Search for direct top squark pair production in events with a Higgs or Z boson, and missing transverse momentum in $\sqrt{s} = 13\,\text{TeV}$ pp collisions with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search for direct top squark pair production resulting in events with either a same-flavour opposite-sign dilepton pair with invariant mass compatible with a Z boson or a pair of jets compatible with a Standard Model (SM) Higgs boson (h) is presented. Requirements on the missing transverse momentum, together with additional selections on leptons, jets, jets identified as originating from b-quarks are imposed to target the other decay products of the top squark pair. The analysis is performed using proton-proton collision data at $\sqrt{s} = 13\,\text{TeV}$ collected with the ATLAS detector at the LHC in 2015–2016, corresponding to an integrated luminosity of $36.1\,\text{fb}^{-1}$. No excess is observed in the data with respect to the SM predictions. The results are interpreted in two sets of models. In the first set, direct production of pairs of lighter top squarks ($\tilde{t}_1$) with long decay chains involving Z or Higgs bosons is considered. The second set includes direct pair production of the heavier top squark pairs ($\tilde{t}_2$) decaying via $\tilde{t}_2 \to Z\tilde{t}_1$ or $\tilde{t}_2 \to h\tilde{t}_1$. The results exclude at 95% confidence level $\tilde{t}_2$ and $\tilde{t}_1$ masses up to about $800\,\text{GeV}$, extending the exclusion region of supersymmetric parameter space covered by previous LHC searches.

https://doi.org/10.1007/JHEP08(2017)006

Contents

1 Introduction

Supersymmetry (SUSY) [1–6] is one of the most studied extensions of the Standard Model (SM). It predicts new bosonic partners for the existing fermions and fermionic partners for the known bosons. If R-parity is conserved [7], SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable, providing a possible dark-matter candidate. The SUSY partners of the charged (neutral) Higgs bosons and electroweak gauge bosons mix to form the mass eigenstates known as charginos ($\tilde{\chi}_k^{\pm}$, $k = 1, 2$) and neutralinos ($\tilde{\chi}_m^0$, $m = 1, \ldots, 4$), where the increasing index denotes increasing mass. The scalar partners of right-handed and left-handed quarks, $\tilde{q}_{\mathrm{R}}$ and $\tilde{q}_{\mathrm{L}}$, mix to form two mass eigenstates, $\tilde{q}_1$ and $\tilde{q}_2$, with $\tilde{q}_1$ defined to be the lighter of the two. To address the SM hierarchy problem [8–11], TeV-scale masses are required [12, 13] for the supersymmetric partners of the gluons (gluinos, $\tilde{g}$) and the top squarks [14, 15]. Furthermore, the higgsino is required not to be heavier than a few hundred GeV.

Top squark production with Higgs (h) or Z bosons in the decay chain can appear either in production of the lighter top squark mass eigenstate ($\tilde{t}_1$) decaying via $\tilde{t}_1 \to t\tilde{\chi}_2^0$ with $\tilde{\chi}_2^0 \to h/Z\tilde{\chi}_1^0$, or in production of the heavier top squark mass eigenstate ($\tilde{t}_2$)
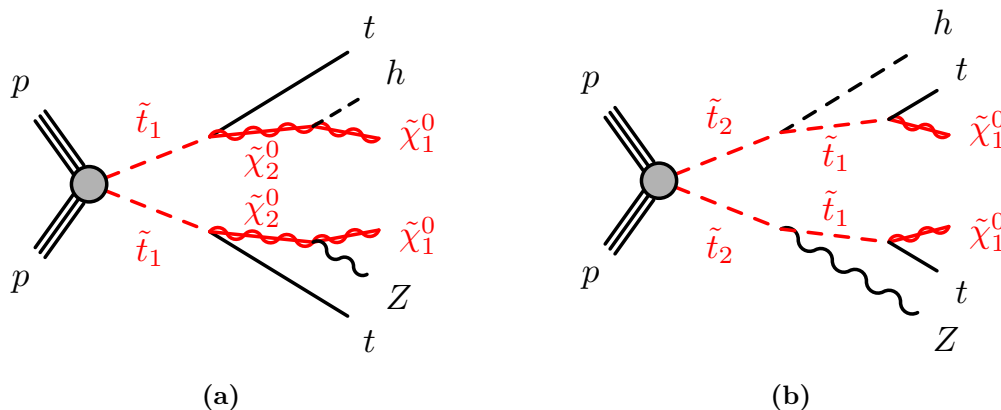
Figure 1. Diagrams for the top squark pair production processes considered in this analysis: (a) $\tilde{t}_1 \to t\tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \to h/Z\tilde{\chi}_1^0$ decays, and (b) $\tilde{t}_2 \to h/Z\tilde{t}_1$ and $\tilde{t}_1 \to t\tilde{\chi}_1^0$ decays.

decaying via $\tilde{t}_2 \to h/Z\tilde{t}_1$, as illustrated in figure 1. Such signals can be discriminated from the SM top quark pair production ($t\bar{t}$) background by requiring a pair of b-tagged jets originating from the $h \to b\bar{b}$ decay or a same-flavour opposite-sign lepton pair originating from the $Z \to \ell^+\ell^-$ decay. Although the pair production of $\tilde{t}_1$ has a cross-section larger than that of the $\tilde{t}_2$, and their decay properties can be similar, searches for the latter can provide additional sensitivity in regions where the $\tilde{t}_1$ falls in a phase space difficult to experimentally discriminate from the background due to the similarities in kinematics with $t\bar{t}$ pair production, such as scenarios where the lighter top squark is only slightly heavier than the sum of the masses of the top quark and the lightest neutralino ($\tilde{\chi}_1^0$).

Simplified models [16–18] are used for the analysis optimisation and interpretation of the results. In these models, direct top squark pair production is considered and all SUSY particles are decoupled except for the top squarks and the neutralinos involved in their decay. In all cases the $\tilde{\chi}_1^0$ is assumed to be the LSP. Simplified models featuring direct $\tilde{t}_1$ production with $\tilde{t}_1 \to t\tilde{\chi}_2^0$ and either $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ are considered. Additional simplified models featuring direct $\tilde{t}_2$ production with $\tilde{t}_2 \to Z\tilde{t}_1$ or $\tilde{t}_2 \to h\tilde{t}_1$ decays and $\tilde{t}_1 \to t\tilde{\chi}_1^0$ are also considered, where the mass difference between the lighter top squark and the neutralino is set to 180 GeV, a region of the mass parameter space not excluded by previous searches for $\tilde{t}_1$ with mass greater than 191 GeV [19].

This paper presents the results of a search for top squarks in final states with h or Z bosons at $\sqrt{s} = 13$ TeV using the data collected by the ATLAS experiment [20] in proton-proton (pp) collisions during 2015 and 2016, corresponding to 36.1 fb^{-1}. Searches for direct $\tilde{t}_1$ pair production have been performed by the ATLAS Collaboration at $\sqrt{s} = 7, 8$ TeV using LHC Run-1 data [19, 21] and $\sqrt{s} = 13$ TeV with 2015 data [22] and by the CMS Collaboration at $\sqrt{s} = 8$ TeV [23–28], searches for direct $\tilde{t}_2$ production were performed at $\sqrt{s} = 8$ TeV by both collaborations [19, 29, 30].

2 ATLAS detector

The ATLAS experiment [20] is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.[1] The interaction point is surrounded by an inner detector (ID) for tracking, a calorimeter system, and a muon spectrometer.

The ID provides precision tracking of charged particles for pseudorapidities $|\eta| < 2.5$ and is surrounded by a superconducting solenoid providing a 2 T axial magnetic field. It consists of silicon pixel and microstrip detectors inside a transition radiation tracker. One significant upgrade for the running period at $\sqrt{s} = 13$ TeV is the presence of the insertable B-layer [31], an additional pixel layer close to the interaction point, which provides high-resolution hits at small radius to improve the tracking performance.

In the pseudorapidity region $|\eta| < 3.2$, high-granularity lead/liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. A steel/scintillator tile calorimeter measures hadron energies for $|\eta| < 1.7$. The endcap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with LAr calorimeters for both the EM and hadronic energy measurements.

The muon spectrometer consists of three large superconducting toroids with eight coils each, and a system of trigger and precision-tracking chambers, which provide triggering and tracking capabilities in the ranges $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively.

A two-level trigger system is used to select events [32]. The first-level trigger is implemented in hardware and uses a subset of the detector information. This is followed by the software-based high-level trigger stage, which runs offline reconstruction and calibration software, reducing the event rate to about 1 kHz.

3 Data set and simulated event samples

The data were collected by the ATLAS detector during 2015 with a peak instantaneous luminosity of $\mathcal{L} = 5.2 \times 10^{33}$ cm^{-2}s^{-1}, and during 2016 with a peak instantaneous luminosity of $\mathcal{L} = 1.4 \times 10^{34}$ cm^{-2}s^{-1}, resulting in a mean number of additional pp interactions per bunch crossing (pile-up) of $\langle\mu\rangle = 14$ in 2015 and $\langle\mu\rangle = 24$ in 2016. Data quality requirements are applied to ensure that all subdetectors were operating at nominal conditions, and that LHC beams were in stable-collision mode. The integrated luminosity of the resulting data set is 36.1 fb^{-1} with an uncertainty of $\pm 3.2\%$. The luminosity and its uncertainty are derived following a methodology similar to that detailed in ref. [33] from a preliminary calibration of the luminosity scale using a pair of x-y beam-separation scans performed in August 2015 and May 2016.

---

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Rapidity is defined as $y = 0.5\ln[(E + p_z)/(E - p_z)]$ where E denotes the energy and p_z is the component of the momentum along the beam direction.

Physics process	Generator	Parton shower	Cross-section normalisation	PDF set	Tune
SUSY Signals	MadGraph5_aMC@NLO 2.2.3 [39]	Pythia 8.186 [40]	NLO+NLL [41–45]	NNPDF2.3LO [46]	A14 [47]
$W(\to \ell\nu)$ + jets	Sherpa 2.2.1 [48]	Sherpa 2.2.1	NNLO [49]	NLO CT10 [46]	Sherpa default
$Z/\gamma^*(\to \ell\ell)$ + jets	Sherpa 2.2.1	Sherpa 2.2.1	NNLO [49]	NLO CT10	Sherpa default
$t\bar{t}$	Powheg-box v2 [50]	Pythia 6.428 [51]	NNLO+NNLL [52–57]	NLO CT10	Perugia2012 [58]
Single-top (t-channel)	Powheg-box v1	Pythia 6.428	NNLO+NNLL [59]	NLO CT10f4	Perugia2012
Single-top (s- and Wt-channel)	Powheg-box v2	Pythia 6.428	NNLO+NNLL [60, 61]	NLO CT10	Perugia2012
$t\bar{t}W/Z/\gamma^*$	MadGraph5_aMC@NLO 2.2.2	Pythia 8.186	NLO [39]	NNPDF2.3LO	A14
Diboson	Sherpa 2.2.1	Sherpa 2.2.1	Generator NLO	CT10	Sherpa default
$t\bar{t}h$	MadGraph5_aMC@NLO 2.2.2	Herwig 2.7.1 [62]	NLO [63]	CTEQ6L1	A14
Wh, Zh	MadGraph5_aMC@NLO 2.2.2	Pythia 8.186	NLO [63]	NNPDF2.3LO	A14
$t\bar{t}WW$, $t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO 2.2.2	Pythia 8.186	NLO [39]	NNPDF2.3LO	A14
tZ, tWZ, $t\bar{t}t$	MadGraph5_aMC@NLO 2.2.2	Pythia 8.186	LO	NNPDF2.3LO	A14
Triboson	Sherpa 2.2.1	Sherpa 2.2.1	Generator LO, NLO	CT10	Sherpa default

Table 1. Simulated signal and background event samples: the corresponding event generator, the parton shower, the cross-section normalisation, the PDF set and the underlying-event tune are shown.

Monte Carlo (MC) simulated event samples are used to aid in the estimation of the background from SM processes and to model the SUSY signal. The choices of MC event generator, parton shower and hadronisation, the cross-section normalisation, the parton distribution function (PDF) set and the set of tuned parameters (tune) for the underlying event of these samples are summarised in table 1, and more details of the event generator configurations can be found in refs. [34–37]. Cross-sections calculated at next-to-next-to-leading order (NNLO) in quantum chromodynamics (QCD) including resummation of next-to-next-to-leading logarithmic (NNLL) soft-gluon terms are used for top quark production processes. For production of top quark pairs in association with vector and Higgs bosons, cross-sections calculated at next-to-leading order (NLO) are used, and the event generator cross-sections from Sherpa (at NLO for most of the processes) are used when normalising the multi-boson backgrounds. In all MC samples, except those produced by Sherpa, the EvtGen v1.2.0 program [38] is used to model the properties of the bottom and charm hadron decays.

SUSY signal samples are generated from leading-order (LO) matrix elements with up to two extra partons, using the MadGraph5_aMC@NLO v2.2.3 event generator interfaced to Pythia 8.186 with the A14 tune for the modelling of the SUSY decay chain, parton showering, hadronisation and the description of the underlying event. Parton luminosities are provided by the NNPDF23LO PDF set. Jet-parton matching is realised following the CKKW-L prescription [64], with a matching scale set to one quarter of the pair-produced superpartner mass. In all cases, the mass of the top quark is fixed at 172.5 GeV. Signal cross-sections are calculated to NLO in the strong coupling constant, adding the resummation of soft-gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [45, 65, 66]. The nominal cross-section and the uncertainty are based on predictions using different PDF sets and factorisation and renormalisation scales, as described in ref. [67].

To simulate the effects of additional pp collisions in the same and nearby bunch crossings, additional interactions are generated using the soft QCD processes as provided by PYTHIA 8.186 with the A2 tune [68] and the MSTW2008LO PDF set [69], and overlaid onto each simulated hard-scatter event. The MC samples are reweighted so that the pile-up distribution matches the one observed in the data. The MC samples are processed through an ATLAS detector simulation [70] based on Geant4 [71] or, in the case of $t\bar{t}t$ and the SUSY signal samples, a fast simulation using a parameterisation of the calorimeter response and Geant4 for the other parts of the detector [72]. All MC samples are reconstructed in the same manner as the data.

4 Event selection

Candidate events are required to have a reconstructed vertex [73] with at least two associated tracks with transverse momentum (p_T) larger than 400 MeV which are consistent with originating from the beam collision region in the x-y plane. The vertex with the highest scalar sum of the squared transverse momentum of the associated tracks is considered to be the primary vertex of the event.

Two categories of leptons (electrons and muons) are defined: "candidate" and "signal" (the latter being a subset of the "candidate" leptons satisfying tighter selection criteria). Electron candidates are reconstructed from isolated electromagnetic calorimeter energy deposits matched to ID tracks and are required to have $|\eta| < 2.47$, a transverse momentum $p_T > 10\,\text{GeV}$, and to pass a "loose" likelihood-based identification requirement [74, 75]. The likelihood input variables include measurements of shower shapes in the calorimeter and track properties in the ID.

Muon candidates are reconstructed in the region $|\eta| < 2.5$ from muon spectrometer tracks matching ID tracks. Candidate muons must have $p_T > 10\,\text{GeV}$ and pass the medium identification requirements defined in ref. [76], based on the number of hits in the different ID and muon spectrometer subsystems, and on the significance of the charge to momentum ratio q/p.

Jets are reconstructed from three-dimensional energy clusters in the calorimeter [77] using the anti-k_t jet clustering algorithm [78] with a radius parameter $R = 0.4$. Only jet candidates with $p_T > 30\,\text{GeV}$ and $|\eta| < 2.5$ are considered as selected jets in the analysis. Jets are calibrated as described in refs. [79, 80], and the expected average energy contribution from pile-up clusters is subtracted according to the jet area [79]. In order to reduce the effects of pile-up, for jets with $p_T < 60\,\text{GeV}$ and $|\eta| < 2.4$ a significant fraction of the tracks associated with each jet must have an origin compatible with the primary vertex, as defined by the jet vertex tagger [81].

Events are discarded if they contain any jet with $p_T > 20\,\text{GeV}$ not satisfying basic quality selection criteria designed to reject detector noise and non-collision backgrounds [82].

Identification of jets containing b-hadrons is performed with a multivariate discriminant that makes use of track impact parameters and reconstructed secondary vertices (b-tagging) [83, 84]. A requirement is chosen corresponding to a 77% average efficiency obtained for b-quark jets in simulated $t\bar{t}$ events. The rejection factors for light-quark and

gluon jets, c-quark jets and $\tau \to$ hadrons $+ \nu$ decays in simulated $t\bar{t}$ events are approximately 380, 12 and 54, respectively. To compensate for differences between data and MC simulation in the b-tagging efficiencies and mis-tag rates, correction factors are applied to the simulated samples [84].

Jet candidates within $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 0.2$ of a lepton candidate are discarded, unless the jet has a value of the b-tagging discriminant larger than the value corresponding to approximately 85% b-tagging efficiency, in which case the lepton is discarded since it probably originated from a semileptonic b-hadron decay. Any remaining electron candidate within $\Delta R = 0.4$ of a non-pile-up jet, and any muon candidate within $\Delta R = \min\{0.4, 0.04 + p_{\mathrm{T}}(\mu)/10\,\mathrm{GeV}\}$ of a non-pile-up jet is discarded. In the latter case, if the jet has fewer than three associated tracks or the muon p_{T} is larger than half of the jet p_{T}, the muon is retained and the jet is discarded instead to avoid inefficiencies for high-energy muons undergoing significant energy loss in the calorimeter. Any muon candidate reconstructed with ID and calorimeter information only which shares an ID track with an electron candidate is removed. Finally, any electron candidate sharing an ID track with a remaining muon candidate is also removed.

Tighter requirements on the lepton candidates are imposed, which are then referred to as "signal" electrons or muons. Signal electrons must satisfy the "medium" likelihood-based identification requirement as defined in refs. [74, 75]. Signal leptons must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$. The associated tracks must have a significance of the transverse impact parameter with respect to the reconstructed primary vertex, d_0, of $|d_0|/\sigma(d_0) < 5$ for electrons and $|d_0|/\sigma(d_0) < 3$ for muons, and a longitudinal impact parameter with respect to the reconstructed primary vertex, z_0, satisfying $|z_0 \sin\theta| < 0.5$ mm. Isolation requirements are applied to both the signal electrons and muons. The scalar sum of the p_{T} of tracks within a variable-size cone around the lepton, excluding its own track, must be less than 6% of the lepton p_{T}. The size of the track isolation cone for electrons (muons) is given by the smaller of $\Delta R = 10\,\mathrm{GeV}/p_{\mathrm{T}}$ and $\Delta R = 0.2\,(0.3)$, that is, a cone of size $0.2\,(0.3)$ at low p_{T} but narrower for high-p_{T} leptons. In addition, in the case of electrons the energy of calorimeter energy clusters in a cone of $\Delta R_\eta = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around the electron (excluding the deposition from the electron itself) must be less than 6% of the electron p_{T}.

Simulated events are corrected to account for minor differences in the signal lepton trigger, reconstruction, identification and isolation efficiencies between data and MC simulation.

The missing transverse momentum vector, whose magnitude is denoted by $E_{\mathrm{T}}^{\mathrm{miss}}$, is defined as the negative vector sum of the transverse momenta of all identified electrons, photons, muons and jets, and an additional soft term. The soft term is constructed from all tracks originating from the primary vertex which are not associated with any identified particle or jet. In this way, the $E_{\mathrm{T}}^{\mathrm{miss}}$ is adjusted for the best calibration of particles and jets listed above, while maintaining pile-up independence in the soft term [85, 86].

The events are required to have a $E_{\mathrm{T}}^{\mathrm{miss}}$ value above 100 GeV and are classified in a further step into two exclusive categories: at least three leptons plus a b-tagged jet ($3\ell 1b$ selection, aimed at top squark decays involving Z bosons), or at least four b-tagged jets and one or two leptons ($1\ell 4b$ selection, aimed at top squark decays involving Higgs bosons).

Requirement / Region	$\mathrm{SR}_\mathrm{A}^{3\ell 1b}$	$\mathrm{SR}_\mathrm{B}^{3\ell 1b}$	$\mathrm{SR}_\mathrm{C}^{3\ell 1b}$
Number of leptons	≥ 3	≥ 3	≥ 3
$n_{b-\text{tagged jets}}$	≥ 1	≥ 1	≥ 1
$|m_{\ell\ell} - m_Z|$ [GeV]	< 15	< 15	< 15
Leading lepton p_T [GeV]	> 40	> 40	> 40
Leading jet p_T [GeV]	> 250	> 80	> 60
Leading b-tagged jet p_T [GeV]	> 40	> 40	> 30
n_jets ($p_\mathrm{T} > 30$ GeV)	≥ 6	≥ 6	≥ 5
E_T^miss [GeV]	> 100	> 180	> 140
$p_\mathrm{T}^{\ell\ell}$ [GeV]	> 150	—	< 80

Table 2. Definition of the signal regions used in the $3\ell 1b$ selection (see text for details).

In the $3\ell 1b$ selection, events are accepted if they pass a trigger requiring either two electrons, two muons or an electron and a muon. In the $1\ell 4b$ selection, events are accepted if they pass a trigger requiring an isolated electron or muon. The trigger-level requirements on the p_T, identification and isolation of the leptons involved in the trigger decision are looser than those applied offline to ensure that trigger efficiencies are constant in the relevant phase space [32].

Additional requirements are applied depending on the final state, as described in the following. These requirements are optimised for the best discovery significance using the simplified models featuring $\tilde{t}_2$ production with $\tilde{t}_2 \to Z\tilde{t}_1$ or $\tilde{t}_2 \to h\tilde{t}_1$ decays.

4.1 $3\ell 1b$ selection

Events of interest are selected if they contain at least three signal leptons (electrons or muons), with at least one same-flavour opposite-sign lepton pair whose invariant mass is compatible with the Z boson mass ($|m_{\ell\ell} - m_Z| < 15$ GeV, with $m_Z = 91.2$ GeV). To maximise the sensitivity in different regions of the mass parameter space, three overlapping signal regions (SRs) are defined as shown in table 2. Signal region $\mathrm{SR}_\mathrm{A}^{3\ell 1b}$ is optimised for large $\tilde{t}_2 - \tilde{\chi}_1^0$ mass splitting, where the Z boson in the $\tilde{t}_2 \to Z\tilde{t}_1$ decay is boosted, and large $p_\mathrm{T}^{\ell\ell}$ and leading-jet p_T are required. Signal region $\mathrm{SR}_\mathrm{B}^{3\ell 1b}$ covers the intermediate case, featuring slightly softer kinematic requirements than in $\mathrm{SR}_\mathrm{A}^{3\ell 1b}$. Signal region $\mathrm{SR}_\mathrm{C}^{3\ell 1b}$ is designed to improve the sensitivity for compressed spectra ($m_{\tilde{t}_2} \gtrsim m_{\tilde{\chi}_1^0} + m_t + m_Z$) with softer jet-$p_\mathrm{T}$ requirements and an upper bound on $p_\mathrm{T}^{\ell\ell}$.

