ep PHYSICS AT HIGH Q^2

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ABSTRACT

This article summarizes a talk presented at the SLAC Summer Institute 2000, SLAC, Stanford, USA.

The HERA *ep* collider allows the measurement of the proton structure and tests of the Standard Model in a large region of phase space that has not been accessible before. Such tests provide the framework for the H1 and ZEUS Collaborations to look for physics beyond the Standard Model.

1 Introduction

The HERA collider provides the H1 and ZEUS detectors with electrons or positrons at an energy of 27.5 GeV and protons with 920 GeV making it a unique place to study the proton structure and to search for physics beyond the Standard Model. Each experiment has collected up to now more than 100 pb^{-1}. The largest fraction stems from positron proton collisions.

In this article, processes with large momentum transfer between the incoming lepton and the proton are described. In the next section, the inclusive cross section and the comparison to the Standard Model is presented. Possible extensions of the Standard Model are compared to the data subsequently.

2 Inclusive Cross Section

The beam particles can interact via neutral or charged current events. In the former, a photon or a Z boson is exchanged,

$$NC : e^{\pm}p \rightarrow e^{\pm}X. \tag{1}$$

In deep-inelastic scattering events, the four-momentum transfered squared Q^2, is large, i.e. the exchanged boson is highly virtual. The proton structure is resolved and only a fraction x of the proton momentum takes part in the scattering. The double differential cross section can be described by

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2(x,Q^2) \mp Y_- x\tilde{F}_3(x,Q^2) - y^2\tilde{F}_L(x,Q^2)\right] \tag{2}$$

with

$$Y_{\pm} = 1 \pm (1-y)^2, \tag{3}$$

where the plus and minus signs apply for an incoming electron respectively positron beam.

There is a strong global dependence on Q^{-4} such that processes at high momentum transfer are strongly suppressed. The main contribution for virtualities well below the Z pole comes from the proton structure function F_2. An additional function xF_3 arises from parity breaking weak interactions which enter through the Z exchange and the γZ interference. The last term describes the longitudinal cross section which is a negligible contribution at high Q^2 and small y.

In charged current processes a $W^{\pm}$ boson with the charge of the incoming lepton is exchanged,

$$CC : e^{\pm}p \to \overset{(-)}{\nu} X. \tag{4}$$

The double differential cross section is — in leading order — given by

$$\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 x\left[(u+c)+(1-y^2)(\bar{d}+\bar{s})\right] \tag{5}$$

with the W mass M_W, the Fermi constant G_F, and the quark densities $u, c, \bar{d}, \bar{s}$. At low Q^2 the charged current process is strongly suppressed compared to the neutral current processes by the mass term. This is also seen in figure 1 where the single differential neutral and charged current cross sections are plotted.

It can be seen that the data of both experiments agree well with each other and with the prediction of the Standard Model over more than six orders of magnitude.

Figure 2 shows the comparison of the neutral current cross section for both charges of the incoming lepton. While the positron proton data taken in the years 1994 till 1997 have been measured at a center of mass energy of $\sqrt{s} = 300$ GeV, the cms energy for the other data was $\sqrt{s} = 320$ GeV. The data from the lower energy running has been corrected to allow a direct comparison to that from the higher energy running.

At low photon virtualities, the cross sections are similar, while at higher Q^2 the electron cross section is significantly higher than the one for positions. The difference is induced by the Z exchange which does not have a visible influence at low Q^2. This is seen more clearly in figure 3 where the single inclusive cross section is displayed in two different regions of the momentum transfer. In the high Q^2 region (bottom plots) a significant difference between the theory predictions with and without Z exchange is found. The sign of the γZ interference differs for electron and positron induced processes and the data are described well in both cases.

This difference allows the extraction of the structure function xF_3 from HERA data alone as is shown in figure 4. The data are — within the still large statistical errors — consistent with those of the global fits of the CTEQ and MRS groups. The contribution of the longitudinal cross section in this region of phase space at large Q^2 and high x is found to be negligible.

Detailed comparisons of data to QCD theory have been performed. A summary of the results can be found in the talk by J. Engelen in these proceedings.[5]

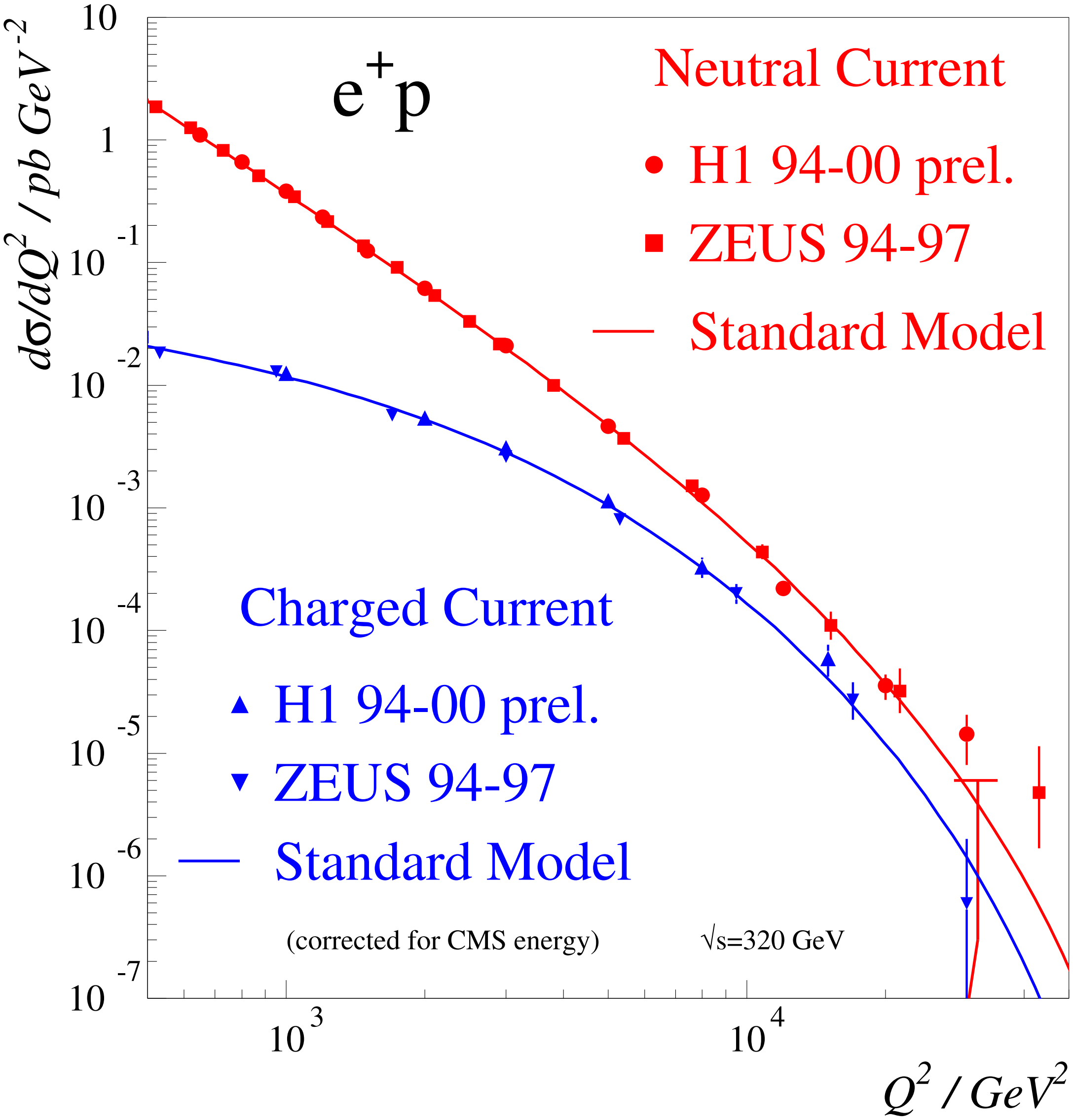

Fig. 1. Comparison of neutral and charged current cross sections for e^+p collisions. The symbols show the data of both experiments and the full line gives the prediction of the Standard Model.[1,2]

