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Theoretical challenges in nucleon structure

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Summary. — In this talk, I will review recent theoretical developments and future challenges in nucleon structure studies.

PACS `13.88.+e` – Polarization in interactions and scattering.
PACS `12.38.Aw` – General properties of QCD (dynamics, confinement, etc.).
PACS `13.60.Hb` – Total and inclusive cross sections (including deep-inelastic processes).
PACS `14.20.Dh` – Protons and neutrons.

1. – Introduction

Nucleon structure is fundamental in sub-atomic physics, and has been under intensive investigation in the last and the beginning of this century. Following the legendary Rutherford experiment, the scientific developments in the last century have revealed the most fundamental structure of the matter in our universe: the nucleus are made of nucleons (protons and neutrons); nucleon is made of partons: quarks and gluons. The latter was discovered by the experiments of deep inelastic scattering (DIS) of lepton on nucleon targets. These discoveries have led to the establishment of the fundamental theory for the strong interaction physics: the quantum chromodynamics (QCD). Inclusive DIS experiments probe the parton distribution functions (PDFs) which describe the momentum distributions of the partons inside the nucleon. There have been tremendous progresses in our understanding of these distributions from various high energy experiments, including DIS, Drell-Yan lepton pair production, and hard inclusive process (jet, electroweak boson production) in nucleon-nucleon collisions. On the other hand, the inclusive measurements of the above processes only probe one-dimension of the parton distributions. In recent years, hadron physics community is pursuing an extension of this picture to including the transverse direction. The goal is to reach a three-dimension tomography of partons inside the nucleon. Since the nucleon is moving in the $\hat{z}$-direction, the extension to the transverse direction can be either in the coordinate space or in the momentum space: the transverse momentum extensions are called the transverse-momentum–dependent parton distributions (TMDs); the transverse coordinate space extensions are called the generalized parton distributions (GPDs).

TMDs and GPDs are conventionally the major focuses of the QCD'N series meetings, and are well covered in this workshop. In the following, I will summarize the current status and future challenges from a theoretical point of view. The selection of topics is undoubtedly based on my personal bias. Fortunately, we do have a wide range of presentations during the workshop, where most of recent developments are discussed. I will start with the fundamental question of nucleon spin, and then discuss TMDs and GPDs. I will also try to highlight recent advances in the connection of the TMDs and small-x saturation physics, which I hope will stimulate further developments.

2. – Nucleon spin and its decomposition

Understanding the proton spin structure has been a driving motive for intense spin-physics activities in hadron physics in the last two decades. Much progress has been made both experimentally and theoretically [1]. The ultimate goal of the spin physics is to understand the contributions that go into fulfilling the spin sum rule,

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta g(\mu) + L(\mu), \tag{1}$$

where $\Delta\Sigma$ and Δg are the total quark and gluon helicity contributions to the proton spin, respectively,

$$\Delta\Sigma(\mu) \equiv \sum_q \int_0^1 \mathrm{d}x[\Delta q(x,\mu) + \Delta\bar{q}(x,\mu)], \qquad \Delta g(\mu) = \int_0^1 \mathrm{d}x \Delta g(x,\mu). \tag{2}$$

$L(\mu)$ is the total contribution of the orbital angular momentum (OAM) from quarks and gluons. The scale μ indicates the momentum scale at which these quantities are measured. The quark and gluon helicity distributions can be studied from the longitudinal spin program, where a longitudinally polarized lepton beam (or proton beam) scatters on a longitudinally polarized nucleon. The polarized quark distributions have been well determined from the polarized DIS experiments, and it was found that the total quark spin contribution to the proton spin is about 30%. In the hadronic reactions at RHIC, the double spin asymmetry can probe the polarized gluon distribution. Both PHENIX and STAR Collaborations have measured the spin asymmetries for various hard processes at RHIC, and the latest results are reported in this meeting. Theoretically, it is very important to perform a global analysis of the polarized parton distributions from fitting to the world-wide experimental data, from which we can extract $\Delta\Sigma$ and Δg. In fig. 1, the current constraints for them from one of the global fits has been shown, from which we can see that we still have large uncertainty for the gluon helicity contribution to the nucleon spin.

