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R-Parity Violating SUSY Results from ATLAS and CMS

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Abstract. Experimental searches for Supersymmetry (SUSY) at the Large Hadron Collider (LHC) often assume R-Parity Conservation (RPC) to avoid theoretical and experimental issues with rapid proton decay. A consequence of RPC is that it implies the existence of a stable SUSY-particle that cannot decay. The search strategies are strongly based on the hypothesis of weakly interacting massive particles escaping without detection - yielding missing transverse energy (MET) to the collision events. It is vital to explore all possibilities considering that no observation of SUSY has been made and that strong exclusion limits have already been placed on RPC-SUSY scenarios. Introducing individual baryon- and lepton-number violating couplings in R-Parity Violating (RPV) models would avoid rapid proton decay. The strong mass and cross-section exclusion set for RPC-SUSY are weakened if RPV couplings are allowed in the SUSY Lagrangian - as these standard searches lose sensitivity due to less expected MET. A summary of a few of the experimental searches for both prompt and long-lived RPV scenarios conducted by the ATLAS and CMS Collaborations will be presented in this document.

INTRODUCTION

Supersymmetry (SUSY) is a concept that introduces a symmetry between fermions and bosons. Numerous theories based on the SUSY framework have been developed in the last decades, making SUSY the most popular way to describe Beyond Standard Model (BSM) physics. Lepton Number (L) and Baryon Number (B) conservations are not enforced in SUSY, instead a new quantity named R-Parity (P_{R}) is introduced. R-Parity relates the Lepton Number (L) and the Baryon Number (B) with the particle's spin (s) (Eq. 1).

$$P_{\mathrm{R}} = (-1)^{3(\mathrm{B}-\mathrm{L})+2\mathrm{s}}. \tag{1}$$

The SM particles have $P_{\mathrm{R}} = 1$ while SUSY particles (sparticles) have $P_{\mathrm{R}} = -1$. Most SUSY theories abide by R-Parity Conservation (RPC) to avoid causing the protons to decay rapidly and have interesting effects on the experimental signatures of sparticle productions and decays. In RPC, sparticles must be created in pairs, and decay to at least one lighter sparticle. This effectively leads to the consequence that there must exist a Lightest Supersymmetry Particle (LSP) that cannot decay further due to the lack of any lighter sparticle to decay to. Experimentally, this means that in RPC scenarios there is a weakly interacting LSP that escapes the detector without decaying and gives the event large amounts of missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ - and indeed, the majority of SUSY searches at the Large Hadron Collider (LHC) includes requirements on events to contain high $E_{\mathrm{T}}^{\mathrm{miss}}$. However, after the completion of the first run of proton-proton collisions at the LHC, the gaping hole of any signs of new physics and strict exclusion limits set from several experimental searches might suggest that the assumption of a stable LSP is not correct - to say the least it is vital to investigate other possibilities, such as R-Parity Violating (RPV) scenarios.

$$\mathscr{L}_{\Delta\mathrm{L}=1} = \frac{1}{2}\lambda^{ijk}L_iL_j\bar{e}_k + \lambda'^{ijk}L_iQ_j\bar{d}_k + \mu'^{i}L_iH_u, \tag{2}$$

$$\mathscr{L}_{\Delta\mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk}\bar{u}_i\bar{d}_j\bar{d}_k, \tag{3}$$

SUSY contains both L violating and B violating terms in the SUSY-Lagrangian; given in Eq. 2 and Eq. 3 respectively. The L and e signify leptons; doublet and singlet respectively. Quarks are denoted by the Q, u, and d; for the quarks, up-type, and down-type respectively. RPV interactions including the Higgs are shown by the H contribution. In all of the L and B violating terms, the interaction strengths are characterized by the couplings λ^{ijk}, λ'^{ijk}, λ''^{ijk}, and μ'^{i}, where the indices ijk denote the generations of the leptons or quarks involved.

Typically, only one of the terms in either Eq. 2 or Eq. 3 is set to non-zero values, while the rest remains zero to avoid contradicting observations of the proton's lifetime. Decays through the different RPV couplings give specific experimental signatures. Sparticle decaying through the first $\Delta L = 1$ term λLLe yields final states with multiple leptons (dropping indices). The second term $\lambda' LQd$ contains both lepton and quarks and decays through this coupling will therefore give final states of both leptons and jets. Finally, the last term in Eq. 2, is a bilinear term yielding signatures of lepton-gaugino mixing. Multi-jets are to be expected when sparticles are allowed to decay through the B-violating couplings (Eq. 3).

