Proposal for a Topical Collaboration in Nuclear Theory for the Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD

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Research area (site) identified in Section I of this Announcement:

c. Radiative corrections for semi-inclusive/exclusive electron scattering
d. Transverse structure of hadrons in exclusive/semi-inclusive scattering
e. Spin structure of the nucleon
k. Applications of effective field theory
t. Computationally enabled nuclear theory

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1 Background/Introduction

Nucleons are the fundamental building blocks of all atomic nuclei and make up essentially all the visible matter in the universe, including the stars, the planets, and us. In Quantum Chromodynamics (QCD), the theory of the strong interactions, the nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons (referred to collectively as partons). The nucleon is not static but has complex internal structure, the dynamics of which are only beginning to be revealed in modern experiments. A deeper understanding of this building block of matter therefore requires that we understand the nucleon's internal structure in terms of its constituents. This is one of the three scientific priorities in Nuclear Physics articulated in the NSAC 2007 Long Range Plan, and is a major theme and the great intellectual challenge of the DOE Nuclear Theory subprogram.

Fifty years of experimental investigations into the nucleon's internal structure have provided remarkable insight into parton dynamics. However, many outstanding questions remain. This is largely because of the color confinement – a defining property of QCD. Even the most advanced detector cannot see quarks and gluons as they are forever bound inside hadrons. A reliable theoretical formalism, known as QCD factorization, is required to connect the hadrons measured in experiments and quarks and gluons inside them. Until recently, the generations of experiments, with the well-developed collinear QCD factorization formalisms, could only provide one-dimensional (longitudinal momentum) snapshots of the nucleon's internal structure. The situation has begun to improve in recent years. New and more precise data sensitive to transverse momentum dependent partonic structure of the nucleon are now available following the running of the COMPASS experiment at CERN, RHIC at BNL, the E906/SeaQuest Drell-Yan experiment at Fermilab, and experiments at JLab. Most importantly, theoretical advances over the past decade have resulted in the development of a powerful new formalism, the transverse momentum dependent (TMD) QCD factorization formalism, that provides quantitative links between new measurements and the *three-dimensional* (3D) partonic structure of nucleon. This more detailed structure is encoded in the transverse momentum dependent parton distributions (or simply, TMDs). With additional data from ongoing experiments, and with forthcoming, dedicated experimental programs at JLab 12 GeV, and a future Electron-Ion Collider, a much sharper and detailed picture of the nucleon's internal landscape could become available. However experiments alone will not suffice. As our narrative will emphasize, a coordinated theoretical effort to improve the QCD factorization formalism, and to analyze and interpret the wealth of new data is essential to uncover the dynamical, three-dimensional structure of the nucleon.

To address the challenge of extracting novel quantitative information about the nucleon's internal landscape, we are proposing to form the TMD Topical Collaboration. Our collaboration will develop new theoretical and phenomenological tools that are urgently needed for precision extraction of the 3D tomography of the confined motion of partons inside the nucleon from current and future data. Our collaboration's work will cast light on some simple yet profound questions regarding the nucleon's internal structure such as

- What are the two dimensional transverse momentum distributions, or confined transverse motion, of quarks and gluons inside a fast moving nucleon?
- How do these distributions vary with change in the longitudinal momentum fraction, x, carried by the parton constituents, and with the probe resolution, Q^2?
- How are these distributions correlated with the nucleon's properties, such as its spin, and with the spins of quarks and gluons?
- Can we extract novel information about the color electric and magnetic force inside the nucleon from these distributions?

- What features of measured transverse momentum distributions are universal nucleon properties, and what features are specific to the particular processes that are studied in experiment?

Addressing these questions requires a three-pronged effort. Firstly, it needs the input of nuclear theorists with expertise in QCD factorization, the formalism that separates short distance parton physics calculable in perturbation theory, from the long distance non-perturbative physics of hadrons. Secondly, it requires phenomenological analysis that connects this rigorous formalism with global analysis of data. Finally, it requires lattice QCD computations to provide the non-perturbative input that will enable a first principles matching of theory to data. As explained in detail in next section, as a collaboration, we will be able to

- further develop the transverse momentum dependent QCD factorization formalism to achieve higher precision;
- identify new physical observables from which the TMD parton structure of the nucleon can be reliably extracted;
- extract the 3D momentum-space landscape of the nucleon by QCD global analysis of data from RHIC, JLab12, and other domestic and international facilities;
- solve existing puzzles, such as the unexpectedly large theoretical uncertainty in the scale variation of the Sivers asymmetry and the apparent sign mismatch between the data on transverse single-spin asymmetries and the expectation based on the Sivers effect alone;
- calculate the internal landscape of the nucleon and other hadrons in lattice QCD;
- test fundamental QCD predictions, such as the sign change of the Sivers function from the Drell-Yan-like process to the semi-inclusive deep inelastic scattering process;
- explore the parton transverse structure inside various nuclei and its dependence on nuclear properties; and
- make detailed predictions and provide important guidance for the experimental programs at future facilities.

The TMD Collaboration aims to establish and formalize the three-pronged scientific effort to maximize the results of the investments of the DOE Office of Nuclear Physics, and to achieve and surpass the goals set out in the NSAC milestone HP13.

The TMD Collaboration is designed to function as a network of experts with a common focus while having different strengths at the different participating institutions to provide a unique environment for sustained interactions and communications, and development of new ideas. As a collaboration, we will be able to address questions and challenges that would be difficult, if not impossible, to attack as individual investigators, and provide broad training to a new generation of students. We are making a concerted effort to bring new people, as well as to train younger people, to work on the physics connected with TMDs. Our proposed physics projects and the budget clearly reflects our effort. Having new tenure-track junior faculty positions available will provide attractive career paths for younger people who enter the field and pay a great dividend to the health and growth of Nuclear Theory in the broader sense. We will establish *two* new tenure-track junior faculty positions at New Mexico State University and Temple University, respectively, committed to open in connection with the TMD collaboration. We also have *six* institutions committed to hire postdocs and *five* institutions committed to have graduate or undergraduate students working with the Collaboration by leveraging support from other resources. In addition, we will host a range of collaboration activities including an annual meeting, several focused and short topical workshops, a summer school for young postdocs and graduate students, and will prepare a handbook on the physics of TMDs that summarizes the central aspects of TMDs and related physics as a resource for the entire community.

2 Proposed Research and Methods

2.1 Factorization and Definition of TMDs

Stewart (coordinator), Ji, Kang, Lee, Prokudin, Rogers, Vitev, Yuan

Transverse momentum dependent parton distribution functions (PDFs) and fragmentation functions (FFs), commonly referred to as transverse momentum distributions (TMDs) have become essential quantities for unraveling the internal structure of hadrons. This includes spin-independent and spin-dependent TMDs, and TMDs for quarks of various flavors, as well as for gluons. Consistent definitions for TMDs in terms of operator matrix elements are required for interpretation of transverse momentum dependent observables in terms of TMDs, lattice QCD (LQCD) calculations, perturbative calculations, as well as the connection of TMDs to experimental observables. Precise definitions are also important when TMDs are considered as a component in the three-dimensional proton tomography program [1, 2].

In general, any TMD definition must be gauge invariant, exhibit universality across different physical processes, and satisfy constraints imposed by factorization. One example of the latter is the fact that for large transverse momentum $k_T \gg \Lambda_{\rm QCD}$, the TMD depending on both x and k_T reduces to a convolution between a k_T dependent coefficient function that is perturbatively calculable as an expansion in α_s, and a standard longitudinal parton distribution function, $f_{i/p}(\xi, \mu)$ with parton momentum fraction ξ and factorization scale μ. In practice, these constraints still leave some residual freedom in the definitions of TMDs, which should be thought of as a scheme dependence. The choice of the scheme will modify both the TMD and the hard perturbative cross section with which the TMDs are convolved to yield physical predictions for electroweak processes like semi-inclusive deep-inelastic scattering (SIDIS), Drell-Yan scattering, and e^+e^- annihilation. While final cross section results are scheme independent, it is important to combine pieces of the calculation consistently in a given scheme, see for example [3]. Compared to the case of longitudinal parton distributions, a complicating factor in the TMD case is the presence of rapidity singularities that must be regulated at intermediate steps. The choice for this rapidity regulator may then influence how the final scheme is defined. This is analogous to how the $\overline{\rm MS}$ scheme is natural within the context of dimensional regularization, but other schemes are more natural when a lattice regulator is used to handle ultraviolet divergences. It should also be emphasized that in the limit of large k_T where the collinear factorization framework becomes relevant, all of the TMD schemes match onto the same results [4].

Currently, there are a number of different definitions or schemes for TMDs used in the literature. Examples include that of Collins-Soper 81 [5], Ji-Ma-Yuan 2004 [6], Collins 2011(JCC) [7], that of Echevarria-Idilbi-Scimemi (EIS) [8, 9], and that of Chiu-Jain-Neill-Rothstein (CJNR) [10]. These definitions differ by whether Wilson lines on or off the light-cone are used in the construction, and by their choice for rapidity regulators. In general, these definitions involve suitable combinations of collinear and soft matrix elements. Given that each definition of TMDs has advantages and disadvantages, the comparison of different definitions is essential and may help shed light on the physics of TMDs. For example, the JCC definition emerges from detailed derivations of TMD factorization, building on Collins-Soper-Sterman (CSS) factorization methods [11] and naturally yielding the

Collins-Soper equation, while those of EIS and CJNR utilize the Soft-Collinear-Effective Theory (SCET) [12, 13, 14, 15] approach to factorization. A significant program to express experimental measurements of transverse momentum dependent cross sections in terms of separate TMD functions defined in the JCC scheme has been carried out in Refs. [16, 17, 18, 19]. Perturbative calculations of non-logarithmic contributions might be simpler in the EIS scheme and the theory, phenomenology, and data analysis in this scheme can be found in Refs. [8, 20, 9, 21, 22]. The equivalence of the JCC and EIS schemes has already been explored in some detail in Ref. [23]. The CJNR scheme is connected to the rapidity renormalization group approach, where rapidity evolution equations are derived in essentially the same manner as those for the standard invariant-mass evolution in μ in the $\overline{\mathrm{MS}}$ scheme. CJNR is the least well studied of the three schemes, and a dedicated study of TMDs for both quark and gluons at next-to-next-to-leading-log (NNLL) in this scheme is warranted. Complete higher order loop calculations within all the different schemes still need to be performed. In particular, further study is needed for the gluon TMDs that have not yet been fully explored [24, 25].

The lattice QCD (LQCD) treatment of TMDs is based on the fundamental correlator

$$\widetilde{\Phi}^{[\Gamma]}(b, P, S, \ldots) \equiv \frac{1}{2}\langle P, S|\ \bar{q}(0)\ \Gamma\ \mathcal{U}_v[0, \ldots, b]\ q(b)\ |P, S\rangle\ , \tag{1}$$

which under certain conditions can be evaluated using lattice methods. The hadron momentum and spin are denoted by P, S, and Γ represents an arbitrary Dirac structure. The quark operators at positions 0 and b are connected by the gauge link $\mathcal{U}_v$, which takes the shape of a staple, characterized by its direction, v, in addition to its width, b. Fourier transformation from transverse quark separation b_T to transverse momentum k_T-dependent correlators yields the TMDs as coefficient functions in a decomposition into the relevant Lorentz structures. Owing to the special role of (Euclidean) time in lattice QCD, the operator in (1) must be defined at a single time. This requirement makes Collins' factorization scheme the one most suited to underpin a lattice calculation; in this scheme, all separations in the operator, including the staple direction, v, are spacelike, and therefore the problem can be boosted to a Lorentz frame in which the operator exists at a single time. Divergences associated with the gauge links are regulated by forming ratios of correlators containing related gauge link structures. An extrapolation of numerical matrix elements is then made to the light-like limit of the staple direction v required by the TMD definition. **We intend to study improvements to these extrapolations, and exploit associated perturbative results that may help control this limit.**

It is important to note that factorization analyses may also imply that different TMDs are relevant for different processes, but remain universal across a class of related processes. This process dependence is independent of any scheme dependence. A standard example is the process dependent sign of the Sivers function. For some transverse momentum dependent observables it is also possible that no description in terms of TMDs is possible, and hence factorization is violated. For example, in hadron-hadron collisions with produced hadrons, Ref. [26] has shown that separate Wilson line structures for each colliding hadron, and which are consistent with perturbatively derived TMD factorization, do not exist. The separate hadronic structures appear to be entangled in a manner that is unique to non-Abelian gauge theories like QCD, and which cannot be accommodated by a simple change in the Wilson line. When gluon distributions are important, "super-leading" contributions cause additional complications in the derivations of factorization [27], and in the context of the factorization violation, they may even lead to new spin observables [28]. **We will map out the range of observables for which factorization is possible, and for which the same TMDs appear for different processes (see also Sec. 2.6).**

In order for the broader TMD program to be successful, it is important to achieve a further understanding of the relationship between different definitions, schemes, and factorization formalisms, to understand the consequences of using one set of definitions over another, and of how different choices affect the results of perturbative and lattice calculations, and the interpretation of experimental data in terms of hadronic bound states. The perturbative QCD and SCET communities have independently developed alternative formalisms for studying factorization, and defining and evolving TMDs, and we plan to perform detailed comparisons and studies. The topical collaboration is an ideal venue to nourish the type of cross-disciplinary interactions needed to make progress on these topics.

2.2 Evolution of TMDs

Prokudin (coordinator), Gamberg, Lee, Metz, Rogers, Yuan

QCD provides very powerful predictions concerning the dependence (evolution) of underlying parton distribution functions on the hard scale Q of the physical process. QCD factorization theorems separate the measured cross sections into the perturbatively calculable hard parts that encode the short distance QCD dynamics and the parton distribution functions and/or fragmentation functions that encode non-perturbartive long distance parton dynamics. Collinear factorization takes advantage of the relative smallness of the intrinsic transverse motion of patrons and results in a one dimensional picture of the nucleon distribution and hadronic fragmentation functions. These functions depend on one variable that describes the momentum fraction of the hadron carried by a quark or gluon. As QCD is a renormalizable theory, one needs to introduce an auxiliary renormalization group scale μ that, roughly speaking, separates ultraviolet (UV) physics from infrared physics. While introducing μ greatly simplifies the physics it has the consequence that logarithms of the type $\alpha_s(\mu)\log(Q^2/\mu^2)$ generally appear in perturbative calculations of UV quantities. In order to maximize the reliability of perturbative calculations, one would set $\mu = Q$, and the measured PDFs and FFs are determined at a specific scale Q. The PDFs and FFs encode detailed information about the large distance parton dynamics. They are universal, so their measurement in one experiment leads to predictions in other experiments. It is in principle possible to predict their general behavior using lattice or other non-perturbative methods. PDFs and FFs evolve according to the so called Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations. DGLAP equations and corresponding hard cross sections can be calculated order by order in the strong coupling constant α_s which in turn depends on the hard scale Q. Current calculations extend to multiple orders in α_s. In addition, in the low-x region one should take into account gluon recombination along with parton splitting, and corresponding evolution equations become non-linear leading to a transition from the dilute parton picture to a dense QCD medium, see Section 2.10.

Transverse momentum dependent factorization is applicable for describing differential cross sections dependent on an additional measured scale Q_T, which allows distributions to be sensitive to the intrinsic transverse motion of quarks and gluons. TMD factorization separates a differential cross section into a hard part and several well-defined universal factors [5, 4, 6, 7], the TMD PDFs and/or TMD FFs, or or simply, TMDs. At $Q_T \gg \Lambda_{\rm QCD}$, but $Q_T \ll Q$, the strong coupling α_s is small and perturbation theory can be enhanced by summing powers of $\alpha_s \log(Q/Q_T)$ to all orders. At very small Q_T, where truly non-perturbative Q_T effects become important, such a "resummation" approximation is no longer valid. There the appropriate expansion parameter is $\alpha_s(Q)$, and a complete TMD factorization formalism that combines non-perturbative effects and perturbative effects is needed. In recent decades, the formalism has been improved greatly using various approaches, see Refs. [6, 29, 7, 30, 31, 8, 10, 32]. A distinct feature of the TMD evolution is dependence on non-perturbative gluon radiation. The treatment of TMD evolution is easiest in transverse coordinate space, b, the Fourier conjugate of transverse momentum of active parton. For instance, in the regime $b \ll 1/\Lambda_{\rm QCD}$, the evolution kernels can be calculated perturbatively, and, at the same time over short transverse distance scales, $1/b$ becomes a legitimate hard scale, and the b dependence of TMDs can be calculated in perturbation theory. Consequently, one can relate TMDs in this regime to the collinear PDFs and FFs, and this relation allows unambiguous predictions for the differential cross section for $W^{\pm}, Z$ production at Tevatron and LHC, for example.

In the large-b region, however, the transverse coordinate dependence of TMDs corresponds to intrinsic non-perturbative behavior associated to the hadron wave function. While the presence of the non-perturbative functions in the formulation of the evolution is a great advantage it is also a challenge. It allows one to study details of non-pertrubative gluon radiation and at the same time it allows a substantial sensitivity to non-perturbative dynamics. That is, even though evolution equations are formally the same, the solutions can vary greatly depending on the choice of the non-perturbative input. Thus implementing the formalism requires an accurate account of the non-perturbative inputs [33, 34, 19, 35, 36, 37] for the TMDs. In recent years, a lot of attention has been paid to the exploration of the non-perturbative aspects of TMD evolution. Information from lattice QCD will be essential as many of the non-perturbative functions have been shown to be process independent and must be extracted from a combination of different processes (see Section 2.3). The confirmation of such process independence would be a very powerful confirmation of QCD.

We aim to extract and parametrize of the non perturbative inputs of the TMDs and describe a broad range of transverse-momentum sensitive processes in terms of TMD factorization. Historically the TMD formalism was applied [33] to high energy processes, where dependence on underlying intrinsic dynamics is very limited. Recent progress had led to successful examples [38] of the description of processes at low and high energies that are sensitive to the dependence of TMDs on a wide range of b. Such descriptions will be extremely important in the future in order to establish TMD evolution as correct and to explore non-perturbative aspects of TMD evolution using both fits to the experimental data, model calculations and lattice QCD calculations.

2.3 Nonperturbative Input to TMD Evolution

Rogers (coordinator), Engelhardt, Fleming, Gamberg, Kang, Lee, Mehen, Qiu, Rogers, Stewart, Vitev, Weiss, Yuan

Non-perturbative contributions to a QCD factorization formula enter into processes that involve TMD functions in a way that is very analogous to the collinear PDFs and FFs that enter into collinear factorization theorems [11]. To elaborate on this analogy, recall the collinear factorization formula for SIDIS process written schematically as

$$d\sigma \sim \int \mathcal{H}(\mu/Q, \alpha_s(\mu)) \otimes f_{q/P}(x;\mu) \otimes d_{H/q}(z;\mu)\,. \tag{2}$$

That is, the calculation of the cross section takes an intuitive form in collinear factorization; for a semi-inclusive production of a hadron H by scattering a lepton off a nucleon P, it becomes a generalized product of a hard scattering $\mathcal{H}(\mu/Q, \alpha_s(\mu))$, which is calculable in perturbative QCD, a probability density $f_{q/P}(x;\mu)$ to find a parton of particular momentum fraction x in the initial state, and a probability density $d_{H/q}(z;\mu)$ for the struck quark to hadronize into a final state hadron carrying momentum fraction z of the struck quark. (In the above notation, red factors denote perturbatively calculable coefficients, whereas blue factors are universal but require non-perturbative input.)

The roles of transverse momentum associated with the incoming bound state, final state hadronization process and other non-perturbative effects are either power suppressed or integrated into PDFs and FFs in Eq. (2). However, for a detailed description of the cross section differential in final state transverse momentum, this is not sufficient. In such cases, the PDFs and FFs must encode the effects of intrinsic transverse momentum. The schematic factorization formula in Eq. (2) becomes

$$d\sigma \sim \int \mathcal{H}(\mu/Q, \alpha_s(\mu)) \otimes F_{q/P}(x, \mathbf{k}_T, \mu, \zeta_1) \otimes D_{H/q}(z, z\mathbf{p}_T, \mu, \zeta_2) + Y \,. \tag{3}$$

The structure of the first term is very similar to the structure of Eq. (2), but now the probability density functions $F_{q/P}(x, \mathbf{k}_T, \mu, \zeta_1)$ and $D_{H/q}(z, z\mathbf{p}_T, \mu, \zeta_2)$ have acquired dependence on intrinsic transverse momentum. This "TMD parton model" summarizes the essential concepts of TMD parton distribution and fragmentation functions.

The last term in Eq. (3) is known as the "Y-term" and is a correction for the region of very large transverse momentum, where a description in terms of TMD functions is not valid. Because of the large transverse momentum involved, it is perturbatively calculable in terms of collinear PDFs. Like the collinear PDFs and fragmentation functions, the full TMD functions in Eq. (3) have auxiliary parameters, along with evolution equations that describe the dependence on those parameters and the resulting scaling violations of cross sections [5, 39, 4, 7]. In the case of TMD functions, however, there are a number of important extensions and qualifications that make phenomenology both more complicated and more interesting.

To get a sense of these complications, consider a single TMD function after it has been evolved to a specific scale, written in the organization of [16]:

$$\begin{aligned}
\tilde{F}_{f/P}(x, \mathbf{b}_T; Q, Q^2) \quad &= \quad \overbrace{\sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{f/j}(x/\hat{x}, b_*; \mu_b^2, \mu_b, g(\mu_b)) f_{j/P}(\hat{x}, \mu_b)}^{\text{AA}} \\
&\times \quad \overbrace{\times \exp\left\{ \ln\frac{Q}{\mu_b} \tilde{K}(b_*; \mu_b) + \int_{\mu_b}^{Q} \frac{d\mu'}{\mu'} \left[\gamma_F(g(\mu'); 1) - \ln\frac{Q}{\mu'} \gamma_K(g(\mu')) \right] \right\}}^{\text{BB}} \\
&\times \quad \overbrace{\exp\left\{ g_{f/P}(x, b_T) + g_K(b_T) \ln\frac{Q}{Q_0} \right\}}^{\text{CC}} \,.
\end{aligned} \tag{4}$$

Here, it is the Fourier transform of the TMD PDF that is shown. The factorization becomes especially simple in transverse coordinate space since the evolution can be solved exactly and various types of contributions appear in a simple product. The large $\mathbf{b}_T$ behavior of the Fourier-transformed TMD PDF describes the main non-perturbative transverse momentum behavior. The sum over j is a sum over flavors. The "AA" factor is the calculation of the TMD PDF in terms of collinear PDFs at fixed order in collinear perturbation theory. This part of the calculation is, naturally, only valid for small transverse sizes. The "BB" factor is the collection of perturbative evolution factors. The interesting non-perturbative input contributions, as regards intrinsic transverse momentum, are in the factor labeled "CC." The function $g_{f/P}(x, b_T)$ describes the non-perturbative x and $\mathbf{b}_T$ dependence that is *specific* to hadron P and flavor f. Aside from its dependence on flavor and hadron, however, it is universal and scale independent. This factor contains the non-perturbative physics most directly associated with the hadron wave function. The other function, $g_K(b_T)$, is also non-perturbative, but it multiplies a logarithm of Q, and so it is associated with evolution. Thus, the transverse momentum dependent evolution has the somewhat unique aspect of involving *non-perturbative* evolution. While the non-perturbative nature of this evolution is a complicating factor, it has the advantage that $g_K(b_T)$ has a property we will call "strong universality." Namely, it is totally independent of the flavor of the quarks involved, the species of the parent hadron, the spins of the particles involved, kinematic variables like x and z, the hard scale, or any other details of the process.

The universality of functions like $g_{f/P}(x, b_T)$ and the strong universality of $g_K(b_T)$ means that many of the properties of these functions can already be deduced from the results of previous experiments, or general known features of non-perturbative physics. In [40], some basic features of these functions were deduced from a chiral soliton picture of the generation of non-perturbative transverse momentum in [41]. An understanding of the exact separation of the $g_{f/P}(x, b_T)$ and $g_K(b_T)$ functions requires a deeper and more detailed understanding of the underlying hadronization and fragmentation processes. Collaboration members and their collaborators are currently engaged in preliminary studies to extend Refs. [41, 40] by formulating these functions in terms of the Lund string model of fragmentation, well known for its successful use in Monte Carlo event generators. This aspect of our research highlights the convergence of work in basic non-perturbative theory and general TMD theory. **We plan to continue to explore ways that functional forms for non-perturbative input could be better constrained by physical considerations.**

The collaborative nature of these efforts is further highlighted by work that has already been initiated in lattice QCD. To obtain non-perturbative input for our studies of TMD systematics, we will capitalize on the by now well established program to calculate a certain class of TMD observables in lattice QCD [42] as will be pursued within this proposal. Data on the b_T behavior of TMDs in the non-perturbative regime will be extracted from the lattice calculations; furthermore, the non-perturbative Collins-Soper evolution of TMD observables can be studied within a limited regime. We are particularly interested in establishing the connection between that regime and the regime in which perturbative evolution equations become applicable; this will also serve to constrain the extrapolation of LQCD results to the infinite momentum frame. We intend to develop an analytical understanding of the systematics observed in LQCD calculations as a function of b_T and evolution scale.

2.4 QCD Global Analysis of the TMDs

Yuan (coordinator), Gamberg, Kang, Lee, Metz, Pitonyak, Prokudin, Qiu, Rogers, Vitev, Yuan

QCD global analysis of PDFs by the CTEQ Collaboration and MRS Collaboration in the late 1980's set up the standard of QCD tests and systematized the extraction of the proton's one-dimensional partonic structure. The method has been applied to the study of parton helicity distributions or polarized PDFs, and has been further developed and refined to include systematic error analyses, as well as new technology, such as the neural network approach. The knowledge of PDFs have played an essential role to connect the cross sections of colliding hadrons to the short-distance scattering between quarks and gluons, and in establishing QCD as the microscopic theory of the strong interaction. Without them, we would not be able to understand the hadronic cross sections with large momentum transfers in high energy collisions, nor would we be able to have discovered the Higgs particle in proton-proton collisions at the LHC.

Tremendous theoretical progress has been made in the last decade in defining TMDs and connecting them to experimental measurements. Compared to our knowledge and experience in extracting PDFs, however, current extractions of TMDs from data are still in their infancy. With the data from the COMPASS experiment at CERN, RHIC at BNL, the E906/SeaQuest Drell-Yan experiment at Fermilab, e^+e^- annihilation experiments at Belle and BaBar, and experiments at JLab, as well as the future programs at JLab12 and the proposed Electron-Ion Collider, it is critically important to develop a consistent QCD global analysis package of TMDs. **A central goal of our proposal is to put in place the tools and formalism required for this and to perform comprehensive global fits to TMD sensitive observables.**

There has been immense progress in phenomenological analyses of the TMDs from the existing experimental data, including the leading order studies such as Refs. [43, 44, 45] and references therein, and more recent developments considering the QCD evolution effects [18, 46, 47, 36, 37, 48]. Some of the participants in this proposal have been heavily involved in these developments. With the experience and expertise of the TMD Collaboration, we are in a unique position to develop a rigorous QCD framework for the global analysis package for extracting the TMDs from various experimental measurements. In the following, we highlight the main issues which are closely related to the global analysis and which will be tackled in our effort.

- TMD evolution and the non-perturbative inputs (Sections 2.2 and 2.3). Theoretically, the perturbative part of the TMD evolution has been worked out at the next-to-leading-logarithmic (NLL) order. However, as a unique feature in the TMD evolution, we have to consider the non-perturbative inputs in the phenomenological applications of the TMDs. Recently, there have been progresses toward a universal non-perturbative function for unpolarized Drell-Yan and SIDIS processes [38, 40]. It is essential to test this universality and to generalize it to the spin-dependent and/or azimuthal angle dependent cross sections.

- Dedicated program package to compute the differential cross sections and spin/azimuthal angular asymmetries. In the phenomenological studies, the TMD differential cross sections are parameterized in the $b_\perp$-space, according to the CSS formalism. However for global fits, we must Fourier transform these expressions into transverse momentum space in order to compare to the experimental data. This is numerically challenging when including all the evolution effects. We plan to improve the existing software to include a user-friendly interface (such as a Python package) for doing general TMD calculations. This is especially important to allow a systematic study on the variations of the TMDs on the input, the renormalization scheme and other details of the perturbative formalism.

- Systematic procedure and method to estimate the theoretical uncertainties in the global fit. The TMD predictions for future experiments crucially depend on how we understand the constraints from the existing experiments. To have a reliable estimate, we will follow previous examples in the global analysis of the unpolarized parton distributions (such as CTEQ [49]) and the helicity parton distributions (such as DSSV [50]). In addition, we will also address the theoretical uncertainties introduced by the non-perturbative inputs for the TMD evolutions.

In order to carry out the global analysis, we plan to investigate the relevant theoretical and phenomenological questions concerning the applications of the TMD factorization in the hard scattering processes as outlined throughout this proposal. These theoretical questions are important to build the foundation for the global analysis, and provide important guidelines for the numeric computations. For example, as discussed in Sec. 2.1, a central question raised recently concerns about the scheme-dependence of the TMD definition and factorization. We expect, however, after solving the evolution equations, TMDs in different schemes can be related using perturbative QCD. Another theoretical/phenomenological issue, discussed in Sec. 2.5, concerns the matching between TMD calculations and collinear calculations in the intermediate transverse momentum region in SIDIS processes [38, 51]. The so-called Y-term contribution which is supposed to help match TMD and collinear calculations in the CSS formalism, is found too large compared to the TMD calculation. This imposes a theoretical challenge to apply the CSS formalism in SIDIS processes. We plan to address this issue rigorously.

2.5 Relation between TMDs and Collinear Parton Correlation Functions

Metz (coordinator), Kang, Pitonyak, Qiu, Rogers, Sterman, Yuan

It is very important to explore in detail the relation between TMDs on the one hand and observables that can be expressed in terms of collinear parton correlation functions on the other. First, such studies are critical for obtaining a smooth description of the transverse momentum dependence of cross sections. Second, they allow one to relate TMD observables to other observables such as transverse single spin asymmetries (SSAs) for single inclusive particle production in hadronic collisions. In general, the relation between TMDs and collinear parton correlators is a field where a close collaboration between theory and phenomenology is critical in order to make any significant progress.

With regard to the transverse momentum dependence of observables, we will thoroughly investigate the unpolarized cross sections of SIDIS, the Drell-Yan process, and e^+e^- annihilation into two hadrons. The TMD factorization expressions for those processes that involve intrinsic transverse momentum k_T rely on having $k_T \ll Q$, with Q denoting the large scale of the process. When $k_T \to Q$, extra terms are needed (the so-called Y-terms discussed above) to account for the behavior for large transverse momenta [4]. The Y-terms are calculable using factorization theorems that involve collinear parton correlation functions. Further developments are necessary in order to get a smooth matching between the region where TMD functions dominate to the region where Y-terms are needed. While for the Drell-Yan process a satisfactory description of the transverse momentum dependence of the cross section has already been obtained [52, 33, 53], it was realized recently that for SIDIS such a smooth matching can not easily be accomplished [38, 51]. Presently, it is unclear how this very important issue can be resolved. **However, one may expect that higher order corrections play a significant role for SIDIS. Therefore, we plan to evaluate such higher order terms for both the TMD factorization formulas and the Y-term.** If they do indeed improve the situation for SIDIS one has to understand why, from a phenomenological point of view, they are less important for the Drell-Yan process. It should also be stressed that a solid understanding of the transverse momentum dependence of the unpolarized cross section for SIDIS is absolutely mandatory in view of planned experiments at an EIC, where this observable can be measured to large transverse momenta with unprecedented accuracy. For e^+e^- annihilation, the transverse momentum dependence is basically unexplored, and thus our efforts in that regard would be truly pioneering.

