Measurement of DIS Cross Section at HERA

Sasha Glazov[1], for the H1 Collaboration
[1] Deutsches Electronen Synchrotron (DESY), Notkestrasse 85, Hamburg, Germany 22607

Received on 25 December, 2006, 2006; revised version received on 18 March, 2007

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:

$$\frac{d^2\sigma^{NC}_{e^{\mp}p}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L \pm \frac{Y_-}{Y_+}xF_3\right) \qquad (1)$$

where $\alpha = 1/137$ is the fine structure constant and y is the inelasticity calculated as $y = Q^2/Sx$ 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_L is negligible compared to the experimental uncertainties while xF_3 becomes significant only at higher Q^2.

The structure function xF_3 arises from γZ interference. At leading order QCD xF_3 is proportional to a non-singlet quark density, $xF_3 = x\sum 2e_q a_q(q-\bar{q})$, here a_q are the axial couplings of the quarks to the Z^0 boson. The structure function xF_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

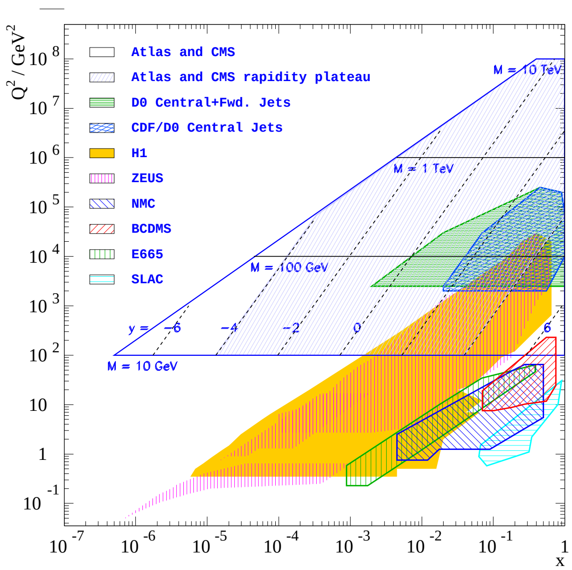

FIG. 1: Kinematic coverage of the DIS and collider pp-$p\bar{p}$ experiments. For pp and $p-\bar{p}$ colliders, the Bjorken x_1 and x_2 of the interacting quarks are related to the mass M of the Drell-Yan pair and its rapidity y as $x_{1,2} = M/\sqrt{S}\exp(\pm y)$ where S is the center of mass energy squared for the experiment.

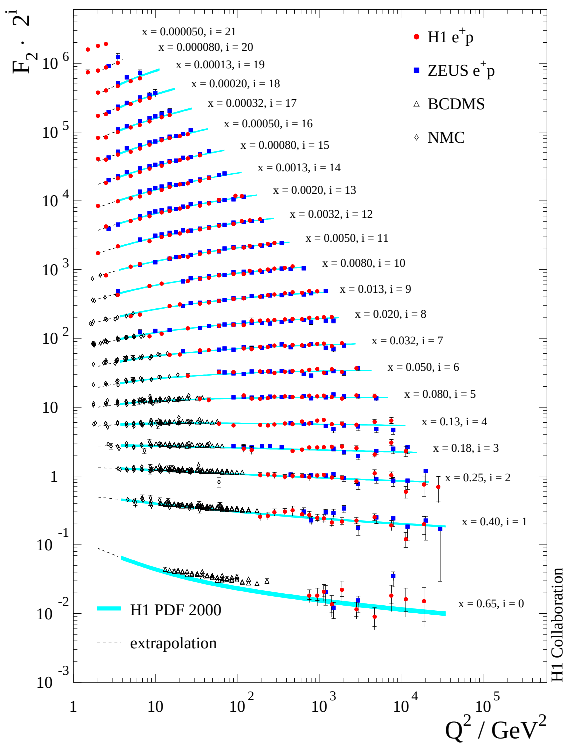

FIG. 2: Structure function F_2 as a function of Q^2 based on HERA-I measurements of H1 [2, 3] and ZEUS [4] collaboration compared to results from fixed target experiments BCDMS [5] and NMC [6].

processes such as Drell-Yan pair production. The QCD Q^2 evolution, now known to Next-to-Next-to-Leading Order (NNLO) [1], allows to calculate the parton densities for a given x for higher values of Q^2. Therefore, PDFs determined in DIS experiments can be used for precise predictions of the production cross sections at pp colliders, for example the LHC. Fig. 1 shows the kinematic coverage of the fixed target DIS experiments and HERA compared to $p\bar{p}$ and pp colliders, the Tevatron and LHC. While the LHC extends the range greatly towards low x for low Drell-Yan pair masses, for the W and Z bosons production ($M \sim 100$ GeV) and for the central rapidity range of the detectors ($|y| < 2.5$) the Bjorken-x range ($0.0005-0.05$) is fully covered by HERA. Furthermore, HERA covers completely the x range for a light Higgs boson ($M_h \sim 128$ GeV), which in the Standard Model is predominantly produced via gg fusion with the top quark in the loop. Measuring the ratio of the Higgs to Z production rate experimentally and using the HERA based predictions for the Z and Higgs rates, it is possible to place strict limits on certain scenarios of non-standard Higgs production.