4.2 $1\ell 4b$ selection

Similarly to the $3\ell 1b$ case, three overlapping SRs are defined in the $1\ell 4b$ selection to have a good sensitivity in different regions of the mass parameter space. Only events with one or two signal leptons are selected to ensure orthogonality with the SRs in the $3\ell 1b$ selection, with at least one lepton having $p_\mathrm{T} > 30$ GeV, and the electron candidates are also required

Requirement / Region	$\mathrm{SR}_\mathrm{A}^{1\ell4b}$	$\mathrm{SR}_\mathrm{B}^{1\ell4b}$	$\mathrm{SR}_\mathrm{C}^{1\ell4b}$
Number of leptons	1–2	1–2	1–2
$n_{b-\text{tagged jets}}$	≥ 4	≥ 4	≥ 4
m_T [GeV]	—	>150	>125
H_T [GeV]	> 1000	—	—
E_T^miss [GeV]	> 120	> 150	> 150
Leading b-tagged jet p_T [GeV]	—	—	<140
m_{bb} [GeV]	95–155	—	—
p_T^{bb} [GeV]	> 300	—	—
n_jets $(p_\mathrm{T} > 60\,\text{GeV})$	≥ 6	≥ 5	—
n_jets $(p_\mathrm{T} > 30\,\text{GeV})$	—	—	≥ 7

Table 3. Definition of the signal regions used in the $1\ell4b$ selection (see text for details).

to satisfy the *tight* likelihood-based identification requirement as defined in refs. [74, 75]. These SRs are defined as shown in table 3.

Signal region $\mathrm{SR}_\mathrm{A}^{1\ell4b}$ is optimised for large $\tilde{t}_2 - \tilde{\chi}_1^0$ mass splitting, where the Higgs boson in the $\tilde{t}_2 \to h\tilde{t}_1$ decay is boosted. In this signal region, the pair of b-tagged jets with the smallest ΔR^{bb} is required to have an invariant mass consistent with the Higgs boson mass ($|m_{bb} - m_h| < 15$ GeV, with $m_h = 125$ GeV), and the transverse momentum of the system formed by these two b-tagged jets (p_T^{bb}) is required to be above 300 GeV. Signal region $\mathrm{SR}_\mathrm{B}^{1\ell4b}$ covers the intermediate case, featuring slightly harder kinematic requirements than $\mathrm{SR}_\mathrm{A}^{1\ell4b}$. Finally, signal region $\mathrm{SR}_\mathrm{C}^{1\ell4b}$ is designed to be sensitive to compressed spectra ($m_{\tilde{t}_2} \gtrsim m_{\tilde{\chi}_1^0} + m_t + m_h$). This region has softer jet p_T requirements and an upper bound on the p_T of the leading b-tagged jet. Signal region $\mathrm{SR}_\mathrm{A}^{1\ell4b}$ includes requirements on H_T (computed as the scalar sum of the p_T of all the jets in the event), while both signal regions $\mathrm{SR}_\mathrm{B}^{1\ell4b}$ and $\mathrm{SR}_\mathrm{C}^{1\ell4b}$ include requirements on the transverse mass m_T computed using the missing-momentum and lepton-momentum vectors: $m_\mathrm{T} = \sqrt{2p_\mathrm{T}^\ell E_\mathrm{T}^\text{miss}\left(1 - \cos[\Delta\phi(\ell, E_\mathrm{T}^\text{miss})]\right)}$.

5 Background estimation

The main SM background processes satisfying the SR requirements are estimated by simulation, which is normalised and verified (whenever possible) with data events in separate statistically independent regions of the phase space. Dedicated control regions (CRs) enhanced in a particular background component, such as the production of top quark pairs in association with a Z boson ($t\bar{t}Z$) and multi-boson production in the $3\ell1b$ selection, and $t\bar{t}$ in the $1\ell4b$ selection, are used for the normalisation. For each signal region, a simultaneous "background fit" is performed to the numbers of events found in the CRs, using a minimisation based on likelihoods with the HistFitter package [87]. In each fit, the normalisations of the background contributions having dedicated CRs are allowed to float freely, while the other backgrounds are determined directly using simulation or from additional independent

studies in data. This way the total post-fit prediction is forced to be equal to the number of data events in the CR and its total uncertainty is given by the data statistical uncertainty. When setting 95% confidence level (CL) upper limits on the cross-section of specific SUSY models, the simultaneous fits also include the observed yields in the SR.

Systematic uncertainties in the MC simulation affect the ratio of the expected yields in the different regions and are taken into account to determine the uncertainty in the background prediction. Each uncertainty source is described by a single nuisance parameter, and correlations between background processes and selections are taken into account. The fit affects neither the uncertainty nor the central value of these nuisance parameters. The systematic uncertainties considered in the fit are described in section 6.

Whenever possible, the level of agreement of the background prediction with data is compared in dedicated validation regions (VRs), which are not used to constrain the background normalisation or nuisance parameters in the fit.

5.1 Background estimation in the $3\ell 1b$ selection

The dominant SM background contribution to the SRs in the $3\ell 1b$ selection is expected to be from $t\bar{t}Z$, with minor contribution from multi-boson production (mainly WZ) and backgrounds containing jets misidentified as leptons (hereafter referred to as "fake" leptons) or non-prompt leptons from decays of hadrons (mainly in $t\bar{t}$ events). The normalisation of the main backgrounds ($t\bar{t}Z$, multi-boson) is obtained by fitting the yield to the observed data in two control regions, then extrapolating this yield to the SRs as described above. Backgrounds from other sources ($t\bar{t}W$, $t\bar{t}h$ and rare SM processes), which provide a subdominant contribution to the SRs, are determined from MC simulation only.

The background from fake or non-prompt leptons is estimated from data with a method similar to that described in refs. [88, 89]. Two types of lepton identification criteria are defined for this evaluation: "tight" and "loose", corresponding to the signal and candidate electrons and muons described in section 4. The leading lepton is considered to be prompt, which is a valid assumption in more than 95% of the cases according to simulations. The method makes use of the number of observed events with the second and third leading leptons being loose-loose, loose-tight, tight-loose and tight-tight in each region. The probability for prompt leptons satisfying the loose selection criteria to also satisfy the tight selection is measured using a data sample enriched in $Z \to \ell^+\ell^-$ ($\ell = e, \mu$) decays. The equivalent probability for fake or non-prompt leptons is measured using events with one electron and one muon with the same charge. The number of events with one or two fake or non-prompt leptons is calculated from these probabilities and the number of observed events with loose and tight leptons. The modelling of the background from fake or non-prompt leptons is validated in events passing a selection similar to the SRs, but removing the E_T^{miss} requirements and inverting the $m_{\ell\ell}$ requirements.

The two dedicated control regions used for the $t\bar{t}Z$ ($\mathrm{CR}_{t\bar{t}Z}^{3\ell 1b}$) and multi-boson ($\mathrm{CR}_{VV}^{3\ell 1b}$) background estimation in this selection are defined as shown in table 4. To ensure orthogonality with the SRs, an upper bound on $E_T^{\mathrm{miss}} < 100$ GeV is required in $\mathrm{CR}_{t\bar{t}Z}^{3\ell 1b}$, while a b-jet veto is applied in $\mathrm{CR}_{VV}^{3\ell 1b}$.

Requirement / Region	$CR_{t\bar{t}Z}^{3\ell1b}$	$CR_{VV}^{3\ell1b}$
Number of leptons	≥ 3	≥ 3
$|m_{\ell\ell} - m_Z|$ [GeV]	< 15	< 15
Leading lepton p_T [GeV]	> 40	> 40
Leading jet p_T [GeV]	> 60	> 30
$n_{b-\text{tagged jets}}$	≥ 1	0
$n_{\text{jets}}(p_T > 30\,\text{GeV})$	≥ 4	≥ 4
E_T^{miss} [GeV]	< 100	—
$p_T^{\ell\ell}$ [GeV]	—	—

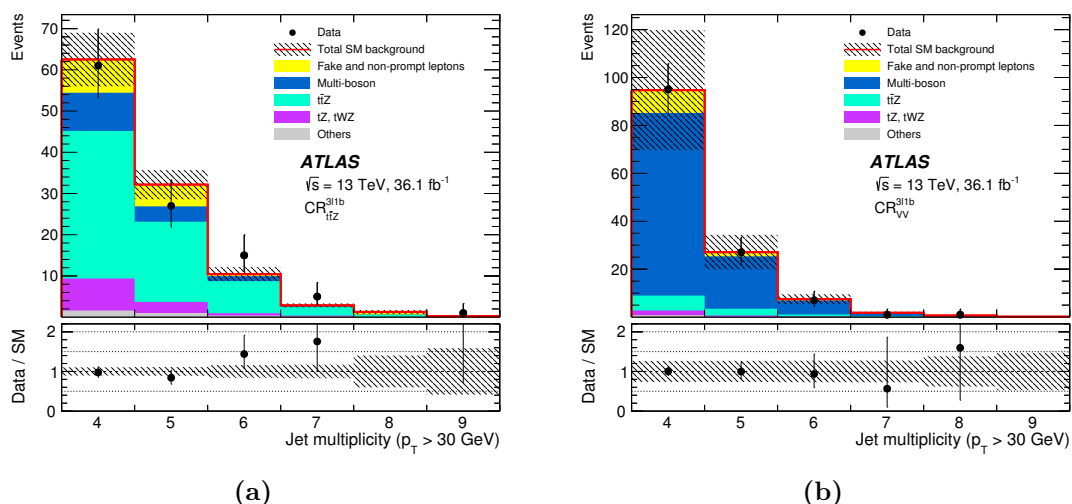**Table 4.** Definition of the control regions used in the $3\ell1b$ selection.

Figure 2. Jet multiplicity distributions in control regions (a) $CR_{t\bar{t}Z}^{3\ell1b}$ and (b) $CR_{VV}^{3\ell1b}$, after normalising the $t\bar{t}Z$ and multi-boson background processes via the simultaneous fit described in section 5. The contributions from all SM backgrounds are shown as a histogram stack; the bands represent the total uncertainty in the background prediction. The "Others" category contains the contributions from $t\bar{t}h$, $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, Wh, and Zh production. The last bin in each figure contains the overflow. The lower panels show the ratio of the observed data to the total SM background prediction, with bands representing the total uncertainty in the background prediction.

Table 5 shows the observed and expected yields in the two CRs for each background source, and figure 2 shows the n_{jet} distribution in these regions after the background fit. The normalisation factors for the $t\bar{t}Z$ and multi-boson backgrounds do not differ from unity by more than 30% and the post-fit MC-simulated jet multiplicity distributions agree well with the data.

5.2 Background estimation in the $1\ell4b$ selection

The dominant SM background contribution to the SRs in the $1\ell4b$ selection is expected to be top quark pair ($t\bar{t}$) production, amounting to more than 80% of the total background.

	$\mathrm{CR}_{t\bar{t}Z}^{3\ell 1b}$	$\mathrm{CR}_{VV}^{3\ell 1b}$
Observed events	109	131
Total (post-fit) SM events	109 ± 10	131 ± 11
Fit output, multi-boson	14.5 ± 2.7	105 ± 13
Fit output, $t\bar{t}Z$	66 ± 14	10.2 ± 2.7
Fake or non-prompt leptons	14 ± 6	12 ± 7
tZ, tWZ	11 ± 6	2.7 ± 1.4
Others	3.2 ± 0.5	1.0 ± 0.3
Fit input, multi-boson	19	137
Fit input, $t\bar{t}Z$	73	11.2

Table 5. Background fit results for the control regions in the $3\ell 1b$ selection. The nominal predictions from MC simulation are given for comparison for those backgrounds ($t\bar{t}Z$, multi-boson) that are normalised to data. The "Others" category contains the contributions from $t\bar{t}h$, $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, Wh, and Zh production. Combined statistical and systematic uncertainties are given. The individual uncertainties can be correlated and do not necessarily add in quadrature to the total systematic uncertainty. The number of events with fake or non-prompt leptons is estimated with the data-driven technique described in section 5.

The normalisation of the $t\bar{t}$ background for each of the three SRs is obtained by fitting the yield to the observed data in a dedicated CR, then extrapolating this yield to the SRs as described above. Other background sources (single top, $t\bar{t}h$ and rare SM processes), which provide a subdominant contribution to the SRs, are determined from MC simulation only. The contribution from events with fake or non-prompt leptons is found to be negligible in this selection. The three $t\bar{t}$ CRs (named $\mathrm{CR}_{t\bar{t},\mathrm{A}}^{1\ell 4b}$, $\mathrm{CR}_{t\bar{t},\mathrm{B}}^{1\ell 4b}$ and $\mathrm{CR}_{t\bar{t},\mathrm{C}}^{1\ell 4b}$) are described in table 6. They are designed to have kinematic properties resembling as closely as possible those of each of the three SRs ($\mathrm{SR}_{\mathrm{A}}^{1\ell 4b}$, $\mathrm{SR}_{\mathrm{B}}^{1\ell 4b}$ and $\mathrm{SR}_{\mathrm{C}}^{1\ell 4b}$, respectively), while having a high purity in $t\bar{t}$ background and only a small contamination from signal. The CRs are built by inverting the SR requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and relaxing or inverting those on m_{bb} or m_{T}. Figure 3 shows the jet multiplicity distributions in these CRs after the background fit. In a similar manner, three validation regions (named $\mathrm{VR}_{\mathrm{A}}^{1\ell 4b}$, $\mathrm{VR}_{\mathrm{B}}^{1\ell 4b}$ and $\mathrm{VR}_{\mathrm{C}}^{1\ell 4b}$) are defined, each of them corresponding to a different CR, with the same requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ as the SR and relaxing or inverting the requirements on m_{bb}, m_{T} or jet multiplicity, as shown in table 6. These VRs are used to provide a statistically independent cross-check of the extrapolation in a selection close to that of the SR but with small signal contamination. Table 7 shows the observed and expected yields in the CRs and VRs for each background source. The large correction to $t\bar{t}$ normalisation after the background fit has also been observed in other analyses [90] and is due to a mismodelling of the $t\bar{t}+b\bar{b}$, $c\bar{c}$ component in the MC simulation. The background prediction is in agreement with the observed data in all VRs.

Requirement / Region	$\mathrm{CR}_{t\bar{t},\mathrm{A}}^{1\ell4b}$	$\mathrm{VR}_{\mathrm{A}}^{1\ell4b}$	$\mathrm{CR}_{t\bar{t},\mathrm{B}}^{1\ell4b}$	$\mathrm{VR}_{\mathrm{B}}^{1\ell4b}$	$\mathrm{CR}_{t\bar{t},\mathrm{C}}^{1\ell4b}$	$\mathrm{VR}_{\mathrm{C}}^{1\ell4b}$
Number of leptons	1–2	1–2	1–2	1–2	1–2	1–2
$n_{b\text{-tagged jets}}$	≥ 4	≥ 4	≥ 4	≥ 4	≥ 4	≥ 4
m_{T} [GeV]	—	—	>100	>150	<125	<125
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	<120	>120	<150	>150	<150	>150
Leading b-tagged jet p_{T} [GeV]	—	—	—	—	<140	<140
m_{bb} [GeV]	95–155	$\notin$ [95,155]	—	—	—	—
n_{jets} $(p_{\mathrm{T}} > 60\,\mathrm{GeV})$	≥ 5	≥ 5	≥ 5	≤ 4	—	—
n_{jets} $(p_{\mathrm{T}} > 30\,\mathrm{GeV})$	—	—	—	—	≥ 7	≥ 7

Table 6. Summary of selection criteria for the control and validation regions in the $1\ell4b$ selection.

	$\mathrm{CR}_{t\bar{t},\mathrm{A}}^{1\ell4b}$	$\mathrm{VR}_{\mathrm{A}}^{1\ell4b}$	$\mathrm{CR}_{t\bar{t},\mathrm{B}}^{1\ell4b}$	$\mathrm{VR}_{\mathrm{B}}^{1\ell4b}$	$\mathrm{CR}_{t\bar{t},\mathrm{C}}^{1\ell4b}$	$\mathrm{VR}_{\mathrm{C}}^{1\ell4b}$
Observed events	863	258	340	86	963	84
Total (post-fit) SM events	863 ± 29	266 ± 34	340 ± 18	96 ± 13	963 ± 31	90 ± 11
Fit output, $t\bar{t}$	783 ± 33	235 ± 33	307 ± 19	88 ± 12	891 ± 33	82 ± 10
Single top	16 ± 5	9.0 ± 2.1	5.5 ± 1.8	1.7 ± 0.9	12.2 ± 2.4	2.5 ± 1.3
V+jets, multi-boson	11.8 ± 2.9	3.1 ± 1.1	4.7 ± 1.4	$0.15_{-0.15}^{+0.20}$	9.8 ± 2.1	1.0 ± 0.4
$t\bar{t}h$, Vh	27 ± 4	7.9 ± 1.3	12.7 ± 2.0	3.9 ± 0.7	31 ± 5	2.7 ± 0.6
$t\bar{t}W$, $t\bar{t}Z$	19 ± 4	7.2 ± 1.6	7.1 ± 1.7	2.2 ± 0.5	15.6 ± 3.1	1.5 ± 0.5
Others	5.0 ± 2.6	3.6 ± 1.9	3.2 ± 1.7	0.57 ± 0.31	2.7 ± 1.4	0.62 ± 0.32
Fit input, $t\bar{t}$	495	148	175	50	578	53

Table 7. Background fit results for the control and validation regions in the $1\ell4b$ selection. The nominal predictions from MC simulation are given for comparison for the $t\bar{t}$ background, which is normalised to data. The "Others" category contains the contributions from $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, tZ, and tWZ production. Combined statistical and systematic uncertainties are given. The individual uncertainties can be correlated and do not necessarily add in quadrature to the total systematic uncertainty.
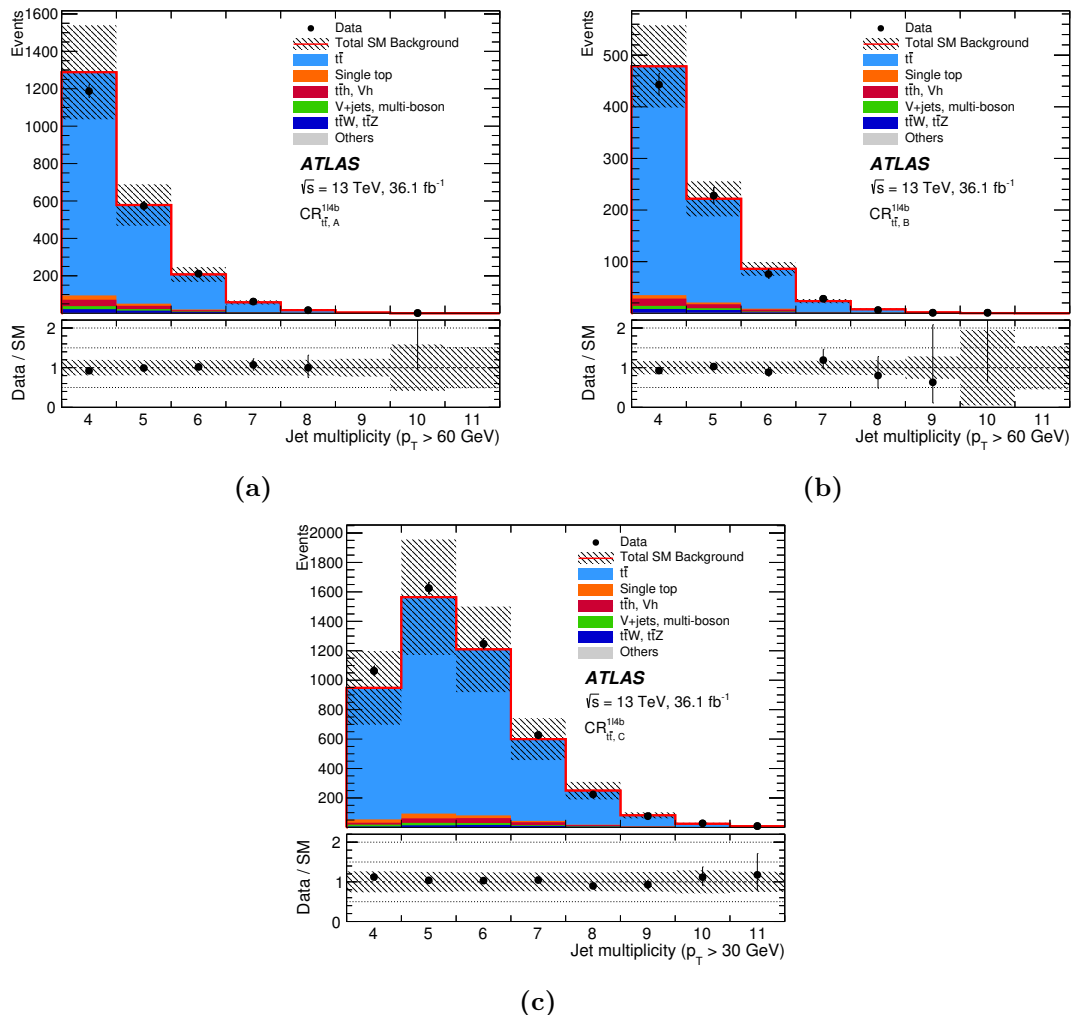
Figure 3. Jet multiplicity distributions in control regions (a) $\mathrm{CR}_{t\bar{t},\mathrm{A}}^{1\ell4b}$ (b) $\mathrm{CR}_{t\bar{t},\mathrm{B}}^{1\ell4b}$ and (c) $\mathrm{CR}_{t\bar{t},\mathrm{C}}^{1\ell4b}$ after normalising the $t\bar{t}$ background process via the simultaneous fit described in section 5. The $t\bar{t}$ background normalisation is constrained to the data observation for jet multiplicity values above the requirements shown in table 6. The contributions from all SM backgrounds are shown as a histogram stack; the bands represent the total uncertainty. The "Others" category contains the contributions from $t\bar{t}h$, $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, Wh, and Zh production. The last bin in each figure contains the overflow. The lower panels show the ratio of the observed data to the total SM background prediction, with the bands representing the total uncertainty in the background prediction.

6 Systematic uncertainties

The primary sources of systematic uncertainty are related to the jet energy scale, the jet energy resolution, the theoretical and the MC modelling uncertainties in the background determined using CRs ($t\bar{t}Z$ and multi-bosons in the $3\ell 1b$ selection, as well as $t\bar{t}$ in the $1\ell 4b$ selection). The statistical uncertainty of the simulated event samples is taken into account as well. The effects of the systematic uncertainties are evaluated for all signal samples and background processes. Since the normalisation of the dominant background processes is extracted in dedicated CRs, the systematic uncertainties only affect the extrapolation to the SRs in these cases.

