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Physics at Highest Q^2

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ABSTRACT

Measurements of deep inelastic *ep* scattering at very high values of Q^2 performed at HERA are presented. The data, based on four years of accumulated luminosity, are compared with expectations from the Standard Model (SM) and tests for physics beyond the SM are performed. In addition, the observation of events with a high P_T lepton and missing transverse momentum is reported. The observed rates and event characteristics are compared to the expectations from W - production.

1 Introduction

With the e-p collider HERA at DESY electron proton scattering processes [1] at a center of mass energy $\sqrt{s} = 300\text{GeV}$ offer the possibility to study deep inelastic scattering (DIS) in charged and neutral current processes up to highest momentum transfers ($Q^2_{max} = s$).

With the large data sample from 1997 both collaborations, H1 and ZEUS, have refined their analyses and measured cross sections up to $Q^2 = 40000\text{GeV}^2$. This extends previous measurements of fixed target experiments by 2 orders of magnitude in Q^2. A new domain in DIS has been explored and searches for possible deviations from the Standard Model, like Leptoquark-production or Contact Interactions, have been performed. We present in this review a selection of recent results, most of them still being preliminary. A detailed description of the H1 and ZEUS experiments can be found in [1)] and [2)] respectively.

[1] Although HERA has run with positrons from 1994 until 1997 throughout the paper the term electron is used for e^+ as well.

2 Deep Inelastic Scattering

At HERA deep inelastic scattering of 27.5GeV positrons on 820GeV protons is studied and cross sections are measured over more than 4 orders of magnitude both in Q^2 and x. The momentum transfer $Q^2 = -q^2 = -(k-k')^2$ is derived from k and k', the four vectors of the initial and final state lepton respectively. In addition further Lorentz-invariant variables are of importance, the Bjorken scaling variable $x = \frac{Q^2}{2Pq}$ and the fractional energy transfer to the proton in its rest frame $y = \frac{Pq}{Pk}$, where P is the four-momentum of the incoming proton. In the quark parton model the mass of the electron quark system is given by $M = \sqrt{sx}$, with s being the ep invariant mass squared. At a given s two of the Lorentz-invariants are needed to fully characterize the kinematics of the ep scattering.

In the data collected during 1994 - 1996 both H1 and ZEUS reported an excess of DIS events at highest Q^2 and high y [3, 4]. With the data recorded in 1997 the statistics available is more than doubled and an extensive analysis of the cross sections were performed. All results quoted below are based on the 1994 - 1997 e^+p data corresponding to accumulated luminosities of $47pb^{-1}$ and $37pb^{-1}$ for ZEUS and H1, respectively. All measured cross sections are corrected for QED radiation effects.

2.1 Neutral Current Cross Sections

Deep inelastic scattering processes mediated by the neutral bosons γ or Z are characterized by the observation of a scattered electron and a hadronic final state. The events are expected to be balanced in transverse momentum. The kinematics can be derived from 4 measurable quantities, the energy E_e and the polar angle θ_e of the scattered electron, as well as the energy E_h and the angle γ_h of the hadronic system [5]. The H1 analysis [3] uses the electron quantities to derive the kinematics (electron method), whereas ZEUS [4] uses the two measured angles (double angle method). Both experiments used the alternative method as a cross check.

The differential cross section is given by

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) - Y_-xF_3(x,Q^2)] \qquad (1)$$

with $Y_\pm = 1 \pm (1-y^2)$.

Fig.1 shows the single differential cross section $d\sigma/dQ^2$ measured by ZEUS. The data agree within error with the Standard Model (SM) predictions based on the CTEQ4D [6] parton parametrizations, with the exception of the highest bin ($Q^2 > 35000\text{GeV}^2$) which contains two events where 0.29 are expected.

The H1 collaboration measured the double differential cross section. The results are presented in figure 2 in the form of a reduced cross section

$$\sigma(e^+p) = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma}{dxdQ^2} \qquad (2)$$

for 6 different x ranges and compared with the standard model expectation based on the MRSH parton distributions [7]. Also shown are the low Q^2 data from SLAC [8], BCDMS [9] and NMC [10]. The low Q^2 data join well the high Q^2 cross sections measured at HERA. Both the standard model expectation based on MRSH parton distributions as well as a next to leading order QCD fit performed by H1 describe the observed cross sections well. Only for $x = 0.45$ and $Q^2 > 15000\text{GeV}^2$ the data points are above the expectation, however with less significance than for the 1994 - 1996 data alone. Table 1 gives the number of observed events seen by H1 above $Q^2 = 15000\text{GeV}^2$ for $0.1 < y < 0.9$, comparing the results from the pre 1997 data with the full statistics including 1997.

