PROCEEDINGS OF SCIENCE

Production of Z^0 bosons in elastic and quasi-elastic ep collisions at HERA

Masahiro KUZE*
(Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551 Japan)
E-mail: `kuze@phys.titech.ac.jp`

The production of Z^0 bosons in the reaction $ep \rightarrow eZ^0 p^{(*)}$, where $p^{(*)}$ stands for a proton or a low-mass nucleon resonance, was studied in ep collisions at a center-of-mass energy of 318 GeV at HERA, using an integrated luminosity of approximately 0.5 fb^{-1} collected by the ZEUS detector. The Z^0 was measured in the hadronic decay mode, imposing a cut on the maximum pseudo-rapidity of the energy deposits in the calorimeter defined with respect to the proton beam direction. A signal was observed at the Z^0 mass, and the measured cross section is in agreement with the Standard Model prediction. This is the first measurement of Z^0 production in ep collisions.

XXI International Workshop on Deep-Inelastic Scattering and Related Subjects
22-26 April, 2013
Marseilles, France

*On behalf of the ZEUS Collaboration.

PoS(DIS 2013)286

1. Introduction

HERA was the only high energy $e^{\pm}p$ collider existed so far, which operated from 1992 to 2007. It collided a proton beam of 920 GeV with an electron[1] beam of 27.6 GeV, giving a center-of-mass energy $\sqrt{s} = 318$ GeV. Its two collider experiments, H1 and ZEUS, each collected ~ 0.5 fb^{-1} of integrated luminosity.

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

At e^+e^- and hadron colliders, the Z and W bosons are abundantly produced via s-channel fermion and anti-fermion annihilation. In contrast, in ep collisions at HERA, this is not the case due to lepton and baryon number conservation. The on-shell production of the electroweak (EW) bosons has a small cross section at HERA via radiation from lepton or quark lines. Still, Z and W bosons play important roles in t-channel (off-shell) exchange which causes neutral-current (NC) and charged-current (CC) deep inelastic scattering (DIS) processes at high Q^2.

In EW physics program at HERA, virtual W and Z exchanges were measured through CC and NC DIS events, and the real W production cross section was measured, using events with high-p_T isolated lepton[2] and missing E_T, to be around 1 pb [1]. The real Z boson production, predicted to have an even smaller cross section of around 0.4 pb, could be regarded as the last missing piece in the HERA EW program. Measuring its production cross section is also important for searches for physics beyond Standard Model (SM) which involves Z bosons in the final state (e.g. $e^* \to eZ$).

2. Event Selection

As the strategy for Z^0 search, its hadronic decay mode was chosen due to the large branching ratio (70 %). This immediately resulted in very large background from QCD multi-jet production, therefore, as the second strategy, the elastic (and quasi-elastic) production was chosen, which has a sizable fraction (about 0.16 pb) of the total cross section. The process is $ep \to eZ^0p(p^*)$, where in elastic events the proton stays intact and in quasi-elastic events is excited to a nucleon resonance (p^*). Experimentally, a condition $\eta_{\max} < 3$ was required, where $\eta_{\max}$ is the maximum pseudo-rapidity[3] of the CAL energy deposits, i.e. η of the one closest to the forward (proton beam) direction. This requirement largely suppressed the inelastic background events, in which $\eta_{\max}$ of much larger than 3 was given by the CAL deposits due to the proton remnant.

Therefore, the event topology to search has two or more high-E_T jets of hadrons resulting from the $Z^0 \to q\bar{q}$ decay, and no energy deposits in CAL around the forward beam pipe, defined by the $\eta_{\max}$ cut. The beam electron, due to the kinematic condition imposed by the large Z^0 mass, is back-scattered in the forward direction and escapes in the beam pipe or is detected in the forward region of CAL (in the latter fraction of the cross section, the $\eta_{\max}$ condition rejected

[1] The term 'electron' refers to both electron and positron throughout the text.

[2] p_T stands for the transverse momentum and E_T the transverse energy.

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

PoS(DIS 2013)286

the event and caused an acceptance loss). Other than those, no particles are expected in the rear (electron beam) direction, so a veto on rear CAL energy deposit and kinematical peak of the total longitudinal momentum ($E - p_Z$) at twice the electron beam energy (55 GeV) were required. These requirements suppressed the background from low-Q^2 DIS and photo-production events.

