NEW PHYSICS BEYOND THE STANDARD MODEL

Electric Dipole Moments in the Generic Supersymmetric Standard Model*

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Abstract—The generic supersymmetric standard model is a model built from a supersymmetrized standard model field spectrum and the gauge symmetries only. The popular minimal supersymmetric standard model differs from the generic version in having $R$ parity imposed by hand. We review an efficient formulation of the model and some of the recently obtained interesting phenomenological features, focusing on one-loop contributions to fermion electric dipole moments. © 2002 MAIK “Nauka/Interperiodica”.

1. INTRODUCTION

Fermion electric dipole moments (EDMs) are known to be extremely useful constraints on (the $CP$-violating part of) models depicting interesting scenarios beyond Standard Model (SM) physics. In particular, the experimental bounds on neutron EDM ($d_n$) and electron EDM ($d_e$) are very stringent. The current numbers are given by $d_n < 6.3 \times 10^{-26} e\text{ cm}$ and $d_e < 4.3 \times 10^{-27} e\text{ cm}$. The SM contributions are known to be very small ($d_n \sim 10^{-22} e\text{ cm}$ and $d_e \sim 8 \times 10^{-41} e\text{ cm}$), given that the only source of $CP$ violation has to come from the phase in (charged current) quark flavor mixings.

Extensions of the SM normally are expected to have potentially large EDM contributions. For instance, for the Minimal Supersymmetric Standard Model (MSSM), there are a few sources of such new contributions. For example, they can come in through $LR$ sfermion mixings. The latter have two parts, an $A$-term contribution as well as a $F$-term contribution. The $F$ term is a result of the complex phase in the so-called $\mu$ term. The resulting constraints on MSSM have been studied extensively. We are interested here in the modified version with $R$ parity not imposed. We will illustrate that there are extra contributions at the same level and will discuss the class of important constraints resulting from them [1–6].

2. THE GENERIC SUPERSYMMETRIC STANDARD MODEL

A theory built with the minimal superfield spectrum incorporating the SM particles and the admissible renormalizable interactions dictated by the SM (gauge) symmetries together with the idea that supersymmetry (SUSY) is softly broken is what should be called the generic supersymmetric standard model (GSSM). The popular MSSM differs from the generic version in having a discrete symmetry, called $R$ parity, imposed by hand to enforce baryon and lepton number conservation. With the strong experimental hints at the existence of lepton-number-violating neutrino masses, such a theory of SUSY without $R$ parity deserves ever more attention. The GSSM contains all kinds of (so-called) $R$-parity-violating (RPV) parameters. These include 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. In order not to miss any plausible RPV phenomenological features, it is important that all of the RPV parameters be taken into consideration without a priori bias. We do, however, expect some sort of symmetry principle to guard against the very dangerous proton decay problem. The emphasis is hence put on the lepton-number-violating phenomenology. The renormalizable superpotential for the GSSM can be written as

$$W = \varepsilon_{ab} \left[ \mu_{ij} \hat{H}_a^i \hat{L}_b^j + h_{ik} \hat{Q}_a^i \hat{H}_b^j \hat{U}_c^k \right] + \lambda_{ijk} \hat{L}_a^i \hat{Q}_b^j \hat{D}_c^k + \frac{1}{2} \lambda_{\alpha\beta k} \hat{L}_a^\alpha \hat{L}_b^\beta \hat{E}_c^k + \frac{1}{2} \lambda'_{ijk} \hat{U}_a^i \hat{D}_b^j \hat{D}_c^k + \frac{1}{2} \lambda''_{ijk} \hat{D}_a^i \hat{D}_b^j \hat{D}_c^k,$$

