Structure Functions and Low-x

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We summarize recent experimental and theoretical results, which were reported in the working group on Structure Functions and Low-x at the DIS 2007 workshop.

1 Introduction

Nucleon structure functions and their scale evolution are closely related to the origins of Quantum Chromodynamics (QCD) as the gauge theory of the strong interaction. With high-precision data from Hera and the Tevatron available and in view of the outstanding importance of hard scattering processes at the forthcoming Lhc, a quantitative understanding of the nucleon's structure in terms of parton distributions is indispensable. In this respect, highlights of the workshop were new Hera measurements at low-Q^2 and large-y, and news on global analyses of parton density functions. The kinematical region of low-x is of particular interest here, because of the rapidly growing gluon density at very small momentum fractions. Consequences of effective theoretical descriptions can for instance be tested on results for measurements of forward jets.

In this summary we give a concise overview of recent experimental and theoretical efforts in this direction, which were presented at our working group [1].

2 Inclusive Structure Function Measurements

The measurement of the inclusive structure functions in deep-inelastic scattering (DIS) is one of the primary tasks of the Hera collider. For the neutral current (NC) process the Hera experiments have reported so far on the measurements of the dominant structure function F_2 and of the structure function xF_3. The scientific program of structure function measurements however is incomplete without measuring the longitudinal structure function F_L and the Hera collider provides a unique opportunity to do so.

2.1 H1 low-Q^2 DIS cross section measurement

A measurement of the DIS cross section by the H1 collaboration in the kinematical domain $0.2 < Q^2 < 12$ GeV^2 was presented by Vargas. The measurement is based on a dedicated "shifted vertex" run which improved the detector acceptance for low Q^2 and a "minimum bias" run with open triggers for low-Q^2 inclusive data. Both runs were done during the Hera-I period in 1999 and 2000. The new preliminary data are combined with the published

H1 results [2] using an averaging procedure which takes into account correlated systematic uncertainties.

As shown in Figure 1, the data are in good agreement with the publications of the ZEUS collaboration at even lower Q^2 [3] and at $Q^2 > 2$ GeV [4]. Moreover, the new data fills the gap in Q^2 between the previous measurements and also extends to high values of the inelasticity, $y = 0.8$, where the cross section is sensitive to the longitudinal structure function F_L although limited to a precision of $\sim 5\%$. For lower values of y, the precision of the new result reaches 1.5% for $Q^2 > 5$ GeV^2, which is an initial step to the ultimate goal of achieving a 1% precision.

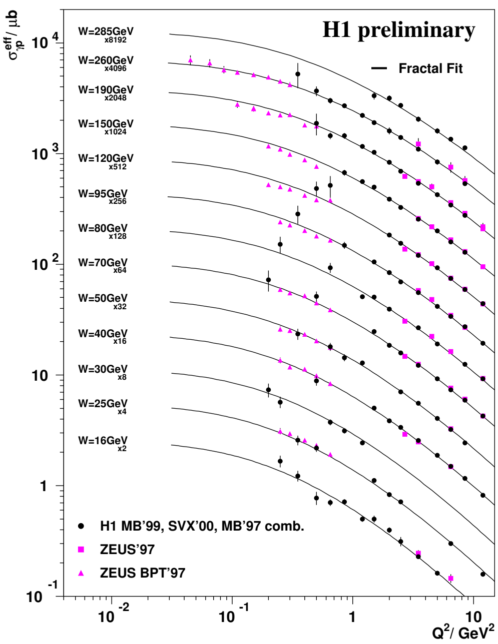

Figure 1: Effective $\gamma^* p$ cross sections at HERA measured by H1, shown as a function of Q^2 at various fixed values of W.

2.2 High-y DIS cross section measurement at low Q^2

A measurement of the longitudinal structure function F_L is the next challenge for the HERA experiments. For this measurement two conditions must be satisfied:

(i) The experiments must measure the DIS cross section for high inelasticity $y > 0.5$ with an accuracy of a few percent.

(ii) HERA must run with different center of mass energies such that the DIS cross section can be determined for the same values of x, Q^2 but at different y.

Results at high-y were presented by Raicevic and Shimizu for the H1 and ZEUS collaborations, respectively. The measurement at high-y is especially difficult at lower Q^2, because of the high level of photoproduction background. High values of y in this kinematical domain correspond to a low energy of the scattered electron which complicates the electron identification.

To that end, H1 has developed a measurement technique in which the background contribution is estimated by using electron candidates with a measured charge opposite to the lepton beam charge. Here, the e^+p data is used to estimate the background for the e^-p data and vice versa. A new preliminary H1 result based on the entire HERA-II sample collected with dedicated low energy triggers utilizes the large e^-p sample, which has not been available during the HERA-I period. The new cross section measurement is based on 96 pb^{-1} of data where 51 pb^{-1} is from e^+p and 45 pb^{-1} from e^-p interactions. This corresponds to more than a ten-fold increase of the total luminosity compared to the previously published result [2]. The measurement covers the range $12 \le Q^2 \le 25$ GeV^2 for the inelasticity

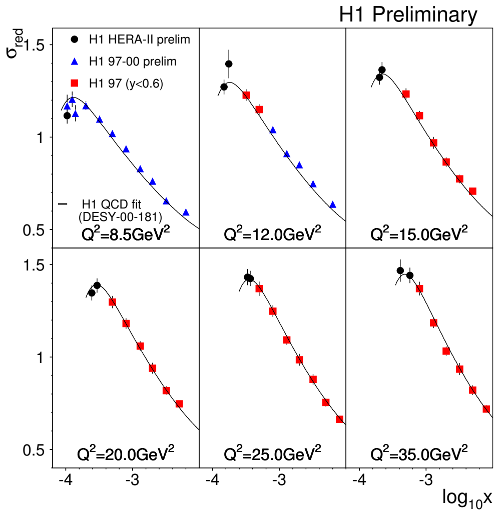

Figure 2: Reduced cross section at low Q^2 and high y at HERA, measured by H1 shown as a function of x at several values of Q^2.

