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Summary of the Structure Functions Working Group

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Presentations on nucleon structure studies in the Structure Functions working group are summarized. Most recent experimental results related to structure functions and parton distributions from HERA, LHC, and intermediate energy experiments are reviewed. Novel developments in theory and phenomenology of the proton structure determination are discussed, including treatment of heavy quarks in QCD analyses and impact on electroweak precision measurements at hadron colliders.

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1. Introduction

Studies of the nucleon structure are vital for high-energy physics. Interpretation of experimental results obtained at modern colliders relies to a large extent on precise knowledge of fundamental QCD parameters and parton distribution functions (PDFs) in the proton. The latter cannot be derived from the first principles and are determined from experimental data using a variety of analytical methods. While DIS experiments provide the staple information about the proton structure at scales Q below a few hundred GeV, the hadron-(anti)hadron collider data that pour in become increasingly competitive in a broad range of energies. Inclusive DIS serves as the standard candle measurement of the proton structure functions, while semi-inclusive DIS processes like production of electroweak bosons, jets, and heavy quarks deliver important insights about the flavor composition of PDFs and their dependence on the QCD coupling strength and heavy-quark masses.

In the analysis of proton structure, essential progress occurs through close collaborative efforts of experiment, theory, and phenomenological analysis of QCD data. This trend was reflected in the the discussions of the current workshop, which were lively and multifaceted. H1, ZEUS, ATLAS, CMS and LHCb experiments presented a variety of experimental results pertinent to determination of the unpolarized PDFs. The BONUS experiment at JLab presented measurements of DIS on deuteron targets, while COMPASS and CLAS presentations focused on spin properties of the nucleon structure. Experimental presentations were matched by updates from several PDF analysis groups and reports on theoretical developments. Special attention was paid to production of heavy flavors and their treatment in the PDF analyses, as well as QCD aspects of electroweak precision physics at the LHC and Tevatron. These topics were covered in joint sessions with the heavy-flavor and electroweak working groups.

2. HERA-II DIS measurements

As reviewed by I. Brock and S. Shushkevich, the H1 and ZEUS collaborations completed the analyses of HERA-II inclusive charged current (CC) and neutral current (NC) DIS, and their measurements are reaching the ultimate precision [1]. For illustration, Fig. 1 (right) shows the reduced cross sections for NC e^+p scattering with different electron beam polarizations measured by ZEUS [2], in comparison to the Standard Model (SM) prediction based on the PDF set HERAPDF1.5. In Fig. 1 (left) the CC cross section for e^-p scattering is shown, as measured by the H1 experiment [3], compared to the QCD prediction using the H1PDF2012. The combination of the H1 and ZEUS data on inclusive NC and CC DIS scattering is ongoing. These data will serve as the backbone for the PDF determination at low and medium x.

3. Combined charm production in DIS, extraction of charm quark mass

Several presentations in our working group focused on a novel type of analysis, determination of the charm-quark mass from production of charm quarks in DIS at HERA [4]. S. Alekhin presented a new study that included precise measurements of D^*-meson production at H1 [5] into a PDF fit to HERA DIS data [6], using DIS coefficient functions in the fixed-flavor-number scheme (FFNS). The $\overline{\mathrm{MS}}$ mass $m_c(m_c)$ of the charm quark was determined at NLO and approximate NNLO

