ELECTROWEAK PHYSICS AT HERA

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The status of results obtained at HERA concerning electroweak physics in deep inelastic electron-proton scattering is reviewed. At HERA I electroweak unification has been demonstrated . In a global fit to the measured proton structure functions QCD and electroweak parameters are determined simultaneously. The availibility of polarized electrons at HERA II allows to determine the chirality properties of NC and CC interactions at high spacelike momentum transfers.

1. Results from the HERA I phase

The electron proton collider operates since 1993 at cms energies above 300 GeV_2. Already the very first data accumulated in 1993 allowed to observe the Charged-Current (CC) deep inelastic scattering (DIS) process at high high spacelike momentum transfers Q^2 and establish the W propagator effect [1]. Figure 1 shows the measured CC cross section converted to an equivalent fix target neutrino nucleon scattering cross section. The rise of the cross section deviates clearly from linear indicating the finite mass in the spacelike W propagator. In the HERA I phase (1993 - 2000) both experiments, H1 and ZEUS, accumulated more than 100 pb^{-1} each in e^+p and e^-p scattering. This amount of luminosity allowed to study electroweak effects extending into kinematic regions where the four momentum tranfer Q exeeds the masses of the gauge bosons W and Z. Figure 2 show the cross sections differential in Q^2 for NC and CC scattering with e^+p and e^-p. Whereas the NC cross sections exeeds the CC cross section at low values of Q^2 by several orders of magnitude they become similar in the region where $Q^2 \sim M_W^2, M_Z^2$. This is the first direct demonstration of electroweak unification in spacelike DIS scattering. The Figure also shows the sensitivity of the cross section to the lepton charge. In NC scattering the difference arises from the Z exchange resulting in different signs of the $\gamma - z$ interference term. The difference in CC scattering results from dependence on the quark type (u or d -type) and the the chirality dependence. All

data sets agree well with the Standard Model (SM) predictions. Since it is evident that the exploration of the high Q^2 region is still statistics limited, the high luminosity phase at HERA II will allow to test this region with much higher precision

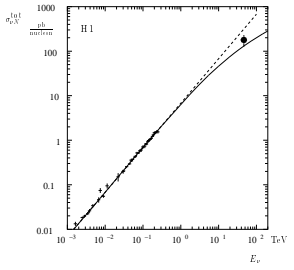

Figure 1. CC crosss sections as function of fixed target lepton energy.

sectionCombined Electroweak-QCD Analysis Using the deep inelastic e^+p and e^-p charged and neutral current scattering cross sections derived from HERA I data, H1 performed a combined electroweak and QCD analysis **??** to determine electroweak parameters accounting for their correlation with parton distributions. The basis for this combined EW-QCD analysis is the H1 QCD analysis, the so-called H1PDF2000 **??**. In that analysis the cross sections were fitted describing the parton distributions by 10 free parameters while fixing the electroweak parameters to their SM values. In the combined EW-QCD anlysis additional electroweak parameters are fitted.

The additional free parameters depend on the choice of the electroweak renormalization scheme. The On-MASS-Shell scheme (OMS) uses the weak boson masses as fundamental parameters, in the Modified-On-MASS-Shell scheme (MOMS) the Fermi constant G_F is taken as a fundamental parameter instead of M_W.

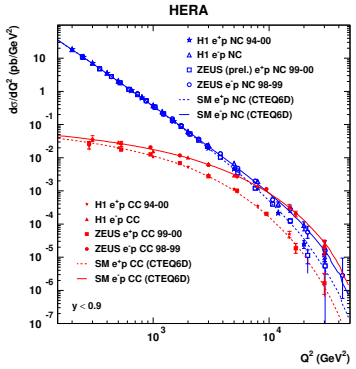

Figure 2. Differentiell cross section for NC and CC e^+-p and e^--p scattering

In the MOMS the CC cross section reads

$$\frac{d^2\sigma^{\rm CC}(e^{\pm}p)}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{M_{prop}^2}{M_{prop}^2+Q^2}\right]^2 \phi_{CC}^{\pm}(x,Q^2)\left(1+\Delta_{CC}^{\pm,weak}\right)\,, \quad (1)$$

$$\text{with} \quad \phi_{CC}^{\pm}(x,Q^2) = \frac{1}{2}\left[Y_+ W_2^{\pm}(x,Q^2) \mp Y_- x W_3^{\pm}(x,Q^2) - y^2 W_L^{\pm}(x,Q^2)\right] \quad (2)$$

