Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics B Proceedings Supplement 00 (2014) 1–??
Nuclear Physics B Proceedings Supplement

Searches for supersymmetry in resonance production and R-parity violating prompt signatures with the ATLAS and CMS detectors

Roger Caminal Armadans[a]

[a] Institut de Física d'Altes Energies (IFAE) - Universitat Autònoma de Barcelona, Campus UAB, Edifici Cn, E-08193 Bellaterra, Barcelona, Spain

Abstract

In R-parity violating supersymmetric scenarios sparticles can be produced individually or in pairs with rates that are detectable at the LHC. Recent results from searches for resonant production and R-parity violating prompt signatures in multi-lepton and multi-jet final states in the data sample recorded by the ATLAS and CMS detectors are presented. New exclusion limits are obtained on the existence of different R-parity violating scenarios.

Keywords: ATLAS, CMS, SUSY, Exotics, RPV

1. Introduction

Supersymmetry (SUSY) [1, 2] is a space-time symmetry that postulates the existence of new SUSY particles, called "sparticles", that differ by one-half unit with respect to their Standard Model (SM) partners. It provides a solution of the hierarchy problem and a mechanism for unifying particle interactions. Assigning R-parity as $R_p = (-1)^{3B+L+2s}$, where B and L are the baryon and lepton numbers, and s is the particle spin, all the SM particles have $R_p = +1$ while all the superpartner fields have $R_p = -1$. In models where R_p is conserved, superpartners can only be produced in pairs in a collider, and the lightest supersymmetric particle (LSP) is stable and a candidate for a dark matter particle. In addition, R_p conservation ensures proton stability.

However, models with R-parity-violating (RPV) interactions conserving either B or L in addition to s can avoid direct contradiction with the proton-lifetime upper limits [3]. The most general gauge-invariant and renormalizable superpotential consists of the R-parity conserving (RPC) main part, and may also contain extra RPV terms:

$$W_{\text{RPV}} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k, \quad (1)$$

where i, j and k are generation indices, L and Q are the lepton and quark $SU(2)_L$ doublet superfields and $\bar{E}$, $\bar{D}$ and $\bar{U}$ are the charged lepton, down-like quark and up-like quark $SU(2)_L$ singlet superfields. The first, second and third terms violate lepton-number conservation, while the fourth term violates baryon-number conservation. The analysis presented in this proceeding consider R-parity violating interactions in order to probe the different RPV λ_{ijk}, λ'_{ijk} and λ''_{ijk} trilinear couplings introduced in Eq. 1.

2. Lepton number violation models

This section presents analyses aiming to probe different lepton number violating models, i.e. models for which any of the second or the third terms in Eq. 1 are different from zero.

2.1. Multi-lepton searches

These searches are performed by the ATLAS [4] and CMS [5] experiments, using 20.3 fb^{-1} and 19.5 fb^{-1} of integrated luminosity, respectively, at a center of mass energy of $\sqrt{s} = 8\,\text{TeV}$ [6, 7]. If the RPV couplings are small, the dynamics of SUSY production is driven by the RPC part. The cascade decays of SUSY particles in the event are also driven by the R-parity conserving part, until a pair of LSPs remains in the end. The RPV component then determines the decay of the LSP into non-SUSY particles. In the RPV simplified models used in these analyses, a bino-like $\tilde{\chi}_1^0$ (considered the LSP) is assumed to decay into two charged leptons and a neutrino via the λ_{ijk} term in Eq. 1. Different event topologies are tested, resulting from different choices of the next-to-lightest SUSY particles (NLSPs): a chargino NSLP, slepton NLSPs, sneutrino NSLPs, gluino NLSPs and squark NLSPs.

RPV decays via the λ_{ijk} couplings give rise to high lepton multiplicities and substantial $E_{\mathrm{T}}^{\mathrm{miss}}$ due to the presence of neutrinos. For this reason, in the analysis performed by ATLAS the signal regions require four or more leptons, and are classified depending on the number of light leptons required. A Z boson veto is also required to optimize them for RPV searches. On the other hand, the CMS signal regions are required to have exactly four isolated leptons, containing at least one opposite sign, same flavor (OSSF) lepton pair. Furthermore, conditions applied to the invariant masses of the pair of leptons are used to define the regions where the signal is enhanced.

