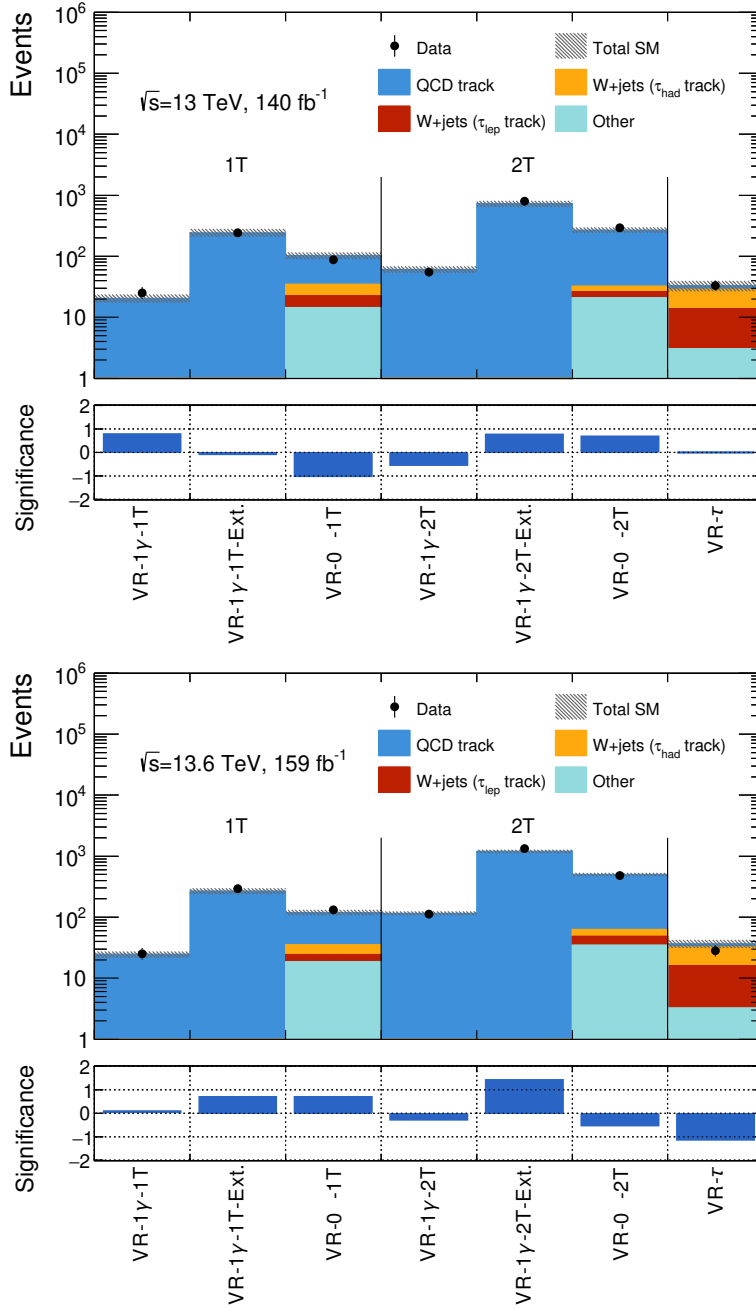


Figure 6.14 – Comparisons of the observed data and the expected post-fit SM backgrounds in the Run 2 (top) and Run 3 (bottom) VRs. The hatched band indicates the total uncertainty on the SM background expectation, including both statistical and systematic uncertainties. The bottom panel shows the statistical significances of the discrepancy between the expected and the observed event yields.

6.7 Systematic Uncertainties

The sensitivity of the analysis presented here is primarily limited by statistics, due to the stringent selections applied to both events and tracks. Systematic uncertainties can still contribute non-negligibly and affect the final results in the SRs by varying the yield or the shape of the event-level NN and track-level pNN score distributions. These systematic uncertainties stem from various sources and can be grouped into three main categories: experimental, theoretical, and analysis-specific uncertainties. They are computed independently for the Run 2 and Run 3 datasets.

6.7.1 Experimental uncertainties

Experimental uncertainties are evaluated for all Monte Carlo samples to account for potential mismodelling of the detector response, imperfections in the calibration of physics objects, as well as uncertainties in luminosity measurements and pileup. Since QCD tracks in V + jets events are estimated via a fully data-driven approach, they are not subject to these uncertainties. The dominant experimental systematic uncertainties arise from the jet calibration procedure, where the energy of reconstructed jets is scaled to recover the full energy scale and the resolution of the simulated samples is calibrated to match data, as well as from the smearing of track impact parameters. Specifically, uncertainties from the jet energy scale (JES) [168], the jet energy resolution (JER) [168], and the impact parameter smearing show the largest contributions to the final estimates in the SRs. Other experimental effects — such as jet vertex tagging (JVT) [171], pileup modelling [226], electron [172] and muon [178] identification and calibration, E_T^{miss} reconstruction [183], trigger efficiencies [172, 225], and luminosity measurements [116, 117] — have all negligible impact on the SRs.

6.7.2 Theoretical uncertainties

No theoretical uncertainties were considered at the time of writing this thesis. Nevertheless, contributions comparable in size to those observed in the cut-based analysis presented in Chapter 5 are expected.

6.7.3 Analysis specific uncertainties

As discussed in Section 6.6.1, a central assumption of the QCD track background estimation strategy is that the track-level pNN output scores are independent of the underlying hard-scattering process, and therefore their distributions can be assumed to be identical across the 0ℓ , 1μ , and 1γ categories used in the analysis. This assumption is validated through a closure test performed on MC simulations, in which the expected number of QCD tracks in V + jets events is evaluated independently in each analysis region. If the background estimation method is valid, the expected number of QCD tracks expected in each SR bin, for both the 1T and 2T selections, is given by Eq. 6.3. Explicitly rewriting this

expression to highlight the TF term yields

$$\frac{N_{\text{SR}_i}^{\text{QCD tracks}} \times (N_{\text{CR-1}\mu\text{-High}}^{\text{data}} - N_{\text{CR-1}\mu\text{-High}}^{\text{non-QCD-track}})}{(N_{\text{CR-1}\mu\text{-Low}_i}^{\text{data}} - N_{\text{CR-1}\mu\text{-Low}_i}^{\text{non-QCD-track}}) \times (N_{\text{CR-0}\ell}^{\text{data}} - N_{\text{CR-0}\ell}^{\text{non-QCD-track}})} = 1. \quad (6.5)$$

Any deviation of the left-hand-side term from unity is interpreted as a measure of the non-closure of the background estimation method. The results of the closure test are summarised in Table 6.11. The largest deviation observed is approximately 10% (5%) in both the 1T and 2T SRs for Run 2 (Run 3). Consequently, a non-closure systematic uncertainty of 10% (5%) is assigned to the fully data-driven QCD track background estimates in all the SRs and VRs using Run 2 (Run 3) data. This uncertainty is treated as uncorrelated across SRs and VRs and between the 1T and 2T selections.

	$\Delta m (\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ [GeV]	1T closure	2T closure
Run 2	0.35	0.96 ± 0.05	1.01 ± 0.05
	0.5	0.94 ± 0.09	0.93 ± 0.04
	0.75	0.91 ± 0.06	0.89 ± 0.04
	1	0.93 ± 0.03	0.96 ± 0.05
Run 3	0.35	0.95 ± 0.03	1.00 ± 0.04
	0.5	0.93 ± 0.07	0.97 ± 0.04
	0.75	0.93 ± 0.06	0.98 ± 0.03
	1	1.00 ± 0.04	0.95 ± 0.05

Table 6.11 – Closure test results for Run 2 and Run 3 MC simulation. The quoted uncertainties are statistical only.

