

# SPECULATIONS ON ISOLATED LEPTON EVENTS AT HERA\*

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Speculations on mechanisms which might be responsible for events with an isolated high  $p_T$  lepton, a hadron jet and missing energy, as observed in the H1 experiment at HERA, are discussed.

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## 1. Introduction

The first event with an isolated high  $p_T$  lepton, a hadron jet and missing energy

$$e^+p \rightarrow e^+/\mu^+ + \text{jet} + p_T^{\text{miss}} \quad (1)$$

observed at HERA by the H1 collaboration was announced more than 10 years ago [1]. An excess of HERA I events above *a priori* expectations (not confirmed by ZEUS, where the analysis was performed in a more restricted phase space, see [2]) has given rise to many speculations on physics beyond the Standard Model. These events continued to appear in runs at HERA II. Both H1 and ZEUS have recently performed an analysis of the electron and muon channels (H1 also of the tau channel) on their respective complete HERA I+II data sets, which correspond to approximately  $0.5 \text{ fb}^{-1}$  per experiment [3, 4]. A total of 59 events are observed in the H1 data, compared to a SM expectation of  $58.9 \pm 8.2$ . When the hadronic transverse

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momentum cut  $p_T^X > 25 \text{ GeV}$  is imposed, 24 events remain compared to  $15.8 \pm 2.5$  expected, with 21 events observed in the  $e^+p$  data and  $8.9 \pm 1.5$  expected. The observed data excess in the HERA I  $e^+p$  data thus remains at the  $3\sigma$  level for the complete H1 data set. In the ZEUS analysis of the complete HERA I+II data, 41 data events are observed in agreement with  $48.3 \pm 6.8$  expected. Unlike in the H1 analysis, agreement between data and SM predictions is also observed in the high  $p_T^X$  region, where 11 events are seen in the  $e^+p$  data compared to  $13.1 \pm 1.8$  expected.

## 2. Theoretical speculations

A potential interpretation of these events is based on  $R$ -parity violating supersymmetry (for a recent review of  $R$ -parity violating SUSY see Ref. [5]). Most speculations assume the formation of fairly light stop particles in  $e^+d$  fusion, via the  $R$ -parity violating interaction  $\lambda'_{131} L_1 Q_3 D_1^c$  in the superpotential, with stops decaying to a  $b$ -jet and a chargino. (Scenarios with a charm squark produced in  $e^+d$  fusion via the  $\lambda'_{121}$  coupling and decays to a  $s$ -jet and a chargino can also be considered, although, due to possible strong mixing in the stop sector, the lightest stop can be expected considerably lighter than the charm squark.) The models differ in the structure of subsequent chargino decay chains.

- (i) Charginos decay to a  $W$ -boson and a neutralino  $\tilde{\chi}_1^0$ , or to a lepton and a sneutrino. Subsequent neutralino/sneutrino decays generate final states more complex than in (1), unless the neutralino or the sneutrino is assumed to be metastable, decaying outside the detector. Such an interpretation is very unlikely, however, since the lifetime of  $\tilde{\chi}_1^0$  is bounded from above by the  $\tilde{\chi}_1^0 \rightarrow b\bar{b} \rightarrow b d \nu$  channel mediated by a virtual  $\tilde{b}$ , and the sneutrino may decay “back” through the channel  $\tilde{\nu}_\tau \rightarrow \tau \tilde{\chi}_1^+ \rightarrow \tau b \tilde{t} \rightarrow \tau b e^+ d$  involving virtual intermediate  $\tilde{\chi}_1^+$  and  $\tilde{t}$  states. The estimated decay widths of the two modes,  $\Gamma(\tilde{\chi}_1^0) \sim 1 \text{ eV}$  and  $\Gamma(\tilde{\nu}_\tau) \sim 10^{-3} \text{ eV}$ , for  $\lambda'_{131} \sim 5 \times 10^{-2}$  and SUSY masses  $\mathcal{O}(100) \text{ GeV}$  needed to explain the production rate, suggest lifetimes of order  $\sim 10^{-15} \text{ sec}$  and  $\sim 10^{-12} \text{ sec}$ , respectively, much too short for the particles to escape the detector before decaying [6].
- (ii) An alternative interpretation is based on  $R$ -parity violation ( $\mathcal{R}_p$ ) in both lepton–quark and lepton–lepton interactions in which the chargino decays to a charged slepton and a neutrino, followed by the subsequent slepton  $\mathcal{R}_p$  decay to a lepton+neutrino pair, giving the characteristic final state of (1), *cf.* Ref. [7]. The production of the intermediate stop particle is governed by the  $\mathcal{R}_p$  term  $\lambda' L Q D^c$  in the superpotential, while the slepton decays to a lepton + neutrino pair by  $\lambda L L E^c$  [6].