The polarized DIS experiments can also provide the constraints on the gluon helicity distributions through the evolution of the polarized structure functions. This is the major emphasis of the planned electron-ion collider (EIC). With the unique coverage in both x and Q^2, the EIC would provide the most powerful constraints on $\Delta\Sigma$ and Δg [1]. Also shown in fig. 1 is the reduction in uncertainties of them with the proposed EIC machine. Clearly, the EIC will make a huge impact on our knowledge of these quantities. Meanwhile, by subtracting the total helicity contributions, we will be able to estimate how large the total orbital angular momentum contributions from the quarks and gluons.

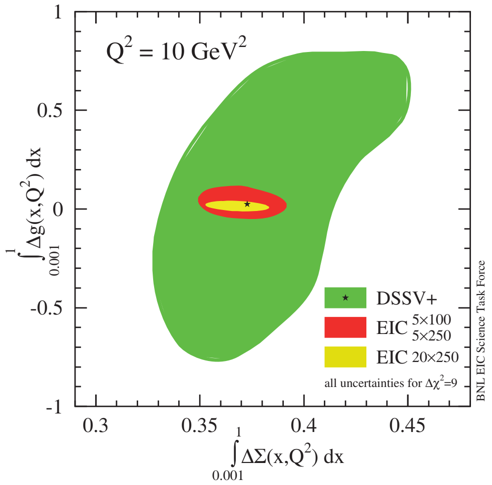

Fig. 1. – State-of-the-art determination (DSSV) of total quark and gluon helicity contributions to the proton spin and future perspective from an electron-ion collider. (The figure is taken from ref. [2].)

Of course, to further determine the individual contributions of the OAM from quarks and gluons, we need more information. This is how the GPD sum rule comes to play an important role, which reads as

$$J_q = \frac{1}{2}\Sigma_q + L_q = \lim_{t\to 0}\frac{1}{2}\int \mathrm{d}x x\left[H^q(x,\xi,t) + E^q(x,\xi,t)\right], \tag{3}$$

where J_q is the total quark contribution to the proton spin, H and E are GPDs. After subtracting the helicity contribution Σ_q, the above equation will provide the quark OAM contribution to the proton spin. The GPDs can be measured in many different experiments, for example, DVCS and hard exclusive meson production. Experimental efforts have been made at various facilities, including HERMES at DESY, Jefferson Lab, COMPASS at CERN. Future JLab with 12 GeV upgrade and the planed EIC will definitely play important roles in these studies. The theoretical framework has been well established for the GPD studies. However, since GPDs depend on three variables (x, ξ, t) in addition to the scale variable μ, it is much more difficult to extract from the experiments than that for the integrated PDFs (which only depend on x). One of the great challenges we face for the GPD studies is to reduce the model-dependence in the extraction of the GPDs from experiments. With more data available in the future, we believe that this should be achieved in light of recent theory developments [3].

To directly probe the quark OAM, we have to further decompose the nucleon helicity contribution,

$$J_q^3 = \int \mathrm{d}^3\vec{\xi} M_q^{+12}(\xi) = \int \mathrm{d}^3\vec{\xi}\left[\overline{\psi}\gamma^+\left(\frac{\Sigma^3}{2}\right)\psi + \overline{\psi}\gamma^+\left(\xi^1(iD^2) - \xi^2(iD^1)\right)\psi\right], \tag{4}$$

where the first term is the quark helicity and the second term the quark OAM. From this expression, we clearly see that the quark OAM involves transverse component of the gluon field, and thus is related to three-parton correlations. However, it has been found recently that we do have a partonic interpretation of parton OAM through the so-called Wigner distributions [4-7].

