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SUSY searches in multi-lepton final states with the ATLAS detector

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Summary. — Searches for the production of supersymmetric particles in proton-proton collisions with the ATLAS detector at the LHC were performed with $13.0\,\mathrm{fb}^{-1}$ of data collected at $\sqrt{s} = 8\,\mathrm{TeV}$. Different final states containing exactly three, or at least four light leptons ($\ell = e, \mu$) were considered. In the absence of any excess, limits were set in several different supersymmetric models.

PACS `12.60.Jv` – Supersymmetric models.

1. – Introduction

Supersymmetry (SUSY) is one of the best motivated extensions to the Standard Model, providing a possible solution to the hierarchy problem and a viable dark matter candidate: a pedagogical introduction is provided in [1]. SUSY models can either conserve or violate R- or matter-parity: examples of both scenarios are considered here. Two searches for SUSY with the ATLAS detector [2] are discussed here, and are documented fully in [3] and [4].

These searches are interpreted in terms of *simplified models* [5, 6]. Instead of postulating an entire mass spectrum and associated phenomenology, these models set the masses of a small number of SUSY particles and use simple choices for branching ratios. Simplified models cannot be realised in nature, but allow for easy re-evaluation of results under changing assumptions.

2. – Three lepton final states: Searches for direct gaugino production

Direct searches for coloured SUSY particles at the LHC have set bounds of $> 1\,\mathrm{TeV}$ on squark and gluino masses in a variety of scenarios. It is possible that weakly produced particles could be the only supersymmetric particles observable at the LHC. Gauginos are linear combinations of Higgs and W/Z boson superpartners, the higgsinos and winos. Gauginos are then classified (in order of increasing mass) as *charginos* ($\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$) and

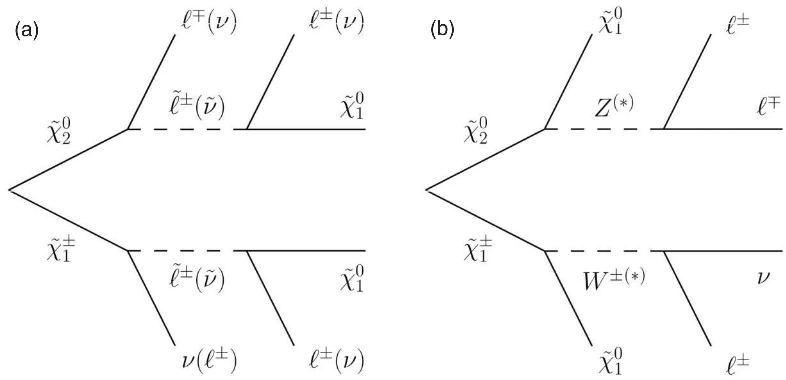

Fig. 1. – Illustration of $\tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0$ production and decay to three lepton final states. (a) Model 1 (via sleptons), (b) Model 2 (via gauge bosons).

neutralinos $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$. The cross sections for gaugino production are much lower than those for strong particle production, and are generally similar to those of electroweak processes such as diboson production. In this analysis, two simplified models are used to interpret the results: both model direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production. Model 1 (shown in fig. 1a) is constrained to have intermediate decays via sleptons and sneutrinos, while in Model 2 (shown in fig. 1b), the gauginos decay via W and Z bosons. Both models conserve R-parity. Since the kinematics of Models 1 and 2 are different, different selection criteria (signal regions) are applied: these requirements are summarised in table I. R-parity conserving neutralino decays always yield same flavour opposite sign (SFOS) lepton pairs: at least one such pair is therefore required in all signal regions. Signal regions are then divided into SR1a/b, which veto Z candidates, and SR2, where a Z boson candidate is required. A $Z \to \ell\ell$ candidate is defined as a SFOS pair with invariant mass within 10 GeV of m_Z. Jets identified as originating from b-quarks (b-tagged jets) are vetoed in SR1a/b in order to reduce the contribution from $t\bar{t}$ production. In SR2, a transverse

TABLE I. – *Signal regions for the three lepton analysis. All signal regions require exactly three leptons including a same-flavour, opposite-sign (SFOS) lepton pair. SR1a and SR1b are most effective for Model 1 (via sleptons), while SR1a and SR2 are most effective for Model 2 (via W and Z bosons). Taken from ref.* [3].