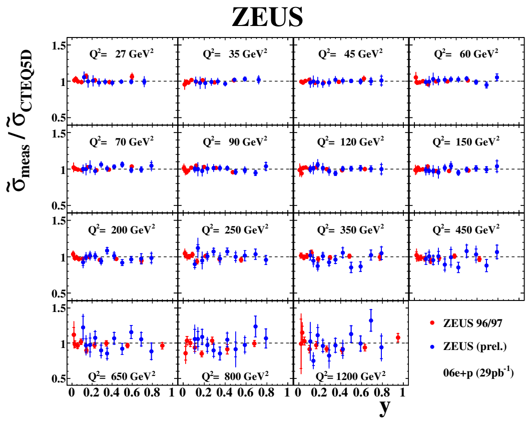

Figure 3: Reduced cross section at high y at HERA as measured by ZEUS and shown in a ratio to the theory prediction as a function of x at several values of Q^2.

$y = 0.825$. Figure 2 shows the measured cross sections together with the previous results. The new preliminary measurement has total uncertainties reduced by factor of two and the total errors are at $2-3\%$ level. Further improvements are possible with a better understanding of the tracking efficiency. The large statistics of the sample is very important for detailed studies of the experimental condition at high-y, as needed for the direct measurement of the structure function F_L.

ZEUS has also performed a cross section measurement optimized for the high-y kinematic range, based on 29.5 pb^{-1} of e^+p collision data collected during year 2006 [5]. In the ZEUS analysis, the photoproduction background is controlled by using a small calorimeter installed close to the beam pipe. It tags electrons which have escaped down the beam pipe in photoproduction events, thus providing a direct measure of the photoproduction background. Compared to the previous measurement [4], the new measurement extends to high values of y up until $y = 0.8$, providing also more data points at $0.1 < y \lesssim 0.8$ and $25 < Q^2 < 1300$ GeV^2, as shown in Figure 3. It serves also as a good demonstration of the feasibility of performing measurements with low energy electrons, which is a necessary prerequisite for future F_L measurements.

2.3 Measurement of xF_3 from ZEUS

Bhadra has reported on a ZEUS measurement of the NC cross sections at large values of Q^2, aiming at pinning down the proton with smallest spatial resolution. The measurement makes use of the full luminosity of e^-p collision data at HERA-II, which amounts to 177 pb^{-1}. The measured cross section showed a good agreement with the Standard Model prediction up to a very large value of $Q^2 \approx 30000$ GeV^2, i.e. down to distances of about 10^{-18} m.

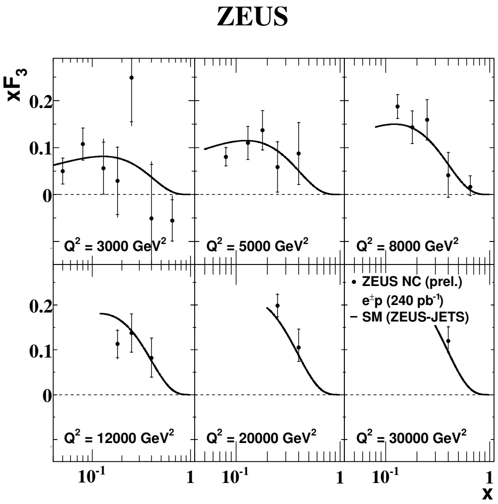

Figure 4: xF_3 measured by ZEUS and shown as a function of x at various values of Q^2.

From this measurement together with the previous e^+p measurement from HERA-I, the structure function xF_3, which is sensitive to the valence quarks, was extracted as shown in Figure 4. The ZEUS measurement will provide important information at smaller x in the region of $10^{-2} \lesssim x \lesssim 10^{-1}$. This is in contrast to fixed target DIS experiments which provide data on xF_3 at large x in the region of $x \gtrsim 0.1$. It was also pointed out that the ZEUS data is collected on a pure proton-target at high Q^2, so that the theoretical uncertainties is significantly less compared to fixed target DIS.

2.4 HERA low energy run

The last three months of HERA operation were dedicated to the measurement of the longitudinal proton structure function F_L using beams with a reduced proton energy. A first look at the machine performance and the data quality collected by the two experiments was presented by Klein. In general the HERA performance exceeded the initial expectations. Instead of the planned data sample of 10 pb^{-1} at a proton energy of $E_p = 460$ GeV, each of the two experiments collected about 13 pb^{-1} at 460 GeV and additionally, about 7 pb^{-1} at 575 GeV. The intermediate proton energy data at 575 GeV should allow for an important cross check of the measurements since the systematic uncertainties, in particular the photoproduction background, are different for the same bins of x, Q^2 but different values of E_p. The online checks of the data show a good quality and near to optimal performance of the detectors. Based on this, Klein concluded that the data for the measurement of the longitudinal structure function F_L were taken successfully, with the next step being a rigorous analysis of these data. Eventually, the measurements will have to be confronted to perturbative QCD predictions [6] and will provide additional information on the gluon distribution at low scales and small x. The latter is in fact poorly known so far, and has led some analyses in the past [7, 8] to prefer a rather small gluon density in this region, to the extend that at NLO in QCD F_L can become almost zero at $Q^2 \lesssim 2$ GeV^2 and very small x.