The irreducible background in both analyses is composed of those processes containing four prompt leptons, and it is estimated using Monte-Carlo (MC), normalized to the cross sections of such processes. The reducible background is composed of those processes containing one or more "fake" leptons, either from semileptonic b or c decays, photon conversions, or jet misidentifications. For these processes data-driven methods specified in detail in Refs. [6, 7] are used for their estimation.

After careful study of the systematic uncertainties in each signal regions, the agreement between the data and the MC simulation of the SM processes can be translated to exclusion contours in terms of the NLSP mass versus the LSP mass for the different models considered. As an example, Figure 1 shows the observed and expected 95% CL exclusion limit contours for the RPV gluino NLSP simplified model. Exclusions for the other models considered can be found in the Ref. [6].

The exclusion contours show strongest constraints for the $\lambda_{121} \neq 0$ and $\lambda_{122} \neq 0$ cases, while for the tau-righ decays via λ_{133} and λ_{233} the limits are less stringent. The limits are in many cases nearly insensitive to the $\tilde{\chi}_1^0$

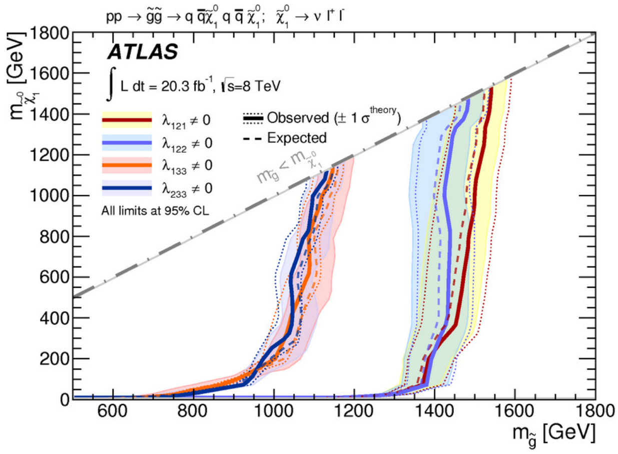

Figure 1: The observed (solid) and expected (dashed) 95% CL exclusion limit contours for the RPV gluino NLSP simplified models, assuming a promptly decaying LSP. The exclusion limits include all uncertainties except the theoretical cross-section uncertainty for the signal, the effect of which is indicated by the dotted lines either side of the observed exclusion limit contours. The shaded bands aorund each expected exclusion limit curve show the $\pm 1\sigma$ results [6].

mass, except where the $\tilde{\chi}_1^0$ is significantly less massive than the NLSP.

2.2. *Multi-lepton + b-jets searches*

The search for anomalous production of events with three or more isolated leptons in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ is performed by the CMS experiment and it is described in detail in Ref. [8]. In this analysis, R-parity violating interactions are considered in which one of the couplings is non-zero while the rest are set to zero. In particular, the analysis presented in this subsection focusses on the second and third terms from Eq. 1, i.e. the λ_{ijk} and λ'_{ijk} trilinear couplings. At least three isolated leptons with at most one hadronic tau lepton are required in the signal regions. The events are then further classified in terms of number of OSSF dilepton pairs, b-tags, number of tau leptons, the scalar sum of the p_{T} of the jets (H_T), or the scalar sum of $E_{\mathrm{T}}^{\mathrm{miss}}$, H_T and the p_{T} of all the isolated leptons (also known as S_T).

The lepton fake contributions are estimated using data driven methods described in [8], while the contributions from $t\bar{t}$, dibosons and rare processes can be estimated from simulation and validated in validation regions, defined with cuts such that the different background processes of interest are enhanced. All in all, the agreement between the data and the MC simulation of the SM processes is interpreted in the context of light RPV stops or first and second generation squarks or gluinos decaying to SM particles via λ_{ijk} couplings or in the context of squarks and gluinos decaying via the λ'_{ijk} coupling into two quarks and a lepton. As an example, limits for the coupling λ'_{231} as a function of the squark and gluino masses are shown in Figure 2, where squark masses up to about 1.4 TeV and gluino masses up to about 1 TeV are excluded for λ'_{231}. Furthermore, this analysis also excludes λ'_{233} for the same squark and gluino masses as for λ'_{231}, while stop masses up to 800 GeV are excluded for λ_{122}, λ_{123} and λ_{233} for $m_{\tilde{\chi}^0_1}$ fixed to 300 GeV.

