High P_T Leptons and W Production at HERA

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Abstract. The H1 and ZEUS Collaborations have observed events with high energy leptons and missing transverse momentum at the electron-proton collider HERA. While some of these events can be explained by the expected properties of W production with leptonic decay, three events with muons observed by H1 show properties atypical for Standard Model processes.

1 Introduction

In the history of high energy physics *leptons* and *missing transverse momentum* have proven to be powerful signatures in searches for new phenomena. In 1994, the H1 Collaboration has within a modest integrated luminosity of $\sim 4pb^{-1}$ observed an outstanding event [1] featuring a high P_T isolated muon, a high P_T hadronic system and a large missing P_T. Although the kinematics of the event was found to be compatible with the production of an on-shell W decaying leptonically, the event was found in a region of phase space not likely to be populated by this process.

By now the luminosity accumulated at HERA in e^+p collisions at an energy of $\sqrt{s} = 300$ GeV is an order a magnitude higher. We report on dedicated searches [2,3] performed by both HERA experiments for events of such topology, with either an isolated electron or muon. We also report on an analysis of most recent data accumulated in e^-p collisions in the years 1998-1999 at an energy of $\sqrt{s} = 318$ GeV.

2 Production of W bosons in electron-proton collisions

Within the Standard Model (SM), the dominant source for events with an isolated high P_T lepton and large missing P_T is the production of W bosons with subsequent leptonic decay. The lowest order diagrams for these processes ($ep \to eW^\pm X, W^\pm \to \nu\ell^\pm$) are shown in figure 1. From the MC simulation (using the program EPVEC [4]) one expects

- a cross section $\sim 50fb^{-1}$ per charge state and leptonic decay channel
- the cross section to increase towards low transverse momenta P_T^X of the hadronic system
- a Jacobian peak in the transverse mass of the lepton-neutrino system.

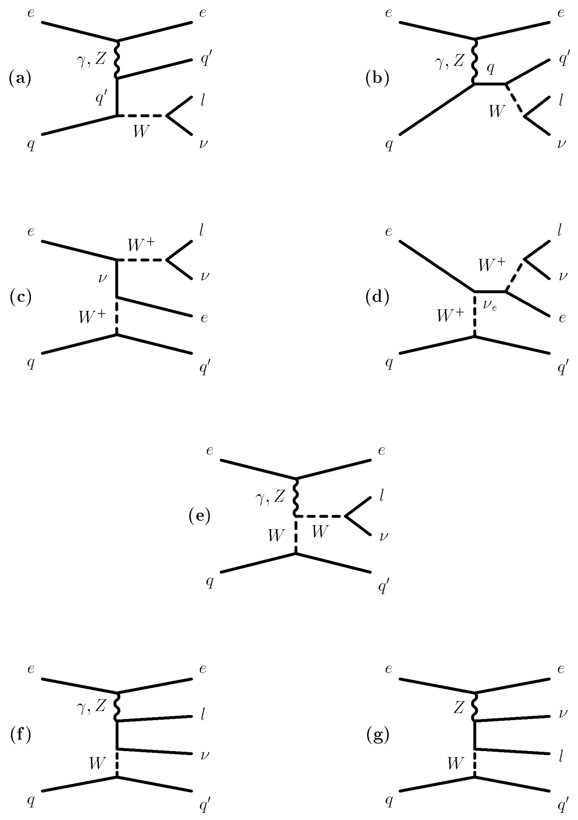

Fig. 1. Parton level diagrams for the process $eq \to eql\nu$.

In EPVEC the cross section is calculated in leading order. Higher order QCD terms might enhance W-production especially at high P_T^X. NLO calculations, which were recently made available [5] for W production processes induced by resolved photon interactions predict cross sections very close to the EPVEC numbers. However, for the high P_T^X part of the cross section, which is dominated by direct photon interactions, NLO calculations are not yet available.

