Elastic Z^0 production at HERA

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Elastic Z^0 events $ep \to eZ^0p^{(*)}$ have been measured in ep collisions at HERA using the ZEUS detector. The analysis is based on the data collected between 1996 and 2007, amounting to 496 pb^{-1} of integrated luminosity. The Z^0 was measured in hadronic decay mode with elastic condition defined by $\eta_{max} < 3.0$, where η_{max} is defined as the pseudorapidity of the energy deposit in the calorimeter closest to the proton beam direction. An excess of events was observed at the Z^0 mass. The cross section was obtaind by fitting the data with signal (MC)+background shapes templates. The shape of the background templates were estimated with a data-driven method. The cross section, $\sigma_{\left(ep\to eZ^0p^{(*)}\right)} = 0.133^{+0.060}_{-0.057}\,(\text{stat.})^{+0.049}_{-0.038}\,(\text{syst.})$ pb, was found to be in agreement with the Standard Model prediction of 0.16 pb.

1 Introduction

The cross section for $W^{\pm}$ production has been measured by H1 and ZEUS [1] to be:

$$\sigma_{(ep\to l\nu X)} = 1.06 \pm 0.16\,(\text{stat.}) \pm 0.07\,(\text{syst.})\ \text{pb}.$$

In contrast, the cross section for Z^0 production in ep collision is expected to be much smaller in the Standard Model (SM), about 0.4 pb, making it difficult to use leptonic decay modes which have very small branching ratios ($BR \simeq 0.03$). In this analysis, the hadronic decay mode ($BR \simeq 0.7$) is used, although the QCD di-jet background is quite large. In order to discriminate signal events from the QCD di-jet background, the measurement of Z^0 production was performed in the elastic regime. A peak in the invariant mass distribution is expected at the Z^0 mass above a broad background from hadronic jets.

2 Datasets and Monte Carlo

Data collected between 1996 and 2007 with total integrated luminosity of 496 pb^{-1} were used. The luminosity was measured using the Bethe-Heitler reaction $ep \to e\gamma p$ by a luminosity detector which consisted of a lead-scintillator calorimeter [2] and an independent magnetic spectrometer [3].

A Monte Carlo (MC) simulation generated by EPVEC [4] interfaced to Pythia hadronic fragmentation was exploited. The cross section of Z^0 production predicted by the SM is 0.16 pb for elastic and quasi-elastic processes and 0.24 pb for deep inelastic scattering and resolved photoproduction.

3 Event selection

The trigger requirements were optimized by MC efficiency studies and imposed on data events.

As the primary cut, at least two jets with high transverse energies, E_T, greater than 25 GeV are required in the event and the invariant mass is calculated by using all jets with $E_T > 4$ GeV and an absolute value of the pseudorapidity, $\eta = -log\left(\tan\frac{\theta}{2}\right)$, less than 2.0. The two jets from the Z^0 decay should be back-to-back in the x-y plane, so that $|\Delta\phi| > 2$ rad is required, where $\Delta\phi$ is the azimuthal difference between the first and second E_T jet. In order to select the elastic process preferentially, a cut on $\eta_{max} < 3.0$ was applied, where eta_{max} is defined as the pseudorapidity of the energy deposit in the calorimeter closest to the proton beam direction calculated by calorimeter cells with $E > 400$ MeV. Due to large mass of the final-state hadronic system, the electron is back scattered to the forward calorimeter or forward beam pipe. Therefore $\theta_e < 80°$ (if electron found), $E_{RCAL} < 2$ GeV and $50 < E - p_Z < 64$ GeV[1] are required in order to suppress low-Q^2 NC background events.

Additionally, some cosmic and beam-gas rejection cuts are applied. If the direction of the selected jet is compatible with that of an electron candidate, then the jet is treated as a misidentified electron and the remaining jet candidates are used to reconstruct M_{jets}.

The total selection efficiency is estimated by MC to be 9% for all processes, and 22% for (quasi-)elastic process. Number of events expected in the final sample is 18.3.

4 Background shape study

Figure 1 shows the invariant mass distributions of the data for various η_{max} slices. No significant η_{max} dependence of M_{jets} was found within the statistical uncertainties of the non-signal region ($\eta_{max} > 3.0$). In addition, the M_{jets} shape outside of the Z^0 mass window in the signal region ($\eta_{max} < 3.0$) is consistent with that in the non-signal region. Therefore, we adopted the shape of M_{jets} in the non-signal region data as a background template in the fit by introducing the term of $N_{bg,i}^{data,\eta_{max}>3.0}$.

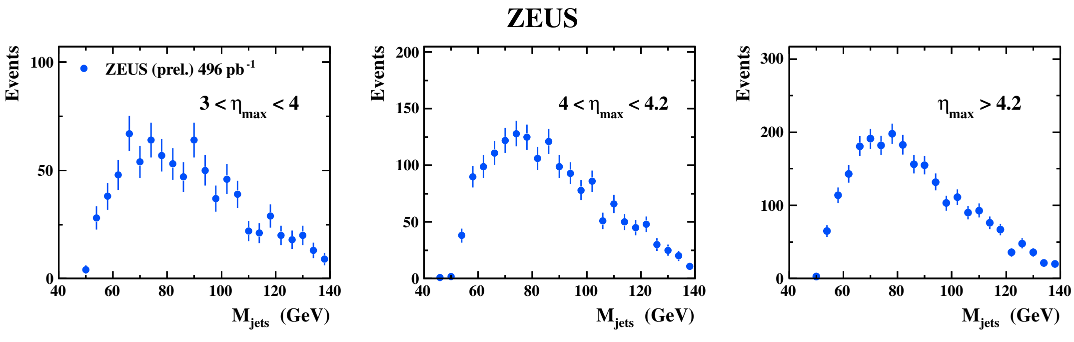

Figure 1: M_{jets} distribution in several η_{max} slices

[1]The nominal value of $E - p_z$ is twice the electron beam energy, 55 GeV.

