SEARCH FOR ELECTRO-WEAK PRODUCTION OF SUSY PARTICLES IN EVENTS WITH LEPTONS IN THE FINAL STATE WITH THE ATLAS DETECTOR AT THE LHC*

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Searches for electro-weak production of supersymmetry with multiple leptons in the final state are presented. The analyses use proton–proton collision data provided by the LHC and recorded with the ATLAS detector at the centre-of-mass energy of $\sqrt{s} = 7$ TeV in 2011 and 8 TeV in 2012. Final states with exactly two leptons, exactly three leptons or at least four leptons are studied.

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1. Introduction

The Large Hadron Collider (LHC) at CERN started operation in 2010. One of the LHC experiments is ATLAS — a multi-purpose particle detector with a forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle. Four superconducting magnet systems comprise a thin solenoid surrounding the inner tracking detector and barrel and endcap toroids to support the muon spectrometer [1]. One of ATLAS main goals, besides testing the Standard Model (SM), is the search for supersymmetry (SUSY) [2–10]. In SUSY models, a super-partner with the same quantum numbers but different spin is associated to each SM particle. Supersymmetry can provide an explanation for Dark Matter, lead to unification of fundamental forces, and solve the hierarchy problem [11–13].

Charged leptons with high transverse momentum (p_{T}) can be produced through the decays of supersymmetric neutralinos, charginos and sleptons.

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Sleptons $\tilde{l}$ are the supersymmetric partners of leptons, and neutralinos $\tilde{\chi}_j^0$ $(j = 1, 2, 3, 4)$ or charginos $\tilde{\chi}_i^{\pm}$ $(i = 1, 2)$ correspond to the mass eigenstates formed from the linear superposition of the supersymmetric partners of the Higgs boson and electro-weak gauge bosons. The search for the existence of light charginos and neutralinos is well motivated by the assumption of naturalness [14, 15]. These sparticles can be produced at the centre-of-mass energies provided by the LHC. We present searches for the electro-weak production of neutralinos, charginos and sleptons.

2. *R*-parity conserving SUSY

R-parity (P_R) is defined by the baryon number B, lepton number L, and spin quantum number s as

$$P_R = (-1)^{2s+3B+L} \,. \tag{1}$$

If R-parity is conserved [16–20], SUSY particles must be produced in pairs. These would subsequently decay through cascades involving other particles, until the lightest SUSY particle (LSP), which is stable, is produced. The LSP is neutral, weakly interacting, and cannot be detected in a typical spectrometer. Thus the expected detector signature can contain multiple SM leptons as well as high missing transverse momentum (with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) from the undetected neutrinos ν and LSP neutralinos $\tilde{\chi}_1^0$.

For the analyses presented here, only electrons and muons are considered as leptons.

2.1. Two leptons in the final state, $\sqrt{s} = 7$ TeV, 4.7 fb^{-1}

Pair produced charginos can decay via intermediate sleptons as in $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \rightarrow 2\ l\tilde{\nu}(\nu\tilde{l}) \rightarrow l^+l^-\nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$. The decay process of pair produced sleptons also can lead to exactly two leptons in the final state: $\tilde{l}^+\tilde{l}^- \rightarrow l^+l^-\tilde{\chi}_1^0\tilde{\chi}_1^0$.

The analysis only uses events which pass a basic data event cleaning and which have well reconstructed electrons, muons and jets [21]. Preselected events are required to have a reconstructed primary vertex with at least five tracks. A combination of single and dilepton triggers is used and the electrons or muons in the final state need to have triggered the events. Electrons need to be reconstructed with 'tight' quality criteria, have p_{T} larger than 10 GeV as well as pseudorapidity[1] $|\eta| < 2.47$, and need to be isolated.

[1] 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 is used by ATLAS. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. In the transverse plane, cylindrical coordinates (r, ϕ) are used, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ by $\eta = -\ln(\tan(\frac{\theta}{2}))$.

Muons are reconstructed using either a full muon spectrometer track matched to an ID track, or a partial muon spectrometer track matched to an ID track. The p_{T} needs to be larger than 10 GeV, $|\eta| < 2.4$, and the muons also need to be isolated. The invariant mass of the same-flavour-opposite-sign (SFOS) dilepton pair must be larger than 20 GeV.

