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Searches for electroweak production of supersymmetric gauginos and sleptons with the ATLAS detector

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A search for the electroweak production of charginos, neutralinos and sleptons decaying to final states involving two or three electrons or muons is presented. The analysis is based on 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV proton-proton collisions recorded by the ATLAS detector at the Large Hadron Collider. No significant deviations from the Standard Model expectation are observed and results are interpreted in a range of scenarios based on simplified models. Considered scenarios include the associated production of mass-degenerate next-to-lightest neutralino and lightest chargino, followed by their decays to final-state leptons and lightest neutralinos via either sleptons or Standard Model gauge bosons; direct production of chargino pairs, which in turn decay to leptons and lightest neutralinos via intermediate sleptons; and slepton pair production, where each slepton decays directly to the lightest neutralino and a lepton. Stringent limits at 95% confidence level are placed on the masses of relevant supersymmetric particles in each of these scenarios.

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1. Introduction

Supersymmetry (SUSY) [1, 2, 3, 4, 5] is one of the most searched extensions of the Standard Model (SM). In its minimal realization (the Minimal Supersymmetric Standard Model, or MSSM) [6], it predicts a new bosonic (fermionic) partner for each fundamental SM fermion (boson), as well as an additional Higgs doublet. These new SUSY particles, or sparticles, can provide an elegant solution to the gauge hierarchy problem [7]. In R-parity conserving models [8], sparticles can only be produced in pairs and the lightest supersymmetric particle (LSP) is stable. This is typically the lightest neutralino $\tilde{\chi}_1^0$, which can then provide a natural candidate for dark matter [9]. When produced in the decay of heavier SUSY particles, a neutralino LSP would escape detection, leading to an amount of missing transverse momentum (of magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) significantly larger than for SM processes, a canonical signature that can be exploited to extract SUSY signals.

This proceedings contribution presents a set of searches for the electroweak production of charginos, neutralinos and sleptons decaying to final states with two or three leptons [10]. These searches exploit proton-proton collision data of an integrated luminosity of 36.1 fb^{-1} delivered by the Large Hadron Collider (LHC) [11] at a center-of-mass energy of $\sqrt{s} = 13$ TeV, and collected and reconstructed with the ATLAS detector [12].

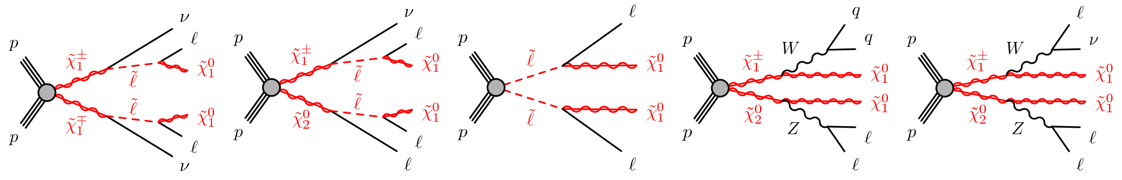
2. SUSY Scenarios

Simplified models [13] are considered in order to explore the direct production of $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ and $\tilde{\ell}\tilde{\ell}$ pairs, in instances where heavier sparticles decay to final states including exactly two or three charged leptons (electrons or muons), two lightest neutralinos and possibly additional SM objects (jets or neutrinos).

In simplified models, the masses of the relevant sparticles are the only free parameters. In particular, the pure wino $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are taken to be mass-degenerate. The same assumption is made for the scalar partners of the left-handed charged leptons and neutrinos as well. Intermediate slepton masses are chosen to be midway between the mass of the heavier charginos and neutralinos and that of the $\tilde{\chi}_1^0$, which is pure bino. For models exploring the $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production, it is assumed that the sleptons are also light and thus accessible in the sparticle decay chains, as illustrated in Figure 1a. Two different classes of models are considered for the $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production: in one case, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ can decay to final-state SM particles plus $\tilde{\chi}_1^0$ via an intermediate left-handed charged slepton or a sneutrino, with a branching ratio of 50% each, as shown Figure 1b; in the other case the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay happens via SM gauge bosons (W/Z), as illustrated in Figures 1d-1e. In models with direct $\tilde{\ell}\tilde{\ell}$ production, each slepton decays to lepton-$\tilde{\chi}_1^0$ with a 100% branching ratio (Figure 1c), and left-handed and right-handed selectrons, smuons and staus are assumed to be degenerate. For the gauge-boson-mediated decays two distinct final states are considered: three-lepton events where both the W and Z boson decay leptonically; or events with two opposite-sign leptons and two jets where the W boson decays hadronically and the Z boson decays leptonically.

