# OBSERVATION OF EVENTS AT HIGH $Q^2$ IN REACTIONS $e^+p \to e^+X$ AT HERA

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On behalf of
*H1 and ZEUS COLLABORATIONS*

Both HERA colliding experiments, H1 and ZEUS have observed in their 1994-96 Neutral Current data an excess of events at high $Q^2$ relative to the Standard Deep-Inelastic model of lepton-nucleon Scattering(DIS).Combining H1 and ZEUS one observes 24 events at $Q^2 \geq 15000\ GeV^2$ where the expectation for DIS is 13.4 $\pm$ 1 events only. The probability P(N $\geq$ Nobs) that the DIS model signal N fluctuates to N $\geq$ Nobs , in a random set of experiments is 0.74%. The difference is mostly due to events at large $x$ and large $y$.

## 1 Introduction

Since 1994 the $ep$ collider HERA is working with positrons ($e^+$) and produces an integrated luminosity that increases steadily from year to year. The positron beam energy $E_e$ is 27.5 GeV and the proton beam energy $E_p$ is 820 GeV such that $\sqrt{s} \simeq 300$ GeV.

In this communication, measurements of the Neutral Current(NC)Deep-Inelastic Scattering (DIS) are presented using the data from 1994 to 1996 that were collected by the two HERA colliding experiments H1 and ZEUS [1,2].The total integrated luminosity amounts to 14.2 $pb^{-1}$ for H1 and to 20.1 $pb^{-1}$ for ZEUS.

## 2 Detectors

A more detailed description of the detectors can be found elsewhere for H1[1] and for ZEUS[2]. For these NC analyses it is mostly the calorimeter part of the detectors that is used, the tracking part being used only to require a vertex in the interaction region and to give the coordinates of this vertex.

The H1 calorimeter is a liquid argon calorimeter very well segmented (44000 cells) leading to a good angular resolution for the scattered electron $\sigma_{\theta_e}$=2-5 mrad.The energy resolution for the scattered electron is $\sigma(E)/E \simeq 12\%/\sqrt{E/GeV} \oplus 1\%$, the corresponding value for the hadronic jet (after offline compensation by a weighting method) is $\sigma(E)/E \simeq 50\%/\sqrt{E/GeV} \oplus 2\%$. The absolute energy scales are known to 3% and 4% for electrons and hadronic jets respectively.

The ZEUS calorimeter is an uranium-scintillator calorimeter thus having a very good energy resolution for hadronic jets $\sigma(E)/E \simeq 35\%/\sqrt{E/GeV} \oplus 3\%$, the corresponding value for the scattered electron is $\sigma(E)/E \simeq 18\%/\sqrt{E/GeV} \oplus 3\%$. The total number of cells is only 6000 but with each cell read out by 2 PMTs such that the angular resolution is $\sigma_{\theta_e}$=5 mrad. The absolute energy resolution is 3% both for electrons and hadrons.

## 3 Deep Inelastic Scattering

### *3.1 Kinematics and Variables*

For NC-DIS the interaction between the initial $e^+$ and proton proceeds by the exchange of a neutral boson: a $\gamma$ or a $Z^0$.This exchange takes place between the initial positron and a quark of the proton(struck quark). In HERA conditions and for $Q^2 \cong 10000 GeV^2$ the $Z^0$ exchange cannot be neglected $(\sigma(\gamma + Z)/\sigma(\gamma) \simeq 50\%)$.

One can define $s, Q^2, x$ and $y$ the usual Lorentz invariants used for NC-DIS. If $p, e, e^{'}, \gamma, q$ and $q^{'}$ denote the four momenta of respectively initial proton ,initial positron ,scattered positron ,exchanged boson,initial quark and final struck quark one have the following expressions:

$\sqrt{s} = (e + p)^2$ is the total center-of-mass energy of the e+p system.

$q^2 = -Q^2 = (e - e^{'})^2 = \gamma^2$ is the four momentum transfer squared between the initial and final positron.

