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Overview of SUSY results from the ATLAS experiment

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Abstract. The search for Supersymmetric extensions of the Standard Model (SUSY) remains a hot topic in high energy phisycs in the light of the discovery of the Higgs boson with mass of 125 GeV. Supersymmetric particles can cancel out the quadratically-divergent loop corrections to the Higgs boson mass and can explain presence of Dark Matter in the Universe. Moreover, SUSY can unify the gauge couplings of the Standard Model at high energy scales. Under certain theoretical assumptions, some of the supersymmetric particles are preferred to be lighter than one TeV and their discovery can thus be accessible at the LHC. The recent results from searches for Supersymmetry with the ATLAS experiment which utilized up to 21 fb^{-1} of proton-proton collisions at a center of mass energy of 8 TeV are presented. These searches are focused on inclusive production of squarks and gluinos, on production of third generations squarks, and on electroweak production of charginos and neutralinos. Searches for long-lived particles and R-parity violation are also summarized in the document.

1 Introduction

Supersymmetry (SUSY) [1–9] is the best-known exstension of the Standard Model (SM): it is a generalization of the space-time symmetries of quantum field theory which transform fermions into bosons and viceversa. It provides a natural solution to the hierarchy problem by canceling out the quadratically divergent quantum corrections to the Higgs boson mass with the introduction of the superpartner of the top quark (hereafter named stop) [10–12]. It also provides unification of the three SM gauge couplings at high energy scales, modifying the running of the couplings above the EW scale [13]. Moreover, if R-parity is conserved[1], the lightest supersymmetric particle (LSP) might be a promising candidate for a stable weakly-interacting massive particle (WIMP) consistent with the observed density of Dark Matter [14].

In the Minimal Supersymmetric Standard Model (MSSM) [15–18] the gauge super-multiplets consist of the gluons and their fermionic superpartners, called gluinos ($\tilde{g}$), and the gauge bosons and their gaugino superpartners. Gauginos and higgsinos, the superpartners of the Higgs bosons, mix to form four neutral physical states (neutralinos, $\tilde{\chi}_i^0, i = 1..4$) and two charged states (charginos, $\tilde{\chi}_{1,2}^{\pm}$). The matter sector consists of three generations of quarks and leptons and their superpartners, squarks ($\tilde{q}$) and sleptons ($\tilde{l}$).

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[1] $R = (-1)^{3(B-L)+2S}$, for a particle of spin S, baryon number B and lepton number L.

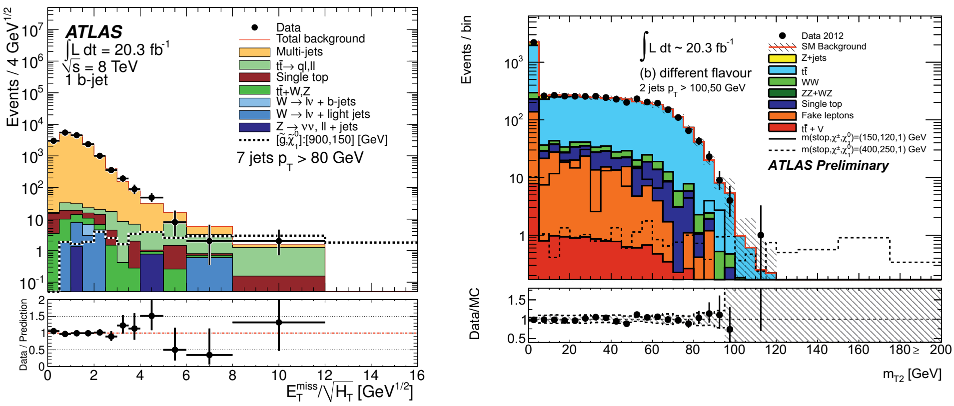


Figure 1. Examples of how kinematic variables discriminate SUSY signals from SM background. Top: $E_T^{miss}/\sqrt{H_T}$ distribution in a signal region used in a search with all-hadronic final states [19]. Bottom: m_{T2}^{ll} distribution in a signal region used in a search with two-lepton final states [20].

The conservation of R-parity has a crucial influence on the SUSY production phenomenology in scattering and decay processes. For example, starting from ordinary R-even particles it follows that SUSY particles must be produced in pairs. In addition, the LSP is stable and must be produced in the end of a decay chain of heavier unstable SUSY particles. An LSP escapes the detector undetected and its presence can be deduced from imbalance of momentum (whose magnitude is hereafter referred as E_T^{miss}).

