ELECTROWEAK RESULTS FROM HERA

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Neutral and charged current deep inelastic ep scattering with longitudinally polarised lepton beams has been studied with the H1 and ZEUS detectors at HERA. The differential cross sections were measured in the range of four-momentum transfer squared, Q^2, up to 50'000 GeV^2, where electroweak effects become clearly visible. The measurements were used to determine the structure function xF_3 and to constrain vector and the axial-vector couplings of the light quarks to the Z^0 boson. The polarisation dependence of the charged current total cross section was also measured.
Limits on flavour changing neutral current processes were computed from the search for single-top production. The elastic Z^0 production cross section was measured to be in agreement with the SM prediction. Limits on new physics phenomena at high Q^2 were also derived within the general framework of four-fermion $eeqq$ contact interactions.

1 Introduction

The HERA accelerator was built at DESY, Hamburg, to study electron-proton and positron-proton collisions at center of mass energies of up to 320 GeV. Scattering events were reconstructed in two multi-purpose detectors, H1[1] and ZEUS[2], both equipped with silicon tracking, drift chambers, hermetic calorimetry and muon detector systems. During the so called HERA I running phase (1994-2000), about 100 pb^{-1} of data were collected per experiment, mainly coming from e^+p collisions. After the collider upgrade in 2000-2001, resulting in significant increase of luminosity, about 400 pb^{-1} of data per experiment were collected in the so called HERA II phase (2002-2007). Moreover, spin rotators installed at the H1 and ZEUS interaction regions allowed the operation with longitudinal electron or positron polarisation. With an average lepton beam polarisation of about 30-40% and a significant increase of integrated luminosity (especially for the e^-p sample), HERA II significantly extended the physics reach of the experiments. Different detector configurations and complementary event reconstruction methods used by two collaborations allowed for an additional reduction of not only the statistical but also the systematic uncertainties in the combined analysis of H1 and ZEUS data.

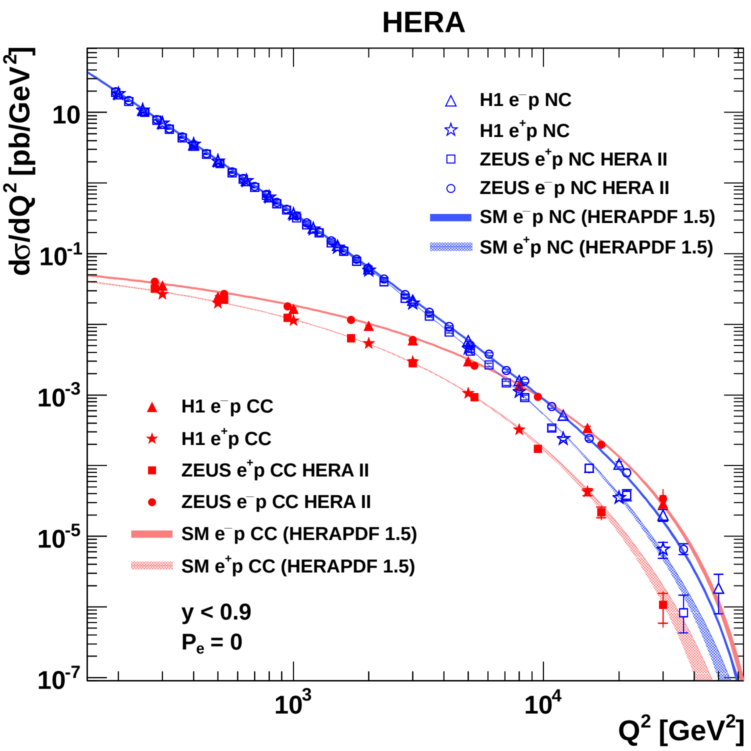

Figure 1: Q^2 dependence of the NC and CC cross sections $d\sigma/dQ^2$ for the combined HERA I+II unpolarised e^-p and e^+p data. The inner and outer error bars represent the statistical and total errors, respectively. The H1 and ZEUS data are compared to the Standard Model expectation based on the HERAPDF 1.5 parametrisation.

