Deuteron PDF Simulation on Lattice QCD

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Introduction

Parton distribution functions(PDFs) contain a lot of information about the intrinsic properties of nuclear and nucleus. They are also the necessary input for us to compute the cross sections in electron-hadron or hadron-hadron collisions. A few years ago, large-momentum effective theory (LaMET) has been proposed [1], which allows us to calculate PDFs directly on Lattice. Among the on-going projects of PDFs calculation, PDFs of of nuclear like Deuteron attract a lot of attention since they can be used to describe the difference between nuclear and free nucleon and can help us better understand the interaction between nucleus. In the following sections, we show a preliminary Lattice study of Deuteron PDFs based on LaMET.

Theoretical Framework

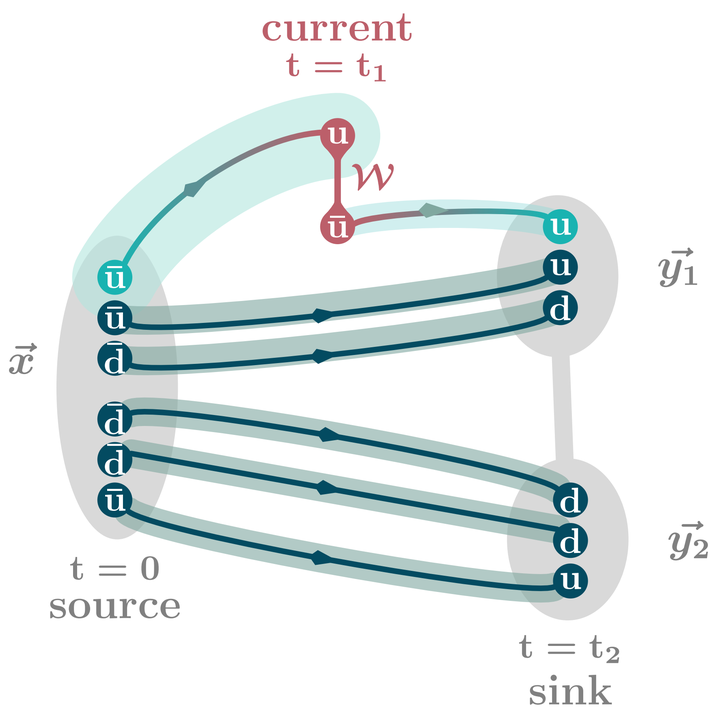
According to LaMET framework, light cone quantities such as PDFs can be extracted from the correlators of static operators which can be directly calculated on lattice. To calculate quark PDFs, one starts with calculating quasi-PDF, which takes the form:

$$\tilde{q}_\Gamma(x,\mu) = \int \frac{dz}{4\pi} e^{-ixP_z} \langle P|\bar{\psi}\Gamma U(z,0)\psi(0)|P\rangle. \quad (1)$$

Here $\langle P|\bar{\psi}\Gamma U(z,0)\psi(0)|P\rangle$ is the equal-time correlator which can be calculated directly on lattice. Γ is chosen as γ_t, which can be matched to PDF in the light cone limit. $|P\rangle$ means the unpolarized Deuteron with momentum P along z direction.

In our simulation the correlator of Deuteron consists a Hexaquark source with six quarks located at the same spatial point and a Dibaryon sink with two nucleons located at different spatial points. The specific form of nucleon and Deuteron operator can be found in Ref. [2].

One possible contraction of equal-time correlator of Deuteron is shown in the lower picture:



The bare quasi correlator contains both linear divergence and logarithmic UV divergence and we adopt the so-called hybrid-scheme to remove the divergences [3]. After that, we can perform a Fourier transform to momentum space, then we match quasi-PDF to light cone PDF through a perturbative matching.