Events with an invariant dilepton mass close to the nominal Z-boson mass (the so-called Z-candidates) as well as events with any signal jets are vetoed in a signal region called SR-m_{T2}. This signal region is described in the following. The leptons can be of the same or different flavour and need to be oppositely charged. $E_{\mathrm{T}}^{\mathrm{miss}}$ needs to be larger than 40 GeV to further purify the selection of signal events.

The definition of the transverse mass m_{T} is

$$m_{\mathrm{T}} = \sqrt{2E_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{l} \left(1 - \cos\Delta\phi_{l,E_{\mathrm{T}}^{\mathrm{miss}}}\right)}\,, \tag{2}$$

where p_{T}^{l} denotes the transverse momentum of a lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$ is the missing transverse energy and $\Delta\phi_{l,E_{\mathrm{T}}^{\mathrm{miss}}}$ is the angle between the lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$ component in the transverse plane. The distribution of m_{T} of two decay products has an endpoint at the mass of the decaying particle.

A kinematic variable which provides sensitivity to the above scenarios is the so-called stransverse mass variable m_{T2}, which is computed using m_{T} [21].

For calculating m_{T2}, the decomposition of the $E_{\mathrm{T}}^{\mathrm{miss}}$ vector, $\vec{q}_{\mathrm{T}}$ or $\vec{r}_{\mathrm{T}}$, is used instead of $E_{\mathrm{T}}^{\mathrm{miss}}$. The vectors satisfy $\vec{q}_{\mathrm{T}} + \vec{r}_{\mathrm{T}} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$. The maximum m_{T} of an event with respect to the p_{T} of lepton l_1 (higher p_{T}) or lepton l_2 (lower p_{T}) is computed. To then obtain m_{T2}, this maximum is minimised by the choice of the possible decompositions of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$

$$m_{\mathrm{T2}} = \min_{\vec{q}_{\mathrm{T}}+\vec{r}_{\mathrm{T}}=\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max\left(m_{\mathrm{T}}\left(\vec{p}_{\mathrm{T}}^{\,l_1}, \vec{q}_{\mathrm{T}}\right), m_{\mathrm{T}}\left(\vec{p}_{\mathrm{T}}^{\,l_2}, \vec{r}_{\mathrm{T}}\right)\right)\right]. \tag{3}$$

For events with identical particles which are produced in pairs and which decay into final states with two visible charged leptons and two invisible particles, it can be shown that the stransverse mass m_{T2} has a characteristic kinematic endpoint [22]. The variable is bound by the chargino mass or by the slepton mass.

SM background processes which have the same signature as the SUSY signal are fully leptonic $t\bar{t}$, $Z\gamma$, Z/γ^*+jets, WW, WZ, ZZ, W^+W^-+jets, single top Wt, $t\bar{t}+W$, $t\bar{t}+Z$, or $b\bar{b}$ production.

Requiring $m_{\mathrm{T2}} > 90$ GeV suppresses much of the diboson background. This can be deduced from the shape of the distributions shown in Fig. 1. Three more signal regions are designed for this analysis which are selected by requiring:

— oppositely charged leptons, a jet-veto, a Z-veto, and $E_{\rm T}^{\rm miss}$ >100 GeV (SR-OSjveto),

— same-sign leptons, a jet-veto, and $E_{\rm T}^{\rm miss}$ >100 GeV (SS-jveto),

— and oppositely charged leptons with the same flavours and at least two jets in the final state, a Z-veto, a b-jet veto, a veto on events which fulfil a special requirement on the contransverse mass $m_{\rm CT}$ to suppress top background, and $E_{\rm T}^{\rm miss}$ >50 GeV (SR-2jets) [21].

