Sensitivity of an Upgraded LHC to R-Parity Violating Signatures of the MSSM

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Abstract

We present a sensitivity study for the pair-production of supersymmetric particles which decay through R-parity violating channels. As the scope of possible RPV signatures is very broad, the reach of several selected signatures spanning a representative variety of possible final states is considered. Preference in representation is given to spectra motivated by naturalness, i.e. light higgsinos, stops and gluinos. The sensitivity studies are presented for proton-proton collisions at 14 TeV with an integrated luminosity of 300 and 3000 fb$^{-1}$, as well as at 33 TeV with an integrated luminosity of 3000 fb$^{-1}$.

1 Introduction

The LHC has proven extremely effective at probing MSSM scenarios with conserved R-parity. However, evidence for SUSY has not been found yet [1, 2], and the impressive experimental constraints are forcing the MSSM toward regions of parameter space unnatural for the Higgs sector. Allowing R-parity violation (RPV) in the decays of superpartners is one mechanism to preserve a natural Higgs sector by evading existing experimental constraints. These collider signatures have been probed in many variations by both theoretical [3–8] and experimental studies [9–15].

In this white paper for the 2013 Snowmass study, an array of possible collider signatures from RPV are analyzed in the context of future LHC upgrade possibilities, particularly 14 TeV with integrated luminosities of 300 and 3000 fb$^{-1}$, as well as at 33 TeV with an integrated luminosity of 3000 fb$^{-1}$. Although single superpartner production is, in principle, possible in RPV, these signatures tend to live on the fringe between what is viable and excluded by indirect bounds. For this reason, we focus this work on the more generic signatures arising from pair-produced superpartners. Each choice of production and decay mode constructs a separate simplified model [16] which could be examined at the LHC.

The particular scenarios considered in the work are selected for several reasons. First, the chosen final states serve to sample a diverse variety of the available options in RPV, covering many possibilities from multi-leptons to jet-only final states. Second, many of the chosen options exhibit naturalness-motivated topologies, here defined to mean decays involving stops and higgsinos [17]. Third, many of the chosen RPV couplings are compatible with those that might arise in the context of an RPV scenario exhibiting a “third-generation dominant” structure to the couplings, such as MFV SUSY [18–22].
The $R$-parity violating superpotential and soft bilinear Lagrangian extension to the MSSM are:

$$W_{\text{RPV}} = \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k + \mu_i L_i H_u$$  \hspace{1cm} (1.1)

$$\mathcal{L}_{\text{soft RPV}} = B_i \tilde{L}_i h_u + \bar{m}_d^2 h_d^\dagger \tilde{L}_i + \text{h.c.}$$  \hspace{1cm} (1.2)

In this study, we will refer to the trilinear couplings in the RPV superpotential, $\lambda_{ijk}$, $\lambda'_{ijk}$, and $\lambda''_{ijk}$, as $\text{LLE}_{ijk}$, $\text{LQD}_{ijk}$, $\text{UDD}_{ijk}$ respectively. The RPV bilinear terms in the superpotential and soft lagrangian together allow for the neutral higgsino to decay as $\tilde{H}^0 \rightarrow W^\pm \tau^\mp$. The benchmark for bilinear RPV will be expressed as $\text{LH3}$.

As the strengths of individual couplings are unknown, but often highly constrained [23, 24], we will utilize a single coupling dominance ansatz to ameliorate issues from indirect constraints. However, as the coupling strength does not generally contribute to pair production cross-sections, the specific value is largely irrelevant except insofar as all RPV decays are assumed to be both prompt and narrower than the detector resolution.

The list of all benchmarks considered in this white paper is provided in Table 1. The next section of this work contains a catalogue of searches and the limits they set on the various simplified models arising from the RPV MSSM. These searches are: multi-leptons, third-generation leptoquark, $\ell +$ many jets and paired dijets. A summary of the projected $2\sigma$ mass reaches is provided at the end of this white paper.
Figure 1: Projected sensitivity from multi-lepton studies on production of degenerate squarks and gluinos decaying to jets and a neutralino which subsequently decays through the LLE122 operator. **Left:** At 14 TeV with 300 fb$^{-1}$ and 3 ab$^{-1}$, the LHC has projected sensitivity to 3.55 TeV and 4.0 TeV respectively. **Right:** At 33 TeV with 3 ab$^{-1}$, the LHC has projected sensitivity to 8.5 TeV. See section 2.1 for details on the model, selections and search regions used in the sensitivity study.