The effect of γ/Z interference in DIS is visible at HERA for the first time. Fig. 3 shows the $d\sigma/dx$ cross section integrated for $Q^2 > 1000GeV^2$ and for $Q^2 > 10000GeV^2$, compared to SM expectations with and without Z exchange. The higher Q^2 data clearly show the need for Z exchange, while they disagree at the 3 standard deviation level if

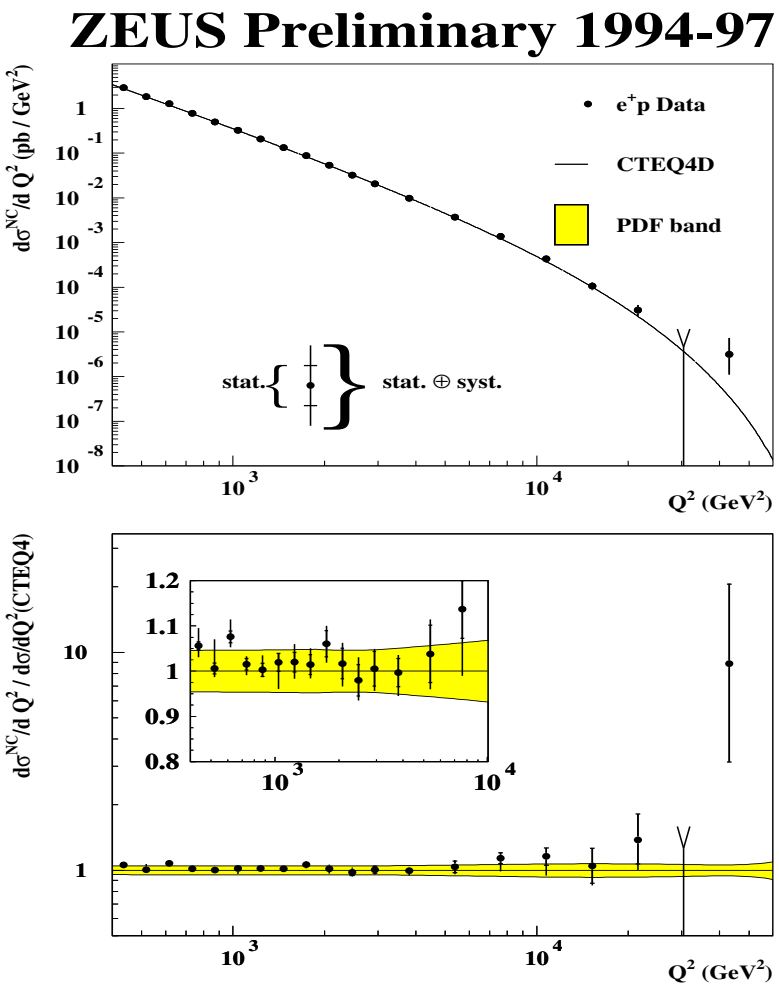

Figure 1: *The e^+p neutral current cross section $\frac{d\sigma}{dQ^2}$ measured by ZEUS (upper figure) and the ratio data/SM (lower figure). The Standard Model expectation shown is based on the CTEQ4D parametrisation of the parton density function. The shaded region indicates the uncertainty in the SM prediction coming from the uncertainties in the PDFs.*

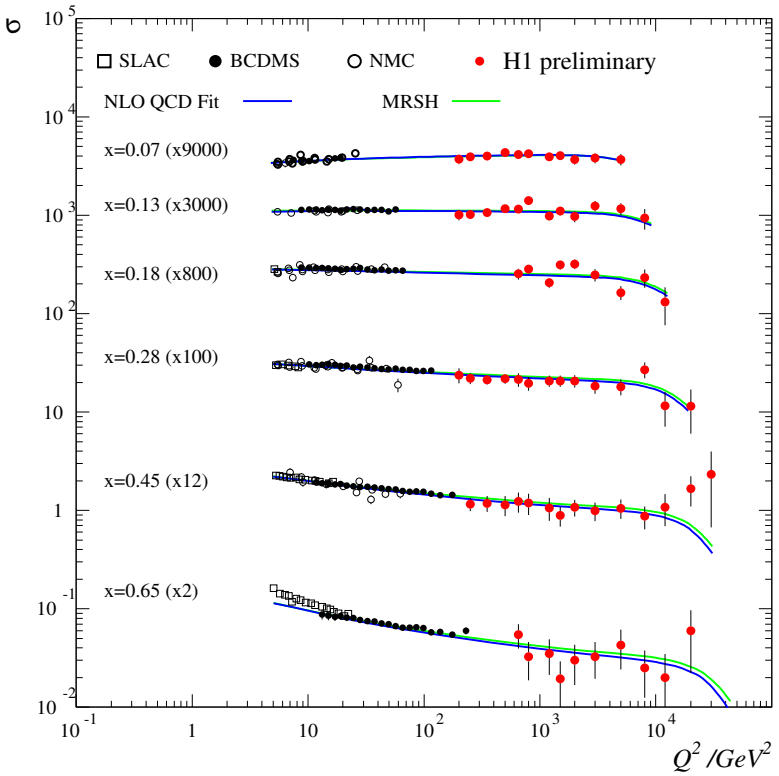

Figure 2: *The e^+p neutral current reduced cross section (see text) measured by H1 is shown together with low Q^2 data from SLAC, BCDMS and NMC. The MRSH based Standard Model expectation and a next to leading order QCD Fit from H1 are shown as curves.*

NC Events with Q^2 $> 15000\text{GeV}^2$	1994 - 1996 data ($14pb^{-1}$)	1994 - 1997 data ($37pb^{-1}$)
N observed	12	22
N expected	4.71 ± 0.76	14.8 ± 2.13
Probability	6×10^{-3}	5.9×10^{-2}

Table 1: *Number of events above $Q^2 > 15000 GeV^2$ measured by H1 compared to the Standard Model expectation for the data up to 1996 and for the full data sample.*

only γ exchange is taken into account.

