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Search for Events with Isolated Leptons and Missing Transverse Momentum

H1 Collaboration

Abstract

The search for events containing isolated leptons (electrons or muons) and missing transverse momentum produced in $e^{\pm}p$ collisions is performed with the H1 detector at HERA in the period 1994–2006. The analysed data sample corresponds to an integrated luminosity of 341 pb^{-1}, which includes 223 pb^{-1} of data from the new HERA II phase. A total of 46 events are observed in the complete HERA data, compared to a Standard Model (SM) prediction of 43.0 $\pm$ 6.0. At large hadronic transverse momentum $P_T^X > 25$ GeV, a total of 18 events are observed compared to a SM prediction of 11.5 $\pm$ 1.8. In this region, 15 events are observed in the e^+p data compared to a SM prediction of 4.6 $\pm$ 0.8, whereas in the e^-p data 3 events are observed compared to a SM prediction of 6.9 $\pm$ 1.0. A new comparison of the efficiency of the H1 and ZEUS experiments to detect events containing isolated electrons or muons and missing transverse momentum is also presented.

1 Introduction

Events containing a high P_T isolated electron or muon associated with missing transverse momentum have been observed at HERA [1–4]. An excess of HERA I (1994–2000) data events compared to the SM prediction at large hadronic transverse momentum P_T^X was reported by the H1 Collaboration [2]. In the HERA I data, 11 electron events and 8 muon events are observed compared to a SM expectation of 11.5 $\pm$ 1.5 and 2.9 $\pm$ 0.5 respectively. At large hadronic transverse momentum $P_T^X > 25$ GeV, 5 electron events and 6 muon events are observed compared to a SM expectation of 1.8 $\pm$ 0.3 and 1.7 $\pm$ 0.3 respectively. The dominant SM contribution is from the production of real W boasons. The HERA I data sample has an integrated luminosity of 104.7 pb^{-1} in e^+p scattering and 13.6 pb^{-1} in e^-p scattering. Presented here is an update of the published H1 analysis, which includes 53 pb^{-1} of e^+p data and 170 pb^{-1} of e^-p data accumulated at HERA II from October 2003 to June 2006.

The observed H1 excess in the HERA I data, most of which was taken in e^+p collisions, was not confirmed by the ZEUS Collaboration, although it should be noted that the anlaysis was performed in a slightly different phase space [4]. The ZEUS analysis has been redone in a kinematic region more similar to the H1 selection criteria [5]. A comparison of the efficiency of the current H1 and ZEUS analyses to detect events containing isolated electrons or muons and missing transverse momentum is presented in section 5.

2 Standard Model Processes

Signal events are defined as those that contain a prominent high P_T isolated lepton accompanied by genuine, large missing transverse momentum. The main SM process that may produce events with this topology is the production of real W bosons via photoproduction with subsequent leptonic decay: $ep \rightarrow eW^{\pm}(\rightarrow l\nu)X$. Additional, smaller contributions arise from the production of W bosons via the charged current process $ep \rightarrow \nu W^{\pm}(\rightarrow l\nu)X$ and the production of Z^0 bosons with subsequent decay to neutrinos $ep \rightarrow eZ^0(\rightarrow \nu\bar{\nu})X$, which only contributes to the electron channel.

The main SM background to events containing isolated electrons arises from neutral current (NC) events, where fake missing transverse momentum is produced by a fluctuation in the detector response, and from charged current (CC) events, where a particle in the hadronic final state or a radiated photon is interpreted as the isolated electron. For events containing an isolated muon the main SM background arises from lepton pair (LP) events, where one muon escapes detection and mismeasurement causes the apparent missing transverse momentum, and from CC events where, similarly to the electron channel, a particle in the hadronic final state is interpreted as the isolated muon.

3 Event Selection

The HERA II event selection is identical to that used in the HERA I analysis and is detailed in table 1.The main selection requirements are as follows: The lepton should have high transverse

Variable	Electron	Muon
θ_l	$5° < \theta_l < 140°$	
P_T^l	> 10 GeV	
$P_T^{\rm calo}$	> 12 GeV	
$P_T^{\rm miss}$	> 12 GeV	
P_T^X	–	> 12 GeV
$D_{\rm jet}$	> 1.0	
$D_{\rm track}$	> 0.5 for $\theta_e \geq 45°$	> 0.5
ζ_l^2	> 5000 GeV^2 for $P_T^{\rm calo} < 25$ GeV	–
$\frac{V_{ap}}{V_p}$	< 0.5 (< 0.15 for $P_T^e < 25$ GeV)	< 0.5 (< 0.15 for $P_T^{\rm calo} < 25$ GeV)
$\Delta\phi_{l-X}$	$< 160°$	$< 170°$
# isolated μ	0	1
$\delta_{\rm miss}$	> 5 GeV †	–

† *if only one e candidate is detected, which has the same charge as the beam lepton.*

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

momentum P_T^l, be observed in the central region of the detector, defined by the polar angle θ_l and be isolated with respect to jets and other tracks in the event. The isolation of the lepton is quantified using the distances in $\eta - \phi$ space to the nearest jet $D_{\rm jet}$ and nearest track $D_{\rm track}$. The event should contain a large transverse momentum imbalance, both measured in the calorimeter, $P_T^{\rm calo}$ and over the complete event, $P_T^{\rm miss}$.