## 2 Sensitivity Studies for the RPV Models

For all studies, Pythia 8 [25] was used to generate the signal events. These were processed using the detector simulator Delphes 3.0.6 or 3.0.9 [26]. The common Snowmass 2013 Energy Frontier Standard Model background samples [27, 28] were used in the majority of studies, except for in the paired dijet study of section 2.4. Cuts were applied as detailed in each subsection.

### 2.1 Multilepton studies

Multilepton searches are extremely powerful probes of new physics. All models with RPV LLE couplings and with bilinear RPV can populate these searches. Additionally, some models with LQD couplings, particularly those with tops, can give rise to multilepton signatures. For this study, six distinct RPV simplified models are examined, however only a single search strategy is used following the framework of CMS multilepton studies [11]. The events are binned exclusively across several variables: total leptons (3, 4+); $S_T$ (0-300, 300-600, 600-1000, 1000-1500, 1500-2000, 2000+); $b$-tags (0, 1, 2+); $\tau$-tags (0, 1+); opposite-sign same-flavor pairs (0, 1, 2); and $Z$ candidates (0, 1+). A combined fit is used to set exclusions.

- **LLE122:** $\tilde{g}/\tilde{q} \to \tilde{B} \to j\tilde{b}$ or $jj\tilde{B}$ — Through various production mechanisms, such as $pp \to \tilde{u}\tilde{u}$, $\tilde{u}\tilde{g}$, $\tilde{u}\tilde{d}$, and $\tilde{d}d^*$, first-generation squarks and gluinos are produced which then promptly decay to $j\tilde{B}$ or $jj\tilde{B}$, respectively. The $\tilde{B}$ then undergoes decays through an off-shell slepton and the LLE122 coupling to give an $e$- and $\mu$-rich final state, either $e^+\mu^-$ or $\mu^+\mu^-$ and an $\nu$ or $\bar{\nu}$. This case has extremely high $S_T (\sim 2m_\tilde{g})$, significant $B_T$ from the neutrinos and large $H_T$ from the jets. We use $m_\tilde{g} : m_\tilde{q} : m_\tilde{B}$ in a $2 : 2 : 1$ hierarchy for our choice of mass assignment (all other
superpartners are decoupled). Deviations from degenerate gluinos and squarks can change the production cross-section significantly, while changes to the bino mass would likely have a very small effect. The LHC can probe extremely high masses in this benchmark allowing for incredible sensitivity. As displayed in Figure 1, LHC 14 with 300 fb$^{-1}$ (14 with 3 ab$^{-1}$ [33 with 3 ab$^{-1}$]) is expected to have sensitivity to $\tilde{g}/\tilde{q}$ masses at 3.55 TeV (4.0 TeV [8.5 TeV]).

- **LLE122**: $\tilde{W}$ — In this benchmark model, charged and neutral winos are produced through an off-shell $W^\pm$ or $Z/\gamma$. The charginos then undergo a prompt decay $\tilde{\chi}^\pm \rightarrow \tilde{\chi}^0(W^{\pm*})$, where the off-shell $W$ is soft enough to be unobservable. The wino-like $\tilde{\chi}^0$ then decays through an off-shell slepton to give an $e^-$- and $\mu^-$-rich final state, either $e^\pm\mu^\mp$ or $\mu^+\mu^-$ and a $\nu$ or $\bar{\nu}$. This case has significant $E_T$ and $S_T \sim 2m_{\tilde{W}}$. For this benchmark simplified model, the $\tilde{W}$ appears alone at the bottom of the spectrum (all other superpartners are decoupled). As displayed in Figure 2, LHC 14 with 300 fb$^{-1}$ (14 with 3 ab$^{-1}$ [33 with 3 ab$^{-1}$]) is expected to have sensitivity to $\tilde{W}$ masses at 1.8 TeV (2.3 TeV [4.4 TeV]).

- **LLE233**: $\tilde{t} \rightarrow \tilde{H}$ — In this benchmark, pair-produced stop squarks decay promptly to $\tilde{H}^\pm b$. The $\tilde{H}^\pm$ then promptly decays through an off-shell $\tilde{\tau}/\tilde{\nu}_r$ to give a $\tau$- and $\mu$-rich final state. This case has significant $E_T$ and $S_T \sim 2m_{\tilde{t}}$. The masses are set so $m_{\tilde{t}} - m_{\tilde{H}} = 100$ GeV (all other states are decoupled) to forbid the $\tilde{t} \rightarrow t\tilde{H}^0$ decay. The spectrum containing a stop and higgsino is motivated by naturalness, while the coupling choice is compatible with a third-generation dominant scenario. As displayed in Figure 3, LHC 14 with 300 fb$^{-1}$ (14 with 3 ab$^{-1}$ [33 with 3 ab$^{-1}$]) is expected to have sensitivity to $\tilde{t}$ masses at 1650 GeV (1950 GeV [3750 GeV]).