The jet energy scale and resolution uncertainties are derived as a function of the p_T and η of the jet, as well as of the pile-up conditions and the jet flavour composition (more quark-like or gluon-like) of the selected jet sample. They are determined using a combination of simulated and data samples, through measurements of the jet response asymmetry in dijet, Z+jet and γ+jet events [91]. Uncertainties associated with the modelling of the b-tagging efficiencies for b-jets, c-jets and light-flavour jets [92, 93] are also considered.

The systematic uncertainties related to the modelling of $E_\mathrm{T}^\mathrm{miss}$ in the simulation are estimated by propagating the uncertainties in the energy and momentum scale of all identified electrons, photons, muons and jets, as well as the uncertainties in the soft-term scale and resolution [85].

Other detector-related systematic uncertainties, such as those in the lepton reconstruction efficiency, energy scale and energy resolution, and in the modelling of the trigger [76], are found to have a small impact on the results.

The uncertainties in the modelling of the $t\bar{t}$ and single-top backgrounds in simulation in the $1\ell 4b$ selection are estimated by varying the renormalisation and factorisation scales, as well as the amount of initial- and final-state radiation used to generate the samples [34]. Additional uncertainties in the parton-shower modelling are assessed as the difference between the predictions from POWHEG showered with PYTHIA and HERWIG, and due to the event generator choice by comparing POWHEG and MADGRAPH5_AMC@NLO [34], in both cases showered with PYTHIA.

The diboson background MC modelling uncertainties are estimated by varying the renormalisation, factorisation and resummation scales used to generate the samples [94]. For $t\bar{t}Z$, the predictions from the MADGRAPH5_AMC@NLO and SHERPA event generators are compared, and the uncertainties related to the choice of renormalisation and factorisation scales are assessed by varying the corresponding event generator parameters up and down by a factor of two around their nominal values [95].

The cross-sections used to normalise the MC samples are varied according to the uncertainty in the cross-section calculation, i.e., 6% for diboson, 13% for $t\bar{t}W$ and 12% $t\bar{t}Z$ production [39]. For $t\bar{t}WW$, tZ, tWZ, $t\bar{t}h$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, and triboson production processes, which constitute a small background, a 50% uncertainty in the event yields is assumed.

Systematic uncertainties are assigned to the estimated background from fake or non-prompt leptons in the $3\ell 1b$ selection to account for potentially different compositions (heavy flavour, light flavour or conversions) between the signal and control regions, as well as the

	SR$_A^{3\ell 1b}$	SR$_B^{3\ell 1b}$	SR$_C^{3\ell 1b}$	SR$_A^{1\ell 4b}$	SR$_B^{1\ell 4b}$	SR$_C^{1\ell 4b}$
Total systematic uncertainty (%)	20	24	15	22	17	30
Diboson theoretical uncertainties (%)	6.7	5.5	2.2	<1	<1	<1
$t\bar{t}Z$ theoretical uncertainties (%)	10	10	4.4	<1	<1	<1
$t\bar{t}$ theoretical uncertainties (%)	—	—	—	17	14	22
Other theoretical uncertainties (%)	9.0	6.8	5.4	1.6	2.4	1.7
MC statistical uncertainties (%)	8.5	18	6	7.3	5.2	13
Diboson fitted normalisation (%)	4.6	3.5	3.8	<1	<1	<1
$t\bar{t}Z$ fitted normalisation (%)	12	11	13	<1	<1	<1
$t\bar{t}$ fitted normalisation (%)	—	—	—	3.4	5.1	3.3
Fake or non-prompt leptons (%)	—	6.5	—	—	—	—
Pile-up (%)	4.7	2.8	0.6	<1	1.4	<1
Jet energy resolution (%)	2.0	2.7	3.0	5.3	<1	13
Jet energy scale (%)	1.0	2.7	3.5	3.2	5.3	6.1
E_T^{miss} resolution (%)	5.3	2.6	1.6	6.8	6.5	4.0
b-tagging (%)	2.4	1.5	3.0	6.8	2.9	3.5

Table 8. Summary of the main systematic uncertainties and their impact (in %) on the total SM background prediction in each of the signal regions studied. The total systematic uncertainty can be different from the sum in quadrature of individual sources due to the correlations between them resulting from the fit to the data. The quoted theoretical uncertainties include modelling and cross-section uncertainties.

contamination from prompt leptons in the regions used to measure the probabilities for loose fake or non-prompt leptons to pass the tight signal criteria.

Table 8 summarises the contributions of the different sources of systematic uncertainty in the total SM background predictions in the signal regions. The dominant systematic uncertainties in the $3\ell 1b$ SRs are due to the limited number of events in CR$_{t\bar{t}Z}^{3\ell 1b}$ and theoretical uncertainties in $t\bar{t}Z$ production, while in the $1\ell 4b$ SRs the dominant uncertainties are due to $t\bar{t}$ modelling.

7 Results

The observed number of events and expected yields are shown in table 9 for each of the six SRs. The SM backgrounds are estimated as described in section 5. Data agree with the SM background prediction within uncertainties and thus exclusion limits for several beyond-the-SM (BSM) scenarios are extracted. Figure 4 shows the E_T^{miss} distributions after applying all the SR selection requirements except those on E_T^{miss}.

The HistFitter framework, which utilises a profile-likelihood-ratio-test statistic [96], is used to estimate 95% confidence intervals using the CL$_s$ prescription [97]. The likelihood is built as the product of a probability density function describing the observed number of events in the SR and the associated CR(s) and, to constrain the nuisance parameters
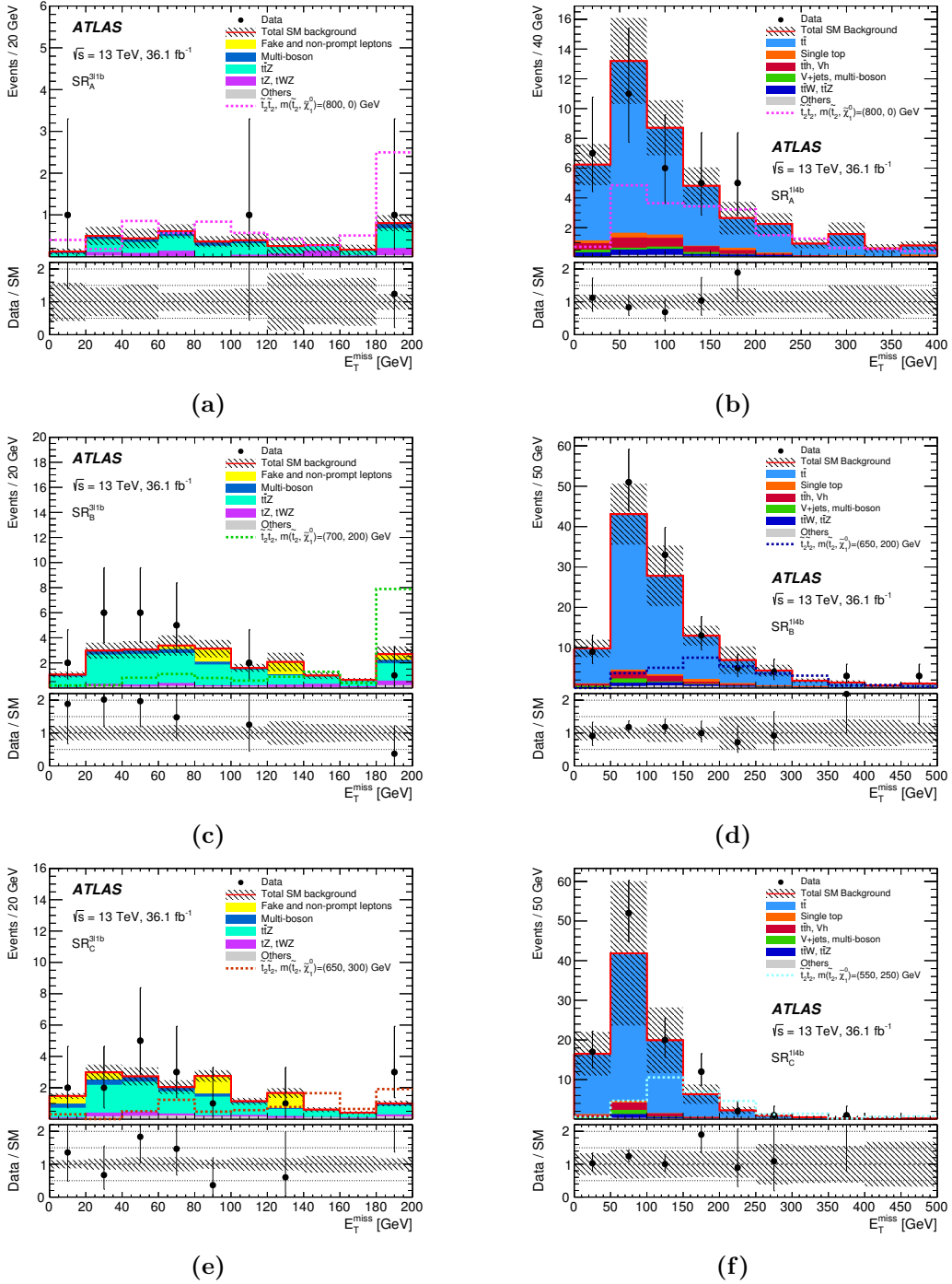
Figure 4. Distribution of E_T^{miss} for events passing all the signal candidate selection requirements, except that on E_T^{miss}, for (a) $SR_A^{3\ell1b}$, (c) $SR_B^{3\ell1b}$, (e) $SR_C^{3\ell1b}$ and (b) $SR_A^{1\ell4b}$, (d) $SR_B^{1\ell4b}$, (f) $SR_C^{1\ell4b}$ after the background fit described in section 5. The contributions from all SM backgrounds are shown; the bands represent the total uncertainty. The expected distributions for signal models with $m(\tilde{t}_2) = 700$ GeV and $m(\tilde{\chi}_1^0) = 0$ GeV, and $m(\tilde{t}_2) = 650$ GeV and $m(\tilde{\chi}_1^0) = 250$ GeV are also shown as dashed lines. The last bin in each figure contains the overflow. The lower panels show the ratio of the observed data to the total SM background prediction, with the bands representing the total uncertainty in the background prediction.

associated with the systematic uncertainties, Gaussian distributions whose widths correspond to the sizes of these uncertainties; Poisson distributions are used instead to model statistical uncertainties affecting the observed and predicted yields in the CRs. Table 9 also shows upper limits (at the 95% CL) on the visible BSM cross-section $\sigma_{\mathrm{vis}} = S^{95}_{\mathrm{obs}}/\mathcal{L}dt$, defined as the product of the production cross-section, acceptance and efficiency.

Model-dependent limits are also set in specific classes of SUSY models. For each signal hypothesis, the background fit is redone taking into account the signal contamination in the CRs, which is found to be below 15% for signal models close to the Run-1 exclusion limits. All uncertainties in the SM prediction are considered, including those that are correlated between signal and background (for instance, jet energy scale uncertainties), as well as all uncertainties in the predicted signal, excluding PDF- and scale-induced uncertainties in the theoretical cross-section. Since the three SRs are not orthogonal, only the SR with best expected sensitivity is used for each signal point. "Observed limits" are calculated from the observed event yields in the SRs. "Expected limits" are calculated by setting the nominal event yield in each SR to the corresponding mean expected background.

Figure 5 shows the limits on simplified models in which pair-produced $\tilde{t}_1$ decay with 100% branching ratio into the $\tilde{\chi}^0_2$ and a top quark, assuming $\mathcal{B}(\tilde{\chi}^0_2 \to Z\tilde{\chi}^0_1) = 0.5$ and $\mathcal{B}(\tilde{\chi}^0_2 \to h\tilde{\chi}^0_1) = 0.5$. A massless LSP and a minimum mass difference between the $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ of 130 GeV, needed to have on-shell decays for both the Higgs and Z bosons, are assumed in this model. Limits are presented in the $\tilde{t}_1$-$\tilde{\chi}^0_2$ mass plane. The two SRs with best expected sensitivity from the $3\ell 1b$ and $1\ell 4b$ selections are statistically combined to derive the limits on this model. For a $\tilde{\chi}^0_2$ mass above 200 GeV, $\tilde{t}_1$ masses up to about 800 GeV are excluded at 95% CL.

Limits for simplified models, in which pair-produced $\tilde{t}_2$ decay with 100% branching ratio into the $\tilde{t}_1$ and either a Z or a h boson, with $\tilde{t}_1 \to t\tilde{\chi}^0_1$, in the $\tilde{t}_2$-$\tilde{\chi}^0_1$ mass plane are shown in figure 6. When considering the $\tilde{t}_2$ decays via a Z boson, probed by the $3\ell 1b$ selection, $\tilde{t}_2$ masses up to 800 GeV are excluded at 95% CL for a $\tilde{\chi}^0_1$ of about 50 GeV and $\tilde{\chi}^0_1$ masses up to 350 GeV are excluded for $\tilde{t}_2$ masses below 650 GeV. Assuming 100% branching ratio into $\tilde{t}_1$ and a h boson, probed by the $1\ell 4b$ selection, $\tilde{t}_2$ masses up to 880 GeV are excluded at 95% CL for a $\tilde{\chi}^0_1$ of about 50 GeV, and $\tilde{\chi}^0_1$ masses up to 260 GeV are excluded for $\tilde{t}_2$ masses between 650 and 710 GeV. These results extend the previous limits on the $\tilde{t}_2$ mass from ATLAS $\sqrt{s} = 8$ TeV analyses [19, 29] by up to 250 GeV depending on the $\tilde{\chi}^0_1$ mass.

Exclusion limits as a function of the $\tilde{t}_2$ branching ratios are shown in figure 7 for representative values of the masses of $\tilde{t}_2$ and $\tilde{\chi}^0_1$. For $\tilde{t}_2$ mass of 600 GeV, SUSY models with $\mathcal{B}(\tilde{t}_2 \to Z\tilde{t}_1)$ above 58% are excluded. For higher top squark mass ($m_{\tilde{t}_2} = 650$ GeV), models with $\mathcal{B}(\tilde{t}_2 \to Z\tilde{t}_1)$ above 50% or $\mathcal{B}(\tilde{t}_2 \to h\tilde{t}_1)$ above 80% are excluded. The region with large $\mathcal{B}(\tilde{t}_2 \to t\tilde{\chi}^0_1)$ can be probed by searches targeting direct $\tilde{t}_1$ pair production [19].

	$\mathrm{SR}_{\mathrm{A}}^{3\ell1b}$	$\mathrm{SR}_{\mathrm{B}}^{3\ell1b}$	$\mathrm{SR}_{\mathrm{C}}^{3\ell1b}$
Observed events	2	1	3
Total (post-fit) SM events	1.9 ± 0.4	2.7 ± 0.6	2.0 ± 0.3
Fit output, multi-boson	0.26 ± 0.08	0.28 ± 0.10	0.23 ± 0.05
Fit output, $t\bar{t}Z$	1.1 ± 0.3	1.4 ± 0.5	1.2 ± 0.3
tZ, tWZ	0.43 ± 0.23	0.36 ± 0.19	0.19 ± 0.10
Fake or non-prompt leptons	$0.00^{+0.30}_{-0.00}$	0.45 ± 0.19	$0.00^{+0.30}_{-0.00}$
Others	0.09 ± 0.02	0.23 ± 0.06	0.36 ± 0.06
Fit input, multi-boson	0.35	0.37	0.30
Fit input, $t\bar{t}Z$	1.2	1.5	1.4
S_{obs}^{95}	4.5	3.8	5.8
S_{exp}^{95}	$4.2^{+1.9}_{-0.4}$	$4.9^{+1.5}_{-1.1}$	$4.4^{+1.8}_{-0.5}$
σ_{vis} [fb]	0.13	0.10	0.16
$p(s=0)$	0.42	0.93	0.23
	$\mathrm{SR}_{\mathrm{A}}^{1\ell4b}$	$\mathrm{SR}_{\mathrm{B}}^{1\ell4b}$	$\mathrm{SR}_{\mathrm{C}}^{1\ell4b}$
Observed events	10	28	16
Total (post-fit) SM events	13.6 ± 3.0	29 ± 5	10.5 ± 3.2
Fit output, $t\bar{t}$	11.3 ± 2.9	24 ± 5	9.3 ± 3.1
Single top	0.50 ± 0.18	1.7 ± 0.4	0.24 ± 0.07
V+jets, multi-boson	0.20 ± 0.15	0.23 ± 0.10	0.01 ± 0.01
$t\bar{t}h$, Vh	0.89 ± 0.16	1.19 ± 0.35	0.56 ± 0.13
$t\bar{t}W$, $t\bar{t}Z$	0.36 ± 0.21	1.09 ± 0.31	0.10 ± 0.10
Others	0.37 ± 0.20	1.33 ± 0.69	0.34 ± 0.18
Fit input, $t\bar{t}$	7.1	14	6.0
S_{obs}^{95}	7.8	14.6	15.6
S_{exp}^{95}	$9.6^{+4.1}_{-2.3}$	$15.5^{+5.6}_{-4.4}$	$10.4^{+4.2}_{-2.6}$
σ_{vis} [fb]	0.21	0.40	0.43
$p(s=0)$	0.63	0.82	0.11

Table 9. Observed and expected numbers of events in the six signal regions. The nominal predictions from MC simulation are given for comparison for those backgrounds ($t\bar{t}Z$, multi-boson for the $3\ell1b$ selection and $t\bar{t}$ for the $1\ell4b$ selection) that are normalised to data in dedicated control regions. For $\mathrm{SR}_{\mathrm{A}}^{3\ell1b}$, $\mathrm{SR}_{\mathrm{B}}^{3\ell1b}$ and $\mathrm{SR}_{\mathrm{C}}^{3\ell1b}$, the "Others" category contains the contributions from $t\bar{t}h$, $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, Wh, and Zh production. For $\mathrm{SR}_{\mathrm{A}}^{1\ell4b}$, $\mathrm{SR}_{\mathrm{B}}^{1\ell4b}$ and $\mathrm{SR}_{\mathrm{C}}^{1\ell4b}$, the "Others" category contains the contributions from $t\bar{t}WW$, $t\bar{t}t$, $t\bar{t}t\bar{t}$, tZ, and tWZ production. Combined statistical and systematic uncertainties are given. Signal model-independent 95% CL upper limits on the visible BSM cross-section (σ_{vis}), the visible number of signal events (S_{obs}^{95}), the number of signal events (S_{exp}^{95}) given the expected number of background events (and $\pm 1\sigma$ variations of the expected background), and the discovery p-value ($p(s=0)$), all calculated with pseudo-experiments, are also shown for each signal region.
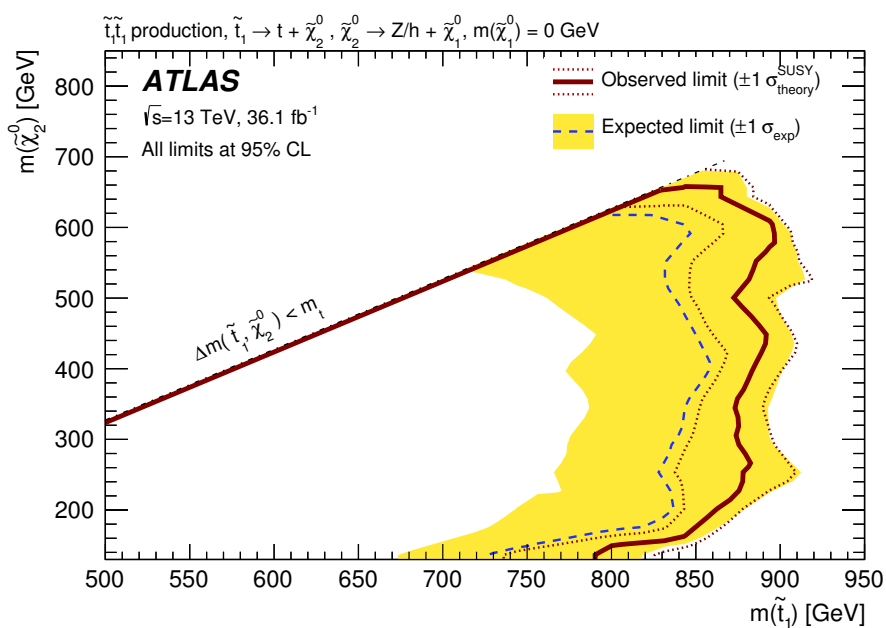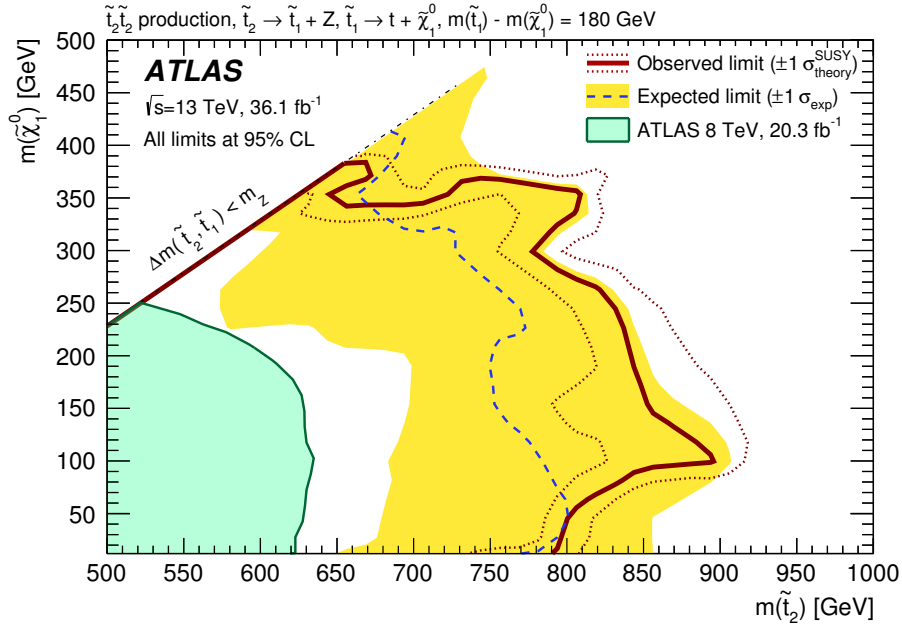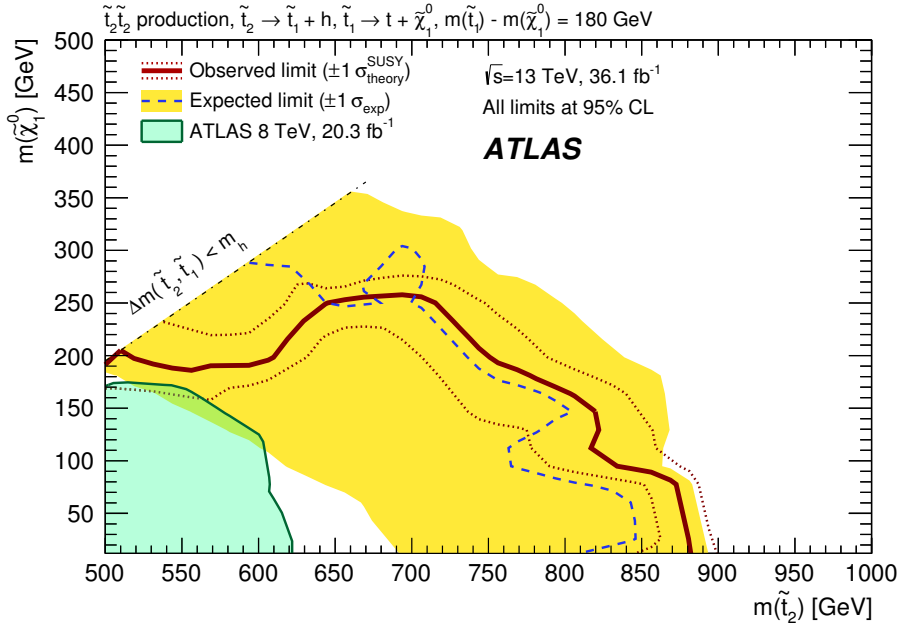
Figure 5. Exclusion limits at 95% CL from the analysis of 36.1 fb^{-1} of 13 TeV pp collision data on the masses of the $\tilde{t}_1$ and $\tilde{\chi}_2^0$, for a fixed $m(\tilde{\chi}_1^0) = 0$ GeV, assuming $\mathcal{B}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 0.5$ and $\mathcal{B}(\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0) = 0.5$. The dashed line and the shaded band are the expected limit and its $\pm 1\sigma$ uncertainty, respectively. The thick solid line is the observed limit for the central value of the signal cross-section. The expected and observed limits do not include the effect of the theoretical uncertainties in the signal cross-section. The dotted lines show the effect on the observed limit when varying the signal cross-section by $\pm 1\sigma$ of the theoretical uncertainty.

