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Search for W production using the electron decay-channel in e^+p collisions at HERA I

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Abstract

A search for the process $e^+p \to WX$, with the subsequent decay $W \to e\nu_e$, was performed using 66 pb^{-1} of e^+p collision data taken with the ZEUS detector during the 1999-2000 running period. The process leads to final states characterised by isolated high transverse energy electrons and large missing transverse momentum $\not{P}_T$. In some cases a hadronic jet from the struck quark is observed. The analysis is performed for final states containing isolated electrons. The results have been used to constrain the cross section for $e^+p \to e^+WX$.

1 Introduction

This paper reports the results of an investigation of the production of W bosons in positron-proton collisions at center-of-mass energy of 318 GeV at HERA. Single W production is a rare Standard Model (SM) process and an important source of background to searches for physics beyond the Standard Model [1, 2]. Investigations of the process $ep \to eWX, W \to l\nu$, where $l = \mu, e$, have been performed at HERA by both the H1 [2,3] and ZEUS [1, 4] collaborations. H1 observes an excess of events with isolated muons or electrons[1] and high missing transverse momentum over the SM prediction, dominated by single W production. The ZEUS results based on searches for isolated electrons and muons at center-of-mass energy of 300 GeV do not confirm this excess. This paper reports the results of a similar search using the larger sample of data taken by ZEUS in the 99-00 running period.

The dominant leading order Feynman diagrams for single W production at HERA are shown in Figure 1. In the electron decay-channel of the W, the event topology contains an isolated electron with high transverse momentum (P_T) and missing total P_T arising from the escaping neutrino. If the negative of the four-momentum transfer squared (Q^2) is greater than a few GeV^2, the scattered electron can be observed in the detector.

The study was performed by selecting events containing well isolated high p_T electrons, and large missing total P_T. The data set corresponds to the 1999-2000 running period, with a total integrated luminosity of 66 pb^{-1}.

2 Monte Carlo simulation of the signal $e^+p \to e^+WX$ and of the background

The leading order (LO) cross section for $e^+p \to e^+WX$ has been calculated using the EPVEC generator [5]. EPVEC calculates the cross section in two regions, corresponding to photoproduction and deep inelastic scattering, which are separated by a cut on the variable u, defined as $(p_q - p_W)^2$, where p_q and p_W are the 4-momenta of the initial state quark and of the W, respectively. The photon (proton) structure functions used in the calculation are GRV-G(LO) (CTEQ4D). The final state simulation does not include hard gluon radiation.

Such calculations yield a total cross section of 0.945 pb for $\sqrt{s}$ =300 GeV and 1.09 pb for $\sqrt{s}$ = 320 GeV. The uncertainties on this value are approximately 5% for the choice of u_{cut} (set at 25 GeV^2), 5% for the choice of proton structure function, 10% for photon

[1] In this paper "electron" refers both to electrons and positrons unless specified.

structure function and 10% from the choice of Q^2 scale [6] used in EPVEC. Next-to-leading order corrections were calculated in [7] and were found to be of the order of 10%; they were however neglected in this analysis.

The most important background to W production in the electron decay-channel arises from high Q^2 charged and neutral current deep inelastic scattering (DIS) events. These DIS events have been simulated using the generator DJANGO6 [8], an interface to the Monte Carlo (MC) programs HERACLES 4.5 [9] and LEPTO 6.5 [10]. Leading order QCD and electroweak radiative corrections were included and higher order QCD effects were simulated via parton cascades using the colour-dipole model ARIADNE [11] or parton shower based on a leading-logarithm approximation (MEPS). The hadronisation of the partonic final state was performed by JETSET [12]. Minor contributions to the background come from two-photon processes which were simulated using the GRAPE [13] dilepton generators and direct and resolved photoproduction processes which were simulated using the HERWIG 6.1 [14] event generator.

The generated events were passed through the GEANT-based [15] ZEUS detector and trigger simulation programs [16]. They were reconstructed and analysed by the same program chain as the data.

3 The ZEUS detector

A detailed description of the ZEUS detector can be found elsewhere [16]. The main components used in this analysis were the compensating uranium-scintillator calorimeter and the central tracking detector.

The high-resolution uranium–scintillator calorimeter (CAL) [17] consists of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part is subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections (HAC). The smallest subdivision of the calorimeter is called a cell. The CAL energy resolutions, as measured under test-beam conditions, are $\sigma(E)/E = 0.18/\sqrt{E}$ for electrons and $\sigma(E)/E = 0.35/\sqrt{E}$ for hadrons (E in GeV).

