SUSY Searches at ATLAS

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Abstract. Recent results of searches for supersymmetry by the ATLAS collaboration in up to 2 fb^{-1} of $\sqrt{s} = 7$ TeV pp collisions at the LHC are reported.

1 Introduction

Due to the high centre-of-mass energy of 7 TeV, the LHC has discovery potential for new heavy particles beyond the Tevatron limits even with little luminosity. This holds in particular for particles with colour charge, such as squarks and gluinos in supersymmetry (SUSY) [1]. However, due to the excellent luminosity performance of the LHC in 2011, sensitivity also exists for electroweak production of charginos and neutralinos, the supersymmetric partners of the electroweak gauge bosons and the Higgs boson. In this document, a number of results of ATLAS searches for supersymmetry with up to 2 fb^{-1} of LHC pp data at $\sqrt{s} = 7$ TeV are summarized. Since none of the analyses have observed any excess above the Standard Model expectation, limits on SUSY parameters or masses of SUSY particles are set. It is, however, important to consider carefully the assumptions made in each of the limits, and the true constraints that they impose on supersymmetry.

2 Searches with jets and missing momentum

Assuming conservation of R-parity, the lightest supersymmetric particle (LSP) is stable and weakly interacting, and will typically escape detection. If the primary produced particles are squarks or gluinos (and assuming a negligible lifetime of these particles), this will lead to final states with energetic jets and significant missing transverse momentum.

ATLAS carries out analyses with a lepton veto [2], requiring one isolated lepton [3], or requiring two or more leptons [4]. In addition, a dedicated search is performed for events with high jet multiplicity [5]. Data samples corresponding to luminosities between 1.0 and 1.3 fb^{-1} are used. Events are triggered either on the presence of a jet plus large missing momentum, or on the presence of at least one high-p_T lepton. Backgrounds to the searches arise from Standard Model processes such as vector boson production plus jets (W + jets, Z + jets), top quark pair production and single top production, QCD multijet production, and diboson production. Backgrounds are estimated
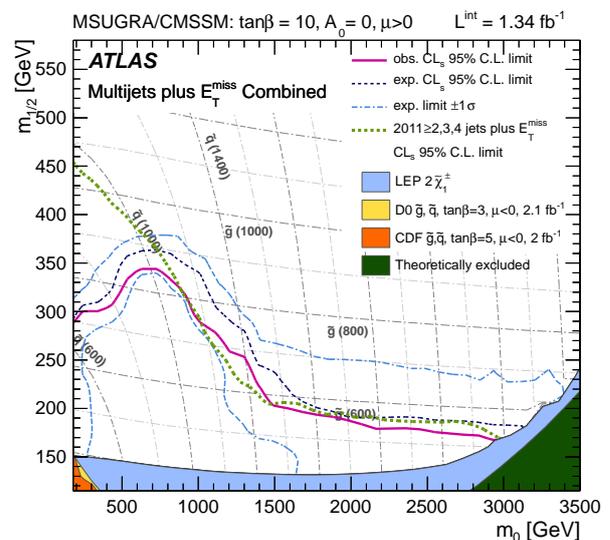

Fig. 1. Exclusion contours in the MSUGRA/CMSSM m_0-$m_{1/2}$ plane for $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$, arising from the analysis with ≥ 2, ≥ 3 or ≥ 4 jets plus missing momentum, and the multijets plus missing momentum analysis.

in a semi-data-driven way, using control regions in combination with a transfer factor obtained from simulation.

The results are interpreted in the MSUGRA/CMSSM model, and in particular as limits in the plane spanned by the common scalar mass parameter at the GUT scale m_0 and the common gaugino mass parameter at the GUT scale $m_{1/2}$, for values of the common trilinear coupling parameter $A_0 = 0$, Higgs mixing parameter $\mu > 0$, and ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta = 10$. Figure 1 shows the results for the analyses with ≥ 2, ≥ 3 or ≥ 4 jets plus missing momentum, and the multijets plus missing momentum analysis. For a choice of parameters leading to equal squark and gluino masses, squark and gluino masses below approximately 1 TeV are excluded. The 1-lepton and 2-lepton results are less constraining in MSUGRA/CMSSM for this choice of parameters, but these analyses are complementary, and therefore no less important.