2 Supersymmetry searches with the ATLAS experiment

The successful running of the Large Hadron Collider (LHC) has fed an impressive variety of searches for Supersymmetry conducted by the ATLAS collaboration. These searches used up to 21 fb^{-1} of data from proton-proton collisions at a center of mass energy of 8 TeV. Since no substantial deviations from the SM predictions were observed, the community has published a series of exclusion limits, at 95% CL, on the visible cross-sections of physics Beyond the Standard Model (BSM), on the SUSY cross-sections and superpartner masses.

Initially, ATLAS strategies for SUSY searches were limited by the total integrated luminosity. The first analyses were then focused on searches for processes with high cross-sections, such as inclusive pair-production of gluinos and squarks. With the increased luminosity, however, new rare processes became accessible and the community dedicated a huge effort to search for production of third generation squarks, either via gluino decay or via direct production. These scenarios are also supported by natural SUSY models [21, 22], which require the third generation squarks to be lighter than one TeV, the neutralinos masses to be around few hundred GeV and the gluinos masses to be below few TeV. The relatively low superpartner masses of these models can be accessible at the LHC. Models with R-parity violation (RPV) have also been explored with dedicated searches.

To discriminate SUSY signals from the SM background, kinematic variables designed for events with one or more invisible particles at the end of the decay chain have been used. Fig. 2 illustrates two examples using the E_T^{miss}, H_T and m_{T2}^{ll} variables[2].

[2] $H_T = \sum p_T^{jets}$, $m_{T2}^{ll} = \min_{\mathbf{q}_T^1+\mathbf{q}_T^2}\left\{\max\left[m_T(\mathbf{p}_T^1,\mathbf{q}_T^1), m_T(\mathbf{p}_T^2,\mathbf{q}_T^2)\right]\right\}$, where $\mathbf{q}_T^1+\mathbf{q}_T^2=\mathbf{q}_T$, $\mathbf{p}_T^{1(2)}$ is the transverse momentum of the first (second) lepton and $\mathbf{q}_T$ is the missing transverse momentum.

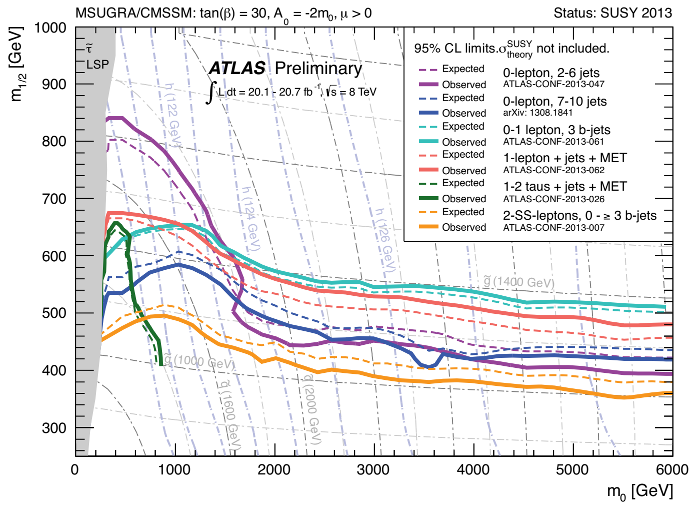


Figure 2. Exclusion limits at 95% CL on the m_0 and $m_{1/2}$ parameters of a Higgs aware mSUGRA/CMSSM model from ATLAS inclusive searches for squarks and gluinos [23].

The results are often interpreted for simplified models with SUSY-like topologies, where only one specific decay chain is considered to happen in the 100% of the cases. For some analyses, limits on production cross-sections are also set for more generic models, such as mSUGRA/CMSSM [24, 25] and GMSB [26–29].

The ATLAS searches for SUSY are categorized as searches for inclusive pair-production of gluinos and squarks, for gluino-mediated production of third generation squarks, for direct production of third generation squarks, for electroweak production of gauginos and sleptons, and for RPV and long-lived particles.

2.1 Inclusive pair-production of gluinos and squarks

Searches for pair-production of gluinos and squarks involve energetic jets, E_T^{miss}, and leptons. The results of these searches are generically interpreted using simplified models with pair production of gluinos ($\tilde{g}\tilde{g}$) or squarks ($\tilde{q}\tilde{q}$) and with a neutralino LSP ($\tilde{\chi}_1^0$) at the end of the decay chain. These models assume that all the squarks have the same mass. The upper limits on production cross-sections are derived as a function of the squarks and neutralino masses or gluino and neutralino masses. Recent analyses exclude simplified models with massless neutralinos and squarks with masses below 740 GeV, where squarks decay through sleptons into final states with two leptons and jets ($\tilde{q} \rightarrow q(ll/l\nu/\nu\nu)\tilde{\chi}_1^0$). These analyses exploited transverse and longitudinal event information (Razor) [30]. Gluinos with masses below 1.2 TeV are excluded for a simplified model where gluinos are produced in pairs and decay through quarks, W and neutralino in final states with one lepton, jets and E_T^{miss} ($\tilde{g} \rightarrow qqW\tilde{\chi}_0^1$) [31].

