Events with an isolated lepton and missing transverse momentum and measurement of W production at HERA

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The H1 and ZEUS Collaborations

Abstract

A search for events containing an isolated electron or muon and missing transverse momentum produced in $e^{\pm}p$ collisions is performed with the H1 and ZEUS detectors at HERA. The data were taken in the period 1994–2007 and correspond to an integrated luminosity of 0.98 fb^{-1}. The observed event yields are in good overall agreement with the Standard Model prediction, which is dominated by single W production. In the $e^{+}p$ data, at large hadronic transverse momentum $P_T^X > 25$ GeV, a total of 23 events are observed compared to a prediction of 14.0 ± 1.9. The total single W boson production cross section is measured as $1.06 \pm 0.16\ (\mathrm{stat.}) \pm 0.07\ (\mathrm{sys.})$ pb, in agreement with an SM expectation of 1.26 ± 0.19 pb.

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1 Introduction

In the Standard Model (SM) events containing an isolated electron[1] or muon of high transverse momentum, P_T, in coincidence with large missing transverse momentum, $P_T^{\rm miss}$, arise from the production of single W bosons with subsequent decay to leptons. Events of this topology have been observed at the electron–proton collider HERA [1–4]. An excess of events containing in addition a hadronic final state of high transverse momentum, P_T^X, was previously reported by the H1 collaboration in 105 pb^{-1} of e^+p data [3]. Both the H1 and ZEUS collaborations have recently performed a search for such events using their complete $e^{\pm}p$ high energy data, corresponding to an integrated luminosity of approximately 0.5 fb^{-1} per experiment [5, 6]. The event yields are found to be in good overall agreement with the SM and a measurement of single W production is performed by both collaborations. An excess of events is however still seen by H1 at high $P_T^X > 25$ GeV in the e^+p data sample, where 17 events are observed compared to a SM prediction of 8.0 ± 1.3 [6].

This paper presents a combined analysis of the H1 and ZEUS data, performed in a common phase space. The analysis makes use of the full data samples available to both experiments allowing a more accurate measurement, as well as a more stringent examination of the high P_T^X region. Total event yields and kinematic distributions of events containing an isolated electron or muon of high transverse momentum and missing transverse momentum are compared to the SM. In addition, total and differential cross sections for single W production are measured.

The analysed data were collected between 1994 and 2007 at HERA using the H1 and ZEUS detectors. The electron and proton beam energies were 27.6 GeV and 820 GeV or 920 GeV respectively, corresponding to centre–of–mass energies, $\sqrt{s}$, of 301 GeV or 319 GeV. The data correspond to an integrated luminosity of 0.98 fb^{-1} comprising 0.39 fb^{-1} of e^-p collisions and 0.59 fb^{-1} of e^+p collisions, with 9% of the total integrated luminosity collected at $\sqrt{s} = 301$ GeV. Data collected from 2003 onwards were taken with a longitudinally polarised lepton beam, with polarisation typically at a level of 35%. The residual polarisation of the combined left–handed and right–handed data periods is less than 3% for both experiments.

2 Standard Model Processes

In this analysis, SM processes are considered signal if they produce events containing a high P_T isolated charged lepton and at least one high P_T neutrino, which escapes detection and leads to $P_T^{\rm miss}$ in the final state. The production of single W bosons with subsequent decay to an electron or a muon, which includes a contribution from leptonic tau–decay, is the main signal contribution to the SM expectation. The EPVEC [9] Monte Carlo (MC) event generator is used to calculate the single W production cross section. The $ep \to eWX$ events from EPVEC are weighted by a factor dependent on the transverse momentum and rapidity of the W, such that the resulting cross section corresponds to a calculation including Quantum Chromodynamics (QCD) corrections at next–to–leading order (NLO) [10]. The estimated uncertainty on this calculation is 15%, which arises from the uncertainties in the parton densities and the scale

[1]Here and in the following, the term "electron" denotes generically both the electron and the positron.

at which the calculation is performed. The contribution of $ep \to \nu_e WX$ events to the total single W production cross section is approximately 7%. The process $ep \to eZ(\to \nu\bar{\nu})X$ also produces high P_T isolated electrons and large $P_T^{\rm miss}$ in the final state. The visible cross section for this process as calculated by EPVEC is less than 3% of the predicted single W production cross section and is neglected in the ZEUS part of the analysis.