5 Cross section extraction

First, the signal+background M_{jets} shape template is defined according to;

$$N_{ref,i} = aN_{sg,i}^{MC,\eta_{max}<3.0}(e) + bN_{bg,i}^{data,\eta_{max}>3.0}$$

where i is the bin number and e is a parameter to account for energy shift i.e. $M_{jets} = (1+e)\,M_{jets}^{MC}$. The quantity $N_{sg,i}^{MC,\eta_{max}<3.0}$ is a signal template estimated from the Z^0 MC and $N_{bg,i}^{data,\eta_{max}>3.0}$ is the data shape outside of the signal region($\eta_{max} > 3.0$), which corresponds to the background shape in the signal region (see section 5). a and b are normalization factors for the signal and background, respectively. Then, the χ^2 is calculated by summing over all bins;

$$\chi^2 = -2\sum_i log\frac{\mathcal{L}(N_{ref,i}, N_{obs,i})}{\mathcal{L}(N_{obs,i}, N_{obs,i})} + \left(\frac{e}{\sigma_e}\right)^2$$

$$log\frac{\mathcal{L}(N_{ref,i}, N_{obs,i})}{\mathcal{L}(N_{obs,i}, N_{obs,i})} = \begin{cases} N_{ref,i} - N_{obs,i} + N_{obs,i} log\left(N_{obs,i}/N_{ref,i}\right) & (\text{if } N_{obs,i} > 0) \\ N_{ref,i} - N_{obs,i} & (\text{if } N_{obs,i} = 0) \end{cases}$$

where $(e/\sigma_e)^2$ is a penalty term of allowed energy shifts with an assigned systematic uncertainty of 3% ($\sigma_e = 0.03$). The best combination of (a,b,e) is found by minimising the χ^2. The best fit 'a' corresponds to the ratio between the observed and expected cross section, i.e. $\sigma_{obs} = a\,\sigma_{SM}$. The maximum and minimum values of 'a' in the interval $\Delta\chi^2 < 1$ define the range of statistical uncertainty.

6 Systematic errors

Several sources of systematic uncertainties were considered and their impact on the measurement was estimated as follows:

- An uncertainty of 3% on $E_{T,jet}$ was assigned to the energy scale of the jets and the effect on the acceptance correction was estimated using the signal MC.
- An uncertainty associated with elastic selection cut was estimated. The acceptance of $\eta_{max} < 3.0$ cut for (quasi-)elastic process was found to be 67%. In this analysis, the lower side of systematic error was estimated very conservatively by assuming 100% acceptance of this cut for (quasi-)elastic process. We found that the acceptance changed by +40%. The upper side of the systematic error was estimated by omitting the energy cut in the selection of the calorimeter cells used to calculate η_{max} with the MC. With this method, the effect was estimated to cause a 26.8% acceptance loss.
- The background shape uncertainty was estimated by using different slices of η_{max} in the fit. The background shape in the region of $3.0 < \eta_{max} < 4.0$ was not used to estimate the systematic error as a small fraction of signal events exist in this η_{max} region. The ratio of signal-to-background in this region is estimated to be 2.6% for $80 < M_{jets} < 100$ GeV while that in the other slices is less than 0.4%.
- The uncertainty associated with the luminosity was estimated to be 1.9%.

All systematics are listed in Table 1.

Source	Errors on cross-section
$E_{T,jet}$	(+2.1%, -1.7%)
η_{max}	(+36.5%, -28.6%)
b.g. shape	± 1.5%
lumi.	± 1.9%
Total	(+36.6%, -28.8%)

Table 1: List of systematic errors on Z^0 production cross-section measurement

7 Results

Figure 2 shows the invariant mass distribution in the signal region(blue points) together with the best fit result(solid line is signal+b.g. and dashed line is b.g. only). The best fit parameter 'a' is equal to 0.82 (the energy scale shift e was 0.028), so that $15.0^{+6.8}_{-6.4}$(stat.) events were observed. The extracted Z^0 elastic production cross-section and uncertainties are:

$$\sigma_{(ep\to eZ^0p^{(*)})} = 0.133^{+0.060}_{-0.057}\,(\text{stat.})^{+0.049}_{-0.038}\,(\text{syst.})\ \text{pb.}$$

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

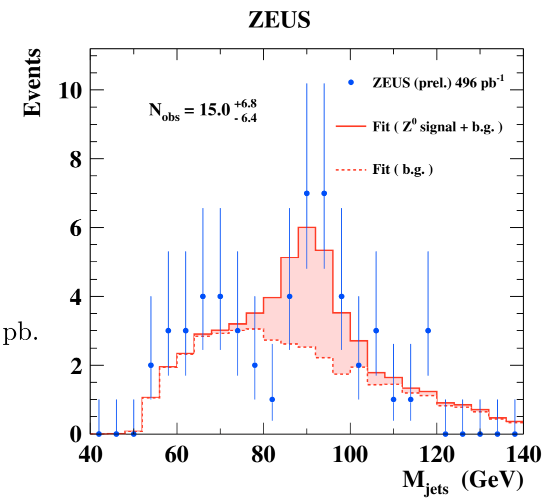

Figure 2: M_{jets} in signal region and best fit result

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