W production at HERA also proceeds via the diagram in figure 1e, i.e. the Triple Gauge Boson Coupling. At HERA, photon exchange dominates over Z exchange allowing for the study of the γWW vertex. The γWW coupling is conventionally described with two parameters labelled κ and λ. In the Standard Model they take the values $\kappa = 1$ and $\lambda = 0$. Anomalous couplings may give rise to harder distributions in the transverse momentum of the W and thus in P_T^X.

3 The Data

3.1 H1 Analysis

The analysis is based on the Charged Current (CC) event selection [6] including the following criteria (for details see [2])

- calorimetric missing transverse momentum $P_T^{calo} > 25$ GeV
- a well measured track with $P_T > 10$ GeV (*High P_T track*)
- a reconstructed vertex in the interaction region
- topological and timing filters against cosmic and halo muons
- rejection of badly measured neutral current events

For the e^+p data sample, corresponding to 36.5 pb^{-1} this selection leads to 124 events.

For this data sample the isolation of the high P_T tracks with respect to jets or other tracks in the event has been investigated. The isolation is measured by the distance of the high P_T track in the $\eta - \phi$-plane (pseudorapidity-azimuthal angle-plane) to its nearest neighbour track (D_{track}) and to the nearest hadron jet (D_{jet}) . Figure 2 shows the data sample in the D_{track}-D_{jet}-plane. The bulk of the 124 events are located at small values of both distances, as expected for genuine Charged Current events where the high P_T track is associated with the hadronic shower. However, six events show a high P_T track clearly isolated in the D_{track}-D_{jet}-plane. All 6 tracks are identified as leptons, five are muons (2 μ^+, 2 μ^- and one μ of undetermined charge) and one is an e^-. The typical characteristics of these events can be seen in fig. 3, where one of the muon-events is shown as an example. Table 1 gives selected kinematic parameters of these

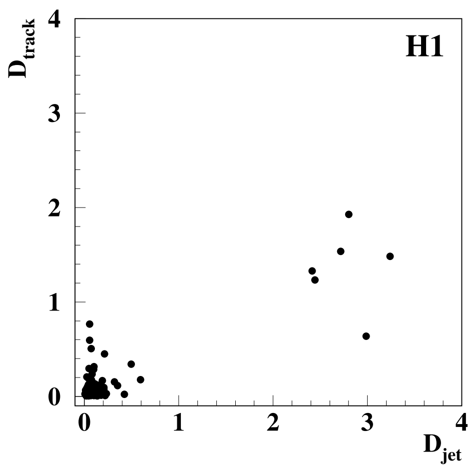

Fig. 2. Correlation between the distances D_{jet} and D_{track} (see text) to the closest hadronic jet and track, for all high P_T tracks.

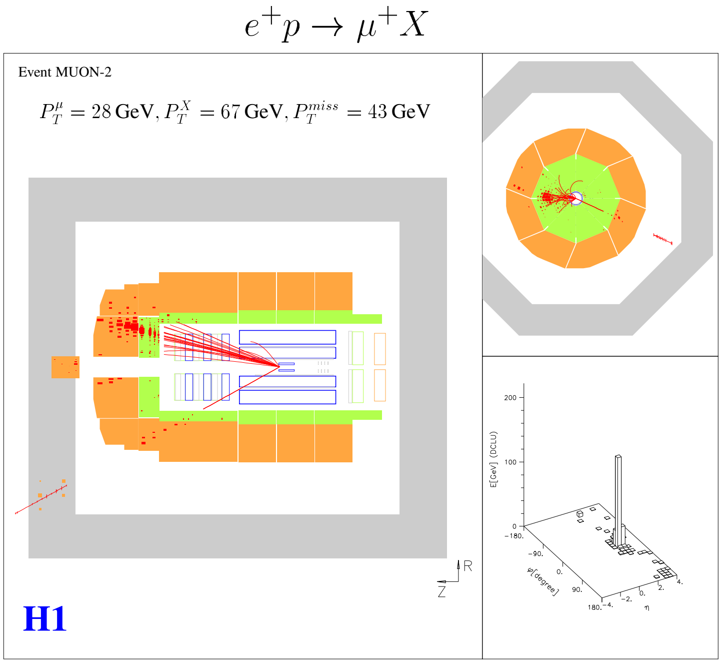

Fig. 3. Display of a H1 muon event. Shown are a longitudinal and a transverse view as well as the energy release as a function of azimuthal angle ϕ and pseudorapidity η.

six events. Although not required in the selection also the muon events show a significant imbalance in the total transverse momentum (P_T^{miss}).