Several experimental searches at the LHC for RPV SUSY have been conducted both by the ATLAS Experiment [1] and the CMS Experiment [2] during LHC's Run-1, targeting a diverse set of production processes, LSPs, and RPV couplings. Mostly, the LSPs are assumed to decay promptly but a handful analyses expect the LSP to be long-lived, giving different signatures.

EXPERIMENTAL SEARCH TECHNIQUES FOR RPV SUSY

A few examples from both experiments are reviewed, dividing the searches into six categories; Lepton Number Violating Re-Interpretation, Resonance Searches, Lepton and Jet Searches, Multi-Lepton Searches, Multi-Jet Searches, and Long-Lived Searches.

Run-1 Lepton Number Violating Re-Interpretation

A re-interpretation of Run-1 RPC and RPV searches on a specific simplified RPV model has been performed by the ATLAS experiment [3], similar re-interpretations by the CMS experiment can be found in Ref. [4]. Certain searches for RPC SUSY have loose requirements on E_T^{miss} and can therefore be adapted on RPV scenarios. Moreover, the analyses targeting RPV often focus on a single coupling with set indices e.g. λ^{112}, greatly limiting the potential of the analysis to constrain a larger area of parameter-space of a given model. Five analyses are combined to cover four models of SUSY targeting all the Lepton Number Violating (LNV) RPV couplings. The result is that by performing a combination of several searches one obtains stricter exclusions limits.

Three simplified SUSY models are adapted, targeting the trilinear couplings λ^{ijk}, λ'^{ijk}, while for the bilinear coupling μ'^{i}, a fourth, phenomenological Minimal Supersymmetric Standard Model (pMMSM) is considered. Throughout, the neutralino $\tilde{\chi}_1^0$ is the LSP and decays promptly through λ^{ijk}, λ'^{ijk}, or μ'^{i} exclusively to SM particles. For all cases the LSP decay limits are split into planes of Branching Ratios (BRs) dependent on the number of heavy leptons or quarks from the LSP decay. For example, a BR plane for LSP decays through λ^{ijk} to two leptons is defined as the ratio of light (electrons, muons) to heavy (taus) leptons. Allover, both gluino and squark production are considered. Kinematics of the events, and especially of the decay itself, depend on the ratio R of the mass between the Next to Lightest Sparticle (NLSP) and the LSP; three values $R = 0.1, 0.5, 0.9$ are studied. Each of the analyses included has its strong points and dominates a certain area of the BR planes. Signal regions and significant backgrounds vary from analysis to analysis and the details will not be reviewed here.

Resonance Searches

Recreating the mass of a decaying particle by its daughter products is a powerful way to search for new particles, referred to as mass resonances. One such search that looks for resonances in the 3-jet invariant mass spectrum has been performed by the CMS experiment [5]. In this analysis, gluinos ($\tilde{g}$) are produced in pairs and are assumed to decay promptly through one of the Baryon Number Violating (BNV) couplings, λ''^{112}, λ''^{113}, or λ''^{223}, to three quarks. Events with multiple (≥ 6) high transverse momentum (p_T) jets are selected. The invariant mass M_{jjj} is formed by all possible 3-jet combination out of the six highest p_T jets in the event. Placing demands on event structures helps reduce the number of allowed combinations for the targeted $\tilde{g}$ decay. Signal events will form a Gaussian peak on top of the mass spectrum from wrongly combined jets. The latter contains the largest background that is Quantum ChromoDynamical (QCD) multijets.

The ATLAS experiment has conducted RPV resonance searches, for instance, one analysis looks for resonances in the dilepton invariant mass spectrum. This search targets production of tau sneutrinos ($\tilde{\nu}_\tau$) from $d\bar{d}$ annihilations, where the $\tilde{\nu}_\tau$ decay to lepton pairs [6].

