

Parton Distribution Functions: Impact of HERA

K. Nagano

On behalf of the H1 and ZEUS Collaborations
KEK, Tsukuba, Ibaraki 305-0081, Japan

Recent progresses of the proton structure measurements and determination of parton distribution functions by ep collisions at HERA are introduced.

1. INTRODUCTION

Deep inelastic scattering (DIS) of leptons off nucleons has been the key for our understanding of the structure of the nucleon. HERA at DESY is a unique facility for colliding electrons (or positrons) with protons. Compared with previous fixed-target DIS experiments, the large center-of-mass energy of about 320 GeV allows an extension of the explorable kinematic phase space by two orders of magnitude both in Q^2 , the negative of the four-momentum transfer squared, and in the Bjorken scaling variable x . The maximum Q^2 reaches almost 10^5 GeV², which corresponds to a spatial resolution of 10^{-16} cm. The minimum x , which means the momentum fraction carried by the struck parton ¹, reaches almost 10^{-5} . The cross section of the neutral-current (NC) DIS interaction, $e^\pm p \rightarrow e^\pm X$, can be written as

$$\frac{d^2\sigma(e^\pm p \rightarrow e^\pm X)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \{Y_+ F_2 \mp Y_- xF_3 - y^2 F_L\}, \quad (1)$$

where α is the fine structure constant, $Y_\pm = 1 \pm (1-y)^2$ with y being the inelasticity, and F_2 , xF_3 and F_L are the structure functions of the proton. In the framework of the perturbative QCD inspired quark parton model, the structure functions can be directly related to the parton distribution functions (PDFs) which are probability densities of partons existing inside proton. At low Q^2 , dominantly contributing to the cross section is F_2 which is an electric-charge squared weighted sum of all flavor quark PDFs. In the low- x region, F_2 is dominated by sea-quark PDFs, and the DGLAP evolution of QCD ascribes the Q^2 -dependence of F_2 (“scaling violation”) as largely owing to gluon splitting into $q\bar{q}$ -pairs. Thus, HERA data provide crucial information on the small- x sea-quark and gluon PDFs. At large Q^2 , xF_3 becomes significant, and gives information on valence quark PDFs. The structure function F_L is zero in the naive quark-parton model, i.e. without QCD, but in leading order QCD, a finite value of F_L is expected in the small x region by being directly related to the gluon PDF. The cross section of the charged-current (CC) DIS interaction, $e^+(e^-)p \rightarrow \bar{\nu}(\nu)X$, can be written as

$$\frac{d^2\sigma(e^+p)}{dx dQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2 + M_W^2)^2} [(\bar{u} + \bar{c}) + (1-y)^2(d+s)], \quad (2)$$

$$\frac{d^2\sigma(e^-p)}{dx dQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2 + M_W^2)^2} [(u+c) + (1-y)^2(\bar{d} + \bar{s})], \quad (3)$$

thus bringing flavor sensitivity of the valence quark PDFs at large x .

Based on about 100 (20) pb⁻¹ of e^+p (e^-p) data collected until the year 2000 (HERA-I), both the H1 and ZEUS experiments at HERA have measured the inclusive $e^\pm p$ NC and CC DIS cross sections [1–10]. After the year 2000, HERA underwent a major upgrade (HERA-II) aiming for higher luminosity ², and until March 2007, HERA provided

¹In the proton’s infinite momentum frame.

²The other aim of HERA-II is to provide collisions with longitudinally polarized e^\pm beams, giving a direct sensitivity to the helicity structure of the Electro-Weak interaction.

about 500 pb^{-1} of $e^\pm p$ collisions to each H1 and ZEUS experiments. The increased statistics provides more sensitivity to the PDFs at large x and large Q^2 , in regions where the precisions of the HERA-I measurements are still statistically limited. In addition, the precision of the structure function measurements by tagging heavy-quarks in the final state can be significantly improved by making use of the increased statistics of HERA-II and also increased capability of heavy-quark identification with newly installed tracking devices. During March to June in the year 2007, HERA made a series of dedicated runs with reduced proton beam energies of 460 and 575 GeV as compared to the nominal one of 920 GeV. These data sets are essential in the first direct measurement of F_L , as will be discussed later. Although HERA ended its 15 years spanning operation history in June 2007, analyses using full data sets are lively ongoing, and significant progresses are being made. In this manuscript, recent results from HERA are presented, and their impacts are discussed.

