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W production in $e^{\pm}p$ collisions at HERA

H1 Collaboration

Abstract

A search for W boson production in the process $ep \to eWX$ has been performed at the electron-proton collider HERA using an integrated luminosity of 36.5 pb^{-1} in e^+p scattering and 12.8 pb^{-1} in e^-p scattering. The analysis extends to new regions of phase space compared with previous results, covering the kinematic region $P_T^X > 0$ (12) GeV for the electron (muon) W decay channel. The tau and hadronic decays of the W are also explored. Eight events are seen in the electron and muon decay channels consistent with the topological criteria associated with W decay. The rate of W production in the electron decay channel is consistent with the expectation of the Standard Model in both e^+p and e^-p interactions. In the muon decay channel the rate of W production in e^+p interactions is consistent with the expectation of the Standard Model for $P_T^X < 40$ GeV, but is higher than expected for $P_T^X > 40$ GeV. In e^-p interactions the rate of W production in the muon decay channel is consistent with the expectation of the Standard Model. No signal is established for W production in the tau or hadronic channels.

1 Introduction

The HERA collaborations have recently reported [1, 2] the observation of events with high P_T isolated leptons and missing transverse momentum in e^+p collisions during the period 1994-7. A search for such events in e^-p collisions during the period 1998-9 is reported in [3]. Within the Standard Model such events can be interpreted as leptonic W decay. In the e^+p data sample H1 has reported [1] one e^- event and 5 $\mu^\pm$ events compared to expectations from the Standard Model of 2.4$\pm$0.5 and 0.8$\pm$0.2 for the $e^\pm$ and $\mu^\pm$ decay channels respectively, which are dominated by W production. For the same data taking period ZEUS has reported [2] 3 (0) e^+ ($\mu^\pm$) events compared to an expectation of 2.0 (0.6) W events and 1.0 ± 0.5 (0.6 ± 0.2) background events for the $e^\pm$ ($\mu^\pm$) decay channel.

In this paper we present results of a new search using the 36.5$\pm$1.1 pb^{-1} of e^+p data (1994-7) and 12.8$\pm$0.4 pb^{-1} of e^-p data (1998-9), which has been developed to maximise the acceptance of W boson production in the processes $e^\pm p \to e^\pm W X$, $W \to e\nu$ or $W \to \mu\nu$. In the e^+p data sample, we also extend the analysis to the tau and hadronic W decay channels, which are investigated for the first time at HERA.

This paper is organised as follows. Section 2 describes the Standard Model processes that contribute signal and background. Section 3 describes the H1 detector and experimental conditions. The selection requirements and the results for the electron[1] and muon decay channels are described in sections 4 and 5. The tau and hadron analyses are described in section 6. The paper is summarised in section 7.

2 Standard Model Processes

In this section the processes within the Standard Model that are expected to contribute to signal and background are outlined. These processes are described in detail in [1].

- W production

  The generator EPVEC [4] was used to calculate the Standard Model expectation for W production.

- Charged Current (CC) processes : $ep \to \nu X$

  A CC DIS event can mimic the topology of leptonic W decay events if a particle in the hadronic final state is misinterpreted as a candidate lepton from W decay. The generator DJANGO [5] was used to calculate this contribution.

- Neutral Current (NC) processes : $ep \to eX$

  The scattered electron in a NC DIS event can be misinterpreted as the lepton from W decay, but the missing transverse momentum can only be produced by fluctuations in the detector response to the final state particles, or by limited geometrical acceptance. The generator DJANGO [5] was used to calculate this contribution.

[1] In this paper "electron" refers generically to both electrons and positrons. Where distinction is required the terms e^- and e^+ are used.

- QCD Photoproduction (γp)

  This background contributes predominantly to the hadronic decay channel. The generator PYTHIA [6] was used to calculate this contribution. Production of heavy flavours was studied with the generator AROMA [7].

- Lepton pair production in two photon ($\gamma\gamma$) interactions

  Inelastic lepton pair production can mimic the topology of W events if one lepton escapes detection. The generator LPAIR [8] was used to calculate this contribution.

In order to determine acceptances and background contributions for the selected events, the detector response to events produced by the above programs is simulated in detail using a program based on GEANT [9]. The simulated events are then subjected to the same reconstruction and analysis chain as the real data.

3 Experimental Conditions

A detailed description of the H1 detector can be found in [10]. Only those components of particular importance to this analysis are described here.

