EXOTIC AND HIGH Q^2 PHYSICS AT HERA

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At the ep collider HERA the Q^2-dependence of the cross sections for Neutral and Charged Current deep inelastic scattering have been measured by the H1 and ZEUS collaborations. Both collaborations used the data collected up to 1995 to perform also a contact interaction analysis and a search for leptoquarks. Moreover a search for excited electrons is presented and a limit on the production cross section is given.

1 Introduction

Data taken by the H1 and ZEUS collaboration during the '93, '94 and '95 running periods at the ep collider HERA are presented. Protons of 820 GeV were collinding with electrons or positrons of 26.7 and 27.5 GeV respectively, resulting in a center of mass energy of $\sqrt{s} \approx 300$ GeV. The analysed data correspond to an integrated luminosity of $\approx 3 - 9\ pb^{-1}$ per experiment. First the experimental setup is explained. After a short introduction in deep inelastic scattering the results on the Q^2 distribution of Charged and Neutral Current events are presented. The good agreement of the data with the Standard Model expectation allows, in the Neutral Current, case to place limits on the compositeness scale parameter Λ. An analysis is presented where the H1 and Zeus collaboration looked for leptoquarks by analysing the M and x distrbution, respectively. Finally a search for excited electrons is shown and limits on the cross section for these processes are given.

2 The Experiments

At HERA ep collisions are recorded by the experiments H1 and ZEUS. The details of the experimental setup are described elsewhere [1,2]. For the analyses presented here the essential parts of the detectors are the drift and proportional chambers surrounding the interaction point and the calorimeters. The system of drift and proportional chambers allows the determination of the interaction point and the measurement of the momenta of charged particles. This tracking system is in case of H1 surrounded by a liquid argon calorimeter (LAr) which measures the energy with a resolution of $\sigma(E)/E = 12\%\sqrt{E} \bigoplus 1\%$ for electrons and $\sigma(E)/E = 50\%\sqrt{E} \bigoplus 2\%$ for pions. The calorimeter is surrounded by a solenoid providing a magnetic field of 1.2 T parallel to the beam axis. The ZEUS tracking system is operating in a magnetic field of 1.4 T. The uranium-scintillator calorimeter (UCAL) encloses the solenoid and has an energy resolution of $\sigma(E)/E = 18\%\sqrt{E} \bigoplus 1\%$ and $\sigma(E)/E = 35\%\sqrt{E} \bigoplus 2\%$. Both experiments use instrumented iron return yokes to measure leakage of hadronic energy and to identify muons. The luminosity is measured by the electron and photon taggers installed in the beampipe via the Bethe-Heitler-process $ep \to ep\gamma$.

3 Deep Inelastic Scattering at High Q^2

3.1 Theoretical Introduction

At HERA the incident positrons are scattered on a quark inside the proton. This is known as deep inelastic scattering (DIS). The interaction is mediated by gauge bosons γ, Z (Neutral Current) or $W^\pm$ (Charged Current). The Feynmandiagram of the leading order process is shown in figure 1.

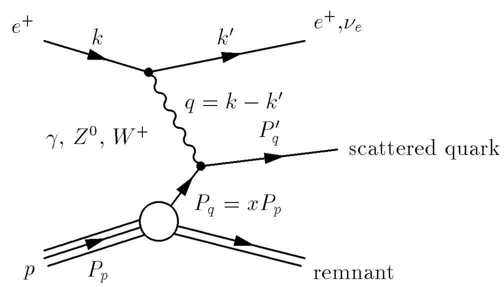

Figure 1: *The Feynmangraph for deep inelastic e^+p scattering.*

In the case of a Neutral Current (NC) interaction the final state consists of the scattered electron and the hadronic final state. The energies and angles of the electron and hadrons are measured in the detector. For Charged Current (CC) interactions only the hadronic final state can be measured, because the scattered neutrino escapes the detection. The hadronic final state consists of the current jet and the proton remnant. The main part of the remnant is lost in the beampipe.

