Measurement of DIS Cross Section at HERA

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This paper presents recent measurements of the inclusive DIS cross section performed by the H1 and ZEUS collaborations at the HERA collider. We discuss relations of the HERA results with the upcoming experiments at the LHC. Importance of the planed measurement of the longitudinal proton structure function $F_L$ is commented.

Keywords: Deep inelastic scattering

I. INTRODUCTION

Deep Inelastic Scattering (DIS) has played an important role in the understanding of the proton structure. The first results obtained at the SLAC electron beam in the 60s lead to the development of the parton model which later evolved into the modern description of the strong interactions via QCD. Further experimental data based on muon and neutrino beams allowed to extend the measurements to larger negative four momentum transfers $Q^2$ and smaller Bjorken-$x$ and also to unfold different quark flavor contributions to proton structure.

An important milestone for the proton structure measurements was the start of operation of the HERA collider located at DESY, Hamburg. HERA collides 920 GeV protons off 27.5 GeV electrons leading to a large center of mass energy of the collisions $\sqrt{s} \approx 320$ GeV. This large energy leads to a wide coverage in $Q^2$ and $x$, thus allowing detailed tests of the QCD evolution and of the QCD validity for the high parton density regime which was discovered at low $x$ at HERA.

While the parton dynamics and properties of the strong interactions are fascinating topics by themselves, the knowledge of the proton structure has an important auxiliary value for the studies of the physics beyond the standard model based on the future $pp$ collider. In particular, measurement of the Higgs boson production at LHC, for light Higgs boson masses, is determined by the proton structure for $x \sim 0.01$.

For low $x$, the gluon density at HERA is measured using scaling violation for the $F_2$ structure function. Alternatively, the gluon density can be determined using the longitudinal structure function $F_L$. $F_L$ allows for not only improved precision of the gluon density but also provides an important cross check of the standard QCD picture for low $x$ dynamics. A measurement of $F_L$ requires operation of the HERA collider at sufficiently different proton beam energies. A HERA run at a reduced proton beam energy dedicated for $F_L$ measurement is planned in 2007, for the last three months of the HERA operation.

II. STRUCTURE FUNCTIONS, PDFS, AND THE LHC

The unpolarized Neutral Current (NC) double differential DIS cross section can be expressed in terms of three structure functions:

$$\frac{d^2 \sigma^{NC}_{e^+p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^2} \left( F_2 - \frac{y^2}{Y_+} F_L \pm \frac{y}{Y_+} x F_3 \right)$$

where $\alpha = 1/137$ is the fine structure constant and $y$ is the inelasticity calculated as $y = Q^2/S x$ and $Y_\pm = 1 \pm (1-y)^2$.

The main source of information on the proton structure comes from the $F_2$ structure function. In the parton model $F_2$ is proportional to a singlet quark density, $F_2 = x \sum e_q^2(q+\bar{q})$. This relation holds to all orders in QCD for the so-called DIS scheme. The $F_2$ structure function has a leading contribution to the DIS cross section across the kinematic plane and thus can be most easily experimentally accessed. The other structure functions usually do not complicate an extraction of $F_2$ from the DIS cross section; for $y < 0.35$ the contribution of $F_1$ is negligible compared to the experimental uncertainties while $x F_3$ becomes significant only at higher $Q^2$.

The structure function $x F_3$ arises from $\gamma Z$ interference. At leading order QCD $x F_3$ is proportional to a non-singlet quark density, $x F_3 = x \sum e_q a_q (q-\bar{q})$, here $a_q$ are the axial couplings of the quarks to the $Z^0$ boson. The structure function $x F_3$ is significantly more difficult to measure experimentally than $F_2$. It can be accessed by measuring charge asymmetry of the DIS cross section for charged lepton beams at high $Q^2$ or by using neutrino beams.

The structure function $F_L$ vanishes in leading order QCD for spin 1/2 quarks. This property, known also as Callan-Gross relation, played an important role for establishing the nature of the partons. In Next-to-Leading Order (NLO) QCD $F_L$ acquires non zero value; for low $x$, $F_L$ is mostly determined by the gluon density $g(x)$. Measuring $F_L$ is a challenging experimental task. The structure function has a significant contribution to the cross section only at high inelasticity $y$, which corresponds to low scattered electron energy and thus is prone to large background. At high $y$, for a fixed center of mass energy, the measured DIS cross section can not be unambiguously decomposed into its $F_2$ and $F_L$ contributions. The decomposition can be achieved by comparing the cross section measured using different center of mass energies.

The proton parton distribution functions (PDF) are determined in QCD fits to the cross section data. To separate different quark flavors, Charged Current (CC) DIS cross section data and data on lepton scattering off the deuteron are used along with NC data for the proton.

