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Searches for Supersymmetry at ATLAS

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Summary. — Recent results of searches for supersymmetry by the ATLAS Collaboration in up to 4.7 fb^{-1} of $\sqrt{s} = 7\,\mathrm{TeV}$ pp collisions recorded with the LHC in 2011 are reported. Emphasis is placed on the different classes of supersymmetric particles being sought and limits are set within the context of a wide variety of models.

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1. – Introduction

With its centre-of-mass energy of 7 TeV, the Large Hadron Collider (LHC) provides a unique facility to test models beyond the Standard Model (SM) of particle physics. Supersymmetry (SUSY) [1] is one of the most promising theories extending the Standard Model as it could solve the gauge hierarchy problem. In its simplest form, the Minimal Supersymmetric Standard Model (MSSM), a supersymmetric partner differing by a half-of-unit of spin is associated to every Standard Model particle. After the symmetry is broken, if solving the hierarchy problem, some of the superpartners should have masses not far from the TeV scale and thus could be observed in pp collisions at the LHC. Depending on the mass spectrum and properties of the new supersymmetric particles, different search strategies are used. In R-parity–conserving models, supersymmetric particles are always produced in pairs and the lightest supersymmetric particle (LSP) is stable, escaping the detector and thus providing a possible dark-matter candidate. In addition, if the superpartners of the quarks, the squarks, or the gluon, the gluino, can be directly produced in pp collisions, then their production dominates the cross section leading to final states with multiple jets, large missing transverse momentum and possibly leptons. This class of signature is treated in sect. **2**. However, if SUSY solves naturally the gauge hierarchy problem, *i.e.* without extensive fine-tuning of the parameters, only the third generation squarks contributing mainly to the Higgs radiative corrections are required to be light. Depending on the mass spectrum, it could be that only third-generation squarks or third-generation squarks plus the gluino can be produced at the LHC leading to more specific final states enhanced in heavy flavor quarks. Those important specific cases are discussed in sect. **3**. Finally, sect. **4** deals with more exotic final states involving a resonance such as can occur if R-parity is not conserved, or long-lived particles obtained when the mass splitting between the lightest and the next-to-lightest supersymmetric particles is sufficiently small that the particle becomes quasi-stable.

2. – Generic strong production signatures

The ATLAS Collaboration is carrying out a set of analyses dedicated to the search of supersymmetric particles produced via strong interaction and leading to the following signatures:

- 0 leptons plus 2-6 jets and large missing transverse momentum [2, 3],
- 0 leptons plus 6-8 jets and moderate missing transverse momentum [4, 5],
- 1 lepton plus 2-4 jets and large missing transverse momentum [6, 7],
- 2 same-sign leptons plus 4 jets and large missing transverse momentum [8],

where a lepton means an isolated electron or muon. Although SUSY particles are produced via strong processes, leptons could appear during the cascade decays when gauginos or sleptons are produced. Since no excess has been observed, all results were interpreted in a number of models and exclusion limits were set. The most common approach is to interpret the results in the MSUGRA/CMSSM model [9] which is modeled via 5 free parameters. The limits are set in a plane spanned by a common scalar mass parameter at the GUT scale m_0 and a common gaugino mass parameter at the GUT scale $m_{1/2}$. The three remaining free parameters are defined to a constant value; $A_0 = 0$ for the common trilinear coupling parameter, $\mu > 0$ for the Higgs missing parameter, and $\tan(\beta) = 10$ for the ratio of the vacuum expectation values of the two Higgs doublets. Figure 1 shows on its left the limits obtained for the different channels studied by ATLAS.

Another common approach is to consider the MSSM keeping only a subset of SUSY particles and possible decays within reach. The right part of fig. 1 shows results obtained with an example of such a model where only the gluino, one common first or second generation squark and the lightest neutralino are considered. Limits are set as a function of the gluino and squark masses when the LSP is massless. For all models and analyses, the $\mathrm{CL_s}$ prescription [10] is used to derive 95% Confidence Level (CL) exclusion regions. Signal cross sections are calculated to next-to-leading order in the strong coupling constant (NLO) [11] including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLL) [12]. In the simplified model with light neutralinos the limit on the gluino mass is approximately 940 GeV, and on the squark mass is 1380 GeV. In the CMSSM/MSUGRA case, equal mass squarks and gluinos are excluded below 1400 GeV.

