2022 Meeting on Lattice Parton Physics from Large Momentum Effective Theory (LaMET2022)

Thursday, December 1, 2022 - Saturday, December 3, 2022

Argonne National Laboratory

Book of Abstracts

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Session I / **1**

Large-Momentum Effective Theory vs. Short-Distance Operator Expansion: Contrast and Complementarity

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Many present lattice QCD approaches to calculate the parton distribution functions (PDFs) rely on a factorization formula or effective theory expansion of certain Euclidean matrix elements in boosted hadron states. In the quasi- and pseudo-PDF methods, the matching coefficient in the factorization or expansion formula includes large logarithms near the threshold, which arise from the subtle interplay of collinear and soft divergences of an underlying 3D momentum distribution. We use the standard prescription to resum such logarithms in the Mellin-moment space at next-to-leading logarithmic accuracy, which also accounts for the DGLAP evolution, and we show that it can suppress the PDF at large x. Unlike the deep inelastic scattering and Drell-Yan cross sections, the resummation formula is away from the Landau pole. We then apply our formulation to reanalyze the published lattice results for the pion valence PDF, and find that within the current data sensitivity, the effect of threshold resummation is marginal for the accessible moments and the PDF at large x.

Session I / **2**

Lattice Calculation of Nucleon Transversity Distribution

Nucleon transversity distribution is an essential quantity that reveals the nucleon's transverse spin structure. It also provides crucial inputs for understanding high-energy collision experiments involving transversely polarized nucleons. As a chiral-odd quantity, it's difficult to measure experimentally. Thus, ab initio lattice QCD calculations play an important complementary role. We report a state-of-the-art lattice calculation of nucleon isovector quark transversity distribution using large-momentum effective theory. The calculation is done with high statistics on six different lattice ensembles. This is the first result extrapolated reliably to the continuum, physical pion mass and infinite momentum limit. It provides guidance for future measurements of nucleon transversity distribution.

Session I / **3**

Flavor-non-singlet Structure of the Nucleon

I describe the structure of the nucleon obtained within the pseudo-PDF framework. In particular I present recent calculations of the unpolarized, helicity and transversity distributions. We employ the distillation framework which allows a more complete sampling of the lattice and, together with momentum smearing, enables us to extend the range of Ioffe time accessible to our computation. This, together with an expansion in terms of Jacobi polynomials, enables us to isolate the leading twist distributions from some of the higher twist contributions and sources of systematic uncertainties. I conclude with the prospects for future calculations.

Session I / **4**

The NNLO unpolarized isovector quark PDF of the nucleon at the

physical point from lattice QCD

We present recent work on the calculation of the unpolarized isovector quark parton distribution function (PDF) of the nucleon at the physical point from lattice QCD utilizing a next-to-next-to-leading order (NNLO) matching. The main observables for these calculations are equal-time spatially-separated matrix elements of a boosted nucleon. There are two main strategies one can employ to obtain information on the PDF from these matrix elements. The first is based on the reduced Ioffe-time pseudo-distribution, which employs an OPE that is valid at short distances. Using this approach, we match to the light-cone Ioffe-time distribution via a deep neural network to solve the inverse problem that arises from this strategy. The second approach is based on Large-Momentum Effective Theory, which allows for a matching in Bjorken-x space. We apply this method with the recently developed hybrid renormalization scheme to produce an x-dependent PDF.

Session II / **5**

The matching and renormalon ambiguity in hybrid renormalization

I will discuss the matching of quasi-PDF and quasi-GPD for the hybrid scheme. The IR renormalon ambiguity of the quasi-PDF in this scheme is also discussed.

Session II / **6**

Origin and Resummation of Threshold Logarithms in the Lattice QCD Calculations of PDFs

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Many present lattice QCD approaches to calculate the parton distribution functions (PDFs) rely on a factorization formula or effective theory expansion of certain Euclidean matrix elements in boosted hadron states. In the quasi- and pseudo-PDF methods, the matching coefficient in the factorization or expansion formula includes large logarithms near the threshold, which arise from the subtle interplay of collinear and soft divergences of an underlying 3D momentum distribution. We use the standard prescription to resum such logarithms in the Mellin-moment space at next-to-leading logarithmic accuracy, which also accounts for the DGLAP evolution, and we show that it can suppress the PDF at large x. Unlike the deep inelastic scattering and Drell-Yan cross sections, the resummation formula is away from the Landau pole. We then apply our formulation to reanalyze the published lattice results for the pion valence PDF, and find that within the current data sensitivity, the effect of threshold resummation is marginal for the accessible moments and the PDF at large x.