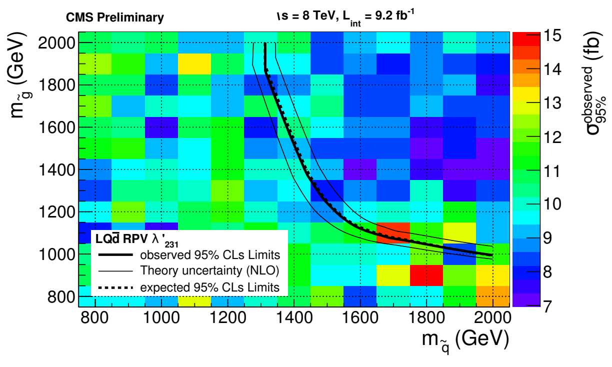

Figure 2: 95% CL limits for the coupling λ'_{231} as a function of the squark and gluino masses. The curves are shown with the observed 95% excluded cross sections [8].

2.3. *Third generation scalar lepto-quark and stop searches*

A data sample of pp collisions corresponding to an integrated luminosity of 19.7 fb^{-1} at a center of mass energy of $\sqrt{s} = 8$ TeV is also used by the CMS experiment to study two different decays of top squarks [9]. On one hand, the two-body lepton number violating decay $\tilde{t}_1 \rightarrow \tau b$ is allowed by the trilinear RPV operators if $\lambda'_{333} neq 0$. In this case, the signal region optimized for this model requires one light lepton, one hadronic τ lepton and at least two jets, from which one of them must be b-tagged. On the other hand, the process $\tilde{t}_1 \rightarrow \tilde{\chi}^{\pm}_1 b$, with $\tilde{\chi}^{\pm}_1 \rightarrow \tilde{\nu} + \tau^{\pm} \rightarrow jj + \tau^{\pm}$ is considered, where the latest decay occurs according to an RPV operator with a coupling constant λ'_{3jk}. In this analysis, only cases with $j, k = 1, 2$ are considered. This process is selected in a signal region with one light lepton, one hadronic τ lepton and at least five jets, with one of them b-tagged. The S_T distribution is then used to extract the limits on both the leptoquark and stop signal scenarios.

The major irreducible background process is the pair production of top quarks, when both the light lepton and the τ_h are produced from decays of genuine τ leptons. This background is estimated data-driven from an observed $e\mu$ sample in a dedicated control region, as detailed in the Reference note. On the other hand, the main reducible background component is formed of hadronic τ leptons misidentified as jets and multi-jet processes. Both the probability of misidentification and the contribution from multi-jet are estimated with the data in dedicated control regions according to Ref. [9]

Finally, the level of systematic uncertainties is estimated in each signal region and the results are translated into exclusion limits for stop and leptoquark masses. In particular, leptoquark masses below 740 GeV can be excluded at 95% CL. Stop masses below 576 GeV can also be excluded at 95% CL as it is shown in Figure 3, and constitutes the first time that the results are interpreted in terms of this stop decay.

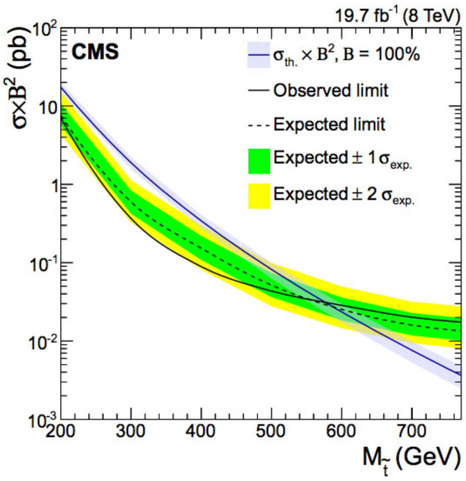

Figure 3: The expected and observed combined upper limits on the top squark pair production cross sections σ times the square of the branching fraction, B^2, at 95% CL as a function of the $\tilde{t}_1$ mass. The green (darker) and yellow (lighter) uncertainty bands represent 68% and 95% CL intervals on the expected limit. The dark blue curve and the hatched light blue band represent the theoretical LQ or $\tilde{t}_1$ pair production cross section, assuming $B = 100\%$ and the uncertainties due to the choice of PDF and renormalization/factorization scales [9].

