

# Isolated Leptons and Missing $P_T$ at HERA

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**Abstract.** The search for events containing isolated leptons (electrons or muons) and missing transverse momentum produced in  $e^\pm p$  collisions is performed individually and in a common phase space with the H1 and ZEUS detectors at HERA in the period 1994–2007. The analysed H1+ZEUS data sample corresponds to an integrated luminosity of  $0.97 \text{ fb}^{-1}$ , and composes of the complete high energy data from the HERA programme. A total of 87 events are observed in the data, compared to a Standard Model (SM) prediction of  $92.7 \pm 11.2$ . At large hadronic transverse momentum  $P_T^X > 25 \text{ GeV}$  in the  $e^+p$  data, luminosity  $0.58 \text{ fb}^{-1}$ , 23 data events are observed compared to a SM prediction of  $14.6 \pm 1.9$ . Production cross section measurements of events containing isolated leptons and missing transverse momentum and single  $W$  production, as well as  $W$  polarisation fractions performed by the H1 Collaboration are also presented. The H1 isolated lepton events are also examined in the context of a search for single top production.

## 1. Introduction

Events containing a high  $P_T$  isolated electron or muon and associated with missing transverse momentum have been observed at HERA [1, 2, 3, 4]. An excess of HERA I data events (1994–2000, mostly in  $e^+p$  collisions) compared to the SM prediction at large hadronic transverse momentum  $P_T^X$  was reported by the H1 Collaboration [2], which was not confirmed by the ZEUS Collaboration, although the analysis was performed in a more restricted phase space [4].

The main SM contribution to the signal topology is the production of real  $W$  bosons via photoproduction with subsequent leptonic decay  $ep \rightarrow eW^\pm(\rightarrow l\nu)X$ , where the hadronic system  $X$  is typically of low  $P_T$ . The equivalent charged current process  $ep \rightarrow \nu W^\pm(\rightarrow l\nu)X$  also contributes to the total signal rate, although only at a level of around 7%. The production of  $Z^0$  bosons with subsequent decay to neutrinos  $ep \rightarrow eZ^0(\rightarrow \nu\bar{\nu})X$  results in a further minor contribution<sup>1</sup> to the total signal rate in the electron channel at a level of 3%.

The event selection employed by the H1 [5] and ZEUS [6] analyses are very similar and may be summarised as follows: The identified lepton should have high transverse momentum  $P_T^l > 10 \text{ GeV}$ , be observed in the central region of the detector and be isolated with respect to jets and other tracks in the event. The event should also contain a large transverse momentum imbalance,  $P_T^{miss} > 12 \text{ GeV}$ . Further cuts are then applied, which are designed to reduce SM background, whilst preserving a high level of signal purity. Event quantities sensitive to the presence of high energy undetected particles in the event are employed such as the azimuthal balance of the event, the difference in azimuthal angle between the lepton and the hadronic system and the longitudinal momentum imbalance. To ensure that the two lepton channels are exclusive and may therefore be combined, electron events must contain no isolated muons.

<sup>1</sup> This process is not included in the present ZEUS analysis.

## 2. Results from the H1 and ZEUS Analyses

Both H1 and ZEUS have recently performed the analysis of the electron and muon channels<sup>2</sup> on their respective complete HERA I+II data sets, which correspond to approximately  $0.5 \text{ fb}^{-1}$  per experiment [5, 6]. A total of 59 events are observed in the H1 data, compared to a SM prediction of  $58.9 \pm 8.2$ . For  $P_T^X > 25 \text{ GeV}$ , a total of 24 events are observed compared to a SM prediction of  $15.8 \pm 2.5$ , where 21 events are observed in the  $e^+p$  data compared to a SM prediction of  $8.9 \pm 1.5$ . The observed data excess in the HERA I  $e^+p$  data thus remains at the  $3.0\sigma$  level for the complete H1  $e^+p$  dataset. In the ZEUS analysis of the complete HERA I+II data, 41 data events are observed in agreement with the SM prediction of  $48.3 \pm 6.8$ . Unlike in the H1 analysis, agreement between data and SM is also observed in the high  $P_T^X$  region, where 11 events are seen in the  $e^\pm p$  data compared to a SM prediction of  $13.1 \pm 1.8$ .

