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Search for events with high-P_T isolated electrons and missing transverse momentum in ep collisions at HERA I and HERA II

ZEUS Collaboration

Abstract

A search for events with isolated high transverse energy electrons and large missing transverse momentum has been performed with the ZEUS detector at HERA using data samples with integrated luminosities of 66 pb^{-1} and 40 pb^{-1} taken during the 1999-2000 and 2003-2004 running periods respectively. The results are compared to the Standard Model predictions.

1 Introduction

This paper reports the results of an investigation of the production of isolated electrons[1] in events with a topology matching the electron decay channel of singly produced W bosons in positron-proton collisions at a centre-of-mass energy of 318 GeV. 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 $l = \mu, e, \tau$, have been performed at HERA by both the H1 [2–4] and ZEUS [1, 5–7] collaborations. The H1 collaboration observes an excess of events with isolated muons or electrons, high missing transverse momentum and large values of hadronic transverse momentum over the SM prediction, dominated by single W production. The ZEUS results based on searches for isolated electrons and muons at a centre-of-mass energy of 300 GeV and 318 GeV do not confirm this excess. The search described in this paper was designed to be more closely comparable to the H1 analysis than previous ZEUS searches.

The dominant leading order Feynman diagrams for single W production at HERA are shown in Fig. 1. In the electron decay-channel of the W, events typically contain an isolated electron with high transverse momentum, P_T^e, and missing total tranverse momentum, $\not{P}_T$, 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 isolated electrons with high P_T^e , in events with large missing P_T. The data set corresponds to the 1999-2000 e^+p running period, with a total integrated luminosity of 66 pb^{-1} (HERA-I) and the 2003-4 e^+p running period with a total integrated luminosity of 40 pb^{-1} (HERA-II). In both running periods the centre-of-mass energy was 318 GeV.

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 [8]. 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

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

calculation are GRV-G(LO) (CTEQ5D). The final state simulation does not include hard gluon radiation.

Such calculations yield a total cross section of 1.1 pb for $\sqrt{s} = 318\,\text{GeV}$. The uncertainties on this value are approximately 5% for the choice of u_{cut} (set at $25\,\text{GeV}^2$), 5% for the choice of proton structure function, 10% for the choice of photon structure function and 10% from the choice of Q^2 scale [9] used in Epvec. Next-to-leading order corrections have been calculated [10] 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 [11], an interface to the Monte Carlo (MC) programs Heracles 4.5 [12] and Lepto 6.5 [13]. Leading order electroweak radiative corrections were included and higher order QCD effects were simulated using the colour-dipole model (CDM) of Ariadne [14] or using a leading-logarithm approximation (MEPS). The hadronisation of the partonic final state was performed by Jetset [15]. Minor contributions to the background come from two-photon processes which were simulated using the Grape [16] dilepton generators and direct and resolved photoproduction processes which were simulated using the Herwig 6.1 [17] event generator.

The generated events were passed through the Geant-based [18] ZEUS detector and trigger simulation programs [19]. 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 [19]. 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) [20] 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) [21], 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, organised in 9 superlayers covering the polar-angle[2] region $15^\circ < \theta < 164^\circ$.

A three-level trigger was used to select events online [22] requiring large missing P_T.

4 Event Reconstruction and Data Selection

The missing transverse momentum is defined as:

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

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 from islands using the energies of individual calorimeter energy deposits corrected [23] for energy loss in inactive material and other offline effects. 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:

$$\delta \equiv \sum_i E_i(1 - \cos\theta_i),$$

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

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

[2] The ZEUS co-ordinate 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 centre of HERA.

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

The quantity ξ_e^2 is defined as

$$\xi_e^2 = 2E_e'E_e(1 + \cos\theta_e),$$

where E_e' is the energy of the final state electron. For neutral current events, where the scattered electron is identified as the isolated lepton, this quantity corresponds to the virtuality, Q^2. Neutral current events will generally have low values of ξ_e^2 whilst electrons from W decay will generally have high values of ξ_e^2.

Events that pass the trigger requirements are further required to have a P_T greater than 12 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 vertex-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 reject beam-gas, cosmic-ray and halo-muon events.

5 Search for isolated electrons

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 [24]. 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 the closest extrapolated 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 and Fig. 4, after requiring that the P_T^e be greater than 5 GeV, the transverse mass M_T

be greater than 10 GeV, that the quantity δ lie in the range $5 < \delta < 60$ GeV and that the polar angle of the electron measured in the calorimeter, θ_e, be less than 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 further requiring δ to be less than 50 GeV and the acoplanarity angle to be greater than 0.3 rad. The hadronic transverse momentum, P_T^X, is required to be greater than 12 GeV. In addition for low values of P_T (< 25 GeV), where neutral current background is highest, ξ_e^2 is required to be greater than 5000 GeV^2. Electrons in the final event sample are required to 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 removes most of the remaining fake electrons.