In order to reduce background contributions, further cuts are then applied using variables sensitive to the presence of high energy undetected particles in the event: The azimuthal balance of the event $\frac{V_{ap}}{V_p}$, the difference in azimuthal angle between the lepton and the hadronic system, $\Delta\phi_{l-X}$ and the longitudinal momentum imbalance $\delta_{\rm miss}$. Additionally, muon events are required to have a minimum P_T^X and electron events with low values of $P_T^{\rm calo}$ are required to have large ζ_l^2, which is equivalent to the four momentum transfer squared Q^2 in NC events. To ensure that the two lepton channels are exclusive, electron events must contain no isolated muons. Further details on these variables and the event selection can be found in [2].

4 Results

The analysis of the HERA II e^+p data ($\mathcal{L} = 53$ pb^{-1}), which was collected between October 2003 and August 2004, yields 9 electron events and 1 muon event compared to an expectation of 4.8 $\pm$ 0.8 and 1.3 $\pm$ 0.2 respectively. The majority of the SM prediction is due to signal processes, dominated by real W production. In the electron channel an excess of events is observed in the data compared to the SM prediction at $P_T^X > 25$ GeV, where 5 events are observed compared to an expectation of 0.8 $\pm$ 0.2. The observation of 1 muon event in the data is in agreement with the SM event yield. Figure 1 displays one of the HERA II e^+p electron events. It shows a high P_T electron and large missing transverse momentum. The absence of any reconstructed hadronic system X makes this event a candidate for elastic W production. Figure 2 shows a HERA II e^+p electron event with high P_T^X. The same features are visible as in figure 1, a high P_T electron and large missing transverse momentum. However, also present in this event is a prominent hadronic jet, giving rise to the large P_T^X.

The analysis of the HERA II e^-p data ($\mathcal{L}$ = 170 pb^{-1}), which was collected between December 2004 and June 2006, yields 15 electron events and 2 muon events compared to an expectation of 17.7 $\pm$ 2.5 and 4.7 $\pm$ 0.7 respectively. Figure 3 shows a HERA II e^-p muon event with high P_T^X. As for the HERA II e^+p data the majority of the SM prediction is due to signal processes, dominated by real W production.

Table 2 shows a summary of the analysis results for the H1 e^+p data ($\mathcal{L}$ = 158 pb^{-1}), H1 e^-p data ($\mathcal{L}$ = 184 pb^{-1}) and the full HERA H1 $e^{\pm}p$ data set ($\mathcal{L}$ = 341 pb^{-1}). In the H1 e^+p data, 19 electron events and 9 muon events are observed compared to SM predictions of 14.6 $\pm$ 2.0 and 3.9 $\pm$ 0.6 respectively. Figure 4 shows the P_T^X spectrum of the e^+p data for the combined electron and muon channels. In the H1 e^-p data, 16 electron events and 2 muon events are observed compared to SM predictions of 19.4 $\pm$ 2.7 and 5.1 $\pm$ 0.7 respectively. The signal contribution is observed to be lower in the e^-p data, due to the higher SM background arising from CC events. Figure 5 shows the P_T^X spectrum of the e^-p data for the combined electron and muon channels.

In the complete H1 HERA data set, 35 electron events and 11 muon events are observed compared to SM predictions of 34.0 $\pm$ 4.7 and 9.0 $\pm$ 1.4 respectively. Figure 6 shows the P_T^X spectrum of the $e^{\pm}p$ data for the combined electron and muon channels. In 11 of the electron events the lepton charge is measured as positive, in 8 events negative and is unmeasured in the remaining 16 events. In 5 of the muon events the lepton charge is measured as positive, in 5 events negative and is unmeasured in the remaining event. The main signal process is expected to produce approximately two thirds positively charged leptons. All background processes are expected to produce approximately similar yields for both lepton charges except neutral current DIS, which produces leptons with the same charge as the lepton beam.

5 A Comparison of H1 and ZEUS Selection Efficiencies

The isolated lepton selections employed by the H1 and ZEUS collaborations are optimised for their respective detectors. The main difference in the selections is due to the cut on the lepton polar angle, which is 5 $^\circ < \theta_l <$ 140 $^\circ$ for H1 and 17 $^\circ < \theta_e <$ 86 $^\circ$, 17 $^\circ < \theta_\mu <$ 115 $^\circ$ in the ZEUS analysis. Consequently, the sensitivity of the detectors to the decay products from single W production differs in some kinematic regions, which are defined in terms of the polar angle θ_l and the transverse momentum of the final state lepton P_T^l.

