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Supersymmetric interpretation of high–Q^2 HERA events and other related issues

Jihn E. Kim[a,b*] and P. Ko[c†]

[a] *Lyman Laboratory of Physics, Harvard University*

Cambridge, Massachusetts 02138

[b] *Department of Physics, Seoul National University*

Seoul 151-742, Korea

[c] *Department of Physics, Hong-Ik University, Seoul 121-791, Korea*

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Abstract

In the framework of the minimal supersymmetric standard model (MSSM) with $R-$parity violation, the high–Q^2 HERA events can be interpreted as the $s-$channel production of a single stop of $M_{\tilde{t}_1} \approx 200$ GeV, whose dominant decay modes are assumed to be the $R-$parity violating $e^+ + d$ and the $R-$parity conserving $\chi^+ + b$. Assuming only one coupling λ'_{131} is nonzero of order $\sim 0.04 - 0.12$, we find that (i) the high$-Q^2$ HERA events can be understood as an $s-$channel stop production with a subsequent decay into $e^+ +$ (single jet), and (ii) the ALEPH 4-jet events can be understood in the scenario suggested by Carena *et al.*. We briefly discuss other physics signals of this scenario at other places such as HERA, LEP200 and Tevatron. The best test for our scenario is to observe the stop decay into $\chi^+ + b$ followed by $\chi^+ \to \tilde{e}^+ + \nu_e$ and $\tilde{e}^+ \to q + \bar{q}'$ via the $R-$parity violating coupling.

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*jekim@huhepl.harvard.edu

†pko@phyc.snu.ac.kr

Recent observation of the high$-Q^2$ event excess in the e^+p deep-inelastic scattering (DIS) at HERA by both H1 and ZEUS Collaboratrions may be a signal of new physics beyond the standard model (SM), if it is confirmed in the forthcoming run this year. H1 reports 12 deep-inelastic events from data of 14 pb^{-1} at $Q^2 > 15,000$ GeV^2 with large e^+-jet invariant mass around $M \equiv \sqrt{xs} = 200$ GeV [1], where only 5 event is expected according to the standard model (SM) prediction. ZEUS reports 5 events from data of 20 pb^{-1} at similar high x and $Q^2 > 20,000$ GeV^2 region where 2 events are expected from the SM, although the events are scattered wider and thus the resonance structure in the Bjorken x variable is not apparent [2]. These two data may not be consistent with each other [3] as well as with the SM prediction as a result of statistical fluctuations, and we have to await more data accumulations before we try to draw any concrete conclusions regarding the possible source of new physics. Combining the H1 and the ZEUS data, one finds that

$$\sigma(e^+ + p \to e^+ + (\text{a single jet}) + X;\ Q^2 > 20,000\ \text{GeV}^2) \approx 0.2\ \text{pb}, \tag{1}$$

whereas the SM contribution is negligible. One simple way to increase the neutral current (NC) cross section at HERA is to modify the parton distribution functions (PDF's). The PDF's at very high x and Q^2 may be altered so that one can have an excess of events of NC process at HERA [4]. However, the possible resonance structure in $x \approx 0.44$ may be hard to explain in such attempts. Also, PQCD corrections to the NC process at HERA should be properly included in order to reduce theoretical uncertainties within the SM [5]. With these remarks kept in mind, it is tantalizing to regard this HERA anomaly as a real physics signal, and to speculate what kind of new physics could explain this high$-Q^2$ HERA events.

There are many possibilities in choosing new physics scenarios beyond the SM. Since the minimal supersymmetric standard model (MSSM) is one of the leading candidates for physics beyond the SM, it provides us with a natural framework in which we can analyze any experimental anomalies that deviate from SM predictions. The R_b and $\alpha_s(M_Z^2)$ constituted such examples, although these problems are gone now [6]. Another anomaly is the ALEPH four-jet events [7] (which was not seen at other detectors, however). Although the experimental situations need to be clarified among four groups at LEP, there have been some attempts to resolve the ALEPH 4-jet anomaly in the framework of the MSSM with $R-$pariy violations [8] [9]. In this work, we try to interpret the high$-Q^2$ HERA events in terms of a single stop ($\tilde{t}_1$) production in the framework of the MSSM *with R-parity violations* [1]. More specifically, we choose the scenario proposed by Carena *et al.* [9] (the CGLW scenario) as a possible solution to the ALEPH 4-jet anomaly, because this scenario deals with pair production and decays of two particles with different masses at LEP in the supersymmetric theories.