6.8 Results

The results of this analysis, as well as the statistical compatibility of the SM expectations with the observed data under different hypotheses, are obtained via a *maximum likelihood* approach implemented via the TREXFITTER tool [247]. To assess the robustness of the background estimation strategy outlined in Section 6.6, a background-only fit is first performed using the CRs and VRs, with any SUSY contributions from Monte Carlo simulations excluded. From this fit, a Normalisation Factor (NF) and two Transfer Factors (TFs) — used to estimate background contributions from τ decay and QCD tracks, respectively — are determined and then extrapolated to the SRs. A model-dependent interpretation of the results in the SRs is then performed, and expected exclusion limits are set on the simplified SUSY models considered in this thesis, demonstrating improved sensitivity arising from the combined effect of the increased statistics and the newly adopted analysis strategy. In the following, background-only fit results are presented for the $\Delta m (\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.5$ GeV 1T and 2T regions only. Results for additional mass splitting hypotheses are provided in Appendix C.

6.8.1 Background only fit

The observed data and the post-fit SM predictions for Run 2 and Run 3 in the CRs and SRs are summarised in Tables 6.12 and 6.13, respectively. At the time of writing this thesis, SRs remain blinded; therefore, no data are reported for these regions. The Run 2 (Run 3) NF, derived from the simultaneous fit in CR- τ_h and CR- τ_ℓ , is found to be 0.85 ± 0.12 (0.97 ± 0.30). The TFs, obtained from the 1μ category control regions, are $(2.9 \pm 0.3) \times 10^{-2}$ and $(15.1 \pm 0.8) \times 10^{-2}$ for the Run 2 1T and 2T SRs, respectively. For Run 3, the corresponding TFs are $(2.3 \pm 0.2) \times 10^{-2}$ and $(15 \pm 1) \times 10^{-2}$. The total post-fit uncertainty on the SR background estimates ranges from 8% to 17%, depending on the mass splitting hypothesis and the category under consideration. In general, the dominant contributions arise from the limited statistics of the CRs used to extract the TFs and the NF, as well as from the finite size MC samples. The second-largest contributions originate from the non-closure systematic uncertainty applied to the QCD track estimates, the jet energy scale uncertainty, and tracking-related systematics. Finally, the background composition varies with the mass splitting: QCD tracks dominate for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35$ and 0.5 GeV, while tracks from hadronic and leptonic τ decays become increasingly significant at larger mass splittings.

	CR-0 ℓ -1T	CR-0 ℓ -2T	CR-1 μ -High-1T	CR-1 μ -High-2T	CR-1 μ -Low-1T	CR-1 μ -Low-2T	CR- τ_ℓ	CR- τ_h
Observed data	325	245	4326	3135	133	496	67	47
SM prediction	325 ± 18	245 ± 15	4330 ± 70	3140 ± 60	133 ± 11	496 ± 22	64 ± 7	50 ± 6
QCD track	305 ± 18	233 ± 15	3820 ± 70	2850 ± 60	113 ± 11	432 ± 22	3.6 ± 1.1	1.3 ± 0.4
$W(\rightarrow \tau_h \nu) + \text{jets}$	3.2 ± 1.4	1.1 ± 0.7	< 1	< 1	< 1	< 1	45 ± 5	< 1
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	3.4 ± 0.7	2.6 ± 0.8	< 1	< 1	< 1	< 1	8.2 ± 2.1	43 ± 6
Other	13.6 ± 1.4	8.7 ± 2.0	505 ± 15	286 ± 12	20.4 ± 2.2	64 ± 5	7.4 ± 1.9	5.1 ± 1.0

	CR-0 ℓ -1T	CR-0 ℓ -2T	CR-1 μ -High-1T	CR-1 μ -High-2T	CR-1 μ -Low-1T	CR-1 μ -Low-2T	CR- τ_ℓ	CR- τ_h
Observed data	501	426	6128	5169	153	805	89	59
SM prediction	501 ± 22	426 ± 20	6130 ± 80	5170 ± 70	153 ± 12	805 ± 27	84 ± 8	64 ± 7
QCD track	473 ± 23	407 ± 20	5400 ± 140	4680 ± 110	123 ± 13	705 ± 32	2.9 ± 1.2	0.9 ± 1.3
$W(\rightarrow \tau_h \nu) + \text{jets}$	4.2 ± 1.1	3.0 ± 1.1	< 1	< 1	< 1	< 1	61 ± 7	0.3 ± 0.2
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	4.9 ± 1.7	3 ± 1	< 1	< 1	< 1	< 1	12 ± 3	57 ± 7
Other	19 ± 4	13.5 ± 3.5	730 ± 120	480 ± 80	30 ± 6	100 ± 16	7.6 ± 2.8	6.0 ± 1.7

Table 6.12 – Number of expected and observed data events from the background-only fit in Run 2 (top) and Run 3 (bottom) CRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

	SR-1T	SR-2T
Observed data	-	-
SM prediction	11 ± 2	40 ± 4
QCD track	9.0 ± 1.3	35 ± 4
$W(\rightarrow \tau_h \nu) + \text{jets}$	0.9 ± 0.4	1.5 ± 0.5
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	0.8 ± 0.5	1.7 ± 0.5
Other	0.5 ± 0.2	1.6 ± 0.6

	SR-1T	SR-2T
Observed data	-	-
SM prediction	15 ± 2	67 ± 4
QCD track	10.8 ± 1.3	61 ± 4
$W(\rightarrow \tau_h \nu) + \text{jets}$	1.9 ± 0.9	1.4 ± 1.3
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	1.8 ± 1.0	1.6 ± 0.5
Other	0.6 ± 0.2	2.3 ± 1.0

Table 6.13 – Number of expected and observed data events from the background-only fit in Run 2 (top) and Run 3 (bottom) SRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

Conclusions



And you're alone for maybe the last time / And you
breathe for a long time / Then you howl like a wolf in
a trap / And you daren't look behind / You fall to the
ground like a leaf from a tree / And look up one time at
that vast blue sky / Scream out aloud as they shoot you
down / No, no I'm not some piece of teenage wildlife

— DAVID BOWIE, *Teenage Wildlife*

This thesis presents two complementary analyses of proton-proton collision data collected by the ATLAS detector at center-of-mass energies of $\sqrt{s} = 13$ TeV and $\sqrt{s} = 13.6$ TeV during the LHC Run 2 and Run 3, corresponding to total integrated luminosities of 140 fb^{-1} and 299 fb^{-1} , respectively. Both analyses focus on a search for supersymmetric higgsinos near the electroweak scale with compressed mass spectra, featuring mass differences in the range $0.35 - 1.5$ GeV. Owing to these small mass differences, the higgsinos are relatively long-lived and decay into pions at distances of a few millimeters from the pp interaction point. As a result, the charged decay products can be reconstructed as tracks with unusually large impact parameters. Since most Standard Model particles decay promptly, selecting events containing such “mildly-displaced tracks” provides an effective means of cornering higgsino decays and gaining sensitivity to supersymmetric scenarios remained unexplored since the legacy searches performed at LEP.

