Dynamical R-Parity Violation

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We present a new paradigm for supersymmetric theories with R-parity violation (RPV). At high scale, R-parity is conserved in the visible sector but spontaneously broken in the SUSY-breaking sector. The breaking is then dynamically mediated to the visible sector and is manifested via non-renormalizable operators at low energy. Consequently, RPV operators originate from the Kähler potential rather than the superpotential, and are naturally suppressed by the SUSY-breaking scale, explaining their small magnitudes. A new set of non-holomorphic RPV operators are identified and found to often dominate over the standard RPV ones. We study the relevant low-energy constraints arising from baryon-number violating processes, proton decay and flavor changing neutral currents, which may all be satisfied if a solution to the Standard Model flavor puzzle is incorporated. The chiral structure of the RPV operators imply new and distinct collider signatures, indicating the need to alter current techniques in searching for RPV at the LHC.

INTRODUCTION

Supersymmetry (SUSY) has long been considered to be the leading candidate for solving the hierarchy problem. However, searches in the first three years of the LHC have failed to uncover evidence for the existence of superpartners, thereby severely constraining the parameter space of the Minimal Supersymmetric Standard Model (MSSM) and pushing the masses of some of the superpartners to uncomfortably high scales. Thus, if supersymmetry is to remain natural, it must manifest itself differently than in standard scenarios.

The vast majority of SUSY searches study events with significant missing energy, as typically follows from the implicit assumption of R-parity conservation. A way to evade many of the bounds is to consider theories in which R-parity is violated [1]. Traditionally RPV models introduce the following holomorphic operators:

\[ \mathcal{O}_{\text{hRPV}} = \frac{1}{2} \lambda_{ijk} L_i L_j \tilde{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \frac{1}{2} \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k, \]

\[ \mathcal{O}_{\text{hBL}} = \mu_i L_i H_u, \quad (1) \]

where \( \mathcal{O}_{\text{hRPV}} \) are the trilinear terms that do not contain dimensionful parameters, while \( \mathcal{O}_{\text{hBL}} \) are the holomorphic bilinear RPV terms, with dimensionful couplings \( \mu_i \). These operators are usually written in a superpotential, \( W_{\text{RPV}} = \mathcal{O}_{\text{hRPV}} + \mathcal{O}_{\text{hBL}} \). The above couplings, however, are strongly constrained as they generically allow for rapid proton decay, di-nucleon decays, neutron-anti-neutron oscillations, flavor changing processes and cosmological depletion of any baryon asymmetries (for a review, see [2]). Thus RPV theories must incorporate extremely small and seemingly ad hoc couplings.

Recently, a proposal for an organizing principle that could explain the smallness and hierarchical nature of the RPV couplings above was introduced [3] (see also [4,5]), based on the Minimal Flavor Violation (MFV) principle, whereby the magnitude of the RPV couplings is related to the small Yukawa couplings of the flavor sector, naturally generating a hierarchy which leads to a viable pattern of RPV. Related models as well as recent studies on the LHC phenomenology of baryonic RPV models can be found in [6-9].

The main goal of this paper is to present an alternative to the traditional approach summarized in [1], by postulating a dynamical origin of RPV. In particular, the visible sector is assumed to be R-parity conserving, while its breaking, which occurs in a hidden sector, is dynamically communicated to the visible sector. An immediate consequence is that RPV-inducing operators naturally appear in the Kähler potential, and are suppressed by the mediation scale, while they may or may not appear in the superpotential. As a result, under some quite general and natural circumstances, the terms in Eq. (1) are not the leading set of RPV operators and are insufficient to describe the low-energy dynamics of the model. In particular, new types of RPV operators with distinct phenomenology naturally arise and must be considered in any search for RPV supersymmetry.

While not necessarily related, it is interesting to postulate a joint mechanism for breaking and mediating both supersymmetry and R-parity (for related ideas see [2]). Since R-parity in the visible sector is equivalent to \((-1)^{3(B-L)+2s}\), where \( s \) is the spin of the particle, the sector which triggers the breaking must be charged under that symmetry too. It is then also natural to consider a flavor-dependent mediation mechanism, such as the so-called flavor mediation models based on the Froggatt-Nielsen (FN) mechanism [10,11], or those which allude to partial compositeness. In such scenarios, additional suppression of the RPV terms is obtained, along the lines mentioned above. These suppressions will typically be present even if the flavor model is unrelated to the mediation scheme.