Lepton and Jet Searches

Especially decays by the RPV coupling λ' produce both leptons and quarks, giving rise to lepton and jet event signatures. Searches, therefore, often rely on both on selecting high p_{T} jets and leptons. A search for a top squark ($\tilde{t}$) has been conducted by the CMS experiment [7]. The $\tilde{t}$ are assumed to be pair produced and decay as $\tilde{t} \rightarrow b\tilde{\chi}^{\pm} \rightarrow \tilde{\nu}_{e/\mu}e^{\pm}/\mu^{\pm}$. The sneutrino decays through λ' to pair of quarks. This search selects events containing opposite signed lepton pairs (same flavour) and at least five jets, one of them is required to contain a b quark (b-jet). The invariant mass of the lepton pairs must be larger than 130 GeV. The search is sensitive to eight RPV couplings; λ'^{i11}, λ'^{i12}, λ'^{i21} and λ'^{i22}. The target couplings are divided into muon and electron selection with index $i = 1$ and $i = 2$ respectively. The major backgrounds come from fully leptonic decays of $t\bar{t}$. Other background contributions are events containing Drell-Yan but these are suppressed by the signal requirement of at least one b-jet. CMS has also performed a complementary search where the muon and electron sneutrinos are replaced by tau sneutrinos. The targeted RPV coupling are then $i = 3$, λ'^{3jk} [8].

The BNV coupling λ'' could potentially yield lepton and jet signatures. The ATLAS experiment has searched for pair produced $\tilde{g}$ decaying to a top and a top squark, where the latter decays through λ''^{323} to a b and a s quark [9]. The search then looks for events with two same-charge leptons or three leptons. The events are also required to have three or more b-jets. Similarly, the CMS collaboration performed a search for nearly the same signature, but assuming direct decay of the $\tilde{g}$ through λ''^{323} to b and s quarks [10]. Additional examples of searches targeting lepton plus jet signatures can be found in references [11, 12].

Multi-Lepton Searches

Final states with multiple leptons are expected from sparticles decaying through the LNV coupling λ. A search from the ATLAS collaboration targets a simplified RPV model with a bino-like neutralino $\tilde{\chi}_1^0$ and is assumed to be the LSP. Four different production mechanism of $\tilde{\chi}_1^0$ are considered (all assumed to be the NLSP in that scenario); $\tilde{g}$, $\tilde{\chi}^{\pm}$, $\tilde{l}_{L/R}$, and $\tilde{\nu}_{L/R}$. The LSP decays to a combination of isolated electrons, muons and taus; $\tilde{\chi}_1^0 \rightarrow ll\nu$ [13]. The analysis is sensitive to several λ_{ijk} by allowing all generations of leptons to be present in the final state. Six signal regions are defined; requiring final states with at least four leptons and minimal requirements of $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ to 100 GeV. The four leptons are divided into groups depending on how many taus are identified in the event. Lastly, to reduce background, each signal region requires a Z-boson veto. The backgrounds in the analysis are from combinations of multiple Z/W-bosons, or t quarks plus Z/W bosons, or Higgs boson decays. These are divided into ”reducible” and ”irreducible” contributions depending on whether they have less than four prompt leptons or at least four prompt leptons. The reducible backgrounds are estimated by a ”weighting method” where the fake rates to have misidentified leptons are derived from Monte Carlo (MC) based simulations and applied to a control sample extracted from data, orthogonal to the signal region. The irreducible backgrounds are quantified by use of MC simulations.

Multi-Jet Searches

Signatures with multiple jets are to be expected with decays through the BNV coupling λ''. A dedicated search from the ATLAS collaboration looks for decays of $\tilde{g} \rightarrow tsb$ with BNV decays through λ''^{323} [14]. The $\tilde{g}$ is the LSP and pairs of $\tilde{g}$ are produced in proton-proton collisions. Signal regions are defined by requirements on the event's jet-multiplicity; 6, 7 or ≥ 8. Moreover, one lepton, either an electron or a muon is required to be present in a signal event. Each signal region is binned in the number of b-jets; from zero up to five. Dominant backgrounds vary depending on the number of b-jets but are mostly $t\bar{t}$+jets.

