Searches for squarks and gluinos with the ATLAS detector

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Abstract. Despite the absence of experimental evidence, weak scale supersymmetry remains one of the best motivated and studied Standard Model extensions. This report summarizes recent results on searches for supersymmetric squarks and gluinos, including third-generation squarks produced directly or via decay of gluinos, using data collected by the ATLAS detector at the LHC. Some models of supersymmetry, including models with R-parity violation, predict that the lightest supersymmetric particle will decay back into Standard Model particles, removing the classical missing transverse momentum signature. These more difficult signatures have also been investigated, and results from these searches are presented.

Keywords: BSM, SUSY, squark, gluino, R-parity violation, LHC, ATLAS

1. Introduction

The standard model (SM) is a very successful model in explaining phenomena observed in particle physics. However, there are still some observed phenomena which cannot be explained only by SM, e.g. the hierarchy problem and dark matter. To explain those phenomena, many extensions to the SM have been proposed. Supersymmetry (SUSY) is one of the most promising extensions to the SM. It introduces a new symmetry associating a fermion/boson Supersymmetric partner to each SM boson/fermion. This symmetry needs to be broken to explain the non-degeneracy of SM and SUSY particles, however, if it is not violated the lightest SUSY particle provides a natural candidate for dark matter, and the new symmetry between fermions and bosons may solve both issues with the SM mentioned previously.

To test SUSY models, a large number of searches for the introduced super-partners have been performed. Since the mass spectrum of SUSY particles depends on the SUSY parameters, various SUSY particles have been searched for. One of the types of SUSY particle are the electroweakinos, the super-partners of Higgs and gauge bosons. Those are represented as mass eigenstates by $\tilde{\chi}_i^0 (i = 1, 2, 3, 4)$ (neutralinos) for neutral particles and $\tilde{\chi}_i^\pm (i = 1, 2)$ (charginos) for charged particles. The other types of SUSY particles are squarks ($\tilde{q}$), the super-partners of the quarks, and gluinos ($\tilde{g}$), the partners of the

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gluons. In this report, searches for the production of squarks and gluinos associated also to electroweakinos at the ATLAS experiment [1] are reported. ATLAS is a multi-purpose detector located at one of the interaction points of the Large Hadron Collider (LHC) operating at CERN. Since 2015, the experiment has been running with a center-of-mass energy of $\sqrt{s} = 13$ TeV. The analyses introduced here are based on 139 fb^{-1} of proton-proton collision data collected in 2015 – 2018.

In SUSY searches, events are selected based on reconstructed objects characterizing the SUSY process. Since most of the SUSY models assume R-parity conservation, the lightest SUSY particle (LSP) cannot decay. In the ATLAS detector, its presence is inferred from missing transverse momentum ($\mathbf{p}_T^{\text{miss}}$) or simply its magnitude (E_T^{miss}). Therefore, E_T^{miss} is one of the main discriminants used to select signal events. Very useful objects are jets: as the targets of the reported searches are strongly interacting particles, a large number of jets are expected in the final state making jet properties very useful for signal selection. In the case that a b -quark is expected in a SUSY process, b -tagged jets are also considered. For some targeted processes, the selection is refined by using also the invariant mass of some of the reconstructed objects. One example is m_{eff} , the invariant mass of all considered objects in the analyses. In final states including leptons, the requirement of a reconstructed lepton is used to strongly reduce QCD background. Those requirements are used to construct the signal regions.

The SUSY processes sharing the same final state can be probed using a common analysis setup to evaluate backgrounds. Therefore, some analyses target several processes, while some analyses are designed to improve sensitivity for specific scenarios. In Section 2, the analysis for squark* and gluino production with final states including jets is presented. In Section 3, the analysis designed for sbottom, which is the super-partner of the b -quark, decaying to multi- b quarks, is described. In contrast to the first two, the analyses reported from Section 4 are for SUSY processes including lepton(s). In Section 4, the analysis for SUSY processes with final states including same-sign leptons is reported. In this analysis, an R-parity violation model is also considered. Finally, the analyses reported in Section 5 and Section 6 are designed for stop, which is the super-partner of the top quark, decaying to a Z boson and via a 3-body decay mode, respectively.