The Y-terms will also be important for clarifying difficult issues in the calculation of spin-dependent observables like transverse SSAs which have quite different large transverse momentum behavior from unpolarized observables. So far, simplified pictures of the large transverse momentum dependent behavior have been applied to the calculation of transverse SSAs, and the collaborative effort would pool the expertise needed to combine treatments of large and small transverse momentum. At large transverse momentum the SSA associated with the Sivers effect [54, 55] is twist-3 (see for instance Ref. [56]). The general qualitative behavior of the transverse momentum distribution is thus expected to be quite different from that of unpolarized distributions, and its treatment lies outside the scope of standard leading twist treatments of the Y-term. Therefore, expertise in both higher twist factorization methods and leading twist TMD methods will ultimately need to be combined to form a more firmly grounded treatment of observables like transverse SSAs over the the full range of transverse momentum.

Transverse SSAs are also relevant in processes like $p^\uparrow p \to hX$ (see for instance [57, 58, 59, 60] for data from RHIC for pion production), as well as the (quantitative) relation of those observables to the Sivers asymmetry [54, 55] and the Collins asymmetry [61] measured in SIDIS and in e^+e^- annihilation. The field of transverse SSAs in hadronic collisions began some 40 years ago with the observation of the large transverse polarization (up to about 30%) of Λ-hyperons in the process $pBe \to \Lambda^\uparrow X$ at FermiLab [62]. It was noticed early on that the naïve collinear parton model cannot generate such large effects [63]. Soon afterwards it was pointed out that those SSAs in hadronic collisions are genuine twist-3 observables for which, in particular, collinear 3-parton correlations have to be taken into account in order to have a proper description within QCD [64, 65]. Later on this formalism was worked out in more detail and also successfully applied to $p^\uparrow p \to hX$ [66, 67, 68, 69, 70, 71, 72, 73, 74]. The twist-3 approach to such SSAs contains a number of contributions. One of them, which for a long time was generally believed to be the most important term, is described by the Qiu-Sterman function T_F [66, 67] which parameterizes a particular (twist-3) quark-gluon-quark correlator for a transversely polarized nucleon. A second contribution, the twist-3 effect associated with the unpolarized nucleon, was shown to be small [75]. Only recently a complete result was obtained for the last term, the twist-3 fragmentation contribution [76] (see also [77] for an earlier study).

The Qiu-Sterman function has a model-independent relation to a particular transverse momentum moment of the Sivers function $f_{1T}^{\perp}$ [78]. This relation can be used in order to compute the SSA in $p^\uparrow p \to \pi X$ based on data for the Sivers effect in SIDIS. The surprising result of such a study was that the resulting SSA in hadronic collisions has a sign opposite to the data [79], which is now known as the "sign-mismatch" puzzle. Moreover, the magnitude of the calculated asymmetry is way too small. Later work suggests that the twist-3 Sivers effect as described by T_F indeed cannot be the main source of the SSAs in $p^\uparrow p \to \pi X$ [80]. Rather, the twist-3 fragmentation contribution could play a very critical role for those observables [81]. We plan to further investigate this in detail. One important missing element in the existing studies is that the aforementioned transverse momentum moment of $f_{1T}^{\perp}$ can only be obtained from the existing data in SIDIS after making simplifying assumptions. A more rigorous treatment would, in particular, take into account the proper TMD evolution of the Sivers function [35, 17, 18, 46, 37], which gives rise to a more complicated relation between $f_{1T}^{\perp}$ and T_F. **We plan to carefully investigate this very crucial point and study its phenomenological implications. Ultimately, this will enable us to include the SSAs in the global analysis of TMDs discussed in Section 2.4.**

2.6 New Physical Observables Sensitive to TMDs

Gamberg (coordinator), Engelhardt, Kang, Mehen, Metz, Prokudin, Schweitzer, Stewart, Rogers

A reliable QCD global analysis of TMDs will require multiple physical observables that are sensitive to the same TMDs. While the classic observables for studying TMDs are semi-inclusive DIS, the Drell-Yan process, and electron-positron annihilation into two hadrons, a major goal of the TMD Collaboration is to explore to what extent other observables can be used in order to extract information about TMDs. In this regard, we will consider processes in *pp*-collisions (accessible for instance at RHIC [82] and LHC). Additionally, while there is preliminary work performed for quark TMDs, gluon TMDs [24] have only recently been studied [83] and their exploration will require new suitable processes. In this respect, an Electron-Ion Collider will be critically needed to develop a consistent QCD global analysis of both quark and gluon TMDs [2, 84].

2.6.1 Gluon TMDs and Higgs Production

Higgs production has been regarded as one of the most important and clean processes to study gluon TMDs [85]. Recently di-photon production in *pp* collisions [83, 86, 87] has been proposed to further explore the spin-dependent gluon distribution, such as linearly polarized gluons and the gluon

Sivers function. Nevertheless, more dedicated work is needed to find out precisely under which conditions one does have TMD factorization for di-photon production. One can systematically study polarization observables in order to see how (gluon) TMDs can be addressed in detail. In order to get a first numerical estimate of various spin observables one can use positivity bounds for gluon TMDs [88], and ideally we can also obtain information on those TMDs via LQCD. Other observables for addressing gluon TMDs are the production of di-jets, hadron plus jet, hadron pairs, and open charm in deep-inelastic lepton nucleon collisions. While first exploratory works exist on those processes, no systematic study is available and we plan to develop the necessary background as this is also extremely important for studies at an EIC.

From a theoretical point of view it is very important to carefully study the role played by soft gluon emissions in all those processes. In general, it can be expected that this is quite different from processes like semi-inclusive DIS. Therefore, one has to quantify the "corrections" that may be needed if one wants to connect different reactions sensitive to TMDs.

2.6.2 Gluon TMD from Υ Production

There is a treasure trove of data available from the Tevatron and LHC colliders that can be used to measure the gluon TMD PDF to high precision. The measurements in question are those of $\Upsilon(nS)$ production at low to moderate transverse momentum, p_T (less than 6 or 7 GeV). At the Tevatron, the CDF collaboration collected data [89] on $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production in $p\bar{p}$ collisions ranging down to almost zero p_T with uncertainties on the order of 20%. At the LHC, the ATLAS [90], CMS [91], and LHCb [92] collaborations have collected data on the same states produced in pp collisions down to zero p_T with percent level uncertainties. A proper analysis of the low p_T region of $\Upsilon(nS)$ production has the potential of providing us with a precision extraction of the gluon TMD, and could shed light on the long standing polarization puzzle of quarkonia production.

The low transverse momentum distribution of Υ production in hadronic collisions was first investigated in Ref. [93], and was recently studied in Ref. [94] in the context of Non-relativistic QCD (NRQCD). In addition, Ref. [93] addressed the connection of the low p_T region to the moderate p_T region. Known EFT tools based on SCET and NRQCD can be used to carry out a systematic analysis of Υ production in hadronic collisions at small to moderate p_T to much higher accuracy, allowing for a precision extraction of the gluon TMD PDF. At lower p_T, the dominant contribution to the cross section comes from configurations where the $b\bar{b}$ which forms the $\Upsilon(nS)$ is produced in a color-octet ${}^1S_0$ state [95, 96]. As a consequence, at non-perturbative values of p_T the production cross section will be a convolution of the gluon TMD PDF and a TMD fragmentation function describing the hadronization of the $b\bar{b}$ pair into the Υ, and the challenge will be to disentangle these two contributions. One possible approach is to utilize input from lattice QCD to constrain the TMD functions, in particular the TMD fragmentation function.

The analysis of quarkonium production using TMD PDFs could also shed light on the long standing polarization puzzle of quarkonia production (see Ref. [97] for extensive details). Most of the world's data on quarkonia production in a wide variety of experiments (e^+e^-, e^-p, pp, $p\bar{p}$ $\gamma\gamma$, etc.) is reasonably well described by NLO NRQCD with both color-singlet and color-octet mechanisms. These calculations use collinear factorization with conventional PDFs for processes with initial state hadrons. However, the NRQCD long-distance matrix elements (LDME) extracted from these global fits predict that J/ψ and Υ should be produced with transverse polarization at large p_T in hadron colliders. It is therefore a puzzle that at both the Tevatron and the LHC no polarization is observed at high p_T. **We plan an analysis of data on quarkonia production at low to moderate p_T with NRQCD factorization and TMD PDFs which we expect**

will lead to a more consistent extraction of LDMEs at both moderate and high p_T.

2.6.3 TMD Observables in pp Scattering and Factorization Breaking

pp collisions have provided a rich source of data to study transverse momentum and transverse spin effects. In fact, they provided the first indication for the necessity to move beyond a collinear picture of QCD to describe nucleon structure. However, while potentially providing essential experimental data to study the 3D structure of the nucleon, advances in QCD theory indicate that factorization breaking [98, 26] in certain processes precludes a simple definition of nucleon structure from these processes both with respect to defining TMDs as well as their universality properties. Though challenging, such processes provide unique opportunities to quantify factorization breaking as well as study the rich QCD phase structure of the nucleon [99, 100, 101, 78, 102, 103, 70, 104, 105, 106, 79].

Two scale processes with $P_{h\perp} \ll Q$ may be amenable to study in terms of TMDs and may also allow us to quantify factorization breaking. Prominent examples of such a process are the transverse momentum distribution of hadrons inside jets [107, 108, 109], as well as di-jet imbalance [110, 105, 98, 111] and photon-jet correlations [112] in pp collisions. Experimentally, an attempt to access the Sivers effect in di-jet imbalance was studied at RHIC [113] yielding a trivial result. Data has also recently been obtained on pions inside a jet at RHIC [114, 115, 82]. However, given the known problems with TMD factorization for processes like the production of two back-to-back hadrons in pp collisions [98, 26], it becomes urgent to develop a generalized framework such that TMD factorization breaking can be clearly quantified in theory and carefully investigated through a detailed comparison with the experimental data.

2.6.4 TMD Evolution: Studies in Coordinate b_T-Space

Recently, a new technique to study the the scale dependence of TMD observables was proposed in [116] using the concept of weighted asymmetries. The approach relies on a model-independent deconvolution of structure functions in terms of Fourier transforms of TMDs from observed azimuthal moments in semi-inclusive processes with polarized and unpolarized targets. The individual structure functions in the cross section can be projected out by means of a generalized set of weights involving Bessel functions. Advantages of employing these Bessel weights are that they employ the language of TMD factorization [117, 16, 7] in Fourier b_T-space, and that they suppress divergent contributions from high transverse momentum. Preliminary studies show that Bessel weighted asymmetries are in many cases less sensitive to the effects of soft gluon effects and universal non-perturbative scale dependence [19, 40].

A first phenomenological study of Bessel weighting was recently published in [118]. There the Bessel weighting procedure was used to reconstruct the double longitudinal spin asymmetry A_{LL} in SIDIS and the Fourier transforms of helicity g_{1L}, and unpolarized f_1 TMDs from a Monte Carlo event generator. **We propose to study the scale dependence of the Sivers and Collins asymmetries and the analyzing powers of various spin sensitive TMDs**. These latter observables are directly related to recent non-perturbative QCD studies of TMDs on the lattice [42, 119] (see Section 2.8). Here an opportunity to study both process dependence and scale dependence of transverse polarization phenomena with the lattice as a laboratory presents a unique opportunity to explore the b_T-space scaling behavior of TMDs. Such b_T-space studies of the scale dependence of TMD observables will benefit from the global analysis of TMDs and further studies of TMD factorization (see Sections 2.2-2.4).

2.7 QCD Factorization for Lattice Calculations of PDFs and TMDs

Qiu (coordinator), Detmold, Fleming, Ji, Mehen, Orginos, Stewart

PDFs and TMDs of a fast moving hadron are nonperturbative, and are defined to absorb all perturbative partonic collinear divergences into non-perturbative distribution functions, and not directly calculable in lattice QCD since their operator definitions are sensitive to the difference between the Minkowski and Euclidian time. Recently, Ji [120] introduced a set of quasi-PDFs, defined in terms of hadronic matrix elements of equal time correlators, calculable in lattice QCD [121], and suggested that the quasi-PDFs become the normal PDFs when the hadron momentum P_z is boosted to the infinity. However, the hadron momentum in lattice QCD calculation is effectively bounded by the lattice spacing, and the $P_z \to \infty$ limit is hard to achieve. Many efforts have been devoted to explore and estimate the corrections due to the finite value of P_z, including the large-momentum effective field theory approach [122] and model calculations [123]. The connection between the PDFs and quasi-PDFs is further complicated by the fact that the operator defining the quasi-PDFs are power ultra-violet (UV) divergent, while the operators defining the normal PDFs have only logarithmic UV divergence.

Recently, it was demonstrated that the quasi-PDFs and the usual longitudinal PDFs, one defined in Euclidian and the other in Minkowski space, respectively, share the same perturbative and logarithmic collinear divergences to all orders in perturbation theory [124, 125]. That is, quasi-PDFs could be perturbatively factorized and matched onto the normal PDFs, provided the power UV divergence of quasi-PDFs could be perturbatively renormalized [125]. In principle, if we can calculate the quasi-PDFs on the lattice, we can extract the normal PDFs using the perturbatively calculated matching coefficients. This approach can in principle be applied more generally, for example, in the context of determining TMDs, generalized parton distributions (GPDs) [120], and other light-cone dominated matrix elements. Here, the matching procedure needs to be explored both theoretically and practically to see if additional complications arise and can be addressed. We intend to carry out these investigations and will refer to this general framework as the *quasi-distribution* approach.

2.7.1 Quasi-Distributions

With the currently available computing resources, quasi-PDF based lattice QCD calculations of PDFs are relevant to the hadron's parton structure at large momentum fraction x, and are complementary to those extracted from fitting high energy scattering data. This approach requires knowledge and expertise of numerical lattice QCD, effective field theory and QCD factorization, as well as techniques in perturbation theory. Such ab initio calculations of hadron structure can be combined with phenomenological information about small-x PDFs and could provide an excellent testing ground for hadronic model calculations. Importantly, quasi-PDF based lattice QCD calculations of parton structure can be applied not only to the proton, but also to hadrons that are hard to access experimentally such as the neutron, pion and kaon, and eventually, to light nuclei. There is still considerable room to develop the connection between PDFs and quasi-PDFs defined by hadronic matrix elements of an off light-cone correlator. We plan to explore such connection in the following areas theoretically as well as phenomenologically:

- UV renormalization of quasi-PDFs. Perturbatively, all logarithmic UV divergences of the operators defining the PDFs can be systematically renormalized, and the renormalization flexibility leads to the scheme dependence of the PDFs. Any valid perturbative matching between the quasi-PDFs and PDFs requires that the quasi-PDFs are perturbatively UV finite [125]. **We will carefully investigate whether all UV divergences, logarithmic as well**

as power-like, of the operators defining the quasi-PDFs could be systematically and perturbatively renormalized.

- Large P_z effective field theory approach. As $P_z \to \infty$, the parton physics described by the quasi-PDFs is mostly related to the dynamics near the light-cone, which are well represented by the PDFs. That is, it is natural to explore the expansion of quasi-PDFs as a power series of $1/P_z$, and to introduce an effective field theory approach [122]. **We will further explore the consistency of operator expansions of the effective field approach, and to quantify the connection between the quasi-PDFs and PDFs as power corrections in $1/P_z$.**

- QCD collinear factorization approach. With a sufficiently large factorization scale, $\mu \sim$ a few GeV, quasi-PDFs are probed/calculated with a large momentum transfer, and can be systematically expanded in terms of a power series of $1/\mu$, and the leading power term can be collinearly factorized into a convolution of PDFs with perturbatively calculable coefficient functions [124, 125]. The corrections in power of $1/\mu$ can be expressed and quantified in terms of matrix elements of high twist multi-parton correlators. In order to extract PDFs from lattice calculation of quasi-PDFs with this collinear factorization approach, we need to calculate the coefficient functions perturbatively by evaluating the quasi-PDFs in lattice QCD perturbation theory and PDFs in perturbative QCD, and go beyond the leading order [125], so that we can match the accuracy of PDFs at lower x extracted from high energy scattering data. SCET could be another valuable approach to explore factorization for quasi-PDFs. We plan to explore this new avenue and develop associated connections.

- Phenomenological application. Although the current resources of computing power limits us to calculate only the large x region of quasi-PDFs, it is already sufficient for us to explore and address many very interesting questions and puzzles. **We plan to explore various ratios of PDFs, such as $d(x)/u(x)$ as $x \to 1$, by evaluating corresponding quasi-PDFs in lattice QCD simulations and perturbative matching coefficient functions; and PDFs of pion or other hadrons that are hard to access experimentally.**

- Beyond quasi-PDFs. The idea to use quasi-PDFs, calculable in lattice QCD, to extract PDFs can in principle be applied more generally, for example, in the context of determining TMDs and GPDs [120], and even generalized TMDs (GTMDs), providing a promising approach to explore the parton structure of hadrons. We plan to expand the early lattice exploration of TMDs and the sign change of Sivers and Boer-Mulders functions further to explore the 3D parton structure of hadron and QCD dynamics [42].

- Model calculations. PDFs at large momentum fraction x are very sensitive to the binding and detail dynamics of hadrons. Model calculations of quasi-PDFs, in particular, its P_z dependence, could help us to understand better the connection and the approximation between the PDFs and quasi-PDFs [123] and will be pursued.

2.7.2 Quasi-distributions for other observables

In collider physics, using SCET or other methods, there are additional nonlocal light-cone operators whose matrix elements provide important physical information. It is interesting to consider whether the quasi-distribution approach can be applied to these quantities and we aim to investigate this both from the perturbative and lattice QCD directions with emphasis on the following examples.

The heavy quark PDF in a heavy-light meson in the static limit (HQET) is known as the shape function, defined through the matrix elements $\langle B|\bar{b}_v(x^-)Y_n[x^-,0]b_v(0)|B\rangle$, where $v^2 = 1$ and $n^2 = 0$. Here the dynamics can be written entirely in terms of Wilson lines, two time-like Y_v corresponding to the b_v fields, and one light-like, Y_n. This is a close analogue of the quasi-PDFs discussed above, where the struck quark is replaced by a Wilson line. These distributions play an important role in describing $B \to X_s\gamma$ and $B \to X_u\ell\nu$ [126, 127, 15, 128, 129].

The light-cone distribution functions involve the same operators as studied in the PDFs in hadron to vacuum matrix elements, for example $\langle\pi|\bar{q}(x^-)Y_n[x^-,0]q(0)|0\rangle$. These matrix elements are relevant for both light mesons, light baryons and heavy hadrons in hard, exclusive interactions amenable to factorization.

Situations with more complicated matrix elements such as fragmentation functions are also worth pursuing through similar quasi-distribution methods. Again, light-like Wilson lines play an important role in the definition of these quantities and can potentially be Euclideanized. They involve an operator $\bar{q}(x^-)Y_n[x^-,\infty]$ producing a hadronic state accompanying radiation and enter into many phenomenological observables discussed above. Another class of important quantities are soft functions that appear in jet production. These are defined as matrix elements with a light-like Wilson lines associated with each jet and and a suitable final state measurement expressed in terms of the energy-momentum tensor [130, 131, 132, 133, 134]. These soft functions describe the leading order hadronization of various jet observables such as event shapes [135, 136, 137].

2.8 New Nonperturbative QCD Approaches for Lattice Calculations of PDFs and TMDs

Detmold (coordinator), Engelhardt, Liu, Negele, Orginos

Traditionally, a mainstay of the non-perturbative lattice QCD study of the partonic structure of the proton has been the calculation of the local matrix elements corresponding to the Bjorken-x moments of quark PDFs and GPDs [138, 139, 140]. In principle, calculation of a large number of moments would provide equivalent information to the x-dependence of the PDFs and GPDs. However, the reduced symmetries of the lattice regulator used at intermediate stages of the calculations mean that determinations of more than a few moments become significantly more difficult. In recent years, a number of approaches to extracting more higher moments, or determining the x-dependence directly have been proposed [141, 142, 143, 120, 122, 125, 144] and in some cases preliminary numerical investigations have been performed [121, 145].

Each of these methods have various potential advantages and disadvantages and we propose to perform a comprehensive investigation of the available methods and attempt to evaluate their efficacy. We will aim to provide numerical implementations of a number of the above approaches in a common set of calculations, thereby enabling a direct comparison. A comparative study has many advantages; for example, calculations of the x-dependence of PDFs can be cross checked by calculations of moments, and by performing calculations in a coherent manner, cost savings can be identified. **We plan to implement the approaches of Refs. [141, 142, 143] as well as to modify our ongoing lattice calculations of TMDs [42, 146] discussed in Section 2.6 above to access the correlators needed in the method of Ref. [120].** A common component to all of these methods is the necessity of resolving physics at a relatively high scale with fidelity. In the approaches of Refs. [142, 143], particular emphasis is placed on having a perturbative scale significantly below the lattice cutoff, while in Ref. [120], a large momentum proton state is required. Additionally, in Ref. [141], a very careful approach to the continuum limit is required, thereby avoiding the problem of renormalization. The approach also requires taking an inverse Laplace transform in time [141] for which recent improvement of the maximum entropy method [147] may be important. Technically, these requirements present a challenge to current lattice QCD methods; small lattice spacings are numerically very expensive and large momentum typically results in statistically poor signals. There are a number of possible approaches to addressing these problems that we envisage. We will consider the use of anisotropic lattices which have a finer discretization scale in one direction and therefore allow a large momentum in that direction. However, the anisotropy breaks the hypercubic symmetry at finite lattice-spacing to a cubic subgroup and the corresponding operator renormalizations must be treated carefully. We will also attempt to construct large-momentum sources for the nucleon interpolating operators using the variational approach of building a basis of interpolators that is then diagonalized to produce optimized source structures for the given momentum. In the same context, we will investigate recently introduced noise-reduction techniques [148] that potentially reduce statistical fluctuations in lattice QCD correlation functions. An alternative approach to large momentum [149] makes use of the step-scaling method [150] in which progressively finer lattice spacing calculations are matched on to coarser ones keeping a particular quantity fixed as the scale is stepped. This method can be repeated, leading to an exponential improvement in the ability to resolve large scales. It is likely that some of these methods will not be particularly efficient or informative. Having discovered this, we will reassess out strategy and prepare for large scale calculations using the successful methods.

In all of these approaches, there is critical need for input from other areas of our collaboration with relevant expertise in perturbative QCD and phenomenology. For example, in the approach of [142], the Wilson coefficients associated with charged current deep-inelastic scattering are required but for currents that are specific to the observables. In the approach of Ref. [120], there are perturbative calculations related to the matching that need to be performed with lattice regulators and will depend on the details of the lattice implementation (actions, exact paths,...); explicit calculations for these are proposed in the previous Section. In determining the x-dependence of PDFs and comparing with calculations of moments, it will be important to get input from phenomenologists in order to continue the region in which x-dependence is extracted to the entire integration region; understanding the expected small (and large) x behavior will be critical.

We also aim to continue our ongoing lattice calculations of TMDs [42, 146]. A significant complication in the treatment of nonlocal operators containing a QCD gauge connection between quark operators separated by a transverse distance b lies in the divergences associated with the gauge connection. Generically, these divergences necessitate cancellation by soft factors depending on b; as a consequence, Fourier transformations with respect to b to extract quark momentum components need to take the soft factors into account. In this respect, the case of TMDs in somewhat more flexible than the case of ordinary PDFs or GPDs. Owing to the staple-link structure of the gauge connection for TMDs, soft factors depend only on the transverse components b_T, but not on the longitudinal component $b \cdot P$ which is Fourier conjugate to the longitudinal quark momentum fraction x. As a consequence, the x-dependence of TMDs can be accessed without explicit construction of the soft factors. In the chiral quark soliton model, it has been suggested that antiquarks have a much broader transverse momentum distribution than quarks [41, 151]. Accessing the x-dependence of TMDs will enable us to test this prediction from first principles.

2.9 TMDs and Parton Orbital Angular Momentum

Negele (coordinator), Burkardt, Engelhardt, Liu, Liuti, Metz, Richards

Recent theoretical developments have provided important insight into decomposition of the nucleon spin into its quark and gluon contributions and further separation of these into spin and orbital components. (see [152] for a timely review). We will study decompositions by Ji [153] and by Jaffe and Manohar (JM) [154]

$$\frac{1}{2} = S_q + L_q^{\mathrm{Ji}} + J_g^{\mathrm{Ji}} \,, \qquad \frac{1}{2} = S_q + L_q^{\mathrm{JM}} + S_g^{\mathrm{JM}} + L_g^{\mathrm{JM}} \tag{5}$$

keeping in mind that gauge-invariant quantities generally include quark and gluon fields. It should be emphasized that the only term common to both decompositions is the quark spin contribution S_q and as discussed below, $L_q^{\mathrm{Ji}} \neq L_q^{\mathrm{JM}}$, where both definitions of quark orbital angular momentum (OAM) have distinct physical meanings. **As described below, we propose to calculate $\mathbf{S_q}$, $\mathbf{L_q^{Ji}}$, $\mathbf{J_g^{Ji}}$, $\mathbf{L_q^{JM}}$, and $\mathbf{S_g^{JM}}$ using lattice QCD.** We also plan to investigate terms in these sum rules by exploiting the recently discovered relation to transverse parton motion [155, 156].

Studying the nucleon gluon structure on the lattice is a challenge since gluon signals are noisier than those of quarks. We propose to calculate the gluon momentum, angular momentum J_g^{Ji} and spin S_g^{JM} with 2+1 flavor dynamical fermions approaching the physical pion mass and continuum limit as far as possible. The gluon momentum and J_g^{Ji} can be calculated from the energy momentum tensor as for quarks. However, the lattice discretization is intrinsically noisy, making it essential to utilize improved operators [157], the overlap Dirac operator [158] or other noise reduction techniques. Momentum and angular momentum sum rules can be used for non-perturbative renormalization of the gluon and quark operators and the quark and gluon mixing can be calculated perturbatively and matched to the $\overline{MS}$ scheme at a specified scale as in Ref. [158].

Making contact with the parton picture, the JM spin decomposition Eq. (5, right) is derived in the light-cone gauge, $A^+ = 0$, with the nucleon in the infinite momentum frame [154], where the gluon helicity distribution is defined through light-cone correlation functions [159]. Whereas this definition of the gluon spin is suitable for hard scattering processes, it is not directly accessible on a Euclidean lattice, which does not accommodate light-cone gauge. However, a gauge invariant decomposition of gluon angular momentum into spin and orbital angular momentum has been proposed [160] in a non-Abelian Coulomb gauge, where the spin operator $S_g = \int d^3x Tr(\vec{E} \times \vec{A}_{\mathrm{phys}})$ is gauge invariant, frame-dependent, and can be calculated on a Euclidean lattice. It has recently been shown [161] that boosting the nucleon to the infinite momentum frame, the nucleon matrix element of this operator reproduces that of the integrated helicity distribution defined with the light-cone correlator, which is the gluon helicity $\Delta G = S_g^{\mathrm{JM}}$. An exploratory lattice calculation of S_g in the non-Abelian Coulomb gauge has been carried out [162], which has large statistical errors and nucleon momentum limited to ~ 1 GeV. We propose to undertake more realistic calculations, improving the gluon spin operator with smearing and using a fine lattice spacing to accommodate large momentum states in order to address the challenges of controlling the large statistical fluctuations and the infinite momentum extrapolation. These calculations will be particularly important qiven the experimental effort devoted to studying the gluon distribution function using deep inelastic scattering and the Drell-Yan process and studying the gluon helicity by the STAR, PHENIX and COMPASS experiments for which a recent analysis [163] has shown evidence of a non-zero gluon helicity in the proton.

Another focus of the present proposal is quark orbital angular momentum (OAM). As shown in [156], both L_q^{Ji} and L_q^{JM} can be given in terms of gauge-invariant transverse momentum-dependent operators [164]. Their difference can be interpreted in terms of the integrated torque experienced by a quark as it is being ejected from the nucleon in a deeply inelastic scattering process [165], which is included in L_q^{JM} and not in L_q^{Ji}. These features are exhibited particularly clearly in a formulation in terms of generalized transverse momentum-dependent parton distributions (GTMDs), given by matrix elements of the form

$$\widetilde{\Phi}^{[\Gamma]}(b, P', P, S, \ldots) \equiv \frac{1}{2} \langle P', S| \; \bar{q}(0) \; \Gamma \; \mathcal{U}[0, \ldots, b] \; q(b) \; |P, S\rangle \; . \tag{6}$$

Here, the generalization compared to standard TMDs is considering nonzero momentum transfer $P' - P$. Fourier transformation with respect to the momentum transfer yields impact parameter information, i.e., information about the separation $\vec{r}$ of the quark from the nucleon center of momentum. As in standard TDMs, Fourier transformation with respect to the quark operator separation b in (6) yields information about quark momentum $\vec{p}$. This combination of information allows one to form $\vec{r} \times \vec{p}$ and thereby obtain direct information about quark OAM in the nucleon.

Understanding of the roles of the two definitions of quark OAM has initiated a fruitful interaction between phenomenology, theory and lattice QCD which we intend to pursue. **To stimulate future experimental efforts to access quark OAM directly, we intend to develop the description of physical processes that permit simultaneous access to a hadron momentum transfer and the transverse momentum of the hadronized ejected quark inherent in the matrix element (6).** In addition, we propose to undertake lattice QCD calculations of (6) both to calculate L_q^{Ji} and L_q^{JM} and with a view towards informing future experimental efforts as to the expected sign and size of OAM effects and the behavior of this matrix element. L_q^{Ji} obtained in this way, can be compared to the standard determination as the difference between the total quark angular momentum specified by GPDs and the quark spin. This can serve to validate the method, in which case the calculation of L_q^{JM} would constitute the first determination of this quantity from first principles, using lattice QCD. We also plan to carry out complementary calculations of L_q^{JM} via the canonical energy-momentum tensor, which will provide a cross-check of the treatment of renormalization.

A further avenue of accessing L_q^{Ji} that has recently begun to attract attention is via the twist-3 sector, in which L_q^{Ji} can be given directly [166, 167, 168] through the GPD G_2, as opposed to the standard method using GPDs mentioned above. In this case, first experimental observables were suggested from which G_2 can be extracted [169, 170, 171], whereas further theoretical development is necessary before a corresponding lattice QCD calculation can be carried out. Given that quark OAM can be obtained both from a GTMD, as discussed above, and a GPD, G_2, it would be useful to understand the relation between these descriptions in more detail. One possible avenue is to consider the form of this relation before integration over transverse momentum where G_2 also originates from GTMDs. This will benefit from TMD studies in other parts of this proposal, which can help understand issues like divergence structures at the GTMD level. Once renormalization is understood, we intend to calculate L_q^{Ji} via G_2. This will complement experimental determinations and further enhance phenomenological understanding of quark OAM.

2.10 TMDs at Small-x and in Nuclei

Venugopalan (coordinator), Detmold, Fleming, Qiu, Stewart, Yuan

There are compelling theoretical arguments and strong experimental hints that suggest that the gluon distribution saturates at small Bjorken-x [172, 173, 174, 175, 1]. Gluon saturation at small-x is an emergent phenomenon that significantly modifies the landscape of parton distributions inside a nucleon or nucleus. In this region of high parton densities in QCD, the effective degrees of freedom and their dynamics will be different when compared to that in the dilute region. In the small x Regge limit of QCD, the dynamical evolution of parton distributions is described by the BFKL equation, and when parton densities become large, by its nonlinear extension, the Balitsky-JIMWLK hierarchy of equations. A central question in high energy QCD is to identify the boundary between the dilute and dense regions, and how the dynamics of quarks and gluons changes through this transition.

In recent years, there have been important developments that have brought to the fore, the connections between the TMD formalism and the small-x Color Glass Condensate (CGC) formalism in various contexts [176, 177, 178]. In particular, it was realized that the TMD-like hard processes, which involve a hard scale Q in addition to the transverse momenta of the observables, offer unique possibilities to probe the saturation regime. The most important feature is that, in this kinematics, one can access unintegrated gluon distributions, which are important ingredients in the saturation framework and are sensitive to multi-parton interactions. Several processes have been proposed in the literature, including semi-inclusive DIS [176], low p_T Drell-Yan [179], and back-to-back dihadron correlations in forward pA processes [180]. Recently, considerable progress has been made that in computing Sudakov double logarithms that can be resummed consistently in the small-x formalism [181]. These computations provide a solid theoretical foundation for further rigorous investigations that probe the dynamics of the saturation regime with hard processes. We will also attempt to exploit recent SCET formalism for small-x physics.

