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

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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, has been studied in ep collisions at HERA using the ZEUS detector. The analysis is based on a data sample collected between 1996 and 2007, amounting to 496 pb^{-1} of integrated luminosity. The Z^0 was measured in the hadronic decay mode. The elasticity of the events was ensured by a cut on $\eta_{\text{max}} < 3.0$, where η_{max} is the maximum pseudorapidity of energy deposits in the calorimeter defined with respect to the proton beam direction. A signal was observed at the Z^0 mass. The cross section of the reaction $ep \rightarrow eZ^0 p^{(*)}$ was measured to be $\sigma\left(ep \rightarrow eZ^0 p^{(*)}\right) = 0.13 \pm 0.06\,(\text{stat.}) \pm 0.01\,(\text{syst.})$ pb, in agreement with the Standard Model prediction of 0.16 pb. This is the first measurement of Z^0 production in ep collisions.

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1. Introduction

The production of electroweak bosons in ep collisions is a good benchmark process for testing the Standard Model (SM). Even though the expected numbers of events for $W^{\pm}$ and Z^0 production are low, the measurement of the cross sections of these processes is important as some extensions of the SM predict anomalous couplings and thus changes in these cross sections. A measurement of the cross section for $W^{\pm}$ production at HERA has been performed by H1 and ZEUS [1] in events containing an isolated lepton and missing transverse momentum, giving a cross section $\sigma(ep \to W^{\pm}X) = 1.06 \pm 0.17\,(\text{stat.} \oplus \text{syst.})\,\text{pb}$, in good agreement with the SM prediction. The cross section for Z^0 production is predicted to be $0.4\,\text{pb}$.

This paper reports on a measurement of the production of Z^0 bosons in $e^{\pm}p$ collisions using an integrated luminosity of about $0.5\,\text{fb}^{-1}$ [2]. The hadronic decay mode was chosen because of its large branching ratio and because it allows the excellent resolution of the ZEUS hadronic calorimeter to be exploited to the full. The analysis was restricted to elastic and quasi-elastic Z^0 production in order to suppress QCD multi-jet background. The selected process is $ep \to eZ^0p^{(*)}$, where $p^{(*)}$ stands for a proton (elastic process) or a low-mass nucleon resonance (quasi-elastic process). In such events there are at least two hadronic jets with high transverse energies, and no hadronic energy deposits around the forward[1] direction, in contrast to what would be expected in inelastic collisions.

2. Experimental set-up

HERA was the world's only high-energy ep collider, with an electron[2] beam of $27.6\,\text{GeV}$ and a proton beam of $920\,\text{GeV}$ ($820\,\text{GeV}$ until 1997). For this analysis, $e^{\pm}p$ collision data collected with the ZEUS detector between 1996 and 2007, amounting to $496\,\text{pb}^{-1}$ of integrated luminosity, have been used.

The ZEUS detector is a standard multi-purpose high-energy physics detector. A detailed description of the ZEUS detector can be found elsewhere [3].

3. Monte Carlo simulations

Monte Carlo (MC) simulations were made to simulate the Z^0 production process. They were used to correct for instrumental effects and selection acceptance and to provide a template for the shape of the invariant-mass distribution of the Z^0 signal. The EPVEC program [4] was used to generate the signal events at the parton level. The following Z^0 production processes are considered in EPVEC:

- elastic scattering, $ep \to eZ^0p$, where the proton stays intact;

[1]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 towards the centre 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.

[2]The term "electron" also refers to positrons if not stated otherwise.

- quasi-elastic scattering, $ep \rightarrow eZ^0 p^*$, where the proton is transformed into a nucleon resonance p^*;
- deep inelastic scattering (DIS), $\gamma^* p \rightarrow Z^0 X$, in the region $Q^2 > 4\,\text{GeV}^2$, where Q^2 is the virtuality of the photon exchanged between the electron and proton;
- resolved photoproduction, $\gamma p \rightarrow \left(q\bar{q} \rightarrow Z^0\right) X$, where one of the quarks is a constituent of the resolved photon and the other quark is a constituent of the proton.

