Structure functions at large x

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Abstract. Structure function data together with other measurements from fixed-target deep inelastic scattering and hadron-hadron collider experiments which contribute to our knowledge of the parton density functions are reviewed. The inclusive cross-section measurements of neutral and charged current interactions at HERA are presented and their impact on the parton density functions is discussed. Future prospects for an improved knowledge of the parton density functions at large x are briefly mentioned.

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1. Introduction

Deep inelastic scattering (DIS) experiments have played important roles in understanding the partonic structure of hadrons and in establishing the theory of quantum chromodynamics (QCD), the strong sector of the Standard Model (SM). Our current knowledge of the parton densities in hadrons is primarily derived from the structure functions measured in these experiments [1].

A precise knowledge of these parton density functions (PDFs) is needed both for providing reliable predictions for processes involved in hadron-hadron colliders such as the Tevatron and the LHC, and for achieving precision measurements at these colliders. A good example is the measurement of the mass of the W boson from the Tevatron. The mass, which is relevant for incisive tests of the SM of electroweak interactions, receives a non-negligible systematic contribution from the uncertainty of the PDFs [2].

The precision of the PDFs also affects directly interpretations of data measured at hadron colliders and searches for physics beyond the SM. One example is the excess of jet events at large transverse energies over perturbative QCD calculations reported earlier by the CDF collaboration [3]. The excess, which has initiated considerable speculations of possible new physics, could well be accommodated by a higher than expected gluon density at large x [4]. Another example is the excess of events at high momentum transfer (Q^2) with respect to the standard DIS expectation reported by both the H1 and ZEUS experiments at HERA based on the earlier low statistics sample taken from 1994 to 1996 [5]. The excess could be due to a statistical fluctuation, an imprecise knowledge of the PDFs at large x, or a resonance production of leptoquarks or scalar quarks in R_p-violating supersymmetric models [6].

In this paper, various constraints on the PDFs from fixed-target DIS experiments and from hadron-hadron colliders will first be briefly reviewed (section 2), the inclusive cross-section measurements at high Q^2 from HERA will then be presented and their impact on the PDFs discussed (section 3).

2. Current knowledge on the parton density functions

The traditional, but still the most important, constraint on the PDFs is from structure function data measured in DIS experiments. Shown in figure 1 are four precise measurements from BCDMS [7], CCFR [8], E665 [9] and NMC [10] and their kinematic ranges [11]. These data constrain the PDFs mainly in the medium and large x range§.

The precision of the structure function data does not, however, imply a good precision for the PDFs since their derivation and error estimation depend on a whole complexity of experimental and theoretical inputs involved in a global analysis such as MRST [12] or CTEQ [13]. Here are a number of sources of uncertainty:

§ The best knowledge on the PDFs at small x is obtained from HERA structure function F_2 data. This is, however, not the subject of this paper.

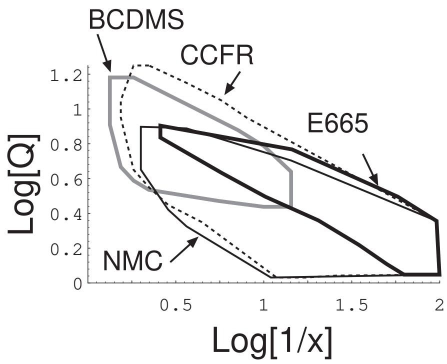

Figure 1. The kinematic coverage [11] of four precise structure function measurements by BCDMS [7], CCFR [8], E665 [9] and NMC [10].

- **Experimental systematic uncertainties:** The most precise data are usually limited by systematic, rather than statistical, uncertainties. The correlations of different systematics on the measurements among and across experiments are not at all trivial to take properly into account.
- **Higher-twist contribution:** The data are located at relative low Q^2 and large x. The higher-twist contribution is expected to be important as it behaves as $[(1-x)Q^2]^{-1}$ with respect to the leading-twist contribution.
- **Parameterization form:** In a global analysis, the parton densities are parameterized in a certain functional form. The freedom in choosing the functional form and the corresponding initial scale is a source of the uncertainty.
- **Large nuclear corrections:** As far as the d valence quark density is concerned, it is constrained mainly by the deuterium data, to which the nuclear binding corrections can be important.

Apart from the structure function data, a few other processes from the fixed-target experiments also provide valuable constraints on the PDFs. This is the case for the lepton-pair production or the Drell-Yan process (the dominant leading-order subprocess being $q\overline{q} \to \gamma^* g, \gamma^* \to l\overline{l}$), which constrains the sea quark distributions in the proton. The asymmetry between the u and d quark flavors, which cannot be easily determined from the structure function data, is constrained by the asymmetry in the Drell-Yan production. The direct constraint on the gluon density could in principle be obtained from the prompt photon production ($qg \to \gamma X$). However, the large discrepancies between measurements and theoretical predictions and among measurements carried out by different experiment groups [14] prevent us from using these data at present. Represented in figure 2(a) are the kinematic ranges for these processes. Figure 2(b) shows other constraining processes from the collider experiments UA2, CDF and D0. In addition to the direct photon process, the W asymmetry constrains the d over u ratio, d/u, for x around 0.1 and for Q around the mass of the W boson. The inclusive jet data from the Tevatron provide a potential source for constraining the gluon density at