In the CGC framework, two different unintegrated gluon distributions (UGDs) are widely used in the literature. The first such distribution, the Weizsäcker-Williams (WW) gluon distribution, is calculated from the correlator of two classical gluon fields of relativistic hadrons [174, 182], and has a clear physical interpretation as the number density of gluons inside the hadron in light-cone gauge. The second gluon distribution, defined as the Fourier transform of the color dipole cross section, does not have a clear parton interpretation but can be directly related to observables. These two gluon distributions form the fundamental building blocks of all the TMD gluon distributions at small x. It has been realized that the WW gluon distribution could be directly accessed in the dijet production process in DIS while the photon-jet correlations measurement in pA collisions can access the dipole gluon distribution directly. In addition, other more complicated dijet production processes in pA collisions will involve both of these gluon distributions through a convolution in transverse momentum space. Related phenomena have also been intensively investigated in the TMD factorization framework [183, 98, 104, 26], where the associated parton distributions are found to be non-universal. Detailed analyses have shown that these results in the TMD formalism can be related to the small-x calculations for dijet production [180]. In addition, the azimuthal correlated (linearly polarized) TMD gluon distribution has played an important role in describing cross sections in hard processes at small-x [178].

We plan to extend the theoretical and phenomenological investigations of the two frameworks outlined at small x, with the aim of obtaining a unified picture of parton distributions in the high parton density regime. A number of challenging issues will be investigated in detail:

1. Small-x evolution of the TMD gluon distributions [184]. The theoretical framework exists to solve the small-x evolution equations for the dipole and WW gluon distributions. We plan to develop an efficient program to numerically solve these equations and gain insight into the TMD gluon distributions at different x. The combination of theory developments and phenomenological applications to the experimental data will help clarify the role of parton dynamics relative to those of "dipoles" and "quadrupole" effective degrees of freedom in the high parton density regime.

2. Systematic study of gluon distributions at small-x at a quantitative level. There has been tremendous progress in small-x phenomenology in last decade. We plan to continue these studies, but focus on the relevant TMD gluon distributions. We will investigate the role played by the polarization of the gluon or the target nucleon in the small-x gluon TMDs. It has been shown that WW distribution of linearly polarized gluons is suppressed as compared to the dipole gluon distribution [178]. Similarly, the target polarization may also affect the gluon distribution, such as the gluon Sivers function at small-x [185]. There is much to explore along these directions, in particular, in light of future experiments at an Electron-Ion Collider

(EIC).

3. Further exploration of probes the TMD quark/gluon distributions in the small-x region. With EIC on the horizon, we plan to address critical questions concerning direct probes for the TMD gluon distributions at small-x. In particular, we will address the universality of distributions in the CGC formalism, as well as the matching of computations in the small x formalism to those in the TMD formalism at large transverse momenta. A specific example, where such matching studies has led to significant phenomenological progress is in Quarkonium production at collider energies [186] as discussed in Section 2.6.

2.11 TMD Collaboration Workshops, Summer Schools and Handbook

2.11.1 Collaboration Meetings

One of the central advantages of our proposal is that it brings together three communities interested in TMDs and hadron structure from the formal, phenomenological and computational perspective in order to collaborate on common goals. In order to achieve this, it is critical to have face-to-face meetings so we propose to organize and run annual collaboration meetings that cover the full scope of the physics in our proposal. The collaboration meetings will be held at a different participating institution each year and will involve most of the senior investigators, project participants and their collaborators as well as others in the experimental and phenomenological communities. The first meeting will be at Brookhaven National Lab with subsequent years to be determined. We anticipate that the meetings will take place over three days, allowing for ample time for presentation of the work of various subgroups and combined discussions. The meeting will be open and we will invite key speakers from outside our collaboration to participate. Experimental colleagues will be particularly encouraged to contribute as we aim to make our work broadly known and of direct relevance to the experimental nuclear physics program.

2.11.2 Collaborative Workshops and Visits

In addition to annual collaboration meetings, we anticipate having a number of smaller topical workshops on more focused issues within the framework of our proposal. The precise topics will be decided according to emerging physics problems as they come up in our research program. There are a number of workshops that we already see to be important at the outset and these exemplify the sorts of issues that we aim to address. In particular, workshops on "TMD fitting methods and optimization", "Large momentum states in lattice QCD", would be natural within the first year. Our plan is to use discussions at the annual collaboration meetings to seed the following years' round of topical workshops. We also envisage supporting limited short term visits of senior investigators and researchers supported under this proposal to collaborating institutions. Such collaborative visits are a key way to make rapid progress on topics of common interest and are a core component of our proposal.

2.11.3 Summer Schools

A set of summer schools on TMDs and related physics is an essential part of the TMD collaboration's training program for the next generation of nuclear theorists. Summer schools have proven to be an effective way to communicate the exciting new developments in nuclear and particle physics to graduate students and postdocs. They allow the young researchers to interact with experts in the field, engage in discussions of the latest theoretical and experimental results, and form new collaborations.

We will organize two summer schools during the five-year funding period. Brookhaven National Lab will host the first summer school during the first year of the funding period to get all prospective and interested students and young postdocs properly trained. The other school is planned for the last year of the funding period to make sure that we will have new people to continue being interested and working on QCD and the physics of the TMDs even after this Topical Collaboration is completed. We target 25-30 students per school with a six and one-half days in length. The program will consist of 3 days of lectures/recitations, plus one half day break, and continued with another 3 days of lecture/recitations. We will invite lecturers, not limited to the collaboration PIs and affiliates, that can deliver pedagogical introductions perturbative QCD, lattice QCD, Soft-Collinear Effective Theory, TMD phenomenology and experimental methods and impact. We will also have lectures dedicated to a focused discussion of advanced TMD topics that are not covered in schools such as the National Nuclear Physics Summer School. We will actively engage with the experimental community and invite experimental graduate students and young postdocs to the school. We will also encourage international students (particularly those from developing countries) to participate in the schools. A detailed budget for the school is given in the Budget Justification of the proposal.

2.11.4 TMD Handbook

The broad scope and impact of TMDs mean that the community has a range of approaches to TMDs and their role in various processes. The notation and terminology is rather fragmented in the TMD literature and a significant amount of clarity could be added by constructing a TMD handbook. This would summarize the components needed for performing calculations of a catalog of processes in an straightforward format, and translate between the various language and terminologies that appear in the literature. Within the TMD collaboration, we propose to produce this handbook which would also survey the state of experimental data relevant to TMDs and introduce basic quantities and concepts in QCD. Ideally this will serve as a comprehensive resource for students entering the field and we expect that the material developed by the lecturers for the Summer Schools will serve as a very good starting point for preparation of a handbook.

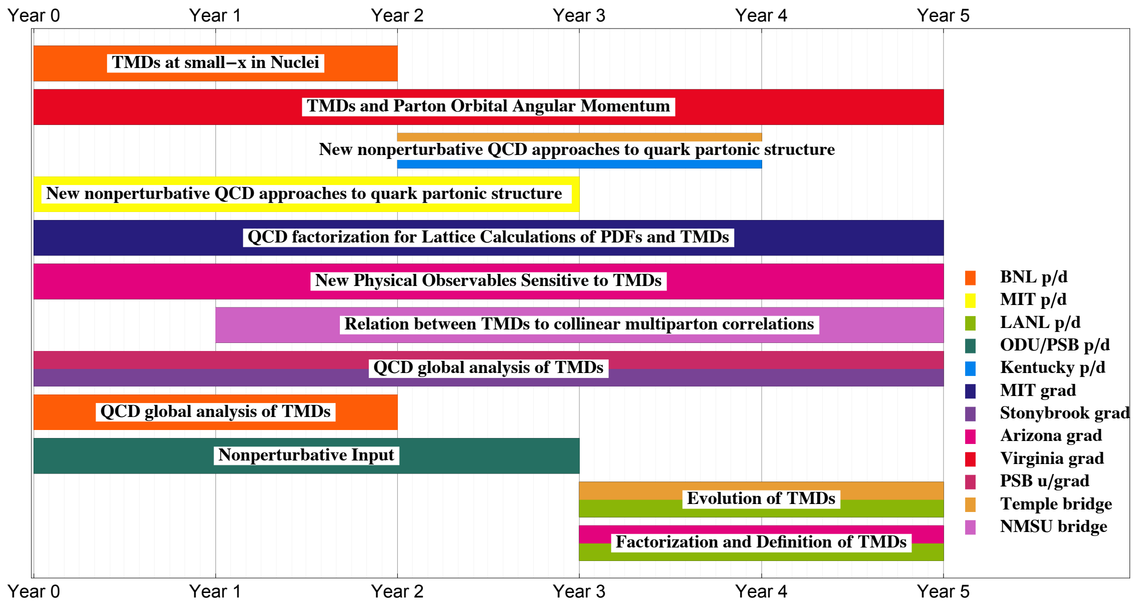
3 Timetable of Activities

The senior investigators will work on the projects for which their names are specified in the different subsections of Section 2 throughout the period of the proposal. Their particular areas of focus are specified in the preceding section. For the funded participants, our expectations for their activities are shown in the figure below. For the bridge positions and postdocs, there will be some shifts in this based on the actual interests of the person that is hired, but the assignments in the figure represent the effort that we think will be committed to projects in the various subareas.

The major milestones and deliverables that we expect to achieve are as follows (the target dates for the milestones are indicated in parentheses)

1. Perform global fit of the quark Sivers functions from the DIS processes and make predictions for future Drell-Yan processes with the next-to-leading logarithmic TMD evolution. Several experiments are going to measure the Sivers single spin asymmetries for Drell-Yan processes in the coming years and it is important to have precise predictions for these experiments. (Year 1)

2. Study scheme dependence in the TMD definitions and applications. It is crucial to understand this scheme dependence to have a unified picture to investigate the associated phenomena.



(Year 1)

3. Solidify the theoretical foundations of the relationship between space-like separated matrix elements calculated using lattice QCD and the TMDs. (Year 1)

4. Extend the TMD framework to small-x in particular in the context of gluon TMDs that will be relevant at the EIC. (Year 2)

5. Investigate factorization relevant for lattice studies of PDFs through the quasi-PDF approach using lattice regulators in perturbative matching. (Year 2)

6. Implement improved global fitting methods and perform global analysis of existing data on SIDIS, Drell-Yan lepton pair production and di-hadron production in e^+e^- in order to present an initial TMD collaboration TMD parameterization set. (Year 2)

7. Perform lattice calculations of parton physics beyond the lowest few moments and through analysis of the Compton tensor. (Year 3)

8. Obtain a smooth description of the transverse momentum dependence of TMD-related unpolarized and polarized cross sections and a simultaneous description of the Sivers asymmetry in SIDIS and transverse SSAs for single-particle production in hadronic collisions. (Year 3)

9. Investigate ways in which the functional forms of the non-perturbative input needed for TMD evolution can be constrained using phenomenology and lattice calculations. (Year 3)

10. Include gluon TMDs in global analysis project using data from Υ production, di-photon production and other observables that are identified. (Year 4)

11. Investigate the theoretical uncertainties in the single spin asymmetry calculations. This includes the model dependence in the non-perturbative inputs for the TMD evolution; scale variations in the phenomenological calculations in the TMD factorization applications; the uncertainties caused by truncation of the theory calculations; Y-term contributions. (Year 4)

12. Extend the global analysis to all other leading order TMDs, such as Boer-Mulders function $h_1^\perp$, transverse spin dependent $h_{1T}^\perp$ and by including higher order corrections and more data. (Year 5)

13. Perform lattice calculations of the x-dependence of PDFs, controlling the perturbative matching and sub-leading power corrections. (Year 5)

14. Perform lattice calculations of the quark and gluon spin, orbital, and total angular momentum contributions S_q, L_q^{Ji}, J_g^{Ji}, L_q^{JM}, S_g^{JM}, and L_g^{JM} appearing in the Ji and Jaffe-Manohar decompositions of the nucleon spin (Year 5)

15. Develop the description of physical processes that permit simultaneous access to the momentum transfer to a nucleon and the transverse momentum of a hadronized ejected quark to stimulate experimental efforts to access quark OAM directly from GTMDs (Year 5)

16. Provide a quantitative understanding of TMDs at small-x. Gluon saturation is an important topic in the future experiments at the LHC and the planed EIC. We will further investigate the unique probes for the TMDs at small-x from the hard scattering processes in these experiments and probe gluon saturation at small-x and/or in a large nucleus. (Year 5)

Achievement of these milestones is the responsibility of the whole collaboration, but primary leadership of each milestone will be from the senior investigators listed as focusing on the related subsection in Section 2.

4 Project Management Plan

The lead institution for the TMD Topical Collaboration is Brookhaven National Laboratory and the lead PI is Jianwei Qiu. Qiu will be responsible for the overall management of the project and the distribution of subawards. The TMD collaboration has elected two spokespersons: William Detmold (MIT) Jianwei Qiu (BNL), who will represent the TMD collaboration in the broader community. Important decisions for the collaboration, including the selection of new spokesperson(s), will be made by the collaboration Council, which includes the co-PIs and senior personnel of the member institutions. Each individual institution and co-PI will be responsible for the training of graduate students and postdoctoral researches, and meeting the milestones to which the institution has committed.

The main mechanism for the TMD collaboration to conduct business will be the collaboration meetings. We expect to have yearly meetings with an average of 30 participants (senior investigators, students and postdocs, and collaborators). The collaboration meeting will take place at member institutions (a potential schedule is BNL, Temple, NMSU/LANL, ODU, MIT). In years when a Summer School is planned, the collaboration meeting could immediately precede or follow the summer school. We anticipate that travel ($400), accommodation costs ($110/day) and per diems ($38/day) will average to $844 per participant per meeting averaged over the different locations and the different distances participants need to travel. The total cost per meeting is estimated at $25,000 + overhead.

The collaboration will be organized in working groups on 1) Factorization and TMD definition, 2) TMD global fitting and hadron structure, and 3) Lattice QCD and non-perturbative approaches to PDFs and TMDs. Each working group will have a lead and progress will be tracked through monthly videoconference meetings. We also envision three short and focused topical workshops, one for each working group, for one or two days, with a total budget of $15,000 + overhead ($5,000 each in average). We also budgeted $12,000 (+ overhead) per year of travel money for the bridged faculty members, postdocs and students to have the collaboration visits or to present the result(s) of the collaboration at major meetings. All travel money remain at BNL for travel reimbursement based upon the needs of the collaboration and the recommendation of the collaboration Council.

The collaboration will organize two summer schools during the five-year funding period. The Lead Institution of this proposal, BNL, will host the first summer school during the first year of the funding period to get all prospective and interested students and young postdocs properly trained. The collaboration is responsible for the physics program. The collaboration will determine the location of the second summer school in one of its future annual collaboration meeting. We budgeted $32,500 (+ overhead) for each summer school. The detailed budget for the school is given in the Budget Justification.

5 Project Objectives

The rich physics involved in the structure of the nucleon provides an exciting and important challenge for contemporary nuclear theory. The broad nature of the problem of providing a complete theoretical understanding of the transverse momentum dependence of quarks and gluons inside the proton means that it is only through bringing together people in multiple different areas of nuclear theory that major progress can be made. This proposal will catalyze the necessary collaboration between the leading nuclear theory groups with expertise in perturbative QCD, lattice QCD, effective field theory and QCD phenomenology, and enable a paradigm shift in our understanding of nucleon structure.

Pursuit of the detailed research goals that we have summarized in this proposal will enable a fundamentally new approach to transverse hadron structure, in which quantitative control over the theoretical constructions will lead to rapid improvements in our understanding of experimental data. The connections that will be made will inform the experimental program and spur further developments of new ways to probe the mysteries of the proton structure, with the eventual goal of mapping out the detailed three-dimensional momentum-space landscape of the nucleon.

The overarching goals of the program we propose are four-fold

1. We aim to carefully scrutinize the different definitions and evolution properties of TMDs and strengthen the theoretical foundations of the field. We will simultaneously broaden our knowledge of the types of processes in which TMDs play a central role and attempt to devise new ways to access them at Jefferson Lab, RHIC, LHC and other facilities around the world, including at the proposed electron-ion collider.

2. We will produce extensive sets of global fits parameterizing the various TMD parton distributions and fragmentation functions using state-of-the-art methods pioneered for collinear parton distributions. Our fits will include next-to-leading order QCD corrections and make use of all the available experimental data. We will provide fast software implementations of the fitted distributions and make them broadly available to the community.

3. We will pursue non-perturbative lattice QCD calculations of TMDs and other aspects of the partonic structure of the nucleon and also elucidate central questions about the nature of the proton's angular momentum distributions.

4. Through this topical collaboration, we aim to provide compelling research and career opportunities for young nuclear theorists – undergraduate and graduate students, postdocs, and junior faculty. Through mentorship, Summer Schools, and other educational programs, we will provide cutting edge training in QCD and the physics of hadron structure to these upcoming researchers as well as to many others in the broader community.

Appendix 1: Biographical Sketches

In this Appendix, we provide the biographical sketch for the principal investigator (PI) and every Co-Investigators who play the key and leading roles in the technical narrative of this proposal, organized according to the following order consistent with the alphabetical order of participating institutions:

Brookhaven National Laboratory:
Jianwei Qiu (PI & Co-Spokesperson), Raju Venugopalan

Duke University:
Thomas Mehen

Jefferson Laboratory and Old Dominion University:
Ted Rogers

Jefferson Laboratory and Penn State Berks:
Alexei Prokudin

Lawrence Berkeley National Laboratory:
Feng Yuan

Los Alamos National Laboratory:
Christopher Lee, Ivan M. Vitev

MIT:
William Detmold (Co-Spokesperson), John Negele, Iain Stewart

New Mexico State University:
Matthias Burkardt, Michael Engelhardt

Penn State University at Berks:
Leonard Gamberg

Temple University:
Andreas Metz

University of Arizona:
Sean P. Fleming

University of Kentucky:
Keh-Fei Liu

University of Maryland:
Xiangdong Ji

University of Virginia:
Simonetta Liuti

Jianwei Qiu

Education and Training:

- M.A. in Physics, Columbia University in the New York City, 1983
- M.Ph. in Physics, Columbia University in the New York City, 1984
- Ph.D., Columbia University in the New York City, 1987
- Postdoctoral Research Associate, Argonne National Laboratory, 1987-89
- Postdoctoral Research Associate, Institute for Theoretical Physics, Stony Brook University, 1989-91

Research and Professional Experience:

- Assistant Professor of Physics and Astronomy, Iowa State University (ISU), 1991
- Associate Professor of Physics and Astronomy, Iowa State University, 1995
- Visiting Physicist, Brookhaven National Laboratory (on-leave from ISU), 1997
- Professor of Physics and Astronomy, Iowa State University, 2001
- Visiting Physicist, Brookhaven National Laboratory (on-leave from ISU), 2006
- Visiting Scientist, Argonne National Laboratory (on-leave from ISU), 2007
- Physicist, Brookhaven National Laboratory, 2010
- Brookhaven Professor, Stony Brook University, 2010 – present
- Senior Physicist, Brookhaven National Laboratory, 2011 – present

Publications Related to the Proposed Research:

1. Y. Q. Ma and J. W. Qiu, *QCD Factorization and PDFs from Lattice QCD Calculation*, Int. J. Mod. Phys. Conf. Ser. **37**, 0041 (2015) [arXiv:1412.2688 [hep-ph]].
2. S. M. Aybat, J. C. Collins, J. W. Qiu and T. C. Rogers, *The QCD Evolution of the Sivers Function*, Phys. Rev. D **85**, 034043 (2012) `http://arXiv.org/abs/1110.6428`.
3. Z. B. Kang, J. W. Qiu, W. Vogelsang and F. Yuan, *An Observation Concerning the Process Dependence of the Sivers Functions*, Phys. Rev. D **83**, 094001 (2011) `http://arXiv.org/abs/1103.1591`.
4. J. W. Qiu, M. Schlegel and W. Vogelsang, *Probing Gluonic Spin-Orbit Correlations in Photon Pair Production*, Phys. Rev. Lett. **107**, 062001 (2011) `http://arXiv.org/abs/1103.3861`.
5. Z. B. Kang and J. W. Qiu, *Testing the Time-Reversal Modified Universality of the Sivers Function*, Phys. Rev. Lett. **103**, 172001 (2009) `http://arXiv.org/abs/0903.3629`.
6. J. C. Collins and J. W. Qiu, *k_T factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions*, Phys. Rev. D **75**, 114014 (2007) `http://arXiv.org/abs/0705.2141`.

7. X. Ji, J. W. Qiu, W. Vogelsang and F. Yuan, *A Unified picture for single transverse-spin asymmetries in hard processes*, Phys. Rev. Lett. **97**, 082002 (2006) `http://arXiv.org/abs/hep-ph/0602239`.
8. J. W. Qiu and X. f. Zhang, *Role of the nonperturbative input in QCD resummed Drell-Yan Q_T distributions*, Phys. Rev. D **63**, 114011 (2001) `http://arXiv.org/abs/hep-ph/0012348`.
9. J. W. Qiu and G. Sterman, *Single transverse spin asymmetries in hadronic pion production*, Phys. Rev. D **59**, 014004 (1999) `http://arXiv.org/abs/hep-ph/9806356`.
10. R. Brock *et al.* [CTEQ Collaboration], *Handbook of perturbative QCD: Version 1.0*, Rev. Mod. Phys. **67**, 157 (1995).

Synergistic Activities:

- **Awards:** SSC Fellowship Award by the SSC Lab of DOE, 1990; DOE Outstanding Junior Investigator Award, 1992; Fellow of American Physical Society, 2005
- **Service:** Co-Editor of a community wide White Paper for making the science case to build a future Electron-Ion Collider in the US: "Electron-Ion Collider: The Next QCD Frontier – Understanding the glue that binds us all" [`http://arXiv.org/abs/1212.1701`]; Member of Executive Committee of American Physical Society Topical Group on Hadron Physics, 2012-13; Member of the International Advisor Committee for "The 25th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter 2015)", Kobe, Japan, 2015, "The 10th Circum-Pan-Pacific Symposium on High-Energy Spin Physics (PacSPIN2015)", Academia Sinica, Taipei, Taiwan, 2015, "The 7th Workshop on Hadron Physics in China and Opportunities Worldwide", Duke Kunshan University, Kunshan, China, 2015, "The Sixth International Workshop on Hadron Physics in China and Opportunities in US", Chinese Academy of Science, Lanzhou, China, 2014, "International Conference on Nuclear Theory in the Supercomputing Era - 2013", Ames, Iowa, 2013, "The second International Conference on "QCD and Hadron Physics", Lanzhou, China, 2013, and "The 5th International Workshop on "Heavy Quark Production in Heavy-ion Collisions", Utrecht, the Netherlands, 2012. Member of the DOE Review Committee for Jefferson Lab Science & Technology Review, 2012.
- **Conference organization:** Co-organizer of "The 23th International Workshop on "Deep-Inelastic Scattering and Related Subjects (DIS 2015)", Southern Methodist University, Dallas, TX, 2015, "International workshop on Electron Ion Collider Users Meeting," Stony Brook University, 2014, "International Symposium on the Frontier of Hadron Physics", Central China Normal University, Wuhan, China, 2014, "MCFP International Mini-Workshop on Lattice Parton Physics Project (LP3)", University of Maryland, College Park, MD, 2014, "International workshop on QCD Frontier 2013 meeting", Jefferson Lab, Newport News, VA, 2013, "The fifth workshop of the APS Topical Group on Hadron Physics (GHP2013)", Denver, Colorado, 2013
- **Peer review:** *Grant reviewer* for DOE High Energy and Nuclear Physics, NSF High Energy and Nuclear Physics, U.S. Civilian Research and Development Foundation (Cooperative Grants Program), Britain-Israel Research and Academic Partnership, The Japan Society for the Promotion of Science (JSPS), The Netherlands Organisation for Scientific Research (NWO), John Simon Guggenheim Memorial Foundation, Alexander von Humboldt Foundation, and City University of New York. *Journal Referee* for Physical Review Letters, Physical Review C, Physical Review D, Nuclear Physics A, Nuclear Physics B, Physics Letters

A, Physics Letters B, Physics Reports, EPL (Europhysics Letters), The European Physical Journal C, Journal of High Energy Physics, Journal of Physics G.

- **Outreach:** Member of CTEQ Collaboration (The Coordinated Theoretical-Experimental Project on QCD), 1990 - now; Lecturer for "CTEQ Summer School on QCD and Electroweak Phenomenology", 2014; Pre-workshop lecturer for "The International Conference on Electromagnetic Interactions with Nucleons and Nuclei (EINN 2013)", 2013; Lecturer for "The 8th TD Lee lecture series" at University of Chinese Academy of Sciences, China, 2012; Lecturer for "CTEQ Summer School on QCD and Electroweak Phenomenology", 2011; and Lecturer for "the JET Collaboration Summer School", 2010.

Collaborators and Co-editors (in the past 48 months):

- **Collaborators:**
S.M. Aybat (NIKHEF, The Netherlands), E.L. Berger (ANL), N. Brambilla (Munich, Tech U, Germany), W.K. Brooks (U. Technica Federico Santa Maria, Chile), M. Butenschoen (Vienna U, Austria), W.C. Chang (Academia Sinica, Taiwan), H.Y. Cheng (Academia Sinica, Taiwan), J.C. Collins (Penn State), F. Dominguez (Saclay, SPhT, France), L. Gamberg (Penn State-Berks), J. Gao (ANL), T.J. Hou (Academia Sinica, Taiwan), T. Ishikawa (RIKEN/BNL), K.F. Liu (Kentucky), X.H. Liu (Maryland), Z.-B. Kang (LANL), Y.-Q. Ma (Maryland), S. Mantry (U. North Georgia), A. Metz (Temple), J.C. Peng (UIUC), M. Schlegel (Tubingen U, Germany), G. Sterman (Stony Brook), P. Sun (LBNL), W. Vogelsang (Tubingen U, Germany), B.W. Xiao (CCNU, China), S. Yoshida (RIKEN/BNL), F. Yuan (LBNL), Hao. Zhang (UC-Santa Barbara), Hong Zhang (Ohio State), J. Zhou (NIKHEF, The Netherlands)

- **Co-editors:**
A. Deshpande (Stony Brook), Z.-E. Meziani (Temple)

Graduate and Postdoctoral Advisors and Advisees:

- **Ph.D. Advisor:**
A.H. Mueller, Columbia University

- **Postdoctoral Advisors:**
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- **Ph.D. Students Advisees:**
H. Zhang, Ph.D. 2014 (Ohio State), K.-B. Kang, Ph.D. 2009 (LANL), R. Rodriguez-Pedraza, Ph.D. 2007 (Ave Maria U), C. Kouvaris, M.S. 2000 (Ph.D. MIT), E. Matathias, M.S. 1999 (Ph.D. Stony Brook), W.-Y. Law, Ph.D. 1998, (IT Company, Denver, CO), X.F. Guo, Ph.D. 1996 (BNL)

- **Postdoctoral Advisees:**
Y.Q. Ma (Maryland), Alberto Accardi (Hampton U/JLab), Ivan Vitev (LANL), X.-f. Zhang (Treasury Dept, DC), M. Luo (Nankai U, China)

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Education and Training:

- Ph.D, Stony Brook, August 1992
- 1996-1998, Danish Research Council Fellow, Niels Bohr Institute
- 1994-1996, Research Associate, INT, Univ. of Washington
- 1992-1994, Research Associate, TPI, University of Minnesota

Professional Experience:

- 2010-present, Group Leader, Nuclear Theory Group, BNL
- 2009-present, Adjunct Professor, Stony Brook University
- 2007-present, Senior Scientist, BNL
- 1998-2002, BNL Asst. Scientist - Scientist Appts., Tenured June 2002
- 1996-1998, Danish Research Council Fellow, Niels Bohr Institute
- 1994-1996, Research Associate, INT, Univ. of Washington
- 1992-1994, Research Associate, TPI, University of Minnesota

Awards:

- Excellence Initiative International Professor Award, University of Heidelberg, 2014-2016
- Fulbright Senior Specialist Award, 2012
- Fellow of the American Physical Society, 2007
- Humboldt Foundation, US Research Fellow, 2004-2005

Publications:

- over 160 publications with 13000 citations, h-index of 58 (INSPIRE)

Names of investigator's graduate and postdoctoral advisors:

M. Prakash	Stony Brook University	graduate advisor
G. E. Brown	Stony Brook University	graduate advisor
J. Kapusta	Univ. of Minnesota	post-doctoral advisor
L. D. McLerran	Univ. of Minnesota	post-doctoral advisor
W. Haxton	INT, Univ. of Washington	post-doctoral advisor
J. Bondorf	Niels Bohr Institute, Denmark	post-doctoral advisor

List of Collaborators & Co-Editors within the last 48 months:
J. Berges (Heidelberg), K. Boguslavski (Heidelberg), A. Bzdak (Krakow), K. Dusling (APS), R. Ent (Jlab), Z.-B. Kang (Los Alamos), T. Lappi (Jyvaskyla), H. Mantysaari (Jyvaskyla), Y.-Q. Ma (Peking Univ.), D. Pitonyak (RBRC), A. Rezaeian (Valparaiso), B. Schenke (BNL), S. Schlichting (BNL), M. Siddikov (Valparaiso), M. Sievert (BNL), P. Tribedy (VECC/BNL), T. Ullrich (BNL), Y. Yin (BNL), H. -F. Zhang (Chongqing)

Graduate student advisees:

M. Mace (Stony Brook), P. Tribedy (VECC), J. Bjoraker (BNP Paribas)

Select synergistic activities:

- National Advisory Committee, INT Seattle, 2015-2017
- member NSAC, 2012-2016
- Chair-Elect, APS Topical Group on Hadron Physics, 2015
- co-Editor, Annals of Physics, 2013-
- co-organizer, 2013 National Nuclear Physics Summer School

Publications of relevance to proposal:

1. *Comprehensive Description of J/Ψ Production in Proton-Proton Collisions at Collider Energies*:
   Y. Q. Ma and R. Venugopalan, *Phys. Rev. Lett.* **113**, no. 19, 192301 (2014).
2. *Quarkonium production in high energy proton-nucleus collisions: CGC meets NRQCD*:
   Z. B. Kang, Y. Q. Ma and R. Venugopalan, *JHEP* **1401**, 056 (2014).
3. *Comparison of the color glass condensate to dihadron correlations in proton-proton and proton-nucleus collisions*:
   K. Dusling and R. Venugopalan, *Phys. Rev.* **D87**, no. 9, 094034 (2013).
4. *The Color Glass Condensate*:
   F. Gelis, E. Iancu, J. Jalilian-Marian and R. Venugopalan, *Ann. Rev. Nucl. Part. Sci.* **60**, 463 (2010).
5. *High energy factorization in nucleus-nucleus collisions*:
   F. Gelis, T. Lappi and R. Venugopalan, *Phys. Rev.* **B78**, 054019 (2008).
6. *Quantitative study of the violation of k-perpendicular-factorization in hadroproduction of quarks at collider energies*:
   H. Fujii, F. Gelis and R. Venugopalan, *Phys. Rev. Lett.* **95**, 162002 (2005).
7. *High-energy pA collisions in the color glass condensate approach. 2. Quark production*:
   J. P. Blaizot, F. Gelis and R. Venugopalan, *Nucl. Phys.* **A743**, 57 (2004).
8. *The Color glass condensate and high-energy scattering in QCD*:
   E. Iancu and R. Venugopalan, In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 249-3363, [hep-ph/0303204].
9. *Fock space distributions, structure functions, higher twists and small x*:
   L. D. McLerran and R. Venugopalan, *Phys. Rev.* **D59**, 094002 (1999).

Thomas Mehen

EDUCATION AND TRAINING

M.A., Ph.D. Physics (1998) Johns Hopkins University, Baltimore, MD

B.S. Physics (1992) University of Virginia, Charlottesville, VA

Research Associate (2001-2002) Department of Physics, The Ohio State University, Columbus, OH

Research Associate (1997-2000) Division of Mathematics, Physics and Astronomy, California Institute of Technology, Pasadena CA

RESEARCH AND PROFESSIONAL EXPERIENCE

2009-present	Associate Professor	Department of Physics Duke University, Durham, NC
2002-2008	Assistant Professor	Department of Physics Duke University, Durham, NC

PUBLICATIONS RELATED TO THE PROPOSED RESEARCH

1. "Probing Quarkonium Production Mechanisms with Jet Substructure", M. Baumgart, A. L. Leibovich, T. Mehen, and I. Z. Rothstein, JHEP **1411** (2014) 003.

