SUSY searches with the ATLAS detector

Osamu Jinnouchi, on behalf of the ATLAS Collaboration
Tokyo Institute of Technology, 2-12-1 H-34 O-Okayama, Meguro, Tokyo 152-8551 Japan
E-mail: jinnouchi@phys.titech.ac.jp

Abstract. Recent searches for physics beyond the Standard Model based on the Supersymmetry model with the ATLAS detector is overviewed. This proceedings reports on the searches using data with an integrated luminosity of up to 80 fb$^{-1}$ taken with 13 TeV $pp$ collisions at the LHC.

1. Introduction
Supersymmetry (SUSY) is a theoretical framework which offers solutions for the shortcomings of the Standard Model (SM), such as the hierarchy problem, Dark Matter in the universe, the unification of the fundamental forces, etc. For decades SUSY has been the favored extension of the SM among high energy physics community for its elegant solutions to the fundamental problems of the SM and for its prediction power in phenomenologies within the reach of the LHC.

In this proceedings, the Run-2 results from the SUSY searches in ATLAS experiment including those based on the integrated luminosity of recent 80 fb$^{-1}$ data with a center of mass energy at $\sqrt{s} = 13$ TeV are reported.

The cross-sections of the SUSY particle pair productions differ for produced supersymmetric particle types. At a given luminosity, ATLAS can probe different production modes with different sensitivities which are reflected in the range of the SUSY masses a certain analysis could explore e.g. a hundred gluino pairs would be produced for a gluino mass of 2.0 TeV with 100 fb$^{-1}$ of $pp$ collisions at center-of-mass energy of 13 TeV.

In ATLAS, dedicated searches for various production modes are conducted, namely (1) Search for strong production of $\tilde{g}$ and the 1st or 2nd generation $\tilde{q}$ where we expect large production cross sections and standard signatures as high $p_T$ jets plus large $E_T^{\text{miss}}$, (2) Search for the production of 3rd generation $\tilde{q}$, where a large number of $b$-tagged jets in an event are expected, (3) Search for electro-weak production of SUSY particles which must deal with small cross sections but can profit clean signatures with multi-leptons and $E_T^{\text{miss}}$. These are basically based on the $R$-parity conserving scenarios. In parallel ATLAS searches for the unconventional signatures to fill the open phase spaces which were so far not covered by the standard analyses. In such models, SUSY events might have cleverly eluded standard analyses. (4) In $R$-parity violation (RPV) searches, since the lightest supersymmetric particles (LSP) can decay, little $E_T^{\text{miss}}$ is expected while signatures with a large number of jets becomes important. Finally, the search

---

1 Copyright 2018 CERN for the benefit of the ATLAS Collaboration. Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.
(5) for Long-Lived Particles (LLP) looks for peculiar signatures inside the detectors produced by SUSY particles with long lifetimes.

In ATLAS, simplified SUSY signal models are adopted in optimization of the analysis and for the interpretation of the results. This is to avoid the complexity caused by numerous free parameters in generic models. More realistic interpretation with the generic model (e.g. pMSSM) and full statistics will be carried out towards the end of the run.

For the background estimation, different strategies are adopted for the two main background categories. For the reducible backgrounds, such as the events with jets faking leptons or photons, data-driven methods called Matrix method, or Fake Factor method, are used. For the irreducible backgrounds, a method based on both data and MC is used i.e. the distribution shape is taken from MC, then the normalization factor is extracted in background enhanced control regions (CR), and is extrapolated to the signal regions (SR), after testing the validity of the extrapolation method in the validation regions (VR).

