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SEARCHES FOR SUPERSYMMETRY WITH THE ATLAS DETECTOR

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This is a review of searches for supersymmetry (SUSY) with the ATLAS detector in proton-proton collisions at a center-of-mass energy of 7 TeV at the Large Hadron Collider at CERN. The review covers results that have been published, or submitted for publication, up to September 2012, many of which cover the full 7 TeV data-taking period. No evidence for SUSY has been seen; some possibilities for future directions are discussed.

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1. Introduction

One of the cornerstones of the physics program at the Large Hadron Collider (LHC) is the search for new phenomena at the TeV scale, motivated by the gauge hierarchy problem. The recent discovery at the LHC of what may be the Higgs boson gives further reality to the hierarchy problem. Among the many possibilities for a solution, supersymmetry (SUSY) is perhaps the most attractive; it is certainly the most studied. A sampling of recent reviews on the hierarchy problem and SUSY can be found in the references [4–11]. Despite the lack of clear experimental evidence, SUSY remains an attractive possibility. In addition to stabilizing the gauge hierarchy in the presence of radiative corrections, SUSY provides an example of the unification of the gauge coupling constants, a mechanism for radiative electroweak symmetry breaking, a possible candidate for dark matter and, unique among models of new phenomena, a framework for the unification of particle physics with gravity.

In the Minimal Supersymmetric Standard Model (MSSM), every Standard Model fermion has a bosonic partner, and vice versa. The Higgs sector of the MSSM contains two Higgs doublets. Gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) are the SUSY partners of gluons and squarks. Charginos ($\tilde{\chi}^{\pm}_i, i = 1, 2$) and neutralinos ($\tilde{\chi}^0_i, i = 1 – 4$) (hereafter collectively referred to as “gauginos”) are the mass eigenstates formed from

*aIt could be argued that the closest exception might be the measurement of the anomalous magnetic moment of the muon [12].
the linear superposition of the SUSY partners of the Higgs and electroweak gauge bosons: higgsinos, winos and the bino. The SUSY partners of the charged leptons and neutrinos are collectively referred to as sleptons ($\tilde{\ell}^\pm$) and sneutrinos ($\tilde{\nu}$), respectively. R-parity conservation is introduced in order to prevent the occurrence of baryon and lepton number violating processes which are severely constrained experimentally. All Standard Model particles have R-parity of 1, while the superpartners have R-parity of -1. R-parity conservation implies that SUSY particles are produced in pairs and that the lightest SUSY particle (LSP) is stable. In a large fraction of the SUSY parameter space, the LSP is the weakly interacting lightest neutralino, $\tilde{\chi}_1^0$, a potential candidate for dark matter; this gives rise to the classic SUSY signature of missing transverse momentum (with magnitude denoted by $E_T^{\text{miss}}$).

If SUSY is to provide a natural solution to the hierarchy problem, this implies bounds on the SUSY particle masses \cite{13, 14}. The bounds depend on a number of factors, not least of which are the definition and amount of fine-tuning, but general expectations (for a recent treatment, see Ref. \cite{15}) in the MSSM are that the higgsinos, top squarks, the left-handed bottom squark and the gluino should not have masses too far above the weak scale, while other SUSY particles could in principle have masses beyond the reach of the LHC. Rough numbers are 200, 600 and 900 GeV for the higgsino, stop/sbottom and gluino masses, respectively. Such a configuration of SUSY particle masses sometimes goes by the name of “Natural SUSY”.

This review summarizes the ATLAS searches for SUSY in 7 TeV proton-proton collisions at the LHC. Unless otherwise specified, the searches are based on the complete dataset taken at the 7 TeV center-of-mass energy, corresponding to an integrated luminosity of 4.7 fb$^{-1}$. The review covers results that have been published, or submitted for publication, up to September 2012. Searches for the SUSY Higgs bosons will not be covered.

2. The ATLAS detector

The ATLAS detector \cite{17, 18} consists of a tracking system (inner detector, ID) surrounded by a thin superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip detectors, surrounded by a straw-tube tracker with transition radiation detection (transition radiation tracker, TRT). The electromagnetic calorimeter is a lead liquid-argon (LAr) detector. Hadronic calorimetry is based on two different detector technologies, with scintillator-tiles or LAr as active media, and with either steel, copper, or tungsten as the absorber material. The MS is based on three large superconducting toroid systems arranged with an eight-fold

$^b$The recent “Higgs” discovery changes this picture somewhat in the MSSM; the mixing between the left- and right-handed stop states needs to be large (see, for example, Ref. \cite{19}) in order to accommodate a Higgs boson mass in the observed range, resulting in a significant mass splitting between the two stop mass eigenstates. Extensions to the MSSM can evade these restrictions.
azimuthal coil symmetry around the calorimeters, and three stations of chambers for the trigger and for precise position measurements.