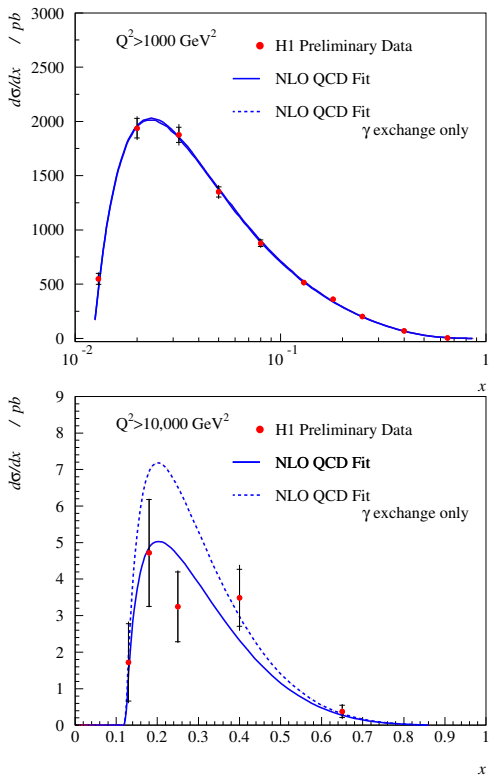

Figure 3: *The e^+p neutral current cross section $d\sigma/dx$ at high Q^2 compared with the Standard Model prediction and with the prediction when the coupling to the Z boson is not taken into account.*

2.1.1 Limits on Leptoquarks

H1 used the neutral current data to search for production of Leptoquarks by comparing the event rate in bins of $M = \sqrt{xs}$ with the Standard Model expectations. Scalar leptoquarks can be produced as s-channel resonances at HERA, leading to a flat cross section $d\sigma/dy$ whereas the standard DIS shows a $1/y^2$ dependence due to the t-channel exchange. By choosing a proper cutoff value y_{cut}, the signal to background ratio can be optimised. Figure 4 shows the mass spectrum for all NC data as well as for data with a mass dependent y_{cut} [11]. The standard model NC DIS expectation is shown for comparison. The excess around $M_e = 200$GeV seen for the data with $y > y_{cut}$ is mainly due to the events already published in [3] and is in this analysis considered to be a fluctuation.

The analysis has three parameters, the unknown coupling λ of the leptoquark to the eq system, the Mass of the leptoquark M and the branching fraction β of the leptoquark decaying into eq. To derive limits for leptoquarks two different approaches are used. Either the coupling λ is assumed to have a given value and the limit is derived in the $M - \beta$ plane, or β is fixed, taken from a specific leptoquark model (here Buchmüller, Rückl, Wyler [12]) and the limits are derived in the $M - \lambda$ plane. The limits for fixed λ

are shown in figure 5. For $\beta = 1$ leptoquarks coupling to e^+u are excluded up to 250GeV at 95% CL, comparable to previous results from D0 [13]. For $\beta < 1$ HERA provides more stringent limits.

2.1.2 Contact Interactions

The ZEUS collaboration has analysed the NC-DIS data in terms of possible signs for Contact Interactions. Contact Interactions lead to additional terms in the Lagrangian

$$\begin{aligned} L_{NC} &= L_{SM} \\ &+ \eta_{LL}(\bar{e}_L\gamma^\mu e_L)(\bar{q}_L\gamma^\mu q_L) + \eta_{LR}(\bar{e}_L\gamma^\mu e_L)(\bar{q}_R\gamma^\mu q_R) \\ &+ \eta_{RL}(\bar{e}_R\gamma^\mu e_R)(\bar{q}_L\gamma^\mu q_L) + \eta_{RR}(\bar{e}_R\gamma^\mu e_R)(\bar{q}_R\gamma^\mu q_R) \end{aligned} \tag{3}$$

Here only the vector terms are taken into account and the convention $\eta = a4\pi/\Lambda^2$ with $a = \pm 1$ is used. The contact interaction analysis is based on a comparison of the measured distributions of the kinematic variables Q^2, x and y with the corresponding results of a MC simulation based on equation (3).