2. H1 AND ZEUS COMBINED ANALYSIS

2.1. Combined cross sections

PDFs are usually determined in global QCD analyses of DIS data, both from HERA and fixed-target experiments as well as jet production data from the TEVATRON [11, 12]. Given that high- Q^2 HERA data which are sensitive to large x PDFs are now available, H1 and ZEUS used their own data alone to make PDF fits (called H1 PDF 2000 and ZEUS-JETS fits, respectively) [13, 14]. Statistical uncertainties of these data are very small at low Q^2 such that total uncertainties are dominated by systematic uncertainties, and data points are correlated through common systematic uncertainties, both within and across the data sets. Thus, consideration of point-to-point correlations between systematic uncertainties was essential. In fact, this issue is faced by all of such QCD analyses; there are basically two methods, the Hessian and Offset methods, but each method has its own advantages and shortcomings, and there is no agreed standard (see e.g. [15]). For example, in the Hessian method, each systematic error source is treated as an additional fit parameter which is optimized by the model provided by QCD. However, difficulties arise when there are inconsistencies between data sets, leading to shifts of systematic error parameters by far more than one standard deviation ³.

These drawbacks can be significantly reduced by averaging the data sets in a model-independent way prior to performing a QCD analysis on them. Recently, the H1 and ZEUS experiments have made a combined analysis on their data in order to obtain such averaged data sets [16]. Almost all inclusive DIS cross section measurements with HERA-I data, including low Q^2 NC as well as high Q^2 NC and CC, are combined [1–10]. Since both sets of cross section data from H1 and ZEUS measure the same true cross-sections, the combination procedure is a χ^2 -minimization in which the parameters are the true values of the cross-section at each (x, Q^2) point and the correlated systematic error parameters. These parameters are thus determined in a model independent way using the Hessian method [17]. This combination procedure cross-calibrates the measurements, such that the overall uncertainty is reduced by much more than the simple average. In total, 1153 individual NC and CC measurements are averaged to 554 unique points, and 43 sources of correlated systematic uncertainty parameters are fitted. This yields a good quality of fit with the $\chi^2/dof=510/599$. In the small Q^2 region of $Q^2 < 12 \text{ GeV}^2$ the combined data set has precision much better than 2%, whereas H1 and ZEUS data each have a precision of $\sim 3 \%$. Figure 1 illustrates the H1 and ZEUS combined cross sections for three selected x bins as a function of Q^2 . The H1 (open circles) and ZEUS data (open squared) are compared to the H1 and ZEUS combined data (closed points). Measurements from the individual experiments have been displaced sideways for clarity. The error bars show the total uncertainty. At low Q^2 where the data are limited by systematic uncertainties, improvement in the total error is impressive. At higher Q^2 the combined data exhibit far smaller fluctuations as compared to individual data due to the increased statistical accuracy.

³Some global QCD analyses thus use non-statistical criteria to estimate the PDF uncertainties ($\delta\chi^2 = T^2 \gg 1$).

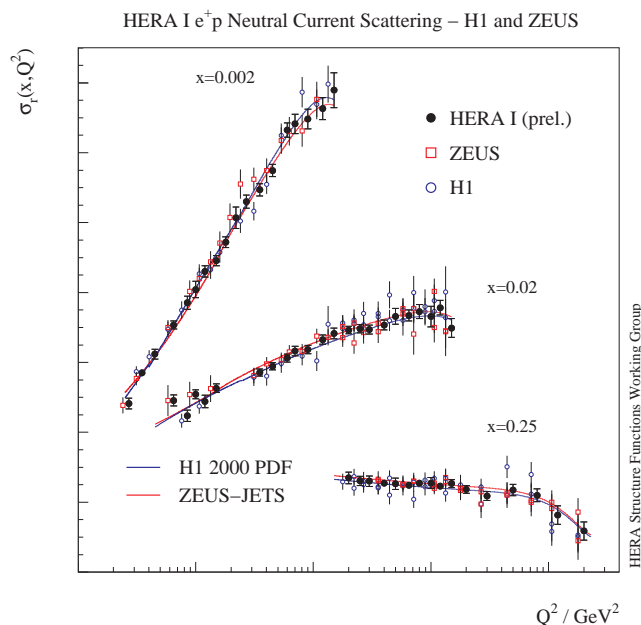


Figure 1: H1 and ZEUS combined cross sections for three selected x bins as a function Q^2 , together with the H1 PDF 2000 and ZEUS-JETS predictions.