In what follows we make the following assumptions:

1. Dynamical RPV (dRPV). RPV is broken dynamically in a hidden sector.
II. RPV is related to SUSY breaking.

These assumptions then imply the appearance of novel non-holomorphic RPV operators,

\[ O_{\text{nhRPV}} = \eta_{ijk} \bar{u}_i \bar{e}_j u_k^d + \eta_{ij} Q_i \bar{u}_j L^\dagger_k + \frac{1}{2} \eta_{ijk} Q_i \bar{Q}_j \bar{d}_k \]

\[ + \kappa_i \bar{e}_i H_u H_d^\dagger, \]

\[ O_{\text{hBL}} = \kappa_i L^\dagger_i H_d, \]

which can show up in the Kähler potential, coupled to a SUSY-breaking spurion \( X = M + \theta^2 F_X \). Here we define all the couplings to be dimensionless. The main consequence of these assumptions is that all RPV interactions will automatically be suppressed by, at least,

\[ \epsilon_X \equiv F_X / M^2, \]

which may vary in size from \( O(1) \text{ to } O(10^{-16}) \) as in gravity mediation. Its smallness may explain why all of these terms are very small at low energy.

We may further assume:

III. Dynamical solution to the SM flavor hierarchy.

With this third assumption additional, flavor-dependent suppression factors arise. One then obtains a natural organizing principle which generates a hierarchy in the RPV couplings. Indeed any solution to the flavor hierarchy, such as the above mentioned FN model or partial compositeness, can be incorporated and would typically produce similar hierarchy in the RPV operators.

The RPV operators related to (2) and (3) have not been studied before. We will argue below that the above three assumptions are sufficient to suppress any flavor-violating transitions, and in particular proton decay, without assuming lepton-number conservation. Moreover, the new operators predict novel and distinct LHC signatures. In this paper we study the basic constraints and phenomenology of the above new operators, demonstrating their unique features, as well as the viability of this scheme. A more detailed LHC study and a UV complete model of dRPV will appear in upcoming publications [12].

FRAMEWORK

In accordance with assumptions (I) and (II) discussed above, we consider a two-scale scenario in which the single spurion, \( X \), breaks both R-parity and supersymmetry in a hidden sector, while providing the messenger mass scale. We will see below that \( F_X / M^2 \ll 1 \) is preferable, following constraints on RPV operators. We further assume that \( M \ll M_{Pl} \) for the mediator scale.

To derive constraints on dRPV, its low energy description must be understood. As is customary when studying supersymmetry breaking, the low energy SM Lagrangian is assumed to be accompanied by the above spurion \( X \), parametrizing the effects of the hidden sector. Depending on the UV completion, \( X \) may be charged under various continuous and discrete symmetries which will constrain its low-energy effective couplings. Nonetheless, a low-energy analysis suffices to restrict the form of the RPV operators which may show up. Indeed, one may assume that \( B - L \) is preserved at low energy in the visible sector, as is typically the case. In order to break R-parity, \( X \) must then be charged under \( B - L \), while we will also consider the possibility that it is additionally charged under an unbroken \( U(1)_R \) symmetry.

As a consequence, since \( O_{\text{nhRPV}} + O_{\text{hBL}} \) and \( O_{\text{hRPV}} + O_{\text{hBL}} \) are charged +1 and −1 under \( B - L \), respectively, they are distinguishable at low energy. If, for example, \( X \) is charged −1 under \( B - L \), the Kähler potential and superpotential take the following form at leading order:

\[ K_{dRPV} = \frac{1}{X^1} O_{\text{nhRPV}} + \frac{X}{M_{Pl}^2} O_{\text{hBL}} + \frac{X^1}{M_{Pl}^1} (O_{\text{hRPV}} + O_{\text{hBL}}) + \text{h.c.}, \]

\[ W_{dRPV} = \frac{X}{M_{Pl}^2} (\rho_{ijk} H_d Q_i Q_j Q_k + \rho'_{ijk} H_d Q_i \bar{u}_j \bar{e}_k). \]

Note that the Kähler term \( \frac{1}{X} O_{\text{hRPV}} \) is removed by a Kähler transformation, while the term \( X O_{\text{nhRPV}} / M_{Pl}^2 \) is subleading. We thus find that in this case the holomorphic RPV operators, when generated dynamically, are highly suppressed in comparison to the new non-holomorphic cubic ones. Furthermore, the non-holomorphic bilinear terms are also suppressed and their effect is negligible as discussed below.