Central and forward[2] tracking detectors consisting of drift chambers are used to measure the charged particle trajectories and to determine the interaction vertex. A magnetic field of 1.15 Tesla allows the measurement of the particle transverse momenta.

Electromagnetic and hadronic final state particles are absorbed in a highly segmented calorimeter [11], which is 5 to 8 interaction lengths deep depending on the polar angle of the particle.

The calorimeter is surrounded by a superconducting coil and an iron yoke instrumented with streamer tubes. Tracks of penetrating charged particles, such as muons, which escape the calorimeter are reconstructed from their hit pattern in the streamer tubes with an efficiency greater than 90%.

In the forward region of the detector two sets of three drift chamber layers (the forward muon system) detect muons. Also in the forward direction, around the beam-pipe, is the plug calorimeter which measures hadronic showers.

The LAr calorimeter is the main trigger for high transverse energy events. The trigger efficiency is $\approx 98\%$ for events with an electron which has transverse momentum above 10 GeV. For events with high missing transverse momentum, determined from an imbalance in energy measured in the calorimeter, P_T^{calo}, the efficiency is 98% when $P_T^{calo} > 25$ GeV and is 50% when $P_T^{calo} = 12$ GeV [12].

[2]The forward direction and the positive z-axis are taken to be that of the proton beam direction.

4 Selection of Electron and Muon W Decays

The selection of events where the W decays to an electron or muon is based on similar requirements to those used in the published isolated lepton analysis of the 1994-7 e^+p data [1], but has been adjusted to maximise the acceptance of W production events. This has allowed the selection to extend to lower values of transverse momentum P_T^X of the recoil hadron system X, where the W production cross section is expected to increase.

The main selection requirements are :

- a calorimetric missing transverse momentum $P_T^{calo} > 12$ GeV (cf. 25 GeV in [1]);
- a total missing transverse momentum $P_T^{miss} > 12$ GeV;
- an identified muon or electron with transverse momentum $P_T^l > 10$ GeV with polar angle in the range $5^o < \theta_l < 145^o$.

Further requirements are imposed to remove the large background arising from NC, CC, γp and $\gamma\gamma$ interactions. These are listed in tables 1 and 2 and are defined in terms of the quantities described below.

- $\delta_{miss} = 2E_e - \sum E_i(1 - \cos\theta_i)$, where E_i and θ_i denote the energy and polar angle of each detected particle in the event and E_e is the electron beam energy. For an event where only longitudinal momentum along the proton direction is undetected $\delta_{miss} = 0$.
- $\Delta\phi_{l-X}$, the difference in azimuthal angle between the lepton and the hadronic final state X.
- $\Delta\phi_{\nu-plug}$, the difference in azimuthal angle of the missing momentum (neutrino) and the hadronic energy deposits in the plug calorimeter. Background events can be produced with a large hadronic transverse momentum at low polar angle that is not measured in the main detector. This energy is, however, often tagged in the plug calorimeter, identifying such events by their low value of $\Delta\phi_{\nu-plug}$.
- V_{ap}/V_p, which is a measure of the isotropy of the event. It is defined as the ratio of the anti-parallel to parallel components of the measured transverse momentum, with respect to the direction of the missing transverse momentum [12].
- $\zeta_l^2 = 4E^l E_e \cos^2\theta_l/2$, where E^l is the energy of the final state lepton. For NC events, where the scattered electron is misinterpreted as a decay lepton from the W, ζ_l^2 is equal to the four momentum transfer squared Q^2. Since the NC cross section falls steeply with Q^2, these events generally have small values of ζ_l^2. Conversely, leptons from W decay have high values of ζ_l^2.

The isolation of high-P_T tracks with respect to other tracks in the event or with respect to jets, is quantified using:

- their distance D_{jet} to the closest hadronic jet in the pseudorapidity-azimuth plane (η - ϕ), defined by $D_{jet} = \sqrt{(\Delta\eta_{track-jet})^2 + (\Delta\phi_{track-jet})^2}$ (for this purpose jets are reconstructed using an inclusive k_T algorithm [13, 14] with $R < 1$ and $E_T^{min} = 5$ GeV);
- their distance D_{track} to the closest track in η - ϕ, defined in an analogous way to D_{jet}, where all tracks with a polar angle greater than 5^o are considered.