The search with two isolated opposite-charge leptons is also interpreted in the framework of minimal gauge mediated supersymmetry breaking (GMSB), as shown in Fig-

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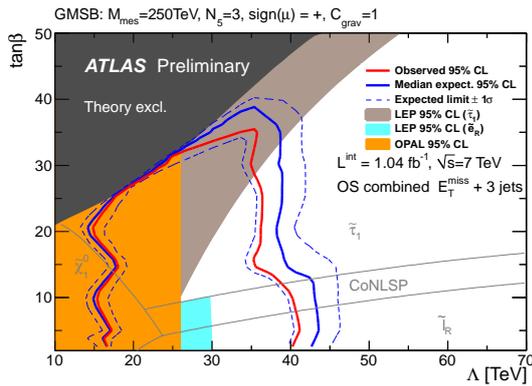
Fig. 2. Exclusion contours in the GMSB Λ-$\tan\beta$ plane, for $M_{mes} = 250$ TeV, $N_5 = 3$ and $\mu > 0$, resulting from the opposite-charge lepton analysis.

ure 2 [6]. Assuming a messenger mass scale M_{mes} of 250 TeV, 3 generations of messengers ($N_5 = 3$) and $\mu > 0$, limits are set on the effective SUSY breaking scale Λ and on $\tan\beta$. These limits significantly improve on the LEP results.

3 Simplified model interpretation

ATLAS has found it useful to not only interpret the results in constrained models, but also in terms of simplified models assuming specific production and decay modes [7]. In such simplified models, the constraints implied by models like MSUGRA/CMSSM or GMSB are relaxed, leaving more freedom for variation of particle masses and decay modes. Interpretations in simplified models thus show better the limitations of the analyses as a function of the relevant kinematic variables, and aid in drawing conclusions from the results.

Inclusive search results with jets and missing momentum are interpreted using simplified models with either pair production of squarks or of gluinos, or production of squark-gluino pairs. Direct squark decays ($\tilde{q} \to q\tilde{\chi}_1^0$) or direct gluino decays ($\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$) are dominant if all other particle masses have multi-TeV values, so that those do not play a role. Additional complexity may be built in, for example by allowing one-step decays to intermediate charginos, $\tilde{\chi}^\pm$, or heavier neutralinos, $\tilde{\chi}_2^0$.

Figure 3 shows the ATLAS results interpreted in terms of limits on (first and second generation) squark and gluino masses, for three values of the LSP ($\tilde{\chi}_1^0$) mass, and assuming that all other SUSY particles are very massive [8]. Further interpretations are done in terms of limits on gluino mass vs LSP mass assuming high squark masses, as shown for example in Figure 4 for direct decays, or in terms of limits on squark mass vs LSP mass assuming high gluino masses [3,8]. Figure 5 shows an example of limits in the gluino-LSP mass plane obtained from one-step gluino decays, $\tilde{g} \to q\bar{q}'\tilde{\chi}^\pm$, $\tilde{\chi}^\pm \to W^{(*)}\tilde{\chi}_1^0$, by the one-lepton analysis. The chargino mass in such decays is a free parameter, characterized by $x = (m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}_1^0})/(m_{\tilde{g}} - m_{\tilde{\chi}_1^0})$, and Figure 5 shows $x = 1/2$ as an example.