The efficiency of the two detectors is studied with a single W production Monte Carlo sample generated with EPVEC [6], using the respective event selections from the H1 [2] and ZEUS [5] analyses. The efficiency is defined as the number of reconstructed events passing the final selection divided by the number of generated events in the kinematic region 5 $^\circ < \theta_l <$ 140 $^\circ$ and $P_T^l >$ 10 GeV.

Figure 7a shows the H1 and ZEUS efficiencies for detecting electrons from single W decay as a function of P_T^X. The observed drop in the ZEUS efficiency in the lowest bin is due to the analysis cut $P_T^X > 12$ GeV. At large P_T^X the efficiencies are seen to be flat and more comparable. The arrows indicate the position of the observed data events. Figure 7b shows the efficiency as a function of θ_e at large hadronic transverse momentum $P_T^X > 25$ GeV, the kinematic region where an excess of data events is observed by H1 over the SM prediction. Here the cut $P_T^X > 25$ GeV is also made at the generator level. The θ_e distribution from EPVEC is also shown. It can be seen that in the common polar angle range the efficiencies of the H1 and ZEUS selection at large P_T^X are similar. Additionally, the majority of the H1 events observed at high P_T^X lie within this common region. The more limited angular range in the ZEUS analysis visible in figure 7b is the main reason for the lower ZEUS efficiency visible at high P_T^X in figure 7a.

The efficiencies in the muon channel are similarly displayed in figures 7c and 7d. As observed in the electron channel, the efficiency as a function of P_T^X is found to be comparable between the H1 and ZEUS analyses and reasonably flat. It can also be seen that all six high P_T^X muon data events observed by H1 fall within the geometrical acceptance of the ZEUS selection.

6 Summary

The search for events containing isolated electrons or muons and large missing transverse momentum produced in $e^{\pm}p$ collisions is performed with the H1 detector at HERA in the period 1994–2006. The analysed data sample corresponds to an integrated luminosity of 341 pb^{-1}. A total of 46 events are observed in the data, compared to a SM prediction of 43.0 $\pm$ 6.0.

At large hadronic transverse momentum $P_T^X > 25$ GeV, a total of 18 events are observed compared to a SM prediction of 11.5 $\pm$ 1.8. In 9 events the lepton charge is positive, in 4 events negative and unmeasured in the remaining 5 events. The probability for the SM expectation to fluctuate to the observed number of events or more in the high P_T^X domain for all data is 0.0673 compared to 0.0015 for the HERA I data (the majority of which is e^+p data). For the e^+p data alone, this probability is 0.0003.

The selection efficiencies of the H1 and ZEUS isolated lepton analyses have been examined and are found to be compatible in the kinematic region where the two analyses are directly comparable. It is also found that the majority of the data events observed by H1 at $P_T^X > 25$ GeV fall into the region of common phase space.

The continued increase in luminosity expected from the HERA II programme in the coming years will improve the precision of the measurement of events with isolated leptons and missing transverse energy and will hopefully clarify the excess observed by H1 in the e^+p data at large hadronic transverse momentum.

References

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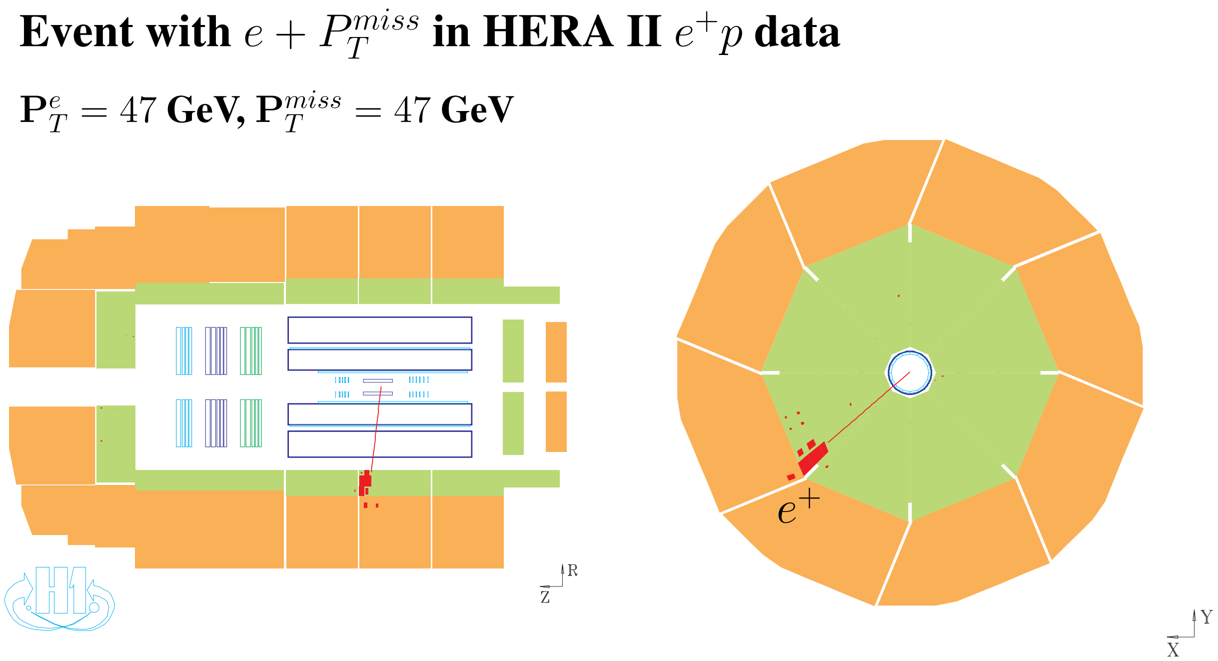