3. Modeling of Standard Model backgrounds and SUSY signal

Samples of simulated events (with a detector simulation [19] based on GEANT4 [20]) are used for estimating the SUSY signal acceptance, the detector efficiency, and for estimating many of the Standard Model backgrounds. For the latter, the simulation is typically used in conjunction with measurements in a background control region which is designed to isolate a given process with the highest achievable purity and with kinematic requirements as similar as possible to the signal region, while at the same time minimizing contamination from potential signal. The simulation is normalized to the event yield in the control region, and the background in the signal region is estimated by extrapolating via simulation the background level from the control region to the signal region. Unless stated otherwise, all searches described in this review adopt this technique for the major background processes. For smaller backgrounds, the background is estimated purely from simulation, using the best available theoretical cross sections.

For many SUSY searches, the most important backgrounds are $t\bar{t}$ and $W$- or $Z$-boson production with multiple jets; these are produced with multi-parton generators such as ALPGEN [21] or SHERPA [22], with (in some cases) up-to six additional partons in the matrix element. The next-to-leading-order (NLO) generators MC@NLO [23] and POWHEG [24] are also used for $t\bar{t}$ and single-top production. Diboson production is usually generated with HERWIG [25]; SHERPA is used when jet and/or photon emission are significant issues. MADGRAPH5 [26] is used for the production of $t\bar{t}$ in association with $W$ or $Z$ bosons. Parton shower and fragmentation processes are simulated with either HERWIG or PYTHIA [27].

The cross section for the production of SUSY particles is calculated in the MSSM at NLO precision in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic (NLO+NLL) accuracy, using PROSPINO and NLL-fast. The subsequent decay of these SUSY particles depends on the SUSY breaking which has approximately 100 associated parameters. As it is impossible to cover the entire parameter space by simulation, several complementary approaches are taken when estimating the sensitivity of the searches to SUSY signals. In the first approach, complete SUSY models are simulated; these models typically impose boundary conditions at a high energy scale, reducing the number of parameters to about five, and making it realistic to scan the parameter space by brute force. Examples studied in ATLAS are MSUGRA/CMSSM, and minimal GMSB and AMSB models. The computation of the SUSY particle masses and branching ratios at the weak scale from the high-scale parameters is performed with a number of publicly available computational tools and is subject to non-negligible

$^c$WW, WZ and ZZ, where Z implies also $\gamma^*$.
theoretical uncertainty [33] which are not taken into account in ATLAS SUSY limits. In the second, so-called “simplified model” [34, 35], approach, the SUSY decay cascades are simplified by setting the masses of most SUSY particles to multi-TeV values, putting them out of range of the LHC. The decay cascades of the remaining particles to the LSP, typically with zero or one intermediate step, is characterized only by the masses of the participating particles allowing studies of the search sensitivity to the SUSY masses and decay kinematics. The third approach is based on the phenomenological MSSM (pMSSM) [36] which reduces the number of MSSM parameters to 22 by assuming the absence of new sources of flavor changing neutral currents and CP violation. By sampling a limited number of pMSSM parameters, the sensitivity of the searches to more “realistic” configurations of SUSY particle masses and branching ratios can be assessed. SUSY signal samples are typically generated with either Herwig++ [37] or MADGRAPH; the latter is usually used (with an additional parton in the matrix element) if initial-state radiation is important to the signal acceptance.

4. Searches for gluinos and squarks

For a fixed particle mass, squarks and gluinos have the largest SUSY production cross sections at the LHC. They are thus prime candidates for the most inclusive searches for SUSY. The production of gluinos and squarks (\(\tilde{g}, \tilde{d}, \tilde{s}, \tilde{c}\)) proceeds via \(pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}\). In simplified models with very heavy squarks, gluinos decay via \(\tilde{g} \rightarrow \tilde{q}\tilde{\chi}_0^0\) or \(\tilde{q}\tilde{q} \rightarrow \tilde{\chi}_{\pm}^0\). If gluinos are very heavy, squarks decay via \(\tilde{q} \rightarrow q\tilde{\chi}_0^0\) or \(q\tilde{\chi}_{\pm}^0\). Ignoring additional jets from initial- or final-state radiation, event topologies with two, three and four jets are therefore expected for \(\tilde{g}\tilde{g}\), \(\tilde{q}\tilde{q}\), and \(\tilde{q}\tilde{g}\) production, respectively. More complicated decay cascades lead to larger numbers of jets in the final state. When gauginos are produced in the decay chain, leptons can be present via the decays \(\tilde{\chi}_{\pm}^0 \rightarrow W^{(*)}\tilde{\chi}_0^0\) or \(\tilde{\chi}_2^0 \rightarrow Z^{(*)}\tilde{\chi}_1^0\). The most inclusive searches for SUSY are therefore based on the presence of multiple jets, one or more leptons, and missing transverse momentum, where the latter arises (in part) from the two LSP’s in the event. Useful observables include \(E^\text{miss}_T\) and \(H_T\), defined as the scalar sum of the transverse momenta of the jets and leptons in the event. The sum \(H_T + E^\text{miss}_T\), sometimes called the effective mass \(m_{\text{eff}}\), reflects the mass difference between the initially-produced SUSY particle and the LSP, and is approximately independent of the details of the intermediate states in the decay cascade.

