PROCEEDINGS OF SCIENCE

Searches for Supersymmetry

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Searches for supersymmetry are a key element of the research programme at the Large Hadron Collider at CERN. The ATLAS and CMS collaborations have performed a large set of direct searches for supersymmetry using proton-proton collision data at centre-of-mass energies ranging from 7 to 13 TeV. In this document we present a selection of these analyses, giving emphasis to the results obtained at $\sqrt{s} = 13$ TeV and, more specifically, based on data recorded in the first part of 2016.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

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PoS(ICHEP2016)017

1. Introduction

Searches for physics beyond the standard model (SM) constitute a key element of the physics programme at CERN's Large Hadron Collider (LHC). One of the most promising and extensively studied extensions of the SM is supersymmetry (SUSY) [1–8]. It predicts a symmetry between fermionic and bosonic degrees of freedom and has the potential to resolve several shortcomings of the SM, such as the hierarchy problem and the lack of a dark matter candidate. During LHC Run I a multitude of searches for the production of supersymmetric partners (sparticles) of the SM particles have been performed by the ATLAS [9] and CMS [10] collaborations at proton-proton centre-of-mass energies of 7–8 TeV, documented in almost 200 publications. The increase of the energy in Run II to $\sqrt{s} = 13$ TeV has lead to a substantial increase in sensitivity, in particular for the highest masses probed: for a gluino (top squark) mass of 1.5 TeV (1 TeV) the cross section for pair production of these sparticles increased by factors of ≈ 35 (14). As a consequence, the mass reach for the corresponding searches was substantially extended after the analysis of data taken in 2015. However, this was not true for all models since the integrated luminosity recorded in 2015 was only about 1/10 of the one of Run I.

This situation changed in 2016, with a dataset available for analysis at the time of ICHEP of about four times the 2015 one. In this contribution, some highlights of the searches for SUSY are presented, based on this first part of the 2016 run, in some cases combined with 2015 data. These searches cover a wide range of event topologies: purely hadronic or single-lepton final states, and events with two or more leptons in different charge and flavour combinations. Most of the searches target R-parity [11] conserving (RPC) SUSY models with the lightest neutralino ($\widetilde{\chi}_1^0$) taking the role of the lightest supersymmetric particle. Under this assumption, missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) or other quantities related to it provide a strong discrimination against SM backgrounds. The transverse mass (M_{T}) between the missing momentum vector and leptons or b jets, and different estimators of particle masses in events with two decay branches, each of them ending with the production of a weakly interacting particle, are used to distinguish SUSY signal events from SM production of W bosons and top quark pairs. Other event variables are derived according to the razor [12] or the "recursive jigsaw reconstruction" (RJR) [13] approach. Finally, with searches probing ever higher mass scales, jet substructure techniques are becoming increasingly important in the identification of events with merged hadronic decay products from highly boosted objects.

Since no significant deviations from the estimated SM background are found the results are interpreted as limits in the parameter space of a variety of models. All search results shown in this contribution are interpreted within the framework of simplified model spectra. In particular this implies that cross section limits are derived assuming 100% branching fraction for the chosen decay channel. Cross section limits are then converted into mass limits based on nominal SUSY production cross sections computed at the highest accuracy available, typically next-to-leading order (NLO) + next-to-leading-logarithm (NLL).

Searches for RPC SUSY are presented in Sections 2 and 3 for the cases of pair production of strongly interacting sparticles and charginos/neutralinos, respectively. Results from selected searches for R-parity violating (RPV) SUSY and for models inspired by gauge-mediated symmetry breaking (GMSB, see [14] for a review) are described in Section 4. Finally, conclusions are drawn in Section 5.

2. Searches for Strong Production of Supersymmetric Particles

Based on the full dataset of LHC Run I, searches for pair production of gluinos or top squarks have probed masses up to about 1400 and 750 GeV, respectively. At these masses, the increase of the production cross section due to the change of centre-of-mass energy is substantial, with factors of the order of 10, making these searches one of the priorities for Run II analyses. In this section a few examples of searches for strong production of gluinos and squarks based on parts of the 2016 dataset are shown.

