

# LOW $Q^2$ STRUCTURE FUNCTIONS INCLUDING THE LONGITUDINAL STRUCTURE FUNCTION

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ON BEHALF OF THE H1 AND ZEUS COLLABORATIONS

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An NLO QCD analysis on the HERA combined cross sections obtained from the measurements using the data up to the year 2000 at both the H1 and ZEUS collaborations provides significantly improved parton distribution functions. In 2007, HERA successfully operated with reduced center-of-mass energies. Direct measurements of  $F_L$  were performed at  $x \sim 10^{-3}$ , giving a good test of the perturbative QCD framework in describing proton structure.

## 1 Introduction

The world's only  $ep$  collider, HERA, successfully operated from 1992 until 2007, and has played a crucial role in our understanding of the proton structure. Precise measurements of the cross section of Deep Inelastic Scattering (DIS) were performed at HERA by both the H1 and ZEUS collaborations. The results revealed that the proton structure can be successfully described by perturbative QCD (pQCD). The parton distribution functions (PDFs) of the proton were well determined mainly based on HERA data. However, further more precise understanding of the proton structure is important, for example to describe proton-proton collisions at the LHC. In this contribution, the HERAPDF0.1 PDFs, which are the PDFs significantly improved by using the HERA combined cross sections<sup>1</sup>, and the direct measurements of the longitudinal structure function are presented.

## 2 DIS and the proton structure

The kinematics of lepton-proton DIS are described in terms of  $x$ , the Bjorken scaling variable,  $Q^2$ , the virtuality of the exchanged boson, and  $y$ , the fractional energy transfer from the lepton to the hadron system in the proton rest frame. Only two of them are independent at given centre-of-mass energy,  $\sqrt{s}$ , due to the relation of  $Q^2 = sxy$ .

The inclusive neutral current (NC) cross section of DIS,  $ep \rightarrow e'X$ , which proceeds via  $\gamma^*/Z$  exchange, can be written using the structure functions,  $F_2$ ,  $F_L$  and  $xF_3$ , as

$$\frac{d^2\sigma(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ \left[ F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \mp \frac{Y_-}{Y_+} xF_3(x, Q^2) \right], \quad (1)$$

where  $Y_\pm = 1 \pm (1 - y^2)$ . The structure functions reflect the momentum distribution of partons in the proton. They are used to determine the PDFs using the relations:

$$F_2 = \sum_i A_i [xq_i + x\bar{q}_i], \quad xF_3 = \sum_i B_i [xq_i - x\bar{q}_i], \quad (2)$$

where  $A_i$  and  $B_i$  include quark couplings to the virtual bosons. The  $Q^2$  dependence of  $F_2$  is indirectly sensitive to the gluon density. The longitudinal structure function,  $F_L$ , which is described later in this contribution, is directly sensitive to the gluon density but contributes to the cross section sizably only at high  $y$ .

The charged current (CC) DIS,  $ep \rightarrow \nu X$ , proceeds via  $W^\pm$  exchange and is a charge-selective process. The  $e^+p$  and  $e^-p$  cross sections are sensitive to the negatively- and positively-charged quark distributions, respectively.

### 3 HERA PDFs

Both the H1 and ZEUS collaborations determined the PDFs using their own measured cross sections by NLO QCD analyses<sup>2,3</sup>. Aiming for the most precise understanding of the proton structure, the collaborations are working on a combination of the results to make full use of the collected data.

The inclusive DIS cross sections were combined<sup>1</sup> with the only assumption being that both collaborations measure the true, hence, the same cross sections. The combining procedure takes full account of systematic correlations, leading to a significant reduction of systematic uncertainties. The combination was done for the low  $Q^2$  NC cross sections from the data collected during 1996-1997 and the high  $Q^2$  NC and CC cross sections from the 1994-2000 data.

An NLO QCD analysis<sup>4</sup> was performed using these HERA combined cross sections as sole input and the PDFs were determined by a fit. The PDFs were parameterized at  $Q_0^2 = 4 \text{ GeV}^2$  for the valence quark,  $xu_v$  and  $xd_v$ , the gluon,  $xg$ , and the sea quarks,  $x\bar{U} = x(\bar{u} + \bar{c})$  and  $x\bar{D} = x(\bar{d} + \bar{s})$ , in the form of

$$xf_i(x) = A_i x^{B_i} (1-x)^{C_i} (1 + D_i x + E_i x^2 + F_i x^3), \quad (3)$$

where  $D_i$ ,  $E_i$  and  $F_i$  were different from zero only if this improved the  $\chi^2$  of the fit significantly. In this analysis,  $F_i$  was always zero and  $D_i$  and  $E_i$  were non zero only for  $u_v$ . Further constraints were applied and in total 11 free parameters describe the PDFs. They were evolved in  $Q^2$  by the DGLAP equation at NLO in the  $\overline{\text{MS}}$  scheme with the renormalization and factorization scales taken to be  $Q^2$ . Heavy quarks were treated in the zero-mass-variable-flavour-number scheme (ZMVFN) with  $m_c = 1.4 \text{ GeV}$  and  $m_b = 4.75 \text{ GeV}$ .