2.2. Combined PDF: HERAPDF

A next-to-leading order (NLO) QCD analysis was performed using the combined HERA-I data set of $e^\pm p$ NC and CC cross sections presented in the previous subsection as the sole input (called HERAPDF0.1) [18]. The PDFs are parameterized at $Q_0^2 = 4 \text{ GeV}^2$ with 11 free parameters. The constraints of the number sum-rules and the momentum sum rule are applied. All the data have values of the invariant mass of the hadronic system, $W^2 > 300 \text{ GeV}^2$ and of $x < 0.65$ such that there is no need to account for target mass corrections or higher twist effects. Also, a cut of $Q^2 > 3.5 \text{ GeV}^2$ is applied to avoid non perturbative effects. As the correlated systematic uncertainties are no longer crucial in the HERA-I combined data sets, different handling of systematic uncertainties resulted in similar fit results. For the central fit, the 43 systematic uncertainties from the individual H1 and ZEUS data sets are quadratically combined to the statistical uncertainties, and the 4 sources of uncertainty from the combination procedure is treated with the Offset method. The χ^2 per degree of freedom of the fit was 477/562.

Figure 2 shows the combined HERA-I cross sections together with the HERAPDF0.1 fit results. The fit gives a good description both to NC and CC cross sections, and both for e^\pm collisions. Figure 3 shows the HERAPDF0.1 at $Q^2=10 \text{ GeV}^2$ (right plot). Plotted together in the left plot are the H1 2000 PDF and ZEUS-JET PDFs, i.e. obtained by H1 and ZEUS fitting to their own data. They have rather different shapes, and the size of the uncertainties are compatible to those of the global PDF analyses. This clearly shows that HERAPDF0.1 has a much better determination benefiting from the high precision of the combined data sets in which inconsistencies between the two data sets are resolved by the cross calibration. It is worth noting that the large amount of HERA-II data are not yet included in the combined data sets, and thus further improvements are foreseen for valence quark PDFs at large x , in particular for the d -quark PDF which will be determined from e^+p CC data. Figure 4 presents the HERAPDF0.1 at large Q^2 of 10000 GeV^2 compared to one of the global PDF analyses (CTEQ 6.5 [12] is chosen here), showing that the improvement in precision of PDFs holds until large Q^2 . The HERAPDF0.1 has a significant impact on the precision of the predictions for Standard Model processes such as W and Z production at LHC [19]. This due to the improved precision of the sea and the gluon PDFs at $Q^2 \sim 10000 \text{ GeV}^2$ and $5 \times 10^{-4} < x < 5 \times 10^{-2}$. In fact, it has been shown that the precision of the predicted cross-sections at LHC is less than 2% in the mid-rapidity range for HERAPDF0.1 PDFs as compared to 15% for pre-HERA PDFs [20].