Selection	SR1a	SR1b	SR2
Number of leptons (e, μ)	Exactly 3		
Lepton charge, flavour	At least one SFOS pair and no SFOS pair with $m_{\ell\ell} < 12$ GeV		
Targeted $\tilde{\chi}_2^0$ decay	$\tilde{l}^{(*)}$ or Z^*		on-shell Z
$Z \to \ell\ell$ candidate	veto		requirement
Number of b-jets	0		any
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 75 GeV		> 120 GeV
m_{T}	any	> 110 GeV	> 110 GeV
p_{T} of leptons	> 10 GeV	> 30 GeV	> 10 GeV

mass ($m_T = \sqrt{2p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \cos\Delta\phi_{\ell,E_{\mathrm{T}}^{\mathrm{miss}}}}$) cut is applied to reduce the contribution from WZ production. The lepton used for the m_T calculation does not form part of the SFOS pair closest to m_Z.

2·1. *Background estimation.* – The different background contributions are classified as *irreducible* if they contain at least three real leptons, and as *reducible* if they contain fewer than three real leptons. The major irreducible backgrounds are WZ, ZZ, $t\bar{t}+W/Z$, WWW, ZWW and ZZZ production, while the major reducible backgrounds are $t\bar{t}$, single top, Z and W production in association with jets. The predictions for irreducible backgrounds are predicted by Monte Carlo (MC) simulations, while experimental data is used to predict the reducible background. WZ is the largest irreducible background and is therefore normalised to data in a control region. The observed scale factor for the WZ MC is found to be $1.03 \pm .0.14$.

For the estimation of reducible backgrounds, leptons are categorised as "real" (R) if they are produced in γ^*/Z, W or SUSY decays, and as "fake" (F) if they come from heavy flavour decays or external conversion. The contribution from light flavour jets faking leptons is found to be negligible for this analysis. Reconstructed leptons are reconstructed with "tight" (T) (low efficiency, high purity) or with "loose" (L) (high efficiency, low purity) identification level. The vector of possible reconstructed lepton combinations $(N_{TTT}, N_{TTL}, \ldots N_{LLL})$ may be written as a linear combination of real and fake contributions $(N_{RRR}, N_{RRF}, \ldots N_{FFF})$, using a matrix $\mathbf{M}$ of identification efficiencies and misidentification probabilities. Inverting the matrix gives an estimate of real and fake background contributions. Since the highest p_{T} lepton is found to be real in 99% of simulated events, the matrix is reduced in size from 8×8 to 4×4. The identification efficiencies and misidentification probabilities are measured in experimental data.

2·2. *Results.* – In order to verify the background prediction, data and MC agreement is checked in dedicated validation regions. Good agreement between data and the background prediction is observed: distributions and a full table of results may be found in ref. [3]. After this validation process, the data in the signal regions are analysed: the results are given in table II, and the distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ in each signal region are shown in fig. 2. No significant excess is seen in any of the signal regions.

TABLE II. – *Expected and observed numbers of events with* $13.0\,\mathrm{fb}^{-1}$ *of data for the three lepton analysis. Errors on the background prediction are statistical and systematic, summed in quadrature. Taken from ref.* [3].

Selection	SR1a	SR1b	SR2
$t\bar{t}+\mathrm{V}$	0.62 ± 0.28	0.13 ± 0.07	0.9 ± 0.4
triboson	3.0 ± 3.0	0.7 ± 0.7	0.34 ± 0.34
ZZ	2.0 ± 0.7	0.30 ± 0.23	0.10 ± 0.10
WZ (normalised)	34 ± 4	1.2 ± 0.6	4.7 ± 0.8
Reducible	10 ± 6	0.8 ± 0.4	$0.012^{+1.6}_{-0.012}$
Total expected events	50 ± 8	3.1 ± 1.0	$6.1^{+2.0}_{-1.2}$
Total observed events	48	4	4
Visible cross section (expected)	$< 1.5\,\mathrm{fb}$	$< 0.4\,\mathrm{fb}$	$< 0.5\,\mathrm{fb}$
Visible cross section (observed)	$< 1.3\,\mathrm{fb}$	$< 0.5\,\mathrm{fb}$	$< 0.4\,\mathrm{fb}$