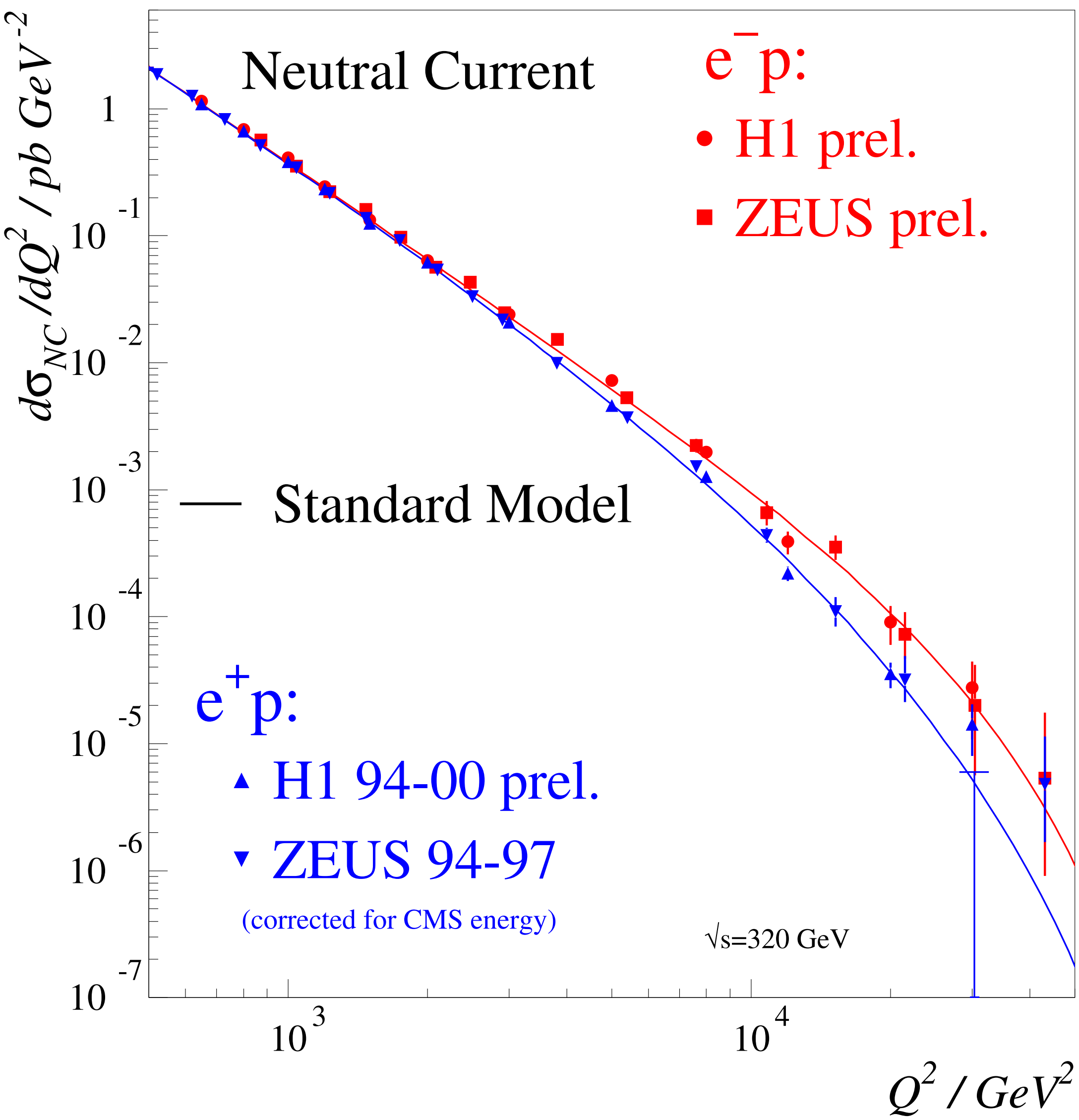

Fig. 2. Comparison of neutral current cross sections for e^+p and e^-p collisions. The e^+p data in the years 1994 till 1997 have been taken at a lower center of mass energy. A correction for the effect of this difference has been applied to allow for a direct comparison (see figure 3). The symbols show the data of both experiments and the full line gives the prediction of the Standard Model.[2–4]

