An Update of the H1 High Q^2 Analysis and Observation of High Energy Isolated Leptons in Events with Missing p_t

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Abstract. Increasing luminosity at HERA now offers the possibility to study ep scattering close to the kinematic limit, given by the available center-of-mass energy of 300 GeV, and to investigate rare event topologies with sufficient statistics. In this context H1 and ZEUS both have reported an excess of events at very high momentum transfers Q^2 in the e^+p data recorded up to the end of 1996. Here a preliminary update of the H1 high Q^2 analysis is presented, including data from the first half of 1997, almost doubling the integrated luminosity of the already published result. In addition, we report on an analysis searching for events with an imbalance in transverse momentum p_t. While the majority of events show topologies typical for charged current processes, five have been observed with an isolated e^- or $\mu^\pm$ with large p_t. The corresponding Standard Model expectation from W production with subsequent decay into leptons is 1.75 events.

INTRODUCTION

At HERA 27.5 GeV positrons collide head on with 820 GeV protons, leading to a center-of-mass energy $\sqrt{s}$ of approximately 300 GeV. The HERA facility, with the two collider experiments H1 and ZEUS, therefore offers the unique possibility to probe the structure of the proton down to very small distances via t-channel exchange of highly virtual gauge bosons. Hitherto the main emphasis was placed on the study of the neutral current process at low values of the 4-momentum transfer squared Q^2, where photon exchange dominates. However, the increasing luminosity at HERA now allows investigation of phase space regions where processes such as the exchange of massive vector bosons become important and evidence for new physics may be found.

Two preliminary H1 analyses are described, both investigating previously unexplored regions of the phase space accessible at HERA. One is an update of the published high Q^2 result [1] which is now based on all available e^+p data up to mid 1997 corresponding in total to an integrated luminosity of 23.7 ± 0.4 pb^{-1}. The second analysis presented is a search for high energy isolated leptons in events which are unbalanced in transverse momentum p_t.

THE H1 DETECTOR

The H1 detector, described in detail elsewhere [2], consists of a number of complex subdetectors designed to provide both complementary and redundant measurements of various aspects of high energy positron-proton collisions. Closest to the interaction point, surrounding the beam pipe, is a silicon tracker for precision measurements of tracks and vertices. Outside this lies a tracking system of interleaved multiwire proportional chambers and drift chambers, providing the primary measurement of charged particles. This is successively surrounded by a highly segmented liquid argon calorimeter (LAr), a superconducting solenoidal magnet generating a field of 1.2 T and an instrumented iron magnet yoke which allows additional energy measurement of shower tails as well as muon detection. Drift chambers and a toroidal iron magnet in the forward direction[1] enable detection and momentum measurement of muons emitted at low angles. In the direction of the incident positron beam a lead scintillating-fibre calorimeter provides further energy measurements of particles scattered into the backward region. Additional detectors, situated at some distance from the apparatus in both beam directions, facilitate measurements of particles at very low angles and of the luminosity delivered to the experiment.

The analyses presented here are largely based on information from the LAr calorimeter. Electromagnetic shower energies are measured with a precision of $\sigma(E)/E = 12\%/\sqrt{E/\mathrm{GeV}}$ and pion-induced hadronic energies with $\sigma(E)/E = 50\%/\sqrt{E/\mathrm{GeV}}$. The overall energy scales are known to 3% and 4% respectively.

OBSERVATION OF EVENTS AT VERY HIGH Q^2

The investigation of the neutral current (NC) and charged current (CC) processes in deep-inelastic scattering (DIS)[2] at high Q^2 and large x provides a fundamental test of our understanding of the valence quark content of the

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1) The z axis of the right-handed coordinate system used by H1 defines the forward direction and is taken to be the incident direction of the proton beam; the origin is then given by the nominal ep interaction vertex.

2) The basic variables used to describe the kinematics of DIS are Q^2, the negative square of the four-momentum transfer, the Bjorken scaling variable x and the inelasticity $y = Q^2/xs$ of which only two are independent at fixed s; alternatively one may choose $M = \sqrt{xs}$.

proton and allows investigation of the validity of QCD evolution up to the highest possible scales.

