TMDs: Towards a Synergy between Lattice QCD and Global Analysis

Report of Contributions

Contribution ID: **1**   Type: **not specified**

Simultaneous Global Analysis of Dihadron Fragmentation Functions and Transversity PDFs

Thursday, 22 June 2023 16:30 (30 minutes)

We propose a new definition of unintegrated dihadron fragmentation functions (DiFFs) which is compatible with the probability interpretation of collinear DiFFs and derive the leading-order evolution equations for these DiFFs. With these new definitions, we perform the first simultaneous extraction of DiFFs and transversity PDFs using data from semi-inclusive annihilation (SIA) in electron-positron collisions, semi-inclusive DIS, and proton-proton collisions. In particular, we include new SIA data from Belle that provides, for the first time, experimental constraints on the unpolarized DiFFs, as well as proton-proton data from STAR at center of mass energy 500 GeV. We present results for the transversity PDFs and tensor charge and explore the impact of theoretical constraints such as the Soffer bound and lattice computations of the tensor charge.

Primary authors: PROKUDIN, Alexei (Penn State Berks); METZ, Andreas (Temple University); COCUZZA, Christopher (Temple University); PITONYAK, Daniel (Lebanon Valley College); SEIDL, Ralf (RIKEN); MELNITCHOUK, Wally (Jefferson Lab); SATO, nobuo (Jefferson Lab)

Presenter: COCUZZA, Christopher (Temple University)

Session Classification: Session IV

Contribution ID: **2**   Type: **not specified**

the role of fragmentation measurements for TMD extractions

Wednesday, 21 June 2023 16:30 (30 minutes)

TMD extractions of Semi-inclusive DIS measurements and in part hadronic collision measurements rely on the knowledge of (TMD) fragmentation functions in order to successfully obtain TMD distribution functions. There exists some access to unpolarized TMD fragmentation functions via SIDIS measurements, but the cleanest approach is via electron-positron annihilation. It is also the only current venue to cleanly obtain polarized fragmentation functions.

The recent TMD related fragmentation function measurements in electron-positron annihilation, most notably at the B factories will be reported.

Primary author: SEIDL, Ralf (RIKEN)

Presenter: SEIDL, Ralf (RIKEN)

Session Classification: Session IV

Contribution ID: **3**   Type: **not specified**

Lattice calculation of the Collins-Soper kernel

Thursday, 22 June 2023 11:30 (30 minutes)

The Collins-Soper (CS) kernel is a nonperturbative function that characterizes the rapidity evolution of transverse-momentum-dependent parton distribution functions and wave functions. In this talk, we show the determination of the CS kernel using lattice QCD in two different strategies. We compare the results obtained from these two methods and also those from literature using various methods.

Primary author: Dr SHU, Hai-Tao

Presenter: Dr SHU, Hai-Tao

Session Classification: Session II

Contribution ID: 4   Type: **not specified**

Accessing TMDs from single pion and kaon SIDIS with CLAS12

Wednesday, 21 June 2023 14:00 (30 minutes)

Semi inclusive deep inelastic scattering is a well established tool to study TMDs and fragmentation functions. With the CLAS12 detector at Jefferson Laboratory (JLab) precise, multidimensional measurements of cross sections and asymmetry observables become possible in the valence quark regime, for the first time.

As a first observable, the structure function ratio $F_{LU}^{\sin\phi}/F_{UU}$ was studied based on beam single spin asymmetries from pion and kaon SIDIS. The talk will present a comprehensive multidimensional study for all pions, as well as charged kaons, and discuss the connection of the observable to TMDs and the impact of the new data on our understanding of the involved TMDs. Furthermore, an overview on ongoing and planed studies to extract the $\cos(\phi)$ and $\cos(2\phi)$ moments of the SIDIS cross section, as well as an LT separation of the ϕ integrated cross section, will be provided.