Figure 1: Display of an event with an isolated electron and missing transverse momentum in the HERA II e^+p data: a candidate for elastic W production.

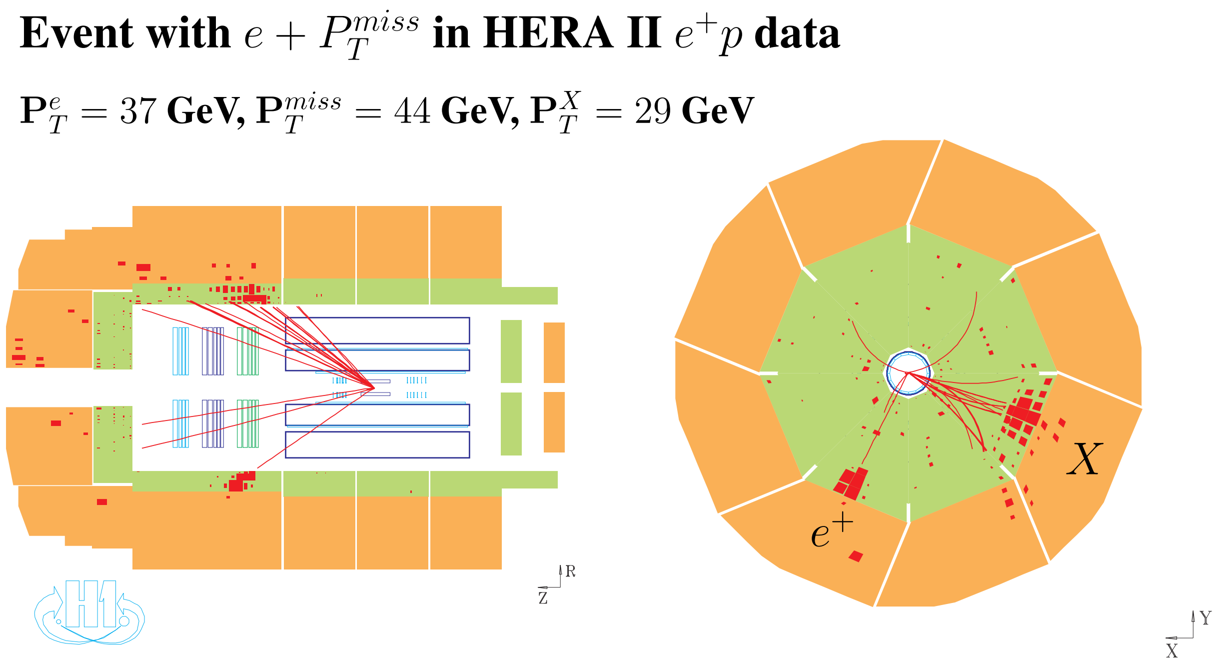

Figure 2: Display of an event with an isolated electron, missing transverse momentum and a prominent hadronic jet in the HERA II e^+p data.

