Inclusive 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 talk summarises recent ATLAS results on inclusive searches for supersymmetric squarks and gluinos, including third generation squarks produced in the decay of gluinos. The searches involved final states containing jets, including those tagged as originating from b-quark decays, missing transverse momentum with and without light leptons, taus or photons. Sensitivity projections for the data that will be collected in 2015 are also presented.

1 Introduction

Supersymmetry (SUSY) [1] is one of the most studied theoretical extensions of the Standard Model (SM). SUSY expands the symmetry group of the SM to include a symmetry between bosons and fermions leading to a doubling of the particle content of the SM. To ensure that the proton is stable in SUSY, R -parity is introduced. This leaves the lightest supersymmetric particle (LSP), normally either the gravitino, $\tilde{G}$, or the lightest neutralino, $\tilde{\chi}_1^0$, stable providing a candidate for Dark Matter.

These proceedings will focus on the searches for the first and second generation of scalar quarks (squarks, $\tilde{q}$) and the fermionic partner of the gluon (gluino, $\tilde{g}$). Of the production cross section of SUSY particles, the cross section for squark and gluino production are the largest. Many decays of squarks and gluinos are considered in simplified models - from direct decays ($\tilde{q} \rightarrow q\tilde{\chi}_1^0$) to more complex decays going through several steps ($\tilde{g} \rightarrow qq\tilde{\chi}_1^\pm \rightarrow qqv_\tau\tilde{\tau} \rightarrow qqv_\tau\tau\tilde{\chi}_1^0$), where branching fractions are set to 100%. More complex theories, such as MSUGRA, are studied as well. The various decays of squarks and gluinos in the simplified models lead to a big variety of final states all of which will have large missing transverse momentum, E_T^{miss} , originating from the only weakly interacting LSP escaping the detector unnoticed.

A selection of searches for squarks and gluinos performed with the 20 fb⁻¹ data collected by the ATLAS experiment [2] with $\sqrt{s} = 8$ TeV are presented. Unfortunately, no excesses have been observed therefore the results will be presented as limits on various SUSY scenarios. Furthermore, the prospects of the SUSY searches for squarks and gluinos with data collected in 2015 at $\sqrt{s} = 13$ TeV is presented.

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2 Selection of recent searches for squarks and gluinos at $\sqrt{s} = 8$ TeV

Searches for SUSY are based on a good understanding of the SM background. SUSY searches are normally performed in places of phase space where the predicted SM cross section is low, i.e. regions with many high- p_T objects and high E_T^{miss} .

There are three methods for estimating the SM background: fully data driven, partial data driven, and purely from simulation. The major irreducible backgrounds (W + jets, Z + jets, and top production) are estimated using a partial data driven technique. In this method the simulated background is normalised in control regions where the yield of the background under study is enhanced. The control regions are designed to be kinematically close and orthogonal to regions where the SUSY signal is enhanced. Through transfer factors, the background estimation is calculated in the signal enhanced regions.

All background estimates derived from control regions are checked by calculating transfer factors to other regions (validation regions) that are close to the signal enhanced regions as well. The background estimation is validated by comparing the number of expected events in the validation regions with observation.

2.1 Searches for direct squark decays

In the simplified model of direct squark decays, the first two generations of squarks are assumed to be light. The squarks will be produced in pairs and each squark will decay directly to a quark and a $\tilde{\chi}_1^0$ (the LSP) with a 100% branching fraction. The masses of the squark and the LSP are varied independently. There are three analyses in ATLAS that are sensitive to this model: the monojet analysis, the 0-lepton 2-6 jets analysis, and the razor analysis.

The monojet analysis [3, 4] selects events with one high- p_T jet, high E_T^{miss} , and no leptons (e/μ). The variables used to define the signal regions are the p_T of the leading jet and E_T^{miss} . This analysis targets especially a compressed mass-spectrum where the mass difference between the squark and the LSP is small (≤ 50 GeV).

The 0-lepton, 2-6 jets analysis [4, 5] selects events with 2-6 jets inclusively, high E_T^{miss} , and no leptons (e/μ). The variables used to discriminate between SUSY signal and SM background are the effective mass, $m_{\text{eff}} = E_T^{\text{miss}} + \sum_{i=1}^{n_{\text{jets}}} |p_T^i(\text{jet})|$, and $E_T^{\text{miss}}/m_{\text{eff}}$. The analysis defines 17 signal regions with various number of jets, and cuts on the discriminating variables targeting many different SUSY models.