2 Deep Inelastic $e^{\pm}p$ Scattering

Deep Inelastic Scattering (DIS) was the main process studied at HERA. Precise HERA data are in excellent agreement with Standard Model predictions over many orders of magnitude, as illustrated in Figure 1. At very high squared momentum transfers Q^2, comparable with masses of the W and Z bosons squared, the contributions from neutral current (NC) and charge current (CC) processes become comparable in size, which is a clear demonstration of electroweak unification.

High Q^2 NC DIS cross section, neglecting radiative corrections, can be written in terms of three generalised structure functions $\tilde{F}_2$, $x\tilde{F}_3$ and $\tilde{F}_L$:

$$\frac{d^2\sigma^{\rm NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^{\pm} \mp Y_- x\tilde{F}_3^{\pm} - y^2\tilde{F}_L^{\pm}\right]$$

where: $Y_{\pm} = 1 \pm (1-y)^2$. The sensitivity to electroweak effects is mainly due to the interference of photon and Z boson exchange which dominates over pure Z exchange effects in most of the kinematic range covered at HERA. Corresponding contributions to the generalised structure functions can be written as:

$$\tilde{F}_2^{\pm} = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z\, F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2\; F_2^Z$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\chi_Z\, xF_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_Z^2\, xF_3^Z$$

where P_e is the lepton beam polarisation and $\chi_Z = \frac{1}{\sin^2 2\theta_W}(\frac{Q^2}{M_Z^2+Q^2})$. Access to electroweak effects is provided by measuring differences between cross section for different charges and polarisation, thereby removing the pure photon-exchange part, described by F_2^{γ}. In particular, polarisation asymmetries can be used to constrain contribution from $F_2^{\gamma Z}$ structure function,

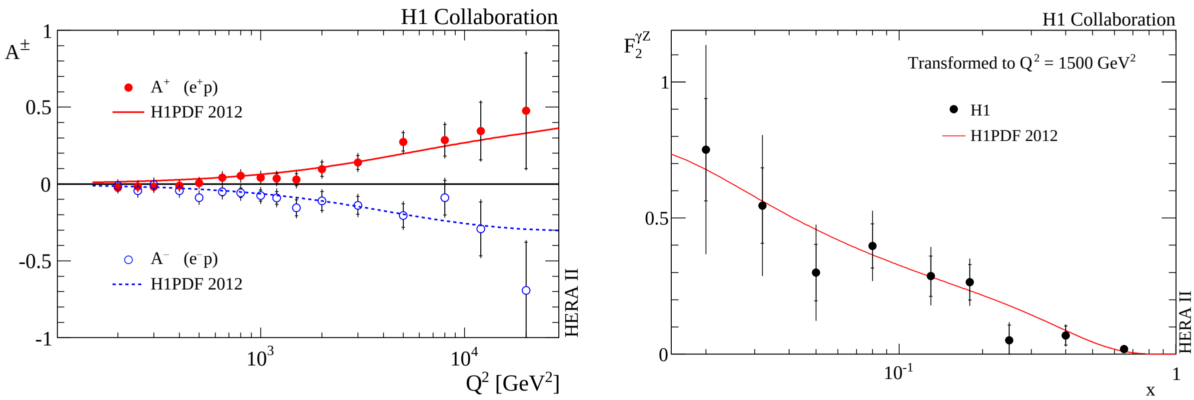

Figure 2: Left: Q^2 dependence of the polarisation asymmetry $A^{\pm}$, as measured by the H1 Collaboration, compared to the Standard Model expectation. Right: structure function $F_2^{\gamma Z}$, extrapolated to $Q^2 = 1\ 500\ \mathrm{GeV}^2$, for the H1 data (solid points) and the expectation from H1PDF 2012 (solid curve). The inner error bars represent the statistical uncertainties and the full error bars correspond to the total uncertainties.

