26: High Q^2 Events at HERA

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Abstract. The H1 and ZEUS collaborations have reported on the observation of an excess of events at very large Q^2 in deep-inelastic ep collisions at HERA. New data from the 97 data-taking up to the summer are included in this paper. In addition, events with a high p_t lepton, hadronic activity and large missing transverse momentum are observed. Their rate is compared to the expectations for $W^\pm$ production and background processes.

1 Introduction

The ep collider HERA allows the proton to be probed at distances down to $\simeq 10^{-16}$ cm via t-channel exchange of a highly virtual gauge boson [1, 2, 3], and to search for s-channel formation of new particles that couple to lepton-parton pairs with masses up to the kinematic limit of $\sqrt{s} \simeq 300\,\mathrm{GeV}$ [4, 5]. Earlier this year [6, 7] both collider experiments, H1 and ZEUS, reported on a measurement of deep-inelastic scattering at high Q^2 using all e^+p data recorded from 1994 to 1996 with respective luminosities of $14.2\,\mathrm{pb}^{-1}$ and $20.1\,\mathrm{pb}^{-1}$ at beam energies of 27.5 GeV and 820 GeV for positrons and protons. The data indicated an appreciable excess of events over the expectation from the DIS Standard Model. This paper gives an update of these analyses, which includes the original data and comprises $23.7\,\mathrm{pb}^{-1}$ and $33.5\,\mathrm{pb}^{-1}$ for H1 and ZEUS, respectively [8]. It extends the previous charged current analysis by a complementary study of a sub-sample with moderate Q^2: some events of the large missing transverse momentum selection yield isolated leptons with extraordinarily large p_T^ℓ which, a priori, can only be caused by decays of real $W^\pm$.

2 Experimental Considerations

In both experiments [9, 10] the calorimeter serves as the primary means of reconstructing the final state. H1 uses liquid argon with lead (steel) absorber as an electromagnetic (hadronic) calorimeter, which is placed inside the large solenoid of 1.2 T. The granularity is optimized to provide approximately uniform segmentation in laboratory pseudorapidity [1] and azimuthal angle ϕ. This arrangement provides particularly good energy resolution for electrons (table 1). ZEUS employs a uranium/scintillator calorimeter optimized for roughly equal response to electrons and pions.

[1] z direction is defined as the direction of the incident proton.

Table 1. Compilation of calorimeter resolutions. σ describes the energy resolution and Δ the uncertainty in the absolute energy scale.

	H1	ZEUS
elm. $\sigma(E)/E$	$12\%\sqrt{E/\mathrm{GeV}} \oplus 1\%$	$18\%\sqrt{E/\mathrm{GeV}} \oplus 2\%$
hadr. $\sigma(E)/E$	$50\%\sqrt{E/\mathrm{GeV}} \oplus 4\%$	$35\%\sqrt{E/\mathrm{GeV}} \oplus 3\%$
elm. $\Delta E/E$	3%	3%
hadr. $\Delta E/E$	4%	3%
σ_{θ_e}	2-5 mrad	5 mrad

The kinematics of lepton-proton scattering at fixed collider beam energies is described by two independent variables. Several Lorentz invariant quantities can be calculated of which the most common are Q^2, x and y (eq. (1) through (5)). Here k and P refer to the 4-vectors of the incoming e^+ and p beams and k' to the 4-vector of the scattered positron. Q^2 describes the virtuality of the exchanged boson, while, in the parton picture, y and M are related to the scattering angle θ^* in the CM system and to the mass, respectively, of the positron-quark interaction.

$$Q^2 = -q^2 = (k - k')^2 \tag{1}$$

$$y = \frac{Pq}{Pk} = \frac{1}{2}(1 + \cos\theta^*) \tag{2}$$

$$x = \frac{Q^2}{2Pq} \tag{3}$$

$$M = \sqrt{sx} \tag{4}$$

$$Q^2 = \frac{P_T^2}{(1-y)} \tag{5}$$

Experimentally, convenient approximations are based on using equation (5) or derivations thereof, where the transverse momentum P_T and the angle related y are measured from either the scattered lepton, the momenta of the scattered hadrons (X) or both. Of the four variables available in neutral current (NC) events H1 obtains the best resolutions when using the angle and energy of the scattered positron (e-method) while ZEUS takes advantage of reducing the energy scale uncertainties by measuring the angle of the scattered lepton and an effective hadron angle (double angle method).