The Born cross section [3,4] for the NC DIS reaction is given by

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left\{Y_+(y)\,\mathcal{F}_2(x,Q^2) - Y_-(y)\,x\mathcal{F}_3(x,Q^2)\right\} \tag{1}$$

where α is the electromagnetic coupling and the functions $Y_\pm = 1 \pm (1-y)^2$ describe the helicity dependence of the electroweak interactions. The small and negative contribution from the longitudinal structure function $\mathcal{F}_L$ is neglected. Then the partonic nature of the proton is contained in the structure functions $\mathcal{F}_2$ and $\mathcal{F}_3$, where the latter reflects the parity violating nature of the electroweak force. For unpolarized beams they can be written as

$$\begin{pmatrix} \mathcal{F}_2(x,Q^2) \\ x\mathcal{F}_3(x,Q^2) \end{pmatrix} = \sum_{q=\mathrm{quarks}} x \begin{pmatrix} C_2^q(Q^2)\,[q(x,Q^2)+\bar{q}(x,Q^2)] \\ C_3^q(Q^2)\,[q(x,Q^2)-\bar{q}(x,Q^2)] \end{pmatrix}. \tag{2}$$

Here, q and $\bar{q}$ are the parton densities depending on x and Q^2 alone, while the coefficient functions C_2^q and C_3^q can be expressed in terms of precisely measured electroweak parameters. The main theoretical uncertainty comes from insufficient knowledge of the parton distribution functions, leading to a systematic error of 5%. This value was extracted from QCD fits to existing fixed target and HERA low Q^2 data and is compatible with what can be derived from a comparison of cross section calculations using HECTOR [5]. Inclusion of uncertainties on the strong coupling constant α_s and higher order QED corrections then leads to an overall theoretical error on the standard NC DIS cross section prediction of 6.5%. In addition, the experimental uncertainties on the integrated luminosity (2.3%) and the electromagnetic (3%) and hadronic (4%) energy scales of the calorimeter are taken into account to determine the overall systematic error. For the charged current process an analogous but somewhat simpler expression due to the exclusive presence of weak interactions can be derived [4], leading to similar theoretical uncertainties.

For the comparison of data with Monte Carlo calculations the event generator DJANGO [6] was used in conjunction with LEPTO [7] and ARIADNE [8] to model higher order QCD effects. The Martin-Roberts-Stirling MRS(H) parton density function parameterisations [9] were taken. Hadronisation was simulated using string fragmentation as implemented in JETSET [10].

Event Selection

The high Q^2 NC and CC event selection uses the criteria described in [1]. Only data are considered for which the main detector components relevant for the analysis were fully operational. Starting with this basic event sample non-ep physics background is rejected by simple requirements including the filtering of cosmic and beam halo muons and demands on the vertex position and event timing. The remaining data are subject to two selection procedures specifically designed to retain the clear signatures of high Q^2 NC and CC DIS events. Both samples are finally restricted to the region $Q^2 > 2500$ GeV^2.

Neutral Current Selection

The NC event selection essentially relies on identification of the scattered positron, fully exploiting the characteristic energy deposition of an electromagnetic shower in the LAr calorimeter [11]. Inclusion of information on cluster-track matching and isolation in the pseudorapidity-azimuthal (η-ϕ) plane results in an identification efficiency which exceeds 90% everywhere within the acceptance cuts, the main loss being due to shower development in the inactive material between calorimeter modules.

Once an isolated positron has been positively identified the following criteria are applied to the remaining candidates to efficiently select NC DIS events up to highest Q^2 values:

- the transverse energy $E_{T,e}$ of the positron has to be greater then 25 GeV,
- the total transverse momentum balance calculated from all energy deposits E_i has to be consistent with zero,
- to reject photoproduction background the momentum loss in the direction of the incident positron, given by $\sum(E_i - E_{z,i})$, must be consistent with the expected value for DIS events of twice the e$^+$-beam energy.

The kinematics are determined by two different methods taking advantage of the inherent redundancy in the measurement of NC DIS events: the e-method [12], where M, y and Q^2 are calculated from the kinematics of the scattered positron alone, and the double angle (2α-) method using the reconstructed polar angles θ_e and θ_h of the positron and the hadronic final state [12] respectively. This allows a study of the systematics and resolution of the reconstruction methods without relying on Monte Carlo simulations. For the final result the e-method is taken, which provides best resolution at large y.