4.1. Searches based on jets plus \(E^\text{miss}_T\) with and without leptons

ATLAS has two searches based on the jets plus \(E^\text{miss}_T\) signature, vetoing events containing electrons or muons in order to be orthogonal to dedicated searches requiring leptons. In the first search [38], eleven different signal regions are defined, based on

\[\text{Branching ratios can be set by hand if desired}\]

\[\text{Unless otherwise specified, leptons identified in ATLAS will refer to electrons and muons.}\]
different requirements on the jet multiplicity and on $m_{\text{eff}}$. Associated with each signal region are five background control regions, each enhanced in one of the main SM backgrounds: semi-leptonic $t\bar{t}$, $W$+jets, $Z$+jets, $\gamma$+jets (for estimating $Z$+jets), and QCD multijets. Transfer factors converting the event yields in the control regions to predictions for the background in the signal region (and cross-contamination of other control regions) are obtained from simulation, except for the case of QCD multijets where the factor comes from data. The background in each signal region is determined with a likelihood fit to the event yields in the control regions, together with the transfer factors. The results from the different signal regions are combined by selecting, for each SUSY signal sample, the signal region that gives the best expected limit.

![Fig. 1. Left: 95% CL exclusion limits in the plane of the squark mass versus gluino mass in a simplified MSSM model consisting of the gluino, squarks of the first and second generation, and the LSP, with direct decays of squarks and gluinos to jets and the LSP. The LSP mass is set to 195 GeV. Right: 95% CL exclusion limits in a simplified model of gluino pair production with decoupled squarks; the 95% CL upper limit on the cross section times branching ratio (in fb) is printed for each model point. For both plots, the band around the median expected limit shows the $\pm 1\sigma$ variations, including all uncertainties except theoretical uncertainties on the signal. The dotted lines around the observed limit indicate the sensitivity to $\pm 1\sigma$ variations on these theoretical uncertainties.

In a simplified model consisting of the gluino, squarks of the first and second generation and the LSP, gluinos (squarks) with a mass below approximately 860 GeV (1320 GeV) are excluded as shown in Fig. 1 (left); these results hold for LSP masses as high as approximately 400 GeV. Limits are also derived in the MSUGRA/CMSSM model, and in simplified models of $\tilde{g}\tilde{g}$ or $\tilde{q}\tilde{q}$ production followed either by direct decay to the LSP or via an intermediate chargino. In models with

\footnote{All exclusion limits are quoted at 95% confidence level.}
only gluino pair production and direct decay to the LSP, gluinos with mass below about 550 GeV are almost entirely excluded, independent of the LSP mass, as shown in Fig. 1 (right); however, no limits can be set for gluino masses above about 600 GeV if the LSP mass is above approximately 400 GeV. Limits are generally weaker in models where SUSY production is limited to squark production, due primarily to the lower production cross section. Limits in a variety of “compressed SUSY” models [39,40] are also derived.

The second search [41] is geared towards final states with high jet multiplicities, ranging from $\geq 6$ to $\geq 9$ jets, requiring the presence of $E_T^{\text{miss}}$ and vetoing on electrons and muons. The search is performed in the variable $E_T^{\text{miss}}/\sqrt{H_T}$. The background from QCD multijets dominates, followed by $t\bar{t}$. The former is estimated by taking advantage of the observation that $E_T^{\text{miss}}/\sqrt{H_T}$ is independent of jet multiplicity, thereby allowing the shape of this quantity to be determined in low jet multiplicity samples. Other backgrounds are estimated using methods similar to the analysis described previously. Results are interpreted in the context of the MSUGRA/CMSSM model and a simplified model of gluino pair production where each gluino decays only via $\tilde{g} \to \tilde{t}\tilde{\chi}_1^0$. Gluinos with mass below about 850 GeV are excluded in both scenarios.