The result of the fits for some selected helicity structures of the contact interaction terms are summarised in table 2. Four typical fit results are shown in fig. 6. The lower limits on the scale parameter Λ are in the range of 2-5 TeV. The ZEUS results are

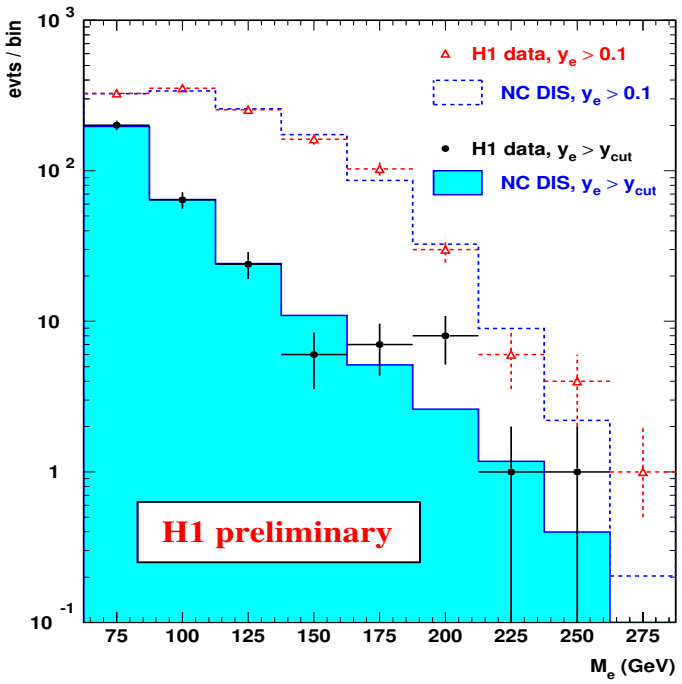

Figure 4: *The mass $M = \sqrt{xs}$ spectrum of neutral current DIS events measured by H1 shown as triangles for the full data sample and as dots for the data with y_{cut} applied. y_{cut} varies from 0.6 at M=60GeV to 0.2 at M=250GeV. The Standard Model expectations are shown as a histograms.*

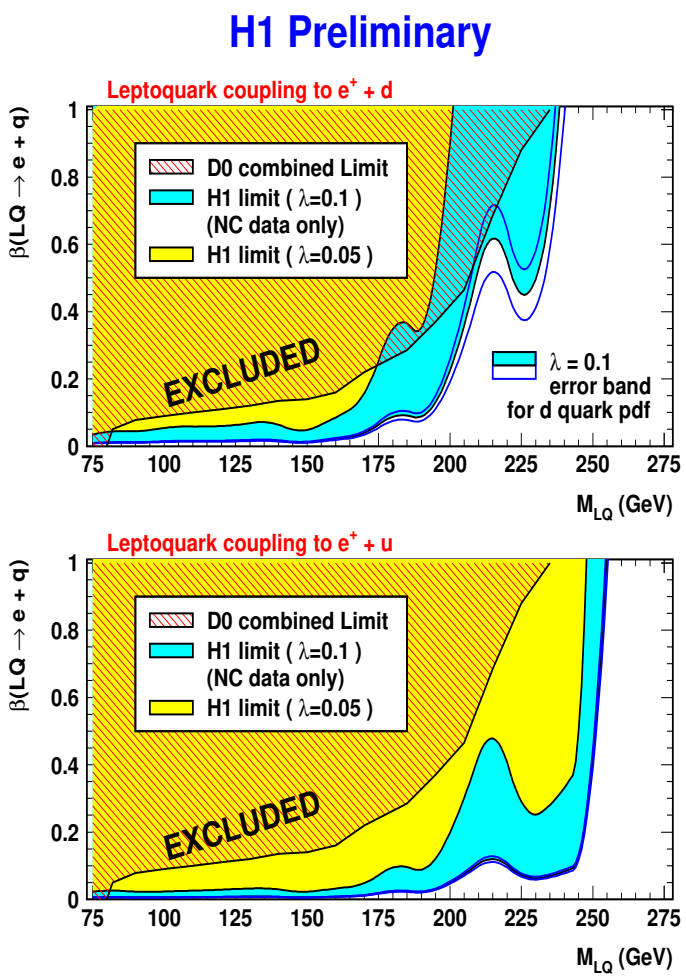

Figure 5: *H1 limits on leptoquarks in the $\beta - M_{LQ}$ plane for 2 different λ values. The results for leptoquarks coupling to the d-quark (upper figure) and to the u-quark (lower figure) are shown. The combined D0 limits are shown for comparison.*

competitive with previously published results from the LEP and Tevatron experiments [14].

2.2 Charged Current Cross Sections

Charged current DIS processes mediated by W bosons have due to the undetected neutrino only the hadronic system visible in the final state and hence show an imbalance in the observed transverse momentum. The kinematics can only be derived from the measured energy and angle of the hadronic system [15].