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 F_2 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 F_2 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].

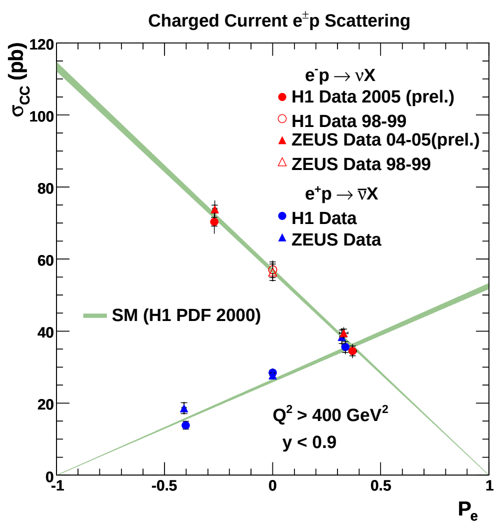

FIG. 3: Charged Current cross section as a function of the lepton beam longitudinal polarization.

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 $Q^2 > 1000$ 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 γZ interference:

$$\Delta F_2 = \kappa(-v_e \mp P a_e) F_2^{\gamma Z}, \qquad (2)$$

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

$$F_2^{\gamma Z} = x \sum 2 e_q v_q (q + \bar{q}), \qquad (3)$$

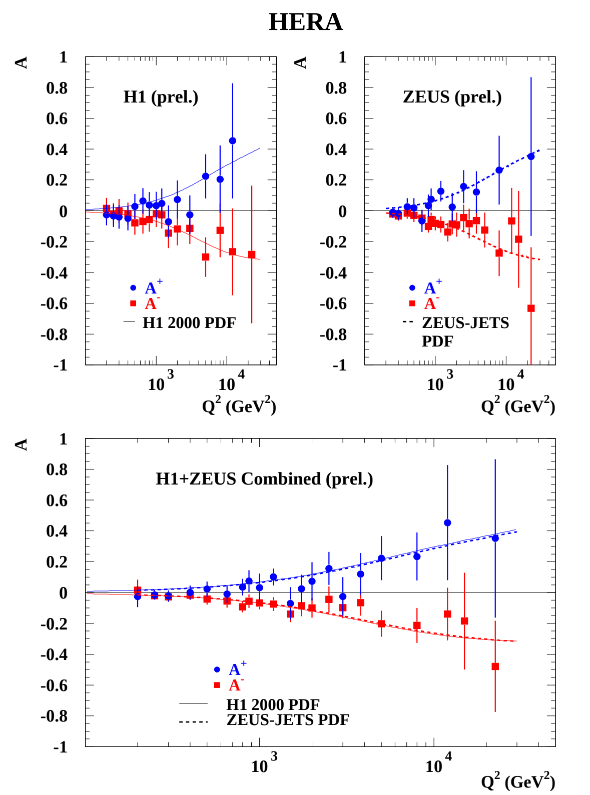

FIG. 4: Polarization dependence of the NC cross section as a function of Q^2, measured by H1 and ZEUS collaborations.

where v_q is the Z vector quark coupling. The measured polarization asymmetry, defined as

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \approx \mp \kappa a_e \frac{F_2^{\gamma Z}}{F_2}, \qquad (4)$$

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 life time. 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 life time 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 xF_3 structure function. This measurement for the H1, ZEUS collaborations and for the combination of the two is represented in Fig. 5.

The xF_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-

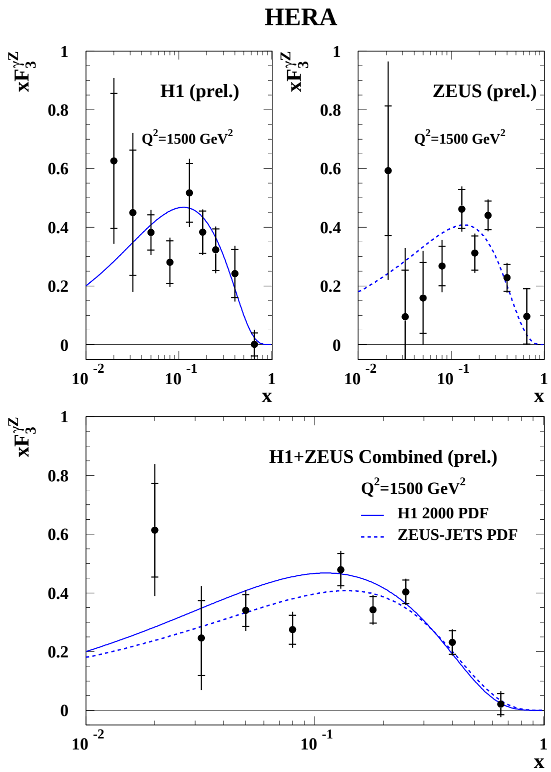

FIG. 5: $xF_3^{\gamma Z}$ structure function as measured by H1 and ZEUS collaborations.

tation. More precise and lower x data are needed for a better check, these data will become available after more detailed study of the systematic uncertainties in a lower Q^2 range. A non-vanishing asymmetry in $q-\bar{q}$ at low x would have important implications for W^+/W^- production at LHC.

