HERA RESULTS ON QCD AND EW PHYSICS *

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Selected HERA results on QCD and EW interactions are presented. They include the measurement of the proton structure function and its analysis in terms of the QCD evolution, as well as results concerning deep inelastic scattering at very low and very high Q^2. Selected HERA limits on new physics and parameters which extend the standard model are also presented.

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1. HERA and the HERA experiments

HERA is the world's first electron-proton collider, built at DESY, Hamburg. It collides 27.5 GeV positrons[1] with 820 GeV protons, giving a center of mass energy of about 300 GeV. This is almost an order of magnitude more than has been available in fixed target DIS experiments. Most of the results presented in this talk are based on data taken in 1993 and 1994, corresponding to a delivered ep luminosity of about 7 pb^{-1} out of which about 4 pb^{-1} was useful for data analysis. The performance of HERA improved significantly every year and until now it has delivered about 30 pb^{-1}. After the HERA upgrade, which is scheduled to take place in 2000 we expect to collect about 170 pb^{-1} per year, which should result in about 1 fb^{-1} of ep luminosity until 2005.

For the study of electron-proton scattering at HERA[2] two multi-purpose detectors H1 [1] and ZEUS [2] were built by international collaborations.

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[1] In 1993 and 1994 also electrons were collided.

[2] In addition to the *ep* experiments, there are two fixed target experiments operating at the HERA ring: the HERMES experiment, aimed to study polarized structure functions in electron scattering on a gas target, and the HERA-B experiment, which is still under construction and is going to search for CP violation in bottom decays.

They both assure almost hermetic and very precise measurement of the produced particles. In case of deep inelastic electron-proton scattering both energy and direction of the scattered electron can be precisely determined by using information from calorimeters and tracking detectors. Additional constraints on event kinematics come from the measurement of the hadronic final state. It should be noted, that in contrast to lepton scattering on the fixed targets, the center-of-mass frame at HERA is boosted significantly in the proton beam direction. This allows precise measurement of the deep inelastic scattering at HERA in a very wide kinematic range. For details of deep inelastic event reconstruction the reader is refered to dedicated papers of H1 [3] and ZEUS [4].

2. DIS at HERA

In deep inelastic scattering the double differential cross section for inclusive ep scattering is given in terms of the structure functions F_2 and F_3, and the longitudinal structure function F_L:

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y^+F_2(x,Q^2) \mp Y^- xF_3(x,Q^2) - y^2F_L(x,Q^2)\right] \times (1+\delta_r(x,Q^2)) ,$$

where Q^2 is the virtuality of the exchanged photon, x is the Bjorken variable, $Y^\pm = 1 \pm (1-y)^2$ with $y = Q^2/xs$, and δ_r represent the electroweak radiative corrections. As the contributions to the cross section from F_3 and F_L are small, F_2^γ, the part of F_2 which corresponds to single photon exchange can be extracted from the measurement using the formula:

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(1+(1-y)^2)F_2^\gamma(1+\delta_Z)(1-\delta_L \mp \delta_3)(1+\delta_r) .$$

In addition to the correction arising from the F_3 and F_L contributions, δ_3 and δ_L, the contribution δ_Z, coming from the Z° exchange and γZ° interference term, is considered.

Figure 1 shows the F_2^γ values as a function of Q^2 for fixed x, as measured by H1 [3] and ZEUS [4]. The results of both HERA experiments are in very good agreement and consistent with data of fixed target experiments in the kinematic region where they overlap. HERA has allowed us to access region of very high Q^2, as well as very small x and extend the measurement of the proton structure function by almost 2 orders of magnitude in both variables. Included on the plot is the result of a NLO QCD fit to the ZEUS data. The observed strong scaling violation, increasing as x decrease, is well described by the standard DGLAP evolution [5].