The kinematic variables are the 4-momentum-transfer of the gauge boson

$Q^2 = -(k-k')^2$, the inelasticity y and the Bjorken scaling variable

$$x_{Bj} = Q^2/ys$$

In the Quark-Parton-Model (QPM) x_{Bj} can be interpreted as the momentum fraction of the proton carried by the struck quark.

The differential Born cross section for the NC process $e^{\pm}p \to e^{\pm}p$ is given [3] by

$$\frac{d^2\sigma^{\pm}}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4 x}\left(y^2 x\tilde{F}_1^{\pm}(x,Q^2) + (1-y)\tilde{F}_2^{\pm}(x,Q^2) + (y-\frac{y^2}{2})x\tilde{F}_3^{\pm}(x,Q^2)\right)$$

$\tilde{F}_1$, $\tilde{F}_2$ and $\tilde{F}_3$ are the generalized proton structure functions and are including the couplings and propagator terms of the electroweak interaction and the quark densities in the proton. $\tilde{F}_3$ results from the interference of γ and Z^0 exchange.

The Born cross section for CC processes $e^{\pm}p \to \nu p$ is given by

$$\frac{d^2\sigma^{-}}{dxdQ^2} = \frac{G_F}{2\pi}\frac{M_W^2}{(M_W^2+Q^2)^2}\left(\sum_{q=u,c} q(x,Q^2) + (1-y)^2 \sum_{q=\bar{d},\bar{s},\bar{b}} \bar{q}(x,Q^2)\right)$$

$$\frac{d^2\sigma^{+}}{dxdQ^2} = \frac{G_F}{2\pi}\frac{M_W^2}{(M_W^2+Q^2)^2}\left(\sum_{q=d,s,b} q(x,Q^2) + (1-y)^2 \sum_{q=\bar{u},\bar{c}} \bar{q}(x,Q^2)\right)$$

G_F denoted the Fermi constant and $q(x,Q^2)$ and $\bar{q}(x,Q^2)$ are the quark densities.

3.2 The measured differential Cross Sections for NC and CC events

The experimental signature of a Neutral Current interaction is the scattered positron (electron) which is well identified in the calorimeter and hadronic activity. For Charged Current processes the characteristic topology is a jet with large transverse momentum which is not balanced in the detector, because the neutrino is not detected. The kinematic variables Q^2, y and x have to be determined from the measured energies and angles of the particles in the final state. There are two angles and energies which can be used to calculate the two independent kinematic variables of the scattering process:

- the electron method can be used for NC interactions. Only the variables of the scattered electron are used, so it is independent of the hadronic final state:

$$y_e = 1 - \frac{E_e - E_e cos\theta_e}{2E_e^0},\ Q_e^2 = \frac{E_{T,e}^2}{1-y_e},\ x_e = \frac{Q_e^2}{sy_e}$$

  E_e is the energy, θ_e the angle of the scattered electron.

- the jacquet blondel method[6] can be used for Charged Current and Neutral Current interactions, because it only uses the observables of the hadronic final state by summing up the energy of all hadronic clusters:

$$y_{JB} = \frac{\sum(E-p_z)}{2E_e^0},\ Q_{JB}^2 = \frac{\sum(p_x^2+p_y^2)}{1-y_{JB}},\ x_{JB} = \frac{Q_{JB}^2}{sy_{JB}}$$

The measured differential cross section as a function of Q^2 for charged current and neutral current processes is shown in figure 2. Here the ZEUS result is given which is in good agreement with the published H1 data[8].

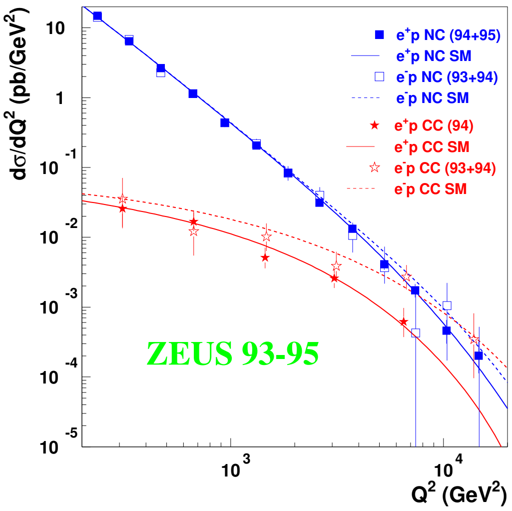

Figure 2: *The cross section $d\sigma/dQ^2$ for NC and CC DIS high Q^2 e^+p scattering.*