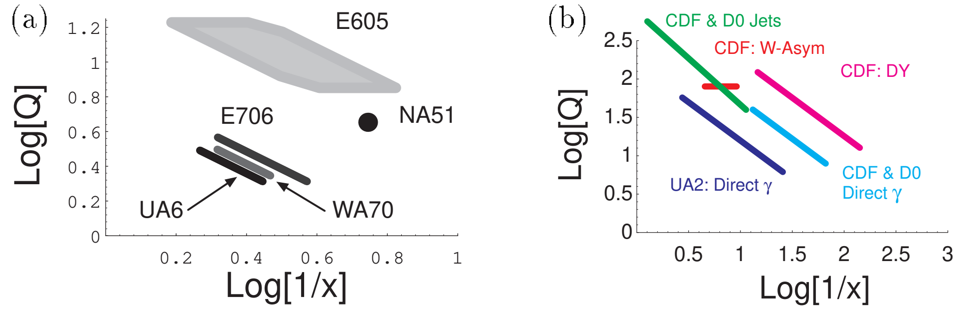

Figure 2. The kinematic coverage [11] of (a) the lepton-pair (Drell-Yan) production from E605 [15], the asymmetry data in the Drell-Yan production from NA51 [16], and the direct photon production data from E706 [17], WA70 [18] and UA6 [19] and of (b) the direct photon (γ) data from UA2 [20], CDF [21] and D0 [22], the Drell-Yan (DY) and W asymmetry data from CDF [23, 24], and the jet data from CDF [3] and D0 [25]. The kinematic ranges of some of the measurements are now extended by new experiments: e.g. E605 [15] by E772 [26], NA51 [16] by E866 [27].

large x.

Despite the large kinematic coverage of the different data, the resulting uncertainty of various PDFs is far from uniform. In general, the precision is best in the medium region but still rather poor towards the kinematic limit at large x. This is well illustrated by the behavior of the d/u ratio at $x \to 1$ (figure 3). On the theoretical side, the model predictions vary considerably between 0 and 0.5 with non-perturbative QCD-motivated predictions at around 0.2 [29]. On the experimental side, for $x < 0.3$, there are precise data from both W asymmetry and DIS data and the nuclear corrections to the DIS data are insignificant; for $0.3 < x < 0.7$, there are only DIS data which may be subject to large nuclear corrections; at larger x, no reliable data are available. In an analysis by Yang and Bodek [30], they showed that the description of the W asymmetry and NMC structure function ratio data is improved with $d/u \to 0.2$ as $x \to 1$ and with the nuclear binding corrections applied to the deuterium data. The analysis by Kuhlmann *et al* [28] showed that if the ratio d/u is around 0.2, the NMC data indeed need a nuclear correction, but the converse is not necessarily true. The large spread of the curves shown in figure 3, corresponding to three possible fits to the existing data, shows how uncertain the current PDFs are at large x.

3. HERA impact on the parton density functions

The structure functions measured by the HERA experiments H1 and ZEUS have provided a unique constraint on the PDFs at small x, in particular on the gluon density [1]. Here we shall present inclusive cross-sections at high Q^2 measured with three important data samples collected by both experiments since 1994, and discuss their impact on the PDFs at large x. The first e^+p data sample, corresponding to an