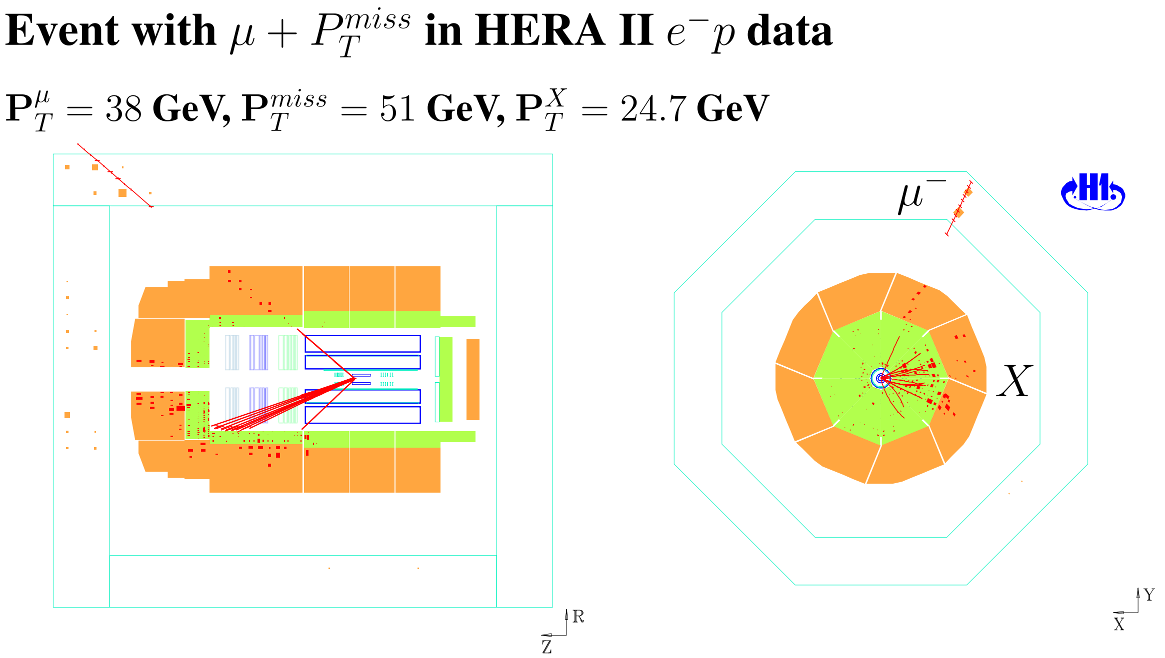

Figure 3: Display of an event with an isolated muon, missing transverse momentum and a prominent hadronic jet in the HERA II e^-p data.

H1 Preliminary		Electron obs./exp. (Signal contribution)	Muon obs./exp. (Signal contribution)	Combined obs./exp. (Signal contribution)
1994-2004 e^+p 158 pb^{-1}	Full Sample	19 / 14.6 $\pm$ 2.0 (70%)	9 / 3.9 $\pm$ 0.6 (84%)	28 / 18.5 $\pm$ 2.6 (73%)
	$P_T^X > 25$ GeV	9 / 2.3 $\pm$ 0.4 (80%)	6 / 2.3 $\pm$ 0.4 (84%)	15 / 4.6 $\pm$ 0.8 (82%)
1998-2006 e^-p 184 pb^{-1}	Full Sample	16 / 19.4 $\pm$ 2.7 (65%)	2 / 5.1 $\pm$ 0.7 (78%)	18 / 24.4 $\pm$ 3.4 (68%)
	$P_T^X > 25$ GeV	3 / 3.8 $\pm$ 0.6 (61%)	0 / 3.1 $\pm$ 0.5 (74%)	3 / 6.9 $\pm$ 1.0 (67%)
1994-2006 $e^{\pm}p$ 341 pb^{-1}	Full Sample	35 / 34.0 $\pm$ 4.7 (68%)	11 / 9.0 $\pm$ 1.4 (80%)	46 / 43.0 $\pm$ 6.0 (70%)
	$P_T^X > 25$ GeV	12 / 6.1 $\pm$ 1.1 (66%)	6 / 5.4 $\pm$ 0.9 (77%)	18 / 11.5 $\pm$ 1.8 (71%)

Table 2: Summary of the H1 results of searches for events with isolated electrons or muons and missing transverse momentum for the e^+p data ($\mathcal{L} = 158$ pb^{-1}), e^-p data ($\mathcal{L} = 184$ pb^{-1}) and the full HERA data set ($\mathcal{L} = 341$ pb^{-1}). The results are shown for the full selected sample and for the subsample at large $P_T^X > 25$ GeV. The number of observed events is compared to the SM prediction. 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.

