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Search for supersymmetry at ATLAS

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Summary. — These proceedings summarize the searches for Supersymmetry (SUSY) with the ATLAS detector at the Large Hadron Collider (LHC), focusing on the results obtained with the full proton-proton collisions data set recorded at a center-of-mass energy of $\sqrt{s} = 8\,\text{TeV}$, corresponding to an integrated luminosity of approximately $20\,\text{fb}^{-1}$. Various searches were carried out in order to explore a large variety of production models and the results matched the Standard Model background expectation, therefore exclusion limits were derived on the production of new physics.

PACS 11.30.Pb – Supersymmetry.
PACS 12.60.Jv – Supersymmetric models.
PACS 14.80.Ly – Supersymmetric partners of known particles.
PACS 14.80.Nb – Neutralinos and charginos.

1. – Introduction

Supersymmetry (SUSY) [1-8] is one of the most promising theory to describe Physics beyond the Standard Model (SM). It predicts the existence of new particles, "super-partners" of SM particles, that have the same quantum numbers and masses but obey different spin-statistics. In particular, this new symmetry associates a complex scalar to each SM fermion, and a fermion to each gauge boson. Since SUSY particles have not been observed yet, this symmetry is assumed to be broken.

Some SUSY scenarios foresee the conservation of R-parity, a quantum number defined as $(-1)^{3(B-L)+2S}$, where B is the baryon number, L is the lepton number and S is the spin. This conservation implies that the Lightest Supersymmetric Particle (LSP) is stable and that SUSY particles are produced in pairs at colliders; in some R-parity conserving (RPC) models the LSP is identified with the lightest neutralino ($\tilde{\chi}_1^0$), which is a massive, neutral, weakly interactive particle suitable to be a good Dark-Matter candidate. In R-parity–violating (RPV) models the LSP is no longer stable and can decay to SM particles.

1·1. *SUSY searches at LHC.* – At the LHC [9] SUSY can be tested up to the TeV scale. The large variety of SUSY breaking models led to a general search approach in simplified scenarios involving a reduced number of parameters. Early searches targeted the inclusive production of strong particles like gluinos ($\tilde{g}$) and first/second generation squarks ($\tilde{q}$), since the production cross-sections for these particles dominates the total SUSY production cross-section at the LHC [10]. Final states for such processes contain energetic jets, missing transverse energy ($E_T^{\rm miss}$) and sometimes leptons.

The sensitivity to intermediate production cross-sections increased as the integrated luminosity increased, so the search for third $\tilde{q}$ generation has become more relevant; third $\tilde{q}$ generation production involves in the final state b-jets, $E_T^{\rm miss}$ and leptons, while *top* events represent the main SM background. In some models, also supported by the "natural" stabilization of the Higgs boson mass argument, light stops ($\tilde{t}$) and sbottoms ($\tilde{b}$) are expected. Lower cross-sections correspond to the ElectroWeak (EW) production of SUSY particles; the latter can be the dominant production mechanism if colored sparticles are too heavy to be produced. These processes are very interesting because are often characterized by multi-lepton and $E_T^{\rm miss}$ signatures and very low SM background.

1·2. *ATLAS search strategy.* – The ATLAS [11] search strategy is designed to cover a broad spectra of the different SUSY breaking models in both RPC and RPV scenarios. For every search, Signal Regions (SRs) are defined using Monte Carlo (MC) simulation and are individually optimized to achieve the best sensitivity. Different Control Regions (CRs) featuring similar signatures as the SRs but with negligible signal contamination are used to evaluate the dominant background processes and to extract normalization factors for MC. Rare background processes are often evaluated using MC simulation, and possible discrepancies are addressed by using correction factors obtained from data.

As general rule, to avoid bias the data remain blinded until the analysis procedure is fully validated. Once the analysis is considered well established, the SRs are unblinded and if no discrepancies between the observed data and the SM expectations are found, limits are set on the SUSY models using the CLs [12] prescription.

2. – Inclusive searches for 1st- and 2nd-generation squarks and gluinos

The search for strong production of 1st and 2nd generation of squarks and gluinos posed strong constraints on several SUSY models.

Figure 1 left summarizes the results of the searches performed in both fully hadronic and semi-leptonic final states, interpreted in the MSUGRA/CMSSM model [15]: squarks and gluinos are excluded for masses up to 1.35 TeV and the highest sensitivity is provided by final states with high jet multiplicity and large $E_T^{\rm miss}$.