V. LOW ENERGY RUN TO MEASURE F_L

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.

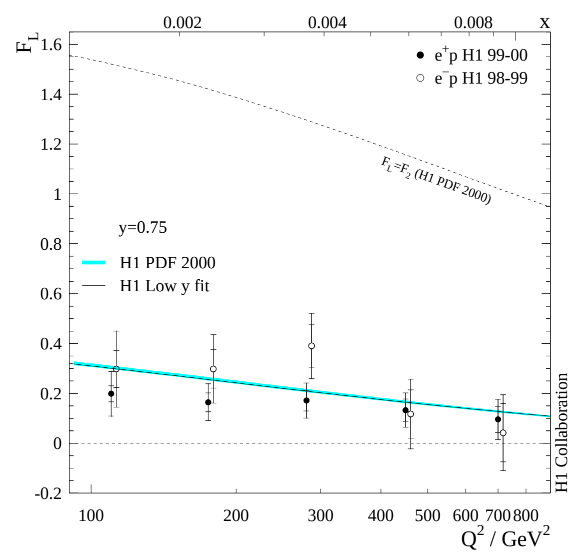

FIG. 6: Structure Function F_L determined in a model dependent way by the H1 collaboration based on e^-p (open circles) and e^+p (closed circles) data collected during HERA-I running period [3]

The H1 collaboration performed a model dependent separation of F_L based on data collected at HERA-I. In this determination, the F_2 structure function was determined for lower Q^2 selecting data at $y < 0.35$, and than 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_2. 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.

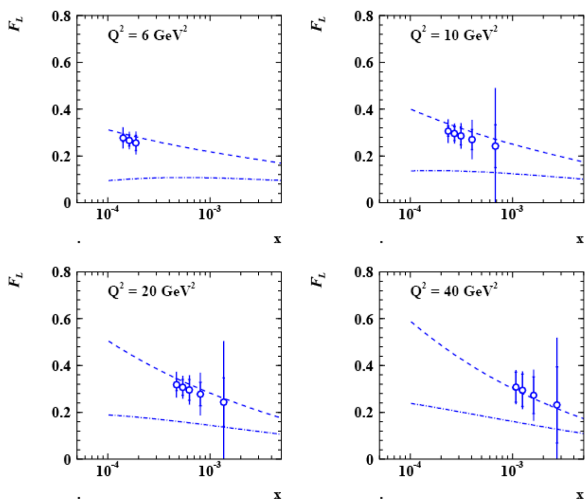

FIG. 7: Open circles: simulation of the F_L structure function measurement based on proposed low $E_p = 460$ GeV energy run. The dashed (dashed-dotted) lines represent predictions based on CTEQ [8] (MRST [9]) parton density functions.

A model independent separation of the F_2 and F_L structure functions is possible by measuring the DIS cross section at the same x, Q^2 values but different y. This can be achieved by lowering the center of mass energy for the experiment. For the maximal cancellation of the experimental uncertainties it is desirable to lower the proton beam energy, in this case the kinematics of the scattered electron is largely unmodified.

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.

[1] S. Moch, J.A.M. Vermaseren, and A. Vogt, Phys. Lett. B **606**, 123 (2005).
[2] C. Adolff *et al.*, Eur. Phys. J. C **21**, 33 (2001).
[3] C. Adolff *et al.*, Eur. Phys. J. C **30**, 1 (2003).
[4] S. Chekanov *et al.*, Phys. Rev. D **67**, 012007 (2003).
[5] A.C. Benvenuti *et al.*, Phys. Lett. B **223**, 485 (1989).
[6] M. Arneodo *et al.*, Nucl. Phys. B **483**, 3 (1997).
[7] A. Glazov, *DIS05, XIII International Workshop on Deep Inelastic Scattering*, Madison, Wisconsin, 2005.
[8] J. Pumplin *et al.*, JHEP **0207**, 12 (2002).
[9] A. D. Martin *et al.*, Eur. Phys. J. C **28**, 455 (2003)
[10] S. I. Alekhin, Phys. Rev. D **68**, 0149002 (2003).
[11] A. De Roeck and H. Jung (eds.), *HERA-LHC Workshop*, CERN-DESY (2005).
[12] J.A.M. Vermaseren, A. Vogt, and S. Moch, Nucl. Phys. B **724**, 3 (2005).