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[1]There is another model-indepedent approach based on the effective lagrangian language. In this framework, the high$-Q^2$ events at HERA can be fit to the following universal contact interaction lagrangian [10] : $-\frac{4\pi}{\Lambda^2}\ \bar{e}\gamma^\mu\gamma_5 e\ \sum_{q=u,d,s} \bar{q}\gamma_\mu\gamma q$ for $\Lambda \simeq 3$ TeV. Such operator can be accomodated in theories with large family symmetry group, $SU(12)$ [11] or $SU(45)$ [12]. However, such contact term seems to be against the other experiments from LEP2 [13] and the muonium hyperfine splitting [14].

In the MSSM, the $R-$parity violation is described by the following renormalizable superpotential,

$$W_{R\!\!\!/_p} = \lambda_{ijk}\ L_i L_j E_k^c + \overline{\lambda'_{ijk}}\ L_i Q_j D_k^c + \lambda''_{ijk}\ U_i^c D_j^c D_k^c + \mu_i L_i H_2. \tag{2}$$

The proton decay can be avoided by setting $\lambda''_{ijk} = 0$. In the CGLW scenario, it is assumed that only one of the couplings, $\overline{\lambda'_{1jk}}$ (with $j,k = 1$ or 2), is nonvanishing [2] in the range of (a few) $\times\, 10^{-4} < \overline{\lambda'_{1jk}} < 10^{-2}$. Then, the ALEPH 4-jet events can be interpreted as $e^+e^- \to \tilde{e}_L \tilde{e}_R$ via neutralino exchanges, followed by the $R-$parity violating decay of the $\tilde{e}_L$ into two jets. The other state, $\tilde{e}_R$, also decays into two jets through the $\tilde{e}_L - \tilde{e}_R$ mixing [9]. CGLW assumed that $M_{\tilde{e}_L} = 58$ GeV, $M_{\tilde{e}_R} = 48$ GeV, in order to fit the dijet invariant masses reported by ALEPH Collaboration. Also $M_1 = 80 - 100$ GeV, and $M_2 > 500$ GeV in order to suppress the sneutrino pair productions in the e^+e^- annihilations at LEP. With this choice of parameters, the lightest neutralino is dominantly bino $\tilde{B}$ [9], with mass around 100–120 GeV.

The $\overline{\lambda'}$ couplings in Eq. (1) are unique in the sense that they can be probed at HERA where $e^-(e^+)$ and $u(d)$ in the proton can make $\tilde{d}_{Rj}$ ($\tilde{u}_{Lj}$) resonance via the $R-$parity violating $\overline{\lambda'_{1j1}}$ coupling ($j = 1, 2$ or 3). Therefore, the CGLW scenario can be tested at DESY if the spectrum of superparticles satisfies certain conditions. There are various constraints on these couplings [15] [16]. It turns out that $\overline{\lambda'_{131}}$ is less constrained than other couplings. Thus we assume that only $\overline{\lambda'_{131}}$ is nonvanishing in Eq. (1). The most stringent limit on this coupling comes from the atomic parity violation (APV). The most important contribution comes from the light stop exchange induced by Eq. (1) (or Eq. (6) below). From the new data on APV [17] [18], we have

$$|\lambda'_{131} \cos\phi_{\tilde{t}}| < 0.12 \tag{3}$$

for $M_{\tilde{t}_1} = 200$ GeV. The $\tilde{t}_L - \tilde{t}_R$ mixing is taken into account in terms of the mixing angle $\phi_{\tilde{t}}$:

$$\tilde{t}_1 = \tilde{t}_L \cos\phi_{\tilde{t}} - \tilde{t}_R \sin\phi_{\tilde{t}}, \tag{4}$$

$$\tilde{t}_2 = \tilde{t}_L \sin\phi_{\tilde{t}} + \tilde{t}_R \cos\phi_{\tilde{t}}. \tag{5}$$

We have assumed $V_{33}^\dagger = 1$ so that $\lambda'_{131} \simeq \overline{\lambda'_{131}}$. (See Eq. (6) below.) This new limit is almost a factor of four improvement compared to the older bound (< 0.4) obtained by Barger *et al.* [15]. Also, note that the above constraint on λ'_{131} is diluted by a factor of $\cos\phi_{\tilde{t}}$ as a result of the $\tilde{t}_L - \tilde{t}_R$ mixing. In our model, we assume that $\cos\phi_{\tilde{t}} = \pi/4$, so that the above constraint becomes

$$0.06 \le |\overline{\lambda'_{131}}| \le 0.17 \tag{6}$$

[2]This kind of assumption is certainly unnatural in a sense. However, in the presence of many $R-$parity violating couplings, it is worth while to make such an assumption, and study its consequences at low energy phenomena and at colliders, especially when we do not have any theories that explain the hierarchies in the fermion masses and the CKM matrix elements.

for $M_{\tilde{t}_1} = 200$ GeV. The lower limit in Eq. (6) comes from the requirement that this coupling is relevant to the HERA high$-Q^2$ anomaly through the $s-$channel single stop production. (See Eq. (20) below.)