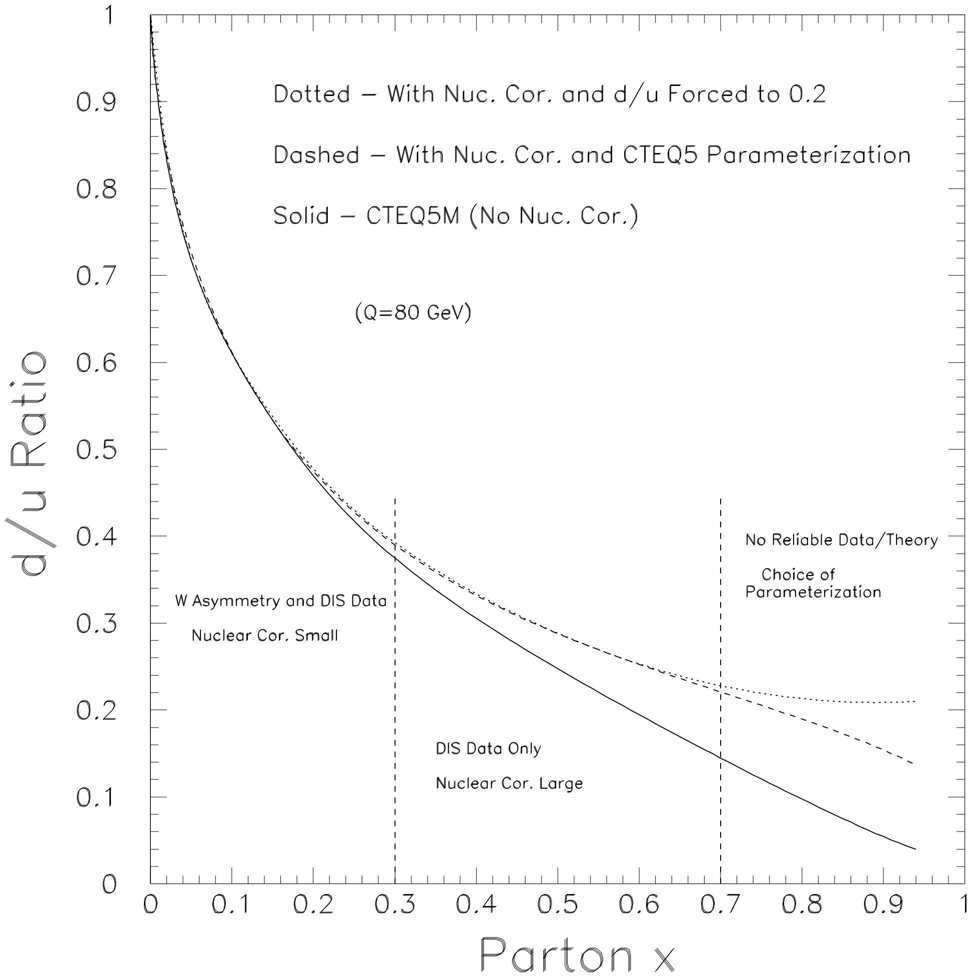

Figure 3. The d/u ratio as a function of x for $Q = 80\,\mathrm{GeV}$ [28]. The solid (dashed) curve corresponds to the parameterization from CTEQ5M without (with) nuclear corrections applied. The dotted curve shows the result when the nuclear corrections are applied and the ratio is forced to be 0.2 at $x = 1$.

integrated luminosity of $35.6\,\mathrm{pb}^{-1}$‖, was taken from 1994 to 1997 at a center-of-mass energy of 300 GeV. Both the e^-p data of 1998-1999 and the e^+p data of 1999-2000 are taken at a center-of-mass energy of 320 GeV resulting from the increased proton energy of 920 GeV. The corresponding integrated luminosities are, respectively, $16.4\,\mathrm{pb}^{-1}$ and $65\,\mathrm{pb}^{-1}$.

Figure 4 shows the neutral current (NC) reduced cross-sections¶ measured with the 1996-1997 e^+p and 1998-1999 e^-p ZEUS data [31, 32]. The e^+p and e^-p cross-sections are found to be comparable+ at low Q^2 ($< 1000\,\mathrm{GeV}^2$ or so). This is understood to be due to the dominance of γ exchange. At higher Q^2, the e^-p cross-sections are measured to be increasingly larger than those of e^+p, demonstrating the $\gamma - Z$ interference

‖ The number shows the integrated luminosity from H1. The data samples from ZEUS are comparable.
¶ The NC reduced cross-section $\tilde{\sigma}_{\rm NC}$ is defined as $\tilde{\sigma} = (xQ^4/2\pi\alpha^2 Y_+)\mathrm{d}^2\sigma/\mathrm{d}x\mathrm{d}Q^2$ with $Y_+ = 1+(1-y)^2$.
+ The difference due to the change in the center-of-mass energies is expected at a few percent level.

