SUSY Searches in the ATLAS Experiment

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Abstract. Recent results from the ATLAS experiment at the LHC in the search for supersymmetry are presented. A focus is placed on searches requiring nonstandard techniques in particularly challenging final states. All searches presented here analyze $p\bar{p}$ collisions with $\sqrt{s} = 8$ TeV collected in 2012. Within these results, in the absence of significant disagreement from the Standard Model expectations, limits are placed on various models in both strong and weak sparticle production as well as on models with long-lived sparticles.

1. Introduction

The Standard Model (SM) leaves one begging for a more complete description of the universe. Despite its successes, with the aesthetic and empirical shortcomings of the theory, new physics entering at or below the TeV scale is highly desirable. The most theoretically elegant way to introduce such physics is via a weak scale supersymmetry (SUSY). Such a theory has the potential to deflate the so-called naturalness problem, explain the dark matter content of the universe, and even tackle issues such as providing a mechanism for neutrino masses. However, in the absence of a SUSY at or below the TeV scale, within the reach of the LHC, the naturalness motivations for SUSY are weakened. It is therefore reasonable for one to hope that if SUSY exists, it enters at these scales.

However, there have been nothing but very strong exclusions placed on the SUSY parameter space since its inception roughly 50 years ago. Most recently, Run I of the LHC has produced the most stringent limits on SUSY to date. Various limits on supersymmetric models can be seen in Figure 1 showing large regions of SUSY parameter space excluded by ATLAS [1].

Despite these strong limits, portions of unexcluded SUSY parameter space exist where the theory is still well motivated. Furthermore, models with signatures that are more difficult to find become more compelling. The results presented here will mainly focus on those signatures that often require the use of interesting, nonstandard techniques.

2. Strongly Produced Sparticles

Supersymmetry can present itself in very different phenomenologies depending on the allowed couplings and the sparticle mass spectra. At a hadron collider like the LHC, the strong production of gluinos and squarks will dominate initial sensitivity given that they are of a mass attainable at the given collision energy. The most likely way to find SUSY is via very inclusive searches for strongly produced sparticles.

A combined analysis is performed searching for excesses in final states containing jets, missing transverse energy ($E_T^{\text{miss}}$), and at least one isolated lepton [2]. Diagrams for example processes can be found in Figure 2. Three classes of signal regions are constructed with separate techniques used for each class.

The first of these channels requires a single hard lepton ($p_T > 25$ GeV) and is sensitive to mid- to high-mass-splittings between the pair-produced sparticles and those through which the cascade decay occurs. A veto is placed on events with multiple leptons where no second lepton with transverse...
momentum above 10 GeV may exist. The primary discriminating variable of choice is the magnitude of the $E_T^{miss}$ or the mass variable

$$m_{eff}^{min} = \sum_{i=1}^{N_i} p_{T,i}^j + \sum_{j=1}^{N_{jet}} p_{T,j} + E_T^{miss}.$$  \hspace{1cm} (1)

An example signal region within this channel additionally requires at least six jets above various $p_T$ requirements, $E_T^{missing} > 350$ GeV, the ordinary transverse mass $m_T > 150$ GeV, and $m_{eff}^{min} > 150$ GeV. An example discriminating distribution for this region can be seen in Figure 3a showing no significant excess above expected backgrounds.

Alternatively, this analysis also looks in a channel with soft leptons to allow for sensitivity to compressed SUSY spectra. This analysis uses a $E_T^{miss}$-significance measure defined by $E_T^{miss} / m_{eff}^{min}$ where the denominator normalizes the quantity to reflect the change in the $E_T^{miss}$ resolution of the detector. This variable is therefore used to remove events with large $E_T^{miss}$ that is the result of a poorly reconstructed jet.

Signal regions with a single soft lepton require one electron (muon) with transverse momentum between 7 (6) GeV and 25 (25) GeV. If a second lepton exists in the event with transverse momentum above 7 (6) GeV, the event is vetoed. An example signal region used in this analysis additionally
require at least five jets above various momentum requirements, \( E_T^{\text{miss}} > 300 \text{ GeV}, m_{\tau} > 100 \text{ GeV}, \) and \( E_T^{\text{miss}}/m_{\text{eff}}>0.3 \). The results from this region can be seen in Figure 3b. Additionally, a region with two soft leptons is studied but not discussed here.

