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Scalar Top Quarks in R-parity Breaking Model for High-Q^2 Events at HERA

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Abstract

We investigate an event excess in the reaction $e^+p \to e^+X$ with large x and high Q^2 observed at HERA and show that the events could naturally be interpreted as a signature of the production of the scalar top quarks (stops) in a supersymmetric model with R-parity breaking interactions. The HERA events are characterized by the broad mass distribution and in fact it can be simulated by our specific scenario if we consider almost degenerate two mass eigenstates $\widetilde{t}_1$ and $\widetilde{t}_2$ of the stops.

Recently both the H1 and ZEUS Collaboration reported that an event excess in the deep inelastic scattering (DIS) $e^+p \to e^+X$ with large x and high Q^2 had been observed [1, 2] at HERA. The total data sample analyzed at the H1 and ZEUS corresponds to respectively accumulated luminosity of 14.2pb^{-1} and 20.1pb^{-1} in positron (27.5GeV) – proton (820GeV) collisions. For high Q^2 ($> 15{,}000\text{GeV}^2$) region 12 events are observed at both the H1 and ZEUS, while the Standard Model expectations are 4.7 ± 0.8 and 8.7 ± 0.7, respectively. Simply combining these results we get $N_{obs} = 24$ ($\sigma_{obs} \simeq 0.71\text{pb}$) against $N_{exp} = 13 \pm 1$ ($\sigma_{exp} \simeq 0.38\text{pb}$).

The event excess is characterized by not only a high four momemtum transfer Q^2 but also a large Bjorken parameter $x \gtrsim 0.3$. Interestingly, the events seem to cluster at invariant mass $M = 200 \sim 220\text{GeV}$, where M is directly determined from x by $M \equiv \sqrt{xs}$. However, while the excess events of the H1 seem to cluster at $M \simeq 200\text{GeV}$, those of the ZEUS have a broader distribution around $M \simeq 220\text{GeV}$. Statistical consistency between the H1 and ZEUS data was discussed in ref.[3], where a possible single resonance structure was assumed. Here we will simply combine both data since each statistical significance is still not so high enough.

Some possible interpretations of the events have already been given by ;

(A) four fermion contact interaction [6, 8, 11]

(B) leptoquark production [3, 6, 7, 9, 11, 12]

(C) scalar quark production in the supersymmetric (SUSY) model with R-parity breaking (RB) interactions [4, 5, 6, 7, 10, 11, 12]

In this letter we investigate one of scenarios of the category (C), the scalar top (stop) [13] production in the RB SUSY model [4, 5, 6, 7]. For we have first proposed the scenario at HERA experiments long since [14, 15]. On the other hand, possibilities of the search for the squarks in the first or second generation at HERA have originally been discussed in ref.[16, 17].

The discussion is based on the minimal SUSY standard model (MSSM) with an RB interaction

$$L = \lambda'_{1jk}(\widetilde{u_{jL}}\overline{d_k}P_L e - \overline{\widetilde{d_{kR}}}\overline{e^c}P_L u_j) + h.c, \tag{1}$$

where $P_{L,R}$ read left and right handed chiral projection operators, respectively. The interaction Lagrangian (1) has been derived from the general RB superpotential [18];

$$W_{\not R} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E^c}_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D^c}_k + \lambda''_{ijk}\hat{U^c}_i\hat{D^c}_j\hat{D^c}_k, \tag{2}$$

where i, j and k are generation indices. The first two terms violate the lepton number L and the last term violates the baryon number B. If we want to explain such unresolved problems as (i) the cosmic baryon number violation, (ii) the origin of the masses and the magnetic moments of neutrinos and (iii) some interesting rare processes in terms of the L and/or B violation, R-parity breaking terms must be incorporated in the MSSM. The coupling Eq. (1) will be most suitable for the ep collider experiments at HERA because the squark $\widetilde{u_{jL}}$ or $\overline{\widetilde{d_{kR}}}$ will be produced in the s-channel in e^+-q sub-processes.