### 3. An $R$ -parity violating stop scenario

The interpretation (ii) requires: (a) the coupling  $\lambda'$  sufficiently large, a few times  $10^{-2}$  for  $\lambda'_{131}$ , to guarantee the necessary stop production rate; (b) the intermediate particles generated on-shell and the coupling  $\lambda$  sufficiently large since otherwise the rates of events (1) fall dramatically; (c) the light chargino and the lightest neutralino higgsino-like to suppress  $\tilde{\chi}_1^+ \rightarrow W^+ \tilde{\chi}_1^0$  decays which would not generate the desired final states; (d) the Higgs mixing parameter  $\tan\beta$  moderate to allow comparable charged slepton and sneutrino decays of the chargino. The reference point  $\mathfrak{R}$  defined in Table I [6] does not appear in conflict with experiment. It is chosen to develop constraints on the  $\mathcal{R}_p$  interpretation of experimental data but it should not be mis-interpreted as an outstanding candidate for explaining existing data. Masses and mixings generated by this reference point are compatible with the bounds on masses and mixings from LEP, Tevatron and HERA. Strictly within the MSSM, the parameters would lead to too low a mass of the lightest Higgs boson; however, this mass can be raised beyond the LEP limit in extended theories without affecting the mass and mixing parameters relevant for our discussion.

TABLE I

Definition of the reference point $\mathfrak{R}$ .	
$\mathfrak{R}$ : Parameters	Values
elw. gaugino masses	$M_2 = 2M_1 = 1.5 \text{ TeV}$
higgsino mass	$\mu = 160 \text{ GeV}$
Higgs mixing	$\tan\beta = 1.5$
scalar lepton masses	$M_L = M_E = 130 \text{ GeV}$
scalar quark masses	$M_Q = M_U = M_D = 420 \text{ GeV}$
trilinear $A$ coupling	$A_t = 840 \text{ GeV}$
$\lambda', \lambda$ couplings	$\lambda'_{131} = \lambda_{322} = \lambda_{321} = 5 \times 10^{-2}$ other $\lambda', \lambda$ very small

Since the  $\mathcal{R}_p$  couplings of the superfields generate several interactions in the (s)quark and (s)lepton sectors of different charges and species, a large variety of experimental signatures can be expected. Events including multi-lepton final states and  $\tau^+$  leptons should be observed, see Fig. 1, with no overwhelming preference for a particular channel but with large uncertainties due to the choice of mass, mixing and  $\lambda', \lambda$  parameters.

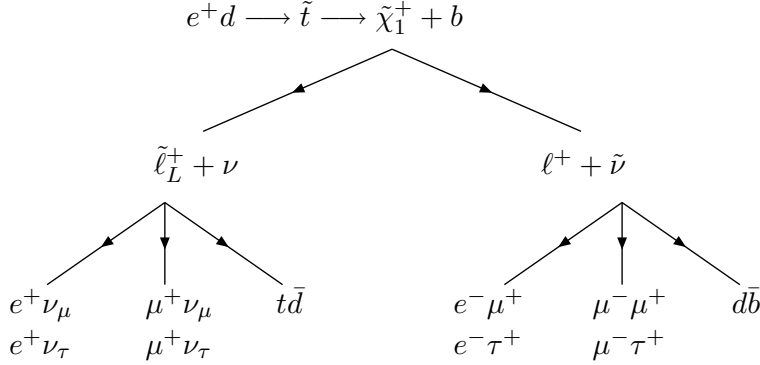


Fig. 1. Mixed  $R$ -parity conserving and  $R$ -parity violating decays of the lighter top squark  $\tilde{t}_1$  which give rise to multi-lepton and jet final states with missing transverse momentum (left cascade) due to escaping neutrinos.