The NC cross section falls rapidly with increasing Q^2. At values $Q^2 \ll M_Z^2$ it is dominated by the pure photon exchange resulting in an equal cross section for e^+p and e^-p. For $Q^2 > 3000\ GeV^2$ the theoretical predictions for e^+p and e^-p scattering are starting to differ, because the γZ^0 interference term acquires a different sign for both channels. However, with the data collected up to 1995 the statistics at high Q^2 is too low to establish the interference term or the pure Z^0 term experimentally.

Also shown in figure 2 is the Charged Current cross section. It is much lower than the NC cross section at small values of Q^2, but becomes of comparable size around $Q^2 = 10^4 GeV^2$. It differs for e^-p and e^+p scattering, because of the couplings to different quark flavours in the proton.

The data agree well with the Standard Model predictions over the whole Q^2 range covered. These predictions include the

- the electroweak couplings
- the parametrized parton densities functions at a starting scale $Q_0^2 = 5\ GeV^2$
- the evolution of the parton density functions from $Q^2 = Q_0^2$ to higher values Q^2 according to the DGLAP [7] evolution equations.

3.3 A Contact Interaction Analysis

HERA has extended the kinematic region of deep inelastic scattering compared to fixed target experiments by an order of magnitude up to values of the four-momentum transfer $Q^2 \approx 10^4\ GeV^2$. It is interesting to check the validity of the Standard Model in this new kinematic domain and to search for new phenomena. A convenient and model independent way to look for possible deviations in the cross section is the contact interaction approach. Interactions mediated by a heavy boson can be approximated by a four-fermion vertex, if the boson mass is much larger than the scale Q^2. An example for this is the Fermi theory of β-decay at low Q^2. Any evidence for a contact interaction at HERA would give an indirect indication of new phenomena. Limits placed on the size of contact interaction can be translated into limits on new physics, e.g. quark compositeness, leptoquarks or new higher mass gauge bosons (Z').

Contact interactions can be described by an additional term in the Lagrangian [9]

$$L = L_{SM} + \sum_q \eta_{LL}(\bar{e}_L\gamma_\mu e_L)(\bar{q}_L\gamma^\mu q_L) + \eta_{LR}(\bar{e}_L\gamma_\mu e_L)(\bar{q}_R\gamma^\mu q_R) + ...$$

η_{if} denotes the interaction coefficient, L and R the chirality of the interacting fermion. Limits on contact interaction are typically quoted in terms of the compositeness scale parameter Λ

$$\eta_{if} = \pm \left(\frac{g}{\Lambda_{if}^{\pm}} \right)^2$$

Here the coupling strength g is unknown and conventionally set to $g = \sqrt{4\pi}$. The $+$ and $-$ stand for constructive or destructive interference with the Standard model amplitude, respectively.

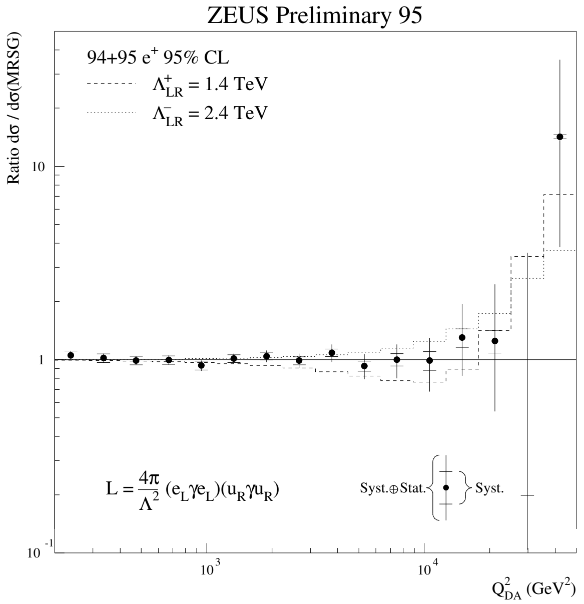

Figure 3: *The ratio of the measured differential cross section $d\sigma_{exp}/d\sigma_{GRV94}$ as a function of Q^2 is compared to models of Contact Interactions for two different choices of the compositeness scale parameter $\Lambda_{LR}^- = 1.1\ TeV$ and $\Lambda_{LR}^+ = 2.2\ TeV$.*