2. Search for squarks and gluinos decaying to jets

In this section, the search for squarks and gluinos decaying to jets [2] is described. In this search the five scenarios shown in Figure 1 are considered as the target scenarios: (1a) squark pair production direct decay ($\tilde{q} \rightarrow q\tilde{\chi}_1^0$), (1b) squark pair production one step decay ($\tilde{q} \rightarrow q\tilde{\chi}_1^\pm \rightarrow qW\tilde{\chi}_1^0$), (1c) gluino pair production direct decay ($\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$), (1d) gluino pair production one step decay ($\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^\pm \rightarrow q\bar{q}W\tilde{\chi}_1^0$) and (1e) inclusive pair production, including squark-gluino pair production, with direct decays. These

* In this report, squark ($\tilde{q}$) does not include 3rd generation

Figure 1: Feynman diagrams of target scenarios for the search for squarks and gluinos decaying to jets. (a) $\tilde{q}\tilde{q}$ direct decay, (b) $\tilde{q}\tilde{q}$ one step decay, (c) $\tilde{g}\tilde{g}$ direct decay, (d) $\tilde{g}\tilde{g}$ one step decay and (e) inclusive direct decay.

scenarios share a topology with multiple jets and large E_T^{miss} but no leptons in the final state.

An advantage of this search is the large signal yields due to the high predicted production cross section. However, huge irreducible backgrounds are also expected. To handle the large backgrounds, two approaches are employed.

Figure 2: The m_{eff} distributions for three considered scenarios [2]. (a) $\tilde{q}\tilde{q}$ direct decay with large $\Delta m(\tilde{q}, \tilde{\chi}_1^0)$, (b) $\tilde{g}\tilde{g}$ direct decay with large $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ and (c) inclusive compressed mass gap scenario.

One approach is the multi bin search. In this approach, shapes of signal kinematics evaluated with simulation are used. Some kinematic variables, e.g. m_{eff} , show different shapes between the signal and the backgrounds. The multiple regions are defined by binning the kinematic space to enhance those differences. The binned multiple regions are simultaneously fitted.

Figure 2 shows the m_{eff} distributions, one of the variables used for binning. This approach considers three different scenarios: (2a) $\tilde{q}\tilde{q}$ direct decay with large $\Delta m(\tilde{q}, \tilde{\chi}_1^0)$ (MB-SSd), (2b) $\tilde{g}\tilde{g}$ direct decay with large $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ (MB-GGd) and (2c) inclusive scenario with compressed mass gap (MB-C). For each scenario, the region is binned based on m_{eff} , number of jets and E_T^{miss}/H_T , where H_T is the scalar sum of the transverse

momenta of all jets.

Figure 3: BDT scores for two scenarios [2]. (a) $\tilde{g} \tilde{g}$ direct decay for $1900 > \Delta m(\tilde{g}, \tilde{\chi}_1^0) > 1600$ GeV and (b) $\tilde{g} \tilde{g}$ one step decay for $2000 > \Delta m(\tilde{g}, \tilde{\chi}_1^0) > 1400$ GeV.

The other approach is based on a multivariate analysis using a Boosted Decision Tree (BDT). This approach considers the $\tilde{g} \tilde{g}$ direct decay (BDT-GGd) and one step decay (BDT-GGo). Both scenarios categorize signal models into four groups based on the $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ of the model. Then the BDT is separately trained using up to 12 variables, selected among E_T^{miss} , m_{eff} , aplanarity, p_T and η of selected jets. Figure 3 shows distributions of BDT scores for two groups. The scores are used for the signal region definitions.