Figure 6. Exclusion limits at 95% CL from the analysis of 36.1 fb^{-1} of 13 TeV pp collision data on the masses of the $\tilde{t}_2$ and $\tilde{\chi}_1^0$, for a fixed $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 180$ GeV and assuming (a) $\mathcal{B}(\tilde{t}_2 \to Z\tilde{t}_1) = 1$ or (b) $\mathcal{B}(\tilde{t}_2 \to h\tilde{t}_1) = 1$. The dashed line and the shaded band are the expected limit and its $\pm 1\sigma$ uncertainty, respectively. The thick solid line is the observed limit for the central value of the signal cross-section. The expected and observed limits do not include the effect of the theoretical uncertainties in the signal cross-section. The dotted lines show the effect on the observed limit when varying the signal cross-section by $\pm 1\sigma$ of the theoretical uncertainty. The shaded area in the lower-left corner shows the observed exclusion from the ATLAS $\sqrt{s} = 8$ TeV analysis [19, 29].
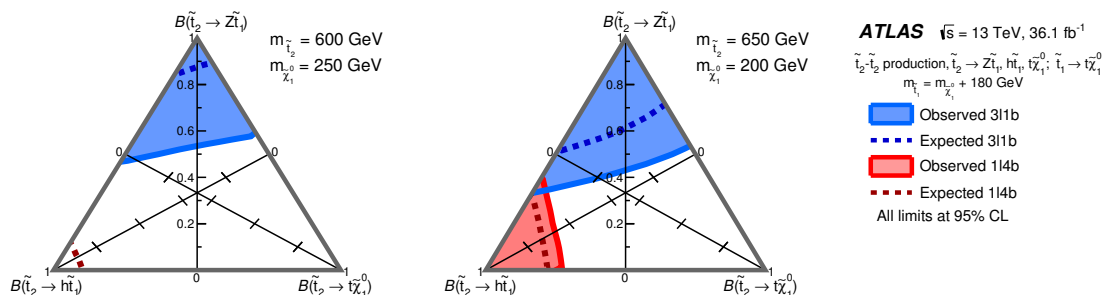
Figure 7. Exclusion limits at 95% CL from the analysis of 36.1 fb^{-1} of 13 TeV pp collision data as a function of the $\tilde{t}_2$ branching ratio for $\tilde{t}_2 \to \tilde{t}_1 Z$, $\tilde{t}_2 \to \tilde{t}_1 h$ and $\tilde{t}_2 \to t\tilde{\chi}_1^0$. The blue and red exclusion regions correspond to the $3\ell 1b$ and $1\ell 4b$ selections respectively. The limits are given for two different values of the $\tilde{t}_2$ and $\tilde{\chi}_1^0$ masses. The dashed lines are the expected limit and the solid lines are the observed limit for the central value of the signal cross-section.

8 Conclusion

This paper reports a search for direct top squark pair production resulting in events with either a leptonically decaying Z boson or a pair of b-tagged jets from a Higgs boson decay, based on 36.1 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment at the LHC in 2015 and 2016. Good agreement is found between the yield of observed events and the SM predictions. Model-independent limits are presented, which allow the results to be reinterpreted in generic models that also predict similar final states in association with invisible particles. The limits exclude, at 95% confidence level, beyond-the-SM processes with visible cross-sections above 0.11 (0.21) fb for the $3\ell 1b$ ($1\ell 4b$) selections.

Results are also interpreted in the context of simplified models characterised by the decay chain $\tilde{t}_1 \to t\tilde{\chi}_2^0$ with $\tilde{\chi}_2^0 \to Z/h\tilde{\chi}_1^0$, or $\tilde{t}_2 \to Z/h\tilde{t}_1$ with $\tilde{t}_1 \to t\tilde{\chi}_1^0$. The results exclude at 95% confidence level $\tilde{t}_2$ and $\tilde{t}_1$ masses up to about 800 GeV, extending the region of supersymmetric parameter space covered by previous LHC searches.

References

[1] Yu. A. Golfand and E.P. Likhtman, *Extension of the algebra of Poincaré group generators and violation of p invariance*, *JETP Lett.* **13** (1971) 323 [*Pisma Zh. Eksp. Teor. Fiz.* **13** (1971) 452] [INSPIRE].

[2] D.V. Volkov and V.P. Akulov, *Is the neutrino a Goldstone particle?*, *Phys. Lett.* **46B** (1973) 109 [INSPIRE].

[3] J. Wess and B. Zumino, *Supergauge transformations in four-dimensions*, *Nucl. Phys.* **B 70** (1974) 39 [INSPIRE].

[4] J. Wess and B. Zumino, *Supergauge invariant extension of quantum electrodynamics*, *Nucl. Phys.* **B 78** (1974) 1 [INSPIRE].

[5] S. Ferrara and B. Zumino, *Supergauge invariant Yang-Mills theories*, *Nucl. Phys.* **B 79** (1974) 413 [INSPIRE].

[6] A. Salam and J.A. Strathdee, *Supersymmetry and non-Abelian gauges*, *Phys. Lett.* **51B** (1974) 353 [INSPIRE].

[7] G.R. Farrar and P. Fayet, *Phenomenology of the production, decay and detection of new hadronic states associated with supersymmetry*, *Phys. Lett.* **76B** (1978) 575 [INSPIRE].

[8] N. Sakai, *Naturalness in supersymmetric GUTs*, *Z. Phys.* **C 11** (1981) 153 [INSPIRE].

[9] S. Dimopoulos, S. Raby and F. Wilczek, *Supersymmetry and the scale of unification*, *Phys. Rev.* **D 24** (1981) 1681 [INSPIRE].

[10] L.E. Ibáñez and G.G. Ross, *Low-energy predictions in supersymmetric grand unified theories*, *Phys. Lett.* **105B** (1981) 439 [InSPIRE].

[11] S. Dimopoulos and H. Georgi, *Softly broken supersymmetry and* SU(5), *Nucl. Phys.* **B 193** (1981) 150 [InSPIRE].

[12] R. Barbieri and G.F. Giudice, *Upper bounds on supersymmetric particle masses*, *Nucl. Phys.* **B 306** (1988) 63 [InSPIRE].

[13] B. de Carlos and J.A. Casas, *One loop analysis of the electroweak breaking in supersymmetric models and the fine tuning problem*, *Phys. Lett.* **B 309** (1993) 320 [`hep-ph/9303291`] [InSPIRE].

[14] K. Inoue, A. Kakuto, H. Komatsu and S. Takeshita, *Aspects of grand unified models with softly broken supersymmetry*, *Prog. Theor. Phys.* **68** (1982) 927 [*Erratum ibid.* **70** (1983) 330] [InSPIRE].

[15] J.R. Ellis and S. Rudaz, *Search for supersymmetry in toponium decays*, *Phys. Lett.* **128B** (1983) 248 [InSPIRE].

[16] J. Alwall, M.-P. Le, M. Lisanti and J.G. Wacker, *Searching for directly decaying gluinos at the Tevatron*, *Phys. Lett.* **B 666** (2008) 34 [`arXiv:0803.0019`] [InSPIRE].

[17] J. Alwall, P. Schuster and N. Toro, *Simplified models for a first characterization of new physics at the LHC*, *Phys. Rev.* **D 79** (2009) 075020 [`arXiv:0810.3921`] [InSPIRE].

[18] LHC New Physics Working Group collaboration, D. Alves, *Simplified models for LHC new physics searches*, *J. Phys.* **G 39** (2012) 105005 [`arXiv:1105.2838`] [InSPIRE].

[19] ATLAS collaboration, *ATLAS run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider*, *Eur. Phys. J.* **C 75** (2015) 510 [*Erratum ibid.* **C 76** (2016) 153] [`arXiv:1506.08616`] [InSPIRE].

[20] ATLAS collaboration, *The ATLAS experiment at the CERN Large Hadron Collider*, 2008 *JINST* **3** S08003 [InSPIRE].

[21] ATLAS collaboration, *Search for scalar top quark pair production in natural gauge mediated supersymmetry models with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett.* **B 715** (2012) 44 [`arXiv:1204.6736`] [InSPIRE].

[22] ATLAS collaboration, *Search for top squarks in final states with one isolated lepton, jets and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, *Phys. Rev.* **D 94** (2016) 052009 [`arXiv:1606.03903`] [InSPIRE].

[23] CMS collaboration, *Search for top-squark pair production in the single-lepton final state in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J.* **C 73** (2013) 2677 [`arXiv:1308.1586`] [InSPIRE].

[24] CMS collaboration, *Search for supersymmetry using razor variables in events with b-tagged jets in pp collisions at $\sqrt{s} = 8$ TeV*, *Phys. Rev.* **D 91** (2015) 052018 [`arXiv:1502.00300`] [InSPIRE].

[25] CMS collaboration, *Searches for supersymmetry using the M_{T2} variable in hadronic events produced in pp collisions at 8 TeV*, *JHEP* **05** (2015) 078 [`arXiv:1502.04358`] [InSPIRE].

[26] CMS collaboration, *Search for supersymmetry in events with soft leptons, low jet multiplicity and missing transverse energy in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett.* **B 759** (2016) 9 [`arXiv:1512.08002`] [InSPIRE].

[27] CMS collaboration, *Search for direct pair production of scalar top quarks in the single- and dilepton channels in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **07** (2016) 027 [*Erratum ibid.* **09** (2016) 056] [arXiv:1602.03169] [INSPIRE].

[28] CMS collaboration, *Search for direct pair production of supersymmetric top quarks decaying to all-hadronic final states in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J.* **C 76** (2016) 460 [arXiv:1603.00765] [INSPIRE].

[29] ATLAS collaboration, *Search for direct top squark pair production in events with a Z boson, b-jets and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, *Eur. Phys. J.* **C 74** (2014) 2883 [arXiv:1403.5222] [INSPIRE].

[30] CMS collaboration, *Search for top-squark pairs decaying into Higgs or Z bosons in pp collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett.* **B 736** (2014) 371 [arXiv:1405.3886] [INSPIRE].

[31] ATLAS collaboration, *ATLAS insertable B-layer technical design report*, CERN-LHCC-2010-013, CERN, Geneva Switzerland, (2010).

[32] ATLAS collaboration, *Performance of the ATLAS trigger system in* 2015, *Eur. Phys. J.* **C 77** (2017) 317 [arXiv:1611.09661] [INSPIRE].

[33] ATLAS collaboration, *Improved luminosity determination in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector at the LHC*, *Eur. Phys. J.* **C 73** (2013) 2518 [arXiv:1302.4393] [INSPIRE].

[34] ATLAS collaboration, *Simulation of top quark production for the ATLAS experiment at $\sqrt{s} = 13$ TeV*, ATL-PHYS-PUB-2016-004, CERN, Geneva Switzerland, (2016).

[35] ATLAS collaboration, *Monte Carlo generators for the production of a W or Z/γ^* boson in association with jets at ATLAS in run* 2, ATL-PHYS-PUB-2016-003, CERN, Geneva Switzerland, (2016).

[36] ATLAS collaboration, *Multi-boson simulation for* 13 *TeV ATLAS analyses*, ATL-PHYS-PUB-2016-002, CERN, Geneva Switzerland, (2016).

[37] ATLAS collaboration, *Modelling of the $t\bar{t}H$ and $t\bar{t}V$ ($V = W, Z$) processes for $\sqrt{s} = 13$ TeV ATLAS analyses*, ATL-PHYS-PUB-2016-005, CERN, Geneva Switzerland, (2016).

[38] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth.* **A 462** (2001) 152 [INSPIRE].

[39] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [arXiv:1405.0301] [INSPIRE].

[40] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A brief introduction to PYTHIA* 8.1, *Comput. Phys. Commun.* **178** (2008) 852 [arXiv:0710.3820] [INSPIRE].

[41] W. Beenakker, R. Hopker, M. Spira and P.M. Zerwas, *Squark and gluino production at hadron colliders*, *Nucl. Phys.* **B 492** (1997) 51 [hep-ph/9610490] [INSPIRE].

[42] A. Kulesza and L. Motyka, *Threshold resummation for squark-antisquark and gluino-pair production at the LHC*, *Phys. Rev. Lett.* **102** (2009) 111802 [arXiv:0807.2405] [INSPIRE].

[43] A. Kulesza and L. Motyka, *Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC*, *Phys. Rev.* **D 80** (2009) 095004 [arXiv:0905.4749] [INSPIRE].

[44] W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen and I. Niessen, *Soft-gluon resummation for squark and gluino hadroproduction*, *JHEP* **12** (2009) 041 [arXiv:0909.4418] [INSPIRE].

[45] W. Beenakker et al., *Squark and gluino hadroproduction*, *Int. J. Mod. Phys.* **A 26** (2011) 2637 [arXiv:1105.1110] [INSPIRE].

[46] H.-L. Lai et al., *New parton distributions for collider physics*, *Phys. Rev.* **D 82** (2010) 074024 [arXiv:1007.2241] [INSPIRE].

[47] ATLAS collaboration, *ATLAS run* 1 *PYTHIA8 tunes*, ATL-PHYS-PUB-2014-021, CERN, Geneva Switzerland, (2014).

[48] T. Gleisberg et al., *Event generation with SHERPA* 1.1, *JHEP* **02** (2009) 007 [arXiv:0811.4622] [INSPIRE].

[49] S. Catani, L. Cieri, G. Ferrera, D. de Florian and M. Grazzini, *Vector boson production at hadron colliders: a fully exclusive QCD calculation at NNLO*, *Phys. Rev. Lett.* **103** (2009) 082001 [arXiv:0903.2120] [INSPIRE].

[50] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [arXiv:1002.2581] [INSPIRE].

[51] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA* 6.4 *physics and manual*, *JHEP* **05** (2006) 026 [hep-ph/0603175] [INSPIRE].

[52] M. Czakon, P. Fiedler and A. Mitov, *Total top-quark pair-production cross section at hadron colliders through $O(\alpha_S^4)$*, *Phys. Rev. Lett.* **110** (2013) 252004 [arXiv:1303.6254] [INSPIRE].

[53] M. Czakon and A. Mitov, *NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction*, *JHEP* **01** (2013) 080 [arXiv:1210.6832] [INSPIRE].

[54] M. Czakon and A. Mitov, *NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels*, *JHEP* **12** (2012) 054 [arXiv:1207.0236] [INSPIRE].

[55] P. Bärnreuther, M. Czakon and A. Mitov, *Percent level precision physics at the Tevatron: first genuine NNLO QCD corrections to $q\bar{q} \to t\bar{t} + X$*, *Phys. Rev. Lett.* **109** (2012) 132001 [arXiv:1204.5201] [INSPIRE].

[56] M. Cacciari, M. Czakon, M. Mangano, A. Mitov and P. Nason, *Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation*, *Phys. Lett.* **B 710** (2012) 612 [arXiv:1111.5869] [INSPIRE].

[57] M. Czakon and A. Mitov, *Top++: a program for the calculation of the top-pair cross-section at hadron colliders*, *Comput. Phys. Commun.* **185** (2014) 2930 [arXiv:1112.5675] [INSPIRE].

[58] P.Z. Skands, *Tuning Monte Carlo generators: the Perugia tunes*, *Phys. Rev.* **D 82** (2010) 074018 [arXiv:1005.3457] [INSPIRE].

[59] N. Kidonakis, *Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production*, *Phys. Rev.* **D 83** (2011) 091503 [arXiv:1103.2792] [INSPIRE].

[60] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-*, *Phys. Rev.* **D 82** (2010) 054018 [arXiv:1005.4451] [INSPIRE].

[61] N. Kidonakis, *NNLL resummation for s-channel single top quark production*, *Phys. Rev.* **D 81** (2010) 054028 [arXiv:1001.5034] [INSPIRE].

[62] G. Corcella et al., *HERWIG* 6*: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)*, *JHEP* **01** (2001) 010 [`hep-ph/0011363`] [ɪɴSPIRE].

[63] S. Dittmaier et al., *Handbook of LHC Higgs cross sections: 2. Differential distributions*, `arXiv:1201.3084` [ɪɴSPIRE].

[64] L. Lönnblad and S. Prestel, *Matching tree-level matrix elements with interleaved showers*, *JHEP* **03** (2012) 019 [`arXiv:1109.4829`] [ɪɴSPIRE].

[65] W. Beenakker, M. Krämer, T. Plehn, M. Spira and P.M. Zerwas, *Stop production at hadron colliders*, *Nucl. Phys.* **B 515** (1998) 3 [`hep-ph/9710451`] [ɪɴSPIRE].

[66] W. Beenakker, S. Brensing, M. Krämer, A. Kulesza, E. Laenen and I. Niessen, *Supersymmetric top and bottom squark production at hadron colliders*, *JHEP* **08** (2010) 098 [`arXiv:1006.4771`] [ɪɴSPIRE].

[67] C. Borschensky et al., *Squark and gluino production cross sections in pp collisions at $\sqrt{s} = 13$, 14, 33 and 100 TeV*, *Eur. Phys. J.* **C 74** (2014) 3174 [`arXiv:1407.5066`] [ɪɴSPIRE].

[68] ATLAS collaboration, *Summary of ATLAS PYTHIA 8 tunes*, ATL-PHYS-PUB-2012-003, CERN, Geneva Switzerland, (2012).

[69] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, *Parton distributions for the LHC*, *Eur. Phys. J.* **C 63** (2009) 189 [`arXiv:0901.0002`] [ɪɴSPIRE].

[70] ATLAS collaboration, *The ATLAS simulation infrastructure*, *Eur. Phys. J.* **C 70** (2010) 823 [`arXiv:1005.4568`] [ɪɴSPIRE].

[71] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: a simulation toolkit*, *Nucl. Instrum. Meth.* **A 506** (2003) 250 [ɪɴSPIRE].

[72] ATLAS collaboration, *The simulation principle and performance of the ATLAS fast calorimeter simulation FastCaloSim*, ATL-PHYS-PUB-2010-013, CERN, Geneva Switzerland, (2010).

[73] ATLAS collaboration, *Vertex reconstruction performance of the ATLAS detector at $\sqrt{s} = 13$ TeV*, ATL-PHYS-PUB-2015-026, CERN, Geneva Switzerland, (2015).

[74] ATLAS collaboration, *Electron efficiency measurements with the ATLAS detector using 2012 LHC proton-proton collision data*, *Eur. Phys. J.* **C 77** (2017) 195 [`arXiv:1612.01456`] [ɪɴSPIRE].

[75] ATLAS collaboration, *Electron identification measurements in ATLAS using $\sqrt{s} = 13$ TeV data with 50 ns bunch spacing*, ATL-PHYS-PUB-2015-041, CERN, Geneva Switzerland, (2015).

[76] ATLAS collaboration, *Muon reconstruction performance of the ATLAS detector in proton-proton collision data at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J.* **C 76** (2016) 292 [`arXiv:1603.05598`] [ɪɴSPIRE].

[77] ATLAS collaboration, *Properties of jets and inputs to jet reconstruction and calibration with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV*, ATL-PHYS-PUB-2015-036, CERN, Geneva Switzerland, (2015).

[78] M. Cacciari, G.P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [`arXiv:0802.1189`] [ɪɴSPIRE].

[79] ATLAS collaboration, *Jet calibration and systematic uncertainties for jets reconstructed in the ATLAS detector at $\sqrt{s} = 13\,TeV$*, ATL-PHYS-PUB-2015-015, CERN, Geneva Switzerland, (2015).

[80] ATLAS collaboration, *Jet global sequential corrections with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 8\,TeV$*, ATLAS-CONF-2015-002, CERN, Geneva Switzerland, (2015).

[81] ATLAS collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8\,TeV$ using the ATLAS detector*, *Eur. Phys. J.* **C 76** (2016) 581 [`arXiv:1510.03823`] [ɪɴSPIRE].

[82] ATLAS collaboration, *Data-quality requirements and event cleaning for jets and missing transverse energy reconstruction with the ATLAS detector in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7\,TeV$*, ATLAS-CONF-2010-038, CERN, Geneva Switzerland, (2010).

[83] ATLAS collaboration, *Performance of b-jet identification in the ATLAS experiment*, 2016 *JINST* **11** P04008 [`arXiv:1512.01094`] [ɪɴSPIRE].

[84] ATLAS collaboration, *Optimisation of the ATLAS b-tagging performance for the* 2016 *LHC run*, ATL-PHYS-PUB-2016-012, CERN, Geneva Switzerland, (2016).

[85] ATLAS collaboration, *Expected performance of missing transverse momentum reconstruction for the ATLAS detector at $\sqrt{s} = 13\,TeV$*, ATL-PHYS-PUB-2015-023, CERN, Geneva Switzerland, (2015).