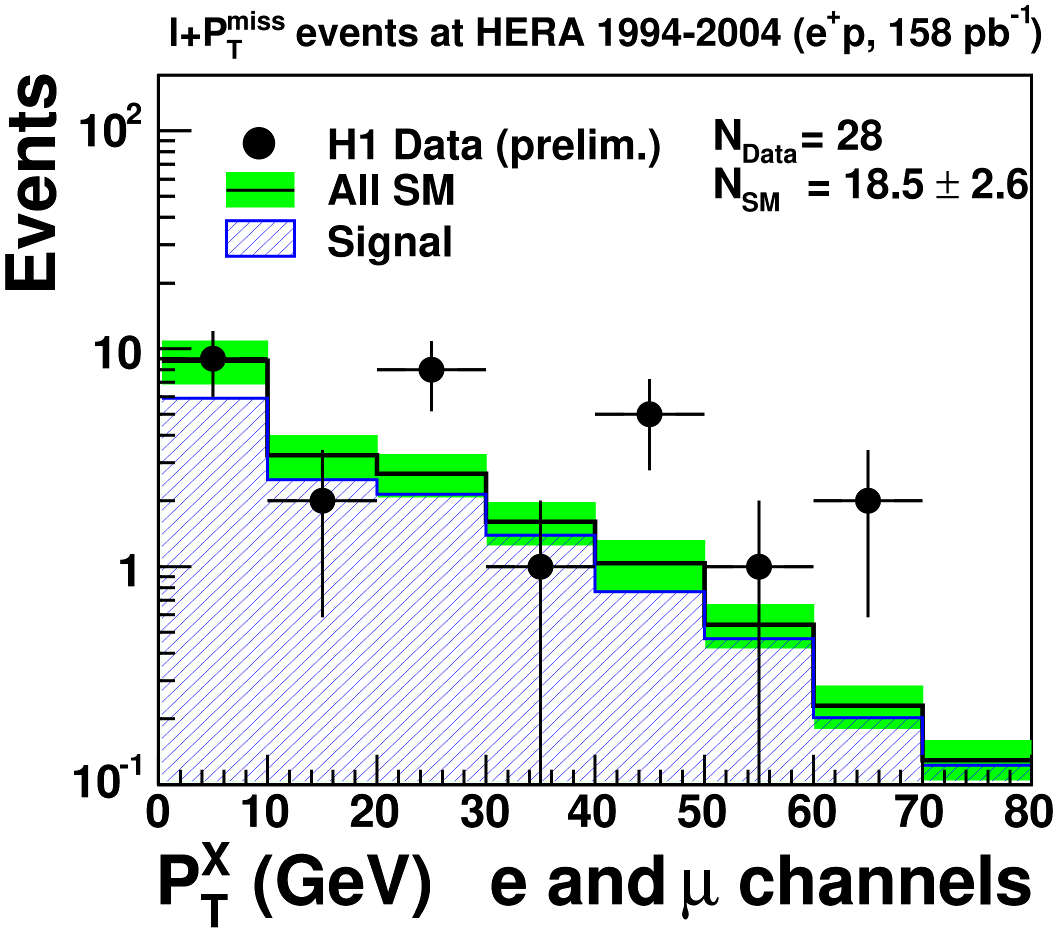

Figure 4: The hadronic transverse momentum distribution in the electron and muon channels combined: data (e^+p, $\mathcal{L} = 158$ pb^{-1}) is compared to the SM expectation (open histogram). The signal component of the SM expectation, dominated by real W production, is given by the hatched histogram. $\mathrm{N_{Data}}$ is the total number of data events observed, $\mathrm{N_{SM}}$ is the total SM expectation. The total error on the SM expectation is given by the shaded band.