2. "Anomalous Dimensions of the Double Parton Fragmentation Functions", S. Fleming, A. K. Leibovich, T. Mehen, and I. Z. Rothstein, Phys. Rev. D **87** (2013) 074022.

3. "The Systematics of Quarkonium Production at the LHC and Double Parton Fragmentation", S. Fleming, A. K. Leibovich, T. Mehen, and I. Z. Rothstein, Phys. Rev. D **86** (2012) 094012.

4. "Resummation of Large Endpoint Corrections to Color-Octet J/ψ Photoproduction", S. Fleming, A. Leibovich and T. Mehen, Phys. Rev. D **74**, 114004 (2006).

5. "Resumming the Color Octet Contribution to $e^+e^- \to J/\psi + X$", S. Fleming, A. Leibovich and T. Mehen, Phys. Rev. D **68**, 094011 (2003).

6. "Λ_c^+/Λ_c^- Asymmetry in Hadroproduction from Heavy-Quark Recombination",E. Braaten, M. Kusunoki, Yu Jia and T. Mehen, Phys. Rev. D **70**, 054021 (2004).

7. "The Leading Particle Effect From Heavy-Quark Recombination", E. Braaten, Yu Jia and T. Mehen, Phys. Rev. Lett. **89**, 122002 (2002).

8. "Reparametrization Invariance for Collinear Operators", A. V. Manohar, T. Mehen, D. Pirjol and I. W. Stewart, Phys. Lett. B **539**, 59 (2002).

9. "Charm Anti-Charm Asymmetries in Photoproduction from Heavy-Quark Recombination", E. Braaten , Yu Jia and T. Mehen, Phys. Rev. D **66**, 014003 (2002).

10. "Leptoproduction of J/ψ", S. Fleming and T. Mehen, Phys. Rev. D **57**, 1846 (1998).

SYNERGISTIC ACTIVITIES

- *Awards*: Outstanding Junior Investigator Award, Department of Energy, Nuclear Physics (2005); University Postdoctoral Fellow, The Ohio State University (2000); John A. McCone Postdoctoral Scholar, California Institute of Technology (1997-2000)
- INT Program Co-Organizer (w/ I. Stewart): , "Effective Field Theory, QCD, and Heavy Hadrons", Institute for Nuclear Theory, University of Washington, Seattle, WA, Mar. 21 - June 10, 2005.
- Conference Co-Organizer (w/ N. Brambilla, J. Soto and A. Vairo): Workshop on *Heavy Quarkonium and Related Heavy Quark States* at the ECT* (European Center for Theoretical Studies in Nuclear Physics and Related Areas) Trento, Italy, August 17-31, 2006.
- INT Program Co-Organizer (w/ S. Fleming and A. Stasto): "Frontiers in QCD", Institute for Nuclear Theory, University of Washington, Seattle, WA, Sep. 19 - Nov. 18, 2011.
- Conference Organizer: SCET2013: Xth Annual Workshop of Soft-Collinear Effective Theory, Duke U., Durham, NC, March 14-16, 2013.

GRADUATE STUDENT ADVISEES

Jie Hu (Asst. Professor, Capital Normal University, Beijing, China) , Josh Powell (Postdoc, Cornell University's Weill Medical College, New York), Di-Lun Yang (Postdoc, U. of Crete & Chung-Yuan Christian U., Taiwan), Reggie Bain (Duke U.), Yiannis Makris (Duke U.)

POSTDOCTORAL ADVISEES

Carlos Schat (Research Faculty, TANDAR Lab.-CNEA, Buenos Aires, Argentina), Brian Tiburzi (Assistant Professor, City College of New York), Chul Kim (Assistant Professor, Seoul National University of Science and Technology, Seoul, Korea), Ahmad Idilbi (Postdoc, Penn State University)

COLLLABORATORS AND ADVISORS

Ph.D. Advisor: A. Falk (Williams College)
Postdoc Advisors: M. Wise (Caltech). R. Furnstahl (Ohio State U.)
Collaborators: M. Baumgart (Carnegie Mellon U.), E. Braaten (Ohio State U.), S. Fleming (U. of Arizona), H. Hammer (Bonn U.), A. Idilbi (Duke U.), C. Kim (Korea), A. Leibovich (Pittsburgh U.), J. Powell (Cornell U.), I. Rothstein (Carnegie Mellon U.), R. Springer (Duke U.), B. Tiburzi (U. of Maryland), U. van Kolck (U. of Arizona), Y.-W. Yoon (Korea)

Ted Rogers

Education and Training:

- B.A., Physics and Mathematics, Kenyon College, 2000
- Ph.D., Physics, Pennsylvania State University, 2006
- Research Associate, Pennsylvania State University, 2006-2008
- Research Associate, VU University Amsterdam, 2008-2011
- Research Associate, Stony Brook University, 2011-2014
- Research Associate, Southern Methodist University, 2014

Research and Professional Experience:

- Assistant Professor of Physics, Old Dominion University, 2014-present

Selected Publications Relevant to Proposed Research:

1. John Collins and Ted Rogers, Understanding the large-distance behavior of TMD parton densities and the Collins-Soper evolution kernel. Phys.Rev. **D 91** (2015) 7, 074020.
2. C. Aidala, B. Field, L. Gamberg, and T. Rogers Limits on TMD Evolution From Semi-Inclusive Deep Inelastic Scattering at Small Q. Phys.Rev. **D89** (2014) 094002.
3. T. C. Rogers, Extra Spin Asymmetries From the Breakdown of TMD-Factorization. Phys.Rev. **D 88** (2013) 014002.
4. J.C. Collins and T.C. Rogers, Equality of Two Definitions of Transverse Momentum Dependent Parton Distribution Functions. Phys. Rev. **D 87** (2013) 034018.
5. S. Mert Aybat, John C. Collins, Jian-Wei Qiu, Ted C. Rogers, The QCD Evolution of the Sivers Function. Phys. Rev. **D 85** (2012) 034043.
6. S. Mert Aybat and Ted C. Rogers, TMD parton distribution and fragmentation functions with full QCD evolution. Phys. Rev. **D 83** (2011) 114042.
7. Ted C. Rogers and Piet J. Mulders, No Generalized TMD-factorization in Hadro-production of High Transverse Momentum Hadrons. Phys. Rev. **D 81** (2010) 094006.
8. Ted C. Rogers, Next-to-Leading Order Hard Scattering Using Fully Unintegrated Parton Correlation Functions. Phys. Rev. **D 78** (2008) 074018.
9. J.C. Collins and T.C. Rogers, The Gluon Distribution Function and Factorization in Feynman Gauge. Phys. Rev. **D 78** (2008) 054012.
10. J.C. Collins, T.C. Rogers, A. M. Stasto, Fully Unintegrated Parton Correlation Functions and Factorization in Lowest Order Hard Scattering. Phys. Rev. **D 77** (2008) 085009.

Synergistic Activities:

- **Workshop organization:** Convener: DIS 2015: 23rd International Workshop on Deep-Inelastic Scattering and Related Subjects; Convener: The Monte Carlo/Double Parton Scattering working group at the 2012 workshop on Multi-Parton Interactions at the LHC, December 3-7, 2012 at CERN, Switzerland.

- **Referee Service:** Physical Review D, Physical Review Letters, European Physical Journal C, and Few Body Systems.

- **Collaborators and Co-editors (in the past 48 months):**
John Collins (*Penn State*), Christine Aidala (*University of Michigan*), Bryan Field (*SUNY, Farmingdale*), Leonard Gamberg (*Penn State, Berks*)

- **Graduate and Postdoctoral Advisors**:
Mark Strikman (*Penn State*), John Collins (*Penn State*), Piet Mulders (*VU University*), George Sterman (*Stony Brook*), Pavel Nadolsky (*Southern Methodist University*)

Alexei Prokudin

Education and Training:
Postdoc Research Associate, The University of Turin and INFN, Turin, Italy, 2008-2009
Postdoc Research Associate, Università del Piemonte Orientale "A. Avogadro", Alessandria, Italy, 2007 - 2008
Postdoc Research Associate, The University of Turin, Turin, Italy, 2001-2007
Ph.D. in Theoretical Physics, The Institute for High Energy Physics, Protvino, Russia 2000
M.Sc. *With Honours* in Physics, Moscow State University, Moscow, Russia 1997

Research and Professional Experience:
Assistant Professor, Penn State Berks, Reading, USA, 2015 -
Staff Scientist, Thomas Jefferson National Accelerator Facility, 2009 - 2015
Staff Scientist, The Institute for High Energy Physics, Protvino, Russia 1998 - 2004

Selected Publications Related to the Proposed Research:

1. Z. B. Kang, A. Prokudin, P. Sun, and F. Yuan,
" Nucleon tensor charge from Collins azimuthal asymmetry measurements", Phys. Rev. D **91**, 071501 (2015).

2. C. Lefky and A. Prokudin,
"Extraction of the pretzelosity distribution from experimental data,"
Phys. Rev. D **91**, 034010 (2015) [arXiv:1411.0580 [hep-ph]].

3. M. Boglione, J. O. G. Hernandez, S. Melis and A. Prokudin,
"A study on the interplay between perturbative QCD and CSS/TMD formalism in SIDIS processes," JHEP **1502**, 095 (2015) [arXiv:1412.1383 [hep-ph]].

4. M. Aghasyan, H. Avakian, E. De Sanctis, L. Gamberg , M. Mirazita, B. Musch, A. Prokudin, P. Rossi,
"Studies of Transverse Momentum Dependent Parton Distributions and Bessel Weighting", JHEP **1503**, 039 (2015).

5. L. Gamberg, Z. B. Kang, A. Metz, D. Pitonyak and A. Prokudin,
"Left-right spin asymmetry in $\ell N^{\uparrow} \to hX$,"
Phys. Rev. D **90**, no. 7, 074012 (2014) [arXiv:1407.5078 [hep-ph]].

6. M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia and A. Prokudin,
"Single Spin Asymmetries in $lp^{\uparrow} \to hX$ processes and TMD factorisation,"
Phys. Rev. D **89**, 114026 (2014) [arXiv:1404.6465 [hep-ph]].

7. L. Y. Dai, Z. B. Kang, A. Prokudin and I. Vitev,
"Next-to-leading order transverse momentum-weighted Sivers asymmetry in semi-inclusive deep inelastic scattering: the role of the three-gluon correlator,"
arXiv:1409.5851 [hep-ph].

8. M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia and A. Prokudin,
"Simultaneous extraction of transversity and Collins functions from new SIDIS and e+e- data,"
Phys. Rev. D **87**, 094019 (2013) [arXiv:1303.3822 [hep-ph]].

9. A. Bacchetta and A. Prokudin,
   "Evolution of the helicity and transversity Transverse-Momentum-Dependent parton distributions,"
   Nucl. Phys. B **875**, 536 (2013) [arXiv:1303.2129 [hep-ph]].

10. L. Gamberg, Z. -B. Kang and A. Prokudin,
    "Indication on the process-dependence of the Sivers effect,"
    Phys. Rev. Lett. **110** (2013) 232301 [arXiv:1302.3218 [hep-ph]].

Selected Professional Awards and Activities:

- **Service:**
  Co-editor of proceedings of QCD Evolution Workshop 2011-2014. Member of International Advisor Committee for "HEPFT", IHEP, Russia, 2013, and Hadron China 2013 Anhui, China, July 2- 6, 2013.

- **Conference organization:** Chair, QCD Evolution Workshop, 2011 - 2015.
  Chair, Informal Pre-Town Meeting at Jefferson Lab, 2014.
  Convener, The 21st International Symposium on Spin Physics, Beijing, China, October 20-24, 2014.
  Convener, XXII International Workshop on Deep Inelastic Scattering and Related Subjects , Warsaw, Poland, April 27-May 3, 2014.
  Convener , XIX International Workshop on Deep Inelastic Scattering and Related Subjects DIS 2011, April 11-15, 2011.

- **Peer review:** *Journal Referee* for Physical Review Letters, Physical Review D, Nuclear Physics B, Physics Letters B, The European Physical Journal

- **Outreach:** Coordinator and lecturer of Hampton University Graduate Studies Program, HUGS summer school, Jefferson Lab, Newport News, USA, 2011-2013.
  Lecturer The 2014 SpinFest summer school.
  Lecturer A pre-workshop summer school held at STIAS, January 27-29, 2012 Stellenbosh, South Africa .
  Lecturer International School of Physics "Enrico Fermi" Course CLXXX, 2011.

- **Mentoring:** Mentor of a Science Undergraduate Laboratory Internships (SULI) undergraduate student Christopher Lefky (Creighton University, Omaha NE), 2013.

Collaborators and Co-editors (in the past 48 months):

- **Collaborators:**
  S.M. Aybat (NIKHEF, The Netherlands), F. Yuan (LBNL), P. Sun (LBNL), L. Gamberg (Penn State), Z. Kang (LANL), A. Bacchetta (University of Pavia), M. Anselmino (The University of Turin), E. Boglione (The University of Turin), A. Metz (Temple University), D. Pitonyak (BNL), S. Melis (The University of Turin), Umberto D'Alesio (Cagliari University & INFN, Cagliari), Francesco Murgia (INFN, Cagliari), Patrizia Rossi (Jefferson Lab), Harut Avakian (Jefferson Lab), J. O. G. Hernandez (The University of Turin), T. C. Rogers (JLab and ODU), A. Accardi (JLab and Hampton University), C. Weiss (JLab), I. Vitev (LANL), L. Y. Dai (Indiana University)

- **Co-editors:**
  A. Radyushkin (ODU and JLab), L. Gamberg (Penn State Berks)

Graduate and Postdoctoral Advisors and Advisees:
Ph. D. Advisor: Vladimir Petrov, IHEP, Russia
Postdoctoral advisors: Enrico Predazzi (The University of Turin), Mauro Anselmino (The University of Turin), Enzo Barone (Università del Piemonte Orientale)
Ph. D. students advised: Christian Turk (The University of Turin)

Feng Yuan

Education and Training:

- B.S. Physics, Peking University, Beijing, 1995
- Ph.D. Physics, Peking University, Beijing, 2000
- Postdoc Research Associate, Heidelberg University, 2000-2002
- Postdoc Research Associate, University of Maryland at College Park, 2002-2004
- Postdoc Research Associate, RIKEN/BNL Research Center, Brookhaven, 2004-2007

Research and Professional Experience:

- Division Fellow and RHIC Fellow, Nuclear Science Division, Lawrence Berkeley Lab, 2007–2012
- Senior Scientist, Nuclear Science Division, Lawrence Berkeley Lab, 2012 – present

Publications Related to the Proposed Research:

1. Z. B. Kang, A. Prokudin, P. Sun and F. Yuan, *Nucleon tensor charge from Collins azimuthal asymmetry measurements*, Phys. Rev. D **91**, 071501 (2015).
2. P. Sun and F. Yuan, *Transverse momentum dependent evolution: Matching semi-inclusive deep inelastic scattering processes to Drell-Yan and W/Z boson production*, Phys. Rev. D **88**, 114012 (2013).
3. X. Ji, X. Xiong and F. Yuan, *Proton Spin Structure from Measurable Parton Distributions*, Phys. Rev. Lett. **109**, 152005 (2012).
4. Z. B. Kang, B. W. Xiao and F. Yuan, *QCD Resummation for Single Spin Asymmetries*, Phys. Rev. Lett. **107**, 152002 (2011).
5. F. Dominguez, C. Marquet, B. W. Xiao and F. Yuan, *Universality of Unintegrated Gluon Distributions at small x*, Phys. Rev. D **83**, 105005 (2011).
6. F. Dominguez, B. W. Xiao and F. Yuan, *k_t-factorization for Hard Processes in Nuclei*, Phys. Rev. Lett. **106**, 022301 (2011).
7. X. Ji, J.W. Qiu, W. Vogelsang, Feng Yuan, *Unified Picture for Single Transverse-Spin Asymmetries in Hard-scattering Processes*, Phys. Rev. Lett. **97**, 082002 (2006).
8. X. Ji, J. P. Ma, and Feng Yuan, *QCD Factorization for Semi-inclusive Deep-inelastic Scattering at Low Transverse Momentum*, Phys. Rev. D71, 034005 (2005).
9. A. V. Belitsky, X. Ji, Feng Yuan, *Quark Imaging in the Proton Via Quantum Phase-Space Distributions*, Phys. Rev. **D69**, 074014 (2004).
10. A. V. Belitsky, X. Ji, Feng Yuan, *Final state interactions and gauge invariant parton distributions*, Nucl. Phys. **B656**, 165 (2003).

Selected Professional Awards and Activities:

- **Awards:** DOE Early Career Award, 2010-2015; APS Fellow, 2014.
- **Conference organization:** Convener of the 21st International Symposium on Spin Physics, Beijing, China, October 20-24, 2014; Co-Organizer of the MCFP Workshop on Lattice Parton Physics, University of Maryland, College Park, March 30-April 1, 2014; Co-Organizer of Berkeley Summer Program on "QCD Landscape of the Nucleon and Atomic Nuclei", Berkeley, August 12-17, 2013.
- **Community Service:** Member of the Organization Committee for APS DNP Long-Range Plan Joint Town Meeting on QCD, Temple University, Philadephia, September 13-15, 2014; Member of the International Advisory Committee for the International workshop of Transversity 2014, Baia Chia-Sardinia, Italy, June 12-17, 2014
- **Peer review:** Grant reviewer for DOE, NSF,NWO-Netherland, FWF-Austria, JSPS-Japan; Referee for Physical Review Letters, Physical Review C and D, Nuclear Physics A and B, Journal of High Energy Physics, Physics Letter B, Annals of Physics, Journal of Physics G, European Physics Journal C.
- **Outreach:** Lecturer for JET Collaboration summer school, 2010; Lecturer for PHENIX Spin Fest, 2011; Lecturer, EIC-Users Meeting, 2014.

Collaborators and Co-editors (in the past 48 months):

- **Collaborators:**
  G. Chirilli (OSU), X. Ji (Maryland), Z. Kang (BNL), C. Lorce (Orsay, IPN), A. Mueller (Columbia), B. Pasquini (Pavia), A. Prokudin (JLab), J. Qiu (Iowa State), W. Voglesang (BNL), A. Stasto (Penn State), B. Xiao (CCNU), X. Xiong (PKU), C.-P. Yuan (MSU), D. Zaslavsky (Penn State), R. Zhu (PKU)

Graduate and Postdoctoral Advisors and Advisees:

- **Ph.D. Advisor:**
  Kuangta Chao, Peking University
- **Postdoctoral Advisors:**
  Hans Pirner (Heidelberg University), Xiangdong Ji (University of Maryland), Werner Vogelsang (BNL)
- **Ph.D. Students Advisees:**
  Xiaonu Xiong (University of Pavia), Jian Zhou (Shandong University), Ruilin Zhu (Shanghai Jiao Tong University)
- **Postdoctoral Advisees:**
  Giovanni Chirilli (OSU), Peng Sun (University of Chinese Academy of Sciences), Bowen Xiao (CCNU).

Christopher Lee

Education and Training:

2000	**Reed College**, Portland, OR, B.A. in Mathematics-Physics
2005	**California Institute of Technology**, Pasadena, CA, Ph.D. in Physics,
2005–07	**Institute for Nuclear Theory, University of Washington**, Seattle, WA, Postdoctoral Research Associate
2007-10	**University of California**, Berkeley, CA, Postdoctoral Scholar, Theoretical High-Energy Physics,
2010-12	**Massachusetts Institute of Technology**, Cambridge, MA, Laboratory for Nuclear Science, Center for Theoretical Physics, Senior Postdoctoral Associate

Research and Professional Experience:

- **2012–present: Los Alamos National Laboratory**, Staff Scientist, Theoretical Division, Group T-2 (Nuclear and Particle Physics, Astrophysics and Cosmology).
  Research in effective field theories of the strong interaction in medium-to-high energy nuclear and particle physics, and in fundamental symmetries and the origin of matter in the early Universe.

Synergistic Activities:

- **Awards:** National Defense Science & Engineering Graduate Fellowship (2001–04), National Science Foundation Graduate Fellowship (2000-01), Leroy Apker Award Finalist (2000), admittance to ΦBK (2000), Barry M. Goldwater Scholarship in Science and Engineering (1997-99).
- **Workshop organization:** Main organizer, 2015 SCET Workshop, Santa Fe, NM; Co-organizer, 2015 APS DNP Fall Meeting, Santa Fe, NM; 2014 QCD Evolution Workshop, Santa Fe, NM; 2011 Boston Jet Physics Workshop, Harvard University.
- **Peer review:** Physical Review D, Physical Review Letters, Journal of High-Energy Physics, and Physics Letters.
- **Invited lectures and colloquia:** Lecture series on Effective Field Theories and SCET, School on Nonperturbative QCD, ICTP-SAIFR, São Paulo, Brazil (2013); lecture on Higgs physics at 2012 National Nuclear Physics Summer School, Santa Fe, NM; colloquia at University of Oregon (2010), University of Colorado–Boulder (2010), Reed College (2005)
- **Invited speaker:** at annual Soft-Collinear Effective Theory workshop (2007–14), LoopFest XIII (New York, 2014), QCD Evolution Workshop (Santa Fe, 2014), ESI Workshop on Jets and Quantum Fields for the LHC and Future Colliders (Vienna, 2013), BOOST Workshop on Jet Substructure (Princeton, 2011), Aspen Winter Conference on New Data from the Energy Frontier (2011), Duke workshop on Effective Probes of QCD Matter (2008), INT Programs on Frontiers in QCD (2011) and EFT, QCD, and Heavy Hadrons (2005)

Publications Related to the Proposed Research:

- D. Kang, C. Lee, and I. W. Stewart, *Analytic Calculation of 1-Jettiness in DIS at $\mathcal{O}(\alpha_s)$*, JHEP 1411 (2014) 132. `http://arXiv.org/abs/1407.6706`
- L. Almeida, S. D. Ellis, C. Lee, G. Sterman, I. Sung, and J. R. Walsh, *Comparing and Counting Logs in Direct and Effective Methods of QCD Resummation*, JHEP 1404 (2014) 174. `http://arXiv.org/abs/1401.4460`
- D. Kang, C. Lee, and I. W. Stewart, *Using 1-Jettiness to Measure 2 Jets in DIS 3 Ways*, Phys. Rev. D 88 (2013) 054004. `http://arXiv.org/abs/1303.6952`
- A. Hornig, C. Lee, J. R. Walsh, and S. Zuberi, *Double Non-Global Logarithms In-N-Out of Jets*, JHEP 1201 (2012) 149. `http://arXiv.org/abs/1110.0004`
- A. Hornig, C. Lee, I. W. Stewart, J. R. Walsh, and S. Zuberi, *Non-global Structure of the $\mathcal{O}(\alpha_s^2)$ Dijet Soft Function*, JHEP 1108 (2011) 054. `http://arXiv.org/abs/1105.4628`
- S. D. Ellis, C. K. Vermilion, J. R. Walsh, A. Hornig, and C. Lee, *Jet Shapes and Jet Algorithms in SCET*, JHEP 1011 (2010) 101. `http://arXiv.org/abs/1001.0014`
- A. Hornig, C. Lee, and G. Ovanesyan, *Effective Predictions of Event Shapes: Factorized, Resummed, and Gapped Angularity Distributions*, JHEP 0905 (2009) 122. `http://arXiv.org/abs/0901.3780`
- C. W. Bauer, S. Fleming, C. Lee, and G. F. Sterman, *Factorization of e^+e^- Event Shape Distributions with Hadronic Final States in Soft Collinear Effective Theory*, Phys. Rev. D 78 (2008) 034027. `http://arXiv.org/abs/0801.4569`
- C. Lee and G. F. Sterman, *Momentum Flow Correlations from Event Shapes: Factorized Soft Gluons and Soft Collinear Effective Theory*, Phys. Rev. D 75 (2007) 014022. `http://arXiv.org/abs/hep-ph/0611061`
- C. W. Bauer, C. Lee, A. V. Manohar, and M. B. Wise, *Enhanced nonperturbative effects in Z decays to hadrons*, Phys. Rev. D 70 (2004) 034014. `http://arXiv.org/abs/hep-ph/0309278`

Collaborators, Advisors and Advisees:

Collaborators and Co-editors (in the past 48 months): Leandro Almeida (*LPT–Orsay*), Vincenzo Cirigliano (*LANL*), Stephen Ellis (*University of Washington*), Andrew Hornig (*LANL*), Daekyoung Kang (*LANL*), Ou Z. Labun (*University of Arizona*), George Sterman (*Stony Brook University*), Ilmo Sung (*Queens College*), Christopher Vermilion (*Private industry*), Sean Tulin (*York University*), Jonathan Walsh (*Lawrence Berkeley National Laboratory*), Saba Zuberi (*Private industry*)

Graduate and Postdoctoral Advisors: Mark Wise (*Caltech*), Michael Ramsey-Musolf (*UMass-Amherst*), Wick Haxton (*UC–Berkeley*), Christian Bauer (*LBNL*), Iain Stewart (*MIT*)

Postdoctoral Advisees: Andrew Hornig (*LANL*), Daekyoung Kang (*LANL*)

Ivan Vitev

Education and Training:

- B.S. and M.S. in Theoretical Physics, Sofia University, Sofia, Bulgaria, 1993 and 1995
- M.S. in Education (Physics), Sofia University, Sofia, Bulgaria, 1995
- M.A. and M. Phil. in Physics, Columbia University, New York, NY, 1998 and 2000
- Ph.D. in Theoretical Nuclear Physics, Columbia University, New York, NY, 2002
- Post Doctoral Fellow, Theoretical Nuclear Physics, Iowa State University, Ames, IA, 2002-2004

Research and Professional Experience:

- J. Robert Oppenheimer Fellow (tenure track), Theoretical and Physics Divisions - Group T-16 Nuclear Theory and Group P-25 Subatomic Physics, Los Alamos National Laboratory, 2004-2007. Description: develop novel theoretical and computational approaches to heavy ion physics
- Staff Scientist, Theoretical Division, Group T-2 Nuclear and Particle Physics, Astrophysics and Cosmology, Los Alamos National Laboratory, 2007-present. Description: lead the theoretical nuclear physics effort in QCD and high-energy nuclear collisions

Publications Related to the Proposed Research:

1. Jianwei Qiu, Ivan Vitev, Resummed QCD power corrections to nuclear shadowing, Phys. Rev. Lett **93**, 262301 (2004)
   `http://arxiv.org/abs/hep-ph/0309094`
2. Brian Neufeld, Ivan Vitev,Benwei Zhang, A possible determination of the quark radiation length in cold nuclear matter, Phys. Lett. B**704**, 590 (2011)
   `http://arXiv.org/abs/1010.3708`
3. Grigory Ovanesyan, Ivan Vitev, An effective theory for jet propagation in dense QCD matter: jet broadening and medium-induced bremsstrahlung, JHEP **1106**, (2011)
   `http://arXiv.org/abs/1103.1074`
4. Grigory Ovanesyan, Ivan Vitev, Medium-induced parton splitting kernels from Soft Collinear Effective Theory with Glauber gluons, Phys. Lett. B**706**, 371 (2012)
   `http://arXiv.org/abs/1109.5619`
5. Zhongbo Kang, Ivan Vitev, Hongxi Xing, Transverse momentum imbalance of back-to-back particle production in p+A and e+A collisions, Phys. Rev. D**86**, 094010 (2012)
   `http://arxiv.org/abs/hep-ph/0309094`
6. Zhongbo Kang, Ivan Vitev, Hongxi Xing, Transverse momentum-weighted Sivers asymmetry in semi-inclusive deep inelastic scattering at next-to-leading order, Phys. Rev. D**87**, 034024 (2013)
   `http://arXiv.org/abs/1212.1221`

7. Miguel Echevarria, Ahmad Idilbi, Zhongbo Kang, Ivan Vitev, QCD Evolution of the Sivers Asymmetry, Phys. Rev. D**89**, 074013 (2014)
`http://arXiv.org/abs/1401.5878`

8. Zhongbo Kang, Ivan Vitev, Hongxi Xing, Next-to-leading order forward hadron production in the small-x regime: rapidity factorization, Phys. Rev. Lett **113**, 062002 (2014)
`http://arXiv.org/abs/1403.5221`

9. Ling-Yung Dai, Zhongbo Kang, Alexei Prokudin, Ivan Vitev, Next-to-leading order transverse momentum-weighted Sivers asymmetry in semi-inclusive deep inelastic scattering: the role of the three-gluon correlator, Phys. Rev. D sumitted
`http://arXiv.org/abs/1409.5851`

10. Leonard Gamberg, Zhongbo Kang, Ivan Vitev, Hongxi Xing, Quasi-parton distribution functions: a study in the diquark spectator model, Phys. Lett. B**743**, 112 (2015)
`http://arXiv.org/abs/1412.3401`

Selected Professional Awards and Activities:

- Awards: DOE Early Career Award, 2012; Presidential Early Career Award for Scientists and Engineers (PECASE), 2009; J. Robert Oppenheimer Fellowship, 2004-2009; Eureka Foundation Fellowship, 1997; St. Cyril and St. Methodius International Foundation & Ministry of Education Recognition for Outstanding Academic Achievements, 1997-1998, Sofia University Fellowship (top of the class), 1990-1995

- Conference organization: Co-organizer of the SCET Workshop, 2015; Co-organizer of the QCD Evolution Workshop, 2014, 2015; Co-organizer (Chair) of the National Nuclear Physics Summer School 2012; Co-organizer of the Workshop on Next-to-Leading Calculations for Heavy Ion Physics 2012; Co-organizer of QCD and the Quark-gluon plasma Workshop at the APS/DNP Fall meeting 2010, 2015, Co-convener of ISMD Jets session 2006; International Advisory Committee of CINPP 2005, Local Organizing Committee of LHC Workshop 2005, Muon Workshop 2005

- Institutional service: Laboratory Team Leader Search Committee 2011; Laboratory Staff Search Committee 2006, 2007, 2013; Laboratory Directed Research and Development (LDRD) Review Committee 2009 - 2011, 2013-2015

- Grant review: Reviewer for DOE Nuclear Physics 2006 - present, Reviewer for NSF Nuclear Physics 2009 - present; Peer review: Referee for Journal of High Energy Physics, Physical Review Letters, Physical Review C, Physical Review D, Physics Letters B, Nuclear Physics A, European Physics Journal C, European Physics Journal A, Journal Of Physics G, Modern Physics Letters A, Journal of Modern Physics E, Heavy Ion Physics

- Lectures, colloquia and outreach: JET Collaboration summer school (4 lecture series), Jyvaskyla nuclear physics school (6 lecture series), Southern Methodist University (2 lecture series), Quark Matter student lecture; Colloquia: The University of Utah, Rutgers University, Iowa State University, Los Alamos National Laboratory (2)

Collaborators and Co-editors (in the past 48 months):

- *Collaborators:*
  Biro, Tamas - RMKI, Budapest, Hungary; Chien, Yang-Ting - LANL, Los Alamos, NM; Dai, Ling-Yun - Jefferson Laboratory, Newport News, VA; Dai, Wei - Central China Normal U., China; Echevarria, Miguel - NIKKEF, Amsterdam, Neatherlands; Fickinger, Michael - Mainz U., Mainz, Germany; Gamberg, Leonard - Penn State U., Berks-Lehigh Valley, PA; Gyulassy, Miklos - Columbia U., New York, NY; He, Yuncun - Central China Normal U., China; Huang, Jinrui - LANL, Los Alamos, NM; Idilbi, Ahmad - Penn State U., College Park, PA; Kang, Zhong-Bo - LANL, Los Alamos, NM; Lashoff-Regas, Robin - UC Santa Barbara, Santa Barbara, CA; Levai, Peter - RMKI, Budapest, Hungary; Neufeled, Bryon - EMA, Lakewood, CO; Ovanesyan, Grigory - UMassL, Amherst, MA; Alexei Prokudin - Jefferson Laboratory, Newport News, VA; Saad, Philip - UC Santa Barbara, Santa Barbara, CA; Sharma, Rishi - TIFR, Mumbai, India; Wang, Enke - Central China Normal U., China; Zhang, Ben-Wei - Central China Normal U., China; Zhang, Chen - Central China Normal U., China

