Inclusive Searches for Squarks and Gluinos with the ATLAS Experiment at LHC

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Abstract. The ATLAS experiment at LHC has conducted searches for the supersymmetric partners of quarks and gluons in the proton-proton collision data collected in 2012, at a centre-of-mass energy of 8 TeV and with an integrated luminosity of 20.3 fb^{-1}, using various topologies corresponding to different decay modes. No significant excess above SM predictions was observed, and exclusion limits were set on the squark and gluino masses in various scenarios. For light neutralinos, the experimental sensitivity reached gluino masses up to 1.3 TeV, and squark masses up to 850 GeV.

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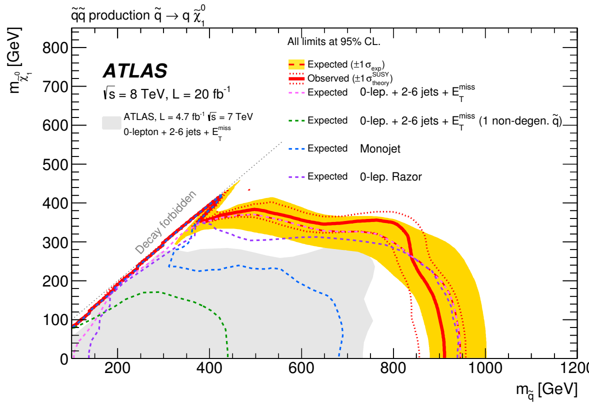
INTRODUCTION

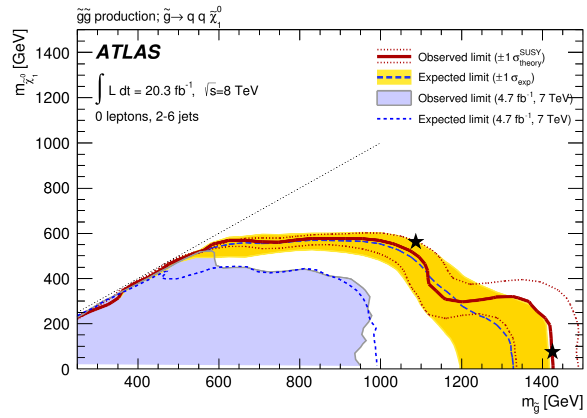
Supersymmetry (SUSY) [1] is one of the most studied frameworks to extend the Standard Model (SM) beyond the electroweak scale. In its minimal realization (MSSM) it predicts a new bosonic (fermionic) partner for each fundamental SM fermion (boson). The partners of the SM quarks and gluons (referred to as squarks and gluinos), that carry SU(3) colour charges, can be pair-produced in proton-proton collisions with sizable cross-sections. Dedicated experimental searches have therefore been conducted at the Large Hadron Collider (LHC) [2] during its first phase of exploitation, at a centre-of-mass energy of 7 then 8 TeV. The ATLAS experiment [3] in particular has extensively searched for squarks and gluinos, and the latest results [4, 5] obtained with the 2012 dataset (integrated luminosity of 20.3 fb^{-1}) are reported in this document.

The results presented here focus on scenarios in which an additional discrete symmetry (R-parity), introduced to prevent large flavour-violating couplings, is preserved in the interactions. The lightest superpartner (LSP) is then stable, and is a viable dark matter candidate. It is generally considered to be either the lightest neutralino[1] $\tilde{\chi}_1^0$ or the gravitino[2] $\tilde{G}$. The squarks or gluinos produced in the hard scattering event decay in cascade up to the LSP, which leads to a final state with energetic jets and large missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$. The latter constitutes the typical minimal signature for squarks and gluinos searches at LHC, which might be completed by other striking features depending on the intermediate particles involved in the decay chain. Several ATLAS searches have thus been conducted targeting different decay modes, mainly distinguished by the multiplicities of charged leptons, b jets or photons. Often, the different experimental signatures provide complementary approaches to probe a particular decay channel. In a recent review of its 8 TeV searches [4], the ATLAS collaboration summarized the current situation in terms of experimental sensitivity to various decay channels, and provided in a few cases a statistical combination of several searches to improve it. In the absence of any significant excess over SM in observed data, exclusion limits were set on the masses of SUSY particles. These constraints are presented here in the context of simplified scenarios in which only gluino (squark) pair production is considered, with a 100% branching ratio assumed for the decay channels of interest; the other SUSY particles not involved in the decay process are assigned arbitrarily large masses.

