

Search for an excess of events with an identical flavour lepton pair and significant missing transverse momentum in $\sqrt{s} = 7$ TeV proton–proton collisions with the ATLAS detector

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Abstract Results are presented of a search for particles decaying into final states with significant missing transverse momentum and exactly two identical flavour leptons (e, μ) of opposite charge in $\sqrt{s} = 7$ TeV collisions at the Large Hadron Collider. This channel is particularly sensitive to supersymmetric particle cascade decays producing flavour correlated lepton pairs. Flavour uncorrelated backgrounds are subtracted using a sample of opposite flavour lepton pair events. Observation of an excess beyond Standard Model expectations following this subtraction procedure would offer one of the best routes to measuring the masses of supersymmetric particles. In a data sample corresponding to an integrated luminosity of 35 pb^{-1} no such excess is observed. Model-independent limits are set on the contribution to these final states from supersymmetry and are used to exclude regions of a phenomenological supersymmetric parameter space.

In this letter the first results are reported of a search for the production of particles at ATLAS in events with exactly two leptons of identical flavour (e or μ) and opposite charge, and significant missing transverse momentum (E_T^{miss}). This signature can be generated in supersymmetry (SUSY) [1–9] events by the correlated production of leptons, for instance via the decay chains $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\ell^\pm \rightarrow \tilde{\chi}_1^0\ell^+\ell^-$ or $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\ell^+\ell^-$. Such events offer one of the best routes to model-independent measurements of the masses of SUSY particles via end-points in the lepton pair invariant mass distribution [10–12]. The dominant sources of Standard Model (SM) background generally possess equal branching fractions for the production of lepton pairs of identical and different flavour, and can therefore be removed with a ‘flavour subtraction’ procedure [10] in which the observation in the

$e\mu$ channel is subtracted from that in the ee and $\mu\mu$ channels. The subtraction reduces the impact on the analysis of various experimental uncertainties, common to both the identical- and different-flavour channels. This method is applicable to a variety of different kinds of new physics. As a benchmark, this letter presents the results in terms of a search for SUSY. The results reported here are complementary to those of inclusive SUSY particle searches using lepton pairs [13], and also to those of inclusive searches requiring jets, E_T^{miss} and zero leptons [14] or one lepton [15]. A search by CMS for SUSY in events with lepton pairs is reported in [16].

The ATLAS detector [17] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle.¹ The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT) which also provides particle identification capability. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimeters. Hadronic coverage is provided by an iron-scintillator tile calorimeter in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids, a system of precision tracking chambers, and detectors for triggering.

¹ATLAS 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 coinciding with the axis of 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 $\eta = -\ln \tan(\theta/2)$.

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The pp -collision data used in this analysis were collected between March and November 2010 at the LHC operating at a centre-of-mass energy of 7 TeV. Application of basic beam, detector and data-quality requirements results in a total integrated luminosity of 35 pb^{-1} . The uncertainty on the luminosity is estimated to be 11% [18]. The data have been collected with a single lepton (e or μ) trigger. The detailed trigger requirements vary throughout the data-taking period due to the rapidly increasing LHC luminosity and the commissioning of the trigger system, but always have a threshold that ensures a trigger efficiency for leptons with transverse momentum $p_T > 20 \text{ GeV}$ at the plateau. The efficiency of the triggers is studied with data, and agrees well with expectations.

Monte Carlo (MC) simulated event samples are used to develop and validate the analysis procedure and to estimate the residual SM backgrounds following flavour subtraction. Samples of QCD jet events are generated with PYTHIA [19], using the MRST2007LO* modified leading-order parton distribution functions (PDF) [20], which are used with all leading-order (LO) MC codes. Production of top quark pairs is simulated with MC@NLO [21, 22] (with a top quark mass of 172.5 GeV) and the next-to-leading order (NLO) PDF set CTEQ6.6 [23], which is used with all NLO MC codes. Samples of W and Z/γ^* production with accompanying jets are produced with ALPGEN [24]. Diboson (WW , WZ , ZZ) production is simulated with HERWIG [25, 26], single top production with MC@NLO [27, 28], and Drell–Yan production with PYTHIA. Fragmentation and hadronization for the ALPGEN and MC@NLO samples are performed with HERWIG, using JIMMY [29] for the underlying event. The MC samples are produced using the ATLAS MC09 parameter tune [30] and a GEANT4 [31] based detector simulation [32].