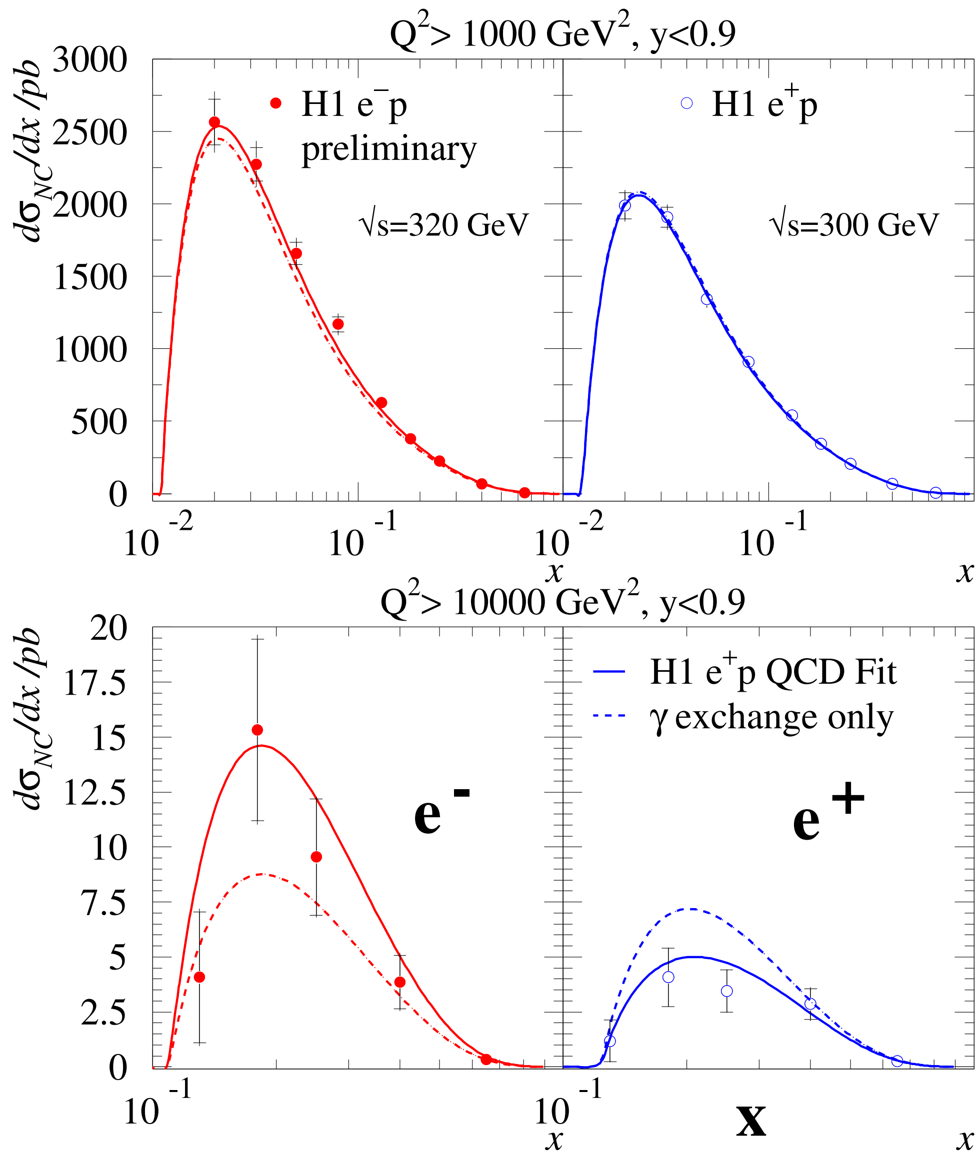

Fig. 3. Influence of the γZ interference in two different regions of four-momentum transfer Q^2. The symbols show the data of the H1 Collaboration and the full line gives a fit of the Standard Model to the data. The dashed line shows the part of the theoretical prediction taking into account the exchange of photons only.[3]

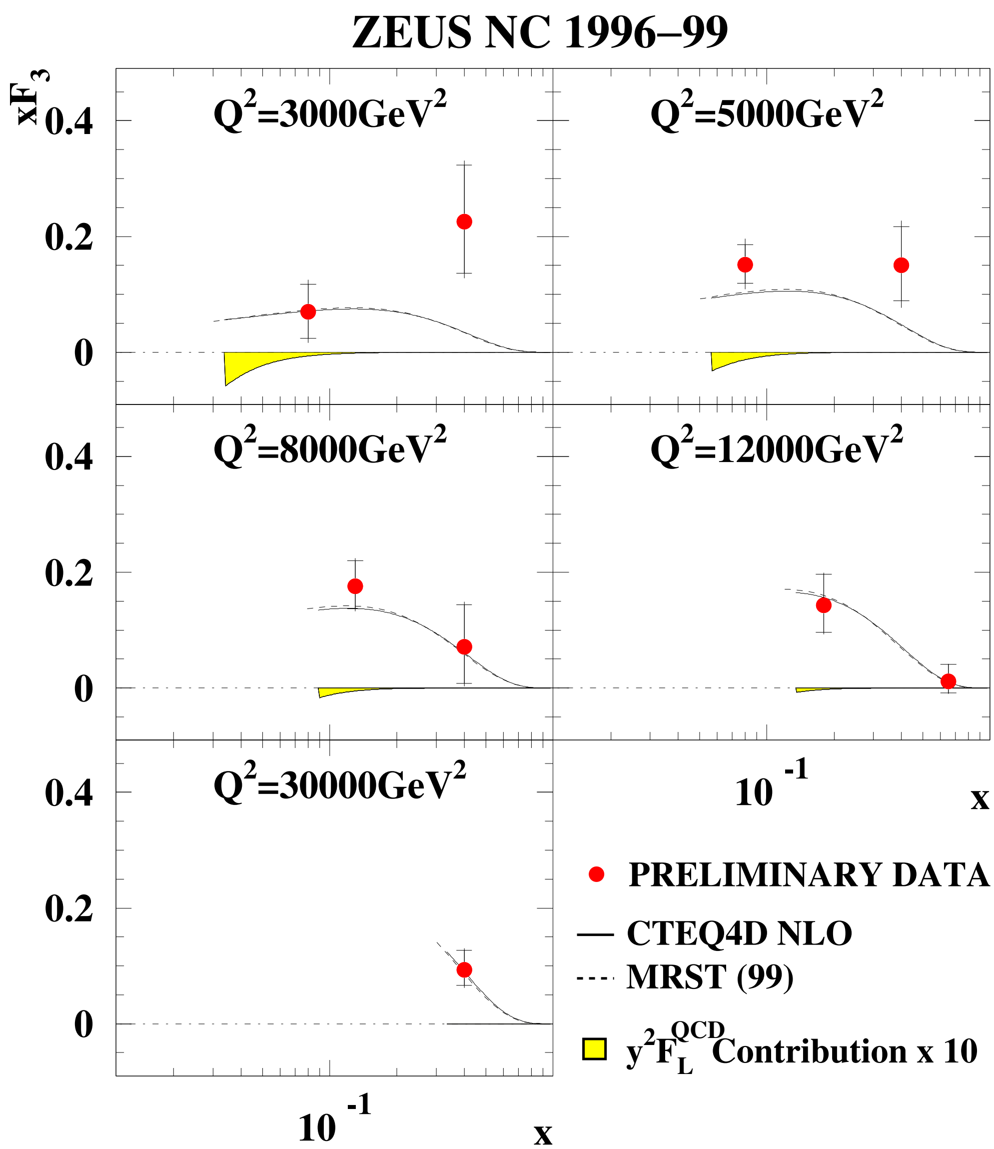

Fig. 4. Extraction of the xF_3 structure function. The symbols show the data of the ZEUS Collaboration. The lines display the value taken from the global parton density fits performed by the CTEQ and MRS groups. The shaded area shows the contribution ($\times$ 10) of the longitudinal structure function.[4]

3 Physics Beyond the Standard Model

One typical signature for physics beyond the Standard Model are mass resonances in the cross section. The center of mass energy squared available in the lepton quark cross section is

$$\hat{s} = xs \tag{6}$$

with the ep center of mass energy $\sqrt{s} = 320$ GeV.

Figure 5 shows the inclusive cross section in different bins of x. The data are well described by a next-to-leading order QCD fit. In figure 6, a more detailed study by the H1 Collaboration is presented with cuts optimized to look for resonances in the lepton quark cross section. While in the early data set a deviation from the Standard Model expectation was seen, the new data set with increased statistics does not confirm this effect. The ZEUS Collaboration also observes, at high Q^2 and x, no significant deviation from the Standard Model expectations in their analysis of 1994-2000 data.[6]

The H1 Collaboration has observed an excess in events containing isolated leptons. A typical event is shown in figure 7. The signature of the events consists of an isolated electron or muon, a significant amount of missing transverse energy and a jet with large transverse momentum (p_T^X). If the missing momentum is attributed to a single neutrino leaving the detector undetected, the transverse mass of the lepton neutrino pair can be extracted and is found to cluster at the mass of the W boson, see figure 8. However, contrary to the distributions of the measured events, the transverse momentum of the jet produced in Standard Model W production is predicted to be small. This is plotted in figures 8 and 9. While the H1 Collaboration observes an excess at high transverse momenta of the jets, the ZEUS Collaboration finds good agreement with the Standard Model expectations. This picture is confirmed by the numbers given in table 1. An analysis with comparable cuts shows that, even though the Monte Carlo expectation is very similar, the H1 Collaboration sees more events than ZEUS.