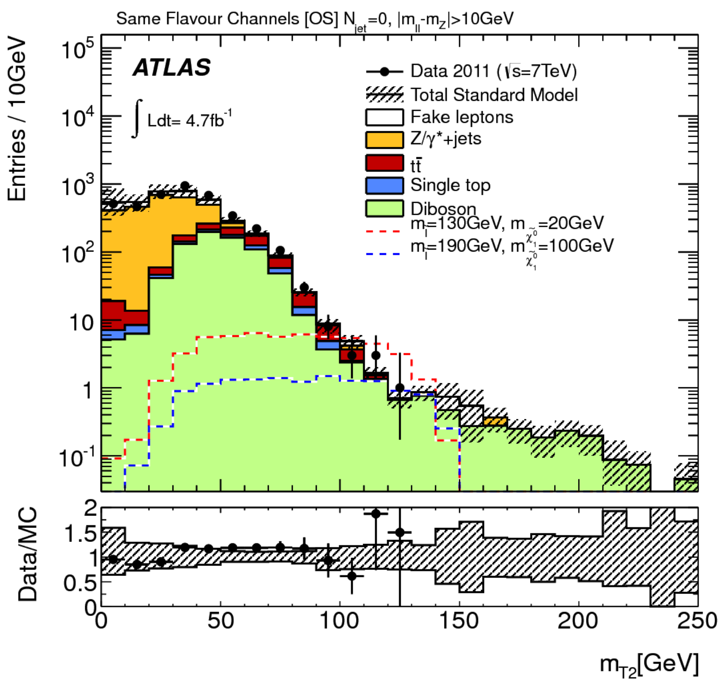

Fig. 1. Analysis with two leptons in the final state. Distribution of the stransverse mass $m_{\rm T2}$ in the signal region SR-$m_{\rm T2}$ [21]. Only the same flavour (SF) channels are shown. All components are taken from MC except for 'fake leptons' which are estimated data-driven. Two signal points for a simplified model with direct slepton pair production are illustrated by dashed lines.

The irreducible background which contributes to two prompt and isolated leptons is evaluated by normalising MC to data in appropriate control regions for top, $Z+X$ and WW decays. The probabilities for heavy and light flavour jets faking prompt, isolated leptons in single top, $t\bar{t}$, W+ jets and $b\bar{b}$ processes (reducible background) are estimated with data-driven techniques.

A comparison of the numbers of expected and observed events does not indicate physics beyond the Standard Model. This allows to interpret the results of this analysis in simplified models where only one single decay mode and special sparticle masses are possible. For the exclusion limits shown in Fig. 2 (left), the scenario where wino-like charginos decay into the LSP via intermediate sleptons is considered. Only the LSP and the chargino masses are varied. The masses of the squarks, gluinos and third generation supersymmetric partners of the fermions are set to 2 TeV. The intermediate sleptons are left-handed and include staus $\tilde{\tau}$ and sneutrinos $\tilde{\nu}$ of mass $m_{\tilde{\nu}} = m_{\tilde{l}_{\mathrm{L}}} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^\pm}/2)$. For the plot in Fig. 2 (left), the best expected limits are obtained by using for each signal point the signal region which provides the best expected p-value, which is calculated with the modified frequentist $\mathrm{CL_s}$ prescription for testing the statistical hypothesis of the SM without a SUSY extension [23]. Chargino masses between 110 and 340 GeV can be excluded for a neutralino mass of 10 GeV.

Signal samples of the direct slepton pair production were generated in the framework of the phenomenological minimal supersymmetric SM (pMSSM) [24, 25]. In Fig. 2 (right), the exclusion limits are shown in the neutralino–slepton mass plane and are based on SR-m_{T2}. A common slepton mass for selectrons and smuons can be excluded between 85 and 195 GeV for neutralino masses of 20 GeV. This extends the exclusion limits from LEP for right-handed smuons [21].