In leading order QCD the e^+p cross section is related to the quark densities by

$$\frac{d^2\sigma_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{1}{1+Q^2/m_W^2}\right)^2(\bar{u}+\bar{c}+(1-y)^2(d+s)). \qquad (4)$$

H1 has measured the double differential reduced cross section defined similar to the neutral

current case by

$$\sigma_{CC} = \frac{2\pi x}{G_F^2}[1 + \frac{Q^2}{M_W^2}]^2 \frac{d^2\sigma_{CC}}{dxdQ^2}. \quad (5)$$

Figure 7 shows the measured cross section in 6 different ranges of Q^2 compared to the MRSH based Standard Model prediction. The single differential cross section $\frac{d\sigma}{dQ^2}$ measured by ZEUS for the charged current is shown in figure 8. Both experiments see, for charged current DIS, good agreement with the standard model expectation up to the highest Q^2.

ZEUS uses the Q^2 dependence of the CC cross section to determine the propagator mass M_W. The result of the fit shown in fig. 9 yields a value of

$$M_W = 78.6^{+2.5}_{-2.4}[stat]^{+3.3}_{-3.0}[syst]GeV \quad (6)$$

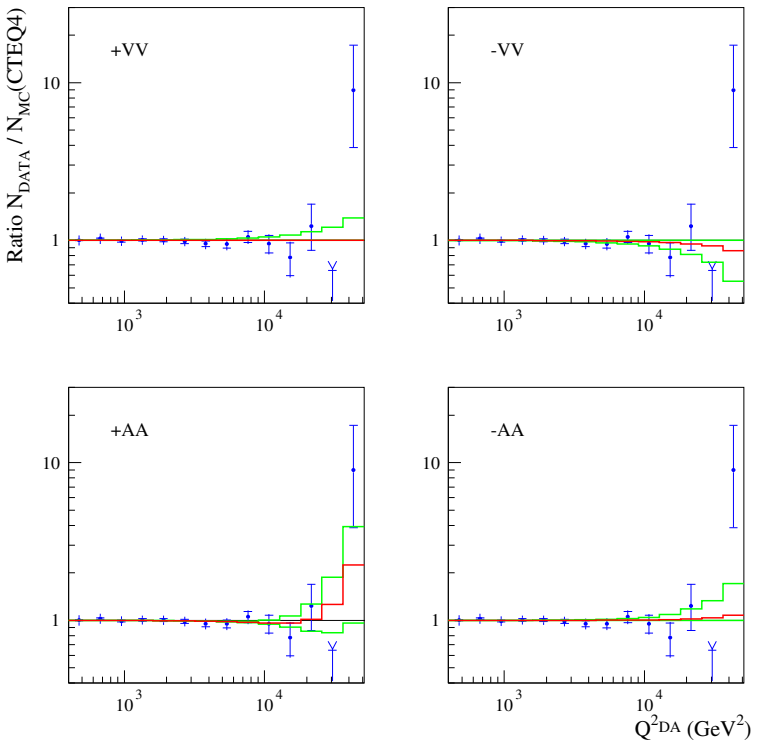

Figure 6: *Examples of contact interaction fit results. The number of events found in each Q^2 interval divided by the Standard Model expectations (CTEQ4 parton distributions) are plotted as points with error bars. The best fit values is plotted as a dark line, the lighter lines indicate the $\pm 1\sigma$ limits.*

Label	a	Fit of Λ ZEUS	Limit on Λ ZEUS	Limit on Λ CDF	Limit on Λ OPAL	Limit on Λ Aleph
VV	+1	∞	4.9	3.5	5.8	3.6
VV	-1	> 10	4.6	5.2	5.8	4.6
AA	+1	2.5	2.0	3.8	5.6	5.0
AA	-1	> 10	4.0	4.8	2.5	3.3
X3	+1	∞	2.8	-	4.3	3.7
X3	-1	> 10	1.5	-	3.4	3.2
X4	+1	∞	4.5	-	4.3	2.7
X4	-1	> 10	4.1	-	5.4	4.3
U4	+1	∞	4.6	-	-	2.1
U4	-1	> 10	4.4	-	-	2.6

Table 2: *Limits (95%CL) on Λ for some selected Contact Interaction terms from the ZEUS analysis, compared to LEP and Tevatron results.*