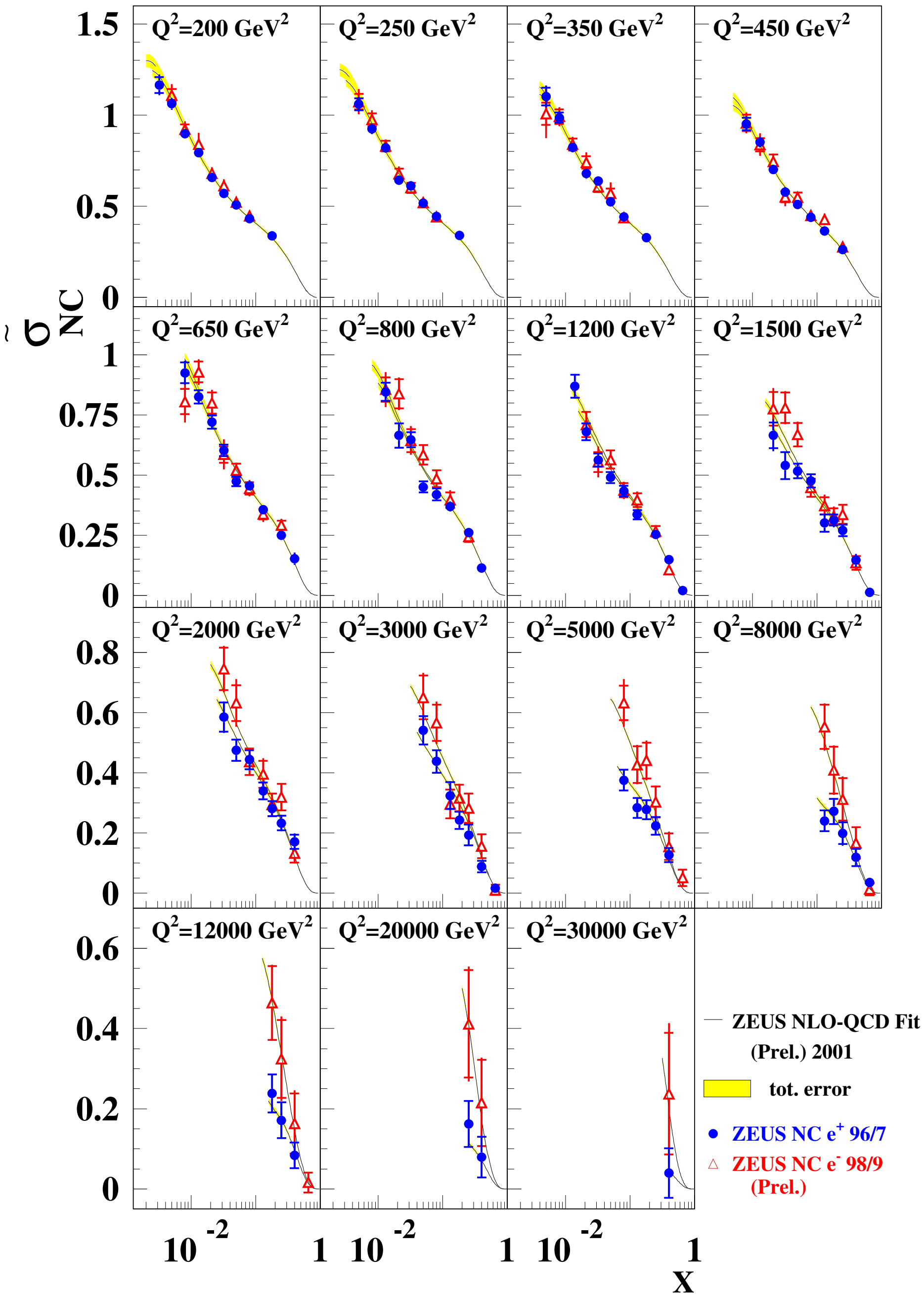

Figure 4. The NC reduced cross-sections measured by ZEUS using the 1996-1997 e^+p and 1998-1999 e^-p data [31, 32]. The curves are the preliminary ZEUS next-to-leading (NLO) order fit [33] based on the fixed-target data and the 1996-1997 ZEUS data.

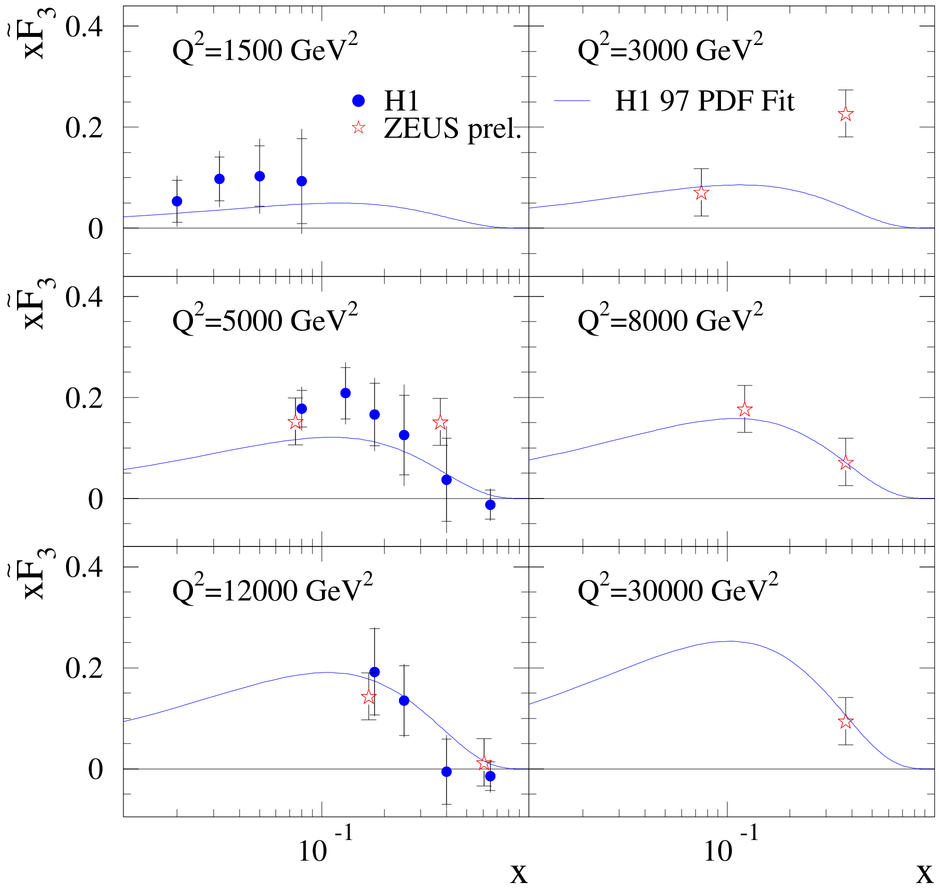

Figure 5. The structure function $x\tilde{F}_3$ measured by H1 and ZEUS [34, 32]. The curves are the results of the H1 97 PDF Fit [35].

contribution. The cross-section asymmetry allows the structure function $x\tilde{F}_3$ (figure 5) to be determined for the first time at HERA [32, 34]. As this structure function measures the difference between the quark and anti-quark densities ($x\tilde{F}_3 \sim 2\sum_i e_i a_i x(q_i - \overline{q}_i)$ with e_i and a_i being, respectively, the electric charge of quark i and its axial coupling to the Z boson), it is thus sensitive to the valence quark densities at large x.