3. Search Strategy

In order to maximize the sensitivity to the electroweak production of supersymmetric particles, three different search channels are defined, which relate to the three different signatures:



(a) (b) (c) (d) (e)

Figure 1: Tree-level Feynman diagrams of considered signal processes.

1. **2ℓ+0jets**: targets $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\tilde{\ell}\tilde{\ell}$ pair production, depicted in Figures 1a and 1c, in signal regions with a jet veto and defined using the "stransverse mass" variable, m_{T2} [14], and the di-lepton invariant mass $m_{\ell\ell}$;

2. **2ℓ+jets**: targets $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production with decays via gauge bosons (shown in Figure 1d) to two same-flavor opposite-sign (SFOS) leptons (from the Z boson) and at least 2 jets (from the W boson);

3. **3ℓ**: targets $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production with decays via intermediate $\tilde{\ell}$ or gauge bosons to three lepton final states (shown in Figures 1b and 1e).

The stransverse mass m_{T2} is defined as:

$$m_{\mathrm{T2}} = \min_{q_T}\left[\max\left(m_{\mathrm{T}}(\boldsymbol{p}_{\mathrm{T}}^{\ell_1},\boldsymbol{q}_{\mathrm{T}}),\, m_{\mathrm{T}}(\boldsymbol{p}_{\mathrm{T}}^{\ell_2},\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}-\boldsymbol{q}_{\mathrm{T}})\right)\right] \tag{3.1}$$

where $\boldsymbol{p}_{\mathrm{T}}^{\ell_1}$ and $\boldsymbol{p}_{\mathrm{T}}^{\ell_2}$ are the transverse momentum vectors of the two leptons, and $\boldsymbol{q}_{\mathrm{T}}$ is a transverse vector that minimizes the larger of $m_{\mathrm{T}}(\boldsymbol{p}_{\mathrm{T}}^{\ell_1},\boldsymbol{q}_{\mathrm{T}})$ and $m_{\mathrm{T}}(\boldsymbol{p}_{\mathrm{T}}^{\ell_2},\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}-\boldsymbol{q}_{\mathrm{T}})$, where

$$m_{\mathrm{T}}(\boldsymbol{p}_{\mathrm{T}},\boldsymbol{q}_{\mathrm{T}}) = \sqrt{2(p_{\mathrm{T}}q_{\mathrm{T}}-\boldsymbol{p}_{\mathrm{T}}\cdot\boldsymbol{q}_{\mathrm{T}})} \tag{3.2}$$

The m_{T2} variable provides, in general, good suppression of SM $t\bar{t}$ and WW backgrounds, which have expected kinematic endpoints at the W-boson mass.

In each channel, the signal regions (SRs) require exactly two or three reconstructed charged leptons which satisfy good identification criteria (signal leptons), with vetoes on any additional leptons with loose identification requirements. The leading and sub-leading leptons are required to have transverse momenta $p_{\mathrm{T}} > 25$ GeV and 20 GeV, respectively. However, in the "2ℓ+jets" and "3ℓ" channels additional (tighter) lepton p_{T} requirements are applied.

In the "2ℓ+0jets" channel the leptons are required to be of opposite electric charge sign and events are separated into "same flavor" (SF) events, corresponding to di-electron and di-muon events, and "different flavor" (DF) events (electron-muon). All events are required to have a di-lepton invariant mass $m_{\ell\ell} > 40$ GeV and a veto is applied on events with central jet and b-jet activity ($|\eta| < 2.4$).

In the "2ℓ+jets" channel two inclusive signal regions are defined to target intermediate and large mass splittings between the $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ and the LSP. The sub-leading lepton is also required to have $p_{\mathrm{T}} > 25$ GeV and events must have at least two signal jets with $p_{\mathrm{T}} > 30$ GeV. A b-jet veto is also applied as in the "2ℓ+0jets" channel. A tight requirement on the m_{T2} variable is also used to particularly suppress the $t\bar{t}$ background.