3 News on Parton density functions

Parton density functions (PDFs) were a central topic of many presentations. This is motivated by the need to have a consistent description of the nucleon's parton content starting from lower scales, were new data sets e.g. from fixed target neutrino-nucleon scattering have become available and theoretical concepts like higher twist are important. Evolution up to high scales by means of perturbative QCD then provides precision predictions for parton luminosities in hard scattering processes at the energy frontier.

3.1 Updates of global PDF analyses

To start with the latter, Thorne has presented a parameterization of PDFs based on a consistent evolution through next-to-next-to-leading order (NNLO) in perturbative QCD. As a new result a PDF set with errors at NNLO is now available [9], where the best fit is supplemented by 30 additional sets representing the uncertainties of the partons (in the Hessian approach). The benefits of NNLO QCD predictions are generally improved stability with respect to scale variations and a consistently better fit than in NLO perturbation theory. Furthermore, higher orders resolve more features of theory, as e.g. the different quark flavor combinations of the PDFs (q_s, q_v, q_-) are all governed by different kernels [10, 11].

Based on this work, Thorne has also reported on a preliminary set of updated NLO PDFs now called MSTW [12] for use at LHC. Main emphasis here besides an improved gluon extraction with the help of jet data from HERA and TEVATRON was on the separation of flavors in the proton. Most importantly, the down quark valence distribution $d_v(x)$ was constrained by lepton asymmetry data from CDF run II. Also, with new results for neutrino-structure functions from CHORUS and NuTeV [13, 14] and the CCFR/NuTeV dimuon cross sections [15] a quantitative extraction of the strange quark and antiquark distributions and their uncertainties has become feasible. Upon relaxing previous assumptions on the parameterization,

$$s(x, Q_0^2) = \bar{s}(x, Q_0^2) = \frac{\kappa}{2}[\bar{u}(x, Q_0^2) + \bar{d}(x, Q_0^2)] \qquad (\kappa \approx 0.5), \tag{1}$$

at the input scale of $Q_0^2 = 1\,\mathrm{GeV}^2$, a direct fit of $s(x)$ and $\bar{s}(x)$ to the CCFR/NuTeV dimuon cross sections now becomes possible.

This point of view has been shared by Tung [16] who presented updates on PDF determinations from global QCD analyses for CTEQ. In particular, CTEQ also determined the strangeness on the proton [17] along with the consequences for the strange asymmetry. The latter are of interest, because a non-zero $s(x) - \bar{s}(x)$ has long been identified as a potential explanation for the "NuTeV anomaly" in the measurement of the weak mixing angle $\sin^2\theta_W$. Current global analyses do not require a non-zero $s(x) - \bar{s}(x)$, but they are consistent with one and the integrated momentum asymmetry for the best fit is small and (mostly) positive.

New measurements of the double differential CC neutrino/anti-neutrino scattering cross section by the NuTeV experiment were reported by Radescu. The new data show agreement with the other neutrino-iron scattering experiments CCFR [18] and CDHSW [19] at lower $x < 0.4$ while for $x > 0.4$ the CCFR result is consistently below NuTeV. For $x = 0.65$ the difference between NuTeV and CCFR is about 18%. The high-x kinematic range is challenging for both experiments and part of the difference can be explained by improvements of the experimental techniques. NuTeV extracts the structure functions F_2 and xF_3 and performs a NLO QCD fit with the charm quark contribution accounted for by using the ACOT scheme [20] to obtain a rather large value $\alpha_S = 0.1247 \pm 0.0020$ exp$^{+0.0030}_{-0.0047}$ th. The controversy surrounding the new NuTeV structure functions measurements is further enhanced if the new results are compared to the predictions of MSTW and CTEQ which agree better with CCFR than with NuTeV. The fits for PDF predictions are based on lepton scattering data. Thus the difference between NuTeV and the former predictions may be explained by the difference of the lepton-iron versus neutrino-iron nuclear screening corrections.

To improve the theoretical treatment of the neutrino scattering data, Rogal reported on the calculation of three-loop QCD corrections to the coefficient functions in Paschos-

Wolfenstein relation [21], i.e. the observable measured by NuTeV to extract $\sin^2\theta_W$. Based on the calculation of first five integer Mellin moments for the charged current structure functions F_2, F_L and F_3 [22] the convergence of the perturbative series could be studied, which is well under control for this observable.

On the theory side, CTEQ has improved the treatment of the charm-threshold in their global analysis by implementing now a general-mass formalism, which is consistent with QCD factorization. The improved description of the (anti-)strange quark distributions leads to interesting implications for collider phenomenology. For instance the production of a charged Higgs boson H^+ via the partonic process $c + \bar{s} \to H^+$, provides an example of a beyond Standard Model (BSM) process that is sensitive to the strange PDF in models with two or more Higgs doublets. The cross section also depends on a possible intrinsic charm component of the proton and the recent PDF set CTEQ6.5c provides various models for such a component [23].

Overall, directly fitting the s and $\bar{s}$ distributions affects the correlated uncertainties on the light sea quarks. An independent uncertainty on s and $\bar{s}$ feeds into that on the $\bar{u}$ and $\bar{d}$ quarks, because the neutral current DIS data on $F_2(x, Q^2)$ constrains the combination $4/9(u + \bar{u}) + 1/9(d + \bar{d} + s + \bar{s})$. As an upshot, the size of the uncertainty on the sea quarks for values $x \sim 10^{-3} - 10^{-2}$ at hard scales $Q^2 \sim M_W^2$ roughly doubles from $\sim 1.5\%$ to $\sim 3\%$ for MSTW. Also CTEQ has reported on significant changes in the light quark PDFs between the new CTEQ6.5 and the older CTEQ6.1 sets. Thorne also reminded that currently in the absence of measurements the error on the gluon density at low-x, say $x = 10^{-5}$ is largely due to the parameterization bias. In summary, the inclusion of new data and the changes in the analysis have had a significant impact on the NLO parton distributions.