Figures 2 and 3 show the expected backgrounds and data. As shown in those figures, no significant deviation from SM expectation is found. Model-dependent fits are performed to evaluate 95% CL exclusion limits for each approach. The limits are combined by selecting the best value. Figure 4 shows the exclusion limits for the scenarios except for the inclusive production with direct decays, and Figure 5 shows the exclusion limits for the inclusive production with direct decay scenario.

For the $\tilde{q} \tilde{q}$ direct decay, the limit of $m(\tilde{\chi}_1^0)$ reaches up to 850 GeV for $m(\tilde{q}) = 1300$ GeV, as shown in Figure 4a. For the massless $\tilde{\chi}_1^0$ scenario, squark masses, $m(\tilde{q})$, up to 1940 GeV are excluded by the multi bin search.

The limit for the $\tilde{g} \tilde{g}$ direct decay is shown in Figure 4b. The diagonal region up to gluino masses, $m(\tilde{g})$, of about 1000 GeV are excluded by the multi bin search for the compressed mass gap scenario (MB-C). For $m(\tilde{\chi}_1^0)$ above 1160 GeV, the limit for $m(\tilde{g})$ reaches up to 1700 GeV as obtained by the BDT search. For the massless $\tilde{\chi}_1^0$ scenario, gluino masses, $m(\tilde{g})$, up to 2350 GeV are excluded by the multi bin search.

The limits for the $\tilde{q} \tilde{q}$ one step decay are shown in Figure 4c with the assumption of $m(\tilde{\chi}_1^\pm) = (m(\tilde{q}) + m(\tilde{\chi}_1^0))/2$ and Figure 4d with the assumption of $m(\tilde{\chi}_1^0) = 60$ GeV. The diagonal region, shown in Figure 4c, up to $m(\tilde{q})$ and $m(\tilde{\chi}_1^0)$ of about 700 GeV are excluded by the multi bin search for the compressed mass gap scenario (MB-C). For the massless $\tilde{\chi}_1^0$ scenario, squark masses, $m(\tilde{q})$, up to 1590 GeV are excluded. With the fixed $m(\tilde{\chi}_1^0)$ assumption, squark masses, $m(\tilde{q})$, up to 1570 GeV are excluded.

Figure 4: Exclusion limits for the scenarios except inclusive production with direct decay [2]. (a) $\tilde{q}\tilde{q}$ direct decay, (b) $\tilde{g}\tilde{g}$ direct decay, (c) $\tilde{q}\tilde{q}$ one step decay assuming $m(\tilde{\chi}_1^\pm) = (m(\tilde{q}) + m(\tilde{\chi}_1^0))/2$, (d) $\tilde{q}\tilde{q}$ one step decay assuming $m(\tilde{\chi}_1^0) = 60$ GeV, (e) $\tilde{g}\tilde{g}$ one step decay assuming $m(\tilde{\chi}_1^\pm) = (m(\tilde{g}) + m(\tilde{\chi}_1^0))/2$ and (f) $\tilde{g}\tilde{g}$ one step decay assuming $m(\tilde{\chi}_1^0) = 60$ GeV.

The limits for the $\tilde{g}\tilde{g}$ one step decay are shown in Figure 4e with the assumption of $m(\tilde{\chi}_1^\pm) = (m(\tilde{g}) + m(\tilde{\chi}_1^0))/2$ and Figure 4f with the assumption of $m(\tilde{\chi}_1^0) = 60$ GeV.

The diagonal region, shown in Figure 4e, up to $m(\tilde{g})$ and $m(\tilde{\chi}_1^0)$ of about 900 GeV are excluded by the multi bin search for the compressed mass gap scenario (MB-C). For the massless $\tilde{\chi}_1^0$ scenario, gluino masses, $m(\tilde{g})$, up to 2190 GeV are excluded. With the fixed $m(\tilde{\chi}_1^0)$ assumption, gluino masses, $m(\tilde{g})$, up to 2150 GeV are excluded.