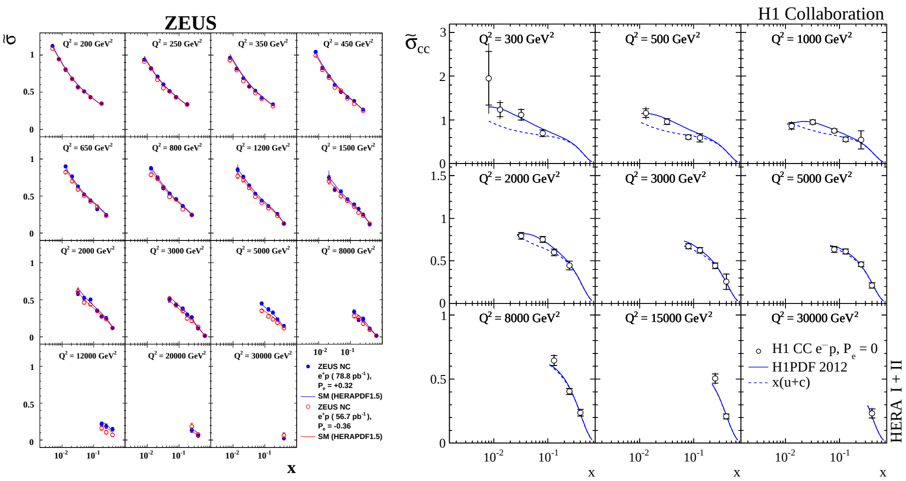

Figure 1: Left: the e^+p NC DIS reduced cross-section as a function of x at fixed Q. The filled (open) circles represent the data for negative (positive) electron polarization. The theory prediction is represented by a solid line. Right: combined HERAI+II unpolarized CC reduced cross sections for ep scattering (open symbols) as measured by the H1 experiment in comparison with the expectation based on H1PDF 2012. The inner and outer error bars represent the statistical and total errors, respectively. The dominant $x(\overset{(-)}{u} + \overset{(-)}{c})$ contribution is shown by a dashed line.

from these data, and a value consistent with the world-average $m_c(m_c)$ was found. Correlation of $m_c(m_c)$ with the strong coupling constant, $\alpha_s(M_Z)$, was also studied, as shown in Fig. 3 (left).

In a parallel development, charm-quark production cross sections from the HERA-I and partial HERA-II data samples by H1 and ZEUS experiments were combined in a unified data set with shared systematic uncertainties [7, 8]. A. Geiser presented the HERA combined reduced charm production cross sections. The precision of the combined data reaches 5% at medium Q. Once the combined charm data were included into the PDF analysis together with the combined HERA inclusive DIS data, significant reduction of the uncertainty on the gluon, charm and the light sea distributions was observed, as shown in Fig. 2 (left). Following the approach [6], $m_c(m_c)$ was determined in FFNS at NLO from the combined data set [10], with similar results as in [6], cf. Fig. 2 (right).

Compatible values of $m_c(m_c)$ were found from the global QCD analyses of the combined data [4, 11, 15] that include data from other scattering processes besides DIS at HERA to impose additional constraints on those PDFs that are correlated with m_c. Fig. 3 (right) shows the confidence levels on $m_c(m_c)$ obtained from the CT global analysis, presented by M. Guzzi. Here, a general-mass variable-flavor number scheme (S-ACOT-χ) at 2 loops was used, and agreement with $m_c(m_c)$ from the FFNS study at this order was observed.

The choice of $m_c(m_c)$ has implications for collider physics, as was demonstrated in a study of the heavy-quark mass dependence utilizing the open-source QCD analysis code HERAFITTER [18]. At 1-loop accuracy in α_s, the predicted W and Z cross sections may change by up to 5% depending on the heavy-quark scheme and m_c value, but the spread of the LHC predictions can be significantly reduced by using the optimal charm mass for each scheme.

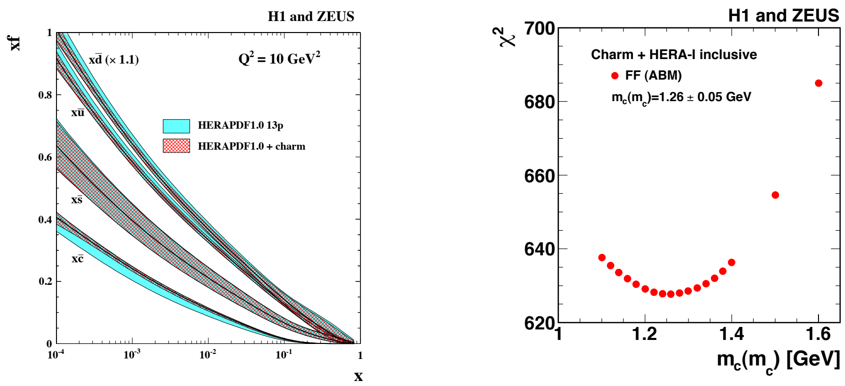

Figure 2: Left: PDFs for sea antiquarks obtained from the HERA analysis of the combined inclusive+charm DIS data (dark shaded bands) and inclusive DIS data only (light shaded bands) as a function of x at $Q^2 = 10$ GeV^2. Right: The figure-of-merit function χ^2 in the PDF fit to the combined inclusive+charm HERA DIS data as a function of the $\overline{MS}$ scheme $m_c(m_c)$ in the FFNS scheme.