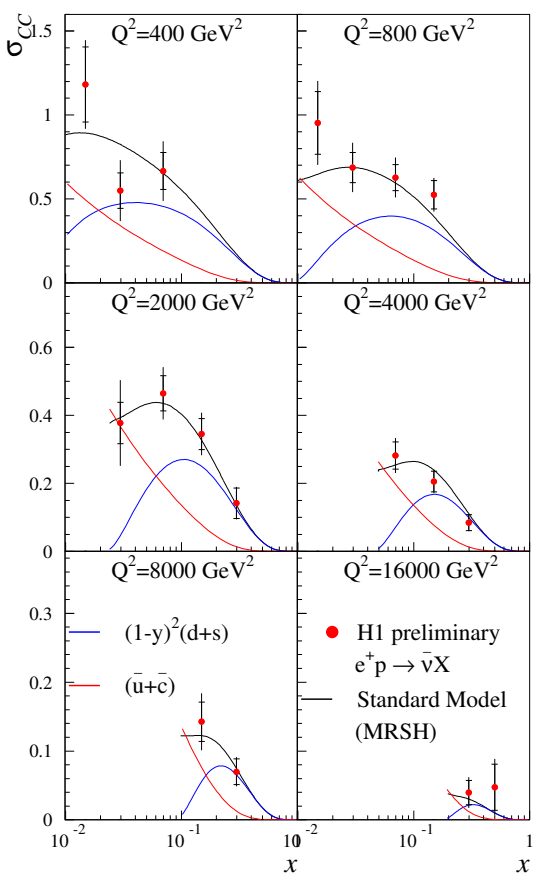

Figure 7: *The e^+p charged current reduced cross section (see text) measured by H1. The Standard Model expectation using the MRSH parametrisation is shown as well as a decomposition into the contributions from quarks and antiquarks.*

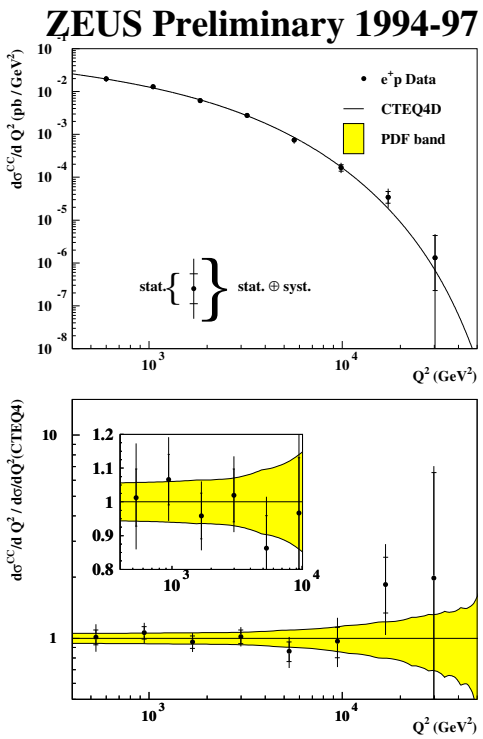

Figure 8: *The e^+p charged current differential cross section measured by ZEUS compared to the Standard Model expectation (upper figure) and the ratio data/SM (lower figure). The shaded region indicates the uncertainty in the Standard Model expectation coming from the uncertainties in the PDFs.*

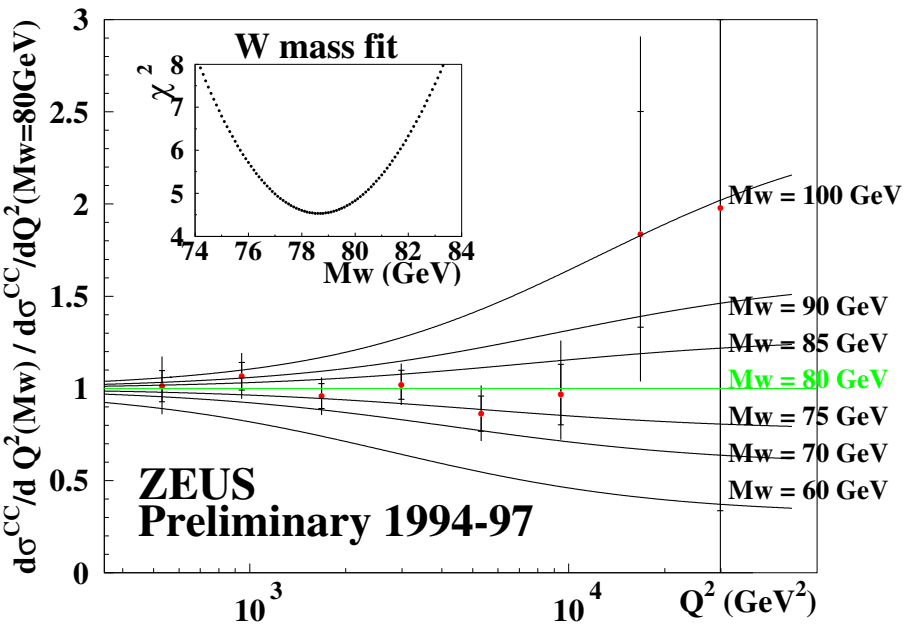

Figure 9: *The dots show the ratio of the measured cross section to the SM prediction. The solid curves show the expected deviation of the cross section from the nominal $M_W = 80GeV$ scenario for various indicated values of M_W.*

3 Events with isolated lepton and missing transverse momentum

The H1 collaboration has searched for events with an isolated high P_T lepton and large missing P_T [16]. Within the Standard Model, processes with this signature are expected from W production with subsequent semileptonic decay [18]. The lowest order diagrams for these processes are shown in figure 10.