The limits for scenario (1e) are evaluated with three assumptions of $m(\tilde{\chi}_1^0)$. For the massless $\tilde{\chi}_1^0$ and $m(\tilde{q}) = m(\tilde{g})$ scenario, $m(\tilde{q}) = m(\tilde{g}) < 3000$ GeV are excluded.

Figure 5: Exclusion limits for inclusive production with direct decay with various assumptions [2]. (a) $m(\tilde{\chi}_1^0) = 0$ GeV, (b) $m(\tilde{\chi}_1^0) = 995$ GeV and (c) $m(\tilde{\chi}_1^0) = 1495$ GeV.

3. Search for sbottom decaying to multi- b quarks

In this section, the search for sbottoms decaying to multi- b quarks [3] is reported. The target scenario is shown in Figure 6. The final state is characterized by the presence of multiple b -jets and E_T^{miss} but no leptons. By requiring the presence of b -tagged jets, non b -jet QCD backgrounds can be suppressed. However, since the expected signal yield is small, it is required to select events efficiently.

The scenarios are categorized into three cases based on kinematics, and three Signal Regions A, B and C (SRA, SRB, SRC) are designed for those cases. SRA is for events

Figure 6: Feynman diagrams and kinematics of target scenario of search for sbottoms decaying to multi- b quarks. (a) all jets are reconstructed, (b) small $\Delta m(\tilde{b}, \tilde{\chi}_2^0)$ with ISR jet and (c) small $\Delta m(\tilde{b}, \tilde{\chi}_2^0)$ without assuming ISR.

where all jets are reconstructed (Figure 6a). However, compressed scenarios have small efficiency in SRA. For compressed scenarios, two more regions are designed. SRB is for events with small $\Delta m(\tilde{b}, \tilde{\chi}_2^0)$ and an Initial State Radiation (ISR) jet (Figure 6b). SRC is for events with small $\Delta m(\tilde{b}, \tilde{\chi}_2^0)$ without assuming an ISR jet (Figure 6c). SRB is designed assuming signal with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV. SRC is designed assuming signal with $m(\tilde{\chi}_1^0) = 60$ GeV.

Figure 7: Kinematic distributions of (a) invariant mass evaluated as a Higgs candidate and (b) m_{eff} [3].

For signals considered in SRA, two b -jets from a Higgs are specified from reconstructed b -jets including the ones from sbottoms, as described in the following. First, $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$ is computed for all the b -jet pairs, and the pair with largest ΔR is selected. This pair is most likely to have been produced by the sbottom decay, as shown in Figure 6a. Therefore, they are removed from the Higgs-decay product candidates. Then, from the remaining b -jet pairs, the one with the smallest ΔR is considered, which is the most likely to have come from the Higgs decay. An invariant

mass of the second pair is used for the selection. The evaluated invariant mass, shown in Figure 7a, should be above 80 GeV. The region is then divided into three regions based on m_{eff} , which is shown in Figure 7b: $1.5 > m_{\text{eff}} > 1.0$ GeV (low m_{eff} , SRA-L), $2.0 > m_{\text{eff}} > 1.5$ GeV (medium m_{eff} , SRA-M) and $m_{\text{eff}} > 2.0$ GeV (high m_{eff} , SRA-H).

Figure 8: Kinematic distributions of (a) p_T of the leading jet for SRB, (b) average of the invariant masses evaluated as Higgs candidates for SRB, and (c) object based E_T^{miss} significance $\mathcal{S}$ for SRC [3].