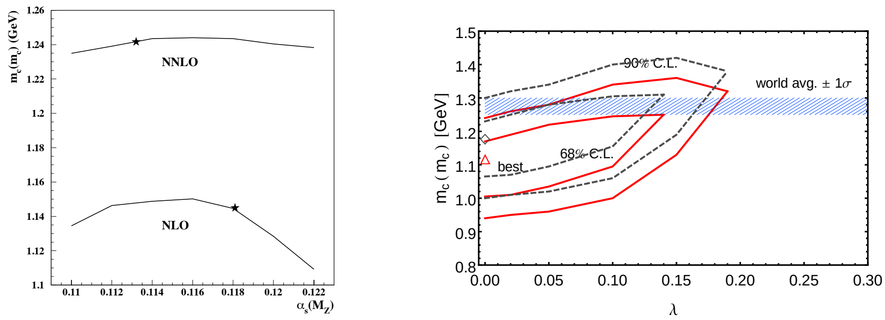

Figure 3: Left: The values of $m_c(m_c)$ obtained in the NLO and approximate NNLO variants of the ABM11 fit to the combined HERA inclusive+charm data for various $\alpha_s(M_Z)$. The stars corresponds the best-fit value of $\alpha_s(M_Z)$. Right: The best-fit values and confidence intervals for $m_c(m_c)$ vs. the rescaling parameter λ in the CT10 analysis in the S-ACOT-χ scheme, for two possible implementations of correlated systematic errors.

At two loops, the associated uncertainties in PDFs and $m_c(m_c)$ are suppressed, but still sizable, as is reflected by the non-negligible difference between the $m_c(m_c)$ values from the NLO and approximate NNLO fits in FFNS [6], and dependence on the rescaling parameter λ seen in Fig. 3 in the 2-loop S-ACOT-χ fit [11].

These findings point to importance of the computation of the exact 3-loop contribution to DIS coefficient functions with massive quarks that is now underway [12]. This tour-de-force calculation is progressing and overcomes challenges associated with distinct species of massive quarks (c and b) in loop integrals and novel mathematical structures, such as hyperlogarithms and harmonic sums. When completed, implementation of the 3-loop coefficient functions with massive quarks will be essential for bringing the PDF uncertainty to a percent level.

A new formulation of the GM VFN scheme was presented by A. Kusina. It involves parallel evolution of PDFs from the same input parametrization using several numbers of active flavors N_f in every scale (Q) range. In principle this approach offers more flexibility in switching from N_f to $N_f + 1$ flavors in QCD cross sections compared to the conventional GM VFN schemes such as ACOT, TR', or FONLL. Finally, models for nonperturbative intrinsic production of charm quarks were discussed. A new CT10 parametrization for intrinsic charm PDFs satisfying the latest experimental constraints was presented [14]. Z. Stavreva reported on a comparison of the NLO calculation of $\gamma + Q$ cross sections with the DØ data that may probe intrinsic charm contributions at the highest p_T of produced photons.

4. Electroweak boson production at the LHC

Measurements of electroweak boson production at the LHC are sensitive to poorly constrained aspects of PDFs, notably to flavor composition of the quark sea at $x < 0.01$. Lepton pair production at ATLAS and CMS covers the medium x range, while LHCb is well-suited for investigating regions of low and high x. S. Tourneur presented recent LHCb results on the Z and W production and asymmetry based on the data collected in 2010 and 2011. LHCb measurements at rapidities $y > 2$ can probe different PDF sets at $x > 0.1$, provided the experimental systematic uncertainty (currently comparable to the PDF errors, cf. Fig. 4 (left)) is reduced. K. Nikolics discussed the sensitivity of ATLAS rapidity distributions of W and Z to the strangeness PDF in the proton. Similar CMS measurements are already sensitive enough to feel the impact of NNLO radiative contributions, as shown by A. Khukhunaishvili. Sensitivity to the strange quark PDFs is enhanced in associated production of W bosons and charm quarks, cf. the talk by E. Vryonidou. The ratios $\sigma(W^+c)/\sigma(W^-c)$, illustrated in Fig. 4 (right), can distinguish between various forms of $s(x,Q)$ at $x < 0.01$, where it is still poorly constrained in the current PDF sets.