Session II / **7**

Resumming Quark's Longitudinal Momentum Logarithms in LaMET Expansion of Lattice PDFs

In the large-momentum expansion for parton distribution functions (PDFs), the natural physics scale is the longitudinal momentum (p_z) of the quarks (or gluons) in a large-momentum hadron. We show how to expose this scale dependence through resumming logarithms of the type $\ln^n p_z/\mu$ in the

matching coefficient, where μ is a fixed renormalization scale. The result enhances the accuracy of the expansion at moderate $p_z > 1$~GeV, and at the same time, clearly shows that the partons cannot be approximated from quarks with $p_z \sim \Lambda_{\rm QCD}$ which are not predominantly
collinear with the parent hadron momentum, consistent with power counting of the large-momentum effective theory. The same physics mechanism constrains the coordinate space expansion at large distances z, the conjugate of p_z,
as illustrated in the example of fitting the moments of the PDFs.

Session III / **8**

Progress in calculation of the fourth Mellin moment of the pion light-cone distribution amplitude using the HOPE method

The light-cone distribution amplitude (LCDA) of the pion carries information about the parton momentum distribution and is an important theoretical input into various predictions of exclusive measurements at high energy, including the pion electromagnetic form factor. This talk presents progress towards a lattice calculation of the fourth Mellin moment of the LCDA using the heavy quark operator product expansion (HOPE) method.

Session III / **9**

Calculation of pion distribution amplitude I: renormalization and power accuracy

Calculating the x-dependence of pion distribution amplitude (DA) using the large-momentum effective theory has entered the era where the systematics need to be controlled. We demonstrate the necessity of a proper renormalization and a corresponding perturbative matching to achieve power accuracy ~$O(\Lambda_{QCD}/xP_z)$. By resumming the leading renormalon in the perturbative series, we are able to extract renormalization factors that improve the consistency of the coordinate-space correlation with predictions from the operator product expansion. Using a matching kernel with the same renormalon resummation, we are able to eliminate the ~$O(\Lambda_{QCD}/xP_z)$ uncertainties, thus improving the accuracy of the lightcone DA extraction.

Session III / **10**

Calculation of pion distribution amplitude II: large-log resummation and complementarity

Session IV / **11**

Lattice QCD prediction of pion and kaon electromagnetic form factor at large Q^2 up to 10 and 28 GeV^2

The electromagnetic form factor, especially its asymptotic behavior for large momentum transfer (Q^2), of pion and kaon provides crucial insight into the partonic structure of a Nambu-Goldstone

boson in the strong interaction. Studies of the electromagnetic form factor of pion and kaon up to Q^2 ~ 6 GeV^2 are underway at the ongoing JLab12 experiment, and its measurements in an extended range of Q^2 ~ 10 –40 GeV^2 are planned at the future Electron-Ion Collider (EIC). For the first time, we will present results for the pion and kaon electromagnetic form factor in the range of Q^2 ~ 0 –10 and 28 GeV^2, respectively, from state-of-the-art lattice QCD calculations carried out using physical values of up, down, and strange quark masses. These results will provide benchmark QCD predictions for model-based studies and the experimental measurements, in particular at the boundaries between the JLab12 and the EIC.