$x = Q^2/2p.\gamma$ is the Bjorken scaling variable equal in the parton model to the fraction of the proton momentum carried by the struck quark.

$y = p.\gamma/p.e$ is the fraction of energy transferred between the electron and the proton in the rest mass referentiel of the proton.

These variables are related by $Q^2 = xys$.

One must also remark that the Compton wavelength of the exchanged boson $\hbar c/Q$ gives the size of this boson $\gamma$ seen as a probe of the proton and for the $Q^2$ of interest $(\geq 10000 GeV^2)$ this size is less than $2^{-16} cm$.

Also the invariant mass of the electron-quark system in the final or initial state is M with :

$M = \sqrt{xs} = (e + q)^2 \simeq (e^{'} + q^{'})^2$

It is also interesting to note that $y = (1 + \cos\theta^{\star})/2$ where $\theta^{\star}$ is the scattered positron polar angle in the center-of-mass frame of the positron-quark system.

In addition to the t-channel NC-DIS process the reaction $e^+p \rightarrow e^+X$ could proceed with an s-channel process leading to the formation of a resonance $e^+p \rightarrow LQ$ and to its subsequent decay $LQ \rightarrow e^{'} + q^{'}$. The two processes are indistinguishable on an event by event basis but they will have very different distributions in x and y: For exemple a scalar resonance LQ of mass M will give an x distribution with a peak at $x_{LQ} = M^2/s$ and its y distribution will be flat in contrast to the y distribution for NC-DIS that is proportional to $1/y^2$, this is at the origin of the y cut ($y \geq$0.25 to 0.40) adopted later in order to isolate a potential resonance.

### *3.2 Events Reconstruction*

For a given $\sqrt{s}$ only two of the other variables are necessary to fully describe the interaction. As for each NC-DIS event 4 variables may be measured (polar angle of the scattered positron and its energy and also polar angle of the final struck quark and its energy) the kinematics of the events is overconstrained and several methods can be used to reconstruct the events:

The electron method uses only measurements of the polar angle and energy of the scattered positron to compute $y_e$ and $M_e$ whereas the double angle method uses only the polar angles of both the scattered positron and of the final struck quark (This latter one being derived from the hadronic final state).The computed values are $y_{2\alpha}$ and $M_{2\alpha}$

In [1] derivations of the formulae can be found for both methods and also for otherones: One must remark that the $2\alpha$-method is insensitive to the absolute energy calibration ,unlike the $e$-method.

In addition to experimental measurement errors initial state radiations (ISR) must be taken into account, mostly for the initial positron.This QED-ISR is most of the time not detected for the event and leads to different errors on $y$ and $M$ depending on the method used. For the $e$-method errors on $y_e$ and $M_e$ are moderate if $y_e > 0.25$. For the $2\alpha$-method $y_{2\alpha}$ is conserved but $M_{2\alpha}$ is over estimated and the error is approximately proportional to $M_{2\alpha}$.

H1 uses the $e$-method and ZEUS the $2\alpha$-method and both collaborations use what they consider as secondary method as a cross-check.

### *3.3 Standard Model of DIS*

The Born term of the cross-section for the NC-DIS process can be written as:

$$\frac{d^2\sigma(e^\pm)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_2\Phi_2^\pm + Y_1 x\Phi_3^\pm\right]$$

where electro-weak radiative corrections and longitudinal cross-section have been neglected. The $Y_i$ with i=1 or 2 are functions of y and the structure functions $\Phi_j^\pm$ with j=2 or 3 depend on:

- Lepton polarisation.
- Electro-weak parameters: $\theta_W$ and mass of the $Z^0$.
- $q(x, Q^2)$ and $\bar{q}(x, Q^2)$: The quarks and antiquarks probability distribution functions versus x at a given $Q^2$.