Here G_F determines the normalization and the W mass entering the formular is the *propagator mass* M_{prop}. Within the OMS scheme the Fermi constant G_F is expressed by

$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}\frac{1}{1-\ Deltar}\,, \quad (3)$$

where $\alpha \equiv \alpha(Q^2=0)$ is the fine structure constant and the term Δr contains the EW radiative corrections, sensitive to the Higgs and top masses.

In the first fit (MOMS scheme) the parameters G_F and M_{prop} in equation **??** are considered as independent. The result of this 12 parameter EW-QCD fit is shown in Figure **??**. Whenthe well measured Fermi constant is fixed to its PDG value the propagator mass found to be

$$M_{\rm prop} = 82.87 \pm 1.82_{\rm exp}\ ^{+0.30}_{-0.16}\big|_{\rm model}\ {\rm GeV}\,. \quad (4)$$

Here the first error is experimental and the second corresponds to uncertainties due to input parameters and model assumptions. The propagator mass is within erros consistent with the W mass as measured by LEP and the Tevatron.

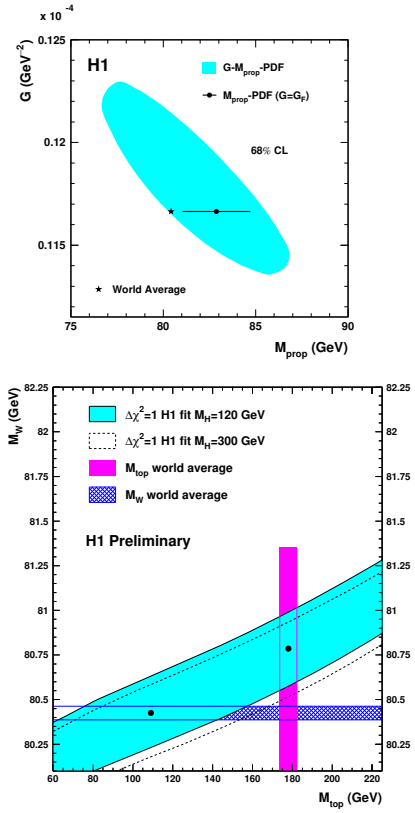

Figure 3. Differentiell cross section for NC and CC e^+-p and e^--p scattering

In the second fit (OMS scheme) essentially the normalization of the CC cross section determines the W mass fit result, in this case beiing sensitive to the parameters (M_H, M_t) in the electroweak radiative corrections. Fixing m_t to its world average value of 178 GeV and assuming $M_H = 120\,\mathrm{GeV}$, the fit M_W-PDF leads to

$$M_W = 80.786 \pm 0.205_{\mathrm{exp}}\, {}^{+0.048}_{-0.029}\big|_{\mathrm{model}} \pm 0.025_{\delta m_t} - 0.084_{\delta M_H} \pm 0.033_{\delta(\Delta r)}\,\mathrm{GeV}\,. \tag{5}$$

Here, in addition to the experimental and model uncertainties, three other error sources are considered: the uncertainty on the top quark mass $\delta m_t = 4.3\,\mathrm{GeV}$ [?], a variation of the Higgs mass from 120 GeV to 300 GeV and the uncertainty of higher-order terms.

At HERA, the NC interactions at high Q^2 receive contributions from γZ interference and Z^0 exchange. Thus the NC data can be used to extract the weak couplings of up- and down-type quarks to the Z^0 boson. At high Q^2 and high x, where the NC $e^{\pm}p$ cross sections are sensitive to these couplings, the up- and down-type quark distributions are dominated by the light u and d quarks. Therefore, this measurement can be considered to determine the light quark couplings. The CC cross section data help disentangle the up and down quark distributions.