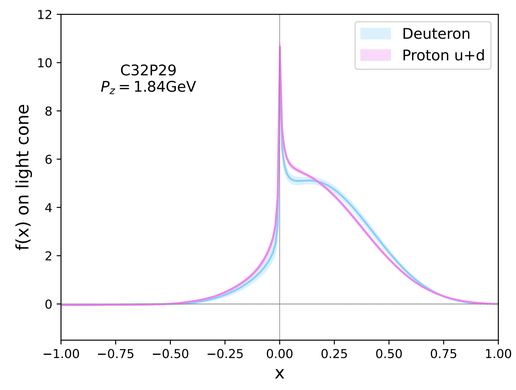
Simulation Setup

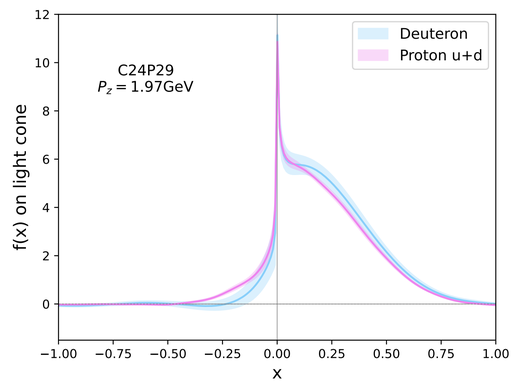
We use ensemble C32P29 and C24P29 with clover fermion action generated by CLQCD collaboration . The parameters of the ensembles used are:

Ensemble	$L^3 \times T$	a (fm)	m_π(MeV)	$m_\pi L$	c_{sw}	N_{cfg}
C32P29	$32^3 \times 64$	0.105	292.9(1.2)	4.9	1.1609	870
C24P29	$24^3 \times 72$	0.105	293.1(1.3)	3.7	1.1609	759

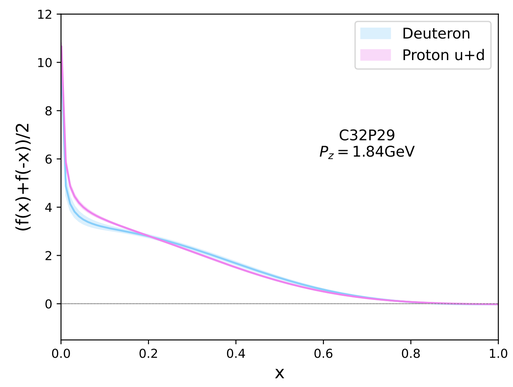
Preliminary Results

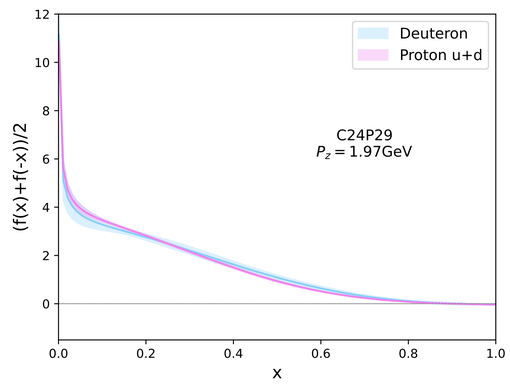
After calculating equal-time correlator of Deuteron and Proton, we perform renormalization at $\mu = \sqrt{10}$ GeV, then we obtain light cone PDF through Fourier transform and perturbative matching. The preliminary results of PDF are shown in the following pictures:





Here P_z represent the momentum of nucleon. The momentum of Deuteron is twice that of nucleon. For Proton we add together u quark and d quark to have a rough comparison with Deuteron. These curves of $f(x)$ contain the mixing of sea quarks which can be eliminated by calculating $(f(x) + f(-x))/2$. The contributions of valence quarks are plotted in the following pictures:





References

[1] Xiangdong Ji. Parton Physics on a Euclidean Lattice. *Phys. Rev. Lett.*, 110:262002, 2013.

[2] Saman Amarasinghe, Riyadh Baghdadi, Zohreh Davoudi, William Detmold, Marc Illa, Assumpta Parreno, Andrew V. Pochinsky, Phiala E. Shanahan, and Michael L. Wagman. Variational study of two-nucleon systems with lattice QCD. *Phys. Rev. D*, 107(9):094508, 2023.

[3] Xiangdong Ji, Yizhuang Liu, Andreas Schäfer, Wei Wang, Yi-Bo Yang, Jian-Hui Zhang, and Yong Zhao. A Hybrid Renormalization Scheme for Quasi Light-Front Correlations in Large-Momentum Effective Theory. *Nucl. Phys. B*, 964:115311, 2021.