A possible production of single top quarks by a flavor violating neutral current vertex has been studied by both collaborations in the leptonic and hadronic decay channels. Since no significant excess has been found, limits have been derived for the photon coupling. Since Z exchange is strongly suppressed, no limits on the Z coupling are calculated. The comparison in figure 10 shows that the limits on the photon coupling are the best limits available.

Supersymmetric extensions of the Standard Model predict the existence of new particles: squarks, the supersymmetric partners of the quarks, and sleptons. Standard

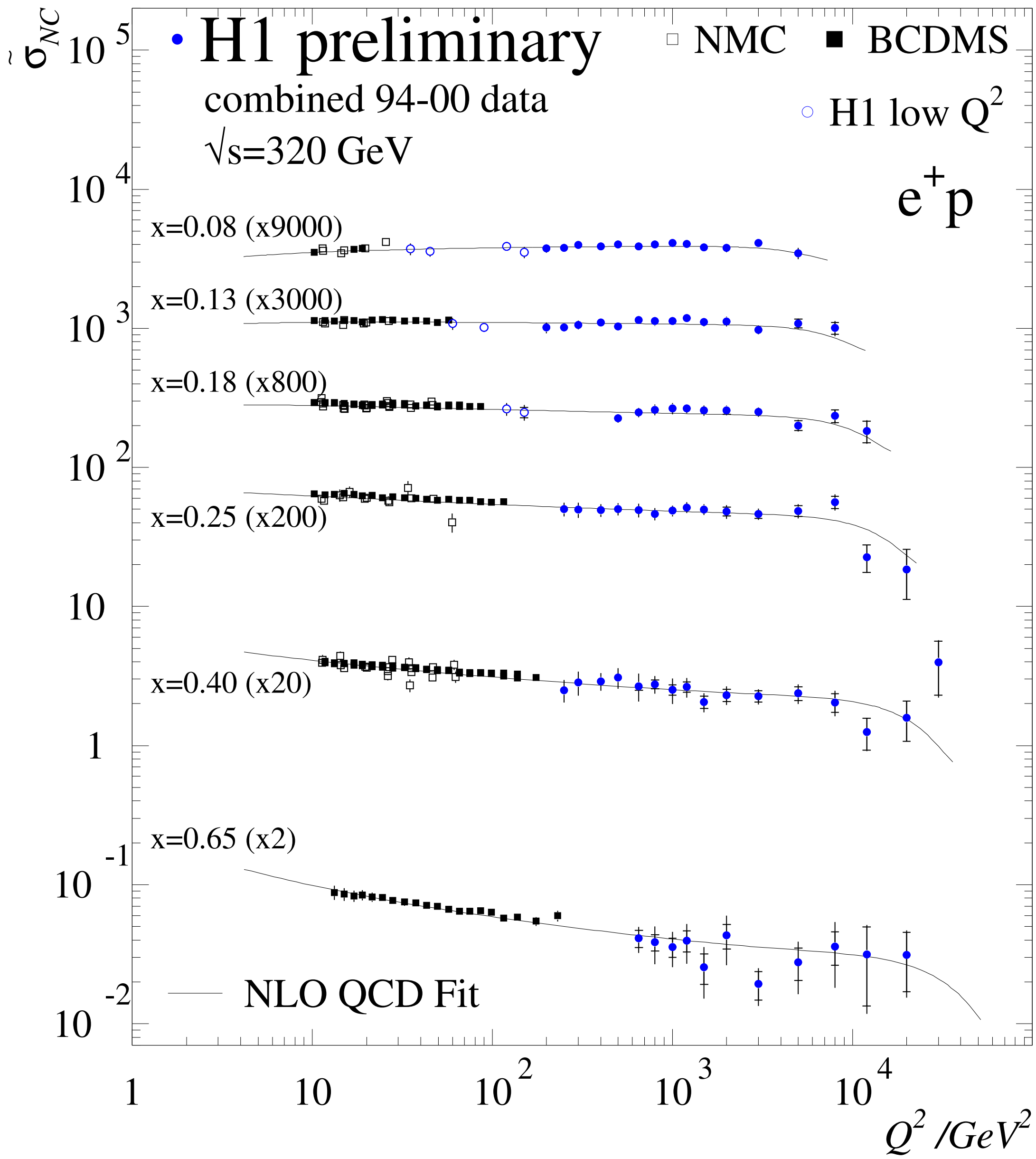

Fig. 5. Double differential inclusive cross section. The symbols show the data of the H1 Collaboration and the fixed target experiments NMC and BCDMS. The lines display a QCD fit to the data.[1]

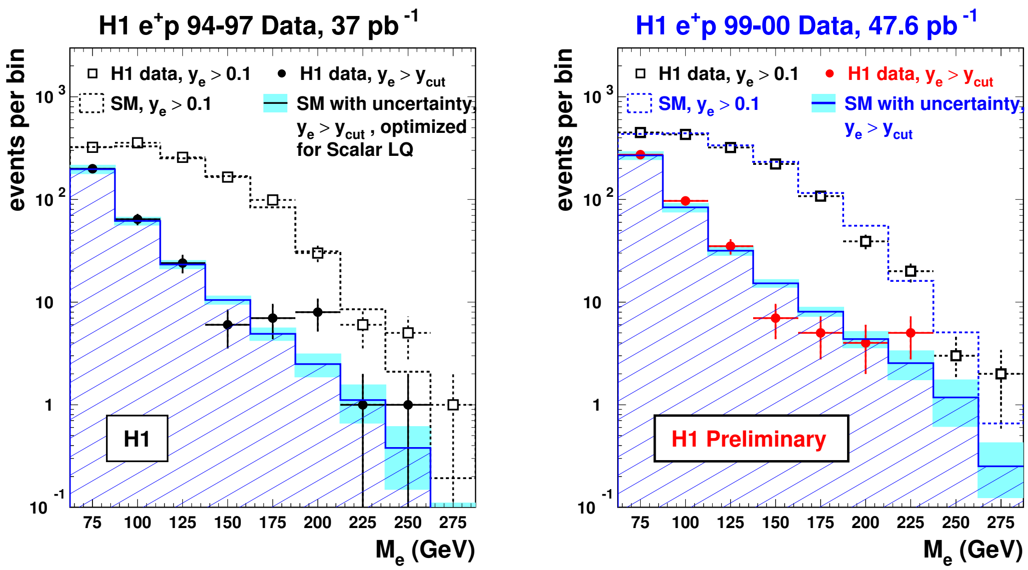

Fig. 6. Cross section as a function of the invariant mass of the lepton quark subprocess. Points show the data of the H1 Collaboration and the histograms give the Standard Model expectation. The left plots show the data of the 1994 to 1997 data taking, the right those of the 1999 and 2000 data set.[7]