$$e^+ + d_k \to \widetilde{u_{jL}} \to e^+ + d_k \tag{3}$$

$$e^+ + \overline{u_j} \to \overline{\widetilde{d_{kR}}} \to e^+ + \overline{u_j}. \tag{4}$$

The upper bounds on the coupling constants λ'_{1jk} have already been settled by some experiments, i.e., neutrinoless double beta decay [19, 20], charged current universality [18, 21], atomic parity violation (APV) [18, 21, 22] and ν_e mass [23]. Among nine candidates of coupling constants λ'_{1jk} some are severely constrained by these experiments. To explain the observed cross section (~ 0.7pb) as well as to circumvent the experimental constraints, we should consider the two kinds of processes (3) in which a valence quark in the proton participates *,

$$e^+ + d \to \widetilde{c_L} \to e^+ + d \tag{5}$$
$$e^+ + d \to \widetilde{t_L} \to e^+ + d. \tag{6}$$

In fact, the most stringent upper bounds on the corresponding coupling constants coming from the recent APV experiments [25] are given by

$$\lambda'_{121}, \lambda'_{131} < 0.055 \qquad (90\%\text{CL}) \tag{7}$$

for $m_{\widetilde{c_L}}$, $m_{\widetilde{t_L}} \simeq 200$GeV. The scalar charm (scharm) $\widetilde{c_L}$ and the stop $\widetilde{t_L}$ cannot couple to any neutrinos via R-breaking interactions. That is, no event excesses are expected in the charged current process $ep \to \nu q X$ in the squark scenarios. This is a unique property of the squark scenarios which could be useful for us to distinguish the squarks from leptoquarks. It should be noted, however, that one of typical signatures of the squarks could be a large missing transverse energy plus multi-jets if they decay into lighter sparticles with R-parity conserving interactions [26] (see also following discussions).

Here we pay attention to a fact that the stops ($\widetilde{t_L}$, $\widetilde{t_R}$) are naturally mixed each other [13] due to a large top quark mass [27] and the mass eigenstates ($\widetilde{t}_1$, $\widetilde{t}_2$) are parametrized by a mixing angle θ_t,

$$\widetilde{t_L} = \widetilde{t}_1 \cos\theta_t - \widetilde{t}_2 \sin\theta_t. \tag{8}$$

In this case the interaction Lagrangian (1) for the stops is written by

$$L = \lambda'_{131}(\cos\theta_t \widetilde{t}_1 \overline{d} P_L e - \sin\theta_t \widetilde{t}_2 \overline{d} P_L e) + h.c.. \tag{9}$$

It should be emphasized that only one scharm $\widetilde{c_L}$ could be coupled to $e^+ d$ in the scenario with $\lambda'_{121} \neq 0$.

Before discussing numerical results, we examine the decay modes of the stop. In the MSSM, the stop lighter than the other squarks in the first and second generations and the gluino can decay into various final states :

$$\begin{aligned}
\widetilde{t} &\to t\,\widetilde{Z}_k && \text{(a)}\\
&\to b\,\widetilde{W}_i && \text{(b)}\\
&\to W\,\widetilde{b} && \text{(c)}\\
&\to b\,\ell\,\widetilde{\nu} && \text{(d)}\\
&\to b\,\nu\,\widetilde{\ell} && \text{(e)}\\
&\to b\,W\,\widetilde{Z}_k && \text{(f)}\\
&\to b\,f\,\overline{f}\,\widetilde{Z}_k && \text{(g)}\\
&\to c\,\widetilde{Z}_1 && \text{(h)}\\
&\to e\,d, && \text{(i)}
\end{aligned}$$

*A possibily for "strange stop" scenario, $e^+ + s \to \widetilde{t_L}$, is discussed in detail by J. Ellis et al. [24].

where $\widetilde{Z}_k$ ($k = 1 \sim 4$), $\widetilde{W}_i (i = 1,2)$, $\tilde{\nu}$ and $\tilde{\ell}$, respectively, denote the neutralino, the chargino, the sneutrino and the charged slepton. (a) $\sim$ (h) are the R-parity conserving decay modes, while (i) is only realized through the RB couplings (9).