Gluinos have been searched for in their decay via virtual squarks to pairs of quarks and either the LSP, or a further cascade involving charginos. These processes would lead to spectacular final states with high jet multiplicities, in particular in the case of decays to top quarks. The ATLAS Collaboration has searched for gluino decays to light quarks with two strategies, either based on M_{eff}, the scalar sum of the transverse momenta of jets and leptons, and the missing transverse energy, or on the "recursive jigsaw reconstruction" (RJR) approach [15]. The latter starts with the assumption of a specific decay tree. It resolves combinatorics and ambiguities due to the presence of several undetected particles based on a set of rules and allows the determination of scale-sensitive and unit-less variables in the rest frames of each level of the decay tree. Fig. 1(left) shows limits at 95% confidence level (CL) in the LSP vs. gluino mass plane under the assumptions of the simplified model. Gluino masses below 1.86 TeV are excluded — a substantial gain w.r.t. the results obtained using the 2015 dataset. Other analyses targeting the same final state are described in Refs. [16, 17].

The decay mode to two b quarks and the LSP is targeted by a search for events with purely hadronic final states [18] (see Refs. [16, 17, 19] for other results for the same model). The basic selection requires at least 4 jets, with at least 3 jets identified as originating from a b quark (b jets). Signal regions are defined in terms of the number of b jets, $E_{\text{T}}^{\text{miss}}$, the minimal M_{T} calculated from the transverse momenta of a b jet and the missing momentum vector, and the mass of large-radius jets, clustered with the anti-k_T algorithm [20] with a size parameter $R = 0.8$ using small-radius ($R = 0.4$) jets. For vanishing LSP mass, the 95% CL limit on the gluino mass extends to approximately 1.9 TeV as shown in Fig. 1(right).

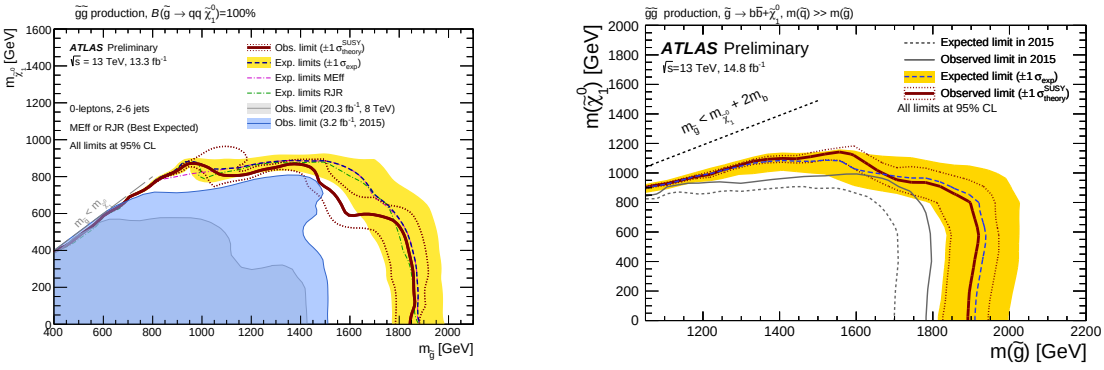

Figure 1: Left: Results of the search for gluino pair production with decays to a pair of light quarks and the LSP [15] in terms of mass limits at 95% CL in the plane of LSP vs. gluino mass. For each point in the plane, the more sensitive of the two approaches (M_{eff} or RJR) is chosen. Right: Results of the search for gluino pair production with decays to a pair of b quarks and the LSP [18] in the same mass plane.

