Some Recent Results from the Complete Theory of SUSY without R-parity *

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Abstract

We review an efficient formulation of the complete theory of supersymmetry without R-parity, where all the admissible R-parity violating terms incorporated. Some interesting recent results will be discussed, including newly identified 1-loop contributions to neutrino masses and electric dipole moments of neutron and electron, resulted from R-parity violating $LR$ squark and slepton mixings.

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SOME RECENT RESULTS FROM THE COMPLETE THEORY OF SUSY WITHOUT R-PARITY

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We review an efficient formulation of the complete theory of supersymmetry without R-parity, where all the admissible R-parity violating terms incorporated. Some interesting recent results will be discussed, including newly identified 1-loop contributions to neutrino masses and electric dipole moments of neutron and electron, resulted from R-parity violating LR squark and slepton mixings.

1 The Generic Supersymmetric Standard Model

Supersymmetry without R-parity is nothing but the generic supersymmetric Standard Model, i.e., a theory built with the minimal superfield spectrum incorporating the Standard Model (SM) particles and interactions dictated by the SM (gauge) symmetries and the idea that SUSY is softly broken. The theory is hence generally better motivated than ad hoc versions of R-parity violating (RPV) theories. Here, however, RPV parameters come in various forms. The latter includes the more popular trilinear ($\lambda_{ijk}$, $\lambda'_{ijk}$, and $\lambda''_{ijk}$) and bilinear ($\mu_i$) couplings in the superpotential, as well as soft SUSY breaking parameters of the trilinear, bilinear, and soft mass (mixing) types. From a phenomenological point of view, there is the related notion of (RPV) “sneutrino VEV’s”. In order not to miss any plausible RPV phenomenological features, it is important that all of the RPV parameters be taken into consideration with a priori bias. To emphasize the point, we call the model the complete theory of SUSY without R-parity.

The most general renormalizable superpotential for the supersymmetric SM (without R-parity) can be written as

$$W = \varepsilon_{ab} \left[ \mu_a \hat{H}_u^a \hat{L}_0^a + h_{ij}^a \hat{Q}_i^a \hat{H}_d^a \hat{U}_k^a c \hat{X}_{sjk}^a \hat{L}_0^a \hat{\tilde{E}}_k^a D_k^a \right] + \frac{1}{2} \left( \lambda_{ijk} \hat{L}_0^a \hat{L}_0^b \hat{E}_k^a \right) + \frac{1}{2} \left( \lambda'_{ijk} \hat{L}_0^a \hat{\tilde{D}}_k^a \hat{D}_k^a \right),$$

where $(a,b)$ are $SU(2)$ indices, $(i,j,k)$ are the usual family (flavor) indices, and $(\alpha, \beta)$ are extended flavor index going from 0 to 3. In the limit where $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$ and $\mu_i$ all vanish, one recovers the expression for the R-parity preserving case, with $\hat{L}_0$ identified as $\hat{H}_d$. Without R-parity imposed, the latter is not a priori distinguishable from the $\hat{L}_i$’s. Note that $\lambda$ is antisymmetric in the first two indices, as required by the $SU(2)$ product rules, as shown explicitly here with $\varepsilon_{12} = -\varepsilon_{21} = 1$. Similarly, $\lambda'$ is antisymmetric in the last two indices, from $SU(3)_C$.

R-parity is exactly an ad hoc symmetry put in to make $\hat{L}_0$, stand out from the other $\hat{L}_i$’s as the candidate for $\hat{H}_d$. It is defined in terms of baryon number, lepton number, and spin as, explicitly, $R = (-1)^{3B+L+2S}$. The consequence is that the accidental symmetries of baryon number and lepton number in the SM are preserved, at the expense of making particles and superparticles having a categorically different quantum number, R-parity. The latter is actually not the most effective discrete symmetry to control superparticle mediated proton decay but is most restrictive in terms of what is admitted in the Lagrangian, or the superpotential alone. On the other hand, R-parity also forbids neutrino masses in the supersymmetric SM. The strong experimental hints for the existence of (Majorana) neutrino masses is an indication of lepton number violation, hence suggestive of R-parity violation.

The soft SUSY breaking part of the La-
grangian is more interesting, if only for the fact that many of its interesting details have been overlooked in the literature. However, we will postpone the discussion till after we address the parametrization issue.