The event rates from all Standard Model processes expected to contribute to the signal are summarized in table 2. W production yields for both lepton channels the highest expected rate. Whereas in the electron channel the observed rate is well compatible with expectation, in the muon channel the observed five events are to be compared with an expectation of 0.8 ± 0.2.

In order to compare the kinematic characteristics of the observed events with those expected from W - production a Monte Carlo simulation of W - production was performed with 500 times the statistics used in the data sample. Figure 4 shows for the $e-$ and $\mu-$channel the simulated events in the plane of hadronic transverse momentum P_T^X and transverse mass $M_T^{l\nu}$, together with the six events under consideration. Here $M_T^{l\nu}$ is calculated from the transverse momentum of the charged lepton and a neutrino, which is assumed to carry the observed missing transverse momentum P_T^{miss}. For W-production one would expect P_T^X to be low and the $M_T^{l\nu}$ distribution is expected to show a Jacobian peak around the W-mass. The observed e^- events shows these characteristics. Also two muon events are in a region of phase space where W- events are expected. In one of them (MUON-3) an additional positron is observed. Identifying this

[GeV]	**ELECTRON**	**MUON-1**	**MUON-2**	**MUON-3**	**MUON-4**	**MUON-5**
Q^l	neg.	pos.	pos.	neg.	neg.	unmeas.
P_T^l	$37.6^{+1.3}_{-1.3}$	$23.4^{+7.5}_{-5.5}$	$28.0^{+8.7}_{-5.4}$	$38.6^{+12.0}_{-7.4}$	$81.5^{+75.2}_{-26.4}$	> 44
P_T^X	8.0 ± 0.8	42.2 ± 3.8	67.4 ± 5.4	27.4 ± 2.7	59.3 ± 5.9	30.0 ± 3.0
P_T^{miss}	30.6 ± 1.5	$18.9^{+6.6}_{-8.3}$	$43.2^{+6.1}_{-7.7}$	$42.1^{+10.1}_{-5.9}$	$29.4^{+71.8}_{-13.9}$	> 18
$M_T^{l\nu}$	67.7 ± 2.7	$3.0^{+1.5}_{-0.9}$	$22.8^{+6.7}_{-4.2}$	$75.8^{+23.0}_{-14.0}$	94^{+157}_{-54}	> 54

Table 1. Reconstructed event kinematics of the H1 events. Given are the charge Q^l of the lepton, the transverse momenta of the lepton P_T^l, of the hadronic system P_T^X, the total missing transverse momentum P_T^{miss} and the transverse lepton-neutrino mass $M_T^{l\nu}$. In case of event MUON-5 2σ limits are quoted for the muon momentum and derived quantities.

	Electron Channel	Muon Channel
Data	$0\ e^+, 1\ e^-$	5
W production	1.65 ± 0.47	0.53 ± 0.11
Z production	0.01 ± 0.01	0.01 ± 0.01
Charged Current	0.02 ± 0.01	0.01 ± 0.01
Neutral Current	$0.51 \pm 0.10\ e^+$, $0.02 \pm 0.01\ e^-$	0.09 ± 0.06
Photoproduction	< 0.02	< 0.02
Heavy Quarks	< 0.04	< 0.04
Photon-Photon	$0.09 \pm 0.03\ e^+$, $0.04 \pm 0.01\ e^-$	$0.14^{+0.14}_{-0.07}$

Table 2. Observed and predicted event rates (H1). The limits given correspond to 95% confidence level. Unless stated otherwise the quoted numbers refer to the summed production of both lepton charged states.

positron with the scattered positron, allows to constrain the kinematics yielding an invariant muon-neutrino mass of $M = 82^{+19}_{-12} GeV$. The remaining three muon events (2 μ^+ and $1\mu^-$) are unlikely to be explained by W production or other SM processes considered.

