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High P_T Leptons and W Production at HERA

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Abstract. Details are given of the observation by H1 of events containing high P_T leptons in addition to large missing P_T. A closely related ZEUS analysis, including a preliminary measurement of the W production cross section, is discussed and the two experiments are compared. Some possible non-Standard Model sources for the events are considered.

1. Introduction

The observation by the H1 experiment of a number of events containing high P_T leptons in addition to large missing P_T, apparently in excess of the number expected from Standard Model processes, has aroused much recent interest and is outlined in section 2 of this article. The Standard Model background is expected to be dominated by W production, a preliminary cross section for which has been measured by the ZEUS experiment. ZEUS have also searched for high P_T tracks in events with missing P_T using similar cuts to H1, the results of which are presented in section 3. A direct comparison between the H1 and ZEUS detector acceptances is shown in section 4. Finally, some theoretical speculations about possible sources of such events in the context of R_p-violating SUSY are presented in section 5.

2. H1 High P_T Lepton Events

The H1 analysis [1] is based on an inclusive search for events with a transverse momentum imbalance measured in the calorimeter, P_T^{calo}, greater than 25 GeV. This cut minimizes the contributions from neutral current and photoproduction processes and has a well understood experimental efficiency. In the selected event sample, 124 events contain high energy tracks with transverse momentum above 10 GeV and polar

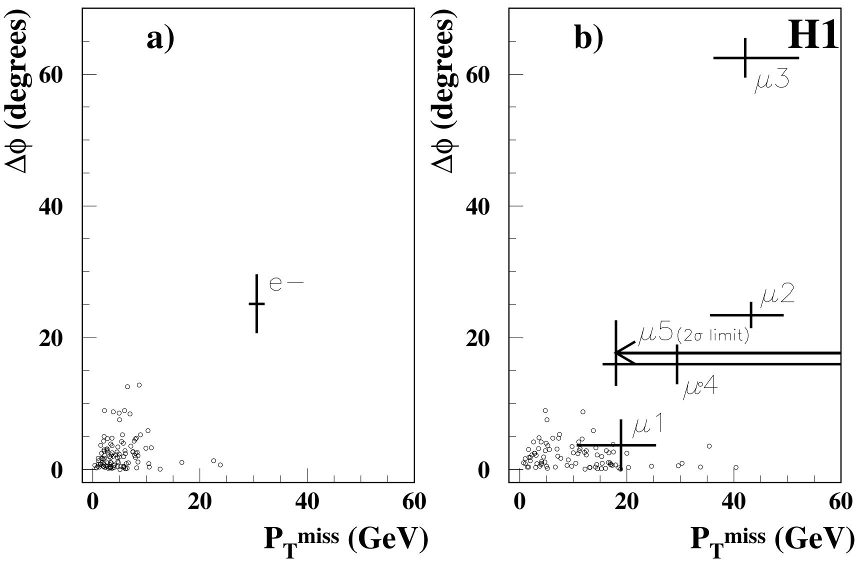

Figure 1. Distribution of events in $P_T^{\rm miss}$ and azimuthal acoplanarity $\Delta\phi$: a) electron channel; b) muon channel. The six events are displayed with their individual measurement errors. The open circles show the distributions for a neutral current control sample, described in the text.

angles with respect to the proton direction above 10°. The vast majority of these events are charged current events containing a high P_T track close to the centre of an hadronic jet. The track isolation with respect to calorimetric deposits ($D_{\rm jet}$) and with respect to other tracks ($D_{\rm track}$) is quantified by the Cartesian distance in the $\eta - \phi$ plane ‡. Six events are found to contain isolated tracks with $D_{\rm jet} > 1.0$ and $D_{\rm track} > 0.5$.

Lepton identification algorithms, based on the signal shape in the calorimeter and muon chamber hits, indicate that the six tracks in fact correspond to high P_T leptons : one event contains an electron (e^-) and five events contain muons (2 μ^+, 2 μ^- and one very energetic muon corresponding to a stiff track whose sign cannot be determined). The muon events are labelled $\mu 1$ to $\mu 5$ in the following. One of the muon events ($\mu 3$) also contains a positron with a lower transverse momentum $P_T(e^+) = 6.7$ GeV.