3. – Signatures involving third-generation supersymmetric particles

As has been mentioned in the introduction, one of the most important motivations for TeV-scale supersymmetry is the fact that SUSY might provide a "natural" way to solve the gauge hierarchy problem, limiting sensitivity of the Higgs boson mass to radiative corrections. To stabilize the Higgs mass naturally, the necessary ingredients should be a relatively light top quark partner, the stop, an associated sbottom quark not much heavier, and a gluino of mass not much larger than approximately 1.5 TeV. The masses

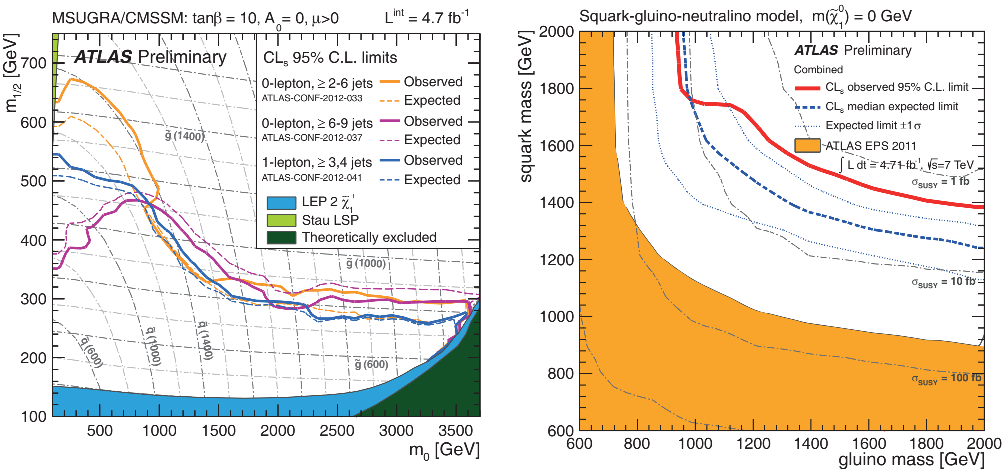

Fig. 1. – Left: Exclusion contours in the MSUGRA/CMSSM m_0-$m_{1/2}$ plane for $A_0 = 0$, $\tan(\beta) = 10$ and $\mu > 0$ [7]. Results are shown for three different analyses with 0 leptons plus 2–6 jets plus missing momentum, 0 leptons plus 6–8 jets plus missing momentum, and 1 lepton plus 2–4 jets plus missing momentum. Right: 95% $\mathrm{CL_s}$ exclusion limits obtained in a simplified MSSM scenario with only strong production of gluinos and first- and second-generation squarks, and direct decays to jets and neutralinos [3].

of other SUSY particles are not significantly constrained by the Higgs mass and can be set to much heavier masses. This model leads, depending on the mass hierarchy of the different remaining particles, to the characteristic signatures:

- If the gluino is sufficiently light, pair production of gluinos decaying subsequently into bottom and top quarks via on-shell or off-shell sbottoms and stops. A large number of b-tagged jets, large missing transverse momentum and possibly leptons (when top quarks decay leptonically) are expected in the final state leading to striking signatures.

- If the gluino is too heavy, the only remaining production process is the direct production of a pair of sbottoms or stops. The former case leads possibly to a final state with exactly two bottom quarks and large missing transverse momentum. The latter case is more complicated to constrain due to its similarity with top quark pair production and the large number of possible decay processes.