Primary author: Dr DIEHL, Stefan (JLU Giessen and UCONN)

Presenter: Dr DIEHL, Stefan (JLU Giessen and UCONN)

Session Classification: Session III

Contribution ID: **5**   Type: **not specified**

Rapidity-only TMD factorization

Friday, 23 June 2023 10:00 (30 minutes)

Typically, a production of a particle with a small transverse momentum in hadron-hadron collisions is described
by CSS-based TMD factorization at moderate Bjorken $x_B \sim 1$ and by k_T-factorization at small x_B.
A uniform description valid for all x_B is provided by rapidity-only TMD factorization developed in a series
of recent papers. In this talk, I will discuss two applications: power
corrections to DY hadronic tensor and one-loop result for
particle (Higgs) production by gluon fusion.

Primary author: Prof. BALITSKY, Ian (JLab/ODU)

Presenter: Prof. BALITSKY, Ian (JLab/ODU)

Session Classification: Session I

Contribution ID: **6**   Type: **not specified**

Transverse Λ polarization in e^+e^- annihilation and SIDIS processes within a TMD framework

Wednesday, 21 June 2023 17:00 (30 minutes)

We present an updated analysis of Belle data for the transverse Λ polarization in e^+e^- annihilation processes within a TMD factorization approach. $SU(2)$ isospin symmetry and charm quark contribution, with their impact on the description of the experimental data as well as on the extraction of the polarizing fragmentation functions, will be discussed.

Predictions for SIDIS processes within different scenarios, at typical energies of the future EIC, will be presented.

Primary author: Prof. D'ALESIO, Umberto (University and INFN Cagliari)

Co-authors: GAMBERG, Leonard (Penn State);   MURGIA, Francesco (INFN Cagliari, Italy);   ZACCHEDDU, Marco (Università degli studi di Cagliari & INFN)

Presenter: Prof. D'ALESIO, Umberto (University and INFN Cagliari)

Session Classification: Session IV

Contribution ID: 7   Type: **not specified**

Small-x TMD factorization at NLO

Friday, 23 June 2023 09:00 (30 minutes)

Two-particle azimuthal correlations provide valuable insights into the dynamics of gluon saturation in collider experiments. In the kinematic regime where the two particles are produced sufficiently forward in rapidity but back-to-back in the transverse plane, the differential cross-section computed in the Color Glass Condensate (CGC) EFT, admits a small-x Transverse Momentum Dependent (TMD) factorization. This so-called TMD-CGC correspondence was shown to hold at leading order (LO) in [1] where TMD operators are related to correlators of Wilson lines in the CGC. At next-to-leading order (NLO), one encounters two types of potentially large contributions: high-energy (small-x) logs and Sudakov (soft) logs, which must be jointly resummed in order to attain reliable theoretical predictions. Their simultaneous resummation was proposed in [2] based on TMD factorization arguments. However, a complete NLO calculation justifying this correspondence has been missing in the literature. The subject of this talk is to elucidate this correspondence.

By examining the back-to-back limit of semi-inclusive dijet production in deep inelastic scattering (DIS) computed in the CGC EFT at NLO [3], we demonstrate that a kinematic constraint on the non-linear small-x evolution equation of the Weizsäcker Williams (WW) gluon distribution [4, 5] is essential for properly separating the phase space of small-x gluons and soft gluons. Remarkably, this kinematic constraint allows us to establish the first proof of small-x TMD factorization at NLO, as we show that all remaining NLO corrections can be fully factorized in terms of an NLO perturbative factor and the WW gluon distribution [6].

I will present preliminary results [6] for the differential cross-section of back-to-back dijets in DIS at small-x kinematics in the CGC EFT at NLO.