A comparison of the charged current (CC) reduced cross-sections* measured by H1 [35, 34] is shown in figure 6. The difference in the cross-sections results mainly from different quark flavors probed by the exchanged $W^{\pm}$ bosons. The CC cross-sections at high Q^2 thus provide a unique source to directly constrain the u and d valence quarks at large x.

The x dependence of the measured NC and CC cross-sections [34, 35, 36] for $Q^2 > 1000\,\mathrm{GeV}^2$ and $y < 0.9$ is compared with the standard DIS expectation in figure 7. From the ratio plots, the NC cross-sections at $x = 0.65$ are seen to lie considerably below the expectations, whereas the CC e^+p cross-sections at large x (dominated by the

* The CC reduced cross-section $\tilde{\sigma}$ is defined as $\tilde{\sigma} = (2\pi x/G_F^2)((Q^2 + M_W^2)/M_W^2)^2 \mathrm{d}^2\sigma/\mathrm{d}x\mathrm{d}Q^2$ with G_F and M_W being, respectively, the Fermi coupling constant and the mass of the exchanged W boson.

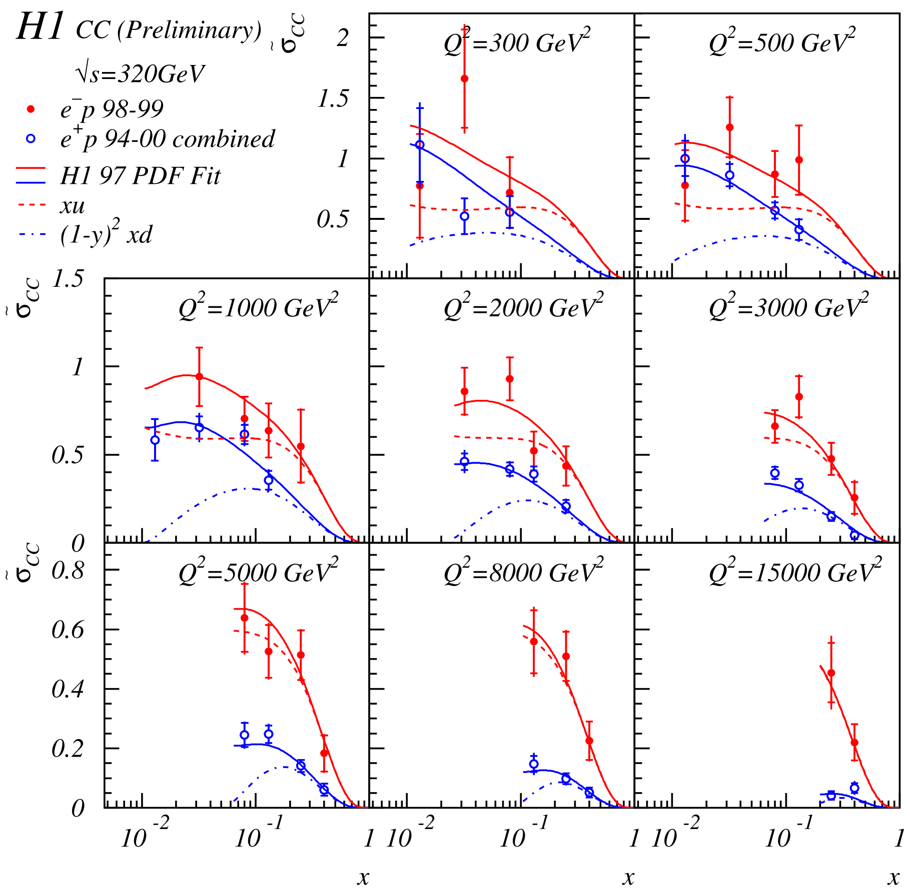

Figure 6. The CC reduced cross-sections $\tilde{\sigma}_{\rm CC}$ measured by H1 using the 1998-1999 e^-p and combined 1994-1997 and 1999-2000 e^+p data [35, 34]. The solid curves show the expectations based the H1 97 PDF Fit [35]. The dashed and dash-dotted curves represent, respectively, the contribution of xu and $(1-y)^2xd$ to the e^-p and e^+p cross-sections.

d valence quark contribution) have the tendency to lie above the expectation although the uncertainty of both the measurement and the expectation are large.

In order to quantify the impact of these measurements on the PDFs at large x, two methods are employed to extract the u and d valence quark densities using the HERA data alone.