Production of W boson associated with a b quark can test heavy-flavor schemes and probe the b-quark PDF [19]. In a complementary $\sqrt{s}$ range, the measurement of unpolarized cross sections for $W^\pm$ production in 500 GeV pp scattering has been performed at the Relativistic Heavy Ion Collider [20]. Here, the ratios $\sigma^{W^+}/\sigma^{W^-}$ of the cross sections probe the u and d (anti-)quark PDFs in the $x > 0.1$ range that is not easily accessible at the LHC. A proof-of-principle measurement of $\sigma^{W^+}/\sigma^{W^-}$ was performed in 2012 and found to be in agreement with the NLO calculation based on the CTEQ6.6 and MSTW'08 sets.

Tight constraints on PDFs in W production are needed, in particular, to reduce the dominant theoretical uncertainty associated with the PDFs in W boson mass measurements at the Tevatron and LHC. A study of the PDF uncertainty in M_W measurement at the Tevatron was presented by J. Rojo. Using a template fit, the PDF uncertainty on M_W in his theoretical analysis was demonstrated to be below 20 MeV, in an overall agreement with, or slightly larger than, the estimates of 10-15 MeV made by the Tevatron experimental collaborations.

5. Inclusive jet production

Jet production at the LHC is sensitive to the gluon distribution in the proton and QCD coupling α_s. ATLAS jet data were included into the PDF fit [21] together with HERA DIS data, using NLO theory. The resulting gluon distribution is harder than the one obtained with inclusive DIS data

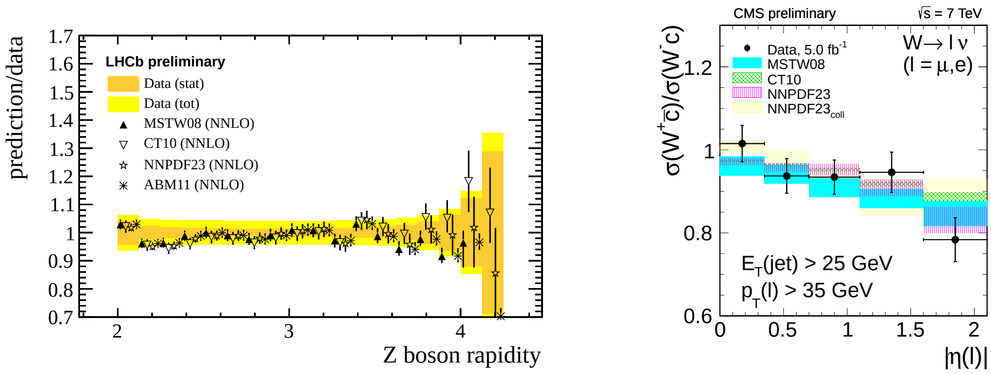

Figure 4: Left: Differential cross-section for Z boson production vs. rapidity of the Z boson, as measured by the LHCb experiment (shaded band), shown as ratios to NNLO QCD predictions based on various PDFs (symbols of different style). Right: Charge ratios of $W+c$ cross sections measured by CMS, as a function of the pseudorapidity of the lepton from the W decay, confronted with theoretical predictions at NLO from MCFM based on several PDF sets.