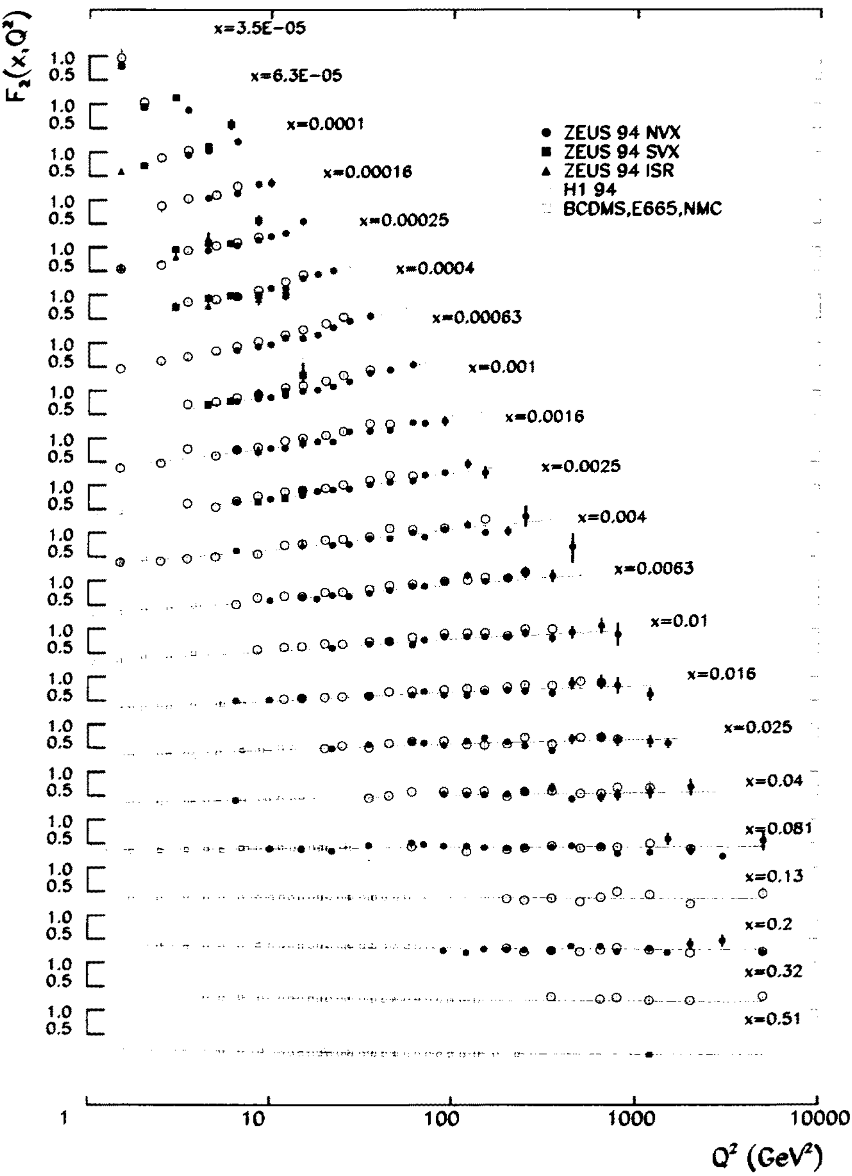

Fig. 1. Structure function F_2^γ as a function of Q^2 for fixed values of x. The data from H1 and ZEUS are compared to results from other experiments, as indicated on the plot. The solid line indicates the NLO QCD fit to the ZEUS data.