For the signal considered in SRB, the b -jet pair associated with the sbottom is boosted by ISR. To allow for boosted sbottoms, only events with leading jet p_T larger than 350 GeV are considered, as shown in Figure 8a. Then, an attempt is made to reconstruct two boosted Higgs particles. As for SRA, ΔR is evaluated for all combinations of b -jets. In the case of signal considered in SRB, the pair showing the largest ΔR is most likely to be b -jets from a Higgs. So, the selected pair is considered as a Higgs candidate. Then, from the remaining b -jets, the largest ΔR pair is selected. The second pair is considered as another Higgs candidate. Based on those two Higgs candidates, the average invariant mass is evaluated. As shown in Figure 8b, the average invariant mass should be within 75 GeV to 175 GeV.

In contrast to the signals considered in SRA and SRB, the ΔR base approach is not

efficient for the signal interested in SRC. Instead, the object based E_T^{miss} significance ($\mathcal{S}$), which gives an indication whether the E_T^{miss} is from invisible objects or mismeasured particles, is used for this region definition, which is shown in Figure 8c. $\mathcal{S}$ is defined as $\sqrt{|\mathbf{p}_T^{\text{miss}}|^2 / \sigma_L^2 (1 - \rho_{LT}^2)}$ where σ_L is the total momentum resolution after being rotated into the plane parallel to the $\mathbf{p}_T^{\text{miss}}$, and ρ_{LT} is the correlation factor between the longitudinal and transverse momentum resolution of each jet or lepton. As shown in Figure 8c, events with invisible objects like signal have large $\mathcal{S}$. The events are required to have $\mathcal{S} > 22$, and are categorized by $\mathcal{S} \in [22, 24]$ (SRC22), $\mathcal{S} \in [24, 26]$ (SRC24), $\mathcal{S} \in [26, 28]$ (SRC26) and $\mathcal{S} > 28$ (SRC28).

Figure 9: Observed data and expected backgrounds for sbottoms decaying to multi- b quarks [3].

Figure 9 shows the expected background and data in each SR. As shown in those figures, no significant deviation from SM expectation is found. Model-dependent fits are performed to evaluate 95% CL exclusion limits using full likelihood [4]. For a scenario assuming $m(\tilde{\chi}_1^0) = 60$ GeV, sbottom masses, $m(\tilde{b})$, up to 1.5 TeV are excluded for $1.1 > m(\tilde{\chi}_2^0) > 0.5$ TeV (Figure 10a). The diagonal region is excluded by SRB and other regions are excluded by SRA. For the scenario assuming $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, sbottom masses, $m(\tilde{b})$, up to 1.3 TeV are excluded for $m(\tilde{\chi}_2^0) < 750$ GeV (Figure 10b). The diagonal region is excluded by SRC and others by SRA.

4. Search for SUSY decaying to same-sign leptons

In this section, the search for SUSY processes with final states including same-sign leptons [5] is introduced. The following four scenarios shown in Figure 11 are selected as benchmark models: (11a) $\tilde{b}_1 \rightarrow tW\tilde{\chi}_1^0$, (11b) $\tilde{t}_1 \rightarrow tW^\pm(W^*)\tilde{\chi}_1^0$, (11c) $\tilde{g} \rightarrow q\bar{q}'WZ\tilde{\chi}_1^0$ and (11d) $\tilde{g} \rightarrow t\tilde{t}_1^* \rightarrow tq\bar{q}'$. In this search, an R-parity violation model, i.e. scenario (11d), is also considered. Those scenarios share the final states with two same-sign leptons or three leptons. The advantage of this search is the limited sources of background with same-sign leptons in the SM. Instead, detector backgrounds need to be considered.

Figure 10: Exclusion limits for sbottoms decaying to multi- b quarks assuming (a) $m(\tilde{\chi}_1^0) = 60$ GeV and (b) $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV [3]

Figure 11: Feynman diagrams of target scenarios for searches for SUSY processes with final states including same-sign leptons. (a) $\tilde{b}_1 \rightarrow tW\tilde{\chi}_1^0$, (b) $\tilde{t}_1 \rightarrow tW^\pm(W^*)\tilde{\chi}_1^0$, (c) $\tilde{g} \rightarrow qq'WZ\tilde{\chi}_1^0$ and (d) $\tilde{g} \rightarrow t\tilde{t}^* \rightarrow tq q'$.