If we consider the RB coupling with $\lambda'_{131} > 0.01$, the decay modes (d) to (h) are negligible due to their large power of α arising from multiparticle final states or one loop contributions. Moreover, in the present case ($m_{\tilde{t}_1} \simeq 200$GeV) the mode (a) will be kinematically suppressed. Then only two body decay modes (b), (c) and (i) are left for our purpose.

In Fig.1 we show the λ'_{131} dependence of the total cross section for the process,

$$e^+ p \to \tilde{t}_1 X \to e^+ q X, \tag{10}$$

where we take $m_{\tilde{t}_1} = 200$GeV, $\theta_t = 0$ and $Q^2 > 15{,}000\text{GeV}^2$. The horizontal lines correspond to the observed cross section at HERA, $\sigma_{obs} = (0.71 \pm 0.15)$ pb. We find the HERA data could be explained by $\lambda'_{131} \simeq 0.04$ and 0.055 for $\text{Br}(\tilde{t}_1 \to e^+ d) = 1.0$ and 0.5, respectively. This is almost the same result with that given by Altarelli et al. [6]. From the Fig.1 we see that $0.03 \lesssim \lambda'_{131} < 0.055$ and $\text{Br}(\tilde{t}_1 \to e^+ d) \gtrsim 0.3$ are needed for us to obtain the required amount of the cross section of about 0.6pb. These facts immediately lead us to another important consequence, $\Gamma_{tot}(\tilde{t}) \lesssim 50$MeV, because

$$\Gamma(\tilde{t}_1 \to e^+ d) = \frac{(\lambda'_{131} \cos\theta_t)^2}{16\pi} m_{\tilde{t}_1} \lesssim \quad 13\text{MeV} \tag{11}$$

and $\Gamma_{tot}(\tilde{t}) = \Gamma(\tilde{t}_1 \to e^+ d)/Br(\tilde{t}_1 \to e^+ d) \lesssim (13\text{MeV})/0.3$. Note that they are applicable to the scharm scenario when we simply replace like $\tilde{t}_1 \to \widetilde{c_L}$ and $\lambda'_{131} \to \lambda'_{121}$.

If we consider a case of $m_{\tilde{t}} < m_b + m_{\widetilde{W}_1}$ and $m_{\tilde{t}} < m_W + m_{\tilde{b}_1}$, the stop will decay into $e^+ d$ with 100% branching ratio. In this case it is difficult to discriminate the stop from one of the leptoquark $\widetilde{S}_{1/2}$ with the charge $Q = \frac{2}{3}$. Such a stop (or leptoquark) could be searched at Tevatron through the production mechanism,

$$p\bar{p} \to \tilde{t}\bar{\tilde{t}} X \to ee X. \tag{12}$$

Recently D0 [28] and CDF [29] groups have reported preliminary bounds on a leptoquark mass as $M_{LQ} > 194$GeV and 210GeV for $\text{Br}(LQ \to e^\pm q) = 1.0$, respectively. These new results suggest that the stop (or leptoquark) with $\text{Br}(\tilde{t} \to e^+ d) = 1.0$ and $m_{\tilde{t}} \sim 200$GeV has been excluded. To reconcile our interpretation of the high Q^2 anomaly at HERA data in terms of stop with the Tevatron bound [26], therefore, we should consider a stop with $\text{Br}(\tilde{t} \to e^+ d) \lesssim 0.8$.

