R-Parity Violation and the HERA Events.

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The excess in high-$Q^2$ events at HERA is introduced and possible explanations within the framework of $R$-parity violating supersymmetry are discussed.

Early this year, the H1 and ZEUS Collaborations at the HERA facility at DESY, Hamburg, created a sensation by announcing that they had an excess in back-scattered positrons (in $e^+p$ collisions) over the deep inelastic scattering (DIS) predictions of the Standard Model (SM). Though statistics were low, it appeared to be a hint of new physics beyond the SM, and a series of theoretical papers investigating the effect followed. Subsequently, the two collaborations presented the results of later runs, in which they again had an excess, though at a lower level. More data have been collected in the subsequent run of HERA, which are still being analysed. This is the current situation. Thus, the case for new physics at HERA — though weaker than it was initially thought to be — still remains the best experimental hint of physics beyond the SM.

The scattering of positrons (beam energy $E^0_e = 27.5$ GeV) from protons (beam energy $E^0_p = 820$ GeV) at HERA can lead to neutral current (NC) final states with a positron ($e^+$) and a jet ($J$) describable by any two of the following observables: $E_e, \theta_e, E_J, \theta_J$ where $E_e, E_J$ are the energies and $\theta_e, \theta_J$ are the scattering angles respectively (with respect to the proton beam direction). The observed excess can be clearly seen in Fig.1(a), which shows the measured cross-section as a function of a cut on the minimum $Q^2$ of the events. As errors are large, the excess is at the $2\sigma$ level, which means that they could well be due to statistical fluctuations. It is
also clear that the H1 Collaboration sees a larger deviation from the SM than the ZEUS Collaboration.

![Graph](image)

**Figure 1:** (a) Comparison of SM Prediction with data (from Ref.2). The solid line shows the DIS prediction. (b) Effects of a resonance of mass 200 GeV and 220 GeV (solid lines) for $\chi_{111}^{(e+J)} = 0.04$.

It is, of course, possible to dismiss the excess as an artefact. Nevertheless, it is interesting to seek theoretical explanations of the effect, in case it should turn out to be a genuine one. Three kinds of solution have, in fact, been tried. These are (a) attempts to modify the proton structure functions, (b) explanations in terms of contact interactions arising out of new physics at a high scale, and (c) the postulate that a new particle resonance, of mass around 200 GeV, is causing the effect. The first two options have been shown not to work well, and it is, thus, to the third possibility that we must appeal. A resonance produced at HERA in a $e^+q$ or $e^+g$ collision must have the quantum numbers of a leptoquark or a leptogluon respectively. As solutions with vector leptoquarks or leptogluons do not fit the kinematic profiles of the observed events well, a better option is to postulate a scalar leptoquark resonance. Such particles are predicted in various extensions of the SM, of
which one is the $R$-parity-violating version of the minimal super-symmetric extension of the SM, where the squarks can behave as leptoquarks.

The Lagrangian describing this last interaction is given by:

$$\mathcal{L} = \lambda'_{ijk} [\bar{\ell}_i P_R d_k \tilde{u}^*_{L_j} - (i \leftrightarrow j)] + \text{H.c.} \quad (1)$$

where $P_R = \frac{1}{2} (1 + \gamma_5)$ and $\tilde{u}_L$ is the scalar superpartner of the left-chiral $u$-quark. The $i, j, k$ are generation indices. If we wish to obtain reasonably large cross-sections, the only relevant couplings are $\lambda'_{121}, \lambda'_{131}, \lambda'_{132}$ corresponding to $e^+ d \rightarrow \bar{c}_L, e^+ d \rightarrow \bar{t}_L$, and $e^+ s \rightarrow \bar{t}_L$ respectively. (For the last option, it is a sea $s$-quark which contributes: the flux being small, one requires a large $\lambda'_{132}$ to get the observed excess.) The calculation is simple and Fig.1(b) shows the results as a function of the minimum $Q^2$. It is obvious that the data are compatible with resonant masses in the 200–220 GeV range, with H1 data preferring the lower and ZEUS data preferring the upper mass value. There will also be some variation with the coupling strength, which is not shown in the figure. One must hope that more data will lead to a better idea of the mass.