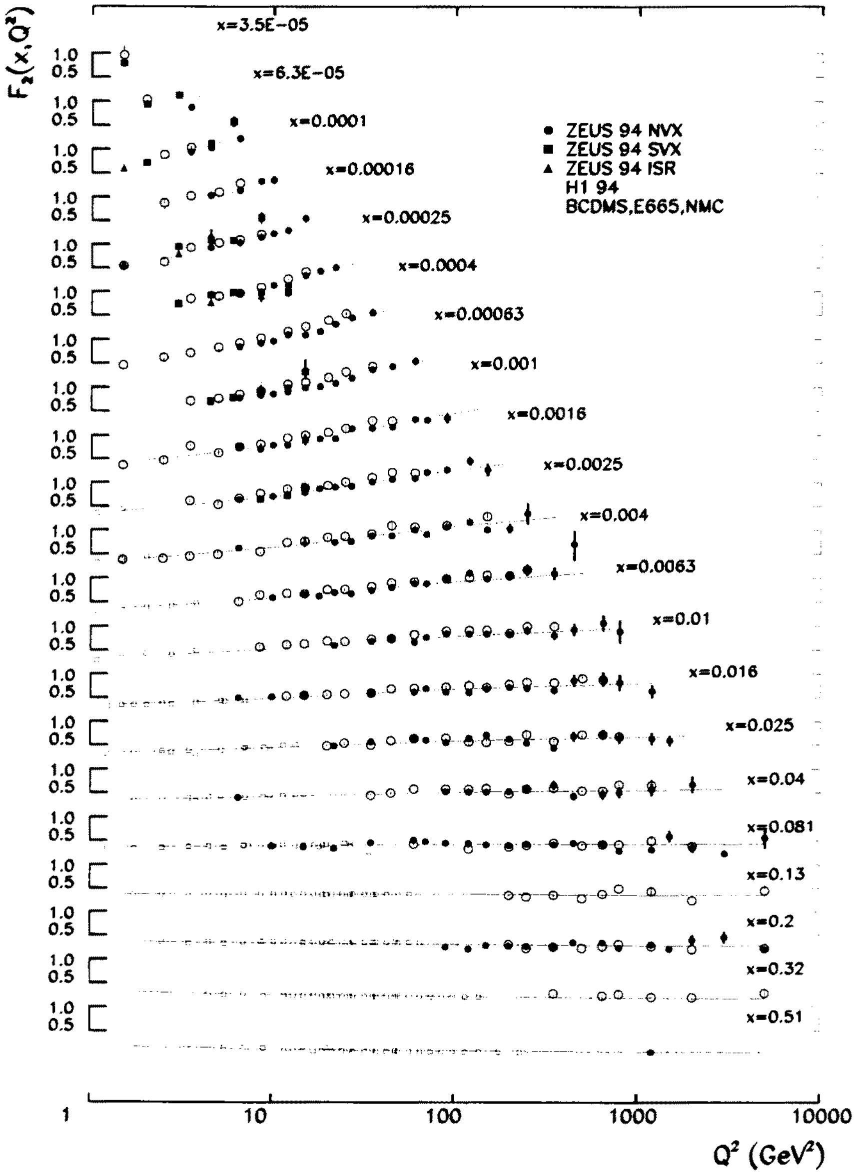

Fig. 2. Structure function F_2^γ as a function of x for fixed values of Q^2. The data from H1 and ZEUS are compared to results from other experiments, as indicated on the plot. The solid line indicates the NLO QCD fit to the ZEUS data.

In figure 2 the same data points are shown as a function of x, in different Q^2 bins. A very strong rise of F_2 towards small x is observed for all Q^2 values, down to Q^2 of 1.5 GeV^2. The QCD fit already mentioned is also indicated on the plot. It provides a good description of the data. The H1 collaboration has shown [3], that the measured F_2 behavior at low x, for high Q^2 values, is consistent with the QCD prediction of double asymptotic scaling[6]. This implies that the parton distributions at low x are driven by the QCD evolution and that there is no intrinsic singular component for $x \to 0$.