3.2 PDF constraints from CDF and DØ

New results from the TEVATRON experiments were presented by Robson and Toole. The TEVATRON $p\bar{p}$ data provides important constraints for d_v and u_v valence quarks via a measurement of the $W^\pm$ charge asymmetry and, of the gluon PDF at high-x by measuring the inclusive jet cross section. Recently, the experiments were focused on the extension of their measurement range to larger rapidities η thus probing the low-x domain. This is of special interest for Standard Model processes at LHC, because kinematically central rapidities $\eta = 0$ at LHC correspond to $\eta = 2$ at TEVATRON.

Robson presented for the CDF collaboration new measurements of the Z rapidity distribution based on 1.1 fb^{-1} of data from run II. The data extends in rapidity to $|\eta| \sim 2.5$ and shows agreement with NNLO QCD predictions. For $|\eta| \sim 2$ the experimental precision is currently about 8%, which should be improved with larger statistics. For the DØ collaboration the measurement of the Z rapidity distribution based on 0.4 fb^{-1} of data was presented by Toole. This data has already a precision of $\sim 6\%$ for $|\eta| = 2$ and is also in good agreement with NNLO QCD predictions as shown in Figure 5. CDF also extended the $W^\pm$ cross section measurements to the forward region of $1.2 < |\eta| < 2.8$. For that purpose they used the forward silicon detectors for lepton identification. They reported on a measurement of the cross section ratio in $|\eta| < 1$ to $1.2 < |\eta| < 2.8$, which provides additional constraints on the PDFs at small x.

Both experiments, CDF and DØ, reported $W^\pm$ charge asymmetry measurement based on their run II data. CDF showed results using the standard approach which relies on the lepton rapidity and a new method which reconstructs $W^\pm$ rapidity with up to two-fold

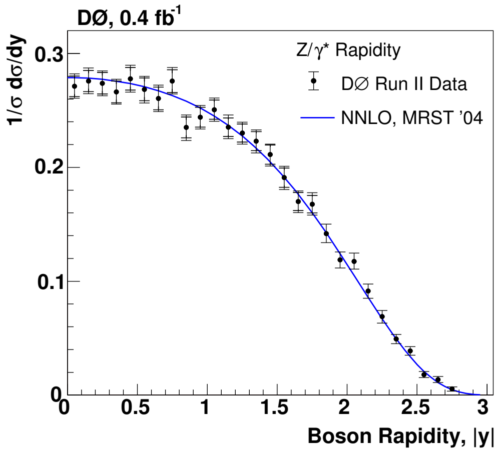

Figure 5: Rapidity distribution of Z produced at Tevatron measured by D∅ in comparison to perturbative QCD predictions at NNLO.

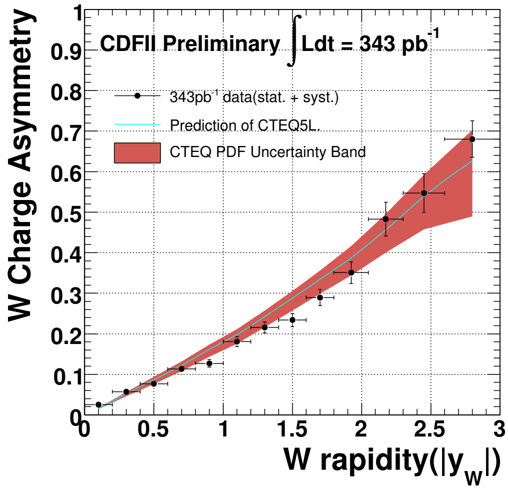

Figure 6: $W^{\pm}$ charge asymmetry at Tevatron, measured by CDF shown as a function of rapidity of the W.

ambiguity based on the W mass as a constraint. Better forward tracking allows to extend the measurement to higher rapidities. For $|\eta| \sim 2.5$ the precision of the measurement is comparable to the current PDF uncertainties. Figure 6 shows the measured $W^{\pm}$ charge asymmetry with the new method. D∅ showed the $W^{\pm}$ asymmetry measurement using $W^{\pm} \rightarrow \mu^{\pm}\nu$ decays. This measurement has a small systematic uncertainty dominated by differences in the efficiencies for positive and negative muons, with the errors being comparable to the present PDF accuracy.

Finally, CDF has shown inclusive jet cross section results using the k_t and the midpoint jet clustering algorithms based on run II data. Figure 7 shows the cross sections in a ratio to QCD theory at NLO as a function of p_t^{jet}. The new results are consistent with the PDF predictions, which in turn are based on run I data. D∅ presented a new measurement of the γ-jet differential cross sections for different γ-system topologies. They observed disagreement between the data and theory prediction for the p_t^{γ} distribution, similar to previous observations by UA2 and CDF, as shown in Figure 8.