Assuming that the only nonvanishing coupling in Eq. (1) is $\overline{\lambda'_{131}}$, let us write down the $R-$parity violating interaction lagrangian in terms of component fields :

$$\begin{aligned}\mathcal{L}_{int,\not{R}_p} = \overline{\lambda'_{131}} \ \Big[\ & \left(\tilde{\nu}_{eL} \overline{d_R} b_L + \tilde{b}_L \overline{d_R} \nu_{eL} + \tilde{d}_R^* \overline{(\nu_{eL})^c} b_L \right) \\ & -V_{3j}^{\dagger} \left(\ \tilde{e}_L \overline{d_R} u_{jL} + \tilde{u}_{jL} \overline{d_R} e_L + \tilde{d}_R^* \overline{(e_L)^c} u_{jL} \ \right) \ \Big] + \text{h.c.}.\end{aligned} \tag{7}$$

Note that a squark in the MSSM behaves like a scalar leptoquark if $\lambda' \neq 0$. However, squarks can also decay through the $R-$parity conserving interactions, which distinguishes the squarks in the MSSM with $R-$parity violation from the usual scalar LQ. All the fields in Eq. (6) are interaction eigenstates, and one has to consider the difference between these states and the mass eigenstates. Since there is no theory of CKM mixing matrix yet, we do not know how to relate the $U_{L,R}$ and $D_{L,R}$ with the $V_{CKM} \equiv V = U_L^{\dagger} D_L$. In other words, only V_{CKM} is known from experiments, and we don't know U_L and D_L separately. One can have $U_L = 1$ or $D_L = 1$ in the extreme, but both U_L and D_L can differ from the unit matrix, either. In this work, we assume that $D_L = 1$ so that $V_{CKM} = U_L^{\dagger}$. In Eq. (6), we have taken into account this flavor mixing effects in the up–quark sector in terms of the CKM matrix elements V_{jk} [3], so that we have the following induced interactions :

$$\delta\mathcal{L}_{int,\not{R}_p} = -\lambda'_{1j1} \left[\ \tilde{e}_L \overline{d_R} u_{jL} + \tilde{u}_{jL} \overline{d_R} e_L + \tilde{d}_R^* \overline{(e_L)^c} u_{jL} \ \right] + \text{h.c.} \ \ (\text{for } j = 1, 2). \tag{8}$$

For $\overline{\lambda'_{131}} \cos \underline{\phi_{\tilde{t}}} \sim 0.04 - 0.12$, the coupling for the induced interaction vertex $\tilde{e}_L \overline{d_R} c_L$ is about $\lambda'_{121} = V_{23} \overline{\lambda'_{131}} \sim (2-6) \times 10^{-3}$, which is in the right order of magnitude suggested by CGLW in order to solve the ALEPH anomaly. This is one of the key observations of this work, which has not been considered in other recent works.

The details of phenomenological aspects of our model presented in this work depend on the superparticle spectra, although the global features would be generic. Since we are aiming at solving both the ALEPH four-jet anomaly and the high$-Q^2$ HERA events by a single $R-$parity violating coupling $\overline{\lambda'_{131}}$ in Eq. (6), we assume the same parameters with the CGLW scenario : namely,

- We assume the same parameters with the CGLW scenario, in order to solve the ALEPH 4–jet anomaly.

$$\begin{aligned} \tan\beta = 1, \quad M_{\tilde{e}_L} = 58 \text{ GeV}, \quad M_{\tilde{e}_R} = 48 \text{ GeV}, \\ M_1 = 80 \text{ GeV}, \quad M_2 = 500 \text{ GeV}. \end{aligned} \tag{9}$$

  These conditions ensure that the $\tilde{e}_L \tilde{e}_R^* + \tilde{e}_L^* \tilde{e}_R$ production cross section at LEP2 is dominant over other channels, such as $e^+ e^- \to \tilde{\nu}_e \tilde{\nu}_e^*, \tilde{e}_L \tilde{e}_L^*, \tilde{e}_R \tilde{e}_R^*$. Note that M_1 and

[3]Most other recent works put the flavor mixing in the down quark sector in terms of the CKM matrix elements. In these cases, one cannot have λ'_{121} and λ'_{131} simultaneously, unlike our case. See the next paragraph.