The razor analysis [4] selects at least two jets, high E_T^{miss} , and no leptons. Two signal regions are defined using a set of variables called the razor variables [6]. The razor variables are designed to discriminate between events with particles coming from a SUSY decay and events coming from SM processes.

The combined exclusion limit of direct squark decays based on the best expected exclusion of the three analyses is seen in Fig. 1. It is seen that the 0-lepton, 2-6 jets analysis, and the razor analysis have similar sensitivity reach, whereas the monojet analysis is strongest in the area of small mass difference between the squarks and the LSP. For a LSP with a mass of 100 GeV, squarks with masses up to 850 GeV are excluded.

Figure 1. Exclusion limits in the mass plane of the LSP and first- and second-generation squarks assuming direct squark decays. The solid and the dashed red lines show respectively the combined observed and expected 95% CL exclusion limits. Expected limits from the individual analyses are shown as well. A previous result from ATLAS using 7 TeV proton-proton collisions is represented by the grey area. A limit obtained with the 0-lepton, 2-6 jets analysis in a scenario with only one light-flavour squark produced is shown in green. Taken from Ref. [4].

2.2 Searches for one-step squark and gluino decays

The simplified SUSY models of one-step decays of squarks and gluinos considered here assume pair production of either squarks or gluinos and an immediate decay through a chargino ($\tilde{\chi}_1^\pm$), $\tilde{q} \rightarrow q\tilde{\chi}_1^\pm \rightarrow qW^\pm\tilde{\chi}_1^0$ and $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^\pm \rightarrow q\tilde{q}W^\pm\tilde{\chi}_1^0$. The masses of the squarks/gluinos and $\tilde{\chi}_1^0$ are kept as free parameters while the mass of $\tilde{\chi}_1^\pm$ is fixed to $x = (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})/(m_{\tilde{q}/\tilde{g}} - m_{\tilde{\chi}_1^0}) = 1/2$.

There are two analyses which show similar sensitivity to squark and gluino production with one-step decays: the 0-lepton, 2-6 jets analysis, and the 1-lepton analysis [4, 7]. The 1-lepton analysis selects events with 1 soft or hard lepton (e/μ), high E_T^{miss} , and more than two high- $p_{T,jets}$. The 0-lepton and the 1-lepton analyses are orthogonal as their signal and control regions don't overlap between the two analyses thus they can be statistically combined to improve their collected sensitivity. The combination define a common set of systematics that can be correlated between the two analyses [4].

As seen in Fig. 2, the exclusion limit for the statistical combination of the 0- and 1-lepton analyses is as strong or stronger than each of the individual analyses at any mass point. For a massless LSP, the exclusion limits of squark and gluino masses reach 810 GeV and 1275 GeV, respectively.

Figure 2. Observed and expected exclusion limits for simplified models of squark-pair (left) and gluino-pair (right) production with one-step decays via $\tilde{\chi}_1^\pm$ into a W-boson and $\tilde{\chi}_1^0$. Squark (left)/gluino (right) and neutralino masses in the area below the observed limit are excluded at 95% CL. The individual limits from the 0-lepton and the 1-lepton analyses are overlaid in green and magenta, respectively. Taken from Ref. [4].

2.3 Searches for gluinos decaying through third generation squarks

Next, a simplified model of gluino pair production is considered with subsequent decay through an off-shell scalar top quark, $\tilde{t}_1$, as $\tilde{g} \rightarrow t\tilde{t}_1$. The stop quark is assumed to be the lightest squark, but heavier than the gluino, thus the stop originating from the gluino decay is produced off-shell and decays immediately with a 100% branching fraction as $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$. If $m_{\tilde{g}} < 2m_t + m_{\tilde{\chi}_1^0}$, one if the top quarks will be produced off-shell leading to a five-body decay, $\tilde{g} \rightarrow tbW\tilde{\chi}_1^0$. The decay of a gluino through a stop quark leads to final states with b -jets, decay products from W -bosons, and E_T^{miss} . There are two analyses that are sensitive to this SUSY model: the same-sign/3-leptons (SS/3L) analysis, and the 0-1 lepton and 3 b -jets analysis.