The first method in essence is a global NLO QCD fit like those performed by the MRST and CTEQ groups [12, 13]. The main difference is in the number of experimental data sets used. The results of the H1 fit [1] are shown in figure 8 together with those obtained from a second method. In the second method, the u and d quark densities are extracted locally from the measured cross-sections $({\rm d}^2\sigma/{\rm d}x{\rm d}Q^2)_{\rm meas}$ as:

$$xq_v(x,Q^2) = ({\rm d}^2\sigma(x,Q^2)/{\rm d}x{\rm d}Q^2)_{\rm meas}\left(\frac{xq_v(x,Q^2)}{{\rm d}^2\sigma(x,Q^2)/{\rm d}x{\rm d}Q^2}\right)_{\rm th} \qquad (1)$$

where the second factor on the right-hand-side of the equation is the theoretical expectation. Only those points where the xq_v contribution is greater than 70% of the

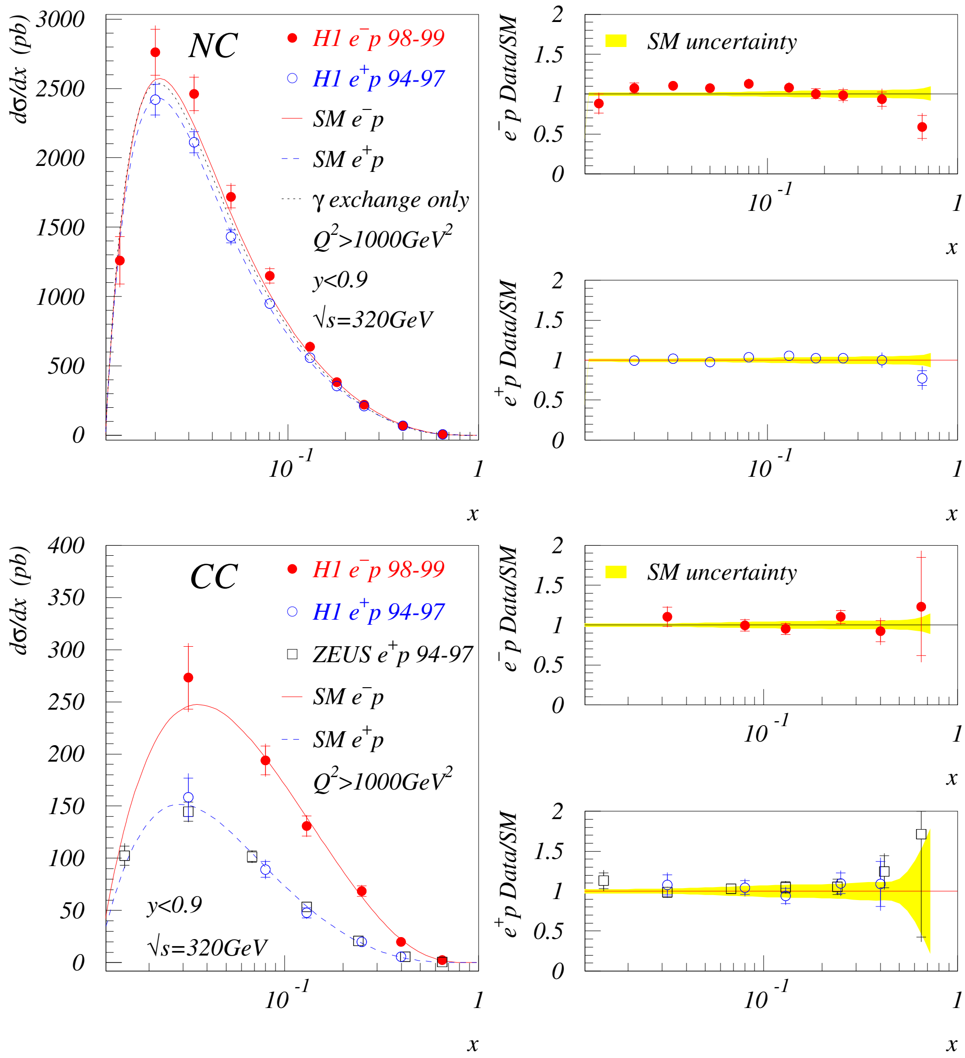

Figure 7. The x dependence of the measured NC (upper) and CC (lower) cross-sections [34, 35, 36, 37] for $Q^2 > 1000\,\mathrm{GeV}^2$ and $y < 0.9$ in comparison with the Standard Model (SM) expectations, which are based on the H1 97 PDF fit [35].

corresponding cross-section are considered♯. The first such extraction was performed by H1 for two values of x at 0.25 and 0.4 using the 1994-1997 e^+p NC and CC cross-sections [35]. With the new e^-p 1998-1999 and e^+p 1999-2000 data, similar extractions were made and were extended to $x = 0.65$ for u [1]. In practice, the d valence quark density is determined from the combined e^+p CC cross-sections, whereas the u valence quark density is determined from the combined e^+p NC, e^-p NC and e^-p CC cross-sections. Three independent determinations of xu_v are then combined.

The valence quark distributions at large x can thus be quantitatively constrained for the first time by the HERA data alone although the experimental uncertainties (between

♯ The extracted parton densities are thus rather independent of the theoretical input as the uncertainty on the dominant valence quark contribution and that of the cross-section largely cancel in the ratio.