Collaboration	Data Set	Events seen	MC expectation
Default analyses of the collaborations			
H1 preliminary	1994-2000 e^+p only, 82 pb^{-1}	9	2.3 ± 0.6
ZEUS prelim.	1994-1999 e^+p and e^-p, 82 pb^{-1}	11	9.8 ± 1.3
Special analyses using similar cuts			
H1 preliminary	1994-2000 e^+p only, 82 pb^{-1}	9	1.78
ZEUS prelim.	1994-1999 e^+p and e^-p, 82 pb^{-1}	1	1.60

Table 1. Comparison of the number of isolated lepton events seen and expected from Monte Carlo simulations of all relevant Standard Model processes. In the upper part, the default analyses of both collaborations are shown. Those are optimized for the detector configurations and specific channels. For comparison, analyses with similar cuts have been performed and are shown in the lower part.[8–10]

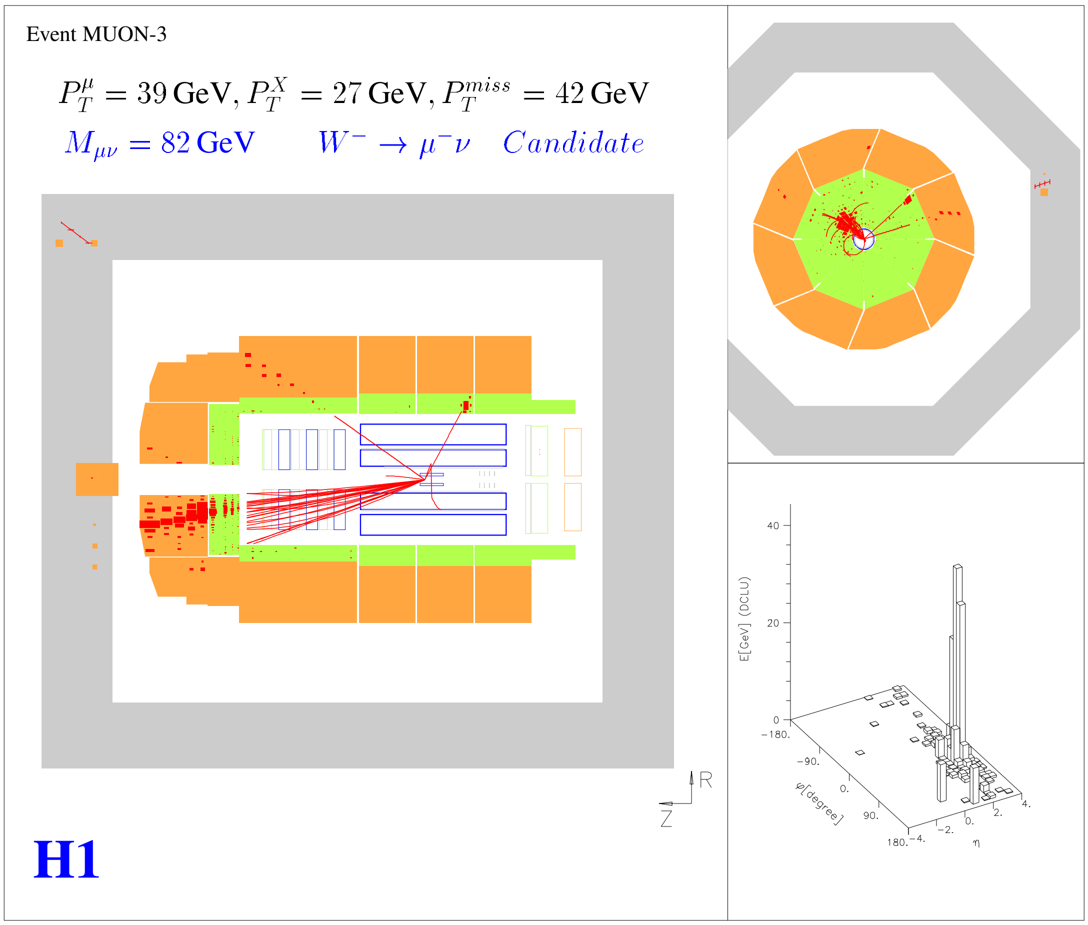

Fig. 7. Event display of an isolated lepton event recorded at the H1 detector.

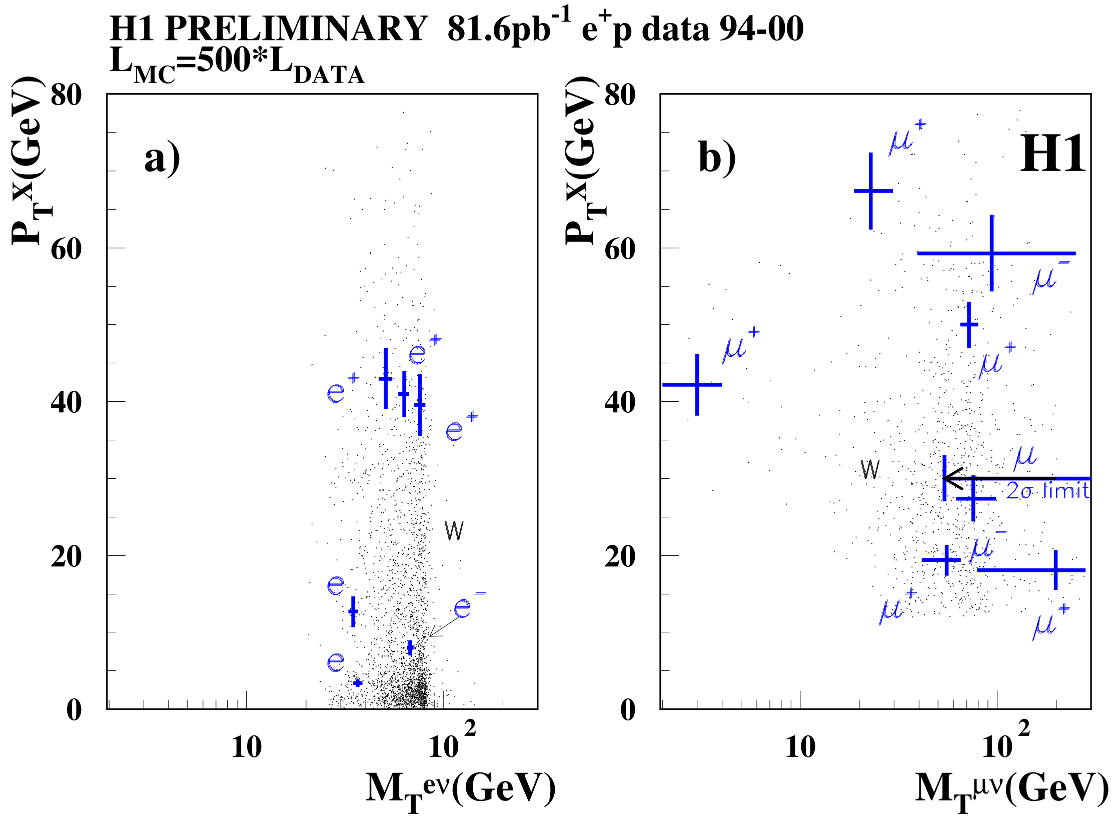

Fig. 8. Event distribution of the isolated lepton events. Shown is the transverse mass of the lepton neutrino pair versus the transverse momentum of the jet for isolated electron and muon events. The events found by the H1 Collaboration are shown as crosses corresponding to the uncertainty in the measurement of the observables. The small points show the event distribution expected from a Monte Carlo simulation of Standard Model W production. The luminosity of the Monte Carlo production exceeds that of the data by a factor 500.[8]