## 3. A Combined H1 and ZEUS Analysis

A study of the selection efficiency for signal process using the event generator EPVEC [8] found the H1 and ZEUS analyses to be compatible in the kinematic region where they are directly comparable [9, 10]. The majority of the data events observed by H1 at  $P_T^X > 25 \text{ GeV}$  are also found to fall into the region of overlap of the two analyses. Nevertheless, in order to coherently combine the results from the two experiments, a common phase space has been established. The common selection is based on the H1 event selection [2, 5], but over a more restricted lepton polar angle range of  $15^\circ < \theta_l < 120^\circ$ , as employed in the ZEUS analysis [6]. The signal expectation rates of the H1 and ZEUS analyses using the common selection are found to be comparable, taking into account the respective luminosities of the data sets and the signal processes included. More details on the combination of the H1 and ZEUS analyses can be found in [11].

The results of the combined H1+ZEUS analysis are summarised in table 1. The signal contribution, dominated by real  $W$  production, is seen to dominate the total SM expectation in all data samples. At large hadronic transverse momentum  $P_T^X > 25 \text{ GeV}$  a total of 29 events are observed in the H1+ZEUS  $e^\pm p$  data compared to a SM prediction of  $25.3 \pm 3.2$ . In the  $e^+p$  data alone, 23 events are observed with  $P_T^X > 25 \text{ GeV}$  compared to a SM prediction of  $14.6 \pm 1.9$ , equivalent to an excess of data over the SM prediction of  $1.8\sigma$ . Seventeen of the 23 data events are observed in the H1 data compared to a SM expectation of  $7.1 \pm 0.9$ , equivalent to an excess of data over the SM prediction of  $2.9\sigma$ . Figure 1 shows the transverse mass,  $M_T^{\ell\nu}$  and  $P_T^X$  distributions of the H1+ZEUS  $e^\pm p$  data for the combined electron and muon channels.

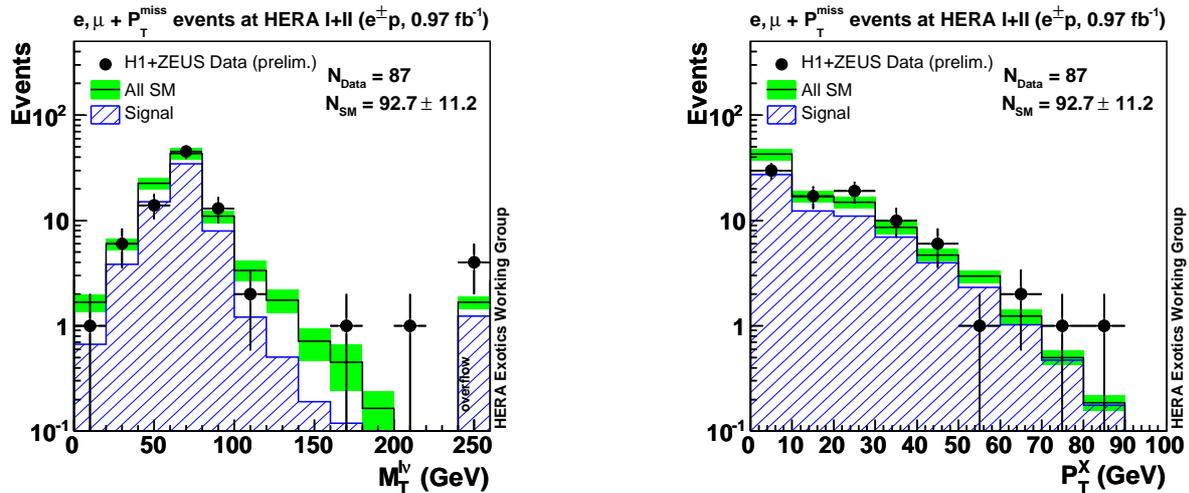
## 4. Cross Sections and $W$ Polarisation Fractions

The H1 selection results described in section 2 are used to calculate production cross sections for events with an energetic isolated lepton and missing transverse momentum ( $\sigma_{\ell+P_T^{\text{miss}}}$ ) and for single  $W$  boson production ( $\sigma_W$ ), for which the branching ratio for leptonic  $W$  decay is taken into account [12]. The results are shown below with statistical (stat) and systematic (sys) uncertainties compared to the SM, quoted with a theoretical systematic error (th.sys) of 15%.