The lepton signature in each case has been investigated in detail and found to be consistent with the assigned hypothesis. For the electron candidate the shower pattern recorded in the calorimeter is compatible with the expectation for an electromagnetic shower, while the isolated track measured in the central tracker has a specific ionisation consistent with a single particle. The muon candidates are measured in the central tracking system, calorimeters and external iron yoke instrumented with muon chambers.

‡ Both H1 and ZEUS coordinate systems are right-handed with the Z-axis pointing in the proton beam direction and the horizontal X-axis pointing towards the centre of HERA. The pseudorapidity variable η is related to the polar angle by $\eta = -\ln(\tan(\theta/2))$.

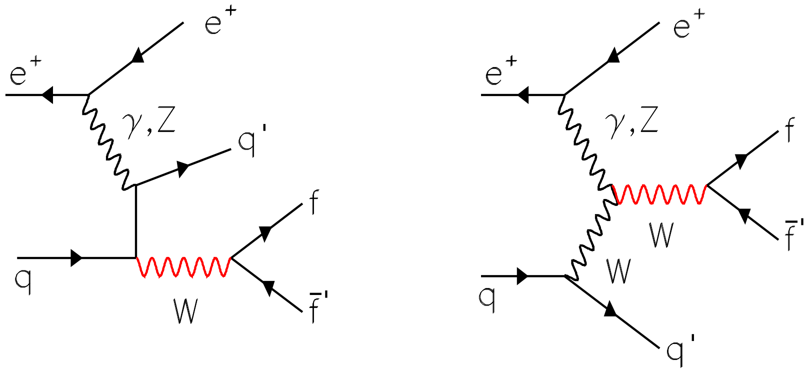

Figure 2. Two Feynman diagrams for the reaction $e^+p \to e^+W^\pm X$. The first is one of the dominating diagrams, the second one involves couplings at the $WW\gamma$ vertex.

For all tracks the specific ionisation in the central tracker is consistent with single minimum ionising particles. The energy depositions in the calorimeters sampled over more than 7 interactions lengths and the signals in the muon chambers are compatible in shape and magnitude with those expected from a minimum ionising particle. The probability that an isolated charged hadron would simulate a muon in both the calorimeter and the instrumented iron is estimated to be less than 3×10^{-3}.

In all events a hadronic shower has been detected in the calorimeters. In the event $\mu5$ no charged particles are found in the core of the high-P_T hadronic jet. In all events an imbalance in the net transverse momentum indicates the presence of at least one undetected particle. This hypothesis is supported by the large value for the lepton-hadron acoplanarity observed in most of the events, defined as the angle in the transverse plane between the hadronic system and the direction opposite to that of the high P_T lepton. The significance of the transverse momentum imbalance and acoplanarity is tested with data using neutral current (NC) events, which are expected to be intrinsically coplanar and balanced in P_T. For comparison to the muon events, the kinematics in the NC sample is reconstructed using the positron track parameters instead of calorimetric information. The six high P_T lepton events are compared to the NC control sample in figure 1. The probability for an NC event to have both $\Delta\phi$ and P_T^{miss} values greater than those measured in a given candidate is estimated from a high statistics simulation to be 1% for $\mu1$ and less than 0.1% for the other candidates.

