Searches for supersymmetry with two same-sign or at least three leptons with the ATLAS experiment

S. Huang, on behalf of the ATLAS collaboration
Department of Physics, University of Hong Kong,
Pokfulam Road, Hong Kong

Searches for supersymmetry (SUSY) in events with two leptons of the same electric charge or at least three leptons are presented. The first search targets at the electroweak productions of gauginos and the second one targets at the strong production of squarks and gluinos. The analyses use 139 fb^{-1} of proton-proton collisions data collected at a centre-of-mass energy of 13 TeV with the ATLAS detector at the LHC. No significant excesses over the Standard Model (SM) predictions are observed. The results are interpreted in the context of R-parity conserving and R-parity violating scenarios. Exclusion limits at 95% CL are set on the masses of the superpartners in the considered scenarios. Model-independent upper limits on the beyond SM (BSM) events that may contribute to the signal regions defined in the analyses are also set.

1 Introduction

Among many theoretical models describing BSM physics, Supersymmetry (SUSY) [1] stands as a compelling extension by introducing a symmetry relating bosonic and fermionic particles in SM, which can provide natural solutions to the hierarchy problem. The simplest realisation of SUSY is the Minimal Supersymmetric Standard Model (MSSM) which gives rise to supersymmetric partners of SM particles after supersymmetry transformations. The SUSY partners for quarks and leptons are squarks ($\tilde{q}$) and sleptons ($\tilde{l}$,$\tilde{\nu}$), and gluinos ($\tilde{g}$) are fermionic partners of SM gluons. For electroweak (EW) bosons and Higgs bosons, their SUSY partners (binos, winos and higssinos) are mixed to form ordered mass eigenstates called neutralinos ($\tilde{\chi}^0_{1,2,3,4}$, ordered by increasing mass value) which are neutral in electric charge and charginos ($\tilde{\chi}^\pm_{1,2}$) for charged ones. A discrete symmetry, with R-parity conservation, is often introduced in SUSY framework. The lightest SUSY particle (LSP) is predicted to be stable in R-parity conserving (RPC) models, therefore can serve as a promising candidate for dark matter. In R-parity violating (RPV) models, the violations on baryon or lepton numbers offer possible explanations for baryon asymmetry [2] or neutrino physics, and they are also well-motivated in many grand unified theories [3]. At the Large Hadron Collider (LHC) [4], the production cross-section of SUSY particles relies heavily on their mass [5,6]. If strongly-interacting SUSY particles ($\tilde{q}/\tilde{g}$) are heavy, the electroweak productions are expected to be the dominant processes motivated by naturalness arguments in the TeV-scale SUSY searches at the ATLAS experiment [7].

The signature of two leptons with same-sign (SS) electric charge or at least three leptons (3L) is experimentally favoured because of rare background in SM, but exists in BSM theories like SUSY. These heavy SUSY particles could decay into SM bosons and top quarks yielding jets plus two same-sign leptons or at least three leptons in the final states. Hence, this peculiar SS-lepton or multi-lepton signature could be a promising probe for BSM searches at LHC.

2 Electroweak gauginos search

This search is targeted at direct electroweak gauginos production with decay into 2 SS or 3L final states described by several SUSY simplified models in context of RPC and RPV scenarios as shown in Figure 1. The two RPC models explored are wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with a W boson and either a SM-like Higgs (h) or a Z boson in the intermediate state, and these particles consecutively decay into 2 SS leptons and LSP in the final state. The LSP and neutrinos will escape from ATLAS detection leading to large missing energy at transevese plane. In R-parity violating scenarios, higgsino-like $\tilde{\chi}_1^0\tilde{\chi}_2^0$ can decay via bilinear lepton-number-violating terms or baryon-number-violating terms, where the later one is referred as UDD RPV.