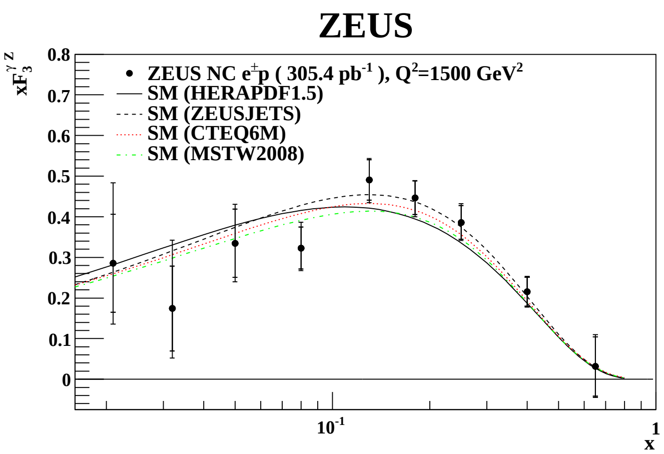

Figure 3: The structure function $xF_3^{\gamma Z}$, extrapolated to $Q^2 = 1\ 500\ \mathrm{GeV}^2$, and plotted as a function of x. The closed circles represent the ZEUS data, with the inner error bars showing the statistical uncertainties while the outer ones show the statistical and systematic uncertainties added in quadrature. The curves show the predictions of the SM evaluated using different PDF parametrisations, as indicated in the plot.

which is sensitive to d/u ratio at high-x and to the vector quark couplings, v_q. A comparison of e^-p and e^+p cross sections, i.e. the measurement of the charge asymmetry, accesses the $xF_3^{\gamma Z}$ contribution, which is dominated by the valence quark distributions at high Q^2 and is sensitive to the axial-vector quark coupling, a_q.

Both, the H1 and ZEUS experiments, have measured neutral current DIS cross sections for both charges and both helicity states. Results on polarised cross-section asymmetries, $A^{\pm}$, as obtained by the H1 Collaboration[3], are shown in Figure 2 (left). Parity violation due to $\gamma - Z$ interference is clearly visible, in agreement with Standard Model expectations. The measurement can also be used to extract the $F_2^{\gamma Z}$ contribution, as illustrated in Figure 2 (right). Shown in Figure 3 is the measurement of the structure function $xF_3^{\gamma Z}$ by the ZEUS Collaboration[4]; a similar measurement has been also performed by H1 [3]. The results agree very well with the Standard Model predictions obtained from NLO QCD fits to inclusive data.

The CC DIS cross-section dependence on the longitudinal lepton-beam polarisation also follows exactly the Standard Model predictions, as shown in Figure 4. For electron beams, only the left-handed initial state contributes to the scattering cross-section, whereas for positrons only the right-handed state contributes. This is expected from the chiral structure of the model. The results can be used to set limits on the possible contribution from right-handed currents.

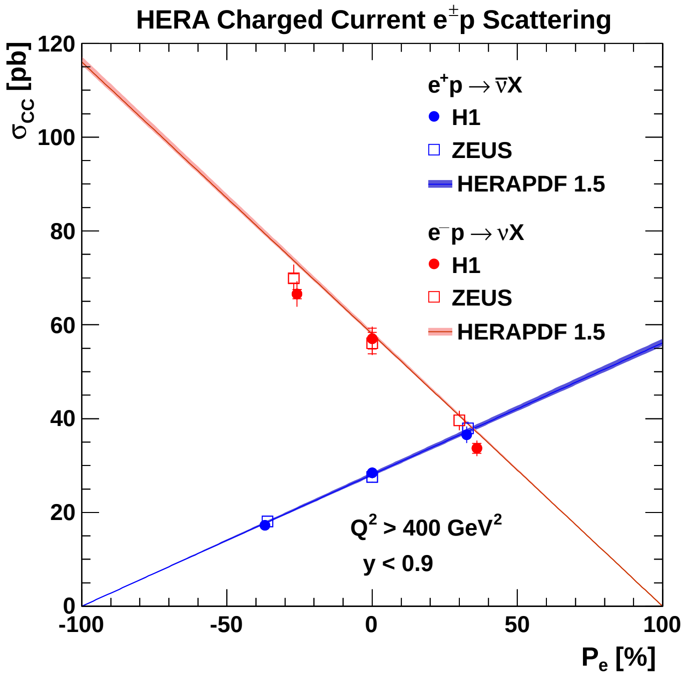

Figure 4: Dependence of the total $e^{\pm}p$ CC cross sections on the longitudinal lepton beam polarisation, P_e. The H1 and ZEUS data are compared to the Standard Model expectations based on the HERAPDF 1.5 parametrisation (shaded bands).

