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Real W and Z bosons production at HERA

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Abstract. The production of real W and Z bosons has been studied in ep collisions at HERA. A combined analysis is performed with the data taken with the H1 and ZEUS detectors corresponding to 0.98 fb^{-1} of integrated luminosity to search for events containing an isolated electron or muon and missing transverse momentum, which is dominated by single W production. The total single W boson production cross section is measured as $1.06 \pm 0.16(\text{stat.}) \pm 0.07(\text{sys.})$ pb, in agreement with the Standard Model (SM) expectation of 1.26 ± 0.19 pb. The production of Z bosons has been studied in the reaction $ep \rightarrow eZp^{(*)}$, where $p^{(*)}$ stands for a proton or a low-mass nucleon resonance, using a data sample collected with the ZEUS detector amounting to 0.5 fb^{-1}. The Z is measured in the hadronic decay mode. The cross section of the reaction $ep \rightarrow eZp^{(*)}$ is measured to be $0.13 \pm 0.06(\text{stat.}) \pm 0.01(\text{syst.})$ pb, in agreement with the SM prediction of 0.16 pb.

1 Introduction

The Standard Model (SM) of particle physics has been tested for a long time by many experiments, and good agreement with data has been reported. In particular, excellent agreement in electro-weak sector, which is mediated by W and $Z/\gamma^{(*)}$ bosons, has been found. An important motivation of the HERA[1] physics program is to figure out the electro-weak interactions in ep collisions in measurements of deep-inelastic scattering (DIS). The cross sections of charged current (CC) and neutral current (NC) DIS were measured precisely with the H1 and ZEUS detectors[2] at HERA [1–3]. The HERA centre-of-mass energy of 318 GeV allowed measurement of them at high–Q^2 region up to 10^4 GeV^2, where Q^2 is the momentum transfer between the electron[3] and proton. In various experimental conditions, H1 and ZEUS reported that measured cross sections agree well with the SM predictions in whole Q^2 range. These results proved the calculations of the virtual exchanges of W and Z bosons in ep collisions in a wide Q^2 range. On the other hand, real W and Z bosons can be produced only from lepton or quark lines in ep collisions with the conservation of L and B numbers. Therefore, the cross sections are expected to be very small. Examples of the tree-level diagrams are shown in Fig. 1. Measurement of the W and Z bosons cross sections is important as a test of the SM. Another motivation is that these

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[1] HERA is the world's only ep collider, operated by DESY during 1992 to 2007.

[2] H1 and ZEUS are general-purpose detectors at HERA, which consist of tracking systems surrounded by electro-magnetic and hadronic calorimeters and muon detectors, covering approximately 4π sr in the solid angle. The x–y plane is called the transverse plane and ϕ is the azimuthal angle. The pseudo-rapidity η is defined as $\eta = -\ln\tan(\theta/2)$, where θ is the polar angle measured with respect to the proton beam direction (denoted as the forward direction).

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

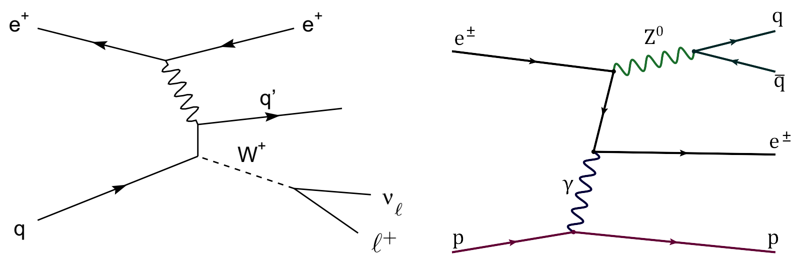

Figure 1. Examples of tree level diagrams of W (left) [7] and Z (right) [5] boson production in ep collisions.

are background processes for some physics beyond the SM. This note reports on the results of the W and Z bosons cross-section measurements in ep collisions at HERA. More details of both analyses can be found in [4] and [5].

2 W boson production measurement

2.1 Strategy of the analysis

Measurement of the W boson cross section has been performed in events with high transverse momentum (p_T) isolated lepton (electron or muon) and large missing transverse momentum, p_T^{miss}. Full data samples available to both H1 and ZEUS corresponding to 0.98 fb^{-1} of integrated luminosity are analyzed. This mode is interesting since existence of physics beyond the SM, e.g. anomalous triple gauge coupling and flavor changing neutral current single top production, may enhance events containing an additional hadronic final state of high transverse momentum, p_T^X. Therefore, in addition to the total single W production cross section, the differential cross section as a function of p_T^X is measured.