The results of the inclusive jets plus missing momentum searches, interpreted in these simplified models, indi-
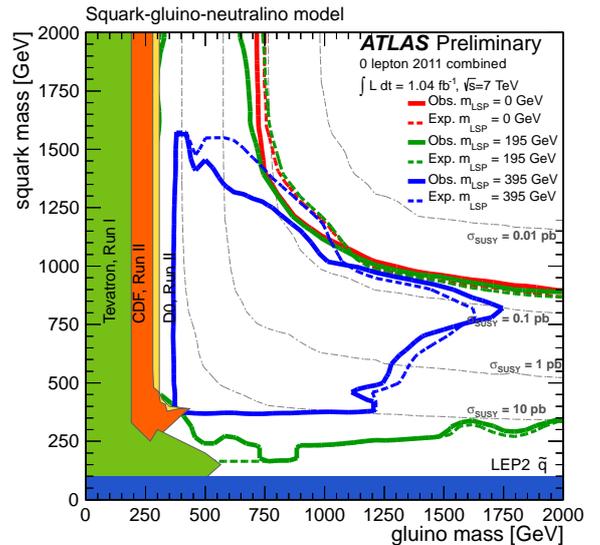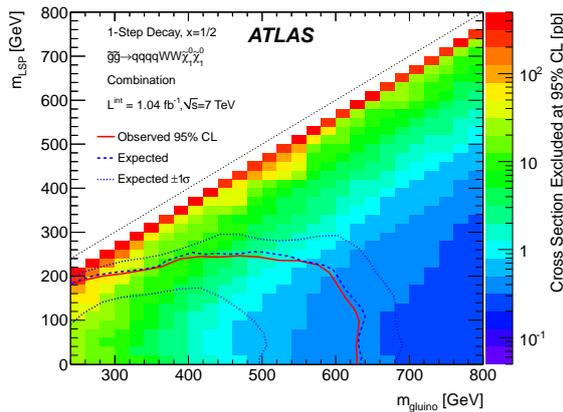

Fig. 3. Exclusion contours in the squark-gluino mass plane, for three values of the LSP mass, using the simplified model described in the text.
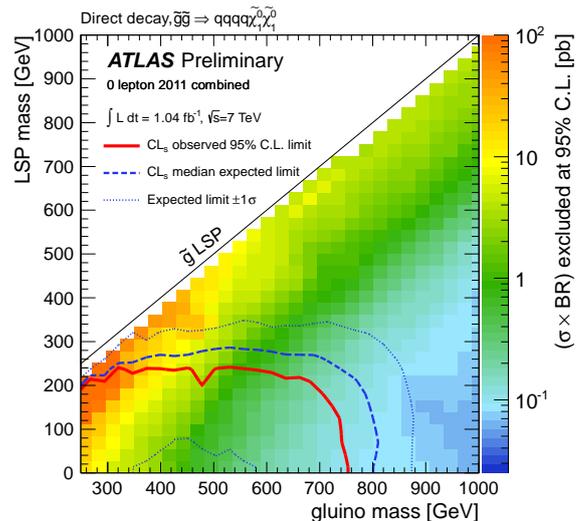
Fig. 4. Cross section limits and exclusion contours in the gluino-neutralino mass plane, for direct gluino decays, $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, as obtained by the no-lepton analysis. All squark masses are assumed to be multi-TeV, so that only gluino pair production takes place, and the direct decay is assumed to occur with 100% branching fraction.

cate that masses of first and second generation squarks and of gluinos must be above approximately 750 GeV. An important caveat in this interpretation is the fact that this is only true for neutralino LSP masses below approximately 250 GeV (as in MSUGRA/CMSSM for values of $m_{1/2}$ below $O(600)$ GeV). For higher LSP masses, the squark and gluino mass limits are significantly less restraining. It will be a challenge for further analyses to extend the sensitivity of inclusive squark and gluino searches to the case of heavy neutralinos. If the LSP is heavy, events are characterized by less energetic jets and less missing transverse momentum. This will be more difficult to trigger on, and lead to higher Standard Model backgrounds in the analysis.