Assuming SM couplings and a light right handed ν_e, the H1 collaboration excluded the existence of right handed weak bosons of masses below 214 (194) GeV for e^-p (e^+p) scattering.

The wide kinematic range covered, and the high precision of the NC and CC DIS measurements for polarised e^-p and e^+p, allow not only the determination of the parton distribution functions of the proton from the HERA data alone, but also allow the simultaneous determination of PDFs and electroweak parameters. Results on the weak neutral current couplings of u and d quarks to the Z^0 boson, as obtained by the H1 Collaboration[5], are presented in Figure 5. Results from the earlier ZEUS analysis and limits determined by the CDF experiment and the LEP EWWG are included for comparison. A good agreement with the Standard Model predictions is observed. Determinations of the light-quark couplings at HERA turn out to be competitive in precision with those obtained from the Tevatron and LEP experiments.

DIS cross sections at HERA are also sensitive to possible new interactions between electrons and quarks involving mass scales above the center-of-mass energy, which could modify the cross sections at high Q^2 via virtual effects. This would result in observable deviations from the Standard Model predictions. Many new interactions, such as processes mediated by heavy leptoquarks, can be modeled as four-fermion contact interactions. The H1 Collaboration applied a common method to search for deviations from SM predictions for different new physics scenarios, which can be considered within this framework. Data on scattering of polarised electrons and positrons collected from HERA II were combined with electron and positron data from HERA I. No significant deviation from the Standard Model predictions was observed, as shown in Figure 6 (left) and 95% limits were derived for the relevant parameters of the models studied. For the general contact-interaction models, limits on the compositeness scale, Λ, ranging from 3.6 to 7.2 TeV were obtained, as shown in Figure 6 (right). The study of leptoquark exchange yielded lower limits on the ratio M_{LQ}/λ between 0.41 and 1.86 TeV. For models with large extra dimensions, scales below 0.96 TeV were excluded. Finally, a quark-charge radius larger than $0.65 \cdot 10^{-16}$ cm was excluded, using the classical form-factor approximation.

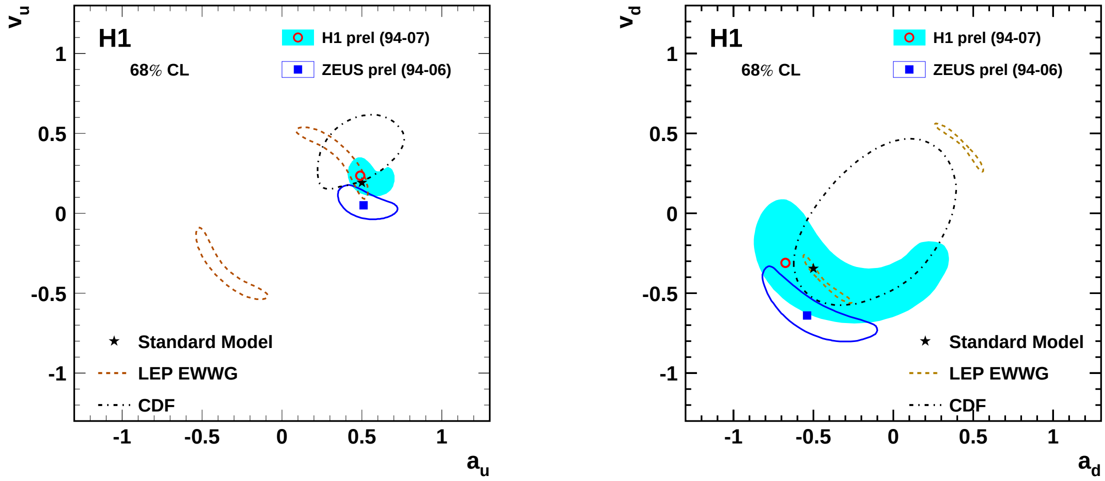

Figure 5: Results at 68% C.L. on the weak neutral current couplings of u (left plot) and d (right plot) quarks to the Z^0 boson, determined from an H1 analysis of HERA I and HERA II data. Results from a ZEUS analysis and limits determined by the CDF experiment and the LEP Electroweak Working Group (open contours) are included for comparison. The stars show the expected SM values.