In this analysis the vector and axial-vector dressed couplings v_u-a_u-v_d-a_d of u and d quarks are treated as free parameters. The results of the fit are shown in Fig. **??**

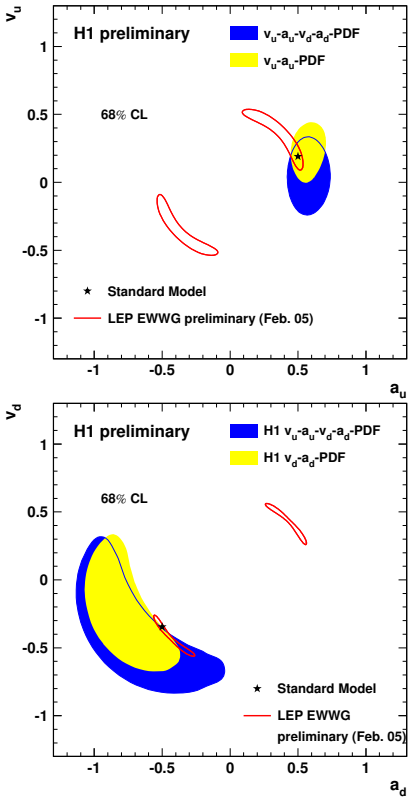

Figure 4. Differentiell cross section for NC and CC e^+-p and e^--p scattering

The measured couplings are in good agreement with the SM expecta-

tions. The results are compared in Figure **??** with similar results obtained from the combined LEP data [?]. The HERA results resolve the sign ambiguity inherent in the LEP results.

2. Results from the HERA II

The HERA accelerator and the experiments have in the years 2000-2002 undergone major modifications in order to achieve significantly higher luminosities. It is planned to accumulate around 700 pb^{-1} per experiment in the HERA II phase (up to 2007). This will significantly reduce the statistical errors in that high Q^2 region of phase space crucial for electroweak phenomena. Another important aspect for electroweak physics is the availibility of longitudinally polarized leptons for the HERA II phase.

The first physics analysis making use of the lepton polarization is the measurement of the CC cross sections as a funtion of the degree of lepton polarization. The double differential CC cross section for collisions of polarised leptons with unpolarised protons corrected for QED radiative effects can be written as

$$\frac{d^2\sigma_{CC}^{e^{\pm}p}}{dxdQ^2} = [1 \pm P_e]\frac{G_F^2}{2\pi x}[\frac{M_W^2}{Q^2 + M_W^2}]^2\Phi_{CC}^{\pm}, \tag{6}$$

where G_F is the Fermi coupling constant, M_W is the mass of the W boson. $\Phi_{CC}^{\pm}$ is the term depending on the partonic content of the proton and ca n be expressed as follows:

$$\Phi_{CC}^{+} = \bar{u} + \bar{c} + (1-y)^2(d + s + b), \tag{7}$$

$$\Phi_{CC}^{-} = u + c + (1-y)^2(\bar{d} + \bar{s} + \bar{b}). \tag{8}$$

Here, P_e is the degree of longitudinal polarisation defined as $P_e = (N_R - N_L)/(N_R + N_L)$ with $N_R(N_L)$ being the number of right (left) handed polarised leptons in the beam. The cross section has a linear dependence on the polarisation of the lepton beam and vanishes due to the V-A structure of the CC interaction for lefthanded positrons and for righthanded electrons.

Both collaborations used the data accumulated in 2003-2005 with polarized e^+ and e^- and combined these with the unpolarized daten taken in the HERA I phase. The luminosities analysed up to now for polarized beams are small (typically 10-30 pb^{-1} per charge and polarisation state) and the degree of polarization only 30-40 %. Nevertheless both collabora-

tions presented in their preliminary analyses clear confirmation of the V-A structure in high Q^2 CC interaction.