3 Hard Scale

The selections described subsequently refer to measurements of large p_T-processes. Associating each calorimeter cluster with a momentum vector $\mathbf{p}_{\mathbf{cl}}$ ($E_{\mathrm{cl}} = |\mathbf{p}_{\mathbf{cl}}|$) from the origin, both the scalar (S) and the vector (V) sums of the transverse momentum components can be used to distinguish different physics processes.

Table 2. Kinematics of the H1 events with leptons and large transverse momentum imbalance. The calculation of the global event quantities includes the measurement of the μ-momenta in the H1 tracking system. When calculating $M_T^{\ell\nu}$, the transverse $\ell\nu$-mass, the missing transverse momentum is assumed to be carried by a single ν. MUON-1 has been published before [5].

	ELECTRON	MUON-1	MUON-2	MUON-3	MUON-4
charge$^\ell$	neg.(5σ)	pos.(5σ)	pos.(5σ)	neg.(5σ)	neg.(2.7σ)
p_T^ℓ [GeV]	$37.6^{+1.3}_{-1.3}$	$23.4^{+7.5}_{-5.5}$	$27.7^{+6.4}_{-4.4}$	$39.4^{+9.4}_{-6.4}$	$81.5^{+47.1}_{-21.9}$
θ^ℓ [$deg.$]	27.3 ± 0.2	46.2 ± 1.3	28.9 ± 0.1	35.2 ± 0.1	28.5 ± 0.1
p_T^X [GeV]	8.0 ± 0.8	42.2 ± 3.8	67.5 ± 5.4	27.5 ± 2.7	59.8 ± 5.9
Event global $P_{T,\mathrm{miss}}$ [GeV]	30.6 ± 1.5	$18.9^{+6.6}_{-8.3}$	$43.5^{+5.4}_{-6.4}$	$43.3^{+8.0}_{-5.3}$	$29.2^{+44.1}_{-13.4}$
δ [GeV]	10.4 ± 0.7	$18.9^{+3.9}_{-3.2}$	$17.0^{+1.9}_{-1.5}$	$27.7^{+3.4}_{-2.6}$	$43.6^{+12.2}_{-6.1}$
$M_T^{\ell\nu}$ [GeV]	67.7 ± 2.7	$3.0^{+1.5}_{-0.9}$	$22.6^{+5.0}_{-3.6}$	$77.8^{+18.0}_{-12.2}$	$93.2^{+100.0}_{-46.5}$

3.1 Large Transverse Momentum Imbalance

A transverse momentum requirement $V > 25\,\mathrm{GeV}$, a priori, preferentially selects charged current (CC) events, in which the ν remains undetected. H1 has performed such a search and found 336 candidate events after applying the standard cosmic and halo filtering [2]. The surprising observation among this sample is a yield of five events with a high-p_t isolated track. The isolation criterion has been based on separation in rapidity-azimuth both from the nearest charged tracks and from a calorimeter jet, separately. All five tracks are well compatible with a lepton: four leptons are identified as muons and one event as an electron. The parameters of the events are listed in table 2.

Production of real $W^\pm$ in $ep \to eW^\pm X$ naturally leads to events with large p_t^ℓ when the W decays leptonically. H1 expects to see 0.41 ± 0.07 (1.34 ± 0.20) in the $\mu^\pm$ and $e^\pm-$ channels respectively, as estimated from a full simulation [11] of the underlying processes. Note, however, that such processes preferentially lead to $M_T^{\ell\nu} \sim m_W$ (and small p_T^X), which is not really evidenced by all events of table 2. Other background processes, such as photoproduction of large E_T-jets or of heavy quarks providing an unobserved ν seem to contribute only little. Another background stems from $\gamma\gamma \to \ell\ell$ ($\ell = \mu$ or e), when one of the leptons remains unobserved in the beam pipe. This process has been studied and cannot contribute to largely imbalanced events (once the μ-momentum is taken into consideration).