The dominant background source in the electron decay channel arises from NC events which have significant P_T^{calo} due to fluctuations in the measurement of the final state particles. To reduce this background, events with NC topology (isotropic and with the lepton and hadronic system diametrically opposite in the transverse plane) are rejected. For low values of ζ_l^2, where the NC background is largest, the requirements on the isotropy and acoplanarity are tightened. A further requirement that the lepton candidate be isolated from the hadronic final state is imposed to reject CC events.

The dominant backgrounds in the muon decay channel are due to photoproduction events which contain a muon, the inelastic $\gamma\gamma$ production of muon pairs, and NC events. The final sample is selected by rejecting isotropic events and events where more than one muon is observed. Elastic lepton pair production is suppressed by rejecting events which have low track multiplicities and where the muon is found to be opposite in azimuth to the hadron system.

To verify that the backgrounds that contribute to the two channels are well understood, event samples are defined according to less stringent criteria (see tables 1 and 2). The events thus selected in the e^+p data sample are shown in figure 1 for the electron decay channel and figure 2 for the muon decay channel. Also included in the figures is the Standard Model expectation and the expectation from W production alone. All quantities that are used for the final selection cuts are found to be well described in both shape and normalisation by the Standard Model expectation. Similar agreement between the data and simulation is obtained for the e^-p data sample.

The final selection requirements for the electron decay channel and muon decay channel are given in tables 1 and 2 respectively.

Following these selection criteria the acceptances as a function of P_T^X are shown in table 3. These acceptancies were calculated using the EPVEC generator for W production. The overall efficiency to select $W \to e\nu$ events is 46% and to select $W \to \mu\nu$ events is 18%. The difference in acceptance between the two channels is due to the cut on P_T^{calo} which acts as a cut on P_T^X because the muon deposits little energy in the calorimeter. There is thus little acceptance in the muon decay channel for $P_T^X < 12$ GeV. For values of $P_T^X > 12$ GeV the acceptances of the two decay channels are comparable.

5 Results in the Electron and Muon Decay Channels

For the e^+p data sample after all selection requirements 3 candidate events are observed in the $W \to e\nu$ channel compared to 2.24 ± 0.67 expected from W production and 0.88 ± 0.19 from background sources. For the e^-p data sample 0 events are observed compared to 0.95 ± 0.28 expected from W production and 0.64 ± 0.14 from background sources.

In the e^+p data sample the electron in one of the candidate events is measured to have negative charge. This event was first reported and discussed in [1]. The charges of the electrons in the other two events are unmeasured since the electrons are produced at low polar angles and they shower in dead material in the tracking detectors.

Details of the dependence of the event rate for the e^+p (e^-p) data sample as a function of the transverse momentum of the hadronic final state, P_T^X, are given in table 4 (5). The three $W \to e\nu$ candidates are seen at low P_T^X, as expected for Standard Model W production.

For the e^+p data sample in the $W \to \mu\nu$ channel 5 candidate events are observed compared to 0.87 ± 0.26 expected from W production and 0.14 ± 0.09 from other Standard Model sources. For the e^-p data sample 0 events are observed compared to 0.35 $\pm$ 0.11 expected from W production and 0.06 $\pm$ 0.03 from other Standard Model sources.

The 5 muon events observed in the e^+p data sample are those first reported and discussed in [1]. Details of the dependence of the event rate for the e^+p (e^-p) data sample as a function of P_T^X are given in table 6 (7). All five $W \to \mu\nu$ candidates are seen at $P_T^X > 25$ GeV, and three of the events are seen at $P_T^X > 40$ GeV where the expection for Standard Model W production is very low.

6 Tau and Hadronic W Decay Channels

These two decay channels are investigated only for the e^+p data sample.

6.1 Tau decay channel selection

A search is performed for $W \to \tau\nu$ events in the hadronic "1-prong" decay channel of the tau. Tau candidates are selected by requiring an isolated track with transverse momentum greater than 4 GeV which is associated with a narrow hadronic shower pattern. The track itself must be measured within the polar range $25^o < \theta_{track} < 145^o$ to keep it within the acceptance of the central tracking detectors. Cuts against background are applied in a manner similar to the other leptonic decay channels and are listed in table 8.

Five events are found and 3.80$\pm$0.88 are expected from Standard Model contributions of which 3.56$\pm$0.87 are from processes other than W production. The large background arises mainly from CC events where a hadronic jet contains only one reconstructed charged particle. The distributions in P_T^X of the data and of the expectation from the Standard Model are shown in figure 3. All events are found to be at low values of P_T^X, consistent with the expectation from the background processes.