Since the resolution in M measured with the e-method degrades with decreasing y, the low y domain is excluded requiring $y > 0.1$. Rejecting also the high y regime, by additionally demanding $y < 0.9$, further suppresses photoproduction background and excludes the region where QED radiative effects are largest.

Charged Current Selection

The CC events at high Q^2 are most effectively selected by simply demanding large values of missing transverse momentum $p_t > 50$ GeV, again calculated from all energy deposits in the calorimeter. Additional requirements on

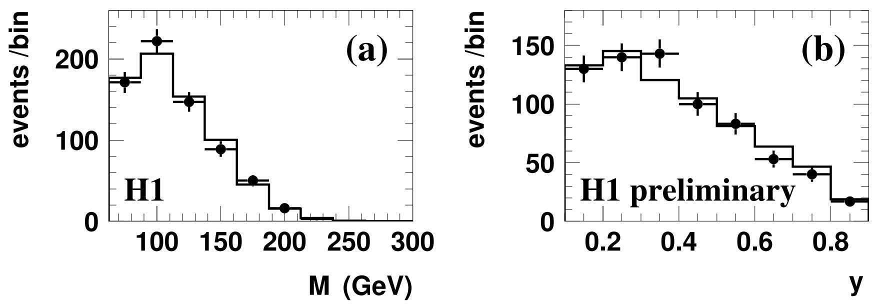


FIGURE 1. Distributions of M and y measured with the e-method for the selected NC DIS candidate events with $2500 < Q^2 < 15000$ GeV^2.

the total transverse energy eliminate remaining photoproduction and NC DIS background. Since the outgoing neutrino cannot be detected, Q^2, y and M are determined from the observed hadronic final state using the Jacquet-Blondel ansatz [12]. The validity of this approach has been cross-checked with the e-method and the 2α-method using the NC sample. Since M and Q^2 determined with the hadron method degrade with increasing y the high y domain is again excluded by demanding $y < 0.9$.

Background Sources

Detailed studies have been made to estimate the contribution from various background sources such as production of real electroweak vector bosons, direct and resolved photoproduction and two-photon processes. Applying the above selection criteria the total remaining background contamination in both samples is found to be below 1%. However, additional requirements [1] are imposed to further reduce the background contribution to the per mille level, leading to an overall contamination which may safely be neglected.

Results

After applying all selection criteria 724 events remain in the NC sample, in good agreement with the standard DIS expectation of 714±69. Correspondingly, 61 events are observed in the CC channel compared to a prediction of 56.3±9.4.

As indicated in Fig. 1, all data up to $Q^2 = 15000$ GeV^2 are well reproduced by the Monte Carlo model, demonstrating that the present understanding of deep-inelastic scattering extends into the previously unexplored high Q^2 region. This can also be seen directly from the Q^2-distribution of the selected NC DIS events in Fig. 2a. However, for $Q^2 > 15000$ GeV^2 an excess of events

TABLE 1. Poisson probabilities for the observation of events at high $Q^2 > 15000$ GeV^2.

	$N_{\rm obs}$	$N_{\rm DIS}$	$\mathcal{P}(N \geq N_{\rm obs}; N_{\rm DIS})$
NC channel	18	8.0±1.2	0.34%
CC channel	6	2.9±1.4	13%

is observed in the NC data; 18 events are found compared to an expectation of 8.0±1.2. Of these 12 were recorded up to the end of 1996 while the 6 additional events result from the updated analysis. The corresponding expectations from the standard DIS model are 4.7 and 3.3 events indicating that the observed excess is still present in the 1997 data. Even though statistically less significant the CC candidates seem to exhibit a similar behaviour (Fig. 2a), where in total 6 events have $Q^2 > 15000$ GeV^2 compared to a prediction of 2.9±1.4.

To quantify this observations the Poisson probability $\mathcal{P}(N \geq N_{\rm obs}; N_{\rm DIS})$ for observing $N_{\rm obs}$ or more events if only $N_{\rm DIS}$ events are expected has been calculated for both the NC and the CC samples. The results for $Q^2 > 15000$ GeV^2 are given in Tab. 1. Moreover, the integrated Born cross section for the NC DIS process above a minimum Q^2 value, Q^2_{min}, is given in Fig. 3. To avoid the region of large x and large y, which suffers from small acceptance, large uncertainties in the structure functions and large radiative corrections, the cross section is given only for $y < 0.9$.