[1] Neutral mass eigenstates $\tilde{\chi}_{1,2,3,4}^0$ (in increasing mass) of the mixed superpartners of the SM Higgs and electroweak gauge bosons.
[2] Physical state formed by the graviton's superpartner absorbing the Goldstone fermionic degrees of freedom induced by the SUSY breaking.



(a) $\tilde{q}\tilde{q}^*$ production, $\tilde{q} \rightarrow q\tilde{\chi}_1^0$



(b) $\tilde{g}\tilde{g}$ production, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

FIGURE 1. 95% CL$_S$ exclusion limits on four-flavour-degenerate squark-antisquark (a) and gluino-gluino (b) pair production with direct decays into LSP and SM quarks, as a function of the squark (gluino) and LSP masses. Ref. [4].

GENERAL SEARCH STRATEGY

The experimental searches performed by the ATLAS Collavoration follow generally similar strategies for the background estimates and the interpretation of the results. Backgrounds from the main SM processes (W/Z+jets, $t\bar{t}$...) are estimated with the help of control regions enriched in the relevant process, with kinematic requirements close to those employed in the signal regions but with limited signal contamination. Monte-Carlo (MC) simulations are then used to extrapolate the background yields from the control to the signal regions. Rarer SM processes are directly predicted from MC and rely on the best theoretical knowledge of their production cross-section. Experimental backgrounds of various natures are estimated through methods relying on data; these include for example fake $E_{\mathrm{T}}^{\mathrm{miss}}$ from mismeasured jet energy, or misidentified leptons.

Exclusion limits are set by comparing signal prediction to the expected background yields in the signal regions, either in a single bin or by fitting the observed distribution of a discriminant variable; sometimes, orthogonal signal regions are statistically combined to improve sensitivity. Limits are provided as 95% confidence level intervals in the CLs formalism [6], using the HistFitter framework [7] which performs statistical test relying on a profile likelihood ratio [8].

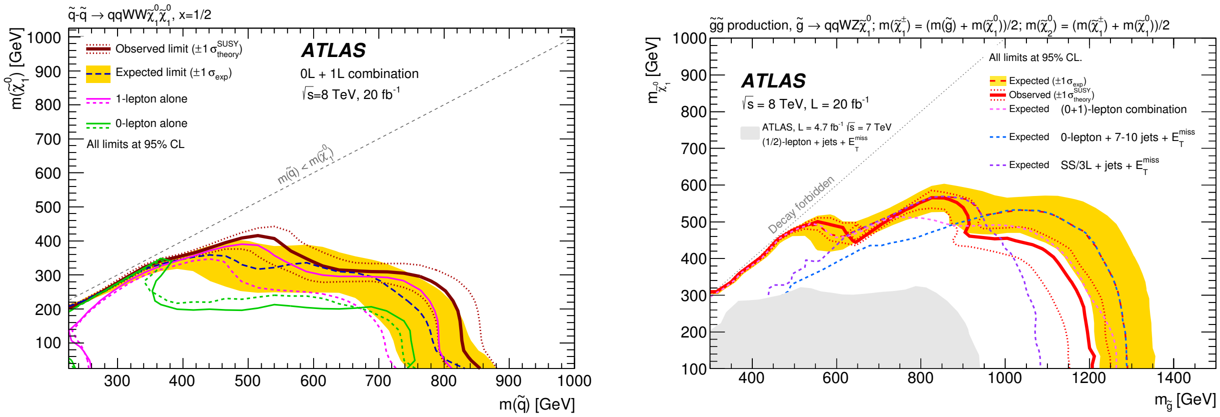
INCLUSIVE SEARCHES

Direct squark and gluino decays to LSP

The most inclusive SUSY search [9] targets direct decays of squarks and gluinos to quarks and LSP, by selecting events with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$, vetoing the presence of identified electrons or muons. The overwhelming QCD background is reduced by stringent requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and the effective mass m_{eff}, the scalar sum of the transverse momentum of selected jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. Seventeen signal regions are defined with varying tightness of the cuts, and are split by the numbers of required jets, which varies from ≥ 2 to ≥ 6.