2.4. *Heavy narrow resoncance decaying to $e\mu$, $e\tau$ and $\mu\tau$*

While lepton flavor quantum numbers are not conserved in neutrino oscillations, lepton flavor violation (LFV) has never been observed in the charged lepton sector, where neutrino induced LFV is predicted to be extremely small in the SM. For this reason, the study of possible LFV processes involving charged leptons is an important topic in the search for physics beyond the SM.

Searches for the production of a particle that decays to a pair of different flavor, opposite-sign leptons ($e^{\pm}\mu^{\mp}$, $e^{\pm}\tau^{\mp}$ or $\mu^{\pm}\tau^{\mp}$) is performed by the ATLAS experiment, using 4.6 fb^{-1} of pp collisions at a center of mass energy of $\sqrt{s}$ = 7 TeV [10]. In particular, the results are interpreted in terms of the production and subsequent decay of a tau sneutrino $\tilde{\nu}_\tau$ in RPV SUSY.

In order to enhance the signal with respect to the SM background, the events are required to have two different flavor opposite charge leptons, separated azimutally by an angle $\Delta\phi(\ell^{\pm}, \ell'^{\mp}) > 2.7$. Furthermore, each signal region is defined with the requirement that the invariant mass of the lepton system, $m_{\tilde{\nu}_\tau}$, is found to be $m_{\ell\ell'} > m_{\tilde{\nu}_\tau} \pm 3\sigma_m$, where σ_m is defined as the mass resolution [1]. In order to validate the background estimations in a region with no signal contamination, a validation region is constructed with the invariant mass cut reverted to $m_{\ell\ell'} < 200$ GeV.

The SM processes that can produce an $\ell\ell'$ signature are divided into two categories: backgrounds that produce prompt-lepton pairs and jet backgrounds where one or both of the candidate leptons is from a misidentified jet. Since the first class is well understood and modeled, they are estimated using MC normalized to cross sections with higher order corrections applied. Instead, the latest class is estimated using semi-data driven methods, described in detail in Ref. [10].

A careful study of the systematic uncertainties is performed. As illustration, the dominant sources of systematic uncertainties for the background predictions arise from the statistical uncertainty on the determination of the W+jets and multijet cross section from data, the theoretical uncertainties on the cross section for the prompt-lepton backgrounds and the luminosity.

Since no significant excess of events above the SM expectation is observed, limits are placed on the production cross section times branching ratio for each sneutrino mass , for different λ and λ' configurations. Figure 4 shows the 95% CL upper limit on the production cross section times branching ratio as a function of sneutrino mass for the $e\mu$ mode, while equivalent figures for the other modes are also displayed in the Reference note.

For a sneutrino mass of 500 (2000) GeV, the observed limits on the production cross section times branching ratio are 3.2 (1.4) fb, 42 (14) fb, and 40 (18) fb for the $e\mu$, $e\tau$ and $\mu\tau$ modes, respectively. In order to extract mass limits it is assumed that only $d\bar{d}$ and the $\ell\ell'$ couple to the sneutrino. Under these assumptions, the lower limits on the $\tilde{\nu}_\tau$ mass are 1610 GeV, 1100 GeV and 1100 GeV for the three modes under consideration, for $\lambda'_{311} = 0.10$ and $\lambda_{i3k} = 0.07$.

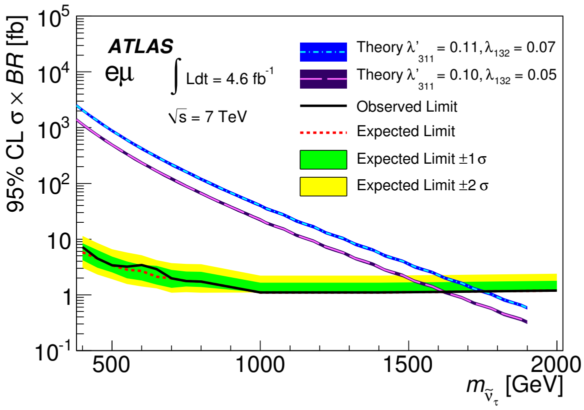

Figure 4: The 95% CL upper limit on the production cross section times branching ratio as a function of sneutrino mass for the $e\mu$ mode. The red dotted curve is the expected limit, the black solid curve is the observed limit, and the yellow and green bands give the ±1 and ±2 standard deviations in the expected limit. The expected theoretical curves for $\lambda'311 = 0.11$, $\lambda i3k = 0.07$ (light blue dot–dash) and $\lambda'311 = 0.10$, $\lambda i3k = 0.05$ (light magenta dashed) are also plotted with their uncertainties [10].