For a similar selection [12] ZEUS find no $\mu^\pm$- and 2 e^+-events, when the expected $W^\pm$ signal and background is estimated to be 0.48 and 4. The two events can be understood as a high-Q^2 di-muon event $e^+p \to e^+\mu\mu X$ and an acoplanar e^++jet event.

Table 3. The observed number of CC events as a function of a lower Q^2-cutoff $Q^2_{\rm min}$. The expectations are based on the SM DIS model. The syst. errors of ZEUS have been separated into an uncertainty due to the energy scale and due to parton distributions (PDF).

	H1		ZEUS			
$Q^2_{\rm min}$ [GeV^2]	**seen**	expected	**seen**	expected	E scale	PDF
1000			**455**	419	$\pm$ 13	$\pm$ 33
2500	**61**	56.30 ± 9.40	**192**	178	$\pm$ 13	$\pm$ 17
5000	**42**	34.70 ± 6.90	**63**	58.5	$\pm$ 9.0	$\pm$ 7.3
10000	**14**	8.33 ± 3.10	**15**	9.4	$\pm$ 2.5	$\pm$ 1.6
15000	**6**	2.92 ± 1.44	**5**	2.0	$^{+0.81}_{-0.54}$	$\pm$ 0.4
20000	**3**	1.21 ± 0.64	**1**	0.46	$^{+0.28}_{-0.16}$	$\pm$ 0.10
30000			**1**	0.034	$^{+0.037}_{-0.016}$	$\pm$ 0.008

3.2 Charged Current Events at high $\mathbf{Q^2}$

Concentrating on the high Q^2 regime a CC selection is accomplished by requiring an even more significant transverse momentum imbalance. The detailed cuts of H1 are: $V > 50\,\text{GeV}$ and $V/S > 0.5$ and $y < 0.9$ to largely eliminate the background from photoproduction. H1 and ZEUS obtain the events of table 3 as a function of Q^2 for their respective selections. Both experiments observe slightly larger event yields for $Q^2 > 10000\,\text{GeV}^2$ than expected. ZEUS finds an event with $Q^2 = 34000\,\text{GeV}^2$. The expectation is based on the Standard Model of DIS. The uncertainty in this prediction is related to the knowledge of the parton distribution functions (PDF) (see below). The largest uncertainty arises from the incomplete knowledge of the absolute energy scale (table 1).

3.3 Neutral Currents

H1 has provided new data at this conference [13] on the measurement of the NC DIS cross sections up to $5000\,\text{GeV}^2$, which are shown in their reduced form

$$\sigma(e^+p) = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{1+(1-y)^2}\frac{\mathrm{d}^2\sigma(e^+p \to e^+X)}{\mathrm{d}x\mathrm{d}Q^2} \tag{6}$$

in fig. 1. Despite the fact that measurements at smaller Q^2 had to be extrapolated over two orders of magnitude the canonical parameterisation of the parton distributions evolved through the DGLAP mechanism is seen to hold up to the largest values of Q^2. It is also seen that for very large x and Q^2 the effect of the structure function F_3 is seen as an apparent decrease of $\sigma(e^+p)$. Not more than $\mathcal{O}(5\%)$ is left as an uncertainty on the cross section and hence the parton evolution at high Q^2 (see also refs. [6, 7]).

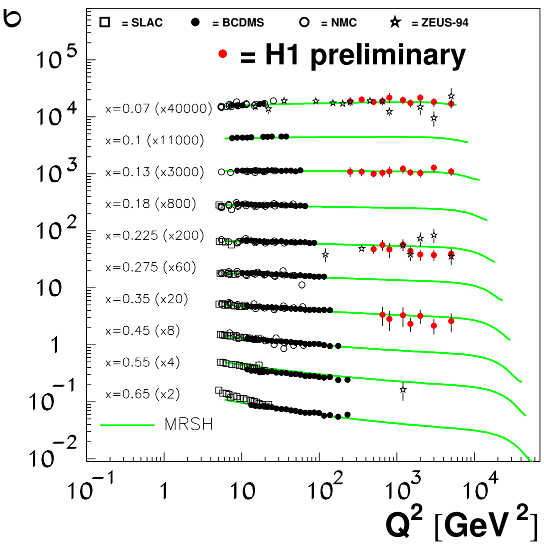

Fig. 1. The reduced cross section of NC scattering (eq. 6) including the preliminary data of ref. [13].