The first source of detector backgrounds is charge-flip, i.e. events where an opposite-sign pair of leptons is reconstructed as a same-sign pair due to the misidentified charge of one of the two leptons. The contribution from this source is evaluated by scaling the normalisation of data events with two opposite-sign leptons using the probability of mis-measurement of lepton charge. This probability is evaluated as $\mathcal{O}(0.1\%)$ at $p_T = 100$ GeV for central electrons ($|\eta| < 1.4$) using simulation of $t\bar{t}$ events. Due to the small probability of charge misidentification, the contribution of charge-flip is considered to be minor in this search.

Another source of detector background is represented by fake or non-prompt (F/NP) leptons. The main sources of F/NP leptons are electroweak decays of hadrons. The contribution is evaluated using a matrix method [6]. In this method, in addition to signal lepton selection criteria, loosened lepton selection criteria are used. The number of events with signal lepton selection criteria $\mathcal{S}$ is related to the proportion of events with F/NP leptons $\mathcal{F}$ as $\mathcal{S} = \epsilon(1 - \mathcal{F}) + \zeta\mathcal{F}$, where ϵ and ζ are the probabilities of prompt

and F/NP leptons passing the signal lepton selection criteria, respectively. Since $\mathcal{S}$ can be measured, if ϵ and ζ are known, $\mathcal{F}$ can be evaluated. The probability ϵ is evaluated based on $t\bar{t}$ simulation, where ζ is evaluated using data taken in a region designed to enrich events with F/NP leptons.

Figure 12: Expected contribution from SM physics and the evaluated contribution from charge-flip and F/NP leptons (a) in the region with loose event selection, and (b) in validation and signal regions [5]. Observed data are shown by the solid points. The ratio between observed data and total expected backgrounds are shown in the bottom plot.

The evaluated contributions in the region with loose selection from charge-flip and F/NP leptons are shown in Figure 12a, with the SM expected backgrounds based on simulation. In the figure, all events are categorized based on the number of b -jets and lepton type. In all categories, the expected number of events including events with charge-flip or F/NP leptons is close to that observed in data. In the same manner, the detector backgrounds are evaluated in the validation regions and signal regions, as shown in Figure 12b. As shown in the figure, no significant deviation is found from the background expectation. Model-dependent fits are performed to evaluate 95% CL exclusion limits.

Figure 13 shows a variety of exclusion limits. The limit for $\tilde{b}_1 \rightarrow tW\tilde{\chi}_1^0$ with the assumption of $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) + 100$ GeV is shown in Figure 13a. The limit for $\tilde{t}_1 \rightarrow tW^\pm(W^*)\tilde{\chi}_1^0$ with the assumption of $m(\tilde{t}_1) = m(\tilde{\chi}_1^0) + m_t = m(\tilde{\chi}_1^0) + 275$ GeV and $m(\tilde{\chi}_1^\pm) \approx m(\tilde{\chi}_1^0)$ is shown in Figure 13b. Both scenarios are excluded up to squark masses of 750 GeV. The limit for $\tilde{g} \rightarrow q\bar{q}'WZ\tilde{\chi}_1^0$ with the assumption of $m(\tilde{\chi}_1^\pm) = (m(\tilde{g}) + m(\tilde{\chi}_1^0))/2$ and $m(\tilde{\chi}_2^0) = (m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))/2$ is shown in Figure 13c. The limit for $\tilde{g} \rightarrow t\bar{t}_1^* \rightarrow tq\bar{q}'$ with the assumption of R-parity violation is shown in Figure 13d. Both scenarios are excluded for $m(\tilde{g})$ up to 1.6 TeV.