The analogous decay via t quarks offers a richer phenomenology: depending on the decay modes of the intermediate W boson searches can be performed using the hadronic, single-lepton, dilepton, or multilepton final state. An example of a search in the hadronic final state is the analysis described in Ref. [17]. The main discriminating variable used in this search is the stransverse mass M_{T2}. The cross section and mass limits obtained from this search for the case of gluino decays to t quarks and the LSP are shown in Fig. 2(left). The right panel of the same figure shows the results of an analysis by the ATLAS Collaboration that focuses on events with high b-jet multiplicity [18]. Other ATLAS and CMS analyses relevant for this model are described in Refs. [16, 19, 21–25].

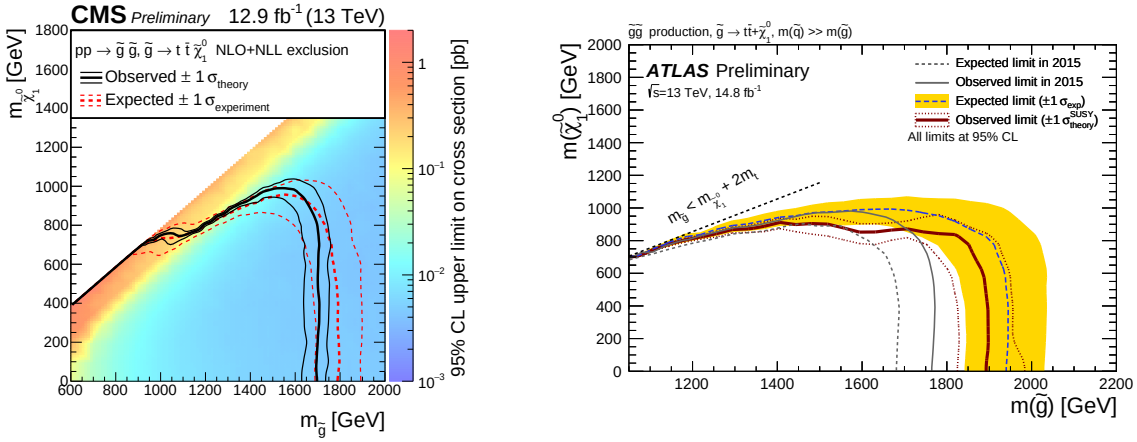

Figure 2: Limits for a model of gluino pair production with subsequent gluino decay to a pair of t quarks and the LSP for two searches using hadronic final states. Left: Cross section and mass limits at 95% CL from an inclusive search with the M_{T2} variable [17]. Right: Mass limits at 95% CL from a search in events with $E_{\mathrm{T}}^{\mathrm{miss}}$ and high b-jet multiplicity [18].

If the lightest chargino is lighter than the gluino, the latter can decay to two light quarks and a chargino that in turn decays to a W boson and the LSP. This scenario can been searched for in leptonic final states. In Fig. 3 the results of two analyses performed by the CMS Collaboration are shown that select events with a single lepton [22] and two leptons of the same charge [23], respectively. The single-lepton search uses the azimuthal angle between the lepton and the W boson candidate, constructed from the lepton momentum and the missing momentum vectors, as a discriminating variable. The same-sign dilepton search uses the fact that same-sign charginos can be produced in the decay of the pair of gluinos. Standard model backgrounds in this topology are small and typically dominated by contributions from leptons that do not stem from the decay of a vector boson, and rare SM processes. In a model where the mass of the chargino is midway between the gluino and LSP mass, the single-lepton search probes gluino masses up to approximately 1.6 TeV. The reach of the same-sign dilepton search is lower in terms of gluino mass, but it keeps better sensitivity when approaching the compressed region with small mass splittings between the sparticles. This is illustrated in a scenario where the mass difference between the chargino and the LSP is fixed to 20 GeV. Other searches covering this model are described in Refs. [15, 16, 24, 26].