The exclusion limits set by this search on the squarks and gluino masses as function of the LSP mass can be seen on Fig. 1. In the case of mass-degenerate $\tilde{u}$, $\tilde{d}$, $\tilde{s}$ and $\tilde{c}$ squarks, masses up to 800 GeV are excluded for LSP masses smaller than 300 GeV, while there is little sensitivity for greater LSP masses. For very close squark and LSP masses, the quarks produced in the decay are too soft to seed the reconstruction of jets; this region of the phase space can nevertheless be explored by tagging events in which the pair-produced $\tilde{q}\tilde{q}^*$ recoils significantly against a jet from initial state radiation, leading to a monojet + $E_{\mathrm{T}}^{\mathrm{miss}}$ signature [10]. The reinterpretation of this search to direct squark decays, proposed in Ref. [4] and also shown in Fig. 1, provides a good complement to the inclusive search, allowing to exclude squarks and LSPs of equal mass up to 400 GeV.

Gluino masses up to 1.3 TeV are excluded for a light LSP, the limit reducing to 1.1 TeV for LSP masses of 200



(a) $\tilde{q}\tilde{q}^*$ production, $\tilde{q} \rightarrow q' W \tilde{\chi}_1^0$ via $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$

(b) $\tilde{g}\tilde{g}$ production, $\tilde{g} \rightarrow q\bar{q}' W Z \tilde{\chi}_1^0$ via $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_2^0$

FIGURE 2. 95% CL_S exclusion limits on four-flavour-degenerate squark-antisquark production with $\tilde{\chi}_1^\pm$-mediated decays (a) and gluino-gluino production with a two-step decay (b), as a function of the squark (gluino) and LSP masses. Ref. [4].

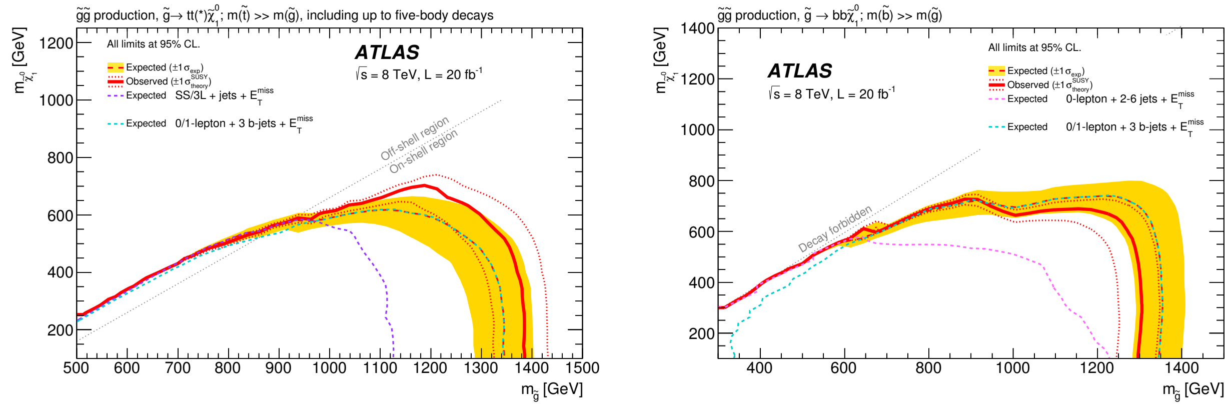
GeV, and with little sensitivity for LSP masses above 500 GeV. The exclusion limit is obtained by choosing in each point of the phase space the most suitable signal region in terms of expected sensitivity. One can for example identify from the shape of the exclusion limit in Fig. 1 a region at $m_{\tilde{g}} > 1.2$ TeV in which the exclusion is driven by a signal region with ≥ 4 jets and tight kinematic requirements, and a region at $m_{\tilde{g}} < 1.1$ TeV which relies on a signal region with ≥ 5 jets and much looser m_{eff} requirements.

Cascade decays, signatures with leptons

More complex cascade decays may occur through the contribution of light neutralinos/ charginos[3], or sleptons, which leads to final states enriched in SM gauge bosons and leptons. The simplest case is a one-step decay through a chargino, $\tilde{q}/\tilde{g} \rightarrow q(q)\tilde{\chi}_1^\pm \rightarrow q(q)W^\pm\tilde{\chi}_1^0$. The sensitivity of the inclusive zero-lepton search to this scenario is complemented by a search requiring at least one electron or muon, together with several jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ [11]. In addition, in the most recent results [4] signal regions identifying the presence of a hadronically decaying W boson (either with a resolved decay into two jets, or through a single jet substructure when significantly boosted) were added to the inclusive search. Figure 2a shows the exclusion limits on the squarks masses in this scenario, as function of the LSP mass. Being statistically orthogonal due to the lepton requirements, the inclusive and one-lepton searches were combined in [4], allowing to exclude squarks masses up to 800 GeV for a light LSP, thus representing a 50 GeV improvement over the performance of either of the analysis considered alone. Overall, the region of the phase space the searches are sensitive to is similar than for direct decays (Fig.1a).

