Status of Polarized and Unpolarized Deep Inelastic Scattering

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Abstract
The current status of deep inelastic scattering is briefly reviewed. We discuss future theoretical developments desired and measurements needed to further complete our understanding of the picture of nucleons at short distances.

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1 Introduction

The discovery of the partonic substructure of nucleons by the SLAC-MIT experiments [1] 35 years ago marks the beginning of the investigation of the nucleon’s short distance structure. During the subsequent decades numerous $e^\pm N$, $\mu^\pm N$ and $\nu(\bar{\nu})N$-experiments were performed at SLAC, FNAL, CERN, DESY and JLAB both for unpolarized and polarized targets to refine our understanding of nucleons in wider and wider kinematic domains and at higher luminosities which allowed rather precise measurements.

Along with this, the theoretical understanding deepened applying Quantum Chromodynamics (QCD) perturbatively to higher orders and investigating some of the related operator matrix elements with non-perturbative methods in the framework of Lattice QCD over the last decades. Deep inelastic scattering data do allow for QCD tests at the 1% level [2] at present, which requires $O(\alpha^3_s)$ accuracy for the perturbative calculations.

In the following I give a brief survey on the present status of deeply inelastic scattering (DIS) and discuss the current challenges for theory and experiment in this field.

2 Theory

The theory of deeply inelastic scattering has a history of about 40 years. Beginning with the early work on the light cone expansion [3] and the parton model [4] a conclusive picture of the twist–2 contributions [5] arose in complementary languages. With the advent of QCD [6] and finding asymptotic freedom [7] the scaling violations of nucleon structure functions were studied systematically. The leading order (LO) results for the anomalous dimensions (1973) [8] were followed by the LO coefficient functions, NLO anomalous dimensions and coefficient functions [9], see Figure 1, until after about 20 years the 3-loop anomalous dimensions and coefficient functions could be calculated recently [10]. These calculations are required to match the current experimental accuracies, in particular to extract the QCD parameter $\Lambda_{QCD}$ with a theoretical error below the experimental accuracy. Similar timescales were necessary to reach the 4-loop level for the QCD $\beta$-function. The step from NLO to NNLO expressions required a significant change in technology and intense use of efficient Computer Algebra programs like FORM [11] due to the proliferation of terms emerging. The calculus of harmonic sums and associated functions [12] was both helpful to design a uniform language for higher order calculations, led to a systematic approach, and gained deeper insight into what eventually is really behind intermediate large expressions generated by Feynman diagrams. Still further progress has to be made in the future. QCD perturbation theory took an enormous development during the last three decades transforming our understanding from an initially qualitative one to highly a quantitative level. Physics, as a quantitative science, knows no other ways but precision calculations to put theoretical ideas and theories to an utmost check. In this way, Quantum Chromodynamics became a well tested, established physical theory, which of course is a process to be continued steadily. The mathematical methods being developed in course to perform this task have a deep beauty and give us insight into quantum field theory on a meta-level. Their uniform applicability has furthermore led to a quick spread into a series of neighboring fields, as electro–weak theory and string theory, and became, only a few years after their development, a common tool of the community.

With the advent of HERA it became possible to probe the small–x region. Much work was devoted to resummations in this particular region. As pioneered by Lipatov and collaborators
both the leading contributions to the splitting and coefficient functions can be derived by arguments of scale invariance.
Resummed NLx corrections were calculated in [14]. All these results are of very importance as all–order predictions for the leading and next-to-leading term for splitting functions and Wilson coefficients. The comparison of these predictions with the corresponding results obtained in complete fixed order calculations showed agreement. Furthermore one should stress, that the LO resummations [13] refer to scheme-invariant, i.e. physical quantities, and do thus predict as well corresponding matching conditions between splitting and coefficient functions.

Unfortunately these resummations turn out to be not dominant in the small $x$ region for the description of structure functions, since the respective kernels have to be convoluted with parton densities, which are strongly rising towards small values of $x$ and formally sub-leading terms contribute at the same strengths [15].

For polarized deep–inelastic scattering the anomalous dimensions and coefficient functions are known to NLO at present. Although the statistical and systematic errors for the polarized parton densities is still large, the NNLO improvement would be desirable to further minimize the factorization and renormalization scale uncertainties [16].

Polarized deep inelastic scattering offers access to twist–3 operator matrix elements and predictions for their scale dependence in QCD. At present, the radiative corrections for these terms are worked out in one-loop order. The understanding of QCD higher twist contributions beyond twist 3 both for unpolarized and polarized deep inelastic scattering is still in its infancy and will require more work in the future having more precise data available. Since higher twist anomalous dimensions and coefficient functions refer to more than one ratio of scales but structure functions contain one scale, $x_{Bj}$, only, it is required in general to measure the corresponding operator matrix elements on the lattice at least for the lowest moments.