All other SM processes are defined as background and contribute to the selected sample mainly through misidentification or mismeasurement. Neutral current (NC) deep inelastic scattering (DIS) events ($ep \to eX$), in which genuine isolated high P_T electrons are produced, form a significant background in the electron channel when fake $P_T^{\rm miss}$ arises from mismeasurement. Charged current (CC) DIS events ($ep \to \nu_e X$), in which there is real $P_T^{\rm miss}$ due to the escaping neutrino, contribute to the background when fake isolated electrons or muons are observed. Lepton pair production ($ep \to e\ell^+\ell^- X$) contributes to the background via events where one lepton escapes detection and/or measurement errors cause apparent missing momentum. A small contribution to the background in the electron channel arises from QED Compton (QEDC) events ($ep \to e\gamma X$) when mismeasurement leads to apparent missing momentum. The background contribution to the analysis from photoproduction is negligible.

3 Experimental Method

The H1 and ZEUS detectors are general purpose instruments which consist of tracking systems surrounded by electromagnetic and hadronic calorimeters and muon detectors, ensuring close to 4π coverage of the $e^{\pm}p$ interaction point. The origin of the coordinate system is the nominal $e^{\pm}p$ interaction point, with the direction of the proton beam defining the positive z–axis (forward region). The x–y plane is called the transverse plane and ϕ is the azimuthal angle. The pseudorapidity η is defined as $\eta = -\ln\tan(\theta/2)$, where θ is the polar angle. Detailed descriptions of the detectors can be found elsewhere [7, 8].

The event selection for isolated electrons or muons and missing transverse momentum is based on those used by the H1 [6] and ZEUS [5] experiments. For the combined analysis, a common phase space is chosen in a region where both detectors have a high and well understood acceptance. The event selection for the electron and muon channels is summarised in Table 1, and uses the variables described below.

Leptons are identified according to the selection criteria employed by the individual experiments [5, 6]. Electron candidates are identified as compact and isolated energy deposits in the electromagnetic calorimeters associated to a track in the inner tracking system. Muon candidates are identified as tracks from the inner tracking system associated with track segments reconstructed in muon chambers or energy deposits in the calorimeters compatible with a minimum ionising particle. Lepton candidates are required to lie within the polar angle range $15^\circ < \theta_\ell < 120^\circ$ and to have transverse momentum, P_T^ℓ, greater than 10 GeV. The lepton is required to be isolated with respect to jets and other tracks in the event. Jets are reconstructed from particles in the event not previously identified as isolated leptons using an inclusive k_T algorithm [11]. The isolation of the lepton is quantified using the distances in η–ϕ space to the nearest jet $D(\ell;{\rm jet}) > 1.0$ and nearest track $D(\ell;{\rm track}) > 0.5$. To ensure that the two channels are exclusive, electron channel events must contain no isolated muons.

The selected events should contain a large transverse momentum imbalance $P_T^{\rm miss} > 12$ GeV. To ensure a high trigger efficiency, the transverse momentum measured in the calorimeter, $P_T^{\rm calo}$, is also required to be greater than 12 GeV. As muons deposit little energy in the calorimeter, $P_T^{\rm calo}$ is similar to P_T^X in the muon channel and therefore the $P_T^{\rm calo}$ requirement effectively acts as a cut on P_T^X. For this reason, the muon channel is restricted to the region $P_T^X > 12$ GeV.

In order to reduce the remaining SM background, a series of further cuts are applied as described in Table 1. A measure of the azimuthal balance of the event, $V_{\rm ap}/V_{\rm p}$, is defined as the ratio of the anti–parallel to parallel momentum components of all measured calorimetric clusters with respect to the direction of the total calorimetric transverse momentum [12]. The difference in azimuthal angle between the lepton and the direction of the hadronic system, $\Delta\phi_{\ell-X}$, is used to reject SM background with back–to–back topologies ($\Delta\phi_{\ell-X} = 180°$) like those in NC and lepton pair events. For events with low hadronic transverse momentum $P_T^X < 1.0$ GeV, the direction of the hadronic system is not well determined and $\Delta\phi_{\ell-X}$ is set to zero. The quantity $\delta_{\rm miss} = 2E_e^0 - \sum_i (E^i - P_z^i)$, where the sum runs over all detected particles and E_e^0 is the electron beam energy, gives a measure of the longitudinal balance of the event. For an event where only momentum in the proton direction is undetected, $\delta_{\rm miss}$ is zero. Further background rejection in the electron channel is achieved using $\zeta_e^2 = 4E_eE_e^0\cos^2\theta_e/2$, where E_e is the energy of the final state electron. For NC events, where the scattered electron is identified as the isolated high transverse momentum electron, ζ_e^2 is equal to the four momentum transfer squared Q_e^2, as measured by the electron method [13]. The lepton–neutrino transverse mass, $M_T^{\ell\nu}$, calculated using the vectors of the missing transverse momentum and the isolated lepton, is used to further reject NC (lepton pair) background in the electron (muon) channel.