3.2 ZEUS Analysis

The ZEUS collaboration has performed two analyses (for details see [3]) using 47.7 pb^{-1} of e^+p data.

One analysis searches for isolated tracks in events which are unbalanced in transverse momentum. The selection criteria are very similar to those applied in the H1 analysis. The main criteria are $P_T^{calo} > 20$ GeV, an isolated track with $P_T > 10$ GeV and at least one hadronic jet with $E_T > 5$ GeV. Three events

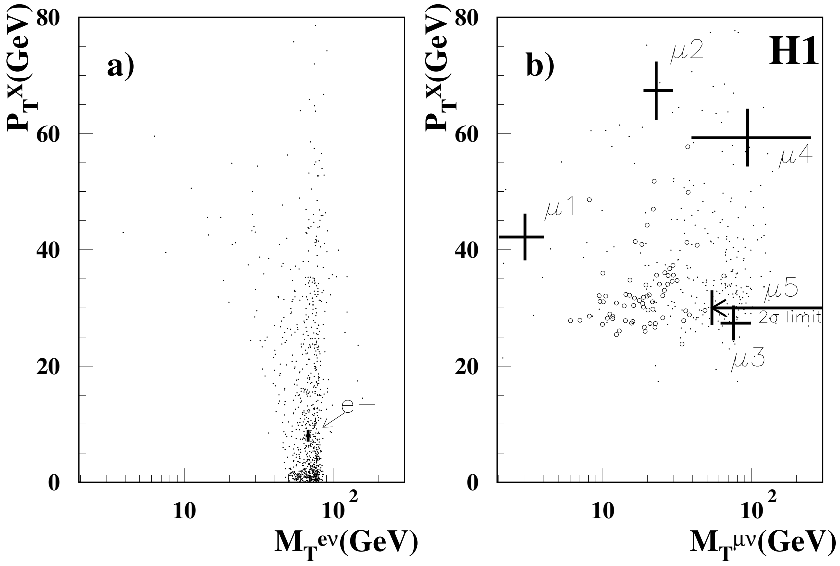

Fig. 4. Distribution of the H1-events in the P_T^X-$M_T^{l\nu}$ plane. Figure a) shows the electron channel, figure b) the muon channel. The 1-σ uncertainties on the measured kinematic parameters are indicated by the crosses. (For event $\mu5$ the 2σ lower limit is shown for $M_T^{l\nu}$.) The dominant SM contributions (dots for W production, open circles for $\gamma\gamma$ processes in the μ channel) are shown for an accumulated luminosity which is a factor 500 higher than in the data. For the μ channel no significant contribution is expected below $P_T^X = 25$ GeV due to the event selection criteria.

pass the selection criteria, in all of them the high P_T track is identified as an e^+. The observed event yield agrees with the SM expectations of 3.5 ± 0.7 electron events and 2.0 ± 0.4 muon events, to which W production contributes 0.9 and 0.4, respectively.

In the other analysis ZEUS performed a dedicated measurement of the W production cross section. Here no hadronic activity was required but an electron or muon signature was requested in the selection. Three events were found in the electron channel (two in common with the first analysis) and zero events in the muon channel. Fig. 5 shows the display of one of the events. The imbalance in transverse momentum is clearly visible. Table 3 shows selected kinematic parameters of the 3 events. In fig. 6 the events are compared with a MC simulation of W production. They are found to be well compatible with expectation. The backgound in the event sample, mainly from CC processes, is estimated to be 1.1 ± 0.3 events. Subtracting this background from the observed 3 events yields a cross section of $\sigma(e^+p \to e^+W^\pm X) = 0.9^{+1.0}_{-0.7}(stat) \pm 0.2(syst)$ pb. This result agrees well with the SM leading order expectation [4] of 0.95 pb.

