Low-energy R-parity violating SUSY with horizontal flavor symmetries

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In this talk, I will present the general structure of RPV couplings when a Froggatt-Nielsen horizontal symmetry is responsible for the flavor structure of both the SM and the MSSM. For sub-TeV (natural) SUSY, lepton number must be an accidental symmetry, while low-energy SUSY is still allowed by baryonic RPV, which lowers the MET signature of superparticles decays. The largest RPV coupling involves the stop, and it is constrained between $10^{-3}$ (from FCNCs) and $10^{-9}$ (from LHC searches).

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1 Introduction

While Supersymmetry (SUSY) is a well-motivated extension of the Standard Model (SM), current LHC searches put stringent bounds on the masses of the superparticles; because they are strongly interacting, gluinos should be easily produced at the LHC, and current bounds are at 1.4 TeV when assuming simplified decay chains to squarks and neutralinos.\(^\star\) In most searches, \(R\)-parity, a symmetry under which superparticles have opposite charges with respect to SM fields, is assumed.\(^\dagger\) Hence, the lightest supersymmetric partner (LSP) is stable and exits the detector, showing up as missing energy (and providing a dark matter candidate). Without \(R\)-parity, the LSP can decay to SM particles, possibly charged and/or colored, and the missing energy signature of a supersymmetric event is greatly reduced.

The strict bounds on \(R\)-parity conserving SUSY might be hinting to the possibility of \(R\)-parity-violating (RPV) SUSY; in particular, one should think of why \(R\)-parity was introduced and if it is superfluous.

\(R\)-parity is introduced to forbid renormalizable operators which violate both lepton number (\(L\)) and baryon number (\(B\)):

\[
W_{RPV} = \bar{\mu}_i L_i \phi_u + \lambda_{ijk} L_i L_j \bar{\ell}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \lambda''_{ijk} u_i d_j d_k.
\] (1)

The first three operators break \(L\), while the last breaks \(B\). A combination of both types is needed for the proton to decay to lighter particles.

Still, there are dimension-5 operators allowed by \(R\)-parity, as \(\frac{1}{M_P} Q_i Q_j Q_k L_l\), that would produce proton decay at dangerous rates if a particular flavor structure is not assumed. It is then reasonable to try to understand the flavor structure of the (MS)SM and see if imposing \(R\)-parity was after all not necessary (a dark matter candidate can be given by the gravitino, if sufficiently long-lived, or an axion/axino mixture).

In ref. \([1]\), we used a Froggatt-Nielsen mechanism of horizontal symmetries \([2, 3]\) to show that the RPV couplings hierarchies are fixed by the observed SM mass hierarchies and mixings (for similar analysis, see \([6, 7]\)). Furthermore, both low-energy and collider phenomenology were studied for this model, leading to the prediction of an accidental lepton number conservation (at the renormalizable level) and a specific range allowed for the largest baryonic RPV coupling, \(\lambda''_{323}\).

In section 2 we review the framework of horizontal symmetries and how it can explain the flavor structure of the MSSM, including the RPV coefficients. Textures for these couplings will be uniquely determined by the measured SM flavor structure. In section 3 we present the phenomenological limits for the coefficients, and the

\(^\star\)Limits on stops, more relevant for the naturalness of the weak scale, are at about 600 GeV, with a strong dependence on the stop branching ratios; regardless, the gluino enters the stop RGE equation, so that a light stop and a heavy gluino would result in a fine-tuning of the stop mass.

\(^\dagger\)\(R\)-parity can be expressed as \(R_p = (-1)^{2S+3B+L}\).
applicable bounds coming from collider searches. We summarize in section 4 and give an outlook for the next LHC searches.

2 Textures from horizontal symmetries

The Froggatt-Nielsen framework [2] assumes a new horizontal symmetry, $U(1)_H$, under which the SM fields have generation-dependent charges. The high-energy theory is invariant under $U(1)_H$, which is broken when a flavon field $S$, with charge $-1$, acquires a vev $\langle S \rangle$. In the low-energy theory, heavy fields that have been integrated out generate effective operators proportional to a spurion $\epsilon = \langle S \rangle / M$, where $M$ is the symmetry-breaking scale. Only terms that are invariant under the symmetry are allowed in the superpotential (including different powers of the spurion). A Yukawa coupling $Y_{ij}^d \phi_d Q_i \overline{d}_j$ is rewritten as

$$m_{ij} = \mathcal{H}[\phi_d] + \mathcal{H}[Q_i] + \mathcal{H}[\overline{d}_j] - r,$$

where $r = 0$ for a non-$R$-symmetry and $r = 2q_\theta$ if $U(1)_H$ is an $R$-symmetry. Unknown $O(1)$ factors have been neglected in front of the operator; one expects that the hierarchies are generated by the different charges and not by order one parameters, and whenever this is not possible a tuning is present. Operators with negative or fractional powers of $\epsilon$ are not allowed in the superpotential. Using the notation $\mathcal{H}[\Phi_i] = \Phi_i$, the Yukawas are

$$Y_{ij}^a = \epsilon^{\phi_u + Q_i + a_i - r}, \quad a = u, d; \quad i, j = 1, 2, 3.$$  