The lepton polar–angle acceptance, which is the same as that used in the ZEUS publication [5], is the main difference in the event selection with respect to the published H1 analysis, where isolated leptons are accepted in the range $5° < \theta_\ell < 140°$ [6]. Additionally, the more restrictive cuts on $\delta_{\rm miss}$ and $V_{\rm ap}/V_{\rm p}$ are taken from the ZEUS analysis [5]. The minimum lepton–neutrino transverse mass and electron multiplicity requirements are taken from the H1 analysis [6]. The overall H1(ZEUS) efficiency in the common phase–space analysis to select SM $W \to e\nu$ events is 30% (31%) and to select SM $W \to \mu\nu$ events is 11% (9%), calculated using EPVEC.

The combination of the H1 and ZEUS results is performed by adding both the data and MC distributions bin by bin. The theoretical uncertainty of 15% on single W production from the reweighted EPVEC prediction is treated as correlated between the experiments and dominates the SM prediction uncertainty. Dedicated studies of the significant SM background contributions are performed by both experiments, using background–enriched control samples. The systematic uncertainties attributed to the SM background processes are derived from the level of agreement between the data and the SM predictions in these control samples. Experimental systematic uncertainties, as well as the uncertainties on the SM background, are treated as uncorrelated between the experiments. The systematic uncertainties determined in the combined analysis are found to be the same as those derived by the individual experiments. A detailed list of the systematic uncertainties considered can be found in the respective publications [5, 6].

H1+ZEUS Isolated Lepton $+P_T^{\rm miss}$ Event Selection		
Channel	Electron	Muon
Basic Event Selection	$15^\circ < \theta_\ell < 120^\circ$	
	$P_T^\ell > 10$ GeV	
	$P_T^{\rm miss} > 12$ GeV	
	$P_T^{\rm calo} > 12$ GeV	
Lepton Isolation	$D(\ell;{\rm jet}) > 1.0$	
	$D(e;{\rm track}) > 0.5$ for $\theta_e > 45^\circ$	$D(\mu;{\rm track}) > 0.5$
Background Rejection	$V_{\rm ap}/V_{\rm p} < 0.5$	
	$V_{\rm ap}/V_{\rm p} < 0.15$ for $P_T^e < 25$ GeV	$V_{\rm ap}/V_{\rm p} < 0.15$ for $P_T^{\rm calo} < 25$ GeV
	$\Delta\phi_{e-X} < 160^\circ$	$\Delta\phi_{\mu-X} < 170^\circ$
	$5 < \delta_{\rm miss} < 50$ GeV	–
	$\zeta_e^2 > 5000$ GeV^2 for $P_T^{\rm calo} < 25$ GeV	–
	$M_T^{\ell\nu} > 10$ GeV	
	–	$P_T^X > 12$ GeV
	# electrons < 3	–

Table 1: Selection requirements for the electron and muon channels in the search for events with an isolated lepton and missing transverse momentum.

4 Results

The event yields of the combined H1 and ZEUS search for events containing an isolated lepton and missing transverse momentum are summarised in Table 2. Results are shown for the electron and muon channels separately as well as combined, for the e^+p data, e^-p data and the full HERA $e^\pm p$ data. The results are shown for the full selected sample and for a subsample at $P_T^X > 25$ GeV.

The signal contribution to the SM expectation, dominated by single W production, is 74% in the combined electron and muon channels for the full HERA $e^\pm p$ data. The H1 and ZEUS parts of the analysis contribute similarly to the total signal expectation. The contribution from signal processes to the total H1 (ZEUS) SM expectation in the electron channel is 76% (65%) and in the muon channel 93% (83%).