One interesting example of these searches is reported in [16], where the final states contain at least one isolated lepton (electron or muon), jets (with or without b-jet requirements) and large $E_T^{\rm miss}$: in particular, the SR containing only one "soft" lepton (*i.e.* having transverse momentum (p_T) < 25 GeV) provided high sensitivity for the compressed spectra where the mass difference between $\tilde{g}$ and $\tilde{\chi}_1^0$ (LSP) is relatively low.

The results in the $E_T^{\rm miss}$ + jets and no leptons final states have been also interpreted in a simplified model framework [14], where only the strong production of gluinos and 1st and 2nd generation of squarks (of common mass) with direct decay to the LSP ($\tilde{\chi}_1^0$) was allowed. In this case ten SRs with different requirements on the jets multiplicity or $E_T^{\rm miss}$ have been defined; among them, the most sensitive ones have been used to set constraints on strong sparticle masses, as shown in fig. 1, right.

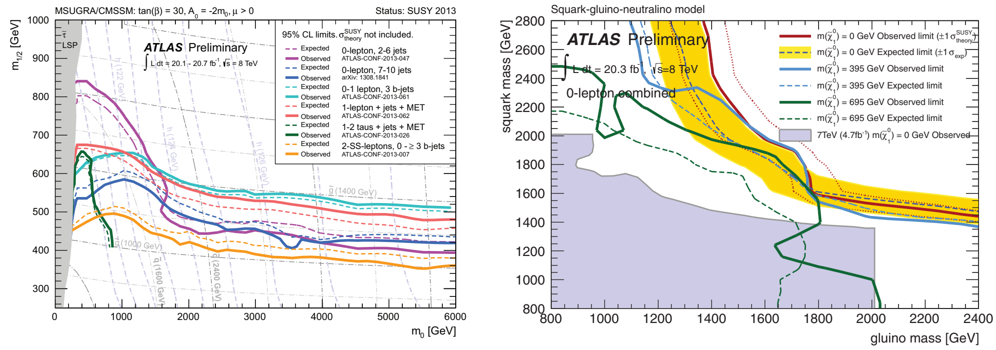

Fig. 1. – Left: Exclusion limits at 95% CL for 8 TeV analysis in the $(m_0, m_{1/2})$-plane for the MSUGRA/CMSSM model where $\tan\beta = 30$, $A_0 = -2\ m_0$, $\mu > 0$. Part of the model plane accommodates a lightest neutral scalar Higgs boson mass of 125 GeV. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross-section uncertainties [13]. Right: Exclusion limits for a simplified model framework with only strong production of gluinos and 1st/2nd-generation squarks (of common mass), with direct decays to jets and $\tilde{\chi}_1^0$ (LSP) for different hypothesis on $m_{\tilde{\chi}_1^0}$. The dashed lines show the expected limits at 95% CL, with the light (yellow) band indicating the 1σ experimental and background-theory uncertainties on the $m_{\tilde{\chi}_1^0} = 0$ limit. Observed limits are indicated by solid curves, while the dotted lines represent the $m_{\tilde{\chi}_1^0} = 0$ observed limits obtained by varying the signal cross-section by the theoretical scale and PDF uncertainties [14].

3. – Searches for 3rd-generation squarks

The exclusions up to the TeV scale of heavy squarks and gluinos has drawn the attention to lighter sparticles production, and the search for bottom and top squarks is currently one of the most active areas in the search for SUSY. RPC models foresee the pair production of third generation squarks at LHC; this production can be either gluino mediated or direct. The outcome of these searches has been interpreted in the simplified models picture, where only the particles of interest can be produced and only the most relevant decay modes are considered with 100% branching ratio (BR), while the other particles are set to very high masses.

3˙1. *Gluino-mediated production.* – Directly produced gluino pairs are assumed to decay to on-shell or off-shell stops or sbottoms (*Gtt* model: $\tilde{g} \to \tilde{t}t$, *Gbb* model: $\tilde{g} \to \tilde{b}b$), which then decay to t or b and $\tilde{\chi}_1^0$ (LSP). Final states contain large $E_T^{\rm miss}$, multiple jets, b-jets and leptons. Figure 2, left, shows one of discriminating variables used for the search [17] for gluino mediated stop production in final states with 7 jets, among which at least three are b-jets, and with either one or no leptons. This variable, called effective mass, is defined as the sum of the $E_T^{\rm miss}$ and of the p_T of the leading jets in the events, and would give indication of the SUSY mass scale if any excess would be observed. This analysis posed the strongest constrains on the *Gtt* model, as can be seen also from fig. 2, right, where the results of the searches for gluino mediated stop production in final states containing different flavor/multiplicity of jets and and lepton are summarized.