The EPVEC [6] Monte Carlo (MC) event generator is used to calculate the single W production cross section. The main reaction is $ep \to eWX$. Its cross section is calculated including quantum chromodynamics correction at next–to–leading order and its uncertainty is 15%, which arises from the uncertainties in the parton densities and scale at which the calculation is performed. The contribution of $ep \to \nu_e WX$ events to the total single W production cross section is approximately 7%. The $ep \to eZ(\to \nu\nu)X$ process has similar event topology with the signal, but is negligible in this analysis (< 3% contribution). The total cross section of single W production at HERA predicted by EPVEC is 1.26 ± 0.19 pb.

The main background processes are NC DIS events ($ep \to eX$) with mis-measured p_T^{miss} and CC DIS events ($ep \to \nu_e X$) with fake isolated leptons. A contribution of lepton pair production ($ep \to el^+l^-X$) is considered, via events where one lepton escapes detection and/or measurement errors cause apparent missing momentum. A small contribution to the background in the electron channel arises from QED Compton events ($ep \to e\gamma X$) when mis-measurement leads to apparent missing momentum. The background contribution to the W production measurement from photoproduction is negligible. All background processes are estimated by the MC.

2.2 Experimental method

The event selection for isolated electrons or muons and missing transverse momentum is based on those used by the H1 [7] and ZEUS [8] experiments. For the combined analysis, a common phase space is chosen in a region where both detectors have a high and well understood acceptance.

We require that there is at least one isolated electron or muon which is defined as the following.

- $p_{\mathrm{T}} > 10\,\mathrm{GeV}$;
- $15^\circ < \theta_l < 120^\circ$, where θ_l is lepton polar angle;
- $D\,(l;\mathrm{jet}) > 1.0$ and $D\,(l;trk) > 0.5$, where $D\,(l;\mathrm{X})$ is distance from nearest jet (track) in η–ϕ plane.

To avoid the overlap of two analyses, the electron channel should not include isolated muon.

The missing p_{T} is required to be greater than 12 GeV. To ensure a high trigger efficiency, p_{T} measured in the calorimeter, $p_{\mathrm{T}}^{\mathrm{calo}}$ is also required to be greater than 12 GeV. The energy deposited by muons in the calorimeter is small, so the $p_{\mathrm{T}}^{\mathrm{calo}}$ requirement is effectively a cut on p_{T}^{X}. Thus, a cut $p_{\mathrm{T}}^{X} > 12\,\mathrm{GeV}$ is applied only for the muon channel.

In order to reduce the remaining SM background (mainly NC events), events are required to satisfy the following cuts:

- $V_{\mathrm{ap}}/V_{\mathrm{p}} < 0.5$, where $V_{\mathrm{ap}}/V_{\mathrm{p}}$ is the ratio of the anti-parallel to parallel momentum components of all measured calorimetric clusters with respect to the direction of the total calorimetric transverse momentum.
- $V_{\mathrm{ap}}/V_{\mathrm{p}} < 0.15$ if $p_{\mathrm{T}}^{X} < 25\,\mathrm{GeV}$;
- $\Delta\phi_{l-X} < 160^\circ$ (170°) for electron (muon) channel, where $\Delta\phi_{l-X}$ is the azimuthal difference between lepton and the hadronic system, to reject back–to–back like SM backgrounds;
- $M_{\mathrm{T}}^{l} > 10\,\mathrm{GeV}$, where M_{T}^{l} is the transverse mass reconstructed by lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$.
- For the electron channel:
  - $5 < \delta_{\mathrm{miss}} < 50\,\mathrm{GeV}$, where $\delta_{\mathrm{miss}} = 2E_e^0 - \sum_i (E_i - p_{\mathrm{Z},i})$; E_e^0 is beam electron energy, E_i is the energy of the i-th calorimeter cell and the sum runs over all cells. δ_{miss} is zero for an event where only momentum in the proton direction is undetected.
  - $\zeta_e^2 = 4E_eE_e^0\cos^2\theta_e/2 > 5000\,\mathrm{GeV}^2$ for $p_{\mathrm{T}}^{\mathrm{calo}} < 25\,\mathrm{GeV}$, where E_e is the energy of the final state electron and θ_e is its polar angle. For NC events, where the scattered electron is identified as the isolated high transverse momentum electron, ζ_e^2 is equal to the four momentum transfer squared Q_e^2, as measured by the electron method [9].