6.2 Hadronic decay channel selection

The process searched for is $e^+p \to e^+WX$, $W \to q\bar{q}$. Events are selected with at least two high-P_T jets, defined using the inclusive k_T algorithm, in the pseudo-rapidity range $-0.5 < \eta < 2.5$.

The hadronic system must be balanced in P_T, so that $P_T^{miss} < 20$ GeV. The jets are ordered in transverse momentum with the requirements that $P_{T_1} > 25$ GeV, $P_{T_2} > 15$ GeV and, if there is a third jet, $P_{T_3} > 10$ GeV. The invariant dijet mass is formed from all possible combinations of two jets and is shown in figure 4(a). In three jet events three combinations are possible and each is included in figure 4(a). For these events the jet that is not included in each dijet combination is taken to be the hadronic recoil system X. The invariant mass distributions for dijet combinations with $P_T^X > 25$ GeV and $P_T^X > 40$ GeV are shown in figures 4(b) and 4(c) respectively. The expectation from the Standard Model, which is dominated by QCD photoproduction, is in good agreement with the data.

The expected contribution from W production, although rising relative to the background with increasing P_T^X, is always much smaller than the other Standard Model processes. Combinatorial background from the three jet events in EPVEC gives rise to entries in the dijet mass spectrum which are far from the W mass. This effect becomes more pronounced for high values of the P_T^X cut, such that no W mass peak is visible. The large QCD photoproduction background is such that the present analysis procedure is not sensitive to W production even at high P_T^X. Without improvements in the analysis procedure which suppress the background by more than a factor of 10, such sensitivity cannot be achieved.

7 Summary

A search for W production events has been performed on an e^+p data sample corresponding to an integrated luminosity of 36.5$\pm$1.1 pb^{-1} and on an e^-p data sample corresponding to an integrated luminosity of 12.8$\pm$0.4 pb^{-1}. The selection has been optimised to increase the acceptance of W production events and it extends to lower values of transverse momentum P_T^X than have been previously explored.

Eight events are found in the e^+p data sample which are kinematically consistent with W production, 3 in the electron decay channel and 5 in the muon decay channel. One electron event and the 5 muon events were first reported and discussed in [1]. No events are found in the e^-p data sample.

The expected rates from the Standard Model are 3.12 ± 0.70 and 1.01 ± 0.28 for the electron and muon decay channels respectively in the e^+p data sample and 1.58 ± 0.32 and 0.41 ± 0.11 for the electron and muon decay channels respectively in the e^-p data sample. The 3 electron events in the e^+p data sample are observed at values of P_T^X less than 25 GeV, consistent with the expectation from the Standard Model for W production of a steeply falling cross section as a function of P_T^X. The rate of W production in the muon decay channel is consistent with the expected rate at low values of P_T^X including the new region of phase space $12 < P_T^X < 25$ GeV. At $P_T^X > 40$ GeV 3 events are observed compared to a Standard Model expectation of 0.31 (e^+ and e^- combined).

There is no evidence for hadronic or tau W decay in the samples selected.

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Selection	Quantity	Cut
Loose	P_T^{miss}	> 12 GeV
	P_T^{calo}	> 12 GeV
	P_T^e	> 10 GeV
	θ_e	$> 5^o$ and $< 145^o$
	V_{ap}/V_p	< 0.5
	$\Delta\phi_{e-X}$	$< 175^o$
	ζ_e^2	> 1000 GeV^2
Tight	δ_{miss}	> 10 GeV (if only one electron is detected)
	P_T^e OR V_{ap}/V_p	> 20 GeV < 0.15
	D_{jet}	> 1.0
	D_{track} OR D_{jet}	> 0.5 > 2.0
(For $\zeta_e^2 < 5000$ GeV^2)	$\Delta\phi_{\nu-plug}$	$> 20^o$
	V_{ap}/V_p	< 0.15
	$\Delta\phi_{e-X}$	$< 150^o$
	P_T^{miss}	> 20 GeV
(For $5000 < \zeta_e^2 < 10000$ GeV^2)	$\Delta\phi_{\nu-plug}$	$> 10^o$
	$\Delta\phi_{e-X}$	$< 170^o$
	P_T^{miss}	> 15 GeV

Table 1: Requirements to select $W \to e\nu$ candidate events. Cuts labelled "loose" are used for background studies. Events that pass the final selection must satisfy both "loose" and "tight" requirements. See main text for definitions of variables.