The 3ℓ channel targets $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production and uses kinematic variables such as $E_{\mathrm{T}}^{\mathrm{miss}}$ and the transverse mass m_{T}. Events are required to have exactly three leptons satisfying the signal lepton requirements and zero b-tagged jets. In addition, two of the leptons must form a SFOS pair, as expected in $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ decays. To resolve ambiguities when multiple SFOS pairings are present, the transverse mass value of the unpaired lepton is calculated for each possible SFOS pairing and the lepton that yields the minimum transverse mass is assigned to the W boson. This transverse mass value is denoted by $m_{\mathrm{T}}^{\mathrm{min}}$, and is used alongside $E_{\mathrm{T}}^{\mathrm{miss}}$, jet multiplicity (in the gauge-boson-mediated scenario) and other relevant kinematic variables to define binned signal regions that have sensitivity to $\tilde{\ell}$-mediated and gauge-boson-mediated decays.

4. Backgrounds

The SM backgrounds contributing in the two- and three-lepton final states can be classified into *irreducible* backgrounds, which contain processes leading to events with prompt and isolated leptons, and *reducible* backgrounds, which contain events that either contain at least one "fake" or non-prompt lepton, or where experimental effects (e.g., detector mis-measurement of reconstructed objects, usually jets) lead to a significant amount of artificial $E_{\mathrm{T}}^{\mathrm{miss}}$. Non-prompt leptons can typically originate from a semi-leptonic decay of a b- or c-hadron, from misidentification of a light-flavored jet, or from a photon conversion.

For the two-lepton channels the dominant backgrounds are irreducible processes including SM diboson production, Z/γ+jets and $t\bar{t}$, where diboson processes dominate the "$2\ell + 0$jets" channel whereas the "2ℓ+jets" channel is dominated by SM processes that give an on-shell Z boson (i.e. diboson and Z/γ+jets). In the "2ℓ+jets" channel, the dominant backgrounds are Z/γ+jets and diboson events. For both the "$2\ell + 0$jets" and "2ℓ+jets" channels, reducible background originates from non-prompt leptons mainly arising from multijet, W+jets and single top quark production, all of which can yield one or two of such charged leptons. For the "3ℓ" channel, the irreducible background is mainly dominated by SM WZ diboson processes.

5. Systematic Uncertainties

Several sources of experimental and theoretical systematic uncertainties are considered in the SM background estimates and signal expectations, and are included in the profile likelihood fit. The primary sources of systematic uncertainties are related to the jet energy scale (JES) and resolution (JER), the Monte Carlo (MC) modeling, the re-weighting procedure applied to simulation to match the distribution of the number of reconstructed vertices observed in data, the systematic uncertainty considered in the non-prompt background estimation and the theoretical cross section uncertainties. The uncertainty related to the finite statistics of the simulated event samples is taken into account as well. The effects of these uncertainties have been evaluated for all signal samples and background processes. Uncertainties on the normalization of the MC prediction for the dominant background processes, which is extracted in dedicated control regions, are also taken into account.

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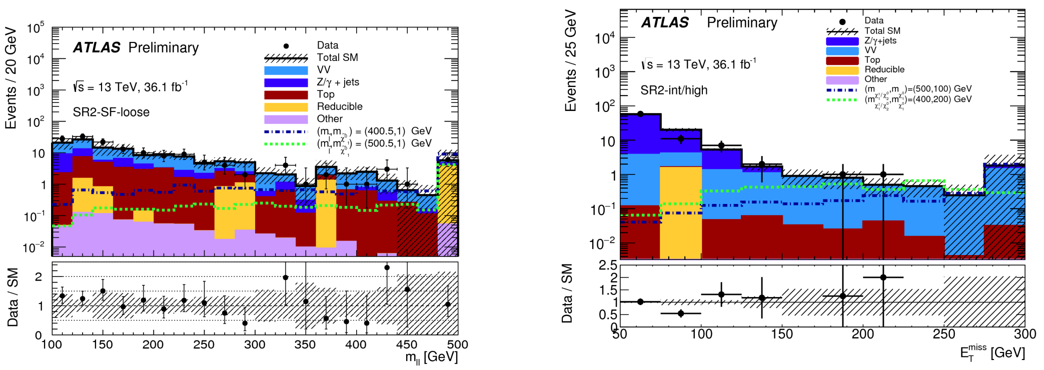
6. Results

A profile-likelihood-ratio test [15] is used for the statistical interpretation of the results with dedicated background-enriched control regions (CRs) (for the "$2\ell+0$jets" and "3ℓ" channels) and SRs both participating in the fit. The likelihood is built as the product of a Poisson probability density function describing the observed number of events in each CR/SR and Gaussian distributions constraining the nuisance parameters associated with the systematic uncertainties whose widths correspond to the sizes of these uncertainties. Poisson distributions are used instead for MC statistical uncertainties. Correlations of a given nuisance parameter across the different sources of backgrounds and the signal are taken into account when relevant.