3.4 Neutral Current Events at high $\mathbf{Q^2}$

H1 and ZEUS have updated [13, 14] their selection of NC events at large Q^2, where, in addition to the positron requirement sufficient balance in $\delta = \sum E(1-\cos\theta)$ as a safeguard against catastrophic initial state radiation has been demanded. The respective numbers of events are 724 (714 ± 69) for $Q^2 > 2500\,\mathrm{GeV}^2$ and 326 (328 ± 15) for $Q^2 > 5000\,\mathrm{GeV}^2$ for H1 and ZEUS, where the numbers in parentheses refer to the expectation.

The comparison of the observed Q^2 dependence is seen in fig. 2. At $Q^2 > 15000\,\mathrm{GeV}^2$ the data start to exceed the SM expectation. Again, ZEUS finds events with *very* large Q^2. These measurements continue to indicate the trend reported on in ref. [6, 7] of exceeding the SM model expectation with probabilities hovering around 1%.

The individual events are shown in the M-y plane in fig. 3 for both experiments. H1 had reported a major contribution to the excess at $M \sim 200\,\mathrm{GeV}$, for which ZEUS sees no particular enhancement. The quantities have been calculated in different manners and are hence susceptible to different systematics, notably with respect to initial state radiation. Initial state radiation leads to an underestimate of the true value of M for the e-method (H1) and to an overestimate in the double angle method (ZEUS). Nevertheless, the consistency of the measurement has been verified [15] experimentally by comparing the results of the two methods of calculation on an event basis.

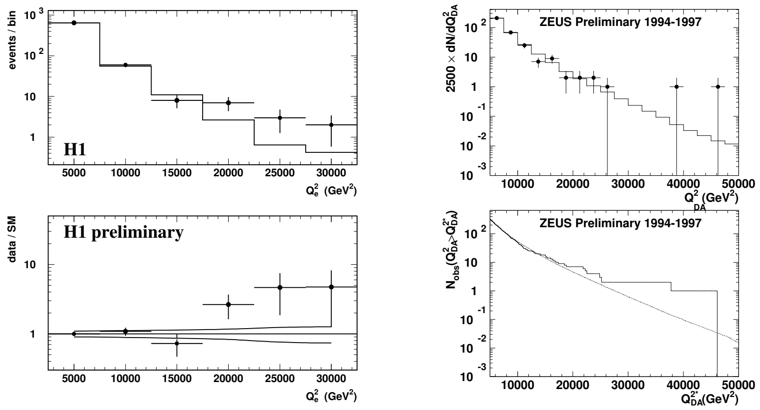

Fig. 2. Q^2 dependence of NC scattering; left: H1, right ZEUS. The ZEUS numbers are given for $Q^2 > Q^2_{DA}$ (integr. distribution). The solid lines refer to the DIS SM model.

As a result it seems unlikely that the enhancement observed in both experiments could be made to agree on a *single* value of M. (ZEUS have confirmed in a separate study on MC events that a large deviation in M due to initial state radiation is indeed very unlikely). On the other hand, if all the residual uncertainty on the energy scale is allowed for, the differences become less striking.

It remains to be noted that H1 continues to see the biggest enhancement around $M \sim 200\,\mathrm{GeV}$, while ZEUS sees several events at extremely large x and y.