Fig. 5. Cross section limits and exclusion contours in the gluino-neutralino mass plane, for one-step gluino decays, $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}^{\pm}$, $\tilde{\chi}^{\pm} \rightarrow W^{(*)}\tilde{\chi}^0_1$, as obtained by the one-lepton analysis. Only gluino pair production is considered, the one-step gluino decay is assumed to occur with 100% branching fraction, and the chargino mass is characterized by $x = 1/2$ (see text).

4 SUSY and naturalness

Important motivations for electroweak-scale supersymmetry are the facts that SUSY might provide a natural solution to the hierarchy problem by preventing "unnatural" fine-tuning of the Higgs sector, and that the lightest stable SUSY particle is an excellent dark matter candidate. It is instructive to consider what such a motivation really requires from SUSY: a relatively light top quark partner (the stop, $\tilde{t}$) (and an associated sbottom-left quark, $\tilde{b}_L$), a gluino not much heavier than about 1.5 TeV to keep the stop light (the stop receives radiative corrections from loops like $\tilde{t} \rightarrow \tilde{g}t \rightarrow \tilde{t}$), and electroweak gauginos below the TeV scale [9]. There are no strong constraints on first and second generation squarks and sleptons; in fact heavy squarks and sleptons make it easier for SUSY to satisfy the strong constraints from flavour physics. Motivated by these considerations, ATLAS explicitly searches for third generation squarks and for electroweak gauginos.

5 Stop and sbottom searches

ATLAS has carried out a number of searches for supersymmetry with b-tagged jets, which are sensitive to sbottom and stop quarks production, either direct, or in gluino decays. Jets are tagged as originating from b-quarks by an algorithm that exploits both track impact parameter and secondary vertex information.

Direct sbottom pair production is searched for in a data sample corresponding to 2 fb^{-1} by requiring two b-tagged jets with $p_T > 130, 50$ GeV and significant missing transverse momentum of more than 130 GeV [10]. The final discriminant is the boost-corrected contransverse mass m_{CT} [11], and signal regions with $m_{CT} > 100, 150, 200$ GeV are considered. No excesses are observed above the expected backgrounds of top, W+heavy flavour and Z+heavy flavour production. Figure 6 shows the resulting limits in the sbottom-neutralino mass plane, assuming sbottom quark pair production and sbottom quark decay into a bottom quark plus
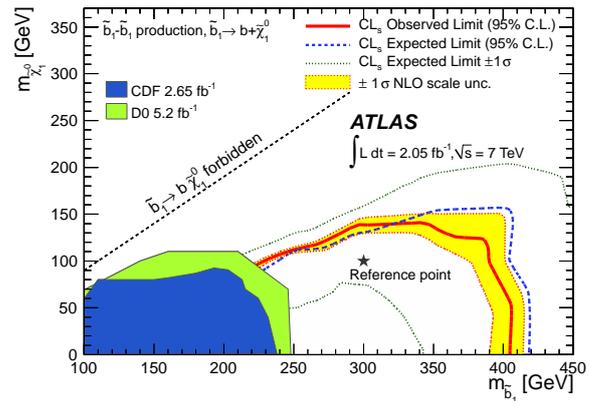
Fig. 6. Exclusion contour in the sbottom-neutralino mass plane resulting from the analysis searching for sbottom quark pair production, assuming sbottom to bottom plus neutralino decay.
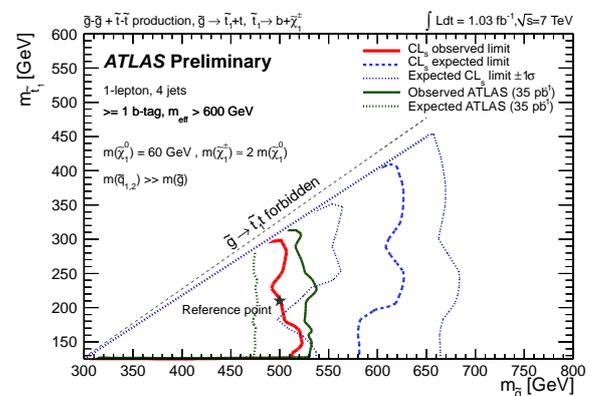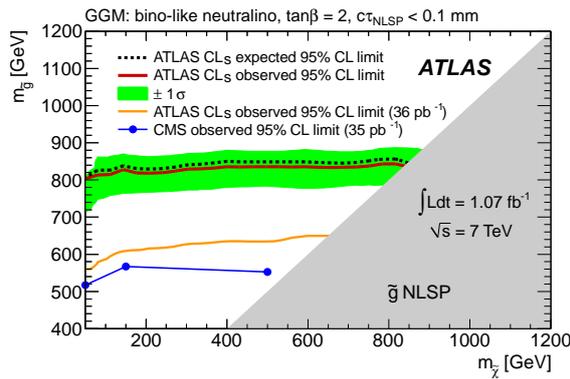

