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SUSY Searches at ATLAS in Multilepton Final States with Jets and Missing Transverse Energy

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Abstract

Results are presented from a search for supersymmetric signals in multilepton final states at ATLAS – with three or more leptons, jets, and moderate missing transverse energy in the final state. Very low levels of Standard Model backgrounds are expected in this channel. In a data sample with an integrated luminosity of 34 pb^{-1} no significant excess of multilepton events is observed. Limits are placed on parameters of the minimal supergravity framework, and in a phenomenological supersymmetric parameter space.

1 Introduction

The Standard Model (SM) of elementary particles, despite its many successes, is known to be an incomplete theory, as for example it does not address the hierarchy problem [1], or the presence of dark matter in our universe. Supersymmetry (SUSY) [2] is one of the most popular extensions of the SM, and it may shed some light on some of the SM's shortcomings. SUSY postulates the existence of a boson (fermion) "superpartner" for each of the SM fermions (bosons), leading to a further multiplication of the particle content of the theory. There are several models for breaking SUSY, with mSUGRA/CMSSM [3] being perhaps the most popular of them. A weakly interacting, electrically neutral lightest supersymmetric particle (LSP), which is also stable in R-parity [4] conserving SUSY models, would be an excellent candidate for dark matter [5].

In SUSY models, charginos ($\tilde{\chi}^{\pm}_j$) and neutralinos ($\tilde{\chi}^0_i$) are mass eigenstates obtained from the linear superposition of supersymmetric partners of gauge bosons (gauginos) and Higgs bosons (higgsinos). Depending on the choice of SUSY parameters, charginos and neutralinos can be produced abundantly in hadron-hadron collisions, either directly or as intermediate states in long decay chains that originate from pairs of coloured sparticles. Charginos and neutralinos can then decay leptonically with a significant rate, either via the emission of real or virtual gauge bosons or via the production of intermediate slepton states that can also be virtual, giving rise to sizable multilepton (with three or more leptons in the final state) SUSY signals. Thanks to the distinctive features of lepton-rich events, and despite the unfavourable suppression from the leptonic branching ratios, multilepton final states have the potential to be effectively separated from the overwhelming hadron-rich SM backgrounds typical of high-energy hadron-hadron collisions.

Multilepton final states are a typical SUSY signature at the Tevatron, and the search for supersymmetry via associated production of $\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ and subsequent decay to three leptons represents the "golden" SUSY channel at both D0 [6] and CDF [7]. Limits on sparticle masses have also been set by LEP experiments [8].

Thanks to its excellent lepton identification capabilities, ATLAS is ideally suited to explore multilepton SUSY signatures at the much higher LHC energies [9]. In the study presented in this paper, final states are selected with three or more isolated leptons, jets, and moderate missing transverse energy. Leptons in this case would typically originate from the decay of charginos and neutralinos produced in cascade decays of upstream coloured sparticles. Note that the term lepton here refers to electrons and muons only, which may potentially also originate from leptonic tau decays. Multilepton signatures where taus are positively identified as such through their hadronic decays are not considered here.

2 The ATLAS Detector

ATLAS [10] is a particle physics detector with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle [11]. The inner detector (ID) consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT). 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.

The data used in this analysis were recorded by ATLAS in 2010 from LHC collisions at a centre-of-mass energy of 7 TeV. Application of basic beam, detector and data-quality requirements results in a total integrated luminosity for these data of 34 pb^{-1}, with an estimated uncertainty of 11% [12]. The data have been collected with a single electron or muon trigger. The detailed trigger requirements varied through the data-taking period due to the rapidly increasing LHC luminosity and the commissioning of the trigger system, but always with a threshold that guarantees, for each configuration, a constant efficiency (with respect to offline lepton selection) of approximately 99% (85%) for electrons (muons) with $p_T > 20$ GeV, averaged over the η range. The apparent lower efficiency for muons is due to the limited geometrical coverage of the muon trigger chambers. The efficiency of the single lepton triggers has been studied in data and shown to agree well with expectations [13].