In the first search, events are selected by requiring the presence of an initial-state radiation jet that recoils against and boost the SUSY system, thereby generating significant missing transverse momentum from the lightest neutralinos used as trigger. For each event, a single mildly-displaced track is selected and categorised into two Signal Regions according to the magnitude of its impact parameter significance. Standard Model (SM) background tracks originating from soft initial- or final-state radiation, interactions between partons not involved in the hard scatter, or from pileup vertices — collectively referred to as QCD tracks — are estimated with a fully data-driven method. Backgrounds from τ lepton decays are instead evaluated with a semi data-driven approach that com-

bines Monte Carlo simulations with data in dedicated Control Regions. No data excess is observed above the SM predictions in either Signal Region (SR), and exclusion limits at 95% CL are set on the higgsino mass and mass splitting within the considered SUSY simplified models. Due to the novel analysis strategy, for the first time since the LEP era, unique sensitivity is achieved in the region of parameter space corresponding to higgsino mass splittings in the range $0.3 - 1$ GeV and higgsino masses up to approximately 170 GeV.

In the second search, an alternative strategy is explored. The event-level and track-level selections are replaced by two indepent machine learning algorithms: one exploiting the global event observables, and the other using the kinematic information of individual tracks. Since the mass splitting assumption affects only the kinematic of the soft, mildly displaced pion tracks produced in higgsino decays, the event-level deep neural network is implemented as a simple binary classifier. In contrast, the track-level multi-class neural network is parameterised to produce an output score that varies continuously with the mass splitting and quantifies the probability for a track to originate from higgsino decays, QCD processes, or hadronic or leptonic τ decays. The output scores of the two classifiers are used as final discriminants for the SR definition, both for events conatining one (1T) or more than one (2T) displaced track. SM backgrounds are estimated following the same procedure as in the first search. The statistical combination of the 1T and 2T SRs, together with the possibility of defining multiple SR bins due to the larger available statistics, is expected to provide improved sensitivity to the considered simplified SUSY and to extend the LHC reach into regions of parameter space that will remain inaccessible to future direct detection DM experiments and will be probed exclusively by collider searches.

Appendices

Two-tracks Signal Region Optimisation



This Appendix presents the optimisation results for the two-tracks (2T) Signal Region (SR) definition. The statistical significance of the considered SUSY signals is computed according to Eq. 5.2. Figure A.1 shows the distributions of the event-level NN score. As in the case of the one-track (1T) SRs, the optimal threshold on this variable is found to be independent of the mass splitting assumption, motivating the use of a common selection across all SRs. Figures A.2 and A.3 show the distributions of the track-level pNN QCD and signal scores, respectively. In some cases, a deliberately sub-optimal selection is adopted in place of the one yielding the maximum statistical significance, in order to balance the available statistics with the 1T SRs while simultaneously allowing the definition of multiple SR bins.

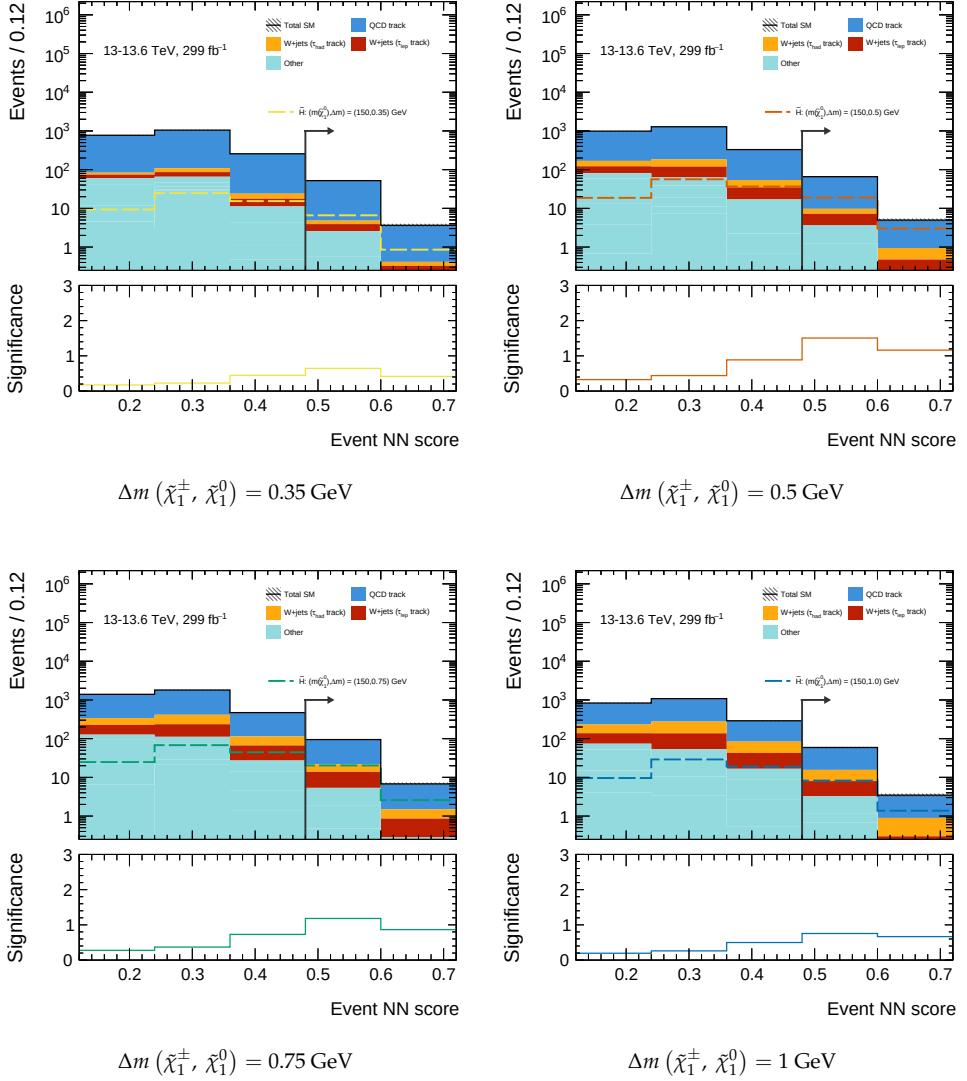


Figure A.1 – Event-level NN score distributions for the two-track SRs, obtained by applying selections on all analysis variables except the one shown. The stacked filled histograms represent SM backgrounds, while SUSY signals are shown as dashed lines. The hatched area indicates MC statistical uncertainties. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, di-boson, $t\bar{t}$, single top, and multi-jet production. The bottom panel shows the statistical significance calculated by accumulating the yields of bins to the right, assuming a total 15% background uncertainty.