In fact, if the $\widetilde{W}_1$ or $\tilde{b}$ is light, i.e., $m_{\widetilde{W}_1} \lesssim m_{\tilde{t}} - m_b$ or $m_{\tilde{b}} \lesssim m_{\tilde{t}} - m_W$, $\text{Br}(\tilde{t} \to b\widetilde{W}_1)$ or $\text{Br}(\tilde{t} \to \tilde{b}W)$ can compete with $\text{Br}(\tilde{t} \to e^+ d)$. In this case, we should take into account the processes

$$ep \to b\widetilde{W}_1 X, \tag{13}$$

$$ep \to \tilde{b} W X. \tag{14}$$

It is expected that the detectable cross sections $\sigma \gtrsim 0.1$ pb for heavy stop with mass $m_{\tilde{t}} \lesssim 250$ GeV for e^+ beams [15]. In our model the LSP, the lightest neutralino $\widetilde{Z}_1$, and $\tilde{b}$

possibly decay into R-even particles via only non-zero RB coupling λ'_{131}. A typical decay chains will be

$$
\begin{aligned}
ep \to b\widetilde{W}_1 X &\to b(\ell\nu\widetilde{Z}_1)X \to b(\ell\nu(bd\nu))X, && (15)\\
ep \to \widetilde{b}WX &\to (b\widetilde{Z}_1)WX \to (b(bd\nu))(\ell\nu)X && (16)\\
&\to (\nu_e d)WX \to (\nu_e d)(\ell\nu)X && (17)\\
&\to (\nu_e d)WX \to (\nu_e d)(q\bar{q}')X && (18)
\end{aligned}
$$

Thus, a possible typical signature of the stop production $ep \to b\widetilde{W}_1 X$ or $ep \to \widetilde{b}WX$ would be $2b$-jets+jet+lepton+ $\not{P}_T$, jet+lepton+ $\not{P}_T$ or jets+$\not{P}_T$. One of the signals to be detected at HERA is characterized by the high P_T spectrum of muons or event excess in the charged current DIS process at high Q^2 regions. The latter could occur when the multi-jets in the process (18) look like a mono-jet. When such event excess could be observed, the stop could clearly be distinguished from the leptoquark $\widetilde{S}_{1/2}$.

Next we investigate the Q^2 and M distributions of the expected events. It should be noted that there are two kinds of method for the reconstruction of M from the experimental observables. The M_{DA} is determined from scattering angles of the final positron and the final quark (jet) and it is mainly used by the ZEUS. On the other hand, the M_e is determined from the energy and the scattering angle of the final positron. This method is adopted by the H1. In the present analysis, we use both the M_{DA} and M_e in combining data of the H1 and ZEUS which are explicitly presented in refs.[1, 2] for the selected events.

Q^2 and M distributions of the expected number of events together with the experimental data are shown in Figs.2 and 3. Figure 2 corresponds to the case that only the lighter stop $\widetilde{t}_1$ with mass $m_{\widetilde{t}_1} = 200$GeV is produced and the heavier one $\widetilde{t}_2$ is decoupled ($\theta_t = 0$). Here we take $\mathrm{Br}(\widetilde{t} \to e^+ d) = 0.7$. While the event excess at high Q^2 is reproduced, the broad M distribution cannot be well explained. It should be noted that the total decay width of the single stop is smaller than about 50MeV as mentioned in the event rate analysis. Consequently, the observed broad M distribution would not be well explained by the single stop resonance scenario or by the equivalent scharm $\widetilde{c_L}$ one.

In Fig.3, on the other hand, we consider the case where two stops are almost degenarate in mass $(m_{\widetilde{t}_1}, m_{\widetilde{t}_2}) = (205\mathrm{GeV}, 225\mathrm{GeV})$ with the finite mixing angle $\theta_t = 1.0$. In this case double resonance peaks could overlap each other and simulate the broad M distribution. The event excess at high Q^2 of the data is also reproduced by this scenario. Difference between the one stop and the two stops scenario could be seen in the very high Q^2 ($>$ 40,000GeV^2) region. Here we take $\mathrm{Br}(\widetilde{t}_{1,2} \to e^+ d) = (0.55, 0.25)$ in the calculation of Figs.2 and 3.