The overall H1(ZEUS) selection efficiency in the common phase space is estimated using EPVEC to be 30% (31%) for SM $W \to e\nu$ events and 11% (9%) for SM $W \to \mu\nu$ events.

2.3 Results

After the all selections, 81 events are observed in the final sample, while 87.8 ± 11.0 events are expected. Fig. 2 shows good agreement between the observed data and MC in all kinematic distributions. The contribution from signal processes to the total H1 (ZEUS) SM expectation in the electron channel is 76% (65%) and in the muon channel 93% (83%). The total systematic uncertainties determined in the combined analysis are found to be the same as those derived by the individual experiments. A detailed list of systematic uncertainties considered can be found in the respective publications [7, 8]. The total W boson production cross section at HERA is measured as:

$$\sigma\,(ep \to WX) = 1.06 \pm 0.16\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{sys.})\ \mathrm{pb}, \tag{1}$$

in agreement with the SM prediction of $1.26 \pm 0.19\,\mathrm{pb}$.

At large hadronic transverse momentum region of $p_{\mathrm{T}}^{X} > 25\,\mathrm{GeV}$, 29 events are observed, which is comparable with the SM prediction of 24.0 ± 3.2. The differential cross section as a function of p_{T}^{X} is shown in Fig. 3, which is calculated by taking into account the acceptance bin by bin using MC. It also agrees well with the SM prediction, even in the high p_{T}^{X} region.