Both H1 and ZEUS use this description of NC-DIS in Monte-Carlo simulations such as the event generator DJANGO [3]. The simulated samples amount to more than 20 times the experimental integrated luminosity and have a very small statistical error but systematic uncertainties are present,they are listed in the table below as given by H1 and ZEUS.

| ORIGIN OF SYSTEMATICS | H1 (%) | ZEUS (%) |
|---|---|---|
| structure functions | 7.0 | 6.5 |
| QCD fits and evolution to high $Q^2$ | 5.0 | 6.2 |
| $\alpha_S$ variations | 4.0 | 2.0 |
| luminosity | 2.3 | 2.3 |
| electro-weak parameters | ... | 0.3 |
| radiative corrections | 2.0 | 2.0 |
| detector simulation + absolute calibration | 3.5 | 4.4 |
| ALL (quadratic sum) | 8.3 | 8.4 |

*3.4 Data Selection and Results*

The event selections are rather similar by H1 and ZEUS and rely mainly on the calorimetric informations except for the definition of the vertex. The cuts used by H1 and ZEUS are listed in the table below.

| CUTS | H1 | ZEUS |
|---|---|---|
| vertex | $\|Z_v - \bar{Z}_v\| < 35.cm$ | $\|Z_v\| < 50.cm$ |
| $\sum_i (E_i - P_{Z_i})$ | [43.,63.GeV] | [40.,70.Gev] |
| identification of scattered positron | yes | yes |
| high energy cut for scattered positron | $E^T_{e'} > 25.GeV$ | $E_{e'} > 20.GeV$ or if $\theta_{e'} < 17.2°$ $E^T_{e'} > 30.GeV$ |
| isolation of the positron in $(\eta, \phi)$plane ($\eta =$ pseudorapidity) | in cone $R(\eta, \phi) \leq 0.25$ $\frac{E_{cluster}}{E_{cone}} \geq 0.98$ | in cone $R(\eta, \phi) \leq 0.8$ $E_{cone} - E_{cluster} \leq 5.GeV$ |
| high $Q^2$ cut | $Q^2_e > 2500.GeV$ | $Q^2_{2\alpha} > 5000.GeV$ |
| track-cluster match | in cone $R(\eta, \phi) \leq 0.25$ Ntrack$\geq 1$ | $\theta_{e'} > 17.2°$ Ntrack=1+$DCA_{track} < 10cm$ $\theta_{e'} < 17.2°$no track no match |
| Compton rejection | rejection if 2 isolated EM clusters back to back in transverse plane | idem |
| $y$ cut | 0.1$\leq y_e \leq 0.9$ | none |
| $\theta_{e'}$ cut | $\theta_{e'} > 10.°$ | none |
| $P_T^{miss}$ cut | $P_T^{miss}(GeV) < 3\sqrt{E_{e'}(GeV)}$ | none |
| cosmics and muon filters | yes including tracking timing | none |

These selections give the following numbers of events for data and simulation.

| items | H1 | ZEUS |
|---|---|---|
| $\int_{94}^{96} LUMI_{e^+}$ | 14.2 $pb^{-1}$ | 20.1 $pb^{-1}$ |
| data (evt.) | $Q^2 > 2500.GeV^2$ 443 | $Q^2 > 5000.GeV^2$ 191 |
| simulation (evt.) | $427 \pm 38$ | $196.5 \pm 10$ |
| efficiency (%) | 77. | 81.5 |

Both experiments are in fair agreement with the global expectation given by the NC-DIS simulation but data exceed these expectations as soon as one adds one of the following high energy cuts: $Q^2 > 15000.GeV^2$ or $E_{e'} > 150.GeV$ or $M > 180.GeV$.

For H1 the $Q^2$ dependence is presented on Fig. 1a and b where it can be seen that the NC-DIS simulation agrees well with the data for $Q_e^2 < 15000.GeV^2$ (see also Fig. 2a and b). Above this value there is an excess of data events relative to the simulation.