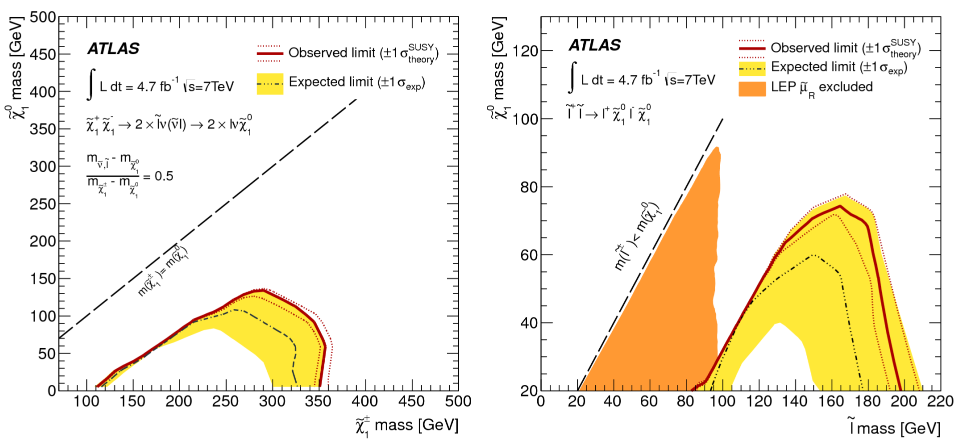

Fig. 2. Analysis with two leptons in the final state. The dashed and solid lines show the 95% C.L. expected and observed limits for a simplified model with pair production of charginos which decay via intermediate sleptons (left). Exclusion limits are also shown for the pMSSM slepton pair production (right) [21].

2.2. Three leptons in the final state, $\sqrt{s} = 8$ TeV, $\int \mathcal{L}\, dt = 13.0$ fb^{-1}

Pair produced charginos and neutralinos can decay into final states with three charged leptons via intermediate sleptons as in $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \tilde{\nu}(\nu\tilde{l})l^+\tilde{l}^+(l^-\tilde{l}^-) \to \nu l^+ l^- \tilde{\chi}_1^0\tilde{\chi}_1^0$ or via SM gauge bosons as in $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to W^+(W^-)\tilde{\chi}_1^0 Z^0\tilde{\chi}_1^0 \to l\nu l^+ l^- \tilde{\chi}_1^0\tilde{\chi}_1^0$. To select SUSY events, three signal regions were designed [26]. The requirements on the p_{T} of the leptons assure that the lepton triggers are fully efficient. A combination of single and dilepton triggers is used.

The signal leptons further need to be well reconstructed and the events pass similar cleaning cuts as described in Sec. 2.1. To suppress background from low-mass resonances, events with the invariant mass of a SFOS dilepton pair below 12 GeV are rejected. In the signal regions SR1a and SR1b, events with Z-candidates are vetoed and $E_{\mathrm{T}}^{\mathrm{miss}} > 75$ GeV is required. In order to suppress background events where heavy-flavour quarks decay into leptons, events with b-tagged jets are rejected. These requirements define the signal region SR1a. To be more sensitive to scenarios with large mass splitting between heavy gauginos and the LSP, the signal region SR1b demands in addition that all three leptons have $p_{\mathrm{T}} > 30$ GeV and that $m_{\mathrm{T}} > 110$ GeV.

The transverse mass m_{T} is also for this analysis defined as in equation (2) where p_{T}^{l} is the transverse momentum of the lepton that is not forming the dilepton pair with the invariant mass closest to the nominal Z-boson mass.

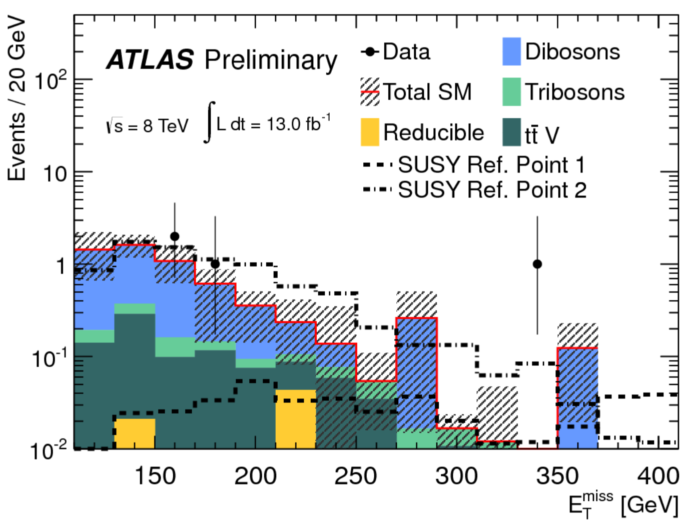

Fig. 3. Analysis with three leptons in the final state. Distribution of the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ in the signal region SR2 [26]. 'SUSY Ref. Point 1' shows the yields for a simplified model with intermediate sleptons, 'SUSY Ref. Point 2' for a simplified model with no sleptons.

