Gluon helicity and parton orbital angular momentum contribution to the proton spin

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In 1987, the European Muon Collaboration (EMC) measured the percentage of the quark spin (or helicity) contribution from polarized deep-inelastic scattering, and discovered that it was consistent with zero [1, 2], which was a strong challenge to the constituent quark model and triggered the search for the missing spin [3]. Now it is understood from the global analysis of polarized DIS data that the quark spin contributes about one third, and the gluon helicity ΔG, as indicated by the RHIC data, also has a positive definite contribution [4, 5]. Besides, it is also believed that the quark and gluon orbital angular momenta (OAM) can play important roles in the proton spin. Nowadays, understanding the proton spin structure is not only an important goal of hadron physics, but also has the potential to provide a new arena for the search of new physics that are sensitive to spin-dependent interactions.

The Electron-Ion Collider (EIC) is expected to precisely measure ΔG and access the canonical quark and gluon OAM after its completion by 2030. The quark and gluon canonical OAM can be measured through twist-three generalized parton distritbutions or the so-called Wigner distribution [6, 7], which can be accessed through hard exclusive processes. For example, it has been shown by some of the authors that the gluon canonical OAM can be probed through the single target spin asymmetry in the exclusive electro-production of quark and anti-quark jets [8, 9]. As a counterpart, the kinematic OAM of quarks and gluons can be measured through deeply virtual Compton scattering [10, 11], though it does not have a simple parton interpretation.

Meanwhile, on the theory side, the quark spin and kinetic OAM are frame and gauge independent, and can be straightforwardly calculated in lattice QCD [12]. After two decades of efforts, now the lattice results of the quark spin contribution are converging to that from global analysis [13]. Unlike the quark spin, ΔG depends on the infinite-momentum frame and cannot be directly calculated on the lattice, so are the canonical quark and gluon OAM. In recent years, a breakthrough was made with the large-momentum effective theory (LaMET) [14–18], where one can match the large-momentum matrix element of a static "gluon spin" operator, which is calculable in lattice QCD, to ΔG in the IMF [14]. The choice of the static "gluon spin" operator is not unique [19], which allows for a class of operators on the lattice to be explored. The same method can also be applied to the lattice calculation of the canonical OAM [17, 20].

The first lattice calculation of ΔG was carried out by the χQCD collaboration [21], of which some of the authors are members. In this calculation, the proton matrix element of the static gluon spin operator was calculated at different momenta. With leading-order matching to the physical ΔG in perturbative QCD, it was found that the gluon helicity contributes about one half to the proton spin with a total relative uncertainty of about 20%, which is consistent with truncated lowest moment of the polarized gluon parton distribution function extracted from RHIC data [4, 5].

In this letter of interest, we propose to calculate the gluon helicity and parton canonical OAM contributions from lattice QCD, as well as the measurement of the canonical OAM from the EIC. The efforts include:

1) Develop a systematic procedure for the nonperturbative renormalization of the static gluon spin operator on the lattice, and its perturbative matching to the physical gluon helicity;

2) Explore different operator choices for the static gluon spin to find the optimal operator that allows for fast convergence to ΔG in the large momentum limit;

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3) Understand the operator mixing for the canonical OAM on the lattice, and develop a systematic procedure for its renormalization and matching to the physical observables;

4) Precision calculation of ΔG and parton canonical OAM from lattice QCD, as well as the kinetic OAM, thus complementing the EIC experiments;

5) Perturbative correction and evolution for the observables that probe the parton canonical OAM;

6) Extraction of parton canonical OAM from experiments at the EIC.

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