(3)

Therefore, the masses and mixings are also written in terms of the horizontal charges:

$$m_{ij}^a / m_{ij}^d \sim \epsilon^{Q_i + a_i - Q_j - a_j}, \quad |V_{ij}| \sim \epsilon^{|Q_i - Q_j|}.$$  

(4)

Similar expression holds for the leptons. Given the experimental values for masses and mixings, and taking the magnitude of the spurion equal to the largest of the “small” SM parameters, $\epsilon = \sin \theta_C$, the charge differences $\Phi_{ij} \equiv \Phi_i - \Phi_j$ are uniquely set as follows:

| $Q_{12}$ | $Q_{13}$ | $Q_{23}$ | $d_{12}$ | $d_{13}$ | $d_{23}$ | $u_{12}$ | $u_{13}$ | $u_{23}$ | $L_{12}$ | $L_{13}$ | $L_{23}$ | $\ell_{12}$ | $\ell_{13}$ | $\ell_{23}$ |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1       | 3       | 2       | 1       | 2       | 1       | 3       | 5       | 2       | 0       | 0       | 0       | 4       | 6       | 2       |

With 17 charges and only 13 independent equations, the solutions depend on the choices of 4 independent variables, which can be taken as $\{Q_3, u_3, d_3, L_3\}$.

\[\text{If } n_\mu = \phi_u + \phi_d < 0, \text{ the } \mu \text{ term } \mu \phi_u \phi_d \text{ is generated by a Giudice-Masiero-like term Kähler correction } \delta K = X \phi_u \phi_d \left(\frac{\epsilon}{M}\right)^{-n_\mu}, \text{ resulting in } \mu = m_3/\epsilon^{\sqrt{n_\mu}}. \text{ The } \mu \text{ term is automatically suppressed with respect to the SUSY breaking scale. If the mixed } U(1)_\mu \text{-gauge anomalies are cancelled by a universal axion, we have } n_\mu \sim -1. \text{ As pointed out in } [5], \text{ non-universal anomalies are more common in string-theory motivated models, so the requirement of anomaly cancellation is not considered.}\]
2.1 \textit{R}-parity violation

In the presence of a horizontal symmetry, the values of the RPV couplings are determined by the horizontal charges of the superfields:

$$\left( \mathcal{M}_i, \lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk} \right) \sim \epsilon^{-r} (m L_i + \phi_u, \epsilon L_i + L_j + \ell_k, \epsilon L_i + Q_j + d_k, \epsilon u_i + d_j + d_k).$$

(5)

Taking the ratio of two couplings, the resulting textures are uniquely determined:

$$\frac{\mathcal{M}_i}{\mathcal{M}_3} = \epsilon^{L_{i2} + L_{j3} + \ell_{k3}}, \quad \frac{\lambda_{ijk}}{\lambda'_{333}} = \epsilon^{L_{i3} + Q_{j3} + d_{k3}}, \quad \frac{\lambda'_{ijk}}{\lambda''_{323}} = \epsilon^{u_{i3} + d_{j2} + d_{k3}},$$

where we can define the largest couplings \( \lambda_{233} = \lambda'_{333} = \epsilon^{n_{LNV}}, \) with \( n_{LNV} = L_2 + Q_3 + d_3 - r, \) and \( \lambda''_{323} = \epsilon^{n_{BNV}}, \) with \( n_{BNV} = u_3 + d_2 + d_3 - r. \) The coefficients \( n_{LNV} \) and \( n_{BNV} \) are undetermined, and will dictate the phenomenology of the theory:

1. If they are fractional, all the RPV operators are forbidden; missing energy LHC searches apply and the weak scale is generically fine-tuned to a degree of \( \mathcal{O}(1\%) \).

2. If they are both integers, \( B \) and \( L \) are not conserved; the leading constraint from upper limits on the proton lifetime \([9]\) is:

$$p \to K^+ \pi: \quad |\lambda'_{i2k} \lambda'^{*}_{11k}| \lesssim 3 \times 10^{-27} \left( \frac{m_{\tilde{b}_R}}{100 \text{ GeV}} \right)^2$$

(6)

For \( k = 3 \), substituting the expressions of the couplings, we have:

$$|\lambda'_{i23} \lambda'^{*}_{113}| = \epsilon^{n_{LNV} + n_{BNV} + 8} \lesssim \epsilon^{41} (m_{\tilde{b}_R} / 100 \text{ GeV})^2.$$  

(7)

This is possible if \( n_{BNV} \) and \( n_{LNV} \) are 17 or higher. In section \([3]\) we will see that the couplings are tiny and either give missing energy events or heavy stable particles. In both cases, generic limits for the sparticle masses go up to and above 1 TeV, so that this scenario does not help with low-energy SUSY.