3 Event Simulation and Selection

Fully simulated Monte Carlo (MC) samples have been used to estimate SM backgrounds that pass the multilepton selection. This approach is supported by the good agreement seen between ATLAS data and MC expectations for SM processes [14, 15]. The top-quark pair production was simulated with MC@NLO [16], while ALPGEN [17] was used to generate the production of electroweak gauge bosons (W, Z/γ^*) in conjunction with jets, as well as Drell-Yan samples. Diboson (WZ, ZZ and WW) events were generated using HERWIG [18], and QCD jet events with PYTHIA [19]. Fragmentation and hadronisation for the ALPGEN and MC@NLO samples is performed with HERWIG, using JIMMY [20] for the underlying event. MC signal events are generated with Herwig++ [21]. The SUSY particle spectra and decay modes are calculated with ISAJET [22] and the SUSY samples are normalised using NLO cross sections as determined by PROSPINO [23]. The MC samples are produced using the ATLAS MC09 parameter tune [24] and a GEANT4 [25] based detector simulation [26].

Criteria for electron and muon identification closely follow those described in [27]. Electrons in the signal region are required to pass selection criteria based on lateral shower shape requirements in the calorimeter and minimal tracking requirements. They must have a transverse momentum $p_T > 20$ GeV and $|\eta| < 2.47$. Electrons are required to be well isolated by asking that the ratio of the transverse energy in a cone $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.2$ around the electron to the electron's transverse momentum be less than 0.15. Electron candidates with an associated calorimeter cluster in a region with a local calorimeter problem are rejected and events are vetoed altogether if an electron is found in the electromagnetic calorimeter transition region, $1.37 < |\eta| < 1.52$. 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 segments in the MS. 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. Only muons with $p_T > 10$ GeV and $|\eta| < 2.4$ are considered. The summed p_T of other ID tracks within a distance $\Delta R < 0.2$ around the muon track is required to be less than 1.8 GeV. 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_t jet clustering algorithm [28] with a radius parameter $R = 0.4$. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the measured noise and that correspond to local maxima in energy. Jets are constructed by performing a four-vector sum over these clusters, treating each cluster as an (E, 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 MC simulations and validated with test-beam and collision data studies [29]. Only jets with $p_T > 20$ GeV and $|\eta| < 2.5$ are considered. If a jet and an electron are both identified within $\Delta R < 0.2$ of each other, the jet is discarded. Furthermore, identified electrons or muons are all required to be separated by $\Delta R > 0.4$ from the closest remaining jet. Electrons and muons found to overlap within $\Delta R < 0.1$ are both discarded. Events are rejected if they contain any jet failing basic quality selection criteria, which reject detector noise and non-collision backgrounds [30]. Events must also possess at least one reconstructed primary vertex with at least five associated tracks. The calculation of the missing transverse energy, $\not{E}_T$, is based on the modulus of the vector sum of the p_T of the reconstructed objects (jets with $p_T > 20$ GeV, but over the full calorimeter coverage $|\eta| < 4.9$, and selected leptons), including non-isolated muons, and the calorimeter clusters not belonging to reconstructed objects.

A range of R-parity conserving SUSY scenarios can give rise to multilepton final states. While the detailed origin of the signal leptons will in general be different for different SUSY scenarios, the presence of three or more leptons in the final state is a strong enough constraint to suppress much of the purely hadronic SM backgrounds typical of the LHC environment. We select signal events to have at least three leptons (electrons or muons) of any charge and flavour combination, with p_T thresholds of 20 GeV for the two leading leptons (either flavour) and of 20 (10) GeV for the third lepton if it is an electron (muon). Other SM backgrounds (such as $t\bar{t}$ or Z+jets) can themselves yield well-isolated final-state leptons of relatively high-p_T and they will be suppressed more effectively by requiring the presence of high-p_T jets and sizable missing transverse energy from the escaping LSPs. At least two jets with $p_T > 50$ GeV (and $|\eta| < 2.5$) are required to be present in the event, and missing transverse energy must satisfy the condition $\not{E}_T > 50$ GeV. Z SM backgrounds are suppressed further by requiring that same-flavour opposite-sign (SFOS) lepton pairs do not yield an invariant mass $m_{l^+l^-}$ within 5 GeV of the nominal Z-boson mass [31]. This will be referred to as the Z-mass veto in the following. Low-mass ($m_{l^+l^-} < 20$ GeV) SFOS pairs are also discarded to suppress Drell-Yan backgrounds. The event selection has been shown to remain effective over a range of mSUGRA scenarios, as well as in less-constrained MSSM scenarios for which details are given below. Signal efficiencies cover a wide range of values, with typical event selection efficiencies (with respect to number of events with three leptons or more) in excess of 50% in scenarios yielding measurable signals in the amount of data collected.