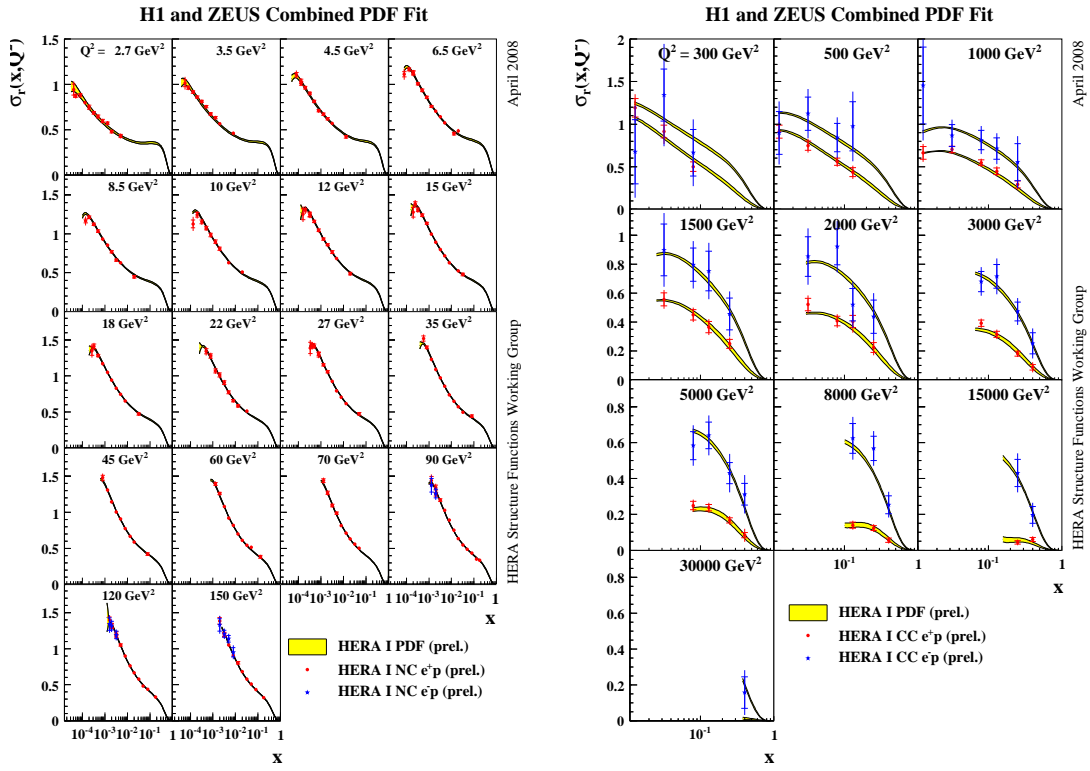


Figure 2: Combined HERA-I $e^\pm p$ NC (left) and CC (right) cross sections, together with the fit results of HERAPDF0.1.

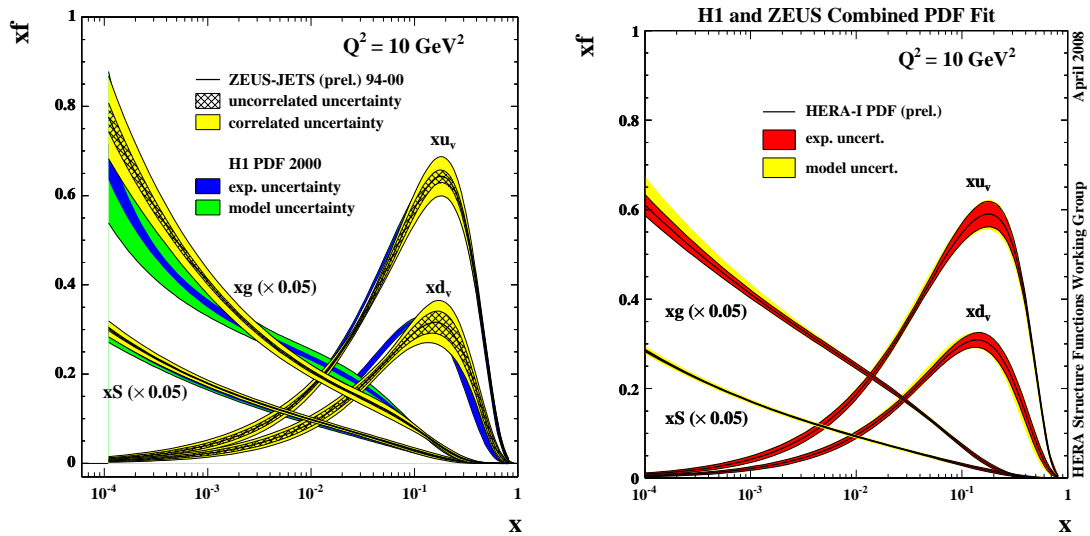


Figure 3: H1 PDF 2000 and ZEUS-JETS PDFs (left) and HERAPDF0.1 PDFs (right) at $Q^2 = 10 \text{ GeV}^2$.

3. DIRECT MEASUREMENT OF F_L

Despite of the remarkable success of QCD as seen in previous sections, there are still several issues to be clarified. For example, validity of the DGLAP formalism should be confirmed more explicitly at small x . This is because the DGLAP equation is a leading log re-summation of $\ln Q^2$ terms, and thus it cannot be expected to work at small x where large $\ln(1/x)$ terms will emerge. Notice also that the gluon PDF is extracted 'indirectly' through the Q^2 -dependence of inclusive cross sections, and thus should be further extensively verified with other processes which

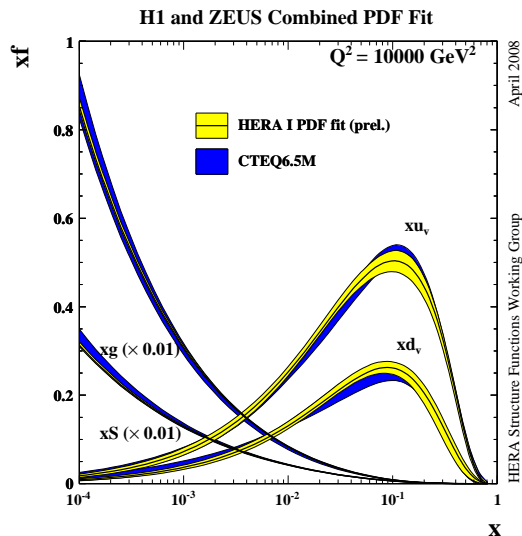


Figure 4: HERAPDF0.1 at $Q^2 = 10000 \text{ GeV}^2$ compared to CTEQ6.5 PDF.

have more direct sensitivity. In both of these senses, a measurement of F_L is of importance. As F_L is zero in a static view of proton, it is related to the dynamical picture of the proton. Therefore, F_L is in particular interesting at small x , and only HERA can perform such measurement. In the DGLAP formalism F_L is related to the gluon PDF at small x , thus giving a confirmation of indirectly determined gluon PDF in QCD analyses.