In the "$2\ell+0$jets" and "3ℓ" channels, a background-only fit is performed which uses data in the CRs to constrain the nuisance parameters of the likelihood function (these include the normalization factors for dominant backgrounds and the parameters associated with the systematic uncertainties). In all channels the background estimates are also used to evaluate the agreement between the expected and observed number of events in the validation regions. This agreement is found to be within uncertainties for all the validation regions.

Figure 2a shows the stransverse mass distribution for data and the estimated SM backgrounds with their associated statistical and systematic uncertainties for the loosest inclusive SR in the "$2\ell+0$jets" channel ("SR2-SF-loose"). Figure 2b shows the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the "SR2-int/SR2-high" signal regions, which are used to target intermediate and large mass splittings between $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ and the LSP in the "2ℓ+jets" channel. Good agreement is observed in all distributions within the uncertainties.



(a) m_{T2} in $2\ell+0$jets SR

(b) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in 2ℓ+jets SR

Figure 2: **Left:** m_{T2} distributions [10] for data and the estimated SM backgrounds for "SR2-SF-loose" (low cut on $m_{\ell\ell}$). **Right:** $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution of data and the expected SM backgrounds for "SR2-int/high". The statistical uncertainties on the background prediction are included in the uncertainty band, as well as the experimental and theoretical uncertainties. The final bins in each histogram also contain the events in the overflow bin.

In the absence of SUSY signal, exclusion limits are set on the masses of the charginos and neutralinos for the simplified models considered in the analyses. In all cases, if the signal regions in a given channel are not mutually exclusive, the observed *CLs* value is taken from the signal region with the best expected *CLs* value.

Figures 3a-3b show the limits in the $2\ell+0$jets channel on the mass of the $\tilde{\chi}_1^0$ as a function of the $\tilde{\chi}_1^\pm$ mass, for $\tilde{\chi}_1^+\tilde{\chi}_1^-$ pair production with $\tilde{\ell}$-mediated decays, and the limits on the $\tilde{\chi}_1^0$ as a function of $\tilde{\ell}$ mass for direct $\tilde{\ell}\tilde{\ell}$ production. The exclusion limits from the $\tilde{\ell}$ channel for $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair production are shown for $\tilde{\ell}$- and gauge-boson-mediated decays in Figures 3c and 3d. Finally, the limit on the $\tilde{\chi}_1^0$ mass as a function of the degenerate masses of the $\tilde{\chi}_1^\pm$ and the $\tilde{\chi}_2^0$ calculated using the "2ℓ+jets" channel, is shown in Figure 3e.

For direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ pair production with decays via intermediate $\tilde{\ell}$ to a $\tilde{\chi}_1^0$, masses up to 750 GeV are excluded for a massless $\tilde{\chi}_1^0$. For $\tilde{\ell}\tilde{\ell}$ pair production where each $\tilde{\ell}$ decays directly to a $\tilde{\chi}_1^0$ and lepton, masses up to 500 GeV are excluded for a massless $\tilde{\chi}_1^0$ assuming degenerate left-handed and right-handed $\tilde{\ell}$. For associated $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production, masses up to 1150 GeV are excluded for a 200 GeV $\tilde{\chi}_1^0$ when each gaugino decays via an intermediate $\tilde{\ell}$ to a $\tilde{\chi}_1^0$, and masses up to 380 (580) GeV are excluded for a massless $\tilde{\chi}_1^0$ when gauge-boson-mediated decays are assumed in the case of the "3ℓ" ("2ℓ+jets") channel.

