PROCEEDINGS OF SCIENCE

Elastic Z^0 production at HERA

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A search for the process $ep \to eZ^0 p$ has been performed in ep collisions at HERA using the ZEUS detector. The search is based on the entire HERA-I and HERA-II data set, amounting to 0.5 fb^{-1} of integrated luminosity. The Z^0 was searched in the hadronic decay mode with the elastic condition defined by $\eta_{\rm max} < 3$, where $\eta_{\rm max}$ is defined as the pseudorapidity of the energy deposit in the calorimeter closest to the proton beam direction. A mass peak is observed at the Z^0 mass and the number of signal events is extracted from a fit to the mass spectrum. The elastic Z^0 production cross section is determined and compared to the SM prediction.

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1. Introduction

HERA was the world's only high energy $e^{\pm}p$ collider which existed so far and operated from 1992 to 2007. The center of mass energy was 318 GeV, from collisions of a proton beam of 920 GeV with an electron[1] beam of 27.6 GeV. There were two collider experiments, H1 and ZEUS, and data corresponding to an integrated luminosity of approximately 0.5 fb^{-1} had been collected in each experiment.

The ZEUS detector was a general-purpose 4π detector, which featured a high-resolution uranium-scintillator calorimeter (CAL). The CAL energy resolutions under test-beam conditions were $\sigma_E/E = 18\%/\sqrt{E}$ for electrons, and $\sigma_E/E = 35\%/\sqrt{E}$ for hadrons, with E in GeV, respectively. The excellent hadronic energy resolution is a key point for this analysis.

At e^+e^-, pp, and $p\bar{p}$ colliders, such as LEP, LHC and Tevatron, Z and W bosons are abundantly produced via s-channel fermion and anti-fermion annihilation. On the contrary, it is not the case in ep collisions at HERA due to lepton and baryon number conservations. The on-shell production of the electroweak (EW) bosons has a small cross section at HERA via radiation from lepton or quark lines, however it is a good benchmark process for testing the Standard Model (SM). Although the predicted cross section at HERA is small, the measurement of the cross sections is important to search for physics beyond the SM, which involves Z bosons in the final state (e.g. $e^* \to eZ$), and those new physics may change the cross section. Electroweak bosons also play important roles in t-channel (off-shell) exchange in neutral-current (NC) and charged-current (CC) deep inelastic scattering (DIS) at high-Q^2.

In the EW physics program at HERA, virtual W and Z exchanges were measured through CC and NC DIS events, and the cross section of real W production was measured, using events with a high-p_T isolated lepton[2] and missing transverse energy, to be around 1 pb [1]. The result was in good agreement with the SM prediction. The cross section of Z boson production is expected to be even smaller, around 0.4 pb in the SM.

2. Event Selection

The search strategy for Z^0 production is to use the hadronic decay mode due to the large branching ratio of 70 %. This resulted in very large background from QCD multi-jet production. Therefore, to suppress such a large background, we also chose the elastic and quasi-elastic production, $ep \to eZ^0p^{(*)}$, which is a sizable fraction ($\sim$0.16 pb) of the total cross section. In the process, the proton stays intact or is excited to a low-mass nucleon resonance (p^*). A condition of $\eta_{\rm max} < 3$ was required, where $\eta_{\rm max}$ is the maximum pseudorapidity[3] of the CAL energy deposits. This requirement largely suppressed the inelastic background events, in which $\eta_{\rm max}$ of much larger than 3 was given by the CAL deposits due to the proton remnant.

Hence, the event topology has two or more high-E_T jets of hadrons resulting from the $Z^0 \to q\bar{q}$ decays, and no energy deposit in the CAL around the forward beam pipe, defined by the $\eta_{\rm max}$

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

[2] p_T stands for the transverse momentum.

[3] The cylindrical coordinate is defined with polar angle $\theta = 0$ at the proton beam direction, with pseudorapidity defined as $\eta = -\ln(\tan\frac{\theta}{2})$. ϕ denotes the azimuthal angle.

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cut. The beam electron is back-scattered in the forward direction due to the kinematic condition imposed by the high Z^0 mass. The electron escapes in the forward beam pipe or is detected in the forward region of the CAL. Moreover, no particles are expected in the rear direction, so a veto on the real CAL energy deposit and kinematical peak of the total longitudinal momentum ($E-p_Z$) at twice the electron beam energy of 55 GeV were required. These requirements suppress the background from low-Q^2 DIS and photo-production events.

The actual event selection criteria, imposed on 496 pb^{-1} of $e^{\pm}p$ data collected in the period from 1996 to 2007, are follows[4]:

- At least two jets in the event, reconstructed by the k_T cluster algorithm [3] in the longitudinally invariant inclusive mode [4], had to satisfy $E_T > 25$ GeV and $|\eta| < 2$. The opening angle between two jets in ϕ is required to be larger than 2 rad. For the invariant mass calculation, all jets with $E_T > 4$ GeV and $|\eta| < 2$ were used. Jets were removed if they overlapped with an identified electron or photon within the distance of $R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} < 1$.