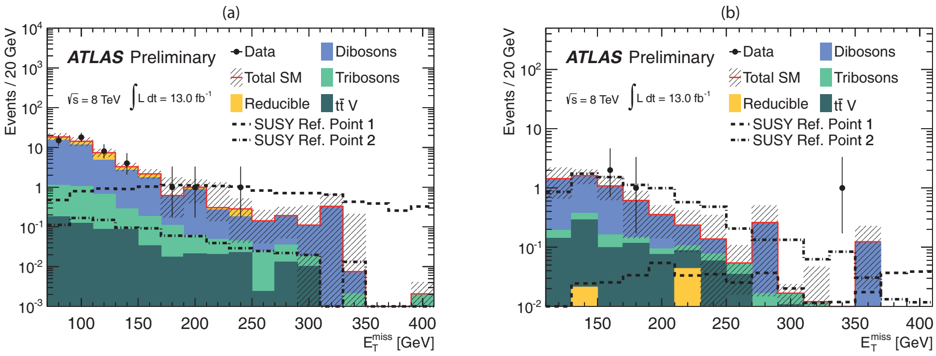

Fig. 2. – $E_{\mathrm{T}}^{\mathrm{miss}}$ in two of the signal regions used in the three lepton analysis. (a) SR1a, (b) SR2. "SUSY Ref. Point 1" with intermediate sleptons, $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_L}, m_{\tilde{\chi}_1^0} = 500, 500, 250, 0\,\mathrm{GeV})$ and "SUSY Ref. Point 2" with no intermediate sleptons, $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0} = 250, 250, 0\,\mathrm{GeV})$ are also presented. The uncertainty band for the background prediction includes both statistical and systematic uncertainty, while the data uncertainties are statistical only. Taken from ref. [3].

2·3. *Interpretation.* – The visible cross section σ_{vis} is defined as the total production cross section multiplied by the detector acceptance and efficiency. σ_{vis} is used to constrain generic models of new physics. Upper limits at 95% confidence level (CL) on σ_{vis} are shown in table II. The results are also interpreted as upper limits on the cross sections of several SUSY models: all upper limits are derived in the modified frequentist CLs formalism [7]. As shown in fig. 3, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ with masses up to 580 GeV are excluded in the scenario with intermediate slepton decays (Model 1) and masses up to 290 GeV are excluded in the scenario with decays via gauge bosons (Model 2)." In the latter model, there are two distinct regions of exclusion: an additional signal region with sensitivity to on-shell Z boson decays and intermediate $E_{\mathrm{T}}^{\mathrm{miss}}$ would be required in order to bridge this gap.

3. – Four lepton final states: searches for R-parity violating SUSY

In their most general form, SUSY theories contain lepton and baryon number violating interactions: the form of such interactions is heavily constrained by the bounds on proton decays and similar processes, so R-parity is often imposed in order to suppress such interactions. However, it is possible that a less stringent symmetry is responsible for proton symmetry while still allowing lepton and baryon number violating interactions. For the models considered in this analysis, lepton number violating SUSY couplings λ_{ijk}, where $(1, 2, 3) = (e, \mu, \tau)$, are set to non-zero values. This has the consequence that the lightest SUSY particle (LSP) is no longer absolutely stable, but can in fact decay to leptons and neutrinos:

$$\tilde{\chi}_1^0 \to \nu_{i/j} \ell^\pm_{j/i} \ell^\mp_k \tag{1}$$

at a rate proportional to λ_{ijk}. Note that for the models considered here, the LSP is always the $\tilde{\chi}_1^0$. In this analysis, two scenarios are considered: one with $\lambda_{121} > 0$, like the decay depicted in fig. 4, and one with $\lambda_{122} > 0$. In these scenarios, the choice of next-