2. Early Run-2 limits
As of Nov. 2018, most of the analyses based on the early Run-2 data (36 fb$^{-1}$, 2015–2016) were finished and published. No significant excesses were found so far, and the lower limits on the supersymmetric particle masses were set for different analyses. This is summarized in Table 1.

| Production mode | Mass limit at 95% CL | Model | Reference |
|----------------|----------------------|-------|-----------|
| Strong inclusive | $\tilde{g}$ mass $> 2.03$ TeV ($m(\tilde{\chi}_1^0) = 0$ GeV) | $\tilde{g}\tilde{g}, \tilde{g} \to q\tilde{\chi}_1^0$ | [4] |
| 3rd gen $\tilde{g}$ | $t_1$ mass $> 0.94$ TeV ($m(\tilde{\chi}_1^0) = 0$ GeV) | $t_1 t_1, t_1 \to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | [4] |
| EW direct prod. | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ mass $> 0.6$ TeV ($m(\tilde{\chi}_1^0) = 0$ GeV) | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ decay via $W/Z$ | [5] |
| RPV | $\tilde{g}$ mass $> 1.9$ TeV ($m(\tilde{\chi}_1^0) = 1.1$ TeV) | $\tilde{g}\tilde{g}, \tilde{g} \to q\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qq$ | [4] |
| LLP | $\tilde{g}$ mass $> 2.4$ TeV ($m(\tilde{\chi}_1^0) = 0.1$ TeV) | meta-stable $\tilde{g}$ R-hadron | [7] |

3. Searches for SUSY in strong production
Gluinos are searched for in the final state with many b-tagged jet ($N_{b\text{-jet}} \geq 3$) and 0 or 1 lepton using 80 fb$^{-1}$ of data [8]. Both analyses based on the inclusive cut & count method and the multi-binning method are carried out. The multi-binning method has the advantage of gaining stronger sensitivities by the statistical combinations. SRs are categorized according to number of jets, $N_{\text{jet}}$, effective mass of the event, $m_{\text{eff}}$, and number of leptons, $m_{\ell}$, into different event signatures covering different signal modes: Gtt (or Gbb), when both gluinos decay with $\tilde{g} \to t\bar{t}$ (or $\tilde{g} \to b\bar{b}$), Gtb, a combination of the two gluino decay modes, and finally, compressed or boosted topologies. $t\bar{t}$ with heavy/light jets events are the main background. Figure 2 shows the event yields in the various SRs for the multi-bin analysis. No excesses over the SM background were observed, and a lower limit of 2.23 TeV (2.19 TeV) on the gluino mass is obtained with a 95% CL for the Gtt (Gbb) simplified model, as shown in Fig. 2.
Figure 1. (upper panel) The observed number of events and the predicted background yields for each SR. The uncertainty band includes all the systematic errors. (lower panel) The pull in each SR. 

Figure 2. Exclusion limits in the $\chi_1^0$ and $\tilde{g}$ mass plane for the Gtt models obtained in the multi-bin analysis. The dashed and solid bold lines show the 95% CL expected and observed limits respectively.

4. Searches for SUSY in stop/stop-bottom production
The pair-production of sbottom ($\tilde{b}$) is searched for with 80 fb$^{-1}$ of data in final states with up to 6 $b$-tagged jets and large $E_T^{miss}$ [9]. The decay chain includes $\tilde{b} \rightarrow b\chi_2^0 \rightarrow hh\chi_1^0$, where the higgs($h$) decays to two $b$-quarks. The reconstructed higgs mass is used to enhance the signal to background separation. The main background contributions are $tt$, $Zbb$. Three signal regions are defined targeting different event topologies. SRA targets a bulk phase space where all 4 $b$-jets from $h$ decays are detectable. SRB and SRC are targeting compressed regions, where part of the $b$-jets from $h$ or $\tilde{b}$ decays are missed as they have low $p_T$ due to the small mass gap $\Delta m(\tilde{b}, \chi_2^0)$.

Effective mass, $m_{eff}$, and object-based $E_T^{miss}$ significance [10] were used as discriminating variables. The object-based $E_T^{miss}$ significance is expected to largely improve the signal sensitivity compared to the ordinary event-based $E_T^{miss}$ significance.

Figure 3 shows the results in each SR. There is no excess observed in all SRs. In SRC, where the compressed region is targeted, the data points are even lower than the SM background prediction, which is reflected in the model dependent limit in Fig. 2 near the diagonal region. Substantial improvement with respect to the Run-1 result is confirmed and $m_{\tilde{b}}$ up to 1.4 TeV is excluded.