A second set of searches targets production of squark pairs. Here the production cross sections are smaller (depending on assumptions on the mass hierarchy in the squark sector), and final states

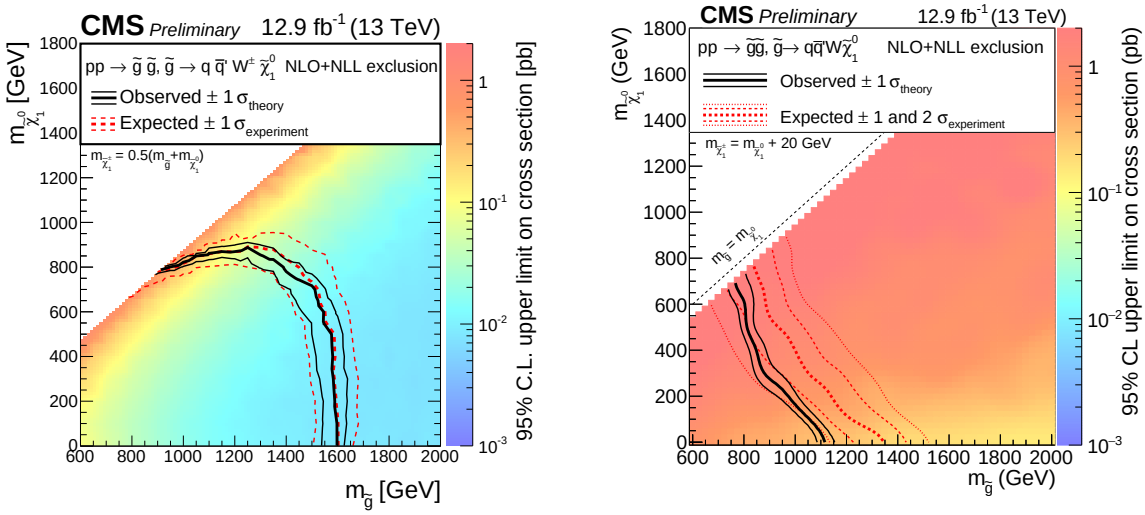

Figure 3: Left: Mass limits at 95% CL obtained using a single-lepton search [22] in a model of gluino pair production with gluino decays to two light quarks and a chargino with a mass midway between the gluino and LSP masses. Right: Mass limits at 95% CL obtained using a same-sign dilepton search [23] under the same assumptions for production and decay, but with a fixed mass difference between chargino and LSP of 20 GeV.

show typically lower jet multiplicities. As a consequence, the mass reach of previous searches was smaller compared to the case of gluino pair production.

Searches for direct top squark pair production receive special interest, as a sparticle spectrum with light top squarks could be one of the features of natural SUSY models. Assuming all other sparticles to be decoupled, and depending on the mass difference to the LSP (ΔM), top squarks could decay via a two-body decay to $t\widetilde{\chi}_1^0$, a three-body decay to $Wb\widetilde{\chi}_1^0$, a four-body decay to $f\bar{f}'b\widetilde{\chi}_1^0$, or a flavour-violating decay to $c\widetilde{\chi}_1^0$. An example for a CMS search for top squark pair production in the purely hadronic final state is described in Ref. [27]. Different selections are optimized for the case of low and high ΔM. In the latter case, jet substructure techniques are used on jets clustered with the anti-k_T algorithm and a size parameter of $R = 0.8$, and then reclustered with the Cambridge-Aachen algorithm, in order to cover the case where the decay products of highly boosted W bosons or t quarks overlap.

Searches for top squark pair production in the single-lepton and opposite charge dilepton channel by the ATLAS collaboration are reported in Refs. [28] and [29], respectively. Both searches use sets of optimized variables, including different variants of transverse masses, quantities relevant for the identification of top quark decay products at low and high p_{T}, and super-razor variables. For the two-body decay channel $\widetilde{t} \to t\widetilde{\chi}_1^0$, the single-lepton analysis sets limits on the $\widetilde{t}$ mass at 95% CL up to 830 GeV as shown in Fig. 4(left). The dilepton search is used to set limits for the case of three-body decays to $bW\widetilde{\chi}_1^0$, excluding masses up to 365 GeV. Top squark pair production at moderate to high ΔM is also covered by the searches described in Refs. [25, 30], as well as inclusive analyses as the ones described in the first part of this section.