4 Results

At the end of the multilepton selection (including the last cut on $\not{E}_T$), and based on MC predictions for SM processes, the total number of SM background events expected for the multilepton channel in 34 pb^{-1} worth of data is $0.109 \pm 0.023^{+0.036}_{-0.025}$. No events in data pass all cuts in the multilepton event selection. Virtually all of the SM backgrounds come from $t\bar{t}$ events, with Z backgrounds contributing less than 0.01 events in total at the end of the event selection. Moreover, thanks to the high lepton multiplicity, and to the additional cuts on jets and $\not{E}_T$, QCD processes are predicted by MC simulations to contribute negligible amounts to the total number of background events. This is corroborated by the very small lepton fake rates measured using data-driven methods developed for the dilepton SUSY channel [32].

The effect of a number of systematic uncertainties on the total number of SM background events has been studied in detail, including effects from: jet energy scale and the jet energy resolution; lepton energy scale and lepton energy resolution (for electrons and muons separately); scaling factors that account for small differences between data and MC simulation for lepton description and lepton trigger efficiencies; uncertainty on theoretical cross-sections; uncertainties on parton density functions (PDF); multiple proton-proton collisions (pile-up). Of these, jet energy scale (∼12%) as well as electron energy scale (∼20%) and electron energy resolution (∼10%) are amongst the dominant ones, together with pile-up (∼11%) and MC cross-sections (∼10%). Effects from limited MC statistics have been taken into account when calculating the systematic uncertainty for MC samples that are seen to contribute to the SM backgrounds. Effects on electron reconstruction from problematic regions in the electromagnetic calorimeter during the 2010 run [27] have also been studied and found not to be dominant.

In the 34 pb^{-1} analysed, a total of 19 events with at least three leptons with p_T above threshold have been observed where 16.6 ± 1.3 are expected. None of these have four or more leptons with p_T above threshold. Only 10 events pass the Z-mass veto stage and of these none pass the p_T cut on jets. There are 3 events with $\not{E}_T > 50$ GeV, but all of them either fail the p_T cut on jets, or the Z-mass veto, or both. The expected number of multilepton events from SM sources can be seen in Table 1, where events have also been distinguished according to the flavour of the three leptons. The number of observed events in data is also given in each channel. Reasonable agreement is seen between data and MC, within uncertainties.

Table 1: Number of SM trilepton events with leptons with p_T above threshold expected in the various channels, as predicted by the MC simulation, and corresponding number of observed events in data. No cut on jets, $\not{E}_T$ or SFOS pairs invariant mass is applied at this stage. Uncertainties shown correspond to statistical and systematic uncertainties summed in quadrature. MC numbers are normalised to 34 pb^{-1}.