M_2 are not related with each other through the usual GUT relation. [4] Since $\tan\beta = 1$ in this model, the weak $SU(2)$ relation

$$M_{\tilde{\nu}_e}^2 = M_{\tilde{e}_L}^2 + (1 - \sin^2\theta_{\rm w})\cos(2\beta) M_Z^2, \tag{10}$$

implies that $M_{\tilde{\nu}_e}^2 = M_{\tilde{e}_L}^2 = 58$ GeV. Also for $\tan\beta = 1$, the light neutral Higgs (h^0) mass entirely arise from the radiative corrections, and $M_h < 80$ GeV. Therefore, the light Higgs is within the reach of LEP2.

- Furthermore, we assume the universal squark masses in order to do more concrete numerical analyses, and require the ligheter stop mass is 200 GeV, assuming it is responsible for the high–Q^2 HERA events.

$$\begin{aligned} M_{\tilde{Q}} = M_{\tilde{U}} = M_{\tilde{D}} &= \tilde{m}, \\ M_{\tilde{t}_1} &= 200 \text{ GeV}, \end{aligned} \tag{11}$$

  For the numerical value of $\tilde{m}$, we choose 250–300 GeV, so that the squarks (except for stops) have masses that could be probed at the Tevatron Upgrade. Then heavier stop ($\tilde{t}_2$) has a mass around 440 GeV. In this case, the SUSY contribution to $\Delta\rho$ is about 0.8×10^{-3}, and the lighter Higgs mass is about 62 GeV.

For given $M_2 = 500$ GeV and $\tan\beta = 1$, the μ parameter is determined from the condition on the chargino mass. For each μ, we calculate the stop masses from the stop mass matrix in the $(\tilde{t}_L, \tilde{t}_R)$ basis :

$$M_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + M_t^2 + M_Z^2(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\rm W})\cos 2\beta & M_t(A_t + \mu\cot\beta) \\ M_t(A_t + \mu\cot\beta) & M_{\tilde{t}_R}^2 + M_t^2 + \frac{2}{3}M_Z^2\sin^2\theta_{\rm W}\cos 2\beta \end{pmatrix} \tag{12}$$

$$\longrightarrow \begin{pmatrix} \tilde{m}^2 + M_t^2 & M_t(A_t + \mu) \\ M_t(A_t + \mu) & \tilde{m}^2 + M_t^2 \end{pmatrix}, \tag{13}$$

so that $\phi_{\tilde{t}} = \pi/4$. We can get A_t by requiring the lighter stop has the mass $M_{\tilde{t}_1} = 200\text{GeV} < \tilde{m}$, and $|A_t| < \tilde{m}$. The latter condition ensures that the ground state is color and charge neutral. For each μ, we can choose such $\tilde{M}$ which meets our above criteria. Since this sector is not of our primary concern, we will not consider this any further in this work.

Now consider the $s-$channel stop (the lighter one, called $\tilde{t}_1$) production cross section at HERA. Neglecting the SM contributions from $t-$channel exchanges of γ and Z bosons, we have

$$\frac{d^2\sigma}{dxdy}(e^+(k,s) + p \rightarrow e^+(k^{'}, s^{'}) + \text{single jet}) \tag{14}$$

$$= \frac{4\pi}{M_{\tilde{t}_1}^2}\, \frac{s\Gamma^2(\tilde{t}_1 \rightarrow e^+ d)}{(xs - M_{\tilde{t}_1}^2)^2 + M_{\tilde{t}_1}^2 \Gamma_{\rm tot}^2(\tilde{t}_1)}\; x d(x, Q^2) \tag{15}$$

$$\rightarrow \frac{4\pi^2}{M_{\tilde{t}_1}\Gamma_{\tilde{t}_1}}\; \Gamma^2(\tilde{t}_1 \rightarrow e^+ d)\; d(x_{\rm res}, Q^2)\; \delta(xs - M_{\tilde{t}_1}^2), \tag{16}$$

[4] The GUT relations on gaugino masses were imposed in Ref. [19], for example.

where $x = \hat{s}/s$, $Q^2 = -(k-k')^2 = xys$, and $\Gamma_{\rm tot}(\tilde{t}_1)$ is the decay rate for the $R-$parity violating $\tilde{t}_1 \to e^+ d$:

$$\Gamma(\tilde{t}_1) = \frac{m_{\tilde{t}_1}}{16\pi} \cos^2\phi_{\tilde{t}} \, |\lambda'_{131} V_{33}|^2 \simeq 39.8 \text{ MeV} \left(\frac{|\lambda'_{131} \ \cos\phi_{\tilde{t}}|}{0.50} \right)^2 . \tag{17}$$