Charged particles are tracked in the central tracking detector (CTD) [18], which operates in a magnetic field of 1.43 T provided by a thin superconducting coil. The CTD consists of 72 cylindrical drift chamber layers, organized in 9 superlayers covering the polar-angle[2] region $15^\circ < \theta < 164^\circ$. The transverse-momentum resolution for full-length tracks is $\sigma(p_T)/p_T = 0.0058 p_T \oplus 0.0065 \oplus 0.0014/p_T$, with p_T in GeV.

A three-level trigger was used to select events online [19] requiring large missing P_T. Algorithms based on the tracking rejected non-ep collisions consisting mainly of proton beam-gas interactions.

4 Event Reconstruction and Data Selection

The missing transverse momentum is defined as:

$$P_T = \sqrt{(\sum_i p_{X,i})^2 + (\sum_i p_{Y,i})^2},$$

where $p_{X,i} = E_i \sin\theta_i \cos\phi_i$ and $p_{Y,i} = E_i \sin\theta_i \sin\phi_i$ are calculated using the energies (E_i) of individual calorimeter cells that are above noise thresholds of 80 MeV (EMC) and 140 MeV (HAC). The angles θ_i and ϕ_i are estimated from the geometric cell centres and the event vertex. In $W \to e\nu$ events, P_T as defined above is an estimate of the missing transverse momentum carried by the neutrino.

Electron (hadron) transverse momenta are defined as sums over those calorimeter cells that are (are not) assigned to the electron candidate cluster. Longitudinal momentum conservation ensures that $E - p_z$ (δ), defined as:

$$E - p_z = \sum_i E_i (1 - \cos\theta_i),$$

peaks at twice the electron beam energy E_e for fully contained events. Small values of δ are expected for proton-gas interactions. Values much greater than $2E_e = 55$ GeV are usually caused by the superposition of a neutral current DIS event with additional energy deposits in the RCAL not related to ep collisions. Only events with $5 < \delta < 60$ GeV were chosen in the preselection.

The acoplanarity angle Φ_{ACOP}, illustrated in Fig. 2 is the azimuthal separation of the outgoing lepton and the vector in the $\{X, Y\}$ plane, that balances the hadronic-P_T vector. For well measured neutral current events, the acoplanarity angle is close to zero, while

[2] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the "forward direction", and the X axis pointing left towards the center of HERA. The coordinate origin is at the nominal interaction point. The pseudorapidity is defined as $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$, where the polar angle, θ, is measured with respect to the proton beam direction.

large acoplanarity angles indicate large missing energies. The transverse mass is defined as:

$$M_T = \sqrt{2P_T^l P_T^\nu (1 - \cos \Phi^{l\nu})},$$

where P_T^l is the lepton transverse momentum, P_T^ν is the magnitude of the P_T and $\phi^{l\nu}$ is the azimuthal separation of the lepton and the P_T vectors as shown in Fig 2.

Events that pass the trigger requirements are further required to have a P_T greater than 9 GeV. The transverse momentum calculated excluding the inner ring of calorimeter cells around the forward beam pipe hole, must also be greater than 9 GeV. These offline cuts are more stringent than the corresponding online trigger thresholds. Other pre-selection cuts are the requirement that the Z-coordinate of the tracking vertex be reconstructed within 50 cm of the nominal interaction point and that there is at least one associated track with transverse momentum greater than 0.2 GeV with a polar angle in the range $15^\circ < \theta < 165^\circ$. Cuts on the calorimeter timing and algorithms based on the pattern of tracks in the CTD reject beam-gas, cosmic-ray and halo-muon events.

5 Search for W production and the decay $W \to e\nu$

A neural-network-based algorithm to identify electrons, trained on Monte Carlo events and optimised for maximum electron-finding efficiency and electron-hadron separation, selects candidate electromagnetic clusters in the calorimeter [20]. A cut on the electromagnetic cluster energy is made at 8 GeV, above which the neural network is fully efficient, except at the boundaries between different calorimeter parts. The impact point at the face of the calorimeter is determined with a resolution of 1 cm using the pulse height information from the pairs of photomutipliers reading out each cell. The distance of closest approach of a matching extrapolated CTD track to the electromagnetic cluster is required to be less than 10 cm; only tracks with $15^\circ < \theta < 165^\circ$ are considered. The background from fake electrons is reduced by requiring that the energy not associated with the electron in an $\{\eta, \phi\}$ cone of radius 0.8 around the electron direction, be less than 4 GeV. In addition, since most fake electrons are misidentified hadrons close to jets, the background is further reduced by requiring that the electron track be separated by at least 0.5 units in $\{\eta, \phi\}$ space from the other tracks associated with the event vertex.