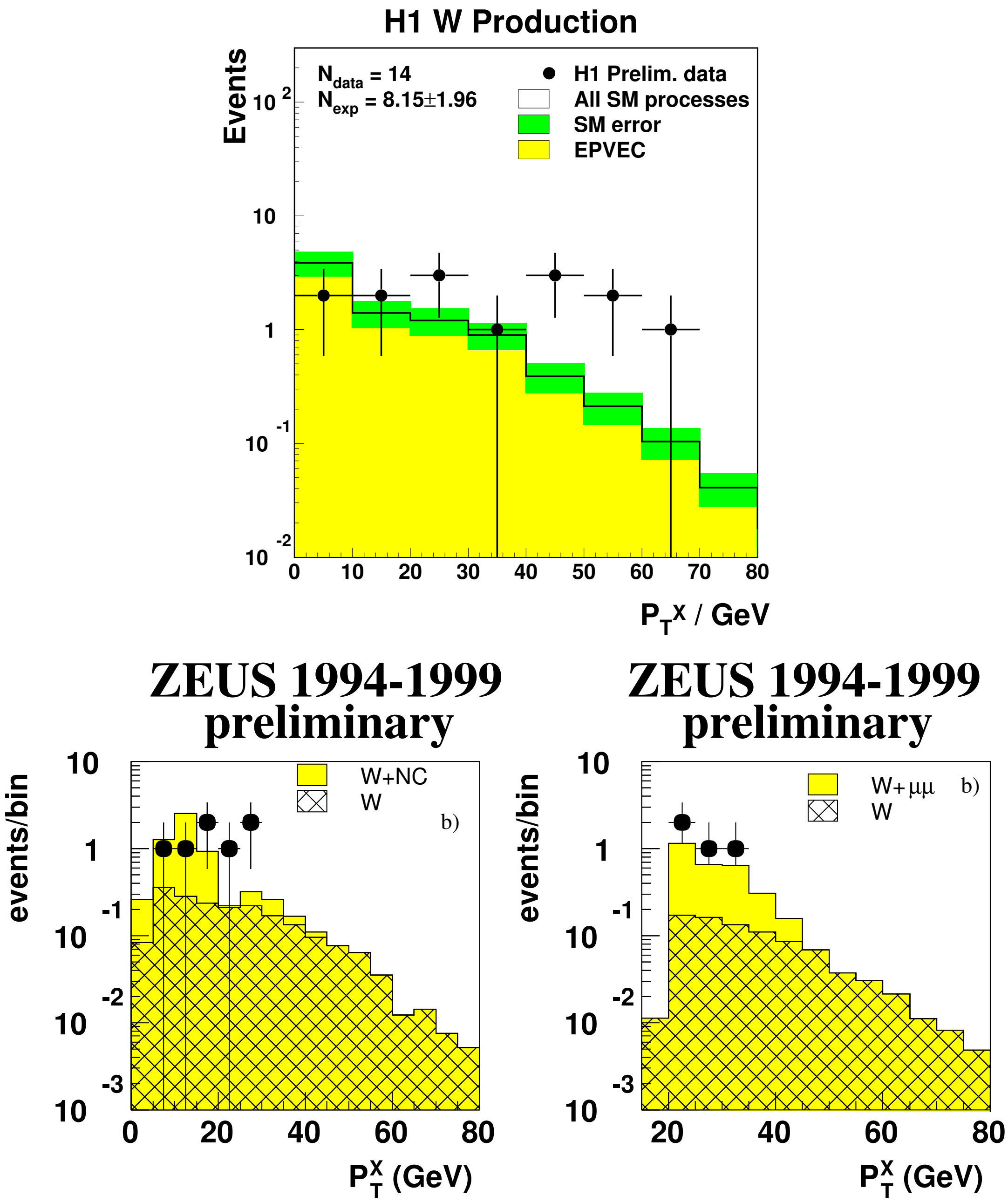

Fig. 9. Distribution of the transverse momentum of the jets in isolated lepton events measured at H1 (top) and ZEUS (bottom, left: electron channel, right: muon channel) Collaboration. Full points show the data, full lines the prediction of the Standard Model.[8,9]