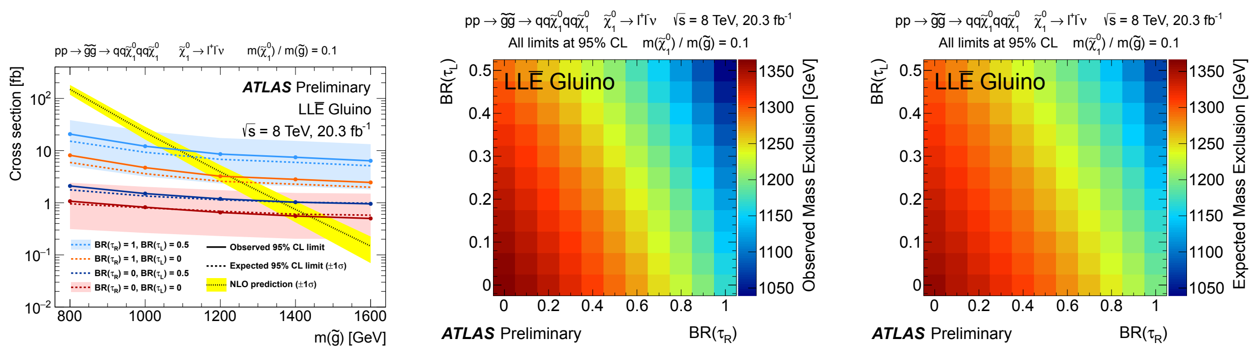
An ATLAS analysis is targeting the same coupling but here the top squark is assumed to be the LSP, decaying to b and s jets [15]. The search strategy is to look for boosted, merged jets from the $\tilde{t}$ decays, with high p_{T} but low mass. A more general analysis, in which one is targeting several of the λ''^{ijk} couplings, has been performed by the ATLAS collaboration [16], defining several signal regions depending on the flavour of the quarks in the final states.

Long-Lived Searches

In case the RPV couplings are relatively small, the LSP could become long-lived. Both the ATLAS and the CMS experiments have looked for displaced vertex signatures from a Long-Lived Particle (LLP) decaying within the detector, the results from these analyses are interpreted using several RPV couplings. The ATLAS analysis attempts to reconstruct the decay point in the tracking volume of the detector [17], while the CMS analysis searches for events containing a pair of jets originating from a displaced vertex [18]. In both cases, the expected SM background is comparatively small due to the exotic signature. Another LLP CMS search looks for events containing long-lived stops decaying through λ' to a lepton and a b quark [19]. Events are selected if they contain isolated electrons and muons, where the tracks linked to the leptons should be displaced, i.e. have large impact parameters relative to the primary interaction point.

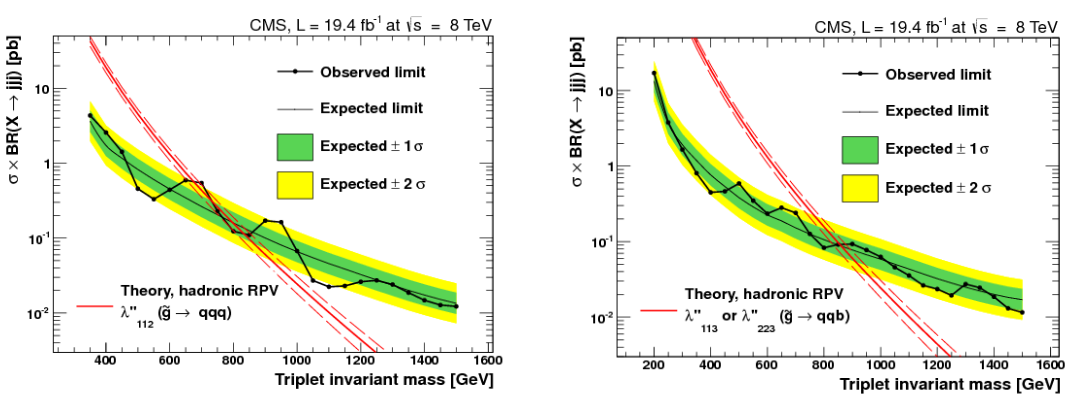
RESULTS

No excesses above the SM expectations are seen in any of the analyses. In the absence of any signal, limits are set, given an RPV coupling, on the production cross section and the mass of production particle. The CL_s method [20] is used by both experiments to present exclusions, set at 95% confidence level. Results reviewed here are example of one analysis from each category, further results are found within the references provided in the previous sections.