While mass limits for the case of high mass differences between the lightest top squark and the

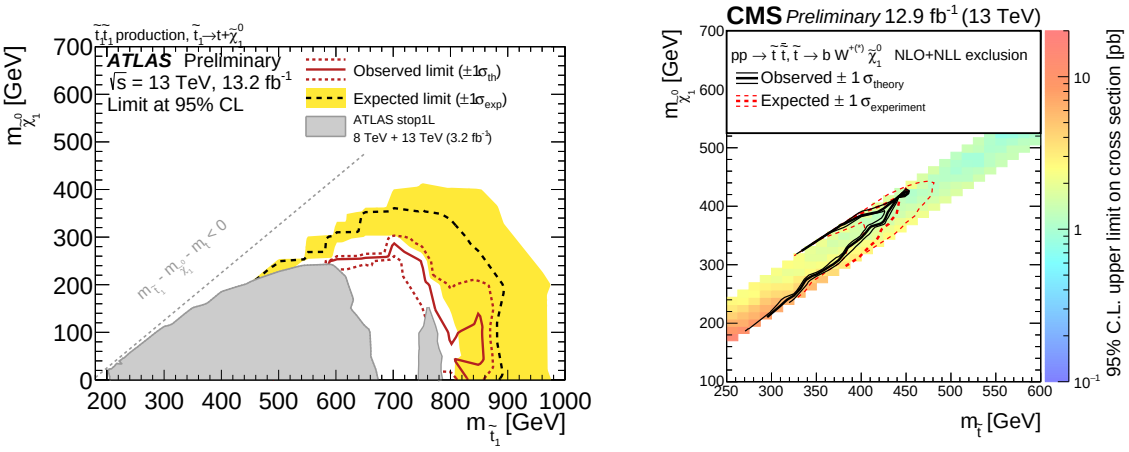

Figure 4: Results of searches for top squark pair production. Left: Mass limits at 95% CL in the LSP vs. $\tilde{t}$ mass plane from a search in the single-lepton channel [28] for decays to $t\tilde{\chi}_1^0$. Left: Limits at 95% CL on production cross sections and masses for $\Delta M < 80\,\text{GeV}$, using the hadronic final state and assuming four-body decays [27].

LSP reach up to 800–900 GeV, the sensitivity for compressed spectra is much lower. In particular for the case $\Delta M < 80\,\text{GeV}$ the acceptance of standard selections is low due to the low momenta of the decay products. Several approaches are exploited to cover this region. The presence of high-momentum jets from initial state radiation and the related boost of the top squark pair can be used as, e.g., demonstrated by the analysis mentioned above [27] for the hadronic final state, or a search for events with low-momentum, oppositely charge lepton pairs [31]. Under the assumption of a four-body decay of the top squark, 95% CL limits on $M(\tilde{t})$ set by these analyses reach up to 350–450 GeV, with the example of a search in the hadronic final state shown in Fig. 4(right). Alternatively, the lightest top squark can be searched for in cascade decays of other sparticles, such as the gluino, in a final state with two highly boosted top quarks and $E_{\text{T}}^{\text{miss}}$ [30], or the heavier top squark, in a multilepton search under the assumption of a decay $\tilde{t}_2 \to Z\tilde{t}_1$ [32]. In the latter case, and for $\Delta M(\tilde{t}_1, \tilde{\chi}_1^0) = 180\,\text{GeV}$, the mass limits for $\tilde{t}_2$ reach 730 GeV.