The cross section of Z^0 production is calculated to be 0.16 pb for elastic and quasi-elastic processes and 0.24 pb for DIS and resolved photoproduction.

After the parton-level generation by EPVEC, PYTHIA 5.6 [5] was used to simulate final-state parton showers with the fragmentation into hadrons using the Lund string model [6] as implemented in JETSET 7.3 [5]. The generated MC events were passed through the ZEUS detector and trigger simulation programs based on GEANT 3.13 [7]. They were reconstructed and analysed by the same programs as the data.

A reliable prediction of background events with the signal topology, which are predominantly due to the diffractive photoproduction of jets of high transverse momentum, is currently not available. Therefore, the background shape of the invariant-mass distribution was estimated with a data-driven method. The normalisation was determined by a fit to the data.

4. Event reconstruction and selection

The events are characterised by the presence of at least two jets of high transverse energy and, for a fraction of events, by the presence of a reconstructed scattered electron. In order to select events with a Z^0 decaying hadronically, jets were reconstructed in the hadronic final state using the k_T cluster algorithm [8] in the longitudinally invariant inclusive mode [9]. The algorithm was applied to the energy clusters in the CAL after excluding those associated with the scattered-electron candidate [10, 11, 12]. Energy corrections [13, 14, 15] were applied to the jets in order to compensate for energy losses in the inactive material in front of the CAL.

In this analysis, only jets with $E_T > 4\,\text{GeV}$ and $|\eta| < 2.0$ were used. Here E_T is the jet transverse energy and η its pseudorapidity. The hadronic Z^0 decay sample was selected by the following requirements on the reconstructed jets:

- at least two jets in the event had to satisfy $E_T > 25\,\text{GeV}$;
- $\left|\Delta\phi_j\right| > 2\,\text{rad}$, where $\Delta\phi_j$ is the azimuthal difference between the first and second highest-E_T jet, as the two leading jets from the Z^0 boson decays are expected to be nearly back-to-back in the X–Y plane.

Electrons were reconstructed using an algorithm that combined information from clusters of energy deposits in the CAL and from tracks [10]. To be defined as well-reconstructed electrons, the candidates were required to satisfy the following selection:

- $E_e^{'} > 5\,\text{GeV}$ and $E_{\text{in}} < 3\,\text{GeV}$, where $E_e^{'}$ is the scattered electron energy and E_{in} is the total energy in all CAL cells not associated with the cluster of the electron but lying within a cone in η and ϕ of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.8$, centred on the cluster;

- If the electron was in the acceptance region of the tracking system, a matched track was required with momentum $p_{\text{track}} > 3\,\text{GeV}$. After extrapolating the track to the CAL surface, its distance of closest approach (DCA) to the electron cluster had to be within 10 cm.

Additional cuts were applied to suppress low-Q^2 neutral-current and direct-photoproduction backgrounds, as well as to remove cosmic and beam–gas backgrounds.

Finally, to select the elastic and quasi-elastic processes preferentially, a cut on η_{max} was introduced,

- $\eta_{\text{max}} < 3.0$.

The quantity η_{max} was defined as the pseudorapidity of the energy deposit in the calorimeter closest to the proton beam direction with energy greater than 400 MeV as determined by calorimeter cells. This cut also rejected signal events which have energy deposits from the scattered electron in the calorimeter around the forward beam pipe, causing an acceptance loss of about 30%.

After all selection cuts, 54 events remained. The total selection efficiency was estimated by the MC simulation to be 22% for elastic and quasi-elastic processes and less than 1% for DIS and resolved photoproduction events. The number of expected signal events in the final sample, as predicted by EPVEC, is 18.3. The contribution from elastic and quasi-elastic processes amounts to 17.9 events.