- *Collaborative projects:*
  JET Nuclear Theory Topical Collaboration, Lead institution LBNL (no common papers); Internal LDRD projects with the PHENIX team at LANL, Lead institution LANL (no common papers)

- *Co-editors:*
  None

Graduate and Postdoctoral Advisors and Advisees:

- *Ph.D. Advisor:*
  Miklos Gyulassy, Columbia University, New York, NY

- *Postdoctoral advisors:*
  Jianwei Qiu, Brookhaven National Laboratory, Upton, NY;
  Terrance Goldman and Mikkel Johnson, LANL, Los Alamos, NM

- *Postdoctoral Advisees:*
  Yang-Ting Chien, LANL, Los Alamos, NM; Bryon Neufeld, LANL, EMA, Lakewood, CO; Grigory Ovanesyan, UMass, Amherst, MA; Rishi Sharma, TIFR, Mumbai, India; Hongxi Xing, LANL, Los Alamos, NM; Ben-Wei Zhang, Central China Normal University, China

William Detmold

Education and Training:

B.Sc. Mathematical Physics, University of Adeladie, 1997
Ph.D. Theoretical Physics, University of Adeladie, 2002
Postdoc Research Associate, University of Washington, 2002-2004

Research and Professional Experience:

Assistant Professor, Massachusetts Institute of Technology, 2012 –
Assistant Professor, College of WIlliam & Mary, 2009 – 2012
Senior Scientist, Thomas Jefferson National Accelerator Facility, 2009 – 2012
Research Assistant Professor, University of Washington, 2004 – 2008

Selected Publications Related to the Proposed Research:

- "Deep-inelastic scattering and the operator product expansion in lattice QCD ", W. Detmold and C. J. D. Lin, Phys.Rev. **D 73**, 014501 (2006)
- "Twist-two matrix elements at finite and infinite volume", W. Detmold and C. J. D. Lin, Phys. Rev. **D 71**, 054510 (2005).
- "Axial couplings and strong decay widths of heavy hadrons ", W. Detmold, C. J. D. Lin, and S. Meinel, Phys. Rev. Lett. **108**, 172003 (2012)
- "$\Lambda_b \to \Lambda\ell^+\ell^-$ form factors and differential branching fraction from lattice QCD ", W. Detmold, C. J. D. Lin, S. Meinel, and M. Wingate, Phys. Rev. **D 87**, 074502 (2013)
- "Signal/noise enhancement strategies for stochastically estimated correlation functions", W. Detmold, and M. Endres, Phys. Rev. **D 90**, 034503 (2014)
- "Generalised parton distributions of the pion in partially-quenched chiral perturbation theory", J.-W. Chen, W. Detmold, and B. Smigielski, Phys. Rev. **D 75**, 074003 (2007)
- "Chiral extrapolation of lattice moments of proton quark distributions", W. Detmold, W. Melnitchouk, J. W. Negele, D. B. Renner, and A. W. Thomas, Phys. Rev. Lett. **87** 172001 (2001)

Synergistic Activities:

Scientific Program Committee, USQCD Collaboration, 2012–
International Advisory Committee, "International Lattice Field Theory Symposium", 2012–2013
Writing Committee, DNP Long-Range Plan Joint Town Meeting on Computational Nuclear Physics , SURA Headquarters, Washington, July 14-15, 2014
Local Organising Committee, "12th International Conference on Meson Nucleon Physics", Williamsburg, 2010
Co-organizer, "Beautiful Mesons and Baryons on the Lattice", ECT Trento, April 2012

Collaborators (in the past 48 months):

Beane, Silas (University of New Hampshire), Brown, Zachary (College of William and Mary), Chang, Emmanuel (Barcelona), Cohen, Saul (University of Washington), Endres, Michael (MIT), Flynn, Micahel (MIT) Junnarkar, Parikshit (University of New Hampshire), Lehner, Christoph (Brookhaven), Lin, C.-J. David (National Chiao-Tung University), Lin, H.-W. (University of Washington), Luu, Thomas (Juelich), McCullough, Matthew (CERN), Meinel, Stefan (MIT), Nicholson, Amy (LBNL), Orginos, Konstantinos (College of William and Mary/Jefferson Lab), Parreño, Assumpta (Barcelona), Pochinsky, Andrew (MIT), Savage, Martin (University of Washington), Shi, Zhifeng (College of William and Mary), Smigielski, Brian (National Taiwan University), Tiburzi, Brian (City College of New York), Vachaspato, Pranjal (UIUC), Walker-Loud, Andre (Lawrence Berkeley Lab), Wingate, Matthew (University of Cambridge)

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Postdoctoral advisor: Gerald Miller (University of Washington)
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Postdoctoral advisees: Abdou Abdel-Rehim (Cyprus) , Stefan Meinel (Arizona), Chris Monahan (Utah), Michael Endres (MIT), Zohreh Davoudi (MIT)

John Negele

Education and Training:

B.S. Engineering Sciences, Purdue University, 1965, With Highest Distinction
Ph.D. Theoretical Physics, Cornell University, 1969
Postdoctoral Fellow, Niels Bohr Institute, Copenhagen, Denmark, 1969 - 1970

Research and Professional Experience:

Professor of Physics, MIT, 1979 -
Director, Center for Theoretical Physics, MIT, 1989 - 1998
Head, Theoretical Division of Department of Physics, MIT, 1988 - 1998
Associate Professor of Physics, MIT, 1972 - 1979
Assistant Professor of Physics, MIT, 1971 - 1972
Visiting Assistant Professor of Physics, MIT, 1969 - 1970

Selected Publications Related to the Proposed Research:

1. J. Green, J. Negele, A. Pochinsky, S. Syritsyn, M. Engelhardt and S. Krieg, *Nucleon electromagnetic form factors from lattice QCD using a nearly physical pion mass*, Phys. Rev. **D 90** (2014) 074507.

2. J. Green, M. Engelhardt, S. Krieg, J. Negele, A. Pochinsky and S. Syritsyn, *Nucleon structure from lattice QCD using a nearly physical pion mass*, Phys. Lett. **B734** (2014) 290.

3. J. Green, J. Negele, A. Pochinsky, S. Syritsyn, M. Engelhardt and S. Krieg, *Nucleon scalar and tensor charges from lattice QCD with light Wilson quarks*, Phys. Rev. **D 86** (2012) 114509.

4. B. Musch, P. Hägler, M. Engelhardt, J. Negele and A. Schäfer, *Sivers and Boer-Mulders observables from lattice QCD*, Phys. Rev. **D 85** (2012) 094510.

5. B. U. Musch, P. Hagler, J. W. Negele and A. Schafer, *Exploring quark transverse momentum distributions with lattice QCD*, Phys. Rev. **D 83**, 094507 (2011).

6. J. D. Bratt, R. Edwards, M. Engelhardt, P. Hägler, H.-W. Lin, M.-F. Lin, H. Meyer, B. Musch, J. Negele, K. Orginos, A. Pochinsky, M. Procura, D. Richards, W. Schroers and S. Syritsyn, *Nucleon structure from mixed action calculations using 2+1 flavors of asqtad sea and domain wall valence fermions*, Phys. Rev. **D 82** (2010) 094502.

7. S. Syritsyn, J. D. Bratt, M. Engelhardt, P. Hägler, T. Hemmert, M.-F. Lin, H. Meyer, J. W. Negele, A. V. Pochinsky, M. Procura and W. Schroers, *Nucleon electromagnetic form factors from lattice QCD using 2+1 flavor domain wall fermions on fine lattices and chiral perturbation theory*, Phys. Rev. **D 81** (2010) 034507.

8. P. Hagler, B. U. Musch, J. W. Negele and A. Schafer, *Intrinsic quark transverse momentum in the nucleon from lattice QCD* Europhys. Lett. **88**, 61001 (2009).

9. A. Walker-Loud, H.-W. Lin, K. Orginos, D. Richards, R. Edwards, M. Engelhardt, G. Fleming, P. Hägler, M.-F. Lin, H. Meyer, C. Morningstar, B. Musch, J. Negele, A. Pochinsky,

M. Procura, D. Renner, W. Schroers and S. Syritsyn, *Light hadron spectroscopy using domain wall valence quarks on an Asqtad sea*, Phys. Rev. **D 79** (2009) 054502.

10. P. Hägler, W. Schroers, J. Bratt, R. Edwards, M. Engelhardt, G. Fleming, B. Musch, J. Negele, K. Orginos, A. Pochinsky, D. Renner and D. Richards, *Nucleon Generalized Parton Distributions from Full Lattice QCD*, Phys. Rev. **D 77** (2008) 094502.

Selected Professional Activities and Awards:

• *Honors and Awards*

Inaugural APS Herman Feshbach Prize in Theoretical Nuclear Physics, 2014
Fellow, American Physical Society and American Association for the Advancement of Science
Alfred P. Sloan Foundation Research Fellowship, 1972-76
Japan Society for the Promotion of Science Fellowship, 1981
John Simon Guggenheim Fellowship, 1982-3
Alexander von Humboldt Foundation Research Award, 1998

• *National Committees*

DOE Advanced Scientific Computing Advisory Committee (ASCAC), 2009 – present
USQCD Executive Committee 1999-present, Program Committee, 1999 – 2008
Chair, American Physical Society Division of Computational Physics, 1992
National Advisory Committee, Institute for Nuclear Theory, Seattle, 1990 – 94, Chair 1992 – 94
Advisory Board and Steering Committee, Institute for Theoretical Physics,
University of California, Santa Barbara 1982 – 86; Chair, 1984 – 85
American Physical Society Division of Nuclear Physics; Program Committee 1980 – 82,
Executive Committee 1982 – 84

• *Conference Organization*

Organizing Committee SciDAC 2006, 2007; SciDAC Tutorials Workshop, 2007
Co-Organizer, Seattle Institute for Nuclear Theory programs:
"Phenomenology and Lattice QCD", 1993
"Exploration of Hadron Structure and Spectroscopy using Lattice QCD", 2006
Chair of Organizing Committee, Lattice 2002
Co-Organizer, NATO Advanced Study Institute, "Hadrons and Hadronic Matter", Cargese, 1989
Chair, Nuclear Structure Gordon Research Conference, 1982
Co-Organizer, Nuclear Many-Body Theory Program, Institute for Theoretical Physics,
Santa Barbara, 1982

Collaborators and Co-Editors (in the past 48 months):

Alexandrou, Constantia (U. Cyprus); Beck, Douglas (U. Illinois); Blum, Thomas (U. Conn.); Bratt, Jonathan (Sapling Learning); Brower, Richard (Boston U.); Edwards, Robert (Jefferson Lab); Engelhardt, Michael (New Mexico State U.); Green, Jeremy (U. Mainz); Gregory, (U. Cyprus); Hägler, Philipp (Regensburg U.); Hemmert, Thomas (Regensburg U.); Izubuchi, Taku (BNL); Jenkins, Elizabeth (U. California, San Diego); Jung, Chulwoo (BNL); Krieg, Stefan (U. Wuppertal); Korzec, Tomasz (Humboldt U., Berlin); Koutsou, Giannis (Cyprus Institute); Lin, Huey-Wen (U. of Washington, Seattle); Lin, Mei-Feng (BNL); Lorce, Cedric (U. Mainz); Manohar, Aneesh (U. California, San Diego); Meyer, Harvey (U. Mainz); Musch, Bernhard (Regensburg U.); OCais, A (Cyprus Institute); Ohta, Shigemi (BNL); Orginos, Kostas (William and Mary); Pochinsky, Andrew (MIT); Procura, Massimiliano (T. U. Munich); Proestos, Yiannis (Cyprus Institute); Richards, David

(Jefferson Lab); Sato, Toru (Osaka U.); Schäfer, Andreas (Regensburg U.); Schroers, Wolfram (NuAS, Berlin); Shintani, Eigo (BNL); Syritsyn, Sergey (BNL); Tsapalis, Antonios (U. Athens); Vanderhaeghen, Marc (U. Mainz); Varilly, Patrick (Berkeley); Walker-Loud, Andre (William and Mary)

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Postdoctoral advisees: Bonche, Paul (Saclay), Burkardt, Matthias (New Mexico State), Capitani, S (U. Mainz) Friar, James (LANL), Hagler, Philipp (U. Regensburg), Jahn, Oliver (MIT), Krewald, Siegfried (Forschungszentrum Jülich), Krieg, Stefan (Wuppertal U.), Lenz, Frieder (U. Erlangen), Levit, Shimon (Weizmann Inst.), Lin, Meifeng (BNL), Meinel, Stefan (U. Arizona), Montero, Alvero (U. Barcelona), Meyer, Harvey (U. Mainz), Onishi, Naoki (Tokyo International U.), Orginos, Kostas (William and Mary), Sauer, Peter (Leibniz U., Hannover), Schroers, Wolfram (founded software company), Swanson, Eric (U. Pittsburgh), Vary, James (Iowa State U.), Vautherin, Dominique (Orsay)

Curriculum Vitae

Iain W. Stewart

Education and Training

University of Manitoba, Canada, B.Sc. (Honors Physics and Mathematics) 1994

University of Manitoba, Canada, M.Sc. (Physics) 1995

California Institute of Technology, Ph.D. (Physics) 1999

University of California, San Diego *Postdoctoral Research Fellow* 1999–2002

Professional Experience

Massachusetts Institute of Technology *Professor of Physics* 2013–Present, *Associate Professor* 2007–2012, *Assistant Professor* 2003–2006

University of Washington, Institute for Nuclear Theory *Research Assistant Professor* 2002–2003

Synergistic Activities

◇ *Honors:* Simons Investigator (2014), Fellow of the American Physical Society (2013), Friedrich Wilhelm Bessel Research Award from the Humboldt Foundation (2008), Alfred P. Sloan Research Fellow (2004), Department of Energy Outstanding Junior Investigator (2003)

◇ *Institute Service:* Nuclear Theory Group Leader (2009–Present), Graduate Student Coordinator (2012–Present), Pappalardo Executive Committee (2009–Present)

◇ *Conference Organizer:* Schrödinger Institute program on "Jets and Quantum Fields for the LHC". Vienna, July 2013. TASI summer school, "Particle Physics: The Higgs Boson and Beyond", Boulder Colorado, June 2013. Workshop on "Precision Measurements of α_s", Munich, Germany, Feb. 2011. Workshop on "Implications of First LHC Data", MIT, August 2010. Organizer for the 6th annual workshop on the Soft-Collinear Effective Theory, SCET 2009, MIT, March, 2009. Advisor for the annual series of SCET workshops 2003-2015. Program Organizer, "Effective Field Theory, QCD, and Heavy Hadrons", INT, Seattle, March to June 2005.

◇ *Summer School Lectures:* Symmetry Breaking 2014, Lake Chiemsee, Germany. TASI summer 2014 on "Journeys through the Precision Frontier", Boulder. TAE School 2012, Madrid, Spain. School on Heavy Quark Physics 2008, Dubna, Russia. Benasque School 2008, Spain. Ringberg Heavy Flavor School 2006, Germany. 19th Taiwan Spring School 2006.

◇ *Global Education:* Created an online freely available graduate course 8.EFTx on "Effective Field Theory", available through edX at http://web.mit.edu/eftx

Recent Publications Related to the Proposed Research

- **Dissecting Soft Radiation with Factorization** (with F.J. Tackmann, W.J. Waalewijn), Phys. Rev. Lett. **114** (2015), 092001 [arXiv:1405.6722]
- **Jet p_T Resummation in Higgs Production at NNLL$'$+NNLO**, (with F.J. Tackmann, J.R. Walsh, S. Zuberi), Phys. Rev. **D89** (2014), 054001 [arXiv:1307.1808]
- **Using 1-Jettiness to Measure 2 Jets in Deep Inelastic Scattering in 3 ways** (with D. Kang and C. Lee), Phys. Rev. **D88** (2013), 054004 [arXiv:1303.6952]

- **Jet Mass Spectra in Higgs + One Jet at NNLL** (with T. Jouttenus, F. Tackmann, and W. Waalewijn), Phys. Rev. **D88** (2013), 054031 [arXiv:1302.0846]
- **Thrust at N^3LL with Power Corrections and a Precision Global Fit for $\alpha_s(m_Z)$** (with R. Abbate, M. Fickinger, A. Hoang, V. Mateu), Phys. Rev. **D83** (2011) 074021 [arXiv:1006.3080]
- **N-jettiness: An Inclusive Event Shape to Veto Jets** (with F. Tackmann and W. Waalewijn), Phys. Rev. Lett. **105** (2010), [arXiv:1004.2489]
- **Quark Fragmentation within an Identified Jet** (with M. Procura), Phys. Rev. **D81** (2010), 074009 [arXiv:0911.4980]
- **Factorization at the LHC: From PDFs to Initial State Jets** (with F. Tackmann and W. Waalewijn), Phys. Rev. **D81** (2010), 094035 [arXiv:0910.0467]
- **Treating the b Quark Distribution Function with Reliable Uncertainties** (with Z. Ligeti and F. Tackmann), Phys. Rev. **D78** (2008) 114014 [arXiv:0807.1926]
- **Jets from Massive Unstable Particles: Top-Mass Determination** (with S. Fleming, A. Hoang, and S. Mantry), Phys. Rev. **D77** (2008) 074010 [hep-ph/0703207]

Graduate Student Advisees

Teppo Jouttenus 2012 (MITx, now at Outlearn), Riccardo Abbate 2012 (JPMorgan), Wouter Waalewijn 2010 (Assistant Professor University of Amsterdam), Claudio Marcantonini 2010 (Robert Schuman Center for Advanced Studies), Ambar Jain 2009 (Assistant Professor IISER Bhopal, India), Chris Arnesen 2007 (Silicon Valley startup), Keith S.M. Lee 2006 (University of Toronto Postdoc), Vivek Mohta 2005 from Harvard (vice president at Advanced Energy Economy), Sonny Mantry 2005 (Assistant Professor University of North Georgia)

Postdoctoral Advisees

Andrew Larkowski (MIT), Duff Neill (MIT), Daekyoung Kang 2011-2014 (LANL), Vicent Mateu, 2011-2012 (Univ. Vienna), Christopher Lee 2010-2012 (LANL), Frank Tackmann 2008-2011 (DESY Hamburg), Carola Berger 2007-2010 (CFB Translations), Ignazio Scimemi 2007 (Univ. Madrid Spain), Alejandro Jenkins 2006-2009 (Florida State Univ.), Bjorn Lange 2004-2007 (Univ. Siegen, Germany), Dan Pirjol 2003-2006 (JPMorgan)

Advisors, Collaborators, and Co-editors

Ph.D. advisor: Mark Wise (Caltech)

Postdoc advisors: Aneesh Manohar (UC San Diego)

Collaborators and Co-editors: Christian Bauer (Lawrence Berkeley Lab), Florian Bernlochner (Bonn U.), Yang-Ting Chien (LANL), Michael Fickinger (Univ. of Mainz), Andre Hoang (U. Vienna), Andrew Hornig (LANL), Daekyoung Kang (LANL), Heiko Lacker (Humboldt Univ., Berlin), Chris Lee (LANL), Zoltan Ligeti (LBL/Berkeley), Vicent Mateu (U.Vienna), Grigory Ovanesyan (U. Massachusetts, Amherst), Massimiliano Procura (U.Vienna), Ira Rothstein (Carnegie Mellon University), David Simmons-Duffin (IAS), Matthew Schwartz (Harvard University), Frank Tackmann (DESY, Hamburg), Kerstin Tackmann (DESY, Hamburg), Jesse Thaler (MIT), Wouter Waalewijn (U.Amsterdam), Jonathan Walsh (UC Berkeley), Saba Zuberi (UC Berkeley)

Matthias Burkardt

Education and Training:

- Diplom in Physics, Universität Erlangen-Nürnberg, 1987
- Ph.D. in Physics, Universität Erlangen-Nürnberg, 1989
- Habilitation in Theoretical Physics, Universität Erlangen-Nürnberg, 1995
- Postdoctoral Research Associate, SLAC 1990-1991
- Postdoctoral Research Associate, MIT 1991-1993

Research and Professional Experience:

- Junior Fellow and Research Assistant Professor, National Institute for Nuclear Theory and University of Washington, 1993-1995
- Assistant Professor of Physics, New Mexico State University, 1995-1999
- Associate Professor of Physics, New Mexico State University, 1999-2004
- Professor of Physics, New Mexico State University, 2004-2012
- Distinguished Achievement Professor of Physics, New Mexico State University, 2012-

Publications Related to the Proposed Research:

1. M. Burkardt, A. Miller, and W.-D. Nowak, *Spin-polarized high-energy scattering of charged leptons on nucleons*, Rept. Prog. Phys. **73** (2010) 016201.
2. M. Burkardt, *Parton Orbital Angular Momentum and Final State Interactions*, Phys. Rev. D **88**, no. 1 (2013) 014014.
3. M. Burkardt and H. BC, *Angular Momentum Decomposition for an Electron*, Phys. Rev. D**79** (2009) 071501.
4. L. Adhikari and M. Burkardt, *Distribution of Angular Momentum in the Transverse Plane*, Nucl. Phys. Proc. Suppl. **251-252** (2014) 105.
5. M. Burkardt, *The Nucleon Spin Sum Rule*, Nuovo Cim. C **036**, no. 05 (2013) 19.
6. M. Burkardt, *Transverse force on quarks in deep-inelastic scattering*, Phys. Rev. D **88** (2013) 114502.

Selected Professional Awards and Activities:

- *Awards:* George Southgate Visiting Fellowship, University of Adelaide, 2014; APS Fellow 2004; Invitation Fellowship, Japanese Society for the promotion of Sciences (JSPS), 1999 and 2001; Von Lynen Fellowship, Alexander von Humboldt Foundation, 1990-1992.
- *Peer review:* Grant reviewer for DOE, NSF and DFG, Panelist for NSF, Journal referee for Physical Review Letters, Physical Review D, Phys. Letters B.

Collaborators (in the past 48 months, excluding graduate students and those no longer active in physics):

T. Primer, W. Kamleh, D. Leinweber (all Adelaide U.)

Graduate and Postdoctoral Advisors and Advisees:

- *Ph.D. Advisor:*
  F. Lenz (Universität Erlangen-Nürnberg)
- *Postdoctoral Advisors:*
  S. Brodsky (SLAC), J. Negele (MIT).
- *Ph.D. Student Advisees:*
  F. Aslan (current); M. Abdallah (current); T. Alhalholy (current); L. Adhikari, Ph.D. 2013 (Iowa State U.); A. Jarrah, Ph.D. 2011 (Talifa Technical U., Jordan); H. BC, Ph.D. 2010 (Pensacola State College); B. Hannafious, Ph.D. 2008 (Polytec Research Foundation, Norway); T. Stevens, Ph.D. 2007; T. Bogue, Ph.D. 2006; S. Seal, Ph.D. 2003 (Oak Ridge Natl. Lab.); B. Klindworth, Ph.D. 1999; H. El Khozondar, Ph.D. 1999 (Islamic U., Gaza).
- *Postdoctoral Advisees:*
  none

Michael Engelhardt

Education and Training:

- Diplom in Physics, Universität Erlangen-Nürnberg, 1989
- Ph.D. in Physics, Universität Erlangen-Nürnberg, 1994
- MINERVA Postdoctoral Fellow, Weizmann Institute of Science, 1994-1996
- Postdoctoral Research Associate, Universität Erlangen-Nürnberg, 1996
- Postdoctoral Research Associate, Universität Tübingen, 1996-1999
- DFG Habilitation fellow, Universität Tübingen, 1999-2001; Habilitation in Theoretical Physics 2001

Research and Professional Experience:

- Privatdozent (Lecturer) and Research Associate, Universität Tübingen, 2001-2002
- Privatdozent (Lecturer), Universität Tübingen, and
  IT Consultant, science+computing ag, Tübingen, 2002-2004
- Assistant Professor of Physics, New Mexico State University, 2004-2010
- Associate Professor of Physics, New Mexico State University, 2010-present

Publications Related to the Proposed Research:

1. J. Green, J. Negele, A. Pochinsky, S. Syritsyn, M. Engelhardt and S. Krieg, *Nucleon electromagnetic form factors from lattice QCD using a nearly physical pion mass*, Phys. Rev. **D 90** (2014) 074507.
2. J. Green, M. Engelhardt, S. Krieg, J. Negele, A. Pochinsky and S. Syritsyn, *Nucleon structure from lattice QCD using a nearly physical pion mass*, Phys. Lett. **B734** (2014) 290.
3. M. Engelhardt, *Strange quark contributions to nucleon mass and spin from lattice QCD*, Phys. Rev. **D 86** (2012) 114510.
4. J. Green, J. Negele, A. Pochinsky, S. Syritsyn, M. Engelhardt and S. Krieg, *Nucleon scalar and tensor charges from lattice QCD with light Wilson quarks*, Phys. Rev. **D 86** (2012) 114509.
5. B. Musch, P. Hägler, M. Engelhardt, J. Negele and A. Schäfer, *Sivers and Boer-Mulders observables from lattice QCD*, Phys. Rev. **D 85** (2012) 094510.
6. J. D. Bratt, R. Edwards, M. Engelhardt, P. Hägler, H.-W. Lin, M.-F. Lin, H. Meyer, B. Musch, J. Negele, K. Orginos, A. Pochinsky, M. Procura, D. Richards, W. Schroers and S. Syritsyn, *Nucleon structure from mixed action calculations using 2+1 flavors of asqtad sea and domain wall valence fermions*, Phys. Rev. **D 82** (2010) 094502.
7. S. Syritsyn, J. D. Bratt, M. Engelhardt, P. Hägler, T. Hemmert, M.-F. Lin, H. Meyer, J. W. Negele, A. V. Pochinsky, M. Procura and W. Schroers, *Nucleon electromagnetic form factors from lattice QCD using 2+1 flavor domain wall fermions on fine lattices and chiral perturbation theory*, Phys. Rev. **D 81** (2010) 034507.
8. A. Walker-Loud, H.-W. Lin, K. Orginos, D. Richards, R. Edwards, M. Engelhardt, G. Fleming, P. Hägler, M.-F. Lin, H. Meyer, C. Morningstar, B. Musch, J. Negele, A. Pochinsky, M. Procura, D. Renner, W. Schroers and S. Syritsyn, *Light hadron spectroscopy using domain wall valence quarks on an Asqtad sea*, Phys. Rev. **D 79** (2009) 054502.

9. P. Hägler, W. Schroers, J. Bratt, R. Edwards, M. Engelhardt, G. Fleming, B. Musch, J. Negele, K. Orginos, A. Pochinsky, D. Renner and D. Richards, *Nucleon Generalized Parton Distributions from Full Lattice QCD*, Phys. Rev. **D 77** (2008) 094502.

10. M. Engelhardt, *Neutron electric polarizability from unquenched lattice QCD using the background field approach*, Phys. Rev. **D 76** (2007) 114502.

Selected Professional Awards and Activities:

- *Awards:* Doctorate Fellowship (Ministry of Culture of the State of Bavaria), 1991-1992; MINERVA Postdoctoral Fellowship, 1994-1996; DFG Habilitation Fellowship, 1999-2001

- *Peer review:* Grant reviewer for DOE, NSF and Alexander von Humboldt Foundation. Journal referee for Physical Review Letters, Physical Review D (APS Outstanding Referee), International Journal of Modern Physics A, Journal of High Energy Physics and European Physical Journal A.

Collaborators (in the past 48 months, excluding graduate students and those no longer active in physics):

D. Altarawneh (Tafila Technical University, Jordan), C. Beetle (Florida Atlantic), T. Bhattacharya (LANL), S. Cisneros (MIT), M. Diehl (DESY), G. Goedecke (NMSU), J. Green (Mainz), R. Gupta (LANL), R. Höllwieser (NMSU), S. Krieg (Jülich), S. Liuti (Virginia), S. Meinel (Arizona), J. W. Negele (MIT), A. V. Pochinsky (MIT), A. Schäfer (Regensburg), S. Syritsyn (BNL), B. Yoon (LANL)

Graduate and Postdoctoral Advisors and Advisees:

- *Ph.D. Advisor:*
  F. Lenz (Universität Erlangen-Nürnberg)

- *Postdoctoral Advisors:*
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- *Ph.D. Student Advisees:*
  J. Saenz, current; D. Altarawneh, Ph.D. 2013 (Tafila Technical University, Jordan); S. Cisneros, Ph.D. 2011 (MIT)

- *Postdoctoral Advisees:*
  R. Höllwieser (NMSU)

Leonard Gamberg

Education and Training:

- Ph.D., in Physics, Tufts University, 1995
- M.S. in Physics, The University of Vermont, 1984
- Postdoctoral Research Associate, The University of Oklahoma, 1996-2000
- Postdoctoral Research Associate, Institut für Theoretische Physik, Tübingen 1994-1996

Research and Professional Experience:

- Professor of Physics, Penn State University-Berks, 2014-present
- Associate Professor of Physics, Penn State University-Berks, 2008-2014
- Visiting Physicist, Theory Division-Jefferson Lab Spring 2010 (Sabbatical Leave)
- Visiting Physicist, Institute for Nuclear Theory, U. Washington (Sabbatical Leave)
- Assistant Professor of Physics, Penn State University-Berks, 2002-2008
- Research Scholar/Lecturer in Physics, University of Pennsylvania, 2000-2002

Publications Related to the Proposed Research:

1. L. Gamberg, Z.-B. Kang, Ivan Vitev, Hongxi Xing, *Quasi-parton distribution functions: a study in the diquark spectator model*, Phys. Lett. B **743**, 112 (2015).
2. M. Aghasyan, H. Avakian, E. De Sanctis, L. Gamberg , M. Mirazita, B. Musch, A. Prokudin, P. Rossi, *Studies of Transverse Momentum Dependent Parton Distributions and Bessel Weighting*, JHEP 1503 (2015) 039.
3. L. Gamberg , Z.-B. Kang , A. Metz, D. Pitonyak , A. Prokudin, *Left-right spin asymmetry in* $\ell\, N^{\uparrow} \rightarrow h\, X$, Phys. Rev. D **90**, 074012 (2014).
4. C.A. Aidala, B. Field, L. Gamberg , T.C. Rogers, *Limits on transverse momentum dependent evolution from semi-inclusive deep inelastic scattering at moderate* Q, Phys. Rev. D89, 094002 (2014).
5. L. Gamberg, Z.-B. Kang, A. Prokudin, *Indication on the Process Dependence of the Sivers Effect*, Phys. Rev. Lett. **110**, 232301 (2013).
6. L. Gamberg, Z.-B. Kang, *Single transverse spin asymmetry of prompt photon production*, Phys. Lett. B **718**, 181 (2012).
7. U. D'Alesio, L. Gamberg, Z.-B. Kang, F. Murgia, C. Pisano, *Testing the process dependence of the Sivers function via hadron distributions inside a jet*, Phys. Lett. B **704**, 637 (2011).
8. D. Boer, L. Gamberg, B. Musch, A. Prokudin, *Bessel-Weighted Asymmetries in Semi Inclusive Deep Inelastic Scattering*, JHEP 1110 (2011) 021.
9. L. Gamberg, Z.-B. Kang, *Process dependent Sivers function and implications for single spin asymmetry in inclusive hadron production*, Phys. Lett. B **696**, 109 (2011).
10. L. Gamberg, A. Mukherjee, P. J. Mulders, *A model independent analysis of gluonic pole matrix elements and universality of TMD fragmentation functions* , Phys. Rev. D **83**, 071503 (2011).