- There must be at most one isolated electron in the detector, with energy greater than 5 GeV and matched with a track, if it was in the acceptance of tracking detectors. In order to suppress background from NC DIS with multi-jets, the event was rejected if the polar angle of the electron was larger than 80 degrees.

- No particles detected in the rear direction. The total energy deposit in the rear CAL had to be less than 2 GeV. In order to ensure that no particle is escaping in the rear beam pipe, $E-p_Z$, which was calculated by summing over all CAL energy deposits, had to be between 50 and 64 GeV.

- Finally, $\eta_{\max} < 3$ was imposed in order to select (quasi-)elastic events.

3. Signal and Background Estimation

We prepare signal MC to make a signal template and to estimate the selection acceptance. The EPVEC program [5], which is a vector-boson generator in *ep* collisions and interfaced to PYTHIA and JETSET [6], was used. The selection acceptance of (quasi-)elastic processes cross section was 22 %, and it expected 17.9 events. The cross section of inelastic process by DIS ($\gamma^* p \to Z^0 X$) and resolved photo-production ($\gamma p \to (q\bar{q} \to Z^0)X$) is expected to be slightly higher, but only 0.4 events are expected to contribute due to the acceptance of less than 1 %, since we require elastic events.

On the other hand, no background MC was used, since background around the Z^0 mass came from the tail of high-E_T diffractive DIS which is hard to model. Instead, data-driven estimation was adopted for background shape. Figure 1 shows invariant mass distributions of data before $\eta_{\max}$ cut, and also in some slices of $\eta_{\max}$ values above 3.0. It is seen the shape of distributions is almost independent of $\eta_{\max}$, therefore the distribution of the events in the region of $\eta_{\max} > 3$ was used as the background template, while EPVEC MC was used for the signal template. Then, the signal region, defined by $\eta_{\max}$ less than 3, was fitted with both signal and background templates.

[4]Details of the selection cuts are shown in [2].

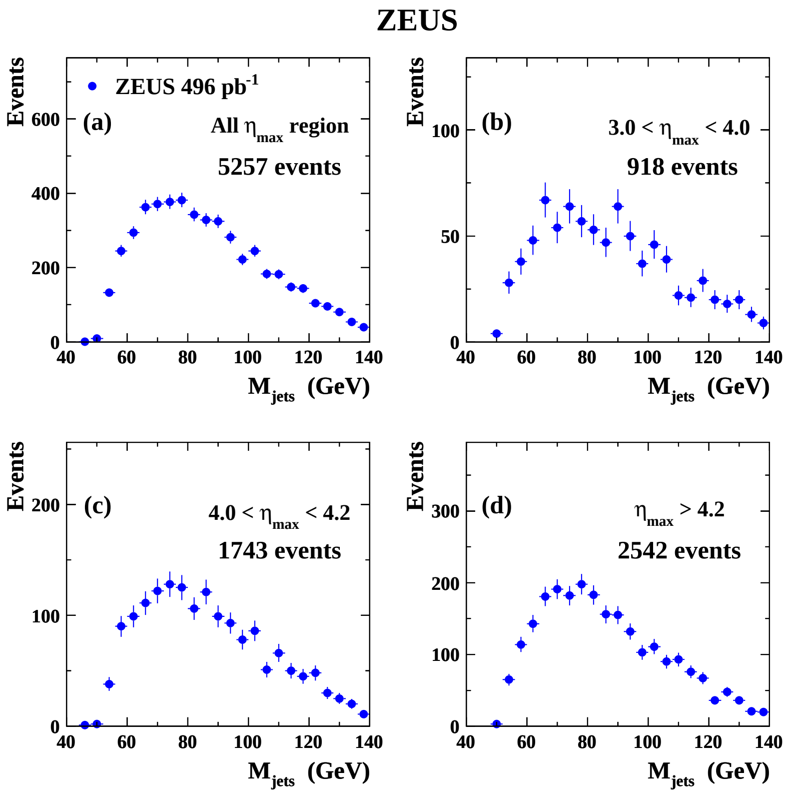

Figure 1: Invariant-mass distribution of the data after all cuts except for $\eta_{\max}$ cuts, in several $\eta_{\max}$ slices.

4. Results

After all selection cuts 54 events remained, and Fig. 2 shows the invariant mass distribution after all selection cuts. A maximum likelihood fit was performed to determine the normalization of the signal and background. In the likelihood fit, a nuisance parameter was introduced to allow the mass peak shift within the energy scale uncertainty of 3 %. The fit gave $15.0^{+7.0}_{-6.4}$ events of Z^0 signal yield, a signal with 2.3 σ significance. The nuisance parameter for the mass shift was 3 ± 2 %, which is consistent with zero.