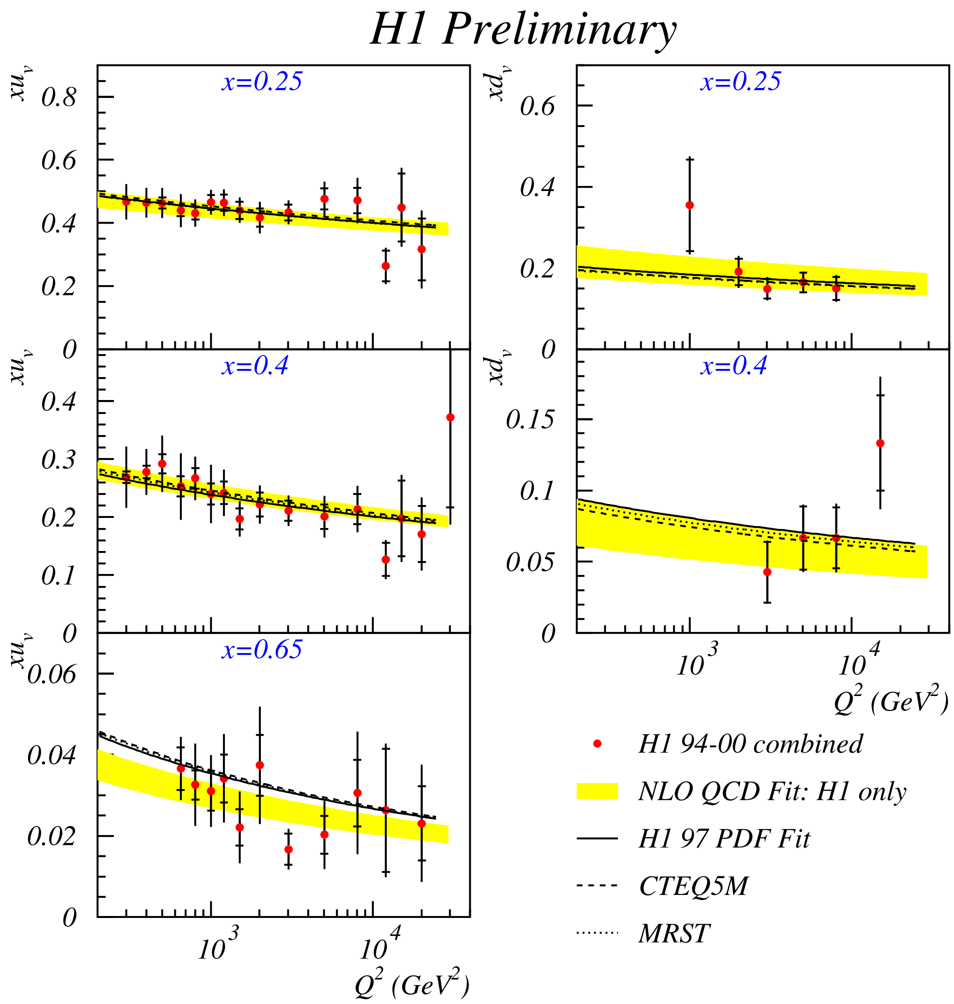

Figure 8. The valence quark densities xu_v and xd_v determined both with an NLO QCD fit using the H1 data only (shaded error bands) and with a local extraction method (data points with the inner and full error bars showing, respectively, the statistical and total uncertainties). For comparison, three other parameterizations (H1 97 PDF Fit [35], CTEQ5M [13] and MRST [12]) are also shown.

6% at $x = 0.25, 0.4$ and $\sim 10\%$ at $x = 0.65$ for xu_v and $\sim 20\%$ for xd_v) are still large. The determined parton densities agree well with those parameterizations, which use the fixed-target data as the main constraining source, except for xu_v at $x = 0.65$, where the former is about $\sim 17\%$ lower than the latter with little dependence on Q^2 in the covered kinematic range. The difference (less than two standard deviations) remains however not very significant.

Similar results [33] from ZEUS based on an NLO QCD fit using ZEUS data only are shown in figure 9. In comparison with the global QCD fit which uses both the fixed-target data and the 1996-1997 e^+p ZEUS data, the ZEUS data prefer a larger xu_v for x around 0.2 and smaller xu_v at larger x. A shift towards large x is also observed in the xd_v distribution although the shift stays essentially within the uncertainty.