The results of the most recent analyses have also been interpreted in the constrained mSUGRA/CMSSM model, where the parameters of the model have been set to accomodate a lightest neutral scalar Higgs boson mass of 125 GeV. In this scenario, gluinos up to 1.35 TeV are excluded for any squark masses, as can be seen from Fig. 2.

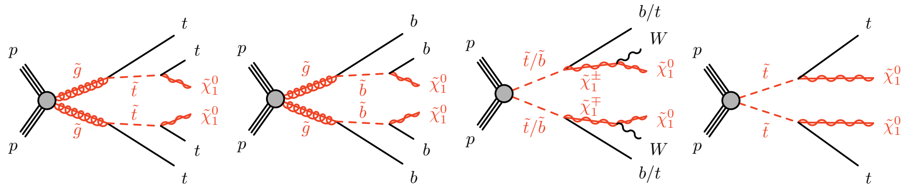
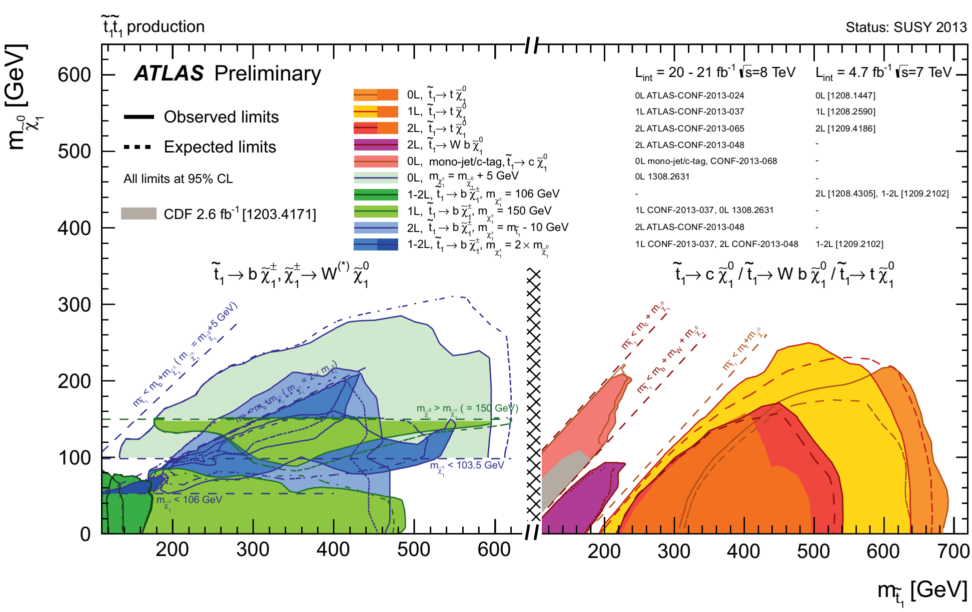


Figure 3. Examples of Feynman diagrams of third generation squarks production and decay. From left to right: gluino mediated stop production, gluino mediated sbottom production, direct production of stop and sbottom decaying via a chargino and direct production of stop decaying to a top quark and a neutralino.

2.2 Production of third-generation squarks

The natural SUSY paradigm constrains the third generation squarks (stop and sbottom) to be lighter than one TeV. Gluinos are also constrained below a few TeV and the charginos and neutralinos below few hundreds GeV. All other particles are decoupled and well above the TeV threshold. Stop ($\tilde{t}_1$) and sbottom ($\tilde{b}$) can thus be produced either from decays of gluinos or directly, as illustrated by the Feynman diagrams of Fig. 3. In a simplified model with gluino-mediated stop production ($\tilde{g} \to t\tilde{t}_1$) and an off-shell stop, upper limits are derived on the gluino and neutralino (LSP) masses. The most stringent limit is obtained in a search with one lepton, jets and E_T^{miss} in the final state and excludes 1.3 TeV gluinos for neutralino masses below 600 GeV [32]. Models with direct pair-production of stops are considered for a variety of its decay modes. The decay phase space depends, among other factors, on the mass hierarchy of the stop, the chargino and the neutralino. Final states that include jets, E_T^{miss} and up to two leptons have been considered. Fig. 4 summarizes the ATLAS stop mass reach for all the considered decay chains. The limits are derived on the stop and neutralino masses and interpreted

Figure 4. Exclusions limits at 95% CL in the stop-neutralino mass plane with different decay modes and several hypotheses on the stop, chargino, neutralino masses hierarchy [23].