Selection	Quantity	Cut
Loose	P_T^{calo}	> 12 GeV
	P_T^{μ}	> 5 GeV
	θ_{μ}	$> 5^o$ and $< 145^o$
	D_{jet}	> 0.5
	D_{track}	> 0.5
Tight	P_T^{miss}	> 12 GeV
	P_T^{μ}	> 10 GeV
	V_{ap}/V_p	< 0.15
	$\Delta\phi_{\mu-X}$	$< 170^o$ (for ≤ 2 central tracks)
	# isolated μ	= 1

Table 2: Requirements to select $W \to \mu\nu$ candidate events. Cuts labelled "loose" are used for background studies. Events that pass the final selection must satisfy both "loose" and "tight" requirements. See main text for definitions of variables.

	Acceptance	
	e	μ
$P_T^X > 0$ GeV	0.46	0.18
$P_T^X > 12$ GeV	0.32	0.35
$P_T^X > 25$ GeV	0.26	0.33
$P_T^X > 40$ GeV	0.19	0.28

Table 3: Acceptances of the final selection for W decay in the electron and muon channels as a function of P_T^X. These acceptances were calculated with the EPVEC generator.

Electron	Data	SM expectation	W	Background
$P_T^X > 0$ GeV	3	3.12 $\pm$0.70	2.24 $\pm$0.67	0.88 $\pm$ 0.19
$P_T^X > 12$ GeV	1	1.15 $\pm$0.25	0.78 $\pm$0.23	0.37 $\pm$ 0.09
$P_T^X > 25$ GeV	0	0.50 $\pm$0.12	0.38 $\pm$0.11	0.12 $\pm$ 0.03
$P_T^X > 40$ GeV	0	0.16 $\pm$0.04	0.14 $\pm$0.04	0.03 $\pm$ 0.01

Table 4: Observed and predicted event rates in the electron decay channel for e^+p data.

Electron	Data	SM expectation	W	Background
$P_T^X > 0$ GeV	0	1.58 $\pm$0.32	0.95 $\pm$0.28	0.64 $\pm$ 0.14
$P_T^X > 12$ GeV	0	0.61 $\pm$0.12	0.35 $\pm$0.10	0.26 $\pm$ 0.06
$P_T^X > 25$ GeV	0	0.25 $\pm$0.06	0.18 $\pm$0.05	0.07 $\pm$ 0.02
$P_T^X > 40$ GeV	0	0.12 $\pm$0.03	0.08 $\pm$0.02	0.05 $\pm$ 0.01

Table 5: Observed and predicted event rates in the electron decay channel for e^-p data.

Muon	Data	SM expectation	W	Background
$P_T^X > 12$ GeV	5	1.01 $\pm$ 0.28	0.87 $\pm$ 0.26	0.14 $\pm$ 0.09
$P_T^X > 25$ GeV	5	0.56 $\pm$ 0.15	0.49 $\pm$ 0.15	0.07 $\pm$ 0.04
$P_T^X > 40$ GeV	3	0.21 $\pm$ 0.06	0.19 $\pm$ 0.06	0.02 $\pm$ 0.01

Table 6: Observed and predicted event rates in the muon decay channel for e^+p data.

Muon	Data	SM expectation	W	Background
$P_T^X > 12$ GeV	0	0.41 $\pm$ 0.11	0.35 $\pm$ 0.11	0.06 $\pm$ 0.03
$P_T^X > 25$ GeV	0	0.24 $\pm$ 0.07	0.21 $\pm$ 0.06	0.03 $\pm$ 0.02
$P_T^X > 40$ GeV	0	0.11 $\pm$ 0.03	0.10 $\pm$ 0.03	0.01 $\pm$ 0.01

Table 7: Observed and predicted event rates in the muon decay channel for e^-p data.

Quantity	Cut
P_T^{calo}	> 12 GeV
P_T^{miss}	> 12 GeV
θ_{track}	$> 25^o$ and $< 145^o$
D_{track}	> 1.0
V_{ap}/V_p	< 0.3
$\Delta\phi_{\nu-plug}$	$> 10^o$
$\Delta\phi_{track-X}$	$< 175^o$
P_T^{calo} OR V_{ap}/V_p	> 20 GeV < 0.15
# τ	= 1
# isolated μ	= 0

Table 8: Requirements to select $W \rightarrow \tau\nu$ candidate events. See main text for definitions of variables.