The structure function F_L can be extracted from sets of cross sections measured with different center-of-mass energies, s , as follows: if we present cross sections in a reduced form σ_r , defined as

$$\sigma_r \equiv \frac{d^2\sigma}{dx dQ^2} \frac{xQ^4}{2\pi\alpha^2 Y_+} = F_2 - \frac{y^2}{Y_+} F_L, \quad (4)$$

F_L can be extracted from measurements of σ_r , made at various s , from the slope of σ_r with y^2/Y_+ ⁴. Note that for measurements at fixed (x, Q^2) variation of y requires variation of s , since $Q^2 = xys$. The precision of the extracted F_L is dominated by the size of the 'lever arm' spanned in the axis of y^2/Y_+ , and thus, extending the measurement up to y as high as possible is crucial. At low Q^2 , high y values correspond to low values of the scattered electron energy. As small energy depositions can also be caused by hadronic final state particles and hence fake electrons, there are large backgrounds expected at high y dominantly due to photoproduction processes at $Q^2 \approx 0 \text{ GeV}^2$. In HERA-II, H1 and ZEUS has developed new measurement techniques optimized for large y . These were then validated with nominal beam energy data [21, 22] before starting the dedicated runs with reduced proton energies. In the H1 analysis, photoproduction backgrounds are statistically subtracted by using the sample in which wrong sign of charge is reconstructed for the track linked to the electron candidates measured in calorimeter. A small correction to charge asymmetry in backgrounds was obtained from comparisons of samples of negative tracks in e^+p scattering with samples of positive tracks in e^-p scattering. In the ZEUS analysis, a part of the photoproduction backgrounds are tagged by using a special detector located close to the beampipe, and are used to understand and normalize the background MC samples. These experimental techniques are used in the analyses of special runs with reduced proton beam energies, i.e. in the F_L measurements. H1 has measured F_L in middle to high Q^2 region, $12 < Q^2 < 800 \text{ GeV}^2$ [23, 24]. Figure 5 shows the reduced cross section measured with the three different proton beam energies, plotted as function of y^2/Y_+ . The data clearly shows a finite value of slope, hence F_L . Figure 6 shows the extracted F_L as a function of x in various Q^2 bins. The result is consistent with the prediction obtained

⁴Contribution from xF_3 can be neglected at small Q^2 .

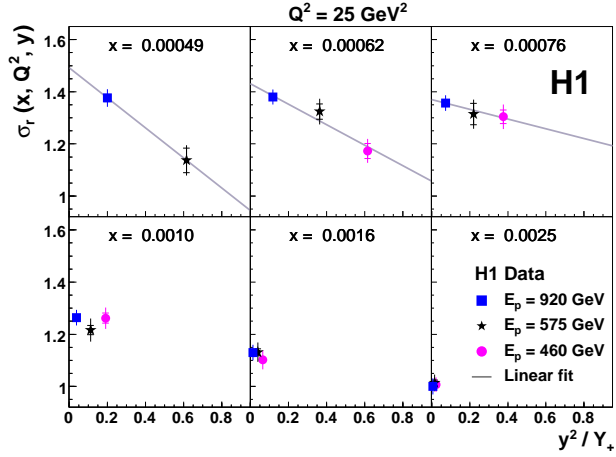


Figure 5: Reduced cross section σ_r at $Q^2 = 25 \text{ GeV}^2$ as a function of y^2/Y_+ , as measured by H1.