3.3 Parton luminosity at Lhc

The imminent question of how these improvements in the parameterizations of PDFs affect predictions for physical cross sections at Lhc was addressed by Cooper-Sarkar [24]. For instance, it was pointed out by her that the predictions for $W^{\pm}$- and Z-production cross sections at Lhc (which are sensitive to PDFs in the $x \sim 10^{-3}$ range) shift by 8% between the PDF sets CTEQ6.5 and CTEQ6.1 – a fact that had also been discussed by Tung. Previously, theory predictions for these processes were thought to be known well enough to be used as a parton luminosity monitor [25]. Therefore, Cooper-Sarkar explored which Lhc measurements may crucially depend on our knowledge of PDFs and, in turn, which might

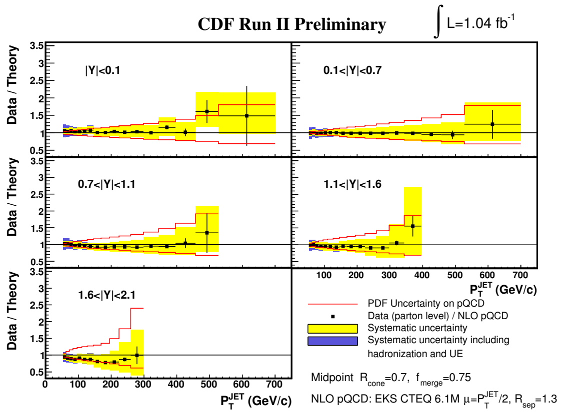

Figure 7: Inclusive jet cross section at TEVATRON, measured by CDF shown in a ratio to QCD theory predictions at NLO.

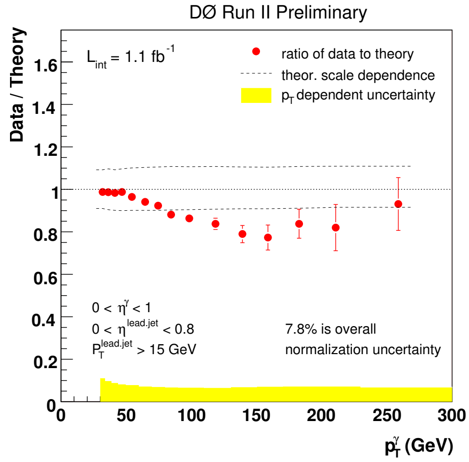

Figure 8: Photon plus jet cross section at TEVATRON, measured by D∅ shown in a ratio to QCD theory prediction.

be used to improve it.

In summary, she stated that PDF uncertainties will have a significant impact on the precision of $W^{\pm}$- and Z-cross-sections, although the $W^{\pm}/Z$-ratio would still be a golden calibration measurement. High-E_t jet cross-sections, hence the discovery of new physics parameterized in terms of contact interactions would also depend on uncertainty of the gluon PDF especially at low-x. On the other hand, PDF uncertainties would not affect the discovery potential of a Higgs in the mass range $100 - 1000$ GeV or a high mass Z' in the mass range $150 - 2500$ GeV. Promising measurements to be conducted at LHC itself include hadronic di-jets and direct photon production to constrain the gluon PDF at low-x or the $W^{\pm}$-asymmetry to pin down the low-x valence PDFs.

Another study by Thorne addressed the issue of combining leading-order (LO) partonic matrix elements with different orders of parton distributions [26]. Different prescription for those combinations were compared to the default standard defined by using NLO in QCD for both matrix elements of the hard scattering process and parton distributions. This investigation aims at determining which parton distributions are most appropriate to use in those cases where only LO matrix elements are available, as e.g. in many Monte Carlo generators. It turned out, that the prescriptions are largely depended on the observable under consideration, but this is an important question to be investigated further in the future.

3.4 Resummations improve global analyses

Further improvements of global PDF analyses rely on the possibility to resum perturbation theory in kinematical regions, where large logarithms occur. Yuan advocated to include transverse momentum (p_t) dependent distributions and he reported on successfully combining the traditional fixed-order global PDF fits with p_t resummation calculations [27].

This stabilizes perturbative predictions in regions of large transverse momentum where the logarithms in p_t require an additional resummation. Combinations of conventional and p_t-resummed global fits can potentially improve the determination of parton degrees of freedom entering for instance in precision W-mass measurements and Higgs phenomenology.

In a different kinematical regime at low-x, White has conducted a global fit to scattering data with Balitsky-Fadin-Kuraev-Lipatov (BFKL) resummations to NLL accuracy [28]. In this approach, logarithms $\ln(1/x)$ in the higher order coefficient and splitting functions are resummed and improved descriptions of DIS data for F_2 and F_L presently available in the kinematical region of low-x (and, simultaneously, of low scales Q^2) are achieved. It was shown that the resummed fit improves over a standard fixed order NLO fit and predicts the turnover of the reduced cross section at high-y consistent with the HERA data. However, the question whether the small-x logarithms are indeed the numerically dominant contribution of the higher order perturbative QCD corrections in the kinematical region considered still needs further studies.

3.5 The low Q^2 region in PDF analyses

Different aspects become important in the determination of PDFs and the analysis of DIS data when switching to the kinematical domain of low-Q^2 scales. The presentation of Alekhin has been particularly devoted to the study low-Q^2 DIS data in the global fit of PDFs. The reasons for doing so are obvious. First of all, the DIS cross section with momentum transferred Q decreases as $1/Q^4$ thus a large part of the experimental data is collected at low-Q^2 and also the perturbative QCD corrections are sizable in this region due to the large value of the strong coupling constant at low scales. Moreover, modeling the low-Q^2 region is important for low energy neutrino experiments and also for spin asymmetries analysis. Phenomenological studies of the data can give important constraints on the value of power corrections (higher twist) and thereby define the region of validity for the parton model. Writing for F_2,

$$F_2^{\rm data}(x,Q^2) = F_2^{\rm twist-2}(x,Q^2) + \frac{H_2^{\rm twist-4}(x,Q^2)}{Q^2[{\rm GeV}^2]} ,$$

one can attempt to parameterize the effect of higher twist. $F_2^{\rm twist-2}$ on the other hand is subject to description within perturbative QCD although target mass corrections still need to be accounted for. In conclusion, Alekhin stated that the existing DIS data at $x \gtrsim 0.001$ can well be described within perturbative QCD in the NNLO approximation down to $Q^2 = 1{\rm GeV}^2$, with the low-Q^2 data providing valuable constraints on the d_v-quark distribution. The contribution of the twist-4 terms was found to be less than 10% in this kinematical region and the higher twist terms in the ratio $R = \sigma_L/\sigma_T$ of the longitudinal over the transverse cross section are generally small.