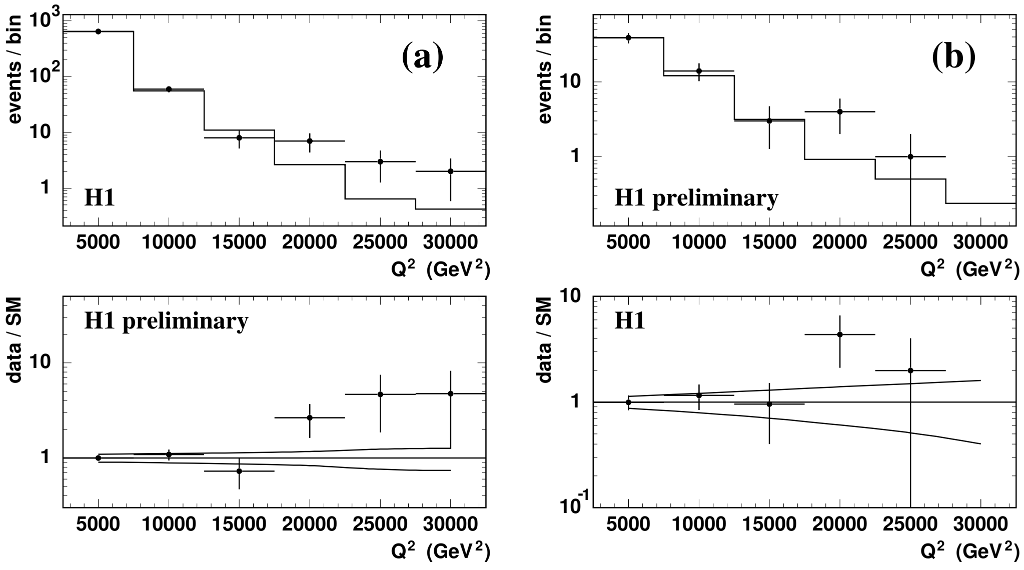
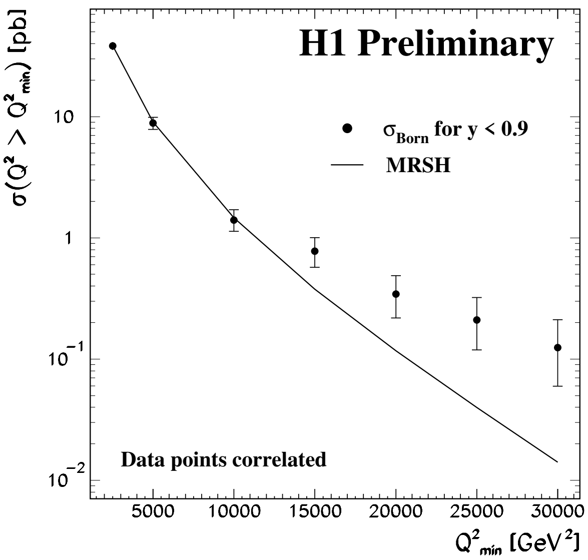


FIGURE 2. The Q^2 distribution of the selected NC (a) and CC (b) samples. The lower plots show the corresponding ratio of the data and Monte Carlo expectation together with the 1σ contour of the systematic error. These errors vary between 8.5% at low and 30% at high Q^2 and are dominated by the uncertainty in the electromagnetic energy scale.



Q^2_{min}	DIS	Measured
2500	38.62	$38.35^{+2.84}_{-2.84}$
5000	9.03	$8.86^{+1.02}_{-1.02}$
10000	1.46	$1.40^{+0.30}_{-0.27}$
15000	0.38	$0.78^{+0.22}_{-0.20}$
20000	0.12	$0.34^{+0.15}_{-0.13}$
25000	0.04	$0.21^{+0.11}_{-0.09}$
30000	0.01	$0.12^{+0.09}_{-0.06}$

FIGURE 3. Integrated Born cross section $\sigma(Q^2 > Q^2_{min})$ for $y < 0.9$ as a function of Q^2_{min}. The points show the H1 measurement while the line gives the standard DIS expectation using MRS(H) and corrected to Born level.