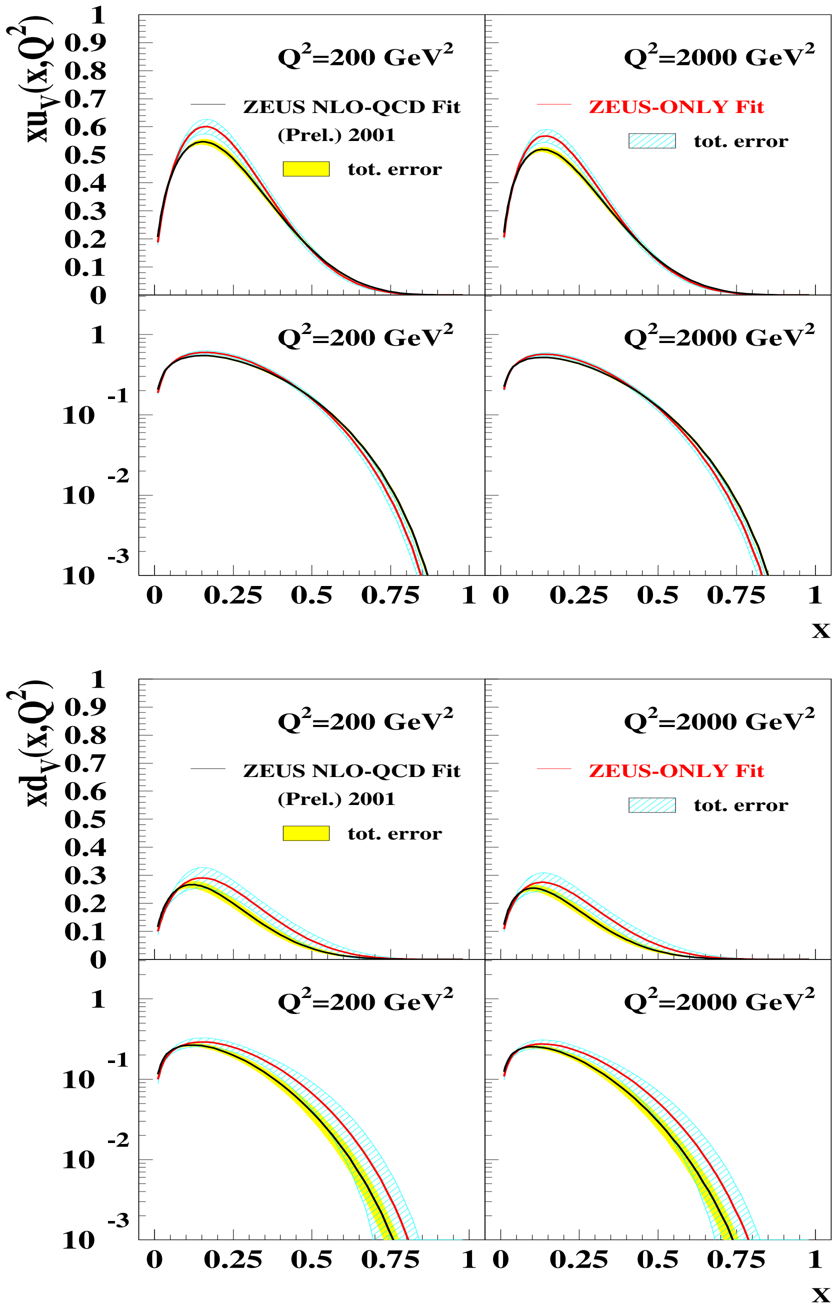

Figure 9. The valence quark densities xu_v (upper) and xd_v (lower) determined [33] for $Q^2 = 200\,\mathrm{GeV}^2$ and $2000\,\mathrm{GeV}^2$ in a fit with ZEUS data only in comparison with those determined in a global fit (ZEUS NOL-QCD Fit) [33] which uses both the fixed-target data and the 1996-1997 e^+p ZEUS data.

4. Summary and future prospects

The structure function and other measurements from fixed-target DIS and hadron-hadron collider experiments have provided us important inputs for constraining the parton density distributions. In the past few years there has been a renewed interest in the parton density distributions at large x, in particular the behavior of the d/u ratio when $x \to 1$. Considerable progress has been made towards understanding some of the uncertainties in the individual measurements that contribute to our knowledge of the large-x parton distributions. The current situation is that the large-x distributions are less well constrained than the medium-x ones and need additional inputs for improvements.

HERA has made steady progress since 1992. The early runs have provided unique structure function data for settling the behavior of parton (in particular the gluon) densities at small x. The high statistics samples taken in the recent years now allow the inclusive cross-sections be measured for both neutral and charged current interactions at high Q^2. These cross-sections have started to give quantitative constraints on the valence quark densities at large x. HERA is finishing its upgrade program. After the upgrade, the machine will provide about a factor of five increase in the peak luminosity and polarized lepton beams. The upgraded machine and the improved detectors will thus significantly improve in the next few years the measurement of the cross-sections and the knowledge of the parton densities at large x. These data are unique as they are free from any nuclear corrections inherent in the structure function data of the deuteron.

There are other possibilities by which the u and d valence quark densities at large x can be further constrained. One possibility [39] is to use semi-inclusive DIS data on hadron production in the current fragmentation region to measure the relative yields of π^+ and π^- mesons. The idea is fairly simple: at large z (z being the fractional energy of the hadron), the u quark fragments primarily into a π^+, while a d fragments into a π^-, so that at large x and z one could have a direct measure of the d/u ratio, again free from the nuclear corrections when a proton target is used.

On the large-x gluon density, future improvements are expected from the direct photon data once the current discrepancies between the data and the predictions and among the data are resolved. The improved Tevatron jet data at Run II should also help. A third possibility [40] is to use the Drell-Yan process in the phase space where the leading-order subprocess $qg \to \gamma^* q, \gamma^* \to \mu^+\mu^-$ dominates.

The uncertainties of the parton density distributions translate directly into uncertainties in essentially every measurement made at a hadron-hadron collider; it is therefore imperative that these distributions be well determined.

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