3˙2. *Direct stop production.* – Figure 3 shows the results obtained by different analyses looking for top squark direct production as a function of the stop and lightest neutralino (LSP) masses for simplified models. The left part of the plot summarizes the searches

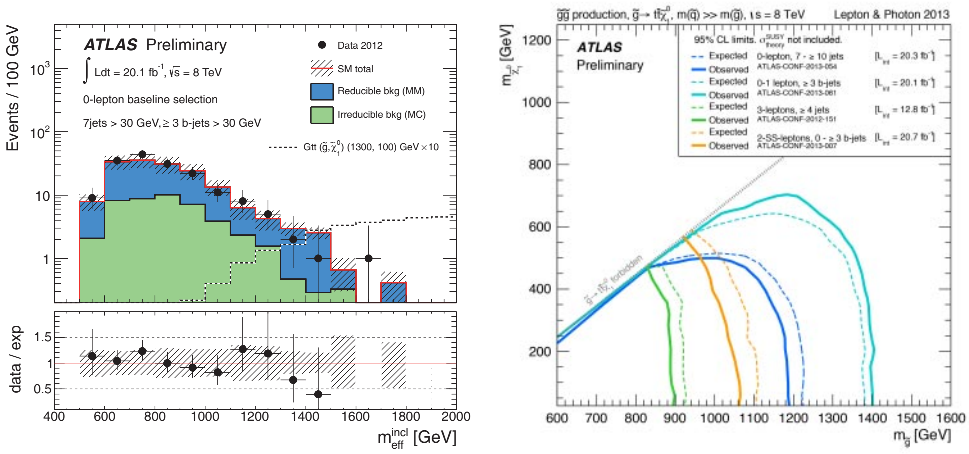

Fig. 2. – Left: Inclusive effective mass distribution for the gluino-mediated stop production in the fully hadronic decay channel with 7 jets, among which at least 3 are b-jets. Data (black points) are compared to the background expectation (filled area) and to one signal point from the *Gtt* model (dotted line). The ratio between the observed event yield and background prediction is also shown [17]. Right: Exclusion limits at 95% CL for 8 TeV analyses in the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$-plane for the *Gtt* simplified model where a pair of gluinos decays promptly via off-shell stop to four top quarks and two lightest neutralinos (LSP). The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross-section uncertainties [13].

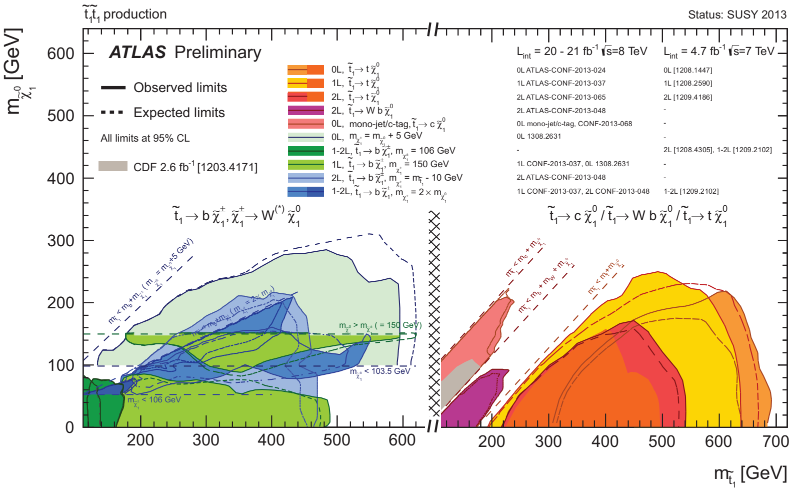

Fig. 3. – Exclusion limits at 95% CL for different 8 TeV and 7 TeV searches for stop pair production in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$-plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross-section uncertainty (PDF and scale) [13].