It has been pointed out that the ALEPH 4-jet events [30] are possibly explained by the production mechanism $e^+e^- \to \widetilde{e_L}\widetilde{e_R} \to c\bar{d}\bar{c}d$ in the scharm scenario with light sleptons $m_{\widetilde{\ell}^-} \lesssim 60$GeV [31]. We have discussed the 4-jet events in the stop scenario [32]. In this case possible mechanism is $e^+e^- \to \widetilde{\nu_e}\widetilde{\nu_e} \to b\bar{d}\bar{b}d$. Recent analysis of the 4-jet events seems to reveal no b-quark enhancements and pair production of equal mass particles will be disfavoured. If ths is the case, our stop scenario may have no relation to the ALEPH 4-jet events.

We have investigated a possible scenario to explain an event excess in the reaction $e^+p \to e^+X$ with large x and high Q^2 observed by the H1 and ZEUS Collabolation at

HERA by the resonance production of the stops with an R-parity breaking interaction in the framework of the MSSM. The HERA events are characterized by not only high Q^2 but also the broad M distribution. It can be simulated by our specific scenario if we consider almost degenerate two mass eigenstates $\widetilde{t}_1$ and $\widetilde{t}_2$ of the stops.

Our scenario would be confirmed or rejected at HERA or at Tevatron through the search for the high P_T muon events or possible event excess in the CC process at high Q^2 region (HERA) or the high P_T ee events (Tevatron). Moreover, in our favourable scenario with $m_{\widetilde{t}_1,\widetilde{t}_2} \simeq (200\mathrm{GeV}, 230\mathrm{GeV})$, one of sbottom $\widetilde{b_L}$ could be lighter than about 175GeV and it can decay into $\nu_e d$ via the RB interactions proportional to λ'_{131}. It will be a good target of LEP2 or future linear colliders. Detailed studies of the sbottom production at e^+e^- colliders in our specific scenario will be reported soon. Needless to say, it would be highly desirable to be carried out the high luminosity run at HERA as to whether or not there really exist the broad M distribution.

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Figure Captions

Figure 1: λ'_{131} dependence of the total cross section $\sigma(e^+p \to \widetilde{t}_1 X \to e^+qX)$. We take $m_{\widetilde{t}_1} = 200\text{GeV}$, $\theta_t = 0$ and $Q^2 > 15{,}000\text{GeV}^2$. The horizontal lines correspond to the experimental value at HERA, $\sigma_{obs} = (0.71 \pm 0.15)$ pb.

Figure 2: Q^2 and M distribution of the expected number of events together with the experimental data. We take $m_{\widetilde{t}_1} = 200\text{GeV}$, $\theta_t = 0$, $\lambda'_{131} = 0.05$, $\text{Br}(\widetilde{t}_{1,2} \to e^+d) = 0.7$ and integrated luminosity $L = 34\text{pb}^{-1}$. For M distribution $Q^2 > 15{,}000\text{GeV}^2$ and $y > 0.3$ are adopted. Dashed line corresponds to the SM expectation.

Figure 3: Q^2 and M distribution of the expected number of events together with the experimental data. We take $m_{\widetilde{t}_1} = 205\text{GeV}$, $m_{\widetilde{t}_2} = 225\text{GeV}$, $\theta_t = 1.0$, $\lambda'_{131} = 0.05$, $\text{Br}(\widetilde{t}_{1,2} \to e^+d) = (0.55,\ 0.25)$ and integrated luminosity $L = 34\text{pb}^{-1}$. For M distribution $Q^2 > 15{,}000\text{GeV}^2$ and $y > 0.3$ are adopted. Dashed line corresponds to the SM expectation.