Supersymmetric signature with $c$-tagged jets in final states are searched aiming at direct $\tilde{c}$-pair production or stop production in the mass compressed region where $\tilde{t}_1$ decays into $c$ and $\chi_1^0$. This study is carried out with 36 fb$^{-1}$ of data [11]. The analysis utilizes a $c$-tagging procedure which is based on the discriminating variables used in $b$-tagging. The main background is $Z$+jets. There was no hint of excess in data, hence limits were set, which again largely ameliorated the Run-1 results.

5. Searches for SUSY in electroweak production
Charginos, $\chi^\pm_1$, are searched for with 80 fb$^{-1}$ of data in direct charginos production modes where the decay product of $\chi^+_1$ contains a $W$ boson, which then decays into leptons [12]. Hence the final state has 2-leptons and $E_T^{miss}$. In this channel, the object-based $E_T^{miss}$ significance was utilized as in the aforementioned search. Several SM processes with di-boson and top quark, leading to multi-lepton final states, represent irreducible backgrounds, i.e. $WW, WZ, ZZ, tt$ and $Wt$. In contrast, reducible backgrounds arise from fake or non-prompt leptons from heavy
Pair-produced chargino-neutralinos are searched for using 36 fb$^{-1}$ of data in final states with two or three leptons and moderate $E_{T}^{\text{miss}}$. Two complementing analyses are performed, one based on the Recursive Jigsaw Reconstruction (RJR) variable [3], and one using conventional variables [13]. In the RJR analysis, local excesses of $\sim 3\sigma$ are observed in the SR bins targeting the compressed region $\Delta m = 100$ GeV as can be seen in the first and fourth bins (from right).

Figure 3. Results of the background-only fit are extrapolated to SRs. (upper panel) The observed number of events and the predicted background yields. (lower panel) The significance in each SR is shown [3].

Figure 4. 95% CL exclusion limits in the $m_{b}$ vs. $m_{\tilde{\chi}_{0}^{0}}$ plane. $m(\tilde{\chi}_{1}^{0}) = 60$ GeV is assumed [3].

Figure 5. The observed and the expected SM background yields in the SRs considering 3-lepton channel. The bottom panel shows the difference in standard deviations between the observed and expected yields [3].

Figure 6. Exclusion limits at 95% CL on the masses of $\tilde{\chi}_{1}^{\pm}$, $\tilde{\chi}_{2}^{0}$ and $\tilde{\chi}_{1}^{0}$. The blue line is the limit from the RJR analysis, and the green is the conventional analysis [3].
of Fig. 5, whereas no significant excess was seen in conventional analysis. The discrepancy of the two analyses is estimated to be less than 2σ, and the comparison of the mass contours is shown in Fig. 6, where the complementarity between the two analyses are confirmed in their own coverage. It is important to revisit this channel with the full statistics of the Run-2 dataset.

6. Searches for SUSY in alternative scenarios

In ATLAS, there is a variety of analyses aiming for the non-conventional signatures. In this proceedings, two selected analyses are picked and reported.

6.1. Search for R-parity violating SUSY

One of the standard RPV scenarios, i.e. UDD model, assumes a non-zero coupling (λ′′) associated to the baryon number violating term of the Lagrangian. Event signature strongly depends on the size of λ′′. If λ′′ is large, ~g promptly decays into three SM quarks. Models with 6 jets in total (6q decay model), or a model assuming even more jets from gluon radiation (cascade model) are considered in this analysis. The main background comes from QCD multi-jet process which is estimated in a data-driven way. The analysis was performed using 36 fb\(^{-1}\) of data. The event selection requires 4-6 jets, additional b-tagging, and large-\(R\) jets. No excess was observed, hence the limits are set (Figure 7). For the cascade model, values of \(m(\tilde{g})\) between 1000 to 1875 GeV are excluded with 95% CL.