The fact, that the high-Q^2 region of lepton-nucleon scattering is typically well understood in terms of PDFs and more detailed studies at low-Q^2 are still being conducted, have led Yang to propose a unified approach to the electron- and neutrino-nucleon DIS cross sections at all values of Q^2. Improvements here would for example be very important for many neutrino oscillation experiments. The model presented by him tries to incorporate higher twist and target mass corrections at low scales. This is done through an effective LO QCD evolution with PDFs based on the set GRV98 [29] although with a modified scaling variable to absorb all these effects as well as missing higher orders. The predictions are in good agreement with the DIS world data as well as photo-production and high-energy neutrino data. Eventually, the model should also describe low energy neutrino cross sections reasonably well and would be useful for Monte-Carlo simulations in experiments like e.g. MINOS, MiniBooNE or K2K.

With a similar motivation, the ALLM parameterization [30] of the total cross section $\sigma_{\rm tot}(\gamma^* p)$ has been updated by Gabbert using new F_2 data to determine its parameters. As an upshot a fit of the world data for inclusive proton DIS cross sections is available which is useful for all extractions requiring F_2 as input and relevant for Monte Carlo simulations at low-Q^2.

3.6 New theory developments

As an alternative to the standard methods of PDF global analyses Rojo presented a general introduction to the neural network approach to parton distributions [31]. The use of neural networks provides a solution to the problem of constructing a faithful and unbiased probability distribution of PDFs based on available experimental information [32]. The talk emphasized the necessary techniques in order to construct a Monte Carlo representation of the data, to construct and evolve neural parton distributions, and to train neural networks in such a way that the correct statistical features of the data are reproduced. As a first application, a determination of the non-singlet quark distribution up to NNLO from available DIS data was presented and compared with those obtained using other approaches. The obvious next step is a complete singlet analysis and the release of the first neural PDF set was announced for summer 2008. In a similar spirit, Liuti reported on first attempts to perform PDF fits with self-organizing maps, and presented LO fits as a proof of principle.

A possible test of the validity of perturbative QCD evolution in a global fit to the proton structure function $F_2^p(x, Q^2)$ was discussed by Pisano [33]. The idea is to probe the range of validity of the NLO and NNLO QCD evolutions of parton distributions in particular in the small-x region using the curvature of F_2^p as a criterion [34]. The characteristic feature to be exploited here is a positive curvature of F_2^p which increases as x decreases. This is a perturbatively stable prediction and turns out to be rather insensitive to the specific choice of the factorization scheme ($\overline{\rm MS}$ or DIS) as well. Therefore, Pisano argued that the curvature of F_2^p does indeed provide a sensitive test of the range of validity of perturbative QCD evolution.

The talk by Zotov discussed the concept of un-integrated PDFs in the k_t-factorization approach, in particular its uses to obtain an un-integrated gluon distribution with k_t-dependence from a fit to measured structure functions F_2 and $F_2^{\rm charm}$ at HERA [35]. As a critical test he then applied the results of his fit to the experimental data for observables like $F_2^{\rm bottom}$ and F_L, all of which are dominated by the gluon PDF.

Finally, the discussions on PDFs were nicely complemented by presentations of Gousset, who reported on research to quantify nuclear modifications of PDFs. For the gluon distribution, they can amount up to 30% and prompt-photon production in p-A collisions offer the chance to study the effects. Detmold contributed from the side of lattice QCD, where moments of PDFs at low scales can be computed in an entirely non-perturbative way.

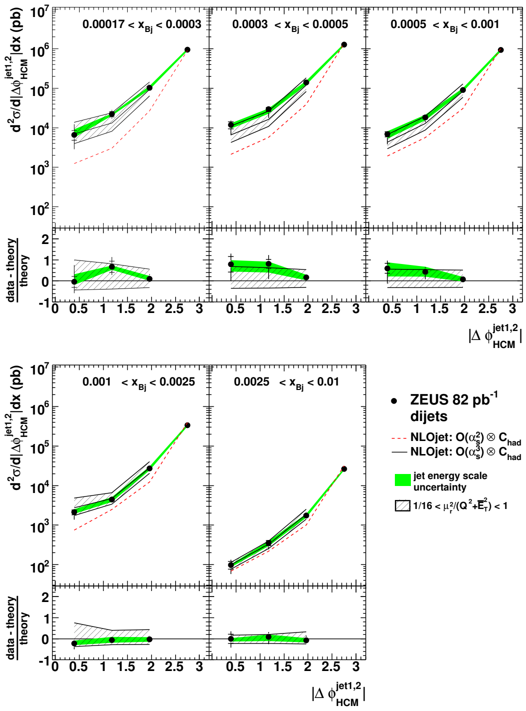

Figure 9: Di-jet cross sections at HERA, measured by ZEUS as a function of the angular separation of the two jets.