3. Searches for Electroweak Production of Charginos and Neutralinos

The cross sections for the direct production of charginos and neutralinos are several orders of magnitude smaller than for the pair production of gluinos or squarks. In addition, for the mass range probed by Run I searches, the gain in cross section due to the increase of the centre-of-mass energy in Run II is smaller than at the limit of sensitivity for strongly produced sparticles. For these reasons, Run II searches start only now to be sensitive to these processes.

If sleptons can be produced in the decays of $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$, the production of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pairs can give rise to events with high lepton multiplicity and low hadronic activity, a topology with low SM backgrounds. A search for events with 3 or 4 leptons, including categories with one or two hadronically decaying tau leptons, has been performed by the CMS Collaboration [33]. In this analysis, signal regions are defined in terms of the flavour and charge combination, $E_{\text{T}}^{\text{miss}}$, and

the ratio of dilepton mass and p_{T}. The sensitivity of the analysis depends on the mass difference between $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$ (assumed to be mass degenerate), the intermediate slepton, and the LSP. If the slepton mass is close to the LSP mass the lepton multiplicity within the acceptance decreases. In this case sensitivity can be recovered by adding a selection of same-sign dilepton events. Results for two scenarios, with the slepton mass either midway between the $M(\widetilde{\chi}_1^{\pm})$ and $M(\widetilde{\chi}_1^0)$, or close to the mass of the LSP ($\Delta M(\widetilde{\ell}, \widetilde{\chi}_1^0) = 0.05 \cdot \Delta M(\widetilde{\chi}_1^{\pm}, \widetilde{\chi}_1^0)$) are shown in Fig. 5.

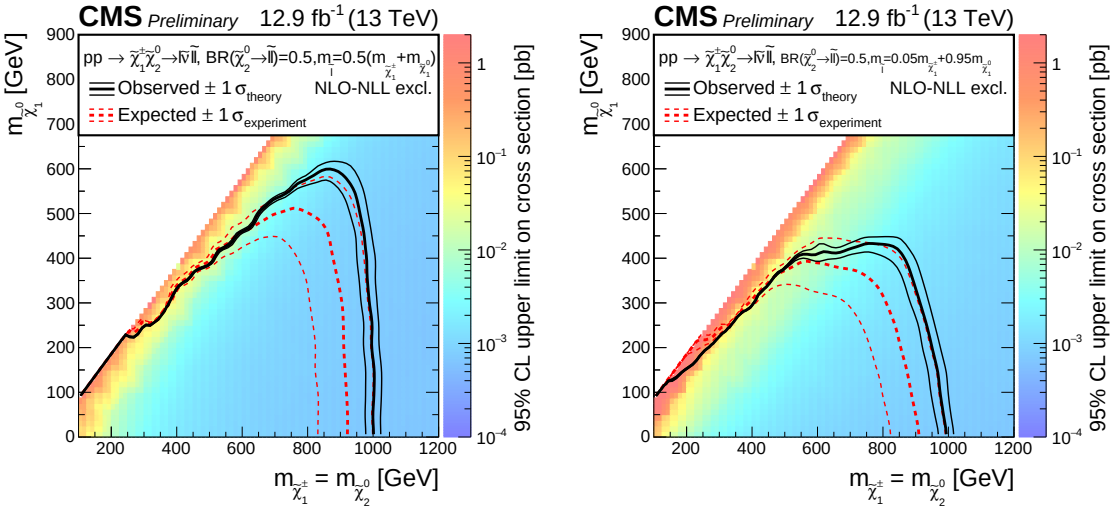

Figure 5: Cross section and mass limits at 95% CL from a search for the production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ pairs [33]. Equal probability of the decays to all three lepton flavours is assumed. Left: Results of the search in final states with three leptons for a slepton mass midway between the common $\widetilde{\chi}_1^{\pm}$-$\widetilde{\chi}_2^0$ mass and the LSP mass. Right: Results of the combination of the three-lepton and the opposite-charge dilepton topologies for small mass differences between $\widetilde{\ell}$ and $\widetilde{\chi}_1^0$.