5. Search for stops decaying to Z boson

In this section, the search designed for stop pair production decaying to Z bosons [7] is presented. In this search, the mass eigenstates from a mix of left-handed and right-handed stops are considered with $\tilde{t}_1$ being the lighter one and $\tilde{t}_2$ the heavier one. The

Figure 13: Exclusion limits for SUSY models decaying to same-sign leptons [5]. (a) $\tilde{b}_1 \rightarrow tW\tilde{\chi}_1^0$, (b) $\tilde{t}_1 \rightarrow tW^\pm(W^*)\tilde{\chi}_1^0$, (c) $\tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$, (d) $\tilde{g} \rightarrow t\bar{t}_1 \rightarrow tq q'$ (RPV)

Figure 14: Feynman diagrams and kinematics of target scenarios for the search for stops decaying to Z bosons. (a) decaying via $\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0 \rightarrow tZ(\text{or } h)\tilde{\chi}_1^0$, (b) decaying via $\tilde{t}_2 \rightarrow Z\tilde{t}_1 \rightarrow Zbf f'\tilde{\chi}_1^0$.

following scenarios (shown in Figure 14) are considered: (14a) pair production of a $\tilde{t}_1$

decaying via $\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0 \rightarrow tZ(\text{or } h)\tilde{\chi}_1^0$, and (14b) pair production of a $\tilde{t}_2$ decaying via $\tilde{t}_2 \rightarrow Z\tilde{t}_1 \rightarrow Zb\bar{b}f'f'\tilde{\chi}_1^0$. These scenarios share the final states with at least 3 leptons, multiple jets and E_T^{miss} . By requesting at least 3 leptons, $t\bar{t}$ events, which are the largest background contribution for other stop searches, are significantly reduced.

For each scenario, two signal regions are designed to cover the possible kinematics of the decay. For $\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0 \rightarrow tZ(\text{or } h)\tilde{\chi}_1^0$, the regions for the scenario with large and small $\Delta(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ are denoted SR1A and SR1B, respectively. For $\tilde{t}_2 \rightarrow Z\tilde{t}_1 \rightarrow Zb\bar{b}f'f'\tilde{\chi}_1^0$, the regions for the scenario with small and large $\Delta(\tilde{t}_2, \tilde{t}_1)$ are designed as SR2A and SR2B, respectively. In the case of SR1A, target signals are expected to be with large $m(\tilde{\chi}_2^0)$. The region is therefore designed with a parameter correlated with $m(\tilde{\chi}_2^0)$. In the case of SR1B, target signals are expected to be with boosted $\tilde{\chi}_2^0$, so large momentum of leptons from boosted Z boson decayed from $\tilde{\chi}_2^0$ are required. In the case of SR2A, target signals are expected to be with soft Z boson, therefore upper limits on the momentum of leptons from Z boson are required. In the case of SR2B, target signals are expected to be with boosted objects in the final state, therefore energetic products in the final state are required.

Figure 15: Observed data and expected backgrounds for stops decaying to Z bosons [7]. For SR1A, SR1B and SR2B, the regions are binned by E_T^{miss} and p_T .

Figure 15 shows the expected background and data in each SR. The F/NP lepton contribution is estimated using a matrix method, in the same way as described in Section 4. As shown in the figure, no significant deviation from SM expectation is found. Model-dependent fits are performed to evaluate 95% CL exclusion limits for each region. The limits are combined by selecting the best value.

Figure 16 shows the evaluated exclusion limits. The limit for $\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0 \rightarrow tZ(\text{or } h)\tilde{\chi}_1^0$ is shown in Figure 16a. For $m(\tilde{\chi}_2^0) > 250$ GeV, lighter top masses, $m(\tilde{t}_1)$, up to about 1050 GeV are excluded. The limit for $\tilde{t}_2 \rightarrow Z\tilde{t}_1 \rightarrow Zb\bar{b}f'f'\tilde{\chi}_1^0$ is shown in Figure 16b. For $m(\tilde{\chi}_1^0) \sim 350$ GeV, heavier top masses, $m(\tilde{t}_2)$, up to about 875 GeV are excluded.