The Standard Model predictions for processes yielding events with isolated leptons and missing energy have been investigated. The predicted rates are dominated by W production via the reaction $e^+p \to e^+W^\pm X$, two diagrams for which are shown in figure 2, followed by the leptonic decay of the W. The cross section of around 60 fb per charge state and leptonic decay channel for this process, calculated using the program EPVEC [3], gives an expected 1.7 ± 0.5 events in the electron channel and 0.5 ± 0.1 events in the muon channel. A recent next to leading order calculation of the resolved photon contribution to the cross section gives a total cross section for $e^+p \to e^+W^\pm X$ of

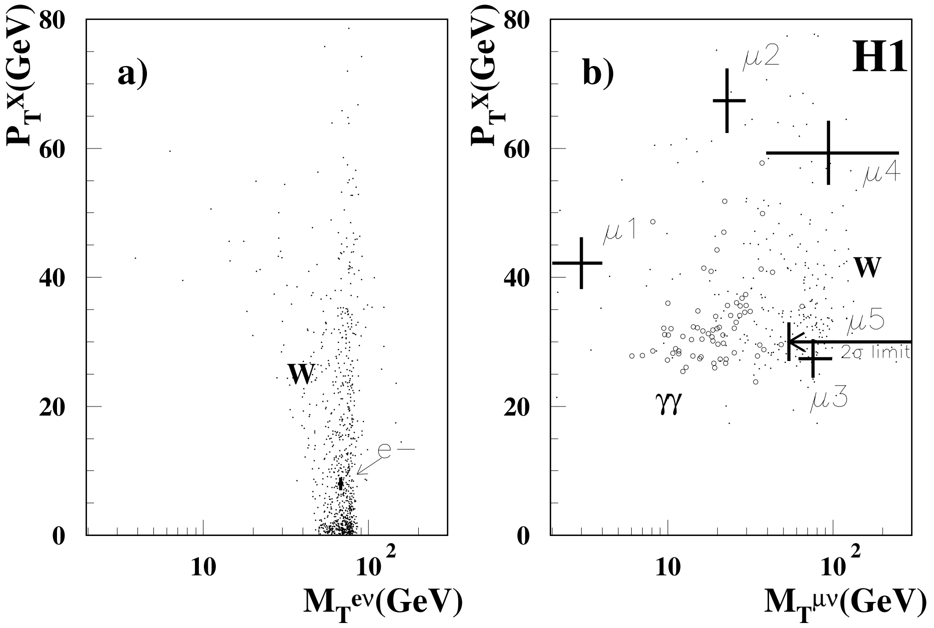

Figure 3. Comparison of the observed events with Standard Model distributions in the plane defined by the hadronic transverse momentum, P_T^X, and the lepton-neutrino transverse mass, $M_T^{\ell\nu}$. The W production and $\gamma\gamma \rightarrow \mu^+\mu^-$ Monte Carlo samples, indicated by points and open circles respectively, correspond to an integrated luminosity a factor 500 greater than the data.

0.97 pb, consistent with the leading order EPVEC estimate [4]. Other significant sources of events with isolated leptons and missing transverse momentum include neutral current DIS in the electron channel and the $\gamma\gamma \rightarrow \mu^+\mu^-$ process in the muon channel. The total predicted rates from all Standard Model processes are 2.4 ± 0.5 events in the $e^\pm$ channel (compared with 1 event observed) and 0.8 ± 0.2 events in the muon channel (compared with 5 events observed).

In figure 3 the observed events are compared to W production Monte Carlo events in the plane of the transverse momentum of the hadronic system, P_T^X, versus the transverse mass of the lepton-neutrino system, $M_T^{\ell\nu}$. The electron event and two of the muon events ($\mu 3$ and $\mu 5$) are kinematically consistent with the Jacobian peak located around the W mass and the low P_T^X expected for W production. Three muon events can only marginally be accommodated within this interpretation. None of the observed muon events are consistent with the distribution expected for $\gamma\gamma \rightarrow \mu^+\mu^-$, also shown in figure 3.