Fig. 7. Exclusion contour in the gluino-stop mass plane resulting from the analysis searching for stop quark production in gluino decays. The assumptions made to derive the plot are listed in the plot.

a neutralino (LSP) with a 100% branching fraction. Under these assumptions, sbottom masses up to 390 GeV are excluded for neutralino masses below 60 GeV.

ATLAS has searched for stop quark production in gluino decays [12] using an analysis requiring at least four high-p_T jets of which at least one should be b-tagged, one isolated lepton, and significant missing transverse momentum. After applying the selection criteria, 74 events are observed in 1.0 fb^{-1} of data, where 55 ± 14 background events are expected from a data-driven estimation procedure, or 52 ± 28 from Monte Carlo simulations. Since there is no significant excess, limits are set in the gluino-stop mass plane, assuming the gluino to decay as $\tilde{g} \rightarrow \tilde{t}t$, and the stop quark to decay as $\tilde{t} \rightarrow b\tilde{\chi}^{\pm}_1$, as shown in Figure 7.

In addition, ATLAS has searched for sbottom production in gluino decays, setting limits in the gluino-sbottom mass plane and in the gluino-neutralino mass plane [13].

Further searches for direct stop quark pair production are in progress. These searches are challenging due to the similarity with the top quark pair production final state for stop masses similar to the top mass, and due to the low cross section for high stop masses. ATLAS has searched for signs of new phenomena in top quark pair events with large missing transverse momentum [14]; such an analysis is sensitive to pair production of massive partners of

Fig. 8. Exclusion contour in the gluino-neutralino mass plane in the general gauge mediation (GGM) model, assuming a bino-like neutralino, resulting from the diphoton plus missing momentum analysis.

Fig. 9. Cross section limits and exclusion contours in the chargino-neutralino mass plane, resulting from the same-charge dilepton analysis. The interpretation is done in a simplified model, details are given in the plot.

the top quark, decaying to a top quark and a long-lived undetected neutral particle. No excess above background was observed, and limits on the cross section for pair production of top quark partners are set. These limits constrain fermionic exotic fourth generation quarks, but not yet scalar partners of the top quark, such as the stop quark.
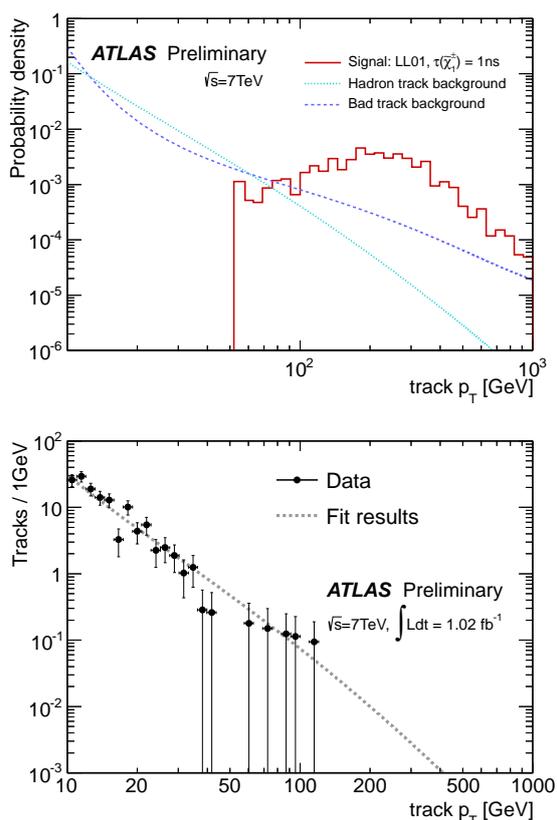
6 Electroweak gaugino searches