The actual event selection criteria [2], imposed on 496 pb^{-1} of $e^{\pm}p$ data collected between 1996 and 2007, were as follows[4]:

- At least two jets, defined by k_T algorithm [3], with $E_T > 25$ GeV and $|\eta| < 2$. The opening angle between the two jets in ϕ had to be larger than 2.0 rad. For the invariant-mass calculation, all jets with $E_T > 4$ GeV and $|\eta| < 2$ were used. Jets were removed from the list if they overlapped with an identified electron or photon within 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 tracking detector acceptance. In order to suppress background from NC DIS with multiple jets, the event was rejected if the polar angle of the electron was larger than 80 degrees.
- No particles detected in the rear direction, nor escaping in the rear beam pipe. The energy in the rear CAL had to be less than 2 GeV, and the $E - p_Z$ variable, calculated by summing over all CAL deposits, had to be between 50 and 64 GeV.
- Finally, the cut $\eta_{\max} < 3$ was imposed to select (quasi-)elastic events.

3. Signal and background estimation

In order to to access the selection acceptance for the signal Z^0 production, and to predict the SM cross section, the EPVEC [4] program was used, after interfacing with PYTHIA+JETSET [5]. For the elastic and quasi-elastic processes, the selection acceptance was 22 % and 17.9 events were expected to remain from the data set after the selection. For the rest of the total cross section, the processes were inelastic DIS ($\gamma^* p \to Z^0 X$) and photo-production ($\gamma p \to (q\bar{q} \to Z^0)X$) and the selection acceptance was less than 1 %, contributing only 0.4 events under the SM hypothesis.

On the other hand, the background events with multi-jet invariant mass

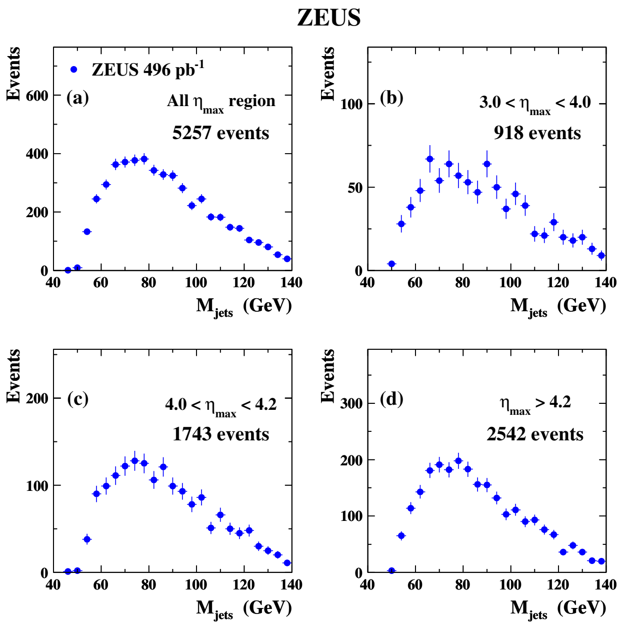

Figure 1: Invariant-mass distribution of the data (a) after all cuts except $\eta_{\max}$, (b,c,d) in several $\eta_{\max}$ slices.

[4]A few other cuts against non-collision events such as cosmic rays and beam-gas background were imposed [2].

around the Z^0 mass peak came from the tail of high-E_{T} diffractive DIS, which is hard to model. Instead, a data-driven estimation was used in this analysis. Figure 1 shows the invariant-mass distribution before the final cut on $\eta_{\max}$, and also in some slices of $\eta_{\max}$ values. It is seen that the invariant-mass shape has little dependence on $\eta_{\max}$. Therefore, the mass distribution of the events in $\eta_{\max} > 3$ region was used as the background template and the EPVEC MC distribution was used as the signal template, and the distribution of the events in signal region ($\eta_{\max} < 3$) was fitted using both the background and signal templates.

4. Results and cross-section extraction

Figure 2 shows the invariant-mass distribution after the final $\eta_{\max} < 3$ cut. A maximum-likelihood fit was performed to determine the normalization of the signal and background, and also a nuisance parameter was introduced to allow the signal mass peak to float within the energy-scale uncertainty (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 %, consistent with zero.