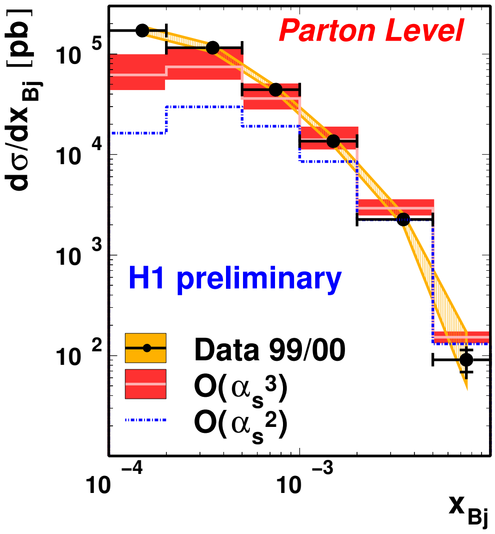

Figure 10: Differential cross section in x for two forward jet at HERA, measured by H1.

4 Forward jets and low-x

4.1 Parton dynamics with DIS multi-jets at HERA

Studies of multiple jet production in DIS have been performed by H1 as reported by Novak and by ZEUS as reported by Danielson. The main goal is to investigate a possible enhancement of gluon radiation, which is expected to become important at low x. ZEUS studied di-jet and tri-jet production in DIS at low-x based on 82 pb^{-1} of data collected during 1998 and 2000 [36]. The kinematic range is $10 < Q^2 < 100$ GeV^2 and $10^{-4} < x < 10^{-2}$. The correlations in angles and p_t between the two highest E_t jets were examined to search for effects of higher orders or from the underlying hard scattering beyond the conventional (i.e. NLO in QCD) Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution. The data were found to be well described by the NLOJET calculations at $O(\alpha_s^3)$, while calculations at $O(\alpha_s^2)$ do not describe data in particular at low x. It was shown that these measurements are very sensitive to QCD higher order effects which can be enhanced by up to a factor ten at the lowest x.

The H1 study is based on 44 pb^{-1} of data collected in 1999 and 2000. The kinematic range of the measurement is focused on the low-x domain, $x < 10^{-2}$ with $5 < Q^2 < 80$ GeV^2. A comparison of the inclusive ≥ 3 jet sample shows that leading order calculations undershoot the data while NLO predictions are marginally consistent, although within a large scale uncertainty. Yet the data tends to be higher compared to the NLO prediction for the smallest x and the largest η. To investigate this kinematic domain in more detail, the 3-jet sample was split in sub-samples with one or two jets in the forward direction. A significant discrepancy was observed for the sample with two forward jets for $x \sim 10^{-4}$. This discrepancy may indicate an enhancement of gluon radiation compared to NLO QCD evolution, but also higher order QCD calculations for the hard scattering may improve the data description.

4.2 Forward jet production at HERA

Khein presented a new ZEUS measurement on forward jet production in DIS with a significant extension in forward region up to rapidities of $\eta^{jet} < 4.3$ [37]. This measurement is expected to highlight the differences between predictions of the BFKL and DGLAP formalism with BFKL resulting in a larger fraction of small-x events with forward-jets than typically present in DGLAP evolution to NLO in QCD.

The measurements were presented for inclusive forward jets as well as for a forward jet accompanied by a di-jet system. As shown in Figure 11, NLO QCD calculations were found to be below the data, in certain regions by as much as a factor of two. Amongst the Monte Carlo models, the color-dipole model (CDM) of ARIANDE was capable of describing the data over the whole phase space. The CASCADE Monte Carlo with the J2003 set-1 and set-2 un-integrated gluon densities however failed to describe the data. Therefore, these measurements can be used for further improvements by adjusting the input parameters of the CASCADE model.

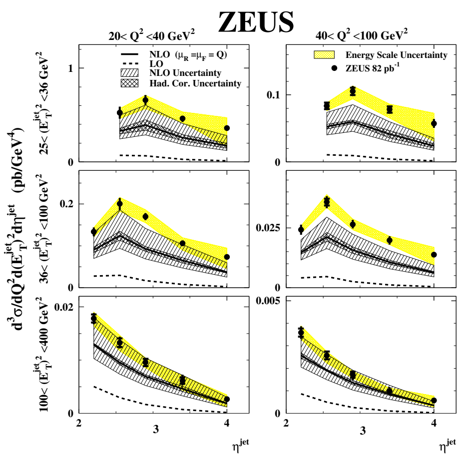

Figure 11: Differential jet cross sections at HERA, measured by ZEUS shown as a function of η^{jet} in different bins of Q^2 and $(E_t^{jet})^2$.

4.3 Theory progress in multiple gluon scattering

On the theory side a number of presentations were concerned with improved predictions and models for the production of forward jets at HERA and multiple gluons in the low-x kinematical region.

Avsar reported on efforts to further improve dipole phenomenology. Starting from the Mueller dipole picture, where the dipoles are assumed to interact independently, he modeled multiple scattering effects typically attributed to Pomeron loops. Putting particular emphasis on a Monte Carlo approach and adding as a new feature color-suppressed effects, he described saturation both in the evolution of dipoles and in the interactions of dipoles with a target by means of an effectively unitary formula for the amplitude. Applications of the formalism for the $\gamma^* p$ total cross sections as measured by HERA and $p\bar{p}$ cross sections at TEVATRON were shown.