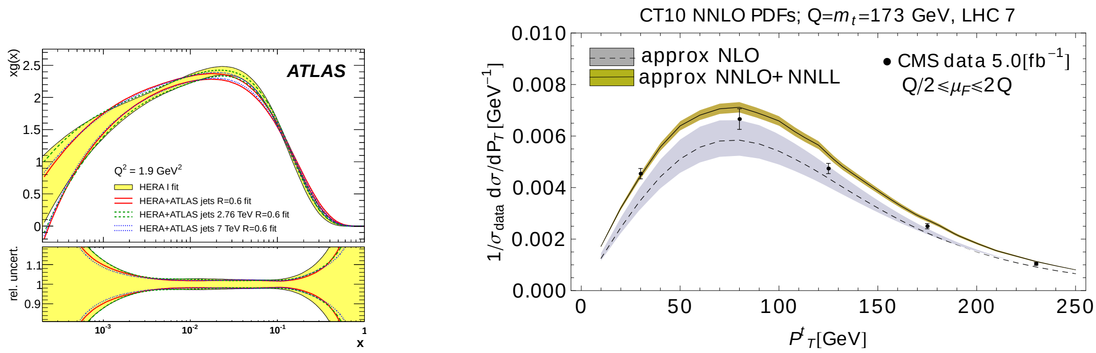

Figure 5: Left: Impact of the ATLAS jet data on the PDFs [21]. Momentum distributions of the gluon are plotted together with the relative experimental uncertainty as a function of x for $Q^2 = 1.9$ GeV^2. The filled area indicates a fit to the HERA data only. Empty bands are for fits to HERA data in combination with ATLAS jet data sets for 2.76 and 7 TeV, and with each ATLAS jet data set separately. Right: Normalized differential cross section for $pp \to t\bar{t}$ at NLO (light shaded band) and approximate NNLO (dark shaded band) as a function of top-quark transverse momentum [30]. Data points are from a CMS measurement.

alone, and its uncertainty is reduced, as illustrated in Fig. 5 (right). Theoretical treatment of the Tevatron and LHC jet cross sections in global fits was discussed in CTEQ [14] and MSTW [22] presentations. The large-x behavior of the gluon PDF extracted from the jet data is affected by the prescription for the implementation of experimental correlated systematic errors and by QCD factorization scales in theoretical cross sections. Various techniques for controlling such effects or reducing them have been presented.

In the MSTW [22] and NNPDF2.3 [16, 23] global analyses, the inclusion of the early ATLAS (7 TeV, 37 pb^{-1}) jet data only mildly modifies the gluon PDF. However, with growing luminosity, the LHC jet data will play a leading role very soon, and appropriate developments in the PDF analysis will be needed. One related theoretical advancement, computation of NLO weak radiative contributions to dijet production, was presented by A. Huss. These corrections may reach up to 10% at the jet's p_T greater than 1 TeV, hence may be non-negligible in future jet studies.

6. Top quark production

Top-quark pairs at the LHC are produced predominantly via gluon-gluon fusion. As discussed by J. Kieseler, measurement of top-pair cross sections is now understood well enough in PQCD to become a source of information about the gluon distribution, top-quark mass and α_s. Precise measurements of inclusive cross sections at CMS are used to determine the top-quark pole mass, and, for the first time, $\alpha_s(M_Z)$, using the QCD calculation at NNLO [28]. If the inclusive cross section measurements in top-pair production at ATLAS and CMS are included into the PDF fit [13, 29], they may impose a significant constraint on the gluon PDF, provided α_s and m_t are also well-known.

Differential measurements of $t\bar{t}$ production at the LHC are measured with high precision, but no supporting exact NNLO calculation exists nowadays. Based on the combination of approximate NNLO calculations by different groups, an open-source code for differential cross-section predictions is being developed [30], and the first results are in very good agreement with the CMS measurements, as illustrated in Fig. 5 (right). Complementary measurements of ratios of single-top and single-antitop production cross sections can constrain the ratio of u and d quark PDFs [31]. Precision of single-top measurements is expected to improve soon with more analyzed data.

7. Progress in the unpolarized PDF analysis

Updates on the analyses of unpolarized PDFs in the proton were presented by several groups: ABM [13], CTEQ-TEA [14], HERA, MSTW [15], and NNPDF [16]. All these groups now provide their PDFs at NNLO accuracy for a variety of QCD applications. The CT10 NNLO set was released last year and can be used as a counterpart with either CT10 or CT10W NLO.

While the PDF fits are dominated by pre-LHC measurements, increasingly the LHC data are included to provide unique new constraints. NNPDF2.3 [16, 23] is the first published PDF set that includes the 7 TeV data on ATLAS W/Z rapidity distributions and inclusive jets, CMS W asymmetry, and LHCb W rapidity distributions. While the LHC data sets still have large uncertainties, they nonetheless somewhat reduce the PDF error bands, especially for the strangeness PDF. Alternatively, inclusion of the LHC data allowed NNPDF to produce the first data set based only on collider experiments (without the fixed-target data). Within the "collider only" PDF set, the LHC data already plays a prominent role, even though we still need to wait for this set to become competitive with the standard sets.

Besides NNPDF, the impact of the LHC data is investigated in preliminary fits by other groups. In the CT1X [14] and MMSTWW [15, 24] analyses, the inclusion of the CMS W charge asymmetry modifies the separation of u, $\bar{u}$, d, $\bar{d}$ PDFs at $x \approx 0.01$, as well as between d and u PDFs at $x > 0.1$. The d quark PDF in the MSTWCPdeut set was revised across the whole range of x to bring it into the agreement with the CMS W asymmetry. In the upcoming CT fit, more flexible parametrizations for $d_{valence}/u_{valence}$ and $\bar{u}/\bar{d}$ will be allowed at $x < 0.01$ to better accommodate the LHC charge asymmetry data.