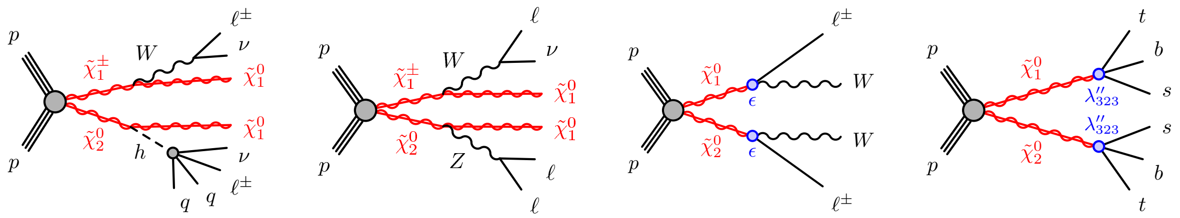

Figure 1 – Example diagrams in direct electroweak gauginos production search from left to right: wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh, wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, higgsino-like $\tilde{\chi}_1^0\tilde{\chi}_2^0$ bilinear RPV and higgsino-like $\tilde{\chi}_1^0\tilde{\chi}_2^0$ UDD RPV [10].

To separate hypothetical SUSY signal processes from similar SM backgrounds, event selections in signal enriched regions (SRs) have been optimized for each simplified model to ensure maximum sensitivity. The selected events are required to have exactly 2 signal leptons with same electric charge or at least three signal leptons. For wino Wh and WZ model, two orthogonal sets of SRs are optimized on top of the m_{T2} variable [8,9], which is introduced to relate the masses on unseen particles to their visible decay products. In high-m_{T2} SRs proposed, additional binning requirements are placed on $E_{\mathrm{T}}^{\mathrm{miss}}$ for wino Wh and its significance $S(E_{\mathrm{T}}^{\mathrm{miss}})$ for wino WZ model. In bilinear RPV scenarios, the orthogonality of corresponding SRs is achieved by the number of signal leptons in the event selections. The UDD RPV SRs are defined by exploiting b-jets multiplicity and then split with refined selections on other kinematic observables. For each signal model, the statistical combination of orthogonal SRs is feasible when interpreting the results.

The concerned SM backgrounds entering regions of interests can be generally divided into reducible and irreducible backgrounds. The reducible backgrounds coming from electrons with incorrect charge and fake/non-prompt leptons are measured by data-driven techniques. Among irreducible backgrounds arising from SM prompt processes which also give contributions to the same-sign prompt leptons, the dominant one in most SRs is WZ. $W^{\pm}W^{\pm}$ has significant contribution as well in wino Wh SRs. Hence, dedicated control regions (CRs) are designed for WZ and $W^{\pm}W^{\pm}$ where Monte Carlo (MC) samples are normalised to data in order to achieve better modelling on these processes.

3 Gluinos and squarks search

The search for strongly interacting SUSY particles with SS/3L signatures is carried out in the pair production of either gluinos or squarks covering both RPC and RPV simplified models presented in Figure 2.

After events pre-selection applied on number of signal leptons (=2l SS or $\geq$ 3l), SR definitions are refined for each model to achieve better signal-to-background separation. In RPC SRs, a veto

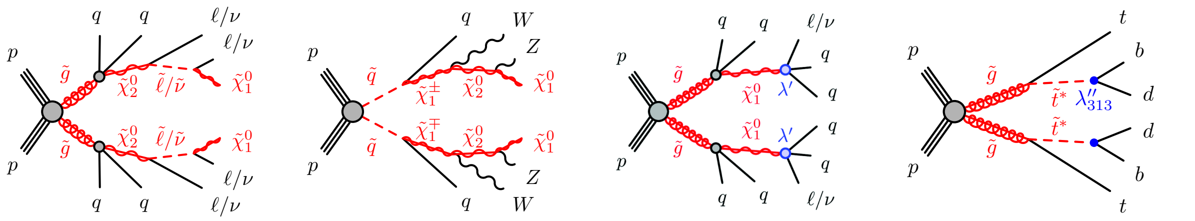

Figure 2 – Representative Feynman diagrams in search for pair-produced $\tilde{g}$ and $\tilde{q}$ from left to right: $\tilde{g}/\tilde{q}$ decay via sleptons, $\tilde{g}/\tilde{q}$ decay via W and Z bosons, direct $\tilde{\chi}_1^0$ decay via RPV LQD coupling λ' and direct $\tilde{t}$ decay via RPV UDD coupling λ'' [11].

