Observation at HERA of Events with an Isolated Charged Lepton and Large Missing Transverse Momentum

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At HERA events are observed, in which a high energy isolated charged lepton is accompanied by an imbalance in the transverse momentum. While some of these events can be explained by the expected level of W production, 3 events remain, which have no probable explanation within the Standard Model.

1. INTRODUCTION

In 1994 the H1 collaboration observed in $e^+ p$ collisions at $\sqrt{s} = 300$ GeV an event with unexpected properties [1], notably a large imbalanced transverse momentum together with an isolated, high P_T μ^+ and a hadronic jet. This event, which due to its kinematic properties could not be readily explained as being due to a process within the Standard Model, was found in the modest integrated luminosity of $\sim$ 4 pb^{-1}. The excellent running of HERA in the following years allowed the accumulation of much larger data samples, and both the H1 and the ZEUS collaboration have now carried out systematic searches for similar events with such topologies. The analyses of both collaborations are shortly described in this report. More experimental details can be found in the recent publications[2,3].

2. THE H1 ANALYSIS

The first event of this kind was discovered in a data sample selected for studies of the Charged Current (CC) deep inelastic scattering (DIS) reaction $e^+ p \rightarrow \nu X$. Large missing transverse momentum, P_T^{miss}, given by the calorimeter measurement, P_T^{calo}, characterises CC reactions and a cut in this quantity is an important selection criterium also in the present analysis:

- $P_T^{calo} > 25$ GeV.

- ≥ 1 charged track with $P_T > 10\,$GeV and with polar angle $\theta > 10°$.

Further cuts serve to remove background (cosmics, beam-gas reactions) and to ensure that the events are well measured. Cuts in the azimuthal balance and in the longitudinal momentum balance are designed to minimize background from the Neutral Current (NC) DIS reaction $e^+ p \rightarrow e^+ X$, which can mimic a large P_T^{calo} value if the positron or the hadronic system X loses energy in calorimeter cracks, or in the beampipe .

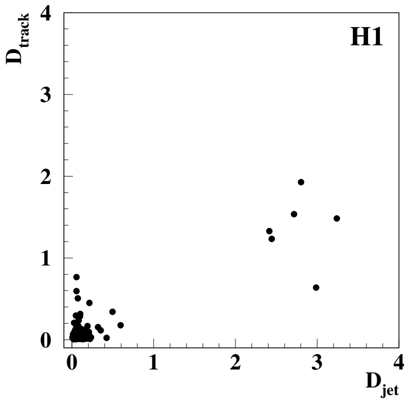

Figure 1. Correlation between the distances D_{jet} and D_{track} (see text) to the closest hadronic jet and charged track, for all high P_T tracks in the event sample.

The $e^+ p$ data sample from 1994-97 corresponds to 36.5 pb^{-1}. 124 events fulfil the selection criteria. All events contain exactly one high P_T track and at least one hadronic jet. In the further study the Cartesian distances of the high P_T tracks to the nearest jet and to the nearest charged track are defined in the plane of azimuth ϕ and pseudorapidity η, D_{jet} and D_{track} respectively. The correlation of D_{jet} and D_{track} is shown in Figure 1. The bulk of the 124 events is located at small values of both distances; these events stem from the CC reaction. However, 6 events are distinguished by having the high P_T tracks well separated from the other tracks and jets in the events.

The high P_T tracks in these 6 events all fulfil lepton identification criteria. Thus one track is an electron ($E^{calo} > 5$ GeV matched to the high P_T track, the electromagnetic fraction of E^{calo} is $> 90\%$) and the other five tracks are muons ($E^{calo} < 5$ GeV in the vicinity of the high P_T track, geometric matching to the Instrumented Iron signal). Specifically, there are $2\mu^+, 2\mu^-, 1\mu$ and $1e^-$; one muon has too high P_T to allow a charge determination. In the following the events are labelled "electron" and "$\mu 1 ... \mu 5$". $\mu 1$ is the event discovered in 1994.