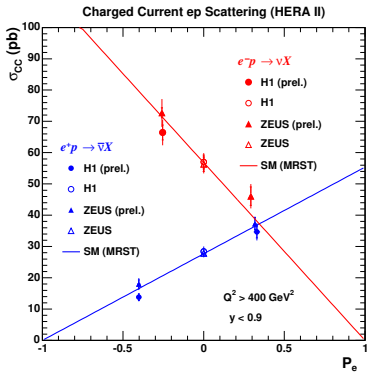

Figure 5. Total CC cross section for e^+p and e^-p scattering as function of the degree of longitudinal lepton polarization P

Fig 6 shows the CC cross sections for e^+p and e^-p scattering in the region $Q^2 > 400GeV^2$ and $y < 0.9$ as function of the degree of longitudinal polarisation P. The data clearly exhibit the linear dependence with P and are compatible with vanishing cross sections for left(right)-handed positrons(electrons). Fitting a linear dependence to the e^+p data results in an extrapolated cross section of $\sigma^{e^+}_{CC}(P=-1) = 0.2 \pm 1.8(stat) \pm 1.6(syst)$ pb, consistent with the SM prediction of zero.

The ZEUS collaboration quoted also polarization dependences of differential CC crosss sections. Fig **??** shows these as funtion of the kinamatic variables x, y and Q^2 for the case of e^+p scattering. As expected, all cross sections depend linear on the degree of Polarization.

The dependence of NC cross sections on the polarisation is more involved due to the contribution of γ and Z exchange in the amplitudes and the different chirality couplings. The bulk of the cross sections is dominated by γ exchange and thus indpendent of P and equal for e^+p and e^-p scattering. Only at highest Q^2 sensitivity to polarization shows up due to the onset of the $\gamma - Z$ interference. In figure refNCpol.dsdQQ the ZEUS results are shown for the dependence of the NC cross section on Q^2 for two polarization states. The bottom part shows the cross section ratio for the two polarisations. Although the polarization dependence is not observed conclusively, it is well in agreement with the expectes SM behaviour.

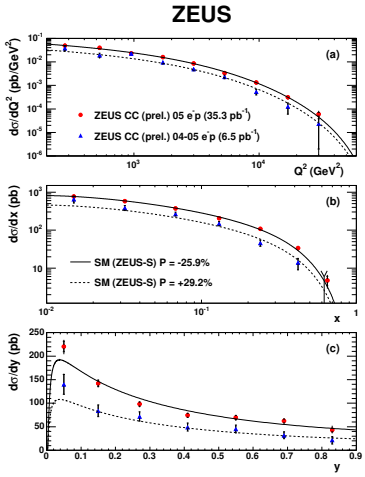

Figure 6. Differentiell cross sections CC e^+-p cross sections for two polarization states

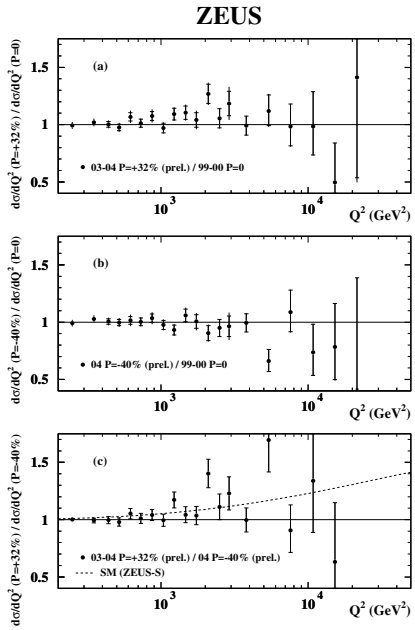

Figure 7. Differentiell cross sections NC e^+-p cross sections for two polarization states a),b). In c) the ratio is shown.

summary

Aspect of electroweak physics at HERA habe been studied at HERA. In the HERA-II phase with unpolarized leptons utilizing $\sim experiment. Measured NC and CC cross section provide clear evidence for electroweak unification as predic$ and the vector and axialvector couplings of the Z to up and down quarks. All results are in afgreement with the SM.

The newly available longitudinal lepton polarization greatly enhances the potential of electrowaek measurements at HERA. Already the very first results based on relatively low luminosity samples give encouraging results. The highlight hereby is the demonstration of the V-A structure of the charged current interaction at the very high spacelike momentum transfer never exploited before in deep inelastic scattering.

Since all the results at high Q^2 are statistics dominated the very high luminosity expected until teh end of HERA operation promises exiting physics results.

Acknowledgments

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References

1. M. Barranco and J. R. Buchler, *Phys. Rev.* **C34**, 1729 (1980).