R-parity violation and the New Events at HERA

S. Lola

Theory Division, CERN, CH-1211, Geneva 23, Switzerland

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Work done with G. Altarelli, J. Ellis, G.F. Giudice and M.L. Mangano

Abstract. We summarise possible explanations of the HERA large-$Q^2$ data, in the framework of R-parity violating supersymmetry. Experimental limits indicate that the most likely production channels are $e^+d \rightarrow \tilde{c}_L$, $e^+d \rightarrow \tilde{t}$ and $e^+s \rightarrow \tilde{t}$. We study the regions of the parameter space that lead to consistent branching ratios, with and without the unification condition for gaugino masses. Cancellations in the coupling of the lightest neutralino to $\tilde{c}_L$, result in a balance between R-parity violating and R-parity conserving decay modes. Such cancellations are not present in the coupling of the neutralino with other particles and an interesting case is $\tilde{\nu}_L$, which could be produced at LEP2 via an $L_1L_{2,3}\tilde{E}_1$ operator. On the other hand, the $\tilde{t}$ branching ratios depend mainly on the mass of the lightest chargino and tend to be dominated by either the R-conserving or the R-violating mode.

The experiments H1 [1] and ZEUS [2] at HERA have reported an excess of deep-inelastic $e^+p$ scattering events at large values of $Q^2$. The events of H1 suggest a resonance with $e^+$-quark quantum numbers and a mass around 200 GeV, while the ZEUS data points are more scattered in mass. More data will be needed, in order to clarify whether the excess is just a statistical fluctuation or an indication of new physics. However, in the meantime, it is important to pursue different possible interpretations of the HERA data [3]. Among the various schemes that have been proposed, R-parity violating supersymmetry seems to be a very promising possibility.

The R-parity violating superpotential, also contains the couplings $L_iL_j\bar{E}_k$, $L_iQ_j\bar{D}_k$ and $\bar{U}_i\bar{D}_j\bar{D}_k$, where $L(Q)$ are the left-handed lepton (quark) superfields, while $\bar{E}$, $\bar{D}$, and $\bar{U}$ are the corresponding right-handed fields. It is possible as a result of symmetries [4], to allow the violation of only a subset of these operators, while being consistent with the limits on proton decay. Among the R-parity violating couplings, 9 could in principle lead to resonant squark production at HERA. However, if one requires to match the HERA data, while satisfying the various experimental constraints, not all possibilities survive. The squark production mechanisms permitted by the $\lambda^i$ couplings include $e^+$

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* Alternative schemes and their possible effects have been discussed at this conference [4].
and valence $d$ collisions to form $\tilde{u}_L, \tilde{c}_L$ or $\tilde{t}_L$, and collisions with sea quarks, of the type $e^+d_i (i = 2, 3)$ or $e^+\bar{u}_i$. The required magnitude of the coupling $\lambda'$ is fixed by the product of the cross section $\sigma$ and the squark branching ratio $B$ for the $R$-parity violating mode $q \to e^+q'$. Then, assuming a total of 10 events in the combined experiments, and for the quoted detector efficiencies, it is found that for the valence production mechanism $\lambda'_{1j1} \approx 0.04/\sqrt{B}$, while for the sea production mechanisms $\lambda' > 0.3/\sqrt{B}$ [6]. Here, we should note that scalar leptoquarks with $B(e^+q) = 1$, are strictly bound from Tevatron data, unless their mass is as high as 210 GeV [7]. On the other hand, a squark with $R$-parity violating couplings [8], has additional decay modes, and accommodates easier the Tevatron constraints.

Among the valence production mechanisms, $\tilde{u}_L$ production is ruled out by limits from $\beta\beta$ decay [7]. For $\tilde{c}_L$ production, the stricter limit on $\lambda'_{1i1}$ arises from $K \to \pi\bar{\nu}\nu$ decays [14], $|\lambda'_{1i1}| \leq 2 \times 10^{-2} (m_{d_{R}}/200 \text{ GeV})$, thus $\tilde{c}_L$ production at HERA implies that $m_{d_{R}} > 400 \text{ GeV}/\sqrt{B}$. However, this bound on $m_{d_{R}}$, which depends on the mixing in the down sector, can be partially relaxed if various non-vanishing coupling constants $\lambda'_{ijk}$ are present. Still, the $\tilde{c}_L$ interpretation of the HERA data suggests that the $R$-parity conserving modes have moderate rates and that $B(K^+ \to \pi^+\nu\bar{\nu})$ is very close to the current experimental limits.

The second valence production mechanism is $e^+d \to \tilde{t}_L$ via $\lambda'_{131}$. For this coupling, the largest constraint arises from atomic parity violation [11]. The most recent value for the bound is $|\lambda'_{131}| \leq 0.08 (m_{t_{L}}/200 \text{ GeV})$ [12, 13], allowing for a sufficient production rate, for $B \geq 0.25$.