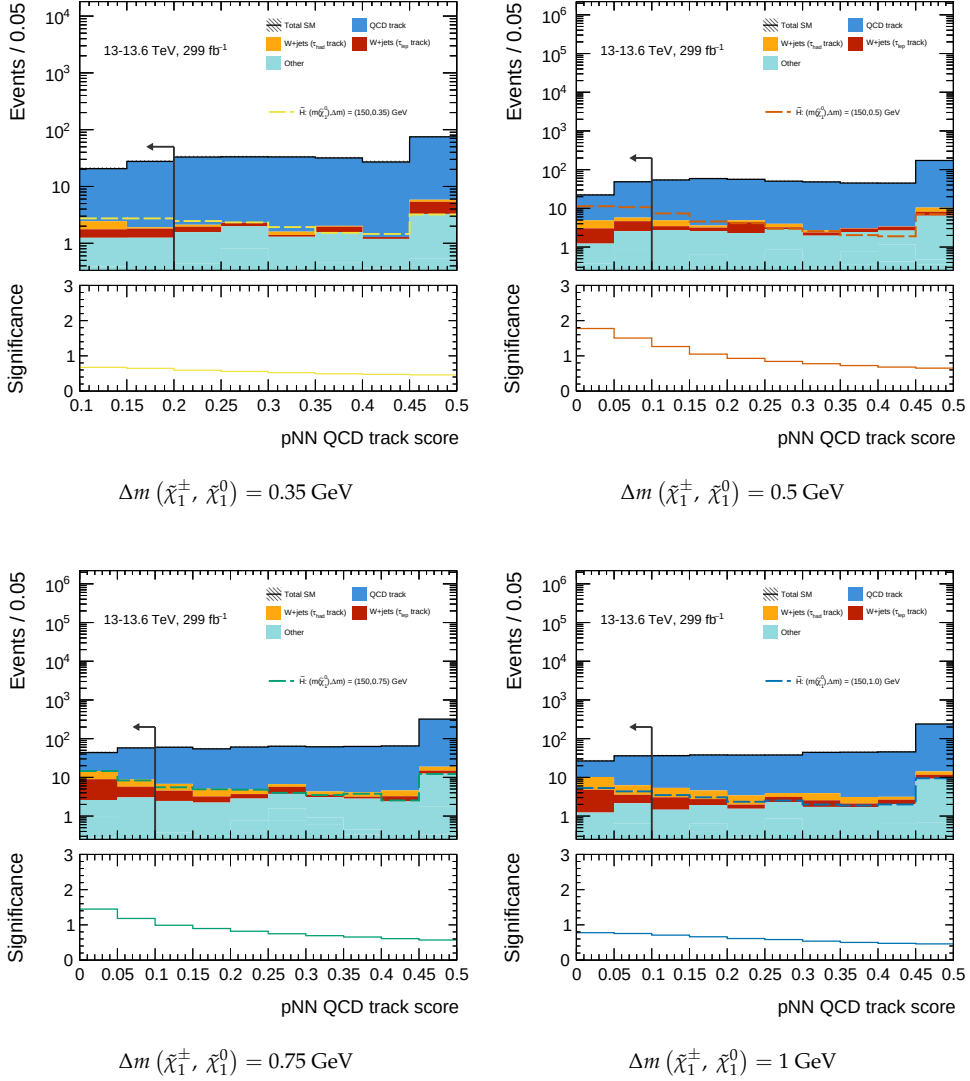


Figure A.2 – pNN QCD track score distributions for the two-track SRs, obtained by applying selections on all analysis variables except the one shown. The stacked filled histograms represent SM backgrounds, while SUSY signals are shown as dashed lines. The hatched area indicates MC statistical uncertainties. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, di-boson, $t\bar{t}$, single top, and multi-jet production. The bottom panel shows the statistical significance calculated by accumulating the yields of bins to the left, assuming a total 15% background uncertainty.

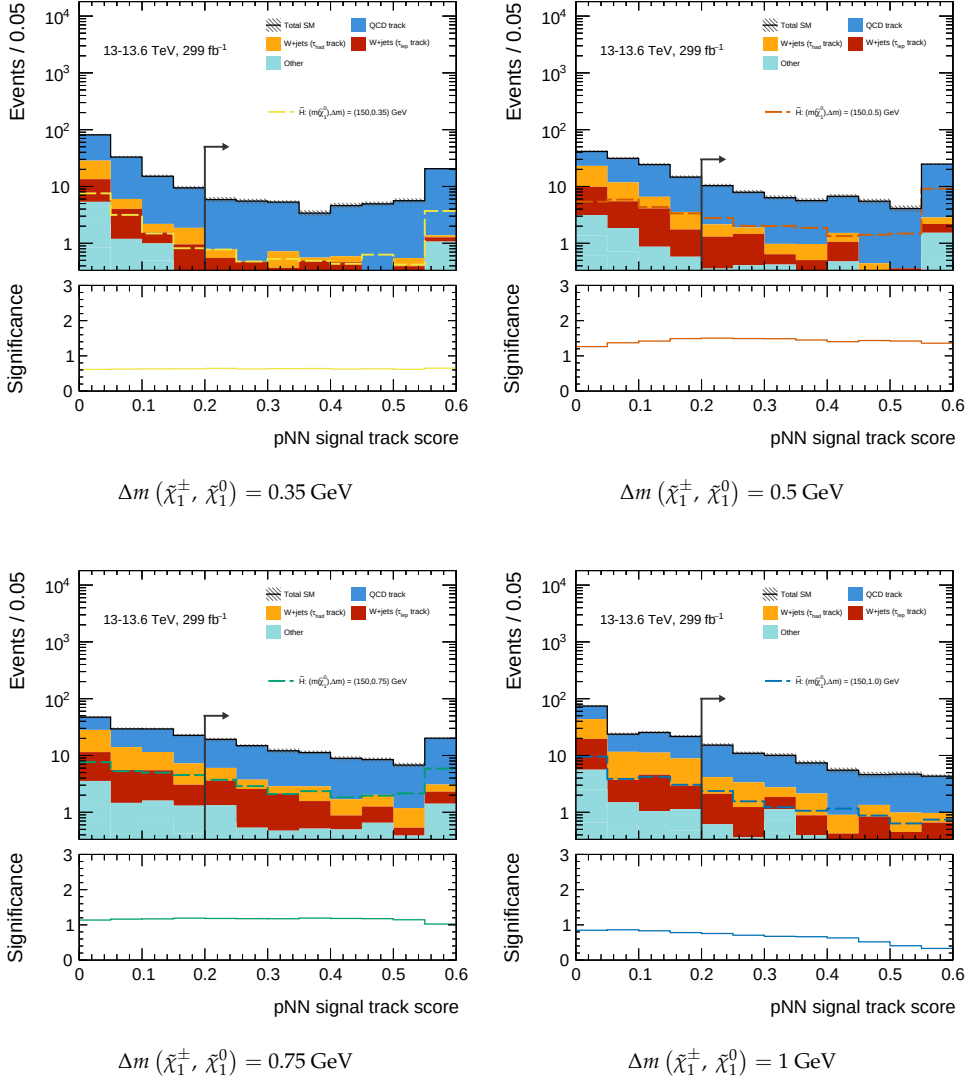


Figure A.3 – pNN signal track score distributions for the two-track SRs, obtained by applying selections on all analysis variables except the one shown. The stacked filled histograms represent SM backgrounds, while SUSY signals are shown as dashed lines. The hatched area indicates MC statistical uncertainties. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, di-boson, $t\bar{t}$, single top, and multi-jet production. The bottom panel shows the statistical significance calculated by accumulating the yields of bins to the right, assuming a total 15% background uncertainty.

Additional details on the background estimation strategy



This Appendix provides a schematic description of the Control Regions (CRs) and Validation Regions (VRs) used in the background estimation and validation strategy for QCD and τ decay tracks in the Signal Regions (SRs) targeting mass splitting hypotheses other than $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.5 \text{ GeV}$, for both the one-track (1T) and two-tracks (2T) selections.