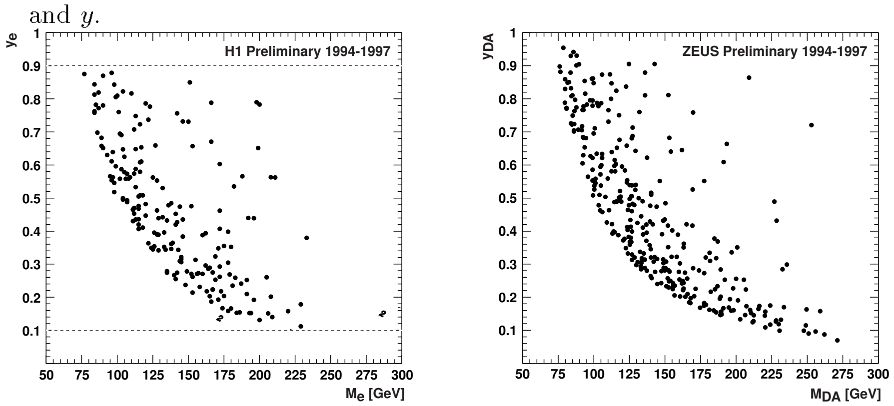

Fig. 3. The observed NC events for $Q^2 > 5000\,\mathrm{GeV}^2$ shown in the y-M plane. Each experiment uses its preferred method to compute M (see text).

4 The NC Cross Section

The observed number of events have been converted into a cross section $\sigma(Q^2 > Q^2_{\rm min})$ (fig. 4). The procedure assumes the validity of the Standard Model of DIS to compute migration corrections, efficiencies, and to extrapolate into the region of large y which is either explicitly excluded ($y < 0.9$, H1) or implicitly restricted by the acceptance of the calorimeter. ZEUS records events to $Q^2 > 40000\,\mathrm{GeV}^2$. (A corresponding upper limit on the cross section in bins, where H1 sees no events, has not been included in fig. 4).

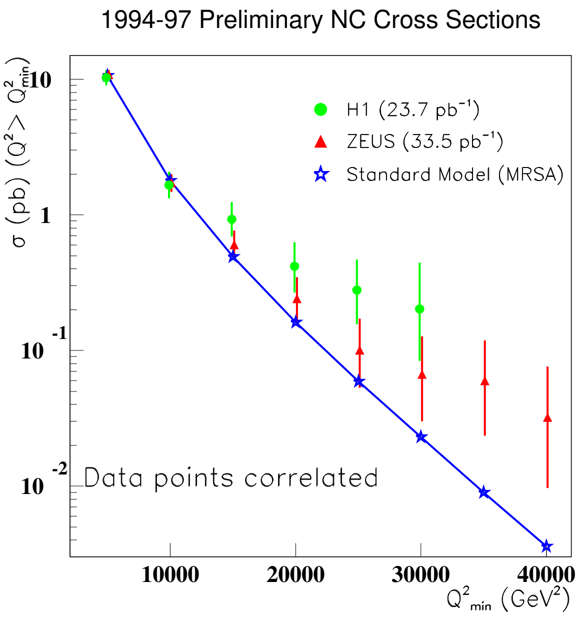

Fig. 4. Preliminary cross section of $e^+p \to e^+X$ for $Q^2 > Q^2_{min}$.

5 Conclusion

Five events with large transverse momentum imbalance show an isolated lepton at large transverse momentum. The rate of μ-events observed by H1 is hard to reconcile with the $W^\pm$ hypothesis, which, after all, has been identified as the most likely production mechanism within the Standard Model.

H1 and ZEUS continue to find an excess of events in deep-inelastic scattering. In NC processes for $Q^2 > 15000\,\mathrm{GeV}^2$ H1 sees 18 events when 8.0 ± 1.2 events are expected. For $Q^2 > 35000\,\mathrm{GeV}^2$ ZEUS sees 2 events with 0.24 ± 0.02

expected. These measurements are in agreement with the observations reported earlier using a sub-sample of the data but they do not improve the statistical significance appreciably. The excess seen in CC processes is based on a small number of events.

Some $10\,\mathrm{pb}^{-1}$ will be added to the data sample by each experiment from the remainder of the 1997 data-taking. 1998 makes possible the study of e^-p data, with a significantly different high energy behaviour. If the observation survives these stringent statistical tests we will be faced with accepting one of the few remaining theoretical explanations [16] beyond the Standard Model which are left open.

References

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