In figure 3 the ratio of the measured cross section over the Standard Model prediction is shown. Within the errors it is in good agreement with 1. Also shown are two examples of a contact interaction, the distribution for destructive interference with $\Lambda_{LR} = 1.1\ TeV$ and for constructive interference with $\Lambda_{LR} = 2.2\ TeV$.

Limits were obtained by H1 [12] and ZEUS on the compositeness scale parameter for all eight possible couplings. They are given in table 1 and compared to the limits obtained by OPAL [10] ($e^+e^- \to q\bar{q}$) and CDF [11] ($q\bar{q} \to e^+e^-$).

Experiment	Λ_{LL}^+	Λ_{LL}^-	Λ_{LR}^+	Λ_{LR}^-	Λ_{RL}^+	Λ_{RL}^-	Λ_{RR}^+	Λ_{RR}^-
H1	2.3	1.0	2.5	1.2	2.5	1.2	2.3	1.0
ZEUS	1.4	1.0	2.1	1.2	2.1	1.2	1.4	1.0
OPAL	2.5	2.1	2.1	2.2	2.1	2.6	2.1	2.3
CDF(DY)	1.7	2.2	-	-	-	-	-	-

Table 1: Limits (95% C.L.) on the compositeness scale parameters obtained by different experiments.

4 Direct Searches for New Particles

4.1 A Search for Leptoquarks

In the Standard Model leptons and quarks interact only through the electroweak gauge bosons. Many extensions of the Standard Model discuss possible other interactions between the particles. One scenario is a coupling of quarks and leptons to so-called leptoquarks (LQ). Examples of such theories have been discussed in the context of Grand Unification and Superstring E(6) models [13], Technicolor [14] and Compositeness [15] . The leptoquark is a colour-triplet boson which carries both lepton and baryon number.

At HERA leptoquarks would be produced as an s-channel resonance from the interaction of the beam electron and one quark of the proton. They may be produced with masses up to the centre of mass energy of $\sqrt{s} = 300\ GeV$. The production cross section and the width of the leptoquark depend on the unknown Yukawa coupling λ. The leptoquarks can decay in eq or $\nu_e q$ (first generation LQs), but may also have the possibility to violate the lepton number and decay in a different lepton (μ or τ).

The topology of the final state of first generation leptoquarks is identical to Standard Model DIS processes. Experimentally such particles would be produced in the s-channel and hence cluster at the value of the invariant mass

$$M_{LQ} = \sqrt{x_p s}$$

where x_p is the momentum fraction of the proton carried by the struck quark. For massless quarks in the initial and the final state, and assuming that the initial transverse momentum of the quark vanishes, x_p is equal to x_{Bj}. For the H1 analysis x_{Bj} was determined by using the measured quantities of the electron for events with eq in the final state, and using the hadronic energy flow for events with outgoing νq. The ZEUS analysis used the angles of the electron and the jet to determine x_{Bj}.

For leptoquarks with masses $M_{LQ} < 250\ GeV$ the expected *measured* width of a leptoquark is $\approx 10\ GeV$ and becomes much worse at larger masses [16].

In order to disentangle leptoquark events from standard DIS processes a cut on y is useful. While the cross section of DIS processes is falling steeply with increasing y scalar leptoquarks are decaying isotropically in the centre of mass system resulting in a flat y-distribution. The y-distribution for vector leptoquarks is $\propto (1-y)^2$. In the H1 analyses a mass dependent y cut was imposed while ZEUS cut on Q^2 which also suppresses the low y values.