Searches for charginos and neutralinos are carried out via analyses of final states involving photons plus missing momentum, or multileptons plus missing momentum.

In gauge mediation models, neutralinos decay to gravitinos plus one or more standard model particles, depending on the neutralino composition. For bino-like neutralinos, the final state consists of a pair of high-p_T photons plus missing transverse momentum. ATLAS has searched for an excess in such final states using 1.1 fb^{-1} of data [15]. The selection requires two photons, identified with "tight" criteria, with $p_T > 25$ GeV, and significant missing transverse momentum. The results are interpreted in the general gauge mediation model (GGM), in terms of limits in the gluino-neutralino mass plane, and assuming the neutralino to be the NLSP. The results are shown in Figure 8. The assumption is made that photons are produced promptly, i.e. $c\tau$ of the NLSP is assumed to be less than 0.1 mm. In this model, a gluino mass below 805 GeV is excluded for bino masses above 50 GeV.

The diphoton plus missing transverse momentum analysis is also interpreted in the minimal gauge mediation model (GMSB), for the SPS8 parameters $M_{mes} = 2\Lambda$, $N_5 = 1$, $\tan\beta = 15$ and $\mu > 0$. The ATLAS results imply a lower limit on Λ for the SPS8 parameters of 145 TeV at 95% CL.

Multilepton analyses [4,16] are sensitive to production of charginos and/or neutralinos other than the LSP, decaying leptonically to the LSP. These analyses comprise the golden search modes at the Tevatron, but are also rapidly gaining relevance at the LHC. ATLAS searches for excesses in final states with three or more leptons on the 2011 data are in progress. ATLAS has published results of various analyses searching for dilepton events plus missing momentum, in 1.0 fb^{-1} of data [4]. Three signal regions are defined for opposite-charge leptons, and two signal regions are defined for same-charge leptons, with varying
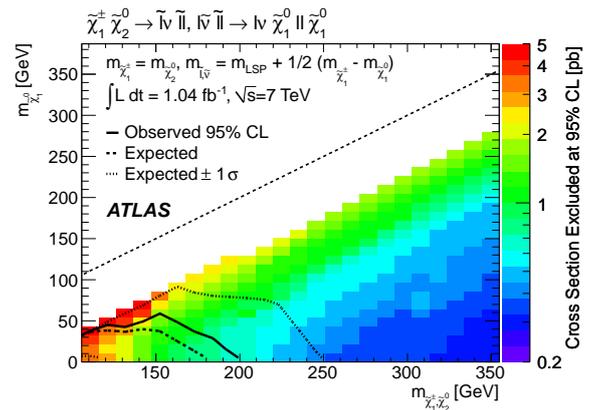
selection criteria on jets and on the missing transverse momentum. For all signal regions, the observed event count agrees with the expected background. The analysis selecting same-charge leptons plus large missing momentum is sensitive to electroweak gaugino production, and results for this analysis are shown in Figure 9. The interpretation is done in a simplified model assuming chargino ($\tilde{\chi}_1^\pm$) plus a heavier neutralino ($\tilde{\chi}_2^0$) production, and decay to leptons and LSPs through intermediate sleptons. Under the assumption of equal mass of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, limits are set in the $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass plane.