Finally, limits on the cross section times branching ratio are converted to limits on the couplings under the assumption that there are no other significant couplings contributing to the decay of the $\tilde{\nu}_\tau$. These limits can also be found in Ref. [10].

3. Baryon number violation models

The analysis aiming to probe baryon number violating models, in which the last term from Eq. 1 is different from zero are presented in this section. If this is the case, the gluino is allowed to decay into three quark jets in the 6-quark model. In the 10-quark model, instead, the gluino decays via RPC operators to two quarks and a neutralino, and it is the latest which decays via this term to three more quarks. In these models it is assumed that the λ''_{ijk} terms lead to short enough lifetimes so that the displacement of the decay vertex of the NLSP is negligible.

The phenomenology of the RPV decays via the trilinear λ''_{ijk} couplings is expected to give rise to high jet multiplicities and to low E_T^{miss}, due to the fact that the LSP decays into SM particles and there is no presence of neutrinos. In the analyses presented, b-tagging is used

[1] if the probed sneutrino mass is higher than 800 GeV, the condition $m_{\ell\ell'} > 800$ GeV is always used

to estimate the branching ratios of RPV decays to different flavors.

3.1. Multijet searches with resolved jets

A search for high-mass gluino pair production is performed by the ATLAS experiment using 20.3 fb^{-1} of pp collisions at a center of mass energy of $\sqrt{s} = 8$ TeV.

Different signal regions are optimized for different branching ratio hypotheses, different gluino masses and the model under consideration, by mainly varying different jet requirements, i.e. the number of jets or the minimum jet p_T cut.

The main background of the analysis is coming from multi-jet production events. The background yield in each signal region is estimated by starting with a signal-depleted control region in data and projecting it into the signal region using a factor that is determined from a multi-jet simulation, with corrections applied to account for additional minor background processes. Rather than treating systematic uncertainties on the background estimation separately, as commonly done, such uncertainties are not divided into categories such as jet energy uncertainties, showering uncertainties, etc. Instead, a single systematic uncertainty on the background yield is determined by comparing the background prediction to the data in a wide variety of control regions. The spread in predictions from many control regions defines the total background uncertainty in the signal region.

The results of this analysis are used to derive model-dependent exclusion limits in the context of RPV SUSY models. From Eq. 1 it is clear that each RPV decay produces exactly two down-type quarks that are of different flavors from one-another and one up-type quark. Since the cross-sections for gluino production are not dependent upon the λ''_{ijk} parameters, it is not possible to directly probe or set limits upon any individual λ''_{ijk} parameter. Instead, results are categorized based upon the probability for an RPV decay to produce a t-quark, a b-quark or a c-quark. The results are determined for different hypotheses on the branching ratios of RPV decays to t, b, c and light flavor quarks. The selection requirements for the signal regions were optimized separately for each of these hypotheses.

Under the assumption that all RPV decays are to light-flavor quarks (thus the branching ratio to top, bottom and charm quarks is zero), gluino masses below 917 GeV are excluded. Alternatively, for the scenario where BR(b) = 100% while the other heavy flavor branching ratios are zero, exclusions of $m_{\tilde{g}} < 929$ GeV are found. More configurations can be found in Ref. [11]. The 10-quark model is separately optimized and fit. Figure 5 shows the expected and observed limits for various gluino masses when the branching ratios for the RPV decay to light flavor quarks. This is the first time that the results of any analysis are interpreted in terms of this model.