For the NC sample the observed excess is most pronounced for $y > 0.4$ and $M > 180$ GeV. This was already observed in the 1994-1996 data, where 7 events were found in the mass bin $187.5 < M < 212.5$ GeV while 0.95 were expected. The corresponding probability for observing such an excess anywhere in the mass range investigated is 1%. In the early 1997 data only one extra event was recorded in this mass region, consistent with the standard DIS model expectation. This leads then to a probability of 1% for the combined sample.

Given the existing experimental data and their interpretation in terms of parton distributions in the proton at high x and low Q^2, and the agreement of the resulting predictions for NC and CC DIS found for Q^2 below 15000 GeV^2, it is unlikely that the excess of events at $Q^2 > 15000$ GeV^2 can be understood within the DIS model. Within this model, the only explanation is therefore a statistical fluctuation. Whether the excess can be interpreted in terms of new physics still requires, however, the acquisition of more data.

ISOLATED LEPTONS IN EVENTS WITH MISSING TRANSVERSE MOMENTUM

In 1994 an event of unusual characteristics [13] was observed in the standard charged current analysis [14] of data with an integrated luminosity of 3.2 pb^{-1}. The event contains an isolated high momentum muon recoiling against a system of hadrons and is unbalanced in transverse momentum, suggesting the

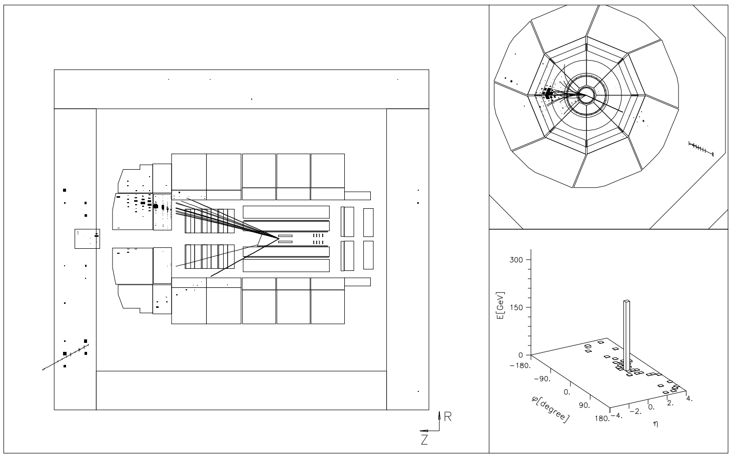


FIGURE 4. Event display of one of the selected events with an isolated μ^+. Shown are a side view (left) and a transverse view for the event. The two-dimensional histogram (bottom right) shows the observed calorimetric energy depositions in the η-ϕ plane.

presence of one or more undetected final state particles.

A new search for high energy isolated leptons in events with missing transverse momentum [15] was performed using data from 1994 to mid 1997, corresponding to a total integrated luminosity of 24.7±0.6 pb^{-1}. The new analysis closely follows the framework of the charged current studies described in [14]. The basic requirement is a missing transverse momentum of more than 25 GeV, defined via the vectorial sum of all energy deposits in the calorimeter. Non-physics background is rejected in similar manner to the high Q^2 analysis. Residual NC events are removed by a visual scan of all selected candidates.

The remaining event sample contains 336 events and is purely inclusive with respect to the presence of isolated charged leptons. To search for such final states two variables $D_{\rm jet}$ and $D_{\rm track}$ are defined for each track with a polar angle of greater than 10° and $p_t > 10$ GeV. These variables measure for each of the high p_t tracks their distance in η-ϕ to the closest hadronic jet or the closest of the remaining charged tracks respectively, and are given by

$$D_{\rm obj=jet,track} = \min_{\rm obj} \left\{ \sqrt{(\Delta\eta_{\rm track-obj})^2 + (\Delta\phi_{\rm track-obj})^2} \right\} . \qquad (3)$$

Investigating the correlation between $D_{\rm jet}$ and $D_{\rm track}$ in the selected CC sample results in five events containing one well-isolated track with $D_{\rm jet,track} > 0.5$. Moreover, imposing standard lepton identification criteria reveals that four of these tracks can be associated with muons while one is recognized as an isolated electron.