On the other hand, sea production processes are excluded by a combination of different experimental constraints; $\tilde{u}_L$ production from sea quarks of the second or third generation is constrained by limits on charged-current universality. Moreover, contributions to the electron neutrino mass, rule out sea-quark production mechanisms involving only second or third generation particles. Finally, the sea process $e^+\bar{u} \to d_{R}$ is also excluded, since otherwise a much larger effect would have been observed in $e^-u \to d_{R}$. Then, the only sea production mechanism that survives is $e^+s \to \tilde{t}_L$ via the $\lambda'_{132}$ coupling [6]. This has been examined in detail, including stop mixing effects [14].

Let us now pass to the squark decay modes. $\tilde{c}_L$, has the following decays: $\tilde{c}_L \to c\chi^0_i$, $\tilde{c}_L \to s\chi^+_j$ and $\tilde{c}_L \to d e^+$, where $\chi^0_i, \chi^+_j$ are neutralinos and charginos. The decay rate for the $R$-parity violating mode (in the absence of stop mixing) is

$$\Gamma = \frac{1}{16\pi} (\lambda'_{121})^2 m_{\tilde{c}_L}$$

The $R$-conserving decays are suppressed either by phase space or, in the $\tilde{c}_L \to c\chi^0_i$ case, by cancellations in the neutralino couplings [3]. The decay rate of $\tilde{c}_L$ to neutralinos is

$$\Gamma' = \frac{g^2}{32\pi} m_{\tilde{c}_L} \left\{ \left( \frac{m_{c}N_{i4}}{M_W \sin \beta} \right)^2 + \left( N_{i2} + \frac{1}{3} \tan \theta_W N_{i1} \right)^2 \right\} \left( 1 - \frac{m_{\chi^0_i}^2}{m_{\tilde{c}_L}^2} \right)^2$$
Here $N_{ij}$ are the elements of the unitary matrix that diagonalises the neutralino mass matrix in the $SU(2) - U(1)$ gaugino basis and $\tan\beta$ is the ratio of Higgs vacuum expectation values. For $\tilde{c}_L$ decays, the term proportional to $m_c$ can be neglected, while the second term is very small, either in the higgsino region or if there is a cancellation $N_{12} \sim -\frac{1}{3}\tan\theta_W N_{11}$, for the lighter neutralino. This cancellation occurs in an acceptable domain of the supersymmetric parameter space, as we can see from Fig.1a. Here, the region where charginos have mass less than 85 GeV, has been subtracted from the plot (for neutralinos, the LEP2 bounds are much weaker). In the figure, $M_2$ is the $SU(2)$ gaugino mass, while the $U(1)$ gaugino mass is determined by the unification relation $M_1 = (5/3)\tan^2\theta_W M_2$.

It is interesting to note that such a cancellation is not present in the coupling of the lightest neutralino to other sfermions. One type of example is given by the couplings to the $SU(2)$ singlets $\tilde{u}_R$, $\tilde{d}_R$ and $\tilde{e}_R$. A second example is the coupling of the neutralino to $\tilde{\nu}_L$, which is of interest, since $\tilde{\nu}_L$ could in principle be produced at LEP2, provided any of the $L_1 L_2 L_3 E_1$ operators is sufficiently large. As shown in Fig.1b, there is no analogous effect as in the $\tilde{c}_L$ case and the decay channels are determined by the mass of the squark and the gauginos.

If we drop the unification condition for gaugino masses, it is possible to go to examples where charginos can be quite heavy, while neutralinos are light. This would occur for large $M_2$, but small $M_1$ values. In such a case, only bounds on neutralino masses from LEP2 would be relevant. For completeness, we show an indicative plot in Fig.1c.

In the case of $\tilde{t}_L$, the neutralino decay mode $\tilde{t}_L \to t\chi^0_1$ is kinematically closed in a natural way and large values of $\mathcal{B}$ are obtained for the region where the chargino decays are suppressed by phase-space. We give the contour plots for this case in Fig.1d. In this particular figure, instead of fixing $\lambda$, we use $\lambda/\sqrt{\mathcal{B}}$. This is done in order to see more explicitly which is the region of parameter space where both the R-violating and the R-conserving decay modes are non-negligible.

Possible tests towards checking the various schemes, include $e^-$ and polarised beam runs at HERA, as well as search for the cascade decays that result from the R-conserving vertices. Squark pair production or single slepton production at the Tevatron, virtual effects at LEP2, observable contributions to $K \to \pi\nu\bar{\nu}$ and/or neutrinoless $\beta\beta$ decays, are also among the possibilities to consider.

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Figure 1: Contours of $B(ed)$ for the $R$-violating decays, in the $\mu - M_2$ plane. Fig.1a is for $\tilde{c}_L$ decays, imposing the unification relation for gaugino masses. Fig.1b is the respective figure for $\tilde{\nu}_L$ decays. Fig.1c is an example of $\tilde{c}_L$ decays, and arbitrary $M_1$ and $M_2$. Finally Fig.1d shows the contours for $\tilde{t}_L$ decays and $M_1 = (5/3) \tan^2 \theta_W M_2$. $\lambda'$ has been fixed to 0.04, except for the last figure, where $\lambda' = 0.04/\sqrt{B}$. In all plots, $\tan \beta = 1$ and $m_{\tilde{q}} = 200$ GeV. The region with a light chargino mass < 85 GeV has been subtracted in (a),(b) and (d), while in (c) charginos are heavy and we applied the LEP2 bounds on neutralinos instead.
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