(a) (b) (c)

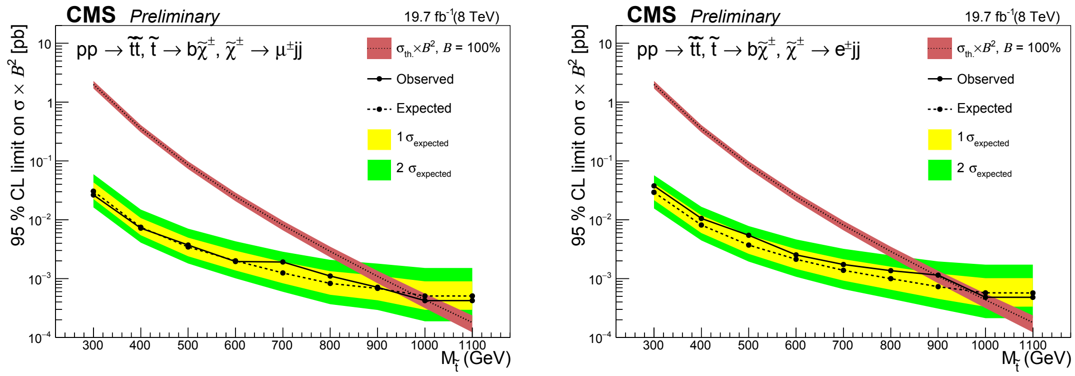
FIGURE 1. Exclusion limits on the cross section as a function of the gluino mass. The solid and dashed lined represent the observed and expected limits at 95% Confidence level. The mass ratio between the NLSP and LSP are set to 0.1, and the LSP is assumed to decay to two leptons and a neutrino. The colored lines correspond to different points in the BR-planes. In the worse case (a), the gluino mass can be excluded up to 1040 GeV. The observed and expected mass exclusion for several points on the BR grid are shown in (b) and (c) respectively [3].



(a) (b)

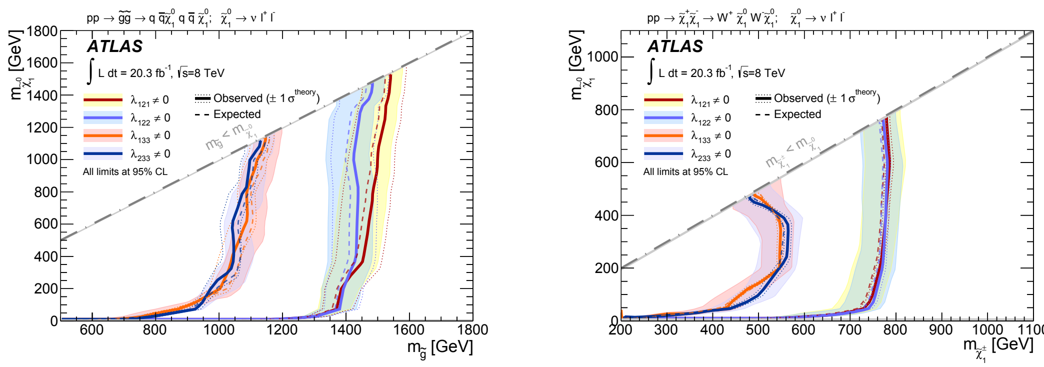
FIGURE 2. Observed and expected exclusions on the cross section times the BR are shown as a function of the triplet invariant mass of the three jets. The limits are set for light flavor jets (a) and heavy flavor jets (b) and are shown for the expectation $\pm 1\sigma$ in green and $\pm 2\sigma$ in yellow. The red lines shows the NLO+NLL predictions and the theoretical uncertainty at 1σ confidence level are illustrated by the red dashed lines [5].

The results from the Run-1 interpretations [3] are given as upper limits on the cross section as a function of the NLSP mass. As an example, Figure 1 (a) shows the limits set for λ where R=0.1, where the black line and yellow band corresponds to the Next to Leading Order (NLO) prediction. The solid and dashed colored lines show the observed and expected values given 4 different relations between the branching ratios of number of right and left handed taus.



(a) (b)

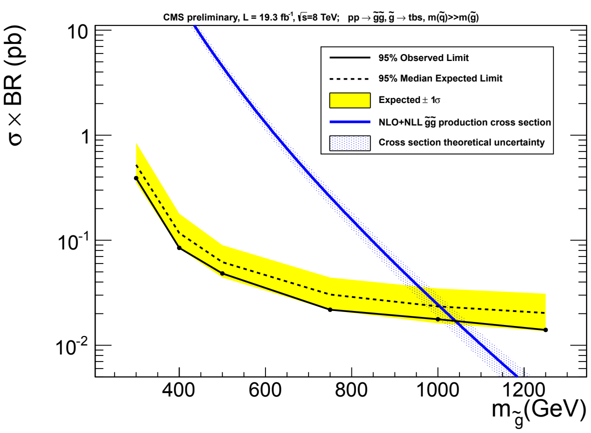
FIGURE 3. Observed and expected limits for the cross section as a function of the stop mass, solid and dashed black lines respectively. The yellow and green error bands corresponds to a $\pm 1\sigma$ and $\pm 2\sigma$ interval. The red line shows the theoretical cross section expectations for the stop at NLO+NLL. Limits for events with muons are shown in (a) while electrons are shown in (b) [7].