To further study these events, the acoplanarity $\Delta\phi$, defined as the difference in azimuth between the hadronic transverse momentum P_T^X and isolated lepton transverse momentum P_T^l, is in Figure 2 plotted against P_T^{miss}. The 6 events are compared to NC events, selected in a similar kinematic region; when comparing the NC events to the muon events, P_T^{miss} is calculated using the drift chamber measurement for the e^+. As seen, the 6 events are well distinguished from the NC events, ensuring that the missing transverse momentum is not faked by measurement uncertainties or by losses of the proton remnant in the beampipe.

A number of Standard Model processes have been considered as possible origin of these events. Of these Standard Model processes, $W^\pm$ production $e^+ p \rightarrow e^+ W^\pm X$ with subsequent decay $W^\pm \rightarrow \nu l^\pm$ can produce the observed signatures; the dominant diagrams are shown in Figure 3. From the MC simulation (using the program EPVEC[4]) of W production one expects, among other features,

- Cross section $\sim$ 60 fb per charge state and leptonic decay channel,
- Cross section increases towards low P_T^X,
- Jacobian peak at the W mass in the lepton neutrino transverse mass $M_T^{l\nu}$, where P_T^{miss} is taken as the ν transverse momentum,
- The scattered e^+ is seen in the detector in 25% of the events.

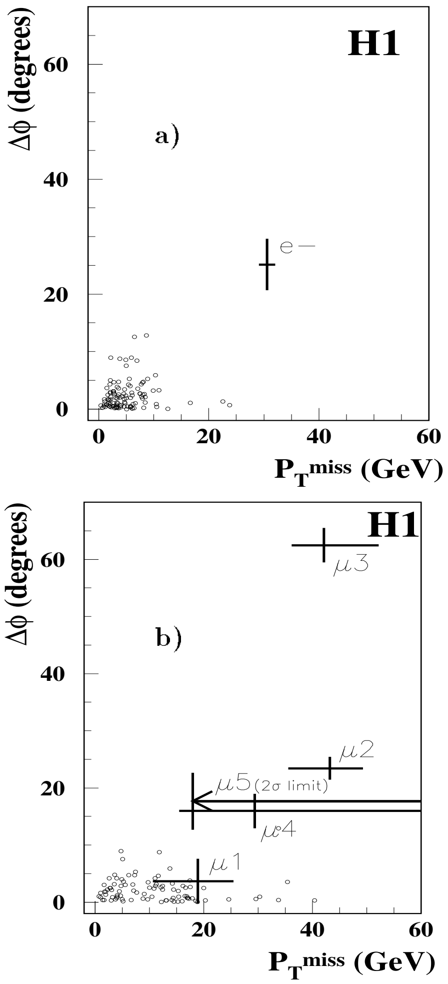

Figure 2. Distribution of events in P_T^{miss} and azimuthal acoplanarity $\Delta\phi$: a) electron channel; b) muon channel. The six events are displayed with their individual measurement errors. Open circles show NC events; in case of b) P_T^{miss} is calculated from the positron track.

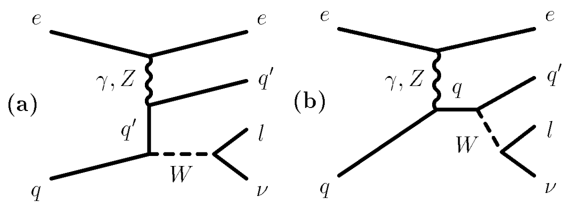

Figure 3. Dominant Feynman diagrams for the process $e\,q \;\rightarrow\; e\,q'\,l\,\nu$.