The systematic uncertainties of the combined cross sections are small enough so that they were added to the statistical ones in quadrature in the fit, except for 4 sources arising from the combination procedure. The effect of these 4 sources was evaluated by the offset method<sup>3</sup>.

The model uncertainties of the PDFs were also evaluated. This was done by varying several parameters such as the heavy quark masses, the fraction of the strange and charm quarks among the sea quarks, the minimum  $Q^2$  cut on the data to be included and  $Q_0^2$ . In addition, further cross checks were performed. The value of  $\alpha_s(M_Z)$  was varied for comparison. The dependence on the choice of the parameterization was investigated by performing the fit using the H1-style<sup>2</sup> and ZEUS-style<sup>3</sup> parameterizations.

The resulting fit is called the HERAPDF0.1 fit. The data is well fitted, as shown in Fig. 1, which also shows that the result of the fit describes the data from fixed target experiments well. The PDFs

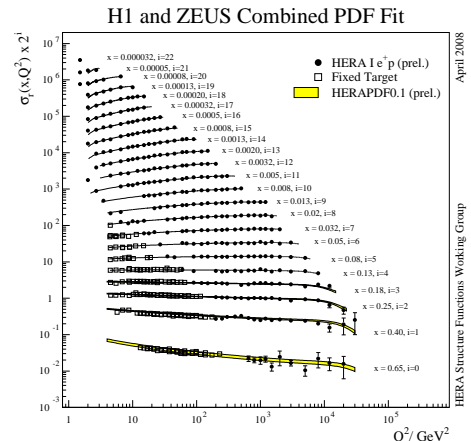


Figure 1: Measured  $F_2$  from HERA and fixed target experiments with the HERAPDF0.1 predictions.

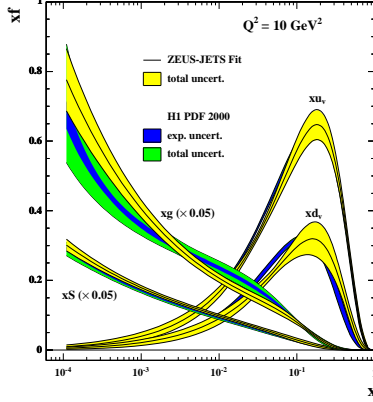


Figure 2: The gluon, sea and  $u$  and  $d$  valence distributions from the H1 PDF 2000 and ZEUS-JETS fits.

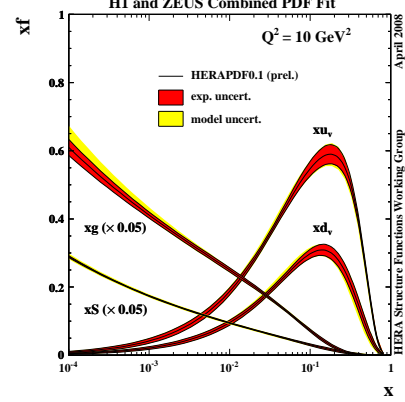


Figure 3: The gluon, sea and  $u$  and  $d$  valence distributions from the HERAPDF0.1 fit.

at  $Q^2 = 10 \text{ GeV}^2$  are shown in Fig. 3. The uncertainties of the PDFs are impressively reduced comparing to the previous determinations using data from a single experiment.

The H1 collaboration recently published a new  $F_2$  result<sup>5</sup> measured at  $12 < Q^2 < 150 \text{ GeV}^2$  for  $2 \cdot 10^{-4} < x < 0.1$  ( $y < 0.6$ ). This result was obtained from data collected during the years 1996-1997 and 2000. The accuracy of the measurement is excellent (1.5% to 2%) and will allow a further improvement of the PDF determination.

#### 4 $F_L$ measurement

The magnitude of  $F_L$  is proportional to the absorption cross section of the longitudinally polarized photons by the proton and  $F_L = 0$  if the proton is composed with co-linear spin  $\frac{1}{2}$  quarks only, as in the naïve QPM. However, gluon radiation in the proton gives non-zero values to  $F_L$ . Therefore,  $F_L$  directly reflects gluon dynamics in the proton. In the PDF determination within the pQCD framework, the gluon distribution is mainly determined from the  $Q^2$  dependence of  $F_2$ . Since its sensitivity to the gluon is different, the measurement of  $F_L$  is an important check for the current understanding of the proton structure in the pQCD framework.