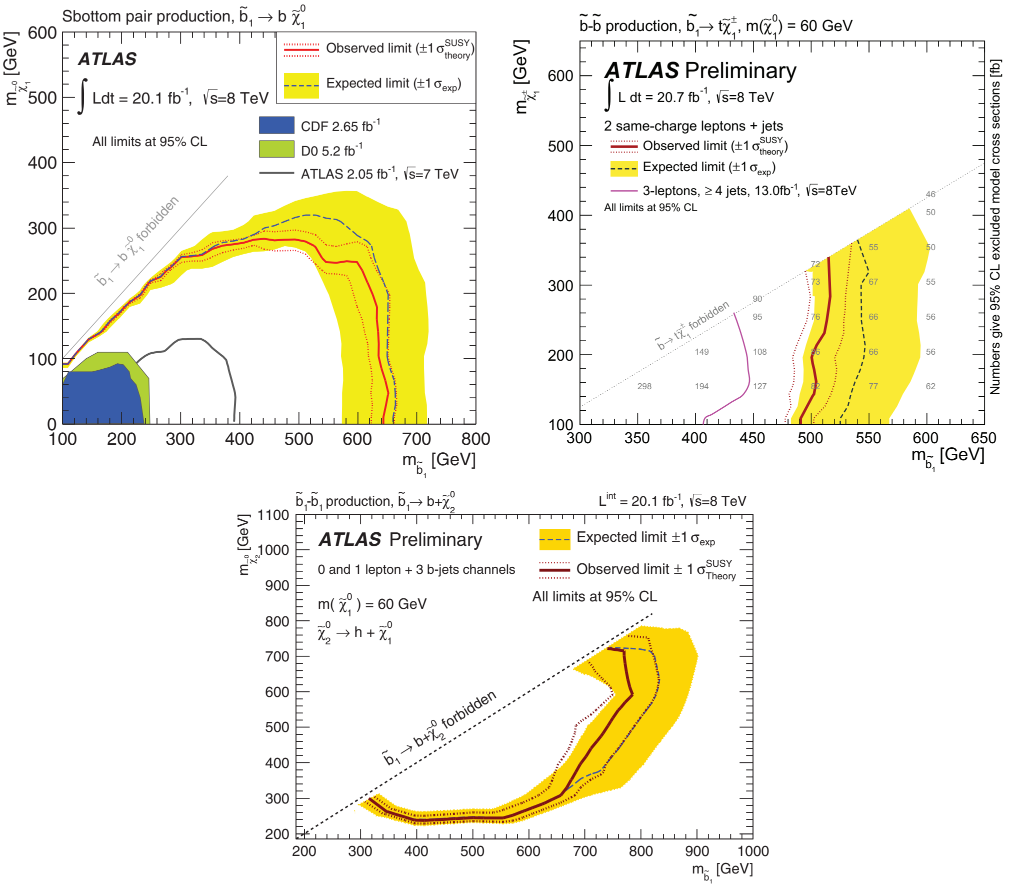

Fig. 4. – Exclusion limits at 95% CL for direct sbottom production search in the $b\tilde{\chi}_1^0$ (top left) [18], in the $t\tilde{\chi}_1^{\pm}$ (top right) [17] and in the $b\tilde{\chi}_2^0$ (bottom) [19] decay modes. The bands around the expected limits show the $\pm 1\sigma$ uncertainties. The dotted lines around the observed limits represent the results obtained when moving the nominal signal cross-section up or down by $\pm 1\sigma$ theoretical uncertainty.

for $\tilde{t}$ decaying to a bottom and a lightest chargino ($\tilde{\chi}_1^{\pm}$), where the $\tilde{\chi}_1^{\pm}$ further decays into the LSP and a W boson, while the right part the searches for the decays in the $t\tilde{\chi}_1^0$, in the $c\tilde{\chi}_1^0$ and in the $Wb\tilde{\chi}_1^0$ channels. For massless $\tilde{\chi}_1^0$, stop masses are excluded up to 700 GeV, while for massive neutralinos of 250–300 GeV these limits fall to 450–500 GeV.

3·3. *Direct sbottom production.* – The dominant decay modes of the sbottom involve either the neutralinos and a b quark ($\tilde{b} \to b\tilde{\chi}_2^0$, $\tilde{b} \to b\tilde{\chi}_1^0$) or the lightest chargino and a top quark ($\tilde{b} \to t\tilde{\chi}_1^{\pm}$). The sbottom pair decays into two lightest neutralinos and $b\bar{b}$ are targeted by analyses requiring lepton veto, two b-jets and a significant amount of $E_T^{\rm miss}$. If the second lightest neutralino is produced, the decays involve a Z or the Higgs boson and additional leptons and b-jets are foreseen in the final states. Finally, if charginos are produced, they decay into W and $\tilde{\chi}_1^0$: this signal scenario is explored by analyses requiring two same-sign leptons or three leptons in the final state. Some of the results of these searches [17-19] are shown in fig. 4.