B.1 $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35 \text{ GeV}$

Variable	0ℓ	1μ	1γ	
Trigger	E_T^{miss}	E_T^{miss}	Single- γ	
$N(\ell_{\text{base}})$	$= 0$	$= 1$	-	
$N(\ell_{\text{signal}})$	-	$= 1$	-	
$N(\gamma_{\text{base}})$	$= 0$	-	$= 1$	
$N(\gamma_{\text{signal}})$	-	-	$= 1$	
$p_T(\ell)$ [GeV]	-	> 10	-	
$p_T(\gamma)$ [GeV]	-	-	> 200	
m_T [GeV]	-	[56, 106]	-	
One-track	SR(CR- 0ℓ)	CR- 1μ -Low(-High)	VR(CR)- 1γ	VR(CR)- 1γ -Extended
Event-level NN score	> 0.48	-	> 0.48	> 0.30
Leading track QCD score	$< 0.14 (> 0.16)$		$< 0.14 (> 0.16)$	
Leading track signal score	$> 0.6 (-)$		$> 0.6 (-)$	
Second-to-leading track signal score (if present)	< 0.2		< 0.2	
Two-tracks	SR(CR- 0ℓ)	CR- 1μ -Low(-High)	VR(CR)- 1γ	VR(CR)- 1γ -Extended
Event-level NN score	> 0.48	-	> 0.48	> 0.30
Leading track QCD score	$< 0.2 (> 0.25)$		$< 0.2 (> 0.25)$	
Leading track signal score	$> 0.2 (-)$		$> 0.2 (-)$	
Second-to-leading track signal score	$> 0.2 (-)$		$> 0.2 (-)$	

Table B.1 – Selection criteria applied across the different categories to define SRs, CRs, and VRs for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35 \text{ GeV}$, employed in the calculation and validation of QCD track transfer factors. Only selections orthogonal to the SRs are listed. The event-level and track-level preselections are omitted as they are identical across all categories, as presented in Section 6.3.

Variable	0ℓ		$1\mu_{\text{base}}$	$0\ell + 1\mu_{\text{base}}$
$N(\ell_{\text{base}})$	$= 0$		$= 1$	$= 0$ OR $= 1$
$N(\mu_{\text{base}})$	$= 0$		$= 1$	$= 0$ OR $= 1$
m_T [GeV]	-		< 50	< 50 (if muon is selected)
	SR-1T (SR-2T)	CR- τ_h	CR- τ_ℓ	VR- τ
Track p_T [GeV]	< 10	$[10, 20]$	$[10, 20]$	< 10
Leading track signal score	> 0.6 (> 0.2)	-	-	< 0.2

Table B.2 – Selection criteria applied across the 0ℓ and $1\mu_{\text{base}}$ categories to define SRs, CRs, and VRs for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35$ GeV, for the calculation and validation of hadronic and leptonic τ decay track normalisation factor. Only selections orthogonal to the SRs are listed. The track-level selection is omitted as it is identical across all categories.

B.2 $\Delta m \left(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right) = 0.75 \text{ GeV}$

Variable	0ℓ	1μ	1γ	
Trigger	E_T^{miss}	E_T^{miss}	Single- γ	
$N(\ell_{\text{base}})$	= 0	= 1	-	
$N(\ell_{\text{signal}})$	-	= 1	-	
$N(\gamma_{\text{base}})$	= 0	-	= 1	
$N(\gamma_{\text{signal}})$	-	-	= 1	
$p_T(\ell)$ [GeV]	-	> 10	-	
$p_T(\gamma)$ [GeV]	-	-	> 200	
m_T [GeV]	-	[56, 106]	-	
One-track	SR(CR- 0ℓ)	CR- 1μ -Low(-High)	VR(CR)- 1γ	VR(CR)- 1γ -Extended
Event-level NN score	> 0.48	-	> 0.48	> 0.30
Leading track QCD score	< 0.04 (> 0.06)		< 0.04 (> 0.06)	
Leading track signal score	> 0.4 (-)		> 0.4 (-)	
Second-to-leading track signal score (if present)	< 0.2		< 0.2	
Two-tracks	SR(CR- 0ℓ)	CR- 1μ -Low(-High)	VR(CR)- 1γ	VR(CR)- 1γ -Extended
Event-level NN score	> 0.48	-	> 0.48	> 0.30
Leading track QCD score	< 0.1 (> 0.15)		< 0.1 (> 0.15)	
Leading track signal score	> 0.2 (-)		> 0.2 (-)	
Second-to-leading track signal score	> 0.2 (-)		> 0.2 (-)	

Table B.3 – Selection criteria applied across the different categories to define SRs, CRs, and VRs for $\Delta m \left(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right) = 0.75 \text{ GeV}$, employed in the calculation and validation of QCD track transfer factors. Only selections orthogonal to the SRs are listed. The event-level and track-level preselections are omitted as they are identical across all categories, as presented in Section 6.3.

Variable	0ℓ		$1\mu_{\text{base}}$	$0\ell + 1\mu_{\text{base}}$
$N(\ell_{\text{base}})$	$= 0$		$= 1$	$= 0$ OR $= 1$
$N(\mu_{\text{base}})$	$= 0$		$= 1$	$= 0$ OR $= 1$
m_T [GeV]	-		< 50	< 50 (if muon is selected)
	SR-1T (SR-2T)	CR- τ_h	CR- τ_ℓ	VR- τ
Track p_T [GeV]	< 10	$[10, 20]$	$[10, 20]$	< 10
Leading track signal score	> 0.4 (> 0.2)	-	-	< 0.2

Table B.4 – Selection criteria applied across the 0ℓ and $1\mu_{\text{base}}$ categories to define SRs, CRs, and VRs for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.75$ GeV, for the calculation and validation of hadronic and leptonic τ decay track normalisation factor. Only selections orthogonal to the SRs are listed. The track-level selection is omitted as it is identical across all categories.

B.3 $\Delta m \left(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right) = 1 \text{ GeV}$

Variable	0ℓ	1μ	1γ
Trigger	E_T^{miss}	E_T^{miss}	Single- γ
$N(\ell_{\text{base}})$	$= 0$	$= 1$	-
$N(\ell_{\text{signal}})$	-	$= 1$	-
$N(\gamma_{\text{base}})$	$= 0$	-	$= 1$
$N(\gamma_{\text{signal}})$	-	-	$= 1$
$p_T(\ell)$ [GeV]	-	> 10	-
$p_T(\gamma)$ [GeV]	-	-	> 200
m_T [GeV]	-	[56, 106]	-
One-track	SR(CR- 0ℓ)	CR- 1μ -Low(-High)	VR(CR)- 1γ VR(CR)- 1γ -Extended
Event-level NN score	> 0.48	-	> 0.48 > 0.30
Leading track QCD score	< 0.06 (> 0.08)		< 0.06 (> 0.08)
Leading track signal score	> 0.2 (-)		> 0.2 (-)
Second-to-leading track signal score (if present)		< 0.2	< 0.2
Two-tracks	SR(CR- 0ℓ)	CR- 1μ -Low(-High)	VR(CR)- 1γ VR(CR)- 1γ -Extended
Event-level NN score	> 0.48	-	> 0.48 > 0.30
Leading track QCD score	< 0.1 (> 0.15)		< 0.1 (> 0.15)
Leading track signal score	> 0.2 (-)		> 0.2 (-)
Second-to-leading track signal score	> 0.2 (-)		> 0.2 (-)

Table B.5 – Selection criteria applied across the different categories to define SRs, CRs, and VRs for $\Delta m \left(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right) = 1 \text{ GeV}$, employed in the calculation and validation of QCD track transfer factors. Only selections orthogonal to the SRs are listed. The event-level and track-level preselections are omitted as they are identical across all categories, as presented in Section 6.3.