If instead \( X \) has charge +1 under \( B - L \), then the leading holomorphic RPV operator is \( \frac{1}{X^1} O_{\text{hRPV}} \), while the leading non-holomorphic term is \( \frac{1}{X^1} O_{\text{nhRPV}} \). At this stage the two terms appear to be of the same order, however the non-holomorphic terms might still be suppressed due to their chiral structure. For instance, the \( QQd^0 \) operator will induce couplings which are suppressed by \( m_d / M \), compared with the \( F_X / M^2 \) suppression of \( O_{\text{hRPV}} \). Similar conclusions are obtained for other choices of charges under \( B - L \).

If \( X \) is further charged under a \( U(1)_R \) symmetry (assuming flavor-independent charges), it is impossible to generate all of the holomorphic and non-holomorphic RPV operators at the same time. Thus, depending on the \( X \) R-charge, only some of the above will appear at low energy. Finally, if the \( B - L \) symmetry is instead promoted to an \( R \)-symmetry, one finds once again that the non-holomorphic RPV operators dominate.

We therefore conclude that in the absence of additional scales, dRPV allows for either the holomorphic or the non-holomorphic RPV operators to be generated, but the non-holomorphic ones should not be neglected. Given
that previous studies consider exclusively holomorphic RPV, we will study below the case when only the non-holomorphic RPV terms appear.

Before analyzing the constraints, let us briefly discuss assumption (III). The inclusion of flavor dynamics implies that the various operators discussed above are suppressed according to their flavor structure. Numerous models that introduce such suppressions exist, including, for example, theories with horizontal symmetries as in FN models [10], or ones with strong interactions [13–15]. Consequently, the low energy parameters, \( \eta, \eta', \eta'' \), \( \kappa \) and \( \kappa' \), are suppressed in a flavor-dependent manner. For example, the \( \eta''_{ijk} \)'s can take the form

\[
\eta''_{ijk} \sim \epsilon |q_i q_j + q_k|\ ,
\]

where \( \epsilon = O(0.1) \) is a small parameter and \( q_a \) are the various charges of the SM fields under the FN symmetry. Similar expressions hold when \( \alpha \) characterize the partial compositeness in the case of an RS-type scenario. While a comprehensive study is beyond the scope of this paper, we stress that all the constraints discussed below are easily satisfied with, for example, a simple choice of FN charges. In particular, a straightforward extension of the alignment model of [16] to the lepton sector allows for a viable dRPV model, without any additional assumption such as the typically needed lepton-number conservation. A complete realization of this scenario will be discussed in an upcoming publication [12].

Finally a remark is in order. Assumption (III) may require introducing an additional spurion (such as the one responsible for breaking the FN symmetry). A spurion of this kind may modify the above discussion which is based on the existence of just two scales, \( X \) and \( M_{pl} \), and as a result the suppression of the holomorphic RPV operators may naively be milder. Complete models, however, will typically include additional symmetries which can forbid the holomorphic operators altogether [12].

LOW ENERGY CONSTRAINTS

The operators in [2] violate baryon (B)- and/or lepton-number (L), in addition to the non-abelian SU(3)_C flavor symmetries of the SM. As a result, low energy bounds exist, which we derive below. As mentioned above, all these bounds are easily satisfied with the inclusion of a simple flavor model.

\[ \Delta B = 2 \text{ Processes} \]

The \( \eta'' \) term in [2] violates baryon-number (B) by one unit. Consequently it is important to check that the bounds on \( \Delta B = 2 \) processes, \( n-\bar{n} \) oscillations and dinucleon decay, obtained by two insertions of this vertex, are obeyed. The simplest way is to integrate out the squarks which will generate a dimension-9 operator. While the most general flavor index structure is allowed, we here display the subset necessary for the constraints. Considering the left diagram of Fig. 1 one finds,

\[
\frac{1}{\Lambda_{ijk}^2} (Q_i Q_j Q_k d_k \bar{d}_k) ,
\]

with the suppression scale,

\[
\frac{1}{\Lambda_{ijk}^2} = \pi \alpha_s \frac{\eta''_{ijk} \eta''_{ikj}}{m_q m_k^2} \epsilon_X^2 .
\]

This leads to \( n-\bar{n} \) oscillations and dinucleon decay \( pp \to \pi^+ \pi^- \) for \( i, j, k = 1 \) and \( pp \to K^+ K^- \) for \( i = j = 1; k = 2 \).