3. ZEUS Results on W Production and High P_T Leptons

The results of a search for W production and leptonic decay in 46.6 pb^{-1} of ZEUS e^+p data have been presented elsewhere in these proceedings [5]. The measured cross

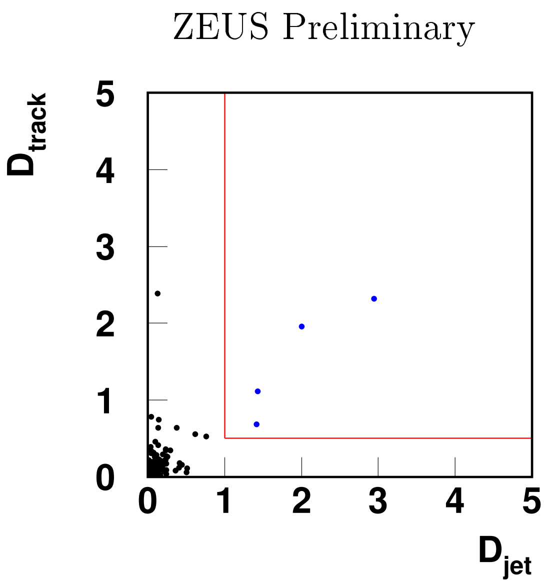

Figure 4. The jet and track $\eta - \phi$ isolation of tracks with $P_T > 10$ GeV in events with calorimeter P_T greater than 25 GeV, for the full 1994-97 ZEUS e^+p data.

section from the electron channel of $1.0\,^{+1.0}_{-0.7}$ (stat) $\pm$ 0.3 (syst) pb is in good agreement with the Standard Model prediction. The absence of any signal in the muon channel is consistent with the smaller efficiency for selecting events on the basis of calorimeter missing P_T, in turn a consequence of the soft hadronic P_T spectrum for Standard Model W production.

In order to avoid any hidden lepton identification inefficiencies, a separate search has been performed for isolated high P_T vertex fitted tracks in events with large missing P_T, applying cuts similar to those outlined in [1]. All events with a calorimeter P_T greater than 25 GeV are selected, with the exception of neutral current candidate events with an acoplanarity angle less than 0.1 rad. The isolation variables $\mathrm{D_{jet}}$ and $\mathrm{D_{track}}$ are defined for a given track, as in the H1 analysis, as the $\eta - \phi$ separation of that track from the nearest jet and the nearest remaining track in the event, respectively. Jets must have $E_T > 5$ GeV, an electromagnetic fraction less than 0.9 and an angular size greater than 0.1 rad. All tracks with $P_T > 10$ GeV in the selected events are plotted in the $\{\mathrm{D_{track}}, \mathrm{D_{jet}}\}$ plane in figure 4. The 4 tracks selected with $\mathrm{D_{jet}} > 1.0$ and $\mathrm{D_{track}} > 0.5$ agrees well with the expectation of 4.2 ± 0.6 tracks from combined Monte Carlo sources. All four isolated tracks are in fact identified as positrons using standard electron finding algorithms and criteria described in [2], consistent with the 2.4 ± 0.5 (1.5 ± 0.4) electron type (muon type) events expected from Monte Carlo. There is therefore no evidence of an excess rate of high P_T tracks, whether identified as leptons or not, in the 1994 to 1997 ZEUS data.