The last line Eq. (16) is obtained in the limit of a narrow approximation for the stop resonance ($x_{\rm res} \equiv M^2_{\tilde{t}_1}/s_{\rm HERA}$). In this limit, the cross section becomes proportional to the branching ratio $B(\tilde{t}_1 \to e^+ d)$ times the decay rate for the same mode. In other words, the stop production cross section is proportional to $B(\tilde{t}_1 \to e^+ d) \times |\lambda'_{131} \cos\phi_{\tilde{t}}|^2$. Using the CTEQ3 PDF [23] and assuming $\sigma(e^+ p \to \tilde{t}_1 \to e^+ + (\text{single jet})) = 0.2$ pb as a representative value of the high$-Q^2$ HERA events, we get

$$\sqrt{B} \times |\lambda'_{131} \cos\phi_{\tilde{t}}| \approx 0.04, \tag{18}$$

which agrees with the others' results. Then, the condition $B \le 1$ implies that

$$0.04 \le |\lambda'_{131} \cos\phi_{\tilde{t}}| \le 0.12 \tag{19}$$
$$B(\tilde{t}_1 \to e^+ d) \ge 0.11. \tag{20}$$

In the presence of nonvanishing λ'_{131} coupling, the stop behaves like a leptoquark that can decay into $e^+ + d$. Therefore the scalar leptoquark (LQ) search at HERA and at the Tevatron via $LQ \to e+$ (single jet) decay mode gives some constraints on the properties of the stop. The D0 limit on the stop mass is 175 GeV for $B(LQ \to e + \text{jet}) = 100\%$ [20]. This limit can pushed upto ~ 215 GeV, when the QCD corrections to the LQ pair prodution at the Tevatron is included [5]. Therefore a stop of $M_{\tilde{t}_1} = 200$ GeV can be safely accomodated if $B(\tilde{t}_1 \to e^+ + d) < 100\%$. In other words, we need an extra decay channel of the stop other than the $R-$parity violating decay, $\tilde{t}_1 \to e^+ d$. At this point, it is worthwhile to remember that there are differences between the stop and the conventional scalar leptoquark. First, the stop does not couple to $\bar{\nu} + u$. Secondly, the stop can have $R-$parity conserving decay modes in addition to the $R-$parity violating mode. For example, one can imagine a stop decay into a chargino (χ^+) plus a bottom quark, if the chargino is light enough. Therefore, we shall assume that the lighter chargino state χ_1, one of the eigenstate of

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & -\mu \end{pmatrix} \to \begin{pmatrix} M_2 & M_W \\ M_W & -\mu \end{pmatrix}, \tag{21}$$

has mass below $M_{\tilde{t}_1} - M_b$ so that the decay $\tilde{t}_1 \to \chi_1^+ + b$ is kinematically allowed. On the other hand, the decay into $t + \chi_1^0$ is kinematically forbidden. This condition constrains a possible range of the μ parameter for a given M_2 and $\tan\beta$.

The decay rate of this mode has been calculated by Kon *et al.* [21] :

$$\begin{aligned} \Gamma(\tilde{t}_1 \to b \chi_k^+) = {} & \frac{\alpha}{4 \sin^2\theta_{\rm W} M^3_{\tilde{t}_1}} \, \lambda^{1/2}(M^2_{\tilde{t}_1}, M_b^2, M^2_{\chi_k}) \\ & \times \left[\left(|G_L|^2 + |G_R|^2 \right) (M^2_{\tilde{t}_1} - M_b^2 - M^2_{\chi_k}) - 4 M_b M_{\chi_k} \text{ Re } (G_R G_L^*) \right], \end{aligned} \tag{22}$$

where

$$G_L = -\frac{M_b U^*_{k2} \cos\phi_{\tilde{t}}}{\sqrt{2} M_W \cos\beta}, \tag{23}$$

$$G_R = V_{k1} \cos\phi_{\tilde{t}} + \frac{M_t V_{k2} \sin\phi_{\tilde{t}}}{\sqrt{2} M_W \sin\beta}. \tag{24}$$

In the above equations, V_{ij}, U_{ij} are matrices that diagonalize the chargino mass matrix (Eq. (21)), $U^* M_{\tilde{\chi}^\pm} V^{-1} = M_D$.

