

Single W and Anomalous Single Top Production at HERA

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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 presented H1+ZEUS data sample corresponds to an integrated luminosity of 0.97 fb^{-1} , and comprises the complete high energy data from the HERA programme. A total of 87 events are observed in the data, compared to a Standard Model prediction of 92.7 ± 11.2 . At large hadronic transverse momentum $P_T^X > 25 \text{ GeV}$ in the e^+p data, luminosity 0.58 fb^{-1} , 23 data events are observed compared to a SM prediction of 14.6 ± 1.9 . Production cross section measurements of events containing isolated leptons and missing transverse momentum and of single W production are performed by H1, where the measured cross sections are found to be in agreement with SM predictions. A complementary search by H1 for events containing an isolated tau lepton and missing P_T is also presented. A measurement of the W polarisation fractions is performed by H1, where the presented results are found to be in agreement with the SM. Finally, the H1 isolated lepton events are examined in the context of a search for anomalous single top production. In the absence of a clear signal, an upper limit on the anomalous top production cross section $\sigma_{ep \rightarrow etX} < 0.16 \text{ pb}$ is established at the 95% confidence level, corresponding to a limit an upper bound on the anomalous magnetic coupling $\kappa_{t\gamma} < 0.14$.

1. The HERA Electron–Proton Collider

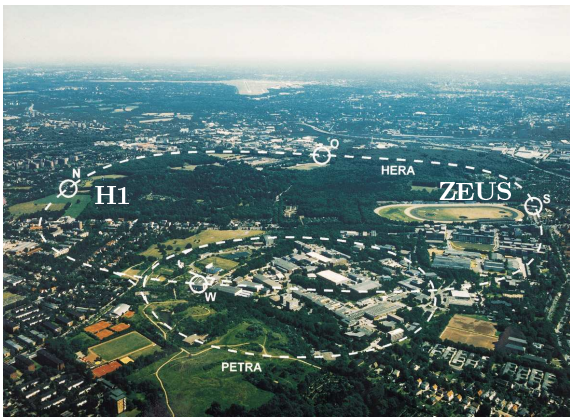


Figure 1. The HERA $e^\pm p$ collider at DESY. The location of the H1 and ZEUS experiments is indicated, as well as the pre-accelerator PETRA.

The HERA $e^\pm p$ collider, located in Hamburg, Germany, and shown in figure 1, was in operation in the years 1992–2007. Protons with an en-

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ergy 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 fb^{-1} of data. Together with measuring the structure of the proton, the deep inelastic collisions (DIS) produced at HERA, at a centre of mass energy up to 318 GeV, provided 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).

2. Events with Isolated Leptons and P_T^{miss}

Events containing a high transverse momentum (P_T) isolated electron or muon and missing P_T have been observed at HERA [1–4]. An excess of HERA I data events (1994–2000 which is 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]. This was not confirmed by the ZEUS Collaboration, although the analysis was performed in a more restricted phase space [4].

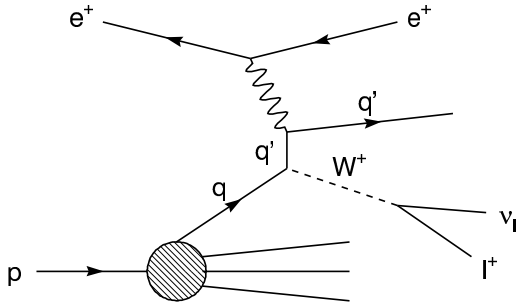


Figure 2. Feynman diagram of the process $ep \rightarrow eW^\pm(\rightarrow l\nu)X$, which is the main SM signal contribution to the search for events with isolated leptons and missing transverse momentum.

The main SM contribution to the signal topology is the production of real W bosons via photoproduction with subsequent leptonic decay $ep \rightarrow eW^\pm(\rightarrow l\nu)X$, as illustrated in figure 2, where the hadronic system X has typically low P_T . The equivalent charged current (CC) process, $ep \rightarrow \nu W^\pm(\rightarrow l\nu)X$, 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 contribution² to the total signal rate in the electron channel at a level of 3%. SM signal processes are modelled using the event generator EPVEC [5]. The main W production via photoproduction component is reweighted to a NLO calculation [6], which has a theoretical uncertainty of 15%.

SM background enters the electron channel due to mismeasured neutral current (NC) 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 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.

²This process is not included in the present ZEUS analysis.