The QCD factorization theorem states that the quark densities can be used universally for other proton scattering
TABLE 1: Kinematic coverage of the DIS and collider pp–p̅p̅ experiments. For pp and p–p̅ colliders, the Bjorken x1 and x2 of the interacting quarks are related to the mass M of the Drell-Yan pair and its rapidity y as x1,2 = M/\sqrt{S} \exp(±y) where S is the center of mass energy squared for the experiment.

III. SUMMARY OF RESULTS FROM THE HERA-I PERIOD

Most of the information on the proton structure function at low x comes so far from the data collected at HERA in 1992–2000 running period (HERA-I). Most of the structure function analyses for this data sample have been finalized, for example Fig. 2 shows a summary of the F2 structure function measurements by the H1 [2, 3] and ZEUS [4] collaborations at HERA and also by fixed target experiments BCDMS [5] and NMC [6].

The precision achieved for the F2 data in 0.0005–0.05 Bjorken-x range is about 2–3% which leads to about 5% PDF uncertainty on the W,Z production cross section at LHC\(^1\). To improve this precision, further analysis of low Q^2 < 100 GeV\(^2\) HERA-I data is in progress by the H1 collaboration. In addition, a better understanding of the systematic uncertainties is possible if H1 and ZEUS data are compared and combined in a common dataset in a model independent way. A procedure for this combination has been developed recently [7], the combination is now under study by the two collaborations.

IV. NEW RESULTS FROM HERA-II

During the shutdown in 2001–2002, HERA underwent an extensive upgrade aimed to increase the luminosity and also  
\(^1\) Two quarks are needed for W,Z production in a Drell-Yan process compared to one probed in DIS, therefore PDF uncertainties for Drell-Yan are generically twice larger than for DIS. For a rigorous study see [11].
provide longitudinal polarization for the electron beam using spin rotators. Since 2003 HERA resumed the operation and experiments started to collect new data (HERA-II period). Significant increase in the luminosity will eventually allow to improve the precision of the structure functions for high \( Q^2 > 1000 \text{ GeV}^2 \), corresponding data analyses have started but detailed studies of the systematic uncertainties will take more time before the data become ready for the publications. For now, the first new results are based on new features of the data, such as polarization and a significant increase of \( e^- \) sample.

Figure 3 shows the first results on the total CC cross section polarization dependence which are published or released as preliminary by the H1 and ZEUS collaborations. The absence in the SM of the right-handed CC interactions requires vanishing \( e^- p \) and \( e^+ p \) cross sections for the right and left handed polarized leptons, respectively. One can see that H1 and ZEUS data are consistent with each other and confirm the expectations of the SM. This measurement provides the first direct determination of the polarization dependence of the CC cross section in \( ep \) scattering.

In summer 2006 new results on the NC polarization dependence have become available. Neglecting the pure Z exchange term, for high \( Q^2 \) the structure function \( F_2 \) attains a correction from the \( \gamma Z \) interference:

\[
\Delta F_2 = \kappa (-v_x + P_a e) F_2^{Z^2},
\]

(2)

where \( \kappa = \frac{1}{4 \sin^2 \theta_W \cos^2 \theta_W} \frac{Q^2}{Q^2 + M_Z^2} \). \( v_x, a_e \) are vector and axial electron couplings to Z, \( P \) is the longitudinal beam polarization, \( \theta_W \) is the Weinberg angle and \( M_Z \) is the Z mass. At leading order

\[
F_2^{Z^2} = x \sum q \varepsilon q (q + \bar{q}),
\]

(3)

allows to study directly the NC cross section parity violation. One can see in Fig. 4 that the data do indeed prefer SM prediction with non-vanishing polarization dependence which is more clearly visible for the combined H1 and ZEUS measurement.

For the most of the HERA-I period, HERA was operating with positrons due to limitations of the electron beam lifetime. Only a small fraction of the luminosity was collected with the negatively charged electron beam. For HERA-II, the problem of the low electron beam lifetime has been solved. From the end of 2004 to summer of 2006 HERA operated with electron beams, allowing a large increase of the \( e^- p \) luminosity and thus a more precise measurement of the \( x F_3 \) structure function. This measurement for the H1, ZEUS collaborations and for the combination of the two is represented in Fig. 5.

The \( x F_3 \) structure function measures the valence quark density which is expected to vanish at low \( x \). This expectation is not a fundamental prediction of the SM but a rather most natural assumption for the behavior of the \( q - \bar{q} \) quark density difference. So far the data is consistent with this expec-
The decomposition of the singlet and gluon density at low $x$ plays an important role for predicting the Higgs to $W,Z$ bosons production cross section ratio at the LHC. $W$ and $Z$ production are singlet dominated processes, for them the dominant diagrams are similar to the $F_2$ structure function. On the contrary, Higgs production is dominated by gluon-gluon fusion.