Multilep. events	All	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
$t\bar{t}$	0.68±0.16	0.032±0.016	0.24±0.07	0.31±0.08	0.096±0.030
Z backgrounds	15.6±1.3	3.8±0.8	1.60±0.34	7.9±1.0	2.4±0.4
Other backgrounds	0.28±0.13	0.02±0.14	0.03±0.06	0.21±0.09	0.01±0.11
Total SM	16.6±1.3	3.8±0.8	1.9±0.4	8.4±1.0	2.5±0.4
Data	19	2	1	10	6

The p_T distribution of the three leading leptons in the 19 events can be seen in Figures 1(a)-1(c), while the invariant mass of SFOS lepton pairs is displayed in Figure 1(d). The jet multiplicity is shown in Figure 2(a), while the p_T distributions of the two leading jets in multilepton events with jets can be seen in Figures 2(b)-(c), respectively. Figure 2(d) shows the missing transverse energy $\not{E}_T$ in multilepton events with lepton p_T above threshold. For all distributions, agreement between data and expected SM backgrounds is observed within uncertainties. For reference, two SUSY benchmark scenarios are also shown in the same plots: one (labelled mSGpt) is an mSUGRA scenario with parameters $(m_0, m_{1/2}, A_0)$ = $(80, 180, 0)$ GeV, $\tan\beta = 3$ and $\mu > 0$; the second one (labelled PGpt1) is a point in the "light neutralino" PhenoGrid3 scenario discussed below, with sparticle masses $m_{\tilde{g}} = 510$ GeV, $m_{\tilde{q}} = 500$ GeV, $m_{\tilde{\chi}_2^0} = 400$ GeV, $m_{\tilde{l}_L} = 250$ GeV, and $m_{\tilde{\chi}_1^0} = 100$ GeV. For the considered integrated luminosity, these two scenarios would correspond to 6.1 ± 1.4 (mSGpt) or 10.9 ± 2.6 (PGpt1) signal events at the end of the selection, including the cut on $\not{E}_T$. The dominant systematics for these signal points are the cross-section (~8-15%), PDF and scale (~10%), luminosity (~11%) and pile-up (~11%) uncertainties.

Limits on SUSY parameters are calculated using a profile-likelihood ratio method as detailed in [33]. The likelihood function L is expressed as a convolution of a Poisson pdf describing the number of observed events, with another pdf that represents the systematic uncertainties. The latter is a convolution of the separate sources of systematic uncertainty, each one of them modelled with a Gaussian pdf. These are the uncertainties on the jet energy scale, the electron energy scale and the luminosity, and then all other systematic uncertainties on the background and all other uncertainties on the signal. Uncertainties on jet energy scale, electron energy scale and luminosity act with 100% correlation on both signal and background, while the other two act on background or signal only, respectively. Using the observed numbers of data events and background expectations, we place an upper limit at 95% C.L. of 62 fb on the cross section times branching ratio times acceptance of new physics processes producing multilepton events with jets and $\not{E}_T$.

Within the mSUGRA/CMSSM framework, the results are interpreted as limits in the $m_0 - m_{1/2}$ plane, for the $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$ slice of the model. A grid in a more general MSSM 24-parameter framework is also studied. For this MSSM–based model 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 third-generation sfermions are set to 2 TeV, and common squark mass and slepton mass parameters are assumed for the first two generations. The remaining free parameters are the three gaugino masses and the squark and slepton masses. Two grids in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane are generated: one with a compressed spectrum yielding