Finally, a class of events with two hard leptons is used to probe these models employing the so-called Razor variables [3]. These variables that attempt to characterize the mass of a new particle by performing boosts into a proxy “R” frame can provide significant sensitivity to new physics. All visible particles are organized into two “megajets” in a configuration that minimizes the sum of the squared masses of the two “megajet” four-momenta. Two masses are constructed in this “R” frame, one representing the longitudinal momentum \( M_R' \) of the system and the other representing the transverse information \( M_T^2 \) with assumptions on the momenta of the escaped particles. \( M_R' \) is defined as

\[
M_R' = \sqrt{(j_{1,E} + j_{2,E})^2 - (j_{1,L} + j_{2,L})^2}
\]

Finally, the Razor variable “R” is constructed from the ratio of the two that tends to peak at low values for SM-like events and tends to be uniformly distributed in the interval [0,1] for SUSY-like events.

In this channel, the ratio \( R \) is used to reduce SM backgrounds, while the final binned variable is the mass \( M_{R'} \). Two opposite-sign leptons are required with the highest \( p_T \) above 14 GeV and the second leading \( p_T > 10 \text{ GeV} \). In an example signal region, at least three jets with \( p_T > 50 \text{ GeV} \) are required. In this region, additional requirements for final signal sensitivity are \( R > 0.35 \) and \( M_R' > 800 \text{ GeV} \). The binned distribution of \( M_{R'} \) for this region can be seen in Figure 3c.

In the absence of a significant excess, limits are placed in the gluino/squark vs. lightest neutralino mass plane. Results from the three channels above are statistically combined into a final exclusion
All limits at 95% CL

Figure 4: Example mass exclusion contours are shown for the channels targeting strong production of squarks and gluinos in leptonic final states.

Figure 5: An example diagram is shown for scharm pair production with decays to a final state of two c-jets and two lightest neutralinos.

result in each of these plots and models are excluded for a very wide range of sparticle masses. These results can be seen in Figure 4.

Supersymmetry deflates the naturalness problem by canceling off those quadratically divergent corrections to the Higgs mass. For this reason, this cancellation must be most effective for heavy SM fermions. It is theoretically desirable to have lower sparticle masses for the super partners of the heavier quarks on naturalness grounds. More dedicated searches are also performed focusing on the strong production of such squarks.

While there are ever increasing limits on the stop and sbottom squarks, there are few dedicated constraints on low mass scharm pair production. The analysis presented here looks for pair produced scharm quarks which each decay to a charm quark and a neutralino lightest supersymmetric particle (LSP) in the process depicted in Figure 5. This analysis employs the novel technology of lifetime-based charm tagging to reduce various backgrounds. The algorithms used here are analogous to lifetime-based taggers that have become commonplace in identifying those jets that contain B hadrons. The algorithm used here is an instance of an existing ATLAS btagger that has been reoptimized for charm efficiency, and calibrated for 2-dimensional use to simultaneously reject b-jets, and jets originating from light quarks and gluons. Multidimensional rejection and efficiency performance of this algorithm can be seen in Figure 6. Efficiencies for selecting b- and c-jets are calibrated in data using t\bar{t} events and jets containing \( D^+ \) hadrons, respectively. The working point used for this analysis represents a tagging efficiency of 19% (12.5%, 0.5%) for tagging c-jets (b-jets, light flavor and gluon jets) in t\bar{t} events.

Control regions are used to constrain background estimations in signal regions. This procedure is validated in orthogonal validation regions.

Signal regions are constructed with \( E_t^{\text{miss}} > 150 \text{ GeV} \) – as events are recorded as the result of \( E_t^{\text{miss}} \) triggers – and two c-tagged jets with \( p_T > 130, 100 \text{ GeV} \). The azimuthal angle between the \( E_t^{\text{miss}} \) and any jet is required to be \( > 0.4 \) to reduce the effects of fake \( E_t^{\text{miss}} \) from jet mismeasurement. A requirement on the \( E_t^{\text{miss}} \) significance (\( E_t^{\text{miss}}/m_{\text{jj}} > 0.25 \)) is placed in a similar way to the previous analysis. A requirement is placed on the invariant mass of the di-c-jet system to reduce backgrounds
Figure 6: Rejection and efficiency curves are shown for the analysis described in the text.

(a) Tagger performance for various $b$-jet $p_T$

(b) Tagger performance as a function of jet efficiencies

Figure 7: Signal region distributions for the charm-tagged scharm search are shown.

(a) $m_{cc}$

(b) $m_{CT}$

Figure 8: Mass exclusion contours in the scharm vs. lightest neutralino mass plane.

from $g \rightarrow c\bar{c}(b\bar{b})$ splittings.