If charginos are heavier than the stop, we have to consider $R-$parity conserving decay via virtual chargino exchange :

$$\begin{aligned} \tilde{t}_1 \to b + \chi^{+*} \to\ & b + (e^+ + \tilde{\nu}_e), \\ & b + (\tilde{e}^+ + \nu_e). \end{aligned}$$

If the lightest neutralino (χ_1^0) is light enough, we have to consider $\tilde{t}_1 \to bW^+\chi_1^0$ as well. This is indeed the case in our framework, since we assue $M_{\tilde{t}_1} = 200$ GeV, and $M_{\chi_1^0} \approx 100 - 120$ GeV. We have also analyzed these three–body decay modes in the limit of a pure bino neutralino ($\chi_1^0 \approx \tilde{B}$), and found that they are all negligible (smaller than 0.1 MeV) compared to the two–body decay modes discussed above : $R-$parity violating decay $\tilde{t}_1 \to e^+ + d$ and $R-$parity conserving decay $\tilde{t}_1 \to b + \chi^+$. Therefore we consider only these two two-body decays of $\tilde{t}_1$ in the following.

In Figs. 1 (a) and (b), we show the branching ratio for $\tilde{t}_1 \to e^+ + d$ as a function of μ for $\mu > 0$ and $\mu < 0$, respectively. We chose five different values of $\lambda'_{131} \cos\theta_{\tilde{t}} = 0.04$ (the solid curve), 0.06, 0.08, 0.10 and 0.12 (the long dashed curve). In Fig. 2, we show the μ dependence of the cross section for $e^+ + p \to \chi^+ + b + X$ for both $\mu > 0$ (the solid curve) and $\mu < 0$ (the dashed curve) for the maximally allowed $\lambda'_{131} \cos\theta_{\tilde{t}} = 0.12$, assuming $M_2 = 500$ GeV and $\tan\beta = 1$ [5]. For smaller λ'_{131} coupling, the cross section should scale as $\sim |\lambda'_{131}|^2$. We note that the cross section is smaller than 0.1 pb for most regions of μ parameters, so that it is unlikely that this mode is a useful place to test our scenario at the e^+p collider. If we chose difference $(M_2, \tan\beta)$, then the corresponding production cross section would change accordingly.

In Tables 1 and 2, we choose six different values of $\lambda'_{131} \cos\phi_{\tilde{t}}$, and find μ parameters which satisfies the conditions (17) and (19) for $\mu > 0$ and $\mu < 0$, respectively. The resulting chargino masses (M_{χ_1}, M_{χ_2}), the decay rates for $\tilde{t}_1 \to \chi^+ + b$ and $\tilde{t}_1 \to e^+ + d$, and the total decay width of the stop, neglecting the three–body decay modes of the stop. In the last row of Tables 1 and 2, we also list the cross section for $e^+ + p \to \chi_1^+ + b$ for $x > 0.1$ and $Q^2 > 15,000$ GeV^2. We note that the cross section for $e^+ + p \to \chi^+ + b + X$ is rather small (< 0.1 pb), which indicates that this channel may not be detected soon.

Finally let us consider the decay rates of the lightest chargino χ_1^+. Its main decay modes are

- Two–body decays : $\chi_1^+ \to \tilde{e}^+ + \nu_e,\ e^+ + \tilde{\nu}_e$

[5] Because of constraints (17) and (19), one gets constraints for μ, which are denoted as filled circles. However, the cross section for $e^+ + p \to e^+ +$(single jet) may be changed in the future after more data are accumulated. Therefore we do not impose these conditions in Figs. 1 (a),(b) and Fig. 2.

- Three–body decays : $\chi_1^+ \to \chi_1^0 + \bar{l}\nu_e,\ \chi_1^0 + q\bar{q}^{'}$.

It turns out that the dominant decay mode for $M_2 = 500$ MeV (and μ considered in Figs. 1 and 2) $\chi_1^+ \to \tilde{e}^+ + \nu_e$, with its width being around several hundred MeV which is quite broad. Other decay modes are all negligible compared with this channel. The final SUSY particles eventually decay into ordinary particles through $R-$parity violating couplings :

- $\tilde{e} \to q + \bar{q}^{'}$
- $\tilde{\nu}_e \to \bar{b} + d$
- $\chi_1^0 \to \tilde{e}^+ + e, \tilde{e} + e^+, \tilde{\nu}_e + \nu_e$.

Therefore, the signal for the $e^+ + p \to \tilde{t}_1 \to \chi_1^+ + b$ would be multijets with missing energy accompanying a soft $b-$jet. However, for our choice of M_2 and μ, the cross section for this channel is too small, < 0.1 pb, which makes almost hopeless to observe it at HERA in the near future.