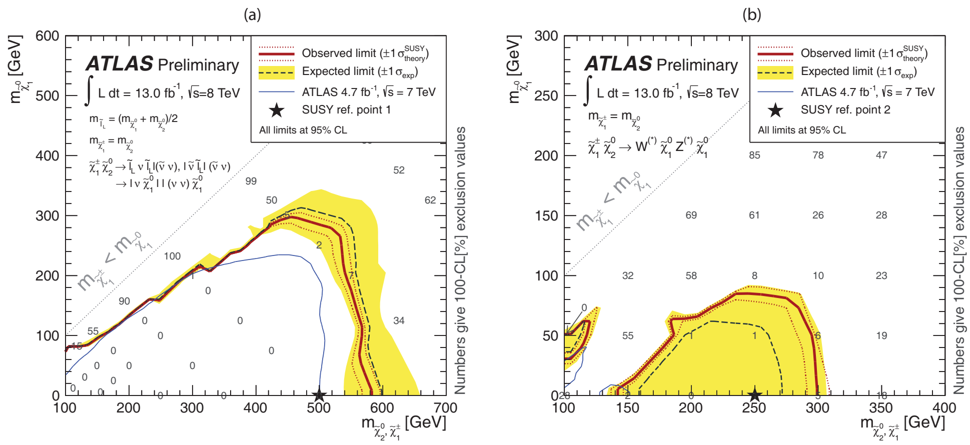

Fig. 3. – Observed and expected 95% CL limit contours in the two models of direct gaugino production considered here. (a) Model 1: Intermediate decay through sleptons and sneutrinos, (b) Model 2: Intermediate decay through W and Z bosons. Both the expected and observed limits are calculated without taking SUSY cross section uncertainties into account. The red dashed band shows the effect of $\pm 1\sigma$ variation of the SUSY signal uncertainty on the observed limit, while the yellow band shows the effect of $\pm 1\sigma$ variation of the experimental uncertainties on the final result. Taken from ref. [3].

to-lightest SUSY particle (NLSP) determines the phenomenology. For each choice of λ_{ijk}, four simplified models of direct NLSP production are considered, with the following NLSP choices:

- Wino: $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$,
- Left-handed slepton: $\tilde{\ell}_L \to \ell\tilde{\chi}_1^0$,
- Sneutrino: $\tilde{\nu}_\ell \to \nu_\ell\tilde{\chi}_1^0$,
- Gluino: $\tilde{g} \to q\bar{q}'\tilde{\chi}_1^0$.

3·1. *Signal regions.* – Two signal regions are defined: one with high $E_{\mathrm{T}}^{\mathrm{miss}}$ and one with high m_{eff}, where

$$m_{\mathrm{eff}} = E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{\mu} p_{\mathrm{T}}^{\mu} + \sum_{e} E_{\mathrm{T}}^{e} + \sum_{\mathrm{jet}} E_{\mathrm{T}}^{\mathrm{jet}}.$$

Note that jet and electron E_{T} refers to the use of calorimeter information to determine the momentum: electrons and jets are taken to be massless in the calculation of m_{eff}. Selected

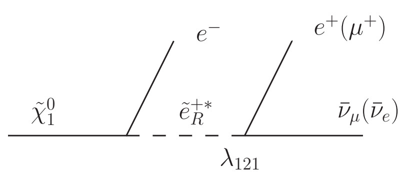

Fig. 4. – Illustration of a λ_{121} $\tilde{\chi}_1^0$ decay. The charge conjugate decay is implied.

TABLE III. – *The selection requirements for the four lepton signal regions. The Z-candidate veto removes events with either a SFOS lepton pair, a SFOS+ℓ triplet, or a combination of two SFOS pairs with invariant mass within* 10 GeV *of* m_Z. *Taken from ref.* [4].

Selection	SR1	SR2
Number of leptons	≥ 4	
Z-candidate	Z-veto	
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 50\,\mathrm{GeV}$	–
m_{eff}	–	$> 300\,\mathrm{GeV}$

RPV decays are expected to have real $E_{\mathrm{T}}^{\mathrm{miss}}$ from neutrinos, and may additionally have high p_{T} leptons. Decays in the gluino NLSP model can have significant hadronic activity, motivating the use of m_{eff}. Since no on-shell Z bosons are expected in the models considered, Z-candidates are vetoed in all signal regions. The Z-candidate requirement is extended to combinations of three or four leptons: the invariant masses $m(\ell^+\ell^-)$ (a single SFOS pair), $m(\ell^+\ell^-\ell')$ (an SFOS pair and additional lepton) and $m(\ell^+\ell^-\ell'^+\ell'^-)$ (two distinct SFOS pairs) must all lie 10 GeV from m_Z. Table III summarises the selection requirements for the four lepton signal regions.