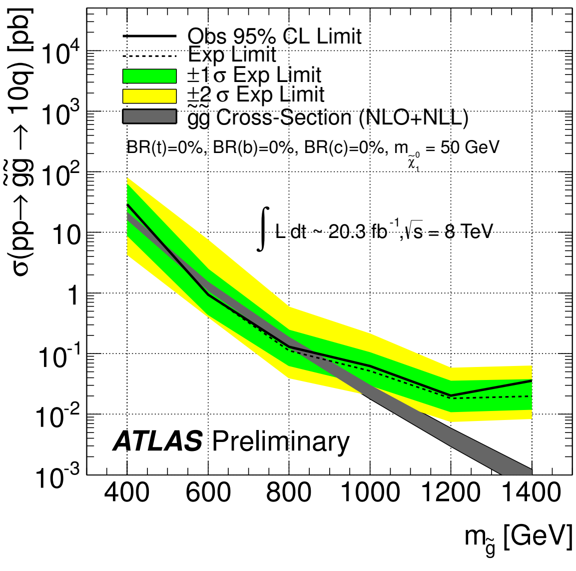

Figure 5: Expected and observed limits for the 10-quark model for various gluino masses when the branching ratios for the RPV decay are (BR(t), BR(b), BR(c)) = (0%, 0%, 0%). $m_{\tilde{\chi}_1^0} = 50$ GeV [11].

A more general plot of excluded masses depending on the branching ratios of the decays is presented in Figure 6 for the 6-quark model and in Ref. [11] for the 10-quark model.

3.2. Multijet searches with boosted jets

The ATLAS experiment has also performed a search for gluinos decaying via the 6-quark model introduced above that exploits the collimation of the decay products that is expected when gluinos are boosted. This analysis is performed using 4.6 fb^{-1} of pp collisions at a center of mass energy of $\sqrt{s} = 7$ TeV. Gluinos produced with a large momentum relative to their mass may result in overlapping jets from each of the three quarks. In this case, a large-radius jet algorithm is used to capture the three-body decay products in a single fat jet. The mass of such jets, as well as properties of their internal structure such as the "n-subjettiness" defined in Ref. [12] that are characteristic of the presence of a massive boosted object, provide discrimination against the SM multijet background.

The main background for this analysis are the multi-jet processes. It is estimated data-driven with the

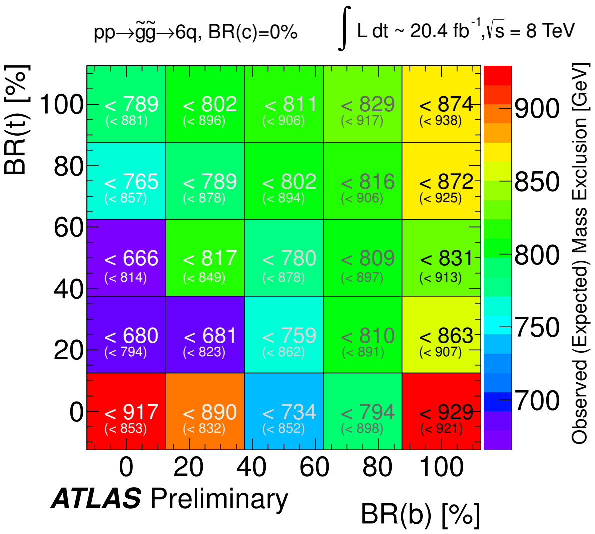

Figure 6: Expected and observed mass exclusions at the 95% CL in the BR(t) vs BR(b) space for BR(c) = 0%. Each point in this space is individually optimized and fit. Masses below these values are excluded in the 6-quark model. Bin centers correspond to evaluated models [11].

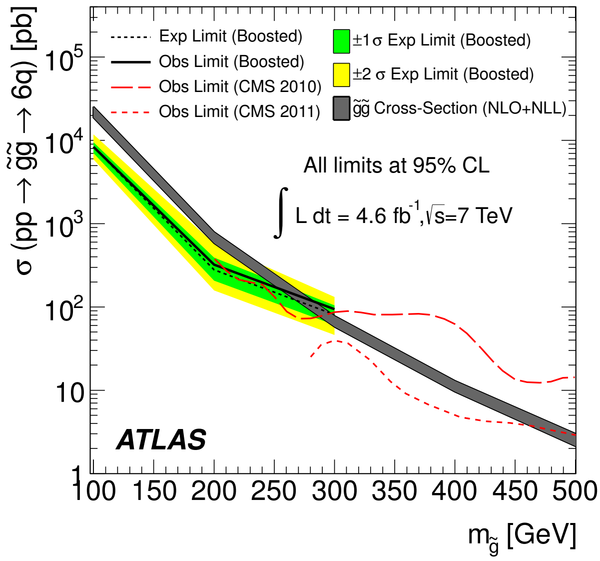

Figure 7: The expected and observed 95% CL limits are shown for the boosted analysis channel. The published CMS results using 35 pb^{-1} of 2010 data and using 5 fb^{-1} of 2011 data are shown for comparison [12].