Sensitivity to the scenario where the neutralino decays into a Z-boson is achieved by introducing a third signal region SR2 which does require a Z-candidate as well as m_{T} >110 GeV to suppress WZ background. From the shape of the $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions shown in Fig. 3, it can be seen that requiring $E_{\mathrm{T}}^{\mathrm{miss}}$ larger than 120 GeV improves the selection of SUSY signal events and further suppresses background processes.

The SM backgrounds are evaluated using a combination of MC simulation and data-driven techniques. The WZ decay is the largest irreducible background. To estimate this background from data, an appropriate control region was defined.

No significant excess of events is observed in the signal regions. The observed and expected numbers of events in the signal regions are used to place limits on the SUSY particle masses. The results of the analysis are interpreted *e.g.* in a simplified model which only considers the decay of a neutralino via gauge bosons, where the slepton masses are fixed by the gaugino masses as in the following: $m_{\tilde{\nu}} = m_{\tilde{l}_{\mathrm{L}}} = (m_{\tilde{\chi}_1^0}+m_{\tilde{\chi}_1^\pm})/2$. Exclusion limits can be shown as a function of the degenerate chargino $\tilde{\chi}_1^\pm$ and neutralino $\tilde{\chi}_2^0$ masses and of the neutralino $\tilde{\chi}_1^0$ masses. Only the masses and the decay modes of the relevant particles $(\tilde{\chi}_1^\pm, \tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\nu}, \tilde{l}_{\mathrm{L}})$ are treated as free parameters. In the exclusion plot shown in Fig. 4 (left), SR2 is responsible for the larger exclusion area far from the diagonal. SR1a is most sensitive in the region with small mass differences between $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$.

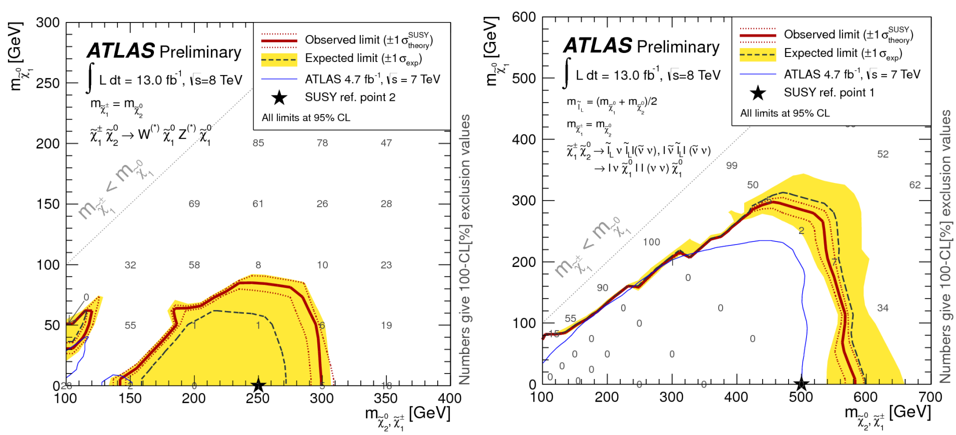

Fig. 4. Analysis with three leptons in the final state. Exclusion limits shown for a simplified model with decay of a neutralino via gauge bosons (left) and via intermediate sleptons (right) [26]. The dashed and solid lines show the 95% CL$_s$ expected and observed, respectively.

A simplified model where the chargino and the neutralino both decay via intermediate sleptons is used in the exclusion plot shown in Fig. 4 (right). The Z-depleted signal region SR1b has the best sensitivity. Degenerate chargino and neutralino masses up to 580 GeV can be excluded for large mass differences from the lightest neutralino $\tilde{\chi}_1^0$ [26].