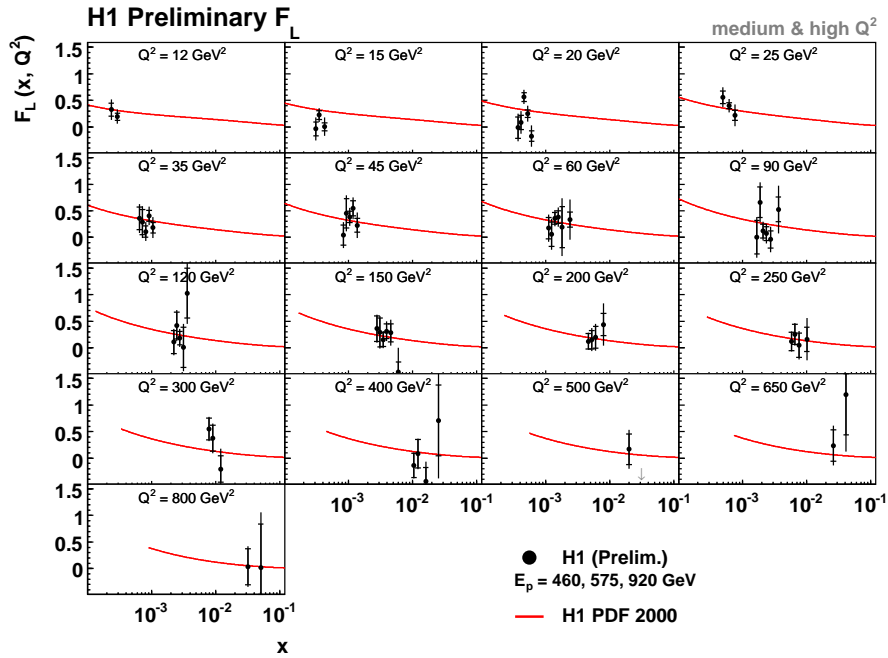


Figure 6: F_L as a function of x at various Q^2 , as measured by H1.

with the H1 PDF 2000 fit. The values on F_L resulting from averages over x at fixed Q^2 are shown in Figure 7. Within the experimental uncertainties, the data are consistent with the QCD predictions, indicating the applicability of the DGLAP formalism at small x at HERA. While, Figure 8 shows the F_L as measured by ZEUS [25]. The measurement is consistent with the ZEUS-JETS prediction of F_L , i.e. a QCD prediction, but also with $F_L = 0$, within the current precision of the measurement.

4. HEAVY QUARK CONTRIBUTION TO F_2

In leading order of QCD, the heavy flavor production in ep collisions is dominated by the photon gluon fusion process (BGF), $\gamma g \rightarrow Q\bar{Q}$. Hence, it is sensitive to the gluon PDF and allows tests of the universality of the gluon PDF. The heavy quark contribution to F_2 , $F_2^{Q\bar{Q}}$, can be obtained by extrapolating the visible measured cross section

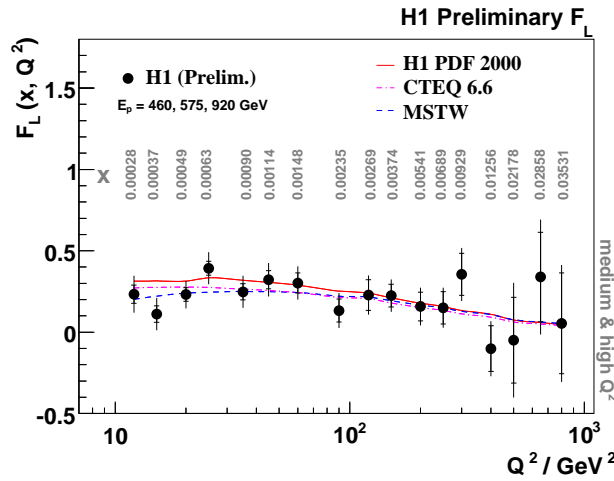


Figure 7: F_L as a function of Q^2 at given values of x , compared with QCD predictions.

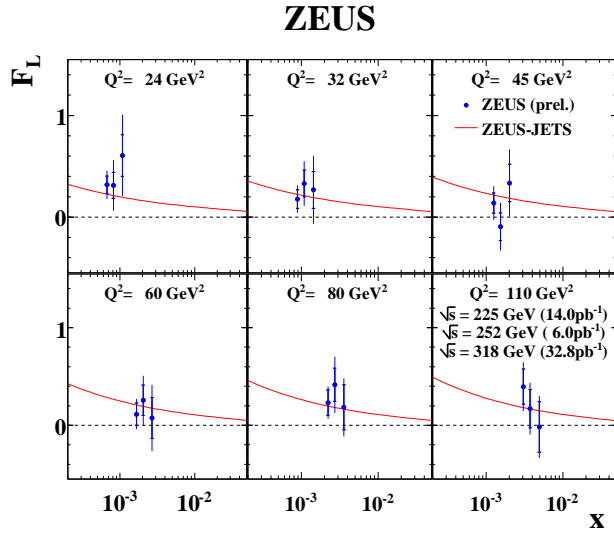


Figure 8: F_L as a function of x at various Q^2 , as measured by ZEUS.

of heavy quark production to the full phase space using NLO QCD calculations.