Using those events, the total cross section of the elastic Z^0 production is extracted. Concerning the systematic uncertainties, the following sources were considered:

- The effect of energy scale uncertainty (± 3 %) on the acceptance was $^{+2.1}_{-1.7}$ %.
- To take into account a possible simulation discrepancy for the $\eta_{\max}$ distribution, the cut was varied by ± 0.2, yielding an acceptance change of $^{+6.4}_{-5.4}$ %.
- Different $\eta_{\max}$ slices were used to produce the background template, which resulted in cross section change of ± 1.5 %.
- The width of the signal peak template (6 GeV) was smeared within the range allowed by the fit, giving a negligible effect on the cross section.

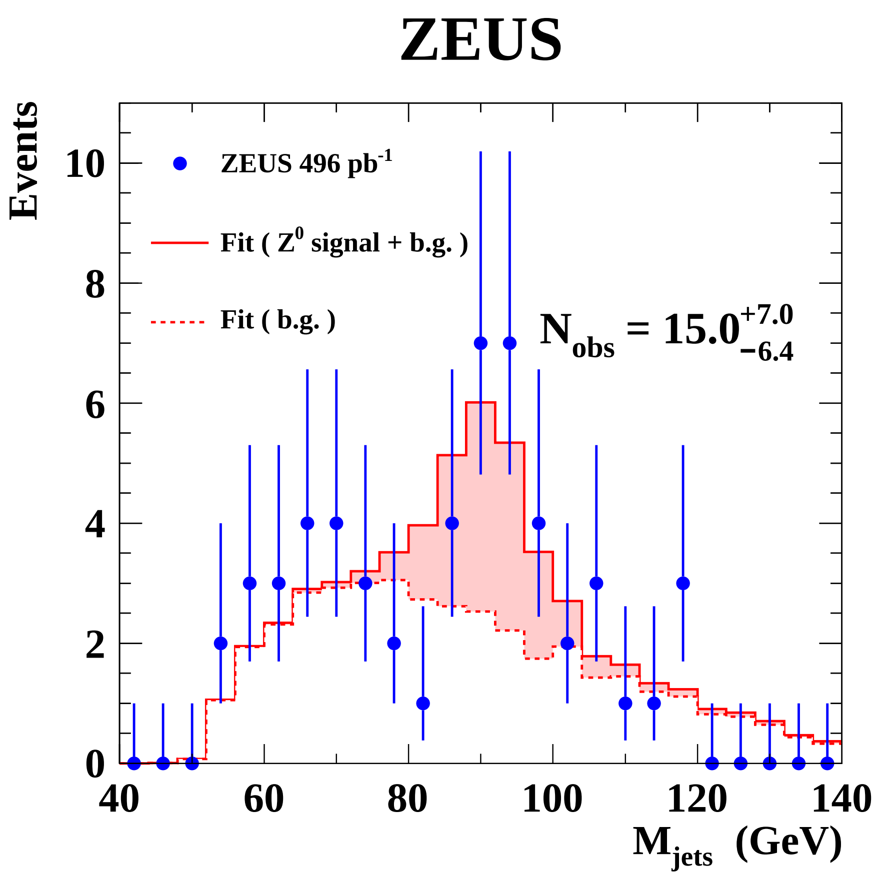

Figure 2: Invariant-mass distribution of data events after all cuts (dots) with the fit result (histograms).

- The luminosity uncertainty of ± 2 %.

Adding these sources in quadrature, the systematic uncertainty on the cross section measurement was $^{+7.2}_{-6.2}$ %.

As a result, the following cross section was measured:

$$\sigma(ep \to eZ^0 p^{(*)}) = 0.13 \pm 0.06\,(\text{stat.}) \pm 0.01\,(\text{syst.})\text{ pb.}$$

It is consistent with the SM prediction of 0.16 pb and it constitutes the first measurement of on-shell Z^0 production cross section in ep collisions.

5. Summary

We searched for on-shell Z^0 production in ep collisions, corresponding to an integrated luminosity of 0.5 fb^{-1}, at HERA using the ZEUS detector. We aimed to select the hadronic Z^0 decay and elastic process, to gain the statistics and suppress the inelastic background. The analysis on the hadronic decay mode demonstrates the excellent energy resolution of the ZEUS uranium calorimeter. A fit on the invariant mass distribution from all jets was performed with signal and background templates, and a peak with a significance of 2.3 σ was observed at the Z^0 mass. This analysis is the first measurement of Z^0 production in ep collisions. The resulting cross section,

$$\sigma(ep \to eZ^0 p^{(*)}) = 0.13 \pm 0.06\,(\mathrm{stat.}) \pm 0.01\,(\mathrm{syst.})\ \mathrm{pb},$$

is in good agreement with the SM elastic and quasi-elastic cross section of 0.16 pb.

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