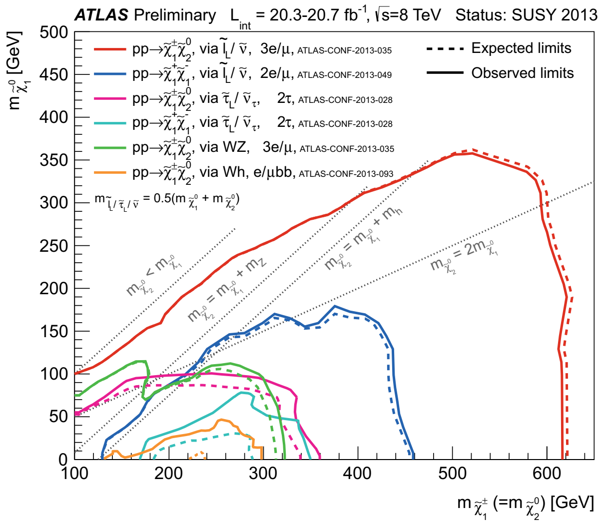


Figure 5. Exclusions limits at 95% CL in the chargino-neutralinos mass plane from EW SUSY production [23].

in simplified models under certain conditions on the masses hierarchy. A $\tilde{t}_1$ below 600-700 GeV is largely excluded, assuming 100% branghing fractions (BR) on either $\tilde{t}_1 \to t\tilde{\chi}_1^0$ or $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$.

2.3 Electroweak production

Electroweak production of SUSY particles includes direct production of charginos ($\tilde{\chi}_1^+\tilde{\chi}_1^-$) or production of charginos and next-to-lightest neutralino ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$). These two processes may be visible if squarks and gluinos masses are large. $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ can decay via sleptons ($\tilde{\chi}_1^{\pm} \to \tilde{l}\nu/l\tilde{\nu}$, $\tilde{\chi}_2^0 \to \tilde{l}l/\tilde{\nu}\nu$) or via bosons ($\tilde{\chi}_1^{\pm} \to W\tilde{\chi}_1^0, \tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$), depending on the region of the parameter space. Final states include leptons, E_T^{miss} and often no jets. ATLAS has derived limits on the masses of the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ and the neutralino LSP ($\tilde{\chi}_1^0$), assuming $m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0)$. Charginos below 600 GeV are excluded for light neutralino in simplified models with intermediate states with sleptons, as shown from the red curve of Fig. 5. The pink and light blue curves refer to the upper limits extracted from a recent search with taus [33] optimized for models with a next-to-LSP (NLSP) stau. The SUSY signal is here extracted by requiring two taus, a jet veto, and large values of E_T^{miss} and m_{T2} of the two taus. Models with intermediate Higgs bosons decaying to a bottom quark pair ($b\bar{b}$) have also been considered in a search with two b-jets in the final state [34]. The $\tilde{\chi}_2^0$ decays exclusively to a Higgs boson and the neutralino LSP ($\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$) if both the LSP and NLSP are mostly formed by states that do not couple to the Z or the photon. This scenario is achieved in the MSSM with a neutral wino-like NLSP and a bino-like LSP, as studied in [35–37]. The upper limit extracted from this search is reported by the orange curve of the figure.

2.4 Long-lived particles and R-parity violation

Long-lived particles can originate from stopped gluinos via heavy squarks (R-hadrons) or compressed spectra (small mass difference between chargino and neutralino). A search for hadronic activity in empty bunches (out-of-time collisions) has observed no deviations from the SM predictions and set exclusion limits on the gluinos mass-lifetime plane [38]. ATLAS conducted a search for heavy particles decaying into a multi-track vertex that contain an energetic muon [39]. The search has not observed any deviations from the SM predictions. Other ATLAS searches exclude gluinos below 900 GeV in RPV scenarios where the stop decays to a bottom and a strange quark ($\tilde{t}_1 \rightarrow bs$) [40]. Exclusion limits have been imposed also on the cross-section of pair production of gluinos decaying to three or five jets via RPV. In this recent ATLAS search gluinos below 930 GeV are excluded for a six-jets model with two b-quarks in the final state [41].