3. *R*-parity violating SUSY

In SUSY models where the R-parity is not conserved, the baryon and lepton numbers are also no longer conserved [27, 28]. The corresponding super-potential term W_{RPV} in the Lagrangian contains three Yukawa couplings λ_{ijk}, $\lambda^{'}_{ijk}$, $\lambda^{''}_{ijk}$, where the indices i, j, k refer to quark and lepton generations [16–20]. As a consequence of R-parity violation (RPV), the proton would have a very short life time. However, a special choice of the RPV couplings, $\lambda_{121} \neq 0$ or $\lambda_{122} \neq 0$ while all other λ_{ijk}, $\lambda^{'}_{ijk}$, $\lambda^{''}_{ijk}$ are set to zero, can protect the proton from decaying for some 10^{32} years. Moreover, the LSP is no longer stable but can decay promptly [29]. As another consequence of RPV, the neutralino is no more a good Dark Matter candidate. However, some special SUSY models assume that $\tilde{\chi}_1^0$ can decay into a gravitino and that a gravitino as a supersymmetric partner to the graviton could make up Dark Matter [30].

3.1. Four or more leptons in the final state, $\sqrt{s} = 8$ TeV, $\int \mathcal{L}\, dt = 13.0$ fb^{-1}

In a SUSY scenario where RPV is assumed, the lightest neutralino can decay via intermediate sleptons or sneutrinos into final states with two charged leptons, as shown in Fig. 5 (left). The signature of such a decay is high lepton multiplicity but low $E_{\mathrm{T}}^{\mathrm{miss}}$.

For SUSY searches in final states with at least four leptons [31], all the events must pass standard cleaning cuts as described in Secs. 2.1 and 2.2 before going through further selection. The events must have been triggered in the same way as described in Sec. 2.2 and with the same p_{T} criteria for the leptons. The leptons must also be isolated with respect to the transverse momentum of tracks in a spatial cone with size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the object. This transverse momentum of tracks is required to be smaller than 16% (12%) of the p_{T} of the electron (muon) candidate. The dilepton mass of any SFOS pair must be above 12 GeV.

The analysis is sensitive to scenarios where the RPV LSP produces neutrinos in the final state as well as to models with large visible particle multiplicities, as a consequence from sparticle cascade decays. For the first case, the selection of signal events can be purified by vetoing events with Z-candidates and by requiring $E_{\mathrm{T}}^{\mathrm{miss}}$ higher than 50 GeV (see Fig. 5 (right)).

These requirements define the first signal region SR1. For the latter scenario and to define the signal region SR2, one takes advantage of the effective mass m_{eff}. This variable is defined as

$$m_{\text{eff}} = E_{\text{T}}^{\text{miss}} + \sum_{\mu} p_{\text{T}}^{\mu} + \sum_{e} p_{\text{T}}^{e} + \sum_{j} p_{\text{T}}^{j}\,, \tag{4}$$

where p_{T}^{μ}, p_{T}^{e} and p_{T}^{j} are the transverse momenta of the muons μ, electrons e and jets j. In SR2, m_{eff} is required to exceed 300 GeV.

The contribution of irreducible background processes with real leptons from ZZ, $t\bar{t}$Z, $t\bar{t}WW$ and ZWW decays is determined with corresponding MC samples and its validity is verified with well-defined validation regions. The reducible background with at least one fake lepton from WZ, $t\bar{t}$, $t\bar{t}W$, WWt or Z processes is estimated with a weighting method which is applied to events with signal leptons and leptons which fulfil loose reconstruction criteria but are not signal leptons.