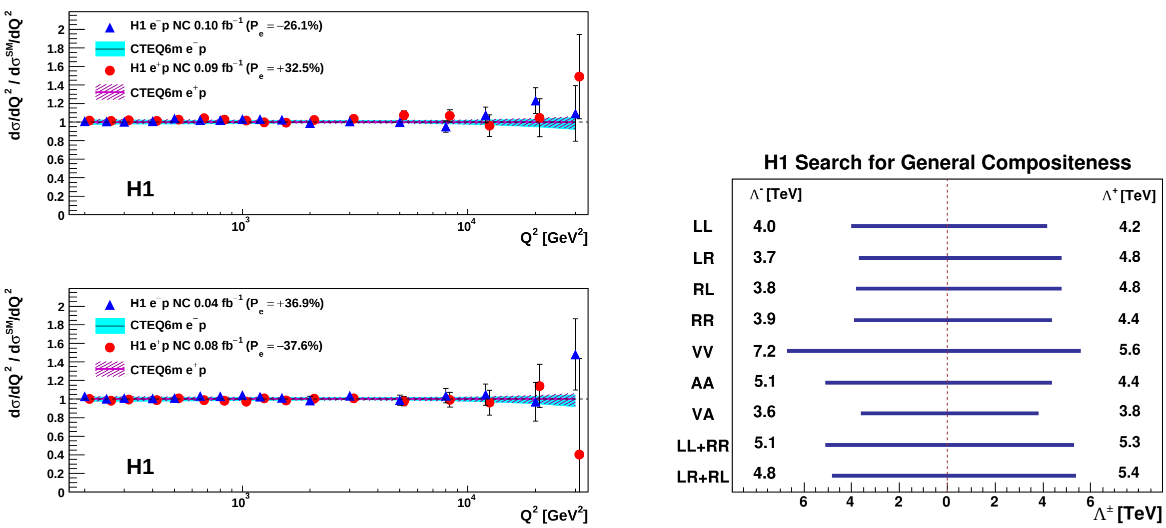

Figure 6: Left: The ratio of the measured cross section to the Standard Model prediction, determined using the CTEQ6m PDF set, for polarised H1 NC DIS data taken from the year 2003 onward for different lepton charge and polarisation data sets. Right: Lower limits at 95% CL on the compositeness scale Λ for various chiral models, obtained from the full H1 data. Limits are given for both signs Λ^- and Λ^+ of the chiral coefficients.

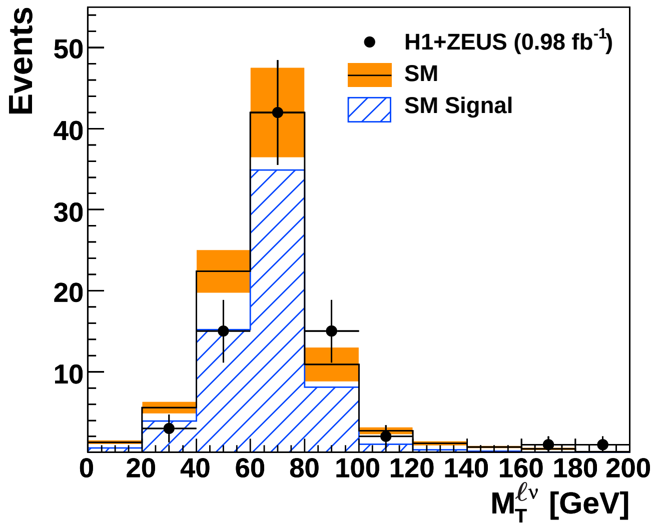

Figure 7: Distribution of the lepton-neutrino transverse mass $M_T^{l\nu}$ for events with an isolated electron or muon and missing transverse momentum in the full HERA $e^{\pm}p$ data sample.