The event selection employed by the H1 [7] and ZEUS [8] analyses is very similar and may be summarised as follows: The identified lepton should have high transverse momentum $P_T^l > 10$ GeV, be observed in the central region of the detector and be isolated with respect to jets and other good quality tracks in the event. The event should also contain a large transverse momentum imbalance, $P_T^{\text{miss}} > 12$ GeV. Further cuts are then applied, which are designed to reduce SM background, whilst preserving a high level of signal purity. Event quantities which are sensitive to the presence of undetected energetic 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.

2.1. Results from H1 and ZEUS Analyses

Both H1 and ZEUS have recently performed the analysis of the electron and muon channels on their respective complete HERA I+II $e^\pm p$ data sets, which correspond to approximately 0.5 fb^{-1} per experiment [7,8].

A total of 59 events are observed in the H1 data, compared to a SM prediction of 58.9 ± 8.2 . For $P_T^X > 25$ GeV, a total of 24 events are observed compared to a SM prediction of 15.8 ± 2.5 , where 21 events are observed in the e^+p data compared to a SM prediction of 8.9 ± 1.5 . The observed data excess in the HERA I e^+p data [2] thus remains at the 3.0σ level for the complete H1 e^+p data [7].

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 ± 6.8 [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 ± 1.8 .

2.2. A Combined H1 and ZEUS Analysis

A study of the selection efficiency for signal processes 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 $P_T^X > 25$ GeV are also found to be in 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.

This common selection is based³ on the H1 event selection [2,7], but covers a more restricted lepton polar angle range of $15^\circ < \theta_l < 120^\circ$, as that employed in the ZEUS analysis [8]. 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, mainly from real W production, is seen to dominate the total SM expectation in all data samples. At large hadronic transverse momentum $P_T^X > 25$ GeV a total of 29 events are observed in the H1+ZEUS $e^\pm p$ data compared to a SM prediction of 25.3 ± 3.2 . In the e^+p data alone, 23 events are observed with $P_T^X > 25$ GeV compared to a SM prediction of 14.6 ± 1.9 , which is equivalent to an excess of data over the SM prediction of 1.8σ . Seventeen of the 23 data events are observed in the H1 data compared to a SM expectation of 7.1 ± 0.9 , equivalent to an excess of data over the SM prediction of 2.9σ .

Figure 3 (top) shows the transverse mass, $M_T^{l\nu}$ and P_T^X distributions of the H1+ZEUS $e^\pm p$ HERA I+II data for the combined electron and muon channels. The distribution of events in $M_T^{l\nu}$ is compatible with the Jacobian peak expected from W production. Similarly, the observed P_T^X spectrum displayed in figure 3 (bottom) is compatible with that expected from W production, peaking at low values of hadronic transverse momentum.

³An additional change with respect to the H1 event selection is that the cut on longitudinal momentum imbalance in the electron channel is simplified in that it is always applied. This is found to make only a negligible difference to the SM expectation.

