Impact on SUSY-Breaking Models of the $R$-Parity Violating Squark Interpretation of the HERA Anomaly

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I. INTRODUCTION

The mechanism of supersymmetry (SUSY) breaking and how it is communicated to the observable sector is still an unsolved puzzle. It has been assumed that the SUSY is broken in a hidden sector at a scale of \(~10^{11}\) GeV and the SUSY breaking is communicated to the visible sector via the gravitational interaction. Recently, another class of models has been proposed where SUSY is broken in a hidden sector at a scale around \(10^5\) GeV and the SUSY breaking is communicated to the visible sector via the standard model gauge interactions [1]. Now the question is how to distinguish between these two scenarios by experiments. One method is the direct search for their signatures in collider experiments. So far all direct searches for SUSY particles at current colliders like the Fermilab Tevatron, LEP, and HERA have been negative. Recent results from HERA [2,3] on deep inelastic scattering have showed an excess of events in the high-$Q^2$ and large $x,y$ region; specifically H1 showed an impressive enhancement in a single $x$ bin corresponding to $M = \sqrt{s_x} \simeq 200$ GeV, 7 events were observed where only one was expected. Further data has given one more event [4] so there are now 8 events where 1 only was expected. Further data has given one more event [4] so there are now 8 events where 1 only was expected. Further data has given one more event [4] so there are now 8 events where 1 only was expected.

Although still more data is needed to confirm this excess in the cross section, many attempts have already been made to explain it. These include eeqq contact interactions [5], leptoquark production [6,7], and $R$-parity violating (RPV) squark production [8]. It is possible to construct models of contact interactions, which satisfy the known constraints such as atomic parity violation, LEP data, and low energy electron-nucleon and neutrino-nucleon scattering data [8], but the effect is very small. The leptoquark explanation also runs into trouble because the latest CDF [9] and D0 [10] bounds rule out the mass of the first generation leptoquark up to 213 and 225 GeV, respectively, at a 95% CL assuming the leptoquark decays entirely into $e\nu$. On the other hand, the RPV squark remains a viable solution. The squark can either be the left-handed scalar charm $c_L$ or the lighter mass eigenstate of the scalar top $\tilde{t}_1$ with a mass around 200 GeV. Such a 200 GeV squark has an important impact on SUSY-breaking models.

In this paper, we point out that it is almost impossible to generate such light squarks in gauge-mediated SUSY-breaking models even if we include large RPV couplings. We show explicitly in the minimal gauge-mediated models that squark masses are excluded up to 300 GeV in the parameter space allowed by the experimental mass limits of the Higgs bosons, the chargino, and the scalar tau. On the other hand, in the supergravity-motivated models it is possible to generate squarks of mass around 200 GeV.

II. THE $R$-PARITY VIOLATING SQUARK SOLUTION

The $R$-parity violation is introduced in the superpotential via additional terms:

$$W_R = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i^c D^c_j D_k^c$$

where $L_i, E^c, Q, U^c, D^c$ denote the superfields and $i, j, k$ are generation indices. Here we already assume the absence of the $L_i H_u$ term and $\lambda'$ to be zero because they are not relevant for the HERA high-$Q^2$ events and zero $\lambda''$‘s can avoid rapid proton decay.