The QCD evolution of the singlet and gluon densities is closely coupled together, yet the densities depend on the initial input values which are not so easy to disentangle experimentally. In particular, gluon density determined by the MRST collaboration [9] at low $Q^2$ and low $x$ differs drastically from the CTEQ [8] and Alekhin [10] determinations. For the predictions of the light Higgs production cross section, this leads to a spread of the central values between the three groups on the order of $5 - 7\%$, larger than the uncertainty associated with each individual prediction.

At low $x$ additional effects may become important which are not included in the standard QCD evolution. These effects may arise from large $1/x$ corrections, requiring additional resummation, or from a large gluon density leading to non-linear interaction effects. An excellent quality of the conventional QCD fits to the $F_2$ structure function may not exclude the presence of these additional contributions. Many small $x$ modifications may be “hidden” in the input parton densities at the starting scale. Since the small $x$ modifications can be different for different processes, the parton densities determined from the fits to $F_2$ may be valid for $F_2$-like (singlet) observable only. The non-universality of the parton densities would have a big impact on the light Higgs production cross section predictions.

The best way to obtain a more reliable decomposition of the gluon and singlet densities at low $Q^2$ and low $x$ as well as to verify the universality of the parton density functions is to measure the other independent structure function, the longitudinal structure function $F_L$. For the conventional QCD, recently NNNLO corrections have become available [12], making $F_L$ one of the cleanest observables from the theoretical point of view. The $F_L$ structure function acquires a non zero value only at NLO, it is more sensitive to the gluon compared to $F_2$. In this sense $F_L$ is closer to the Higgs production compared to $F_2$ which is closer to $W,Z$ production at LHC.

The DIS cross section is sensitive to the $F_L$ structure function only for high inelasticity values, $y > 0.5$, see Eq. 1. For this kinematic region, both $F_2$ and $F_L$ structure function contribute significantly to the DIS cross section, thus an additional constraint is required in order to separate the individual contributions.

V. LOW ENERGY RUN TO MEASURE $F_L$

The H1 collaboration performed a model dependent separation of $F_L$ based on data collected at HERA-I. In this deter-

![Graph](image_url)
mination, the $F_2$ structure function was determined for lower $Q^2$ selecting data at $y < 0.35$, and then evolved using the standard QCD evolution to higher $Q^2$ and thus higher $y$ values. Fixing the $F_2$ contribution to the conventional QCD prediction allowed the H1 collaboration to extract the $F_L$ structure function. This model dependent determination works better for higher $Q^2$ values, since in this case a larger evolution range is available for the determination of $F_L$. Fig. 6 shows this $F_L$ determination for $Q^2 > 100$ GeV$^2$ kinematic range. Good agreement between the determination and the QCD prediction provides an important consistency check in the $x$ range important for the LHC measurements. Higher statistics HERA-II data should allow to improve the precision of this measurement.

Lowering of the proton beam energy leads to a reduction of the luminosity as $\sim 1/E_p^2$. To increase sensitivity to $F_L$, a measurement at lowest possible beam energy is desired. A compromise between luminosity loss and the sensitivity is reached at about half the nominal proton beam energy, $E_p = 460$ GeV. Taking into account that currently both H1 and ZEUS experiments collect about 20 pb$^{-1}$ of data per month each, an about 3 month long low energy run is needed to obtain 10 pb$^{-1}$ of low energy data per experiment. This low energy run is foreseen to be performed in April-June 2007, at the end of the HERA operation.

A possible outcome of this low energy run is illustrated in Fig. 7 which shows a simulation of the $F_L$ structure function measurement. One can see that the precision of these data should be sufficient to distinguish between predictions based on MRST and CTEQ parton distribution functions, thus this measurement should allow to reduce uncertainties in the gluon density.

VI. SUMMARY AND OUTLOOK

HERA continues to provide a large amount of inclusive DIS data interesting for deeper understanding of the QCD and the Standard Model electroweak physics. The parton density functions determined based on these measurements will play an important role for the LHC.

HERA-II upgrades enriched the physics outcome of the experiments. Higher luminosity will eventually lead to a more precise determination of the proton structure functions also in the high $Q^2$ kinematic domain. The longitudinal polarization of the electron beam allows to study the polarization dependence of the charged current cross section, provides additional sensitivity to the vector quark couplings. A large $e^-$ sample improves the determination of the $xF_3$ structure function.

The HERA-II operation is scheduled to be stopped at the end of June-2007. Before that, a dedicated special low proton energy run is foreseen in order to measure the longitudinal structure function $F_L$. This measurement will allow a decompose the contributions of the $F_L$ and $F_2$ structure functions to the DIS cross section at low $Q^2$, it will provide an important cross check of the conventional QCD at low $x$ and will allow to improve the knowledge of the gluon density.

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