Variable	0ℓ		$1\mu_{\text{base}}$	$0\ell + 1\mu_{\text{base}}$
$N(\ell_{\text{base}})$	$= 0$		$= 1$	$= 0$ OR $= 1$
$N(\mu_{\text{base}})$	$= 0$		$= 1$	$= 0$ OR $= 1$
m_T [GeV]	-		< 50	< 50 (if muon is selected)
	SR-1T (SR-2T)	CR- τ_h	CR- τ_ℓ	VR- τ
Track p_T [GeV]	< 10	$[10, 20]$	$[10, 20]$	< 10
Leading track signal score	> 0.2 (> 0.2)	-	-	< 0.2

Table B.6 – Selection criteria applied across the 0ℓ and $1\mu_{\text{base}}$ categories to define SRs, CRs, and VRs for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1$ GeV, for the calculation and validation of hadronic and leptonic τ decay track normalisation factor. Only selections orthogonal to the SRs are listed. The track-level selection is omitted as it is identical across all categories.

Additional background-only fit results



This Appendix provides a schematic overview of the background-only fit results in the Signal Regions (SRs), Control Regions (CRs), and Validation Regions (VRs) for mass splitting hypotheses other than $\Delta m (\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.5 \text{ GeV}$, for both the one-track (1T) and two-tracks (2T) selections.

C.1 $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35 \text{ GeV}$

	SR-1T	SR-2T
Observed data	-	-
SM prediction	36 ± 4	29 ± 3
QCD track	32.9 ± 3.5	26.7 ± 3.4
$W(\rightarrow \tau_h \nu) + \text{jets}$	0.8 ± 0.3	0.3 ± 0.1
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	1.4 ± 0.5	0.6 ± 0.3
Other	1.4 ± 0.3	1.1 ± 0.7

	SR-1T	SR-2T
Observed data	-	-
SM prediction	51 ± 4	56 ± 5
QCD track	44 ± 3	54 ± 5
$W(\rightarrow \tau_h \nu) + \text{jets}$	2.6 ± 0.8	0.7 ± 0.2
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	1.9 ± 0.4	0.5 ± 0.3
Other	2.6 ± 0.4	1.6 ± 0.6

Table C.1 – Number of expected and observed data events from the background-only fit in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35 \text{ GeV}$ SRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

C. ADDITIONAL BACKGROUND-ONLY FIT RESULTS

	CR-0 ℓ -1T	CR-0 ℓ -2T	CR-1 μ -High-1T	CR-1 μ -High-2T	CR-1 μ -Low-1T	CR-1 μ -Low-2T	CR- τ_ℓ	CR- τ_h
Observed data	284	88	3728	1289	462	416	67	48
SM prediction	284 $\pm$ 16	88 $\pm$ 8	3730 $\pm$ 60	1290 $\pm$ 40	462 $\pm$ 21	416 $\pm$ 20	66 $\pm$ 7	49 $\pm$ 6
QCD track	270 $\pm$ 16	83 $\pm$ 9	3310 $\pm$ 60	1170 $\pm$ 40	403 $\pm$ 21	376 $\pm$ 20	4.7 $\pm$ 1.0	1.2 $\pm$ 0.5
$W(\rightarrow \tau_h \nu) + \text{jets}$	1.1 $\pm$ 1.0	< 1	< 1	-	< 1	-	46 $\pm$ 5	< 1
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	0.9 $\pm$ 0.5	1.4 $\pm$ 0.7	< 1	-	-	-	8.1 $\pm$ 2.1	42 $\pm$ 6
Other	11.7 $\pm$ 1.3	3.1 $\pm$ 1.1	416 $\pm$ 14	119 $\pm$ 6	59 $\pm$ 4	40 $\pm$ 4	7.5 $\pm$ 1.8	5.2 $\pm$ 1.0

	CR-0 ℓ -1T	CR-0 ℓ -2T	CR-1 μ -High-1T	CR-1 μ -High-2T	CR-1 μ -Low-1T	CR-1 μ -Low-2T	CR- τ_ℓ	CR- τ_h
Observed data	444	200	5403	2441	585	696	92	58
SM prediction	444 $\pm$ 20	200 $\pm$ 15	5400 $\pm$ 70	2440 $\pm$ 50	585 $\pm$ 23	696 $\pm$ 26	86 $\pm$ 9	63 $\pm$ 6
QCD track	425 $\pm$ 21	191 $\pm$ 15	4810 $\pm$ 110	2220 $\pm$ 60	504 $\pm$ 26	622 $\pm$ 28	3.9 $\pm$ 1.6	1.4 $\pm$ 1.5
$W(\rightarrow \tau_h \nu) + \text{jets}$	1.9 $\pm$ 0.5	< 1	-	-	< 1	-	63 $\pm$ 7	< 1
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	1.9 $\pm$ 0.9	1.4 $\pm$ 0.7	< 1	-	-	-	12.5 $\pm$ 2.9	56 $\pm$ 7
Other	15.2 $\pm$ 3.2	5.9 $\pm$ 1.3	590 $\pm$ 80	222 $\pm$ 30	81 $\pm$ 11	74 $\pm$ 11	7.5 $\pm$ 2.5	5.6 $\pm$ 1.7

Table C.2 – Number of expected and observed data events from the background-only fit in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35$ GeV CRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

	VR-1 γ -1T	VR-1 γ -Extended-1T	VR-1 γ -2T	VR-1 γ -Extended-2T
Observed data	98	990	57	636
SM prediction	75 ± 9	889 ± 102	46 ± 7	576 ± 69
QCD track	75 ± 9	889 ± 102	46 ± 5	576 ± 69
$W(\rightarrow \tau_h \nu) + \text{jets}$	-	-	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	-	-	-	-
Other	-	-	-	-

	VR-1 γ -1T	VR-1 γ -Extended-1T	VR-1 γ -2T	VR-1 γ -Extended-2T
Observed data	131	1393	121	1232
SM prediction	101 ± 8	1108 ± 79	93 ± 8	996 ± 71
QCD track	101 ± 8	1108 ± 79	93 ± 8	996 ± 71
$W(\rightarrow \tau_h \nu) + \text{jets}$	-	-	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	-	-	-	-
Other	-	-	-	-

Table C.3 – Number of expected and observed data events in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35$ GeV 1 γ VRs for both the 1T and 2T selections. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

	Run 2 VR- τ	Run 3 VR- τ
Observed data	50	50
SM prediction	46 ± 6	51 ± 11
QCD track	10 ± 2	12 ± 4
$W(\rightarrow \tau_h \nu) + \text{jets}$	20 ± 3	20 ± 4
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	11 ± 2	15 ± 4
Other	4.9 ± 1.0	3.4 ± 1.3