Criteria for electron and muon identification closely follow those described in Ref. [33]. Candidate electrons are required to pass “tight” electron selection criteria and isolation requirements, and have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.47$. Identified electrons are used to select events for both the signal region of the analysis and control regions used to estimate backgrounds. “Medium” electron selection criteria are mainly based on lateral shower shape requirements in the calorimeter, while E/p (where E is the shower energy in the calorimeter and p the track momentum in the ID) and TRT cuts are applied for the tight electron selection, which provides additional rejection against conversions and fakes from hadrons. The electron isolation criteria require that the total transverse energy within a cone size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the electron, is less than 0.15 of the electron p_T . Events are always vetoed if a medium electron is found in the transition region between the barrel and end-cap electromagnetic calorimeter, $1.37 < |\eta| < 1.52$. Muons are required to be identified

either in both the ID and MS systems (combined muons) or as a match between an extrapolated ID track and one or more track segments in the MS. The ID track is required to have at least one pixel hit, more than five SCT hits, and a number of TRT hits that varies with η . For combined muons, a good match between ID and MS tracks is required, and the p_T values measured by these two systems must be compatible within the resolution. Isolation requirements are imposed, whereby the summed p_T of other ID tracks above 500 MeV within a distance $\Delta R < 0.2$ around the muon track is required to be less than 1.8 GeV. Only muons with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.4$ are considered. For the final selection, the distance between the z coordinate of the primary vertex and that of the extrapolated muon track at the point of closest approach to the primary vertex must be less than 10 mm. Jets are reconstructed using the anti- k_r jet clustering algorithm [34] with a distance parameter $D = 0.4$. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the measured noise. Jets are constructed by performing a four-vector sum over these clusters, treating each cluster as an (E, \mathbf{p}) four-vector with zero mass. Jets are corrected for calorimeter non-compensation, material and other effects using p_T - and η -dependent calibration factors obtained from Monte Carlo and validated with test-beam and collision-data studies [35]. Only jets with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$ are considered. If a jet and a medium electron are both identified within a distance $\Delta R < 0.2$ of each other, the jet is discarded. Furthermore, identified medium electrons or muons are only considered if they satisfy $\Delta R > 0.4$ with respect to the closest remaining jet. Events are discarded if they contain any jet failing basic quality selection criteria, which rejects detector noise and non-collision backgrounds [36]. The calculation of the missing transverse momentum, E_T^{miss} , is based on the modulus of the vector sum of the p_T of the reconstructed objects (jets with $p_T > 20 \text{ GeV}$, but over the full calorimeter coverage $|\eta| < 4.9$, and selected leptons), any additional non-isolated muons, and the calorimeter clusters not belonging to reconstructed objects.

“Signal region” events that contain lepton pairs of identical flavour (e^+e^- and $\mu^+\mu^-$) and different flavour ($e^\pm\mu^\mp$) are selected, with the two populations subsequently used to calculate the excess of identical-flavour events. Selected events must contain exactly two opposite sign leptons (e or μ), with invariant mass ($m_{\ell\ell}$) greater than 5 GeV. The E_T^{miss} must exceed 100 GeV in order to reject SM Z +jets events whilst maintaining efficiency for a range of SUSY models. Events must also possess at least one reconstructed primary vertex with at least five associated tracks. A flavour subtraction is performed through the use of the quantity \mathcal{S}

defined as

$$S = \frac{N(e^\pm e^\mp)}{\beta(1 - (1 - \tau_e)^2)} - \frac{N(e^\pm \mu^\mp)}{1 - (1 - \tau_e)(1 - \tau_\mu)} + \frac{\beta N(\mu^\pm \mu^\mp)}{(1 - (1 - \tau_\mu)^2)}, \tag{1}$$

which measures the excess of identical-flavour events (first and third terms) over different-flavour events (second term), taking into account the electron and muon plateau trigger efficiencies (τ_e and τ_μ) and the ratio of electron to muon efficiency times acceptance (β). The trigger efficiencies for offline reconstructed objects are $\tau_e = (98.5 \pm 1.1)\%$ and $\tau_\mu = (83.7 \pm 1.9)\%$, respectively, while β is determined from data to be 0.69 ± 0.03 , with the quoted errors including both systematic and statistical uncertainties.

