

# Isolated Leptons and Single Top at HERA

**David M. South**<sup>\*†</sup>

*Technische Universität Dortmund*

*Experimentelle Physik V*

*44221 Dortmund, Germany*

*E-mail: david.south@desy.de*

The search for events containing isolated leptons 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. The combined H1 and ZEUS data sample corresponds to an integrated luminosity of  $0.98 \text{ fb}^{-1}$  and comprises the complete high energy data from the HERA programme. A total of 81 events are observed in the data, compared to a Standard Model prediction of  $87.8 \pm 11.0$ , which is dominated by single  $W$  production. At large hadronic transverse momentum  $P_T^X > 25 \text{ GeV}$  in the  $e^+ p$  data, integrated luminosity  $0.58 \text{ fb}^{-1}$ , 23 data events are observed compared to a SM prediction of  $14.0 \pm 1.9$ . The total single  $W$  production cross section is measured as  $1.06 \pm 0.16(\text{stat.}) \pm 0.07(\text{sys.})$  in agreement with a SM expectation of  $1.26 \pm 0.19$ . The isolated lepton events are examined in the context of a search for anomalous single top production, where the hadronic decays of the  $W$  are additionally considered. Although several top-like candidates are present in the H1 data no clear signal is observed and an upper limit on the anomalous single top production cross section of  $\sigma_{ep \rightarrow etX} < 0.25 \text{ pb}$  is established at the 95% confidence level. This limit corresponds to an upper bound on the anomalous magnetic coupling of  $\kappa_{t\gamma} < 0.18$  assuming a top mass of 175 GeV.

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<sup>\*</sup>Speaker.

<sup>†</sup>on behalf of the H1 and ZEUS Collaborations

## 1. Introduction

At HERA, protons with an energy up to 920 GeV were brought into collision with electrons or positrons of energy 27.6 GeV at two experiments, H1 and ZEUS, each of which collected about  $0.5 \text{ fb}^{-1}$  of data in the period 1994–2007. The collisions produced at HERA at a centre of mass energy of up to 319 GeV provide an ideal environment to study rare processes, set constraints on the Standard Model (SM) and search for new particles and physics beyond the Standard Model (BSM). Events containing isolated leptons and missing transverse momentum in the final state may be a signature of rare processes and such events have been observed at HERA [1, 2, 3]. An excess of data events compared to the SM prediction at large hadronic transverse momentum  $P_T^X$  was observed by the H1 Collaboration [3] in an analysis of the HERA I data (1994–2000), which was mostly  $e^+p$  collisions. This was not confirmed by the ZEUS Collaboration in a more restricted phase space [4]. The analyses of the complete H1 [5] and ZEUS [6] data have now been finalised, as well as a combined analysis performed in a common phase space [7], which makes use of the full  $0.98 \text{ fb}^{-1}$  of HERA data. Furthermore, the selected events have been examined in the context of anomalous single top production via a flavour changing neutral current (FCNC) interaction.

## 2. Events with Isolated Leptons and Missing Transverse Momentum

The main SM contribution to the signal<sup>1</sup> topology is the production of real  $W$  bosons via photoproduction with subsequent leptonic decay  $ep \rightarrow eW^\pm(\rightarrow \ell\nu)X$ , where the hadronic system  $X$  has typically low transverse momentum  $P_T$ . The equivalent charged current (CC) process  $ep \rightarrow \nu W^\pm(\rightarrow \ell\nu)X$ , also contributes to the total signal rate, although only at a level of about 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>2</sup> to the total signal rate in the electron channel at a level of 3%. SM background enters the electron channel due to mismeasured neutral current (NC) deep inelastic scattering (DIS) events and the muon channel due to lepton pair (LP) events in which one muon escapes detection, both cases resulting in apparent (fake) missing transverse momentum. CC DIS background, which contains intrinsic missing transverse momentum, enters the final sample in both lepton channels, where a final state particle is interpreted as the isolated electron or muon.