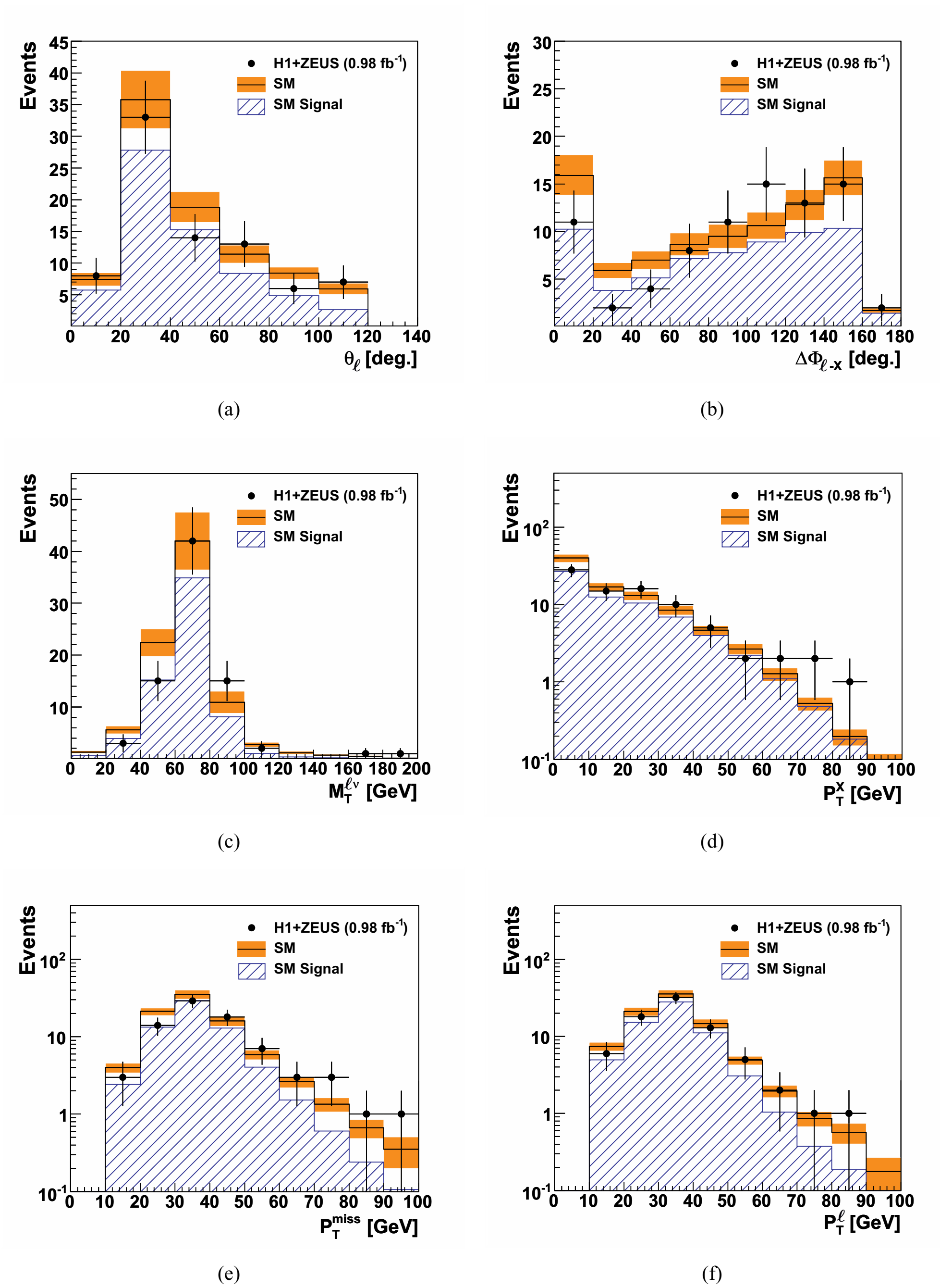

Figure 2. Distributions of kinematic variables of events with an isolated electron or muon and missing transverse momentum in the full HERA $e^{\pm}p$ data [4]. Shown are: the polar angle of the lepton θ_l (a), the difference in the azimuthal angle of the lepton and the hadronic system $\Delta\phi$ (b), the lepton-neutrino transverse mass $M_{\mathrm{T}}^{l\nu}$ (c), the hadronic transverse momentum p_{T}^{X} (d), the missing transverse momentum $p_{\mathrm{T}}^{\mathrm{miss}}$ (e) and the transverse momentum of the lepton p_{T}^{l} (f). The data (points) are compared to the SM expectation (open histogram). The signal component of the SM expectation is shown as the hatched histogram. The total uncertainty on the SM expectation is shown as the shaded band.

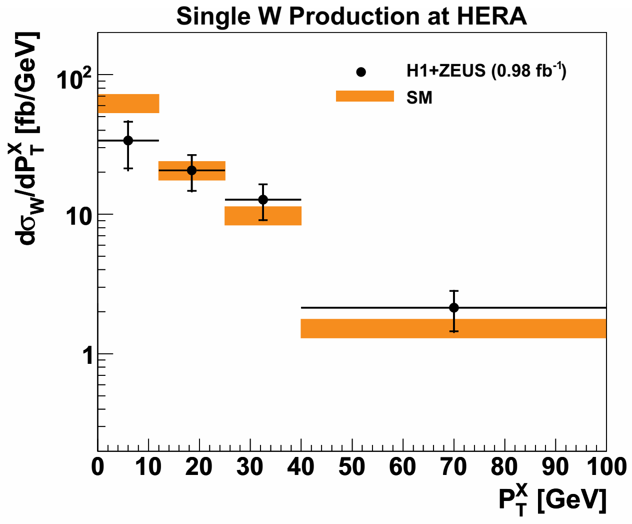

Figure 3. The single W production cross section as a function of the hadronic transverse momentum, p_{T}^{X}, measured using the combined H1 and ZEUS data [4]. The inner error bar represents the statistical error and the outer error bar indicates the statistical and systematic uncertainties added in quadrature. The shaded band represents the uncertainty on the SM prediction.

3 Z boson production measurement

3.1 Analysis overview

The production of Z bosons has been measured using data collected with the ZEUS detector corresponding to $0.5\,\mathrm{fb}^{-1}$. The Z cross section is much smaller than W, so the hadronic decay mode is chosen because of the large branching ratio. It allows the excellent resolution of the ZEUS hadronic calorimeter to be exploited to the full. The analysis is restricted to elastic and quasi-elastic Z production in order to suppress QCD multi-jet background. The selected process is $ep^{(*)} \to eZp^{(*)}$, 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 direction, in contrast to what would be expected in inelastic collisions.

Single Z production simulated events are generated by the same MC event generator as used for W production, EPVEC. The cross section in the (quasi-) elastic reaction ($ep^{(*)} \to eZp^{(*)}$) is calculated to be 0.16 pb and those of DIS ($\gamma^{*}p \to ZX$) and resolved photoproduction ($\gamma p \to (q\bar{q} \to Z)\,X$) is 0.24 pb. The difference between $e^{+}p$ and $e^{-}p$ cross sections is negligible for this analysis ($< 1\%$ for the DIS process).

A reliable prediction of the 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 is estimated with a data-driven method. The normalization is determined by a fit to the data.