A complementary approach is pursued by CTEQ/Jefferson Lab (CJ) collaboration, emphasizing constraints on valence quark PDFs at $x > 0.1$ from extensive DIS data on nuclear fixed targets (BCDMS, NMC, SLAC) [17]. In the CJ12 NLO analysis that was recently released, the uncertainty in the d/u ratio in the $x \to 1$ limit is evaluated by allowing for a range of models of nuclear effects and large-x power corrections. The associated variations in theoretical predictions can be estimated using the PDF sets CJ12min and CJ12max, corresponding to two extreme large-x forms of d/u that are still compatible with the DIS data and explored models. Differences between the CJ12min and CJ12max predictions are most pronounced in forward scattering processes at the Tevatron and LHC.

For purposes of various measurements, it is essential to quantify the remaining differences between the NNLO PDF sets. This has been accomplished in the 2012 benchmark comparison of NNLO PDFs [16, 25], as well as in a complementary study [13, 26]. The CT10, HERA1.5, MSTW'08, and NNPDF2.1 NNLO sets were found to be in a good overall agreement. The PDF uncertainties in the HERA set, which does not include all experiments considered by the global fits, may be smaller or larger than in three global fits. The ABM'11 set is more distinct from the other sets and would require to use the $\alpha_s(M_Z)$ and m_t^{pole} values at about $3-5\sigma$ away from their current world-average values to agree with the recently measured LHC W/Z and $t\bar{t}$ production cross sections. The source of the difference between the ABM and other PDF sets has been revisited at the workshop. It has been confirmed, for example, that the usage of FFN scheme (adopted solely by ABM) may produce comparable differences in the PDFs [15], rather than varied implementations of higher-twist contributions in DIS or treatment of fixed-target experiments.

8. Nuclear modifications in parton distribution functions...

...is an area of growing importance for understanding of hadronic matter, ongoing nuclear scattering experiments at LHC and RHIC, and neutrino physics. With a variety of data collected on nuclear targets, several groups are pursuing the global analysis of PDFs in heavy nuclei. A review of nuclear PDF sets and an update on the nCTEQ analysis of nuclear PDFs was presented by K. Kovarik. The nCTEQ collaboration obtained a preliminary set of error PDFs for various atomic numbers and compared their PDF uncertainty bands against analogous bands from the HKN'2007 and EPS'2009 groups. The possible breaking of QCD factorization for CC DIS on heavy nuclei, or the absence of thereof, was revisited by H. Paukkunen, who examined consistency of neutrino-nucleus DIS data sets from NuTeV, Chorus, and CDHSW experiments with the help of a PDF reweighting technique.

On a complementary note, R. Ent (on behalf of E. Piasetsky) discussed how nuclear-medium modifications to nucleon PDFs observed by EMC can be related to the strength of short-range correlations (SRC) among nucleons inside a heavy nucleus. One can observe a correlation between the Bjorken x dependence of R_{EMC}, the ratio of DIS cross sections per nucleon on a heavy target and deuteron, and the strength of two-nucleon and three-nucleon scattering correlations inside the nucleon, quantified by the ratio $a_2(A,d) = \sigma^A/\sigma_d$ of the cross sections on the nucleus A and deuteron d in the plateau region at Bjorken $x > 1$. This correlation suggests the common dynamical origin of the EMC effect and SRC from scattering of nucleons of high virtuality, which in turn can be used to predict in-medium corrections to nucleon PDFs extracted from the nuclear data. In

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particular, it predicts a significant correction due to the nucleon motion in the deuteron at $x \to 1$, when extracting the ratio $d(x,Q)/u(x,Q)$ in the nucleon from DIS on deuterium targets.

Ongoing and envisioned experiments will shed more light on nuclear PDFs. Among them, the *ed* DIS experiment BONUS in Hall-B at Jefferson Lab uses a promising "spectator tagging" technique to reconstruct the nucleon binding correction in the deuterium by measuring the energy of the spectator proton in each DIS event. This approach effectively allows one to measure DIS cross sections on free neutrons and reliably reconstruct the $d(x,Q)/u(x,Q)$ ratio in the nucleon in the $x \to 1$ limit in an extended range of W. Spectator tagging is confirmed to work in the newest JLab measurements; it opens the door for greatly reducing the errors on d/u in the planned 12 GeV JLab run.