Selected Professional Activities:

- **Conference Organization**: Co-Organizer-6th Workshop of the APS Topical Group on Hadronic Physics, April 8-10, 2015, Baltimore, MD: Co-Organizer-pre-Town Meeting, JLAB, August 13-16, 2014, Jefferson Lab, Newport News, VA: Co-Organizer-QCD Evolution Workshop, May 14-17, 2012-Jefferson Lab Newport News, VA; May 6-10, 2013-Jefferson Lab, Newport News, VA; May 12-16, 2014-Santa Fe, NM; May 26-30, 2015-Jefferson Lab, Newport News, VA

- **Service to Community**: Elected Member of Executive Committee, APS Topical Group on Hadron Physics, 2014-2017

- **Peer Review**: *Grant Reviewer*-DOE Nuclear Physics; Italian Ministry of Education, University and Research (MIUR) General Directorate for the coordination and development of Research Office V: *Referee*-Physical Review Letters, Physical Review D, Physics Letters B, Journal of High Energy Physics, Nuclear Physics B

- **Mentoring:** Mentor of Science Undergraduate Laboratory Internship (SULI) undergraduate student Daniel Banks (Penn State University Berks) at JLAB, Summer 2013.

Collaborators and Co-editors (in the past 48 months):

- *Collaborators:*
  Bernhard Musch (Regensburg University), Daniel Boer (University of Groningen), Piet Mulders (VU University in Amsterdam & NIHKEF, The Netherlands), Zhong-Bo Kang (Los Alamos National Lab), Alexei Prokudin (Jefferson Lab), Jianwei Qiu (Brookhaven National Lab & Stony Brook University), Ted Rogers (Old Dominion University & Jefferson Lab), Andreas Metz (Temple University), Matthias Burkardt (New Mexico State University), Christine Aidala (University of Michigan) Enzo De Sanctis (Frascati, INFN), Stan Brodsky (Stanford Linear Accelerator), Marc Schlegel (Tübingen University, Germany), Daniel Pitonyak (RHIC/Brookhaven National Lab), Umberto D'Alesio (Cagliari University & INFN, Cagliari), Francesco Murgia (INFN, Cagliari), Cristian Pisano (Cagliari University & INFN, Cagliari) Patrizia Rossi (Jefferson Lab), Harut Avakian (Jefferson Lab), Ivan Vitev (Los Alamos National Lab), Hongxi Xing (Los Alamos National Lab),

- *Co-editors:*
  A. Radyushkin (Old Dominion-Jefferson Lab), A. Prokudin (Penn State Berks-Jefferson Lab)

Graduate and Postdoctoral Advisors:

- *Ph.D. Advisor:*
  Gary R. Goldstein, Tufts University

- *Postdoctoral Advisors:*
  Hugo Reinhardt (Tübingen University), Kimball Milton (The University of Oklahoma)

Andreas Metz

Education and Training:

- Ph.D. Physics, University of Mainz, 1997
- Postdoctoral Fellow, University of Heidelberg, 1998 – 1999
- Postdoctoral Fellow, SPhN Saclay, 1999 – 2000
- Postdoctoral Fellow, Free University Amsterdam, 2000 – 2002
- Research Associate, University of Bochum, 2002 – 2007

Research and Professional Experience:

- Assistant Professor, Temple University, 2007 – 2013
- Associate Professor, Temple University, 2013 – present

Publications Related to the Proposed Research:

1. K. Kanazawa, Y. Koike, A. Metz and D. Pitonyak, *Transverse single-spin asymmetries in* $p^{\uparrow}p \to \gamma X$ *from quark-gluon-quark correlations in the proton*, Phys. Rev. D **91**, 014013 (2015).
2. K. Kanazawa, Y. Koike, A. Metz, D. Pitonyak, *Towards an explanation of transverse single-spin asymmetries in proton-proton collisions: the role of fragmentation in collinear factorization*, Phys. Rev. D **89**, 111501(R) (2014).
3. K. Kanazawa, C. Lorcé, A. Metz, B. Pasquini, M. Schlegel, *Twist-2 generalized TMDs and the spin/orbital structure of the nucleon*, Phys. Rev. D **90**, 014028 (2014).
4. A. Metz, D. Pitonyak, *Fragmentation contribution to the transverse single-spin asymmetry in proton-proton collisions*, Phys. Lett. B **723**, 365 (2013).
5. A. Metz, D. Pitonyak, A. Schäfer, M. Schlegel, W. Vogelsang, J. Zhou, *Single-spin asymmetries in inclusive DIS and multi-parton correlations in the nucleon*, Phys. Rev. D **86**, 094039 (2012).
6. S. Meissner, A. Metz, M. Schlegel, *Generalized parton correlation functions for a spin-1/2 hadron*, JHEP **0908**, 056 (2009).
7. S. Meissner, A. Metz, *Partonic pole matrix elements for fragmentation*, Phys. Rev. Lett. **102**, 172003 (2009).
8. A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P. Mulders, M. Schlegel, *Semi-inclusive deep inelastic scattering at small transverse momentum*, JHEP **0702**, 093 (2007).
9. J. C. Collins, A. Metz, *Universality of soft and collinear factors in hard scattering factorization*, Phys. Rev. Lett. **93**, 252001 (2004).
10. A. Metz, *Gluon exchange in spin-dependent fragmentation*, Phys. Lett. B **549**, 139 (2002).

Selected Professional Awards and Activities:

- *Conference organization:* Co-Organizer, APS DNP Long-Range Plan Joint Town Meeting on QCD, Temple University, September 2014, Philadephia, USA; Co-convener, Working group on Hadronic Physics and Spin, 11th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2012), May 2012, St. Petersburg, USA; Co-organizer, INT workshop on 3-Dimensional Parton Structure of the Nucleon encoded in GPDs and TMDs, September 2009, Seattle, USA; Co-convener, Working group on Spin Physics, 16th International Workshop on Deep-Inelastic Scattering and Related Topics (DIS 2008), April 2008, London, Great Britain; Co-organizer, ECT workshop on Transverse Momentum, Spin, and Position Distributions of Partons in Hadrons, June 2007, Trento, Italy.

- *Community Service:* Coordinator of the European program I3-HP (Integrated Infrastructure Initiative Hadronic Physics) for the node Bochum for *Hadron Theory* and *Transversity*, July 2004 – June 2007; Member of the International Advisory Committee for the International workshop of Transversity 2014, Baia Chia-Sardinia, Italy, June 2014

- *Peer review:* Grant reviewer for Research Foundation Flanders; Referee for European Physical Journal A, Few-Body Systems, Journal of Physics G, Nuclear Physics A, Physical Review C and D, Physical Review Letters, Physics Letters B, Progress in Particle and Nuclear Physics.

Collaborators and Co-editors (in the past 48 months):

- *Collaborators:*
  L. Gamberg (Penn State Berks), K. Kanazawa (Temple University), Z. Kang (LANL), J. Koempel (Temple University), Y. Koike (Niigata University), P. Kroll (University of Wuppertal), Z. Liang (Shandong University), C. Lorcé (University of Liège), B. Pasquini (University of Pavia), D. Pitonyak (BNL), A. Prokudin (Jefferson Lab), J. Qiu (BNL), A. Schäfer (University of Regensburg), M. Schlegel (University of Tübingen), Y. Song (CUST Hefei), W. Vogelsang (University of Tübingen), J. Zhou (Free University Amsterdam and NIKHEF).

- *Co-editors:*
  None

Graduate and Postdoctoral Advisors and Advisees:

- *Ph.D. Advisor:*
  Dieter Drechsel (University of Mainz)

- *Postdoctoral Advisors:*
  Hans-Jürgen Pirner (University of Heidelberg), Pierre Guichon (SPhN, Saclay), Piet Mulders (Free University Amsterdam), Klaus Goeke (University of Bochum)

- *Ph.D. Students Advisees:*
  John Koempel (Epic Systems Corporation, Madison, WI), Pierre Phou (Rowan University), Daniel Pitonyak (BNL).

- *Postdoctoral Advisees:*
  Koichi Kanazawa (Temple University), Jian Zhou (Free University Amsterdam).

Sean Fleming

Education and Training:

- B.S., Physics, Georgetown University, 1984
- Ph.D. Physics, Northwestern University, 1995
- Research Associate, University of Wisconsin Madison, 1995-1997
- Research Associate, University of Toronto, 1997-2000
- Research Associate, Carnegie Mellon University, 2000-2004
- Research Associate, University of California San Diego, 2004-2005

Research and Professional Experience:

- Associate Professor of Physics, University of Arizona, 2011-present
- Assistant Professor of Physics, University of Arizona, 2005-2011

Selected Publications Relevant to Proposed Research:

1. S. Fleming, "The role of Glauber exchange in soft collinear effective theory and the Balitsky-Fadin-Kuraev-Lipatov Equation", Phys. Lett. **B735** (2014) 266.
2. S. Fleming, A.K. Leibovich, T. Mehen, and I.Z. Rothstein, "Anomalous dimensions of the double parton fragmentation functions", Phys. Rev. D **D87** (2013) 074022.
3. S. Fleming and O. Zhang, "Rapidity Divergences and Deep Inelastic Scattering in the Endpoint Region", accepted for publication in Phys. Rev. **D**, `arXiv:1210.1508`.
4. S. Fleming, A.K. Leibovich, T. Mehen, and I.Z. Rothstein, "The Systematics of Quarkonium Production at the LHC and Double Parton Fragmentation", Phys. Rev. **D86** (2012) 094012.
5. C. W. Bauer, S. Fleming, C. Lee, G. F. Sterman, "Factorization of e+e- Event Shape Distributions with Hadronic Final States in Soft Collinear Effective Theory", Phys. Rev. **D78** (2008) 034027.
6. S. Fleming, A. H. Hoang, S. Mantry, I. W. Stewart, "Top Jets in the Peak Region: Factorization Analysis with NLL Resummation ", Phys. Rev. **D77** (2008) 114003.
7. S. Fleming, A. H. Hoang, S. Mantry, I. W. Stewart, "Jets from massive unstable particles: Top-mass determination", Phys. Rev. **D77** (2008) 074010 .
8. S. Fleming, A. K. Leibovich, T. Mehen, "Resummation of Large Endpoint Corrections to Color-Octet J/? Photoproduction", Phys. Rev. **D74** (2006) 114004.
9. C. Bauer, S. Fleming, D. Pirjol, and I.W. Stewart, "An Effective Field Theory for Collinear and Soft Gluons: Heavy to light decays", Phys. Rev. **D63** (2001) 114020.
10. E. Braaten and S. Fleming, "Color Octet Fragmentation and the ψ' Surplus at the Tevatron", Phys. Rev. Lett. **74** (1995) 3327.

Synergistic Activities:

- Principal Investigator, DOE grant DE-FG02-04ER41338, 2014-present
- Organizer, INT program on "Frontiers in QCD", Sep. 19 - Nov. 18, 2011

Collaborators and Co-editors:

A. Jain (Indian Institute of Science Education and Research)
A. K. Leibovich (University of Pittsburgh)
I. Z. Rothstein (Carnegie Mellon University)

Graduate and Postdoctoral Advisors and Advisees:

V. Barger (University of Wisconsin, Madison)
E. Braaten (Ohio State University)
M. Luke (University of Toronto, Canada)
A. Manohar (University of California, San Diego)
I.Z. Rothstein (Carnegie Mellon University)
M. Fickinger (Johannes Gutenberg-Universität Mainz, Germany)
M. Kusunoki (current affiliation unknown)
E. Mereghetti (Lawrence Berkeley National Laboratory)
D. Perrodin (Osservatorio Astronomico di Cagliari, Italy)

Keh-Fei Liu

Education and Training:

- BS – Tunghai University, Taiwan, 1968
- MS – Stony Brook University, 1971
- PhD – Stony Brook University, 1975
- CEN Saclay, Service de Physique Theorique, France, Visiting Research Scientist, 1974 – 1976
- University of California, Los Angeles, Research Associate , 1976 – 1979

Research and Professional Experience:

- Adjunct Assistant Professor, University of California, Los Angeles, 1979 – 1980
- University of Kentucky, Associate Professor, 1980 – 1986
- Professor, University of Kentucky, 1986 – present

Publications Related to the Proposed Research:

1. M. Deka, T. Doi, Y.B. Yang, B. Chakraborty, S.J. Dong, T. Draper, M. Glatzmaier, M. Gong, H.W. Lin, K.F. Liu et al, *A Lattice Study of Quark and Glue Momenta and Angular Momenta in the Nucleon*, Phys. Rev. D**91**, 014505 (2015), [arXiv:1312.4816].
2. M. Gong, A. Alexandru, Y. Chen, T. Doi, S.J. Dong, T. Draper, W. Freeman, M. Glatzmaier, K.F. Liu, and Z.F. Liu, *Strangeness and charmness content of nucleon from overlap fermions on 2+1- flavor domain-wall fermion configurations*, Phys. Rev. D **88**, 014503 (2013), [arXiv:1304.1194].
3. K.F. Liu, W.C. Chang, H.Y. Cheng, and J.C. Peng, *Connected-Sea Partons*, Phys. Rev. Lett. **109**, 252002 (2012), [arXiv:1206.4339].
4. T. Doi, M. Deka, S.J. Dong, T. Draper, K.F. Liu, D. Mankame, N. Mathur, T. Streuer, *Nucleon strangeness form factors from N(f) = 2+1 clover fermion lattice QCD*, Phys. Rev. D **80**, 094503 (2009), [arXiv:0903.3232].
5. K.F. Liu, A. Alexandru, and I. Horvath, *Gauge field strength tensor from the overlap Dirac operator*, Phys. Lett. B **659** 773 (2008), [arXiv:hep-lat/0703010].
6. K.F. Liu, *Parton degrees of freedom from the path integral formalism*, Phys. Rev. D **62**, 074501 (2000), [hep-ph/9910306].

Selected Awards and Recent Synergistic Activities

1. Fellow of APS, 1997
2. Alexander von Humboldt Award for Senior Scientist, 1990
3. Member of USQCD Collaboration
4. Foreign Editorial Board, Chinese Physics C
5. NSTAR International Advisory Committee, 2011 – present
6. Local Organization Committee, Extreme QCD 2012 Conference

Collaborators (in the past 48 months):

Alexandru, Andrei – George Washington University
Chakraborty, Bipasha – University of Glasgow
Chen, Ying – IHEP, Chinese Academy of Sciences
Chang, Wen-Chen – Academia Sinica
Cheng, Hai-Yang, –Academia Sinica
Deka, Mridupawan, Dubna
Doi, Takumi – Nishina Center, RIKEN
Dong, Shao-Jing –University of Kentucky
Draper, Terrence – University of Kentucky
Freeman, Walter – Syracuse University
Glatzmaier, Michael – University of Kentucky
Gong, Ming – IHEP, Chinese Academy of Sciences
Hall, Jonathan – Adeliade University
Hasenfratz, Anna – University of Colorado
Horvath, Ivan – University of Kentucky
Lang, Christian – Graz University
Lee, Frank – George Washington University
Leinweber, Derek – Adeliade University
Li, Anyi – Explorys
Li, Gang – Qufu Normal University
Li, Hsiang-nan – Academia Sinica
Limmer, Markus – Graz Univeristy
Lin, Huey-Wen – University of Washington
Liu, Zhaofeng – Chinese Academy of Sciences
Lujan, Michael – George Washington University
Ma, Jian-Ping – ITP, China
Mathur, Nilmani – Tata Institute of Fundamental Research
Meng, Xiangfei – Natl. Supercomputing Ctr., Tianjin
Mohler, Daniel – Fermilab
Peng, Jen-Chieh – University of Illinois
Prelovsek, Sasa – Ljubljana University
Qiu, Jianwei – BNL
Sufian, Raza – University of Kentucky
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Thomas, Anthony – Adeliade University
Yang, Yibo – University of Kentucky
Zhang, Jianbo – Zhejiang University

Graduate and Postdoctoral Advisors and Advisees:

- *Ph.D. Advisor:*
  G.E. Brown, Stony Brook University
- *Postdoctoral Advisors:*
  G. Ripka, M. Rho (Saclay), C.W. Wong (UCLA)
- *Ph. D. Student Advisees:*
  A. Li, Ph. D. 2010 (Explorys - IBM), M. Deka, Ph. D. 2007 (JINR, Dubna), C. Thron, Ph. D. 1997 (NEC), H.D. Luo, Ph. D. 1987

- *Postdoctoral Advisees:*
  G. Black, W. Wilcox (Baylor U.), S. Nadkarni, Y. Liang (USAir), S.J. Dong (U. Kentucky), C. McNeile (U. Glasgow), J.-F. Lagae, M. Peardon (Trinity College), J. Sloan, J. Zhang (Zhejiang U), D. Lin (Chiao-Tong U.), B. Joo (JLab), N. Mathur (TIFR, Mumbai), A. Alexandru (George Washington U.), I. Horvath (U. Kentucky), Y. Chen (IHEP, Beijing), S. Tamhankar (Seattle U.), T. Streuer (Munich), T. Doi (RIKEN, Japan), M. Gong (IHEP, Beijing), M. Glatzmaier (Minneapolis), Y. Yang (U. Kentucky)

Xiangdong Ji

Education and Training:

- B.S. Physics, Tong Ji University, Shanghai, 1982
- Ph.D. Physics, Drexel University, Philadelphia, 1987
- Postdoc Research Associate, Caltech, 1987-1989
- Postdoc Research Associate, MIT, 1989-1991

Research and Professional Experience:

- Assistant Professor, MIT, 1991-1996
- Assistant, Associate, Full Professor, University of Maryland, 1996-present

Publications Related to the Proposed Research:

1. X. Ji, *Parton Physics from Large-Momentum Effective Field Theory*, Sci. China Phys. Mech. Astron.57, 1407 (2014).
2. H.W. Lin, J. W. Chen, S.D. Cohen, X. Ji, *Flavor Structure of the Nucleon Sea from Lattice QCD*, Phys. Rev. D91, 054510 (2014).
3. X. N. Xiong, X. Ji, J. H. Zhang, Y. Zhao, *One-loop matching for parton distributions: Non-singlet case*, Phys. Rev. D90, 014051 (2014).
4. Y. Hatta, X. Ji, Y. Zhao, *Gluon Helicity form Universality class of operators on a lattice*, Phys. Rev. D89, 085030 (2014).
5. X. Ji, *Parton Physics on a Euclidean Lattice*, Phys. Rev. Lett. 100, 262002 (2013).
6. X. Ji, J. H. Zhang, Y. Zhao, *Physics of the gluon-helicity contribution to proton spin*, Phys. Rev. Lett. 111, 112002 (2013).
7. X. Ji, X. Xiong and F. Yuan, *Proton Spin Structure from Measurable Parton Distributions*, Phys. Rev. Lett. **109**, 152005 (2012).
8. X. Ji, J.W. Qiu, W. Vogelsang, Feng Yuan, *Unified Picture for Single Transverse-Spin Asymmetries in Hard-scattering Processes*, Phys. Rev. Lett. **97**, 082002 (2006).
9. X. Ji, J. P. Ma, and Feng Yuan, *QCD Factorization for Semi-inclusive Deep-inelastic Scattering at Low Transverse Momentum*, Phys. Rev. D71, 034005 (2005).
10. A. V. Belitsky, X. Ji, Feng Yuan, *Final state interactions and gauge invariant parton distributions*, Nucl. Phys. **B656**, 165 (2003).

Selected Professional Awards and Activities:

- **Awards:** Humboldt Research Award (2014), APS Fellow (2000)
- **Conference organization:** Organizer of the 21st International Symposium on Spin Physics, Beijing, China, October 20-24, 2014; Organizer of the MCFP Workshop on Lattice Parton Physics, University of Maryland, College Park, March 30-April 1, 2014; Co-Organizer of Berkeley Summer
- **Community Service:** Member, Advisory Committe on Electron-Ion Collider

- **Peer review:** Grant reviewer for DOE, NSF Referee for Physical Review Letters, Physical Review C and D, Nuclear Physics A and B, Journal of High Energy Physics, Physics Letter B

- **Outreach:** Summer school lectures, public talks etc.

Collaborators and Co-editors (in the past 48 months):

- **Collaborators:**
  F. Yuan (BNL), J. H. Zhang (Regensburg), Y. Hatta (U. Kyoto)

Graduate and Postdoctoral Advisors and Advisees:

- **Ph.D. Advisor:**
  B. H. Wildenthal, University of Texas, Dallas

- **Postdoctoral Advisors:**
  Steve Koonin (Caltech), John Negele (MIT)

- **Ph.D. Students Advisees:**
  X. N. Xiong (University of Pavia), Y. Zhang (Caltech), H. P. An (Caltech), Y. C. Zhang, A. Idilbi (Penn State)

- **Postdoctoral Advisees:**
  A. Belitsky (Arizona), A. Balitksy (ODU), F. Yuan (LBL), W. Melnithouk (Jlab), J. W. Chen (National Taiwan U), Y. Q. Ma (Peking U)

Simonetta Liuti

Education and Training:

- Laurea in Fisica, University of Perugia, 1984
  Adviser: B.A. de Tollis
- Physics Ph.D., University of Rome "La Sapienza", 1989
  Adviser: C. Ciofi degli Atti
- Post-doctoral Fellow, Istituto Nazionale di Fisica Nucleare (INFN)-Rome, 1989-90

Research and Professional Experience:

- Research Associate Professor, University of Virginia, Department of Physics, 2007- present
- Research Assistant Professor, University of Virginia, Department of Physics, 2001- 2007
- Permanent Research Staff, Istituto Nazionale di Fisica Nucleare (INFN)-Rome, 1991-2001
- Visiting Professor, Department of Physics, College of William and Mary, 1995-96

Publications Related to the Proposed Research:

1. A. Courtoy, G. R. Goldstein, J. O. Gonzalez Hernandez, S. Liuti and A. Rajan, *"On the Observability of the Quark Orbital Angular Momentum Distribution,"* Physics Letters B **731** (2014) ; arXiv:1310.5157 [hep-ph].
2. A. Courtoy, G. R. Goldstein, J. O. Gonzalez Hernandez, S. Liuti and A. Rajan, *"Identification of Observables for Quark and Gluon Orbital Angular Momentum,"* submitted to Physics Letters B; arXiv:1412.0647 [hep-ph].
3. A. Courtoy and S. Liuti, *"Extraction of α_s from deep inelastic scattering at large x,"* Phys. Lett. B **726**, 320 (2013)
4. E. M. Askanazi, K. A. Holcomb and S. Liuti, *"Exploring Nucleon Structure with the Self-Organizing Maps Algorithm,"* J. Phys. G **42**, no. 3, 034030 (2015) [arXiv:1411.2487 [hep-ph]].
5. J. Carnahan, H. Honkanen, S. Liuti, Y. Loitiere and P. R. Reynolds, *"New avenue to the Parton Distribution Functions: Self-Organizing Maps,"* Phys. Rev. D**79**, 034022 (2009); arXiv:0810.2598 [hep-ph].
6. G. R. Goldstein, J. O. Gonzalez Hernandez and S. Liuti, *"Flexible Parametrization of Generalized Parton Distributions: The Chiral-Odd Sector,"* to be published in Physical Review D; arXiv:1311.0483 [hep-ph].
7. J. O. Gonzalez-Hernandez, S. Liuti, G. R. Goldstein and K. Kathuria, *"Interpretation of the Flavor Dependence of Nucleon Form Factors in a Generalized Parton Distribution Model,"* Phys. Rev. C **88**, 065206 (2013)
8. S. K. Taneja, K. Kathuria, S. Liuti and G. R. Goldstein, *"Angular momentum sum rule for spin one hadronic systems"* Phys. Rev. D **86**, 036008 (2012); arXiv:1101.0581 [hep-ph]
9. G. R. Goldstein, J. O. G. Hernandez, S. Liuti, *"Flexible Parametrization of Generalized Parton Distributions from Deeply Virtual Compton Scattering Observables,"* Phys. Rev. **D84**, 034007 (2011). [arXiv:1012.3776 [hep-ph]].
10. G. R. Goldstein and S. Liuti, *"The Use of Dispersion Relations in Hard Exclusive Processes and the Partonic Interpretation of Deeply Virtual Compton Scattering,"* Phys. Rev. D **80**, 071501 (2009); arXiv:0905.4753 [hep-ph].

Selected Professional Awards and Synergistic Activities:

- *Membership and Service*
  South Eastern APS (SESAPS) Chair (present)

  CSWP Blewett Fellowship Selection Committee (2015 Award)

  APS Topical Group on Hadronic Physics Nominating Committee (2009)

  Co-Editor of SPIN 2008, 18th International Spin Physics Symposium, (AIP Conference Proceedings 1149, 2009)

  Organizer of several international workshops including at ECT* (Trento), INFN Laboratori Nazionali di Frascati, Jefferson Lab.

  Convener, Spin Section, DIS 2010, April 19-23, Florence (Italy)

  Co-spokeperson on several Jefferson Lab experimental proposals and letters of intent.

- *Peer review:* Grant reviewer for DOE, NSF, and European funding agencies (Netherlands, Italy). Journal referee for Physical Review Letters, Physical Review D, Physical Review C, Physics Letters B, International Journal of Modern Physics G, Nuclear Physics A, Few Body Physics.

Collaborators (in the past 48 months:

H. Avakian (Jefferson Lab), S. Baessler (U. Virginia), A. Courtoy (U. Liege, Belgium and U. Guanajuato, Mexico), P. Di Nezza (INFN, LNF), M. Engelhardt (NMSU), M. Gonzalez-Alonso (IPNL, U. Lyon), O. Gonzalez Hernandez (INFN, Torino), G. R. Goldstein (Tufts), S. Pisano (INFN, LNF).

Graduate and Postdoctoral Advisees:
• *Ph.D. Student Advisees:* Evan Askanazi, Abha Rajan, current; Kunal Kathuria, Ph.D. 2013 (U. Virginia, Medical School); J. Osvaldo Gonzalez Hernandez, Ph.D. 2012 (INFN, Torino); Saeed Ahmad, Ph.D. 2008 (Bloomsburg U.); Swadhin K. Taneja, Ph.D. 2006 (Dalhousie U.)
• *Postdoctoral Advisees:* Heli Honkanen (U. Virginia, 2005-07)

Appendix 2: Current and Pending Support

In this Appendix, we list the Current and Pending Support of all co-investigators of this proposal, organized according to the alphabetical order of participating institutions:

Brookhaven National Laboratory:

Jianwei Qiu

- Principal Investigator: *Raju Venugopalan*
  Source of Support: *DOE Office of Science*
  B& R # KB0301020
  DOE Program Manager: *George Fai*
  Nuclear Physics Program
  Title: *Nuclear Physics Theory* FWP: PO006
  Total Expected Funding for project 08618 in FY 2016: \$2,850,000
  Description: Core Nuclear Theory Grant at BNL
  Period Covered: 10/1/15 9/30/16
  Committed Effort: 12 months
  Potential Overlap: None

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: \$2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Raju Venugopalan

- Principal Investigator: *Raju Venugopalan*
  Source of Support: *DOE Office of Science*
  B&R # KB0301020
  DOE Program Manager: *George Fai*
  Nuclear Physics Program
  Title: *Nuclear Physics Theory* FWP: PO006
  Total Expected Funding for project 08618 in FY 2016: \$2,850,000
  Description: Core Nuclear Theory Grant at BNL
  Period Covered: 10/1/15 9/30/16
  Committed Effort: 12 months
  Potential Overlap: None

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: \$2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

- Title: *"Topical Collaboration on Quantifying Uncertainties in Knowledge-Extraction from Relativistic Heavy-Ion Collisions (QURHIC)"*
  Principal Investigator: *S.A. Bass*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*

Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
Committed Effort: None

- Title: *"Topical Collaboration on Beam Energy Scan Theory (BEST Collaboration)"*
  Principal Investigator: *S. Mukherjee*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Duke University:

Thomas Mehen

- Title: *"Lattice and Effective Field Theory Studies of Quantum Chromodynamics"*
  Principal Investigator: *Co-PIs: S. Chandrasekharan, T. Mehen, R. P. Springer*
  Granting Agency: *DOE, Office of Science, Nuclear Physics Program*
  Status/Award Number: *Current, DE-FG02-05ER41368*
  Total Award Amount: $1,065,000 (3/15/2014 – 3/14/2017)
  Support Type: Summer support and travel for PIs, computer cluster for S. Chandrasekharan's lattice studies, support for graduate students and postdoctoral fellow.

- Title: *"Topical Collaboration on Effective Field Theory for Precision Jet and Heavy Flavor Physics"*
  Principal Investigator: *S. Fleming*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $1,500,000 (Oct 2016 – Sept 2020)
  Committed Effort: None
  Potential Overlap: None.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Jefferson Laboratory and Old Dominion University:

Ted C. Rogers

- Title: *Early Career: QCD and the Physics of Transverse Momentum Dependent Observables in Hard Collisions*
  Principal Investigator: *T. C. Rogers*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: *Pending*
  Committed Effort: *6–9 months*
  Description: Early Career grant in preparation.
  Potential Overlap: Covers similar topics.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*

Granting Agency: *Department of Energy*
Status/Award Number: *Pending*
Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
Committed Effort: None

Jefferson Laboratory and Penn State Berks:

Alexei Prokudin

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Lawrence Berkeley National Laboratory:

Feng Yuan

- Principal Investigator: *Volker Koch*
  Source of Support: *DOE Office of Science*
  B& R # KB030102
  DOE Program Manager: *George Fai*
  Nuclear Physics Program
  Title: *Nuclear Physics Theory* Total Expected Funding for project in FY 2016: $1,620,000
  Description: Core Nuclear Theory Grant at LBNL
  Period Covered: 10/1/15 9/30/16
  Committed Effort: 12 months
  Potential Overlap: None

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Los Alamos National Laboratory:

Christopher Lee

- Title: *"Los Alamos Nuclear Theory"*
  Principal Investigator: *J. Carlson*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, DE-AC52-06NA25396*
  Total Award Amount: $1,250,000/yr (Oct 2014 – Sep 2015)
  Committed Effort: *6 months* Description: LANL core nuclear theory grant, includes research in QCD and hadronic physics and fundamental symmetries in nuclear physics.
  Potential Overlap: This grant will fund research by C. Lee that is orthogonal to the current proposal.

- Title: *"Illuminating the Origin of the Nucleon Spin"*
  Principal Investigator: *I. Vitev*

Granting Agency: *LANL internal LDRD*
Status/Award Number: *Current, 20130019DR*
Total Award Amount: $1,600,000/yr (Oct 2013–Sep 2016)
Committed Effort: *3 months* Description: Development of experiment E1039 at Fermilab on polarized Drell-Yan and theoretical support.
Potential Overlap: the LDRD DR will perform some preliminary explorations of TMD definitions and computations, especially in SCET, that can lead into further more advanced development and phenomenological application under the current proposal. The LDRD will fund the staff PIs (Lee and Vitev) on the current proposal (until 2016), which would instead fund a postdoc at LANL to devote part of his time to the TMD Collaboration.

- Title: *"Quantum Kinetics of Neutrinos in the Early Universe and Supernovae"*
  Principal Investigator: *V. Cirigliano*
  Granting Agency: *LANL internal LDRD*
  Status/Award Number: *Current, 20140252ER*
  Total Award Amount: $350,000/yr (Oct 2013–Sep 2016)
  Committed Effort: *3 months* Description: Nonequilibrium field theory applied to solving for neutrino flavor densities in the early universe and inside supernovae.
  Potential Overlap: the research herein is orthogonal to the current proposal.

- Title: *Early Career: Precision Probes of the Strong Interaction*
  Principal Investigator: *C. Lee*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $500,000/yr (August 2015 – July 2020)
  Committed Effort: *6–9 months*
  Description: Early Career grant, application submitted and under consideration. Will replace Lee support from LANL Nuclear Theory core grant if awarded.
  Potential Overlap: If awarded, this proposal would support the time of the PI Lee to research some of the topics in the current proposal, such as definitions and evolution of TMDPDFs in SCET. The current proposal, if funded, would not support the PI's time but instead support a postdoc at LANL in FY2019–20 to work on the proposed research, who would not be funded by Lee's EC, which would instead fund a postdoc to work on topics orthogonal to the current proposal.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

- Title: *"Topical Collaboration on Effective Field Theory for Precision Jet and Heavy Flavor Physics"*
  Principal Investigator: *S. Fleming*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $300,000/yr (October 2015 – September 2020)
  Committed Effort: None
  Description: NT Topical Collaboration Proposal
  Potential Overlap: None

Ivan Vitev

- Title: *Early Career: Jet Probes as a New State of Matter*
  Principal Investigator: *I. Vitev*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, 2012LANL7033*
  Total Award Amount: $500,000/yr (June 2012 – May 2017)
  Committed Effort: *6 months*
  Description: Early Career grant.
  Potential Overlap: the research herein is orthogonal to the current proposal.