- **LLE233**: $\tilde{H}$ — In this benchmark, charged and neutral higgsino production are followed by prompt decays $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1(Z^*)$ or $\tilde{\chi}^\pm(W^{\pm*})$ and $\tilde{\chi}^\pm \rightarrow \tilde{\chi}^0_1(W^{\pm*})$, where the off-shell $W$s and $Z$s...
Figure 3: Projected sensitivity from multi-lepton studies on production of stops which decay into charginos which then decay through the LLE233 operator. **Left:** At 14 TeV with 300 fb$^{-1}$ and 3 ab$^{-1}$, the LHC has projected sensitivity to 1.65 TeV and 1.95 TeV respectively. **Right:** At 33 TeV with 3 ab$^{-1}$, the LHC has projected sensitivity to 3.75 TeV. See section 2.1 for details on the model, selections and search regions used in the sensitivity study.

Figure 4: Projected sensitivity from multi-lepton studies on production of higgsinos which then decay through the LLE233 operator. **Left:** At 14 TeV with 300 fb$^{-1}$ and 3 ab$^{-1}$, the LHC has projected sensitivity to 950 GeV and 1300 GeV respectively. **Right:** At 33 TeV with 3 ab$^{-1}$, the LHC has projected sensitivity to 2.9 TeV. See section 2.1 for details on the model, selections and search regions used in the sensitivity study.

are soft enough to be unobservable. The neutral $\tilde{H}$ then decays through an off-shell $\tau/\tilde{\nu}_\tau$ to give a $\tau$- and $\mu$-rich final states. This case has significant $E_T$. A light higgsino is motived by naturalness, while the coupling is compatible with a third-generation dominant scenario. As displayed in Figure 4, LHC 14 with 300 fb$^{-1}$ (14 with 3 ab$^{-1}$ [33 with 3 ab$^{-1}$]) is expected to have sensitivity to $\tilde{H}$ masses at 950 GeV (1300 GeV [2900 GeV]).
Figure 5: Projected sensitivity from multi-lepton studies on production of gluinos which decay to stops which subsequently decay through the LQD232 operator. **Left:** At 14 TeV with 300 fb$^{-1}$ and 3 ab$^{-1}$, the LHC has projected sensitivity to 2.5 TeV and 2.8 TeV respectively. **Right:** At 33 TeV with 3 ab$^{-1}$, the LHC has projected sensitivity to 6.3 TeV. See section 2.1 for details on the model, selections and search regions used in the sensitivity study.

- **LQD232:** $\tilde{g} \rightarrow \tilde{t}$ — Gluinos are pair-produced in this benchmark before decaying to $\tilde{t}\tilde{t}$. The stop then decays to a leptoquark-like final state ($\mu j$). As a benchmark simplified model, we propose $m_\tilde{g} - m_\tilde{t} = 200$ GeV (with all other states decoupled). Although a multilepton search is used to determine the sensitivity to this simplified model, same-sign dilepton or leptoquark resonance searches could have comparable sensitivity. As displayed in Figure 5, LHC 14 with 300 fb$^{-1}$ (14 with 3 ab$^{-1}$ [33 with 3 ab$^{-1}$]) is expected to have sensitivity to $\tilde{g}$ masses at 2.5 TeV (2.8 TeV [6.3 TeV]).

- **LH3:** $\tilde{H}$ — This benchmark has charged and neutral higgsino production with subsequent prompt decays $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 (Z^*)$ or $\tilde{\chi}_2^\pm (W^*\pm)$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 (W^\pm\mp)$, followed by $\tilde{\chi}_1^0 \rightarrow W^\pm \tau^\mp$. As a benchmark simplified model, $\tilde{H}$ appears alone at the bottom of the spectrum (with all other states decoupled). The higgsino at the bottom of the spectrum is motivated by naturalness, while the LH3 coupling is compatible with a third-generation dominant ansatz. As displayed in Figure 6, LHC 14 with 300 fb$^{-1}$ (14 with 3 ab$^{-1}$ [33 with 3 ab$^{-1}$]) is expected to have sensitivity to $\tilde{H}$ masses at 530 GeV (610 GeV [2800 GeV]).

### 2.2 Third-generation leptoquark study

R-parity violating stops can mimic leptoquarks (LQ). Due to the enhanced motivation from third-generation dominance, the LQD333 operator is chosen to be studied as a benchmark.