Figure 9 shows the charm contribution to F_2 , $F_2^{c\bar{c}}$, as measured by H1 and ZEUS [26–34]. By using about 160 pb^{-1} of luminosity of HERA-II data, ZEUS has measured the $D^{*\pm}$ meson production cross section by tagging it with slow π [26]. Production of D^\pm and D^0 mesons have also been measured making use of the capability of secondary vertex identification of the Micro Vertex Detector (MVD) which was installed at HERA-II [27]. A signed 2-dimensional decay length significance with respect to the beamspot measured in MVD gives a significant improvement in the signal to noise ratio, and thus in the statistical uncertainty of the measured cross section. These analyses are based on HERA-II data of about 130 pb^{-1} of luminosity. The results are plotted in the left plot of Figure 9, together with previous measurements by using HERA-I data, i.e. without the advantage of the MVD [28]. H1 has measured $D^{*\pm}$ meson production [29], as well as the inclusive charm and beauty production [30] cross sections, based on HERA-II data of about 350 and 190 pb^{-1} of luminosities, respectively. In the inclusive analysis, the charm and beauty fractions are determined using a neural network which includes the impact parameter of tracks to the primary vertex and the position of the secondary vertex as measured using the Vertex Detector (VTX). These results are also shown in the left plot of Figure 9, compared to previous measurements using HERA-I data set [31–33]. The $F_2^{c\bar{c}}$ measurement using the VTX gives a consistent result with that measured using the technique of tagging $D^{*\pm}$ meson, thus providing

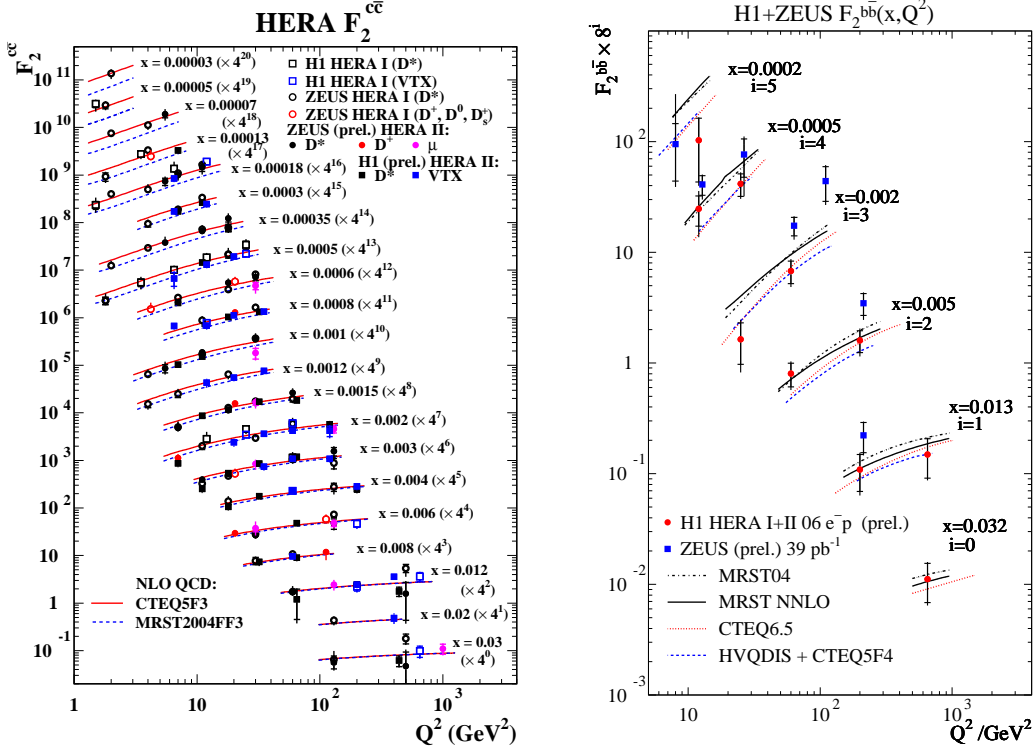


Figure 9: Heavy quark contribution to the structure function F_2 : charm contribution $F_2^{c\bar{c}}$ (left) and bottom contribution $F_2^{b\bar{b}}$ (right).

a proof of the VTX analysis.