The definition of signal and control regions for this analysis uses the cotransverse mass $m_{CT}$ [4] to reduce backgrounds. Processes with characteristic scales exhibit a kinematic endpoint in this variable above which contributions are suppressed. In $t\bar{t}$ events, if the identified $c$-jets are the real $b$-jets from top decays, this variable is expected to have a kinematic endpoint at around 135 GeV. As a result, regions are constructed with requirements of $m_{CT} > 150, 200, 250$ GeV to reduce most backgrounds significantly. An additional signal region is constructed from the results of a search for stop squarks [5].
targeting compressed spectra with a selection for monojet-like events.

The results of this analysis can be found in Figure 7. In the absence of a significant excess, limits are placed on scharm pair production as a function of the masses of the scharm and lightest neutralino and can be found in Figure 8.

3. Electroweak Sparticle Production

In the limit that the strongly produced sparticles are most often produced offshell, production of the EWKinos may dominate and will most likely be found via multilepton final states. A relatively new handle in such searches is the now known mass of the SM Higgs. Given this knowledge, targeted searches can be performed for higgsino-like neutralinos where additional kinematic constraints can be used to suppress backgrounds. The search presented here [6] uses several decay modes of the Higgs to search for associated production of neutralinos and charginos giving final states via a 125 GeV Higgs and a W boson in each event. Diagrams for example processes can be found in Figure 9.

This analysis also employs three search channels, each focusing on a particular Higgs decay. The W is always assumed to decay leptonically, and studied decays of the h are to $b\bar{b}$, $\gamma\gamma$, and $WW \rightarrow qq\ell\nu$ final states.

In a way similar to the other analyses, individual significant backgrounds are estimated by obtaining normalizations from dedicated control regions. A transverse mass variable is used to suppress background in the lepton plus two $b$-jet channel. The results of this channel can be seen in Figure 10a and no excess over the SM expectation is observed. The lepton plus diphoton channel performs an unbinned fit in the diphoton invariant mass spectrum. The expected contribution from the Higgs within the window around 125 GeV is taken from simulation while other background contributions are taken from the sidesbands of this distribution. The results of this channel can be seen in Figure 10b. Finally, for when the Higgs decays to $WW \rightarrow qq\ell\nu$, the two isolated leptons in the event are required to be of the same sign to reduce SM backgrounds. The sensitive variable used here is the partially reconstructed Higgs mass $m_{ljj}$. When the two jets and lepton from the Higgs decay are properly identified, this mass should be strictly less than the mass of the Higgs. Other backgrounds, such as combinatoric effects or background processes, will result in masses generally larger than the 125 GeV mass of the Higgs. In this way, a signal region can be constructed requiring a low value of this $m_{ljj}$ invariant mass. An example signal region can be seen in Figure 10c. Each of these channels comprises several signal regions and a small sample of them are shown here for illustration.

In the absence of a significant excess, limits are set on chargino and neutralino production. These limits can be seen in Figure 11. For a massless lightest neutralino, EWKino masses up to roughly 250 GeV are excluded. Increasing this lightest neutralino mass to around 40 GeV reduces the exclusion to roughly 170 GeV in EWKino mass.

4. Long Lived Particles

New particles that are long-lived or stable can also exist in many models and provide a very different phenomenology for collider experiments. Searches for these effects require unique analysis techniques
and use modern detectors in ways they were not designed for. The ATLAS experiment has performed several such searches looking for SUSY signatures that would otherwise skirt existing limits.

The first of these discussed is a search for photons that appear to not have been produced in the hard interaction [7]. Such a photon can present itself either as a non-pointing photon, using the high granularity EM calorimeter of ATLAS to determine the pointing angle of EM showers, or as a late photon as seen by a late-arriving EM shower resolved by the very sensitive timing of the calorimeter.

The non-pointing nature of a photon is quantified in the variable $z_{\text{origin}}$, which is the distance along the beam axis between the detector origin and the intersection of the axis with the projected photon momentum. The sensitive variable is

$$\Delta z_{\gamma} = |z_{\text{origin}} - z_{\text{PV}}|$$

where $z_{\text{PV}}$ is the $z$ location of the identified primary vertex. The resolution on this pointing is measured in $Z \rightarrow ee$ events for low values. Simulated signal processes show agreement in this region and resolutions for higher distances are shown in Figure 12a.