The process relevant to the HERA events is $e^+d \rightarrow \tilde{c}_L(\tilde{t}_L) \rightarrow e^+d$. The weak eigenstates $\tilde{t}_L$ and $\tilde{t}_R$ of the stop mix to form the mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$. The values of $\lambda'_{121}$ and $\lambda''_{131}$ needed to explain the large cross sections at HERA are $(0.03 - 0.04)/\sqrt{B}$ [11], where $B$ is the branching ratio for the squark to decay into $e^+d$. To satisfy the constraints from atomic parity violation and from the leptoquark search at the Tevatron the branching ratio $B$ must be within the range $0.3 - 0.5 \lesssim B \lesssim 0.75$ [11,12], which implies $0.03 \lesssim \lambda'_{121}, \lambda''_{131} \approx 0.07$. The production of $\tilde{c}_L$ cannot explain the anomaly because the coefficient $\lambda'_{111}$ is tightly constrained by neutrinoless double beta decay [12]. The production via sea partons also requires large $\lambda''$, which are either already ruled out or close to the allowed limits [8]. Thus, the most likely explanation within SUSY is the production of $\tilde{c}_L$ or $\tilde{t}_1$ with $\lambda'_{121}$ or $\lambda''_{131}$ of order $0.03 - 0.07$. These coefficients
\(\lambda'_{21}\) and \(\lambda'_{31}\) are sufficiently small that the sparticle spectrum is not affected appreciably by their presence. However, there are still some \(\lambda'_{ijk}\) that are neither constrained by present experiments nor necessarily small due to symmetry; in particular \(\lambda'_{233}\) and \(\lambda'_{333}\).

The relevant RPV terms in our RGE analysis correspond to \(\lambda'_{233}\) and \(\lambda'_{333}\) in the superpotential \(W_R\). The corresponding trilinear terms are \(C'_{ijk} \tilde{L}_i \tilde{Q}_j \tilde{D}_k\) with \(ijk = 233, 333\). For example, the RGE for \(M^2_{Q_L}\) is given by:

\[
\frac{dM^2_{Q_L}}{dt} = \frac{2}{16\pi^2} \left[ -\frac{1}{15} g^2_1 M^2_1 - 3 g^2_2 M^2_2 - \frac{16}{3} g_3^2 M^2_3 + h^2侍 + h^2表 \right. \\
+ C'_{233}^2 + C'_{333}^2 + \lambda'_{233}^2 M^2_{L_2 t_2} + \lambda'_{333}^2 M^2_{L_3 t_3} + \lambda'_{233}^2 + \lambda'_{333}^2 \left( M^2_{Q_L} + M^2_{\nu_R} \right) \right],
\]

where the notation can be found in Ref. [13]. The first line of Eq. (2) contains the \(R\)-parity conserving contributions and the rest are \(R\)-parity violating. Although \(\lambda'_{233}\) and \(\lambda'_{333}\) are not constrained by existing experiments, we restrict them by requiring all Yukawa couplings and these \(\lambda'\) to be perturbative up to the GUT scale. We find that in the range \(\tan\beta = 2 - 50\), \(\lambda'_{233}\) and \(\lambda'_{333}\) are required to be less than 0.5 - 0.7 at the weak scale in order to keep all Yukawa couplings perturbative.

III. THE MINIMAL GAUGE-MEDIATED MODELS

In the minimal gauge-mediated model, the standard model gauge interactions communicate the SUSY breaking to the visible sector and give masses to the gauginos and the scalars:

\[
M_i = n g \left( \frac{\Lambda}{M} \right) \frac{\alpha_i(M)}{4\pi} \Lambda, \quad m^2_0 = 2 n f \left( \frac{\Lambda}{M} \right) \Lambda^2 \sum_{i=1}^{3} k_i \left( \frac{\alpha_i(M)}{4\pi} \right)^2,
\]

where \(\Lambda\) is the SUSY breaking scale and \(M\) is the scale at which the soft masses are introduced. The sum is over \(SU(3) \times SU(2)_L \times U(1)_Y\), with \(k_1 = \frac{3}{5}, k_2 = \frac{3}{2}\) for \(SU(2)_L\) doublets and zero for singlets, and \(k_3 = \frac{1}{2}\) for color triplets and zero for color singlets. \(n\) is the number of multiplets in the messenger sector, and \(g(\Lambda/M)\) and \(f(\Lambda/M)\) are the messenger-scale threshold functions. The soft SUSY-breaking parameters \(A, C_{233}',\) and \(C_{333}'\) are set to zero at the scale \(M\) because they are induced only by higher loops.