7. Conclusion

Searches for the electroweak production of neutralinos, charginos and sleptons decaying into final states with exactly two or three electrons or muons and missing transverse momentum are performed using 36.1 fb^{-1} of $\sqrt{s}=13$ TeV proton-proton collisions recorded by the ATLAS detector at LHC. Different search channels are considered targeting $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\ell}\tilde{\ell}$ and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair production. No significant excess above the SM expectation is observed in any of the signal regions considered across the three channels, and the results are used to calculate exclusion limits in several simplified model scenarios.

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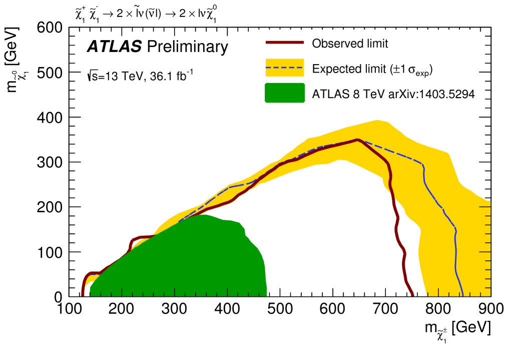
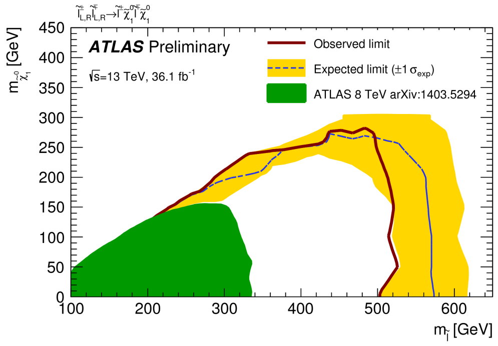
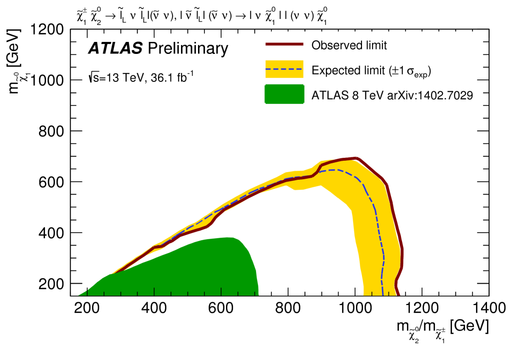


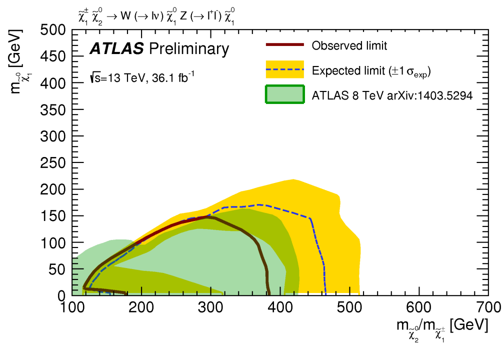
(a) Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ pair production with $\tilde{\ell}$-mediated decays



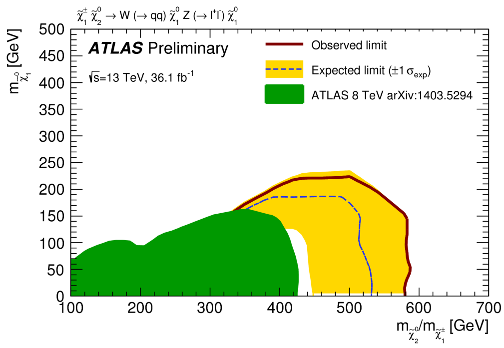
(b) Direct $\tilde{\ell}$ pair production ($\tilde{\ell}_L$ and $\tilde{\ell}_R$ contributions combined)



(c) Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production with $\tilde{\ell}$-mediated decays



(d) Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production with W/Z-mediated decays



(e) Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production with decays via gauge bosons ("2ℓ+jets" channel)

Figure 3: Observed and expected exclusion limits [10] on the $\tilde{\chi}_1^{\pm}$, $\tilde{\ell}$, $\tilde{\chi}_1^0$ and the degenerate $\tilde{\chi}_2^0/\tilde{\chi}_1^{\pm}$ masses in the context of SUSY scenarios with simplified mass spectra of the produced sparticle pair. The contours of the band around the expected limit are the $\pm 1\sigma$ results, including all uncertainties except theoretical uncertainties on the signal cross-section. All limits are computed at 95% *CL*.

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