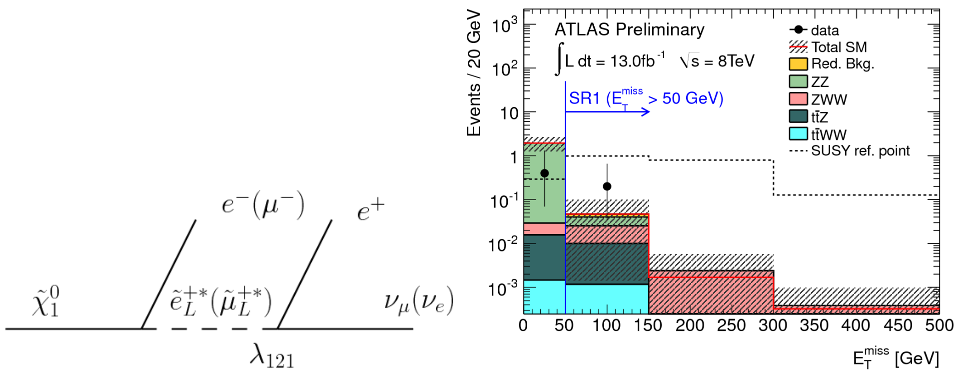

Fig. 5. RPV analysis with at least four leptons in the final state. Left: Illustration of $\tilde{\chi}_1^0$ decay. Right: The distribution of missing transverse energy $E_{\text{T}}^{\text{miss}}$ in events with at least four leptons and no Z-candidate for the signal region SR1 [31]. 'SUSY Ref. point' shows the yields for a RPV wino simplified model with $\lambda_{121} > 0$.

Good agreement between data and SM expectations is observed in both signal regions. Six RPV simplified models for electro-weakly produced SUSY, where the pair produced next-to lightest sparticle (NLSP) promptly decays into a neutralino LSP are considered. All sparticle masses except for the LSP and NLSP masses are set to 4.5 TeV. One of the Yukawa couplings, either λ_{121} or λ_{122}, is set to non-zero while the other couplings are set to 0.

As an example, one can assume an electro-weakly produced wino-like chargino which decays into a $\tilde{\chi}_1^0$ and a W-boson an in $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$, where the W may be virtual. The exclusion limits based on the observed and expected numbers of events in the signal regions are shown in Fig. 6. Chargino masses up to 710 GeV can be excluded for neutralino masses above 10 GeV. The previous ATLAS exclusion area (dark grey/purple) as well as the LEP (light grey/green) and the Tevatron exclusion areas (grey/orange) are extended by the new limit [31].

Two other scenarios which were also considered for the interpretation of the results are the decay of left-handed sleptons or sneutrinos as in $\tilde{l}_{\mathrm{L}} \to l\tilde{\chi}_1^0$ and $\tilde{\nu}_l \to \nu_l\tilde{\chi}_1^0$. The exclusion plots can be seen in [31].

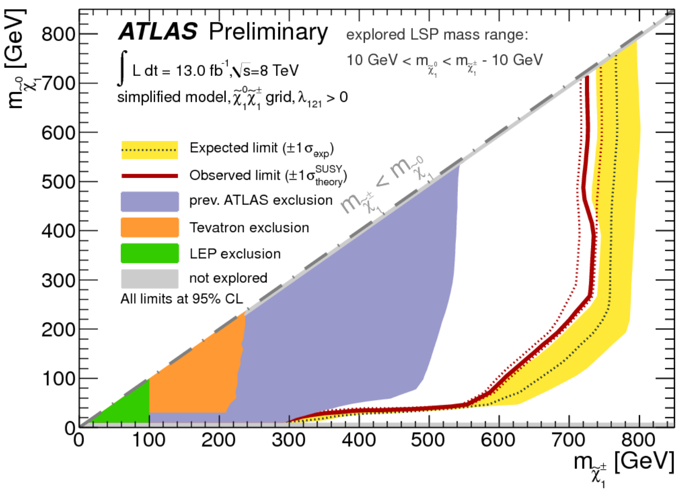

Fig. 6. RPV analysis with at least four leptons in the final state. Exclusion limits shown for the RPV wino simplified model, where $\lambda_{121} > 0$ at 95% C.L. [31].

4. Conclusion

A selection of analyses looking for SUSY with leptons in the final states was presented based on data delivered by the LHC and collected by ATLAS in 2011 at $\sqrt{s} = 7$ TeV or at $\sqrt{s} = 8$ TeV in 2012. The analyses are sensitive to electro-weak production. Limits on slepton, neutralino and chargino masses have been derived using simplified models. The results improve on the previous searches for electro-weak SUSY.

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