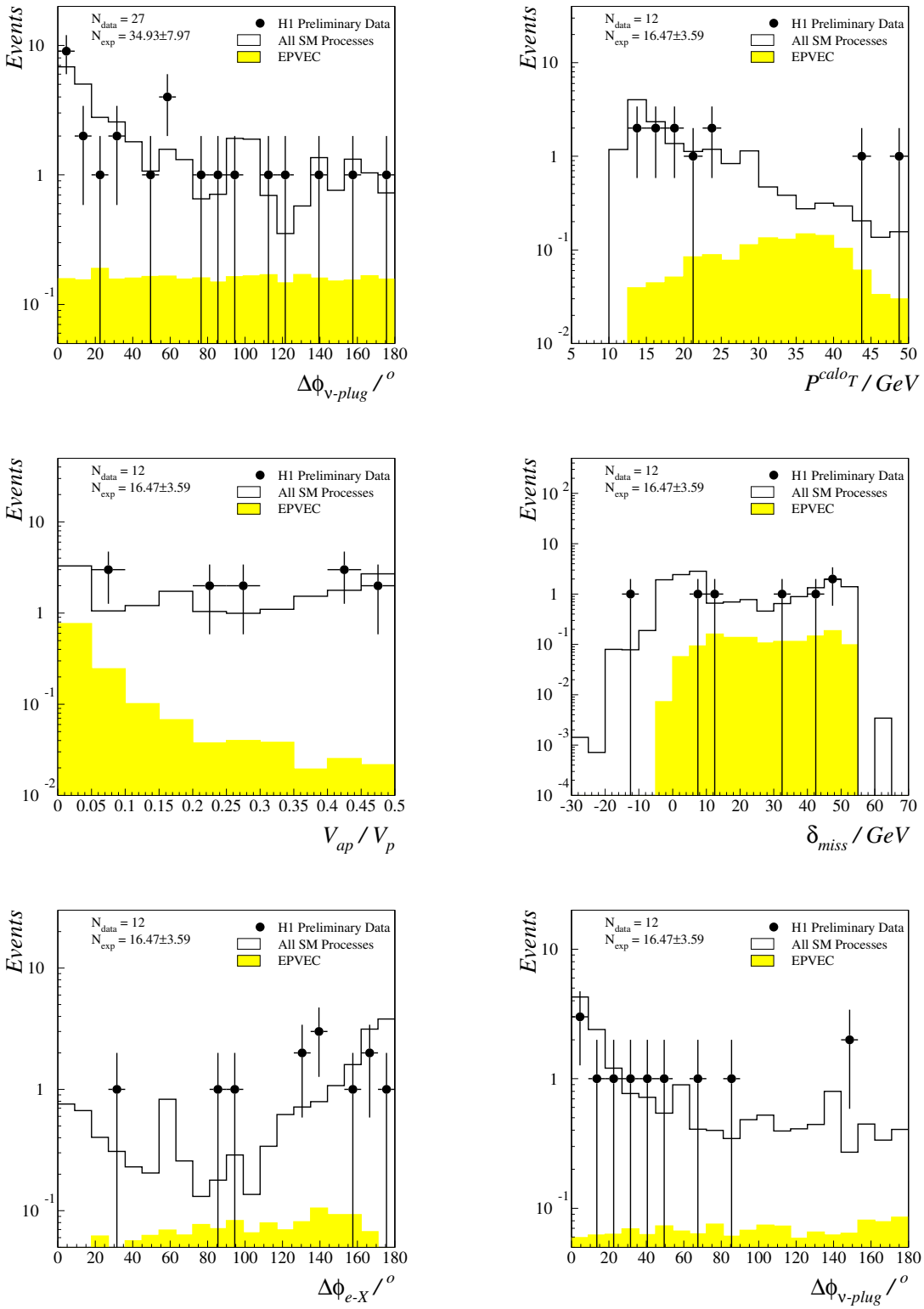

Figure 1: A comparison of the e^+p data selected with the loose requirements (see table 1) in the electron decay channel compared to the combined Standard Model expectation (open histogram). The W production component of the Standard Model expectation is given by the shaded histogram.