In the e^+p data, 37 electron events and 16 muon events are observed compared to SM predictions of 38.6 ± 4.7 and 11.2 ± 1.6 respectively. In the e^-p data, 24 electron events and 4 muon events are observed compared to SM predictions of 30.6 ± 3.6 and 7.4 ± 1.1 respectively. Eleven events in the H1 publication [6] are not in the common phase space: nine events (eight in the electron channel and one in the muon channel) have $\theta_\ell < 15^\circ$ and two additional electron channel events fail the stricter δ_{miss} condition. With respect to the published ZEUS analysis [5], one event is not in the common phase space due to the cut on transverse mass. All twelve events rejected in the combined analysis analysis exhibit $P_T^X < 25$ GeV.

At large hadronic transverse momentum $P_T^X > 25$ GeV, a total of 29 events are observed in the complete HERA $e^{\pm}p$ data compared to a SM prediction of 24.0 ± 3.2. In the e^+p data alone, where an excess of data over the SM is reported in the H1 analysis [6], 23 events are observed with $P_T^X > 25$ GeV compared to a SM prediction of 14.0 ± 1.9. Seventeen of these 23 data events are observed in the H1 data, compared to a SM expectation of 6.7 ± 1.1.

Fig. 1 shows kinematic distributions of the complete HERA $e^{\pm}p$ data for the combined electron and muon channels. The data are in good agreement with the SM prediction, dominated by single W production. The distribution of the lepton polar angle, θ_ℓ, shows that the identified lepton is produced mainly in the forward direction. The first bin of the $\Delta\phi_{\ell-X}$ distribution is mainly populated by events with very low values of P_T^X. The shape of the transverse mass $M_T^{\ell\nu}$ distribution shows a Jacobian peak as expected from single W production. The observed P_T^X, P_T^{miss} and P_T^ℓ distributions are also indicative of single W production, where the decay products of the W peak around 40 GeV and the hadronic final state has typically low P_T^X. Fig. 2 shows the P_T^X distribution separately for the combined e^+p and e^-p data.

The total and differential single W production cross sections are evaluated bin by bin from the number of observed events, subtracting the number of background events, and taking into account the acceptance and luminosity of the two experiments. The acceptance, defined as the number of W events reconstructed in a bin divided by the number of events generated in that bin, is evaluated using EPVEC and is used to extrapolate the measured cross section to the full phase space. The acceptances for the two experiments are found to be similar in each P_T^X bin and vary between 27% and 37% in the electron channel and between 18% and 38% in the muon channel. The purity of the cross section measurement is greater than 70% in all bins and is also found to behave similarly for the two experiments. For $P_T^X < 12$ GeV, the electron measurement is used to estimate the muon cross section under the assumption of lepton universality. Leptonic tau decays from $W \to \tau\nu$ events are taken into account in the cross section calculation. The cross sections are quoted at the luminosity–weighted mean centre–of–mass energy $\sqrt{s} = 317$ GeV of the complete HERA data.

The total single W boson production cross section at HERA is measured as:

$$1.06 \pm 0.16\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{sys.})\ \mathrm{pb},$$

which agrees well with the SM prediction of 1.26 ± 0.19 pb. The measured differential cross sections, in bins of P_T^X, are shown in Fig. 3 and given in Table 3. The differential cross section agrees well with the SM prediction.

5 Conclusions

A search for events containing an isolated electron or muon and large missing transverse momentum produced in $e^{\pm}p$ collisions is performed with the H1 and ZEUS detectors at HERA in a common phase space. The full HERA $e^{\pm}p$ high energy data sample from both experiments is analysed, corresponding to a total integrated luminosity of 0.98 fb^{-1}. A total of 81 events are observed in the data, compared to a SM prediction of 87.8 ± 11.0. In the e^+p data, at large hadronic transverse momentum $P_T^X > 25$ GeV, a total of 23 data events are observed compared to a SM prediction of 14.0 ± 1.9. The total and differential single W production cross sections are measured and are found to be in agreement with the SM predictions.