[1] F. Dominguez, C. Marquet, B-W. Xiao, and F. Yuan. Phys.Rev.D 83 (2011) 105005
[2] A. Mueller, B-W. Xiao, and F. Yuan. Phys.Rev.D 88 (2013) 11, 114010
[3] P. Caucal, F. Salazar and R. Venugopalan, JHEP 11 (2021) 222⊠
[4] P. Caucal, F. Salazar, B. Schenke and R. Venugopalan. JHEP 11 (2022) 169
[5] P. Taels, T. Altinoluk, G. Beuf, C. Marquet. JHEP 10 (2022) 184⊠
[6] P. Caucal, F. Salazar, T. Stebel, B. Schenke and R. Venugopalan (arXiv: 2304.03304).

Primary authors: SCHENKE, Bjoern (BNL); SALAZAR, Farid (UCLA/UCB/LBNL); CAUCAL, Paul (Brookhaven National Laboratory); VENUGOPALAN, Raju (BNL); STEBEL, Tomasz (Jagiellonian University)

Presenter: SALAZAR, Farid (UCLA/UCB/LBNL)

Session Classification: Session I

Contribution ID: **8** Type: **not specified**

QCD Global Analysis of (Single-Hadron Fragmentation) Transverse Single-Spin Asymmetries: the Role of Lattice QCD in Phenomenology

Thursday, 22 June 2023 16:00 (30 minutes)

I will report on a recent QCD global analysis of single-spin asymmetries involving observables where single-hadron fragmentation is relevant. This includes measurements of the Sivers, Collins, and \sin(\phi_S) effects in SIDIS, Collins effect in electron-positron annihilation, Sivers effect in Drell-Yan, and AN in single-inclusive proton-proton collisions, which are sensitive to important TMD and collinear twist-3 (quark-gluon-quark) functions. In particular, I will focus on the transversity function, which then can be used to calculate the tensor charges of the nucleon, and discuss the role of lattice QCD in the phenomenological analysis.

Presenter: PITONYAK, Daniel (Lebanon Valley College)

Session Classification: Session IV

Contribution ID: **9**   Type: **not specified**

Global extraction of unpolarized Transverse Momentum Distributions

Wednesday, 21 June 2023 11:00 (30 minutes)

We present a global extraction of unpolarized Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDFs) and Fragmentation Functions (FFs) from two different types of processes: Semi-Inclusive Deep Inelastic Scattering (SIDIS) and Drell–Yan (DY). The analysis is performed in the TMD factorization framework and is based on data from several experiments and kinematic ranges.
The extraction reaches the state-of-the art perturbative accuracy of N^3LL^-.

We discuss the introduction of (pre-computed) normalization coefficients for SIDIS data.
The fit is performed taking into account correlated and uncorrelated uncertainties and we found that present data are very well described by our choice of non-perturbative functions.

Primary authors: BACCHETTA, Alessandro (University of Pavia and INFN); SIGNORI, Andrea (University of Turin and INFN); BISSOLOTTI, Chiara (Argonne National Laboratory); PIACENZA, Fulvio; BOZZI, Giuseppe (University of Cagliari and INFN, Cagliari); RADICI, Marco (INFN - Sezione di Pavia); CERUTTI, Matteo (Università di Pavia and INFN); BERTONE, Valerio (IRFU, CEA, Université Paris-Saclay)

Presenter: BISSOLOTTI, Chiara (Argonne National Laboratory)

Session Classification: Session II

Contribution ID: **10**   Type: **not specified**

Transversely Polarized Distribution from Lattice QCD

Thursday, 22 June 2023 14:30 (30 minutes)

We report an ongoing analysis of the lattice-QCD calculation of the isovector quark transversity distribution of the proton at physical pion mass at lattice spacing 0.06~fm using large-momentum effective theory. We compare our results with previous lattice calculations and discuss potential synergies with global analysis.

Primary authors: LIN, Huey-Wen (member@msu.edu;faculty@msu.edu;employee@msu.edu); HOLLIGAN, Jack (University of Maryland)

Presenter: LIN, Huey-Wen (member@msu.edu;faculty@msu.edu;employee@msu.edu)

Session Classification: Session III

Contribution ID: **11**   Type: **not specified**

Unpolarized TMDPDFs of the Nucleon from Lattice QCD

Thursday, 22 June 2023 10:00 (30 minutes)

We present a first calculation of the unpolarized proton's isovector transverse-momentumdependent 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 $Nf = 2 + 1 + 1$ MILC ensemble with valence clover fermions on a highly improved staggered quark sea (HISQ) to 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. Our results are qualitatively comparable with phenomenological TMDPDFs, which provide an opportunity to predict high energy scatterings from the first principles.