on b-jets has been imposed to suppress the background contribution coming from top quarks. For those RPC models decay with absence of a Z boson, the invariant mass reconstructed from any pair of two same-flavour opposite-sign leptons is required not falling into the Z-boson mass range, e.g. $m_{\mathrm{SFOS}} \notin [81, 101]$ GeV. One of the most discriminant observables used across all SRs is m_{eff}, the effective mass, which is the scalar sum of transverse momentum of jets, leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event. Similarly to the electroweakions search, sophisticated multi-bin SRs are designed on top of several kinematic variables, e.g. m_{eff}, $E_{\mathrm{T}}^{\mathrm{miss}}$, sum of jet p_{T} ($\sum p_{\mathrm{T}}^{\mathrm{jet}}$), the ratio between $E_{\mathrm{T}}^{\mathrm{miss}}$ and sum of lepton p_{T} ($E_{\mathrm{T}}^{\mathrm{miss}}/\sum p_{\mathrm{T}}^{l}$), that demonstrate powerful separation between signal and background.

The background estimation strategy stays consistent to the EW search but with only one CR defined to constraint WZ processes, since the contribution from $W^{\pm}W^{\pm}$ is negligible in the SRs. The final background estimation results are obtained with a profile likelihood fit [12], performed simultaneously in CR and SRs for RPC models. A simplified approach is adopted by applying the normalisation factor derived from WZ CR directly into SRs instead of performing a simultaneous fit for RPV models.

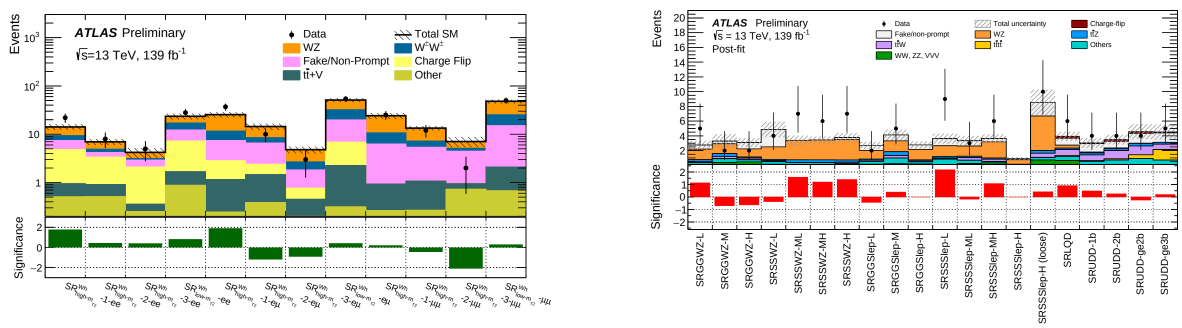

Figure 3 – Data yields and post-fit SM background composition in SRs defined for wino Wh model (left) and gluinos/squarks searches (right) [10, 11].

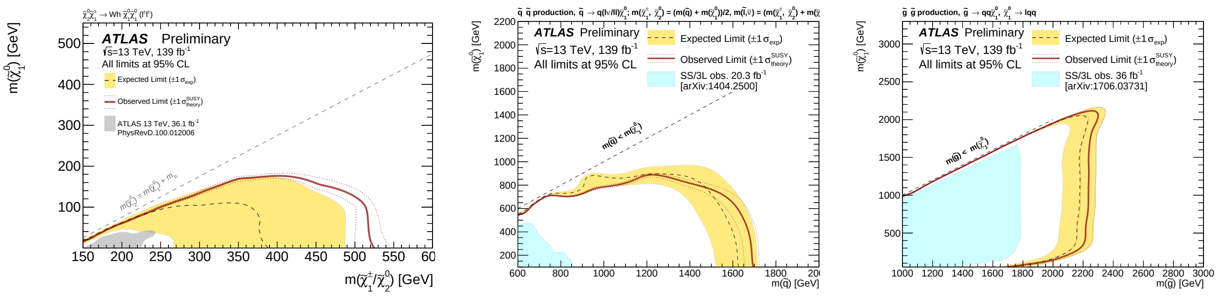

Figure 4 – Exclusion limits at 95% CL shown for two RPC models [10, 11]: wino Wh model (left), $\tilde{q}\tilde{q}^*$ decay via sleptons (middle), and RPV LQD model (right)