Another possible Standard Model process, which can contribute to the observed event signatures, is the inelastic $\gamma\gamma \;\rightarrow\; l^+l^-$ reaction, in which one lepton remains undetected. Simulations show that only the $\mu^+\mu^-$ process contributes within the selection criteria.
In Figure 4 the kinematics of the 6 events are compared to MC simulations of both, W production and $\gamma\gamma$ processes; the integrated luminosity of the MC simulations is 500 times larger than that of the data. The comparison shows that the "electron" event is well compatible with W production, sitting in the Jacobian peak of $M_T^{e\nu}$ and at a relatively low P_T^X value. The same is true for the $\mu3$ and $\mu5$ events; their kinematic properties agree with the expectation for W production. Indeed, the $\mu3$ event has an observed scattered e^+, which enables the calculation of the mass $M^{\mu\nu}$. The latter is found to be 82^{+19}_{-12} GeV, nicely confirming the W production interpretation for this event.
Considering all possible Standard Model processes, the expectation is 2.4 ± 0.5 electron events and $0.8 \;\pm\; 0.2$ muon events, of which $1.6 \;\pm\; 0.5$ and $0.5 \;\pm\; 0.1$ events are due to W production. This is in good agreement with the observation that 2, maybe 3 of the 6 events have the characteristics expected from W production and decay.

However, 3 events remain, all with an isolated, high P_T muon. There are $2\mu^+$ and $1\mu^-$. These three muon events have no probable explanation within the Standard Model.

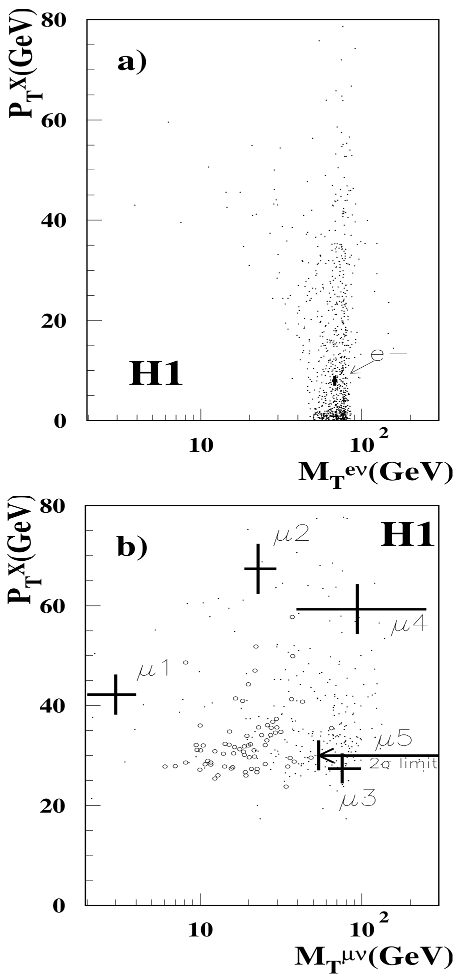

Figure 4. Distribution of events in P_T^X and $M_T^{l\nu}$: a) electron channel; b) muon channel. The 6 events are displayed with their individual errors. MC simulations (dots for W production, open circles for $\gamma\gamma$ processes) are shown for an integrated luminosity 500 times larger than that of the data.

3. THE ZEUS ANALYSES

The ZEUS collaboration have performed two analyses, using $\sim$ 48 pb^{-1} of $e^+\,p$ data from 1994-97. The first analysis is a search for events with isolated high P_T leptons and large P_T^{miss}. The selection criteria are similar to those used by the H1 collaboration:

- $P_T^{calo} > 20$ GeV.
- ≥ 1 charged track with $P_T > 10$ GeV and with polar angle θ in the range $0.3-2.0$ rad.
- ≥ 1 hadronic jet with $E_T > 5$ GeV.

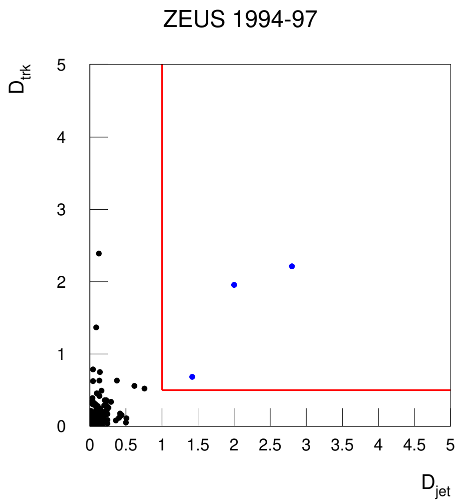

Figure 5. Correlation between the distances D_{jet} and D_{track} to the closest hadronic jet and charged track, for all highP_T tracks in the event sample.