Session IV / **12**

Interpolation method from instant form to the light-front dynamics

As is well known, it is difficult to compute quantities defined on the light-front in a lattice approach, since the light-front dynamics is strictly in the Minkowski space, while the lattice formulation is in the Euclidean space. I will introduce a method to connect the light-front dynamics (LFD) to the ordinary instant form dynamics (IFD), which is called the interpolation method. By having an angle parameter called the interpo- lation angle, denoted as δ, which runs between 0° and 45°, we can unify the IFD and LFD formalisms into one. Letting $\delta \longrightarrow 0$ gets back to the IFD, and properties of the LFD are recovered by letting $\delta \longrightarrow \pi/4$. The light-front zero mode issues can be examined by studying the limit of $\delta \longrightarrow \pi/4$. In this talk, I will present the quasi-PDFs in 't Hooft model (large Nc QCD in 1+1 space-time dimensions), obtained by solving the Bethe-Salpeter equation numerically in a general interpolation form. I will compare the results of letting δ get close to $\pi/4$, versus boosting to a large momentum in the instant form.

Session I / **13**

TMD Evolution from Lattice QCD

I will present a lattice QCD calculation of the nonperturbative Collins-Soper kernel, which describes the rapidity evolution of quark transverse-momentum-dependent parton distribution functions. I will discuss ongoing work to perform the first determination of the Collins-Soper kernel using approximately physical quark masses and various challenges and systematic uncertainties that arise, including power corrections and Fourier transform truncation effects.

Session I / **14**

Unpolarized Nucleon TMDPDFs from Lattice QCD: I

In this work, we present the first ab-initio numerical results of unpolarized proton's isovector transverse-momentum-dependent parton distribution functions (TMDPDFs), which are essential for exploring the inner pictures of nucleon, as well as for predicting the observables in multi-scale, non-inclusive high energy processes such as semi-inclusive deep-inelastic scattering and Drell-Yan scattering at the large hadron collider (LHC) or electron ion collider (EIC). We adopt a $N_f = 2 + 1 + 1$ MILC ensemble with valence clover fermions on a highly improved staggered quark sea (HISQ) to generate the Euclidean correlations related to quasi TMDPDFs, employ the state-of-art techniques in the processes as renormalization, extrapolation in correlation distance and so on. Associating with the

up-to-date results of intrinsic soft function and Collins-Soper kernel, and introducing the renormalization group evolution improved one-loop matching in the framework of large-momentum effective theory (LaMET), we obtain the numerical results of light-cone TMDPDFs. In the uncertainties estimation, we explore the dependence on pion mass and hadron momentum, and take into account both statistical errors and systematic errors. The results shown in our manuscript give a reliable description of nucleons'inner structure from the view of the parton distribution, and also can be accessible to a wide community of collider physics.

Session I / **15**

Unpolarized Transverse-Momentum-Dependent Parton Distributions from Lattice QCD: II

We present a first calculation of the unpolarized proton's
isovector transverse-momentum-dependent parton distribution functions (TMDPDFs) from lattice QCD, which are essential to predict observables of multi-scale, semi-inclusive processes in the standard model. We use a $N_f = 2 + 1 + 1$ MILC ensemble with valence clover fermions on a highly improved staggered quark sea (HISQ), and compute the quark momentum distributions in large-momentum protons on the lattice. The state-of-the-art techniques in renormalization and extrapolation in correlation distance on the lattice are adopted. The one-loop contributions in the perturbative matching kernel to the light-cone TMDPDFs are taken into account, and the dependence on the pion mass and hadron momentum is explored. The final results are compared with those from recent global analyses.

Session I / **16**

Connecting Euclidean to lightcone correlations: From forward to non-forward kinematics

According to large momentum effective theory (LaMET), the parton observables can be extracted from lattice calculations of quasi-observables through a perturbative matching relation. In this talk, I present a unified framework for the perturbative factorization connecting Euclidean correlations to light-cone correlations. We derive the flavor singlet and non-singlet matching kernel for the generalized distribution functions (GPDs), parton distribution functions (PDFs) and distribution amplitudes (DAs) at one-loop level, including the unpolarized, longitudinally and transversely polarized cases. Our results provide a manual of factorization approach for extracting all leading-twist GPDs, PDFs as well as DAs from lattice simulations of Euclidean correlations, following the state-of-the-art renormalization and matching strategy, either in coordinate, pseudo and momentum space.