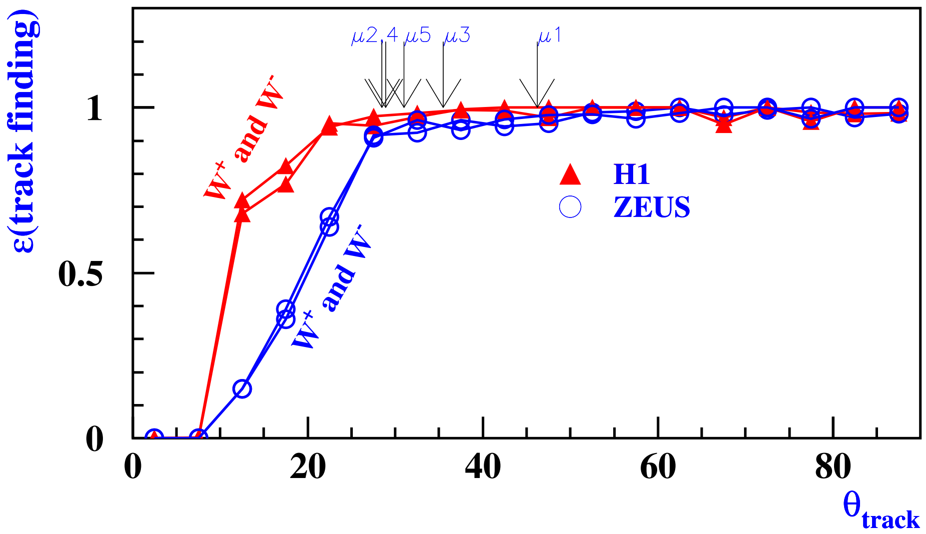

Figure 5. The $P_T > 10$ GeV track finding efficiency as a function of polar angle for muons from W^+ and W^- decay passed through the H1 and ZEUS detector simulations. The polar angles of the H1 high P_T muons are also indicated.

4. Comparison of H1 and ZEUS Results

As pointed out in [5], the ZEUS muon data at large calorimeter missing P_T disfavours high hadronic P_T W production as the source of all the H1 high P_T muon events. This is consistent with the kinematic properties of the H1 events themselves. While the low statistics of the H1 and ZEUS observations cannot currently exclude a statistical fluctuation, it is nevertheless interesting to ask whether any source of events with a topology similar to the H1 events would be observed at ZEUS. In particular, the leptons in the H1 events are concentrated at small polar angles, close to where the ZEUS central tracking chamber track reconstruction efficiency is expected to fall off.

Using W production Monte Carlo events passed through the H1 and ZEUS detector simulations, the efficiency with which muons from $W \to \mu\nu$ decay have a corresponding track reconstructed with $P_T > 10$ GeV can be calculated. The efficiencies for both W^+ and W^- production are plotted as a function of polar angle in figure 5. Also indicated are the polar angles of the H1 high P_T muons, further details of which may be found in [1]. It can be seen that the H1 events lie in a region where the ZEUS track reconstruction efficiency is equally high, lending weight to the argument that a signal ought to have been seen in the ZEUS analyses presented here. However, the positions of the H1 and ZEUS turn on curves are significantly different and are currently being checked using suitable data samples.

Although more data will clearly be required to fully understand the source of the H1 high P_T lepton events, it is nevertheless worthwhile at this point to consider new mechanisms that might give rise to events of this type.

5. Theoretical Speculations

To date, non-Standard Model production mechanisms for the isolated muon events have been proposed in [6] and [7]. In both papers the discussion is performed in the framework of the supersymmetric standard model with R_p-breaking. The primary process is the s-channel production of a single scalar top quark ($\tilde{t}_1$) in e^+d_k collisions

$$e^+d_k \to \tilde{t} \tag{1}$$

through the R_p-breaking interaction Lagrangian

$$L = \lambda'_{13k}\cos\theta_t(\tilde{t}_1\,\bar{d}_{kR}\,e_L + \tilde{t}_1^*\,\bar{e}_L\,d_{kR}) \tag{2}$$

where λ'_{13k} denotes the R_p-violating coupling to the down quark of the k-th generation. The angle θ_t denotes the mixing angle in the scalar top quark sector; a similar term involving the heavier stop $\tilde{t}_2$ is also present with $\cos\theta_t$ replaced by $\sin\theta_t$.

The interaction Lagrangian (2) originates from the general R_p-breaking ($\not{R}_p$) superpotential

$$W_{\not{R}_p} = \lambda_{ijk}L_iL_jE^c{}_k + \lambda'_{ijk}L_iQ_jD^c{}_k + \lambda''_{ijk}U^c{}_iD^c{}_jD^c{}_k, \tag{3}$$

where the left-handed lepton (quark) superfield doublets are denoted by L (Q), the right-handed lepton (quark) singlets by E (U and D), and i, j, k are generation indices. The first two terms violate lepton number and the last term violates baryon number. The couplings λ, λ' and λ'' are subject to many constraints from low-energy and high-energy LEP, HERA and Tevatron data [8].