- **LQD333:** $\tilde{t}$ — Stops are pair-produced followed by a direct decay to $\tau b$. This signal is identical to a third-generation leptoquark. As a benchmark simplified model, we propose $m_\tilde{t}$ is at the bottom of the spectrum with all other states decoupled. A light stop is motivated by naturalness and the coupling strength is suggestive of a third-generation dominant scenario.
Figure 6: Projected sensitivity from multi-lepton studies on production of higgsinos which then decay through the bilinear RPV LH3 operator to $W^\pm \tau^\mp$. **Left:** At 14 TeV with 300 fb$^{-1}$ and 3 ab$^{-1}$, the LHC has projected sensitivity to 530 GeV and 610 GeV respectively. **Right:** At 33 TeV with 3 ab$^{-1}$, the LHC has projected sensitivity to 2800 TeV. See section 2.1 for details on the model, selections and search regions used in the sensitivity study.

For this study, the following selections are applied:

- Require a $\mu$ with $p_T > 30$ GeV and $|\eta| < 2.1$
- Require a $\tau_h$ with $p_T > 50$ GeV, $|\eta| < 2.3$ and a charge that is the opposite sign of the $\mu$
- Require two $b$-tagged jets with $p_T > 30$ GeV and $|\eta| < 2.4$
- All objects separated by $\Delta R \geq 0.5$

To reject the major backgrounds $-t\bar{t}+\{\text{jets}\}$, $Z+\{\text{jets}\}$ and $W+\{\text{jets}\}$ – additional mass-dependent cuts are applied to $S_T$ and the invariant mass of the hadronic $\tau$ and $b$-jet:

- $S_T \equiv p_T(\mu) + p_T(\tau_h) + p_T(b_1) + p_T(b_2) > 1.25m_t$
- $M(\tau_h, b_i) > 0.5m_t$, where $i \in \{1, 2\}$ is the choice that minimizes $|M(\tau_h, b_i) - M(\mu_h, b_{\neq i})|$

For this study, only the $\mu\tau_h$ final state is used, but the inclusion of $e\tau_h$ could increase sensitivity by a factor of $\sim 2$. For 3 ab$^{-1}$ (140 PU), the systematic uncertainties due to object identification or misidentification rates were inflated by 50% from the nominal values. As displayed in Figure 7, LHC 14 with 300 fb$^{-1}$ (14 with 3 ab$^{-1}$) is expected to have sensitivity to $\tilde{t}$ masses at 1.30 TeV (1.65 TeV).

### 2.3 $\ell + \text{many jets}$ study

The UDD RPV operators can easily give rise to very high jet multiplicities. The possibility of tops or $W$s appearing in viable, simple decays motivates searches for $\ell + n$ jets.
Figure 7: Limits on stops decaying to a $\tau b$ final state through the LQD333 operator. This signature is identical to third-generation leptoquarks in terms of both pair production cross-section and decay modes. For this study, only the $\mu\tau b$ signature is used, the addition of electrons would increase sensitivity by a factor of $\sim 2$. With $300 \text{ fb}^{-1}$, LHC 14 could exclude these stops (third-generation scalar leptoquarks) up to 1.3 TeV, while with $3 \text{ ab}^{-1}$ projected exclusion reaches 1.65 TeV. See section 2.2 for details on the model, selections and search regions used in the sensitivity study.

- **UDD212**: $\tilde{t} \to \tilde{B}$ — In this benchmark, pair-produced stop squarks each decay to $t\tilde{B}$. The $\tilde{B}$ subsequently decays then through an off-shell $\bar{q}$ to give a three light jet resonance. We use $m_{\tilde{t}} : m_{\tilde{B}}$ in a 2 : 1 hierarchy with all other states decoupled. The presence of a light stop is motivated by naturalness.

For this study, the following selections are applied:

- Require exactly one $e$ or $\mu$ with $p_T > 30 \text{ GeV}$ and $|\eta| < 2.1$
- Require seven or more jets with $p_T > 50 \text{ GeV}$ and $|\eta| < 2.5$
- Require at least one $b$-tagged jet with $p_T > 50 \text{ GeV}$ and $|\eta| < 2.5$