Whichever is the decay process, results are interpreted in term of simplified models where only the relevant SUSY particles are considered. Gluino-mediated sbottom pair production is tested in channels with no lepton, at least three jets, large missing transverse momentum and at least one or two b-tagged jets [13]. Figure 2 on the left shows the exclusion limits obtained in a MSSM model where the gluino decays exclusively into the lightest sbottom and a bottom quark, and the sbottom decays into a bottom and a neutralino. The neutralino mass is set to 60 GeV. Gluino masses below 920 GeV are excluded for sbottom masses up to about 800 GeV. In order to constrain the gluino-mediated stop pair production, two channels are used, either with one lepton, at least four jets, large missing transverse momentum and one b-tagged jet, or with two same-sign leptons, at least four jets, and large missing transverse momentum. Results are

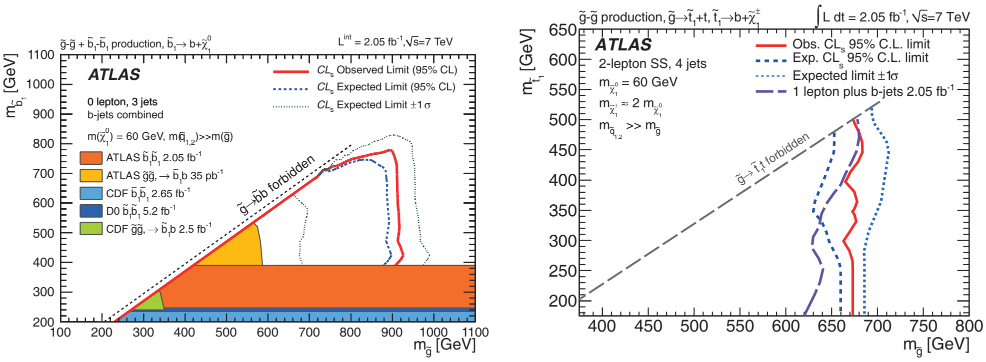

Fig. 2. – Left: 95% $\mathrm{CL_s}$ exclusion limits obtained in the context of a MSSM model in the $m_{\tilde{g}}$-$m_{\tilde{b}_1}$ plane [13]. Right: 95% $\mathrm{CL_s}$ exclusion limits obtained in the context of a MSSM model in the $m_{\tilde{g}}$-$m_{\tilde{t}_1}$ plane [8].

interpreted in a MSSM model with each gluino decaying into a stop and a top, a stop decaying into a bottom quark and a chargino, and a chargino decaying to the neutralino plus a W. Figure 2 on the right shows the exclusion limits in the $m_{\tilde{g}}$-$m_{\tilde{t}_1}$ plane with the chargino and neutralino masses set to $m(\tilde{\chi}_1^{\pm}) = 2 \cdot m(\tilde{\chi}_1^0)$ and $m(\tilde{\chi}_1^0) = 60\,\mathrm{GeV}$, respectively. Gluino masses below 660 GeV are excluded for stop masses up to about 460 GeV. The search for sbottom pair production has been performed when assuming that the sbottom fully decays into a bottom quark and the lightest neutralino leading to a characteristic signature with exactly two b-tagged jets and large missing transverse momentum [14]. Results are interpreted in the plane $m(\tilde{b}_1) - m(\tilde{\chi}_1^0)$ and shown in fig. 3 (left). Sbottom masses up to 390 GeV are excluded for neutralino masses below 60 GeV.