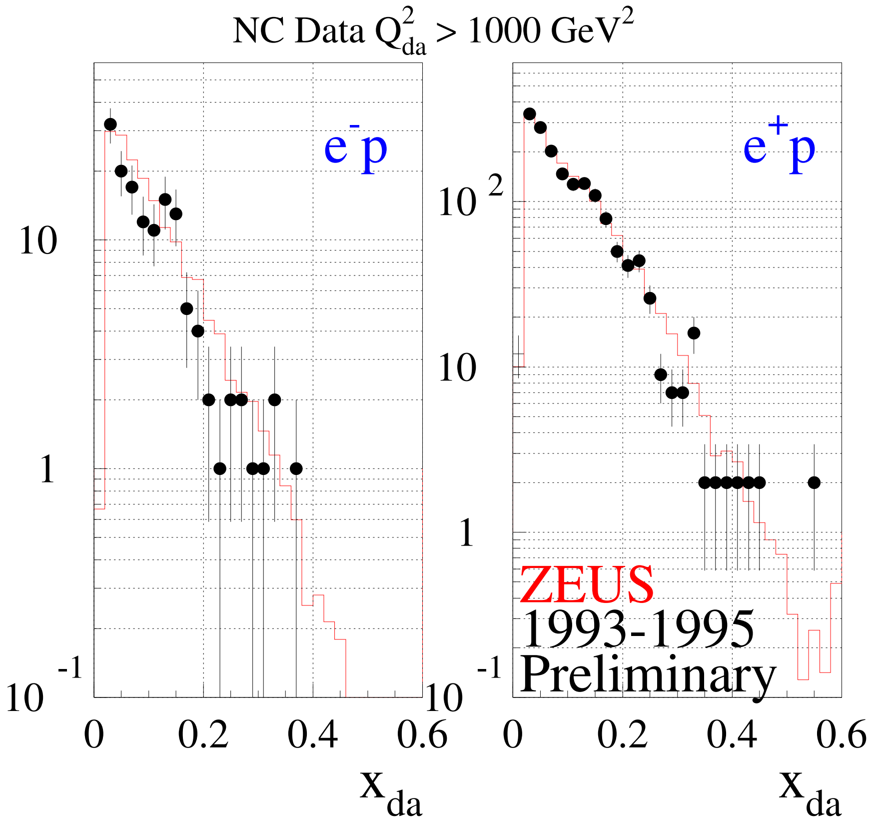

Figure 4: *The x distribution for e^-p and e^+p data.*

Figure 4 show the x distribution as measured by ZEUS[17] in e^-p NC data correspondig to a luminosity of 0.5 pb^{-1} and e^+p data using a luminosity of 9 pb^{-1}. In figure 5 the mass spectrum measured by H1 using a luminosity of 2.8 pb^{-1} is shown for the NC and CC channel[18]. The H1 data are compared to the predictions for standard DIS processes. Within statistical errors there is good agreement between data and Standard Model expectation.

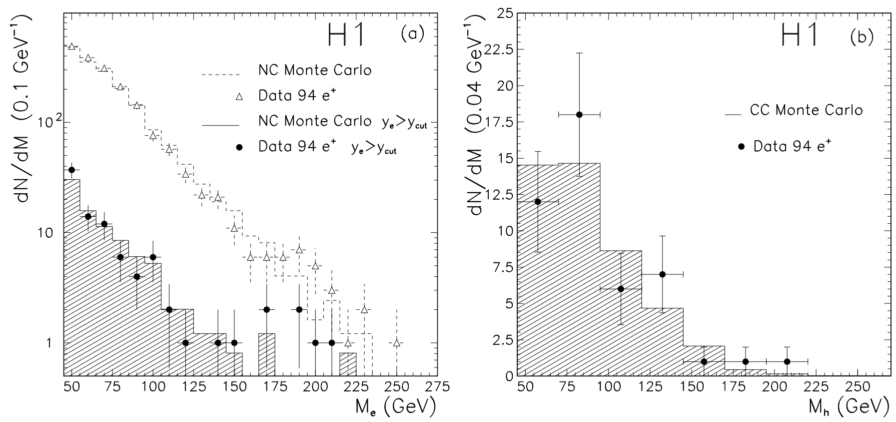

Figure 5: *The mass distribution for e^+p data for NC and CC like events. The open triangles show the data befor a mass dependent y cut was applied. The filled circles show the data after this cut that was imposed to enhance a possible signal. Both datasets are compared to a Standard Model prediction.*

4.2 A Search for Excited Electrons

In composite models excited fermions are occuring naturally. At HERA they may be produced up masses of $\sqrt{s} = 300\,GeV$ via the process $ep \rightarrow f^*X$ where f^* denotes an excited fermion. In this note only the search for excited electrons is presented, but searches for excited neutrinos and quarks have also been performed[19].