The input parameters are \(M, A,\) and \(\tan\beta = v_2/v_1\), where \(v_1\) and \(v_2\) are the vacuum expectation values of the two Higgs doublets. We vary the minimal model by adding more multiplets to the messenger sector, represented by \(n > 1\). The procedures for running the RGE is as follows: (i) we use the inputs \(m^{phys}_1 = 175\) GeV which is related to \(m_t(m_t)\) by \(m^{phys}_1 = m_t(m_t)(1 + 4\alpha_t/3\pi)\), \(m_\tau(m_\tau) = 4.25\) GeV, \(m_\tau(m_\tau) = 1.784\) GeV, \(\alpha_{em}(M_Z) = 128.06\) at \(M_Z = 125.1 \text{GeV}\), and \(\alpha_s(M_Z) = 0.118\). We chose \(M_{\text{weak}} = m_t(m_t)\). The values for \(\lambda'_{233}\) and \(\lambda'_{333}\) are chosen between 0.05 and 0.5 at \(M_{\text{weak}}\); (ii) we evolve all the gauge, Yukawa, and RPV couplings from \(M_{\text{weak}}\) to the scale \(M\) using the SUSY RGE [13,14]. At the scale \(M\) we calculate the gaugino and scalar masses using Eq. (3); (iii) we evolve all the soft SUSY parameters except \(B\) and \(\mu\) from \(M\) down to \(M_{\text{weak}}\). Then we use the full 1-loop effective potential and by minimization solve for \(\mu\) and \(B\). The \(\mu\) parameter is determined up to a sign, and the CLEO data on the inclusive decay \(b \rightarrow s\gamma\) prefers \(\mu < 0\) [2]. In order to maintain perturbative unification we consider only \(n \leq 4\). In the absence of late inflation cosmological constraints put an upper bound on the gravitino mass of about \(10^4\) eV [22], which restricts \(M/\Lambda = 1.1 - 10^4\).

For the supergravity motivated models we assume the universal boundary conditions at the GUT scale, i.e., a common scalar mass \((m_0)\), a common gaugino mass \((m_{1/2})\), and a common trilinear coupling \((A)\). We run all the soft parameters from the GUT scale down to the weak scale.

IV. RESULTS

Figures 1 and 2 show our main result. From Fig. 1, we conclude that it is very difficult, if not impossible, to generate a squark, either \(\tilde{c}_L\) or \(\tilde{t}_1\), of mass 200 GeV in minimal gauge-mediated models for \(n = 1 - 4\) and \(M/\Lambda = 1.1 - 10^4\). In Fig. 2, the shaded regions are excluded by the lower bound on the lighter neutral Higgs boson, \(m_{h^0} < 60\) GeV, which already covers the radiative electroweak-symmetry breaking. Contours of squark masses for \(M_{\tilde{c}_L}\) (dot-dashed) and \(M_{\tilde{t}_1}\) (dashed) are shown. It is clear that a squark mass of 200 GeV is almost impossible in all 4 cases shown, \(n = 1, 4\) and \(M/\Lambda = 1.1, 10^4\). Up to this point, we have not used any mass limits on the SUSY particles. Constraints on SUSY particle masses depend on whether the neutralino or the scalar tau is the NLSP (the gravitino is the LSP and \(\tilde{\nu}_{\tau L}\) is heavier than \(\tilde{\tau}_1\) in most of the parameter space.) In Fig. 2, we show the contour of \(r = M_{\tilde{\tau}_1}/M_{\chi_1^0} = 1\); above