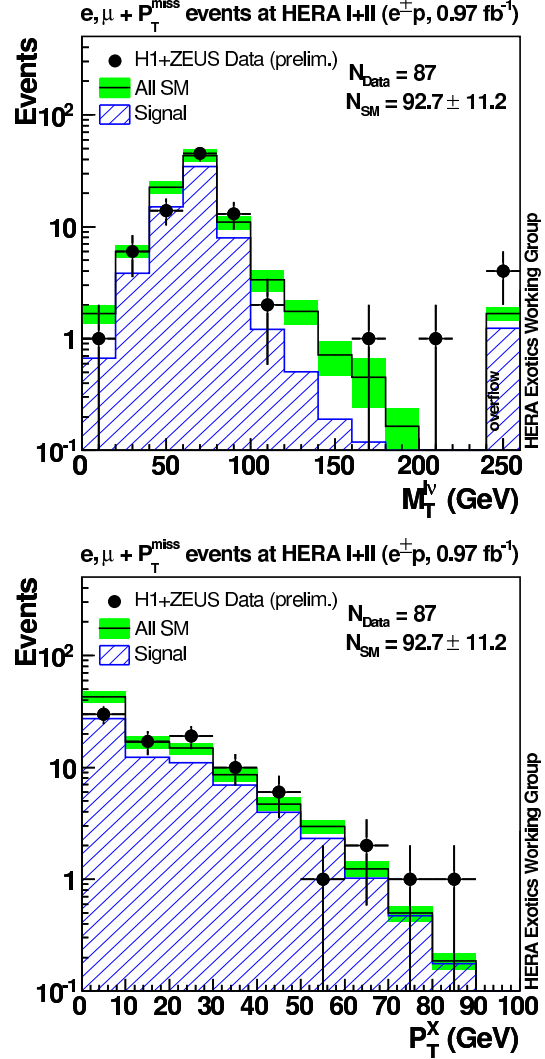


Figure 3. The transverse mass $M_T^{l\nu}$ (top) and hadronic transverse momentum P_T^X (bottom) distributions of the combined H1+ZEUS $e^\pm p$ HERA I+II data. The data (points) are compared to the SM expectation (open histogram). The signal component of the SM expectation is given by the striped histogram. N_{Data} is the total number of data events observed and N_{SM} is the total SM expectation. The total uncertainty on the SM expectation is given by the shaded band.

Table 1

Summary of the combined H1+ZEUS results in the search for events with isolated electrons or muons and missing transverse momentum, shown for the electron and muon channels separately and 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 sample and for events with $P_T^X > 25$ GeV. The signal component of the SM expectation, dominated by real W production, is given as a percentage of the total SM prediction in parentheses. The uncertainties contain statistical and systematic uncertainties added in quadrature.

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 ± 5.0 (70%)	18 / 11.8 ± 1.6 (85%)	57 / 53.1 ± 6.4 (73%)
	$P_T^X > 25$ GeV	12 / 7.4 ± 1.0 (78%)	11 / 7.2 ± 1.0 (85%)	23 / 14.6 ± 1.9 (81%)
1998-2006 e^-p 0.39 fb $^{-1}$	Full Sample	25 / 31.6 ± 4.1 (63%)	5 / 8.0 ± 1.1 (86%)	30 / 39.6 ± 5.0 (68%)
	$P_T^X > 25$ GeV	4 / 6.0 ± 0.8 (67%)	2 / 4.8 ± 0.7 (87%)	6 / 10.6 ± 1.4 (76%)
1994-2007 $e^\pm p$ 0.97 fb $^{-1}$	Full Sample	64 / 72.9 ± 8.9 (67%)	23 / 19.9 ± 2.6 (85%)	87 / 92.7 ± 11.2 (71%)
	$P_T^X > 25$ GeV	16 / 13.3 ± 1.7 (73%)	13 / 12.0 ± 1.6 (86%)	29 / 25.3 ± 3.2 (79%)

3. Cross Sections

The H1 results described in section 2.1 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 (σ_W), for the latter of which the branching ratio ($\Gamma=0.24$) for leptonic W decay is taken into account [12]. For the isolated lepton cross section, $\Gamma = 1$. The cross sections are measured in the phase space $5^\circ < \theta_\ell < 140^\circ$, $P_T^\ell > 10$ GeV, $P_T^{\text{miss}} > 12$ GeV, and where the lepton is isolated from any jet by at least one unit in $\eta - \phi$.

Cross sections are calculated using the formula:

$$\sigma = \frac{N_{\text{data}} - N_{\text{bkd}}^{\text{MC}}}{\mathcal{L} \Gamma \mathcal{A}} \quad \text{with} \quad \mathcal{A} = \frac{N_{\text{rec}}^{\text{MC}}}{N_{\text{gen}}^{\text{MC}}}, \quad (1)$$

where N_{data} is the number of data events, $N_{\text{bkd}}^{\text{MC}}$ is the Monte Carlo (MC) estimate of number of background events and \mathcal{L} is the total data luminosity. \mathcal{A} is the acceptance, where $N_{\text{rec}}^{\text{MC}}$ and $N_{\text{gen}}^{\text{MC}}$ are the number of reconstructed and generated events in the signal MC, respectively. SM signal processes are described in section 2. It should be noted that the small SM contribution to $N_{\text{rec}}^{\text{MC}}$ from Z^0 production is signal for $\sigma_{\ell+P_T^{\text{miss}}}$, whereas it is considered background for σ_W .

The results are shown in table 2 with statistical (stat) and systematic (sys) uncertainties and are found to be in good agreement with the SM predictions.

4. Events with an Isolated Tau and P_T^{miss}

The H1 Collaboration has also performed a search for events with an isolated tau lepton and large missing transverse momentum, using the full HERA I+II $e^\pm p$ data and the hadronic one-prong tau decay mode [13]. This search is complementary to the electron and muon searches described above, and provides a test of lepton universality. In addition, some BSM scenarios favour the third lepton generation, which could lead to an enhancement from the subsequent leptonic decay of the tau lepton.