The arrival time of the EM shower also provides discrimination for certain signals. This is measured as $t_{\gamma}$, directly from the EM calorimeter. The resolution on this time is roughly around 300 ns, though much of this resolution is from a collision timing spread of roughly 220 ns. This resolution can be seen in Figure 12b as a function of cell energy.

These handles are used to probe processes in which a long-lived particle decays to photons and escaped energy. The signature discussed here contains two non-pointing photons and large $E_T^{\text{miss}}$. The results are specifically interpreted in a GMSB model (SPS8) where the gravitino is the LSP.
Figure 12: Expected and validated resolutions on the measured pointing and timing of photons is shown.

Figure 13: Signal region results and associated mass exclusions are shown for the nonpointing and delayed photon analysis.

Low $E_{\text{miss}}^\gamma$ control regions are used and $Z \rightarrow ee$ calibration regions show good agreement in $t_{\gamma}$. Signal regions are constructed by requiring $E_{\text{miss}}^\gamma > 75$ GeV as shown in Figure 13a. These distributions agree well with the control region predictions and no significant deviation is observed. As a result, limits can be set on GMSB model-space excluding lightest neutralino masses up to 430 GeV for lifetimes of order 1 ns. These exclusions can be seen in figure Figure 13b.

Another analysis focuses on particles that are long-lived enough to pass through some portion of the detector [8]. Such particles are motivated by many beyond the SM theories – splitSUSY, GMSB, UED, etc. The goal is to identify particles that are moving measurably slower than the speed of light.

If such a particle is electrically charged and passes through layers of the ATLAS pixel detector, these can be identified by exotic Bethe-Bloch contours in $dE/dx$ vs $q_p$ space. This gives a measurement of the particle’s relativistic $\beta_{\gamma}$. The detector limits this range to within roughly the interval $[0.2,1.5]$ with about a 20% resolution. Alternatively, if the particle arrives at the calorimeter system, precise calorimeter timing can provide a measurement of the particle’s relativistic $\beta$. If the particle lives long enough to also pass through the muon system, located furthest away from the interaction, additional timing resolution is created from this additional timing information. This resolution can be found in Figure 14a.

This analysis looks at mass spectra defined by

$$m_{\beta_{\gamma}} = \frac{p}{\beta_{\gamma}}$$

for measurements from the pixel detector, and
In the absence of a significant excess, limits are placed on various models that give rise to this signature. Long-lived staus in GMSB contexts are excluded for masses up to around 380-440 GeV for various values of $\tan \beta$. Stop R-hadrons, bound states including a stop, are excluded up to masses of roughly 880 GeV and gluino R-hadrons are excluded up to roughly 1250 GeV. Long-lived chargino masses are excluded up to 620 GeV. These exclusions, which represent just a portion of the exclusions performed by the analysis, can be seen in Figure 15.

5. Indirect Searches

Finally, in the absence of direct evidence for supersymmetry, it may still be that new particles are hidden among the SM spectrum. In such cases, indirect searches can be useful. It is expected that for a stop with mass at or near the top mass, one of the most sensitive probes is the measurement of the $t\bar{t}$ spin correlation which is sensitive to contributions from the scalar nature of the stop.
In this analysis, a standard dilepton $t\bar{t}$ selection is used where the azimuthal angle between the two leptons is used as the measure of spin correlation [9]. The angular asymmetry given by this spin correlation is found to be in good agreement with the Standard Model. Near-degenerate stop contributions to this spin correlation can deviate significantly from the pure-top distribution. A standard dileptonic $t\bar{t}$ selection is applied and the measured asymmetry $A_{\text{helicity}} = 0.38 \pm 0.04$ agrees well with the SM prediction of $0.318 \pm 0.005$. The sensitive angular distribution can be seen in Figure 16a. Given this agreement, assuming a massless neutralino and a 100% branching ratio of $\tilde{t} \rightarrow t + \chi_1^0$, stop masses are excluded between the top mass and 191 GeV as seen in Figure 16b.

6. Conclusions

Many results have been presented across the SUSY search program at the ATLAS experiment. A wide range of final states have been explored utilizing novel techniques and extending the ATLAS detector to provide measurements it was not designed to make. While the results presented here contain nothing but exclusions of SUSY, LHC Run II holds much promise in finding a weak scale supersymmetry providing sensitivity to the majority of the most motivated model spaces with an increased collision energy. As collisions go above high mass production thresholds, production cross sections greatly increase allowing for new discovery potential. So despite the negative landscape at hand, we are still in a hopeful era for supersymmetry.

7. References

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