Session II / **17**

Frame-independent methods to access GPDs from lattice QCD

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Traditionally, lattice QCD computations of GPDs have been carried out in a frame, where the transferred momentum is symmetrically distributed between the incoming and outgoing hadrons. However, such frames are inconvenient for lattice QCD calculations since each value of the momen-

tum transfer requires a separate calculation, increasing the computational cost. In a recent work (arXiv:2209.05373), we lay the foundation for more effective calculations of GPDs applicable for any frame, with freedom in the transferred momentum distribution. An important aspect of the approach is the Lorentz covariant parameterization of the matrix elements in terms of Lorentz-invariant amplitudes, which allows one to relate matrix elements in different frames. We demonstrate the efficacy of the formalism through numerical calculations using one ensemble of N_f=2+1+1 twisted mass fermions with a clover improvement. The value of the light-quark masses lead to a pion mass of about 260 MeV. Concentrating on the proton and zero skewness, we extract the invariant amplitudes from matrix element calculations in both the symmetric and asymmetric frame, and obtain results for the twist-2 light-cone GPDs for unpolarized quarks, H and E.

Session II / **18**

Extraction of pion GPD from lattice QCD using an asymmetric frame

Historically, GPDs have been defined in the symmetric frame, where the momentum transfer between the initial and final hadron state is equally distributed to the two states.
Such a setup is computationally very costly for their frame-dependent counterparts in lattice QCD, such as the quasi-GPDs. In this work we present a calculation of the pion GPD using the methodology proposed recently in Ref. [1], in which the lattice matrix elements decompose into Lorentz invariant amplitudes. These amplitudes can be calculated in any frame and can then be related to the light-cone GPDs. For this proof- of-concept calculation, we use one ensemble of ⊠f =2+1+1 twisted mass fermions and a clover improvement with a pion mass of 260 MeV to calculate the H-GPD for the pion.

Session III / **19**

Updates on gluon distributions from HadStruc

I will present the recent calculations of gluonic matrix elements related to the nucleon's unpolarized and helicity gluon PDF. Gluon matrix elements are notoriously noisy. By leveraging the tools of distillation and summed GEVP, HadStruc has reach a necessary precision to compare results to phenomenological determinations of gluon structure. Recently, doubt has been given to the applicability of PDF positivity constraints in phenomenological global analyses. Removal of constraints lead to two distinct bands of helicity gluon PDFs which are consistent with experiments. Lattice calculations, on the other hand, favor only one of these solutions.

Session III / **20**

Gluon Parton Distribution of the Nucleon from Lattice QCD in the $2+1+1$ Physical-Continuum Limit

We present the first physical-continuum limit x-dependent nucleon gluon distribution from lattice QCD using the pseudo-PDF approach, on lattice ensembles with $2+1+1$ flavors of highly improved staggered quarks (HISQ), generated by MILC Collaboration. We use clover fermions for the valence action on three lattice spacings $a \approx 0.9$, 0.12 and 0.15~fm and three pion masses $M_\pi \approx 220$, 310 and 690~MeV, with nucleon two-point measurements numbering up to $O(10^6)$ and nucleon

boost momenta up to 3~GeV. We study the lattice-spacing and pion-mass dependence of the reduced pseudo-ITD matrix elements obtained from the lattice calculation, then extrapolate them to the continuum-physical limit before extracting $xg(x)/\langle x\rangle_g$. We use the gluon momentum fraction $\langle x\rangle_g$ calculated from the same ensembles to determine the nucleon gluon unpolarized PDF $xg(x)$ for the first time entirely through lattice-QCD simulation. We compare our results with previous single-ensemble lattice calculations, as well as selected global fits.

Session III / **21**

Unpolarized gluon PDF for the proton using the twisted mass formulation

We present results of the x-dependence of the unpolarized gluon PDF for the proton. We use an Nf = 2 + 1 + 1 ensemble of maximally twisted mass fermions with clover improvement and the Iwasaki improved gluon action. The quark masses are tuned so that the pion mass is 260 MeV. We use a 32^3 × 64 lattice size with a lattice spacing a = 0.093 fm giving a spatial extent of 3 fm. We employ the pseudo-distribution approach and obtain the light-cone Ioffe time distribution (ITD) combining data for nucleon momentum boosts up to 1.67 GeV and Wilson line length, z, up to 0.56 fm. We explore systematic effects such as the dependence on the maximum value of z entering the fits to obtain the ITD. We also study various options to reconstruct the x-dependence of the gluon PDF.