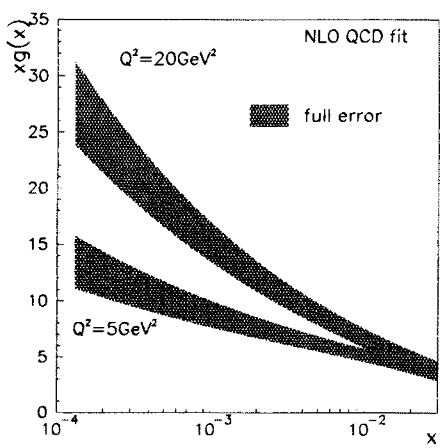

Fig. 3. The gluon density $xg(x)$ at $Q^2 = 5\ \text{GeV}^2$ and $Q^2 = 20\ \text{GeV}^2$ extracted from the NLO QCD fit to the H1 data. An additional systematic error of 10% coming from the uncertainty of α_s is not included.

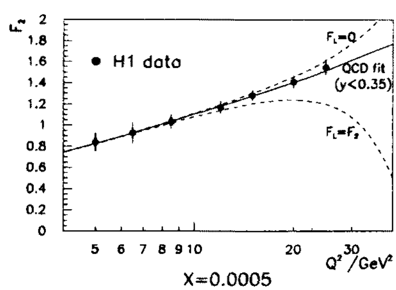

Fig. 4. Measured F_2 from H1 for $x = 0.0005$ together with the NLO QCD fit to the data at $y < 0.35$ extrapolated to higher y values. The dashed curves indicate the corresponding F_2 assuming $F_L = 0$ (upper curve) or $F_L = F_2$ (lower curve).

From the QCD fit to the data the gluon distribution in the proton can be extracted. Figure 3 shows the gluon distribution $xg(x)$ as obtained by H1 for two different Q^2 values of 5 and 20 GeV^2. The gluon density increases rapidly towards small x as expected from the QCD evolution. Based on a QCD fit to the F_2 data, H1 has recently presented a first estimation of the longitudinal structure function F_L at HERA [7]. The F_L contribution to the DIS cross section can be extracted by performing a QCD fit to the data at low y, where contributions from F_L are negligible, and extrapolating F_2

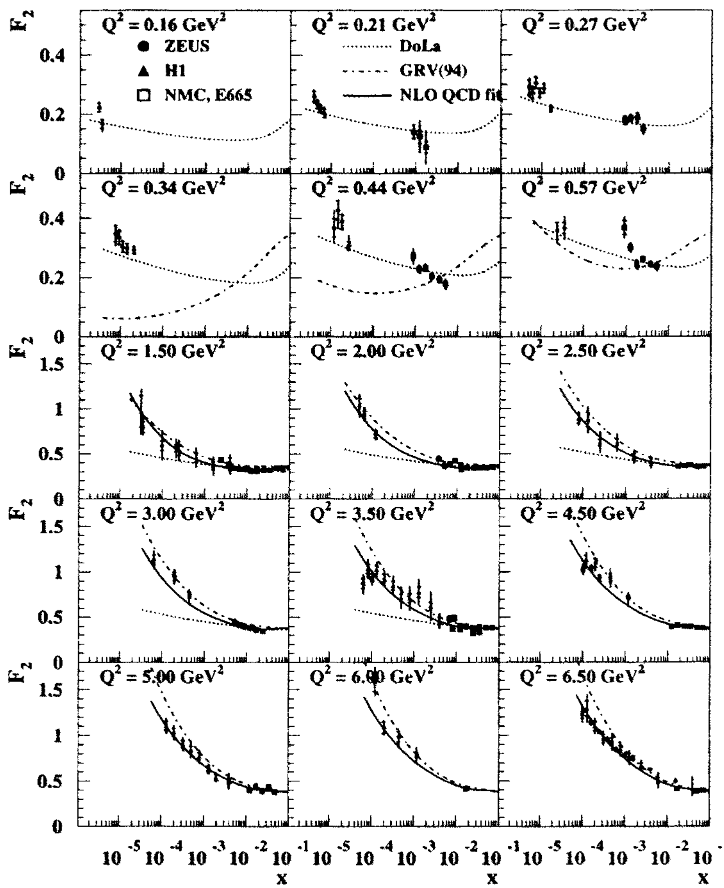

Fig. 5. Structure function F_2 as a function of x for constant Q^2 values. The data from ZEUS and H1 are compared to results from other experiments, as indicated on the plot. Also shown are the predictions of GRV and DL models, as well as the NLO QCD fit to the ZEUS data above $Q^2 = 1.5$ GeV^2. For Q^2 below 1 GeV^2 F_L is assumed to be zero, a QCD NLO prediction is taken for higher Q^2.