"ABCD" method, in which event yields in orthogonal control regions constructed by reverting the condition on the mass of the fat jets are used to predict the total number of events expected in the signal region.

Systematic uncertainties are carefully studied. The primary systematic uncertainties affecting this analysis are those related to the kinematic scales of the jets used to define the signal regions as well as those that affect the background estimation method. Other systematic uncertainties such as the factorization and renormalization scales or the effect of the PDF set variations are also considered.

Since no excess is observed in data, a limit-setting procedure is performed. The boosted approach is sensitive to the low gluino mass region where gluinos may be produced with transverse momenta significantly greater than their mass. At 95% confidence level, this analysis is able to exclude gluino masses lower than 255 GeV, as it is shown in Figure 7.

An important consideration to take into account is that although the resolved analysis presented in subsection 3.1 is able to exclude a much wider gluino mass range, this analysis establishes the use of boosted objects for future SUSY searches in the ATLAS experiment.

3.3. Search for three-jet resonances in multijet final states

The CMS experiment also has a dedicated search for gluino pair production in terms of RPV SUSY [13]. Presented here are the results of a dedicated search for pair-produced three-jet resonances decaying into light- and heavy-flavor quarks in multijet events in pp collisions (the so-called "6-quark model" in subsection 3.1). The results are based on a data sample corresponding to an integrated luminosity of 19.5 fb^{-1} of proton-proton collisions at $\sqrt{s}$ = 8 TeV. The search criteria are optimized in the context of the gluino model mentioned above, with the assumption that the gluinos decay with a 100% branching fraction to quark jets (either only light-flavor or both light- and heavy-flavor).

Since this analysis targets pair-produced three-jet resonances that naturally yields to high jet multiplicity, the events passing the selection are required to contain at least six jets. This analysis performs all the possible combinations with the six jets with highest p_T and reconstructs the two three-jet masses. In case of the heavy-flavor gluinos, b-jet identification is also used to search for potential new physics signals. High-mass signal events, whether light- or heavy-flavor, have more spherical shape than background events, which typically contain back-to-back jets and thus have a more pencillike shape. To significantly reduce the backtround in the high-mass searches, a sphericity variable defined in the documentation is used as a discriminant.

The dominant background for this search are QCD multi-jet events, which arise from hard two-particle interactions combined with initial- and final-state radiation. Since the triplet invariant mass background distribution is smoothly falling, a four-parameter function fit directly to the data is used to model this background, except in the low mass region of the b-tagged sample, where the shape of the QCD multi-jet background is taken from a statistically independent data sample constructed by imposing a veto on all b-tagged jets while retaining all the other requirements. Besides, for the low-mass region of the b-tagged data sample, there is an additional background contribution from all-hadronic $t\bar{t}$ events, whose expectation is determined from the next-to-leading-order cross section.

A careful study of the systematic uncertainties is performed as described in [13]. The data is compared to the SM expectations, and since no excesses are present upper limits can be placed on the cross section times branching fraction for the production of three-jet resonances. The production of RPV gluinos decaying into light-flavor jets is excluded at 95% CL for gluino masses below 650 GeV. On the other hand, gluinos that decay into heavy-flavor jets are excluded for masses between 200 GeV and 835 GeV, which is the most stringent mass limit up to date on this model of RPV gluino decay. Figure 8 shows the observed and expected cross section limits for heavy-flavor gluinos.