To reject the major backgrounds – $t\bar{t} + \{\text{jets}\}$, $Z + \{\text{jets}\}$ and $W + \{\text{jets}\}$ – a boosted decision tree (BDT) is used with $N_j$, $N_b$, $S_T$ and the $p_T$, $\phi$ and $\eta$ of the lepton and leading 6 jets. In an analysis of real data, the BDT-based analysis would be extensively validated with a simpler, though slightly less potent, cut-based analysis. As displayed in Figure 8, LHC 14 with $300 \text{ fb}^{-1}$ (14 with $3 \text{ ab}^{-1}$) is expected to have sensitivity to $\tilde{t}$ masses at 1200 GeV (1650 GeV).
Figure 8: **Left:** Limits on stops decaying to a $t\tilde{\chi}^0 \rightarrow t \{jjj\}$ final state through the UDD212 operator. With 300 fb$^{-1}$, LHC 14 could exclude these stops up to 1.2 TeV, while with 3 ab$^{-1}$ projected exclusion reaches 1.65 TeV. **Right:** Projected discovery significance for the same model. See section 2.3 for details on the model, selections and search regions used in the sensitivity study.

### 2.4 Paired dijet study

A very interesting possibility for concealing supersymmetry with RPV is the possibility of pair-produced stops decaying to a pair of dijet resonances.

- **UDD312: $\tilde{t}$** — For this benchmark, stops are pair-produced followed by a direct decay to $jj$, giving the signature of a pair of dijet resonances. This model has the stop at the bottom of the spectrum with all other states decoupled. A light stop is motivated by naturalness. This coupling is not motivated from third-generation dominance, however, this is a more difficult signature than the much easier $\{jb\}$ resonant pairs arising from the third-generation dominant UDD323.

This study requires four or more jets with $p_T > 120$ and $|\eta| < 2.5$. From the four highest $p_T$ jets, all three unique combinations of paired dijets are composed, e.g. the dijet composed from the first and second leading jets will be paired with the dijet constructed from the third and fourth leading jets. The combination resulting in the lowest fractional mass difference, i.e. $\frac{|M_a-M_b|}{(M_a+M_b)/2}$, is selected. Additionally, we define $\Delta$ to be the difference between the scalar sum of the transverse momenta of the two jets in the dijet and the average pair mass in the event, e.g. $\Delta = \sum_{1,2} |p_T^j| - (M_a+M_b)/2$. As stops with greater boost would have higher $\Delta$, a cut of 50 GeV is implemented to efficiently remove the enormous QCD multi-jet background. After all selection requirements have been satisfied,
Figure 9: Limits on pair-produced stops each decaying to a $jj$ final state through the UDD312 operator. With 300 fb$^{-1}$, LHC 14 could exclude (conservatively : optimistically) these RPV stops up to 750 (680 : 840) GeV, while with 3 ab$^{-1}$ projected exclusion reaches 1070 (1000 : 1180) GeV. See section 2.4 for details on the model, selections and search regions used in the sensitivity study.

the average mass distribution is investigated for the sensitivity of signal in the presence of QCD background events.

Because no monte carlo simulation is expected to be reliable for a background estimate, we instead employ a data-driven background scaling. In the CMS analysis [15], the background QCD distribution is modeled by a four-parameter function:

$$f(x) = P_0 \frac{(1 - x\sqrt{s})^{P_1}}{(x\sqrt{s})^{P_2 + P_3 \log x \sqrt{s}}}$$  \hspace{1cm} (2.1)$$

Using the parameter values based on those from the fit to the 7 TeV data, an estimate of the background can be made simply by scaling up the normalization, $P_0$. The ratio between the $t\bar{t}$ cross-sections at 7 TeV and 14 TeV is taken as the scaling factor representing the nominal background expectation. A second, high background case is considered, quantified via increasing this ratio by 40%. At both the nominal and high backgrounds, three choices of jet-energy scale (JES) uncertainty (1%, 3% and 5%) are used to further gauge the plausible variation. As displayed in Figure 9, LHC
14 with 300 fb$^{-1}$ (14 with 3 ab$^{-1}$) is expected to have sensitivity to $\tilde{t}$ masses at 750 GeV (1070 GeV) with nominal backgrounds and a 3% JES uncertainty.

### 3 Summary

In this work, a representative variety of plausible collider signatures arising in R-parity violating supersymmetry were catalogued and studied. These signatures were chosen as they sample the breadth of possibilities available in RPV SUSY. Many of the signatures were selected due to their compatibility with a natural Higgs sector and/or a third-generation dominant ansatz for the RPV couplings. At 14 TeV with both 300 fb$^{-1}$ and 3000 fb$^{-1}$ (represented by 50 pile-up events and 140 pile-up events respectively), sensitivity studies were performed gauging the reach of future colliders to these simplified models. In some cases, 33 TeV with 3 ab$^{-1}$ was also studied. These limits are summarized in Table 2.

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