3. – Parton orbital angular momenta and nucleon tomography

The parton Wigner distribution was introduced as the quantum phase space distribution of parton in nucleon [4], which depends on momentum and coordinate space variables. Naturally, the Wigner distribution unifies the TMDs and GPDs. A partonic picture of the orbital contribution to the nucleon helicity necessarily involves parton's transverse momentum. To define a gauge invariant TMD parton distributions, we have to include a gauge link extended from the location of parton field to infinity along the conjugating light-cone direction n^μ,

$$\Psi_{LC}(\xi) = P\left[\exp\left(-ig\int_0^\infty \mathrm{d}\lambda n\cdot A(\lambda n+\xi)\right)\right]\psi(\xi). \tag{5}$$

where P indicates path ordering. In practical applications, we can also choose a straight-line gauge link along the direction of spacetime position ξ^μ,

$$\Psi_{FS}(\xi) = P\left[\exp\left(-ig\int_0^\infty \mathrm{d}\lambda \xi\cdot A(\lambda \xi)\right)\right]\psi(\xi). \tag{6}$$

This link reduces to unity in Fock-Schwinger gauge, $\xi\cdot A(\xi) = 0$. With the above definitions, we can write down the quark Wigner distribution as,

$$W_{\mathcal{P}}(k^+ = xP^+, \vec{b}_\perp, \vec{k}_\perp) = \frac{1}{2}\int \frac{\mathrm{d}^2\vec{q}_\perp}{(2\pi)^3}\int \frac{\mathrm{d}k^-}{(2\pi)^3} e^{-i\vec{q}_\perp\cdot\vec{b}_\perp}\left\langle \frac{\vec{q}_\perp}{2}\left|\hat{\mathcal{W}}_{\mathcal{P}}(0,k)\right| - \frac{\vec{q}_\perp}{2}\right\rangle, \tag{7}$$

with the Wigner operator,

$$\hat{\mathcal{W}}_{\mathcal{P}}(\vec{r},k) = \int \overline{\Psi}_{\mathcal{P}}(\vec{r}-\xi/2)\gamma^+\Psi_{\mathcal{P}}(\vec{r}+\xi/2)e^{ik\cdot\xi}\,\mathrm{d}^4\xi, \tag{8}$$

where $\mathcal{P}$ denotes the path choice of LC or FS, $\vec{r}$ is the quark phase-space position and k the phase-space four-momentum.

It can be shown that the total OAM sum rule in term of parton's Wigner distribution,

$$\frac{\langle PS|\int \mathrm{d}^3\vec{r}\,\overline{\psi}(\vec{r})\gamma^+(\vec{r}_\perp\times i\vec{D}_\perp)\psi(\vec{r})|PS\rangle}{\langle PS|PS\rangle} = \int(\vec{b}_\perp\times\vec{k}_\perp)W_{FS}(x,\vec{b}_\perp,\vec{k}_\perp)\mathrm{d}x\,\mathrm{d}^2\vec{b}_\perp\,\mathrm{d}^2\vec{k}_\perp \tag{9}$$

which gives a parton picture for the gauge-invariant OAM [7].

Similarly, the canonical OAM in light-cone gauge acquires the simple but gauge-dependent parton sum rule in the quantum phase space [5,6],

$$\begin{aligned} l_q &= \frac{\langle PS|\int \mathrm{d}^3\vec{r}\,\overline{\psi}(\vec{r})\gamma^+(\vec{r}_\perp\times i\vec{\partial}_\perp)\psi(\vec{r})|PS\rangle}{\langle PS|PS\rangle} \\ &= \int(\vec{b}_\perp\times\vec{k}_\perp)W_{LC}(x,\vec{b}_\perp,\vec{k}_\perp)\mathrm{d}x\,\mathrm{d}^2\vec{b}_\perp\,\mathrm{d}^2\vec{k}_\perp. \end{aligned} \tag{10}$$

The measurability of this Wigner distribution and directly probe to the quark OAM will be an important challenge in future studies. Nevertheless, we can set up a standard way to picture the nucleon tomography with the Wigner distribution constructed from the light-cone wave functions [8], which provides multi-dimension imaging of partons in nucleon.