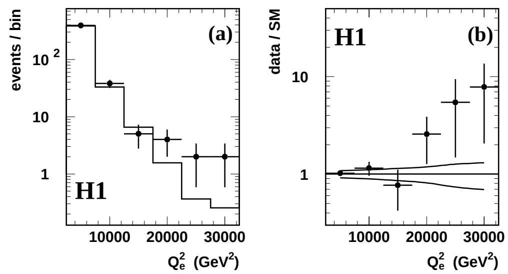


Figure 1: (a) $Q_e^2$ distribution of the selected NC-DIS candidate events for the data ($\bullet$ symbols) and for standard NC-DIS expectation (histogram); (b) ratio of the observed and expected number of events as a function of $Q_e^2$; the lines above and below unity specify the $\pm 1\sigma$ levels determined using the combination of statistical and systematic errors of the NC-DIS expectation.

These events in excess are mostly at high $M_e$ and high $y_e$ as it can be seen in Fig. 2c,d and e,f(see caption).

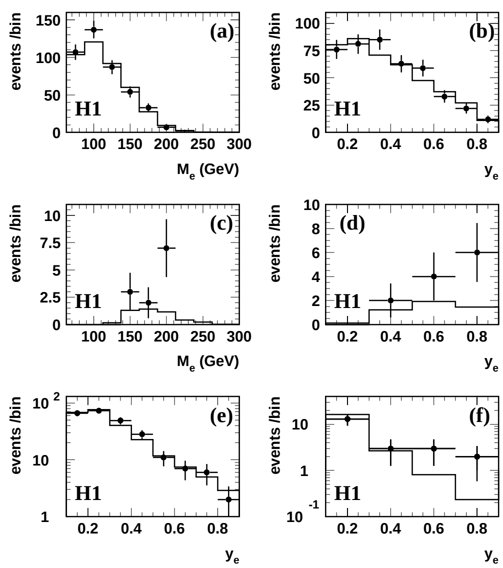


Figure 2: Distributions of $M_e$ and $y_e$ for selected NC-DIS candidate events, (a) and (b) for $2500\,\mathrm{GeV}^2 < Q_e^2 < 15000\,\mathrm{GeV}^2$, (c) and (d) for $Q_e^2 > 15000\,\mathrm{GeV}^2$; distribution of $y_e$ (e) for $100 < M_e < 180$ GeV and (f) for $M_e > 180$ GeV; superimposed on the data points ($\bullet$ symbols) are histograms of the expectation of standard NC-DIS.

For ZEUS the $Q^2$ and the x distributions are respectively given in Fig. 3 and in Fig. 4 where an excess is present for $Q_{2\alpha}^2 > 20000.GeV$ and for $x_{2\alpha} > 0.5$.

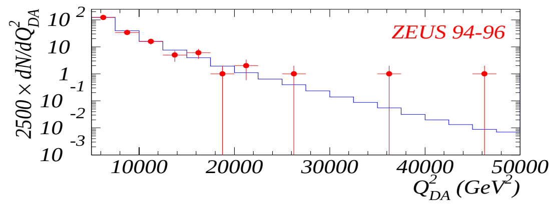


Figure 3: (a) $Q^2_{2\alpha}$ distribution of the selected ZEUS candidate events for the data (• symbols) and for standard NC-DIS expectation (histogram)

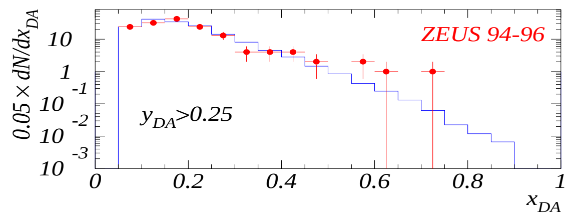


Figure 4: (a) $x_{2\alpha}$ distribution of the selected ZEUS candidate events for the data (• symbols) and for standard NC-DIS expectation (histogram)

Both experiments have chosen particular kinematical regions in the $(M, y)$ plane to characterize their excess:

For H1 it is the box $y_e > 0.40$ and $M_e > 180.GeV$ where Nobs=7 events for an expectation of N=1.83±0.33 events leading to a probability P(N $\geq$ Nobs)=0.4%.