An intensive search has also been carried out at the Tevatron for a pair of leptoquarks (or squarks), which can be produced through the same interaction as the above. The signal would be a dielectron and one or two jets. These searches have proved negative, leading to the bound $m_{\tilde{q}} > 240$ GeV for branching ratio $B.R.(e^+ J) = 1$, 206 GeV for $B.R.(e^+ J) = 0.5$. Thus, if the HERA events are to be explained by a leptoquark/squark resonance of mass around 200 GeV, this particle must have a $B.R.(e^+ J)$ of 0.4 or less. This is possible for a charge-$\frac{2}{3}$ leptoquark if it mixes with another leptoquark, but such models look a little contrived. On the other hand, a squark can easily have $R$-parity conserving decay modes to gaugino states. In a sense, therefore, the negative results of the leptoquark searches at the Tevatron make supersymmetry the most attractive explanation of the HERA excess. Another interesting possibility is
– that of seeing like-sign dileptons from gluino pair-production in the event of a $\tilde{c}_L$ resonance around 200 GeV – has been investigated by the CDF Collaboration with negative results, this leads to fresh bounds on the gluino mass if the HERA events have a genuine supersymmetric solution.

The question which immediately arises as a result of the above reflections is: are the other decay channels observable? The most likely other decay channel, to $\bar{\nu}_e + J$, must lead, at HERA, to a corresponding excess in the charged current (CC) DIS data. In fact, the H1 Collaboration has found a tentative CC excess; the ZEUS Collaboration has practically none. As the $\bar{\nu}_e J$ decay mode will have a branching ratio of 0.6 or more, one must postulate low detection efficiencies, in which case a mixed leptoquark solution runs into difficulties. In supersymmetry, however, it is possible to have scenarios with low efficiencies. One of these assumes a light sneutrino, of mass 60 – 80 GeV, in addition to a $\tilde{c}_L$ squark (with a $\lambda'_{121}$ coupling). Unfortunately, this scenario also predicts an excess of four-jet events at LEP, which has not been found (despite early excitement over the ALEPH Collaboration’s results). Another suggestion that a resonant $\tilde{t}_L$ may directly decay into a $\tilde{b}_L$ (which goes to $\bar{\nu}_e d$ through $\lambda'_{131}$) leads to problems with the number of jets and is rather difficult to fit in with $\rho$-parameter constraints.

Two possible solutions which do not have these drawbacks require a $\tilde{t}_1$ resonance, where $m_{\tilde{t}_1} - m_{\tilde{b}_L} < 35$ GeV and $m_{\tilde{t}_1} > m_{\chi^+_1} > m_{\tilde{b}_L}$, and a mixed stop state is required to have the small splitting in stop-bottom masses. It is worth mentioning that there are theoretical drawbacks associated with a light $\tilde{c}_L$ which do not apply in the case of a $\tilde{t}$. One could now have (a) a neutralino $\chi^0_1$ lying between the $\chi^+_1$ and the $\tilde{b}_L$ in mass, which leads to the decay chain $\tilde{t}_1 \to b\chi^+_1 \to b f \bar{f}' \chi^0_1 \to b f \bar{f}' \tilde{b} \tilde{L} \to b f \bar{f}' \tilde{b} \tilde{\nu}$. For the assumed mass-spectrum most of the jets resulting from the cascade decays are soft and would pass undetected. Single hard jets would
result from the last decay and the observed level of excess CC events can be explained. Alternatively (b) the chargino produced in the first decay can undergo the Cabibbo-Kobayashi-Maskawa-suppressed decay $\tilde{\chi}_1^+ \to c\tilde{b}_L$ where $\tilde{b}_L \to \bar{\nu}d$ as before. Once again, one can have single jet events, though one requires rather large values of the soft supersymmetry-breaking parameter $\mu$ to obtain the observed CC excess. Fortunately, such values do not contradict current low-energy bounds on supersymmetric models.

To conclude, a great deal of excitement has been generated by the HERA excess for which it seems that $R$-parity violating supersymmetry is the best explanation. With the present level of statistics it is hard to make a more definite statement. Further results from HERA are, therefore, eagerly awaited.

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