Table C.4 – Number of expected and observed data events in Run 2 and Run 3 $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35$ GeV τ decay VR. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

	VR-0 ℓ -1T	VR-0 ℓ -2T
Observed data	271	238
SM prediction	276 ± 29	235 ± 27
QCD track	238 ± 28	217 ± 27
$W(\rightarrow \tau_h \nu) + \text{jets}$	6.1 ± 4.2	1.3 ± 1.9
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	3.5 ± 1.9	1.8 ± 1.5
Other	28 ± 4	14 ± 2

	VR-0 ℓ -1T	VR-0 ℓ -2T
Observed data	405	386
SM prediction	380 ± 25	434 ± 31
QCD track	312 ± 23	403 ± 30
$W(\rightarrow \tau_h \nu) + \text{jets}$	7.8 ± 4.8	2.5 ± 2.4
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	8.1 ± 6.0	3.9 ± 3.6
Other	52 ± 7	25 ± 5

Table C.5 – Number of expected and observed data events in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.35$ GeV VR-0 ℓ -1T and VR-0 ℓ -2T. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

C.2 $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.75 \text{ GeV}$

	SR-1T	SR-2T
Observed data	-	-
SM prediction	34 ± 6	56 ± 5
QCD track	17.5 ± 2.3	47.7 ± 4.7
$W(\rightarrow \tau_h \nu) + \text{jets}$	7 ± 6	2.9 ± 1.0
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	7.3 ± 1.7	2.9 ± 0.9
Other	2.9 ± 1.2	2.1 ± 0.4

	SR-1T	SR-2T
Observed data	-	-
SM prediction	49 ± 4	86 ± 5
QCD track	22 ± 2	72 ± 5
$W(\rightarrow \tau_h \nu) + \text{jets}$	13 ± 2	5.4 ± 1.7
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	11 ± 3	4.9 ± 1.1
Other	2.7 ± 1.3	3.2 ± 1.0

Table C.6 – Number of expected and observed data events from the background-only fit in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.75 \text{ GeV}$ SRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

C. ADDITIONAL BACKGROUND-ONLY FIT RESULTS

	CR-0 ℓ -1T	CR-0 ℓ -2T	CR-1 μ -High-1T	CR-1 μ -High-2T	CR-1 μ -Low-1T	CR-1 μ -Low-2T	CR- τ_ℓ	CR- τ_h
Observed data	704	376	9225	4576	263	650	65	47
SM prediction	704 $\pm$ 26	376 $\pm$ 19	9220 $\pm$ 100	4580 $\pm$ 70	263 $\pm$ 16	650 $\pm$ 25	63 $\pm$ 7	49 $\pm$ 6
QCD track	660 $\pm$ 27	356 $\pm$ 19	8290 $\pm$ 100	4180 $\pm$ 70	220 $\pm$ 16	559 $\pm$ 25	3.9 $\pm$ 1.0	1.2 $\pm$ 0.3
$W(\rightarrow \tau_h \nu)$ +jets	8.8 $\pm$ 2.1	4.4 $\pm$ 2.0	< 1	< 1	-	-	44 $\pm$ 5	< 1
$W(\rightarrow \tau_\ell \nu)$ +jets	8.1 $\pm$ 1.4	2.8 $\pm$ 0.8	< 1	-	< 1	< 1	8.3 $\pm$ 1.8	42 $\pm$ 6
Other	27.2 $\pm$ 1.8	12.9 $\pm$ 2.2	935 $\pm$ 28	401 $\pm$ 14	43.0 $\pm$ 3.2	91 $\pm$ 6	7.1 $\pm$ 1.8	5.0 $\pm$ 0.9

	CR-0 ℓ -1T	CR-0 ℓ -2T	CR-1 μ -High-1T	CR-1 μ -High-2T	CR-1 μ -Low-1T	CR-1 μ -Low-2T	CR- τ_ℓ	CR- τ_h
Observed data	1000	537	12471	6128	325	909	89	58
SM prediction	1000 $\pm$ 32	537 $\pm$ 22	12470 $\pm$ 110	6130 $\pm$ 80	325 $\pm$ 18	909 $\pm$ 29	84 $\pm$ 8	63 $\pm$ 6
QCD track	943 $\pm$ 32	510 $\pm$ 23	11250 $\pm$ 210	5580 $\pm$ 110	264 $\pm$ 20	787 $\pm$ 35	3.0 $\pm$ 1.3	1.2 $\pm$ 1.3
$W(\rightarrow \tau_h \nu)$ +jets	11.1 $\pm$ 2.2	6.2 $\pm$ 1.7	< 1	< 1	< 1	< 1	61 $\pm$ 7	< 1
$W(\rightarrow \tau_\ell \nu)$ +jets	12.9 $\pm$ 2.6	4.3 $\pm$ 1.6	< 1	< 1	-	-	12.6 $\pm$ 3.0	56 $\pm$ 7
Other	33 $\pm$ 7	16 $\pm$ 4	1220 $\pm$ 180	550 $\pm$ 80	61 $\pm$ 10	122 $\pm$ 20	7.2 $\pm$ 2.4	5.6 $\pm$ 1.5

Table C.7 – Number of expected and observed data events from the background-only fit in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.75$ GeV CRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau)$ +jets, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

	VR-1 γ -1T	VR-1 γ -Extended-1T	VR-1 γ -2T	VR-1 γ -Extended-2T
Observed data	34	464	81	1066
SM prediction	41 ± 5	467 ± 59	84 ± 10	997 ± 111
QCD track	41 ± 5	467 ± 59	84 ± 10	997 ± 111
$W(\rightarrow \tau_h \nu) + \text{jets}$	-	-	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	-	-	-	-
Other	-	-	-	-

	VR-1 γ -1T	VR-1 γ -Extended-1T	VR-1 γ -2T	VR-1 γ -Extended-2T
Observed data	57	585	135	1435
SM prediction	52 ± 5	568 ± 50	135 ± 10	1383 ± 91
QCD track	52 ± 5	568 ± 50	135 ± 10	1383 ± 91
$W(\rightarrow \tau_h \nu) + \text{jets}$	-	-	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	-	-	-	-
Other	-	-	-	-

Table C.8 – Number of expected and observed data events in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.75$ GeV 1 γ VRs for both the 1T and 2T selections. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

	Run 2 VR- τ	Run 3 VR- τ
Observed data	38	36
SM prediction	37 ± 7	41 ± 10
QCD track	4.9 ± 1.9	4.2 ± 2.2
$W(\rightarrow \tau_h \nu) + \text{jets}$	17.5 ± 4.2	21 ± 6
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	10.9 ± 2.2	12 ± 3
Other	3.7 ± 1.2	3.0 ± 0.8

Table C.9 – Number of expected and observed data events in Run 2 and Run 3 $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.75$ GeV τ decay VR. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

	VR-0 ℓ -1T	VR-0 ℓ -2T
Observed data	251	386
SM prediction	240 ± 22	375 ± 36
QCD track	126 ± 16	298 ± 33
$W(\rightarrow \tau_h \nu) + \text{jets}$	48 ± 12	25 ± 9
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	23 ± 5	15.6 ± 5.0
Other	44 ± 4	36 ± 3