Primary authors: HE, Jinchen (University of Maryland, College Park); Prof. ZHANG, Qi-An; Prof. WANG, Wei

Presenter: HE, Jinchen (University of Maryland, College Park)

Session Classification: Session I

Contribution ID: **12** Type: **not specified**

TMDs from Various Avenues

Wednesday, 21 June 2023 10:00 (30 minutes)

In this talk, we will provide different ways of exploring TMDs, both the standard processes (SIDIS, Drell-Yan, and e+e- collisions) and those beyond which have been developed in recent years, such as the ones via jets, jet substructures, and energy-energy correlators. We will provide some recent progress on the (polarized) TMD phenomenology and global analysis, in connection with the theme of the workshop.

Primary author: KANG, Zhongbo (UCLA)

Presenter: KANG, Zhongbo (UCLA)

Session Classification: Session I

Contribution ID: **13**   Type: **not specified**

Transversity PDFs and GPDs from lattice QCD

Thursday, 22 June 2023 14:00 (30 minutes)

Generalized parton distributions (GPDs) are important quantities that characterize the 3-D structure of hadrons, and complement the information extracted from TMDs. They provide information about the partons' momentum distribution and also on their distribution in position space. Most of the information from lattice QCD is on the Mellin moments of GPDs, namely form factors and their generalizations. Recent developments in calculations of matrix elements of boosted hadrons coupled with non-local operators opened a new direction for extracting the x dependence of GPDs.

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 momentum transfer requires a separate calculation, increasing the computational cost. Here, we present results extracted through a new Lorentz invariant parametrization that leads to more effective calculations of GPDs applicable for any frame, with freedom in the transferred momentum distribution. We demonstrate the efficacy of the formalism through numerical calculations using one ensemble of $_f = 2+1+1$ 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, ⊠ and ⊠, as well as polarized quarks, $\widetilde{H}$.

Primary author: CONSTANTINOU, Martha (Temple University)

Presenter: CONSTANTINOU, Martha (Temple University)

Session Classification: Session III

Contribution ID: **14**   Type: **not specified**

Disentangling long and short distances in momentum-space TMDs

Wednesday, 21 June 2023 16:00 (30 minutes)

The extraction of nonperturbative TMD physics is made challenging by prescriptions that shield the Landau pole, which entangle long- and short-distance contributions in momentum space. The use of different prescriptions then makes the comparison of fit results for underlying nonperturbative contributions not meaningful on their own. We propose a model-independent method to restrict momentum-space observables to the perturbative domain. This method is based on a set of integral functionals that act linearly on terms in the conventional position-space operator product expansion (OPE). Artifacts from the truncation of the integral can be systematically pushed to higher powers in $\Lambda_{\mathrm{QCD}}/k_T$. We demonstrate that this method can be used to compute the cumulative integral of TMD PDFs over $k_T \leq k_T^{\mathrm{cut}}$ in terms of collinear PDFs, accounting for both radiative corrections and evolution effects. This yields a systematic way of correcting the naive picture where the TMD PDF integrates to a collinear PDF, and for unpolarized quark distributions we find that when renormalization scales are chosen near k_T^{cut}, such corrections are a percent-level effect. We also show that, when supplemented with experimental data and improved perturbative inputs, our integral functionals will enable model-independent limits to be put on the non-perturbative OPE contributions to the Collins-Soper kernel and intrinsic TMD distributions.