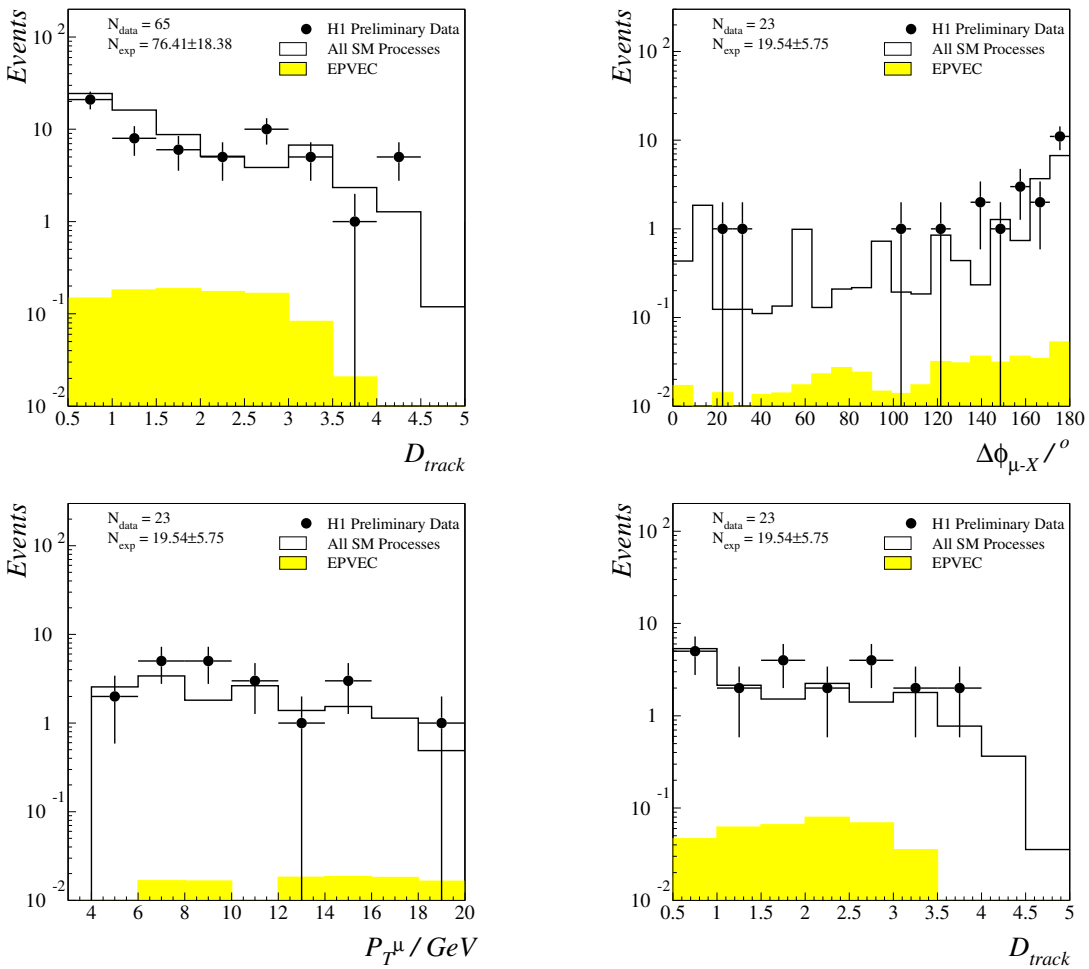

Figure 2: A comparison of the e^+p data selected with the loose requirements (see table 2) in the muon decay channel compared to the combined Standard Model expectation (open histogram). The W production component of the Standard Model expectation is given by the shaded histogram.

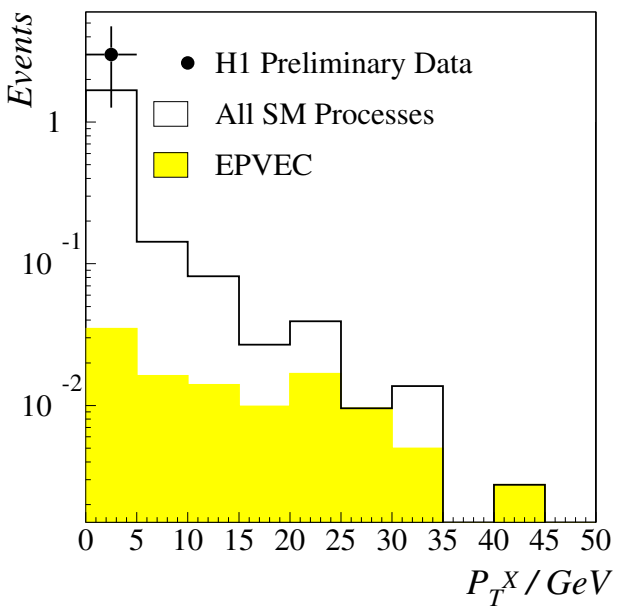

Figure 3: The distribution in P_T^X of the e^+p data with the tau selection compared to the combined Standard Model expectation (open histogram). The W production component of the Standard Model expectation is given by the shaded histogram.