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H1+ZEUS 1994–2007 e^+p 0.59 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	37	38.6 ± 4.7	28.9 ± 4.4	9.7 ± 1.4
	$P_T^X > 25$ GeV	12	7.4 ± 1.0	6.0 ± 0.9	1.5 ± 0.3
Muon	Total	16	11.2 ± 1.6	9.9 ± 1.6	1.3 ± 0.3
	$P_T^X > 25$ GeV	11	6.6 ± 1.0	5.9 ± 0.9	0.8 ± 0.2
Combined	Total	53	49.8 ± 6.2	38.8 ± 5.9	11.1 ± 1.5
	$P_T^X > 25$ GeV	23	14.0 ± 1.9	11.8 ± 1.9	2.2 ± 0.4

H1+ZEUS 1998–2006 e^-p 0.39 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	24	30.6 ± 3.6	19.4 ± 3.0	11.2 ± 1.9
	$P_T^X > 25$ GeV	4	5.6 ± 0.8	4.0 ± 0.6	1.6 ± 0.4
Muon	Total	4	7.4 ± 1.1	6.6 ± 1.0	0.9 ± 0.3
	$P_T^X > 25$ GeV	2	4.3 ± 0.7	3.9 ± 0.6	0.4 ± 0.2
Combined	Total	28	38.0 ± 3.4	26.0 ± 3.4	12.0 ± 2.0
	$P_T^X > 25$ GeV	6	10.0 ± 1.3	7.9 ± 1.2	2.1 ± 0.5

H1+ZEUS 1994–2007 $e^{\pm}p$ 0.98 fb^{-1}		Data	SM Expectation	SM Signal	Other SM Processes
Electron	Total	61	69.2 ± 8.2	48.3 ± 7.4	20.9 ± 3.2
	$P_T^X > 25$ GeV	16	13.0 ± 1.7	10.0 ± 1.6	3.1 ± 0.7
Muon	Total	20	18.6 ± 2.7	16.4 ± 2.6	2.2 ± 0.5
	$P_T^X > 25$ GeV	13	11.0 ± 1.6	9.8 ± 1.6	1.2 ± 0.3
Combined	Total	81	87.8 ± 11.0	64.7 ± 9.9	23.1 ± 3.3
	$P_T^X > 25$ GeV	29	24.0 ± 3.2	19.7 ± 3.1	4.3 ± 0.8

Table 2: Summary of the combined H1 and ZEUS search for events with an isolated electron or muon and missing transverse momentum for the e^+p data (top), e^-p data (middle) and the full HERA data set (bottom). The results are shown for the full selected sample and for the subsample with hadronic transverse momentum $P_T^X > 25$ GeV. The number of observed events is compared to the SM prediction. The SM signal (dominated by single W production) and the total background contribution are also shown. The quoted uncertainties contain statistical and systematic uncertainties added in quadrature.

H1+ZEUS Differential Single W Production Cross Section		
P_T^X [GeV]	Measured $\pm$ stat. $\pm$ sys. [fb / GeV]	SM NLO [fb / GeV]
$0 - 12$	$33.6 \pm 12.3 \pm 5.0$	62.7 ± 9.4
$12 - 25$	$20.6 \pm 6.0 \pm 1.9$	20.7 ± 3.1
$25 - 40$	$12.7 \pm 3.6 \pm 1.0$	9.8 ± 1.5
$40 - 100$	$2.1 \pm 0.7 \pm 0.2$	1.5 ± 0.2

Table 3: The differential single W boson production cross section dσ_W/dP_T^X, with statistical (stat.) and systematic (sys.) errors, measured using the combined H1 and ZEUS data. The cross sections are quoted at a centre–of–mass energy $\sqrt{s} = 317$ GeV. Also shown are the expectations, including the theoretical uncertainties, for the Standard Model calculated at next–to–leading order (SM NLO).