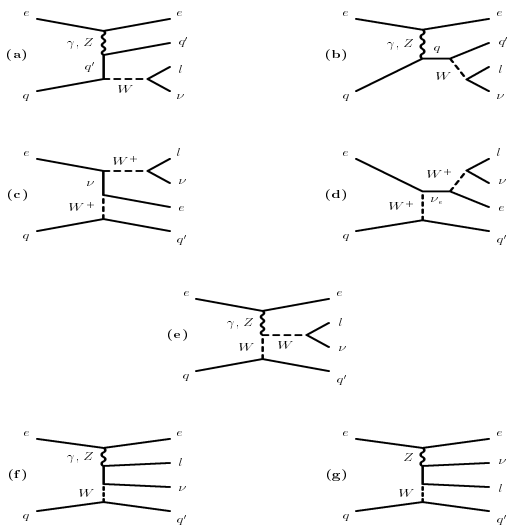

Figure 10: *Parton level diagrams for the process* $eq \to eql\nu$.

The analysis performed is based on the charged current event selection [17] including the following criteria (for details see [16]):

- calorimetric missing transverse momentum > 25 GeV
- a well measured track with $P_T > 10$ GeV (*High* P_T *track*)
- a reconstructed vertex in the interaction region
- topological and timing filters against cosmic and halo muons
- rejection of badly measured neutral current events

leading to 124 events.

For this data sample the isolation of the high P_T tracks with respect to jets or other tracks in the event has been investigated. The isolation is measured by the distance of the track in the $\eta - \phi$-plane to its nearest neighbour track (D_{track}) and to the nearest hadron jet (D_{jet}) . Figure 11 shows the data sample in the D_{track}-D_{jet}-plane. Six events show a single high P_T track clearly isolated in the D_{track}-D_{jet}-plane. All 6 tracks are identified as leptons, five are muons (2 μ^+, 2 μ^- and one μ of unidentified charge) and one is an e^-.

H1	$N_{observed}$	$N_{expected}$
$e^{\pm}$	1	2.4 ± 0.5 (1.7 ± 0.1 from W)
$\mu^{\pm}$	5	0.8 ± 0.2 (0.5 ± 0.1 from W)
ZEUS	$N_{observed}$	$N_{expected}$
e^{+}	4	3.5 ± 0.4 (2.22 ± 0.02 from W)
$\mu^{\pm}$	0	1.3 ± 0.2 (0.46 ± 0.02 from W)

Table 3: *Number of events with an isolated high P_T lepton observed by H1 and ZEUS compared to Standard Model expectations*

In order to compare the characteristics of the observed events with those expected from W - production and leptonic decay ($W \to e\nu, W \to \mu\nu$) a Monte Carlo simulation of W-production was performed with 500 times the statistics used in the data sample. Figure 12 shows for the $e-$ and $\mu-$ channel the generated events in the plane of hadronic transverse momentum, P_T^X, and transverse mass M_T, together with the six events under consideration. Here M_T is calculated from the transverse momentum of the charged lepton and a neutrino, which is assumed to carry the missing transverse momentum observed. For W-production one would expect P_T^X to be low and the M_T distribution is expected to show a Jacobian peak around the W-mass. The observed e^- events shows these characteristica. While two muon events populate a region of phase space where W-events are expected, the remaining three muon events are unlikely to be explained by this production mechanism. Table 3 compares the observed event rates whith those expected in the SM. In the muon channel an excess is observed with respect to the SM prediction.

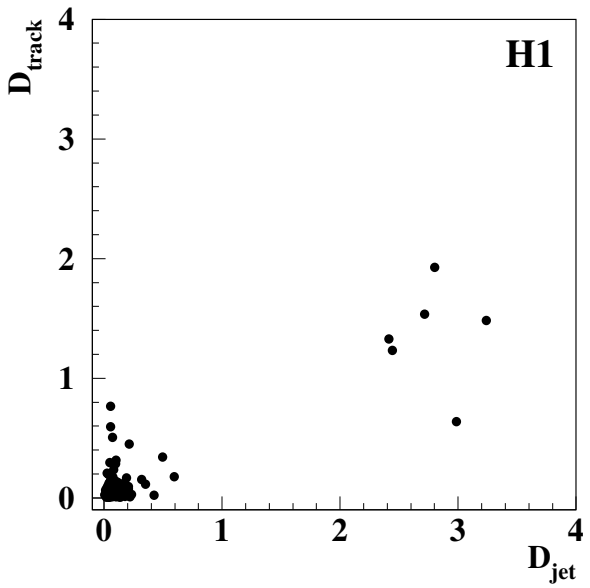

Figure 11: *Correlation between the distances D_{jet} and D_{track} (see text) to the closest hadronic jet and track, for all high p_t tracks.*