3˙2. *Background estimation.* – Irreducible backgrounds are defined to have at least four "real" leptons and zero "fake" leptons, while reducible backgrounds must have at least one "fake" lepton. MC simulation is used directly for irreducible backgrounds, while a weighting method is used to estimate the reducible background. Leptons are classified according to whether they pass the tight requirements (ℓ_T) or fail the tight requirements, but pass the loose requirements (ℓ_L). The total number of four lepton events with at least one fake lepton is then approximated by a single linear equation containing contributions from data and MC events with a maximum of two loose leptons. Events with more than two fake leptons are found to be negligible in simulation. Relative to the matrix method used for the three-lepton analysis (discussed in sect. **2**˙1), the weighting method is better suited to the lower statistics of the four lepton analysis.

3˙3. *Results.* – In order to verify the background prediction, data and MC agreement is checked in dedicated validation regions. Good agreement between the data and background prediction is observed: distributions and a full table of results may be found in ref. [4]. After this validation process, the data in the signal regions are analysed: the results are shown in table IV and fig. 5. No significant excess is seen in any of the signal regions.

3˙4. *Interpretation.* – Upper limits on the visible cross section (σ_{vis}) at 95% CL are derived in both signal regions: the definition of σ_{vis} and the statistical procedure are discussed in sect. **2**˙3. In the absence of excess, these results are interpreted in the four simplified models defined: limits in the NLSP-LSP mass plane are shown in fig. 6 for the case where $\lambda_{121} > 0$. The NLSP is excluded for masses up to 700, 400, 450 or 1300 GeV in scenarios where the NLSP is the wino, L-slepton, sneutrino or gluino respectively. The results are also interpreted with $\lambda_{122} > 0$ in ref. [4].

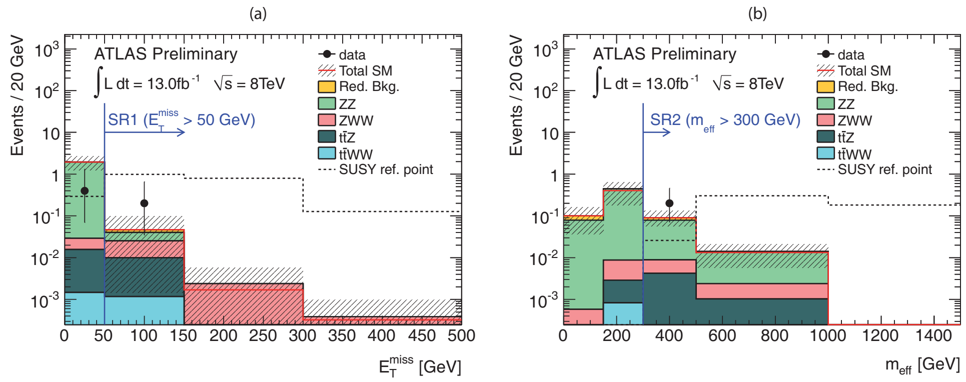

Fig. 5. – Distributions of events with at least four leptons and no Z boson candidates. Events with $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$ are classified as SR1 (a), while those with m_{eff} are in SR2 (b). "SUSY ref. point" is a scenario from the RPV Wino λ_{121} simplified model, with $m_{\tilde{\chi}_1^\pm} = 600\,\mathrm{GeV}$, $m_{\tilde{\chi}_1^0} = 400\,\mathrm{GeV}$. The uncertainty band for the background prediction includes both statistical and systematic uncertainty, while the data uncertainties are statistical only. Taken from ref. [4].