The value of S obtained from selected identical-flavour and different-flavour lepton SM events is expected to be small but non-zero, due primarily to Z/γ^* boson production. The contributions to S expected from SM processes are estimated using a combination of Monte Carlo simulation and data-driven techniques. Contributions from single top and diboson events are estimated using the MC samples described above, scaled to the luminosity of the data sample. Contributions from Z/γ^* +jets, $t\bar{t}$ and events containing fake leptons (from QCD jets and W +jets events) are estimated using MC samples normalised to data in an appropriate control region. The Z/γ^* control region contains lepton pair events satisfying the same selection criteria as the signal region but with $E_T^{\text{miss}} < 20$ GeV and an additional $81 < m_{\ell\ell} < 101$ GeV requirement. The $t\bar{t}$ control region [13] contains ‘‘top-tagged’’ lepton pair events again satisfying the same selection criteria as signal candidates but with $60 < E_T^{\text{miss}} < 80$ GeV and an additional requirement of ≥ 2 jets with $p_T > 20$ GeV. The top-tagging requirement is imposed through the use of the variable m_{CT} [37], which can be calculated from the four-vectors of the selected jets and leptons:

$$m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2, \tag{2}$$

where v_i can be a lepton, a jet, or a lepton-jet combination, transverse momentum vectors are denoted by \mathbf{p}_T and transverse energies E_T are defined as $E_T = \sqrt{p_T^2 + m^2}$. This quantity is bounded from above by analytical functions of the top quark and W masses as described in [38]. Top-tagged events are required to possess m_{CT} values calculated from combinations of jets and leptons consistent with the expected bounds from $t\bar{t}$ events, as well as lepton-jet invariant mass values consistent with top quark decays. An electron control region for fake lepton events requires events to possess $E_T^{\text{miss}} < 60$ GeV, $\Delta\phi$ between the E_T^{miss} vector and

Table 1 Expected numbers of SM background events in the signal region for each of the three lepton flavour combinations. The estimates are obtained using the procedures described in the text. The quoted error includes systematic and statistical uncertainties, taking into account correlations. The negative number of fakes predicted in the $e^\pm \mu^\mp$ channel is an artifact of the matrix method used to estimate this contribution. In the ‘Total SM’, the number of fakes in this channel is taken to be zero. The probabilities for the SM to fluctuate to the respective observation are $e^\pm e^\mp$ 48%, $e^\pm \mu^\mp$ 14% and $\mu^\pm \mu^\mp$ 6%

| | $e^\pm e^\mp$ | $e^\pm \mu^\mp$ | $\mu^\pm \mu^\mp$ |
|--------------------|-----------------|------------------|-------------------|
| Data | 4 | 13 | 13 |
| Z/γ^* +jets | 0.40 ± 0.46 | 0.36 ± 0.20 | 0.91 ± 0.67 |
| Dibosons | 0.30 ± 0.11 | 0.36 ± 0.10 | 0.61 ± 0.10 |
| $t\bar{t}$ | 2.50 ± 1.02 | 6.61 ± 2.68 | 4.71 ± 1.91 |
| Single top | 0.13 ± 0.09 | 0.76 ± 0.25 | 0.67 ± 0.33 |
| Fakes | 0.31 ± 0.21 | -0.15 ± 0.08 | 0.01 ± 0.01 |
| Total SM | 3.64 ± 1.24 | 8.08 ± 2.78 | 6.91 ± 2.20 |

a jet < 0.1 and an electron with $p_T > 30$ GeV. A single muon control region for fake lepton events requires events to possess $E_T^{\text{miss}} < 30$ GeV, a muon with $p_T < 40$ GeV and a transverse mass $m_T(\mu, E_T^{\text{miss}}) < 30$ GeV. The electron and muon identification criteria are relaxed, to obtain a ‘looser’ sample dominated by fakes. A loose-tight matrix method is then used to estimate the number of events with fake leptons in the signal region after final selection criteria. This method, which uses the probabilities derived from data for loosely selected leptons and hadrons to satisfy the tight selection criteria to predict the mixture of real and fake leptons in the final sample, is similar to that described in [39]. The dominant uncertainties in the data-normalised background estimates arise from limited numbers of events in the control regions, theoretical uncertainties (including choice of generator, initial and final state radiation), an approximate $\sim \pm 7\%$ jet energy scale uncertainty [40] and an approximate $\sim 14\%$ jet energy resolution uncertainty [41]. The latter uncertainties affect the shapes of the MC E_T^{miss} distributions. Uncertainties on backgrounds estimated solely with MC are dominated by the jet energy scale and resolution.