where $(a, b)$ are $SU(2)$ indices, $(i, j, k)$ are the usual family (flavor) indices, and $(\alpha, \beta)$ are extended flavor indices going from 0 to 3. At the limit where $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$, and $\mu_i$ all vanish, one recovers the expression for the $R$-parity preserving MSSM, with $\hat{L}_0$ identified as $\hat{H}_d$. Without $R$ parity imposed, the
latter is not a priori distinguishable from $\hat{L}_i$. 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 $\bar{L}_0$ stand out from the other $\hat{L}_i$ as the candidate for $\tilde{H}_d$. It is defined in terms of baryon number, lepton number, and spin as, explicitly, $R = (-1)^{3B+L+2S}$. The consequence is that the random 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 [7], 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 [8] is an indication of lepton-number violation, hence suggestive of $R$-parity violation.

The soft SUSY-breaking part of the Lagrangian 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 of its interesting details to a future paper.

3. 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 the GSSM, the choice of an optimal parametrization mainly concerns the $4\hat{L}_\alpha$ flavors. We use here the single-VEV parametrization [9, 10] (SVP), in which flavor bases are chosen such that: (1) among the $\hat{L}_\alpha$, only $\bar{L}_0$ bears a VEV, i.e., $(\hat{L}_i) \equiv 0$; (2) $h_{jk}^e(\equiv \lambda_{0jk}) = (\sqrt{2}/v_0)\text{diag}(m_1, m_2, m_3)$; (3) $h_{jk}^d(\equiv \lambda_{0jk}) = -(\sqrt{2}/v_0)\text{diag}(m_d, m_s, m_b)$; (4) $h_{jk}^\nu = (\sqrt{2}/u_0)\text{V}^\text{CKM}_{\nu} \text{diag}(m_u, m_c, m_t)$, where $v_0 \equiv \sqrt{2}(\bar{L}_0)$ and $u_0 \equiv \sqrt{2}(\tilde{H}_u)$. The big advantage of the SVP is that it gives the complete tree-level mass matrices of all the states (scalars and fermions) the simplest structure [1, 10].

4. LEPTONS IN GSSM

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

\[
\mathcal{M}_c = \begin{pmatrix}
M_2 & \frac{g_s v_0}{\sqrt{2}} & 0 & 0 & 0 \\
\frac{g_s v_0}{\sqrt{2}} & \mu_0 & \mu_1 & \mu_2 & \mu_3 \\
0 & 0 & m_1 & 0 & 0 \\
0 & 0 & 0 & m_2 & 0 \\
0 & 0 & 0 & 0 & m_3
\end{pmatrix}.
\]

Moreover, each $\mu_i$ parameter here directly characterizes the RPV effect on the corresponding charged lepton ($l_i = e, \mu$, and $\tau$). This, as well as the corresponding neutrino–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 [9].

Neutrino masses and oscillations are no doubt one of the most important aspects of the model. Here, it is particularly important that the various RPV contributions to neutrino masses, up to the one-loop level, be studied in a framework that makes no assumption on the other parameters. Our formulation provides such a framework. Interested readers are referred to [1, 11–14].

5. SOFT SUSY-BREAKING TERMS AND THE SCALAR MASSES

Obtaining the squark and slepton masses is straightforward once all the admissible soft SUSY-breaking terms are explicitly written [1]. The soft SUSY-breaking part of the Lagrangian can be written as

\[
V_{\text{soft}} = \epsilon_{ab} B_\alpha H_u^a \bar{L}_\alpha \bar{E}_b + \epsilon_{ab}[A_{ij}^U \tilde{Q}_i^c H_u^b \tilde{U}_j^c + A_{ij}^D \tilde{U}_d^a \tilde{D}_j^b \tilde{L}_i^c + A_{ij}^E \tilde{E}_j^d \tilde{E}_i^a] + \text{h.c.}
\]

where we have separated the $R$-parity-conserving $A$ terms from the RPV ones (recall $\tilde{H}_d \equiv \bar{L}_0$). Note that $\bar{L}_i^c \tilde{H}_u^a \tilde{L}$, unlike the other soft mass terms, is given