Further cuts against backgrounds are also similar to the ones made in the H1 analysis. The correlation of the Cartesian distances D_{jet} and D_{track} is shown in Figure 5. The isolation cuts $D_{jet} > 1, D_{track} > 0.5$ are fulfilled by three events. The high P_T tracks in these three events are all identified as positrons. One event is compatible with being a NC background event, in which the positron has a large energy leakage into the ZEUS backing calorimeter. The observed event rate is compared to the expectation from Standard Model processes: 3.5 ± 0.7 electron events, 2.0 ± 0.4 muon events, to which W production contributes 0.9 and 0.4 events, respectively. The W production cross section is estimated in leading order using the program EPVEC[4]. Thus the observation is in good agreement with the SM expectations. There is no excess of events with isolated, high P_T charged leptons and large missing P_T.

In their second analysis of the data the ZEUS collaboration perform a dedicated measurement of the W production cross section. For this purpose, the event selection criteria are modified as follows

- The Decay $W \rightarrow e\,\nu$
  - $P_T^{calo} > 20$ GeV,
  - Electron identification via Neural Network techniques,
  - $\theta^e < 1.5\,rad$, $P_T^e > 10$ GeV,
  - Acoplanarity between electron and hadronic jet > 0.3 rad,
  - $D_{track} > 0.5$ for the electron.
- The Decay $W \rightarrow \mu\,\nu$
  - $P_T^{calo} > 15$ GeV,
  - Muon identification via calorimeter MIP signature, CTD track matching,
  - $\theta^\mu < 2.0$ rad, $P_T^\mu > 5$ GeV.

3 events are found in the electron channel, 0 events in the muon channel. Two of the three electron events are identical with two of the events found in the previous analysis, while the third event (labelled event 1 below), which has a very forward directed hadronic jet, failed the $E_T > 5$ GeV cut used in that selection.

The 3 electron events are compared to the MC simulation of W production in Figure 6. In the scatterplots of Hadronic P_T vs. Transverse mass, and Electron P_T vs. Missing P_T, all 3 events are well compatible with the kinematics expected from W production. The background, mainly from CC DIS events and di-lepton production from $\gamma\gamma$ processes, is estimated to be 1.1 ± 0.3 events. After subtraction of this background, the 3 events provide the measured cross section

$$\sigma(e^+p \rightarrow e^+W^\pm X) = 0.9^{+1.0}_{-0.7}(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{pb}$$

This result agrees well with the SM leading order expectation [4] for the cross section, 0.95 pb.

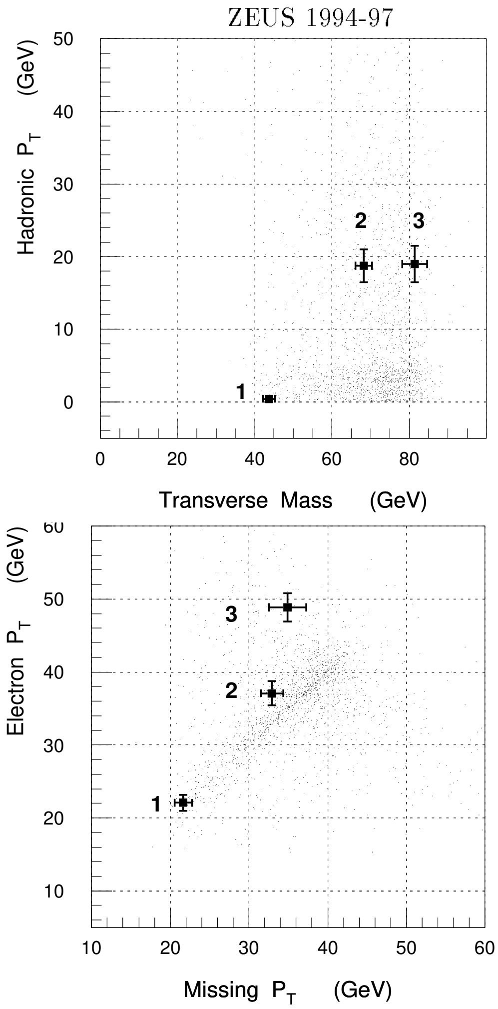

Figure 6. The 3 electron events in comparison with a MC simulation of W production, corresponding to an integrated luminosity 1000 times larger than that of the data.