3. If only \( n_{BNV} \) is fractional, \( B \) is conserved and lepton violation is allowed. This gives rise to collider signatures with multiple leptons and LHC searches put limits near or above a TeV for a stop LSP. Again, this is not satisfactory for low-energy SUSY.

4. If \( n_{LNV} \) is fractional, the only RPV operator is \( \mathcal{M}_{\overline{u}d}, \) which lets a stop LSP decay to jets and little missing energy.\([4]\) Experimental searches typically involve multi-jets (6 to 10), or same-sign dileptons coming from top decays.

We will now consider the last scenario and put bounds on the magnitude of \( \lambda'' \). For semi-integer \( n_{LNV} \), the \( L \)-violating operators are forbidden, but Weinberg’s neutrino mass operator is allowed, thus providing correct order-of-magnitude estimates for the neutrino masses.

\( ^6 \)Some missing energy will arise from the decays of top quarks.
3 Phenomenological constraints

First, let us explain why arbitrarily small RPV coefficients are excluded at the LHC: in this case, the LSP does not decay in the detector, and either exits the detector as missing energy (if neutral), or hadronizes into an R-hadron (if colored). CMS currently excludes $R$-hadrons formed by a stop LSP up to 850 GeV \[8\]. As

$$\Gamma(\bar{t} \to d_i d_j) = \frac{m_{\bar{t}}}{8\pi} \sin^2 \theta_{\tilde{t}} |\lambda''_{3ij}|^2,$$

for $\lambda''_{323} \lesssim \epsilon^{13}$, the decay length is $c\tau > 1\text{m}$ and the stop would hadronize. Then, a stop LSP lighter than 850 GeV has to decay in the detector and it can do so only if $\lambda''_{323} \gtrsim \epsilon^{13} \sim 10^{-9}$. The same argument forbids a light stop decaying through a tiny coefficient in front of the operator $LQ\bar{d}$. Because the RPV couplings cannot be too small, $B$ and $L$ cannot be violated at the same time.

We have just presented a lower limit on the $\lambda''_{323}$; from low-energy nucleon stability, we can estimate an upper limit; for a non-R horizontal symmetry, the stronger limit comes from the neutron decay $n \to \Xi$:

$$|\lambda''_{112}| \lesssim 10^{-8.5} \left( \frac{m_{\tilde{g}}}{100 \text{ GeV}} \right)^{1/2} \left( \frac{m_{\tilde{g}R}}{100 \text{ GeV}} \right)^2 \left( \frac{10^{32} \text{yr}}{\tau_{NN}} \right)^{1/4} \left( \frac{10^{-6} \text{ GeV}^6}{\langle N|ududss|\Xi \rangle} \right)^{1/2},$$

This corresponds to $n_{BNV} \gtrsim 3$. Therefore, if low-energy supersymmetry is hidden at the LHC by baryonic $R$-parity violation, a horizontal symmetry predicts a definite texture for the couplings, and the largest couplings lays between $10^{-9}$ and $10^{-3}$.

Let us mention how low-energy SUSY is reconciled with meson mixing and the Higgs mass measurement, which both seem to point to a higher SUSY scale. First, an horizontal symmetry is naturally able to produce quark-squark alignment, in which the quark and squark mass matrices are diagonal in the same basis in which the gluino interactions are diagonal. This way, FCNCs contributing to $K - \bar{K}$ (and other mesons) mixing are suppressed. Second, in order to get a 126 GeV Higgs with light stops, additional tree-level contributions are needed; in [1], we considered a singlet field $N$, with a NMSSM coupling $\lambda N \phi_u \phi_d$.

4 Conclusions

Limits from direct stop decays in the baryonic RPV scenario are around 100 GeV and they are still coming from LEP and Tevatron.\footnote{See B.Tweedie’s contribution in this conference [12] for a search strategy to update those limits at the LHC.} For gluinos, the situation is better: in [10] two same-sign leptons in the final state are searched for, as a signature of two gluinos decaying as $\tilde{g} \to \tilde{t} \tilde{t} \to \tau \bar{\tau} b$. The 95% confidence level limit on the gluino mass is ...
is $m_{\tilde{g}} > 890$ GeV. In \[11\], gluinos decaying to multiple jets were investigated, and the 95\%CL limits are at 874 GeV (these limits depend on the gluino branching ratios, which in our model can be computed). As mentioned above, the stops cannot be too much lighter than the gluinos, or we would incur in another fine tuning.

We have seen that models that explain the flavor structure of the SM naturally give hierarchical RPV couplings, suppressing those involving the first two generations, and that $R$-parity seems a superfluous assumption when looking for supersymmetric particles. If supersymmetry is to be found at LHC14, it will be stimulating to see which incarnation is reflected in the real world.

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