Best limits on anomalous couplings were obtained when considering only the phase space region of higher values of P_T^X and combining the electron and muon channel. For $P_T^X > 20$ GeV zero events were observed compared to a SM

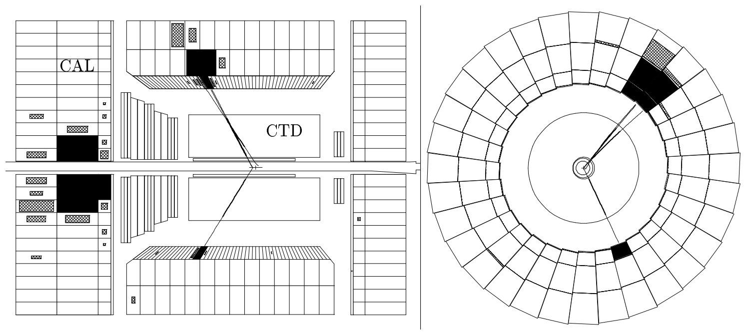

Fig. 5. Display of a ZEUS electron event. Shown are a longitudinal and a transverse view.

[GeV]	**e1**	**e2**	**e3**
P_T^l	22.1 ± 1.1	37.1 ± 1.6	48.8 ± 2.0
P_T^X	0.4 ± 0.1	18.7 ± 2.2	19.0 ± 2.5
P_T^{miss}	21.7 ± 1.1	32.9 ± 1.4	34.9 ± 2.4
$M_T^{l\nu}$	43.7 ± 1.6	68.2 ± 2.2	81.4 ± 3.2

Table 3. Reconstructed event kinematics of the three ZEUS events. Given are the transverse momenta of the lepton P_T^l, the hadronic system P_T^X ,the total event P_T^{miss} and the transverse lepton-neutrino mass $M_T^{l\nu}$.

expectation of 1.2 events from W and 0.52 ± 0.18 events from other sources. From this an upper limit (95% C.L.) on the cross section of $\sigma(P_T^X > 20\text{GeV}) < 0.58$ pb is derived which translates into limits of

$$
\begin{array}{ll}
-4.7 < \Delta\kappa < 1.5 & \text{for} \quad \lambda = 0 \\
-3.2 < \lambda < 3.2 & \text{for} \quad \Delta\kappa = 0
\end{array}
$$

on the anomalous $WW\gamma$ couplings ($\Delta\kappa = \kappa - 1, \lambda$). With the present statistics this result is not yet competitive with the limits derived at the Tevatron and LEP, but will clearly improve with larger statistics.

4 Results from $e^- p$ HERA running

In the years 1998/1999 HERA was operated with electrons of 27.5 GeV colliding with protons of 920 GeV resulting in $\sqrt{s} = 318$ GeV. Both experiments applied the same analysis procedures as explained above.

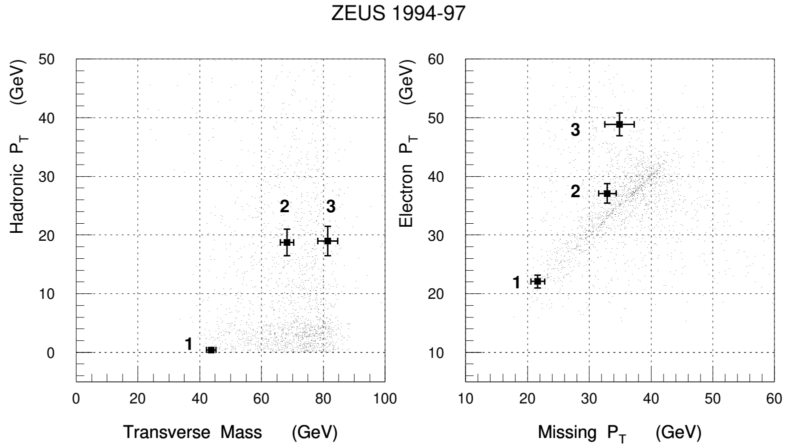

Fig. 6. Distribution of the three e^+ events observed by ZEUS in the P_T^X- $M_T^{l\nu}$ plane and in the P_T^e - P_T^{miss} plane, compared with a Monte Carlo study of W production with a luminosity of $50 fb^{-1}$.