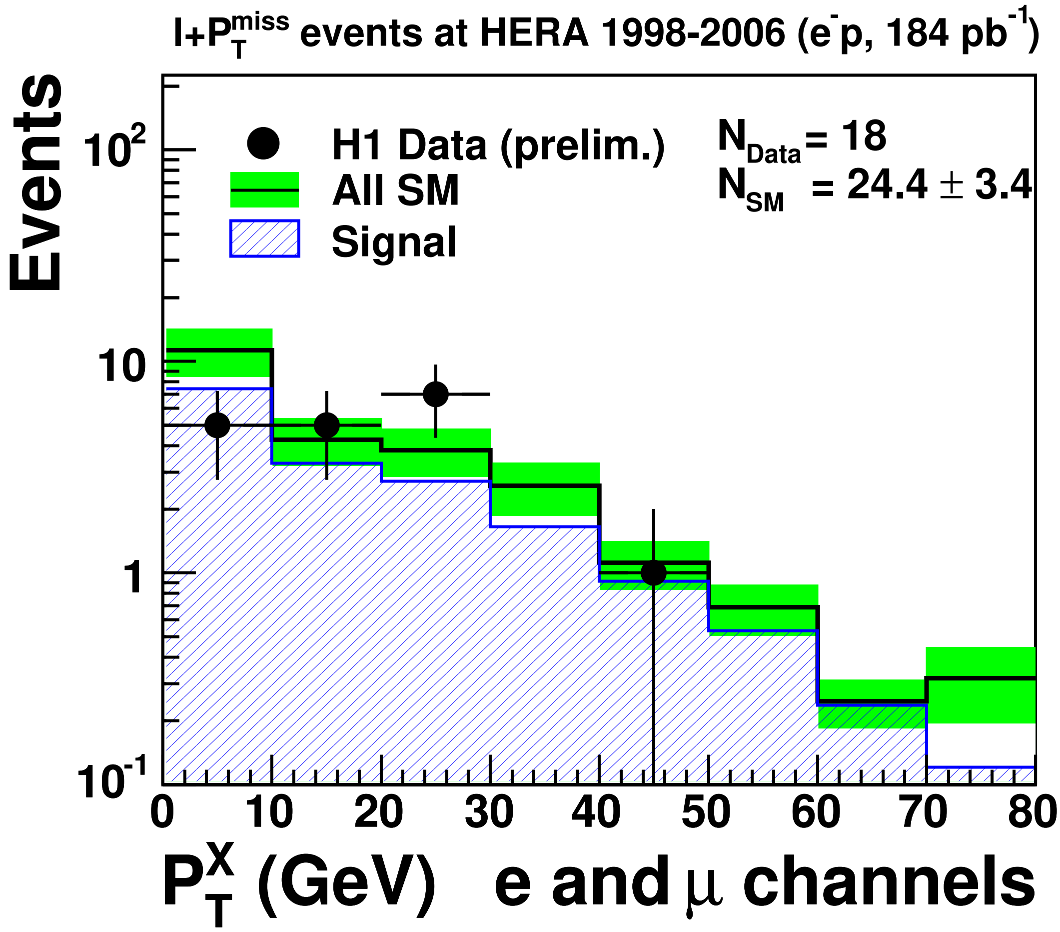

Figure 5: The hadronic transverse momentum distribution in the electron and muon channels combined: data (e^-p, $\mathcal{L}$ = 184 pb^{-1}) is compared to the SM expectation (open histogram). The signal component of the SM expectation, dominated by real W production, is given by the hatched histogram. $\mathrm{N_{Data}}$ is the total number of data events observed, $\mathrm{N_{SM}}$ is the total SM expectation. The total error on the SM expectation is given by the shaded band.

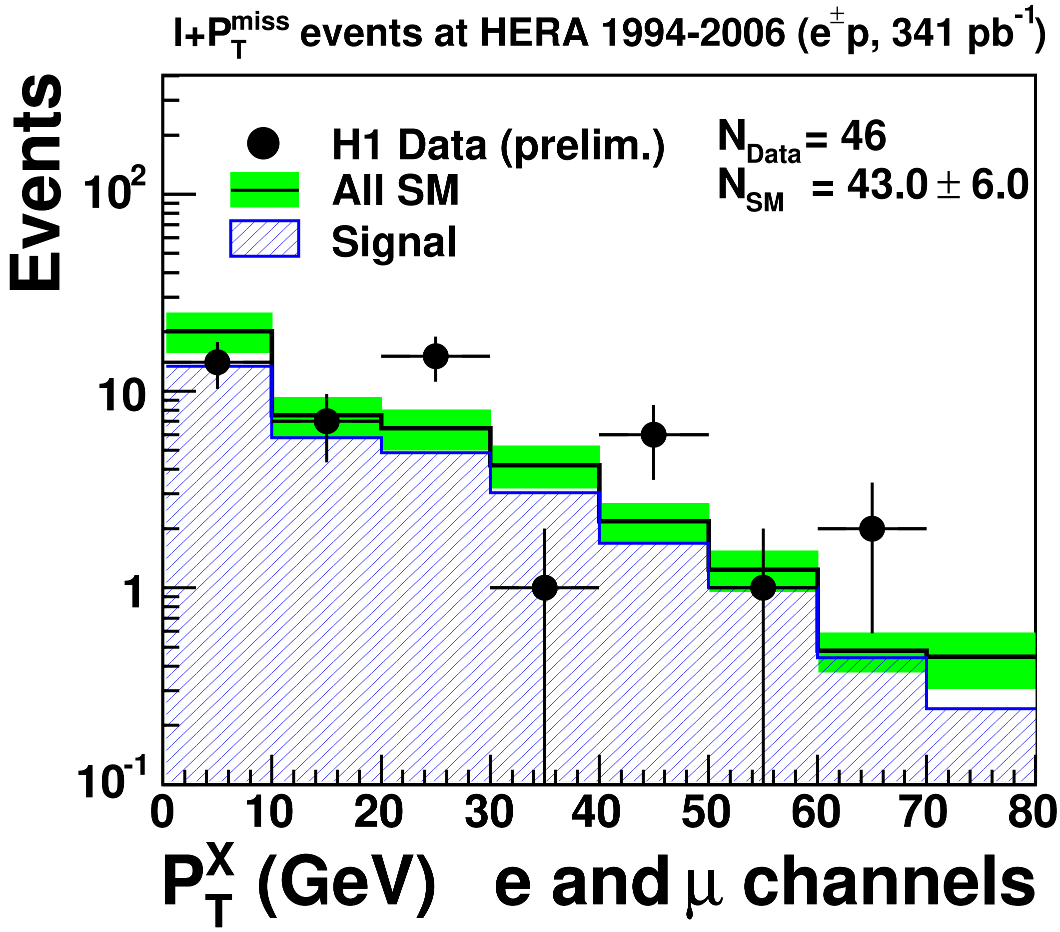

Figure 6: The hadronic transverse momentum distribution in the electron and muon channels combined: data ($e^{\pm}p$, $\mathcal{L} = 341$ pb^{-1}) is compared to the SM expectation (open histogram). The signal component of the SM expectation, dominated by real W production, is given by the hatched histogram. $\mathrm{N_{Data}}$ is the total number of data events observed, $\mathrm{N_{SM}}$ is the total SM expectation. The total error on the SM expectation is given by the shaded band.