Session I / **23**

TMD wave functions and Soft functions at one-loop in LaMET

In large-momentum effective theory (LaMET), the transverse-momentum-dependent (TMD) light-front wave functions and soft functions can be extracted from the simulation of a four-quark form factor and equal-time correlation functions. In this work, using expansion by regions we provide a one-loop proof of TMD factorization of the form factor. For the one-loop validation, we also present a detailed calculation of $\mathcal{O}(\alpha_s)$ perturbative corrections to these quantities, in which we adopt a modern technique for the calculation of TMD form factor based on the integration by part and differential equation. The one-loop hard functions are then extracted. Using lattice data from Lattice Parton Collaboration on quasi-TMDWFs, we estimate the effects from the one-loop matching kernel and find that the perturbative corrections depend on the operator to define the form factor, but are less sensitive to the transverse separation. These results will be helpful to precisely extract the soft functions and TMD wave functions from the first principle in the future.

Session I / **24**

Renormalization of Transverse-Momentum-Dependent Parton Distribution on the Lattice

To calculate the transverse-momentum-dependent parton distribution functions (TMDPDFs) from lattice QCD, an important goal yet to be realized, it is crucial to establish a viable nonperturbative renormalization approach for linear divergences in the corresponding Euclidean quasi-TMDPDF correlators in large-momentum effective theory. We perform a first systematic study of the renormalization property of the quasi-TMDPDFs by calculating the relevant matrix elements in a pion state

at five lattice spacings ranging from 0.03 fm to 0.12 fm. We demonstrate that the square root of the Wilson loop combined with the short distance hadron matrix element provides a successful method to remove all ultraviolet divergences of the quasi-TMD operator, and thus provides the necessary justification to perform a continuum limit calculation of TMDPDFs. In contrast, the popular regularization independent momentum subtraction renormalization (RI/MOM) scheme fails to eliminate all linear divergences.

Session I / **25**

Lattice QCD Calculations of Transverse-momentum-dependent Soft Function at one-loop accuracy

Soft function plays an important role in TMD factorization. We present a lattice QCD calculation for the rapidity-independent (or intrinsic) part of soft function at one-loop accuracy with a coherent normalization in large-momentum effective theory. The calculation is performed on CLS dynamic ensemble with a=0.098 fm and MILC ensemble with a=0.12 fm. Our results based on two ensembles are close to each other and make an agreement to perturbative calculation.

Session I / **26**

Lattice calculation of transverse momentum dependent wave function by large-momentum effective theory

We present a state-of-the-art lattice QCD calculation of transverse momentum dependent wave function (TMDWF) of pion in large-momentum effective theory. The calculation is performed at clover fermion action ensembles with lattice spacing a=0.12fm generated by MILC Collaboration with and CLS ensembles with lattice spacing a=0.098fm. On each of the two ensembles we calculated three momentum up to 3.01 and 3.16 GeV. With the one-loop soft function and CS kernel, we extract the light cone TMDWF. Our results show agreement with the phenomenological result.

Session IV / **27**

First Glimpse into the Kaon Gluon Parton Distribution Using Lattice QCD

In this work, we present the first results on the gluon parton distribution of the kaon from lattice quantum chromodynamics.
We carry out the lattice calculation at pion mass around 310~MeV and two lattice spacings, 0.15 and 0.12~fm, using $2+1+1$-flavor HISQ ensembles generated by MILC Collaboration. The kaon correlators are calculated using clover fermions and momentum-smearing sources with maximum boost momentum around 2~GeV and high statistics (up to 324,000 measurements). We study the dependence of the resulting reduced Ioffe-time pseudo-distributions at multiple boost momenta and lattice spacings. We then extract the kaon gluon distribution function in the $\overline{\text{MS}}$ scheme at $\mu = 2$~GeV, neglecting the mixing between the gluon and singlet-quark sectors. Our results at the smaller lattice spacing are consistent with phenomenological determinations.

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Welcome

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