An excited electron may decay into $e\gamma$, eZ or νW. The channel including a γ in the final state provides the cleanest signature in the experiment. The selection requires two electromagnetic clusters in the calorimeter. One of them is required to have a track link, the other one not. The main background is the QED Compton process (Wide Angle Bremsstrahlung WAB) which has the same signature. A minor background are two photon processes with three electrons in the final state where one electron escapes detection and the track of one of the two remaining e is not measured.

While excited electrons are expected to cluster at a fixed invariant mass of the $e\gamma$ system this behaviour is not expected for the background processes. This allows to disentangle the signal from the background on statistical basis using the $e\gamma$ mass spectrum.

Figure 6 shows the data as measured by H1 in e^+p scattering. The data are well described by the Monte Carlo predictions for WAB and two-photon processes.

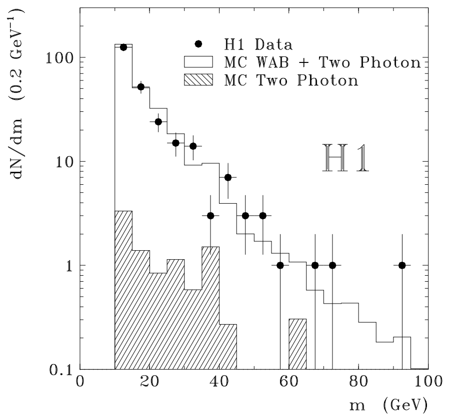

Figure 6: *The distribution of the invariant mass of the $e\gamma$ system for e^+p data for H1 data (closed circles) compared to Monte Carlo expectation for the two background processes.*

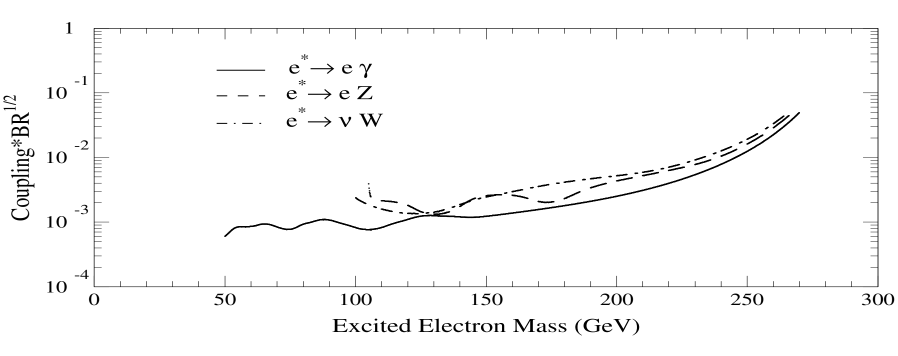

Figure 7: *Upper limits on the production cross section of excited electrons.*

Searches for excited electrons have also been performed by the ZEUS collaboration for the Ze and $W\nu$ decay channels. Also there no significant deviation from Standard model expectation has been observed. Upper limits on the production cross $\sigma \cdot BR$ were derived (figure 7).

A production cross section $\sigma \cdot BR$ larger than 1 $pb^{-}1$ can be excluded at 95% C.L. for masses up to 270 GeV. The most stringent limits on the mass of these particles have been derived by various LEP experiments[20,21,22], they exclude masses $M_{e*} < 81\ GeV$.

5 Conclusions

H1 and ZEUS have searched for deviations from the Standard model expectation and within the statistics collected up to '95 no significant deviation was found. Both collaborations have in the meantime performed an analysis based on a significant increase of luminosity (including 1996 data)[23,24].

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