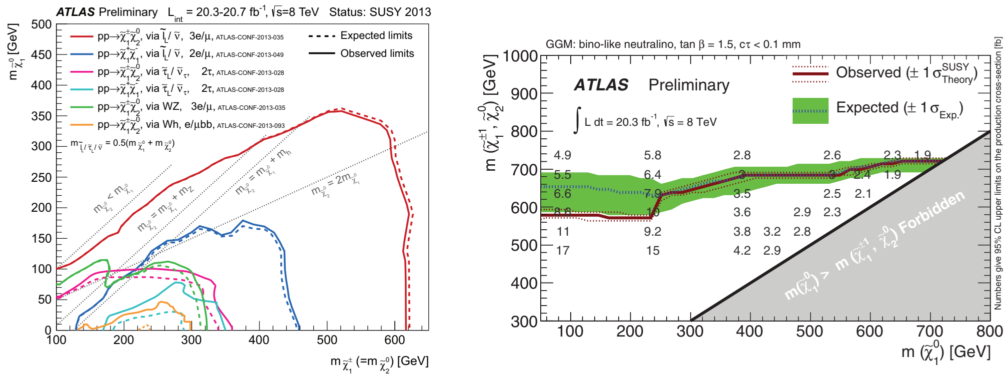

Fig. 5. – Left: Summary of ATLAS searches for electroweak production of charginos and neutralinos for different 8 TeV analyses. Exclusion limits at 95% CL are shown in the $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$-plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross-section uncertainties [13]. Right: Expected and observed 95% CL lower limits on the *wino* mass as a function of the neutralino mass in the GGM model with a *bino*-like lightest neutralino (NLSP). The lower bound of the excluded cross-section (in fb^{-1}) is displayed at each grid point. The green band shows the expected-limit $(\pm 1\sigma)$, while the three contours correspond to three observed-limits: one for the nominal *wino* production cross-section, and one each for a cross-section augmented or diminished by one standard deviation of the cross-section uncertainty [21].

4. – EW production

The most recent and powerful ATLAS result on the direct production of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ is reported in [20]. The search is performed in final states containing three leptons and E_T^{miss}. Four SRs have been used to target $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decays to $\tilde{\chi}_1^0$ (LSP) via either all three generations of sleptons, staus only, gauge bosons, or Higgs bosons in simplified SUSY scenarios where $\tilde{\chi}_1^0$ is 100% *bino*-like while $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are 100% *wino*-like and mass degenerate. Data were found in agreement with the SM expectations and limits have been set in the $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0/\tilde{\chi}_1^\pm})$ mass plane for each SR. In the limit of massless $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ are excluded up to 700 GeV, 380 GeV, 345 GeV, or 148 GeV respectively. Previous searches for charginos and neutralinos are summarized in fig. 5.

Limits on the $\tilde{\chi}_1^0$ mass in the GGM [22] scenario are set in [21]. In this case $\tilde{\chi}_1^0$ is the next to lightest supersymmetric particle (NLSP) and is mostly *bino*-like, while the LSP is the gravitino, therefore the search is performed in final states involving two real photons and E_T^{miss}.

5. – Searches for long-lived particles

Long-lived particles having a proper decay length $c\tau > 1\,\mathrm{mm}$ are predicted in both RPC and RPV SUSY models. For instance, the LSP $(\tilde{\chi}_1^0)$ in RPV SUSY models is allowed to decay; for lifetimes in the picosecond-to-nanosecond range, the expected final states involve a muon and many charged tracks originating from a single displaced vertex (DV). The results of the ATLAS search [23] for such signals were found to be consistent with the background expectations, thus limits were set, for instance, as a function of the neutralino lifetime for a range of neutralino masses and velocities.