As a further check to this scenario, let us note that the $t-$channel stop exchange can modify the $e^+e^- \to d\bar{d}$ by interference with the SM constributions from the $s-$channel γ, Z exchanges. This effect may be observed at LEP2 upto $\sqrt{s} = 190$ GeV. We find that the stop exchange contribution is negligible for $|\lambda_{131}^{'} \cos\phi_{\tilde{t}}| < 0.12$. In Fig. 3 (a), we show the deviation of the cross section from the SM value for $e^+e^- \to d\bar{d}$ as a function of $\sqrt{s}$ upto $\sqrt{s} =$ 200 GeV with $\lambda_{131}^{'} \cos\phi_{\tilde{t}} = 0.12$ (the solid curve) and 0.04 (the dashed curve), respectively. Deviations from the SM prediction is less than 0.8 % for the maximal $\lambda_{131}^{'} \cos\phi_{\tilde{t}} = 0.12$, which is hardly discernable unless the integrated luminosity at LEP2 becomes larger than $O(1) fb^{-1}$.

The $t-$channel stop exchange also contributes to the Drell–Yan (DY) prodution of the e^+e^- (but not $\mu^+\mu^-$) pair at the Tevatron through the parton level subprocess, $d\bar{d} \to e^+e^-$. Using the CTEQ3 PDF [23] and including the valence quark contributions only, we obtained the e^+e^- invariant mass spectrum at the Tevatron (with $\sqrt{s} = 1.8$ TeV and the rapidity cut $|y| < 1$), along with the SM prediction in Fig. 4. We have included the heavier stop ($\tilde{t}_2$) effect as well. The stop exchange enhances the DY yield of the e^+e^- pair at large invariant mass M_{ee}. However, the difference between the SM prediction (the dashed curve) and our model stop (the solid curve) with the maximal value of the coupling $\lambda_{131}^{'} \cos\phi_{\tilde{t}} = 0.12$ is at the level of a few % or less because of the small coupling $\lambda_{131}^{'}$, so that it would be impossible to test our model via the DY production at the Tevatron. However the leptoquark search at the Tevatron will be cover some part of $B(\tilde{t}_1 \to e^+ + d)$ for $M_{\tilde{t}_1} = 200$ GeV.

In summary, we assumed that $R-$parity violation in the MSSM occurs through only one $R-$parity violating coupling $\overline{\lambda_{131}^{'}}$ in the interaction basis, and that it induces effective couplings $\lambda_{121}^{'}$ and $\lambda_{111}^{'}$ in the mass eigenstates by the flavor mixing among the up quark sector (see Eq. (3)). If $\overline{\lambda_{131}^{'}}$ $\cos\phi_{\tilde{t}} \sim 0.04 - 0.12$, the induced $\lambda_{121}^{'}$ and $\lambda_{111}^{'}$ lie in the range where the ALEPH 4-jet events find a solution in terms of $e^+e^- \to \tilde{e}_L\tilde{e}_R$ and subsequent decays of the selectrons into $u + \bar{d}$ (and its charge conjugate state) *á la* CGLW.

We also considered implications of such scenario at other colliders such as LEP and the Tevatron. Deviations from the SM predictions for the cross section and the polar angle distribution for $e^+e^- \to d\bar{d}$ and the DY yield of e^+e^- are at most a few % or less, and it would not be easy to detect the vritual stop effects at such colliders. One possibility is to discover such stop of $M_{\tilde{t}} = 200$ GeV at the Tevatron for large $B(\tilde{t}_1 \to e^+ d)$. It would be very interesting to see if the high$-Q^2$ HERA events survive more data accumulations this year and if the production cross section at HERA for $e^+ + p \to \tilde{t}_1 \to \chi^+ + b$ (followed by $\chi^+ \to \tilde{e}^+ + \nu_e$ and $\tilde{e}^+ \to q + \bar{q}^{'}$ via the $R-$parity violating coupling) is in the same order of magnitude given in this work.

A few remarks are in order before closing, regarding the ALEPH 4–jet anomaly and the high$-Q^2$ HERA events which were considered simultaneously in the present work. We have assumed that the ALEPH 4–jet anomaly *was real* and could be solved in terms of the $R-$parity violating interaction *á la* CGLW. In case that the ALEPH 4–jet events disappear in the future, overall features of our scenario would not change very much, except that we can have different values of the gaugino masses, M_1 and M_2, from those adopted in Ref. [9]. We also assumed that the universal squark masses in this work, so that the $\tilde{t}_L - \tilde{t}_R$ mixing angle was $\phi_{\tilde{t}} = \pi/4$. This mixing angle can change if the universal squark masses do not hold. Still, qualitative features of our predictions will not change, unless $\phi_{\tilde{t}} = \pi/2$ (an extreme).