7 Special final states

The number of different final states sensitive to SUSY production is very large. SUSY particles may be long-lived, when their decay is suppressed kinematically (split SUSY, R-hadrons, anomaly-mediated SUSY breaking, certain parts of phase space of gauge-mediated SUSY breaking) or by very small couplings (e.g. R-parity violation). ATLAS has carried out searches for stable massive particles [17], for stopped gluinos [18], for kinked or disappearing tracks [19] and for secondary vertices of decaying massive particles [20]. Furthermore, there is a dedicated search for third generation sneutrinos decaying to an electron-muon pair in R-parity violation scenarios [21]. It is also noteworthy that ATLAS has searched for a scalar partner of the gluon [22].

Kinked or disappearing tracks are a possible signature of high-p_T massive particles decaying in the detector volume to an almost degenerate daughter particle, such as $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ in anomaly-mediated SUSY breaking (AMSB) models, where $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are almost degenerate, and the resulting pion track has low p_T and is easily missed in the reconstruction. ATLAS has searched for such signatures in 1.0 fb^{-1} of data [19], demanding a track p_T of at least 10 GeV, good reconstruction quality in the silicon tracking detectors and in the inner layers of the transition radiation tracker (TRT), but no, or only few hits in the outer layer of the TRT. Backgrounds arise from tracks interacting with the TRT material (dominant), or from misreconstructed low-p_T tracks. Figure 10 (top) shows probability density functions (pdfs) in p_T for signal and background

Fig. 11. Vertex mass and number of tracks in the secondary vertex, for vertices selected by the analysis searching for high mass secondary vertices.

in triggering, and in dealing with high pile-up conditions. In the longer term, increasing the LHC beam energy to > 6 TeV will again enable the crossing of kinematical barriers and open the way for multi-TeV SUSY searches.

Fig. 10. Top: Probability density functions for signal (AMSB model) and expected background distributions of track p_T for tracks satisfying the kinked-track selection. Bottom: Distribution of track p_T for 185 tracks in data satisfying the kinked-track selection, and the result of the pdf fit. The fit is consistent with the background-only hypothesis.
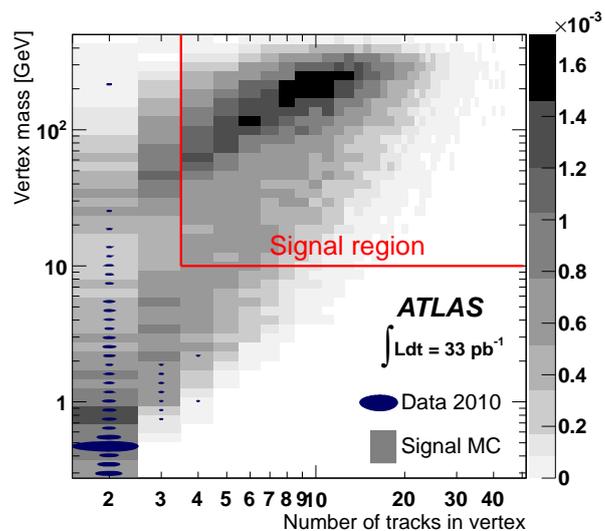
tracks; Figure 10 (bottom) shows the p_T distribution of the 185 tracks in data satisfying the selection criteria, and the pdf fit to the data. The data is consistent with the background expectation, and upper limits on the signal are set.

ATLAS has also searched for high-mass secondary vertices, consistent with the decay of massive particles, in 33 pb^{-1} of data collected in 2010. The analysis is designed in particular for the decay $\tilde{\chi}^0 \to \tilde{\mu}\mu$ and the R-parity violating decay $\tilde{\mu} \to q\bar{q}'$ through a non-zero λ'_{2ij} coupling [20]. Backgrounds arise from interactions in the inner detector material, and the fiducial volume of this analysis excludes regions with such detector material. A signal region is defined requiring a vertex mass of 10 GeV or more, with at least four tracks in the vertex, as shown in Figure 11. The data is consistent with the background hypothesis.