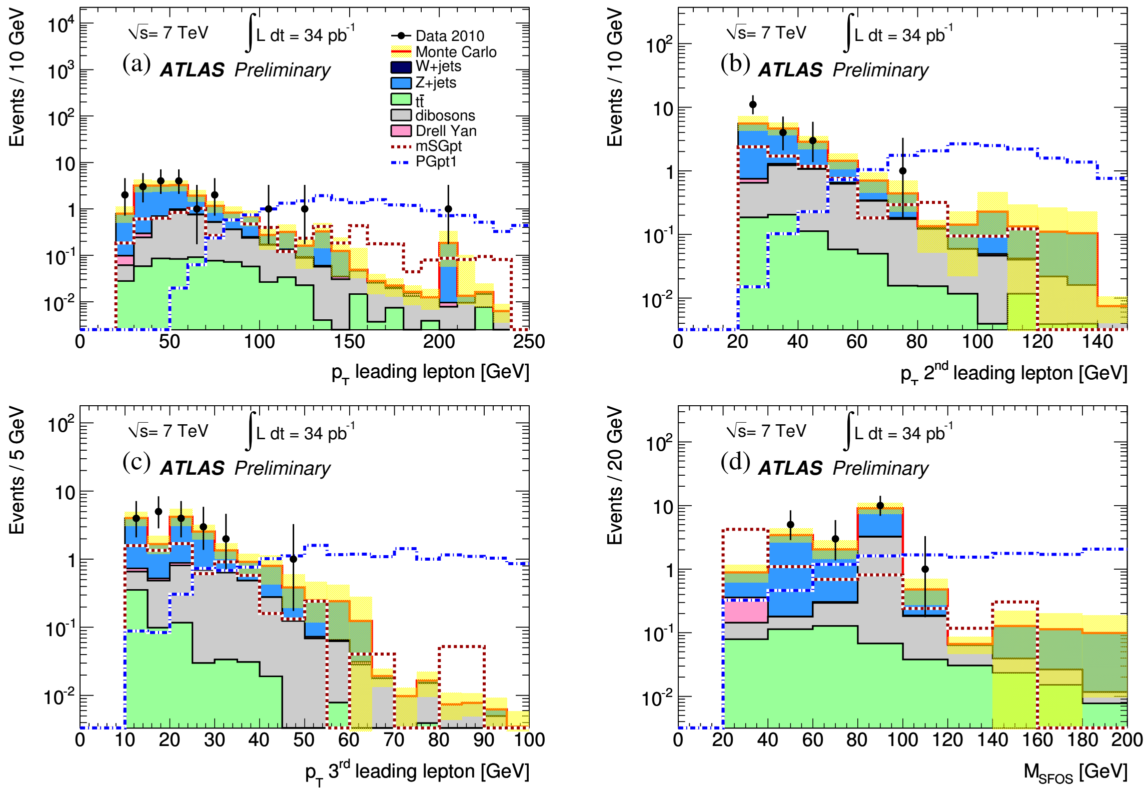

Figure 1: Lepton distributions in data, along with simulated SM and SUSY samples (see text for details): p_T of the (a) leading, (b) second-leading and (c) third-leading lepton; and (d) dilepton invariant mass for SFOS pairs in the event. The yellow bands show the statistical and systematic uncertainty summed in quadrature. Distributions are shown for multilepton events with lepton p_T above threshold, as discussed in the text. MC distributions are normalised to 34 pb^{-1}.