In the right plot of Figure 9 shown is the bottom-quark contribution to F_2 , $F_2^{b\bar{b}}$, as measured by H1 in the inclusive analysis using VTX [30, 32, 33]. Also plotted is the ZEUS measurement tagging bottom quarks by requiring muon associated with jet, based on HERA-II data sample of about 40 pb⁻¹ [34]. In these $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ measurements, it is shown that a significant fraction of F_2 is owed by heavy quarks, about 30% by charm and about 3% by bottom, increasing with Q^2 . Precision of determining heavy-quark PDFs will be further improved by the analyses with full HERA-II data.

5. MEASUREMENT OF xF_3

The difference of cross sections between e^+p and e^-p collision data determines xF_3 as seen in Eq. 1. At HERA, xF_3 is, to a very good approximation, dominated only by the γ - Z interference term, $xF_3^{\gamma Z}$, as

$$\sigma_r(e^-) - \sigma_r(e^+) = -2 \frac{Y_-}{Y_+} a_e k_Z x F_3^{\gamma Z}, \quad (5)$$

where σ_r is the reduced cross section defined in Section 3, $k_Z = \frac{1}{4 \sin^2 \theta_W \cos^2 \theta_W} \frac{Q^2}{Q^2 + M_Z^2}$ with M_Z being the mass of Z boson and θ_W being the Weinberg angle, and $a_e = -1/2$ is the axial-vector coupling of electron to the Z boson. In leading order QCD, $xF_3^{\gamma Z}$ can be written as

$$xF_3^{\gamma Z} = 2x[e_u a_u u_V + e_d a_d d_V], \quad (6)$$

with an assumption that $\Delta_u = (u_{sea} - \bar{u} + c - \bar{c})$ and $\Delta_d = (d_{sea} - \bar{d} + s - \bar{s})$ are zero, where e_u and a_u are the charge and axial-vector couplings to the Z of the u -quark, and e_d and a_d are the corresponding quantities for the d -quark.

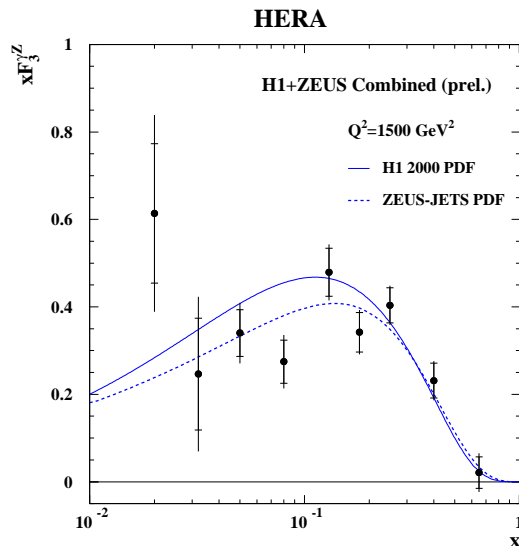


Figure 10: The γ -Z interference term of the structure function xF_3 , $xF_3^{\gamma Z}$.

A sum rule holds in leading order as

$$\int_0^1 xF_3^{\gamma Z} \frac{dx}{x} = \frac{1}{3} \int_0^1 (2u_V + d_V) dx = \frac{5}{3}. \quad (7)$$

The structure function $xF_3^{\gamma Z}$ is thus determined by the valence quark PDFs and predicted to be only very weakly depending on Q^2 .

Figure 10 shows the $xF_3^{\gamma Z}$ measured by using both H1 and ZEUS high Q^2 NC cross sections from HERA-I and HERA-II [35]. The measurement is well described by the H1 2000 PDF and ZEUS-JETS fits. The small difference between the H1 and ZEUS fits indicates weak constraints on the behavior of the valence quark PDFs at smaller x . In the range of acceptance, the integral of $F_3^{\gamma Z}$ is measured to be

$$\int_{0.02}^{0.65} F_3^{\gamma Z} = 1.21 \pm 0.09(stat) \pm 0.08(syst), \quad (8)$$

which is consistent with the results of the H1 and ZEUS QCD fits, 1.12 ± 0.02 and 1.06 ± 0.02 , respectively.

6. SUMMARY

HERA has provided the most precise inclusive structure function measurements, which has brought significant improvements to our knowledge on proton structure. For further comprehensive understanding, analyses with new techniques and with the full amount of data are being performed, and new high precision results are being produced. Final publications with ultimate precision will come in the next years.

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