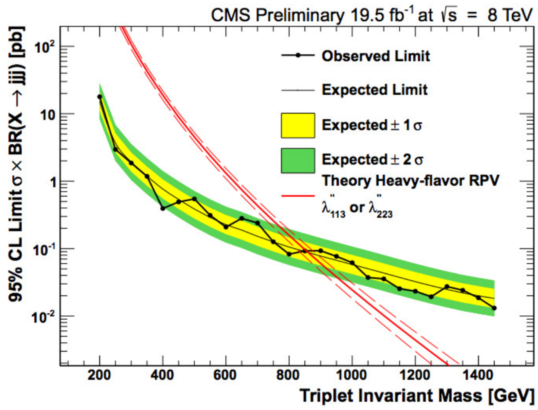

Figure 8: Observed and expected frequentist CLs cross section limits using the asymptotic calculator, for heavy-flavor gluinos. The limits for heavy-flavor gluinos cover two searches, one for low-mass gluinos ranging from 200 – −600 GeV, and one for high-mass gluinos covering the remainder of the mass range up to 1400 GeV. The solid red lines show the NLO+NLL predictions, and the dashed red lines the corresponding one-σ uncertainty bands [13].

4. Conclusions

This contribution presents the results of many searches in resonance production and R-parity violating supersymmetry performed by the ATLAS and the CMS experiments and obtained from proton-proton collision data at center of mass energies of 7 TeV and 8 TeV. Whenever it has been possible, data-driven techniques have been used to determine the most important Standard Model backgrounds for each analysis. Good agreement is observed between data and the SM predictions in all cases. The results are translated into improved limits on different scenarios for new physics beyond the SM. Furthermore, new interpretations have been studied for the first time.

References

[1] H. E. Haber and G. L. Kane, “The Search for Supersymmetry: Probing Physics Beyond the Standard Model,” Phys. Rept. **117**, 75 (1985).

[2] S. P. Martin, “A Supersymmetry primer,” Adv. Ser. Direct. High Energy Phys. **21**, 1 (2010) [hep-ph/9709356].

[3] J. Beringer *et al.* [Particle Data Group Collaboration], “Review of Particle Physics (RPP),” Phys. Rev. D **86**, 010001 (2012).

[4] G. Aad *et al.* [ATLAS Collaboration], “The ATLAS Experiment at the CERN Large Hadron Collider,” JINST **3**, S08003 (2008).

[5] S. Chatrchyan *et al.* [CMS Collaboration], “The CMS experiment at the CERN LHC,” JINST **3**, S08004 (2008).

[6] [ATLAS Collaboration], “Search for supersymmetry in events with four or more leptons in 21 fb^{-1} of pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector,” ATLAS-CONF-2013-036. `http://cds.cern.ch/record/1532429`

[7] CMS Collaboration [CMS Collaboration], “Search for RPV SUSY in the four-lepton final state,” CMS-PAS-SUS-13-010. `http://cds.cern.ch/record/1550552`

[8] [CMS Collaboration], “Search for RPV supersymmetry with three or more leptons and b-tags,” CMS-PAS-SUS-12-027. `http://cds.cern.ch/record/1494689`

[9] CMS Collaboration [CMS Collaboration], “Search for pair production of third-generation scalar leptoquarks and stops,” CMS-PAS-EXO-12-032. `http://cds.cern.ch/record/1668411`

[10] G. Aad *et al.* [ATLAS Collaboration], “Search for a heavy narrow resonance decaying to $e\mu$, $e\tau$, or $\mu\tau$ with the ATLAS detector in $\sqrt{s}$ = 7 TeV pp collisions at the LHC,” Phys. Lett. B **723**, 15 (2013) [arXiv:1212.1272].

[11] The ATLAS collaboration, “Search for massive particles in multijet signatures with the ATLAS detector in $\sqrt{s}$ = 8 TeV pp collisions at the LHC,” ATLAS-CONF-2013-091, ATLAS-COM-CONF-2013-081. `http://cds.cern.ch/record/1595753`

[12] G. Aad *et al.* [ATLAS Collaboration], “Search for pair production of massive particles decaying into three quarks with the ATLAS detector in $\sqrt{s}$ = 7 TeV pp collisions at the LHC,” JHEP **1212**, 086 (2012) [arXiv:1210.4813 [hep-ex]].

[13] CMS Collaboration [CMS Collaboration], “Search for light- and heavy-flavor three-jet resonances in multijet final states at 8 TeV,” CMS-PAS-EXO-12-049. `http://cds.cern.ch/record/1563139`