The \( n-\bar{n} \) oscillation time is approximately given by

\[
\tau_{n-\bar{n}} \approx \frac{\Lambda_{111}^S}{2 \pi \Lambda_{QCD}^6} ,
\]

where \( \Lambda_{QCD} \) is the hadronic matrix element which we estimate at 200 MeV. We find,

\[
\tau_{n-\bar{n}} \approx 3 \times 10^8 \text{ s} \left( \frac{m_{q_{12}}}{\text{TeV}} \right)^4 \left( \frac{m_{\bar{q}}}{\text{TeV}} \right) \left( \frac{4 \times 10^{-2}}{\eta_{111}''} \right)^2 \left( \frac{10^{-5}}{\epsilon_X} \right)^2 ,
\]

(11)

to be compared with the experimental bound \( \tau_{n-\bar{n}} > 2.44 \times 10^9 \) s [17].

The same operator also contributes to the dinucleon decay process \( pp \to \pi^+ \pi^- (K^+ K^-) \). The approximate expression for the width is given by [18],

\[
\Gamma \approx \frac{8}{\pi} \frac{\rho_N}{m_N} \frac{\Lambda_{QCD}^{10}}{\Lambda_{pp}^{10}} ,
\]

(12)
where \( \rho_N \simeq 0.25 \text{ fm}^{-3} \) is the nuclear matter density and \( \Lambda_{pp} \equiv \min\{\Lambda_{1k1}, \Lambda_{1k1}\} \) under the assumption that only one operator dominates the process. Here \( k = 1 \) or 2, depending on whether the decay is to pions or kaons. The bound on the lifetime is \( \tau_{pp} \geq 1.7 \times 10^{32} \) years \(^{11} \) while in our model we find,

\[
\tau_{pp} \simeq 5 \times 10^{32} \text{ yr} \left( \frac{m_{d_{R,k}}^2}{\text{TeV}^{10}} \right) \left( \frac{10^{-1}}{\eta_{pp}''} \right)^4 \left( \frac{10^{-5}}{\epsilon_X} \right)^4 ,
\]

where \( \eta_{pp}'' \equiv \max\{\eta_{11k}'', \eta_{11k1}'\} \).

\[ \Delta F = 2 \text{ Processes} \]

Within the Standard Model, flavor changing neutral currents (FCNC) are absent at tree-level, and highly suppressed by the GIM mechanism at one loop. Thus, FCNC observables are extremely sensitive to new physics. In models of RPV, FCNC operators are generated at tree-level, with the strongest constraints obtained from the \( \Delta F = 2 \) neutral meson-mixing processes. If either of the operators, \( Q_i^\dagger u_j L_k^c \) or \( Q_i^\dagger d_k^c \), are present, neutral meson-mixing is generated once the squarks and sleptons are integrated out. The diagrams are shown on the right of Fig. [1] and the corresponding operators generated are,

\[
\begin{align*}
Q_1^{\dagger q_j} & \equiv - \frac{1}{\Lambda_1^2} (Q_i^a Q_i^{\beta}) (Q_j^{\alpha} Q_j^{\beta}) \epsilon_X, \\
Q_4^{\dagger q_j} & \equiv \frac{1}{\Lambda_4^2} u_j^\dagger Q_j^{\dagger \beta} u_i^\dagger \epsilon_X.
\end{align*}
\]

Here the suppressions are given by,

\[
\frac{1}{\Lambda_1^2} = \frac{m_{d_{R,k}}^4}{m_{d_{L,k}}^2} \epsilon_X, \quad \frac{1}{\Lambda_4^2} = \frac{|\eta_{jjk}''|^2}{m_{d_{L,k}}^2} \epsilon_X.
\]

Taking \( m_{Q} \simeq \text{TeV} \) the bounds from neutral meson mixing are \(^{20} \). \(^{20} \)

\[
\begin{align*}
\Delta m_K & : |\eta_{11k}'| \approx 10^{-10} , \\
\Delta m_D & : |\eta_{12k}'| \approx 10^{-8} , \\
\Delta m_{B_d} & : |\eta_{12k}'| \approx 10^{-5} , \\
\Delta m_{B_s} & : |\eta_{23k}'| \approx 10^{-7} .
\end{align*}
\]

All of the dRPV operators are within the above limits for \( \epsilon_X = \mathcal{O}(10^{-5}) \), with or without additional flavor suppressions. We note that the operator \( Q_4^{\dagger d_2} \), which is strongly constrained by \( K - \bar{K} \) mixing, is not generated at tree-level in nonholomorphic RPV, while it is in the standard holomorphic case.