Searches based on jets plus $E_T^{\text{miss}}$ and additional leptons [42] reach generally similar conclusions in MSUGRA/CMSSM as well as in simplified models with intermediate charginos. Additional interpretations include limits in GMSB and in simplified models with two intermediate states, for example gluino decay to a chargino (or $\tilde{\chi}_2^+$) followed by decay to the LSP via intermediate sleptons, sneutrinos or gauge bosons. Searches involving taus [43,44] as well as same-sign dileptons [45] ($e$ and $\mu$) have also been published, albeit for an integrated luminosity of 2.05 fb$^{-1}$.

### 4.2. Searches for gluinos and squarks of the third generation

Searches for gluinos and squarks of the third generation have been performed in a number of channels, including jets plus $E_T^{\text{miss}}$ with high jet multiplicity [41], same-sign dileptons [45], and one or more $b$-tagged jets with and without additional leptons [46], the last two with an integrated luminosity of 2.05 fb$^{-1}$. Such searches are particularly well-motivated by the “Natural SUSY” scenario. The most sensitive search [47] requires four or six jets of which three or more must be $b$-tagged, no leptons and significant $E_T^{\text{miss}}$. The requirement on the $b$-jet multiplicity is effective in reducing the dominant $t\bar{t}$ background. Limits are derived in several simplified models with gluino pair production followed by the decays $\tilde{g} \to b\bar{b}$ or $\tilde{g} \to t\bar{t}$ where the bottom/top squark can be virtual. The final state for each gluino is the same, whether or not the intermediate squark is real or virtual: $b\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$. For the models with real bottom and top squarks, the LSP mass is fixed to 60 GeV, while for the models with virtual squarks, the limits are provided in the plane of gluino and LSP masses. For a LSP mass of 60 GeV, gluinos with mass below about 1000 (820) GeV are excluded for bottom (top) squark masses up to about 870 (640) GeV.
4.3. **Searches with photons plus $E_{T}^{\text{miss}}$**

An inclusive search based on two or more photons and $E_{T}^{\text{miss}}$ [48] is motivated by gauge-mediated SUSY models in which the next-to-lightest SUSY particle (NLSP) is a bino-like neutralino decaying to the gravitino LSP via $\tilde{\chi}_1^0 \to \gamma \tilde{G}$. The search makes very few requirements other than two or more photons and $E_{T}^{\text{miss}}$; in particular, no jet requirements are applied. The main backgrounds ($\gamma \gamma + X$, $\gamma + \text{jets} + X$, multijets, $W \to e\nu + X$ and $t\bar{t} \to e\nu + X$) are estimated directly from the data. Based on a general gauge mediation [49–51] model in which the mass of the NLSP and either the squark or gluino are free parameters, squarks (gluinos) with a mass below 870 (1070) GeV are excluded for bino masses above 50 GeV.

4.4. **Searches for stable gluinos and squarks**

The possibility of a bound state containing a gluino or a squark, the so-called R-hadron, was raised already in the earliest papers on MSSM phenomenology [52]. For more recent reviews of stable massive particles, see Ref. [53, 54]. To date, ATLAS has published results on R-hadrons only on data taken in 2010, corresponding to an integrated luminosity of 31-37 pb$^{-1}$, although this was one of the earliest SUSY publications from ATLAS. Preliminary results with the full 2011 dataset have been shown in conferences but will not be discussed here. The experimental signature for R-hadrons is complicated by the fact that they could have a significant probability of undergoing hadronic reactions in the detector material [55]. Several searches are therefore designed, utilizing different portions of the ATLAS detector.

In the first approach [56], the strategy combines a search for heavily ionizing particles in the pixel detector with a search for a slow-moving massive particle based on timing information from the hadronic calorimeter. This search is potentially sensitive to R-hadrons even if they interact in the dense calorimeter material. Triggering is a challenge as R-hadron pair production could be accompanied by very little other detector activity. A $E_{T}^{\text{miss}}$ trigger is therefore used to trigger on events where the production of R-hadrons is in association with initial-state radiation in the $pp$ collision. The background, primarily from mis-measured muons, is estimated entirely from the data, utilizing the lack of correlation between the particle momentum, ionization and time-of-flight. Stable sbottoms, stops and gluinos with masses below 294, 309 and 562 GeV, respectively, are excluded, using a conservative model for R-hadron scattering.

The second search [57] utilizes the time-of-flight to the muon spectrometer, with its superior timing resolution, as an additional handle; this search is complementary to the first search in that it is sensitive to R-hadrons that do not leave detectable signals in the inner part of the detector, for example by being neutral at birth. Backgrounds are estimated directly from the data as in the first search. Gluino R-hadrons with masses below 530 GeV are excluded.