The SS/3L analysis [4, 8] selects events with either two leptons (e/μ) of identical electrical charge or 3 leptons together with up to 3 jets originating from b -quarks, and high E_T^{miss} . Five signal regions are defined using various jet and b -jet multiplicity. The effective mass, m_{eff} , is used as a discriminating variable.

The 0-1 lepton, 3 bjets analysis [4, 9] selects events without of with one lepton, 4-7 jets of which at least three are b -jets, and high E_T^{miss} . Nine signal regions are defined based on lepton multiplicity and jet multiplicity. Three variables are used to discriminate signal from background: m_{eff} , $m_{\text{eff}}/\sum_{i=1}^4 |p_T^i(\text{jet})|$, and the transverse mass, $m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \Delta\phi(\ell, E_T^{\text{miss}}))}$.

The limits in the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ -plane of the SS/3L, and the 0-1 lepton, 3 b -jets analyses are shown together with the combined expected and observed exclusion limits in Fig. 3. The Off-shell/On-shell diagonal separates the region where the gluino decays to two on-shell top quarks (below the line) from the region where the gluino decays into an on-shell and an off-shell top quark (above the line). For a low $m_{\tilde{\chi}_1^0}$, gluino masses up to 1320 GeV have been excluded.

Figure 3. Exclusion limits for the simplified models of gluino decaying through off-shell scalar top quarks. In the region below the grey dashed line labelled "On-shell region", the gluinos decay to two real top quarks, whereas in the "Off-shell region", the gluino decay involves an off-shell top quark. The solid red line and the dashed red line show respectively the combined observed and expected 95% CL exclusion limits. Expected limits from the SS/3L, and the 0-1 lepton, 3 b -jets analyses are shown in purple and cyan, respectively. Taken from Ref. [4].

2.4 Searches for gauge-mediated SUSY breaking models

In general gauge-mediated SUSY breaking models (GGM), the lightest SUSY particle is the gravitino, $\tilde{G}$. The final state depends on the nature for the second lightest particle, the NLSP ($\tilde{\chi}_1^0$). In these proceedings we consider a GGM SUSY model with higgsino-bino mixing in the NLSP. We consider gluino pair production with a one-step decay, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow qq(\gamma/h)\tilde{G}$, where the higgs, h , is assumed to decay directly to a pair of b -quarks. This leads to final states with photons, jets, b -jets, and E_T^{miss} .

The analysis sensitive to this GGM scenario, is selecting events with at least one photon, 2-4 jets, 1 or 2 b -jets, E_T^{miss} , and no leptons [10]. Two signal regions are defined for this SUSY model using the invariant mass of the two b -jets, and the transverse mass of the photon and the E_T^{miss} .

The expected and observed limits on the GGM scenario with higgsino-bino mixing in the NLSP, is shown in Fig. 4. For NLSP masses below approximately 450 GeV, the direct production of gaugino becomes dominant thus making the analysis insensitive to the gluino mass.

Figure 4. Exclusion limits in the gluino-NLSP mass plane, for the higgsino-bino GGM model. The solid red line and the dashed red line show the combined observed and expected 95% CL exclusion limits, respectively. Taken from Ref. [10].

2.5 Searches for CMSSM/mSUGRA

The mSUGRA/CMSSM model is given by five parameters: a universal scalar mass (m_0), a universal gaugino mass ($m_{1/2}$), a universal trilinear scalar coupling (A_0), all defined at the grand unification scale, $\tan\beta$, and the sign of the higgsino mass parameter (μ). The masses of all the SUSY particles increase with increasing $m_{1/2}$. The masses of the squarks and the sleptons will depend on m_0 as well. In the model shown here, the values $\tan\beta = 30$, $A_0 = -2m_0$ and $\mu > 0$ are chosen, such that the lightest scalar Higgs boson mass is approximately 125 GeV in a large fraction of the $(m_0, m_{1/2})$ parameter space.