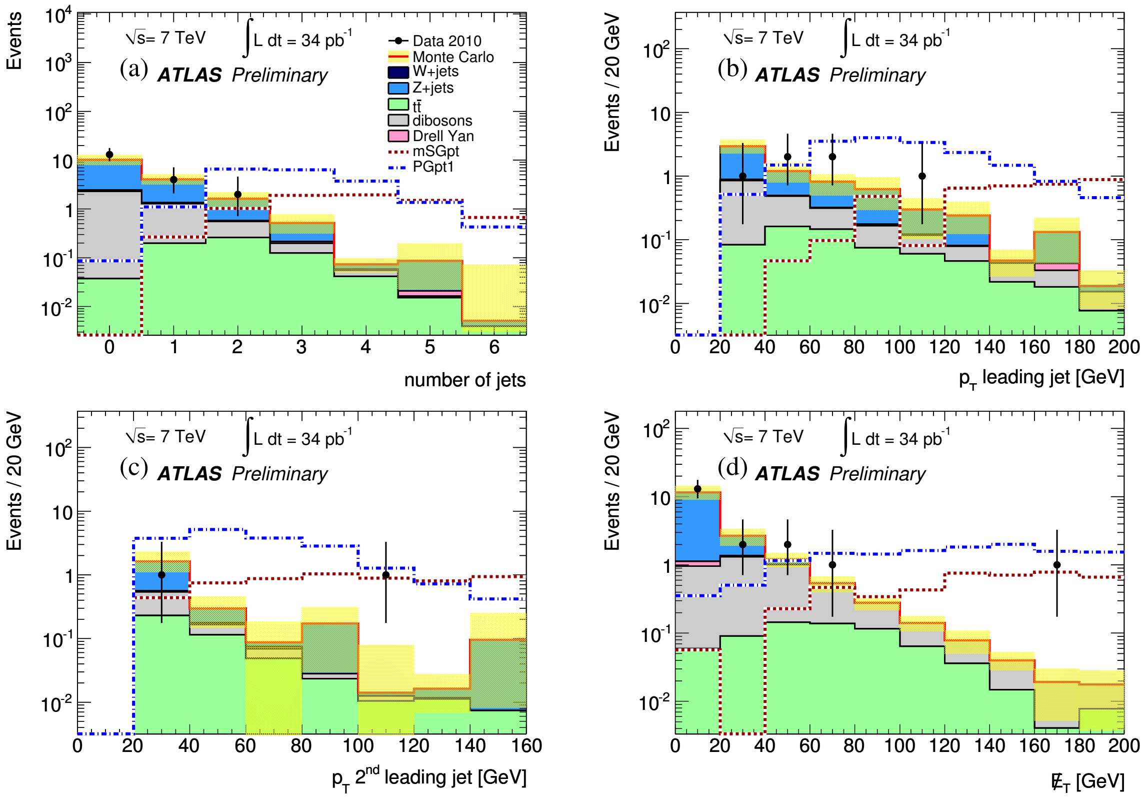

Figure 2: Jet and $\not\!\!E_T$ distributions observed in data, along with simulated SM and SUSY samples (see text for details): (a) number of jets; p_T of the (b) leading and (c) second-leading jet in events where jets are present; and (d) missing transverse energy. The yellow bands show the statistical and systematic uncertainties summed in quadrature. Distributions are shown for multilepton events with lepton p_T above threshold, as discussed in the text. MC distributions are normalised to 34 pb^{-1}.

a soft final state kinematics, defined by $m_{\tilde{\chi}^0_2} = M - 50$ GeV, $m_{\tilde{\chi}^0_1} = M - 150$ GeV and $m_{\tilde{l}_L} = M - 100$ GeV, where M is the minimum of the gluino and squark mass ("compressed spectrum" models); and one with a very light LSP, yielding a harder spectrum of leptons, jets and $\not\!\!E_T$ with $m_{\tilde{\chi}^0_2} = M - 100$ GeV, $m_{\tilde{\chi}^0_1} = 100$ GeV and $m_{\tilde{l}_L} = M/2$ GeV ("light neutralino" models). There are referred to as "PhenoGrid2" grids. Two other grids (labelled "PhenoGrid3") are obtained from these by pushing right-handed squarks and sleptons to high mass values.

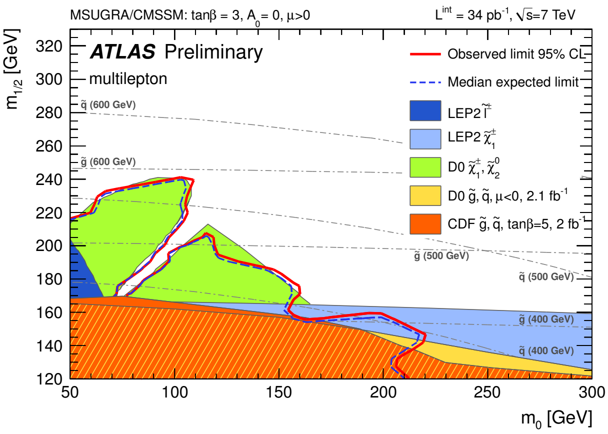

Figure 3: Expected and observed exclusion limits in mSUGRA. The dashed blue line corresponds to the expected 95% C.L. limit, while the red line is the observed 95% C.L. limit. Exclusion limits from other experiments are also shown (see text for details).