In the third search [58], R-hadrons that have stopped in the calorimeter material are searched for by looking for calorimeter activity during periods in the LHC bunch
structure without \( pp \) collisions. This search complements the previous two searches which are less sensitive to particles with \( \beta \ll 1 \). The dominant background from cosmic rays is measured from the data, utilizing periods with long live time but small integrated luminosity. Gluinos with mass between 200 and 341 GeV are excluded for lifetimes between \( 10^{-5} \) and \( 10^{3} \) seconds, assuming a LSP mass of 100 GeV.

Although these searches cover a broad range of mechanisms for R-hadron interactions, there remains the possibility that a R-hadron remains neutral through the entire detector. This case would be covered by the search for a monojet plus \( E_T^{\text{miss}} \) signal, discussed in Sec. 7.

5. Searches for third-generation squarks

Searches for third-generation squarks are well-motivated by “Natural SUSY” considerations. As discussed in Sec. 4 if gluinos are accessible at the LHC, it is likely that third-generation squarks would first be seen in gluino decay cascades. To cover the possibility where the gluinos are beyond reach, searches for direct production of third-generation squarks have also been made by ATLAS. The first dedicated search in ATLAS for stop production was performed with 2.05 fb\(^{-1}\) of data, motivated by a “natural” GMSB scenario \(^{[59]}\) with light stops and light higgsinos where the higgsino NLSP decays to the gravitino via \( \tilde{\chi}_1^0 \rightarrow Z \tilde{G} \) with a branching ratio ranging from 0.65 to 1, depending on the higgsino mass, and the stops decay via either \( \tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm \) or (if kinematically allowed) via \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0(2) \). The search requires two leptons consistent with coming from a Z-boson, two or more jets, of which at least one must be \( b \)-tagged, and significant \( E_T^{\text{miss}} \). Stops with mass below 240 GeV are excluded for all NLSP masses (provided the NLSP mass is greater than the Z boson mass). For NLSP masses between 115 and 230 GeV, the limit on the stop increases to 310 GeV.

Less model-dependent searches for stops have been performed in a number of channels. The stop decay chains considered are \( \tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm \rightarrow b W^{(*)} \tilde{\chi}_1^0 \) and, if kinematically allowed, \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \). The searches are challenging due to the similarity of these final states to the high background from \( t \bar{t} \) production. A search \(^{[60]}\) for stops lighter than the top quark looks for evidence of the decay chain \( \tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm \) in events with two opposite-sign leptons, at least one jet, and significant \( E_T^{\text{miss}} \). Assuming a chargino mass of 106 GeV, identical to that assumed in a previous analysis by CDF \(^{[61]}\), top squarks with mass below 130 GeV are excluded for LSP masses between 1 and 70 GeV.

Searches for stop with mass heavier than the top quark have been performed in the decay mode \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \). The final state, consisting of two top quarks and \( E_T^{\text{miss}} \), has been searched for in the cases where both tops decay hadronically \(^{[62]}\) and where one top decays semi-leptonically \(^{[63]}\). In the all-hadronic analysis, six or more jets are required, one or more of which are \( b \)-tagged, and three of which are required to have a mass consistent with that of the top quark. Leptons are vetoed; kinematic cuts are used to suppress the dominant background from semi-leptonic
Searches for supersymmetry with the ATLAS detector

$t\bar{t}$ production where the lepton is lost or mis-identified. $E_T^{\text{miss}}$ is used as the final discriminant. Top squarks with mass between 370 and 465 GeV are excluded for a nearly massless LSP. In the single-lepton analysis, in addition to the presence of a lepton, four or more jets are required, one or more of which are $b$-tagged. The dominant background from di-leptonic $t\bar{t}$ (where one lepton is lost or mis-identified) is suppressed by requiring three jets to have a mass consistent with that of the top quark and by requiring large transverse mass between the lepton and $E_T^{\text{miss}}$. Top squarks with mass between 230 and 440 GeV are excluded for a nearly massless LSP. Stop masses around 400 GeV are excluded for LSP masses up to 125 GeV; for lower stop masses (but still greater than 230 GeV), stops are excluded for all LSP masses ranging up to approximately 50 GeV of the kinematic limit.

It should be noted that the above stop mass limits are weakened if the stop decays with a mixture of branching ratios. Scans in the pMSSM parameter space in a region compatible with “Natural SUSY” indicate that a mixture of at least two decay modes is very likely [64].