ZEUS observed in a luminosity of $16 pb^{-1}$ two events with isolated tracks, both being identified as electrons (e^-). The result is consistent with the expectation of 1.6 ± 0.4 events from SM processes, of which 0.8 ± 0.4 and 0.8 ± 0.1 are in the electron and muon channel, respectively. Both events observed show a Neutral Current event topology where the missing transverse momentum P_T^{miss} is in one event due to a large energy leakage out of the main calorimeter and in the other event due to an energetic muon associated to the hadronic shower.

H1 analysed a data sample corresponding to $14 pb^{-1}$. No event was found fullfilling the selection criteria for the search for events with isolated tracks and P_T^{miss}. The SM expectation is 1.0 ± 0.2 events in the electron channel and 0.4 ± 0.1 events in the muon channel.

The good agreement between observation and SM expectation in both experiments implies that within the present statistical accuracy there is no evidence of an excess of events with an isolated lepton and missing P_T in $e^- p$ scattering at HERA.

5 Interpretation of the H1-Muon-Events beyond the Standard Model

Considering the low probability of the signal observed by H1 in the muon channel in $e^+ p$ data to be explained within the SM it is worthwhile investigating which processes beyond the SM could explain the observed events.

- The interpretation of a lepto-quark produced by positron-quark fusion and decaying into a muon-quark system can be discarded because the measured event kinematics is incompatible with a 2-body decay.
- In the hypothesis of a resonance decaying into a quark and an onshell W which decays leptonically, the escaping neutrino can be reconstructed using the W mass constraint. The resulting invariant mass of the system formed by the W and the measured hadronic system X is for the events MUON-2 and MUON-4 within measurement errors found to be compatible with the top mass. While the SM expectation for top production at HERA is unmeasurably small, it could be significantly enhanced in dynamical models for fermion mass generation [7].
- Another hypothesis is the production of squarks in Supersymmetric Models with R-parity violation. Stop quark production ($e^+ d \to \tilde{t}$) has been discussed by T. Kon et al. [8]. Events of the observed topology could be due to a decay $\tilde{t} \to W\tilde{b}$ with the sbottom quark decaying via $\tilde{b} \to d\nu$. This process would naturally produce events with a high P_T lepton of positive charge, a high P_T hadronic jet and significant missing P_T. The kinematics of the muon events is found to be compatible with a scenario with a stop mass of 200 GeV and a sbottom mass of 100 GeV.

  In order to investigate this hypothesis further an analysis has been performed by H1 selecting events with at least two jets and missing transverse momentum. In this class of events one would accept those stop decays in which the W decays hadronically. No events in excess of the SM expectation have been observed. From this fact a 95% upper limit on the expectation in the muon channel of $N_{observed}(W \to \mu\nu) < 0.36$ events can be derived. This result does not support the hypothesis that the three outstanding muon events could be due to this process.

6 Summary and outlook

At the HERA electron proton collider events have been observed which feature a high P_T charged lepton together with a significant imbalance in the overall event transverse momentum. Some of the observed events can be understood in terms of a production of on-shell W bosons, decaying leptonically. This constitutes the first observation of this process in lepton hadron scattering. The cross section observed agrees with Standard Model expectations.

In the H1 experiment three events have been observed in the muon channel, which are unlikely to be due to W production or other SM processes. The origin of these events will most probably only be clarified with much higher luminosities. The prospects to accumulate luminosities at least an order of magnitude higher than available now, are very good, since in 2000 the HERA machine is undergoing a major luminosity upgrade.

7 Acknowledgements

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