While the proton-lead and lead-lead scattering at the LHC is expected to provide a wealth of data about the nuclear PDFs, even more insightful information can be gathered at the dedicated Electron-Ion Collider and LHeC. The *e*Ca and *e*Pb DIS at the LHeC would probe the nuclear PDFs in a previously unexplored region $10^{-6} < x < 0.01$ [27]. Q dependence of DIS cross sections at the LHeC will provide key information about the gluon PDF in heavy nuclei, hardly known at present.

9. Semi-inclusive kaon production in *ep* DIS...

...can potentially constrain strangeness PDF $s(x,Q)$ in the proton, if dependence on final-state fragmentation functions is placed under control or cancels in cross-section ratios. This motivation drives an updated analysis of semi-inclusive DIS by HERMES [32], which found some modifications in $s(x,Q)$ that they now extract compared to their original publication reported in 2008. The strange PDF is consistent with being zero within the measurement errors at $x \geq 0.15$, while it is below the 2008 parametrization by about 40% at smaller x, where it is now consistent with the NNPDF2.1 $s(x,Q)$ within uncertainties. The shape of $s(x,Q)$ may provide telling clues about the proton structure, as it may contain two components associated with valence-like contributions in the proton wavefunction and radiatively generated $s\bar{s}$ pairs produced from gluon splittings, respectively.

10. The DGLAP picture of collinear factorization...

...underlying the above theoretical calculations may be superseded by alternative theoretical formalisms (BFKL, CCFM, BK/JIMWLK, ...) at very small momentum fractions x accessed in the large-W limit in DIS or in low-mass or forward rapidity processes at the LHC. Several talks in our working group explored formalisms describing the small-x QCD dynamics when the DGLAP framework is unreliable or inapplicable. For example, at $x < 0.01$, rapid growth and large scaling violations in DIS structure functions hint at worsening stability of PQCD series in the DGLAP factorization formalism, as well as at potentially important differences between predictions of various factorization schemes. When predicting the Q dependence of the DIS structure functions, one may choose to solve a system of NLO evolution equations for the whole structure functions, instead of using their factorized expresssions based on the PDFs that evolve according to DGLAP equations. Numerical comparisons of these two solutions for the Q dependence were discussed by M. Hentschinski. At NLO, growing differences between the two solutions are observed as x

decreases, caused by a large contribution from the NLO longitudinal $g \to q$ coefficient function that drives the scaling violations in the first evolution method.

H. Jung reviewed developments in the transverse-momentum-dependent (TMD) factorization formalism for small-x scattering implementing the k_T-unordered evolution picture, and M. Hentschinski reported on implementation of TMD contributions from scattering of sea quarks in the showering program CASCADE. In this approach, parametrizations for TMD PDFs are first found by fitting Monte-Carlo predictions to F_2 measurements at HERA; they differ from the collinear PDFs due to effects of parton showering (with CCFM ordering at LO and x-dependent k_T ordering at NLO) and intrinsic transverse momentum. It can be shown, for example, that the gluon PDF in the available TMD parametrizations is already known with a small uncertainty at small x, while its experimental uncertainty grows to 15-20% at medium x, toward the x region where the DGLAP factorized picture is more appropriate. The TMD PDFs are employed in the Monte-Carlo program CASCADE, which may be superior to the DGLAP Monte-Carlos in handling kinematics of multiple parton emissions in small-x processes. While the CASCADE program continues to evolve, it agrees with the experimental data on select benchmark observables, such as DIS reduced cross sections at HERA or $W+$jet cross sections at the LHC.

Connections to studies of spin-dependent properties of hadronic structure were touched upon in presentations on the Helium Compton form factor and generalized parton distributions studied by CLAS by E. Voutier; on a statistical model for unpolarized and polarized PDFs by J. Soffer; and on the program of studies of unpolarized and spin-dependent structure functions in (semi)inclusive DIS at COMPASS by B. Badelek. In all these talks, interconnected nature of various QCD domains was brought into the spotlight. The entirety of discussions in the working group confirmed the necessity to explore the key QCD issues from various directions in order to complete the picture of hadronic matter.

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