2 Parametrization

Doing phenomenological studies without specifying a choice of flavor bases is ambiguous. It is like doing SM quark physics with 18 complex Yukawa couplings, instead of the 10 real physical parameters. As far as the SM itself is concerned, the extra 26 real parameters are simply redundant, and attempts to relate the full 36 parameters to experimental data will be futile. In SUSY without R-parity, the choice of an optimal parametrization mainly concerns the 4 $\hat{L}_a$ flavors. We use here the single-VEV parametrization (SVP), in which flavor bases are chosen such that: 1/ among the $\hat{L}_a$’s, only $\hat{L}_0$ bears a VEV, i.e. $\langle \hat{L}_0 \rangle \equiv 0$; 2/ $h_{ijk}^e (\equiv \lambda_{ijk}) = \frac{v}{\sqrt{2}} \text{diag}(m_1, m_2, m_3)$; 3/ $h_{ijk}^d (\equiv \lambda_{ijk}^d) = \frac{v}{\sqrt{2}} \text{diag}(m_d, m_s, m_b)$; 4/ $h_{ik}^\nu = \frac{v_u}{\sqrt{2}} \text{diag}(m_u, m_c, m_t)$, where $v_0 \equiv \sqrt{2} \langle \hat{L}_0 \rangle$ and $v_u \equiv \sqrt{2} \langle \hat{H}_u \rangle$. Thus, the parametrization singles out the $\hat{L}_0$ superfield as the one containing the Higgs. As a result, it gives the complete RPV effects on the tree-level mass matrices of all the states (scalars and fermions) the simplest structure. The latter is a strong technical advantage.

There are, in fact, many subtle issues involved in a consistent formulation of the complete theory. One has to be particularly careful when the perspective of adding the various RPV terms to the MSSM is taken. Such issues will be addressed in a forthcoming review, to which the readers are referred.

3 Fermion Sector Phenomenology

The SVP gives quark mass matrices exactly in the SM form. For the masses of the color-singlet fermions, all the RPV effects are parameterized by the $\mu_i$’s only. For example, the five charged fermions (3 charged leptons + Higgsino + gaugino), we have

$$M_C = \begin{pmatrix} M_2 & \frac{2\lambda_2}{\sqrt{2}} & 0 & 0 & 0 \\ \frac{2\lambda_2}{\sqrt{2}} & \mu_1 & \mu_2 & \mu_3 & 0 \\ 0 & 0 & m_1 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & 0 & m_3 \end{pmatrix}. \quad (2)$$

Moreover each $\mu_i$ parameter here characterizes directly the RPV effect on the corresponding charged lepton ($\ell_i = e, \mu, \tau$). This, and the corresponding neutralino-neutralino masses and mixings, has been exploited to implement a detailed study of the tree-level RPV phenomenology from the gauge interactions, with interesting results.

Neutrino masses and oscillations is no doubt a central aspect of any RPV model. In our opinion, it is particularly important to study the various RPV contributions in a framework that takes no assumption on the other parameters. Our formulation provides such a framework. Interested readers are referred to Refs. [1-3].

4 Interesting Phenomenology from SUSY Breaking Terms

The soft SUSY breaking part of the Lagrangian can be written as

$$\begin{align*}
\mathcal{V}_{\text{soft}} &= \bar{Q}^i \tilde{\chi}^0_i \tilde{Q} + \bar{U}^i \tilde{\chi}^0_i \tilde{U} + \bar{D}^i \tilde{\chi}^0_i \tilde{D} + \bar{L}^i \tilde{\chi}^0_i \tilde{L} \\
&\quad + \bar{\ell}^i \tilde{\nu}^c_i \tilde{\ell} + \tilde{\nu}^c_i |H_u|^2 + \left[ \frac{M_1}{2} \bar{B} \tilde{B} + \frac{M_2}{2} \tilde{W} \tilde{W} \right] \\
&\quad + \frac{M_3}{2} \tilde{\nu} \tilde{\nu} + \epsilon_{\alpha} \left( b_{\alpha} \tilde{H}^u_{\alpha} \tilde{L}_{\alpha} + c_{\alpha} \tilde{\chi}^0_{\alpha} \tilde{H}^c_{\alpha} \tilde{\nu}^c_{\alpha} \right) \\
&\quad + \tilde{\alpha} \tilde{H}^c_{\alpha} \tilde{\lambda}^c_{\alpha} \tilde{\nu}^c_{\alpha} + \tilde{\alpha} \tilde{H}^c_{\alpha} \tilde{\lambda}^c_{\alpha} \tilde{\nu}^c_{\alpha} + \tilde{\alpha} \tilde{H}^c_{\alpha} \tilde{\lambda}^c_{\alpha} \tilde{\nu}^c_{\alpha} + \tilde{\alpha} \tilde{H}^c_{\alpha} \tilde{\lambda}^c_{\alpha} \tilde{\nu}^c_{\alpha} + \tilde{\alpha} \tilde{H}^c_{\alpha} \tilde{\lambda}^c_{\alpha} \tilde{\nu}^c_{\alpha} + \text{h.c.} \right] \end{align*}$$