H1	HERA I+II Data	SM
$\sigma_{\ell+P_T^{\text{miss}}}$	$0.24 \pm 0.05 \text{ (stat)} \pm 0.05 \text{ (sys)}$	$0.26 \pm 0.04 \text{ (th.sys)}$
$\sigma_W$	$1.23 \pm 0.25 \text{ (stat)} \pm 0.22 \text{ (sys)}$	$1.31 \pm 0.20 \text{ (th.sys)}$

A measurement of the  $W$  polarisation fractions is also performed by H1, as described in [12]. Using a 2D fit, optimal values of the left-handed ( $F_-$ ) and longitudinal ( $F_0$ ) fractions are extracted, as shown in figure 2 (left) compared to the SM and a FCNC single top model.

<sup>2</sup> The H1 Collaboration have also performed the analysis of the tau decay channel using the full HERA I+II data and the hadronic 1-prong tau decay mode [7]. In this search, where the signal purity is much lower at around 14%, 20 events are observed in the data compared to a SM prediction of  $19.5 \pm 3.2$ .



**Figure 1.** The transverse mass  $M_T^{\nu}$  (left) and hadronic transverse momentum  $P_T^X$  (right) distributions of the combined H1+ZEUS  $e^\pm p$  HERA I+II data. The data (points) are compared to the SM expectation (open histogram). The signal component of the SM expectation is given by the hatched histogram.  $N_{\text{Data}}$  is the total number of data events observed,  $N_{\text{SM}}$  is the total SM expectation. The total error on the SM expectation is given by the shaded band.

## 5. Search for Single Top Quark Production

A search for single top quark production at HERA is performed by H1 as an extension of the search for isolated lepton events, using the full HERA I+II  $e^\pm p$  data [13, 14]. The investigated model considers anomalous production of top quarks in a Flavour Changing Neutral Current process involving the coupling  $\kappa_{t\bar{u}\gamma}$ . A multivariate analysis is performed to discriminate top from SM background (dominated by real  $W$  production). No evidence for single top production is observed. An upper limit on the anomalous top production cross section of  $\sigma_{ep \rightarrow etX} < 0.16$  pb is established at 95% CL. The corresponding H1 limit on the coupling  $\kappa_{t\bar{u}\gamma} < 0.14$  is shown in figure 2 (right) and is currently the best limit compared to those from other colliders<sup>3</sup>.

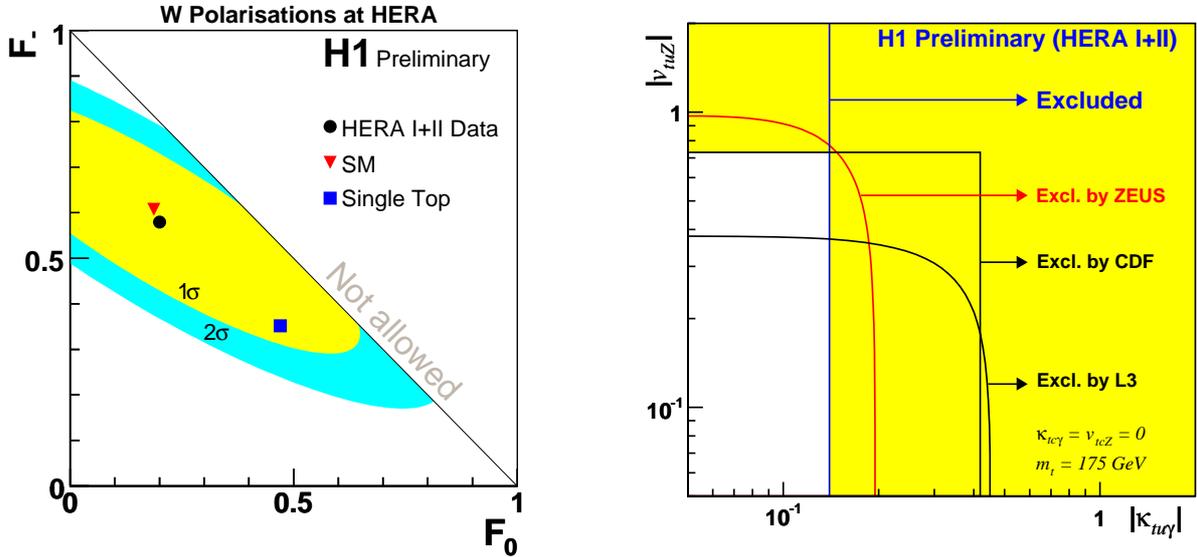
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<sup>3</sup> An improved limit on  $\nu_{t\bar{u}Z}$  by the CDF Collaboration was presented at the HEP-EPS 2007 conference; see [17].