To probe decay channels that lead to larger amount of particles in the final states, several other searches were performed, requiring notably no lepton and $\geq 7-10$ jets [12], or two leptons and jets [11], or at least two leptons of identical charge and jets [13]. The increased rarity of these final states for SM processes allows to relax the tight kinematic requirements imposed in the more inclusive searches. For example, typical $E_{\mathrm{T}}^{\mathrm{miss}}$ requirements are about 500 GeV for the zero-lepton and 300 GeV for the one-lepton searches, but reduced to about 100 and 150 GeV for [12] and [13], the latter even featuring a signal region without any $E_{\mathrm{T}}^{\mathrm{miss}}$ cut. This notably helps improving the sensitivity to SUSY scenarios with compressed mass spectra. Figure 2b shows for example exclusion limits on the gluino mass in the context of a two-step decay $\tilde{g} \rightarrow qq'\tilde{\chi}_1^\pm \rightarrow qq'W^\pm\tilde{\chi}_2^0 \rightarrow qq'W^\pm Z\tilde{\chi}_1^0$. Several of the searches mentioned above are sensitive to this final state, and their complementarity is illustrated by an improvement of the exclusion limit by about 50 GeV on the LSP mass compared to inclusive searches alone. The overall sensitivity is here again similar to the one seen for direct gluino decays (Fig.1b), with gluino masses excluded up to 1150 GeV for a light LSP.

[3] Charged mass eigenstates $\tilde{\chi}_{1,2}^\pm$ (in increasing mass) of the mixed superpartners of the SM Higgs and electroweak gauge bosons.



(a) $\tilde{g}\tilde{g}$ production, $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ (b) $\tilde{g}\tilde{g}$ production, $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$

FIGURE 3. 95% CL$_S$ exclusion limits on gluino-gluino pair production with $\tilde{t}$- (left) or $\tilde{b}$-mediated (right) decays to LSP and a $t\bar{t}$ ($b\bar{b}$) pair, as a function of the gluino and LSP masses. Ref. [4].

More specific discriminant variables

In addition to the searches mentioned so far, which relied on rather simple discriminant variables to build signal regions, other searches used more involved techniques, based on specific characteristics of the considered final states. Beside providing complementarity to the simpler approaches, these techniques could have brought further information about the properties of BSM events, in the case of an observed excess, helping characterize the nature of the underlying process. For example, the Razor variables described in [14] were employed for zero-lepton and two-lepton final states [4, 11], in which they notably replace $E_{\mathrm{T}}^{\mathrm{miss}}$ requirements. The sensitivity of the former to direct squark decays is shown on Fig. 1a, the performance of this search being very similar to the "standard" zero-lepton search relying on $E_{\mathrm{T}}^{\mathrm{miss}}$.

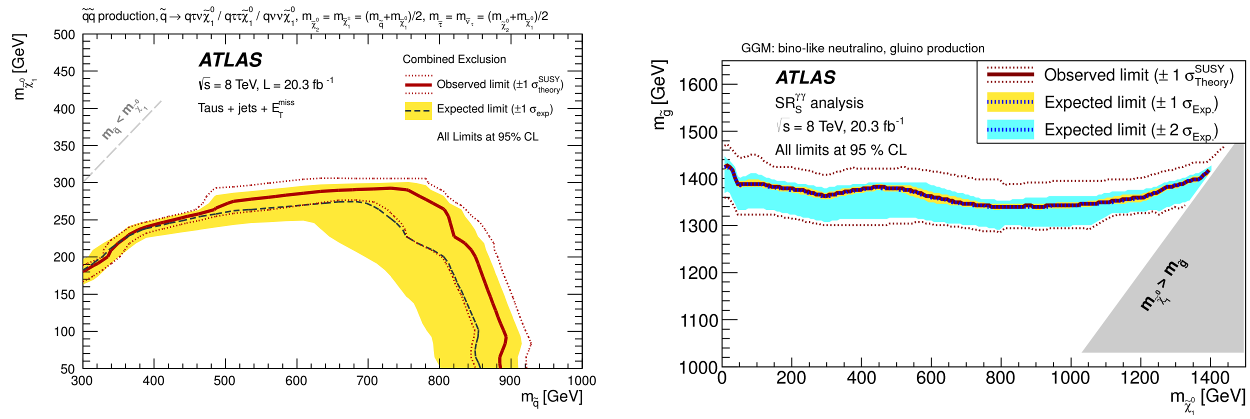
Another search [15] scrutinized the dilepton invariant mass line shape for pairs of opposite-charge electrons or muons, either identifying Z bosons present e.g. in $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \to q\bar{q}Z\tilde{G}$ decays, or looking for non-resonant edges in the lineshape such as those caused by slepton-mediated $\tilde{g} \to q\bar{q}\tilde{\ell}\ell \to q\bar{q}\ell^+\ell^-\tilde{\chi}_1^0$ decays. This search reported the largest deviation with respect to SM among the ATLAS searches for squarks and gluinos, quoting an excess with a significance of three standard deviations in the signal region selecting events with on-shell $Z \to \ell\ell$.

