Positive gluon helicity in the nucleon from lattice QCD[†]

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An outstanding problem in nuclear and particle physics remains to explain why the quark spin contributes approximately 30% to the proton spin, known as the "proton spin puzzle" for more than three decades.[1)] An ongoing effort in theoretical and experimental nuclear physics, including the future Electron-Ion Collider (EIC), is to realize the proton spin decomposition in terms of the quark and gluon spin, and their orbital angular momenta. One significant challenge is to discern how much of the remaining spin budget is contributed by gluons. In this article, we present the first lattice QCD determination of the gluon helicity parton distribution function, $\Delta g(x)$ as a function of momentum fraction x in a fast-moving proton, with numerical evidence toward disfavoring negative gluon polarization in the nucleon.

To determine the Euclidean correlation function associated with the gluon helicity distribution, we calculate matrix elements of the gluon field $G_{\mu\nu}$ and its dual $\widetilde{G}_{\lambda\beta} = (1/2)\epsilon_{\lambda\beta\rho\gamma}G^{\rho\gamma}$ separated by a spatial Wilson line[2)] of length z. However, the renormalized Euclidean matrix elements involve a contamination term when expressed in terms of invariant amplitudes:[3)]

$$\begin{aligned}\Delta\mathfrak{M}(\omega, z^2) &= [\Delta\mathcal{M}_{sp}^{(+)}(\omega, z^2) - \omega\Delta\mathcal{M}_{pp}(\omega, z^2)] \\ &\quad -\frac{m_p^2}{p_z^2}\omega\Delta\mathcal{M}_{pp}(\omega, z^2), \qquad (1)\end{aligned}$$

where $\omega = zp_z$ and p_z is the hadron boost. In contrast, the light cone correlation that gives access to $x\Delta g(x, \mu)$ at a scale μ does not receive contribution from the contamination term $(m_p^2/p_z^2)\omega\Delta\mathcal{M}_{pp}(\omega, z^2)$ present in the lattice QCD matrix elements. In a recent publication indicated in the footnote,[†] we proposed a solution to eliminate this term, and using physics-informed neural network analysis, for the first time, obtained the light-cone correlation function $\Delta\mathcal{I}_g(\omega, \mu)$ from the lattice QCD matrix elements, which can give access to the $\Delta g(x)$ distribution according to the following relation,

$$\begin{aligned}\Delta\mathcal{I}_g(\omega, \mu) &\equiv i[\Delta\mathcal{M}_{sp}^{(+)}(\omega, \mu) - \omega\Delta\mathcal{M}_{pp}(\omega, \mu)] \\ &= \frac{i}{2}\int_{-1}^{1} dx e^{-ix\omega} x\Delta g(x, \mu). \qquad (2)\end{aligned}$$

In Fig. 1, we present the lattice QCD determination of gluon helicity parton distribution function. While lattice QCD determination of parton distribution functions are limited in the moderate to large x region, from Fig. 1, it is evident that the lattice QCD calculation of $x\Delta g(x)$ disfavors the negative $x\Delta g(x)$ solution

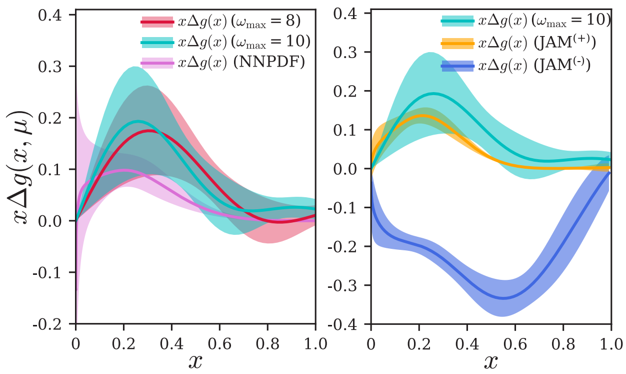

Fig. 1. Functional form independent gluon helicity distributions (red and cyan bands) from the lattice data for two different ranges of ω and comparison with the PDFs from NNPDF[4)] (left panel) and the JAM positive and negative solutions[5)] (right panel) at scale $\mu = 2$ GeV.

from the global analysis in Ref. 5). This is the most important physics outcome of this calculation regarding the constraint on the large negative gluon helicity parton distribution function in the moderate to large-x values.

We obtain, the gluon helicity in the proton, $\Delta G(\mu = 2\text{ GeV}) = 0.405(196)_{\text{stat}}(081)_{\text{sys}}$, which is remarkably consistent with $\Delta G = 0.251(47)_{\text{stat}}(16)_{\text{sys}}$ obtained in the only lattice QCD calculation[6)] at the physical pion mass, continuum, and infinite volume limits using a local matrix element.

In conclusion, we have presented the first lattice QCD calculation that supports a positive gluon helicity distribution, and therefore a positive gluon spin contribution to the proton spin budget, in contrast to the most recent global analysis. Given the current challenges in the extraction of the gluon helicity from the available experimental data, this lattice QCD calculation has the potential to open an avenue for elucidating the role of gluons in the nucleon's spin structure.

References

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