The data are compared to the expectation from the Monte Carlo simulation in Fig 3, after requiring that the transverse momentum of the electron P_T^e be greater than 5 GeV and the polar angle of the electron measured in the calorimeter, θ_e, be less that 2.0 rad. Neutral current background events dominate the sample at this stage of the selection, as is evident from the steeply falling P_T spectrum and the concentration of events at small acoplanarity angles. A Jacobian peak structure is visible in the transverse mass distribution for the Monte Carlo simulation of the signal events.

The neutral current background is strongly suppressed by requiring the P_T to be greater than 20 GeV and the acoplanarity angle to be greater than 0.3 rad. The latter cut is applied only to events with a hadronic transverse momentum (P_T^X) in excess of 4 GeV, for which the acoplanarity is well defined. Electrons in the final event sample must have $P_T^e > 10$ GeV and $\theta_e < 1.5$ rad. Finally, requiring that the matching electron track have a transverse momentum greater than 5 GeV, as measured in the CTD, removes most of the remaining fake electrons.

Five data events survive these final cuts, their properties are outlined in table 1. The highest transverse mass candidate is shown in Figure 4. The expectation for W production from EPVEC Monte Carlo is 3.2 ± 0.1 (Stat.) $^{+1.1}_{-1.0}$ (Syst.) events corresponding to an efficiency of selecting decays of the W in the electron channel of 39%. From other SM processes 3.5 ± 0.6 (Stat.) $^{+1.7}_{-1.6}$ (Syst.) events are expected. The program described in [21], using Feldman-Cousins ordering, was used to extract a 95% confidence limit on the total cross section for single W production of:

$$\sigma(e^+p \to e^+WX) < 2.8 \text{ pb},$$

a stronger limit than that obtained in [4].

The systematic effects on the background and signal expectations considered were:

- Using the electron finder described in [22], rather than the neural network based finder.
- Using the MEPS model instead of the Ariadne model for hadronisation in the background simulation.
- Varying the absolute energy scale of the CAL by $\pm 1.5\%$.

The dominant systematic effect on signal efficiency arose from using the alternative electron finder. In the case of the background, the dominant systematic uncertainy arose from the choice of hadronisation model.

6 Summary

A search was made for the decay in the electron channel of singly produced W bosons at HERA in electron-proton collisions at centre-of-mass energies of 318 GeV using an integrated luminosity of 66.3 pb^{-1}. A sample of events characterized by large P_T and isolated high-p_T electrons was selected. A 95% confidence limit was extracted on the total single W production cross section of:

$$\sigma(e^+p \to e^+WX) < 2.8 \text{ pb}.$$

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Candidate	1	2	3	4	5
electron polar angle (rad)	1.33	1.02	1.33	0.38	0.58
P_T^e (GeV)	20.3	33.5	52.8	28.0	30.6
hadronic P_T^X (GeV)	9.3	17.0	35.2	2.82	29.4
missing P_T (GeV)	25.2	20.0	25.1	29.2	48.4
transverse mass (GeV)	44.9	50.4	69.0	57.2	73.5

Table 1: *The properties of the five surviving events in the search for W production candidates.*