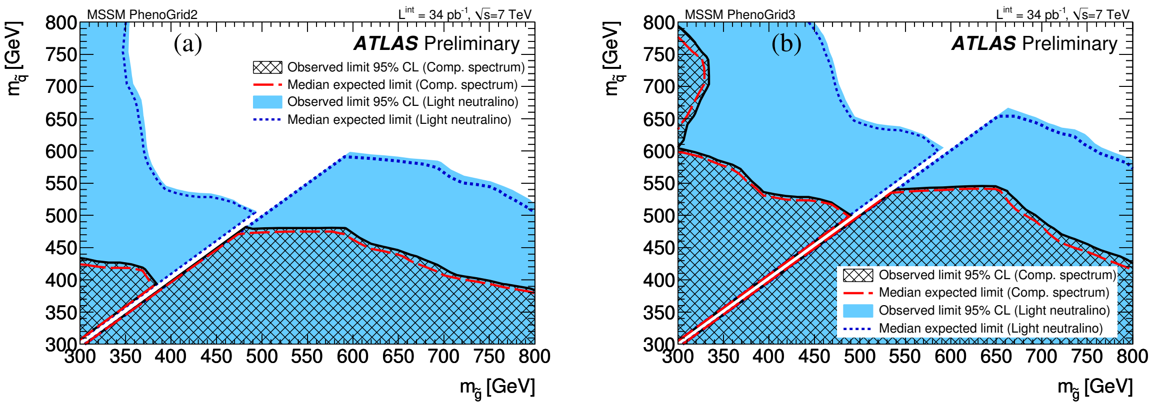

Figure 4: Expected and observed exclusion limits in the MSSM PhenoGrid2 (a) and PhenoGrid3 (b) scenarios discussed in the text. The dashed red line corresponds to the expected 95% C.L. limit of the compressed spectrum and the hatched area corresponds to the observed 95% C.L. limit of the compressed spectrum. The dashed blue line corresponds to the expected 95% C.L. limit of the light neutralino spectrum and the light blue area corresponds to the observed 95% C.L. limit of the light neutralino spectrum.

The expected and observed limits in the $m_0 - m_{1/2}$ mSUGRA plane are shown in Figure 3, together with exclusion limits from other experiments [6, 34, 35]. In the excluded region the uncertainty from limited signal MC statistics is of the order of 10 – 20% and is amongst the dominant uncertainties that have an effect on the measured limit. The mSUGRA region excluded by ATLAS is similar to that excluded by the Tevatron experiments based on the study of trilepton final states.

For the MSSM grids the results are shown in the $m_{\tilde{g}} - m_{\tilde{q}}$ plane in Figure 4(a) (PhenoGrid2) and Figure 4(b) (PhenoGrid3). The empty strip at $m_{\tilde{g}} = m_{\tilde{q}}$ is due to the discontinuity in the lepton branching ratios, which may drop dramatically for $m_{\tilde{g}} > m_{\tilde{q}}$ if the $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$ decay becomes dominant. As a consequence, limits on the squark mass are given for $m_{\tilde{g}} = m_{\tilde{q}} + 10$ GeV. Under this assumption, the limits on the squark mass are 480 (600) GeV in the "compressed spectrum" ("light neutralino") PhenoGrid2 scenarios, while the corresponding limits in PhenoGrid3 scenarios are 540 (670) GeV.

5 Conclusions

A first analysis of ATLAS data to search for SUSY signatures in multilepton final states has been performed, based on a total integrated luminosity of 34 pb^{-1} collected in 2010 at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. An event selection based on the presence of at least three well isolated leptons, jets, and moderate missing transverse energy in the event is seen to reduce SM backgrounds to approximately 0.1 events. This selection is expected to yield measurable SUSY signals in a range of SUSY scenarios. No significant excess of events has been seen in the analysed data sample, where observations are found to agree with SM expectations within uncertainties. No events in data pass all cuts in the multilepton event selection. An mSUGRA interpretation of this result leads to an exclusion limit that is compatible with existing results from trilepton SUSY searches at the Tevatron. Limits in less constrained MSSM scenarios than mSUGRA have also been extracted.

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