**Proton Decay**

Perhaps the strongest constraint in RPV theories occurs in the case where both B and L are violated (or only B is violated but the gravitino is light), and as a consequence, the proton becomes unstable. The leading contribution to proton decay comes from the diagram on the left in Fig. [2] and gives the decays \( p^+ \to (\pi^0 \text{ or } K^0)(e^+ \text{ or } \mu^+) \). The matrix element for the process is,

\[
\mathcal{M} \simeq 2\eta_{m_{\ell k}}'' \frac{2}{\Lambda_{QCD}^2} \left( \frac{m_{d_{R,k}}}{\text{TeV}} \right) ^4 \left( \frac{10^{-14}}{|\eta_{m_{\ell k}}''|} \right)^2 \left( \frac{10^{-5}}{\epsilon_X} \right)^4 ,
\]

where \( m = 1(2) \) for a pion(kaon) and \( \ell = 1(2) \) for electron(muon). Taking, as before, \( \Lambda_{QCD} = 200 \text{ MeV} \), one finds a lifetime of order,

\[
\tau_p \simeq 5 \times 10^{33} \text{ yr} \left( \frac{m_{d_{R,k}}}{\text{TeV}} \right) ^4 \left( \frac{10^{-14}}{|\eta_{m_{\ell k}}''|} \right)^2 \left( \frac{10^{-5}}{\epsilon_X} \right)^4 .
\]

The above should be compared to the relevant limit. The strongest is found for the \( p \to e^+ \pi^0 \) decay mode, \( \tau_p \gtrsim 8.2 \times 10^{33} \) years \(^{21} \). \(^{21} \)

Another channel for proton decay can appear if the gravitino is light, leading to the decays \( p \to (\pi, K) + \tilde{G} \) as shown in the center of Fig. [2]. The matrix element is estimated to be

\[
|\mathcal{M}|^2 \sim \frac{1}{3} \eta''_{1111} \epsilon_X^2 \frac{m_{\tilde{\Lambda}_{QCD}^2}}{m_{d_{R,k}}^2 m_{d_{L,k}}^2} \epsilon_X ,
\]

and the corresponding lifetime is

\[
\tau_p \sim 2 \times 10^{33} \text{ yr} \left( \frac{m_{d_{R,k}}}{\text{TeV}} \right) ^4 \left( \frac{M}{10^9 \text{GeV}} \right)^2 \left( \frac{10^{-8} \eta_{1111}''}{|\eta_{1111}''|} \right)^2 \left( \frac{F}{F_X} \right)^2 .
\]

Here \( F = \sqrt{3} m_{3/2} M_{pl} \), while \( F_X \) denotes, as above, the F-term for \( X \). In the case of a single SUSY-breaking sector one has \( F = F_X \); more generally, additional sources of SUSY-breaking can exist and will relax the constraint. In this case, the strongest constraint is obtained from a search for \( p \to \nu K \) which gives \(^{21} \), \( \tau_p > 2.3 \times 10^{33} \) years. \(^{21} \)

Finally, proton decay may also result from the lepton number violating operators parameterized by \( \kappa, \kappa' \). These will induce mass and kinetic mixing between the charged leptons and the charginos (via their charged higgsino components). The mixing will lead to proton decay through the diagram shown on the right of Fig. [2]. The decay amplitude is given by,

\[
\mathcal{M} \simeq \eta''_{1111} \kappa_{\nu}^\text{eff} \epsilon_X \frac{\Lambda_{QCD}^2}{m_{d_{R,k}}^2} ,
\]

where \( \kappa_{\nu}^\text{eff} = \kappa_{\nu} m_{\nu} + \kappa_{\nu} m_{\tilde{\nu}} m_{\nu} + \kappa_{\nu} M_{\tilde{\nu}} \) defines the effective mixing between the electron and the chargino. The resulting proton lifetime is

\[
\tau_p \simeq 3 \times 10^{33} \text{ yr} \left( \frac{m_{d_{R,k}}}{\text{TeV}} \right) ^4 \left( \frac{3 \times 10^{-20}}{|\kappa_{\nu}''\eta_{1111}''|} \right)^2 \left( \frac{10^{-5}}{\epsilon_X} \right)^2 .
\]
Cosmology