Searches for direct production of bottom squarks have been published with an integrated luminosity of 2.05 fb$^{-1}$ [65]. The search assumes that the sbottom decays exclusively via $b_1 \rightarrow b \tilde{\chi}^0_1$ and looks for final states with two high-$p_T$ $b$-jets and significant $E_T^{\text{miss}}$. Leptons are vetoed. The final discriminant is the boost-corrected contransverse mass [66]. The major backgrounds are $t\bar{t}$, single-top and vector bosons produced in association with $b$-jets. For LSP masses below 60 GeV, sbottom masses below 390 GeV are excluded.

6. Searches for sleptons

The search for directly produced, promptly decaying, sleptons is challenging due to the small cross section and the large backgrounds from diboson and $t\bar{t}$ backgrounds. The ATLAS search [67] is based on the decay chain $\tilde{\ell} \rightarrow \ell \tilde{\chi}^0_1$, and looks for two opposite-sign, same-flavor leptons with significant $E_T^{\text{miss}}$ and no jets in the event. The final discriminating variable is $m_{T2}$ [68, 69] which falls off above the $W$-boson mass for the background. Left-handed selectrons and smuons with masses between 85 and 195 GeV are excluded, assuming a LSP mass of 20 GeV; no limit is possible for LSP masses above approximately 75 GeV.

Limits on sleptons with detector-scale lifetimes (or longer) can be derived from the slow-particle searches described in Sec. 4. The MS-based search of Ref. [57] excludes stable $\tilde{\tau}$s for masses below 136 GeV in a particular GMSB model. Directly-produced sleptons, which are expected to be less model-dependent, are excluded below a mass of 110 GeV in the same model.

7. Searches for charginos and neutralinos

Direct pair production of gauginos at the LHC is dominated by $\tilde{\chi}^+_1 \tilde{\chi}^-_1$ and $\tilde{\chi}^+_1 \tilde{\chi}^-_2$ production. Chargino pair production has been probed in a search based on a dilepton plus $E_T^{\text{miss}}$ signature (in $ee$, $\mu\mu$ and $e\mu$ channels) and a veto on jets and $Z$-
bosons [67], exploiting the decay $\tilde{\chi}_1^+ \to \ell^+ \nu \tilde{\chi}_1^0$. The interpretation is performed in a simplified model where the chargino decays to the LSP via an intermediate slepton or sneutrino, i.e. $\tilde{\chi}_1^+ \to \ell_L \nu \to \ell \nu \tilde{\chi}_1^0$ or $\tilde{\chi}_1^+ \to \nu \ell \to \ell \nu \tilde{\chi}_1^0$, where the mass of the intermediate state is set halfway between those of the chargino and LSP. Using the signal region based on $m_{T2}$ devised for the prompt slepton search, charginos with mass between 110 and 340 GeV are excluded for a near-massless LSP. For charginos between 110 and approximately 300 GeV, the excluded region extends to all LSP masses up to approximately 100 GeV below the chargino mass. It is important to note that there is no exclusion sensitivity for the case where the chargino decays via a (real or virtual) $W$-boson, without intermediate sleptons/sneutrinos.

The search for associated chargino-neutralino production is performed in both dilepton and trilepton plus $E_T^{miss}$ channels. In the trilepton analysis [70] three signal regions are defined. Two of the regions veto events containing either $b$-jets or a lepton pair consistent with the $Z$-boson; in one of these two regions the transverse mass, computed from the unpaired lepton and the $E_T^{miss}$ is required to be past the endpoint for $W$-bosons, while for the other region, more stringent $p_T$ requirements are applied instead to all three leptons. The third signal region requires the presence of a $Z$-boson in the final state and applies the transverse mass requirement. The final discriminating observable is $E_T^{miss}$. In the dilepton analysis [67], the signal region based on $m_{T2}$ for the slepton/chargino search is employed. Results are interpreted in a pMSSM framework where the strongly interacting SUSY particles are all decoupled and the gaugino mass parameters ($M_1, M_2$ and $\mu$) are varied. To boost the leptonic branching ratios, a slepton is inserted halfway in between the two lightest neutralino states. The dilepton and trilepton channels are combined, with the dilepton channel contributing especially for higher values of $M_1$. Results are also interpreted in two simplified models of $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ production. In the first, the gaugino decays to the LSP via an intermediate slepton or sneutrino. In the second model, the decay proceeds via $W$ and $Z$ bosons. The trilepton analysis has better sensitivity for these models. In the model with intermediate sleptons/sneutrinos, degenerate $\tilde{\chi}_1^+, \tilde{\chi}_2^0$ with masses up to 500 GeV are excluded for large mass differences from the LSP. Small regions of the parameter space are excluded as well in the model with decays via gauge bosons.