4 Results

The event yields using full Run-2 dataset are observed to be compatible with the SM expectation in all SRs, as shown in Figure 3. Given no significant deviation from SM, these results are interpreted as model-dependent exclusion limits at 95% confidence level (CL) on masses of $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ and $\tilde{g}/\tilde{q}$ involved in considered SUSY benchmark models using the CLs method [13, 14], with some examples in Figure 4. The observed 95% CL model-independent upper limits on BSM visible cross section are also set for every SR.

5 Conclusions

Two searches for TeV-scale SUSY production with 2 SS or at least 3 leptons signature using full Run-2 data collected by ATLAS experiment are discussed in this document. The latest results have excluded masses of $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ up to 525 GeV and $\tilde{g}$ ($\tilde{q}$) up to 2.2 (1.7) TeV for a massless LSP, which significantly improved existing constraints. In addition, these orthogonal search regions proposed allow future statistical combination together with other ATLAS analyses, which have great potential to enhance the sensitivity of BSM physics searches in larger phase spaces.

References

1. S. P. Martin. A Supersymmetry primer, *Adv. Ser. Direct. High Energy Phys.* **18**, 1 (1998), arXiv:hep-ph/9709356
2. A. D. Sakharov. Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe, *Pisma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967)
3. H. K. Dreiner. An Introduction to explicit R-parity violation, *Adv. Ser. Direct. High Energy Phys.* **21**, 565 (2010), arXiv: hep-ph/9707435
4. Lyndon Evans and Philip Bryant. LHC Machine. *JINST* **3**, S08001 (2008)
5. B. Christoph, M. Krämer, A. Kulesza, M. Mangano, S. Padhi, T. Plehn, and X. Portell. Squark and gluino production cross sections in pp collisions at $\sqrt{s}$= 13, 14, 33 and 100 TeV, *Eur. Phys. J. C* **74**, 3174 (2014), arXiv:1407.5066 [hep-ph]
6. B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering. Precision predictions for electroweak superpartner production at hadron colliders with RESUMMINO, *Eur. Phys. J. C* **73**, 2480 (2013), arXiv:1304.0790 [hep-ph]
7. ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider, *JINST* **3**, S08003 (2008)
8. C. G. Lester and D. J. Summers. Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders, *Phys. Lett. B* **463**, 99 (1999), arXiv: hep-ph/9906349.
9. A. Barr, C. Lester and P. Stephens. m_{T2}: The Truth behind the glamour, *J. Phys. G* **29**, 2343 (2003), arXiv: hep-ph/0304226.
10. ATLAS Collaboration. Search for direct production of winos and higgsinos in events with two same-sign or three leptons in pp collision data at 13 TeV with the ATLAS detector. ATLAS-CONF-2022-057, September 2022. https://cds.cern.ch/record/2826603.
11. ATLAS Collaboration. Search for pair production of squarks or gluinos decaying via sleptons or weak bosons in final states with two same-sign or three leptons with the ATLAS detector. ATLAS-CONF-2023-017, March 2023. https://cds.cern.ch/record/2855335.
12. M. Baak, G.J. Besjes, D. Cote, A. Koutsman, J. Lorenz, D. Short. HistFitter software framework for statistical data analysis. *Eur. Phys. J. C* **75**, 153 (2015), arXiv:1410.1280 [hep-ex]
13. G. Cowan, K. Cranmer, E. Gross and O. Vitells. Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* **71**, 1554 (2011), arXiv:1007.1727 [physics.data-an]
14. A. L. Read. Presentation of search results: the CLs technique. J. Phys. G: Nucl. Part. Phys. **28**, 2693 (2002)