[86] ATLAS collaboration, *Performance of missing transverse momentum reconstruction for the ATLAS detector in the first proton-proton collisions at $\sqrt{s} = 13\,TeV$*, ATL-PHYS-PUB-2015-027, CERN, Geneva Switzerland, (2015).

[87] M. Baak, G.J. Besjes, D. Côte, A. Koutsman, J. Lorenz and D. Short, *HistFitter software framework for statistical data analysis*, *Eur. Phys. J.* **C 75** (2015) 153 [`arXiv:1410.1280`] [ɪɴSPIRE].

[88] ATLAS collaboration, *Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s} = 7\,TeV$*, *Eur. Phys. J.* **C 71** (2011) 1577 [`arXiv:1012.1792`] [ɪɴSPIRE].

[89] ATLAS collaboration, *Measurement of the top quark pair production cross section in pp collisions at $\sqrt{s} = 7\,TeV$ in dilepton final states with ATLAS*, *Phys. Lett.* **B 707** (2012) 459 [`arXiv:1108.3699`] [ɪɴSPIRE].

[90] ATLAS collaboration, *Search for the Standard Model Higgs boson decaying into $b\bar{b}$ produced in association with top quarks decaying hadronically in pp collisions at $\sqrt{s} = 8\,TeV$ with the ATLAS detector*, *JHEP* **05** (2016) 160 [`arXiv:1604.03812`] [ɪɴSPIRE].

[91] ATLAS collaboration, *Jet calibration and systematic uncertainties for jets reconstructed in the ATLAS detector at $\sqrt{s} = 13\,TeV$*, ATL-PHYS-PUB-2015-015, CERN, Geneva Switzerland, (2015).

[92] ATLAS collaboration, *Calibration of b-tagging using dileptonic top pair events in a combinatorial likelihood approach with the ATLAS experiment*, ATLAS-CONF-2014-004, CERN, Geneva Switzerland, (2014).

[93] ATLAS collaboration, *Calibration of the performance of b-tagging for c and light-flavour jets in the* 2012 *ATLAS data*, ATLAS-CONF-2014-046, CERN, Geneva Switzerland, (2014).

[94] ATLAS collaboration, *Multi-boson simulation for* 13 *TeV ATLAS analyses*, ATL-PHYS-PUB-2016-002, CERN, Geneva Switzerland, (2016).

[95] ATLAS collaboration, *Expected performance of the ATLAS b-tagging algorithms in run-2*, ATL-PHYS-PUB-2015-022, CERN, Geneva Switzerland, (2015).

[96] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J.* **C 71** (2011) 1554 [*Erratum ibid.* **C 73** (2013) 2501] [arXiv:1007.1727] [INSPIRE].

[97] A.L. Read, *Presentation of search results: the CL_s technique*, *J. Phys.* **G 28** (2002) 2693 [INSPIRE].

[98] ATLAS collaboration, *ATLAS computing acknowledgements* 2016–2017, ATL-GEN-PUB-2016-002, CERN, Geneva Switzerland, (2016).

The ATLAS collaboration

M. Aaboud[137d], G. Aad[88], B. Abbott[115], O. Abdinov[12,*], B. Abeloos[119], S.H. Abidi[161],
O.S. AbouZeid[139], N.L. Abraham[151], H. Abramowicz[155], H. Abreu[154], R. Abreu[118],
Y. Abulaiti[148a,148b], B.S. Acharya[167a,167b,a], S. Adachi[157], L. Adamczyk[41a], J. Adelman[110],
M. Adersberger[102], T. Adye[133], A.A. Affolder[139], T. Agatonovic-Jovin[14], C. Agheorghiesei[28c],
J.A. Aguilar-Saavedra[128a,128f], S.P. Ahlen[24], F. Ahmadov[68,b], G. Aielli[135a,135b], S. Akatsuka[71],
H. Akerstedt[148a,148b], T.P.A. Åkesson[84], E. Akilli[52], A.V. Akimov[98], G.L. Alberghi[22a,22b],
J. Albert[172], P. Albicocco[50], M.J. Alconada Verzini[74], S.C. Alderweireldt[108], M. Aleksa[32],
I.N. Aleksandrov[68], C. Alexa[28b], G. Alexander[155], T. Alexopoulos[10], M. Alhroob[115], B. Ali[130],
M. Aliev[76a,76b], G. Alimonti[94a], J. Alison[33], S.P. Alkire[38], B.M.M. Allbrooke[151], B.W. Allen[118],
P.P. Allport[19], A. Aloisio[106a,106b], A. Alonso[39], F. Alonso[74], C. Alpigiani[140], A.A. Alshehri[56],
M.I. Alstaty[88], B. Alvarez Gonzalez[32], D. Álvarez Piqueras[170], M.G. Alviggi[106a,106b],
B.T. Amadio[16], Y. Amaral Coutinho[26a], C. Amelung[25], D. Amidei[92],
S.P. Amor Dos Santos[128a,128c], A. Amorim[128a,128b], S. Amoroso[32], G. Amundsen[25],
C. Anastopoulos[141], L.S. Ancu[52], N. Andari[19], T. Andeen[11], C.F. Anders[60b], J.K. Anders[77],
K.J. Anderson[33], A. Andreazza[94a,94b], V. Andrei[60a], S. Angelidakis[9], I. Angelozzi[109],
A. Angerami[38], A.V. Anisenkov[111,c], N. Anjos[13], A. Annovi[126a,126b], C. Antel[60a], M. Antonelli[50],
A. Antonov[100,*], D.J. Antrim[166], F. Anulli[134a], M. Aoki[69], L. Aperio Bella[32], G. Arabidze[93],
Y. Arai[69], J.P. Araque[128a], V. Araujo Ferraz[26a], A.T.H. Arce[48], R.E. Ardell[80], F.A. Arduh[74],
J-F. Arguin[97], S. Argyropoulos[66], M. Arik[20a], A.J. Armbruster[32], L.J. Armitage[79], O. Arnaez[161],
H. Arnold[51], M. Arratia[30], O. Arslan[23], A. Artamonov[99], G. Artoni[122], S. Artz[86], S. Asai[157],
N. Asbah[45], A. Ashkenazi[155], L. Asquith[151], K. Assamagan[27], R. Astalos[146a], M. Atkinson[169],
N.B. Atlay[143], K. Augsten[130], G. Avolio[32], B. Axen[16], M.K. Ayoub[119], G. Azuelos[97,d],
A.E. Baas[60a], M.J. Baca[19], H. Bachacou[138], K. Bachas[76a,76b], M. Backes[122], M. Backhaus[32],
P. Bagnaia[134a,134b], M. Bahmani[42], H. Bahrasemani[144], J.T. Baines[133], M. Bajic[39],
O.K. Baker[179], E.M. Baldin[111,c], P. Balek[175], F. Balli[138], W.K. Balunas[124], E. Banas[42],
A. Bandyopadhyay[23], Sw. Banerjee[176,e], A.A.E. Bannoura[178], L. Barak[32], E.L. Barberio[91],
D. Barberis[53a,53b], M. Barbero[88], T. Barillari[103], M-S Barisits[32], J.T. Barkeloo[118], T. Barklow[145],
N. Barlow[30], S.L. Barnes[36c], B.M. Barnett[133], R.M. Barnett[16], Z. Barnovska-Blenessy[36a],
A. Baroncelli[136a], G. Barone[25], A.J. Barr[122], L. Barranco Navarro[170], F. Barreiro[85],
J. Barreiro Guimarães da Costa[35a], R. Bartoldus[145], A.E. Barton[75], P. Bartos[146a], A. Basalaev[125],
A. Bassalat[119,f], R.L. Bates[56], S.J. Batista[161], J.R. Batley[30], M. Battaglia[139], M. Bauce[134a,134b],
F. Bauer[138], H.S. Bawa[145,g], J.B. Beacham[113], M.D. Beattie[75], T. Beau[83], P.H. Beauchemin[165],
P. Bechtle[23], H.P. Beck[18,h], H.C. Beck[57], K. Becker[122], M. Becker[86], M. Beckingham[173],
C. Becot[112], A.J. Beddall[20e], A. Beddall[20b], V.A. Bednyakov[68], M. Bedognetti[109], C.P. Bee[150],
T.A. Beermann[32], M. Begalli[26a], M. Begel[27], J.K. Behr[45], A.S. Bell[81], G. Bella[155],
L. Bellagamba[22a], A. Bellerive[31], M. Bellomo[154], K. Belotskiy[100], O. Beltramello[32],
N.L. Belyaev[100], O. Benary[155,*], D. Benchekroun[137a], M. Bender[102], K. Bendtz[148a,148b],
N. Benekos[10], Y. Benhammou[155], E. Benhar Noccioli[179], J. Benitez[66], D.P. Benjamin[48],
M. Benoit[52], J.R. Bensinger[25], S. Bentvelsen[109], L. Beresford[122], M. Beretta[50], D. Berge[109],
E. Bergeaas Kuutmann[168], N. Berger[5], J. Beringer[16], S. Berlendis[58], N.R. Bernard[89],
G. Bernardi[83], C. Bernius[145], F.U. Bernlochner[23], T. Berry[80], P. Berta[131], C. Bertella[35a],
G. Bertoli[148a,148b], F. Bertolucci[126a,126b], I.A. Bertram[75], C. Bertsche[45], D. Bertsche[115],
G.J. Besjes[39], O. Bessidskaia Bylund[148a,148b], M. Bessner[45], N. Besson[138], C. Betancourt[51],
A. Bethani[87], S. Bethke[103], A.J. Bevan[79], J. Beyer[103], R.M. Bianchi[127], O. Biebel[102],
D. Biedermann[17], R. Bielski[87], K. Bierwagen[86], N.V. Biesuz[126a,126b], M. Biglietti[136a],
T.R.V. Billoud[97], H. Bilokon[50], M. Bindi[57], A. Bingul[20b], C. Bini[134a,134b], S. Biondi[22a,22b],

T. Bisanz[57], C. Bittrich[47], D.M. Bjergaard[48], C.W. Black[152], J.E. Black[145], K.M. Black[24],
R.E. Blair[6], T. Blazek[146a], I. Bloch[45], C. Blocker[25], A. Blue[56], W. Blum[86,*], U. Blumenschein[79],
S. Blunier[34a], G.J. Bobbink[109], V.S. Bobrovnikov[111,c], S.S. Bocchetta[84], A. Bocci[48], C. Bock[102],
M. Boehler[51], D. Boerner[178], D. Bogavac[102], A.G. Bogdanchikov[111], C. Bohm[148a], V. Boisvert[80],
P. Bokan[168,i], T. Bold[41a], A.S. Boldyrev[101], A.E. Bolz[60b], M. Bomben[83], M. Bona[79],
M. Boonekamp[138], A. Borisov[132], G. Borissov[75], J. Bortfeldt[32], D. Bortoletto[122],
V. Bortolotto[62a,62b,62c], D. Boscherini[22a], M. Bosman[13], J.D. Bossio Sola[29], J. Boudreau[127],
J. Bouffard[2], E.V. Bouhova-Thacker[75], D. Boumediene[37], C. Bourdarios[119], S.K. Boutle[56],
A. Boveia[113], J. Boyd[32], I.R. Boyko[68], J. Bracinik[19], A. Brandt[8], G. Brandt[57], O. Brandt[60a],
U. Bratzler[158], B. Brau[89], J.E. Brau[118], W.D. Breaden Madden[56], K. Brendlinger[45],
A.J. Brennan[91], L. Brenner[109], R. Brenner[168], S. Bressler[175], D.L. Briglin[19], T.M. Bristow[49],
D. Britton[56], D. Britzger[45], F.M. Brochu[30], I. Brock[23], R. Brock[93], G. Brooijmans[38], T. Brooks[80],
W.K. Brooks[34b], J. Brosamer[16], E. Brost[110], J.H Broughton[19], P.A. Bruckman de Renstrom[42],
D. Bruncko[146b], A. Bruni[22a], G. Bruni[22a], L.S. Bruni[109], BH Brunt[30], M. Bruschi[22a],
N. Bruscino[23], P. Bryant[33], L. Bryngemark[45], T. Buanes[15], Q. Buat[144], P. Buchholz[143],
A.G. Buckley[56], I.A. Budagov[68], F. Buehrer[51], M.K. Bugge[121], O. Bulekov[100], D. Bullock[8],
T.J. Burch[110], S. Burdin[77], C.D. Burgard[51], A.M. Burger[5], B. Burghgrave[110], K. Burka[42],
S. Burke[133], I. Burmeister[46], J.T.P. Burr[122], E. Busato[37], D. Büscher[51], V. Büscher[86],
P. Bussey[56], J.M. Butler[24], C.M. Buttar[56], J.M. Butterworth[81], P. Butti[32], W. Buttinger[27],
A. Buzatu[35c], A.R. Buzykaev[111,c], S. Cabrera Urbán[170], D. Caforio[130], V.M. Cairo[40a,40b],
O. Cakir[4a], N. Calace[52], P. Calafiura[16], A. Calandri[88], G. Calderini[83], P. Calfayan[64],
G. Callea[40a,40b], L.P. Caloba[26a], S. Calvente Lopez[85], D. Calvet[37], S. Calvet[37], T.P. Calvet[88],
R. Camacho Toro[33], S. Camarda[32], P. Camarri[135a,135b], D. Cameron[121],
R. Caminal Armadans[169], C. Camincher[58], S. Campana[32], M. Campanelli[81], A. Camplani[94a,94b],
A. Campoverde[143], V. Canale[106a,106b], M. Cano Bret[36c], J. Cantero[116], T. Cao[155],
M.D.M. Capeans Garrido[32], I. Caprini[28b], M. Caprini[28b], M. Capua[40a,40b], R.M. Carbone[38],
R. Cardarelli[135a], F. Cardillo[51], I. Carli[131], T. Carli[32], G. Carlino[106a], B.T. Carlson[127],
L. Carminati[94a,94b], R.M.D. Carney[148a,148b], S. Caron[108], E. Carquin[34b], S. Carrá[94a,94b],
G.D. Carrillo-Montoya[32], J. Carvalho[128a,128c], D. Casadei[19], M.P. Casado[13,j], M. Casolino[13],
D.W. Casper[166], R. Castelijn[109], V. Castillo Gimenez[170], N.F. Castro[128a,k], A. Catinaccio[32],
J.R. Catmore[121], A. Cattai[32], J. Caudron[23], V. Cavaliere[169], E. Cavallaro[13], D. Cavalli[94a],
M. Cavalli-Sforza[13], V. Cavasinni[126a,126b], E. Celebi[20d], F. Ceradini[136a,136b], L. Cerda Alberich[170],
A.S. Cerqueira[26b], A. Cerri[151], L. Cerrito[135a,135b], F. Cerutti[16], A. Cervelli[18], S.A. Cetin[20d],
A. Chafaq[137a], D. Chakraborty[110], S.K. Chan[59], W.S. Chan[109], Y.L. Chan[62a], P. Chang[169],
J.D. Chapman[30], D.G. Charlton[19], C.C. Chau[161], C.A. Chavez Barajas[151], S. Che[113],
S. Cheatham[167a,167c], A. Chegwidden[93], S. Chekanov[6], S.V. Chekulaev[163a], G.A. Chelkov[68,l],
M.A. Chelstowska[32], C. Chen[67], H. Chen[27], J. Chen[36a], S. Chen[35b], S. Chen[157], X. Chen[35c,m],
Y. Chen[70], H.C. Cheng[92], H.J. Cheng[35a], A. Cheplakov[68], E. Cheremushkina[132],
R. Cherkaoui El Moursli[137e], E. Cheu[7], K. Cheung[63], L. Chevalier[138], V. Chiarella[50],
G. Chiarelli[126a,126b], G. Chiodini[76a], A.S. Chisholm[32], A. Chitan[28b], Y.H. Chiu[172],
M.V. Chizhov[68], K. Choi[64], A.R. Chomont[37], S. Chouridou[156], V. Christodoulou[81],
D. Chromek-Burckhart[32], M.C. Chu[62a], J. Chudoba[129], A.J. Chuinard[90], J.J. Chwastowski[42],
L. Chytka[117], A.K. Ciftci[4a], D. Cinca[46], V. Cindro[78], I.A. Cioara[23], C. Ciocca[22a,22b], A. Ciocio[16],
F. Cirotto[106a,106b], Z.H. Citron[175], M. Citterio[94a], M. Ciubancan[28b], A. Clark[52], B.L. Clark[59],
M.R. Clark[38], P.J. Clark[49], R.N. Clarke[16], C. Clement[148a,148b], Y. Coadou[88], M. Cobal[167a,167c],
A. Coccaro[52], J. Cochran[67], L. Colasurdo[108], B. Cole[38], A.P. Colijn[109], J. Collot[58],
T. Colombo[166], P. Conde Muiño[128a,128b], E. Coniavitis[51], S.H. Connell[147b], I.A. Connelly[87],
S. Constantinescu[28b], G. Conti[32], F. Conventi[106a,n], M. Cooke[16], A.M. Cooper-Sarkar[122],

F. Cormier[171], K.J.R. Cormier[161], M. Corradi[134a,134b], F. Corriveau[90,o], A. Cortes-Gonzalez[32],
G. Cortiana[103], G. Costa[94a], M.J. Costa[170], D. Costanzo[141], G. Cottin[30], G. Cowan[80],
B.E. Cox[87], K. Cranmer[112], S.J. Crawley[56], R.A. Creager[124], G. Cree[31], S. Crépé-Renaudin[58],
F. Crescioli[83], W.A. Cribbs[148a,148b], M. Cristinziani[23], V. Croft[108], G. Crosetti[40a,40b], A. Cueto[85],
T. Cuhadar Donszelmann[141], A.R. Cukierman[145], J. Cummings[179], M. Curatolo[50], J. Cúth[86],
S. Czekierda[42], P. Czodrowski[32], G. D'amen[22a,22b], S. D'Auria[56], L. D'eramo[83], M. D'Onofrio[77],
M.J. Da Cunha Sargedas De Sousa[128a,128b], C. Da Via[87], W. Dabrowski[41a], T. Dado[146a],
T. Dai[92], O. Dale[15], F. Dallaire[97], C. Dallapiccola[89], M. Dam[39], J.R. Dandoy[124], M.F. Daneri[29],
N.P. Dang[176], A.C. Daniells[19], N.S. Dann[87], M. Danninger[171], M. Dano Hoffmann[138], V. Dao[150],
G. Darbo[53a], S. Darmora[8], J. Dassoulas[3], A. Dattagupta[118], T. Daubney[45], W. Davey[23],
C. David[45], T. Davidek[131], D.R. Davis[48], P. Davison[81], E. Dawe[91], I. Dawson[141], K. De[8],
R. de Asmundis[106a], A. De Benedetti[115], S. De Castro[22a,22b], S. De Cecco[83], N. De Groot[108],
P. de Jong[109], H. De la Torre[93], F. De Lorenzi[67], A. De Maria[57], D. De Pedis[134a],
A. De Salvo[134a], U. De Sanctis[135a,135b], A. De Santo[151], K. De Vasconcelos Corga[88],
J.B. De Vivie De Regie[119], W.J. Dearnaley[75], R. Debbe[27], C. Debenedetti[139], D.V. Dedovich[68],
N. Dehghanian[3], I. Deigaard[109], M. Del Gaudio[40a,40b], J. Del Peso[85], D. Delgove[119], F. Deliot[138],
C.M. Delitzsch[7], A. Dell'Acqua[32], L. Dell'Asta[24], M. Dell'Orso[126a,126b], M. Della Pietra[106a,106b],
D. della Volpe[52], M. Delmastro[5], C. Delporte[119], P.A. Delsart[58], D.A. DeMarco[161], S. Demers[179],
M. Demichev[68], A. Demilly[83], S.P. Denisov[132], D. Denysiuk[138], D. Derendarz[42],
J.E. Derkaoui[137d], F. Derue[83], P. Dervan[77], K. Desch[23], C. Deterre[45], K. Dette[46], M.R. Devesa[29],
P.O. Deviveiros[32], A. Dewhurst[133], S. Dhaliwal[25], F.A. Di Bello[52], A. Di Ciaccio[135a,135b],
L. Di Ciaccio[5], W.K. Di Clemente[124], C. Di Donato[106a,106b], A. Di Girolamo[32], B. Di Girolamo[32],
B. Di Micco[136a,136b], R. Di Nardo[32], K.F. Di Petrillo[59], A. Di Simone[51], R. Di Sipio[161],
D. Di Valentino[31], C. Diaconu[88], M. Diamond[161], F.A. Dias[39], M.A. Diaz[34a], E.B. Diehl[92],
J. Dietrich[17], S. Díez Cornell[45], A. Dimitrievska[14], J. Dingfelder[23], P. Dita[28b], S. Dita[28b],
F. Dittus[32], F. Djama[88], T. Djobava[54b], J.I. Djuvsland[60a], M.A.B. do Vale[26c], D. Dobos[32],
M. Dobre[28b], C. Doglioni[84], J. Dolejsi[131], Z. Dolezal[131], M. Donadelli[26d], S. Donati[126a,126b],
P. Dondero[123a,123b], J. Donini[37], J. Dopke[133], A. Doria[106a], M.T. Dova[74], A.T. Doyle[56],
E. Drechsler[57], M. Dris[10], Y. Du[36b], J. Duarte-Campderros[155], A. Dubreuil[52], E. Duchovni[175],
G. Duckeck[102], A. Ducourthial[83], O.A. Ducu[97,p], D. Duda[109], A. Dudarev[32], A.Chr. Dudder[86],
E.M. Duffield[16], L. Duflot[119], M. Dührssen[32], M. Dumancic[175], A.E. Dumitriu[28b],
A.K. Duncan[56], M. Dunford[60a], H. Duran Yildiz[4a], M. Düren[55], A. Durglishvili[54b],
D. Duschinger[47], B. Dutta[45], D. Duvnjak[1], B.S. Dziedzic[42], C. Eckardt[45],
K.M. Ecker[103], R.C. Edgar[92], T. Eifert[32], G. Eigen[15], K. Einsweiler[16], T. Ekelof[168],
M. El Kacimi[137c], R. El Kosseifi[88], V. Ellajosyula[88], M. Ellert[168], S. Elles[5], F. Ellinghaus[178],
A.A. Elliot[172], N. Ellis[32], J. Elmsheuser[27], M. Elsing[32], D. Emeliyanov[133], Y. Enari[157],
O.C. Endner[86], J.S. Ennis[173], J. Erdmann[46], A. Ereditato[18], M. Ernst[27], S. Errede[169],
M. Escalier[119], C. Escobar[170], B. Esposito[50], O. Estrada Pastor[170], A.I. Etienvre[138], E. Etzion[155],
H. Evans[64], A. Ezhilov[125], M. Ezzi[137e], F. Fabbri[22a,22b], L. Fabbri[22a,22b], V. Fabiani[108],
G. Facini[81], R.M. Fakhrutdinov[132], S. Falciano[134a], R.J. Falla[81], J. Faltova[32], Y. Fang[35a],
M. Fanti[94a,94b], A. Farbin[8], A. Farilla[136a], C. Farina[127], E.M. Farina[123a,123b], T. Farooque[93],
S. Farrell[16], S.M. Farrington[173], P. Farthouat[32], F. Fassi[137e], P. Fassnacht[32], D. Fassouliotis[9],
M. Faucci Giannelli[80], A. Favareto[53a,53b], W.J. Fawcett[122], L. Fayard[119], O.L. Fedin[125,q],
W. Fedorko[171], S. Feigl[121], L. Feligioni[88], C. Feng[36b], E.J. Feng[32], H. Feng[92], M.J. Fenton[56],
A.B. Fenyuk[132], L. Feremenga[8], P. Fernandez Martinez[170], S. Fernandez Perez[13], J. Ferrando[45],
A. Ferrari[168], P. Ferrari[109], R. Ferrari[123a], D.E. Ferreira de Lima[60b], A. Ferrer[170], D. Ferrere[52],
C. Ferretti[92], F. Fiedler[86], A. Filipčič[78], M. Filipuzzi[45], F. Filthaut[108], M. Fincke-Keeler[172],
K.D. Finelli[152], M.C.N. Fiolhais[128a,128c,r], L. Fiorini[170], A. Fischer[2], C. Fischer[13], J. Fischer[178],