4. – Transverse-momentum–dependent parton distributions and small-x saturation

Theoretical studies of TMDs started long ago. Recent developments have made great progress in the exploration of these distribution functions and the associated single spin asymmetry phenomena [9]. They provide not only the intuitive picture of the nucleon tomography [10], but also the important opportunities to investigate the the nontrivial QCD dynamics associated with these physics: the QCD factorization, the universality of the parton distributions and fragmentation functions, and their scale evolutions.

Among those TMD parton distributions and fragmentation functions, two functions have been mostly discussed: the Sivers quark distribution and the Collins fragmentation function. The Sivers quark distribution represents a distribution of unpolarized quarks in a transversely polarized nucleon, through a correlation between the quark's transverse momentum and the nucleon polarization vector. The Collins function represents a correlation between the transverse spin of the fragmenting quark and the transverse momentum of the hadron relative to the "jet axis" in the fragmentation process. Although they both belong to the so-called "naive-time-reversal-odd" functions, they do have different universality properties. For the quark Sivers function, because of the initial/final state interaction difference, they differ by signs for the semi-inclusive hadron production in DIS (SIDIS) and Drell-Yan processes,

$$\text{Sivers SSA}|_{\text{DY}} = -\text{Sivers SSA}|_{\text{DIS}}. \tag{11}$$

It is of crucial to test this nontrivial QCD predictions by comparing the SSAs in these two processes. The Sivers single spin asymmetry in SIDIS process has been observed by the HERMES Collaboration, and the planned Drell-Yan measurement at RHIC and other facility will test this prediction. On the other hand, there have been several studies showing that the Collins function is universal between different processes, primarily in the SIDIS and e^+e^- annihilation, and recently in pp collisions.

In the last couple of years, there has been very exciting progress in studying the scale evolution for the TMDs and the QCD resummation for the SSA observables [11-14]. In particular, the next-to-leading order hard factors are calculated for single spin-dependent cross-sections in Drell-Yan and SIDIS processes, and the QCD resummation formalisms are obtained [11]. Future challenges will be to apply these evolution and resummation formalisms to the processes we are interested in and study the associated QCD dynamics. Early progresses have been made along this direction [13], which however acquires important cross-checks.

More recently, important developments have been made on the connections between the TMD formalism and the small-x saturation physics in various aspects. The emergence of the gluon saturation at small-x changes the landscape of parton distributions inside the nucleon/nucleus. In the dense region, the QCD dynamics will be different as compared to that in the dilute region. For example, the evolution equation has to be modified to account for the high density gluon distribution. The QCD dynamics in the dilute region, aka, the DGLAP evolution, has been systematically studied in the last three decades thanks to the vast experimental data generated from various high energy facilities. On the other hand, the investigation of the small-x dynamics (either BFKL or BK-JIMWLK) had just started very recently, although the theoretical arguments have been put in place in the late 70s. A central question is to identify the boundary between the dilute and dense regions, the so-called saturation limit.

It was realized that the semi-inclusive processes, which involve a hard scale Q in addition to the transverse momenta of the observables, have unique feature to probe the saturation physics. The most important advantage is that they can directly access to the unintegrated gluon distributions, which are important ingredients in the saturation physics. They unveil the importance of the multiple interaction effects in the factorization of the hard processes in the small-x calculations, and have close relation to the TMDs discussed above [15]. Several processes have been proposed in the literature, including semi-inclusive DIS, low p_t Drell-Yan, and back-to-back di-hadron correlations in forward pA processes. Another important theoretical progress has recently been made that the Sudakov double logarithms can be resummed consistently in the small-x formalism [16]. This provides a solid theoretical foundation for rigorous investigation of saturation physics with hard processes. I hope this will stimulate more developments in the near future.

5. – Summary

In summary, there have been great progresses in theoretical developments of nucleon structure studies, and many challenges ahead of us as well. It is very exciting time.

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