Mass spectra with small mass splittings between $\widetilde{\chi}_1^{\pm}/\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$ have received special interest since they would also occur in the case when these lightest chargino and neutralino states are mainly higgsinos, as favoured in scenarios of natural SUSY. A specific search in the opposite-charge dilepton channel by the CMS Collaboration is described in Ref. [31]. In this analysis, at least one high-momentum jet associated with initial state radiation is required, and the acceptance for leptons is extended down to transverse momenta of 3.5–5 GeV. Based on the production cross section for wino-like $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$ states with decays via W and Z bosons, respectively, 95% CL limits on their common mass up to 195 GeV are obtained. Other results for electroweak production of supersymmetric particles are derived from the searches described in Refs. [34, 35].

4. Searches in Supersymmetry with Gauge-Mediated Symmetry Breaking or R-Parity Violation

In models motivated by gauge-mediated SUSY breaking, sparticle decay chains terminate with the almost massless gravitino. In these models the lighest neutralino — typically the next-to-lightest SUSY particle (NLSP) — decays to the gravitino and a Z boson or a photon, leading to characteristic photon + $E_{\mathrm{T}}^{\mathrm{miss}}$ final states. A search by the ATLAS Collaboration investigated final

states with at least one photon, high $E_{\mathrm{T}}^{\mathrm{miss}}$, and jets. The results of this analysis are interpreted in a model of gluino pair production, with gluino decays to a pair of light quarks and the NLSP. Depending on the mass splitting between the gluino and the NLSP, 95% CL limits on the gluino mass reach up to 2 TeV. A search for pairs of opposite-charge leptons with a mass compatible with $M(Z)$ has been performed by the CMS Collaboration and is interpreted in the same model under the assumption of a 100% branching fraction for $\widetilde{\chi}_1^0 \to Z\widetilde{G}$ [34]. An ATLAS search for top squark pair production in a GMSB model motivated by natural gauge mediation [36], with a tau slepton NLSP and decays $\widetilde{t} \to b\nu\widetilde{\tau}$ and $\widetilde{\tau} \to \tau\widetilde{G}$, is described in Ref. [37].

Supersymmetric models with R-parity violation include lepton-number violating couplings λ_{ijk} and λ'_{ijk}, and baryon-number violating couplings λ''_{ijk}, where the indices refer to generations. Strong constraints exist on these couplings from measurements of nucleon stability, and the scenarios discussed below allow only one of λ, λ' or λ'' to be different from zero. Releasing the constraint of R-parity conservation leads to dramatically different signal event topologies. In particular, the events are not expected to show high values of $E_{\mathrm{T}}^{\mathrm{miss}}$, which is one of the most powerful tools for discrimination of SM backgrounds in RPC SUSY searches.

The ATLAS collaboration has conducted a series of searches targeting models of gluino pair production, with the final decay in the chain proceeding via a non-vanishing λ'' coupling. A search in multijet events [38] is interpreted for the case of gluino decays to three quarks, with equal probability for all possible λ'' flavour combinations. In the analysis, the multiplicity of large $R = 1$ jets and the scalar sum of the leading four of these jets are used as main discriminating variables. In this model, gluino masses below 1080 GeV are excluded at 95% CL as shown in Fig. 6(left). A CMS search based on data taken in 2015 [39] reaches a similar sensitivity for the same model, but in this case gluino decays are assumed to yield only t, b, and s quark combinations. The ATLAS multijet RPV search is also interpreted in a model with a cascade decay via an intermediate $\widetilde{\chi}_1^0$, leading to final states with 10 quarks. In this case the 95% CL mass limits depend also on the neutralino mass and extend up to 1550 GeV.