The common event selection is based on those used by H1 [5] and ZEUS [6]. Lepton candidates are required to have  $P_T^\ell > 10 \text{ GeV}$ , to be in the central region of the detector  $15^\circ < \theta_\ell < 120^\circ$  and to be isolated from tracks and identified jets in the event. The event must also exhibit significant missing transverse momentum,  $P_T^{\text{miss}} > 12 \text{ GeV}$ . Further topological and kinematic cuts are applied to reject the remaining SM background. A full description of the event selection is presented in [7].

The results of the analysis of the complete  $e^\pm p$  HERA data are shown in table 1. In general, a good agreement is observed between the data and the SM prediction, where the signal component forms the main part of the expectation. The lepton–neutrino transverse mass distribution is shown in figure 1 (left) and displays the Jacobian peak expected from single  $W$  production. For  $P_T^X > 25 \text{ GeV}$ , 29 events are observed in the data, compared to a SM prediction of  $24.0 \pm 3.2$  for the

<sup>1</sup>Processes are defined as *signal* if they produce events containing a high  $P_T$  isolated, electron or muon and at least one high  $P_T$  neutrino, which escapes detection and leads to  $P_T^{\text{miss}}$  in the final state.

<sup>2</sup>This process is not included in the ZEUS analysis.

Channel		Data	SM	Signal (W)	Background
Electron	Total	61	$69.2 \pm 8.2$	$48.3 \pm 7.4$	$20.9 \pm 3.2$
	$P_T^X > 25 \text{ GeV}$	16	$13.0 \pm 1.7$	$10.0 \pm 1.6$	$3.1 \pm 0.7$
Muon	Total	20	$18.6 \pm 2.7$	$16.4 \pm 2.6$	$2.2 \pm 0.5$
	$P_T^X > 25 \text{ GeV}$	13	$11.0 \pm 1.6$	$9.8 \pm 1.6$	$1.2 \pm 0.3$
Combined	Total	81	$87.8 \pm 11.0$	$64.7 \pm 9.9$	$23.1 \pm 3.3$
	$P_T^X > 25 \text{ GeV}$	29	$24.0 \pm 3.2$	$19.7 \pm 3.1$	$4.3 \pm 0.8$

**Table 1:** Observed and predicted number of events with an isolated electron or muon and missing transverse momentum in  $0.98 \text{ fb}^{-1}$  of HERA data. The results are shown for the full selected sample and for a sub-sample with  $P_T^X > 25 \text{ GeV}$ . The signal, total SM and background contributions are shown. The quoted errors contain statistical and systematic uncertainties added in quadrature.

complete HERA  $e^\pm p$  data. In the  $e^+ p$  data alone, where a small excess of data is seen in the H1 analysis [5], 23 events are observed in the data, compared to a SM prediction of  $14.0 \pm 1.9$ .

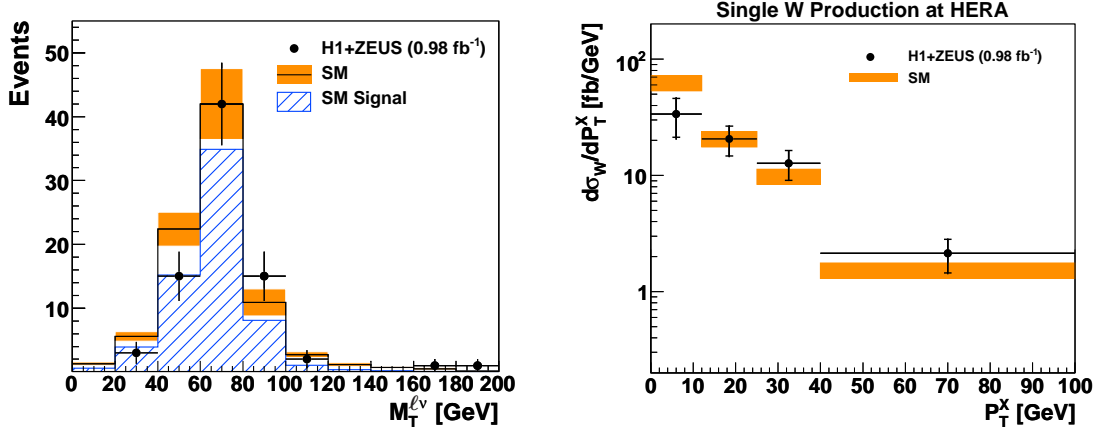
The total and differential single  $W$  production cross sections are evaluated from the number of observed events, subtracting the number of background events and taking into account the acceptance and integrated luminosity of the two experiments. The single  $W$  cross section is measured as  $1.06 \pm 0.16(\text{stat.}) \pm 0.07(\text{sys.}) \text{ pb}$ , in agreement with the SM prediction of  $1.26 \pm 0.19 \text{ pb}$ . The cross section is also measured as a function of  $P_T^X$ , as shown in figure 1 (right).