3 Electroweak cross sections

Both the H1 and ZEUS Collaborations have used the high statistics of the collected data to study a variety of processes sensitive to electroweak interactions, in particular the production of heavy weak bosons and the top quark. One of the interesting signatures, which was considered in the combined H1 and ZEUS analysis, is production of isolated high-p_T leptons (electrons or muons) and a large missing transverse momentum. The main SM process that may produce events with this topology is the production of real W bosons via photoproduction with a subsequent leptonic decay: $ep \rightarrow eW^{\pm}(\rightarrow l\nu)X$. Only with the full HERA high energy data, corresponding to an integrated luminosity of 0.98 fb^{-1}, a cross section measurement for $W^{\pm}$ production in this process became accessible. The expected numbers of signal and background events, after the final selection cuts, were 64.7±9.9 and 23.1±3.3 respectively (total of 87.8±11.0) and observed in the final data sample were 81 events. The distribution of the lepton-neutrino transverse mass, $M_T^{l\nu}$, for the final sample of selected H1 and ZEUS events is shown in Figure 7. The resulting cross section estimate is:

$$\sigma_W \quad = \quad 1.06 \pm 0.16(stat.) \pm 0.07(sys.)\ pb\ ,$$

in agreement with the SM prediction of 1.26 ± 0.19 *pb*.

A similar selection procedure can be used to search for single-top production at HERA. In addition to an isolated lepton and missing transverse momentum, a large hadronic transverse momentum, P_T^{had}, is expected. A b-tagging algorithm can additionally be used to suppress the W production background. Even though the SM cross section for single top production at HERA is below 1 fb, the measurement of this process is important, as a significant enhancement is expected in several BSM scenarios due to FCNC couplings. A search for anomalous single top production was performed using the data collected with the ZEUS detector and a limit on the production cross section $\sigma < 0.13$ pb (95% CL) was set[8]. The cross section limits were converted into limits on the anomalous top quark couplings and the branching ratios $t \rightarrow u\gamma$ and $t \rightarrow uZ$, as shown in Figure 8.

Also in case of the Z^0 production at HERA, the SM cross section is predicted to be very low, about 0.4 pb. The ZEUS Collaboration studied this process using an integrated luminosity of about 0.5 fb^{-1}. Thanks to the excellent energy resolution of the ZEUS hadronic calorimeter, the

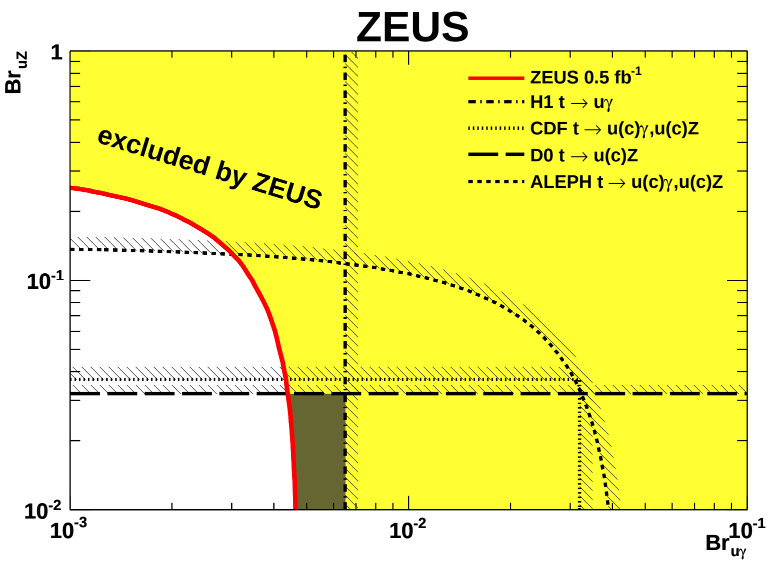

Figure 8: ZEUS limits on the anomalous top quark couplings shown in the BR($t \to u\gamma$) vs BR($t \to uZ$) plane. Also shown are corresponding boundaries from H1, CDF, D0 and ALEPH experiments. The shaded area is excluded. The dark shaded region denotes the area uniquely excluded by ZEUS.