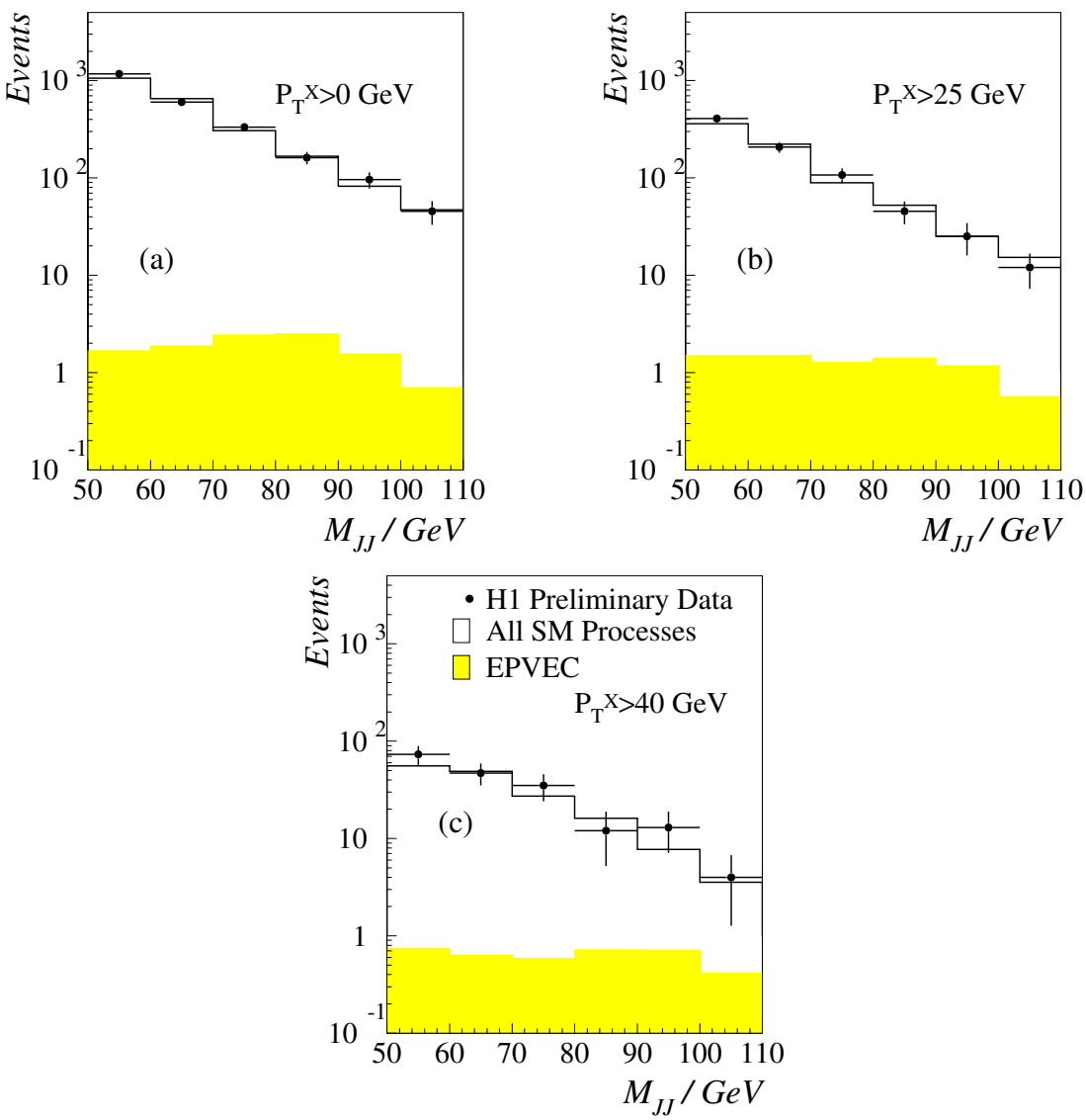

Figure 4: The invariant dijet mass distribution in the e^+p data for various ranges in the transverse momentum of the third jet P_T^X compared to the combined Standard Model expectation (open histogram). The W production component of the Standard Model expectation is given by the shaded histogram.