- Title: *"Los Alamos Nuclear Theory"*
  Principal Investigator: *J. Carlson*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, DE-AC52-06NA25396*
  Total Award Amount: $1,250,000/yr (Oct 2014 – Sep 2015)
  Committed Effort: *1 month, 0.1 FTE*
  Description: LANL core nuclear theory grant, includes research in QCD and hadronic physics.
  Potential Overlap: This grant will fund research by I. Vitev that is orthogonal to the current proposal.

- Title: *"Illuminating the Origin of the Nucleon Spin"*
  Principal Investigator: *A. Klein and I. Vitev*
  Granting Agency: *LANL internal LDRD*
  Status/Award Number: *Current, 20130019DR*
  Total Award Amount: $1,600,000/yr (Oct 2013–Sep 2016)
  Committed Effort: *5 months, 0.4 FTE*
  Description: Development of experiment E1039 at Fermilab on polarized Drell-Yan and theoretical support.
  Potential Overlap: the LDRD DR will perform some preliminary explorations of TMD definitions and computations, especially in SCET, that can lead into further more advanced development and phenomenological application under the current proposal. The LDRD will fund the staff PIs (Lee and Vitev) on the current proposal (until 2016), which would instead fund a postdoc at LANL in FY2019–20 to devote part of his time to the TMD Collaboration.

- Title: *"Topical Collaboration on Quantitative Jet and Electromagnetic Tomography (JET)"*
  Principal Investigator: *X.-N. Wang*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, 2010LANLE8RM*
  Total Award Amount: $477,000/yr (July 2010 – July 2015)
  Committed Effort: *0 month, 0 FTE*
  Description: Ending Topical Collaboration.
  Potential Overlap: This is orthogonal to the current proposal and does not fund research at LANL.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

- Title: *"Topical Collaboration on Effective Field Theory for Precision Jet and Heavy Flavor Physics"*
  Principal Investigator: *S. Fleming*
  Granting Agency: *Department of Energy*

Status/Award Number: *Pending*
Total Award Amount: $300,000/yr (October 2015 – September 2020)
Committed Effort: None
Description: NT Topical Collaboration Proposal
Potential Overlap: None

MIT:

William Detmold

- Title: *"From Quarks to the Cosmos"*
  Principal Investigator: *W. Detmold*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, DE-SC0010495*
  Total Award Amount: $750,000 (July 2013 – July 2018)
  Committed Effort: *2 months*
  Description: Lattice QCD studies of multi-nucleon systems.
  Potential Overlap: the research herein is orthogonal to the current proposal.

- Title: *"Load balancing, fault tolerance and workflow optimization in lattice QCD for nuclear physics"*
  Principal Investigator: *W. Detmold*
  Granting Agency: *National Science Foundation*
  Status/Award Number: *Pending*
  Total Award Amount: $648,000 (July 2015 – July 2018)
  Committed Effort: *0.5 months*
  Description: Lattice QCD software development.
  Potential Overlap: the research herein is orthogonal to the current proposal.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

John Negele

- Title: *"Theoretical Nuclear Physics"*
  Principal Investigator: *Richard Milner*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, DE-SC0011090*
  Total Award Amount: $3,304,000 (January 1, 2014 – October 31, 2016)
  Committed Effort: *0 months* summer salary for John Negele
  Description: Core nuclear theory grant at MIT
  Potential Overlap: none

- Title: *"Load balancing, fault tolerance and workflow optimization in lattice QCD for nuclear physics"*
  Principal Investigator: *W. Detmold*
  Granting Agency: *National Science Foundation*
  Status/Award Number: *Pending*
  Total Award Amount: $648,000 (July 2015 – July 2018)
  Committed Effort: *0.5 months* Description: Lattice QCD software development.
  Potential Overlap: the research herein is orthogonal to the current proposal.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Iain Stewart

- Title: *"Theoretical Nuclear Physics"*
  Principal Investigator: *Richard Milner*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, DE-SC0011090*
  Total Award Amount: $3,304,000 (January 1, 2014 – October 31, 2016)
  Committed Effort: *2 months* summer salary for Iain Stewart Description: Core nuclear theory grant at MIT
  Potential Overlap: none

- Title: *"Effective Field Theory: New Windows into the Strong Interaction and Beyond"*
  Principal Investigator: *Iain Stewart*
  Granting Agency: *Simons Foundation*
  Status/Award Number: *Current*, 327942
  Total Award Amount: $100,000/year (August 2014 – July 2019)
  Committed Effort: *0.3 months* of summer salary for Iain Stewart Potential Overlap: none

- Title: *"Topical Collaboration on Effective Field Theory for Precision Jet and Heavy Flavor"*
  Principal Investigator: *Sean Fleming*
  Granting Agency: *DOE, Office of Science, Nuclear Physics Program*
  Status/Award Number: *Pending*
  Total Award Amount: $300,000/year (October 2015 – September 2020)
  Committed Effort: This proposal, if awarded, would support a PhD student for three years and half of a postdoc for one year at MIT.
  Potential Overlap: none

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

New Mexico State University:

Matthias Burkardt

- Title: "Quark-gluon structure of hadrons in QCD"
  Principal Investigator: Matthias Burkardt
  Granting Agency: Department of Energy
  Status/Award Number: Current, DE-FG02-96ER40965
  Total Award Amount: $480,000 (April 2014 – March 2017)
  Committed Effort: 2 months summer salary Potential Overlap: none

- Title: *"Topical Collaboration on Effective Field Theory for Precision Jet and Heavy Flavor Physics"*

Principal Investigator: *S. Fleming*
Granting Agency: *Department of Energy*
Status/Award Number: *Pending*
Total Award Amount: $300,000/yr (Oct 2015 – Sep 2020)
Committed Effort: *0 month, 0 FTE*
Description: NT Topical Collaboration proposal.
Potential Overlap: none.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Michael Engelhardt

- Title: "Quark-gluon structure of hadrons in QCD"
  Principal Investigator: Matthias Burkardt
  Granting Agency: Department of Energy
  Status/Award Number: Current, DE-FG02-96ER40965
  Total Award Amount: $480,000 (April 2014 – March 2017)
  Committed Effort: 2 months summer salary Potential Overlap: none
- Title: *"Topical Collaboration on Effective Field Theory for Precision Jet and Heavy Flavor Physics"*
  Principal Investigator: *S. Fleming*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $300,000/yr (Oct 2015 – Sep 2020)
  Committed Effort: *0 month, 0 FTE*
  Description: NT Topical Collaboration proposal.
  Potential Overlap: none.
- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Penn State University at Berks:

Leonard Gamberg

- Title: *Transverse Spin and Momentum Structure of Hadrons in QCD*
  Principal Investigator: *Leonard Gamberg*
  Granting Agency: *Department of Energy*
  Status/Award Number: Current / Grant DE-FG02-07ER41460
  Nuclear Physics Program
  Total Award Amount: $ 120,000
  Period Covered: November 15, 2012 - November 14, 2015
  Committed Effort: 2 months of summer salary
  Potential Overlap: only partial overlap with the current proposal

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

Temple University:

Andreas Metz

- Title: *"Hard Scattering Processes in QCD"*
  Principal Investigator: *A. Metz*
  Granting Agency: *National Science Foundation*
  Status/Award Number: *Current, PHY-1205942*
  Total Award Amount: $240,000 (June 2012 – May 2015)
  Committed Effort: *2 months*
  Description: (1) Spin asymmetries in hadronic collisions, (2) hadron tomography
  Potential Overlap: only partial overlap with the current proposal

- Title: *"Hard Scattering Processes in QCD"*
  Principal Investigator: *A. Metz*
  Granting Agency: *National Science Foundation*
  Status/Award Number: *Pending*
  Total Award Amount: $437,289 (June 2015 – May 2018)
  Committed Effort: *2 months*
  Description: (1) Spin-asymmetries in hadronic collisions, (2) Wigner functions
  Potential Overlap: only partial overlap with the current proposal

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

University of Arizona:

Sean P. Fleming

- Title: *"Effective theories of the stong interaction"*
  Principal Investigator: *S. Fleming*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, DE-FG02-04ER41338*
  Total Award Amount: $570,000 (Aug 2014 – July 2017)
  Committed Effort: *2 months* Description: Systematically applying EFTs to: (1) hadronic distribution functions; (2) the nuclear many-body problem; (3) fundamental symmetries in low-energy nuclear physics.
  Potential Overlap: some of the research proposed herein is a first step in understanding aspects of TMD functions which would naturally lead into the research in the current proposal.

- Title: *"Topical Collaboration on Effective Field Theory for Precision Jet and Heavy Flavor Physics"*
  Principal Investigator: *S. Fleming*

Granting Agency: *Department of Energy*
Status/Award Number: *Pending*
Total Award Amount: $1,500,000 (Oct 2016 – Sept 2020)
Committed Effort: This proposal, if awarded, would support just over half a postdoctoral associate in 2016-2019, and half a graduate student in 2017-2020.
Description: The goal of this proposal is to significantly improve the treatment of the physics of hard collisions with jets and heavy quark hadrons in the presence of the medium induced by heavy ion collisions using EFT techniques.
Potential Overlap: none.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

University of Kentucky:

K.F. Liu

- Title: *"Lattice Calculation of Nucleon Structure"*
  Principal Investigator: *K.F. Liu*
  Co-PI: *T. Draper* Granting Agency: *Department of Energy*
  Status/Award Number: *Current, DE-SC0013065*
  Total Award Amount: $440,000 (Feb. 2015 – Jan. 2017)
  Committed Effort: *1.5 months* Description: Lattice QCD calculation of quark and glue structure of the nucleon
  Potential Overlap: the proposed project of parton distribution function is related but not included in this grant.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*
  Principal Investigator: *J. Qiu*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Pending*
  Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
  Committed Effort: None

University of Virginia:

Simonetta Liuti

- Title: *"Studies of Quantum Chromodynamics at the Intersection between the perturbative"*
  Principal Investigator: *Simonetta Liuti*
  Granting Agency: *Department of Energy*
  Status/Award Number: *Current, DE-FG02-01ER41200*
  Total Award Amount: $180,000 (May 2013 – April 2016)
  Committed Effort: *2 months*
  Description: QCD phenomenology studies of parton distributions and generalized parton distributions in nucleons and nuclei.
  Potential Overlap: the research herein is orthogonal to the current proposal.

- Title: *"Topical Collaboration on Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD"*

Principal Investigator: *J. Qiu*
Granting Agency: *Department of Energy*
Status/Award Number: *Pending*
Total Award Amount: $2,500,000 (Jan 2016 – Dec 2020)
Committed Effort: None

Appendix 3: Bibliography and References

[1] D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang, *et al.*, "Gluons and the quark sea at high energies: Distributions, polarization, tomography", `arXiv:1108.1713`.

[2] A. Accardi, J. Albacete, M. Anselmino, N. Armesto, E. Aschenauer, *et al.*, "Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all", `arXiv:1212.1701`.

[3] S. Catani, D. de Florian, and M. Grazzini, "Universality of nonleading logarithmic contributions in transverse momentum distributions", *Nucl.Phys.* **B596** (2001) 299–312, `arXiv:hep-ph/0008184`.

[4] J. C. Collins, D. E. Soper, and G. Sterman, "Transverse Momentum Distribution in Drell-Yan Pair and W and Z Boson Production", *Nucl. Phys.* **B250** (1985) 199.

[5] J. C. Collins and D. E. Soper, "Back-To-Back Jets in QCD", *Nucl.Phys.* **B193** (1981) 381.

[6] X.-d. Ji, J.-p. Ma, and F. Yuan, "QCD factorization for semi-inclusive deep-inelastic scattering at low transverse momentum", *Phys.Rev.* **D71** (2005) 034005, `arXiv:hep-ph/0404183`.

[7] J. Collins, "Foundations of perturbative QCD", 2011, *Foundations of Perturbative QCD*, Cambridge, UK: Univ.Pr.

[8] M. G. Echevarria, A. Idilbi, and I. Scimemi, "Factorization Theorem For Drell-Yan At Low q_T And Transverse Momentum Distributions On-The-Light-Cone", *JHEP* **1207** (2012) 002, `arXiv:1111.4996`.

[9] M. G. Echevarra, A. Idilbi, and I. Scimemi, "Soft and Collinear Factorization and Transverse Momentum Dependent Parton Distribution Functions", *Phys.Lett.* **B726** (2013) 795–801, `arXiv:1211.1947`.

[10] J.-Y. Chiu, A. Jain, D. Neill, and I. Z. Rothstein, "A Formalism for the Systematic Treatment of Rapidity Logarithms in Quantum Field Theory", *JHEP* **1205** (2012) 084, `arXiv:1202.0814`.

[11] J. C. Collins, D. E. Soper, and G. F. Sterman, "Factorization of Hard Processes in QCD", *Adv.Ser.Direct.High Energy Phys.* **5** (1988) 1–91, `arXiv:hep-ph/0409313`.

[12] C. W. Bauer, S. Fleming, and M. E. Luke, "Summing Sudakov logarithms in $B \to X_s\gamma$ in effective field theory", *Phys.Rev.* **D63** (2000) 014006, `arXiv:hep-ph/0005275`.

[13] C. W. Bauer, S. Fleming, D. Pirjol, and I. W. Stewart, "An Effective field theory for collinear and soft gluons: Heavy to light decays", *Phys.Rev.* **D63** (2001) 114020, `arXiv:hep-ph/0011336`.

[14] C. W. Bauer and I. W. Stewart, "Invariant operators in collinear effective theory", *Phys.Lett.* **B516** (2001) 134–142, `arXiv:hep-ph/0107001`.

[15] C. W. Bauer, D. Pirjol, and I. W. Stewart, "Soft collinear factorization in effective field theory", *Phys.Rev.* **D65** (2002) 054022, `arXiv:hep-ph/0109045`.

[16] S. Aybat and T. C. Rogers, "TMD Parton Distribution and Fragmentation Functions with QCD Evolution", *Phys.Rev.* **D83** (2011) 114042, `arXiv:1101.5057`.

[17] S. M. Aybat, J. C. Collins, J.-W. Qiu, and T. C. Rogers, "The QCD Evolution of the Sivers Function", *Phys.Rev.* **D85** (2012) 034043, `arXiv:1110.6428`.

[18] S. M. Aybat, A. Prokudin, and T. C. Rogers, “Calculation of TMD Evolution for Transverse Single Spin Asymmetry Measurements”, *Phys.Rev.Lett.* **108** (2012) 242003, arXiv:1112.4423.

[19] C. Aidala, B. Field, L. Gamberg, and T. Rogers, “Limits on TMD Evolution From Semi-Inclusive Deep Inelastic Scattering at Moderate Q”, *Phys.Rev.* **D89** (2014) 094002, arXiv:1401.2654.

[20] M. G. Echevarria, A. Idilbi, A. Schfer, and I. Scimemi, “Model-Independent Evolution of Transverse Momentum Dependent Distribution Functions (TMDs) at NNLL”, *Eur.Phys.J.* **C73** (2013), no. 12, 2636, arXiv:1208.1281.

[21] M. G. Echevarria, A. Idilbi, and I. Scimemi, “Unified treatment of the QCD evolution of all (un-)polarized transverse momentum dependent functions: Collins function as a study case”, *Phys.Rev.* **D90** (2014), no. 1, 014003, arXiv:1402.0869.

[22] U. D’Alesio, M. G. Echevarria, S. Melis, and I. Scimemi, “Non-perturbative QCD effects in q_T spectra of Drell-Yan and Z-boson production”, *JHEP* **1411** (2014) 098, arXiv:1407.3311.

[23] J. C. Collins and T. C. Rogers, “Equality of Two Definitions for Transverse Momentum Dependent Parton Distribution Functions”, *Phys.Rev.* **D87** (2013), no. 3, 034018, arXiv:1210.2100.

[24] P. Mulders and J. Rodrigues, “Transverse momentum dependence in gluon distribution and fragmentation functions”, *Phys.Rev.* **D63** (2001) 094021, arXiv:hep-ph/0009343.

[25] S. Meissner, A. Metz, and K. Goeke, “Relations between generalized and transverse momentum dependent parton distributions”, *Phys.Rev.* **D76** (2007) 034002, arXiv:hep-ph/0703176.

[26] T. C. Rogers and P. J. Mulders, “No Generalized TMD-Factorization in Hadro-Production of High Transverse Momentum Hadrons”, *Phys.Rev.* **D81** (2010) 094006, arXiv:1001.2977.

[27] J. Collins and T. Rogers, “The Gluon Distribution Function and Factorization in Feynman Gauge”, *Phys.Rev.* **D78** (2008) 054012, arXiv:0805.1752.

[28] T. C. Rogers, “Extra spin asymmetries from the breakdown of transverse-momentum-dependent factorization in hadron-hadron collisions”, *Phys.Rev.* **D88** (2013), no. 1, 014002, arXiv:1304.4251.

[29] J. C. Collins and A. Metz, “Universality of soft and collinear factors in hard-scattering factorization”, *Phys.Rev.Lett.* **93** (2004) 252001, arXiv:hep-ph/0408249.

[30] S. Mantry and F. Petriello, “Factorization and Resummation of Higgs Boson Differential Distributions in Soft-Collinear Effective Theory”, *Phys.Rev.* **D81** (2010) 093007, arXiv:0911.4135.

[31] T. Becher and M. Neubert, “Drell-Yan Production at Small q_T, Transverse Parton Distributions and the Collinear Anomaly”, *Eur.Phys.J.* **C71** (2011) 1665, arXiv:1007.4005.

[32] X. Ji, P. Sun, X. Xiong, and F. Yuan, “Soft factor subtraction and transverse momentum dependent parton distributions on the lattice”, *Phys.Rev.* **D91** (2015), no. 7, 074009, arXiv:1405.7640.

[33] F. Landry, R. Brock, P. M. Nadolsky, and C. Yuan, “Tevatron Run-1 Z boson data and Collins-Soper-Sterman resummation formalism”, *Phys.Rev.* **D67** (2003) 073016, arXiv:hep-ph/0212159.

[34] J.-W. Qiu and X.-f. Zhang, "QCD prediction for heavy boson transverse momentum distributions", *Phys.Rev.Lett.* **86** (2001) 2724–2727, arXiv:hep-ph/0012058.

[35] Z.-B. Kang, B.-W. Xiao, and F. Yuan, "QCD Resummation for Single Spin Asymmetries", *Phys.Rev.Lett.* **107** (2011) 152002, arXiv:1106.0266.

[36] P. Sun and F. Yuan, "Transverse momentum dependent evolution: Matching semi-inclusive deep inelastic scattering processes to Drell-Yan and W/Z boson production", *Phys.Rev.* **D88** (2013), no. 11, 114012, arXiv:1308.5003.

[37] M. G. Echevarria, A. Idilbi, Z.-B. Kang, and I. Vitev, "QCD Evolution of the Sivers Asymmetry", *Phys.Rev.* **D89** (2014), no. 7, 074013, arXiv:1401.5078.

[38] P. Sun, J. Isaacson, C. P. Yuan, and F. Yuan, "Universal Non-perturbative Functions for SIDIS and Drell-Yan Processes", arXiv:1406.3073.

[39] J. C. Collins and D. E. Soper, "Parton Distribution and Decay Functions", *Nucl.Phys.* **B194** (1982) 445.

[40] J. Collins and T. Rogers, "Understanding the large-distance behavior of TMD parton densities and the Collins-Soper evolution kernel", arXiv:1412.3820.

[41] P. Schweitzer, M. Strikman, and C. Weiss, "Intrinsic transverse momentum and parton correlations from dynamical chiral symmetry breaking", *JHEP* **1301** (2013) 163, arXiv:1210.1267.

[42] B. Musch, P. Hagler, M. Engelhardt, J. Negele, and A. Schafer, "Sivers and Boer-Mulders observables from lattice QCD", *Phys.Rev.* **D85** (2012) 094510, arXiv:1111.4249.

[43] M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, *et al.*, "Sivers Distribution Functions and the Latest SIDIS Data", arXiv:1107.4446.

[44] M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, *et al.*, "Transversity and Collins functions from SIDIS and e+ e- data", *Phys.Rev.* **D75** (2007) 054032, arXiv:hep-ph/0701006.

[45] M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, *et al.*, "Simultaneous extraction of transversity and Collins functions from new SIDIS and e+e- data", *Phys.Rev.* **D87** (2013) 094019, arXiv:1303.3822.

[46] M. Anselmino, M. Boglione, and S. Melis, "A Strategy towards the extraction of the Sivers function with TMD evolution", *Phys.Rev.* **D86** (2012) 014028, arXiv:1204.1239.

[47] D. Boer, "TMD evolution of the Sivers asymmetry", *Nucl.Phys.* **B874** (2013) 217–229, arXiv:1304.5387.

[48] Z.-B. Kang, A. Prokudin, P. Sun, and F. Yuan, "Nucleon tensor charge from Collins azimuthal asymmetry measurements", *Phys.Rev.* **D91** (2015), no. 7, 071501, arXiv:1410.4877.

[49] J. Gao, M. Guzzi, J. Huston, H.-L. Lai, Z. Li, *et al.*, "CT10 next-to-next-to-leading order global analysis of QCD", *Phys.Rev.* **D89** (2014), no. 3, 033009, arXiv:1302.6246.

[50] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, "Extraction of Spin-Dependent Parton Densities and Their Uncertainties", *Phys.Rev.* **D80** (2009) 034030, arXiv:0904.3821.

[51] M. Boglione, J. O. G. Hernandez, S. Melis, and A. Prokudin, "A study on the interplay between perturbative QCD and CSS/TMD formalism in SIDIS processes", *JHEP* **1502** (2015) 095, arXiv:1412.1383.

[52] C. Balazs and C. Yuan, "Soft gluon effects on lepton pairs at hadron colliders", *Phys.Rev.* **D56** (1997) 5558–5583, arXiv:hep-ph/9704258.

[53] A. V. Konychev and P. M. Nadolsky, "Universality of the Collins-Soper-Sterman nonperturbative function in gauge boson production", *Phys.Lett.* **B633** (2006) 710–714, arXiv:hep-ph/0506225.

[54] D. W. Sivers, "Single spin production asymmetries from the hard scattering of point - like constituents", *Phys. Rev.* **D41** (1990) 83.

[55] D. W. Sivers, "Hard scattering scaling laws for single spin production asymmetries", *Phys. Rev.* **D43** (1991) 261–263.

[56] X. Ji, J.-W. Qiu, W. Vogelsang, and F. Yuan, "A Unified picture for single transverse-spin asymmetries in hard processes", *Phys.Rev.Lett.* **97** (2006) 082002, arXiv:hep-ph/0602239.

[57] **BRAHMS** Collaboration, I. Arsene *et al.*, "Single Transverse Spin Asymmetries of Identified Charged Hadrons in Polarized p+p Collisions at s**(1/2) = 62.4-GeV", *Phys.Rev.Lett.* **101** (2008) 042001, arXiv:0801.1078.

[58] **STAR** Collaboration, B. Abelev *et al.*, "Forward Neutral Pion Transverse Single Spin Asymmetries in p+p Collisions at s**(1/2) = 200-GeV", *Phys.Rev.Lett.* **101** (2008) 222001, arXiv:0801.2990.

[59] **STAR** Collaboration, L. Adamczyk *et al.*, "Transverse Single-Spin Asymmetry and Cross-Section for π^0 and η Mesons at Large Feynman-x in Polarized $p + p$ Collisions at $\sqrt{s} = 200$ GeV", *Phys.Rev.* **D86** (2012) 051101, arXiv:1205.6826.

[60] **PHENIX** Collaboration, A. Adare *et al.*, "Measurement of transverse-single-spin asymmetries for midrapidity and forward-rapidity production of hadrons in polarized p+p collisions at $\sqrt{s}$ =200 and 62.4 GeV", *Phys.Rev.* **D90** (2014), no. 1, 012006, arXiv:1312.1995.

[61] J. C. Collins, "Fragmentation of transversely polarized quarks probed in transverse momentum distributions", *Nucl.Phys.* **B396** (1993) 161–182, arXiv:hep-ph/9208213.

[62] G. Bunce, R. Handler, R. March, P. Martin, L. Pondrom, *et al.*, "Lambda0 Hyperon Polarization in Inclusive Production by 300-GeV Protons on Beryllium.", *Phys.Rev.Lett.* **36** (1976) 1113–1116.

[63] G. L. Kane, J. Pumplin, and W. Repko, "Transverse Quark Polarization in Large p(T) Reactions, e+ e- Jets, and Leptoproduction: A Test of QCD", *Phys.Rev.Lett.* **41** (1978) 1689.

[64] A. Efremov and O. Teryaev, "On Spin Effects in Quantum Chromodynamics", *Sov.J.Nucl.Phys.* **36** (1982) 140.

[65] A. Efremov and O. Teryaev, "QCD Asymmetry and Polarized Hadron Structure Functions", *Phys.Lett.* **B150** (1985) 383.

[66] J.-W. Qiu and G. Sterman, "Single transverse spin asymmetries", *Phys. Rev. Lett.* **67** (1991) 2264–2267.

[67] J.-W. Qiu and G. Sterman, "Single transverse spin asymmetries in direct photon production", *Nucl. Phys.* **B378** (1992) 52–78.

[68] H. Eguchi, Y. Koike, and K. Tanaka, “Single Transverse Spin Asymmetry for Large-p(T) Pion Production in Semi-Inclusive Deep Inelastic Scattering”, *Nucl.Phys.* **B752** (2006) 1–17, `arXiv:hep-ph/0604003`.

[69] H. Eguchi, Y. Koike, and K. Tanaka, “Twist-3 Formalism for Single Transverse Spin Asymmetry Reexamined: Semi-Inclusive Deep Inelastic Scattering”, *Nucl.Phys.* **B763** (2007) 198–227, `arXiv:hep-ph/0610314`.

[70] C. Kouvaris, J.-W. Qiu, W. Vogelsang, and F. Yuan, “Single transverse-spin asymmetry in high transverse momentum pion production in p p collisions”, *Phys. Rev.* **D74** (2006) 114013, `hep-ph/0609238`.

[71] Y. Koike and K. Tanaka, “Universal structure of twist-3 soft-gluon-pole cross-sections for single transverse-spin asymmetry”, *Phys.Rev.* **D76** (2007) 011502, `arXiv:hep-ph/0703169`.

[72] Y. Koike and T. Tomita, “Soft-fermion-pole contribution to single-spin asymmetry for pion production in pp collisions”, *Phys.Lett.* **B675** (2009) 181–189, `arXiv:0903.1923`.

[73] K. Kanazawa and Y. Koike, “New Analysis of the Single Transverse-Spin Asymmetry for Hadron Production at RHIC”, *Phys.Rev.* **D82** (2010) 034009, `arXiv:1005.1468`.

[74] K. Kanazawa and Y. Koike, “A phenomenological study on single transverse-spin asymmetry for inclusive light-hadron productions at RHIC”, *Phys.Rev.* **D83** (2011) 114024, `arXiv:1104.0117`.

[75] Y. Kanazawa and Y. Koike, “Chiral odd contribution to single transverse spin asymmetry in hadronic pion production”, *Phys.Lett.* **B478** (2000) 121–126, `arXiv:hep-ph/0001021`.

[76] A. Metz and D. Pitonyak, “Fragmentation contribution to the transverse single-spin asymmetry in proton-proton collisions”, *Phys.Lett.* **B723** (2013) 365–370, `arXiv:1212.5037`.

[77] Z.-B. Kang, F. Yuan, and J. Zhou, “Twist-three fragmentation function contribution to the single spin asymmetry in p p collisions”, *Phys.Lett.* **B691** (2010) 243–248, `arXiv:1002.0399`.

[78] D. Boer, P. J. Mulders, and F. Pijlman, “Universality of t-odd effects in single spin and azimuthal asymmetries”, *Nucl. Phys.* **B667** (2003) 201–241, `hep-ph/0303034`.

[79] Z.-B. Kang, J.-W. Qiu, W. Vogelsang, and F. Yuan, “An Observation Concerning the Process Dependence of the Sivers Functions”, *Phys.Rev.* **D83** (2011) 094001, `arXiv:1103.1591`.

[80] A. Metz, D. Pitonyak, A. Schafer, M. Schlegel, W. Vogelsang, *et al.*, “Single-spin asymmetries in inclusive deep inelastic scattering and multiparton correlations in the nucleon”, *Phys.Rev.* **D86** (2012) 094039, `arXiv:1209.3138`.

[81] K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak, “Towards an explanation of transverse single-spin asymmetries in proton-proton collisions: the role of fragmentation in collinear factorization”, *Phys.Rev.* **D89** (2014), no. 11, 111501, `arXiv:1404.1033`.

[82] E.-C. Aschenauer, A. Bazilevsky, M. Diehl, J. Drachenberg, K. O. Eyser, *et al.*, “The RHIC SPIN Program: Achievements and Future Opportunities”, `arXiv:1501.01220`.

[83] J.-W. Qiu, M. Schlegel, and W. Vogelsang, “Probing Gluonic Spin-Orbit Correlations in Photon Pair Production”, *Phys.Rev.Lett.* **107** (2011) 062001, `arXiv:1103.3861`.

[84] E.-C. Aschenauer, I. Balitsky, L. Bland, S. J. Brodsky, M. Burkardt, *et al.*, “Pre-Town Meeting on Spin Physics at an Electron-Ion Collider”, `arXiv:1410.8831`.

[85] M. G. Echevarria, T. Kasemets, P. J. Mulders, and C. Pisano, "QCD evolution of (un)polarized gluon TMDPDFs and the Higgs q_T-distribution", arXiv:1502.05354.

[86] C. Pisano, D. Boer, S. J. Brodsky, M. G. Buffing, and P. J. Mulders, "Linear polarization of gluons and photons in unpolarized collider experiments", *JHEP* **1310** (2013) 024, 1307.3417.

[87] W. J. den Dunnen, J.-P. Lansberg, C. Pisano, and M. Schlegel, "Accessing the Transverse Dynamics and Polarization of Gluons inside the Proton at the LHC", *Phys.Rev.Lett.* **112** (2014) 212001, arXiv:1401.7611.

[88] D. Boer, W. J. den Dunnen, C. Pisano, M. Schlegel, and W. Vogelsang, "Linearly Polarized Gluons and the Higgs Transverse Momentum Distribution", *Phys.Rev.Lett.* **108** (2012) 032002, arXiv:1109.1444.

[89] **CDF** Collaboration, D. Acosta *et al.*, "Υ production and polarization in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$-TeV", *Phys. Rev. Lett.* **88** (2002) 161802.

[90] **ATLAS** Collaboration, G. Aad *et al.*, "Measurement of Upsilon production in 7 TeV pp collisions at ATLAS", *Phys. Rev.* **D87** (2013), no. 5, 052004, arXiv:1211.7255.

[91] **CMS** Collaboration, V. Khachatryan *et al.*, "Upsilon Production Cross-Section in pp Collisions at $sqrts = 7$ TeV", *Phys. Rev.* **D83** (2011) 112004, arXiv:1012.5545.

[92] **LHCb** Collaboration, R. Aaij *et al.*, "Production of J/ψ and Υ mesons in pp collisions at $\sqrt{s} = 8$ TeV", *JHEP* **1306** (2013) 064, arXiv:1304.6977.

[93] E. L. Berger, J.-W. Qiu, and Y.-l. Wang, "Transverse momentum distribution of υ production in hadronic collisions", *Phys.Rev.* **D71** (2005) 034007, arXiv:hep-ph/0404158.

[94] P. Sun, C.-P. Yuan, and F. Yuan, "Heavy Quarkonium Production at Low Pt in NRQCD with Soft Gluon Resummation", *Phys.Rev.* **D88** (2013) 054008, arXiv:1210.3432.

[95] P. L. Cho and A. K. Leibovich, "Color octet quarkonia production", *Phys. Rev.* **D53** (1996) 150–162, arXiv:hep-ph/9505329.