31

W.C. Fisher[93], N. Flaschel[45], I. Fleck[143], P. Fleischmann[92], R.R.M. Fletcher[124], T. Flick[178],
B.M. Flierl[102], L.R. Flores Castillo[62a], M.J. Flowerdew[103], G.T. Forcolin[87], A. Formica[138],
F.A. Förster[13], A. Forti[87], A.G. Foster[19], D. Fournier[119], H. Fox[75], S. Fracchia[141],
P. Francavilla[83], M. Franchini[22a,22b], S. Franchino[60a], D. Francis[32], L. Franconi[121], M. Franklin[59],
M. Frate[166], M. Fraternali[123a,123b], D. Freeborn[81], S.M. Fressard-Batraneanu[32], B. Freund[97],
D. Froidevaux[32], J.A. Frost[122], C. Fukunaga[158], T. Fusayasu[104], J. Fuster[170], C. Gabaldon[58],
O. Gabizon[154], A. Gabrielli[22a,22b], A. Gabrielli[16], G.P. Gach[41a], S. Gadatsch[32], S. Gadomski[80],
G. Gagliardi[53a,53b], L.G. Gagnon[97], C. Galea[108], B. Galhardo[128a,128c], E.J. Gallas[122],
B.J. Gallop[133], P. Gallus[130], G. Galster[39], K.K. Gan[113], S. Ganguly[37], Y. Gao[77], Y.S. Gao[145,g],
F.M. Garay Walls[49], C. García[170], J.E. García Navarro[170], J.A. García Pascual[35a],
M. Garcia-Sciveres[16], R.W. Gardner[33], N. Garelli[145], V. Garonne[121], A. Gascon Bravo[45],
K. Gasnikova[45], C. Gatti[50], A. Gaudiello[53a,53b], G. Gaudio[123a], I.L. Gavrilenko[98], C. Gay[171],
G. Gaycken[23], E.N. Gazis[10], C.N.P. Gee[133], J. Geisen[57], M. Geisen[86], M.P. Geisler[60a],
K. Gellerstedt[148a,148b], C. Gemme[53a], M.H. Genest[58], C. Geng[92], S. Gentile[134a,134b],
C. Gentsos[156], S. George[80], D. Gerbaudo[13], A. Gershon[155], G. Geßner[46], S. Ghasemi[143],
M. Ghneimat[23], B. Giacobbe[22a], S. Giagu[134a,134b], N. Giangiacomi[22a,22b], P. Giannetti[126a,126b],
S.M. Gibson[80], M. Gignac[171], M. Gilchriese[16], D. Gillberg[31], G. Gilles[178], D.M. Gingrich[3,d],
N. Giokaris[9,*], M.P. Giordani[167a,167c], F.M. Giorgi[22a], P.F. Giraud[138], P. Giromini[59],
G. Giugliarelli[167a,167c], D. Giugni[94a], F. Giuli[122], C. Giuliani[103], M. Giulini[60b], B.K. Gjelsten[121],
S. Gkaitatzis[156], I. Gkialas[9,s], E.L. Gkougkousis[139], P. Gkountoumis[10], L.K. Gladilin[101],
C. Glasman[85], J. Glatzer[13], P.C.F. Glaysher[45], A. Glazov[45], M. Goblirsch-Kolb[25], J. Godlewski[42],
S. Goldfarb[91], T. Golling[52], D. Golubkov[132], A. Gomes[128a,128b,128d], R. Gonçalo[128a],
R. Goncalves Gama[26a], J. Goncalves Pinto Firmino Da Costa[138], G. Gonella[51], L. Gonella[19],
A. Gongadze[68], S. González de la Hoz[170], S. Gonzalez-Sevilla[52], L. Goossens[32],
P.A. Gorbounov[99], H.A. Gordon[27], I. Gorelov[107], B. Gorini[32], E. Gorini[76a,76b], A. Gorišek[78],
A.T. Goshaw[48], C. Gössling[46], M.I. Gostkin[68], C.A. Gottardo[23], C.R. Goudet[119],
D. Goujdami[137c], A.G. Goussiou[140], N. Govender[147b,t], E. Gozani[154], L. Graber[57],
I. Grabowska-Bold[41a], P.O.J. Gradin[168], J. Gramling[166], E. Gramstad[121], S. Grancagnolo[17],
V. Gratchev[125], P.M. Gravila[28f], C. Gray[56], H.M. Gray[16], Z.D. Greenwood[82,u], C. Grefe[23],
K. Gregersen[81], I.M. Gregor[45], P. Grenier[145], K. Grevtsov[5], J. Griffiths[8], A.A. Grillo[139],
K. Grimm[75], S. Grinstein[13,v], Ph. Gris[37], J.-F. Grivaz[119], S. Groh[86], E. Gross[175],
J. Grosse-Knetter[57], G.C. Grossi[82], Z.J. Grout[81], A. Grummer[107], L. Guan[92], W. Guan[176],
J. Guenther[65], F. Guescini[163a], D. Guest[166], O. Gueta[155], B. Gui[113], E. Guido[53a,53b],
T. Guillemin[5], S. Guindon[2], U. Gul[56], C. Gumpert[32], J. Guo[36c], W. Guo[92], Y. Guo[36a],
R. Gupta[43], S. Gupta[122], G. Gustavino[134a,134b], P. Gutierrez[115], N.G. Gutierrez Ortiz[81],
C. Gutschow[81], C. Guyot[138], M.P. Guzik[41a], C. Gwenlan[122], C.B. Gwilliam[77], A. Haas[112],
C. Haber[16], H.K. Hadavand[8], N. Haddad[137e], A. Hadef[88], S. Hageböck[23], M. Hagihara[164],
H. Hakobyan[180,*], M. Haleem[45], J. Haley[116], G. Halladjian[93], G.D. Hallewell[88], K. Hamacher[178],
P. Hamal[117], K. Hamano[172], A. Hamilton[147a], G.N. Hamity[141], P.G. Hamnett[45], L. Han[36a],
S. Han[35a], K. Hanagaki[69,w], K. Hanawa[157], M. Hance[139], B. Haney[124], P. Hanke[60a],
J.B. Hansen[39], J.D. Hansen[39], M.C. Hansen[23], P.H. Hansen[39], K. Hara[164], A.S. Hard[176],
T. Harenberg[178], F. Hariri[119], S. Harkusha[95], R.D. Harrington[49], P.F. Harrison[173],
N.M. Hartmann[102], M. Hasegawa[70], Y. Hasegawa[142], A. Hasib[49], S. Hassani[138], S. Haug[18],
R. Hauser[93], L. Hauswald[47], L.B. Havener[38], M. Havranek[130], C.M. Hawkes[19], R.J. Hawkings[32],
D. Hayakawa[159], D. Hayden[93], C.P. Hays[122], J.M. Hays[79], H.S. Hayward[77], S.J. Haywood[133],
S.J. Head[19], T. Heck[86], V. Hedberg[84], L. Heelan[8], S. Heer[23], K.K. Heidegger[51], S. Heim[45],
T. Heim[16], B. Heinemann[45,x], J.J. Heinrich[102], L. Heinrich[112], C. Heinz[55], J. Hejbal[129],
L. Helary[32], A. Held[171], S. Hellman[148a,148b], C. Helsens[32], R.C.W. Henderson[75], Y. Heng[176],

S. Henkelmann[171], A.M. Henriques Correia[32], S. Henrot-Versille[119], G.H. Herbert[17], H. Herde[25],
V. Herget[177], Y. Hernández Jiménez[147c], H. Herr[86], G. Herten[51], R. Hertenberger[102], L. Hervas[32],
T.C. Herwig[124], G.G. Hesketh[81], N.P. Hessey[163a], J.W. Hetherly[43], S. Higashino[69],
E. Higón-Rodriguez[170], K. Hildebrand[33], E. Hill[172], J.C. Hill[30], K.H. Hiller[45], S.J. Hillier[19],
M. Hils[47], I. Hinchliffe[16], M. Hirose[51], D. Hirschbuehl[178], B. Hiti[78], O. Hladik[129], X. Hoad[49],
J. Hobbs[150], N. Hod[163a], M.C. Hodgkinson[141], P. Hodgson[141], A. Hoecker[32], M.R. Hoeferkamp[107],
F. Hoenig[102], D. Hohn[23], T.R. Holmes[33], M. Homann[46], S. Honda[164], T. Honda[69], T.M. Hong[127],
B.H. Hooberman[169], W.H. Hopkins[118], Y. Horii[105], A.J. Horton[144], J-Y. Hostachy[58], S. Hou[153],
A. Hoummada[137a], J. Howarth[87], J. Hoya[74], M. Hrabovsky[117], J. Hrdinka[32], I. Hristova[17],
J. Hrivnac[119], T. Hryn'ova[5], A. Hrynevich[96], P.J. Hsu[63], S.-C. Hsu[140], Q. Hu[36a], S. Hu[36c],
Y. Huang[35a], Z. Hubacek[130], F. Hubaut[88], F. Huegging[23], T.B. Huffman[122], E.W. Hughes[38],
G. Hughes[75], M. Huhtinen[32], P. Huo[150], N. Huseynov[68,b], J. Huston[93], J. Huth[59], G. Iacobucci[52],
G. Iakovidis[27], I. Ibragimov[143], L. Iconomidou-Fayard[119], Z. Idrissi[137e], P. Iengo[32],
O. Igonkina[109,y], T. Iizawa[174], Y. Ikegami[69], M. Ikeno[69], Y. Ilchenko[11,z], D. Iliadis[156], N. Ilic[145],
G. Introzzi[123a,123b], P. Ioannou[9,*], M. Iodice[136a], K. Iordanidou[38], V. Ippolito[59], M.F. Isacson[168],
N. Ishijima[120], M. Ishino[157], M. Ishitsuka[159], C. Issever[122], S. Istin[20a], F. Ito[164],
J.M. Iturbe Ponce[62a], R. Iuppa[162a,162b], H. Iwasaki[69], J.M. Izen[44], V. Izzo[106a], S. Jabbar[3],
P. Jackson[1], R.M. Jacobs[23], V. Jain[2], K.B. Jakobi[86], K. Jakobs[51], S. Jakobsen[65], T. Jakoubek[129],
D.O. Jamin[116], D.K. Jana[82], R. Jansky[52], J. Janssen[23], M. Janus[57], P.A. Janus[41a], G. Jarlskog[84],
N. Javadov[68,b], T. Javůrek[51], M. Javurkova[51], F. Jeanneau[138], L. Jeanty[16], J. Jejelava[54a,aa],
A. Jelinskas[173], P. Jenni[51,ab], C. Jeske[173], S. Jézéquel[5], H. Ji[176], J. Jia[150], H. Jiang[67], Y. Jiang[36a],
Z. Jiang[145], S. Jiggins[81], J. Jimenez Pena[170], S. Jin[35a], A. Jinaru[28b], O. Jinnouchi[159], H. Jivan[147c],
P. Johansson[141], K.A. Johns[7], C.A. Johnson[64], W.J. Johnson[140], K. Jon-And[148a,148b],
R.W.L. Jones[75], S.D. Jones[151], S. Jones[7], T.J. Jones[77], J. Jongmanns[60a], P.M. Jorge[128a,128b],
J. Jovicevic[163a], X. Ju[176], A. Juste Rozas[13,v], M.K. Köhler[175], A. Kaczmarska[42], M. Kado[119],
H. Kagan[113], M. Kagan[145], S.J. Kahn[88], T. Kaji[174], E. Kajomovitz[48], C.W. Kalderon[84],
A. Kaluza[86], S. Kama[43], A. Kamenshchikov[132], N. Kanaya[157], L. Kanjir[78], V.A. Kantserov[100],
J. Kanzaki[69], B. Kaplan[112], L.S. Kaplan[176], D. Kar[147c], K. Karakostas[10], N. Karastathis[10],
M.J. Kareem[57], E. Karentzos[10], S.N. Karpov[68], Z.M. Karpova[68], K. Karthik[112],
V. Kartvelishvili[75], A.N. Karyukhin[132], K. Kasahara[164], L. Kashif[176], R.D. Kass[113],
A. Kastanas[149], Y. Kataoka[157], C. Kato[157], A. Katre[52], J. Katzy[45], K. Kawade[70], K. Kawagoe[73],
T. Kawamoto[157], G. Kawamura[57], E.F. Kay[77], V.F. Kazanin[111,c], R. Keeler[172], R. Kehoe[43],
J.S. Keller[31], J.J. Kempster[80], J Kendrick[19], H. Keoshkerian[161], O. Kepka[129], B.P. Kerševan[78],
S. Kersten[178], R.A. Keyes[90], M. Khader[169], F. Khalil-zada[12], A. Khanov[116], A.G. Kharlamov[111,c],
T. Kharlamova[111,c], A. Khodinov[160], T.J. Khoo[52], V. Khovanskiy[99,*], E. Khramov[68],
J. Khubua[54b,ac], S. Kido[70], C.R. Kilby[80], H.Y. Kim[8], S.H. Kim[164], Y.K. Kim[33], N. Kimura[156],
O.M. Kind[17], B.T. King[77], D. Kirchmeier[47], J. Kirk[133], A.E. Kiryunin[103], T. Kishimoto[157],
D. Kisielewska[41a], V. Kitali[45], K. Kiuchi[164], O. Kivernyk[5], E. Kladiva[146b],
T. Klapdor-Kleingrothaus[51], M.H. Klein[92], M. Klein[77], U. Klein[77], K. Kleinknecht[86],
P. Klimek[110], A. Klimentov[27], R. Klingenberg[46], T. Klingl[23], T. Klioutchnikova[32], E.-E. Kluge[60a],
P. Kluit[109], S. Kluth[103], E. Kneringer[65], E.B.F.G. Knoops[88], A. Knue[103], A. Kobayashi[157],
D. Kobayashi[159], T. Kobayashi[157], M. Kobel[47], M. Kocian[145], P. Kodys[131], T. Koffas[31],
E. Koffeman[109], N.M. Köhler[103], T. Koi[145], M. Kolb[60b], I. Koletsou[5], A.A. Komar[98,*],
Y. Komori[157], T. Kondo[69], N. Kondrashova[36c], K. Köneke[51], A.C. König[108], T. Kono[69,ad],
R. Konoplich[112,ae], N. Konstantinidis[81], R. Kopeliansky[64], S. Koperny[41a], A.K. Kopp[51],
K. Korcyl[42], K. Kordas[156], A. Korn[81], A.A. Korol[111,c], I. Korolkov[13], E.V. Korolkova[141],
O. Kortner[103], S. Kortner[103], T. Kosek[131], V.V. Kostyukhin[23], A. Kotwal[48], A. Koulouris[10],
A. Kourkoumeli-Charalampidi[123a,123b], C. Kourkoumelis[9], E. Kourlitis[141], V. Kouskoura[27],

A.B. Kowalewska[42], R. Kowalewski[172], T.Z. Kowalski[41a], C. Kozakai[157], W. Kozanecki[138],
A.S. Kozhin[132], V.A. Kramarenko[101], G. Kramberger[78], D. Krasnopevtsev[100], M.W. Krasny[83],
A. Krasznahorkay[32], D. Krauss[103], J.A. Kremer[41a], J. Kretzschmar[77], K. Kreutzfeldt[55],
P. Krieger[161], K. Krizka[33], K. Kroeninger[46], H. Kroha[103], J. Kroll[129], J. Kroll[124], J. Kroseberg[23],
J. Krstic[14], U. Kruchonak[68], H. Krüger[23], N. Krumnack[67], M.C. Kruse[48], T. Kubota[91],
H. Kucuk[81], S. Kuday[4b], J.T. Kuechler[178], S. Kuehn[32], A. Kugel[60a], F. Kuger[177], T. Kuhl[45],
V. Kukhtin[68], R. Kukla[88], Y. Kulchitsky[95], S. Kuleshov[34b], Y.P. Kulinich[169], M. Kuna[134a,134b],
T. Kunigo[71], A. Kupco[129], T. Kupfer[46], O. Kuprash[155], H. Kurashige[70], L.L. Kurchaninov[163a],
Y.A. Kurochkin[95], M.G. Kurth[35a], V. Kus[129], E.S. Kuwertz[172], M. Kuze[159], J. Kvita[117],
T. Kwan[172], D. Kyriazopoulos[141], A. La Rosa[103], J.L. La Rosa Navarro[26d], L. La Rotonda[40a,40b],
F. La Ruffa[40a,40b], C. Lacasta[170], F. Lacava[134a,134b], J. Lacey[45], H. Lacker[17], D. Lacour[83],
E. Ladygin[68], R. Lafaye[5], B. Laforge[83], T. Lagouri[179], S. Lai[57], S. Lammers[64], W. Lampl[7],
E. Lançon[27], U. Landgraf[51], M.P.J. Landon[79], M.C. Lanfermann[52], V.S. Lang[60a], J.C. Lange[13],
R.J. Langenberg[32], A.J. Lankford[166], F. Lanni[27], K. Lantzsch[23], A. Lanza[123a],
A. Lapertosa[53a,53b], S. Laplace[83], J.F. Laporte[138], T. Lari[94a], F. Lasagni Manghi[22a,22b],
M. Lassnig[32], P. Laurelli[50], W. Lavrijsen[16], A.T. Law[139], P. Laycock[77], T. Lazovich[59],
M. Lazzaroni[94a,94b], B. Le[91], O. Le Dortz[83], E. Le Guirriec[88], E.P. Le Quilleuc[138], M. LeBlanc[172],
T. LeCompte[6], F. Ledroit-Guillon[58], C.A. Lee[27], G.R. Lee[133,af], S.C. Lee[153], L. Lee[59],
B. Lefebvre[90], G. Lefebvre[83], M. Lefebvre[172], F. Legger[102], C. Leggett[16], G. Lehmann Miotto[32],
X. Lei[7], W.A. Leight[45], M.A.L. Leite[26d], R. Leitner[131], D. Lellouch[175], B. Lemmer[57],
K.J.C. Leney[81], T. Lenz[23], B. Lenzi[32], R. Leone[7], S. Leone[126a,126b], C. Leonidopoulos[49],
G. Lerner[151], C. Leroy[97], A.A.J. Lesage[138], C.G. Lester[30], M. Levchenko[125], J. Levêque[5],
D. Levin[92], L.J. Levinson[175], M. Levy[19], D. Lewis[79], B. Li[36a,ag], Changqiao Li[36a], H. Li[150],
L. Li[36c], Q. Li[35a], S. Li[48], X. Li[36c], Y. Li[143], Z. Liang[35a], B. Liberti[135a], A. Liblong[161], K. Lie[62c],
J. Liebal[23], W. Liebig[15], A. Limosani[152], S.C. Lin[182], T.H. Lin[86], R.A. Linck[64], B.E. Lindquist[150],
A.E. Lionti[52], E. Lipeles[124], A. Lipniacka[15], M. Lisovyi[60b], T.M. Liss[169,ah], A. Lister[171],
A.M. Litke[139], B. Liu[153,ai], H. Liu[92], H. Liu[27], J.K.K. Liu[122], J. Liu[36b], J.B. Liu[36a], K. Liu[88],
L. Liu[169], M. Liu[36a], Y.L. Liu[36a], Y. Liu[36a], M. Livan[123a,123b], A. Lleres[58], J. Llorente Merino[35a],
S.L. Lloyd[79], C.Y. Lo[62b], F. Lo Sterzo[153], E.M. Lobodzinska[45], P. Loch[7], F.K. Loebinger[87],
A. Loesle[51], K.M. Loew[25], A. Loginov[179,*], T. Lohse[17], K. Lohwasser[141], M. Lokajicek[129],
B.A. Long[24], J.D. Long[169], R.E. Long[75], L. Longo[76a,76b], K.A. Looper[113], J.A. Lopez[34b],
D. Lopez Mateos[59], I. Lopez Paz[13], A. Lopez Solis[83], J. Lorenz[102], N. Lorenzo Martinez[5],
M. Losada[21], P.J. Lösel[102], X. Lou[35a], A. Lounis[119], J. Love[6], P.A. Love[75], H. Lu[62a], N. Lu[92],
Y.J. Lu[63], H.J. Lubatti[140], C. Luci[134a,134b], A. Lucotte[58], C. Luedtke[51], F. Luehring[64],
W. Lukas[65], L. Luminari[134a], O. Lundberg[148a,148b], B. Lund-Jensen[149], M.S. Lutz[89], P.M. Luzi[83],
D. Lynn[27], R. Lysak[129], E. Lytken[84], F. Lyu[35a], V. Lyubushkin[68], H. Ma[27], L.L. Ma[36b],
Y. Ma[36b], G. Maccarrone[50], A. Macchiolo[103], C.M. Macdonald[141], B. Maček[78],
J. Machado Miguens[124,128b], D. Madaffari[170], R. Madar[37], W.F. Mader[47], A. Madsen[45],
J. Maeda[70], S. Maeland[15], T. Maeno[27], A.S. Maevskiy[101], V. Magerl[51], J. Mahlstedt[109],
C. Maiani[119], C. Maidantchik[26a], A.A. Maier[103], T. Maier[102], A. Maio[128a,128b,128d],
O. Majersky[146a], S. Majewski[118], Y. Makida[69], N. Makovec[119], B. Malaescu[83], Pa. Malecki[42],
V.P. Maleev[125], F. Malek[58], U. Mallik[66], D. Malon[6], C. Malone[30], S. Maltezos[10], S. Malyukov[32],
J. Mamuzic[170], G. Mancini[50], I. Mandić[78], J. Maneira[128a,128b], L. Manhaes de Andrade Filho[26b],
J. Manjarres Ramos[47], K.H. Mankinen[84], A. Mann[102], A. Manousos[32], B. Mansoulie[138],
J.D. Mansour[35a], R. Mantifel[90], M. Mantoani[57], S. Manzoni[94a,94b], L. Mapelli[32], G. Marceca[29],
L. March[52], L. Marchese[122], G. Marchiori[83], M. Marcisovsky[129], M. Marjanovic[37], D.E. Marley[92],
F. Marroquim[26a], S.P. Marsden[87], Z. Marshall[16], M.U.F Martensson[168], S. Marti-Garcia[170],
C.B. Martin[113], T.A. Martin[173], V.J. Martin[49], B. Martin dit Latour[15], M. Martinez[13,v],