to the higher y values, as shown in figure 4. A preliminary average value of $F_L = 0.54 \pm 0.03(stat) \pm 0.22(\text{syst})$ is obtained for a Bjorken x range $0.00011 < x < 0.00080$, in agreement with QCD expectations from scaling violation of F_2 [8], relating F_L to the gluon distribution at low x.

For very low Q^2, $Q^2 < 1$ GeV^2 (see figure 5), both QCD fit to data at higher Q^2, as well as the perturbative QCD inspired GRV model [9], based on the DGLAP evolution, fails to described the F_2 data [10]. A moderate rise of the F_2 with x at very low Q^2 values is however described by the model of Donnachie and Landshoff, based on the dominance of a soft Pomeron [11]. This demonstrates that at HERA we are able to study precisely the transition region between "soft" and hard, perturbative QCD dominated physics. This transition is also clearly visible when comparing the elastic ρ° production cross section measured at high $\gamma^* p$ center-of-mass energy W by H1 [12] and ZEUS [13], with that measured at lower W by NMC. As can be seen in figure 6 for high Q^2 the cross section rises strongly with W, approximately like $W^{0.9}$. This behavior is expected from perturbative QCD for a gluon density in the proton which increases towards small x. For the very low Q^2 and for photoproduction (Q^2=0) the rise of the cross section is much smaller and is consistent with the prediction of the Donnachie-Landshoff model assuming the exchange of a soft Pomeron.

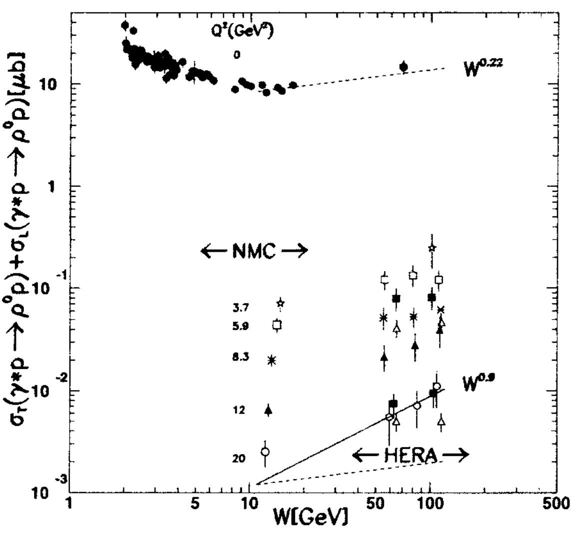

Fig. 6. Elastic ρ° production cross section as a function of the $\gamma^* p$ center-of-mass energy W, for different photon virtualities Q^2 and for photoproduction (Q^2=0). The H1 1994 data (open triangles) and the ZEUS 1993 data (solid squares) are scaled to Q^2 of 8.3 and 20 GeV^2 for comparison with ZEUS 1994 results.

3. Jet studies

Additional information about the proton structure and the underlying physics processes can be obtained from the study of jet production. In deep inelastic ep scattering only one hadron jet is observed in the detector in most of events. This corresponds to the leading order scattering diagram, when a single valence or sea quark is scattered out of the proton. Higher order diagrams lead to multiple jet production. At low Bjorken x two jet production is dominated by the photon-gluon fusion process, and can be used to determine the gluon distribution in the proton.