Further studies of events with isolated leptons and missing transverse momentum are performed by H1 [5]. A complementary search for events with an isolated tau lepton and missing  $P_T$  is done by selecting tau candidates, identified as narrow hadronic jets resulting from 1-prong decays, in coincidence with large missing transverse momentum. In the final event sample, 18 events are selected, compared to a SM expectation of  $23.2 \pm 3.8$ , which is dominated by CC DIS background. Additionally, the  $W$  cross section measured by H1 is used to derive single parameter limits on the  $WW\gamma$  gauge coupling parameters  $\Delta\kappa$  and  $\lambda$  at 95% CL. Finally, the  $W$  polarisation fractions are measured for the first time at HERA by H1 and found to be consistent with the SM expectation.

### 3. Search for Anomalous Single Top Production

The production of single top quarks is kinematically possible via the  $ep$  collisions at HERA due to the large centre of mass energy, although the dominant SM process has a negligible cross section of less than 1 fb. However, in several extensions of the SM the top quark is predicted to undergo Flavour Changing Neutral Current (FCNC) interactions, which could lead to a sizeable anomalous single top production cross section at HERA [8]. The interaction of a top quark with  $U$ -type quarks via a photon is described in the effective Lagrangian by a magnetic coupling  $\kappa_{tU\gamma}$ . Dedicated searches for anomalous single top production have been performed at HERA I, where no conclusive signal was observed [9, 4] and the HERA II data have now been analysed [10, 11].

The top quark is detected via its decay  $t \rightarrow bW^+$ . In the case of leptonic  $W$  decays, the signature is the same as the topology described in section 2, where the hadronic final state exhibits high  $P_T^X$  originating from the fragmentation of the  $b$  quark, thus providing a possible explanation



**Figure 1:** Left: The lepton–neutrino transverse mass  $M_T^{\ell\nu}$  of events with an isolated electron or muon and missing transverse momentum. The data (points) are compared to the SM expectation (open histogram). The signal component of the SM expectation, dominated by single  $W$  production, is shown as the striped histogram. The total uncertainty on the SM expectation is shown as the shaded band. Right: The single  $W$  production cross section as a function of the hadronic transverse momentum,  $P_T^X$ . The inner error bar represents the statistical error and the outer error bar indicates the statistical and systematic uncertainties added in quadrature. The shaded band represents the uncertainty on the SM prediction.