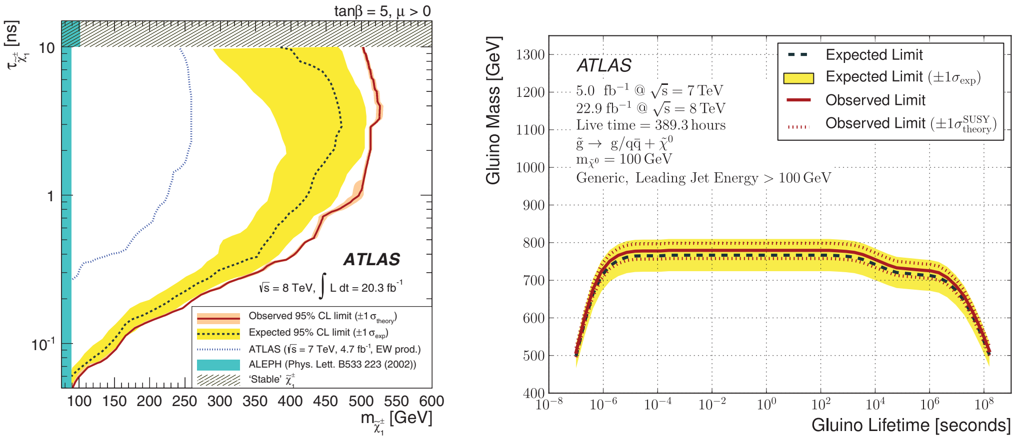

Fig. 6. – Left: Constraints on long-lived charginos in the ($\tau_{\tilde{\chi}_1^\pm}$-$m_{\tilde{\chi}_1^\pm}$)-plane. The black dashed line shows the expected limits at 95% CL, with the surrounding shaded bands indicating the 1σ exclusions due to experimental uncertainties. Observed limits are indicated by the solid bold contour representing the nominal limit and the surrounding shaded bands are obtained by varying the cross-section by the theoretical scale and PDF uncertainties [25]. Right: Bayesian lower limits on $\tilde{g}$ mass *versus* its lifetime in the ATLAS stopped gluino search [26].

In AMSB models [24] as well the LSP is the lightest neutralino, and in this case it is nearly mass degenerate with lightest chargino. The small mass splitting ($\sim 160\,\text{MeV}$) between these two particles results in a considerable chargino lifetime, and therefore its decays, mainly into $\tilde{\chi}_1^\pm\ \pi^\mp$ pairs, are expected to be observed as "disappearing" tracks outside the tracker volume, as the $\pi^\mp$ is not reconstructed. The constraint posed on such events by ATLAS [25] are shown in fig. 6, right.

Color-singlet states of R-mesons ($\tilde{g}q\bar{q}$), R-baryons ($\tilde{g}qqq$) and R-gluinoballs ($\tilde{g}g$), generally called R-hadrons, may occur in some RPC scenarios like split SUSY [27], where gluinos are much lighter than squarks and their decays are suppressed. In RPV SUSY long-lived squarks may also form an R-hadron (*e.g.* $\tilde{t}q$) having similar phenomenology as in the RPC R-hadrons but smaller production cross-sections. The ATLAS search for long-lived R-hadrons which may loose energy and stop in the detector material can be found in [26]. A strong suppression of the main sources of background (cosmic rays, beam halo) is obtained by selecting empty bunch crossings trigger events with some calorimeter activity, energetic jets in the central pseudorapidity region and no tracks in the Muon Spectrometer. Also in this case no excess is found and limits are set on the mass of the long-lived hadronizing particles: as an example, fig. 6 shows the limits obtained for $\tilde{g}$ masses as a function of $\tilde{g}$ lifetime.

Finally, a search for long-lived charged sleptons using $16\,\text{fb}^{-1}$ of integrated luminosity collected during 2012 is reported in [28]; in this case the sleptons are expected decay outside the detector volume and appear as if they are heavy muons, charged and penetrating. Mass limits are set on long-lived $\tilde{\tau}$ (NLSP) production in the GMSB scenario [29]; model independent limits are also set on the direct production of long-lived sleptons and on the direct production of gauginos decaying to long-lived staus.

6. – Summary

The search for SUSY is one of the most important part of the LHC physics programme. Several searches have been carried out in ATLAS to cover a wide multiplicity of SUSY scenarios, and in all of them the results were found in agreement with the background expectations. Data so far collected allowed to exclude strong production of 1st- and 2nd-generation squarks and gluinos up to the TeV scale. Naturalness arguments favor the existence of light top and bottom squarks; exclusions for the masses of these particles are set up to $\sim 700\,\text{GeV}$. EW SUSY production of chargino and neutralinos have been investigated in multi-lepton final states, and the most sensitive analysis posed limits on the mass of these particles up to $\sim 700\,\text{GeV}$. Several searches for long-lived particles have been performed; all the results, consistent with the background expectations, have been interpreted both in RPC and RPV scenarios.

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