The invariant mass distributions of lepton pairs in selected data events, prior to applying the E_T^{miss} requirement, are presented in Fig. 1, weighted by the multiplicative factors in (1) to yield the identical-flavour and different-flavour contributions to S . After applying the $E_T^{\text{miss}} > 100$ GeV requirement 4, 13 and 13 events are observed in the $e^\pm e^\mp$, $e^\pm \mu^\mp$ and $\mu^\pm \mu^\mp$ channels, respectively. The expected numbers of events in these channels, determined using the techniques described above, are listed in Table 1 and are in reasonable agreement for the given luminosity as suggested by the probabilities for the SM to fluctuate at least to the level of observed events. The dominant contribution to each channel arises from $t\bar{t}$ production. Using the observed numbers of

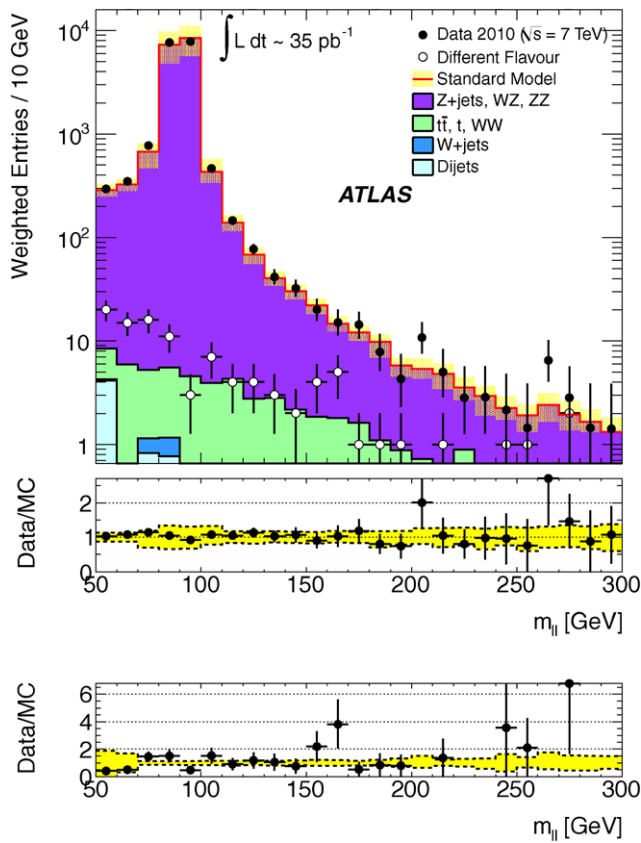


Fig. 1 Invariant mass distribution of identical-flavour lepton pairs prior to applying the E_T^{miss} requirement, weighted by the acceptance and efficiency factors as in (1). The stacked histograms show the expected distributions from MC samples normalised to the luminosity of the data. The band indicates the uncertainty on the expectation from finite statistics, cross section, luminosity, jet and lepton energy scales and resolutions. Also shown is the observed distribution for different-flavour pairs, weighted according to (1). In the region with $m_{\ell\ell} < 100$ GeV, the dominant contributions to the different-flavour data events are expected to come from $t\bar{t}$, QCD and $Z/\gamma^* + \text{jets}$ events. The lower of the two Data/MC ratios is the comparison between data and MC normalised to the luminosity of the data for different-flavour events

events in each channel together with the measured values of τ_e , τ_μ and β , the observed value of \mathcal{S} is found to be $\mathcal{S}_{\text{obs}} = 1.98 \pm 0.15(\beta) \pm 0.02(\tau_e) \pm 0.06(\tau_\mu)$, where the uncertainties are those from the respective efficiency parameters. The expected mean value of \mathcal{S} from SM background events alone is $\bar{\mathcal{S}}_b = 2.06 \pm 0.79(\text{stat.}) \pm 0.78(\text{sys.})$. The observation agrees very well with the SM background which is, however, expected to fluctuate considerably (see Fig. 2). The dominant contributions to $\bar{\mathcal{S}}_b$ are from $Z/\gamma^* + \text{jets}$ and diboson processes. The dominant contributions from $t\bar{t}$ events to the individual channels largely cancel when calculating \mathcal{S} , as expected. The $t\bar{t}$ population nevertheless has a significant impact on this analysis because the range of observed \mathcal{S} values expected from a large number of hypothetical signal-free experiments is dominated by statistical fluctuations in the numbers of selected $t\bar{t}$ events in each channel.