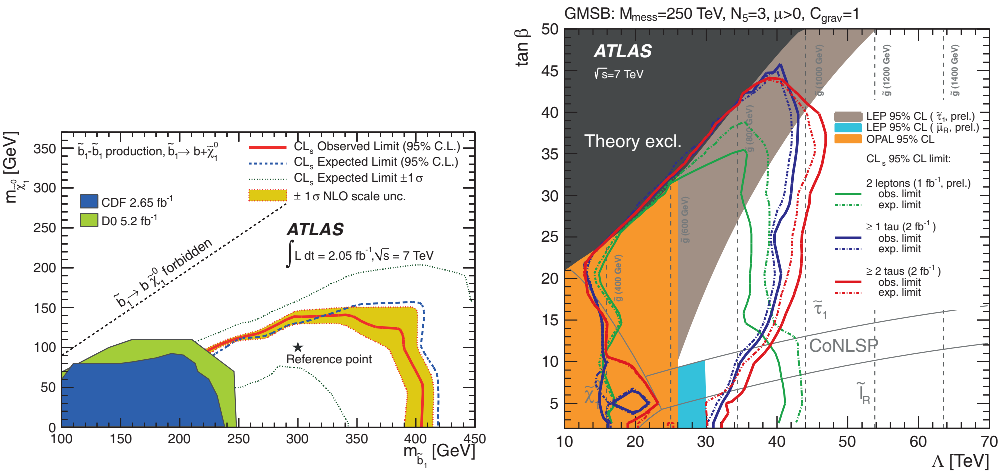

Fig. 3. – Left: 95% $\mathrm{CL_s}$ exclusion limits in the $m(\tilde{b}_1)$-$m(\tilde{\chi}_1^0)$ plane for a model assuming 100% decay of the lightest sbottom into a bottom quark and the lightest neutralino [14]. Right: 95% $\mathrm{CL_s}$ exclusion limits obtained for the minimal GMSB model in the Λ-$\tan(\beta)$ plane [18]. The CoNLSP region means that both the $\tilde{\tau}_1$ and the $\tilde{l}_R$ are the NLSP.

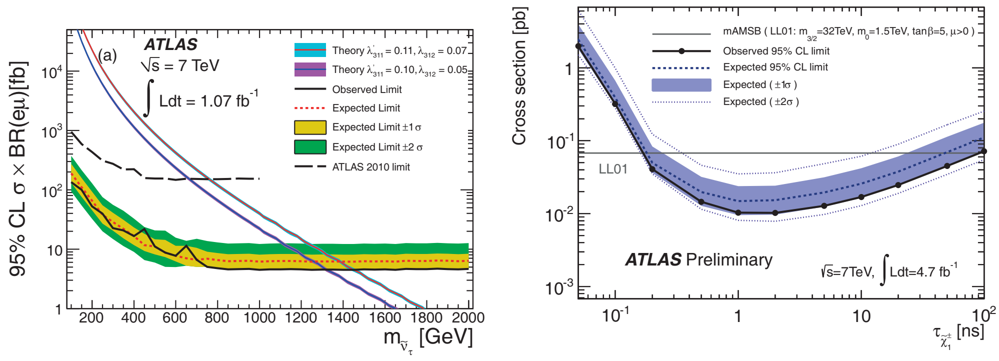

Fig. 4. – Left: 95% CL upper limits on $\sigma(pp \to \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \to e\mu)$ as a function of $m(\tilde{\nu}_\tau)$ [19]. Right: 95% CL upper limits on the signal cross section as a function of chargino lifetime for $m(\tilde{\chi}_1^\pm) = 90.2\,\text{GeV}$ [23].

For a given flavor, third generation SUSY particles are generally lighter than the first and second generation sparticles because of the mixing between the left-handed and the right-handed states which is proportional to the Standard Model particle mass. In particular, in Gauge Mediated Supersymmetry Breaking (GMSB) models [15], the SUSY partner of the tau lepton, the stau, could be the next-to-lightest SUSY particle leading to final states with a substantial number of tau leptons. In order to search for such a possible scenario, channels with one or two hadronic tau candidates, multiple jets and high missing transverse momentum have been designed [16, 17]. Since no excess was found, results have been interpreted in the minimal GMSB model which is formalized as a function of 6 free parameters: the SUSY breaking mass scale felt by the low-energy sector Λ, the messenger mass M_{mess}, the number of $SU(5)$ messengers N_5, the ratio of the vacuum expectation values $\tan(\beta)$, the Higgs sector mixing parameter μ, and the scale factor for the gravitino mass C_{grav}. Assuming $M_{mess} = 250\,\text{TeV}$, $N_5 = 3$, $\mu > 0$, and $C_{grav} = 1$, exlusion limits are set in the Λ-$\tan(\beta)$ plane and shown on fig. 3(right).

4. – Exotic signatures with resonances or long-lived particles

While most signatures studied in sects. **2** and **3** incorporate requirements for significant missing transverse momentum, this constraint can be evaded in some supersymmetric scenarios and require specific search studies. This is the case when R-parity is violated and the SUSY particle promptly decays to Standard Model particles. There are many possible R-parity violating couplings, which can lead to numerous possible final states. As an example, lepton and baryon violating couplings although constrained by precision electroweak data could exist and lead to the direct production of $e\mu$ pairs either via exchange of an s-channel tau neutrino SUSY partner $\tilde{\nu}_\tau$ exchange [19] or via exchange of a t-channel top quark SUSY partner $\tilde{t}_1$ [20]. The s-channel $\tilde{\nu}_\tau$ exchange leads to a final state with an $e\mu$ resonance, while the t-channel $\tilde{t}_1$ exchange results in an $e\mu$ continuum excess. Figure 4 (left) shows the upper limit obtained on $\sigma(pp \to \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \to e\mu)$ as a function of $m(\tilde{\nu}_\tau)$. Assuming coupling values $\lambda_{311} = 0.10$ and $\lambda_{312} = 0.05$, tau sneutrinos with a mass below 1.32 TeV are excluded.