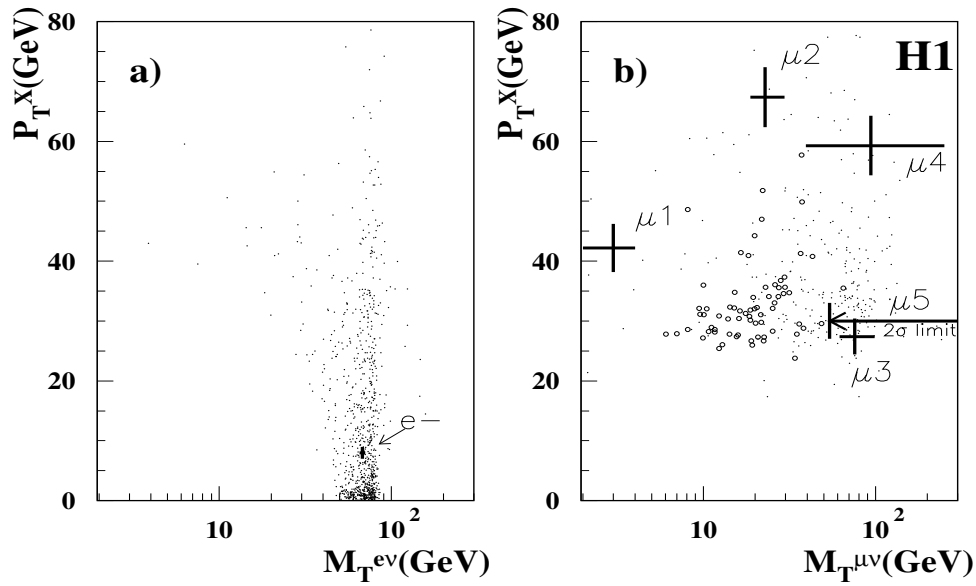

Figure 12: *Distribution of the events in the P_T^X-M_T plane measured by H1. Figure a) shows the electron channel, figure b) the muon channel. The 1-σ uncertainties on the measured kinematic parameters are indicated by the crosses. (For event $\mu 5$ the 2σ lower limit is shown for M_T.) The dominant SM contributions (dots for W production, open circles for $\gamma\gamma$ processes in the μ channel) are shown for an accumulated luminosity which is a factor 500 higher than in the data. For the μ channel no significant contribution is expected below $P_T^X = 25$ GeV due to the event selection criteria.*

ZEUS performed a similar analysis, resulting in four events found in the e^+-channel and none in either the e^- - or μ - channel. The results are shown in figure 13 and in Table 3. The ZEUS observations agree with the SM predictions.

Further studies with higher statistics are needed to clarify the situation.

4 Summary and Outlook

Using the full data sample 1994 - 1997 the H1 and ZEUS collaborations measured deep inelastic e^+p scattering cross sections up to $Q^2 = 40000\text{GeV}^2$. The measured cross sections are well described by the Standard Model over more than 4 orders of magnitude in Q^2. A slight excess of events observed at very high Q^2 and high y remains to be investigated with improved statistics in coming years.

With the data available a new domain for tests of the Standard Model became accessible and searches for new phenomena have been performed by both experiments, pushing the limits for leptoquarks well above the 200GeV mass range and restricting the Λ parameters for contact interaction terms to values above a few TeV.

H1 has seen six events with an isolated high P_T lepton and large missing p_t, three of them cannot easily be explained by Standard Model processes. ZEUS does not observe an anomaly in this channel.

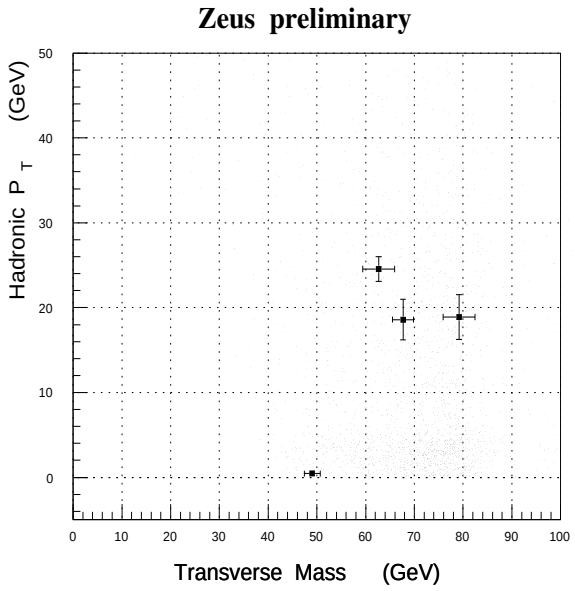

Figure 13: *Distribution of the four e^+ events observed by ZEUS in the $P_T^{hadronic}$- M_T plane , compared with a Monte Carlo study of W production with a luminosity $L_{MC} = 1000 * L_{data}$*

In the 1998/1999 data taking period HERA will operate with electrons and the proton beam energy will be raised to 920GeV. An anticipated luminosity of $50nb^{-1}$ in this running conditions should help in obtaining improved measurements in the topics mentioned above. In the year 2000 HERA will upgrade its luminosity by a factor of five, providing an integrated luminosity of $1fb^{-1}$ for each experiment by the year 2005. The availability of longitudinally polarized electrons from the year 2000 onwards will enlarge the scope of electroweak physics at HERA.

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