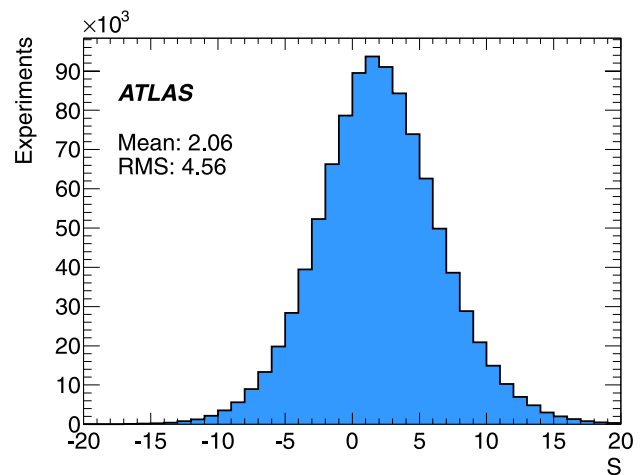


Fig. 2 Distribution of observed \mathcal{S} values from one million hypothetical signal-free experiments. The shape is driven by statistical Poisson fluctuations in the expected rates of identical-flavour and different-flavour events, dominated by $t\bar{t}$ events

To quantify the consistency between the observed \mathcal{S} value and the SM prediction the expected distribution of \mathcal{S}_b in the absence of SUSY must be determined. This distribution possesses a mean given by $\bar{\mathcal{S}}_b$ and a width dominated by statistical fluctuations in the numbers of events observed in each channel. The distribution can be determined by generating pseudo-experiments using the estimated mean numbers of background events from Table 1 as input. For each pseudo-experiment the mean number of background events in each channel and from each source are sampled, taking appropriate account of correlations between the uncertainties in the estimates of these means. The resulting total mean number of background events in each channel is then used to construct a Poisson distribution from which the observed number of events in that channel is drawn. The resulting sampled event counts in each channel are then used with (1), taking care also to sample values of τ_e , τ_μ and β according to their means and uncertainties, to determine a value of \mathcal{S}_b . The distribution of \mathcal{S}_b values obtained in this way is used to estimate the probability of observing a value of \mathcal{S} at least as large as \mathcal{S}_{obs} .

The distribution of \mathcal{S} values obtained from one million signal-free experiments using this procedure is shown in Fig. 2. The shape of the distribution is dominated by statistical fluctuations in the numbers of events in each channel, with the uncertainty on $\bar{\mathcal{S}}_b$ being negligible by comparison. The probability of observing a value of \mathcal{S} at least as large as \mathcal{S}_{obs} is 49.7% and hence no evidence of an excess of identical-flavour events beyond SM expectations is observed.

Limits are set on $\bar{\mathcal{S}}_s$, the mean contribution to \mathcal{S} from SUSY. The statistical procedure employed follows that used to determine the consistency of the observed value of \mathcal{S} with the background expectation. The pseudo-experiments

are modified by adding signal event contributions to the input mean numbers of background events in each channel. An assumption must be made regarding the relative branching ratio of SUSY events into identical-flavour and different-flavour channels, as adding flavour uncorrelated SUSY contributions to the identical-flavour and different-flavour channels increases the width of the \mathcal{S} distribution. Given such an assumption, a model-independent limit can be set on \bar{S}_s by comparing \mathcal{S}_{obs} with the distribution of \mathcal{S} values obtained from the new set of signal-plus-background pseudo-experiments.

If the assumption is made that the branching fractions for $e^\pm e^\mp$ and $\mu^\pm \mu^\mp$ final states in SUSY events are identical, and the branching fraction for $e^\pm \mu^\mp$ final states is zero, a limit $\bar{S}_s < 8.8$ is set at 95% confidence level. Alternatively, if SUSY events are assumed to possess a different-flavour branching fraction of one half that for identical-flavour events, then the limit becomes $\bar{S}_s < 12.6$ at 95% confidence. The limits are driven by the statistical fluctuations in \mathcal{S} , rather than systematic and statistical uncertainties in \bar{S}_b and in the variance of the \mathcal{S}_b distribution.