#### 4. Constraints on the SUSY $\mathcal{R}_p$ interpretation

Many consistency conditions for the proposed SUSY scenario can be derived from the kinematic properties of leptons and jets in the final state. Using the  $\tilde{t}_1$  4-momentum from the on-shell  $\tilde{t}_1$  production in  $e^+d$  collisions and the measured  $b$ -jet energy  $E_b$  and longitudinal  $z$ -momentum  $p_b^z$  along the proton direction, the  $\tilde{\chi}_1^+$  mass condition  $m_{\tilde{\chi}_1^+}^2 = (p_{\tilde{t}_1} - p_b)^2$  can be cast in the form

$$m_{\tilde{\chi}_1^\pm}^2 = m_{\tilde{t}_1}^2 [1 - (E_b - p_b^z)/2E_e] - 2E_e(E_b + p_b^z). \quad (2)$$

With the *a priori* unknown stop and chargino masses, each event with measured values of  $b$ -jet energy and longitudinal momentum defines, according to Eq. (2), a line in the  $(m_x^2, m_y^2)$  plane, the coordinates labeled by  $(m_x^2, m_y^2)$ . If the considered  $\mathcal{R}_p$  scenario is the correct interpretation of the data, lines corresponding to the signal events must cross at the single point corresponding to the true values of stop and chargino masses  $(m_x^2, m_y^2) = (m_{\tilde{t}_1}^2, m_{\tilde{\chi}_1^\pm}^2)$ , and lie within the double cone formed by the line with slope = 1 and cutting the  $m_y^2$ -axis at  $-(m_{\tilde{t}_1}^2 - m_{\tilde{\chi}_1^\pm}^2)$ , and the line crossing the origin with slope  $= m_{\tilde{\chi}_1^\pm}^2/m_{\tilde{t}_1}^2$ , both intercept and slope given by the true mass values. The opening angle of the cone increases apparently with the  $\tilde{t}_1 - \tilde{\chi}_1^\pm$  mass gap.

On the other hand, lines corresponding to background events do not cross at a single point but rather form an irregular mesh over the  $(m_x^2, m_y^2)$  plane. This is shown in Fig. 2 for a few examples of signal events (left), and for background (right) for which the jet parameters are identified with values derived from  $W$ -photoproduction  $\gamma q \rightarrow W q'$ .

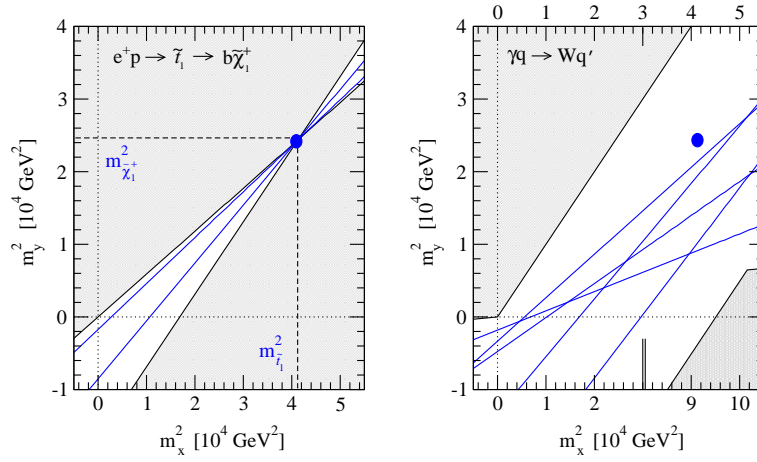


Fig. 2. Left: All  $R_p$  signal lines must lie within the double cone and cross at the true mass values,  $m_x^2 \rightarrow m_{\tilde{t}_1}^2$  and  $m_y^2 \rightarrow m_{\tilde{\chi}_1^+}^2$ . Right: Lines corresponding to background events from  $W$ -photoproduction  $\gamma q \rightarrow Wq'$ . The kinematically excluded regions are shaded (the lower  $x$ -axis is cut to accommodate the forbidden wedge on the right).

The on-shell requirements provide many more consistency conditions. For example, in the decay chain ending with  $t\bar{d}$  the events must cluster at the invariant mass  $M[jt] = m_{\tilde{e}_L}$ , while in the decay chain ending with  $d\bar{b}$  they must cluster at the triple point  $M[jj] = m_{\tilde{\nu}_e}$ ,  $M[e^+jj] = m_{\tilde{\chi}_1^+}$ ,  $M[e^+jjj] = m_{\tilde{t}_1}$  ( $j$  stands for a non- $t$  jet). More constraints can be derived for final states with  $\tau$  since the  $\nu_\tau$  3-momentum can be reconstructed fully in single  $\tau$  events.

## 5. Conclusions

Independent of the specific reference point, two generic implications have emerged from the study:

- Kinematical constraints relate the observed jet and lepton energies and momenta with masses of stop, chargino and sneutrino, and clusters of invariant masses must be observed experimentally;
- $R$ -parity violating couplings connect leptons and sleptons of different charges and species, implying that also events including multi-lepton final states and  $\tau^+$  leptons should be observed.

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