[96] P. L. Cho and A. K. Leibovich, "Color octet quarkonia production. 2.", *Phys. Rev.* **D53** (1996) 6203–6217, arXiv:hep-ph/9511315.

[97] N. Brambilla, S. Eidelman, B. Heltsley, R. Vogt, G. Bodwin, *et al.*, "Heavy quarkonium: progress, puzzles, and opportunities", *Eur. Phys. J.* **C71** (2011) 1534, arXiv:1010.5827.

[98] J. Collins and J.-W. Qiu, "k_T factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions", *Phys. Rev.* **D75** (2007) 114014, arXiv:0705.2141.

[99] A. V. Belitsky, X. Ji, and F. Yuan, "Final state interactions and gauge invariant parton distributions", *Nucl. Phys.* **B656** (2003) 165–198, hep-ph/0208038.

[100] S. J. Brodsky, D. S. Hwang, and I. Schmidt, "Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering", *Phys. Lett.* **B530** (2002) 99–107, hep-ph/0201296.

[101] X.-d. Ji and F. Yuan, "Parton distributions in light-cone gauge: Where are the final-state interactions?", *Phys. Lett.* **B543** (2002) 66–72, hep-ph/0206057.

[102] D. Boer and W. Vogelsang, "Asymmetric jet correlations in p p uparrow scattering", *Phys.Rev.* **D69** (2004) 094025, arXiv:hep-ph/0312320.

[103] C. Bomhof, P. Mulders, and F. Pijlman, "Gauge link structure in quark-quark correlators in hard processes", *Phys.Lett.* **B596** (2004) 277–286, arXiv:hep-ph/0406099.

[104] W. Vogelsang and F. Yuan, "Hadronic Dijet Imbalance and Transverse-Momentum Dependent Parton Distributions", *Phys.Rev.* **D76** (2007) 094013, arXiv:0708.4398.

[105] J.-W. Qiu, W. Vogelsang, and F. Yuan, "Single Transverse-Spin Asymmetry in Hadronic Dijet Production", *Phys.Rev.* **D76** (2007) 074029, arXiv:0706.1196.

[106] L. Gamberg and Z.-B. Kang, "Process dependent Sivers function and implications for single spin asymmetry in inclusive hadron production", *Phys. Lett.* **B696** (2011) 109–118, arXiv:1009.1936.

[107] F. Yuan, "Azimuthal asymmetric distribution of hadrons inside a jet at hadron collider", *Phys.Rev.Lett.* **100** (2008) 032003, arXiv:0709.3272.

[108] U. D'Alesio, F. Murgia, and C. Pisano, "Azimuthal asymmetries for hadron distributions inside a jet in hadronic collisions", *Phys.Rev.* **D83** (2011) 034021, arXiv:1011.2692.

[109] U. D'Alesio, L. Gamberg, Z.-B. Kang, F. Murgia, and C. Pisano, "Testing the process dependence of the Sivers function via hadron distributions inside a jet", *Phys.Lett.* **B704** (2011) 637–640, arXiv:1108.0827.

[110] W. Vogelsang and F. Yuan, "Single-transverse spin asymmetries: From DIS to hadronic collisions", *Phys.Rev.* **D72** (2005) 054028, arXiv:hep-ph/0507266.

[111] C. Bomhof, P. Mulders, W. Vogelsang, and F. Yuan, "Single-Transverse Spin Asymmetry in Dijet Correlations at Hadron Colliders", *Phys.Rev.* **D75** (2007) 074019, arXiv:hep-ph/0701277.

[112] A. Bacchetta, C. Bomhof, U. D'Alesio, P. J. Mulders, and F. Murgia, "Sivers single-spin asymmetry in photon-jet production", *Phys. Rev. Lett.* **99** Nov (2007) 212002.

[113] **STAR** Collaboration, B. Abelev *et al.*, "Measurement of transverse single-spin asymmetries for di-jet production in proton-proton collisions at s**(1/2) = 200-GeV", *Phys.Rev.Lett.* **99** (2007) 142003, arXiv:0705.4629.

[114] **STAR** Collaboration, N. Poljak, "STAR results and perspectives on transverse spin asymmetries", *Nuovo Cim.* **C035N2** (2012) 193–198, arXiv:1111.0755.

[115] **STAR** Collaboration, R. Fatemi, "Constraining Quark Transversity through Collins Asymmetry Measurements at STAR", *AIP Conf.Proc.* **1441** (2012) 233–237, arXiv:1206.3861.

[116] D. Boer, L. Gamberg, B. Musch, and A. Prokudin, "Bessel-Weighted Asymmetries in Semi Inclusive Deep Inelastic Scattering", *JHEP* **1110** (2011) 021, arXiv:1107.5294.

[117] J. C. Collins and D. E. Soper, "Back-To-Back Jets: Fourier Transform from B to K-Transverse", *Nucl.Phys.* **B197** (1982) 446.

[118] M. Aghasyan, H. Avakian, E. De Sanctis, L. Gamberg, M. Mirazita, *et al.*, "Studies of Transverse Momentum Dependent Parton Distributions and Bessel Weighting", *JHEP* **1503** (2015) 039, arXiv:1409.0487.

[119] B. U. Musch, P. Hagler, J. W. Negele, and A. Schafer, "Exploring quark transverse momentum distributions with lattice QCD", *Phys.Rev.* **D83** (2011) 094507, arXiv:1011.1213.

[120] X. Ji, "Parton Physics on a Euclidean Lattice", *Phys.Rev.Lett.* **110** (2013) 262002, arXiv:1305.1539.

[121] H.-W. Lin, J.-W. Chen, S. D. Cohen, and X. Ji, "Flavor Structure of the Nucleon Sea from Lattice QCD", *Phys.Rev.* **D91** (2015) 054510, arXiv:1402.1462.

[122] X. Ji, "Parton Physics from Large-Momentum Effective Field Theory", *Sci.China Phys.Mech.Astron.* **57** (2014), no. 7, 1407–1412, arXiv:1404.6680.

[123] L. Gamberg, Z.-B. Kang, I. Vitev, and H. Xing, "Quasi-parton distribution functions: a study in the diquark spectator model", *Phys.Lett.* **B743** (2015) 112–120, arXiv:1412.3401.

[124] Y.-Q. Ma and J.-W. Qiu, "Extracting Parton Distribution Functions from Lattice QCD Calculations", arXiv:1404.6860.

[125] Y.-Q. Ma and J.-W. Qiu, "QCD Factorization and PDFs from Lattice QCD Calculation", *Int.J.Mod.Phys.Conf.Ser.* **37** (2015) 0041, arXiv:1412.2688.

[126] M. Neubert, "Analysis of the photon spectrum in inclusive $B \to X_s\gamma$ decays", *Phys.Rev.* **D49** (1994) 4623–4633, arXiv:hep-ph/9312311.

[127] G. P. Korchemsky and G. Sterman, "Infrared factorization in inclusive b meson decays", *Phys. Lett.* **B340** (1994) 96–108, hep-ph/9407344.

[128] S. W. Bosch, B. O. Lange, M. Neubert, and G. Paz, "Factorization and shape-function effects in inclusive b- meson decays", *Nucl. Phys.* **B699** (2004) 335–386, hep-ph/0402094.

[129] Z. Ligeti, I. W. Stewart, and F. J. Tackmann, "Treating the b quark distribution function with reliable uncertainties", *Phys. Rev. D* **78** (2008) 114014, arXiv:arXiv:0807.1926.

[130] N. Sveshnikov and F. Tkachov, "Jets and quantum field theory", *Phys.Lett.* **B382** (1996) 403–408, arXiv:hep-ph/9512370.

[131] G. P. Korchemsky, G. Oderda, and G. F. Sterman, "Power corrections and nonlocal operators", *AIP Conf.Proc.* **407** (1997) 988, arXiv:hep-ph/9708346.

[132] A. V. Belitsky, G. P. Korchemsky, and G. Sterman, "Energy flow in QCD and event shape functions", *Phys. Lett.* **B515** (2001) 297–307, hep-ph/0106308.

[133] C. W. Bauer, S. P. Fleming, C. Lee, and G. F. Sterman, "Factorization of e+e- Event Shape Distributions with Hadronic Final States in Soft Collinear Effective Theory", *Phys.Rev.* **D78** (2008) 034027, arXiv:0801.4569.

[134] V. Mateu, I. W. Stewart, and J. Thaler, "Power Corrections to Event Shapes with Mass-Dependent Operators", *Phys. Rev.* **D87** (2013) 014025, arXiv:1209.3781.

[135] G. P. Korchemsky and G. Sterman, "Power corrections to event shapes and factorization", *Nucl. Phys.* **B555** (1999) 335–351, hep-ph/9902341.

[136] C. Lee and G. Sterman, "Momentum flow correlations from event shapes: Factorized soft gluons and soft-collinear effective theory", *Phys. Rev.* **D75** (2007) 014022, hep-ph/0611061.

[137] R. Abbate, M. Fickinger, A. H. Hoang, V. Mateu, and I. W. Stewart, "Thrust at $\mathrm{N^3LL}$ with Power Corrections and a Precision Global Fit for alphas(mZ)", *Phys.Rev.* **D83** (2011) 074021, arXiv:1006.3080.

[138] G. Martinelli and C. T. Sachrajda, "A Lattice Study of Nucleon Structure", *Nucl.Phys.* **B316** (1989) 355.

[139] P. Hagler, "Hadron structure from lattice quantum chromodynamics", *Phys.Rept.* **490** (2010) 49–175, arXiv:0912.5483.

[140] K. Can, A. Kusno, E. Mastropas, and J. Zanotti, "Hadron Structure on the Lattice", *Lect.Notes Phys.* **889** (2015) 69–105.

[141] K.-F. Liu, "Parton degrees of freedom from the path integral formalism", *Phys.Rev.* **D62** (2000) 074501, arXiv:hep-ph/9910306.

[142] W. Detmold and C. D. Lin, "Deep-inelastic scattering and the operator product expansion in lattice QCD", *Phys.Rev.* **D73** (2006) 014501, arXiv:hep-lat/0507007.

[143] Z. Davoudi and M. J. Savage, "Restoration of Rotational Symmetry in the Continuum Limit of Lattice Field Theories", *Phys.Rev.* **D86** (2012) 054505, arXiv:1204.4146.

[144] C. Monahan and K. Orginos, "Locally smeared operator product expansions in scalar field theory", arXiv:1501.05348.

[145] C. Alexandrou, K. Cichy, V. Drach, E. Garcia-Ramos, K. Hadjiyiannakou, *et al.*, "First results with twisted mass fermions towards the computation of parton distribution functions on the lattice", *PoS* **LATTICE2014** (2014) 135, arXiv:1411.0891.

[146] M. Engelhardt, B. Musch, P. Hgler, A. Schfer, and J. Negele, "The Boer-Mulders Transverse Momentum Distribution in the Pion and its Evolution in Lattice QCD", *Int.J.Mod.Phys.Conf.Ser.* **37** (2015) 1560034.

[147] A. Rothkopf, "Improved Maximum Entropy Analysis with an Extended Search Space", *J.Comput.Phys.* **238** (2013) 106–114, arXiv:1110.6285.

[148] W. Detmold and M. G. Endres, "Signal/noise enhancement strategies for stochastically estimated correlation functions", *Phys.Rev.* **D90** (2014), no. 3, 034503, arXiv:1404.6816.

[149] D. B. Renner, "Status and prospects for the calculation of hadron structure from lattice QCD", *PoS* **LAT2009** (2009) 018, arXiv:1002.0925.

[150] M. Luscher, P. Weisz, and U. Wolff, "A Numerical method to compute the running coupling in asymptotically free theories", *Nucl.Phys.* **B359** (1991) 221–243.

[151] P. Schweitzer, M. Strikman, and C. Weiss, "Sea quark transverse momentum distributions and dynamical chiral symmetry breaking", *Int.J.Mod.Phys.Conf.Ser.* **25** (2014) 1460010, arXiv:1309.2990.

[152] E. Leader and C. Lorcé, "The angular momentum controversy: What is it all about and does it matter?", *Phys.Rept.* **541** (2014) 163–248, arXiv:1309.4235.

[153] X.-D. Ji, "Gauge-Invariant Decomposition of Nucleon Spin", *Phys.Rev.Lett.* **78** (1997) 610–613, arXiv:hep-ph/9603249.

[154] R. Jaffe and A. Manohar, "The G(1) Problem: Fact and Fantasy on the Spin of the Proton", *Nucl.Phys.* **B337** (1990) 509–546.

[155] C. Lorce and B. Pasquini, "Quark Wigner Distributions and Orbital Angular Momentum", *Phys.Rev.* **D84** (2011) 014015, arXiv:1106.0139.

[156] Y. Hatta, "Notes on the orbital angular momentum of quarks in the nucleon", *Phys.Lett.* **B708** (2012) 186–190, arXiv:1111.3547.

[157] H. B. Meyer and J. W. Negele, "Gluon contributions to the pion mass and light cone momentum fraction", *Phys.Rev.* **D77** (2008) 037501, arXiv:0707.3225.

[158] M. Deka, T. Doi, Y. Yang, B. Chakraborty, S. Dong, *et al.*, "Lattice study of quark and glue momenta and angular momenta in the nucleon", *Phys.Rev.* **D91** (2015), no. 1, 014505, `arXiv:1312.4816`.

[159] A. V. Manohar, "Parton distributions from an operator viewpoint", *Phys.Rev.Lett.* **65** (1990) 2511–2514.

[160] X.-S. Chen, X.-F. Lu, W.-M. Sun, F. Wang, and T. Goldman, "Spin and orbital angular momentum in gauge theories: Nucleon spin structure and multipole radiation revisited", *Phys.Rev.Lett.* **100** (2008) 232002, `arXiv:0806.3166`.

[161] X. Ji, J.-H. Zhang, and Y. Zhao, "Physics of the Gluon-Helicity Contribution to Proton Spin", *Phys.Rev.Lett.* **111** (2013) 112002, `arXiv:1304.6708`.

[162] R. S. Sufian, M. J. Glatzmaier, Y.-B. Yang, K.-F. Liu, and M. Sun, "Glue Spin S_G in The Longitudinally Polarized Nucleon", `arXiv:1412.7168`.

[163] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, "Evidence for polarization of gluons in the proton", *Phys.Rev.Lett.* **113** (2014), no. 1, 012001, `arXiv:1404.4293`.

[164] K. Kanazawa, C. Lorc, A. Metz, B. Pasquini, and M. Schlegel, "Twist-2 generalized transverse-momentum dependent parton distributions and the spin/orbital structure of the nucleon", *Phys.Rev.* **D90** (2014), no. 1, 014028, `arXiv:1403.5226`.

[165] M. Burkardt, "Parton Orbital Angular Momentum and Final State Interactions", *Phys.Rev.* **D88** (2013), no. 1, 014014, `arXiv:1205.2916`.

[166] D. Kiptily and M. Polyakov, "Genuine twist three contributions to the generalized parton distributions from instantons", *Eur.Phys.J.* **C37** (2004) 105–114, `arXiv:hep-ph/0212372`.

[167] M. Penttinen, M. V. Polyakov, A. Shuvaev, and M. Strikman, "DVCS amplitude in the parton model", *Phys.Lett.* **B491** (2000) 96–100, `arXiv:hep-ph/0006321`.

[168] Y. Hatta and S. Yoshida, "Twist analysis of the nucleon spin in QCD", *JHEP* **1210** (2012) 080, `arXiv:1207.5332`.

[169] A. Courtoy, G. R. Goldstein, J. O. G. Hernandez, S. Liuti, and A. Rajan, "On the Observability of the Quark Orbital Angular Momentum Distribution", *Phys.Lett.* **B731** (2014) 141–147, `arXiv:1310.5157`.

[170] A. Courtoy, G. R. Goldstein, J. O. Gonzalez Hernandez, S. Liuti, and A. Rajan, "Identification of Observables for Quark and Gluon Orbital Angular Momentum", `arXiv:1412.0647`.

[171] **HERMES** Collaboration, A. Airapetian *et al.*, "Exclusive Leptoproduction of Real Photons on a Longitudinally Polarised Hydrogen Target", *JHEP* **1006** (2010) 019, `arXiv:1004.0177`.

[172] L. Gribov, E. Levin, and M. Ryskin, "Semihard Processes in QCD", *Phys.Rept.* **100** (1983) 1–150.

[173] A. H. Mueller and J.-W. Qiu, "Gluon Recombination and Shadowing at Small Values of x", *Nucl.Phys.* **B268** (1986) 427.

[174] L. D. McLerran and R. Venugopalan, "Computing quark and gluon distribution functions for very large nuclei", *Phys.Rev.* **D49** (1994) 2233–2241, `arXiv:hep-ph/9309289`.

[175] E. Iancu and R. Venugopalan, "The Color glass condensate and high-energy scattering in QCD", `arXiv:hep-ph/0303204`.

[176] C. Marquet, B.-W. Xiao, and F. Yuan, "Semi-inclusive Deep Inelastic Scattering at small x", *Phys.Lett.* **B682** (2009) 207–211, arXiv:0906.1454.

[177] F. Dominguez, B.-W. Xiao, and F. Yuan, "k_t-factorization for Hard Processes in Nuclei", *Phys.Rev.Lett.* **106** (2011) 022301, arXiv:1009.2141.

[178] A. Metz and J. Zhou, "Distribution of linearly polarized gluons inside a large nucleus", *Phys.Rev.* **D84** (2011) 051503, arXiv:1105.1991.

[179] R. Baier, A. Mueller, and D. Schiff, "Saturation and shadowing in high-energy proton nucleus dilepton production", *Nucl.Phys.* **A741** (2004) 358–380, arXiv:hep-ph/0403201.

[180] C. Marquet, "Forward inclusive dijet production and azimuthal correlations in p(A) collisions", *Nucl.Phys.* **A796** (2007) 41–60, arXiv:0708.0231.

[181] A. Mueller, B.-W. Xiao, and F. Yuan, "Sudakov Resummation in Small-x Saturation Formalism", *Phys.Rev.Lett.* **110** (2013), no. 8, 082301, arXiv:1210.5792.

[182] Y. V. Kovchegov and A. H. Mueller, "Gluon production in current nucleus and nucleon - nucleus collisions in a quasiclassical approximation", *Nucl.Phys.* **B529** (1998) 451–479, arXiv:hep-ph/9802440.

[183] C. Bomhof, P. Mulders, and F. Pijlman, "The Construction of gauge-links in arbitrary hard processes", *Eur.Phys.J.* **C47** (2006) 147–162, arXiv:hep-ph/0601171.

[184] A. Dumitru, J. Jalilian-Marian, T. Lappi, B. Schenke, and R. Venugopalan, "Renormalization group evolution of multi-gluon correlators in high energy QCD", *Phys.Lett.* **B706** (2011) 219–224, arXiv:1108.4764.

[185] Y. V. Kovchegov and M. D. Sievert, "Sivers function in the quasiclassical approximation", *Phys.Rev.* **D89** (2014), no. 5, 054035, arXiv:1310.5028.

[186] Y.-Q. Ma and R. Venugopalan, "Comprehensive Description of J/ Production in Proton-Proton Collisions at Collider Energies", *Phys.Rev.Lett.* **113** (2014), no. 19, 192301, arXiv:1408.4075.

Appendix 4: Facilities and Other Resources

All participants affiliated with this proposal have access to sufficient workspace and computing to carry out the proposed research. Importantly, there is also workspace available at the various institutions for collaborative visits.

In this Appendix, we provide a list of committed key domestic investigators who will be affiliated with this proposal as active collaborators, which is a crucial resource of our proposal, and the information on the Facilities and Other Resources of the Lead Institution, as well as all participating Institutions of this proposal, organized according to the alphabetical order of the participating institutions.

Affiliated key investigators (in alphabetical order of the name of the investigator):

A. Alexandru - George Washington University,
T. Bhattacharya - Los Alamos National Lab,
S.J. Brodsky - Standford Linear Accelerator Center,
J.C. Collins - Penn State University,
R. Gupta - Los Alamos National Lab,
Z.-B. Kang - Los Alamos National Lab,
S. Meinel - University of Arizona,
K. Orginos - The College of William & Mary,
D. Pitonyak - RIKEN/BNL Research Center, BNL,
D. Richards - Jefferson Lab,
P. Schweitzer - University of Connecticut,
G. Sterman - Stony Brook University,
M. Strikman - Penn State University,
S. Syritsyn - Jefferson Lab, and
C. Weiss - Jefferson Lab.

Brookhaven National Laboratory:

Brookhaven National Laboratory is home to the Relativistic Heavy Ion Collider (RHIC), where polarized proton-proton collisions have provided novel information on the gluon contribution to the proton's spin, and on single spin asymmetries. The upcoming 2017 polarized proton-proton run will provide data whose interpretation will likely provide fresh insight into transverse momentum distributions in the proton. Achieving the physics goals of the TMD topical collaboration is therefore a high priority to the RHIC program and to BNL.

The Nuclear and Particle Physics Directorate and Physics Department at BNL have committed to supporting the Topical Collaboration Effort by providing adequate office space, computing resources, and administrative support, as well as limited support for workshops and summer schools at BNL. Matching funds for supporting a postdoctoral research associate working on the identified projects of the TMD Collaboration have been promised by the Department. The medium energy group at BNL is strongly supportive of the TMD collaboration and will assist in providing resources and tools to achieve the required global analysis of data.

In addition, the RIKEN-BNL Research Center (RBRC) at BNL, have significant resources for helping host workshops and meetings devoted to the physics of TMD distributions, as well as computing resources for the TMD Collaboration's lattice calculation effort.

Los Alamos National Laboratory:

Adequate office space and excellent administrative support are available for the senior investigators, the Postdoctoral Research Associates and visitors at the Los Alamos National Laboratory.

LANL will also provide generous computational support for this project. The Nuclear and Particle Physics, Astrophysics and Cosmology Group T-2 has acquired a 128 node Linux cluster with 1 AMD Opteron CPUs per node, operating at 2.4GHz. 2GB of memory per node is available and we have an estimated 24TB of disk space. This resource is extremely valuable for moderate size computations and for developing codes for very large-scale computations. We have performed most of the numerical calculations associated with our recent reported progress in spin and heavy ion theory on this cluster.

Our current assessment is that the local T-2 cluster at LANL will be sufficient to meet the computational requirements for successful completion of our tasks on this project. Should the need for additional processing power arise, we will apply for LANL Institutional Computing. For example, we have access to the linux cluster ”Ganglia” at the Center for Non-Linear Studies (CNLS) and can apply for High Performance Computing time.

A valuable resource at LANL is a large heavy-ion and spin physics experimental group, which participates in the PHENIX collaboration at RHIC and has worked actively with the CMS collaboration at the LHC. It has active involvement at Fermilab in the fixed target Drell-Yan E906 exteriment and will lead a proposed polarized target Drell-Yan experiment E1039. We have an established strong track record of working with the heavy-ion and spin phsics collaborations at all accelerator facilities and of providing much-needed theoretical predictions for their hard probes and nucleon structure programs. At LANL, we have initiated a number of successful high-impact projects funded by our Laboratory Directed Research and Development program (LDRD). These collaborations will continue in the future and provide first-hand experimental guidance on the most exciting TMD applications of the theory of that we will develop.

MIT:

The nuclear theory group benefits critically on a daily basis from support provided within the Center for Theoretical Physics (CTP) by an administrator, Scott Morley, one full-time support staff, Charles Suggs, and one part-time support staff, Joyce Berggren. Morley and his staff provide a wide array of indispensable services for the nuclear theory group, plus two other theory groups within the CTP. They provide assistance with travel, seminar speakers, long- and short-term visitors to the CTP, account finances, the coordination of RA and TA assignments, postdoctoral fellow support, computer support, and various other types of administrative functions. All postdocs and students in the CTP are provided with desktop computers and office space.

Nuclear and high energy physics research at MIT is conducted within the Laboratory for Nuclear Science (LNS). LNS Central Facility provides the administrative infrastructure and support services for researchers in nuclear and particle physics. The Director of LNS is appointed by and reports to the Dean of Science at MIT. The Dean of Science is advised by an Advisory Committee for LNS composed of eminent outside experts in nuclear and particle physics which meets biannually.

LNS administrative functions include personnel, travel, fiscal, property and general services. The financial support for these services is provided through an administrative allocation applied to all activities administered by the laboratory. It is applied to the Modified Total Direct Costs (MTDC, which excludes equipment and tuition) less employee benefits and vacation accrual, and carries no Facilities and Administration (F&A) overhead charge. The administrative allocation rate is 7.6% for salaries and 0.6% for materials and services. These rates are evaluated yearly and are approved by the Research Group Leaders in the Laboratory, by the Office of Cost Analysis within the Office of Sponsored Programs of MIT and by the Office of Naval Research.

New Mexico State University:

Computational studies are an essential part of our work. For large-scale Lattice QCD production purposes, we apply, or join broader collaborative applications for access to computational resources at facilities available to the USQCD Collaboration, as well as at other DOE facilities such as NERSC. On the other hand, for code development and test purposes as well as lower-volume computations, adequate facilities are available to us locally at NMSU, including a 176 core cluster at the NMSU computer center.

Adequate office space and administrative support are available to the senior investigators, and will be extended to the new faculty member to be hired under a bridge position agreement within this Topical Collaboration.

Temple University:

Temple University provides adequate office space for postdocs and graduate students. High performance computing is available, for instance through the *Owl's Nest* environment. General computer support is provided by the University and the College of Science and Technology. The Temple University Physics Department has three full time secretaries which strongly support the work of faculty, postdocs and graduate students.

University of Arizona:

The University of Arizona Physics Department provides return on overhead in the form of administrative, bookkeeping, and information-technology support. It also provides support for graduate students in the first two years of graduate studies and occasionally also later. All students are also provided with office space by the department. Department infrastructure provides administrative support for assistance with travel, seminar speakers, visitors, account finances, graduate students, postdoctoral fellows, computer support, and miscellaneous functions.

The Nuclear Theory group provides financial support through DOE grants to graduate student RAs, and to postdoctoral fellows. In addition to salary there is travel support and each is provided with a computer.

Appendix 5: Equipment

There are no major items of equipment needed for this proposal.

Appendix 6: Data Management Plan

In this Appendix, we provide a Data Management Plan (DMP) for all relevant projects proposed in the Narrative section of this proposal:

Global fitting analyses

The global TMD analyses undertaken in this project will collate large datasets of experimental results from different sources in a coherent format along with appropriate metadata describing the origin and context of the data. This collated data and the associated metadata will be made available publicly on the internet once first publications are produced and will be maintained and updated throughout the lifetime of the TMD collaboration.

The software used in performing the global fits will also be archived on the hepforge webpages. A hepforge page already underway, and which would likely be folded into the project, is maintained by T. Rogers and can be seen here `http://tmd.hepforge.org/`. The dissemination of TMD parametrizations will follow a model similar to that of collinear distributions. The results of fits will be made publicly available both through the website and through publications in journal articles. As fits are updated, older ones will be kept available, along with records of changes, modifications and improvements.

In addition, software for generating transverse momentum dependent observables from models, fits, and perturbative calculations will be made publicly available through public repositories such as the hepforge website. Web interfaces for generating TMD distributions, with sensitivity to non-perturbative parametrizations, will be developed (for an older example developed in the context of high energy physics, see `http://hep.pa.msu.edu/wwwlegacy/`). This software is currently being developed at Jefferson Lab and is hosted on `https://github.com/JeffersonLab/TMD/subscription`. We plan for this work ultimately to be built as public branches of open-source software.

Finally, the TMD distribution generation software, along with publicly available fits, will be interfaced with parallel projects in lattice QCD. Part of the global fitting analysis project will be to facilitate the incorporation of lattice information into global fitting.

Lattice QCD calculations

The raw physics simulation data created by the lattice QCD calculations project will be in the form of simulation results stored in standard lattice QCD data formats (`http://usqcd.jlab.org/usqcd-docs/c-lime/`). These are very large files (tens of thousands of files, each of many GB) and some will be stored only temporarily as it is more cost effective to recreate the simulations than store such amounts of data. Parameter files, important configuration files and post-processed summary files will be kept indefinitely. The physics research output associated with this project will be made available publicly either as journal articles (with preprints freely available at arxiv.org) or conference presentations.

An important component of the data produced by this project will be the software infrastructure that is created to study x-dependence of parton distributions and TMDs and related. Software will be built as public branches of current open-source software projects that are hosted on `http://github.com` and on MIT repositories (`https://github.com/JeffersonLab/chroma`, and `https://usqcd.lns.mit.edu/w/index.php/QLUA`) All software will be made available for free under the MIT license[1] and will remain freely available to anyone for non-commercial use.

Rights and access management

The raw data will be freely available to other users after the first paper resulting from it has been published. The research publications, software and algorithms will be freely available as specified in

[1] `http://opensource.org/licenses/MIT`

the open access policies of the various participating institutions. The data acquired and preserved in the context of this proposal will be further governed by relevant institutional policies pertaining to intellectual property, record retention, and data management.

Archival policy

Physics simulation data and data collations that are to be retained in the long term will be archived either locally or at national supercomputing facilities where much of the computing work in the project will be performed. Critical data will be r eplicated in multiple distinct physical locations.

Appendix 7: Other Attachments

In this Appendix, we provide a copy of the two letters from the Dean of College of Arts and Science of New Mexico State University and the Dean of College of Science and Technology of Temple University, respectively, committing the regular, tenure-track Assistant Professor positions in Nuclear Physics Theory as the bridged positions in connection with our proposal, along with supporting letters from various participating institutions.

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March 23, 2015

Professor Jianwei Qiu
Physics Department
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973

Dear Professor Qiu,

The College of Arts and Sciences at New Mexico State University is very proud of the accomplishments of its faculty members in the Department of Physics. Our university has several excellent nuclear physicists in the College of Arts and Sciences, both in experiment and theory, with strong ties to DOE National Laboratories, including LANL, BNL, FNAL and TJNAF. The university's support for these programs is mirrored in our recent hire of a nuclear experimentalist working with the PHENIX experiment at BNL, and an offer we are about to make to a neutrino physicist who will participate in corresponding experiments at FNAL. The proposed hire will be the third hire in five years in nuclear and particle physics, significantly strengthening the largest area in the NMSU physics department.

The present letter will confirm that if the Department of Energy funds this Topical Collaboration proposal under National Laboratory Announcement Number LAB 15-1269, with BNL as the lead institution and with participation by NMSU, the College of Arts and Sciences will allocate one tenure track position in nuclear theory at the rank of assistant professor to the Department of Physics. NMSU will contribute 33% of the 9-month salary and fringe benefits for this faculty member for the first three years of his/her employment. NMSU will become responsible for faculty member's entire salary and fringe benefits beginning in the fourth year of employment and continuing into the future if the faculty member is awarded tenure. The faculty member will be responsible for a commensurately reduced teaching load during the first three years. We will contribute to start-up costs at an appropriate level.

This tenure track faculty member will promote teaching and research in nuclear physics at NMSU, and will provide service and outreach that will benefit the community. We are confident that the new faculty member will join colleagues at our campus in expanding our understanding of the universe, and will become a prominent leader in the field of nuclear physics.

Sincerely,

Christa Slaton

Christa Slaton
Dean

College of Science and Technology
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April 8th 2015

Dr. Timothy Hallman, Associate Director Office of Science for Nuclear Physics
Dr. George Fai, Program Manager Nuclear Theory
Office of Nuclear Physics, SC-26
U.S. Department of Energy
19901 Germantown Road, Germantown, MD 20874-1290

Subject:

Bridge position at Temple University through the Topical Collaboration "*Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD*"

Dear Dr. Hallman and Dr. Fai,

Andreas Metz from the Department of Physics at Temple is participating in the proposal for the Topical Collaboration "*Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD*".

The College of Science and Technology at Temple is very enthusiastic about this proposal. In particular, Temple is willing to support a bridge faculty position via this Topical Collaboration. Specifically, Temple will provide 50% of the academic year salary for such a position for four years.

In addition, Temple will provide its customary summer salary support for Assistant Professors (one month per year) as part of the start-up package. Importantly, subject to satisfactory performance (e.g., mid-term review) after the initial four years the position will be fully supported by Temple. The position will be further continued subject to a successful tenure review.

Sincerely

M. Klein

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Dean, College of Science & Technology

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