The production mechanism (1) is based on the resonant formation of $\tilde{t}$ in e^+p collisions since the rate associated with virtual $\tilde{t}$ production would be too small. These phenomena could be related to a possible surplus of high Q^2, high x events in neutral current scattering seen in the 1994-1996 HERA data. However, even if the NC events cannot be interpreted as $\tilde{t}$ resonance production (not necessarily *one single* resonance), or are interpreted as a statistical fluctuation, there is still room left for speculation regarding the source of the isolated μ^+ events in the SUSY sector based on top squarks in the mass range of 200 – 230 GeV, so long as the branching ratio B_{eq} for the R_p-violating decay $\tilde{t} \to e^+q$ is small and the R_p-conserving decay modes are dominant.

In [6], the $\tilde{t}$ is produced in collisions of positrons with valence d-quarks in the proton, *i.e.* $k = 1$ in equation 2 (down-stop scenario), whereas in [7] the case $e^+s \to \tilde{t}$ ($k = 2$, strange-stop scenario) is considered in addition. The papers also differ in the assumed squark decay chains, shown in figure 6, that give rise to the characteristic features of the muon events.

For a stop mass in the range 100 – 200 GeV and with λ'_{131} large enough for stop production to be relevant, there is a wide range of parameters where the decay $\tilde{t} \to b\tilde{\chi}_1^+$ dominates over other decay modes. Then the decay chain shown in figure 6a, $\tilde{t} \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to \mu^+\nu\tilde{\chi}_1^0$ generates an isolated muon and a b quark jet at large transverse momenta. Since the muon originates from the virtual W^+, similar events with isolated positrons should be observed. Moreover, to account for the topology of the events with large

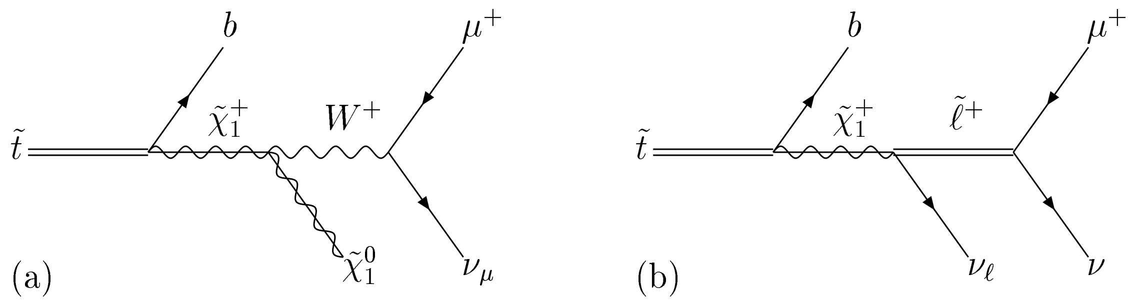

Figure 6. Possible decay chains of the stop leading to isolated muon + jet + missing P_T: $\tilde{t} \to b\tilde{\chi}_1^+$ followed by (a) $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \mu^+ \nu_\mu$ ([6]); (b) $\tilde{\chi}_1^+ \to \nu_\ell \mu^+ \nu$ ([7]).

missing P_T, the neutralino $\tilde{\chi}_1^0$ must be assumed very long-lived ($\Gamma_{\tilde{\chi}_1^0} \lesssim 10^{-7}$ eV), so that it may escape detection despite the presence of R_p-conserving decay channels. Since parameters are not easily arranged that give rise to such a long lifetime, alternative decay channels have been considered in [7].

If trilinear lepton couplings λLLE^c are also present in supersymmetric theories with sleptons in the mass range of 100 to 200 GeV, another possibility for stop and subsequent chargino decays is open, as shown in figure 6b. The chargino may decay into a neutrino and a slepton, followed by the R_p-violating slepton decay to a positively charged muon and a neutrino. Such a chain can account for the observed final state, *i.e.* a jet, a single positively charged muon and missing transverse momentum.