	VR-0 ℓ -1T	VR-0 ℓ -2T
Observed data	371	601
SM prediction	342 ± 24	576 ± 35
QCD track	177 ± 18	464 ± 32
$W(\rightarrow \tau_h \nu) + \text{jets}$	57 ± 11	35 ± 8
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	48 ± 13	29 ± 8
Other	60 ± 11	38 ± 10

Table C.10 – Number of expected and observed data events in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 0.75$ GeV VR-0 ℓ -1T and VR-0 ℓ -2T. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

C.3 $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1 \text{ GeV}$

	SR-1T	SR-2T
Observed data	-	-
SM prediction	113 ± 10	33 ± 3
QCD track	63 ± 7	26.6 ± 3.1
$W(\rightarrow \tau_h \nu) + \text{jets}$	26 ± 10	3.0 ± 0.9
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	17 ± 3	1.6 ± 0.6
Other	6.7 ± 1.0	1.5 ± 0.3

	SR-1T	SR-2T
Observed data	-	-
SM prediction	187 ± 10	65 ± 5
QCD track	88 ± 6	45 ± 5
$W(\rightarrow \tau_h \nu) + \text{jets}$	49 ± 6	8.5 ± 2.9
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	39 ± 6	7 ± 4
Other	11 ± 3	4.4 ± 2.1

Table C.11 – Number of expected and observed data events from the background-only fit in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1 \text{ GeV}$ SRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

C. ADDITIONAL BACKGROUND-ONLY FIT RESULTS

	CR-0 ℓ -1T	CR-0 ℓ -2T	CR-1 μ -High-1T	CR-1 μ -High-2T	CR-1 μ -Low-1T	CR-1 μ -Low-2T	CR- τ_ℓ	CR- τ_h
Observed data	2333	273	28421	3179	880	351	63	41
SM prediction	2330 $\pm$ 50	273 $\pm$ 16	28420 $\pm$ 170	3180 $\pm$ 60	880 $\pm$ 30	351 $\pm$ 18	60 $\pm$ 7	44 $\pm$ 5
QCD track	2190 $\pm$ 60	258 $\pm$ 16	25810 $\pm$ 190	2900 $\pm$ 60	744 $\pm$ 31	299 $\pm$ 19	4.0 $\pm$ 1.0	1.1 $\pm$ 0.4
$W(\rightarrow \tau_h \nu) + \text{jets}$	25 $\pm$ 5	3.1 $\pm$ 1.9	< 1	-	< 1	-	41 $\pm$ 5	< 1
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	19 $\pm$ 4	1.9 $\pm$ 0.6	< 1	-	-	-	7.4 $\pm$ 1.9	38 $\pm$ 5
Other	95 $\pm$ 33	10.3 $\pm$ 2.0	2610 $\pm$ 80	278 $\pm$ 12	136 $\pm$ 8	52 $\pm$ 4	7.2 $\pm$ 1.9	4.9 $\pm$ 1.0

	CR-0 ℓ -1T	CR-0 ℓ -2T	CR-1 μ -High-1T	CR-1 μ -High-2T	CR-1 μ -Low-1T	CR-1 μ -Low-2T	CR- τ_ℓ	CR- τ_h
Observed data	2992	329	34401	3564	1158	422	82	54
SM prediction	2990 $\pm$ 50	361 $\pm$ 20	34400 $\pm$ 190	3530 $\pm$ 60	1157 $\pm$ 34	457 $\pm$ 22	83 $\pm$ 8	63 $\pm$ 7
QCD track	2820 $\pm$ 60	340 $\pm$ 20	31300 $\pm$ 400	3210 $\pm$ 70	980 $\pm$ 40	394 $\pm$ 25	2.3 $\pm$ 0.8	0.6 $\pm$ 0.5
$W(\rightarrow \tau_h \nu) + \text{jets}$	33 $\pm$ 4	6.7 $\pm$ 1.6	< 1	-	< 1	-	60 $\pm$ 6	< 1
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	35 $\pm$ 6	3.8 $\pm$ 1.0	< 1	< 1	-	-	14 $\pm$ 4	58 $\pm$ 7
Other	107 $\pm$ 16	11.0 $\pm$ 1.7	3080 $\pm$ 320	320 $\pm$ 40	181 $\pm$ 22	63 $\pm$ 10	6.7 $\pm$ 1.9	4.4 $\pm$ 1.0

Table C.12 – Number of expected and observed data events from the background-only fit in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1$ GeV CRs. The “Other” category includes contributions from minor background processes including $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty. The uncertainty associated with the expected number of events includes both the systematic and the statistical uncertainties.

	VR-1 γ -1T	VR-1 γ -Extended-1T	VR-1 γ -2T	VR-1 γ -Extended-2T
Observed data	112	1135	54	655
SM prediction	108 ± 12	1216 ± 132	51 ± 7	589 ± 70
QCD track	108 ± 12	1216 ± 132	51 ± 7	589 ± 70
$W(\rightarrow \tau_h \nu) + \text{jets}$	-	-	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	-	-	-	-
Other	-	-	-	-

	VR-1 γ -1T	VR-1 γ -Extended-1T	VR-1 γ -2T	VR-1 γ -Extended-2T
Observed data	131	1622	62	733
SM prediction	149 ± 10	1601 ± 100	67 ± 6	731 ± 60
QCD track	149 ± 10	1601 ± 100	67 ± 6	731 ± 60
$W(\rightarrow \tau_h \nu) + \text{jets}$	-	-	-	-
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	-	-	-	-
Other	-	-	-	-

Table C.13 – Number of expected and observed data events in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1$ GeV 1 γ VRs for both the 1T and 2T selections. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

	Run 2 VR- τ	Run 3 VR- τ
Observed data	69	66
SM prediction	63 ± 12	82 ± 14
QCD track	11 ± 2	18 ± 5
$W(\rightarrow \tau_h \nu) + \text{jets}$	29 ± 8	32 ± 6
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	16 ± 4	25 ± 5
Other	7 ± 1	5.7 ± 1.4

Table C.14 – Number of expected and observed data events in Run 2 and Run 3 $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1$ GeV τ decay VR. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

	VR-0 ℓ -1T	VR-0 ℓ -2T
Observed data	579	245
SM prediction	531 ± 39	213 ± 24
QCD track	299 ± 33	155 ± 19
$W(\rightarrow \tau_h \nu) + \text{jets}$	105 ± 18	29 ± 12
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	44 ± 7	11 ± 4
Other	82 ± 7	19 ± 3

	VR-0 ℓ -1T	VR-0 ℓ -2T
Observed data	837	304
SM prediction	848 ± 41	299 ± 25
QCD track	464 ± 33	227 ± 21
$W(\rightarrow \tau_h \nu) + \text{jets}$	176 ± 22	23 ± 12
$W(\rightarrow \tau_\ell \nu) + \text{jets}$	102 ± 17	19 ± 6
Other	105 ± 13	30 ± 5

Table C.15 – Number of expected and observed data events in Run 2 (top) and Run 3 (bottom) $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 1$ GeV VR-0 ℓ -1T and VR-0 ℓ -2T. The “Other” category includes contributions from $Z(\rightarrow \tau\tau) + \text{jets}$, $t\bar{t}$, single top, and di-boson production. The individual uncertainties can be correlated and do not necessarily sum up in quadrature to the total uncertainty, which includes contribution from the systematic uncertainty and the statistical uncertainty due to the limited statistics of the CRs.

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¹From the song *Time*, on David Bowie's album *Aladdin Sane*.

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