At high x the gluon contribution to the scattering decreases and multi-jet production in deep inelastic scattering results predominantly from the gluon radiation from the initial and final quark lines. The measurement of the two-jet event fraction can thus be used to extract the value of the strong coupling constant α_s at the given hard scale defined by Q^2. Results of the ZEUS analysis [14] performed using the JADE algorithm for the jet reconstruction are shown in figure 7. The measured values are consistent with the QCD prediction that α_s decreases with Q^2. The value of α_s extrapolated to the Z° mass scale is:

$$\alpha_s(M^2_{Z^\circ}) = 0.117 \pm 0.005(\mathrm{stat}) \ ^{+0.004}_{-0.005}(\mathrm{syst_{exp}}) \ \pm 0.007(\mathrm{syst_{theory}}) \, .$$

H1 has also published a result on α_s [15].

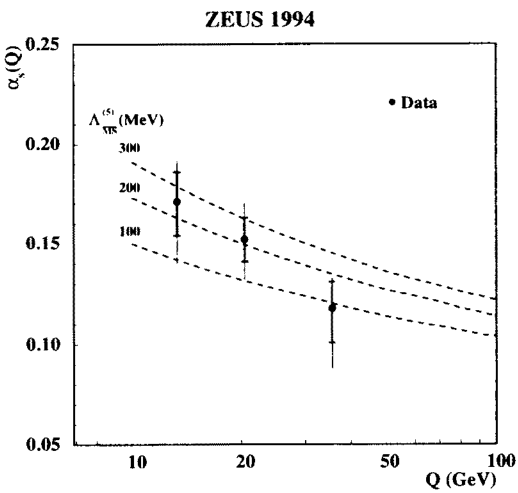

Fig. 7. α_s(Q) values for three different Q regions, as measured by ZEUS. The dashed curves represent the QCD prediction for different $\Lambda^{(5)}_{\overline{MS}}$ values, as indicated in the plot.

An interesting result, which confirms basic assumptions of QCD, has been recently presented by ZEUS on dijet production in photoproduction [16]. In the so called direct photoproduction, in which the photon participates directly in the hard scattering, dijet production is dominated by gamma-gluon fusion, with quark exchange in the t-channel. In resolved photoproduction the photon participates in hard scattering through its partonic structure and dijet production is dominated by processes with gluon exchange. Due to the different spin of the exchanged particle we expect different angular distribution of dijets in direct and resolved photoproduction. As shown in figure 8, the ZEUS data agree very well with QCD prediction

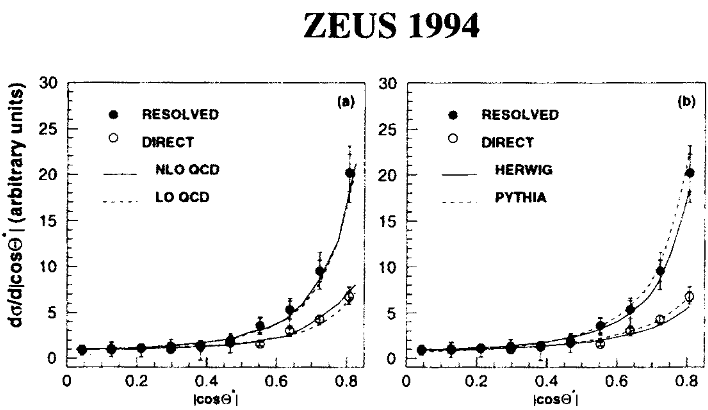

Fig. 8. Angular jet distribution (normalized to one at $\cos\theta^{\star} = 0$) for resolved (black dots) and direct (open dots) photoproduction. ZEUS data are compared to LO and NLO QCD predictions (a) and to MC simulation (b).

at the parton level and with Monte Carlo simulations which include the fragmentation of the quarks into jets. It should be noticed that already LO QCD calculations describe the data very well and the NLO corrections as well as the influence of parton showering and hadronisation models (as included in MC simulation) are very small. Therefore the measurement of the jet angular distribution allows us to test fundamental aspects of quantum chromodynamics.