Two data events, both from the HERA-I sample, pass these final cuts. The expectation from the SM and the fraction arising from the single W production MC, in bins of P_T^X, are given in Table 1 together with the numbers observed in similar searches by the H1 collaboration [2,4,25]. The fraction of the SM prediction arising from the signal is higher than in previous ZEUS searches and, in the highest P_T^X bin, similar to that expected by H1. No excess over the Standard Model predictions is observed by ZEUS.

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

- Using CDM instead of MEPS for hadronisation in the background simulation;
- Varying the absolute energy scale of the CAL by $\pm 3\%$;
- A systematic uncertainty on the integrated luminosity of 2.25% (5%) for the 1999-2000 (2003-4) running period.

Theoretical uncertainities on the W production cross section were not included in the errors on the SM prediction.

6 Summary

A search was made for isolated high-P_T electrons, in events with large missing P_T, compatible with single W production with decay in the electron channel. The search was made in positron-proton collisions at centre-of-mass energies of 318 GeV using two data samples with integrated luminosities of 66 pb^{-1} and 40 pb^{-1}. The rate of production of such events at high hadronic transverse momentum was found to be consistent with the Standard Model predictions. The excess in these type of events observed by the H1 collaboration is not confirmed.

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Isolated e candidates	$12 < P_T^X < 25$ GeV	$P_T^X > 25$ GeV
ZEUS (prel.) 99-00 e^+p (66 pb^{-1})	$1/1.04 \pm 0.11(57\%)$	$1/0.92 \pm 0.09(79\%)$
ZEUS (prel.) 03-04 e^+p (40 pb^{-1})	$0/0.46 \pm 0.10(64\%)$	$0/0.58^{+0.08}_{-0.09}(76\%)$
H1 1994-2000 e^+p (104.7 pb^{-1})	$1/1.96 \pm 0.27(74\%)$	$4/1.48 \pm 0.25(86\%)$
H1 (prel.) 1994-2005 $e^{\pm}p$ (192 pb^{-1})	-	$11/2.9 \pm 0.6(81\%)$

Table 1: *Summary of the results of searches for events with isolated electrons and missing transverse momentum at HERA. The number of observed events is compared to the SM prediction (observed/expected). The signal component of the SM expectation, which is dominated by real W production, is given as a percentage in parentheses. The quoted errors contain statistical and systematic uncertainties added in quadrature. Only the H1 results directly comparable to the ZEUS results are quoted in this table.*