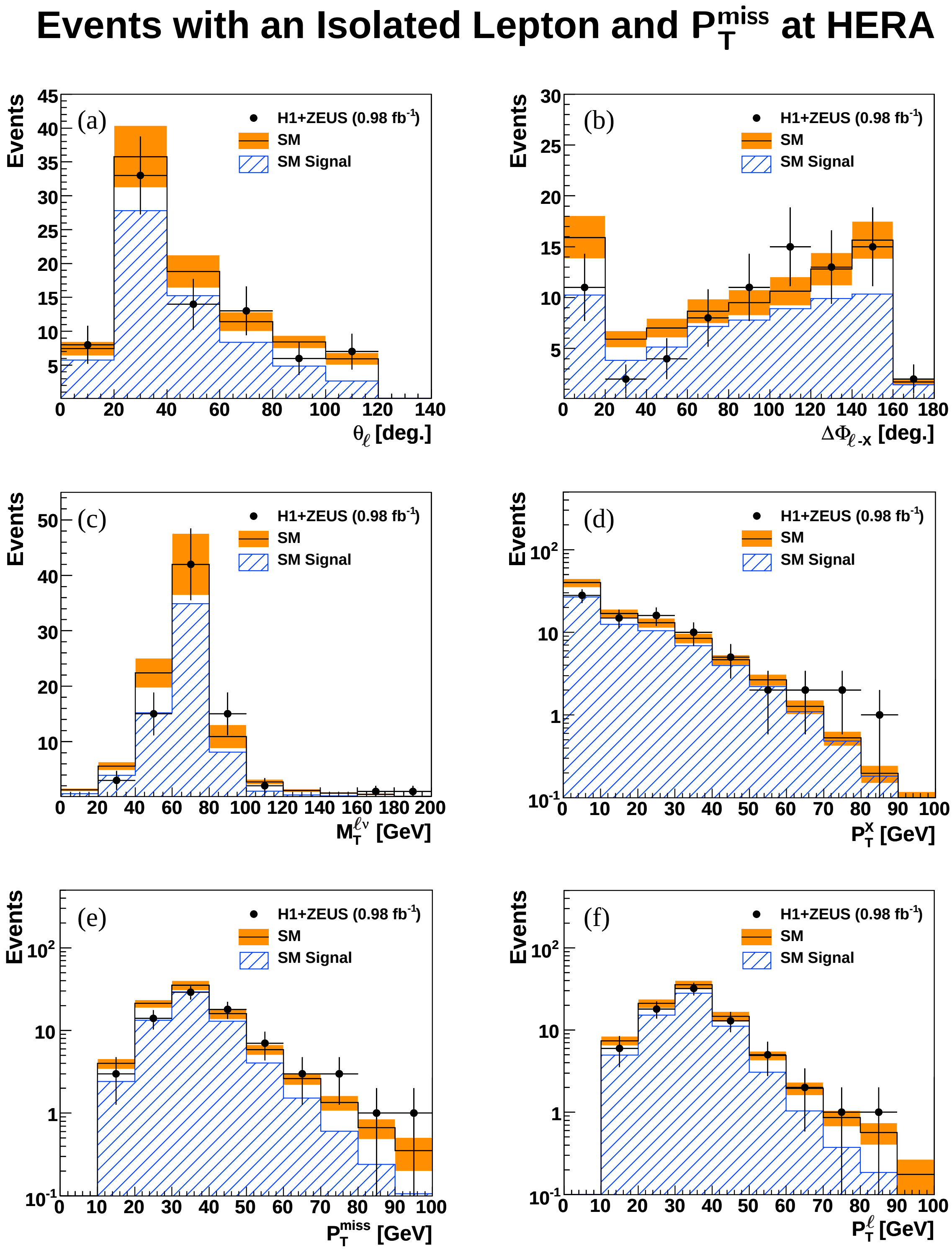

Figure 1: Distributions of kinematic variables of events with an isolated electron or muon and missing transverse momentum in the full HERA $e^{\pm}p$ data. Shown are: the polar angle of the lepton θ_ℓ (a), the difference in the azimuthal angle of the lepton and the hadronic systems $\Delta\phi_{\ell-X}$ (b), the lepton–neutrino transverse mass $M_T^{\ell\nu}$ (c), the hadronic transverse momentum P_T^X (d), the missing transverse momentum $P_T^{\rm miss}$ (e) and the transverse momentum of the lepton P_T^ℓ (f). 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 hatched histogram. The total uncertainty on the SM expectation is shown as the shaded band.