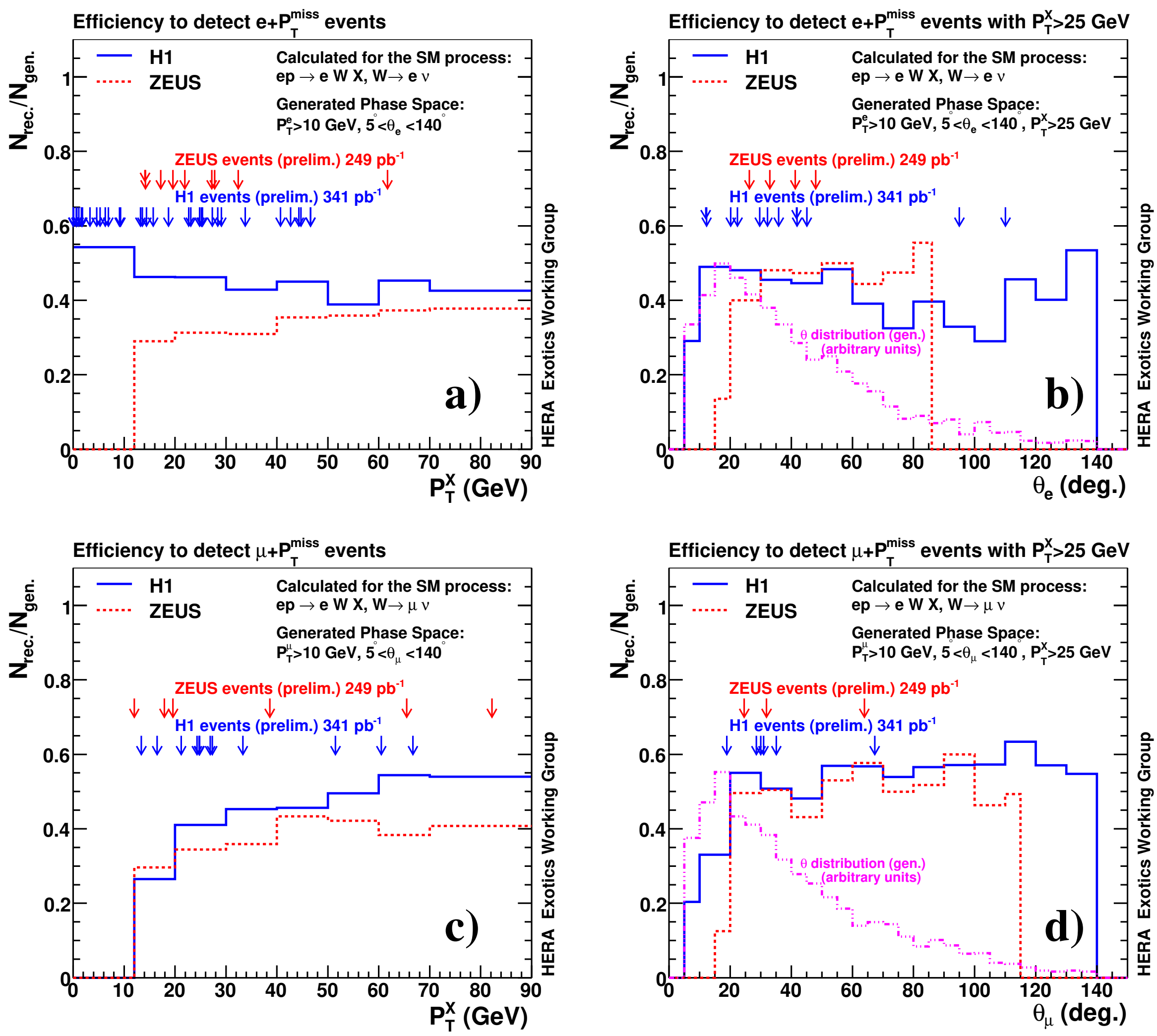

Figure 7: Comparisons of the efficiencies of the H1 and ZEUS analyses to select events containing isolated electrons or muons and missing transverse momentum. Figure a) displays the efficiency, defined as N_{rec} / N_{gen}, as a function of hadronic transverse momentum P_T^X in the electron channel. Figure b) displays the efficiency in the electron channel at large $P_T^X > 25$ GeV as a function of electron polar angle. Figure c) displays the efficiency as a function of hadronic transverse momentum P_T^X in the muon channel. Figure d) displays the efficiency in the muon channel at large $P_T^X > 25$ GeV as a function of muon polar angle. In all figures the H1 (ZEUS) efficiency is given by the solid (dashed) line. The data events observed by each experiment are indicated by the arrows. The θ_l distribution from EPVEC is also shown in figures b) and d).