In the case of stop production in e^+d collisions (down stop scenario), the chargino must be heavy with $m_{\tilde{\chi}_1^+} \approx 180 - 190$ GeV to account for the required balance of R_p-conserving and violating stop decay modes implied by the low-energy, HERA and Tevatron data. By contrast, for the strange stop scenario $e^+s \to \tilde{t}$ with a larger value of λ'_{132} than λ'_{131}, one finds a solution for lighter chargino masses $m_{\tilde{\chi}_1^+} \sim 100 - 140$ GeV.

Assuming a given value for $m_{\tilde{t}}$, the mass $m_{\tilde{\chi}_1^+}$ recoiling against the hadronic b jet can be estimated from the calculated 4-momentum of the top squark and the measured 4-momentum of the b jet: $m^2_{\tilde{\chi}_1^+} = (p_{\tilde{t}} - p_b)^2$. The recoil masses must cluster for the observed events; if not, two-body decays of the stop resonance are not the origin of the events, or more than one stop is produced. It is amusing to observe that if both stops with masses $m_{\tilde{t}_1} = 200$ GeV and $m_{\tilde{t}_2} = 230$ GeV are responsible for the H1 events, the estimated recoiling mass $m_{\tilde{\chi}_1^+}$ falls in the range 130 – 140 GeV, compatible with the strange stop scenario.

The branching ratio for the chargino decay $\tilde{\chi}_1^+ \to \nu_\ell \tilde{\ell}^+$ can be expected to be close to 1/6. The subsequent decay $\tilde{\ell}^+ \to \mu^+\nu$ has to compete with other R_p-violating and also with R_p-conserving decay modes. The semi-quantitative discussion performed in [7] suggests that a decay chain $\tilde{t} \to b\tilde{\chi}_1^+ \to b\nu\tilde{\ell}^+ \to b\nu\nu\mu^+$, leading to the observed topology, could be realized in supersymmetric theories with R_p-breaking couplings. However, a large number of other final states with rather complex topologies should be observed at HERA in e^+p collisions generated by the mixed R_p-conserving and violating decay modes. Single and multi-lepton states associated with one or more jets and, in most cases, missing transverse momentum due to escaping neutrinos can be expected,

$$\begin{aligned} e^+p &\to \tilde{t} \to \tilde{\chi}_1^+ b \to \ell^+ \mathrm{j}\nu\nu,\ \ell^+\ell^+\ell^-\mathrm{j},\ \ell^+\mathrm{jjj},\ \mathrm{jjj}\nu \\ e^+p &\to \tilde{c} \to \tilde{\chi}_1^0 c \to \ell^+\ell^-\mathrm{j}\nu,\ \ell^\pm\mathrm{jjj},\ \mathrm{jjj}\nu \end{aligned} \tag{4}$$

where ℓ, ν, j generically denote charged leptons, neutrinos and jets. However, not all combinations are possible in principle. For example single negatively charged lepton events can be accompanied by jets but not by neutrinos. Kinematical constraints imposed by the fixed masses of the intermediate supersymmetric particles can be exploited to check whether such hypothetical decay chains are realized or not.

From the above discussion it is clear that isolated μ^+ events in e^+p scattering can occur in supersymmetric scenarios with R_p-violating interactions. The presence of both $\lambda' LQD^c$ and λLLE^c terms in the superpotential provides a large variety of mechanisms. If true, a wealth of other interesting phenomena could be observed, not only at HERA.

6. Summary and Conclusions

The ZEUS results, along with the kinematic analysis of the events themselves, have shown that W production alone is unlikely to account for all the H1 high P_T lepton events. Moreover, it is likely that events of a similar topology to those observed by H1 would have been found by ZEUS in a similar high P_T track based search. It is intriguing that high P_T lepton events of the kind observed by H1 can naturally arise in certain R_p-violating SUSY scenarios. Nevertheless, only more data will allow the source of the events to be finally established.

Acknowledgments

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