The event selection is based on that used in [14], with improvements to the tau identification algorithm, in particular to the track isolation [13]. The event signature is a narrow, low track multiplicity jet (tau-jet) in coincidence with missing transverse momentum.

The hadronic transverse momentum distribution of the final sample is shown in figure 4, where 20 events are observed in the data compared to a SM prediction of 19.5 ± 3.2 . The latter

Table 2

The measured H1 cross section for events with an isolated lepton and large missing transverse momentum ($\sigma_{\ell+P_T^{\text{miss}}}$) and for single W production (σ_W) with statistical (stat.) and systematic (sys.) uncertainties. The results are compared to the SM prediction with the associated theory uncertainty (th.).

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

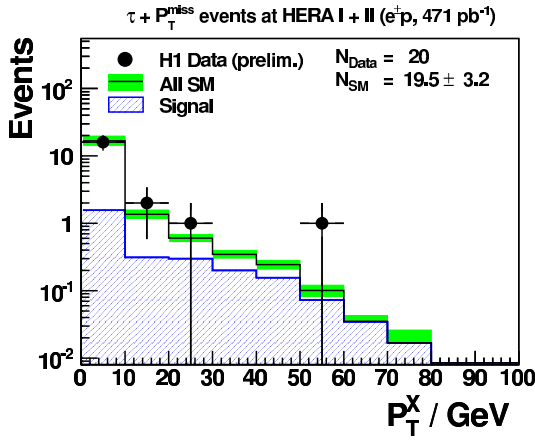


Figure 4. The hadronic transverse momentum distribution of $\tau + P_T^{\text{miss}}$ events in the H1 $e^\pm p$ HERA I+II data. The data (points) are compared to the SM expectation (open histogram). The signal component of the SM expectation is given by the striped histogram. N_{Data} is the total number of data events observed and N_{SM} is the total SM expectation. The total uncertainty on the SM expectation is given by the shaded band.

is dominated by charged current events and the signal purity is observed to be much lower than the electron muon channels, at around 14%. For $P_T^X > 25$ GeV one event is selected in the data, compared to a SM prediction of 0.99 ± 0.13 .

5. Measurement of the W Boson Polarisation Fractions

The H1 measurement of the W boson polarisation fractions at HERA makes use of the $\cos \theta^*$

distributions in the decay $W \rightarrow e/\mu + \nu$, where θ^* is defined as the angle between the W boson momentum in the lab frame and the charged decay lepton in the W boson rest frame. The left handed F_- , longitudinal F_0 and right handed F_+ polarisation fractions are constrained by the relation $F_+ \equiv 1 - F_- - F_0$. The $\cos \theta^*$ distributions for W^+ bosons are given [15] by:

$$\begin{aligned} \frac{dN}{d\cos \theta^*} &\propto (1 - F_- - F_0) \cdot \frac{3}{8} (1 + \cos \theta^*)^2 \\ &+ F_0 \cdot \frac{3}{4} (1 - \cos^2 \theta^*) \\ &+ F_- \cdot \frac{3}{8} (1 - \cos \theta^*)^2. \end{aligned} \quad (2)$$

For W^- bosons the $\cos \theta^*$ distributions have opposite sign. To allow the combination of the different W boson charges, the value of $\cos \theta^*$ is multiplied by the sign of the lepton charge $q_\ell = \pm 1$.

Starting from the H1 event sample described in section 2.1, events are selected for which a W boson can be successfully reconstructed, based on the method described in [16]. Additional selection criteria are applied to ensure a reliable charge measurement, so that the resulting charge misidentification is well below 1% [12]. Electron and muon events originating from tau decays of W bosons are considered background in this analysis, since for these events the $\cos \theta^*$ distributions are not expected to be described by equation 2. The final event sample consists of 21 electron events and 10 muon events with an overall signal purity of 83%.