5. Cross-section extraction

A fit to the sum of the signal and a background template for the M_{jets} distribution was used for the cross-section extraction. The template $N_{\text{ref},i}$ is defined according to:

$$N_{\text{ref},i} = aN^{\text{MC}}_{\text{sg},i}(\varepsilon) + bN^{\text{data}}_{\text{bg},i}, \tag{5.1}$$

where i is the bin number of the M_{jets} distribution. The parameter ε accounts for a possible energy shift, i.e. $M_{\text{jets}} = (1+\varepsilon)M^{\text{MC}}_{\text{jets}}$, where $M^{\text{MC}}_{\text{jets}}$ is the invariant-mass distribution of the signal Z^0 MC. The quantity $N^{\text{MC}}_{\text{sg},i}$ is a signal template estimated from the Z^0 MC distribution after all cuts, normalised to data luminosity. The quantity $N^{\text{data}}_{\text{bg},i}$ is a background template determined from the data outside the selected region. The parameters a and b are the normalisation factors for the signal and background, respectively. The likelihood of the fit, $\mathscr{L}$, is defined as follows:

$$\mathscr{L} = \mathscr{L}_1(N_{\text{obs}}, N_{\text{ref}}) \times \mathscr{L}_2(\varepsilon, \sigma_\varepsilon), \tag{5.2}$$

with

$$\mathscr{L}_1 = \prod_i \frac{\exp(-N_{\text{ref},i})\,(N_{\text{ref},i})^{N_{\text{obs},i}}}{N_{\text{obs},i}!} \quad \text{and} \quad \mathscr{L}_2 = \exp\left(-\frac{\varepsilon^2}{2\sigma_\varepsilon^2}\right). \tag{5.3}$$

Here $\mathscr{L}_1(N_{\text{obs}}, N_{\text{ref}})$ is the product of Poisson probabilities to observe $N_{\text{obs},i}$ events for the bin i when $N_{\text{ref},i}$ is expected. The term $\mathscr{L}_2(\varepsilon, \sigma_\varepsilon)$ represents the Gaussian probability density for a shift ε of the jet energy scale from the nominal scale, which has a known systematic uncertainty of $\sigma_\varepsilon = 3\%$. From the likelihood, a chi-squared function is defined as

$$\tilde{\chi}^2 = -2\ln\frac{\mathscr{L}_1(N_{\text{obs}}, N_{\text{ref}})}{\mathscr{L}_1(N_{\text{obs}}, N_{\text{obs}})} - 2\ln\mathscr{L}_2 = 2\sum f_i + \left(\frac{\varepsilon}{\sigma_\varepsilon}\right)^2, \tag{5.4}$$

with

$$f_i = \begin{cases} N_{\mathrm{ref},i} - N_{\mathrm{obs},i} + N_{\mathrm{obs},i} \ln\left(N_{\mathrm{obs},i}/N_{\mathrm{ref},i}\right) & (\mathrm{if}\, N_{\mathrm{obs},i} > 0) \\ N_{\mathrm{ref},i} & (\mathrm{if}\, N_{\mathrm{obs},i} = 0)\,. \end{cases} \tag{5.5}$$

The best combination of (a,b,ε) is found by minimising $\tilde{\chi}^2$. The value of a after this optimisation gives the ratio between the observed and expected cross section, i.e. $\sigma_{\mathrm{obs}} = a\sigma_{\mathrm{SM}}$. The maximum and minimum values of a in the interval $\Delta\tilde{\chi}^2 < 1$ define the range of statistical uncertainty.