3.2 Event selection

The hadronic Z decay sample is selected by the following requirements on the reconstructed jets:

- at least two jets in the event with $E_T > 25\text{GeV}$, where E_T is the jet transverse energy;
- $|\Delta\phi_j| > 2.0$ 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 boson decays are expected to be nearly back-to-back in the x–y plane.

The invariant mass, M_{jets} is reconstructed by using all of jets with $E_T > 4\text{GeV}$ and $|\eta| < 2.0$.

The following cuts are applied to suppress low-Q^2 NC and direct photoproduction backgrounds:

- $E_{\text{RCAL}} < 2\text{GeV}$, where E_{RCAL} is the total energy deposit in rear calorimeter;
- $-5 < \delta_{\text{miss}} < 9\text{GeV}$: as explained in Sec. 2.2, δ_{miss} is zero for an event where only momentum in the proton direction is undetected;
- There is at most one electron with $\theta_e < 80°$, to take into account that beam electron is back scattered to the forward calorimeter or forward beam pipe due to large mass of the produced Z boson.

Finally, in order to require elastic and quasi-elastic scattering, a condition of $\eta_{\text{max}} < 3.0$ is required, where η_{max} is the maximum pseudo-rapidity of the calorimeter energy deposits. This requirement largely suppress the inelastic background events, in which η_{max} of much larger than 3.0 is given by the calorimeter deposits due to the proton remnant.

After all selection cuts, 54 events remain. The total selection efficiency is 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 purity of elastic and quasi-elastic processes is 98%.

3.3 Background estimation

Figure 4 (a) shows the M_{jets} distribution after all the selection criteria except for the η_{max} requirement. Figs. 4 (b)-(d) show the M_{jets} distributions in various η_{max} slices after the same selection. No significant dependence on η_{max} of the M_{jets} distribution beyond that caused by statistical fluctuations is observed in the non-signal region. In addition, the shape of the M_{jets} distribution outside of the Z mass window in the signal region ($\eta_{\text{max}} < 3.0$) is found to be consistent with that in the non-signal region (Fig. 5). Therefore, the shape of the M_{jets} distribution in the non-signal region is adopted as a background template in a fit to the data in the signal region.

3.4 Cross-section extraction

The cross section is obtained by the fitting the sum of the signal and a background template for the M_{jets} distribution to the observed data. The template $N_{\text{ref},i}$ is defined according to:

$$N_{\text{ref},i} = aN_{MC}^{\text{sg},i}(\epsilon) + bN_{\text{data}}^{\text{bg},i}, \tag{2}$$

where i is the bin number of the M_{jets} distribution. The parameter ϵ accounts for a possible energy shift, i.e. $M_{\text{jets}} = (1+\epsilon)\,M_{\text{jets}}^{\text{MC}}$, where $M_{\text{jets}}^{\text{MC}}$ is the invariant mass distribution of signal MC. $N_{MC}^{\text{sg},i}$ is the number of signal expectation after the all selection cuts quoted by the MC. $N_{\text{data}}^{\text{bg},i}$ is the number of events observed in $\eta_{\text{max}} > 3.0$ region. The parameters 'a' and 'b' are normalization factors for the signal and background, and treated as free parameters in a binned maximum likelihood fit. The ϵ is also the fitting parameter, and a possible shift of the Z mass peak by ϵ of 3% is taken into account in the likelihood. The best fit parameter a is determined to be $0.82^{+0.38}_{-0.35}$. Figure 5 shows the M_{jets} distribution after all the selections. It also shows the fit result. The main source of the systematic