The measured $q_\ell \cos \theta^*$ distribution, corrected for acceptance and detector effects, is shown in figure 5 (top), compared to the SM prediction. The cross section fit to the model defined in equa-

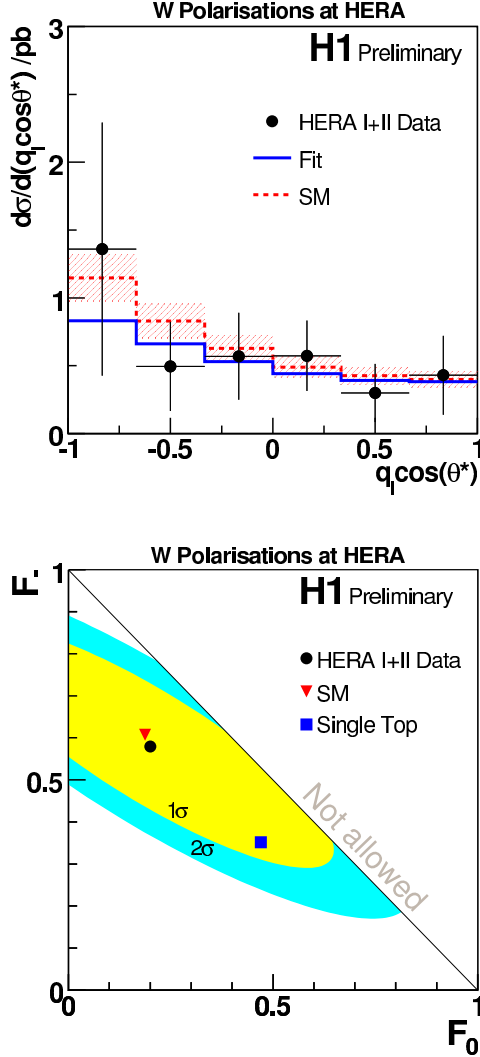


Figure 5. Top: A simultaneous fit (solid histogram) of F_- and F_0 to the measured differential cross section (points), where the error bars denote the statistical uncertainty only. The SM prediction (dashed histogram) is shown with a 15% theoretical systematic uncertainty (hatched area). Bottom: The fit result for the simultaneously extracted W boson polarisation fractions F_- and F_0 (point) with 1 and 2 σ CL contours. The predictions for the SM prediction (triangle) and anomalous single top production via FCNC (square) are also shown.

tion 2 is also shown. In the fit, the optimal values for F_- and F_0 are simultaneously extracted, the result of which is shown in figure 5 (bottom). The measured W boson polarisation fractions are found to be in good agreement with the SM prediction and compatible with anomalous single top production via FCNC within 1 σ confidence level (CL).

Values of F_- and F_0 are also extracted in fits where one parameter is fixed to its SM value. The results are presented in table 3 and show good agreement with the SM. The quoted systematic uncertainties are propagated from the differential cross section calculations.

6. Search for Anomalous Single Top Quark Production

The production of single top quarks is kinematically possible in ep collisions at HERA due to the large centre of mass energy of up to $\sqrt{s} = 320$ GeV. The dominant SM process for single top production at HERA is the charged current reaction $e^+p \rightarrow \bar{\nu}t\bar{b}X$ ($e^-p \rightarrow \nu t\bar{b}X$), which 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 [17].

Such events are of interest as the signature of the top decay to b and W with subsequent leptonic decay matches that of the isolated lepton events discussed in section 2. In particular, the hadronic final state from the fragmentation of the b quark would exhibit high P_T , and thus this process could provide an explanation of the data excess observed at high P_T^X by the H1 experiment.⁴

Anomalous single top production is described by an effective Lagrangian where the interaction of a top with u -type quarks via a photon is described by a magnetic coupling $\kappa_W \gamma$. The contribution from the charm quark is expected to be small at the large proton longitudinal momentum fraction x needed to produce a top quark, and is

⁴Although it should be noted that single top production cannot explain the observed difference between the H1 e^+p and e^-p data.

Table 3

One parameter fit results by H1 of the W polarisation fractions F_- and F_0 with statistical (stat.) and systematic (sys.) uncertainties. The central values are obtained by fixing one parameter to the SM prediction and fitting the other. The SM prediction is obtained from a two parameter fit to the SM $q_\ell \cos \theta^*$ distribution, where the quoted uncertainty is statistical only.

	H1 HERA I+II Data	SM
F_-	0.58 ± 0.15 (stat.) ± 0.12 (sys.)	0.61 ± 0.01 (stat.)
F_0	0.15 ± 0.21 (stat.) ± 0.09 (sys.)	0.19 ± 0.01 (stat.)

therefore neglected ($\kappa_{tc\gamma} \equiv 0$). The vector couplings to a Z^0 boson v_{tUZ} are suppressed at HERA due to the large Z^0 mass, and are also neglected in the present H1 analysis ($v_{tUZ} \equiv 0$).