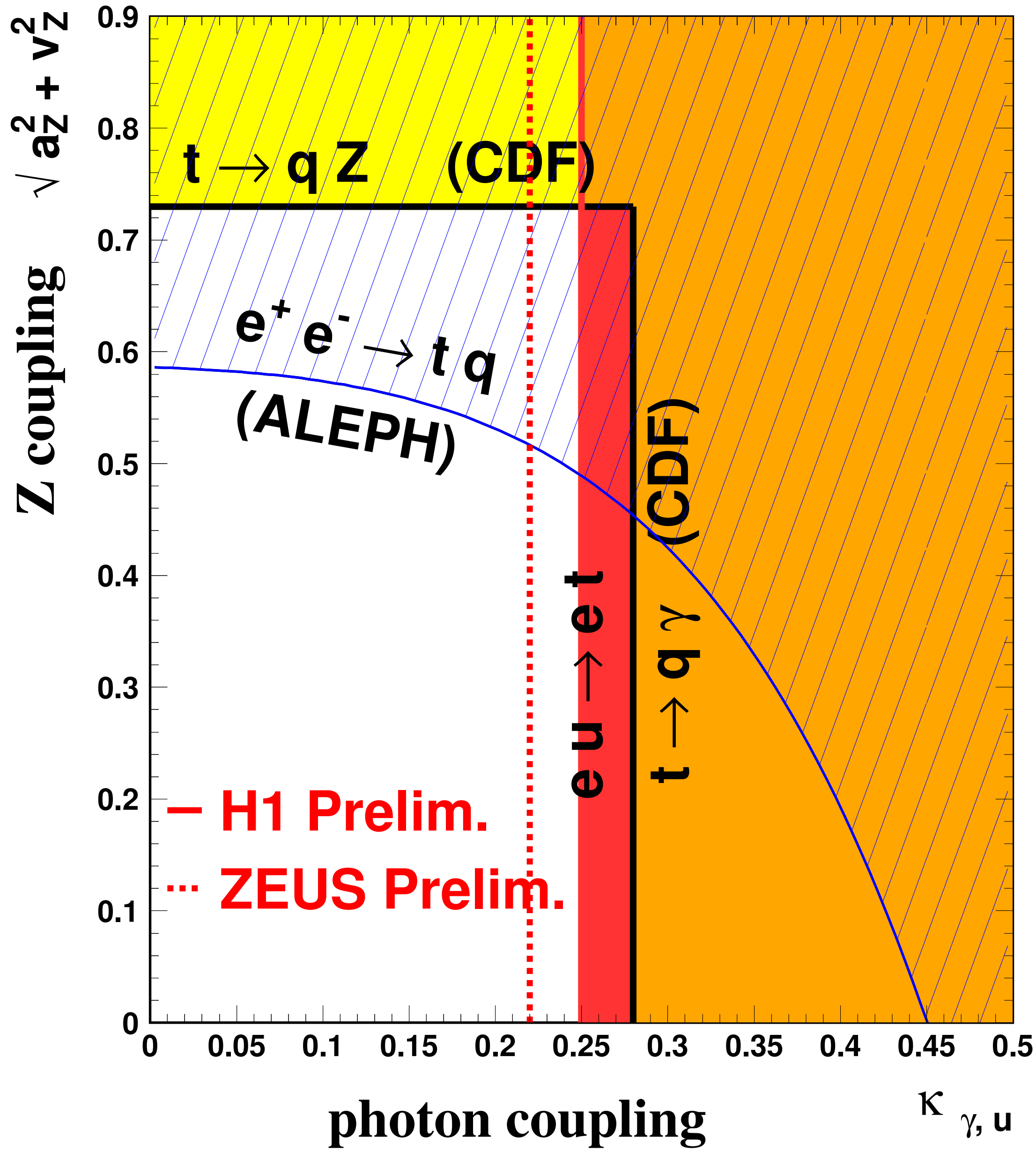

Fig. 10. Limits on the photon coupling for single top production as extracted from the H1 and ZEUS Collaborations. For comparison, the limits of the CDF and ALEPH Collaboration are shown.[9,11]

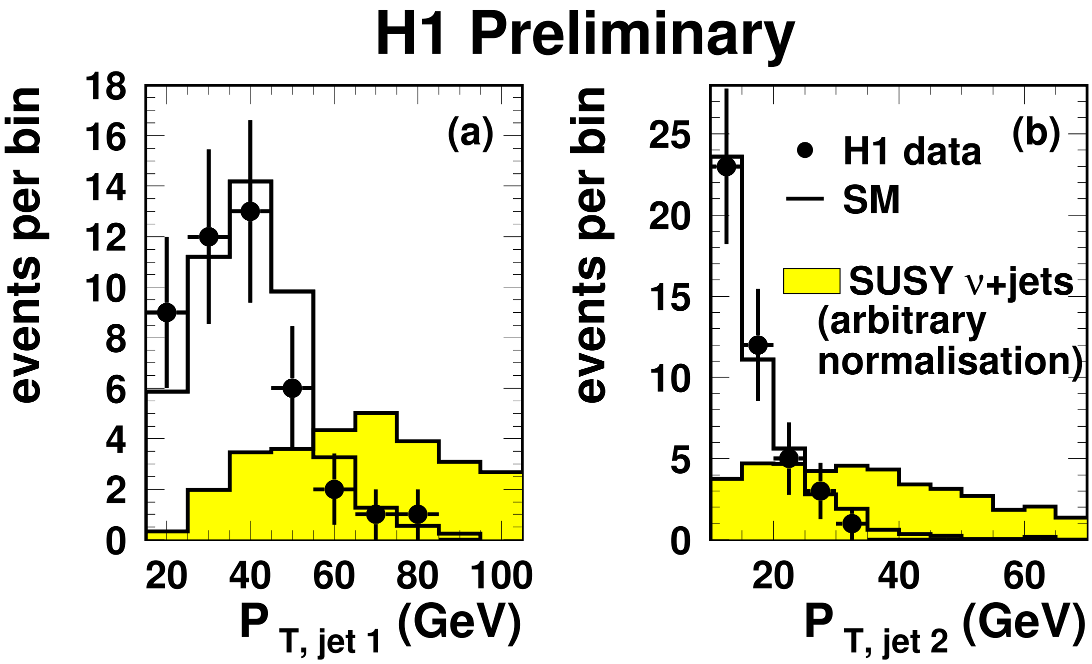

Fig. 11. Distribution of the transverse momentum of the jets in the neutrino plus multiple jet event sample. The full points show the data and the open histograms the expectation of the Standard Model. The filled histogram displays the contribution as calculated by a signal Monte Carlo.[13]

Model particles have an R parity of +1 while SUSY sparticles have -1. In R parity conserving theories, sparticles can only be produced together with their anti-sparticles. In R parity violating theories, sparticles can be produced e.g. at lepton quark vertices where the HERA ep collider has a unique detection potential.

Many decay channels for sparticles have been looked at. As an example, the transverse momentum distribution of the jets in the neutrino plus multiple jet channel is shown in figure 11.

The distributions for all channels are well described by the Standard Model and no excess is found. Therefore, limits on R parity violating couplings have been extracted, see figures 12 and 13. The limits are found to depend only weakly on the SUSY parameters μ and M_2 and are the best limits available.

Additional studies have been performed and limits on e.g. minimal super-gravity theories,[13] contact interactions, extra dimensions,[14] or excited fermions[15] have been extracted.