3 Conclusions

No significant excesses over the SM predictions have been observed in SUSY searches with the ATLAS experiment. The inclusive searches exclude gluinos with masses below 1.3 TeV at 95% CL for the Higgs-aware mSUGRA/CMSSM model. Natural SUSY is also strongly constrained by ATLAS: stop masses below 600-700 GeV are largely excluded by direct stop searches, assuming 100% BR on different stop decays. The searches are also sensitive to electroweak production without intermediate sleptons. The community is expecting to improve the sensitivity of the searches with the upcoming LHC run at 13 TeV. The full mass reach of all ATLAS searches for Supersymmetry is reported in Fig. 6.

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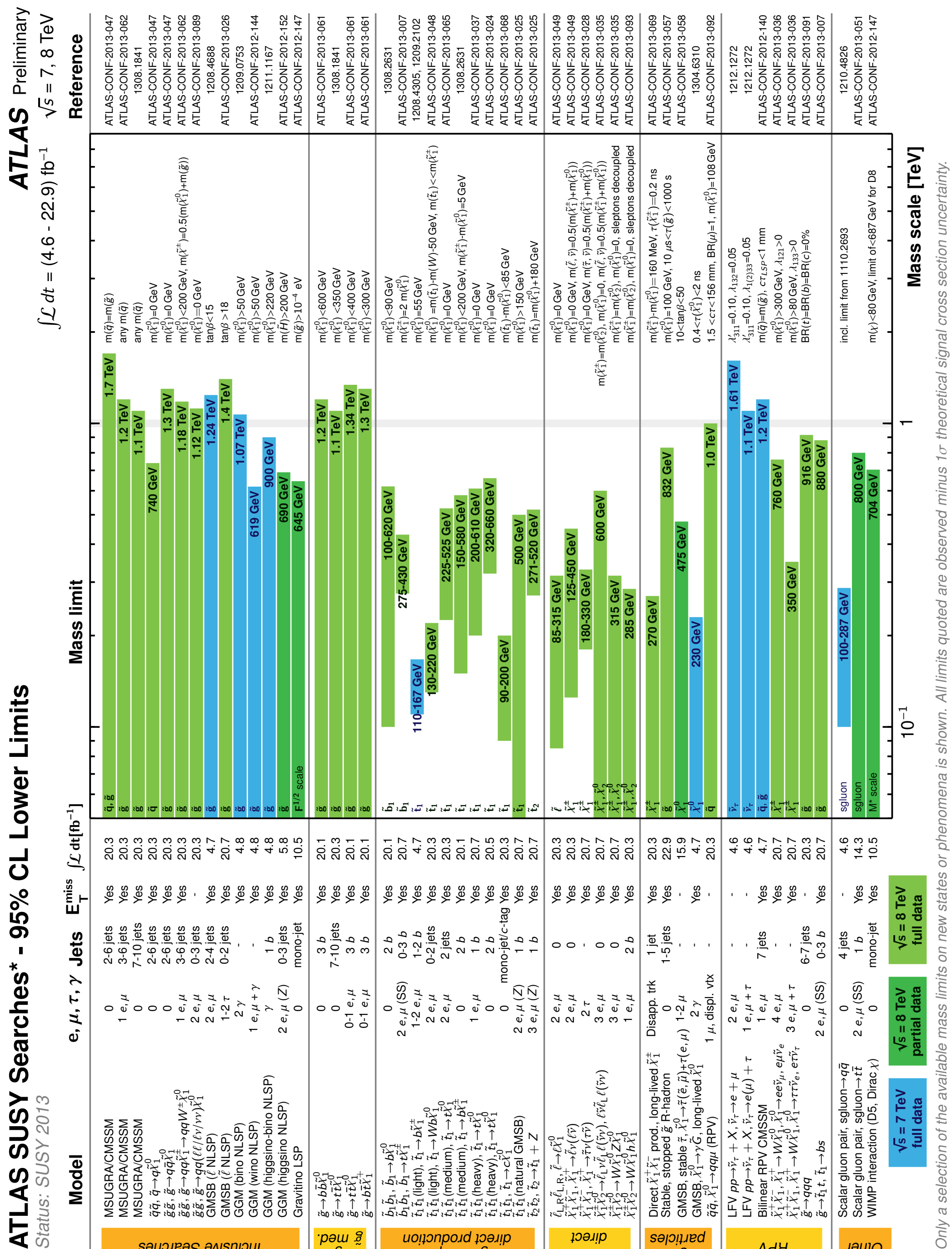

Figure 6. Mass reach of ATLAS searches for Supersymmetry, updated to September 2013.