Limits on directly produced gauginos have also been derived in minimal GMSB scenarios in the diphoton plus $E_T^{miss}$ analysis [48], assuming the SPS8 model [71]. A lower limit of 196 TeV is set on the SPS8 breaking scale, corresponding to lower limits on $\tilde{\chi}_1^+$ and $\tilde{\chi}_1^0$ masses of approximately 530 and 280 GeV, respectively.

A search for unstable charginos in an AMSB-inspired scenario has been performed with an integrated luminosity of 1 fb$^{-1}$. In these scenarios, the lightest chargino and the LSP are nearly degenerate such that the chargino decay proceeds via $\tilde{\chi}_1^+ \to \pi^+ \tilde{\chi}_1^0$ where the pion has a momentum of the order of 100 MeV. The search looks for events in which an isolated, high-$p_T$ charged track “disappears” in the ATLAS tracking volume, the low-momentum pion going unobserved. The main
Searches for supersymmetry with the ATLAS detector

11

backgrounds are from charged hadrons interacting with the detector material and from poorly reconstructed low-\(p_T\) tracks which scatter in the tracker. Templates for the shape of the track \(p_T\) distribution from these two background sources are determined from control regions in the data. Limits are derived from a fit to the track \(p_T\) distribution in data, using the above background templates and signal templates derived from simulation. Charginos with mass less than 92 GeV and a lifetime between 0.5 and 2 ns are excluded in this scenario.

A search for a high-\(p_T\) jet plus significant \(E_T^{\text{miss}}\) would be sensitive to scenarios of direct gaugino production where the gaugino decay products are too soft to be detected, or more generally to production of weakly interacting particles [72, 73] in association with a jet from initial-state radiation. ATLAS has published one search for the monojet signature [74] with 33 pb\(^{-1}\) of data. The result is interpreted in terms of limits on a model of large extra dimensions; ATLAS provides no dark matter interpretation. The subject of collider searches for dark matter is beyond the scope of this review, but examples of limits derived from LHC results can be found in Ref. [75, 76].

8. Searches for R-parity violating SUSY

R-parity conservation is imposed by hand in order to evade strong experimental constraints on baryon and lepton number violation. Although R-parity conservation has the feature that the LSP is stable and therefore a candidate for dark matter, R-parity violation (RPV) is perhaps equally well-motivated theoretically. The first consequence of RPV is an increase in the number of parameters, making signal modeling even more challenging. Other consequences are that SUSY particles may be singly produced in \(pp\) collisions and that the LSP can decay. The decay of the LSP implies lower \(E_T^{\text{miss}}\), thereby evading many of the searches described above, but resulting in a higher multiplicity of final state objects such as jets and leptons, typically with a resonant structure.

A few searches have been performed in ATLAS with an explicit RPV SUSY interpretation. A search for a high-mass, opposite-sign \(e\mu\) resonance [77], with an integrated luminosity of 1 fb\(^{-1}\), is sensitive to the process \(\tilde{t}\tilde{\tau} \rightarrow \tilde{\nu}_\tau \rightarrow e\mu\). A limit on the cross section times branching ratio \(\sigma(pp \rightarrow \tilde{\nu}_\tau) \times \text{BR}(\tilde{\nu}_\tau \rightarrow e\mu)\) is set as a function of the \(\tilde{\nu}_\tau\) mass, with a value of 4.5 fb for a mass of 1 TeV. A search employing the same final-state but with a non-resonant signature [78] is sensitive to the \(t\)-channel exchange of a lightest R-parity violating up-type squark, assumed to be the top squark. From an analysis of 2.1 fb\(^{-1}\) of data, a limit on the cross section \(\sigma(pp \rightarrow e\mu)\) via \(t\)-channel top squark exchange is derived as a function of the \(\tilde{t}\) mass, with a value of 30 fb for a mass of 1 TeV.

The inclusive search for SUSY in the lepton plus jets plus \(E_T^{\text{miss}}\) channel [79] with 1 fb\(^{-1}\) of data provides an interpretation in the framework of a model where bilinear RPV couplings are embedded in a MSUGRA/CMSSM SUSY production model. For a chosen set of MSUGRA/CMSSM parameters, the bilinear RPV parameters are...
fixed by a fit to neutrino oscillation data. Limits are then derived as a function of MSUGRA/CMSSM parameters.