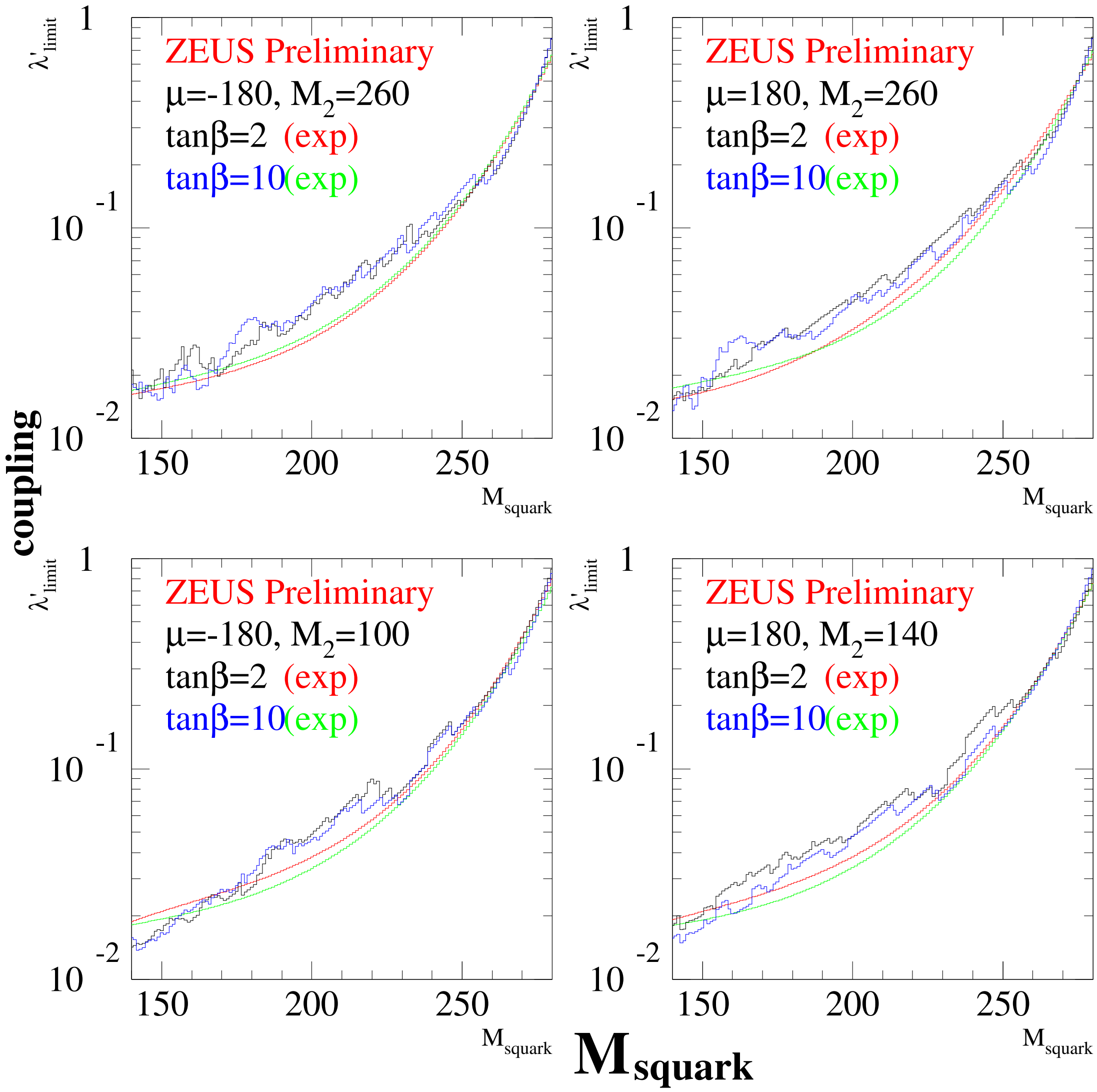

Fig. 12. 95% confidence limits for SUSY processes as extracted by the ZEUS Collaboration. The histograms show the limits for different combinations of the SUSY parameters μ and M_2.[12]

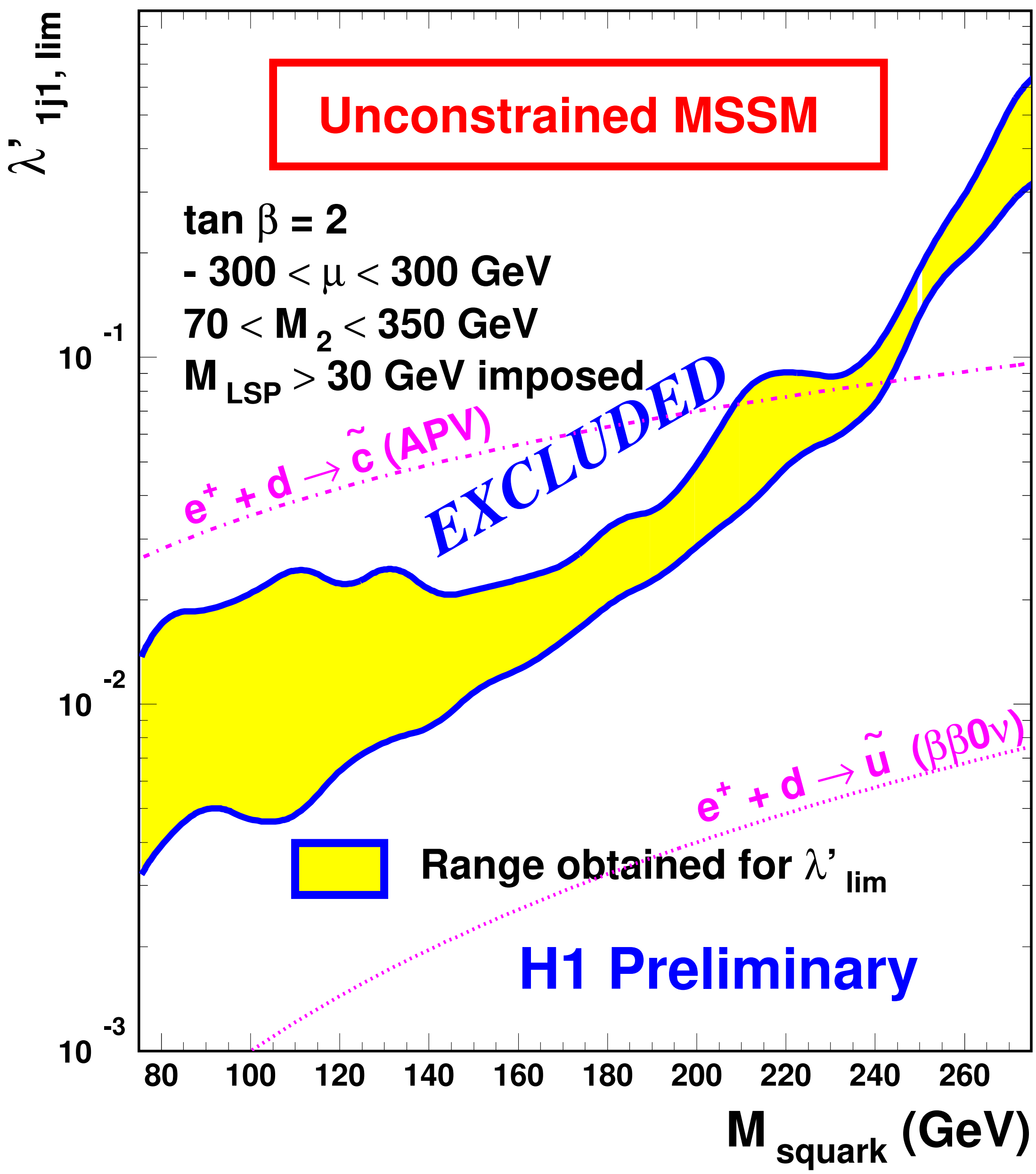

Fig. 13. Limits for SUSY processes as extracted by the H1 Collaboration. The shaded area shows the dependence on the SUSY parameters, the region above the area is excluded for all parameter combinations. For comparison, limits from the neutrinoless double beta decay and atomic parity violations are shown. These are valid for first and second, respectively, generation squarks only, while the H1 limit is valid for all generation of squarks.[13]

4 Summary

The collider experiments at the HERA storage ring have collected a large amount of ep data in the last eight years.

Studies of the proton structure at the H1 and ZEUS Collaborations have shown a remarkable agreement with the Standard Model. The neutral current as well as the charged current inclusive cross section allow the extraction of the proton structure and tests of QCD predictions. The influence of weak contributions is clearly seen.

The HERA ep collider also provides a unique testing ground for physics beyond the Standard Model. No signal was found in searches for leptoquarks, for single top production, and for R parity violating SUSY. Corresponding limits have been extracted and are in large regions of the parameter space the best limits available. The H1 Collaboration has seen an excess of events with an isolated lepton, large missing momentum, and a jet with large p_T^X. This excess is not confirmed by the ZEUS Collaboration. Whether these events are the first signals of physics beyond the Standard Model or a simple statistical fluctuation can only be decided after more data has been collected. The next data taking period will begin after a significant upgrade of both detectors and the storage ring, and startup is expected in the middle of next year.

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