Primary authors: STEWART, Iain (MIT);   MICHEL, Johannes K. L. (MIT CTP);   SUN, Zhiquan (MIT);   EBERT, Markus (MIT)

Presenter: SUN, Zhiquan (MIT)

Session Classification: Session IV

Contribution ID: **15** Type: **not specified**

TMDs from Collins-Soper-Sterman Resummation

Wednesday, 21 June 2023 09:30 (30 minutes)

In this talk, I will summarize the TMDs from the Collins-Soper-Sterman Resummation formalism. Phenomenological results from recent global analysis of ResBos approach will also be presented, including the TMDs and the associated Collins-Soper evolution kernel.

Primary author: YUAN, Feng (Lawrence Berkeley National Laboratory)

Presenter: YUAN, Feng (Lawrence Berkeley National Laboratory)

Session Classification: Session I

Contribution ID: **16**   Type: **not specified**

Semi-inclusive diffractive deep inelastic scattering at small-x

Friday, 23 June 2023 09:30 (30 minutes)

We propose semi-inclusive
diffractive deep inelastic scattering (SIDDIS) to investigate the gluon tomography in the nucleon and
nuclei at small-x. The relevant diffractive quark and gluon parton distribution functions (DPDF) are
computed in terms of the color dipole S-matrices in the fundamental and adjoint representations.
respectively.

Primary author: HATTA, Yoshitaka (BNL)

Presenter: HATTA, Yoshitaka (BNL)

Session Classification: Session I

Contribution ID: **17**   Type: **not specified**

Lattice QCD calculations of transverse momentum-dependent (TMD) observables

Thursday, 22 June 2023 11:00 (30 minutes)

The status of an ongoing program of evaluating TMD observables within Lattice QCD is reviewed. These lattice calculations are based on a definition of TMDs through hadronic matrix elements of quark bilocal operators containing staple-shaped gauge connections. A parametrization of the matrix elements in terms of invariant amplitudes serves to cast them in the Lorentz frame preferred for a lattice calculation. A survey of the twist-2 TMD sector as well as selected twist-3 TMD results are presented, and advances in establishing control over systematic uncertainties are exhibited.

Primary author: ENGELHARDT, Michael (New Mexico State University)

Presenter: ENGELHARDT, Michael (New Mexico State University)

Session Classification: Session II

Contribution ID: **18**   Type: **not specified**

Collins-Soper kernel from lattice QCD at the physical pion mass

Thursday, 22 June 2023 12:00 (30 minutes)

This work presents a determination of the quark Collins-Soper kernel, which relates transverse-momentum-dependent parton distributions (TMDs) at different rapidity scales, using lattice Quantum Chromodynamics (QCD). This is the first lattice QCD calculation of the kernel at quark masses corresponding to a close-to-physical value of the pion mass, with next-to-next-leading order matching to TMDs from the corresponding lattice-calculable distributions, and includes a complete analysis of systematic uncertainties arising from operator mixing. The kernel is extracted at transverse momentum scales $240\,\mathrm{MeV} < q_T < 1.7\,\mathrm{GeV}$ with a precision sufficient to discriminate between different phenomenological models in the non-perturbative region.

Primary authors: AVKHADIEV, Artur (Massachusetts Institute of Technology); WAGMAN, Michael (MIT); SHANAHAN, Phiala (MIT); ZHAO, Yong (member@anl.gov)

Presenter: AVKHADIEV, Artur (Massachusetts Institute of Technology)

Session Classification: Session II

Contribution ID: **19**   Type: **not specified**

A Better Angle on Hadron Transverse Momentum Distributions at the EIC

Wednesday, 21 June 2023 14:30 (30 minutes)

We propose an observable q_* sensitive to transverse momentum dependence (TMD) in $eN \rightarrow ehX$, with q_*/E_N defined purely by lab-frame angles. In 3D measurements of confinement and hadronization this resolves the crippling issue of accurately reconstructing small transverse momentum P_{hT}. We prove factorization for $\mathrm{d}\sigma_h/\mathrm{d}q_*$ for $q_* \ll Q$ with standard TMD functions, enabling q_* to substitute for P_{hT}. A double-angle reconstruction method is given which is exact to all orders in QCD for $q_* \ll Q$. q_* enables an order-of-magnitude improvement in the expected experimental resolution at the EIC.