\[1\] It was pointed out in Ref. [13] that a small neutrino mass is generated through the vev of the sneutrino by the renormalization group equations. The neutrino mass then constrains severely the \(\lambda'\). On the other hand, it was pointed out in Ref. 16 that there are ambiguities on these bounds due to rotations in the \((L_u, H_u)\) space and the effect can actually be suppressed by a dynamical alignment mechanism or a horizontal symmetry. We therefore do not consider this neutrino mass constraint in picking the values for \(\lambda'\).
or to the right of this contour $\tilde{\tau}_1$ is the NLSP, otherwise $\chi_0^0$ is the NLSP. When $\tilde{\tau}_1$ is the NLSP we use the constraint $M_{\tilde{\tau}_1} > 45$ GeV; when $\chi_0^0$ is the NLSP we use the chargino-mass constraint $M_{\chi_1^0} > 80$ GeV [23]. In RPV theories, the chargino can decay into jets or multi-jets plus leptons or missing energy, which ALEPH has searched for and put a bound on $M_{\chi_1^0} > 83 - 85$ GeV [23] (we use a conservative value of 80 GeV); when $\tilde{\tau}_1$ is the NLSP there is no published limit, but we argue that $\tilde{\tau}_1$ decays into jets, $\tilde{\tau}_1 \rightarrow q\bar{q}'$, via RPV couplings and should have been copiously seen in LEP1 if $M_{\tilde{\tau}_1} < 45$ GeV. From Fig. 1 this chargino or scalar tau mass constraint can easily exclude squark masses up to 300 GeV for $n = 1 - 4$ and $M/\Lambda = 1.1 - 10^4$.

We have used large RPV couplings ($\lambda_{333} = \lambda_{233} = 0.45$) in the figures. Other values of $\lambda$ give similar results. We have repeated our RGE analysis with much smaller $\chi_0^0 = 10^4$, $\tilde{\tau}_1$ or $\tilde{\chi}_1^0$, via the RPV couplings (the quark-squark mode is no hard photons in the final state of SUSY particle de-
cays in gauge-mediated models with R-parity violation. In supergravity-motivated models with R-parity violation, the lightest neutralino decays with similar signatures. Consequently, these two different SUSY-breaking scenarios cannot be distinguished by the decay patterns of the SUSY particles if R-parity is violated. Nevertheless, evidence of squarks ($\tilde{c}_L$ or $\tilde{t}_1$) of mass around 200 GeV can distinguish rather cleanly between gauge-mediated and supergravity-motivated models.

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FIG. 1. Contour plots of scalar top (dashed) and scalar charm (dot-dashed) masses in the plane of $\Lambda$ vs $\tan \beta$. The shaded region is excluded by the radiative electroweak-symmetry breaking and $M_{h^0} < 60$ GeV. The lightest chargino mass $M_{\tilde{\chi}_1^+} = 80$ GeV, the scalar tau $M_{\tilde{\tau}_1} = 45$ GeV, and the ratio $r \equiv M_{\tilde{\tau}_1}/M_{\tilde{\chi}_1^0} = 1$ are also plotted. The region excluded by the chargino and the scalar tau masses are: (i) when the neutralino is the NLSP (i.e. below or to the left of the curve $r = 1$) the region to the left of the curve $M_{\tilde{\chi}_1^+} = 80$ GeV is excluded; (ii) when the scalar tau is the NLSP (i.e. above or to the right of the curve $r = 1$) the region above or to the left of the curve $M_{\tilde{\tau}_1} = 45$ GeV is excluded.
FIG. 2. Contour plots of the scalar top $\tilde{t}_1$ (dashed) and the scalar charm $\tilde{c}_L$ (dot-dashed) in the plane of $m_{1/2}$ vs $m_0$ in supergravity models. The value of $A_G$ at the GUT scale is chosen as $A_G = -250$ GeV. In addition, we use $\tan \beta = 3$, and $\lambda'_{233} = \lambda'_{333} = 0.45$. The shaded region is excluded by the constraints: $m_{\tilde{t}_0} < 60$ GeV, $M_{\tilde{\chi}^+} < 80$ GeV, $M_{\tilde{\tau}_1} < 45$ GeV, and $M_{\tilde{\nu}_{\tau L}} < 45$ GeV.