For ZEUS the kinematical box is $y_{2\alpha} > 0.25$ and $M_{2\alpha} > 222.GeV$ with Nobs=4 and N=0.9±0.08 events and a probability P(N $\geq$ Nobs)=0.72%.

The combined significance of H1 and ZEUS is indicated in the table below:

| | H1 | | ZEUS | | H1 + ZEUS | | |
|---|---|---|---|---|---|---|---|
| | $e$ method<br>$y < 0.9$<br>$\Theta_e > 10^o$ | | $2\alpha$ method<br>$E_e > 20$ GeV<br>($P_{T,e} > 30$ GeV<br>for $\Theta_e < 17^o$) | | | | |
| $Q^2 cut (GeV^2)$ | data | NC exp. | data | NC exp. | data | NC exp. | P($N \geq N_{obs}$) |
| $Q^2 > 10000$ | 20 | 18. ± 2.4 | 33 | 32. ± 2.0 | 53 | 50. ± 3.1 | 0.37 |
| $Q^2 > 15000$ | 12 | 4.7 ± 0.8 | 12 | 8.7 ± 0.7 | 24 | 13. ± 1.0 | 0.0074 |
| $Q^2 > 20000$ | 5 | 1.3 ± 0.3 | 5 | 2.8 ±0.2 | 10 | 4.1 ± 0.4 | 0.010 |
| $Q^2 > 25000$ | 3 | 0.5 ± 0.2 | 3 | 1.0 ±0.1 | 6 | 1.5 ± 0.2 | 0.0053 |
| $Q^2 > 30000$ | 2 | .23 ± .05 | 2 | .37 ±.04 | 4 | 0.6 ± .06 | 0.0035 |
| $Q^2 > 35000$ | 0 | .08 ± .04 | 2 | .15 ±.01 | 2 | .23 ± .04 | 0.023 |

### *3.5 Background and Interpretations*

The significance of the results as given by statistical analyses done by H1 and ZEUS is high enough to search for an explanation other than a malign statistical fluctuation.

First one cannot explain this excess of events by backgrounds. It has been shown by

H1 and ZEUS that the events are so clear and characteristic (one positron of very high energy,very much back-scattered and balanced in $P_T$ by a hadronic jet) that for these high $Q^2$ selections there is pratically no background.

Another proposed interpretation is that the partons distributions used in the simulations are not the good ones,because the evolution from high x,low $Q^2$ to high x,high $Q^2$ is done not taking into account hypothetical second order effects such as extra valence quarks or intrinsic charm.

All other interpretations are connected to the Physics Beyond the Standard Model such as production of lepto-quark or SUSY Rp-violating squark or also presence of a contact term interfering with NC-DIS. Of course all these exotic interpretations are for the moment very speculative but nevertheless very interesting and are detailed on a WEB site [4].

## 4 Conclusions and Prospects

For $Q^2$ above 15000 $GeV^2$ both HERA experiments agree on an excess of events relative to the Standard Model.This very interesting anomaly, if it is not a fluctuation, cannot be easily explained inside the Standard Model and could be a sign of New Physics? The solution of this question needs more statistics at HERA but also more studies of related processes at the TEVATRON or at LEP.

## References


1. H1 Collaboration,C.Adloff et al.,Z.Phys.C74(1997)191.
2. ZEUS Collaboration,Z.Phys. C74,207 (1997).
3. DJANGO6.2;G.A. Schuler and H.Spiesberger,Proc. of the Workshop "Physics at HERA",October 1991,DESY-Hamburg ,Vol. 3 p. 1419.
4. http://www-zeus.desy.de/ ukatz/ZEUS-PUBLIC/hqex/hqex