Primary authors: GAO, Anjie (MIT);   STEWART, Iain (MIT);   MICHEL, Johannes K. L. (MIT CTP);   SUN, Zhiquan (MIT)

Presenter: MICHEL, Johannes K. L. (MIT CTP)

Session Classification: Session III

Contribution ID: **20**   Type: **not specified**

Transverse Momentum Distributions of Heavy Hadrons and Polarized Heavy Quarks

Friday, 23 June 2023 12:00 (30 minutes)

We initiate the study of transverse momentum-dependent (TMD) fragmentation functions for heavy quarks, demonstrate their factorization in terms of novel nonperturbative matrix elements in heavy-quark effective theory (HQET), and prove new TMD sum rules that arise from heavy-quark spin symmetry. We discuss the phenomenology of heavy-quark TMD FFs at B factories and find that the Collins effect, in contrast to claims in the literature, is not parametrically suppressed by the heavy-quark mass. We further calculate all TMD parton distribution functions for the production of heavy quarks from polarized gluons within the nucleon and use our results to demonstrate the potential of the future EIC to resolve TMD heavy-quark fragmentation in semi-inclusive DIS, complementing the planned EIC program to use heavy quarks as probes of gluon distributions.

Primary authors: MICHEL, Johannes K. L. (MIT CTP); VON KUK, Rebecca (DESY Hamburg); SUN, Zhiquan (MIT)

Presenter: MICHEL, Johannes K. L. (MIT CTP)

Session Classification: Session II

Contribution ID: **21**   Type: **not specified**

TMDs at Hadron Colliders

Wednesday, 21 June 2023 09:00 (30 minutes)

The turn-on of high energy hadron colliders, such as RHIC and the LHC, have created a new arena for the study of TMDs. The collisions of protons over a wide range of center-of-mass energies allow for tests of universality and factorization as well as the study of evolution effects. The wide-acceptance and variety of technologies featured in typical collider detectors have paved the way for the simultaneous measurement of a variety of observables, including inclusive hadrons, jets and W/Z bosons. This talk will provide a broad survey of TMD results, focusing on the most recent spin-dependent and spin-integrated TMD measurements from RHIC and the LHC. Special attention will be paid to opportunities for future measurements in the forward region at RHIC and their connection to the TMD program at the future EIC.

Primary author: FATEMI, Renee (University of Kentucky)

Presenter: FATEMI, Renee (University of Kentucky)

Session Classification: Session I

Contribution ID: **22**   Type: **not specified**

Understanding TMD structure using jets

Wednesday, 21 June 2023 15:00 (30 minutes)

In this talk, I will discuss how jets provide powerful new processes to understand both the TMD distributions and TMD fragmentation functions. In this talk, I will discuss three different processes involving jets that are useful to studying TMD functions at the EIC:

i) back-to-back production of e+jet

ii) TMD hadron distribution inside an inclusive jet production process

iii) TMD hadron distribution inside an inclusive jet produced back-to-back with e.

Primary author: LEE, Kyle (MIT)

Presenter: LEE, Kyle (MIT)

Session Classification: Session III

Contribution ID: **23**   Type: **not specified**

Transversity PDF of the proton from lattice QCD with physical quark masses

Thursday, 22 June 2023 15:00 (30 minutes)

The transversity PDFs, which describe the difference between probabilities to find a parton spin aligned and anti-aligned to the transversely polarized parent nucleon, is considerably less constrained from experiments due to their chiral-odd nature. Complementary information from lattice QCD is desired. In this talk, we report a calculation using a $N_f = 2 + 1$ HISQ ensemble with physical-mass quarks and a lattice spacing of $a = 0.076$ fm. Applying short distance factorization to the ratio-scheme renormalized bi-local matrix elements of nucleon boosted up to 1.5 GeV, we extract the first few Mellin moments and reconstruct the Bjorken-x dependence using a deep neural network (DNN). We also present the results from large-momentum effective theory approach utilizing a hybrid renormalization scheme.