V.I. Martinez Outschoorn[169], S. Martin-Haugh[133], V.S. Martoiu[28b], A.C. Martyniuk[81],
A. Marzin[32], L. Masetti[86], T. Mashimo[157], R. Mashinistov[98], J. Masik[87], A.L. Maslennikov[111,c],
L. Massa[135a,135b], P. Mastrandrea[5], A. Mastroberardino[40a,40b], T. Masubuchi[157], P. Mättig[178],
J. Maurer[28b], S.J. Maxfield[77], D.A. Maximov[111,c], R. Mazini[153], I. Maznas[156], S.M. Mazza[94a,94b],
N.C. Mc Fadden[107], G. Mc Goldrick[161], S.P. Mc Kee[92], A. McCarn[92], R.L. McCarthy[150],
T.G. McCarthy[103], L.I. McClymont[81], E.F. McDonald[91], J.A. Mcfayden[81], G. Mchedlidze[57],
S.J. McMahon[133], P.C. McNamara[91], R.A. McPherson[172,o], S. Meehan[140], T.J. Megy[51],
S. Mehlhase[102], A. Mehta[77], T. Meideck[58], K. Meier[60a], B. Meirose[44], D. Melini[170,aj],
B.R. Mellado Garcia[147c], J.D. Mellenthin[57], M. Melo[146a], F. Meloni[18], A. Melzer[23],
S.B. Menary[87], L. Meng[77], X.T. Meng[92], A. Mengarelli[22a,22b], S. Menke[103], E. Meoni[40a,40b],
S. Mergelmeyer[17], C. Merlassino[18], P. Mermod[52], L. Merola[106a,106b], C. Meroni[94a], F.S. Merritt[33],
A. Messina[134a,134b], J. Metcalfe[6], A.S. Mete[166], C. Meyer[124], J-P. Meyer[138], J. Meyer[109],
H. Meyer Zu Theenhausen[60a], F. Miano[151], R.P. Middleton[133], S. Miglioranzi[53a,53b], L. Mijović[49],
G. Mikenberg[175], M. Mikestikova[129], M. Mikuž[78], M. Milesi[91], A. Milic[161], D.W. Miller[33],
C. Mills[49], A. Milov[175], D.A. Milstead[148a,148b], A.A. Minaenko[132], Y. Minami[157],
I.A. Minashvili[68], A.I. Mincer[112], B. Mindur[41a], M. Mineev[68], Y. Minegishi[157], Y. Ming[176],
L.M. Mir[13], K.P. Mistry[124], T. Mitani[174], J. Mitrevski[102], V.A. Mitsou[170], A. Miucci[18],
P.S. Miyagawa[141], A. Mizukami[69], J.U. Mjörnmark[84], T. Mkrtchyan[180], M. Mlynarikova[131],
T. Moa[148a,148b], K. Mochizuki[97], P. Mogg[51], S. Mohapatra[38], S. Molander[148a,148b],
R. Moles-Valls[23], R. Monden[71], M.C. Mondragon[93], K. Mönig[45], J. Monk[39], E. Monnier[88],
A. Montalbano[150], J. Montejo Berlingen[32], F. Monticelli[74], S. Monzani[94a,94b], R.W. Moore[3],
N. Morange[119], D. Moreno[21], M. Moreno Llácer[32], P. Morettini[53a], S. Morgenstern[32], D. Mori[144],
T. Mori[157], M. Morii[59], M. Morinaga[157], V. Morisbak[121], A.K. Morley[32], G. Mornacchi[32],
J.D. Morris[79], L. Morvaj[150], P. Moschovakos[10], M. Mosidze[54b], H.J. Moss[141], J. Moss[145,ak],
K. Motohashi[159], R. Mount[145], E. Mountricha[27], E.J.W. Moyse[89], S. Muanza[88], F. Mueller[103],
J. Mueller[127], R.S.P. Mueller[102], D. Muenstermann[75], P. Mullen[56], G.A. Mullier[18],
F.J. Munoz Sanchez[87], W.J. Murray[173,133], H. Musheghyan[32], M. Muškinja[78],
A.G. Myagkov[132,al], M. Myska[130], B.P. Nachman[16], O. Nackenhorst[52], K. Nagai[122],
R. Nagai[69,ad], K. Nagano[69], Y. Nagasaka[61], K. Nagata[164], M. Nagel[51], E. Nagy[88], A.M. Nairz[32],
Y. Nakahama[105], K. Nakamura[69], T. Nakamura[157], I. Nakano[114], R.F. Naranjo Garcia[45],
R. Narayan[11], D.I. Narrias Villar[60a], I. Naryshkin[125], T. Naumann[45], G. Navarro[21], R. Nayyar[7],
H.A. Neal[92], P.Yu. Nechaeva[98], T.J. Neep[138], A. Negri[123a,123b], M. Negrini[22a], S. Nektarijevic[108],
C. Nellist[119], A. Nelson[166], M.E. Nelson[122], S. Nemecek[129], P. Nemethy[112], M. Nessi[32,am],
M.S. Neubauer[169], M. Neumann[178], P.R. Newman[19], T.Y. Ng[62c], T. Nguyen Manh[97],
R.B. Nickerson[122], R. Nicolaidou[138], J. Nielsen[139], V. Nikolaenko[132,al], I. Nikolic-Audit[83],
K. Nikolopoulos[19], J.K. Nilsen[121], P. Nilsson[27], Y. Ninomiya[157], A. Nisati[134a], N. Nishu[35c],
R. Nisius[103], I. Nitsche[46], T. Nitta[174], T. Nobe[157], Y. Noguchi[71], M. Nomachi[120], I. Nomidis[31],
M.A. Nomura[27], T. Nooney[79], M. Nordberg[32], N. Norjoharuddeen[122], O. Novgorodova[47],
M. Nozaki[69], L. Nozka[117], K. Ntekas[166], E. Nurse[81], F. Nuti[91], K. O'connor[25], D.C. O'Neil[144],
A.A. O'Rourke[45], V. O'Shea[56], F.G. Oakham[31,d], H. Oberlack[103], T. Obermann[23], J. Ocariz[83],
A. Ochi[70], I. Ochoa[38], J.P. Ochoa-Ricoux[34a], S. Oda[73], S. Odaka[69], A. Oh[87], S.H. Oh[48],
C.C. Ohm[16], H. Ohman[168], H. Oide[53a,53b], H. Okawa[164], Y. Okumura[157], T. Okuyama[69],
A. Olariu[28b], L.F. Oleiro Seabra[128a], S.A. Olivares Pino[34a], D. Oliveira Damazio[27],
A. Olszewski[42], J. Olszowska[42], A. Onofre[128a,128e], K. Onogi[105], P.U.E. Onyisi[11,z], H. Oppen[121],
M.J. Oreglia[33], Y. Oren[155], D. Orestano[136a,136b], N. Orlando[62b], R.S. Orr[161], B. Osculati[53a,53b,*],
R. Ospanov[36a], G. Otero y Garzon[29], H. Otono[73], M. Ouchrif[137d], F. Ould-Saada[121],
A. Ouraou[138], K.P. Oussoren[109], Q. Ouyang[35a], M. Owen[56], R.E. Owen[19], V.E. Ozcan[20a],
N. Ozturk[8], K. Pachal[144], A. Pacheco Pages[13], L. Pacheco Rodriguez[138], C. Padilla Aranda[13],

S. Pagan Griso[16], M. Paganini[179], F. Paige[27], G. Palacino[64], S. Palazzo[40a,40b], S. Palestini[32],
M. Palka[41b], D. Pallin[37], E.St. Panagiotopoulou[10], I. Panagoulias[10], C.E. Pandini[126a,126b],
J.G. Panduro Vazquez[80], P. Pani[32], S. Panitkin[27], D. Pantea[28b], L. Paolozzi[52],
Th.D. Papadopoulou[10], K. Papageorgiou[9,s], A. Paramonov[6], D. Paredes Hernandez[179],
A.J. Parker[75], M.A. Parker[30], K.A. Parker[45], F. Parodi[53a,53b], J.A. Parsons[38], U. Parzefall[51],
V.R. Pascuzzi[161], J.M. Pasner[139], E. Pasqualucci[134a], S. Passaggio[53a], Fr. Pastore[80],
S. Pataraia[86], J.R. Pater[87], T. Pauly[32], B. Pearson[103], S. Pedraza Lopez[170], R. Pedro[128a,128b],
S.V. Peleganchuk[111,c], O. Penc[129], C. Peng[35a], H. Peng[36a], J. Penwell[64], B.S. Peralva[26b],
M.M. Perego[138], D.V. Perepelitsa[27], F. Peri[17], L. Perini[94a,94b], H. Pernegger[32],
S. Perrella[106a,106b], R. Peschke[45], V.D. Peshekhonov[68,*], K. Peters[45], R.F.Y. Peters[87],
B.A. Petersen[32], T.C. Petersen[39], E. Petit[58], A. Petridis[1], C. Petridou[156], P. Petroff[119],
E. Petrolo[134a], M. Petrov[122], F. Petrucci[136a,136b], N.E. Pettersson[89], A. Peyaud[138], R. Pezoa[34b],
F.H. Phillips[93], P.W. Phillips[133], G. Piacquadio[150], E. Pianori[173], A. Picazio[89], E. Piccaro[79],
M.A. Pickering[122], R. Piegaia[29], J.E. Pilcher[33], A.D. Pilkington[87], A.W.J. Pin[87],
M. Pinamonti[135a,135b], J.L. Pinfold[3], H. Pirumov[45], M. Pitt[175], L. Plazak[146a], M.-A. Pleier[27],
V. Pleskot[86], E. Plotnikova[68], D. Pluth[67], P. Podberezko[111], R. Poettgen[148a,148b],
R. Poggi[123a,123b], L. Poggioli[119], D. Pohl[23], G. Polesello[123a], A. Poley[45], A. Policicchio[40a,40b],
R. Polifka[32], A. Polini[22a], C.S. Pollard[56], V. Polychronakos[27], K. Pommès[32], D. Ponomarenko[100],
L. Pontecorvo[134a], G.A. Popeneciu[28d], A. Poppleton[32], S. Pospisil[130], K. Potamianos[16],
I.N. Potrap[68], C.J. Potter[30], G. Poulard[32], T. Poulsen[84], J. Poveda[32], M.E. Pozo Astigarraga[32],
P. Pralavorio[88], A. Pranko[16], S. Prell[67], D. Price[87], M. Primavera[76a], S. Prince[90], N. Proklova[100],
K. Prokofiev[62c], F. Prokoshin[34b], S. Protopopescu[27], J. Proudfoot[6], M. Przybycien[41a], A. Puri[169],
P. Puzo[119], J. Qian[92], G. Qin[56], Y. Qin[87], A. Quadt[57], M. Queitsch-Maitland[45], D. Quilty[56],
S. Raddum[121], V. Radeka[27], V. Radescu[122], S.K. Radhakrishnan[150], P. Radloff[118], P. Rados[91],
F. Ragusa[94a,94b], G. Rahal[181], J.A. Raine[87], S. Rajagopalan[27], C. Rangel-Smith[168], T. Rashid[119],
S. Raspopov[5], M.G. Ratti[94a,94b], D.M. Rauch[45], F. Rauscher[102], S. Rave[86], I. Ravinovich[175],
J.H. Rawling[87], M. Raymond[32], A.L. Read[121], N.P. Readioff[58], M. Reale[76a,76b],
D.M. Rebuzzi[123a,123b], A. Redelbach[177], G. Redlinger[27], R. Reece[139], R.G. Reed[147c], K. Reeves[44],
L. Rehnisch[17], J. Reichert[124], A. Reiss[86], C. Rembser[32], H. Ren[35a], M. Rescigno[134a],
S. Resconi[94a], E.D. Resseguie[124], S. Rettie[171], E. Reynolds[19], O.L. Rezanova[111,c], P. Reznicek[131],
R. Rezvani[97], R. Richter[103], S. Richter[81], E. Richter-Was[41b], O. Ricken[23], M. Ridel[83], P. Rieck[103],
C.J. Riegel[178], J. Rieger[57], O. Rifki[115], M. Rijssenbeek[150], A. Rimoldi[123a,123b], M. Rimoldi[18],
L. Rinaldi[22a], G. Ripellino[149], B. Ristić[32], E. Ritsch[32], I. Riu[13], F. Rizatdinova[116], E. Rizvi[79],
C. Rizzi[13], R.T. Roberts[87], S.H. Robertson[90,o], A. Robichaud-Veronneau[90], D. Robinson[30],
J.E.M. Robinson[45], A. Robson[56], E. Rocco[86], C. Roda[126a,126b], Y. Rodina[88,an],
S. Rodriguez Bosca[170], A. Rodriguez Perez[13], D. Rodriguez Rodriguez[170], S. Roe[32], C.S. Rogan[59],
O. Røhne[121], J. Roloff[59], A. Romaniouk[100], M. Romano[22a,22b], S.M. Romano Saez[37],
E. Romero Adam[170], N. Rompotis[77], M. Ronzani[51], L. Roos[83], S. Rosati[134a], K. Rosbach[51],
P. Rose[139], N.-A. Rosien[57], E. Rossi[106a,106b], L.P. Rossi[53a], J.H.N. Rosten[30], R. Rosten[140],
M. Rotaru[28b], J. Rothberg[140], D. Rousseau[119], A. Rozanov[88], Y. Rozen[154], X. Ruan[147c],
F. Rubbo[145], F. Rühr[51], A. Ruiz-Martinez[31], Z. Rurikova[51], N.A. Rusakovich[68], H.L. Russell[90],
J.P. Rutherfoord[7], N. Ruthmann[32], Y.F. Ryabov[125], M. Rybar[169], G. Rybkin[119], S. Ryu[6],
A. Ryzhov[132], G.F. Rzehorz[57], A.F. Saavedra[152], G. Sabato[109], S. Sacerdoti[29],
H.F-W. Sadrozinski[139], R. Sadykov[68], F. Safai Tehrani[134a], P. Saha[110], M. Sahinsoy[60a],
M. Saimpert[45], M. Saito[157], T. Saito[157], H. Sakamoto[157], Y. Sakurai[174], G. Salamanna[136a,136b],
J.E. Salazar Loyola[34b], D. Salek[109], P.H. Sales De Bruin[168], D. Salihagic[103], A. Salnikov[145],
J. Salt[170], D. Salvatore[40a,40b], F. Salvatore[151], A. Salvucci[62a,62b,62c], A. Salzburger[32],
D. Sammel[51], D. Sampsonidis[156], D. Sampsonidou[156], J. Sánchez[170], V. Sanchez Martinez[170],

A. Sanchez Pineda[167a,167c], H. Sandaker[121], R.L. Sandbach[79], C.O. Sander[45], M. Sandhoff[178],
C. Sandoval[21], D.P.C. Sankey[133], M. Sannino[53a,53b], Y. Sano[105], A. Sansoni[50], C. Santoni[37],
H. Santos[128a], I. Santoyo Castillo[151], A. Sapronov[68], J.G. Saraiva[128a,128d], B. Sarrazin[23],
O. Sasaki[69], K. Sato[164], E. Sauvan[5], G. Savage[80], P. Savard[161,d], N. Savic[103], C. Sawyer[133],
L. Sawyer[82,u], J. Saxon[33], C. Sbarra[22a], A. Sbrizzi[22a,22b], T. Scanlon[81], D.A. Scannicchio[166],
M. Scarcella[152], J. Schaarschmidt[140], P. Schacht[103], B.M. Schachtner[102], D. Schaefer[32],
L. Schaefer[124], R. Schaefer[45], J. Schaeffer[86], S. Schaepe[23], S. Schaetzel[60b], U. Schäfer[86],
A.C. Schaffer[119], D. Schaile[102], R.D. Schamberger[150], V.A. Schegelsky[125], D. Scheirich[131],
M. Schernau[166], C. Schiavi[53a,53b], S. Schier[139], L.K. Schildgen[23], C. Schillo[51], M. Schioppa[40a,40b],
S. Schlenker[32], K.R. Schmidt-Sommerfeld[103], K. Schmieden[32], C. Schmitt[86], S. Schmitt[45],
S. Schmitz[86], U. Schnoor[51], L. Schoeffel[138], A. Schoening[60b], B.D. Schoenrock[93], E. Schopf[23],
M. Schott[86], J.F.P. Schouwenberg[108], J. Schovancova[32], S. Schramm[52], N. Schuh[86], A. Schulte[86],
M.J. Schultens[23], H.-C. Schultz-Coulon[60a], H. Schulz[17], M. Schumacher[51], B.A. Schumm[139],
Ph. Schune[138], A. Schwartzman[145], T.A. Schwarz[92], H. Schweiger[87], Ph. Schwemling[138],
R. Schwienhorst[93], J. Schwindling[138], A. Sciandra[23], G. Sciolla[25], M. Scornajenghi[40a,40b],
F. Scuri[126a,126b], F. Scutti[91], J. Searcy[92], P. Seema[23], S.C. Seidel[107], A. Seiden[139], J.M. Seixas[26a],
G. Sekhniaidze[106a], K. Sekhon[92], S.J. Sekula[43], N. Semprini-Cesari[22a,22b], S. Senkin[37],
C. Serfon[121], L. Serin[119], L. Serkin[167a,167b], M. Sessa[136a,136b], R. Seuster[172], H. Severini[115],
T. Sfiligoj[78], F. Sforza[32], A. Sfyrla[52], E. Shabalina[57], N.W. Shaikh[148a,148b], L.Y. Shan[35a],
R. Shang[169], J.T. Shank[24], M. Shapiro[16], P.B. Shatalov[99], K. Shaw[167a,167b], S.M. Shaw[87],
A. Shcherbakova[148a,148b], C.Y. Shehu[151], Y. Shen[115], N. Sherafati[31], P. Sherwood[81], L. Shi[153,ao],
S. Shimizu[70], C.O. Shimmin[179], M. Shimojima[104], I.P.J. Shipsey[122], S. Shirabe[73],
M. Shiyakova[68,ap], J. Shlomi[175], A. Shmeleva[98], D. Shoaleh Saadi[97], M.J. Shochet[33], S. Shojaii[94a],
D.R. Shope[115], S. Shrestha[113], E. Shulga[100], M.A. Shupe[7], P. Sicho[129], A.M. Sickles[169],
P.E. Sidebo[149], E. Sideras Haddad[147c], O. Sidiropoulou[177], A. Sidoti[22a,22b], F. Siegert[47],
Dj. Sijacki[14], J. Silva[128a,128d], S.B. Silverstein[148a], V. Simak[130], Lj. Simic[14], S. Simion[119],
E. Simioni[86], B. Simmons[81], M. Simon[86], P. Sinervo[161], N.B. Sinev[118], M. Sioli[22a,22b],
G. Siragusa[177], I. Siral[92], S.Yu. Sivoklokov[101], J. Sjölin[148a,148b], M.B. Skinner[75], P. Skubic[115],
M. Slater[19], T. Slavicek[130], M. Slawinska[42], K. Sliwa[165], R. Slovak[131], V. Smakhtin[175],
B.H. Smart[5], J. Smiesko[146a], N. Smirnov[100], S.Yu. Smirnov[100], Y. Smirnov[100],
L.N. Smirnova[101,aq], O. Smirnova[84], J.W. Smith[57], M.N.K. Smith[38], R.W. Smith[38],
M. Smizanska[75], K. Smolek[130], A.A. Snesarev[98], I.M. Snyder[118], S. Snyder[27], R. Sobie[172,o],
F. Socher[47], A. Soffer[155], A. Søgaard[49], D.A. Soh[153], G. Sokhrannyi[78], C.A. Solans Sanchez[32],
M. Solar[130], E.Yu. Soldatov[100], U. Soldevila[170], A.A. Solodkov[132], A. Soloshenko[68],
O.V. Solovyanov[132], V. Solovyev[125], P. Sommer[51], H. Son[165], A. Sopczak[130], D. Sosa[60b],
C.L. Sotiropoulou[126a,126b], R. Soualah[167a,167c], A.M. Soukharev[111,c], D. South[45], B.C. Sowden[80],
S. Spagnolo[76a,76b], M. Spalla[126a,126b], M. Spangenberg[173], F. Spanò[80], D. Sperlich[17],
F. Spettel[103], T.M. Spieker[60a], R. Spighi[22a], G. Spigo[32], L.A. Spiller[91], M. Spousta[131],
R.D. St. Denis[56,*], A. Stabile[94a], R. Stamen[60a], S. Stamm[17], E. Stanecka[42], R.W. Stanek[6],
C. Stanescu[136a], M.M. Stanitzki[45], B.S. Stapf[109], S. Stapnes[121], E.A. Starchenko[132], G.H. Stark[33],
J. Stark[58], S.H Stark[39], P. Staroba[129], P. Starovoitov[60a], S. Stärz[32], R. Staszewski[42],
P. Steinberg[27], B. Stelzer[144], H.J. Stelzer[32], O. Stelzer-Chilton[163a], H. Stenzel[55], G.A. Stewart[56],
M.C. Stockton[118], M. Stoebe[90], G. Stoicea[28b], P. Stolte[57], S. Stonjek[103], A.R. Stradling[8],
A. Straessner[47], M.E. Stramaglia[18], J. Strandberg[149], S. Strandberg[148a,148b], M. Strauss[115],
P. Strizenec[146b], R. Ströhmer[177], D.M. Strom[118], R. Stroynowski[43], A. Strubig[49], S.A. Stucci[27],
B. Stugu[15], N.A. Styles[45], D. Su[145], J. Su[127], S. Suchek[60a], Y. Sugaya[120], M. Suk[130],
V.V. Sulin[98], DMS Sultan[162a,162b], S. Sultansoy[4c], T. Sumida[71], S. Sun[59], X. Sun[3], K. Suruliz[151],
C.J.E. Suster[152], M.R. Sutton[151], S. Suzuki[69], M. Svatos[129], M. Swiatlowski[33], S.P. Swift[2],

