I. INTRODUCTION

Deep Inelastic Scattering (DIS) always played an important role for understanding of the proton structure. The first results obtained at the SLAC electron beam in the 60s lead to 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 perform quark flavor decomposition.

An important milestone for the proton structure measurements was the start of operation of the HERA collider located at DESY, Hamburg. HERA provides 920 GeV protons colliding with 27.5 GeV electrons leading to a large center of mass energy of the collisions \( \sqrt{S} \approx 330 \) 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 low \( x \) regime.

While the parton dynamics and properties of the strong interactions are fascinated topics by themself 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 low \( x \sim 0.01 \). For this kinematic range, the Higgs boson is produced predominantly via gluon-gluon fusion making precise measurement of the gluon density an extremely important task.

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 dedicated for \( F_L \) measurement HERA run at reduced proton beam energy is planned in 2007, for the last three months of the HERA operation.

II. STRUCTURE FUNCTIONS, PDFS, AND LHC

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

\[
\frac{d^2 \sigma^{NC}_{pp}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left( F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \right) \left( \frac{y}{Y_+} xF_3(x,Q^2) \right)
\]  

where \( \alpha = 1/137 \) is the fine structure constant and \( y \) is 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 weighted by electric charge singlet quark density, \( F_2 = x \sum q_i^2(x) \), the same relation holds to all orders in QCD for 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 don’t complicate extraction of \( F_2 \) from the DIS cross section; for \( y < 0.35 \) contribution of \( F_L \) is negligible and \( xF_3 \) becomes significant only at higher \( Q^2 \).

The structure function \( xF_3 \) arises from \( \gamma Z \) interference. At leading order QCD \( xF_3 \) is proportional to a non-singlet quark density, \( xF_3 = x \sum 2e_\alpha a_\alpha q(x) - \bar{q}(x) \), here \( a_\alpha \) is the axial cou-
The structure function $F_1$ 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 NLO QCD $F_1$ acquires non zero value; for low $x$ $F_1$ is mostly determined by the gluon density $g(x)$. Measuring $F_1$ 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 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 $F_1$ and $F_2$, structure function, 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 the 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 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 LHC. Figure 1 shows kinematic coverage of the fixed target DIS experiments and HERA compared to $pp$ colliders, Tevatron and LHC. While 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 is 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 productions.

### III. SUMMARY OF THE HERA RESULTS FROM 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 Figure 2 shows a summary of the $F_2$ structure function measurements by 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 [13]. To improve precision, further analysis of low $Q^2 < 100$ GeV$^2$ HERA-I data is in progress by 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 – 2003, HERA underwent an extensive upgrade aimed to increase the luminosity and also 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 precision of the structure functions for high $Q^2 > 1000$ GeV$^2$, corresponding data analyses have started but detail 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 significant increase of $e^-$ sample.

Figure 3 shows the first results on the total CC 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 of the $e^- p$ and $e^+ p$ cross section 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.

Last summer 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 $Z$ interference:

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

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, $\theta_W$ is the Weinberg angle and $M_Z$ is the Z mass. At the leading order

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

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

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

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

For the most of HERA-I period, HERA was operating with positrons which allowed to improve the lepton 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. During end of 2004 — middle of 2006 HERA operated with electron beams, allowing significant increase of $e^- p$ luminosity and thus more precise measurement of the $x F_2$ structure function. This measurement for the H1, ZEUS collaborations and for the combination of the two is represented in Figure 5.

The $x F_2$ structure function measures the valence quark density which is expected to vanish at low $x$. This expectation is not fundamental prediction of the SM but rather most natural assumption for the behavior of $q - \bar{q}$ quark density difference. So far the data is consistent with this expectation. 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.
Decomposition of the singlet and gluon densities are 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 MRST collaboration [9] at low $Q^2$ and low $x$ differs drastically with 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, not included in the standard QCD evolution effects may become important. These effects may arise from large $1/x$ corrections, requiring additional resummation, or from 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 presence of these additional contributions. Many small $x$ modifications maybe “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 better 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 observable from the theoretical point of view. The $F_L$ structure function acquires non zero value only at NLO, it is more sensitive to gluon compared to $F_2$. In this sense $F_L$ is more close to the Higgs production compared to $F_2$ being more close 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 Equation 1. For this kinematic region, both $F_2$ and $F_L$ structure function contribute to the DIS cross section, an additional constraint is required in order to separate the individual contributions.

![FIG. 5: $xF_3^L$ structure function as measured by H1 and ZEUS collaborations.](image)

![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].](image)
important consistency check in the $x$ range important for the LHC measurements. Higher statistics HERA-II data should allow to improve precision of this measurement.

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 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.

A possible outcome of this low energy run is illustrated in Figure 7 which shows 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 the 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 future $pp$ colliders.

HERA-II upgrades enriched the physics outcome of the experiments. Higher luminosity will eventually lead to more precise determination of the proton structure functions for 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 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 complete decomposition of the DIS cross section at low $Q^2$, it will provide important cross check of the conventional QCD and will allow to improve the knowledge of the gluon density.

[13] Two quarks are needed for a $W,Z$ 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].