Finally, exclusive production of charm squarks with direct decays $\tilde{c} \to c\tilde{\chi}_1^0$ has been looked for in Ref. [16] through the tagging of c-quark jets, leading to excluded charm squark masses below 500 GeV for a light LSP, a performance similar to the one obtained for generic squark searches (Fig.1a).

FINAL STATES WITH B JETS, TAU LEPTONS OR PHOTONS

The decay chains presented so far were rather generic in terms of the flavour of the (s)quarks and (s)leptons involved in the intermediate and final states. However, in many SUSY models, third generation sleptons and squarks can play an enhanced role in the decay chains, because of their lighter masses. For example, even if one assumes flavour unification at large energy scales, the large Yukawa couplings of the t, b quarks and τ leptons compared to the first two fermion generations can lead to lighter top, bottom squarks or tau sleptons [1] through increased contributions to the running masses in the renormalization group equations, as well as a larger induced mixing of the superpartners of the left- and right-handed chiral degrees of freedom. This can lead to signatures often containing t or b quarks, or taus.

Most of the decay chains also assume SUGRA-like scenarios, in which the LSP is the lightest neutralino. But in gauge-mediated SUSY breaking scenarios, the LSP is instead the gravitino, enforcing e.g. signatures with photons or taus if the next-to-LSP (NLSP) is a bino-like neutralino ($\tilde{\chi}_1^0 \to \gamma\tilde{G}$) or a stau ($\tilde{\tau} \to \tau\tilde{G}$).



(a) $\tilde{q}\tilde{q}^*$ production, $\tilde{q} \to q'\tau\nu\tilde{\chi}_1^0$ / $q\tau\tau\tilde{\chi}_1^0$ / $q\nu\nu\tilde{\chi}_1^0$ (b) $\tilde{g}\tilde{g}$ production, $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \to q\bar{q}\gamma\tilde{G}$

FIGURE 4. 95% CL$_S$ exclusion limits on quark-antisquark production with $\tilde{\tau}$-mediated decay to LSP (left), and gluino-gluino production in a GGM scenario with a $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ decay (right), as a function of the gluino and neutralino masses. Refs. [4, 5].

Final states with b jets

Light top squarks are further favored by constraints enforced by the resolution of the SM hierarchy problem in the frame of SUSY models, which require their masses not to exceed the TeV scale. Masses of bottom squarks are also limited to some extent, being related to top squarks through $SU(2)$ invariance. While the direct production of third generation squarks is the subject of dedicated ATLAS searches [17], gluino decays mediated by top or bottom squarks, such as $\tilde{g} \to t\bar{t}\chi_1^0$ or $\tilde{g} \to b\bar{b}\chi_1^0$, might also be significantly enhanced. Such decays lead to peculiar final states with four bottom or top quarks.

A search was performed [18] to specifically target these final states, selecting events with at least three b-tagged jets. Figure 3 shows exclusion limits on the gluino mass as function of the LSP mass in the two decay scenarios mentioned previously. Gluino masses up to 1.3 TeV are excluded, similarly to the case of decays into light flavour quarks (Fig. 1b). However, thanks to the lower SM background for b-enriched final states, the sensitivity to regions of the phase space with large LSP masses is significantly improved, allowing exclusion for LSP masses up to 600 GeV.