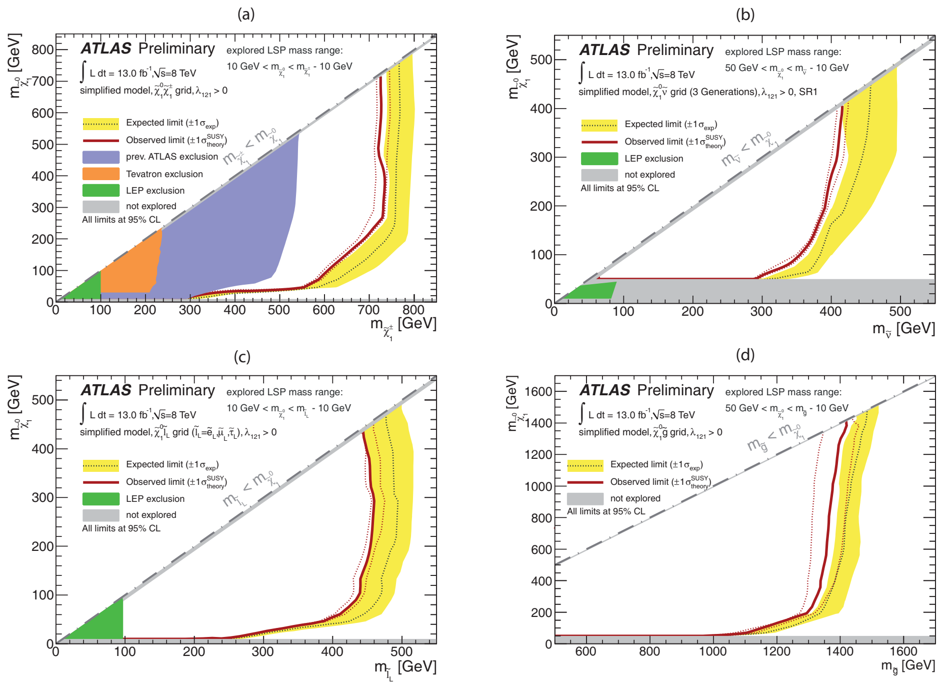

Fig. 6. – Observed and expected 95% CL limit contours in RPV models with the coupling $\lambda_{121} > 0$. The chosen NLSP is the following: (a) Wino NLSP, (b) Sneutrino NLSP, (c) L-slepton NLSP, (d) Gluino NLSP. Both the expected and observed limits are calculated without taking SUSY cross section uncertainties into account. The red dashed band shows the effect of $\pm 1\sigma$ variation of the SUSY signal uncertainty on the observed limit, while the yellow band shows the effect of $\pm 1\sigma$ variation of the experimental uncertainties on the final result. Taken from ref. [4].

TABLE IV. – *Expected and observed numbers of events with* $13.0\,\mathrm{fb}^{-1}$ *of data in the four lepton analysis. Errors on the background prediction are statistical and systematic, summed in quadrature. Taken from ref.* [4].

	SR1	SR2
ZZ	$0.07^{+0.18}_{-0.08}$	$0.99^{+0.66}_{-0.63}$
triboson	$0.10^{+0.01}_{-0.01}$	$0.08^{+0.01}_{-0.01}$
$t\bar{t}Z$	$0.04^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$
$t\bar{t}WW$	$0.01^{+0.01}_{-0.00}$	$0.00^{+0.00}_{-0.00}$
Reducible	$-0.01^{+0.14}_{-0.19}$	$0.09^{+0.17}_{-0.17}$
Total expected events	$0.25^{+0.29}_{-0.25}$	$1.2^{+0.5}_{-0.4}$
Total observed events	1	2
Visible cross section limit (expected)	$< 0.28\,\mathrm{fb}$	$< 0.38\,\mathrm{fb}$
Visible cross section limit (observed)	$< 0.34\,\mathrm{fb}$	$< 0.28\,\mathrm{fb}$

4. – Conclusion

Searches for SUSY in events with exactly three or at least four leptons were performed using $13.0\,\mathrm{fb}^{-1}$ of data recorded at $\sqrt{s} = 8\,\mathrm{TeV}$ with the ATLAS detector in 2012. No significant excess of events above background was observed in either analysis, and limits in a variety of different SUSY models were obtained.

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