6. Results and conclusions

Figure 1 shows the invariant-mass distribution of the selected events. It also shows the fit result for the signal plus background and the background separately. The fit yielded a result for the parameter a from Eq. 5.1 of $a = 0.82^{+0.38}_{-0.35}$. That translates into a number of observed Z^0 events of $15.0^{+7.0}_{-6.4}$ (stat.), which corresponds to a signal with a $2.3\,\sigma$ statistical significance. The fit yielded a value for the energy shift ε of $0.028^{+0.021}_{-0.020}$, which is compatible with zero. The quality was evaluated according to Eq. 3; the value of $\tilde{\chi}^2/ndf = 17.6/22$, where ndf is the number of degrees of freedom, indicates a good fit. The cross section for the elastic and quasi-elastic production of Z^0 bosons, $ep \to eZ^0 p^{(*)}$, at $\sqrt{s} = 318\,\mathrm{GeV}$, was calculated to be

$$\sigma(ep \to eZ^0 p^{(*)}) = 0.13 \pm 0.06\,(\mathrm{stat.}) \pm 0.01\,(\mathrm{syst.})\,\mathrm{pb}. \tag{6.1}$$

This result is consistent with the SM cross section calculated with EPVEC of 0.16 pb. This represents the first observation of Z^0 production in ep collisions.

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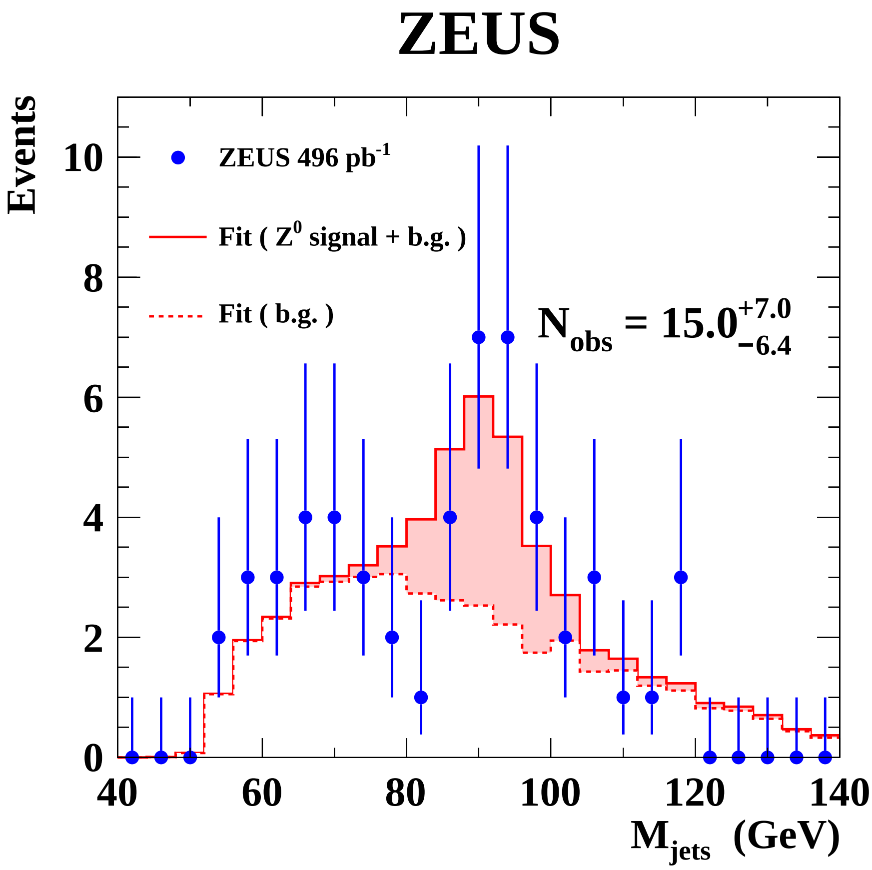

Figure 1: The M_{jets} distribution and the fit result. The data are shown as points, and the fitting result of signal+background (background component) is shown as solid (dashed) line. The signal contribution is also indicated by the shaded area and amounts to a total number of N_{obs} events. The error bars represent the approximate Poissonian 68% CL intervals, calculated as $\pm\sqrt{n+0.25}+0.5$ for a given entry n.