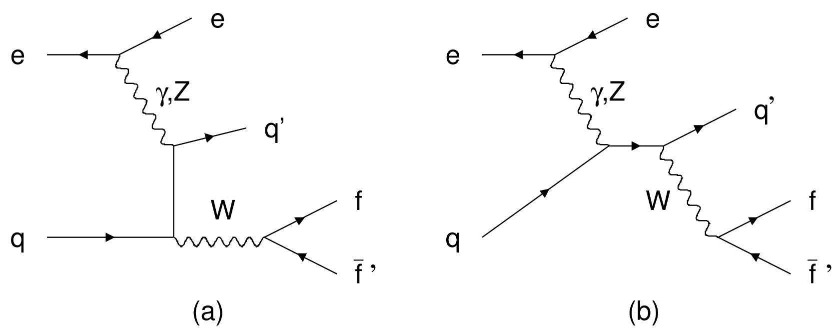

Figure 1: *Main leading order Feynman diagrams for the process $ep \to eWX$.*

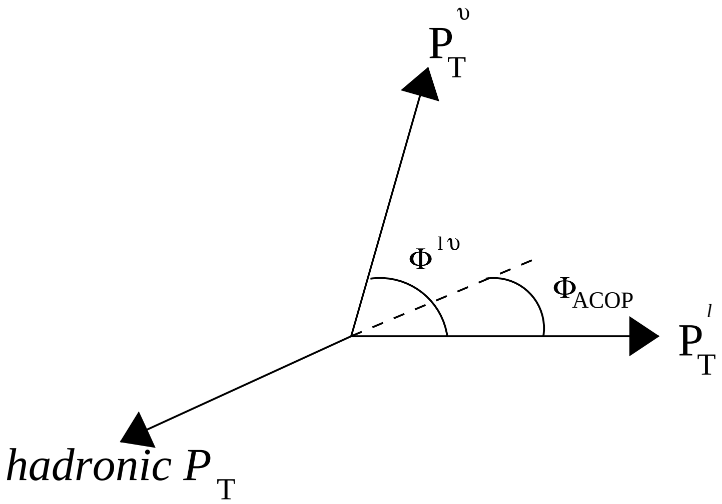

Figure 2: *The definition of the acoplanarity angle, $\Phi_{\rm ACOP}$, and the azimuthal separation of the neutrino and the outgoing lepton, $\Phi^{l\nu}$, in the transverse plane. The dashed line balances the hadronic P_T.*

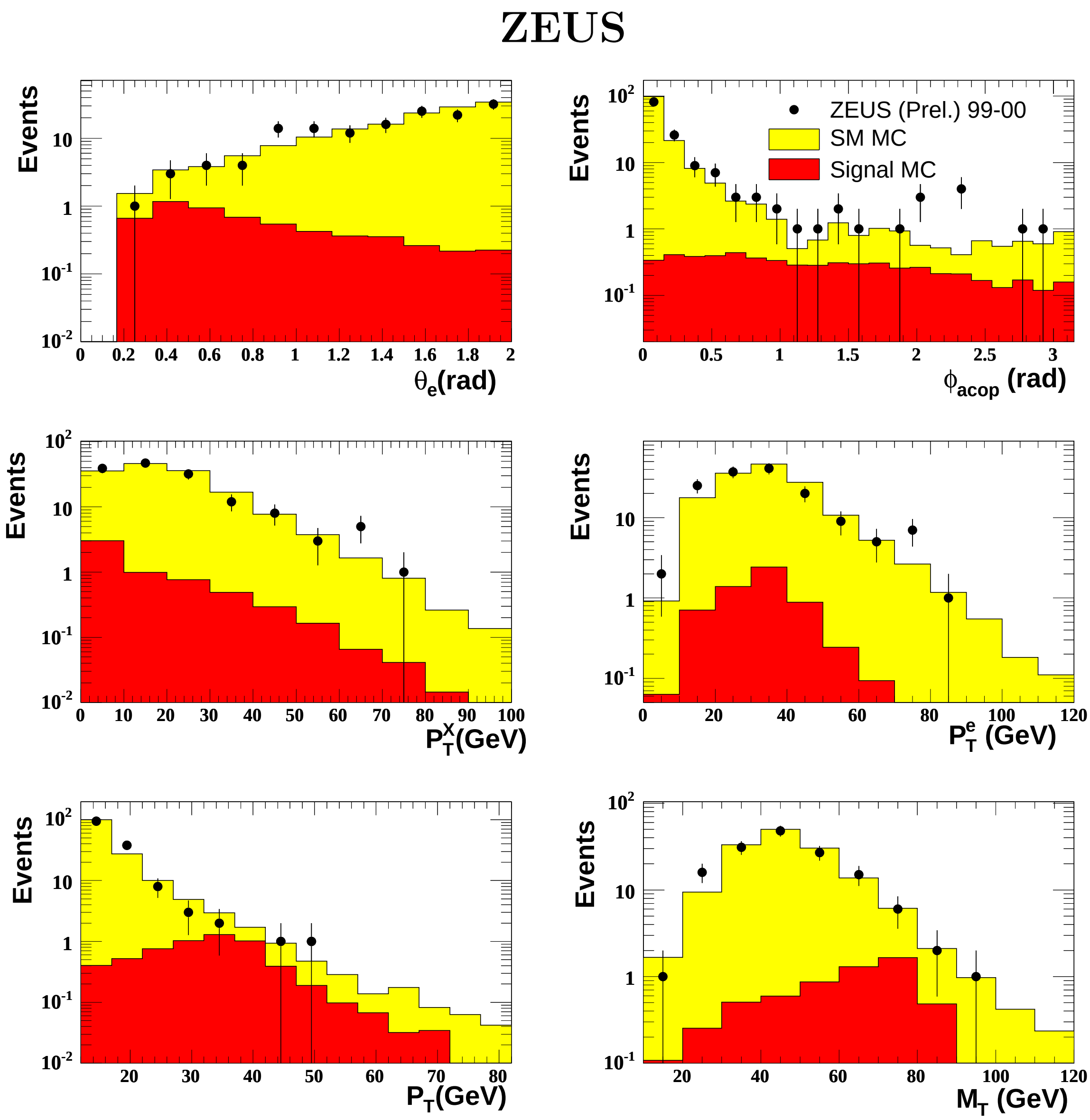

Figure 3: *Data (points) compared to absolutely-normalised Monte Carlo for the 1999-2000 running period. The light shaded histogram represents the Standard Model (SM) MC prediction, the dark shaded area the signal ($e^+p \rightarrow e^+WX$) prediction. The variables shown are described in detail in the text.*