I. Sykora[146a], T. Sykora[131], D. Ta[51], K. Tackmann[45], J. Taenzer[155], A. Taffard[166],
R. Tafirout[163a], E. Tahirovic[79], N. Taiblum[155], H. Takai[27], R. Takashima[72], E.H. Takasugi[103],
T. Takeshita[142], Y. Takubo[69], M. Talby[88], A.A. Talyshev[111,c], J. Tanaka[157], M. Tanaka[159],
R. Tanaka[119], S. Tanaka[69], R. Tanioka[70], B.B. Tannenwald[113], S. Tapia Araya[34b], S. Tapprogge[86],
S. Tarem[154], G.F. Tartarelli[94a], P. Tas[131], M. Tasevsky[129], T. Tashiro[71], E. Tassi[40a,40b],
A. Tavares Delgado[128a,128b], Y. Tayalati[137e], A.C. Taylor[107], G.N. Taylor[91], P.T.E. Taylor[91],
W. Taylor[163b], P. Teixeira-Dias[80], D. Temple[144], H. Ten Kate[32], P.K. Teng[153], J.J. Teoh[120],
F. Tepel[178], S. Terada[69], K. Terashi[157], J. Terron[85], S. Terzo[13], M. Testa[50], R.J. Teuscher[161,o],
T. Theveneaux-Pelzer[88], F. Thiele[39], J.P. Thomas[19], J. Thomas-Wilsker[80], P.D. Thompson[19],
A.S. Thompson[56], L.A. Thomsen[179], E. Thomson[124], M.J. Tibbetts[16], R.E. Ticse Torres[88],
V.O. Tikhomirov[98,ar], Yu.A. Tikhonov[111,c], S. Timoshenko[100], P. Tipton[179], S. Tisserant[88],
K. Todome[159], S. Todorova-Nova[5], S. Todt[47], J. Tojo[73], S. Tokár[146a], K. Tokushuku[69],
E. Tolley[59], L. Tomlinson[87], M. Tomoto[105], L. Tompkins[145,as], K. Toms[107], B. Tong[59],
P. Tornambe[51], E. Torrence[118], H. Torres[144], E. Torró Pastor[140], J. Toth[88,at], F. Touchard[88],
D.R. Tovey[141], C.J. Treado[112], T. Trefzger[177], F. Tresoldi[151], A. Tricoli[27], I.M. Trigger[163a],
S. Trincaz-Duvoid[83], M.F. Tripiana[13], W. Trischuk[161], B. Trocmé[58], A. Trofymov[45],
C. Troncon[94a], M. Trottier-McDonald[16], M. Trovatelli[172], L. Truong[147b], M. Trzebinski[42],
A. Trzupek[42], K.W. Tsang[62a], J.C-L. Tseng[122], P.V. Tsiareshka[95], G. Tsipolitis[10],
N. Tsirintanis[9], S. Tsiskaridze[13], V. Tsiskaridze[51], E.G. Tskhadadze[54a], K.M. Tsui[62a],
I.I. Tsukerman[99], V. Tsulaia[16], S. Tsuno[69], D. Tsybychev[150], Y. Tu[62b], A. Tudorache[28b],
V. Tudorache[28b], T.T. Tulbure[28a], A.N. Tuna[59], S.A. Tupputi[22a,22b], S. Turchikhin[68],
D. Turgeman[175], I. Turk Cakir[4b,au], R. Turra[94a], P.M. Tuts[38], G. Ucchielli[22a,22b], I. Ueda[69],
M. Ughetto[148a,148b], F. Ukegawa[164], G. Unal[32], A. Undrus[27], G. Unel[166], F.C. Ungaro[91],
Y. Unno[69], C. Unverdorben[102], J. Urban[146b], P. Urquijo[91], P. Urrejola[86], G. Usai[8], J. Usui[69],
L. Vacavant[88], V. Vacek[130], B. Vachon[90], K.O.H. Vadla[121], A. Vaidya[81], C. Valderanis[102],
E. Valdes Santurio[148a,148b], S. Valentinetti[22a,22b], A. Valero[170], L. Valéry[13], S. Valkar[131],
A. Vallier[5], J.A. Valls Ferrer[170], W. Van Den Wollenberg[109], H. van der Graaf[109],
P. van Gemmeren[6], J. Van Nieuwkoop[144], I. van Vulpen[109], M.C. van Woerden[109],
M. Vanadia[135a,135b], W. Vandelli[32], A. Vaniachine[160], P. Vankov[109], G. Vardanyan[180], R. Vari[134a],
E.W. Varnes[7], C. Varni[53a,53b], T. Varol[43], D. Varouchas[119], A. Vartapetian[8], K.E. Varvell[152],
J.G. Vasquez[179], G.A. Vasquez[34b], F. Vazeille[37], T. Vazquez Schroeder[90], J. Veatch[57],
V. Veeraraghavan[7], L.M. Veloce[161], F. Veloso[128a,128c], S. Veneziano[134a], A. Ventura[76a,76b],
M. Venturi[172], N. Venturi[32], A. Venturini[25], V. Vercesi[123a], M. Verducci[136a,136b], W. Verkerke[109],
A.T. Vermeulen[109], J.C. Vermeulen[109], M.C. Vetterli[144,d], N. Viaux Maira[34b], O. Viazlo[84],
I. Vichou[169,*], T. Vickey[141], O.E. Vickey Boeriu[141], G.H.A. Viehhauser[122], S. Viel[16], L. Vigani[122],
M. Villa[22a,22b], M. Villaplana Perez[94a,94b], E. Vilucchi[50], M.G. Vincter[31], V.B. Vinogradov[68],
A. Vishwakarma[45], C. Vittori[22a,22b], I. Vivarelli[151], S. Vlachos[10], M. Vogel[178], P. Vokac[130],
G. Volpi[126a,126b], H. von der Schmitt[103], E. von Toerne[23], V. Vorobel[131], K. Vorobev[100],
M. Vos[170], R. Voss[32], J.H. Vossebeld[77], N. Vranjes[14], M. Vranjes Milosavljevic[14], V. Vrba[130],
M. Vreeswijk[109], R. Vuillermet[32], I. Vukotic[33], P. Wagner[23], W. Wagner[178], J. Wagner-Kuhr[102],
H. Wahlberg[74], S. Wahrmund[47], J. Wakabayashi[105], J. Walder[75], R. Walker[102], W. Walkowiak[143],
V. Wallangen[148a,148b], C. Wang[35b], C. Wang[36b,av], F. Wang[176], H. Wang[16], H. Wang[3],
J. Wang[45], J. Wang[152], Q. Wang[115], R. Wang[6], S.M. Wang[153], T. Wang[38], W. Wang[153,aw],
W. Wang[36a], Z. Wang[36c], C. Wanotayaroj[118], A. Warburton[90], C.P. Ward[30], D.R. Wardrope[81],
A. Washbrook[49], P.M. Watkins[19], A.T. Watson[19], M.F. Watson[19], G. Watts[140], S. Watts[87],
B.M. Waugh[81], A.F. Webb[11], S. Webb[86], M.S. Weber[18], S.W. Weber[177], S.A. Weber[31],
J.S. Webster[6], A.R. Weidberg[122], B. Weinert[64], J. Weingarten[57], M. Weirich[86], C. Weiser[51],
H. Weits[109], P.S. Wells[32], T. Wenaus[27], T. Wengler[32], S. Wenig[32], N. Wermes[23], M.D. Werner[67],

P. Werner[32], M. Wessels[60a], K. Whalen[118], N.L. Whallon[140], A.M. Wharton[75], A.S. White[92],
A. White[8], M.J. White[1], R. White[34b], D. Whiteson[166], B.W. Whitmore[75], F.J. Wickens[133],
W. Wiedenmann[176], M. Wielers[133], C. Wiglesworth[39], L.A.M. Wiik-Fuchs[51], A. Wildauer[103],
F. Wilk[87], H.G. Wilkens[32], H.H. Williams[124], S. Williams[109], C. Willis[93], S. Willocq[89],
J.A. Wilson[19], I. Wingerter-Seez[5], E. Winkels[151], F. Winklmeier[118], O.J. Winston[151],
B.T. Winter[23], M. Wittgen[145], M. Wobisch[82,u], T.M.H. Wolf[109], R. Wolff[88], M.W. Wolter[42],
H. Wolters[128a,128c], V.W.S. Wong[171], S.D. Worm[19], B.K. Wosiek[42], J. Wotschack[32],
K.W. Wozniak[42], M. Wu[33], S.L. Wu[176], X. Wu[52], Y. Wu[92], T.R. Wyatt[87], B.M. Wynne[49],
S. Xella[39], Z. Xi[92], L. Xia[35c], D. Xu[35a], L. Xu[27], T. Xu[138], B. Yabsley[152], S. Yacoob[147a],
D. Yamaguchi[159], Y. Yamaguchi[120], A. Yamamoto[69], S. Yamamoto[157], T. Yamanaka[157],
M. Yamatani[157], K. Yamauchi[105], Y. Yamazaki[70], Z. Yan[24], H. Yang[36c], H. Yang[16], Y. Yang[153],
Z. Yang[15], W-M. Yao[16], Y.C. Yap[83], Y. Yasu[69], E. Yatsenko[5], K.H. Yau Wong[23], J. Ye[43], S. Ye[27],
I. Yeletskikh[68], E. Yigitbasi[24], E. Yildirim[86], K. Yorita[174], K. Yoshihara[124], C. Young[145],
C.J.S. Young[32], J. Yu[8], J. Yu[67], S.P.Y. Yuen[23], I. Yusuff[30,ax], B. Zabinski[42], G. Zacharis[10],
R. Zaidan[13], A.M. Zaitsev[132,al], N. Zakharchuk[45], J. Zalieckas[15], A. Zaman[150], S. Zambito[59],
D. Zanzi[91], C. Zeitnitz[178], G. Zemaityte[122], A. Zemla[41a], J.C. Zeng[169], Q. Zeng[145], O. Zenin[132],
T. Ženiš[146a], D. Zerwas[119], D. Zhang[92], F. Zhang[176], G. Zhang[36a,ay], H. Zhang[35b], J. Zhang[6],
L. Zhang[51], L. Zhang[36a], M. Zhang[169], P. Zhang[35b], R. Zhang[23], R. Zhang[36a,av], X. Zhang[36b],
Y. Zhang[35a], Z. Zhang[119], X. Zhao[43], Y. Zhao[36b,az], Z. Zhao[36a], A. Zhemchugov[68], B. Zhou[92],
C. Zhou[176], L. Zhou[43], M. Zhou[35a], M. Zhou[150], N. Zhou[35c], C.G. Zhu[36b], H. Zhu[35a], J. Zhu[92],
Y. Zhu[36a], X. Zhuang[35a], K. Zhukov[98], A. Zibell[177], D. Zieminska[64], N.I. Zimine[68],
C. Zimmermann[86], S. Zimmermann[51], Z. Zinonos[103], M. Zinser[86], M. Ziolkowski[143], L. Živković[14],
G. Zobernig[176], A. Zoccoli[22a,22b], R. Zou[33], M. zur Nedden[17] and L. Zwalinski[32]

1   *Department of Physics, University of Adelaide, Adelaide, Australia*
2   *Physics Department, SUNY Albany, Albany NY, United States of America*
3   *Department of Physics, University of Alberta, Edmonton AB, Canada*
4   [(a)] *Department of Physics, Ankara University, Ankara;* [(b)] *Istanbul Aydin University, Istanbul;* [(c)] *Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
5   *LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France*
6   *High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America*
7   *Department of Physics, University of Arizona, Tucson AZ, United States of America*
8   *Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America*
9   *Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
10   *Physics Department, National Technical University of Athens, Zografou, Greece*
11   *Department of Physics, The University of Texas at Austin, Austin TX, United States of America*
12   *Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
13   *Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain*
14   *Institute of Physics, University of Belgrade, Belgrade, Serbia*
15   *Department for Physics and Technology, University of Bergen, Bergen, Norway*
16   *Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America*
17   *Department of Physics, Humboldt University, Berlin, Germany*
18   *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
19   *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
20   [(a)] *Department of Physics, Bogazici University, Istanbul;* [(b)] *Department of Physics Engineering, Gaziantep University, Gaziantep;* [(d)] *Istanbul Bilgi University, Faculty of Engineering and Natural*

Sciences, Istanbul; [e] *Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*

21 *Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*

22 [a] *INFN Sezione di Bologna;* [b] *Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*

23 *Physikalisches Institut, University of Bonn, Bonn, Germany*

24 *Department of Physics, Boston University, Boston MA, United States of America*

25 *Department of Physics, Brandeis University, Waltham MA, United States of America*

26 [a] *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;* [b] *Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora;* [c] *Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei;* [d] *Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*

27 *Physics Department, Brookhaven National Laboratory, Upton NY, United States of America*

28 [a] *Transilvania University of Brasov, Brasov;* [b] *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;* [c] *Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;* [d] *National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca;* [e] *University Politehnica Bucharest, Bucharest;* [f] *West University in Timisoara, Timisoara, Romania*

29 *Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*

30 *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*

31 *Department of Physics, Carleton University, Ottawa ON, Canada*

32 *CERN, Geneva, Switzerland*

33 *Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America*

34 [a] *Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;* [b] *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*

35 [a] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;* [b] *Department of Physics, Nanjing University, Jiangsu;* [c] *Physics Department, Tsinghua University, Beijing 100084, China*

36 [a] *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui;* [b] *School of Physics, Shandong University, Shandong;* [c] *Department of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai(also at PKU-CHEP), China*

37 *Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*

38 *Nevis Laboratory, Columbia University, Irvington NY, United States of America*

39 *Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*

40 [a] *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati;* [b] *Dipartimento di Fisica, Università della Calabria, Rende, Italy*

41 [a] *AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;* [b] *Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*

42 *Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*

43 *Physics Department, Southern Methodist University, Dallas TX, United States of America*

44 *Physics Department, University of Texas at Dallas, Richardson TX, United States of America*

45 *DESY, Hamburg and Zeuthen, Germany*

46 *Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*

47 *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*

48 *Department of Physics, Duke University, Durham NC, United States of America*

49 *SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*

50 *INFN e Laboratori Nazionali di Frascati, Frascati, Italy*

51 *Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*

52 *Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland*

53 [a] *INFN Sezione di Genova;* [b] *Dipartimento di Fisica, Università di Genova, Genova, Italy*

54 [(a)] *E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;* [(b)] *High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*

55 *II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*

56 *SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*

57 *II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*

58 *Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France*

59 *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America*

60 [(a)] *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* [(b)] *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*

61 *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*

62 [(a)] *Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong;* [(b)] *Department of Physics, The University of Hong Kong, Hong Kong;* [(c)] *Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*

63 *Department of Physics, National Tsing Hua University, Taiwan, Taiwan*

64 *Department of Physics, Indiana University, Bloomington IN, United States of America*

65 *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*

66 *University of Iowa, Iowa City IA, United States of America*

67 *Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America*

68 *Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*

69 *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*

70 *Graduate School of Science, Kobe University, Kobe, Japan*

71 *Faculty of Science, Kyoto University, Kyoto, Japan*

72 *Kyoto University of Education, Kyoto, Japan*

73 *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*

74 *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*

75 *Physics Department, Lancaster University, Lancaster, United Kingdom*

76 [(a)] *INFN Sezione di Lecce;* [(b)] *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*

77 *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*

78 *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*

79 *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*

80 *Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*

81 *Department of Physics and Astronomy, University College London, London, United Kingdom*

82 *Louisiana Tech University, Ruston LA, United States of America*

83 *Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*

84 *Fysiska institutionen, Lunds universitet, Lund, Sweden*

85 *Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain*

86 *Institut für Physik, Universität Mainz, Mainz, Germany*

87 *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*

88 *CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France*

89 *Department of Physics, University of Massachusetts, Amherst MA, United States of America*

90 *Department of Physics, McGill University, Montreal QC, Canada*

91 *School of Physics, University of Melbourne, Victoria, Australia*

92 *Department of Physics, The University of Michigan, Ann Arbor MI, United States of America*

93 *Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America*

94   [a] *INFN Sezione di Milano;* [b] *Dipartimento di Fisica, Università di Milano, Milano, Italy*

95   *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*

96   *Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus*

97   *Group of Particle Physics, University of Montreal, Montreal QC, Canada*

98   *P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*

99   *Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*

100 *National Research Nuclear University MEPhI, Moscow, Russia*

101 *D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia*

102 *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*

103 *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*

104 *Nagasaki Institute of Applied Science, Nagasaki, Japan*

105 *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*

106 [a] *INFN Sezione di Napoli;* [b] *Dipartimento di Fisica, Università di Napoli, Napoli, Italy*

107 *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America*

108 *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*

109 *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*

110 *Department of Physics, Northern Illinois University, DeKalb IL, United States of America*

111 *Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*

112 *Department of Physics, New York University, New York NY, United States of America*

113 *Ohio State University, Columbus OH, United States of America*

114 *Faculty of Science, Okayama University, Okayama, Japan*

115 *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America*

116 *Department of Physics, Oklahoma State University, Stillwater OK, United States of America*

117 *Palacký University, RCPTM, Olomouc, Czech Republic*

118 *Center for High Energy Physics, University of Oregon, Eugene OR, United States of America*

119 *LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*

120 *Graduate School of Science, Osaka University, Osaka, Japan*

121 *Department of Physics, University of Oslo, Oslo, Norway*

122 *Department of Physics, Oxford University, Oxford, United Kingdom*

123 [a] *INFN Sezione di Pavia;* [b] *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*

124 *Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America*

125 *National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia*

126 [a] *INFN Sezione di Pisa;* [b] *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*

127 *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America*

128 [a] *Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;* [b] *Faculdade de Ciências, Universidade de Lisboa, Lisboa;* [c] *Department of Physics, University of Coimbra, Coimbra;* [d] *Centro de Física Nuclear da Universidade de Lisboa, Lisboa;* [e] *Departamento de Fisica, Universidade do Minho, Braga;* [f] *Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada;* [g] *Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*

129 *Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*

130 *Czech Technical University in Prague, Praha, Czech Republic*

131 *Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*

132 *State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia*

133 *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*

134 [a] *INFN Sezione di Roma;* [b] *Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*

135 [a] *INFN Sezione di Roma Tor Vergata;* [b] *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*

136 [a] *INFN Sezione di Roma Tre;* [b] *Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*

137 [a] *Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;* [b] *Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat;* [c] *Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;* [d] *Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;* [e] *Faculté des sciences, Université Mohammed V, Rabat, Morocco*

138 *DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France*

139 *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America*

140 *Department of Physics, University of Washington, Seattle WA, United States of America*

141 *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*

142 *Department of Physics, Shinshu University, Nagano, Japan*

143 *Department Physik, Universität Siegen, Siegen, Germany*

144 *Department of Physics, Simon Fraser University, Burnaby BC, Canada*

145 *SLAC National Accelerator Laboratory, Stanford CA, United States of America*

146 [a] *Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava;* [b] *Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*

147 [a] *Department of Physics, University of Cape Town, Cape Town;* [b] *Department of Physics, University of Johannesburg, Johannesburg;* [c] *School of Physics, University of the Witwatersrand, Johannesburg, South Africa*

148 [a] *Department of Physics, Stockholm University;* [b] *The Oskar Klein Centre, Stockholm, Sweden*

149 *Physics Department, Royal Institute of Technology, Stockholm, Sweden*

150 *Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America*

151 *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*

152 *School of Physics, University of Sydney, Sydney, Australia*

153 *Institute of Physics, Academia Sinica, Taipei, Taiwan*

154 *Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel*

155 *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*

156 *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*

157 *International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan*

158 *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*

159 *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*

160 *Tomsk State University, Tomsk, Russia*

161 *Department of Physics, University of Toronto, Toronto ON, Canada*

162 [a] *INFN-TIFPA;* [b] *University of Trento, Trento, Italy*

163 [a] *TRIUMF, Vancouver BC;* [b] *Department of Physics and Astronomy, York University, Toronto ON, Canada*

164 *Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan*

165 *Department of Physics and Astronomy, Tufts University, Medford MA, United States of America*

166 *Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of*

America

167 (a) *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;* (b) *ICTP, Trieste;* (c) *Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*

168 *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*

169 *Department of Physics, University of Illinois, Urbana IL, United States of America*

170 *Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain*

171 *Department of Physics, University of British Columbia, Vancouver BC, Canada*

172 *Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*

173 *Department of Physics, University of Warwick, Coventry, United Kingdom*

174 *Waseda University, Tokyo, Japan*

175 *Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*

176 *Department of Physics, University of Wisconsin, Madison WI, United States of America*

177 *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*

178 *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*

179 *Department of Physics, Yale University, New Haven CT, United States of America*

180 *Yerevan Physics Institute, Yerevan, Armenia*

181 *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*

182 *Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan*

a *Also at Department of Physics, King's College London, London, United Kingdom*

b *Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*

c *Also at Novosibirsk State University, Novosibirsk, Russia*

d *Also at TRIUMF, Vancouver BC, Canada*

e *Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America*

f *Also at Physics Department, An-Najah National University, Nablus, Palestine*

g *Also at Department of Physics, California State University, Fresno CA, United States of America*

h *Also at Department of Physics, University of Fribourg, Fribourg, Switzerland*

i *Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*

j *Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain*

k *Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal*

l *Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia*

m *Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China*

n *Also at Universita di Napoli Parthenope, Napoli, Italy*

o *Also at Institute of Particle Physics (IPP), Canada*

p *Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*

q *Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia*

r *Also at Borough of Manhattan Community College, City University of New York, New York City, United States of America*

s *Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece*

t *Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa*

u *Also at Louisiana Tech University, Ruston LA, United States of America*

v *Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain*

w *Also at Graduate School of Science, Osaka University, Osaka, Japan*

x *Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*

y *Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University*

Nijmegen/Nikhef, Nijmegen, Netherlands

[z] Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America

[aa] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia

[ab] Also at CERN, Geneva, Switzerland

[ac] Also at Georgian Technical University (GTU),Tbilisi, Georgia

[ad] Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan

[ae] Also at Manhattan College, New York NY, United States of America

[af] Also at Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

[ag] Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

[ah] Also at The City College of New York, New York NY, United States of America

[ai] Also at School of Physics, Shandong University, Shandong, China

[aj] Also at Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Portugal

[ak] Also at Department of Physics, California State University, Sacramento CA, United States of America

[al] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

[am] Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland

[an] Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

[ao] Also at School of Physics, Sun Yat-sen University, Guangzhou, China

[ap] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria

[aq] Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia

[ar] Also at National Research Nuclear University MEPhI, Moscow, Russia

[as] Also at Department of Physics, Stanford University, Stanford CA, United States of America

[at] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

[au] Also at Giresun University, Faculty of Engineering, Turkey

[av] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

[aw] Also at Department of Physics, Nanjing University, Jiangsu, China

[ax] Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

[ay] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

[az] Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

[*] Deceased