The light–cone expansion as used in deep inelastic scattering can be generalized to a series of other processes. This more general view concerns non–forward scattering at large space–like virtualities [17]. In this way one may access the angular momentum of partons [18], which is important for the understanding of the spin–structure of nucleons. Moreover, the framework provides several projections on various inclusive quantities of interest. During the last decade a lot of progress has been made in this field calculating the corresponding LO and NLO anomalous dimensions and Wilson coefficients both for the unpolarized and polarized case and understanding conformal symmetry and its breaking for this process in QCD. A related picture was developed also to describe diffractive $ep$–scattering [19], which yields a proper description of this process using the notion of an observed rapidity gap only, without referring to the concept of a pomeron.

3 Experiment

Deep inelastic scattering has been probed by now in a wide kinematic range: $10^{-5} < x < 0.8$, $4 < Q^2 \lesssim 50,000 \text{GeV}^2$. Figure 2 gives an overview on different experiments and facilities showing also the luminosities reached or planned. The proton structure function $F_2^p(x, Q^2)$ is a well measured quantity in all this range. Both to perform flavor separation and QCD tests, it is highly desirable to know the neutron structure function $F_2^n(x, Q^2)$ [20] at comparable accuracy in the same kinematic region. This has been the case for fixed target experiments. Both measurements allow to extract the $u_{val}$ and $d_{val}$ distributions at comparable precision not only in the valence region $x \gtrsim 0.3$ but also in the region below, supplementing the DIS data with Drell-Yan data on $d(x) - u(x)$. A non–singlet QCD analysis to $O(\alpha_s^3)$ was performed [21], widely free on assumptions on the gluon and sea-quark densities. The error of $\alpha_s$ is of $\sim 3\%$. 
The HERA experiments extended the kinematic region by two orders of magnitude both in $x$ and $Q^2$. From the high $Q^2$ large $x$ data the valence distributions will be measured in a yet widely unexplored region, in which potentially new physics may be found. These measurements can be compared to those at lower values of $Q^2$ by evolution. Statistically very precise measurements were performed in the medium and lower $Q^2$ and small $x$ region, which gives access to the charge–weighted sea–quark and gluon distributions. As the detailed knowledge of the gluon and sea–quark distributions is instrumental to the future physics at LHC, HERA plays a key role in determining these quantities. In the case of $F_2(x, Q^2)$ the gluon distribution enters indirectly and determines the slope in $\ln(Q^2)$ of the structure function rather its value. From the measurement of both the slope and value of the structure function one may uniquely unfold the gluon and sea quark contribution without reference to a priori choices of shapes, cf. [22]. Further important input for a measurement of the gluon distribution come from precise data on $F_2^c(x, Q^2)$ and $F_L(x, Q^2)$. For both these structure functions the gluon distribution enters linearly already in the lowest order. Combined non-singlet and singlet NNLO QCD analyses, partly including collider data, were performed in [23,24] measuring $\alpha_s$ to a precision of $2 - 3\%$ with central values.
in complete accordance with that of the non–singlet analysis [21].

The singlet quark distribution can well be extracted from \( ep \)–structure function measurements. On the other hand, the flavor structure of the sea quark distributions is hard to be resolved in neutral current interactions. Here future high luminosity neutrino experiments at high energy will contribute. Drell–Yan data [25] provide information on the difference \( \bar{u}(x) - \bar{d}(x) \). Still higher precision data is needed to resolve as well the \( Q^2 \) dependence. Information about the strange quark distributions \( s(x) \) is currently gotten in a rather indirect way from the di–muon sample in DIS neutrino scattering. The high statistics measurements stem from iron targets and very little is known on the EMC–effect on strangeness in the lower \( x \) region. The charm and beauty quark production in deep inelastic \( ep \) scattering is well described by the heavy flavor Wilson coefficients calculated to NLO [26]. Very recently the NNLO corrections in the case of the longitudinal structure function \( F_{LL}^{Q_Q} \) for \( Q^2 \gg m^2 \) were derived as the first result at \( O(\alpha_s^3) \) [27].