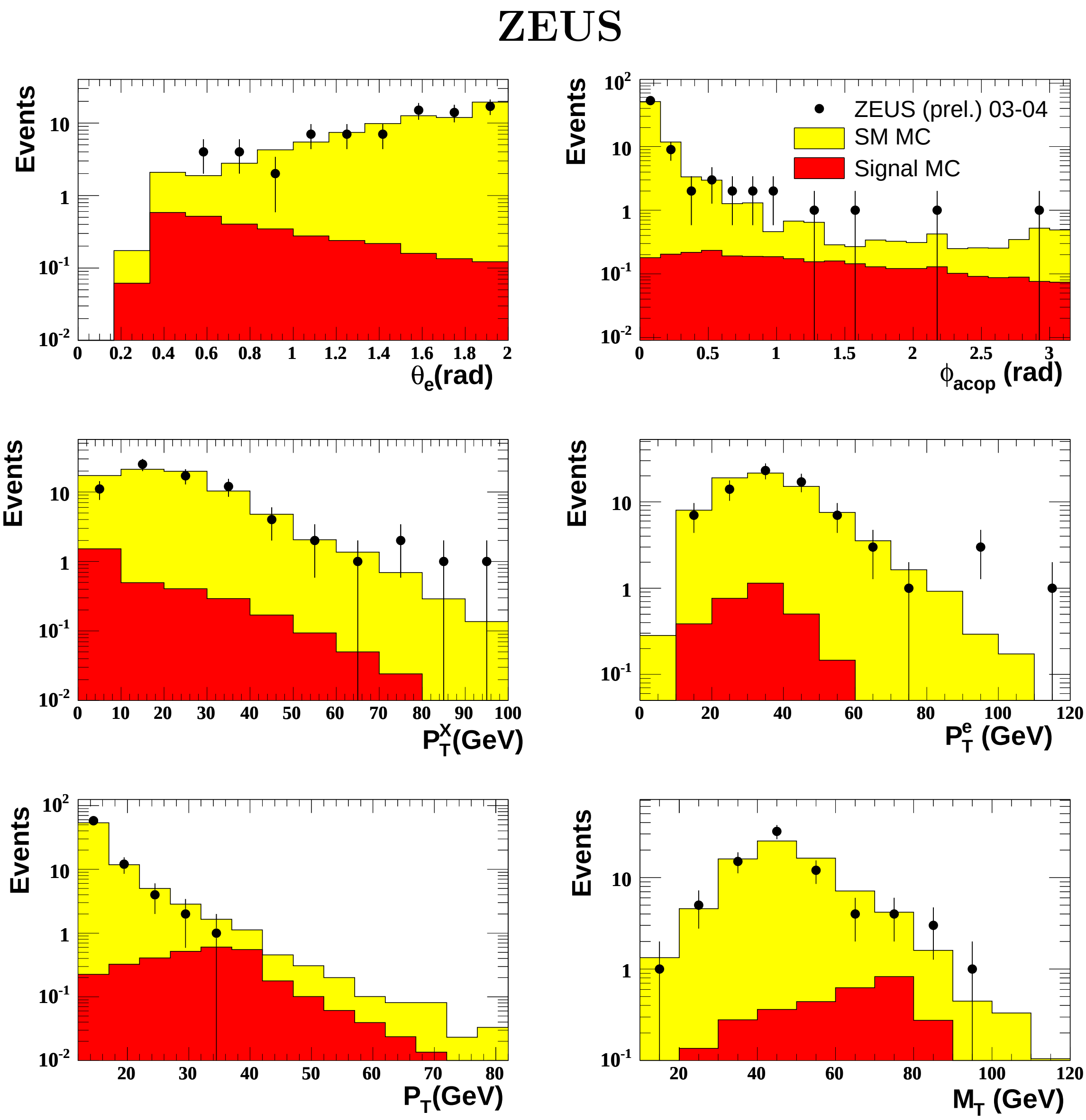

Figure 4: *Data (points) compared to absolutely-normalised Monte Carlo for the 2003-4 running period. Other details as in Fig. 3.*