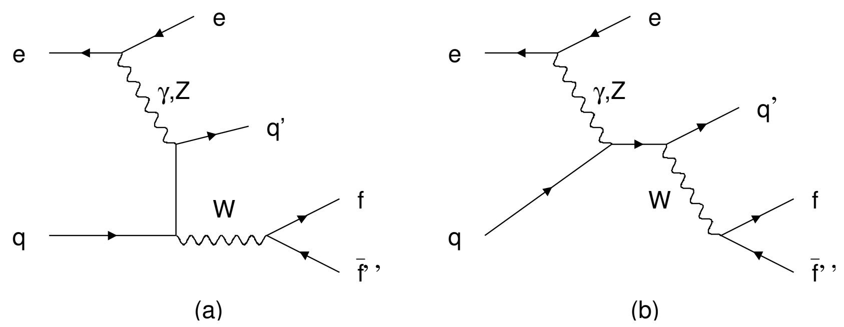

Figure 1: *Main leading order Feynman diagrams for the process $ep \to eWX$.*

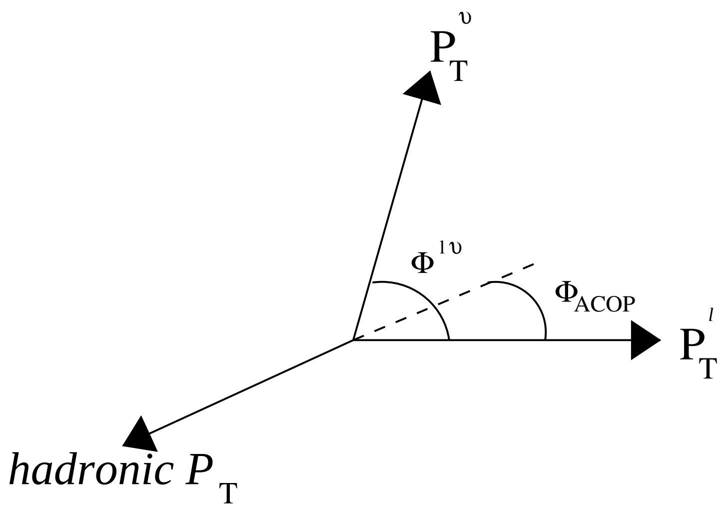

Figure 2: *The definition of the acoplanarity angle, $\Phi_{\rm ACOP}$, and the azimuthal separation of the neutrino and the outgoing lepton, $\Phi^{l\nu}$, in the transverse plane. The dashed line balances the hadronic P_T.*