where we have separated the R-parity conserving $A$-terms from the RPV ones (recall $\tilde{H}_d \equiv \hat{L}_0$). Note that $\tilde{L}^i \tilde{\mu}^2 \tilde{L}$, unlike the other soft mass terms, is given by a $4 \times 4$ matrix. Explicitly, $\tilde{m}_{\nu_{0\mu}}^2$ corresponds to $\tilde{m}_{\mu_0}^2$ of the MSSM case while $\tilde{m}_{\nu_{0\mu}}^2$’s give RPV mass mixings.

Obtaining the squark and slepton masses is straight forward. The only RPV contribu-
tion to the squark masses is given by a $- (\mu_i^* X_{ijk}^I) \sqrt{\frac{2}{3}}$ term in the $LR$ mixing part. Note that the term contains flavor-changing $(j \neq k)$ parts which, unlike the $A$-terms ones, cannot be suppressed through a flavor-blind SUSY breaking spectrum. Hence, it has very interesting implications to quark electric dipole moments (EDMs) and related processes such as $b \to s \gamma$.

For instance, it contributes to neutron EDM at 1-loop order, through a simple gluino diagram of the $d$ squark. If one naively imposes the constraint for this RPV contribution itself not to exceed the experimental bound on neutron EDM, one gets roughly $\text{Im}(\mu_i^* X_{ijk}^I) \lesssim 10^{-6}$ GeV, a constraint that is interesting even in comparison to the bounds on the corresponding parameters obtainable from asking no neutrino masses to exceed the Super-Kamiokande atmospheric oscillation scale.

Things in the slepton sector are more complicated. The $1 + 4 + 3$ charged scalar masses are given in terms of blocks

$$
\widetilde{M}_{L}^2 = \tilde{m}_L^2 + \mu_L^* \mu_L + M_\mu^2 \cos^2 \beta \left[ \frac{1}{2} - \sin^2 \theta_W \right] + M_\epsilon^2 \sin^2 \beta \left[ 1 - \sin^2 \theta_W \right],
$$

$$
\widetilde{M}_{H}^2 = \tilde{m}_H^2 + m_{\tilde{e}}^2 \mu_\mu + M_{\mu}^2 \cos 2 \beta \left[ \frac{1}{2} + \sin^2 \theta_W \right] + \left( M_\mu^2 \cos^2 \beta \left[ 1 - \sin^2 \theta_W \right] \begin{pmatrix} 0_{1x3} \\ 0_{3x3} \end{pmatrix} \right) + (\mu_\mu^* \mu_\mu),
$$

$$
\widetilde{M}_{H}^{\mu R} = \tilde{m}_H^2 + m_{\tilde{e}} \mu_\mu^* + M_{\mu}^2 \cos 2 \beta \left[ - \sin^2 \theta_W \right]; \quad (4)
$$

and

$$
\widetilde{M}_{L}^{\mu R} = (B_\alpha^I) + \left( \frac{1}{2} M_\epsilon^2 \sin 2 \beta \left[ 1 - \sin^2 \theta_W \right] \right)_{0_{1x3}}, \quad (5)
$$

$$
\widetilde{M}_{H}^{\mu R} = - (\mu_\mu^* \lambda_{\alpha \beta}) \frac{v_0}{\sqrt{2}}, \quad (6)
$$

$$
(\widetilde{M}_{L}^{\mu R})^T = \left( 0_{3x3} \right) \frac{v_0}{\sqrt{2}} - (\mu_\mu^* \lambda_{\alpha \beta}) \frac{v_0}{\sqrt{2}}. \quad (7)
$$

We have to skip the neutral scalar part here. The RPV contributions to the charged, as well as neutral, scalar masses and mixings give rise to new terms in quarks and electron EDM's, $b \to s \gamma$, $\mu \to e \gamma$, and neutrino masses diagrams that have been largely overlooked. The last includes diagrams corresponding to a SUSY version of the popular Zee neutrino mass model. Details are to be found in the cited references.

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