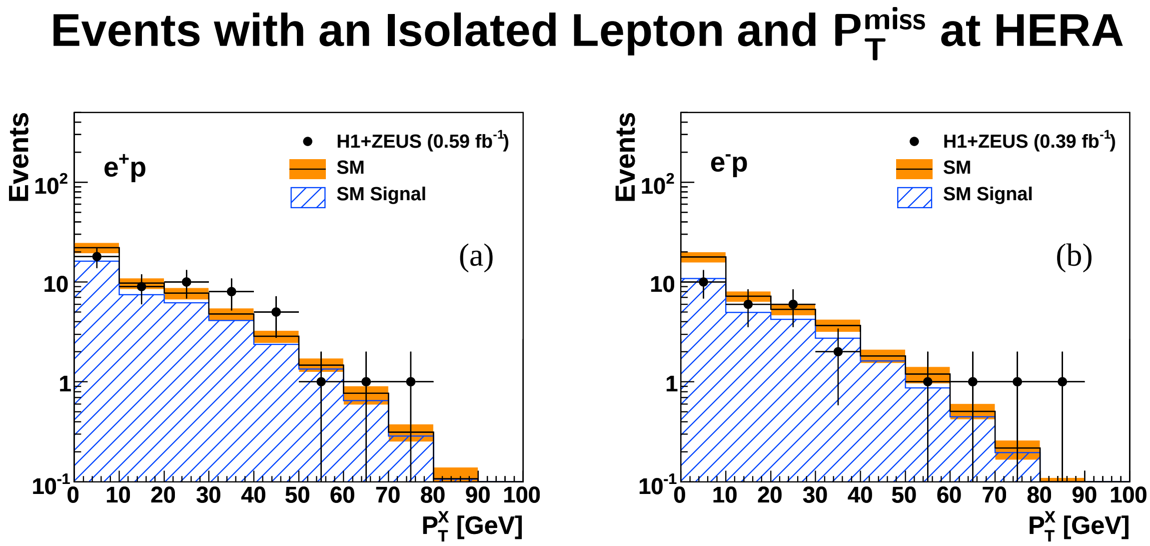

Figure 2: Distributions of the hadronic transverse momentum P_T^X of events with an isolated electron or muon and missing transverse momentum for the e^+p (a) and e^-p (b) HERA data. The data (points) are compared to the SM expectation (open histogram). The signal component of the SM expectation, dominated by single W production, is shown as the hatched histogram. The total uncertainty on the SM expectation is shown as the shaded band.

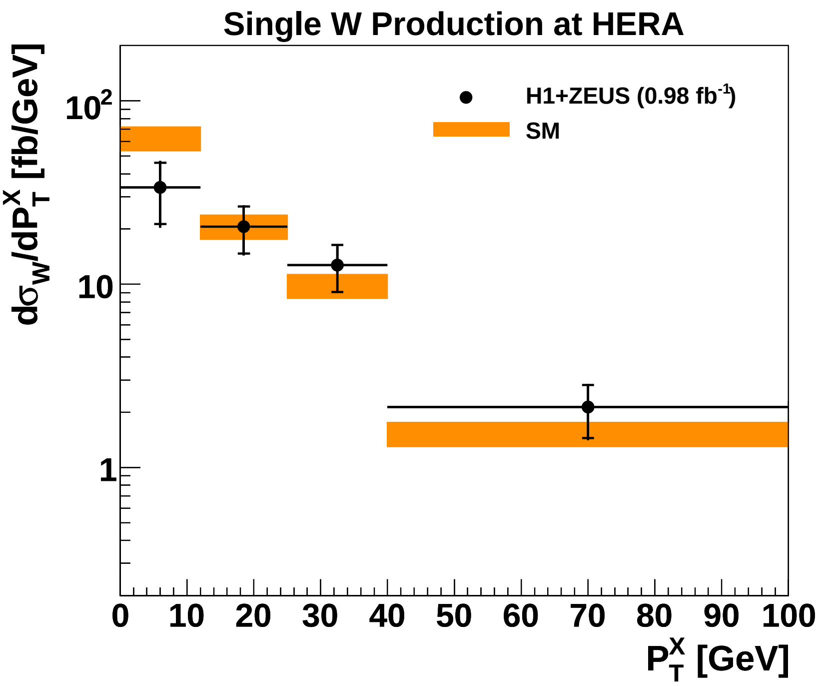

Figure 3: The single W production cross section as a function of the hadronic transverse momentum, P_T^X, measured using the combined H1 and ZEUS data at a centre–of–mass energy of $\sqrt{s} = 317$ GeV. The inner error bar represents the statistical error and the outer error bar indicates the statistical and systematic uncertainties added in quadrature. The shaded band represents the uncertainty on the SM prediction.