The observed and expected limits of all analysis providing limits in this CMSSM/mSUGRA model are shown in Fig. 5 along with the best combined expected and observed limits. It is seen that at low m_0 , the combination of the 0- and 1-lepton analyses is the strongest, whereas at higher m_0 the 0-1 lepton, 3 b -jets analysis is the strongest. [4]

Figure 5. Exclusion limits in the $(m_0, m_{1/2})$ plane for the mSUGRA/CMSSM model. The solid red line and the dashed red line show the combined observed and expected 95% CL exclusion limits, respectively. Expected (dashed lines) and observed (solid lines) limits from the individual analyses are also shown. Taken from Ref. [4].

3 Prospects for searches for squarks and gluinos at $\sqrt{s} = 13$ TeV

With an increase in the collision energy of the LHC from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 13$ TeV, the production cross section for heavy particles, such as squarks and gluinos, will increase more than the cross section of the SM background. This provides a better opportunity to discover SUSY particles if they exist.

The prospects of searching for SUSY at $\sqrt{s} = 13$ TeV have been studied for two simplified SUSY models both assuming gluino pair production, but with different decays. One of the models assume a direct decay of the gluino, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$, with a massless LSP, $m_{\tilde{\chi}_1^0} = 0$ GeV, similar to the squark model described in Sec. 2.1. The other model studied assumes a one-step decay of the gluino, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^\pm \rightarrow q\tilde{q}W^\pm\tilde{\chi}_1^0$, assuming $m_{\tilde{\chi}_1^0} = 25$ GeV and that the mass difference between the gluino and the chargino is $x = (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})/(m_{\tilde{g}} - m_{\tilde{\chi}_1^0}) = 1/2$, similar to the model described in Sec. 2.2.

Two analyses are studying their sensitivity to these models at $\sqrt{s} = 13$ TeV; the 0 lepton, 2-6 jets analysis is studying the SUSY model containing the direct decay of the gluino, and the 1 lepton analysis is studying its sensitivity to the model with the one-step decay of the gluino [11]. Both analyses are relying on the corresponding analyses performed at $\sqrt{s} = 8$ TeV, described in Ref. [5, 7]. The analyses are based on simulations of the Standard Model background with an assumption on the systematic uncertainty on the background of 20% for the 0 lepton analysis and 25% for the 1 lepton analysis. Four integrated luminosity scenarios are studied, 1 fb⁻¹, 2 fb⁻¹, 5 fb⁻¹, and 10 fb⁻¹, with corresponding optimisations of the signal regions for each luminosity.

The sensitivity for simplified SUSY models with direct gluino decays and one-step gluino decays are shown in Fig. 6 left and right, respectively, with the gluino masses already excluded by the $\sqrt{s} = 8$ TeV analyses shaded in grey. The sensitivity for observation of SUSY particles at $\sqrt{s} = 13$ TeV is expected to exceed that of full $\sqrt{s} = 8$ TeV data sample at an integrated luminosity of 5 fb⁻¹ for directly decaying gluinos and 2 fb⁻¹ for gluinos decaying through charginos.

Figure 6. Discovery p_0 values as a function of the gluino mass in the gluino pair production and direct to two quarks and $\tilde{\chi}_1^0$ (left), and decay via $\tilde{\chi}_1^\pm$ and two quarks to $\tilde{\chi}_1^0$ and a W -boson. The neutralino mass is set to $m_{\tilde{\chi}_1^0} = 0$ GeV (left) and $m_{\tilde{\chi}_1^0} = 25$ GeV (left). Different integrated luminosities were assumed in the optimisation: 1, 2, 5 or 10 fb⁻¹. The total uncertainty on the background is assumed to be 20 % (left) and 25 % (right). Taken from Ref. [11].

4 Conclusion

A wide range of searches for squarks and gluinos have been performed at $\sqrt{s} = 8$ TeV with the ATLAS detector. No excesses have been observed above the Standard Model expectation. A selection of searches for squarks and gluinos have been presented in Sec. 2.

With the increase in collision energy of the LHC to $\sqrt{s} = 13$ TeV, a new era for SUSY searches can begin, as much higher masses of squarks and gluinos can be probed due the vast increase in their production cross section. Thus, already with an integrated luminosity of 2 fb⁻¹, the sensitivity for observation of gluino pair production will exceed the current limits.

References

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