4. DIS at very high Q^2

At very high Q^2 values the measurement of the deep inelastic ep scattering is not only useful for the F_2 structure function measurement and jet studies, but gives us also possibility to study electro-weak interactions and look for signals of new physics. At HERA we can study both neutral current

(NC) scattering, where contribution from the Z° exchange and γZ° interference to the cross section become important for Q^2 above 1000 GeV^2, as well as the charged current (CC) scattering corresponding to the $W^\pm$exchange between electron and the proton. Figure 9 shows the differential NC and

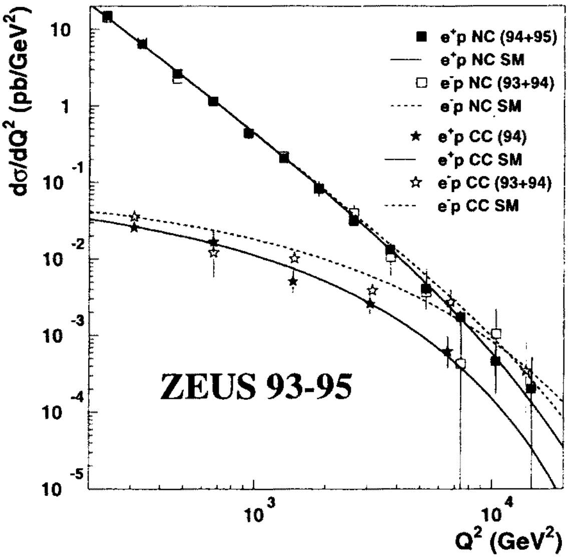

Fig. 9. Differential NC and CC DIS cross section as a function of Q^2. ZEUS data for e^-p and e^+p are compared with SM predictions, as indicated in the plot.

CC DIS cross section as a function of Q^2, as measured by the ZEUS experiment for both e^+p and e^-p scattering [17, 18] (similar results have also been presented by H1, see [19]). Standard Model predictions (SM) are also indicated. Good agreement with SM expectations is observed for all distributions. At very high Q^2 the cross section for CC scattering becomes comparable with that of NC scattering demonstrating the unification of weak and electromagnetic forces. Also seen is the difference in the CC cross section for e^-p and e^+p scattering resulting from the valence quark composition of the proton. From the Q^2 dependence of the differential CC cross section the $W^\pm$propagator mass can be extracted. The combined result of both HERA experiments is

$$M_W = 81.5 \, ^{+6}_{-5} \pm 3\text{GeV} \, .$$

This agrees, however with large errors with the world average $M_W = 80.33 \pm 0.15$ GeV [20].

5. Searches for "New Physics"

Agreement between the measured high Q^2 NC DIS cross section and the standard model expectations can be studied in terms of limits on "new physics". For a broad range of new phenomena, as for example second generation heavy gauge bosons, lepto-quarks or compositeness we expect deviation from the SM cross section, which can be approximated by an $eq \to eq$ contact interactions. The most general contact interaction Lagrangian can be written:

$$L = \frac{g^2}{\Lambda^2} \sum_q \sum_{i,j=L,R} \eta^q_{ij} \left(\bar{e}_i \gamma^\mu e_j\right) \left(\bar{q}_i \gamma^\mu q_j\right) ,$$

where g is the coupling and η the relative size and sign of the individual terms. By convention, we set $g^2 = 4\pi$ and $|\eta| = 1$, in which case limits on new physics can be quoted in terms of the effective mass Λ. Depending on