Rapid $B$ and $L$ violating interactions induced by RPV operators may wash out any pre-existing baryonic or leptonic asymmetry. Consequently, such processes should be highly suppressed at low temperatures. Since sphalerons, active above the weak-scale, violate $B+L$, it is typically required that the RPV-induced rates are sufficiently slow above that scale. The bounds on the dRPV operators are similar to those in standard holomorphic RPV. One finds $\epsilon_X \eta \lesssim 10^{-7}$ and $\kappa_\text{eff} \lesssim 10^{-6}$ where $\eta$ stands for any $\eta_{ijk}$, $\eta'_{ijk}$ or $\eta''_{ijk}$ [2, 22, 23].

As we show below, these cosmological bounds typically imply displaced decays at the LHC. Nonetheless these bounds can be easily evaded in several ways (see [2] and references therein). For example, the bounds are irrelevant if the baryon asymmetry is generated at or below the electroweak scale. Conversely, as discussed in [11, 22], when a single lepton flavor number is approximately conserved the bounds can be significantly weaker.

LHC PHENOMENOLOGY

The phenomenology of models with dRPV can be very different from those with R-parity conservation and even from those with traditional RPV described by [1]. The details depend greatly on the identity of the lightest supersymmetric particle (LSP). Here we briefly comment on three interesting possibilities which crucially differ in their collider phenomenology from standard RPV: stop LSP, gluino LSP and sneutrino LSP, with the first two most relevant for naturalness. Further details on these and other interesting possibilities will be given in [12].

Consider first the stop LSP. In all of the non-holomorphic operators of [2], stop decays are induced from SUSY-conserving interactions in which the stop is extracted from one of the chiral fields. As a consequence, the resulting operators in the Lagrangian all have derivative couplings and hence the decay rate is chirally suppressed. One finds that the dominant decay mode is typically $\tilde{t} \to b\bar{b}$, with a decay length,

$$c\tau_{\tilde{t}} \approx 1 \text{ mm} \left( \frac{300 \text{ GeV}}{m_{\tilde{t}}} \right) \left( \frac{M_{\tilde{t}}}{10^8 \text{GeV}} \right)^2 \frac{1}{\eta''_{333}}. \tag{24}$$

Thus the stop LSP case may manifest itself uniquely as four displaced b’s, where each pair reconstructs to a single displaced vertex, and the two pairs have a similar invariant mass. The situation is illustrated in Fig. 3. We stress that such decays do not exist in the holomorphic RPV scenario. The collider search for a stop LSP should be significantly altered in order to discover dRPV.

Next consider the case of a sneutrino LSP, where the LSP decay is governed by the $\eta'$ couplings which induce the operators $u_L \eta'_{R\tau} \nu_{\overline{b}} + d_L u'_{R\tau} e_{L\tau}$. Since the 3rd generation couplings are typically least suppressed, the leading decay mode will be $\nu_{\overline{b}} \to t_L t_R^\dagger$ with a decay length

$$c\tau_{\nu_{\overline{b}}} \approx 1 \text{ mm} \left[ \frac{10^{-2}}{\eta'_{331}} \right]^2 \left( \frac{10^{-5}}{\epsilon_X} \right)^2 \frac{165 \text{ GeV}}{(1 - 2 \frac{m_{\nu_{\overline{b}}}}{m_{t'}})^2} \sqrt{m_{\nu_{\overline{b}}}^2 - 4m_t^2}. \tag{25}$$

For $\eta'_{331} \lesssim 10^{-2}$ this vertex will be displaced, leading to the interesting LHC signal of 4 displaced top quarks in
the final state.

Finally, a gluino LSP decays via an off-shell stop to two bottoms and a top, \(\tilde{g} \to tbb\). The decay length here is estimated at,

\[
c r_g \simeq 1 \text{ mm} \left(\frac{m_t}{400 \text{ GeV}}\right)^2 \left(\frac{350 \text{ GeV}}{m_g}\right)^5 \left(\frac{M}{10^6 \text{ GeV}}\right)^2.
\]

A late decaying gluino is less constrained than a promptly decaying one. This possibility may allow for a lighter gluino to be produced at the LHC [12].

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