hadronic decay mode could be used in this analysis, significantly increasing the expected event rate. The analysis[9] was restricted to elastic and quasi-elastic Z^0 production in order to suppress QCD multi-jet background. Figure 9 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 invariant mass distribution measured for inelastic events was used as a background template in the fit. The fitted number of observed Z^0 events is $15.0^{+7.0}_{-6.4}$, which corresponds to a 2.3 σ statistical significance. The cross section for the elastic and quasi-elastic production of Z^0 bosons at $\sqrt{s} = 318$ GeV was calculated to be

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

This result is consistent with the SM cross section estimate of 0.16 pb.

4 Conclusions

With high luminosity and lepton beam polarisation, HERA provided a unique window for precise electroweak studies. Although data taking was completed in 2007, the H1 and ZEUS collaborations are still working hard, making progress in understanding the detector and finalizing various data analyses. The results presented at this conference are only a small selection of recently completed work.

The presented results on the NC and CC DIS at high Q^2, including charge and polarisation asymmetries, are in very good agreement with the SM. With the high precision and the large kinematic coverage of the data, the NLO QCD analysis was extended to extract not only parton densities in the proton but to fit electroweak parameters as well. The obtained constraints on the light-quark couplings to the Z^0 boson are in good agreement with the Standard Model predictions and are competitive in precision with LEP and Tevatron measurements. The precise measurements of deep inelastic $e^{\pm}p$ scattering at large Q^2 were also exploited to search for possible "new physics" beyond the Standard Model. As no significant deviation from the Standard Model predictions was observed, limits were derived for different models of new physics.

The production of electroweak bosons and top quarks in ep collisions are also good benchmark processes for testing the Standard Model. The full HERA data sample from both experiments was analysed, corresponding to a total integrated luminosity of 0.98 fb^{-1}, in a search for

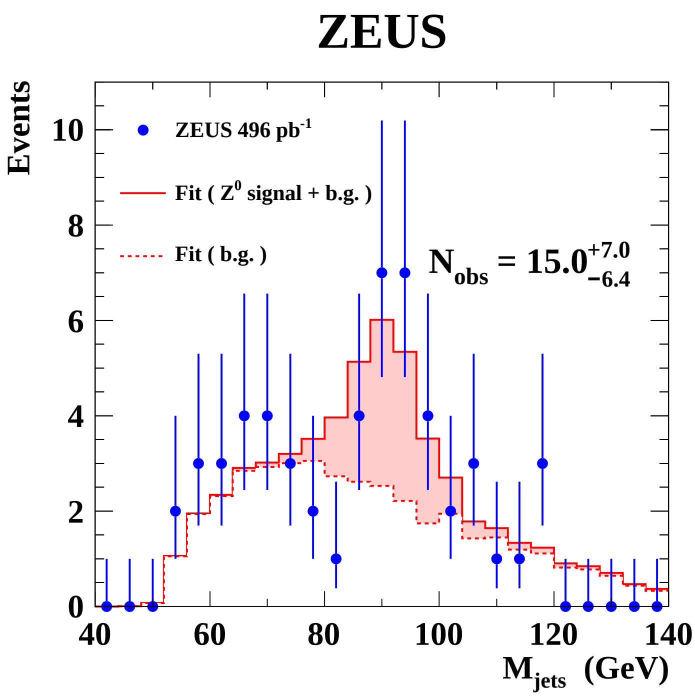

Figure 9: The invariant-mass distribution for the selected sample of elastic and quasi-elastic Z^0 production events. ZEUS data (solid points) are compared with the fit result for the signal plus background and the background shape template based on the inelastic events.

$W^\pm$ production. The total and differential single W production cross sections were measured to be in agreement with the SM predictions. An analysis of the ZEUS Collaboration resulted in the first observation of Z^0 production in ep collisions, with $15.0^{+7.0}_{-6.4}$ signal events, corresponding to a 2.3 σ statistical significance. The resulting cross section for elastic and quasi-elastic production of Z^0 bosons is consistent with the SM prediction.

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