Concerning the systematic uncertainties, the following sources were considered:

- The effect of energy scale uncertainty ($\pm$3 %) on the acceptance was (+2.1, -1.7) %.
- To account for possible simulation discrepancy for $\eta_{\max}$ distribution, the cut was varied by $\pm$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 $\pm$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.
- The luminosity uncertainty of $\pm$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:

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

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

A search for on-shell Z^0 production in *ep* collisions at HERA was conducted using the ZEUS detector, on a data sample of approximately 0.5 fb^{-1}. Hadronic decay of the Z boson was used, and (quasi-)elastic process was aimed in order to suppress inelastic multi-jet backgrounds. A cut $\eta_{\max} < 3$ was used for elastic selection. The background template was made from $\eta_{\max} > 3$ data

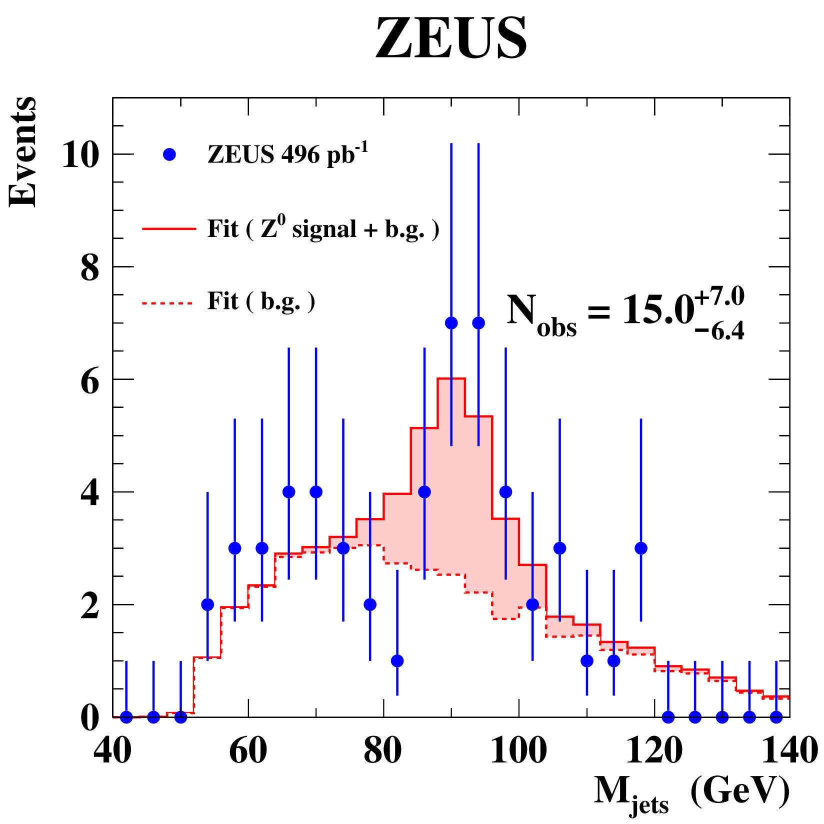

Figure 2: Invariant-mass distribution of data events after all cuts (dots) with the fit result (histograms).

events. A fit on 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. The resulting cross section,

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

is consistent with the SM prediction of 0.16 pb and constitutes the first measurement of Z^0 production in *ep* collisions.

References

[1] H1 and ZEUS Collaborations, F.D. Aaron et al., *Events with an Isolated Lepton and Missing Transverse Momentum and Measurement of W Production at HERA*, *JHEP* **03** (2010) 035 [arXiv:0911.0858].

[2] ZEUS Collaboration, H. Abramowicz et al., *Production of Z^0 bosons in elastic and quasi-elastic ep collisions at HERA*, *Phys. Lett.* **B718** (2013) 915 [arXiv:1210.5511].

[3] S. Catani et al., *Longitudinally invariant K_t clustering algorithms for hadron hadron collisions*, *Nucl. Phys.* **B406** (1993) 187.

[4] U. Baur, J.A.M. Vermaseren and D. Zeppenfeld, *Electroweak vector boson production in high-energy ep collisions*, *Nucl. Phys.* **B375** (1992) 3.

[5] T. Sjöstrand, *PYTHIA 5.6 and JETSET 7.3: Physics and manual*, CERN-TH-6488-92 (1992).