A similar procedure can be used to set limits within a specific SUSY parameter space. In this case the mean numbers of signal events added to each channel are sampled according to the expectations from each point in the parameter space of the model together with the uncertainties in these expectations. The fraction of resulting pseudo-experiments with $\mathcal{S} < \mathcal{S}_{\text{obs}}$ gives the probability of the signal-plus-background hypothesis being falsely rejected. If the probability of being falsely rejected is $< 5\%$, the point is excluded at 95% confidence.

As an example, two-dimensional grids in the parameter space of a 24-parameter MSSM model [42] are considered (to be referred to as ‘MSSM PhenoGrid2’). The 24-parameter MSSM is a generic MSSM on which flavour and CP violation have been imposed. For these grids the following parameters are fixed: $m_A = 1000$ GeV, $\mu = 1.5 \min(m_{\tilde{g}}, m_{\tilde{q}})$, $\tan \beta = 4$, $A_t = \mu / \tan \beta$, $A_b = \mu \tan \beta$, and $A_l = \mu \tan \beta$. The masses of the 3rd generation sfermions are set to 2 TeV, and common squark mass and slepton mass parameters are assumed for the first two generations. Two grids in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane are studied: one with a compressed spectrum yielding a soft final state kinematics, defined by $m_{\tilde{\chi}_2^0} = M - 50$ GeV, $m_{\tilde{\chi}_1^0} = M - 150$ GeV and $m_{\tilde{L}} = M - 100$ GeV, where M is the minimum of the gluino and squark mass (‘compressed spectrum’); and one with a very light LSP, yielding a harder spectrum of leptons, jets and E_T^{miss} , with $m_{\tilde{\chi}_2^0} = M - 100$ GeV, $m_{\tilde{\chi}_1^0} = 100$ GeV and $m_{\tilde{L}} = M/2$ GeV (‘light neutralino’). Signal events are generated with HERWIG for the MSSM grids. The cross sections are calculated at NLO with PROSPINO [43]. Theoretical and experimental uncertainties are determined for each model and used when sampling the mean numbers of signal

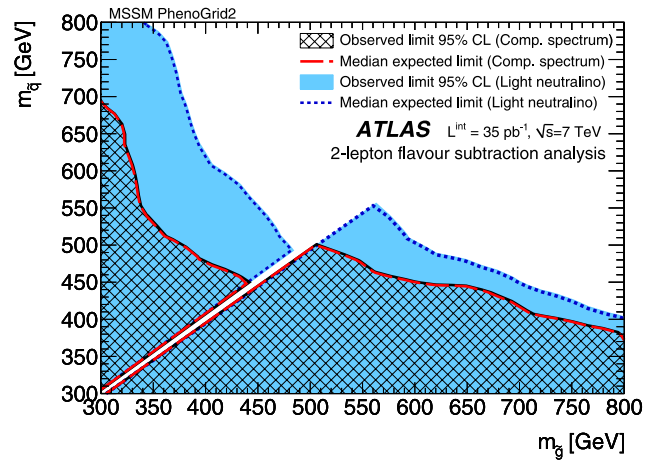


Fig. 3 Observed and expected 95% C.L. exclusion limits in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane for two 24-parameter MSSM models

events in each channel. Theoretical uncertainties are evaluated by varying the factorisation and renormalisation scales and the CTEQ6.6 PDF sets [23] used for the cross section calculation. Experimental uncertainties are dominated by the uncertainty on the jet energy scale and resolution. An 11% luminosity uncertainty is included. The results are shown in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane in Fig. 3. For ‘compressed spectrum’ (‘light neutralino’) models and $m_{\tilde{g}} = m_{\tilde{q}} + 10$ GeV, the 95% confidence lower limit on $m_{\tilde{q}}$ is 503 (558) GeV.

In summary, a flavour subtraction technique has been used to search for an excess beyond SM expectations of high missing transverse momentum events containing opposite charge identical-flavour lepton pairs. No significant excess has been observed, allowing limits to be set on the model-independent quantity \bar{S}_s , which measures the mean excess from SUSY taking into account flavour-dependent acceptances and efficiencies. This search and limit is of course applicable to other new physics scenarios, not just the SUSY scenario described here.

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The ATLAS Collaboration

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