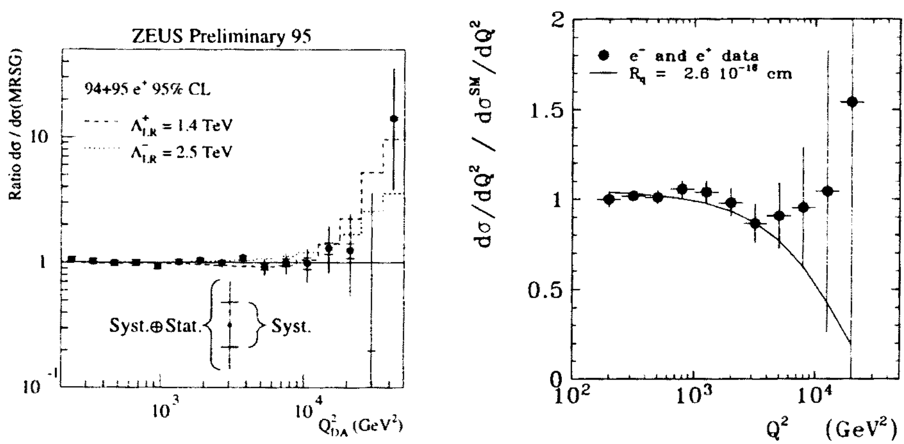

Fig. 10. Ratio of the measured over the expected number of NC DIS events in bins of Q^2. The measured ratio is compared with the model expectations for contact term interactions (ZEUS limit on left-handed electron to right-handed quark coupling; in the left plot) and for quark compositeness (H1 limit on the quark radius; in the right plot).

the sign and the helicity of the coupling, both experiments have put limits on the Λ parameter between 1 and 2.5 TeV [18, 21]. An example of the limits from the ZEUS experiment is presented in figure 10.

In the deep inelastic scattering at very high Q^2 we can also test the point like nature of quarks. The effect of a possible finite quark size on the NC

DIS cross section can be approximated by multiplying the cross section by a quark form factor $(1 - R^2Q^2/6)^2$, where R is the effective quark radius. From comparison of the measured cross section with the SM expectations the H1 collaboration has put limit of $R < 2.6 \cdot 10^{-16}$ cm [21] from the data taken in 1994, as plotted in figure 10. The corresponding limit from the 94+95 data of the ZEUS experiment is $R < 1.4 \cdot 10^{-16}$ cm [18].

Many interesting new phenomena are also available for the direct searches at HERA. For example, in the 1994 data H1 collaboration has found an interesting event, for which the only explanation within the standard model is the W^+ production with the subsequent $W^+ \rightarrow \mu^+\nu_\mu$ decay [22]. From the standard model $W^\pm$production cross section however only 0.03 events are expected assuming full acceptance. After the accelerator upgrade, HERA will be able to put limits on the parameters describing possible anomalous $W^\pm$production competitive with that coming from experiments at other colliders, like LEP2 or Tevatron [23].

6. Summary

HERA, which collides lepton and hadron beams, has opened a new "window" for studies of QCD and EW interactions. Perturbative QCD describes well the HERA results, down to Q^2 values of about 1 GeV^2. The region of lower Q^2 has been opened for studies of transition between perturbative QCD and "soft" physics. The HERA experiments also probe the description of EW interactions and search for "new physics".

In this paper it was only possible to cover a small fraction of HERA physics results. Both HERA experiments study a wide range of physics phenomena, from the elastic vector meson photoproduction up to searches for SUSY particles. Most of the new HERA results have been recently presented on the 28th International Conference on High Energy Physics in Warsaw [24–26].

We are grateful to the HERA machine group, whose outstanding efforts made these experiments possible. Also invaluable has been the strong support and encouragement of the DESY directorate. The author would like to thank all members of H1 and ZEUS collaborations, who helped him in preparing this talk. He would also like to thank the DESY directorate for the support of his work at DESY and for enabling him to participate in the symposium.

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[25] Papers contributed to ICHEP96 by the H1 collaboration can be found under WWW page
http://dice2.desy.de/h1/www/psfiles/confpap/warsaw96/list.html .

[26] Papers contributed to ICHEP96 by the ZEUS collaboration can be found under WWW page
http://zow00.desy.de:8000/zeus_papers/warsaw_papers.html .