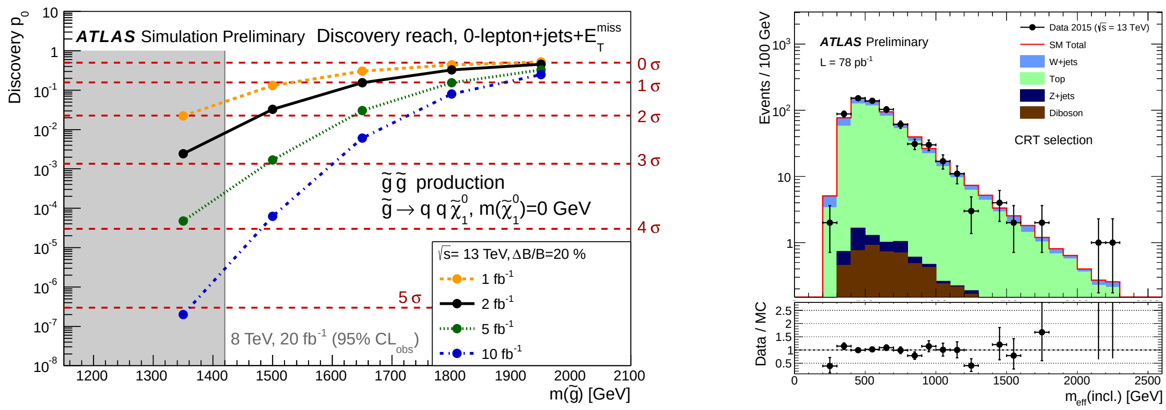
Final states with tau leptons

The largely increased rates of tau leptons with respect to electrons or muons in final states associated to scenarios with a tau slepton as NLSP lead to a dedicate search [19], which selected for events with at least one tau, jets and E_T^{miss}, and further categorized them as function of the number of taus and other light leptons. A reinterpretation of the analysis results was proposed recently in Ref. [4], in the context of squarks or gluino decays to a neutralino LSP via tau sleptons, $\tilde{q} \to q(\tilde{\chi}_1^{\pm}|\tilde{\chi}_2^0)$ with $\tilde{\chi}_1^{\pm} \to (\tilde{\tau}\nu|\tau\tilde{\nu})\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to (\tilde{\tau}\tilde{\tau}|\tilde{\nu}\tilde{\nu})\tilde{\chi}_1^0$, leading to final states with up to four taus. The corresponding exclusion limits on the gluino mass is shown on Fig. 4a, reaching here again 850 GeV for a light LSP.

Final states with photons

Searches with photons and jets in the final state [5] are mainly motivated by the presence of a $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ decay within the squark or gluino decay, which occurs in gauge-mediated SUSY breaking scenarios. Events with at least one photon are selected, and are categorized depending on the presence of additional features (another photon, lepton, b-tagged jet), with additional requirements on E_T^{miss} varying from 100 to 300 GeV.

Figure 4b shows the exclusion limits on the gluino mass in the simplest scenario, with a direct decay $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ which relies on a signal region built from events with at least two photons and jets. In that case, gluino masses up to 1.3 Tev are excluded, independently of the neutralino mass which this time acts only as an intermediate state in the decay chain. Other signal regions requiring leptons or b-tagged jets allow to probe scenarios with concurrent decay channels, for example $\tilde{\chi}_1^0 \to h\tilde{G}$ with $h \to b\bar{b}$, or $\tilde{\chi}_1^0 \to Z\tilde{G}$ with $Z \to \ell\ell$. Exclusion limits are provided in Ref. [5] on minimal gauge-mediated models that feature such decays, which also lead to exclude gluino masses below O(1 TeV).



(a) (b)

FIGURE 5. Projection at $\sqrt{s}$ = 13 Tev of the sensitivity to gluino pair production (a), and first 2015 data / Monte-Carlo comparisons (b), for the inclusive search with zero lepton, jets and E_T^{miss}. Refs. [20, 21].

CONCLUSION

The ATLAS experiment has conducted several searches for squarks and gluinos using various topologies corresponding to different decay modes, that included final states requiring leptons, *b*-tagged jets, taus or photons. No significant excess above SM predictions was observed, and exclusion limits were set on the squark and gluino masses in various scenarios. For light neutralinos, the experimental sensitivity reached gluino masses up to 1.3 TeV, and squark masses up to 900 GeV. In general, the constraints are not varying much with the decay mode, except for heavy LSPs where particular topologies with low expected SM background can lead to an improvement of the sensitivity.

The focus is now set on the second phase of exploitation of the LHC at an increased center-of-mass energy of 13 TeV and a higher integrated luminosity, for which a large improvement in sensitivity to gluino and squarks production is foreseen (Fig. 5a).

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