H1+ZEUS Preliminary $l+P_T^{\text{miss}}$ events at HERA I+II		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
1994-2007 $e^+p$ 0.58 fb $^{-1}$	Full Sample	39 / 41.3 $\pm$ 5.0 (70%)	18 / 11.8 $\pm$ 1.6 (85%)	57 / 53.1 $\pm$ 6.4 (73%)
	$P_T^X > 25$ GeV	12 / 7.4 $\pm$ 1.0 (78%)	11 / 7.2 $\pm$ 1.0 (85%)	23 / 14.6 $\pm$ 1.9 (81%)
1998-2006 $e^-p$ 0.39 fb $^{-1}$	Full Sample	25 / 31.6 $\pm$ 4.1 (63%)	5 / 8.0 $\pm$ 1.1 (86%)	30 / 39.6 $\pm$ 5.0 (68%)
	$P_T^X > 25$ GeV	4 / 6.0 $\pm$ 0.8 (67%)	2 / 4.8 $\pm$ 0.7 (87%)	6 / 10.6 $\pm$ 1.4 (76%)
1994-2007 $e^\pm p$ 0.97 fb $^{-1}$	Full Sample	64 / 72.9 $\pm$ 8.9 (67%)	23 / 19.9 $\pm$ 2.6 (85%)	87 / 92.7 $\pm$ 11.2 (71%)
	$P_T^X > 25$ GeV	16 / 13.3 $\pm$ 1.7 (73%)	13 / 12.0 $\pm$ 1.6 (86%)	29 / 25.3 $\pm$ 3.2 (79%)

**Table 1.** Summary of the combined H1+ZEUS results in the search for events with isolated electrons or muons and missing transverse momentum. Results are shown for the electron and muon channels separately as well as combined for the full HERA I+II  $e^+p$ ,  $e^-p$  and  $e^\pm p$  data. The number of observed data events is compared to the SM prediction. The results are shown for the full selected sample and for a subsample at large  $P_T^X > 25$  GeV. The signal component of the SM expectation, dominated by real  $W$  production, is given as a percentage in parentheses. The quoted errors contain statistical and systematic uncertainties added in quadrature.



**Figure 2.** Left: The fit result for the simultaneously extracted left handed ( $F_-$ ) and longitudinal ( $F_0$ )  $W$  boson polarisation fractions (point) at 1 and  $2\sigma$  CL (contours). Also shown are the values for the SM prediction (triangle) and anomalous single top production via FCNC (square). Right: Exclusion limits at the 95% CL in the search for single top production on the anomalous  $\kappa_{tu\gamma}$  and  $v_{tuZ}$  couplings obtained at the TeVatron (CDF experiment [15]), LEP (L3 experiment [16]) and HERA (H1 [14] and ZEUS [4] experiments). Anomalous couplings of the charm quark are neglected  $\kappa_{tc\gamma} = v_{tcZ} = 0$ . Limits are shown assuming a top mass  $m_t = 175$  GeV.