Fig. 4 shows one of the selected events, demonstrating the clean signature of the isolated high p_t track. In all the events both an imbalance in total transverse momentum as well as a momentum deficit in the longitudinal direction is observed as expected if one or more particles escape the detector unseen.

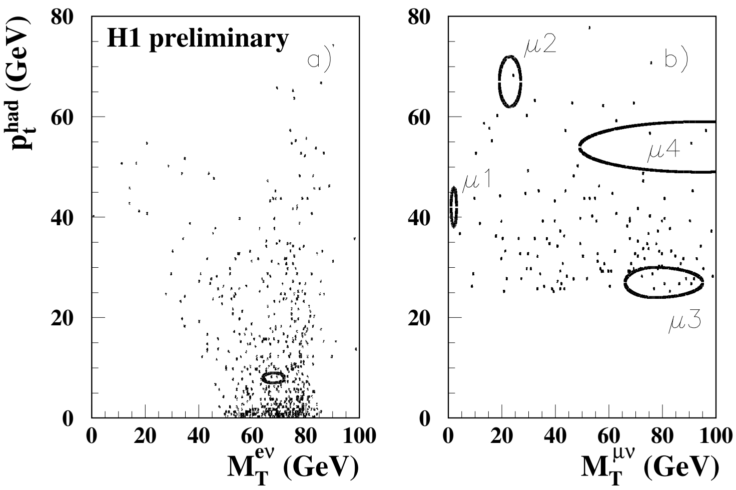


FIGURE 5. Distribution of the five events (ellipses) in transverse momentum p_t and transverse $\ell\nu$-mass $M_t^{\ell\nu}$: (a) electron channel, (b) muon channel. The ellipse contours correspond to the 1σ uncertainty on the measured parameters of each event. The points show the standard model expectation for W production for about 500 times the luminosity available in the data.

Hadronic activity is recorded in the calorimeter for all event candidates and a careful investigation of the signals seen in the central track detector, the calorimeter and the instrumented iron system strongly support the interpretation of the isolated tracks as a muon or electron.

The dominant processes expected to yield a sizeable rate of events with missing p_t and a high energy isolated lepton are those involving production and subsequent leptonic decay of a W boson. The corresponding cross sections are quantitatively evaluated in [16]. The main contribution to this cross section arises from photoproduction with radiation of a real $W^{\pm}$ from a quark line. If the W decays leptonically the Standard Model expectation per channel and charge is $\sim$ 70 fb. Furthermore, about 10% of the cross section is due to virtual W exchange in the t-channel. With the selection cuts described above including $D_{\mathrm{jet,track}} > 0.5$ the overall acceptance for these processes is 40% for the electron and 12% for the muon case. This leads to an overall expectation from W production of 1.34 and 0.41 events in the electron and muon channels respectively. All other sources potentially generating the investigated topology, such as the production of heavy quark pairs with subsequent leptonic decay or τ pair events from two-photon reactions, turn out to be negligible after applying the above selection cuts.

Fig. 5 shows the data together with the expected distribution of events in the $(p_t^{\mathrm{had}}, M_T^{\ell\nu})$ plane, where p_t^{had} is the transverse momentum of the recoiling hadronic system and $M_T^{\ell\nu}$ the transverse invariant mass of the lepton-neutrino pair, which is expected to show a Jacobian peak close to the W mass. The interpretation of all five events arising from W production is kinematically acceptable. However, only two of the observed events lie in a region of phase space where this process is expected to be dominant.

CONCLUSION

Approaching the kinematic limits of the available phase space at HERA, the H1 collaboration has made two unexpected observations. A preliminary update of the high Q^2 analysis shows that the excess of NC events at large values of Q^2 previously published by H1 [1] and ZEUS [17] is still present in the 1997 data. Furthermore, events with missing transverse momentum and an isolated high p_t lepton have been investigated. Five such events are found, compared to a prediction from W production of 1.75. Within the standard DIS model both observations can only be explained as statistical fluctuations. Whether they can be interpreted in terms of new physics requires, however, additional data to be taken.

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