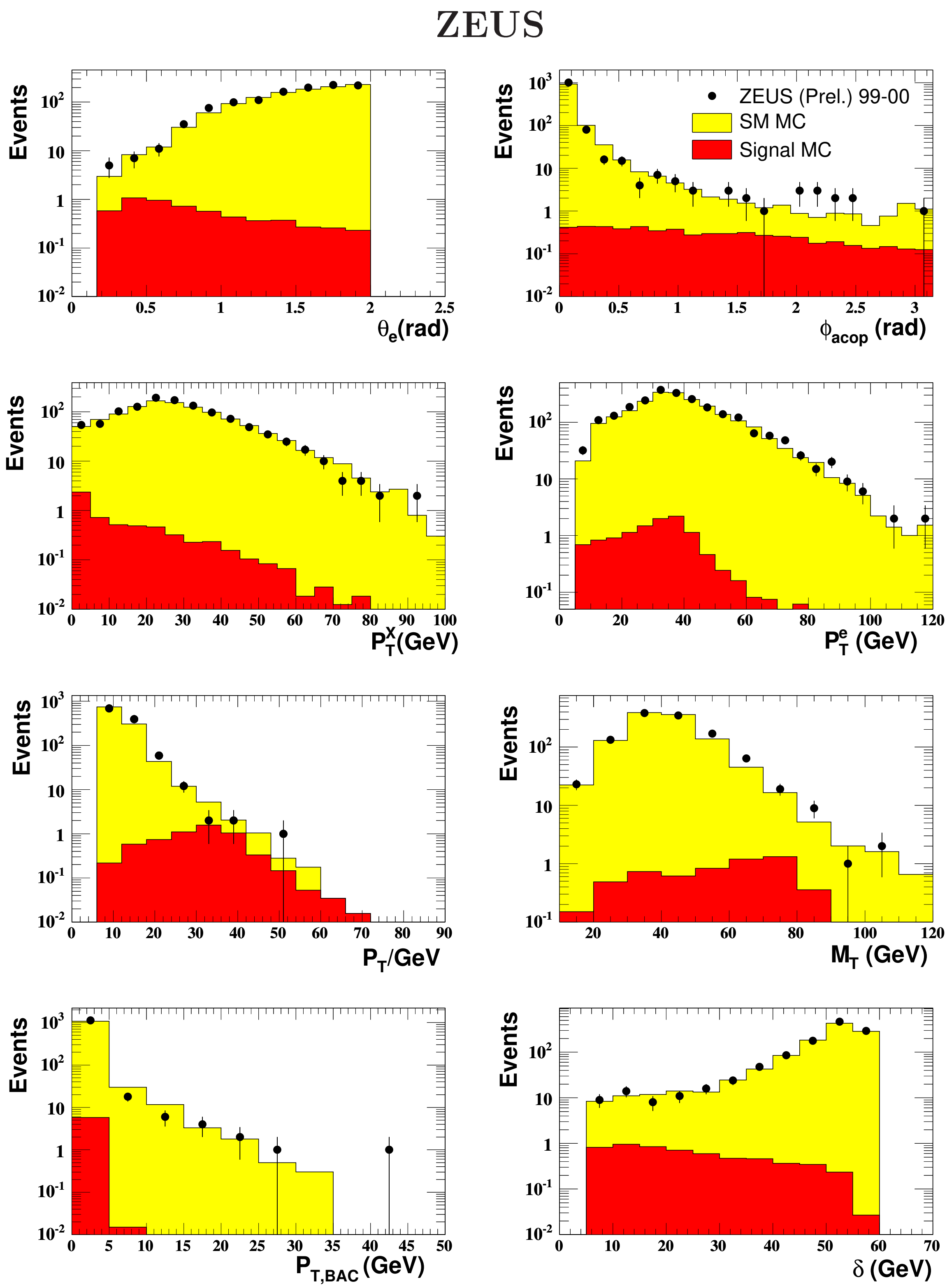

Figure 3: *Data (points) compared to luminosity-normalised Monte Carlo. The light shaded histogram represents the Standard Model (SM) MC prediction, the dark shaded area the signal ($e^+p \rightarrow e^+WX$) prediction. The variables shown are described in detail in the text.*

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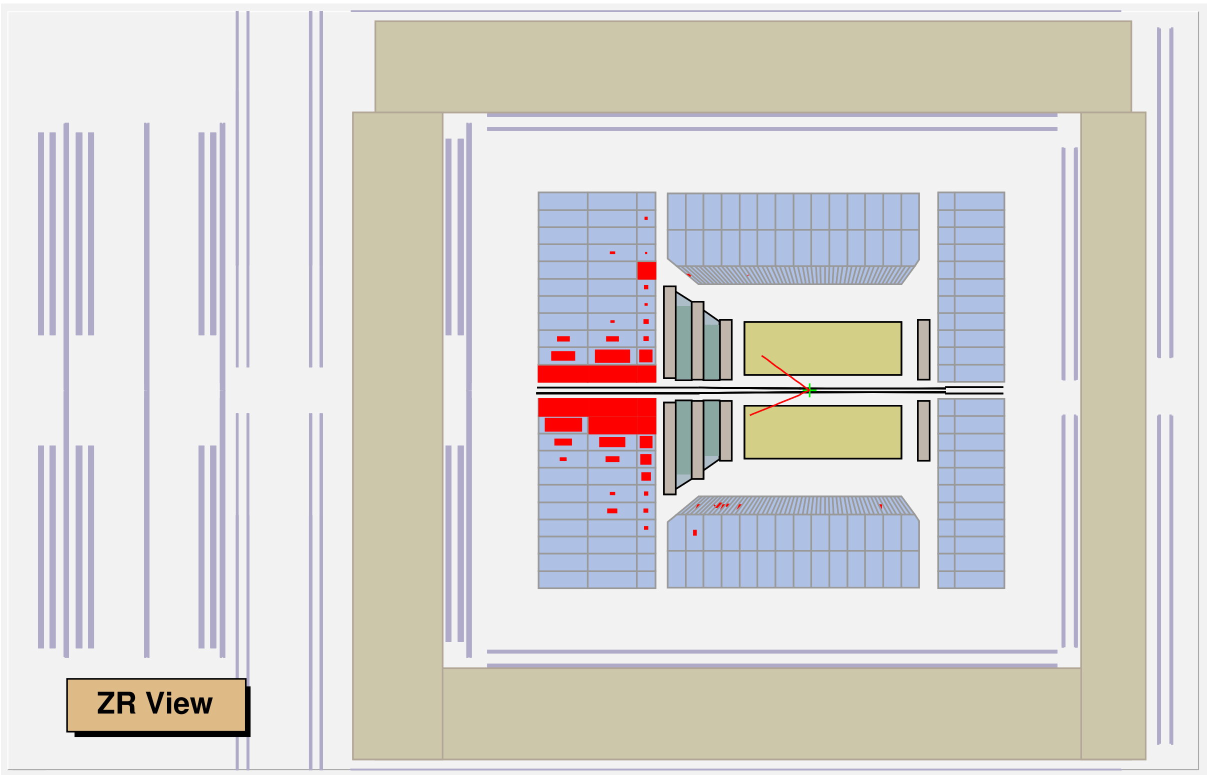

Figure 4: *An isolated electron candidate event that survives the final selection. This event is candidate 5 from table 1.*