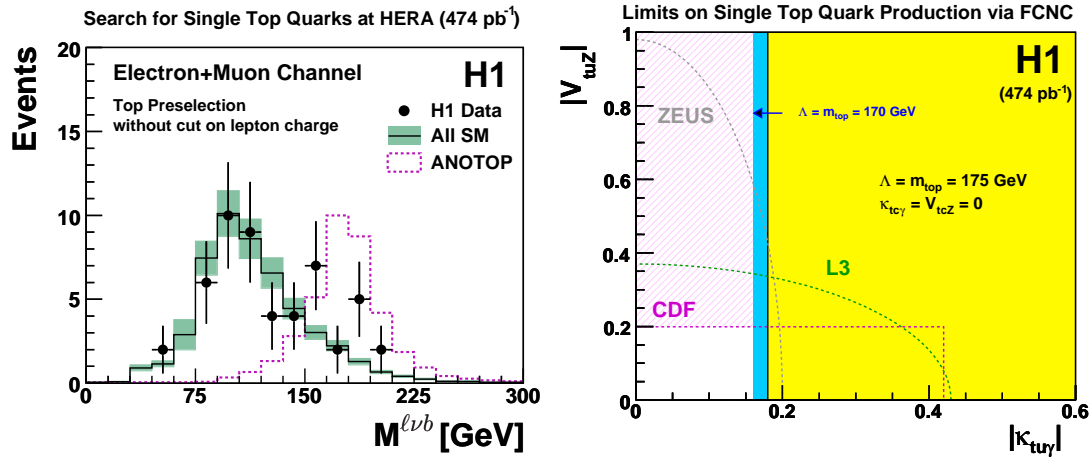
of the data excess observed by the H1 experiment<sup>3</sup>. In the case of the hadronic  $W$  boson decays, the signature of single top quark production consists of three high  $P_T$  jets with an invariant mass compatible with the top quark mass.

An H1 publication [10] examines both the leptonic and hadronic decay channels, where for the former the selection is based on the full sample of events selected in the isolated leptons analysis [5]. The distribution of the reconstructed top mass  $M^{\ell\nu b}$  in the leptonic channels after neutrino reconstruction, but before a requirement is made on a positive lepton charge, is shown in figure 2 (left). In order to separate a potential FCNC top signal from the SM background, both the leptonic and hadronic decay channels combine relevant event level observables into a multi-variate discriminant, trained using single top Monte Carlo (MC) as the model and  $W$  MC as the SM background. In the absence of a top signal, limits on the signal cross section are extracted from the discriminator spectra using a maximum likelihood method [10]. An upper bound on the cross section of  $\sigma_{ep \rightarrow etX} < 0.25$  pb at 95% CL is found, which is translated into an upper bound on the coupling  $\kappa_{t\gamma} < 0.18$  for a top mass  $m_{top} = 175$  GeV. This limit is shown in figure 2 (right) in comparison to results from other colliders [12, 13, 14]. A preliminary result from ZEUS using HERA II data [11], which examines only the leptonic  $W$  decay channel and is not shown in figure 2 (right), sets limits of  $\sigma_{ep \rightarrow etX} < 0.13$  pb and  $\kappa_{t\gamma} < 0.13$  for a top mass  $m_{top} = 171.2$  GeV.

#### 4. Conclusions

Analyses of events with isolated leptons with  $P_T^{\text{miss}}$  have recently been published individually and as a combined analysis by H1 and ZEUS. In general, a good agreement is observed with the SM

<sup>3</sup>It should be noted that single top production cannot explain the observed difference between the  $e^+p$  and  $e^-p$  data.



**Figure 2:** Left: Distribution of the reconstructed top mass  $M^{\ell\nu b}$  in the electron and muon channels after neutrino reconstruction but before the cut on the lepton charge. The data are the points, the total SM expectation as the open histogram. The total uncertainty on the SM is shown as the shaded band. The single top prediction is shown with arbitrary normalisation (dashed histogram). Right: Various exclusion limits at 95% CL on the anomalous  $\kappa_{tU\gamma}$  and  $V_{tUZ}$  couplings for a top mass of 175 GeV, obtained at HERA (H1 [10] and ZEUS [4] experiments), at the Tevatron (CDF experiment [12, 13]) and at LEP (L3 experiment [14]). Anomalous couplings of the charm quark are neglected  $\kappa_{tc\gamma} = V_{tcZ} = 0$ , as are vector couplings to the  $Z^0$  boson  $v_{tUZ} = 0$  in the case of the H1 limit.

and the single  $W$  production cross section is measured as  $\sigma_W = 1.06 \pm 0.16(\text{stat.}) \pm 0.07(\text{sys.})$  pb. Searches for FCNC single top production are also performed and in the absence of a signal an upper limit on the cross section and anomalous coupling  $\kappa_{tU\gamma}$  are derived.

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