3.1. Triple Gauge Boson Couplings

W production at HERA also proceeds via the diagram shown in Figure 7, i.e. via the Triple Gauge Boson Coupling. At HERA, photon exchange dominates over Z^0 exchange, and this fact provides a very clean experimental situation for studying the γWW vertex. In particular, it is of interest to investigate if there are anomalous contributions to the cross section[5],

$$\sigma_{tot} = \sigma_{SM} + a\,\sigma_{int} + a^2\,\sigma_{anomal}$$

a stands for the anomalous γWW couplings, usually called $\Delta\kappa$ and λ. In the Standard Model, both $\Delta\kappa$ and λ have value 0. Their being non-zero would change the cross section substantially, and a measurement of the W production cross section can thus be used to test the Standard Model in this respect.

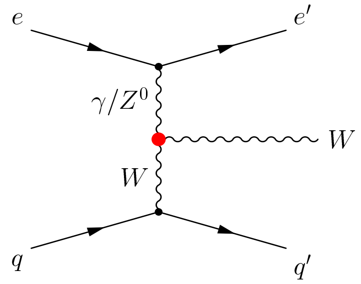

Figure 7. Triple Gauge Boson Coupling diagram.

To this end, the ZEUS collaboration use the observation of 3 and 0 events in the decay modes $W \to e\nu$ and $W \to \mu\nu$ to determine upper limits of the cross section,

$$\sigma(e^+p \to e^+W^\pm X) < 3.3 \text{ pb } (95\%\text{C.L.}),$$
$$\sigma(e^+p \to e^+W^\pm X) < 3.7 \text{ pb } (95\%\text{C.L.}),$$

respectively. These upper limits, which are determined individually in the electron and muon channel, are then further combined, while at the same time increasing the cut for the P_T of the hadronic system to 20 GeV. With the thus obtained new 95% C.L. limit on the production cross section (for hadronic $P_T > 20$ GeV), 0.58 pb, upper limits are derived at 95% C.L. for the values of the anomalous couplings,

$$-4.7 < \Delta\kappa < 1.5,$$
$$-3.2 < \lambda < 3.2.$$

In both cases, the limit on one coupling is obtained while assuming the SM value 0 for the other coupling. The reason for using this method is that with non-zero anomalous couplings the average hadronic P_T increases; and increasing hadronic P_T increases the detection efficiency in the $W \to \mu\nu$ decay channel. MC studies indicate that the best limits on the anomalous couplings are obtained when applying the cut hadronic $P_T > 20$ GeV.
The limits measured at HERA for the anomalous couplings $\Delta\kappa$ and λ can be compared to the Tevatron limits[6], obtained from an analysis of the $p\bar{p} \to W\gamma X$ reaction: $-0.93 < \Delta\kappa < 0.94$ and $-0.31 < \lambda < 0.29$. Still better limits have been obtained by combining D0 and LEP results[7], $-0.14 < \Delta\kappa < 0.48$ and $-0.22 < \lambda < 0.13$. However, for the latter results SU(2) relations were assumed at the γWW and Z^0WW vertices.
Clearly, the HERA result will improve with larger statistics. Substantial increase of statistics can be expected in a few years, after the planned luminosity upgrade of HERA.

4. BSM explanations

The results of the analyses performed by the H1 and ZEUS collaborations in the e^+p data from 1994-97 can be simply summarized:

- W production is observed and measured, in agreement with SM expectations,

- 3 events with large missing P_T and isolated, high P_T $\mu^\pm$ are observed in ~ 85 pb^{-1} of data. A Standard Model origin of these events is unlikely.