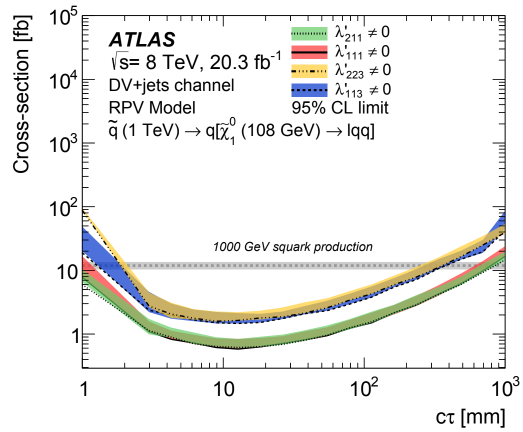
(a) (b)

FIGURE 4. Exclusion limits at 95% confidence level are shown as the excluded masses of the NLSP and LSP in RPV simplified models. The various colors shows the limits for a set of four different RPV scenarios where different couplings are set to non zero values. The solid lines show the observed values while the dashed lines show the expectations. Limits for gluino production are shown in (a) while the limits for chargino production are shown in (b) [13].

The limits on the observed and expected exclusions are shown in (b) and (c) in the form of the BR-plane. In the worst case (light blue line), a mass of $\tilde{g}$ less than 1040 GeV is excluded. Observed and expected limits on the cross sections as a function of the mass of the three jet resonance [5] are shown for light and heavy flavour jets in Fig 2 (a) and (b) respectively. Gluino mass of up to 650 GeV is excluded for light flavor jets, while the exclusion is made for 200 to 835 GeV considering heavy flavor jets for the given decay process. Figure 3 shows the results for chargino-mediated stop decay [7], in form of limits on the cross section times the branching ratio squared, as a function of the $\tilde{t}$ mass. The stop mass is excluded up to 1000 GeV for muons (Fig. 3 (a)) and 890 GeV for electrons (Fig. 3 (b)). Results from the multi-lepton analysis [13] are given as mass exclusions of the LSP mass versus the NLSP mass (Fig 4). The analysis excludes $\tilde{g}$ masses up to 1350 GeV (Fig 4 (a)) and $\tilde{\chi}^{\pm}$ masses up to 750 GeV (Fig 4 (b)). More exclusion plots are found within the given reference. The multi-jet search [14] produce results in the form of cross section time BR as a function of the $\tilde{g}$ mass, exclusions are set assuming 100% BR for the decay $\tilde{g} \to tbs$. Mass of the gluino up to 1036 GeV is excluded (Fig. 5). In case of the LLP search [17] the limits are set on the cross section of the targeted production and decay process as a function of average lifetime $c\tau$, and for the optimal range the exclusions are set to values from 0.5 fb to 5 fb.



(a)



(b)

FIGURE 5. Cross section times the BR exclusions at a 95% confidence level as a function of the mass of the gluino pair production (a). The observed and expected limits are drawn with solid and dashed lines, respectively. The theoretically caculated cross section is shown by the blue line with given uncertainties [14]. Upper limits on the cross section as a function of $c\tau$ for the long-lived particle (b). For the given scenario, where a neutalino decays to a lepton and two quarks, the limits are shown for four different RPV couplings, targeting both light and heavy flavour jets [17].

CONCLUSION

RPV SUSY are in LHC searches explored to a lesser extent than RPC scenarios. The requirement on large amount of $E_{\mathrm{T}}^{\mathrm{miss}}$ implemented with the assumption of a stable LSP makes the currently set RPC limits not applicable on RPV SUSY. However, there exist dedicated experimental searches for RPV SUSY, adopting a wide variety of search strategies for a decaying LSP. A few examples have been reviewed; A large scale Run-1 re-interpretation for LNV RPV, Resonance searches, Lepton and Jet searches, Multi-lepton searches, Multi-jet searches and long-lived searches. The analyses cover different production mechanisms and RPV couplings and even lifetimes of the SUSY particles. Limits are set on the masses of the NLSP or the LSP given a specific RPV coupling strength and decay chain.

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