Figure 16: Exclusion limits for stops decaying to a Z boson [7]. (a) $\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0 \rightarrow tZ$ (or h) $\tilde{\chi}_1^0$, (b) $\tilde{t}_2 \rightarrow Z\tilde{t}_1 \rightarrow Zbff'\tilde{\chi}_1^0$

6. Search for stops in the 3-body decay mode

In this section, the search for stops in the 3-body decay mode [8] is introduced. This search is dedicated to stop pair production with direct 3-body decays, as shown in Figure 17a. This scenario is realized as a direct decay scenario in the case that $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$ is larger than the top mass (otherwise it undergoes a 2-body decay, $t\tilde{\chi}_1^0$), and smaller than the W mass and b mass (otherwise it undergoes 4-body decays, $bff'\tilde{\chi}_1^0$ or $c\tilde{\chi}_1^0$), as shown in Figure 17b.

Figure 17: Feynman diagram and phase space of a stop search scenario [8]. (a) diagram of 3-body decay, (b) possible phase space of stop direct decay

This search is characterized by a signature including one leptonic decay of the W , at least 4 jets and E_T^{miss} . This scenario is hard to separate from SM $t\bar{t}$ decays, so a machine learning approach is used to achieve a better signal to background ratio.

A neural network is trained using simulation samples. Then, an output score is

Figure 18: Distribution of neutral network score and observed data in the control and validation regions [8]. (a) Distribution of neutral network, (b) E_T^{miss} distribution of data and backgrounds in the control region and (c) m_T distribution of data and backgrounds in the validation region.

used as a criterion to define the signal region. Figure 18a shows the score for signals and backgrounds. A score above 0.65 is required for the signal region, while a score between 0.6 to 0.65 is used as a validation region criterion, and a score between 0.4 to 0.6 is used as a control region criterion. The E_T^{miss} distribution of the control region and the $m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\Delta\phi(\ell, \mathbf{p}_T^{\text{miss}})))}$ distribution of the validation region are shown in Figure 18b and Figure 18c, respectively. In Figure 18b and Figure 18c, data are also shown by the solid points, and good agreement between data and expected backgrounds can be seen.

Figure 19: (a) Observed data in the control, validation and signal regions with estimated backgrounds. (b) Exclusion limits for stop direct decay [8].

Figure 19a shows the data in the SR, CR and VR. As shown in the figure, no significant deviation from SM expectation is found. Model-dependent fits are performed to evaluate 95% CL exclusion limits. For the limit evaluation, 2-body and 4-body scenarios are also considered. The evaluated limits are shown in Figure 19b. The limit on $m(\tilde{t})$ reaches up to 720 GeV.

7. Conclusions

Five SUSY searches using 139 fb^{-1} of proton-proton collision data at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ collected in 2015 – 2018 by the ATLAS detector at the LHC are introduced. No significant deviation from SM expectation in any search is observed. The first search, for the squarks and gluinos decaying to multi-jets, excludes $m(\tilde{q})$ up to 1940 GeV and $m(\tilde{g})$ up to 2350 GeV. The second search, for the sbottom decaying to multi- b quarks, excludes $m(\tilde{b})$ up to 1.5 TeV. The third search, for SUSY processes with final states including same-sign leptons, excludes $m(\tilde{b}, \tilde{t})$ up to 750 GeV and $m(\tilde{g})$ up to 1.6 TeV. The fourth search, for stop pair production decaying to a Z boson, excludes $m(\tilde{t}_1)$ up to 1140 GeV and $m(\tilde{t}_2)$ up to 875 GeV. The fifth search, for stops via a direct 3-body decay, excludes $m(\tilde{t})$ up to 720 GeV.

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