\[\text{Figure 7. Exclusion contours for the expected (dashed) and observed (solid) limits in the } (m_{\tilde{g}}, m_{\chi_1^0}) \text{ plane for the } \tilde{g} \text{ cascade decay model.}\]

6.2. Search for highly ionizing particle

Slow moving heavy charged particle highly ionizes the materials, and deposit more energies in the inner tracker than light particles. For instance, in the Split SUSY scenario, gluinos are long-lived and expected to form a heavy particle so called \(R\)-hadron which is expected to leave such peculiar signature. Using the inner tracker, the momentum (\(p\)) of the track is measured from its trajectory, the velocity (\(\beta\)) can be estimated from \(dE/dx\) measurements in the Pixel detector, then one can reconstruct the mass of the heavy particle, i.e. \(m = p/(\beta)\). The search for such slow heavy particle is carried out using the data of 36 fb\(^{-1}\), based on the \(E_T^{\text{miss}}\) trigger, with the following requirements on the track: \(p_T > 150\text{ GeV} \) and \(dE/dx > 1.8\text{ MeV}\cdot\text{g}^{-1}\cdot\text{cm}^2\). The SM backgrounds are estimated purely in data-driven way, and the comparison to the observation
is made. SR events are sub-divided into two categories. One is the stable SR, which requires activity in the calorimeter right behind the track. The other one is called meta-stable SR, requiring no-response in the calorimeter. There is a mild excess of $2.4\sigma$ (local) in the stable SR at masses around 500-800 GeV (Figure 8), while no excess was confirmed in the meta-stable SR.

7. Conclusions
Selected SUSY searches including the recent new results from the analyses using 80 fb$^{-1}$ of 13 TeV data are reviewed. For each analysis, dedicated tools and techniques are developed and customized to gain higher sensitivities. All the results including the ones shown in this proceedings are published in the ATLAS SUSY public results web site [15].

As a prospect, in the near future with the full Run-2 and Run-3 data statistics, electroweak SUSY searches becomes more interesting, given the observed mild excesses and the potential for improvements with statistics. Therefore, they will be followed up with high priority in the coming years. Conversely, no significant improvements are expected in the strong production channels, where the systematics uncertainties are dominant compared to the statistical uncertainties. In order to tackle this, ATLAS needs to take systematic and organized approaches for convoluted and realistic models. New ideas and techniques are vital to significantly improve the potential of the experiment in the coming years, especially during the Long shutdown 2 (2019-2020) and at the beginning of Run-3 (2021-2023).

Acknowledgement
The author would like to acknowledge the support by JSPS Grand-in-Aid for Scientific Research on Innovative Areas (Grant Number JP16H06489).

References
[1] L. Evans and P. Bryant (editors) 2008 JINST 3 S08001.
[2] ATLAS Collaboration, 2008 JINST 3 S08003.
[3] ATLAS Collaboration, 2018 Phys. Rev. D 97 112001
[4] ATLAS Collaboration, 2018 JHEP 06 108
[5] ATLAS Collaboration, 2018 Phys. Rev. D 98 092012
[6] ATLAS Collaboration, 2018 Phys. Rev. D 97 05212
[7] ATLAS Collaboration, 2018 Phys. Lett. B 785 136
[8] ATLAS Collaboration, ATLAS-CONF-2018-041, URL http://cdsweb.cern.ch/record/2632347
[9] ATLAS Collaboration, ATLAS-CONF-2018-040, URL http://cdsweb.cern.ch/record/2632345
[10] ATLAS Collaboration, ATLAS-CONF-2018-038, URL http://cdsweb.cern.ch/record/2630948
[11] ATLAS Collaboration, 2018 JHEP 09 050
[12] ATLAS Collaboration, ATLAS-CONF-2018-042, URL http://cdsweb.cern.ch/record/2632578
[13] ATLAS Collaboration, 2018 Eur. Phys. J. C 98 032009
[14] ATLAS Collaboration, 2018 Phys. Lett. B 788 96
[15] URL https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SuperconductorPublicResults