Standard Model Tests at very high Q^2 at HERA

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Abstract. With the e-p collider HERA at DESY tests of the Standard Model at highest available Q^2 have been performed. Recent results on the cross section for deep inelastic e-p scattering up to $Q^2 = 40000\mathrm{GeV}^2$ are presented. An analysis of events with high missing transverse momentum p_t and an isolated lepton is discussed. Limits on the production of leptoquarks, excited fermions and on Contact Interactions are given.

INTRODUCTION

With the e-p collider HERA at DESY electron proton scattering processes [1] at a maximum center of mass energy $\sqrt{s} = 300\mathrm{GeV}$ offer the possibility to study deep inelastic scattering (DIS) in charged and neutral current processes up to a momentum transfer of $Q^2 = 90000\mathrm{GeV}^2$.

With the large data sample from 1997 both collaborations H1 and ZEUS have refined their analyses and measured cross sections up to $Q^2 = 40000\mathrm{GeV}^2$. 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 Leptoquarks or Contact Interactions) have been performed. With increased luminosity new limits on excited fermions have been derived extending beyond the LEP mass range. A detailed description of the H1 and ZEUS experiments can be found in [1] and [2] respectively.

DIS

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

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1) Although HERA has run with positrons instead of electrons from 1994 until 1997 throughout the paper the name electron is used for e^+ as well.

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 lepton respectively. In addition further Lorentz-invariants can be defined:

the Bjorken scaling variable:

$$x = \frac{Q^2}{2Pq} \tag{1}$$

and the fractional energy transfer to the proton in its rest frame:

$$y = \frac{Pq}{Pk}, \tag{2}$$

where P is the 4-momentum of the incoming proton. In the quark parton model the mass in 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.

Neutral Current Cross Sections

Neutral current DIS mediated by the neutral bosons γ or Z show 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 :

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) - Y_-xF_3(x,Q^2)] \tag{3}$$

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

Fig.1 shows the single differential cross section $d\sigma/dQ^2$ measured by the ZEUS collaboration using the data from 1994 to 1997. All points agree with the Standard Model (SM) predictions within error, with the exception of the highest bin ($Q^2 > 35000\mathrm{GeV}^2$) which contains two events where 0.29 are expected.

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

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

in figure 2 for 6 different x ranges compared with the standard model expectation based on the MRSH evolution equations [6]. Also shown are the low Q^2 data from SLAC [7], BCDMS [8] and NMC [9]. The low Q^2 data join well the high Q^2 cross section. Both the standard model expectation based on MRSH parton distributions as well as a next to leading order H1 fit describe the observed cross section over 4 orders of magnitude for all ranges in x. 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 up to 1997.

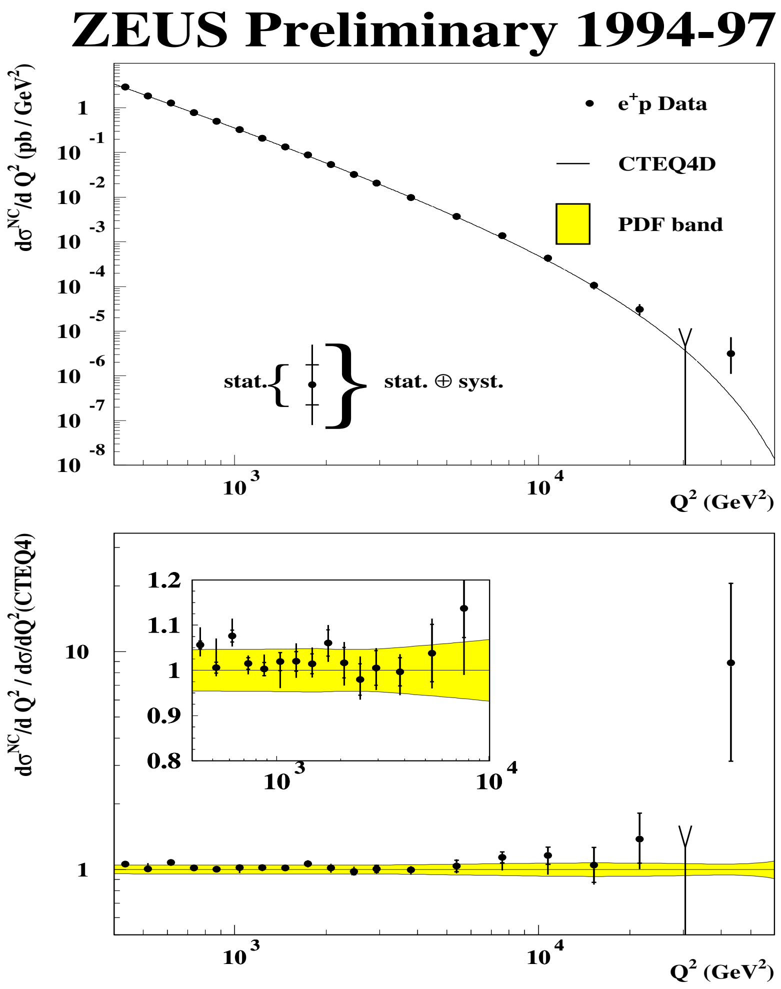

FIGURE 1. The e^+p neutral current cross section $\frac{d\sigma}{dQ^2}$ measured by ZEUS (upper figure) and the ratio data/SM (lower figure) is shown. The Standard Model expectation shown is based on the CTEQ4D parametrisation of the parton density function.

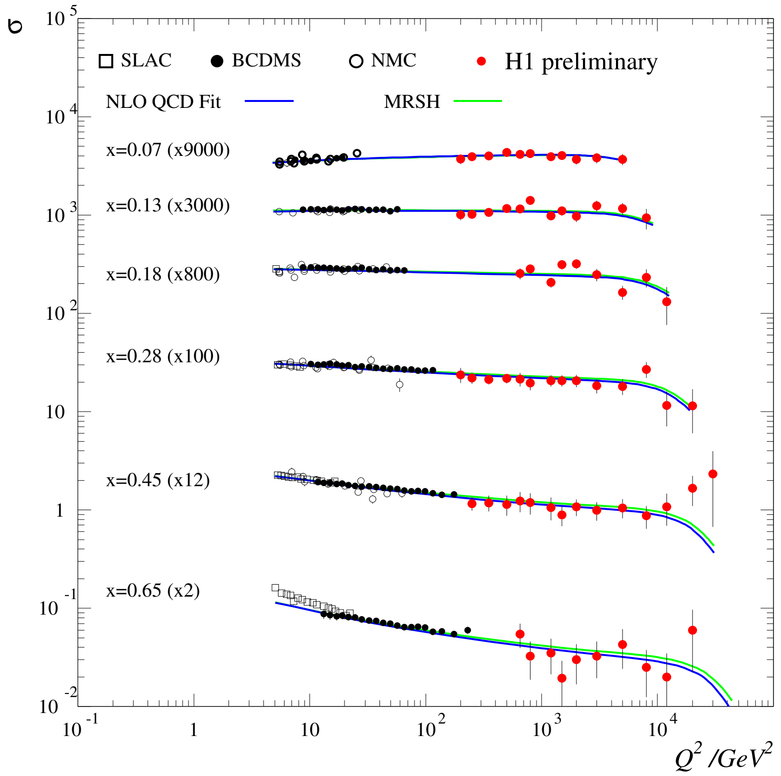

FIGURE 2. The e^+p neutral current reduced cross section (see text) measured by H1 is shown together with low Q^2 data from SLAC, BCDMS and NMC. The MRSH based Standard Model expectation and a next to leading order QCD Fit from H1 are shown as curves.

TABLE 1. Number of events above $Q^2 > 15000\text{GeV}^2$ measured by H1 and the Standard Model expectation in comparison for the data up to 1996 and the full data sample

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}

H1 analysed the neutral current data sample in terms of Leptoquarks by comparing the event rate at various M bins with the Standard Model expectations, interpreting a possible deviation from the SM as a signal for Leptoquarks. Scalar leptoquarks can be produced as s-channel resonances at HERA, leading to a flat cross section $d\sigma/dy$ whereas the t-channel exchange in standard DIS leads to a $1/y^2$ dependence. By choosing a proper cutoff value y_{cut} for the data to be analysed, the signal to background ratio can be optimised. Figure 3 shows the mass spectrum

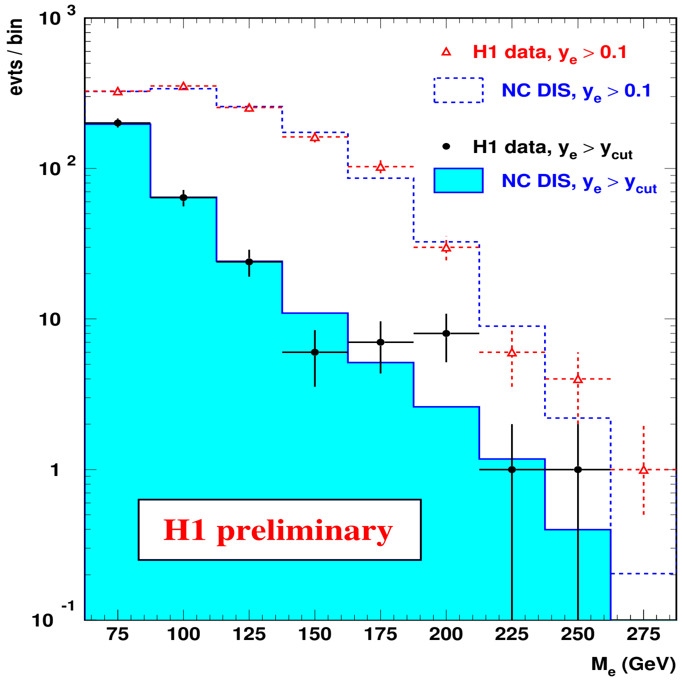

FIGURE 3. The Mass spectrum of the measured neutral current DIS events by H1 shown as triangles for the full data sample and as circles for the data with y_{cut} applied. y_{cut} varies from 0.6 at M=60GeV to 0.2 at M=250GeV. The Standard Model expectation is shown as a histogram.

for all NC data as well as for data with a mass dependent y_{cut} [10] applied. 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 e-q 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, Rückel, Wyler [11]) and the limits are derived in the $M-\lambda$ plane. The limits for fixed λ are shown in figure 4. For $\beta = 1$ leptoquarks are excluded

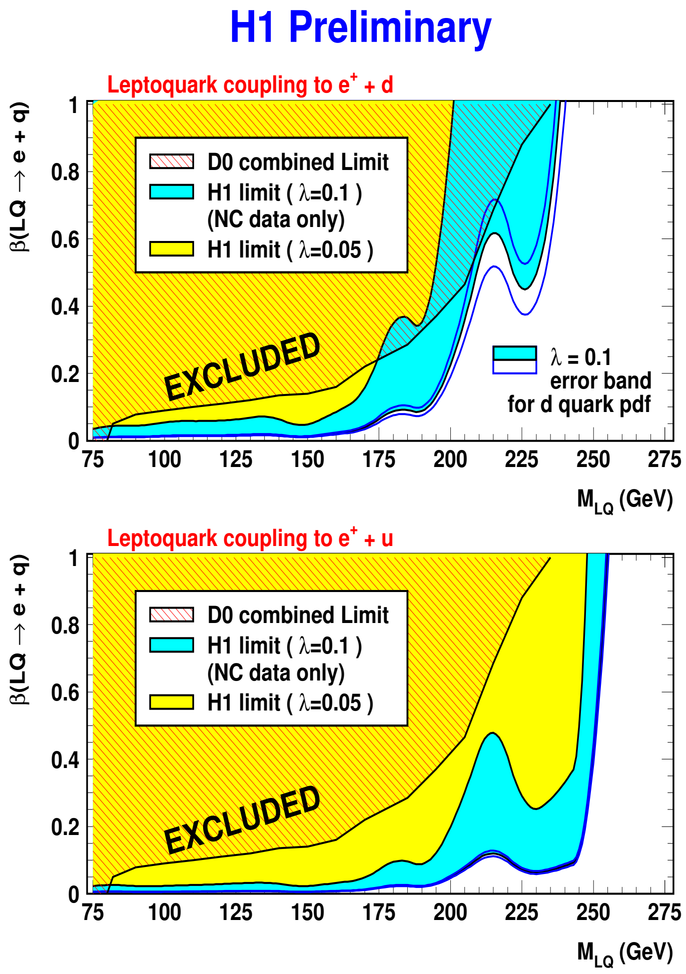

FIGURE 4. H1 limits on leptoquarks in the $\beta - M_{LQ}$ plane for 2 different λ values. The results for the leptoquarks coupling to the d-quark (upper figure) and for the u-quark (lower figure) are shown. The combined D0 limits are shown for comparison.

up to 250GeV at 95% CL, comparable to previous results from D0 [12]. But for $\beta << 1$ there is still a high discovery potential for leptoquarks even below 200GeV.

Contact Interaction

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 as shown in equation 5.

$$\begin{aligned} L_{NC} = {} & L_{SM} \\ & + \eta_{LL}(\bar{e}_L\gamma^\mu e_L)(\bar{q}_L\gamma^\mu q_L) + \eta_{LR}(\bar{e}_L\gamma^\mu e_L)(\bar{q}_R\gamma^\mu q_R) \\ & + \eta_{RL}(\bar{e}_R\gamma^\mu e_R)(\bar{q}_L\gamma^\mu q_L) + \eta_{RR}(\bar{e}_R\gamma^\mu e_R)(\bar{q}_R\gamma^\mu q_R) \end{aligned} \tag{5}$$

TABLE 2. Parameter combinations considered in the Contact Interaction analysis by ZEUS

Label	η^u_{LL}	η^u_{LR}	η^u_{RL}	η^u_{RR}	η^d_{LL}	η^d_{LR}	η^d_{RL}	η^d_{RR}
VV	+a	+a	+a	+a	+a	+a	+a	+a
AA	+a	-a	-a	+a	+a	-a	-a	+a
VA	+a	-a	+a	-a	+a	-a	+a	-a
X1	+a	-a	0	0	+a	-a	0	0
X2	+a	0	+a	0	+a	0	+a	0
X3	+a	0	0	+a	+a	0	0	+a
X4	0	+a	+a	0	0	+a	+a	0
X5	0	+a	0	+a	0	+a	0	+a
X6	0	0	+a	-a	0	0	+a	-a
U5	0	+a	0	+a	0	0	0	0
U1	+a	0	-a	0	0	0	0	0
U4	0	+a	+a	0	0	0	0	0

with a = -1 or +1

TABLE 3. Limits on Λ for Contact Interactions from the ZEUS analysis

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

Here only the vector terms are taken into account and the convention $\eta = a4\pi/\Lambda^2$ with $a = \pm 1$ is used. A binned as well as an unbinned likelihood analysis has been performed considering the following constraints :

- From atomic parity violation results : $\eta^q_{LL} + \eta^q_{LR} - \eta^q_{RL} - \eta^q_{RR} = 0$
- SU(2) symmetry implies $\eta^u_{iL} = \eta^d_{iL}$
- At high x the cross section at HERA is dominated by up quarks

The possible combinations of the parameters considered are shown in table 2. The result of the fit is summarised in table 3. The ZEUS results are competitive with previously published results from the LEP and Tevatron experiments [13]. The lower limits on the scale Λ are in the range of 2-5 TeV.

Charged Current Cross Sections

Charged current DIS processes mediated by W bosons have due to the undetected neutrino ν only a hadronic system visible in the final state and hence an imbalance in the detected transverse momentum. The kinematics can only be derived from the measured energy and angle of the hadronic system [14].

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

$$\frac{d^2\sigma_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{1}{1+Q^2/m_W^2}\right)^2(\bar{u}+\bar{c}+(1-y)^2(d+s)). \tag{6}$$

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

$$\sigma_{CC} = \frac{x2\pi}{G_F^2}[1+\frac{Q^2}{M_W^2}]^2\frac{d^2\sigma_{CC}}{dxdQ^2}. \tag{7}$$

Figure 5 shows the measured cross section in 6 different ranges of Q^2 up to $Q^2 = 16000\mathrm{GeV}^2$ compared to the MRSH based Standard Model prediction.

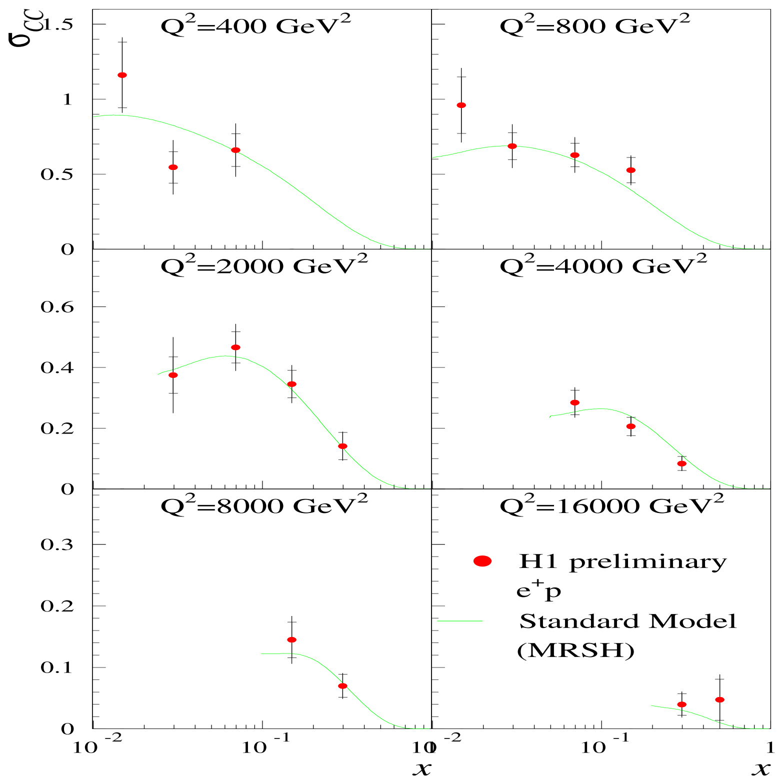

FIGURE 5. Charged current reduced cross section (see text) measured by H1. The Standard Model expectation using the MRSH parametrisation is shown as dotted line.

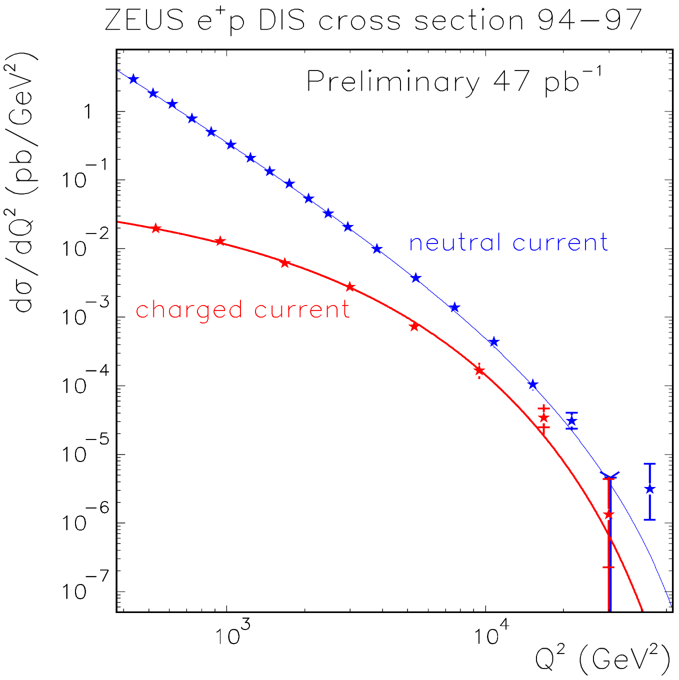

FIGURE 6. Charged and neutral Current differential cross sections measured by ZEUS. The Standard Model expectation is shown as full line

The single differential cross section $\frac{d\sigma}{dQ^2}$ measured by ZEUS for both the neutral current as well as the charged current is shown in figure 6. Both experiments see, for charged current DIS, good agreement with the standard model expectation up to highest Q^2.

EVENTS WITH ISOLATED LEPTON AND LARGE MISSING P_T

The H1 collaboration has observed events with an isolated lepton and large missing p_t and has searched for possible explanations of these events [15]. Within the Standard Model, processes with this signature are expected from W production with subsequent leptonic decay [17]. The lowest order diagrams for these processes are shown in figure 7.

A dedicated analysis has been performed by using the charged current event selection [16] including the following criteria (for details see [15]):

- $P_{trans}(Calorimetry) > 25\mathrm{GeV}$
- requiring a well measured central track with $p_t > 10\mathrm{GeV}$
- 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 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 a track in the $\eta-\phi$-plane to its nearest neighbor track (D_{track}) and to the nearest jet (D_{jet}) . Figure 8 shows the data sample in the D_{track}-D_{jet}-plane, after the above mentioned cuts. Six tracks are clearly displaced in the D_{track}-D_{jet}-plane, all of them fulfill the H1 lepton criteria [15]. For five events an isolated μ and for one event an isolated e^- is detected.

To further study the kinematics a Monte Carlo simulation of the Standard Model W-production was performed with 500 times the statistics used in the data sample. Figure 9 shows the generated events in the plane of hadronic transverse momentum, P_T^X, and transverse mass M_T, together with the six isolated tracks found in the data for the e^- and the μ candidates separately, here M_T is calculated out of

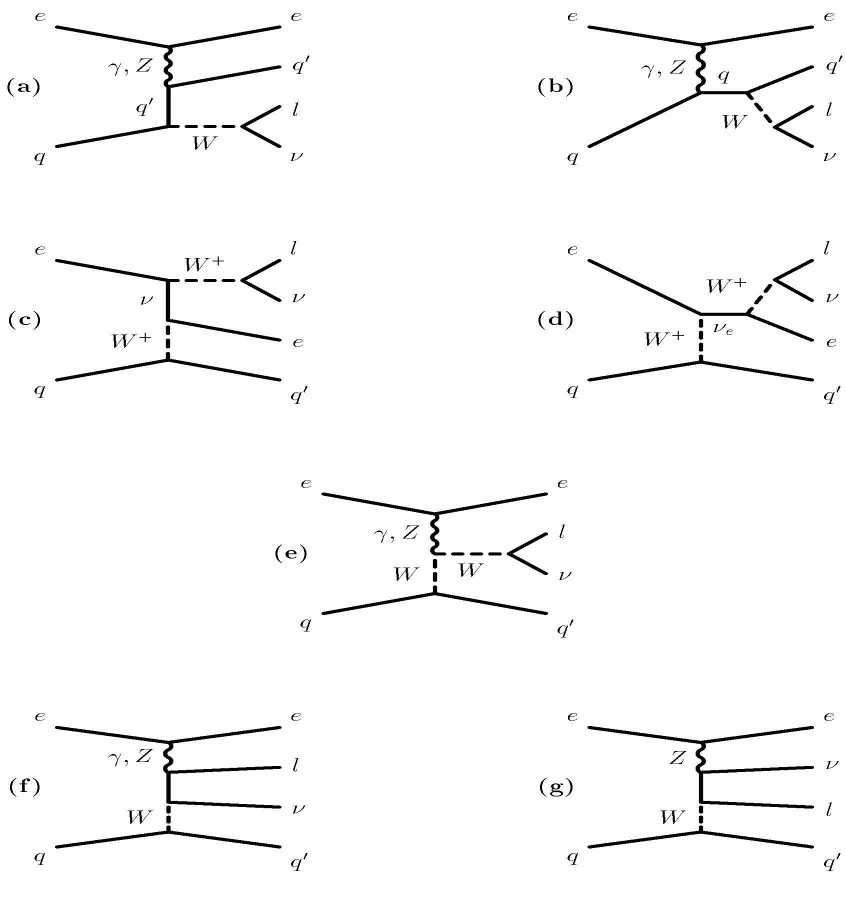

FIGURE 7. Parton level diagrams for the process $eq \to eql\nu$.

TABLE 4. Number of events with an isolated high p_t lepton observed by H1

H1	N_{obs}	$N_{exp}(W)$	background
e^-	1	1.65 ± 0.47	<0.14
$\mu^\pm$	5	0.53 ± 0.11	<0.28

TABLE 5. Number of events with an isolated high p_t lepton measured by ZEUS

ZEUS	N_{obs}	$N_{exp}(W)$	background
e^+	4	2.22 ± 0.2	1.24
$\mu^\pm$	0	0.46 ± 0.02	0.84

the transverse momentum of the lepton and the neutrino. The missing transverse energy is hereby attributed to a hypothetical neutrino. Due to the kinematics of the process one would expect P_T^X to be low and to observe a Jacobean Peak around the W-mass, which is clearly seen for the Monte Carlo events. Table 4 summarises the results. The expectation from standard model W-production as well as the expected background is shown.

ZEUS did a similar analysis and Monte Carlo study, the result is shown in figure 10 for the e^+ case and summarised in Table 5.

Whereas H1 sees 3 muon events in a region which is not preferred by the standard model W-production, ZEUS does not see any excess above Standard Model expec-

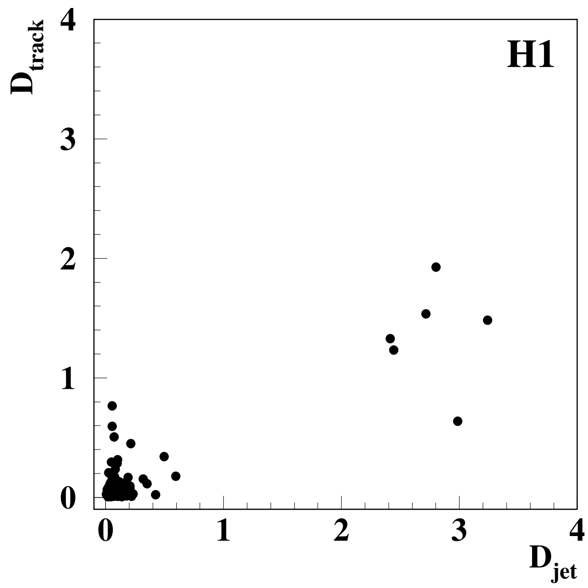

FIGURE 8. Correlation between the distances D_{jet} and D_{track} (see text) to the closest hadronic jet and track, for all high p_t tracks.

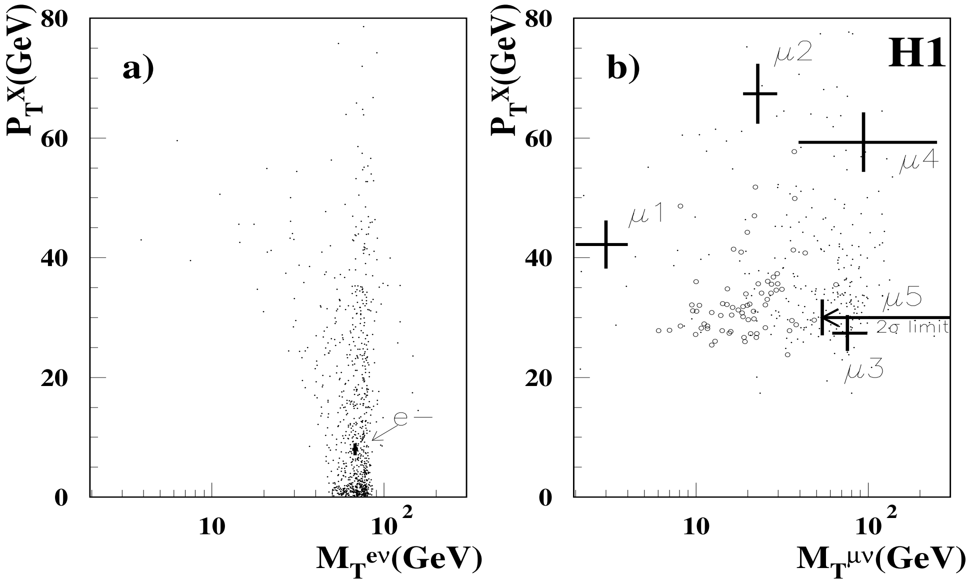

FIGURE 9. Distribution of the events in the P_T^X-M_T plane measured by H1. Figure a shows the electron channel figure b the muon channel. The 1-σ uncertainty on the measured kinematic parameters are indicated by the crosses. (For event $\mu 5$ the 2σ lower limit is shown.) The dominant SM contributions (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 because of a cut in the event selection.

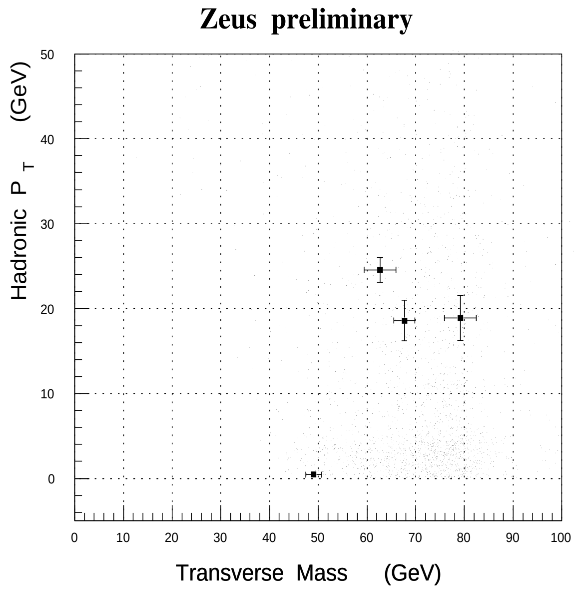

FIGURE 10. Distribution of e^+ events in the $p_t^{hadronic}$ M_T plane observed by ZEUS, compared with a Monte Carlo study of W production with $L_{MC} = 1000 * L_{data}$

tation. Further studies with higher statistics will certainly clarify the situation.

LIMITS ON EXCITED FERMIONS

With the full statistics of 1994 - 1997 data, H1 did a search for excited fermions and improved production limits considerably compared to previous published HERA results [19]. The processes considered, the event selection and the observed events are listed in table 6.

TABLE 6. Excited lepton channels analysed by H1

Channel	Selection	Data	Background	Efficiency
$e^* \to e\gamma$	$2EMclusters$	223	239± 7	85%
$e^* \to eZ \to ee$	$3EMclusters$	3	1.4± 0.3	78%
$e^* \to eZ \to \nu\bar{\nu}$	$1e + P_t^{miss}$	1	3.6± 0.7	70%
$e^* \to eZ \to q\bar{q}$	$2jets + 1e$	38	48± 3	41%
$e^* \to \nu W \to e\nu$	$1e + P_t^{miss}$	1	3.6± 0.7	70%
$e^* \to \nu W \to q\bar{q}$	$2jets + P_t^{miss}$	3	3.8± 0.5	40%
$\nu^* \to \nu\gamma$	$1phonton + P_t^{miss}$	0	1.3± 0.8	38%
$\nu^* \to \nu Z \to ee$	$2e + P_t^{miss}$	0	0.38± 0.2	40%
$\nu^* \to \nu Z \to q\bar{q}$	$2jets + P_t^{miss}$	3	3.8± 0.5	40%
$\nu^* \to eW \to e\nu$	$2e + P_t^{miss}$	0	0.38± 0.2	40%
$\nu^* \to eW \to q\bar{q}$	$2jets + 1e$	38	48 ± 3	41%

As an example the invariant mass spectrum for the $e\gamma$ channel is shown in figure 11, compared with the Standard Model expectation. From the derived cross section,

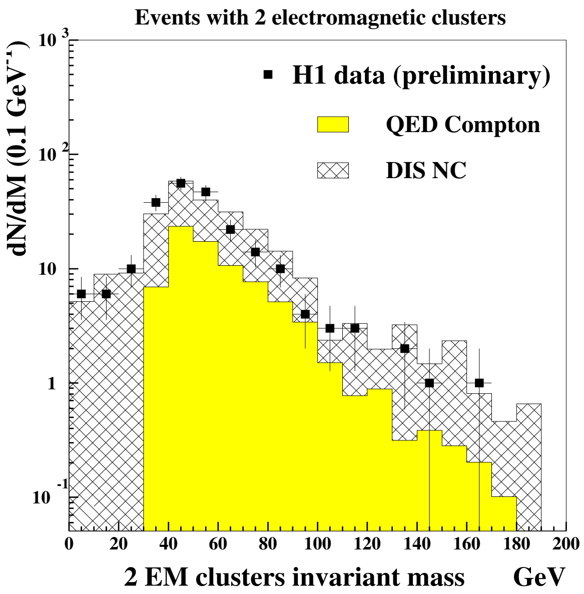

FIGURE 11. Invariant mass of 2 electro magnetic clusters compared with the QED compton and DIS neutral current simulations

limits on the characteristic coupling f/Λ [18] are obtained. The limits for the excited electron channels are shown as an example in figure 12. The limits extend

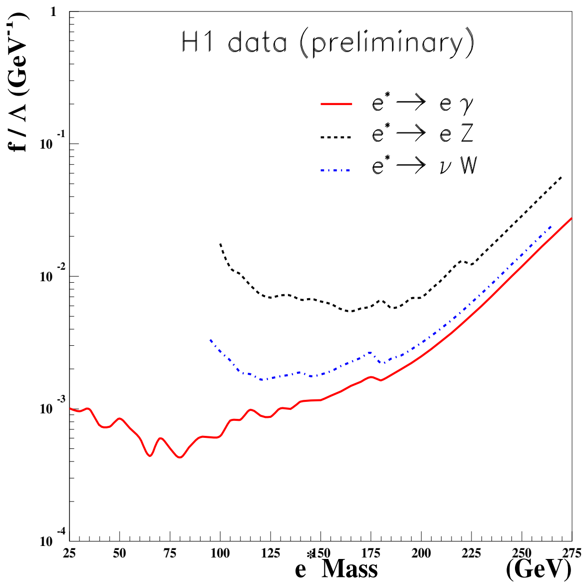

FIGURE 12. Upper limits at 95% confidence level on the coupling f/Λ as a function of the mass for the excited electron

well above the LEP mass range and exclude excited electrons up to 275GeV for $f/\lambda > 3 * 10^{-2}\mathrm{GeV}^{-1}$.

SUMMARY AND OUTLOOK

Using the full data sample 1994 - 1997 the H1 and ZEUS collaborations measured the deep inelastic scattering cross sections up to $Q^2 = 40000\mathrm{GeV}^2$ extending measurements from previous fixed target experiments by two orders of magnitude. The results from H1 and ZEUS in deep inelastic scattering are well described by the standard model over more than 4 orders of magnitude in Q^2.

With the data available a new domain for Standard Model tests is accessible and searches for new phenomena have been performed by both experiments, pushing the limits for leptoquarks and contact interaction well above the 200GeV mass range. A slight excess of events with very high Q^2 at high y remains to be clarified with improved statistics in coming years.

H1 has seen 6 events with an isolated high p_t lepton and large missing p_t, 3 of them cannot easily be explained by Standard Model W processes.

Searches for excited leptons have been performed and previously published limits from HERA have been improved by a factor of 2.

In the 1998/1999 data taking period HERA will go back to electron operation and the proton beam energy will be raised from 820GeV to 920GeV. An expected $50nb^{-1}$

of 27.5GeV e^- on 920GeV p should help in obtaining improved measurements in the above mentioned topics. In the year 2000 HERA will considerably upgrade its capability and a factor of five more luminosity is expected from then on, providing $1fb^{-1}$ to each experiment by the year 2005.

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