8 Conclusion and Outlook

The results of ATLAS supersymmetry searches are summarized in Figure 12.

Although no signs of SUSY have been found so far, it is important to realize that actual tests of "natural" SUSY are only just beginning [23]. In this respect, the LHC run of 2012, with an expected luminosity of more than 10 fb^{-1}, possibly at $\sqrt{s}$ = 8 TeV, will be very important. However, experimentally there will be considerable challenges

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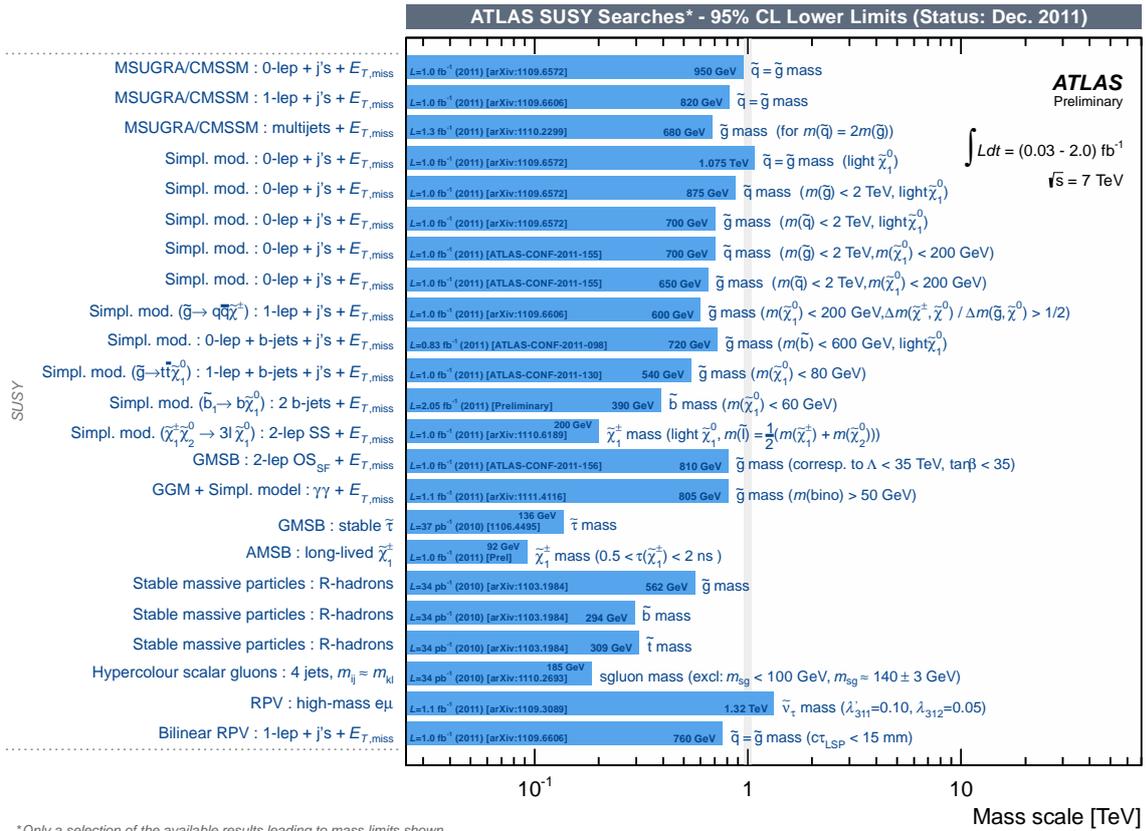
Fig. 12. Summary of limits set on SUSY particle masses by ATLAS, resulting from analyses of up to 2 fb^{-1} of pp collision data at $\sqrt{s}$ = 7 TeV.