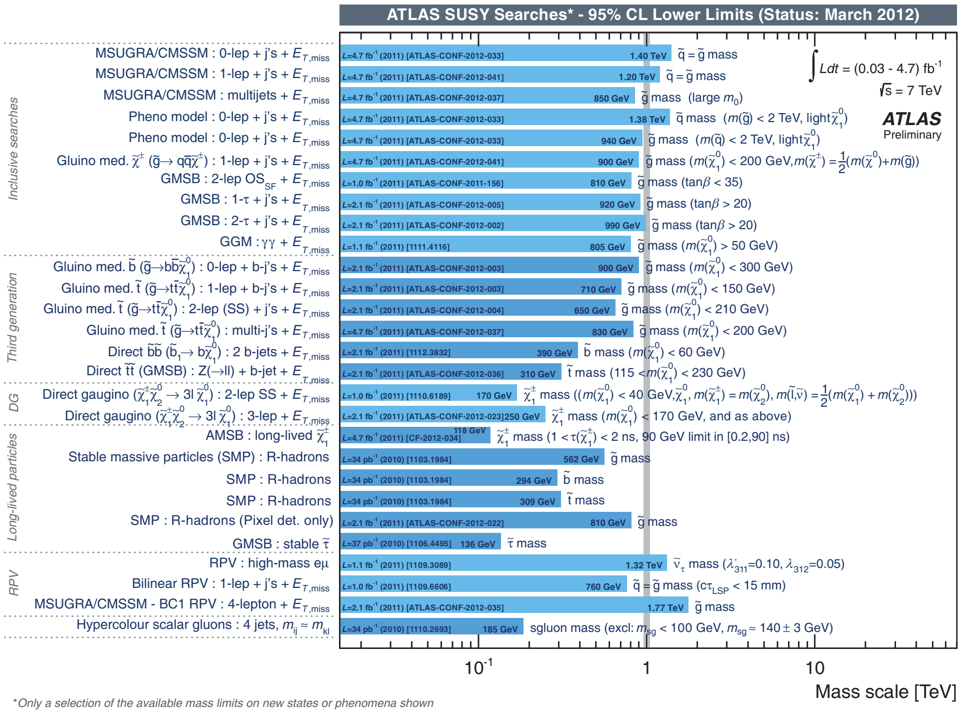

Fig. 5. – Mass reach of ATLAS searches for Supersymmetry [28]. Only a representative selection of the available results is shown.

Another SUSY search strategy involves seeking long-lived SUSY particles inside the ATLAS detector. Depending on the lifetime and the nature of the SUSY particle, the ATLAS Collaboration has been searching for displaced vertices [21], for kinked or disappearing tracks [22, 23], and for stable massive particles [24-26]. Kinked or disappearing tracks could exist in Anomaly Mediated Supersymmetry-Breaking (AMSB) models [27] when the lightest chargino $\tilde{\chi}_1^{\pm}$ and the lightest neutralino $\tilde{\chi}_1^0$ are almost degenerate. Results are interpreted as a function of the chargino mass and lifetime and upper limits are set on the cross-section as a function of these parameters as shown in fig. 4 (right). Other parameters from the minimal AMSB model are set to $m_{3/2} = 32\,\text{TeV}$ for the gravitino mass, $m_0 = 1.5\,\text{TeV}$ for the universal scalar mass, $\tan(\beta) = 10$ for the ratio of Higgs vacuum expectation values, and $\mu > 0$ for the sign of the higgsino mass term.

5. – Conclusion

Key figures from ATLAS supersymmetry searches are summarized in fig. 5 [28]. No evidence for supersymmetry has been found but new data with increased centre-of-mass energies and the study of new channels will bring new opportunities for the discovery of a potential excess.

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