The H1 search for single top production is based on the full sample of events selected in the HERA I+II data described in section 2.1, so that the present analysis investigates the leptonic W decay channels to electrons and muons. The first step in the analysis forms a *top preselection* of this event sample, by demanding good top quark reconstruction and lepton charge compatible with single top production [19]. Three observables are investigated in this preselection, namely: the transverse momentum of the reconstructed b quark candidate, the reconstructed top mass, and the W decay angle calculated as the angle between the lepton momentum in the W rest frame and the W direction in the top quark rest frame. The observed data distributions of these quantities agree well with the SM expectation within the uncertainties and no evidence for single top production is observed.

The observables are then combined into a multi-variate discriminator, which is trained using a single top MC as the signal model and a W boson MC as the background model. The resulting discriminator output for the electron and muon channels is found to provide good separation between W and top MC events.

Limits on the signal cross section are extracted from the discriminator spectra using a maximum likelihood method [19]. Likelihood functions are calculated for the electron and muon channel separately. An upper bound on the cross section of $\sigma_{ep \rightarrow etX} < 0.16$ pb at 95% CL is found, which is translated into an upper bound on the coupling

$\kappa_{tu\gamma} < 0.14$.

Figure 6 shows existing limits on the anomalous couplings $\kappa_{tu\gamma}$ and v_{tuZ} . The top mass is assumed to be $m_t = 175$ GeV in order to compare with previous results. The new preliminary H1 result presented here extends the bound on $\kappa_{tu\gamma}$ into a region so far uncovered by current colliders. Also shown in figure 6 are results from the L3 experiment at LEP [20], the CDF experiment at the Tevatron [21] and results from the ZEUS experiment using HERA I data [4]. A new result from CDF [22], not shown in figure 6, derives a limit on the branching ratio $B(t \rightarrow Zq)$ of 3.7%, which translates as an upper limit on the anomalous vector coupling of $v_{tuZ} \lesssim 0.2$ and is the strictest limit to date.

7. Summary

Searches for events containing isolated leptons and missing transverse momentum produced in $e^\pm p$ collisions at HERA are presented, performed individually and in a common phase space with the H1 and ZEUS detectors at HERA in the period 1994–2007. In the complete H1+ZEUS high energy data sample, luminosity 0.97 fb^{-1} , a total of 87 events are observed in the data, compared to a Standard Model (SM) prediction of 92.7 ± 11.2 . At large hadronic transverse momentum $P_T^X > 25$ GeV in the e^+p data, luminosity 0.58 fb^{-1} , 23 data events are observed compared to a SM prediction of 14.6 ± 1.9 . The observed excess is dominated by the H1 data.

Production cross section measurements of events containing isolated leptons and missing transverse momentum and single W production are performed by H1, as well as a measurement

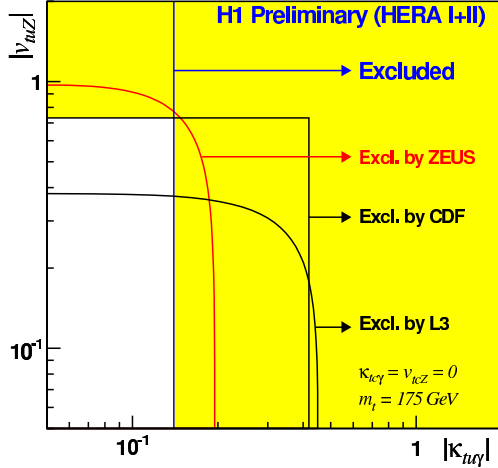


Figure 6. Exclusion limits at 95% CL on the anomalous $\kappa_{tu\gamma}$ and v_{tuZ} couplings obtained at HERA (H1 [19] and ZEUS [4] experiments), LEP (L3 experiment [20]) and at the TeVatron (CDF experiment [21]). Anomalous couplings of the charm quark are neglected $\kappa_{tc\gamma}$. Limits are shown assuming a top mass $m_t = 175$ GeV.

of the W polarisation fractions. The H1 isolated lepton events are also examined in the context of a search for single top production. No clear signal is observed, and an upper limit on the anomalous top production cross section of $\sigma_{ep \rightarrow etX} < 0.16$ pb is established at the 95% confidence level.

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