It must be stressed that the fact that all 3 muon events are observed by the H1 collaboration is no contradiction between H1 and ZEUS at the present level of statistics.
With no likely SM explanation for these 3 events, the question arises: Do these events have a BSM (Beyond the Standard Model) origin? Since the first observation in 1994 of such an event, theory has provided various explanations, all invoking BSM mechanisms. Two of these are mentioned here, for the purpose of illustrating the importance of the electron beam polarity in the further study of such events:

- Top Quark production at HERA has recently been discussed by H. Fritzsch and D. Holtmannspötter[8]. While the SM expectation is unmeasurably small, the photoproduction of the top quark off a c sea quark via an anomalous vertex $t \to c\gamma$ can proceed with a measurable cross section ($\sim 10^{-2}$ pb), in particular if the $c, \bar{c}$ distribution is stiff ("intrinsic charm"); the reaction $ec \to et$ is kinematically possible if $x_c > 0.34$. Thus, the reaction $ep \to etX$, $t \to bW$, $W \to l\nu$ could provide a few events in the HERA data sample, with the observed topology.

  This reaction is a pure photoproduction reaction, and can proceed with either polarity of the electron beam, e^+ or e^-.

- Stop Quark production at HERA has been discussed by T. Kon et al.[9]. The e^+ reacts with the valence d quark in the proton, via the non-zero coupling λ'_{131}. The produced stop quark decays via $\tilde{t}_1 \to W^+\tilde{b}_1$ and the sbottom quark decays via the same non-zero coupling λ'_{131}, $\tilde{b}_1 \to d\bar{\nu}_e$.
  This reaction can only proceed in e^+p collisions; there is no corresponding valence quark reaction with changed electron beam polarity. The reaction $e^-\bar{d} \to \bar{\tilde{t}}_1$, where the $\bar{d}$ quark comes from the proton sea, should be much suppressed[1].

As already stated, the 3 observed muon events were all produced in e^+p collisions. These 2 examples of theoretical explanations clearly illustrate the importance of investigating also e^-p collisions for the presence of such events, since an observation, or non-observation in data with different electron beam polarity will help in constraining the theoretical explanations.

[1] Since the $\tilde{t}_1$ decay only produces a W^+ in the final state, the event $\mu4$, which contains a μ^-, cannot be explained by the $\tilde{t}_1$ production hypothesis.

5. FIRST LOOK AT e^-p DATA

Since 1998 HERA is operated with an e^- beam. At the same time, the proton beam energy has been increased to 920 GeV, raising the available $\sqrt{s}$ energy to 320 GeV. Till now, each experiment has accumulated $\sim 15\,\mathrm{pb}^{-1}$ of e^-p collision data, and each experiment has so far analyzed $\sim 1/3$ of this data, performing searches for anomalous events similar to the three muon events observed in the e^+p data.

The result of these searches is simply stated: so far, none of the collaborations have found a similar event. One candidate event, seen by the ZEUS collaboration, turns out to be a background event (a NC event in which the electron has a large energy leakage into the backing calorimeter).

This result of no observed event is in agreement with the SM expectation. Clearly, it is also in no contradiction to the earlier observation of three anomalous muon events in $\sim 85\mathrm{pb}^{-1}$ of e^+p data. Indeed, non-observation in several $100\,\mathrm{pb}^{-1}$ of e^-p data is needed to significantly state that such events do not occur in e^-p collisions.

From the start-up after the spring 1999 shutdown, HERA is again operated with an e^+ beam. Results of the full analysis of the $\sim 30\,\mathrm{pb}^{-1}$ of e^-p data are expected to be announced at the summer 1999 conferences.

6. OUTLOOK

The observation at HERA of three outstanding events, with large missing P_T and isolated, high P_T muons, awaits explanation. The high luminosity upgrade of HERA will take place from May 2000 onwards. It is hoped that each of the collaborations, H1 and ZEUS, will have accumulated $\sim 500\,\mathrm{pb}^{-1}$ by the year 2005. This order of magnitude increase in integrated luminosity will certainly bring deeper understanding of these intriguing events, which currently constitute one of the most interesting aspects of the physics at HERA.

7. ACKNOWLEDGEMENTS

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