The polarized deep inelastic parton densities are unfolded in QCD analyses of the structure function \( g_1^N(x, Q^2) \), presently at NLO, [28]. \( \Delta u_v(x, Q^2) \) and \( \Delta d_v(x, Q^2) \) are constrained best and an average statement can be made for the polarized sea under some assumptions as \( SU(3)_F \) symmetry or fixed ratios among some of the sea quark distributions. Flavor tagged measurements were performed [29] to determine \( \Delta q_i/q_i \) explicitly. These are first steps and higher luminosity measurements are required to reduce the errors further in the future. Constraints on the polarized gluon density are gotten through the QCD analysis and measuring open charm production. Yet the gluon density has a wide error band with mainly positive central values. First experimental results were obtained for the transversity structure function \( h_1(x, Q^2) \) [30].

Important experimental tests concern the search for twist–3 contributions to polarized structure functions. For purely photonic interactions they are present in the structure function \( g_2(x, Q^2) \) and, in the low \( Q^2 \) region, due to target mass effects, also in \( g_1(x, Q^2) \) [31]. Similar to the Wandzura-Wilczek relation and other twist–2 relations in case of electro–weak interactions, the twist 3 contributions are related by integral relations, which can be tested in high luminosity experiments operating in the lower \( Q^2 \) region.

There is an ongoing programme to study deeply–virtual Compton scattering both at HERA and JLAB for a large set of observables. In course of these investigations one may hope to derive more information on the transverse sub–structure of nucleons and, potentially in the long term, information on parton angular momentum.

### 4 Future Avenues

Various important questions on the short–distance structure of nucleons are yet open and require further experimentation and more theoretical work. In the short run HERA will collect higher luminosity and measure \( F_2(x, Q^2) \), \( F_L^{Q_Q}(x, Q^2) \) with much higher precision. Different experiments will yield more detailed results on \( g_2(x, Q^2) \) and the transversity distribution \( h_1(x, Q^2) \). One of the central issues is to measure \( F_L(x, Q^2) \) with high accuracy in different ranges of \( Q^2 \) and it would be essential to perform this measurement at HERA due to its unique kinematic domain. Much of our understanding of the gluon distribution depends on this measurement.

RHIC and LHC will lead to improved constraints on the gluon and sea quark distributions both for polarized and unpolarized nucleons. JLAB will contribute with high precision measurements in the large \( x \) domain both for unpolarized and polarized nucleons, yet at low values of \( Q^2 \), which will increase with the advent of the higher energy option soon. These measurements
supplement HERA’s high precision measurements at small $x$. The possibility to investigate unpolarized and polarized deep inelastic scattering at the same experiments is crucial to minimize systematic errors. JLAB provides ideal facilities to experimentally explore twist–3 effects in $g_2$ at high precision and to extract higher twist effects for unpolarized structure functions in unified analyses including data from large virtuality DIS at CERN and HERA.

For the time after HERA different $ep$ projects are discussed\(^2\). Two of the projects are ERHIC and ELIC. The kinematic regions for both proposals is situated between the domain explored at CERN and HERA before, cf. Figure 2. While ERHIC reaches somewhat lower values of $x$, ELIC will have the higher luminosity, increasing that of HERA by a factor of 1000 to 8000. As we saw before, various precision measurements are yet to be performed in this region. The programme will not concern inclusive quantities only but explore with sufficient luminosity also more rare channels, which are otherwise inaccessible but yield important theory tests. The high luminosity programme will answer many of the present open questions in the central kinematic region and yield challenging non-trivial tests of Quantum Chromodynamics both concerning perturbative and non–perturbative predictions. On the theory side, perturbative higher order calculations will continue at the level of $O(\alpha_s^3)$ corrections and heavy quark mass effects will be included. As much of the information during the next decade will come from proton–colliders, the respective processes have to be understood at higher precision. At the same time essential progress is expected in the systematic understanding of the moments of parton distributions on the lattice and for measuring the QCD scale $\Lambda_{QCD}$. In this way, high luminosity experimental results, high order perturbative calculations, and highly advanced non-perturbative techniques together will detail our understanding both of the strong force and the nature of nucleons at short and longer distances.

Particle physics always went along two avenues: i) the search for new particles in annihilation processes at ever increasing energies; ii) the search for new sub–structures of matter in resolving shorter and shorter distances, the atomic nucleus and finally the nucleons. At present it seems that quarks are point–like particles. Since this may be temporarily an impression, the search for their possible sub–structure has to be continued with suitable facilities in the future.

\(^2\)Future high-luminosity muon– and neutrino–factories will yield essential contributions to DIS, in particular concerning a detailed exploration of the sea-quark sector both for unpolarized and polarized nucleons. These projects are somewhat further ahead in time.
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