On the analytical side, Shoshi discussed the Balitsky-Kovchegov (BK) equation as basis for the high-energy scattering of a dipole off a nucleus/hadron in the mean field approximation [38]. Although the BK-equation results in a geometric scaling behavior of the scattering amplitude and a roughly power-like energy dependence of the saturation scale, it is known that it needs improvements, as it misses for instance Pomeron loops. Shoshi reviewed recent progress in understanding the small-x dynamics beyond the mean field approximation, guided by the natural requirements of unitarity and Lorentz invariance. He pointed out relations between high-energy QCD and statistical physics inspired by dynamics of reaction-diffusion processes. As an upshot, fluctuations in gluon number from one scattering event to another lead to corrections to the geometric scaling which will be modified to diffusive scaling at large energies. He concluded that Pomeron loops and fluctuations in the gluon number will strongly influence predictions for instance for diffractive scattering or the forward gluon production cross section, although it is too early to make the phenomenological consequences quantitative.

Lublinsky on the other hand pointed out that multi-gluon production via high energy evolution can also be modeled by improvements within the JIMWLK high energy evolution. He presented results for the multi-gluon cross section in terms of a generating functional for arbitrary numbers of gluons n, which extends the dipole approximation (and the previously known results for single and double gluon inclusive cross sections) and which generalizes for an arbitrary multi-gluon amplitude in terms of Feynman diagrams of Pomeron-like objects coupled to an external rapidity dependent field. He discussed some general properties of the expressions and suggested a line of argument to simplify the approach further.

The presentations of the theory framework were nicely complemented by Royon and Sabio Vera. The contribution by Royon was concerned with the phenomenology of forward jets at Hera and Mueller-Navelet jets at hadron colliders (Tevatron, Lhc) [39], both being sensitive to low-x physics and, potentially, well described within the BFKL formalism. In particular Mueller-Navelet jets are ideal processes to study BFKL resummation effects with two jets having similar tranverse momenta and being separated by a large interval in rapidity. There, a typical observable to look for BFKL effects is the measurement of the azimuthal correlations between both jets. Fixed order perturbative (i.e. NLO) QCD predictions based on DGLAP predict a distribution peaked towards π as it is typical for back-to-back jets. On the other hand, multiple gluon emissions at small-x in the BFKL formalism smoothen this distribution. Fits to H1 data from Hera were presented and suggestions for measurements by CDF at Tevatron were made.

Also Sabio Vera [40] looked at the azimuthal angle correlation of Mueller-Navelet jets. In particular, he highlighted the need of collinear improvements in the BFKL kernel to obtain stable theory results, and better fits to the Tevatron data of D∅ which has analyzed data for Mueller-Navelet jets at $\sqrt{s} = 630$ and 1800 GeV many years ago. He estimated several uncertainties and suggested improvements depending on the conformal spins. For Lhc where larger rapidity differences will occur the Mueller-Navelet jets will be a very useful tool to investigate the importance of BFKL effects in multi-jet production in particular for the azimuthal dependence which is driven by the BFKL kernel with increasing rapidity.

5 Theory outlook

A lot of the success of QCD in the theoretical description of DIS structure functions relies on the possibility to predict the scale dependence, which is governed by anomalous dimensions of composite Wilson operators that arise in the operator product expansion of conserved currents. The anomalous dimensions reflect the symmetries of the underlying gauge theory and depend on the quantum numbers of the Wilson operators such as Lorentz spin.

For operators with large Lorentz spin the anomalous dimensions scale logarithmically with the spin. Recent higher order QCD calculations of twist-two anomalous dimensions [10, 11] revealed the existence of intriguing underlying structures in the large spin expansion. In his presentation Basso discussed this structure of inheritance across orders in perturbation theory for terms suppressed by powers of the Lorentz spin [41]. He argued that it relates to the properties of a conformal field theory (CFT) where the corresponding anomalous dimensions are functions of their conformal spin only and supplemented with well determined modifications in higher loops [42].

For a more symmetric relative of QCD, the $\mathcal{N} = 4$ supersymmetric Yang-Mills (SYM) theory, the corresponding anomalous dimensions display very interesting integrability properties, which have been reviewed in the presentation of Lipatov. Using an inspired observation, he had earlier been able to obtain the $\mathcal{N} = 4$ SYM results from the "leading-transcendentality" contributions of QCD [43] up to three loops. In the planar limit the $\mathcal{N} = 4$ SYM theory is believed to be dual to weakly-coupled gravity in five-dimensional anti-de Sitter (AdS) space. Based on the AdS/CFT correspondence, Lipatov related the Pomeron at low-x in the strong coupling limit of the gauge theory to the graviton in the weakly-coupled gravity. These investigations based on integrability and strong-weak duality offer not only great chances to improve our understanding of $\mathcal{N} = 4$ SYM theory by providing us with conjectures for the exact four-loop anomalous dimension of twist-two operators [44], but in the future they will hopefully also lead to new insights into QCD.

6 Summary

Many new results on nucleon structure functions and subjects related to low-x physics were presented at this workshop, which covered both, theory and experiment. On the latter side, the experimental contributions came not only from DIS experiments (e.g. H1, ZEUS) but also from hadron-collider experiments (e.g. CDF, D∅), which we believe is a clear demonstration of the importance of our field and of the presence of lively activities. In view of the forthcoming LHC, particular attention was paid to a further precise understanding of the QCD dynamics. This includes the gluon density at low-x in particular, and also a more precise and robust determination of parton distribution functions in general. Clearly, the progress reported here was remarkable. The first F_L measurement at HERA is foreseen in near future. It becomes possible with the newly developed experimental techniques reported at this workshop and is expected to give new insight into low-x physics and the gluon density. In summary, the various efforts made, many of them being based on new and unique ideas, are likely to improve our understanding of structure functions in near future. We believe that the field continues to contribute to fruitful research in the LHC era.

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