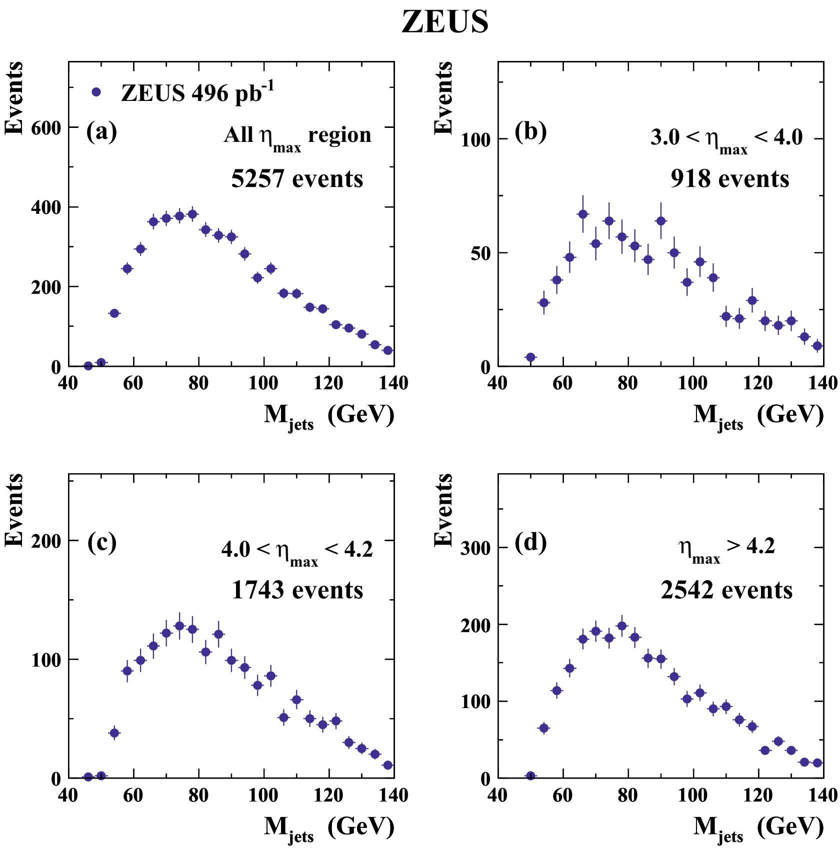

Figure 4. The reconstructed Z mass distribution of the data (a) after all selection criteria, except for the $\eta_{\max}$ cut, (b-d) in several $\eta_{\max}$ slices [5].

uncertainty comes from the difference of the shapes of $\eta_{\max}$ distributions between data and MC. The total systematic uncertainty is (+7.2, -6.2)%. More details can be found in [5]. The observed cross section of the reaction $ep \to eZp^{(*)}$ obtained by the fit is:

$$\sigma\left(ep \to eZp^{(*)}\right) = 0.13 \pm 0.06\,(stat.) \pm 0.01\,(sys.)\,, \tag{3}$$

in agreement with the SM prediction of 0.16 pb.

4 Conclusion

Measurements of cross sections of W and Z bosons in ep collisions have been performed. These processes are important not only to test the Standard Model but also to understand the background processes for physics beyond the Standard Model. The total W boson cross section is measured in the search for events with isolated lepton and missing transverse momentum to be $1.06 \pm 0.16\,(\text{stat.}) \pm 0.07\,(\text{sys.})$ pb, using combined data of H1 and ZEUS experiments amounting to 0.98 fb^{-1} of integrated luminosity. The differential cross section as a function of p_T^X is also derived. The Z boson cross

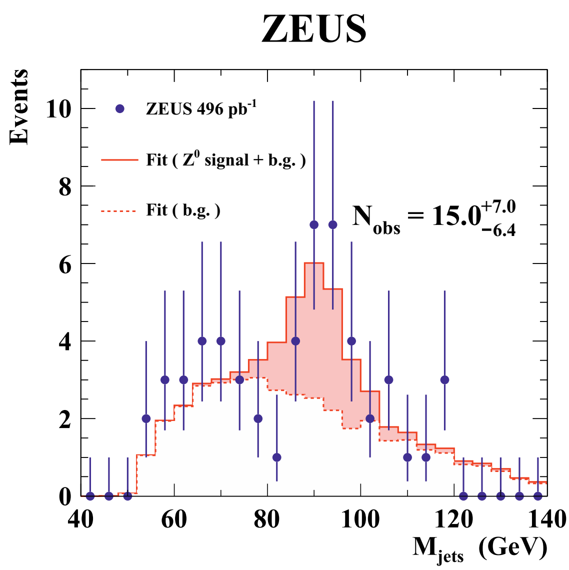

Figure 5. The reconstructed Z mass distribution and the fit result [5]. The data are shown as points, and the fitting result of signal+background (background component) is shown as solid (dashed) line. The error bars represent the approximate Poisson 68% C.L. intervals, calculated as $\pm\sqrt{n + 0.25} + 0.5$ for a given entry n.

section in elastic or quasi-elastic scattering is obtained as 0.13 ± 0.06 (stat.) ± 0.01 (sys.) pb. The Z is measured in the hadronic decay mode, using 0.5 fb^{-1} data collected with ZEUS. Both results are in good agreement with the Standard Model predictions.

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