Primary authors: HANLON, Andrew (Brookhaven National Laboratory); GAO, Xiang; KARTHIK, Nikhil (BNL); PETRECZKY, Peter (BNL); SHI, Qi (BNL&CCNU); SYRITSYN, Sergey (RIKEN-BNL Research Center); MUKHERJEE, Swagato (Brookhaven National Laboratory); ZHAO, Yong (member@anl.gov)

Presenter: GAO, Xiang

Session Classification: Session III

Contribution ID: **24**   Type: **not specified**

Three dimensional imaging in Nuclei

Wednesday, 21 June 2023 12:00 (30 minutes)

In this talk, I'll discuss our recent work where we perform the first simultaneous global QCD extraction of the transverse momentum dependent (TMD) parton distribution functions and the TMD fragmentation functions in nuclei. We have considered the world set of data from semi-inclusive electron-nucleus deep inelastic scattering and Drell-Yan di-lepton production. In total, this data set consists of 90 data points from HERMES, Fermilab, RHIC and LHC. Working at next-to-leading order and next-to-next-to-leading logarithmic accuracy, we achieve a $\chi^2/dof = 1.196$. In this analysis, we perform the first extraction of nuclear modified TMDs and compare these to those in free nucleons. We also make predictions for the ongoing JLab 12 GeV program and future EIC measurements.

Primary author: TERRY, John (UCLA)

Presenter: TERRY, John (UCLA)

Session Classification: Session II

Contribution ID: **25**   Type: **not specified**

TMD Factorization and Renormalization at Next-to-Leading Power

Friday, 23 June 2023 11:30 (30 minutes)

Since shortly after the discovery of partons, people have thought about probing their transverse momentum inside hadrons. For example, in 1978 it was shown to give rise to an azimuthal cos(phi) asymmetry of the outgoing hadrons in the process of semi-inclusive DIS (SIDIS), known as the Cahn effect. The cos(phi) distribution, as well as a number of other asymmetries in both SIDIS and Drell-Yan, are difficult to study since in QCD they first appear at subleading order in the small transverse momentum expansion. These observables have traditionally been studied at tree level using the parton model. In this talk I show that the use of effective field theory makes it possible to treat these observables systematically. Utilizing the soft-collinear effective theory formalism we completely determine the structure of contributions to all orders in perturbation theory. Interestingly, we find that dynamical soft gluon contributions remains simple at this power. We show that the only new ingredients are a set of the quark-gluon-quark (qgq) correlators, which come along with only one new Wilson coefficient. Perturbative matching calculations for the qgq correlators reveal novel additive rapidity divergences as well as endpoint divergences in the convolution of energy fractions, thus making the renormalization and factorization nontrivial and interesting. I discuss our solution to removing these divergences to define renormalized qgq correlators. Our results for the subleading power azimuthal asymmetries, establish them as useful observables within QCD, and enable higher precision predictions.

Presenter: GAO, Anjie (MIT)

Session Classification: Session II

Contribution ID: **26**   Type: **not specified**

Tomography of pions and protons via transverse momentum dependent distributions

Wednesday, 21 June 2023 11:30 (30 minutes)

I will present our work, https://inspirehep.net/literature/2628962, on the first simultaneous extraction of parton collinear and transverse degrees of freedom from low-energy fixed-target Drell-Yan data in order to compare the transverse momentum dependent (TMD) parton distribution functions (PDFs) of the pion and proton. We demonstrate that the transverse separation of the quark field encoded in TMDs of the pion is more than $\sim 5\,\sigma$ smaller than that of the proton. We also consider the nuclear modification of TMDs, we find clear evidence for a transverse EMC effect. We comment on possible explanations for these intriguing behaviors, which call for a deeper examination of tomography in a variety of strongly interacting quark-gluon systems.