Note added While we were preparing this work, there appeared several papers [24] which tried to interprete the high$-Q^2$ HERA events in terms of the MSSM with $R-$parity violations. However, there are some differences in the choice of the SUSY parameters, the sparticle spectra and the decay channels of the stop. Leptoquark scenarios were considered in Refs. [25], and other approaches can be found in Refs. [26].

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FIGURES

FIG. 1. The branching ratio for $\tilde{t}_1 \to e^+ + d$ as a function of the μ parameter for $M_2 = 500$ GeV : (a) for $\mu > 0$, and (b) for $\mu < 0$. The five curves corresponds to $\lambda'_{131} \cos\phi_{\tilde{t}} = 0.12$ (long dashed), $0.10, 0.08, 0.06$, and $\lambda'_{131} \cos\phi_{\tilde{t}} = 0.04$ (solid), respectively.

FIG. 2. Production cross section for $e^+ + p \to b + \chi^+ + X$ as a function of the μ parameter for $x > 0.1$ and $Q^2 > 15,000$ GeV^2. We choose $M_2 = 500$ GeV, and the maximal allowed value of $\lambda'_{131} \cos\phi_{\tilde{t}} = 0.12$. The solid and the dashed curves correspond to $\mu > 0$ and $\mu < 0$, respectively.

FIG. 3. The cross section for $e^+e^- \to d\bar{d}$ as a function of $\sqrt{s}$ for the SM (solid), and the stop contribution ($M_{\tilde{t}_1} = 200$ GeV) with $\lambda'_{131} \cos\phi_{\tilde{t}} = 0.12$ (the dashed) and 0.04 (the dotted), respectively.

FIG. 4. The Drell–Yan prodution of the e^+e^- pair at the Tevatron for the SM (the dashed) and the stop exchange with $\lambda'_{131} \cos\phi_{\tilde{t}} = 0.12$ (the solid). We imposed the rapidity cut $|y| < 1$, but ignored the radiative QCD corrections.

TABLES

TABLE I. The $\mu(>0)$ parameter, the chargino masses, the decay rates and the cross sections at HERA for $\tilde{t}_1$ into $e^+ + d$ and $\chi^+ + b$, for six different values of λ'_{131}, $M_2 = 500$ GeV, $\tan\beta = 1$, $\phi_{\tilde{t}} = \pi/4$, and $M_b = 5.3$ GeV,

$\lambda'_{131}\cos\phi_{\tilde{t}}$	0.04	0.06	0.08	0.10	0.12
μ (GeV)	207	203	195	184	170
M_{χ_1} (GeV)	517.2	517.1	516.8	516.3	515.9
M_{χ_2} (GeV)	195.2	191.4	183.8	173.3	159.9
$\Gamma(\tilde{t}_1 \to e^+ d)$ (MeV)	6.4	14.3	25.5	39.8	57.3
$\Gamma(\tilde{t}_1 \to \chi_1^+ + b)$ (MeV)	0.0	19.5	137.0	212.7	453.8
$\Gamma_{\rm tot}(\tilde{t}_1)$ (MeV)	6.4	33.8	162.5	252.5	511.1
$\sigma(\chi^+ + b)$ (pb)	0.0	0.27×10^{-4}	0.9×10^{-4}	0.50×10^{-3}	0.89×10^{-2}

TABLE II. The $\mu(<0)$ parameter, the chargino masses, the decay rates and the cross sections at HERA for $\tilde{t}_1$ into $e^+ + d$ and $\chi^+ + b$, for six different values of λ'_{131}, $M_2 = 500$ GeV, $\tan\beta = 1$, $\phi_{\tilde{t}} = \pi/4$, and $M_b = 5.3$ GeV,

$\lambda'_{131}\cos\phi_{\tilde{t}}$	0.04	0.06	0.08	0.10	0.12
μ (GeV)	-194	-191	-184	-174	-160
M_{χ_1} (GeV)	512.0	512.3	512.3	512.2	512.1
M_{χ_2} (GeV)	195.0	191.8	185.0	175.3	161.7
$\Gamma(\tilde{t}_1 \to e^+ d)$ (MeV)	6.4	14.3	25.5	39.8	57.3
$\Gamma(\tilde{t}_1 \to \chi_1^+ + b)$ (MeV)	0	18.5	75.6	205.7	425.0
$\Gamma_{\rm tot}(\tilde{t}_1)$ (MeV)	6.4	32.8	101.1	245.5	482.3
$\sigma(\chi^+ + b)$ (pb)	0.0	0.53×10^{-3}	0.12×10^{-2}	0.2610^{-2}	0.14×10^{-1}