A search for new, heavy particles that decay at a significant distance from their production point into a final state consisting of charged hadrons in association with a muon has been performed with 33 \( \text{pb}^{-1} \) of data [80]. The search is sensitive, for example, to a neutralino LSP decaying via \( \tilde{\chi}^0_1 \to \mu\mu \to \mu qq' \). The vertex position is required to be at a radius greater than 4 mm and within the fiducial volume of the pixel detector \((r < 180 \text{ mm} \ \text{and } |z| < 300 \text{ mm})\). After vetoing on vertices emerging from locations of known detector material, signal is distinguished from background using the number of tracks in the vertex and the vertex mass. The main background source is a low-mass vertex arising from a particle interaction with air, randomly matched with another track, possibly from a different primary interaction. The expected number of background events in the signal region, obtained from simulation validated against data, is very low \((<0.03 \text{ events})\), and no events are observed. A limit on the production cross section times branching ratio is obtained as a function of neutralino decay distance.

A search for resonances in 4-jet final states has been performed with 34 \( \text{pb}^{-1} \) of data. A unique pairing of the four highest-\( p_T \) jets is defined for each event by minimizing the pair-wise spatial separation, and the dijet mass distribution is examined for signs of a resonance above background. The shape of the background mass distribution is obtained from the data by using two largely uncorrelated variables: the scattering angle of the reconstructed particle in the rest frame of the 4-jet system, and the relative mass difference between the two jet pairs. The results are interpreted in terms of the production of two scalar gluons, the supersymmetric partners of Dirac gluinos [81–83], each of which decay to two gluons. Scalar gluons with masses between 100 and 185 GeV are excluded. Although the process of a scalar gluon decaying to two gluons is R-parity conserving, the search for resonances in 4-jet final states is sensitive to RPV decays as discussed, for example, in Ref. [84].

Many other searches have been performed in ATLAS for physics beyond the Standard Model. Such searches are often sensitive to RPV SUSY, although no such interpretation is provided by ATLAS. A comprehensive discussion of RPV limits from the re-interpretations of ATLAS results is beyond the scope of this review. Some recent examples in the literature include Ref. [85] and [86].

9. Conclusion

The discovery at the LHC of what may be the Higgs boson puts the gauge hierarchy problem front and center. If SUSY is to be a solution to the hierarchy problem, limits on the masses of SUSY particles are implied. Such expectations are starting to be challenged by searches at the LHC.

This review has covered the searches for SUSY conducted by ATLAS at the LHC with a center-of-mass energy of 7 TeV. The review is limited to results in publication or submitted for publication up to September 2012. Many analyses covering the
entire 7 TeV data-taking period have been summarized here. Preliminary results, updating many of the remaining SUSY searches to the full 7 TeV dataset, have been shown in conferences; first preliminary results from the 8 TeV data-taking are also available. No evidence for SUSY has been seen.

The most serious challenge to weak-scale SUSY comes from the searches for gluinos, with and without lighter squarks. A large variety of searches for gluinos are reaching lower mass limits of 850 GeV or higher. Some of the traditional ways out, such as compressed decay spectra, or multi-step decay chains, are starting to get restricted. The situation is less dire for the other SUSY particles required at the weak scale: third-generation squarks and gauginos. Searches for direct production of bottom and top squarks (assuming gluinos are just out of reach) are entering interesting territory, but limits degrade quickly when assumptions on decay branching ratios are relaxed. There also remains a challenging window where the stop mass is close to the top mass. The most stringent limits on direct gaugino production are obtained only by boosting the leptonic content by assuming intermediate sleptons in the decay chains. Limits are still very weak (or non-existent) in the case where the decay is only via gauge bosons.

Several other “escape routes” have been discussed in the literature. One is to lowering the production cross section of the colored superpartners by assuming that the gluino acquires a large Dirac mass; for a recent discussion, see Ref. [87]. Another is the possibility of “stealth SUSY”; see Ref. [88] for a survey of “stealth” models. And finally there is the possibility of R-parity violation, which weakens the $E_T^{miss}$ signature on which so many SUSY searches rely, and which comes with an even larger parameter space. Many searches have been performed in ATLAS for physics beyond the Standard Model. Only some have been interpreted by ATLAS in the context of RPV SUSY models. For a large number of searches, ATLAS provides auxiliary information in HEPdata [89] to ease the re-interpretation of ATLAS results; this is an ongoing dialogue with the community which can be expected to evolve as the needs become clearer.

ATLAS is currently taking data at a center-of-mass energy of 8 TeV. The size of the dataset is expected to be on the order of 20 fb$^{-1}$, and further inroads into the territory of weak-scale SUSY can be expected. The rapidly evolving implications from the Higgs sector may influence future SUSY search strategies. If the newly discovered particle turns out to be the Standard Model Higgs boson, the complete exploration of the relevance of SUSY to the hierarchy problem will require the full LHC program at 14 TeV.

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8The full list of ATLAS results can be found at http://twiki.cern.ch/twiki/bin/view/AtlasPublic
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