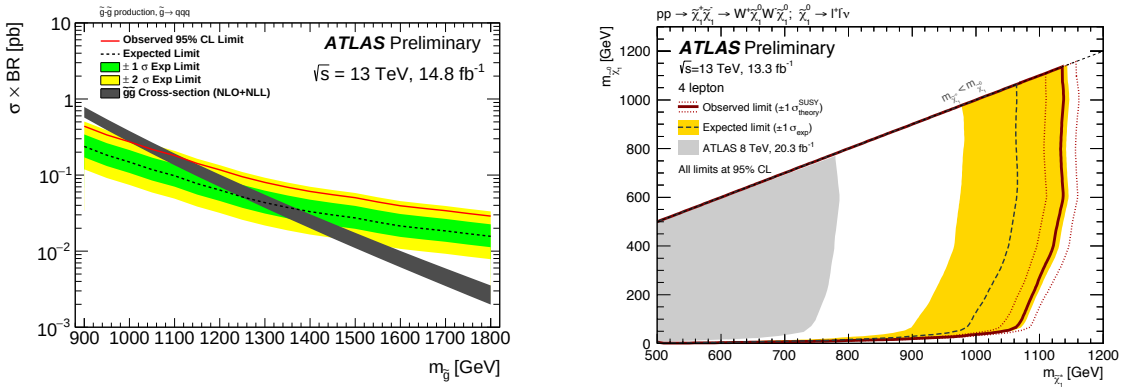

Figure 6: Left: Cross section limit at 95% CL as a function of the gluino mass for gluino pair production in an RPV model with subsequent direct gluino decays to three quarks [38]. Right:.Mass limits at 95% CL in the neutralino vs. chargino mass plane from a search for production of chargino pairs in an RPV model with leptonic $\widetilde{\chi}_1^0$ decays [40].

A search has also been conducted for electroweak production of charginos [40], where the

charginos would decay to $W\widetilde{\chi}_1^0$, with a subsequent decay of the $\widetilde{\chi}_1^0$ to $\ell\ell\nu$ via an RPV λ_{12k} coupling, with $k = 1, 2$. The analysis selects four-lepton events, with signal regions with different M_{eff} requirements. The results of this search are interpreted as limits in the neutralino vs. chargino mass plane as shown in Fig. 6(right). Other results for RPV models are described in Ref. [41].

5. Conclusions

Proton-proton collision data at $\sqrt{s} = 13\,\text{TeV}$ recorded by the ATLAS and CMS collaborations in the first half of 2016 correspond to an integrated luminosity of about $13\,\text{fb}^{-1}$ for each of the experiments or about four times the integrated luminosity obtained in the first year of LHC Run II. This substantial increase in the dataset allowed a significant extension in the sensitivity for searches for supersymmetry. These searches have been designed and optimized for a wide range of SUSY models. In all analyses, the observed yields in the signal regions are found to be compatible with expectations from standard model processes.

For *R*-parity conserving SUSY models, and with the $\widetilde{\chi}_1^0$ as LSP, models of gluino and squark pair production are investigated. Within the context of the simplified models used for interpretation, mass limits at 95% CL reach as high as 1900, 900, and 1400 GeV for gluinos, top squarks, and mass-degenerate first or second generation squarks, respectively. Scenarios with compressed mass spectra, with mass differences between the top squark and the LSP below $M(t)$ or $M(W)$, have also been searched for, either in decay chains of other sparticles, or by focussing on events with hard initial state radiation. Here the mass limits for the lightest top squark reach up to about 450 GeV.

The large dataset recorded in the first part of 2016 has allowed to address electroweak production modes for the first time in Run II. Limits are set for the production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ pairs under different assumptions for their decay modes. Depending on these assumptions, 95% CL mass limits reach up to approximately 1 TeV. Compressed mass spectra have also been investigated for this production mode, again using the presence of jets from initial state radiation and extending the acceptance to low lepton transverse momenta. The data expected in the remaining part of 2016 and in the following years will allow an extension of the sensitivity of existing searches and a broadening of the SUSY search programme in the near future.

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