Primary authors: GAMBERG, Leonard (Penn State); BARRY, Patrick (Jefferson Lab); MELNITCHOUK, Wally (Jefferson Lab); MOFFAT, Eric (Argonne National Lab); PITONYAK, Daniel (Lebanon Valley College); PROKUDIN, Alexey (avp5627@psu.edu); SATO, Nobuo (Jefferson Lab)

Presenter: GAMBERG, Leonard (Penn State)

Session Classification: Session II

Contribution ID: **27**　　　　　　　　　　　　　　　　Type: **not specified**

A journey through the heavy-light Sudakov universality class in LaMET: from quasi-TMDPDF at large Pz to quasi-PDFmatching kernel in the threshold limit

Thursday, 22 June 2023 09:00 (30 minutes)

In this talk we will provide a survey of three fundamental objects: quasi-TMDPDF, quasi-LFWF amplitudes and (quark non-singlet) quasi-PDF matching kernel that appears naturally in the application of LaMET to lattice calculation of various parton distribution functions. We demonstrate how TMD factorization or threshold factorization works for the corresponding objects with a common perturbative hard kernel: the universal heavy-light Sudakov form factor. We show how the universal TMDPDF/LFWF amplitudes can be extracted by combining factorization theorems for the quasi-TMD quantities with an auxiliary space-like form factor. Finally, we explain how the NNLO heavy-light Sudakov form factor can be extracted through the threshold limit of quasi-PDF matching kernel.

Presenter: LIU, Yizhuang (Jagiellonian University)

Session Classification: Session I

Contribution ID: **28**
Type: **not specified**

Determination of Collins-Soper kernel from lattice and global analysis

Thursday, 22 June 2023 09:30 (30 minutes)

I review the latest progress in the determination of Collins-Soper kernel. There are two main subjects to be discussed. The first one is the recent N4LL global analysis of the Drell-Yan data, which provides a very precise control of the evolution due a huge span of energies (from 4 GeV to 1000 GeV). The second one is the determination of the Collins-Soper kernel from the twist-three TMD distributions.

Presenter: VLADIMIROV, Alexey (Universidad Complutense de Madrid)

Session Classification: Session I

Contribution ID: **29**   Type: **not specified**

Proton spin at small-x

Friday, 23 June 2023 11:00 (30 minutes)

Resolution of the proton spin puzzle, which is inability of the constituent quark model to explain discrepancy between the spin-1/2 of the proton and the amount of spin carried by its quarks and gluons, as measured in experiment, is an outstanding problem in modern hadronic physics. One possibility is that ''missing" spin of the proton may be found at small values of Bjorken-x. I'll give an overview of the current status of the theory of spin at small-x. Starting with a conventional approach which is based on a high-energy expansion in the shock-wave background, I'll discuss the small-x evolution of the gluon and flavour-singlet quark helicity distributions. The evolution contains mixing between different types of operators appearing as sub-eikonal corrections to the leading order shock-wave approximation. The evolution is consistent with the spin-dependent DGLAP evolution at small-x. At the same time, I'll show that the helicity evolution doesn't provide a complete picture of the problem since it lacks the anomaly contribution. I'll demonstrate that there is a class of spin-dependent observables which are dominated by the triangle anomaly in both Bjorken ($Q^2 \to \infty$) and Regge ($x_B \to 0$) asymptotics. The anomaly manifests itself as an infrared pole which appears in both limits. The cancellation of this pole involves a subtle interplay of perturbative and nonperturbative physics that is deeply related to the $U_A(1)$ problem in QCD. I'll demonstrate the fundamental role played by a Wess-Zumino-Witten term, coupling the topological charge density to a "primordial" isosinglet meson, both in the cancellation of the infrared pole and topological mass generation of the eta prime meson. I'll argue that such topological effects can be measured in polarized DIS at a future Electron-Ion Collider.

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