The measured variable is the reduced cross section,  $\tilde{\sigma}$ , which is a combination of  $F_2$  and  $F_L$  at low  $Q^2$ ,

$$\tilde{\sigma} = \frac{Q^4 Y_+}{2\pi\alpha^2} \frac{d^2\sigma}{dx dQ^2} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2). \quad (4)$$

The direct separation of  $F_2$  and  $F_L$  requires  $\tilde{\sigma}$  measurements at the same  $(x, Q^2)$  but different  $y$ , which means measurements at multiple beam energies. For the last three months of running, HERA successfully operated with significantly lowered proton beam energies. It was the first opportunity to perform a direct  $F_L$  measurement in the low  $x$  region,  $x \sim 10^{-3}$ , where gluons are dominant in the proton. The measurement allows extraction of the structure functions without any QCD assumptions, whereas previous  $F_2$  measurements use QCD calculations to estimate the  $F_L$  contribution, as well as a consistency check of the pQCD framework for the proton structure.

Both the H1 and ZEUS collaborations collected data with  $\sqrt{s} = 318, 252$  and  $225 \text{ GeV}$ . As it can be seen from Eq. 4, in order to have a sizable  $F_L$  contribution, the cross section measurement has to be done in the high  $y$  region, where the energy of the scattered positron is small. Mis-identification of the scattered positron introduces a large contamination of background events. The H1 and ZEUS collaborations took different strategies for the estimation of the contamination. The H1 collaboration used the event distribution of the scattered positron candidates with wrong sign and ZEUS used Monte Carlo simulation, which was validated against photoproduction events identified with a dedicated electron tagger.

The DIS reduced cross sections were measured at each beam energy for  $12 < Q^2 < 90 \text{ GeV}^2$  and  $35 < Q^2 < 800 \text{ GeV}^2$  by H1<sup>6,7</sup> and  $24 < Q^2 < 110 \text{ GeV}^2$  by ZEUS<sup>8</sup>. The extraction of  $F_L$  was performed using these reduced cross section measurements. Figure 4 shows directly separated  $F_2$  and  $F_L$  by ZEUS. A non-zero  $F_L$ ,  $0 < F_L < F_2$ , is supported by the measurement. In the figure, the measurements are compared to the pQCD prediction based on the ZEUS-JETS PDFs<sup>3</sup>. The prediction is consistent with the measurement. Figures 5 and 6 show  $F_L$  and  $R = \frac{F_L}{F_2 - F_L}$  averaged in each  $Q^2$  bin at a given  $x$  from H1 and ZEUS, respectively. The measurements are compared to predictions using several PDFs and pQCD frameworks but are not sensitive to the differences between them. The measurements are consistent with all the predictions. An overall value of  $R$  was provided by ZEUS as  $R = 0.18^{+0.07}_{-0.05}$ .

## 5 Summary

Electron-proton scattering at HERA provides precise information on the structure of the proton. The HERAPDF0.1 PDFs, obtained using the combined cross sections of the H1 and ZEUS collaborations, have impressive precision, much improved with respect to the PDFs determined by the individual collaborations. The direct measurements of  $F_L$  were performed. For the first time,  $F_L$  was separated from  $F_2$  without any QCD assumption. A non-zero  $F_L$  is supported. The measurements are in good agreement with existing models.

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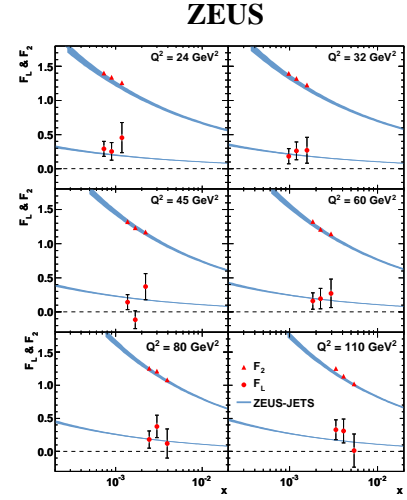


Figure 4:  $F_2$  and  $F_L$  measured by the ZEUS collaboration.

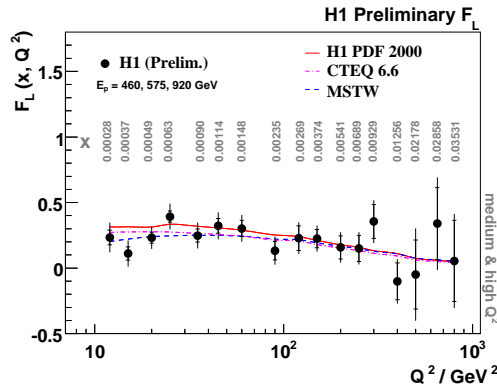


Figure 5: Averaged  $F_L$  measured by H1.

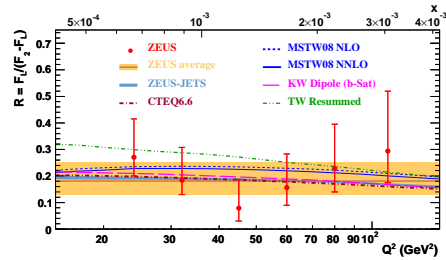


Figure 6:  $R = \frac{F_L}{F_2 - F_L}$  measured by ZEUS.