

2026 Spring Summary and Summer Plan

Chueng-Ryong Ji

North Carolina State University

Group Meeting, May 1, 2026

Outline

- **Progress Report in Spring 2026**
- **Tentative Plan in Summer 2026**
 - **Biweekly Group Meetings for May ~ August**
- **Big Picture**
 - **Science Questions vs. Funding Status**
- **Pending Renewal Proposal for 2026-2029**
- **Outlook**
 - **What to think about**
 - **What we need to work on**

Spring 2026 schedule (9:30am EST) for Group Meetings

Date	Speaker	Informal Topic or Title
1/9/26	Chueng Ji	Overview and Plan for Spring 2026
1/16/26	Arianna Harris	Group Page Development
1/23/26	David Brown	Dirac-Bergmann Algorithm in Classical Mechanics Lecture 1
1/30/26	David Brown	Dirac-Bergmann Algorithm in Classical Mechanics Lecture 2
2/6/26	Connor Donovan	The Feynman path integral formulation of non-dispersive Airy wave packets and applications
2/13/26	Paul Ferrante	A Mellin-Space Perspective on Casimir Energy and Scale Symmetric Theories
2/20/26	Hunter Duggin	Unitary fermi gas GFF calculation using pionless EFT on the lattice
2/27/26	Ping Wang	Nonlocal ChEFT
3/6/26	Deepasika Dayananda	Interpolating Relativistic Spacetimes and Quantum Fields between IFD and LFD
3/13/26	Sangyeong Son	Non-diagonal hard exclusive reactions for studying transition GPDs
3/20/26	Deepasika Dayananda	PhD Defense
3/27/26	Narider Kumar	Generalized parton distributions of the photon and ρ meson
4/3/26	Daniel Piasecki	Koopman-von Neumann Classical Spinors
4/10/26	Sangwoo Ha	Peer Instruction in Physics Education
4/17/26	Satyajit Puhan	Extraction of pion GPDs from charge form factors
4/24/26	Ronaldo Tibes	Higher-order derivatives in quantum field theory
5/1/26	Chueng Ji	Review of Spring and Plan for Summer 2026

“Origin of the Covariant Wigner Operator as a Quantum Amplitude in QCD” [arXiv:2604.01248 [hep-ph]], pending for Symmetry (with D.. Piasecki)

“Quantum orientation entanglement analysis of the interpolating helicity states between the instant form dynamics and the light-front dynamics,” [arXiv:2603.18208 [hep-th]] Phys.Rev.D in correspondence (with D. Dayananda)

“Interpolating conformal algebra in (1+1) dimensions between the instant form and the light-front form of relativistic dynamics,” Phys.Rev.D in print, [arXiv:2601.19251 [hep-th]] (with H. Ravikumar)

“The Feynman path integral formulation of non-dispersive Airy wave packets and their applications to the heavy meson mass spectra and ultra-cold neutrons,” Int. J. of Theo. Phys. 65, no. 4, 102 (2026) (with P. Ferrante and C. Donovan)

“Axial anomaly and confinement in two-dimensional QED: Singular behavior of vacuum polarization at threshold,” Phys.Lett.B 873, 140215 (2026) (with B. Ma)

“(3+1)-dimensional scalar field model analysis of beam spin asymmetry in the electro- production of a scalar meson off a scalar target,” Phys.Rev.D 113, no.1, 016003 (2026) (with A.Lundeen, Y.Choi and H.-M.Choi)

“Nonlocal Effective Field Theory and Its Applications,” Symmetry 18, no.1, 31 (2026)
(with P.Wang, Z. Gao, F. He, W. Melnitchouk and Y. Salamu)

“Structure of the lightest nucleus in the visible Universe,” Phys.Rev.D 113, no.5, 054008 (2026)
(with S.Kaur, C. Mondal and X. Zhao)

Origin of the Covariant Wigner Operator as a Quantum Amplitude in QCD

Chueng-Ryong Ji[†] and Daniel W. Piasecki

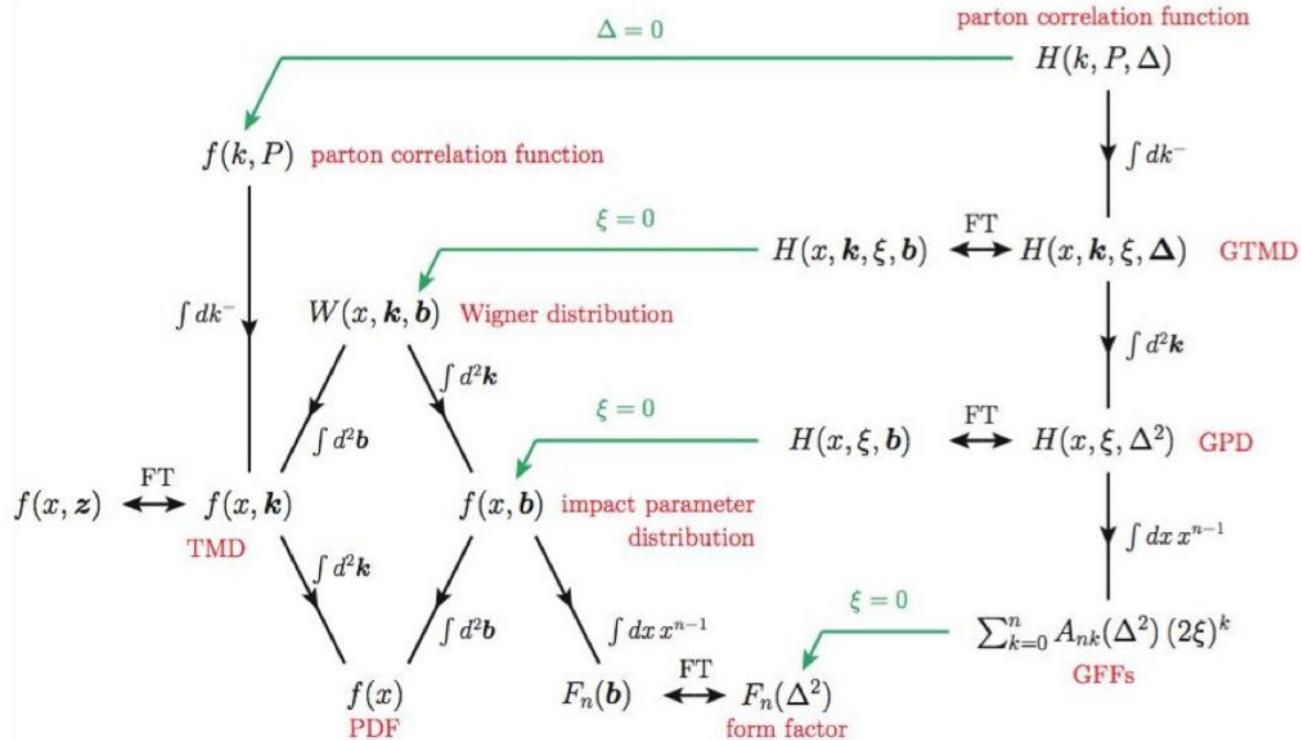
arXiv:2604.01248v2 [hep-ph] 6 Apr 2026

$$W(x, p) = \frac{1}{2\pi} \int d\lambda_p \rho\left(x - \frac{\hbar}{2}\lambda_p, x + \frac{\hbar}{2}\lambda_p\right) e^{ip\lambda_p}$$

$$\int dp W(x, p) = \rho(x)$$



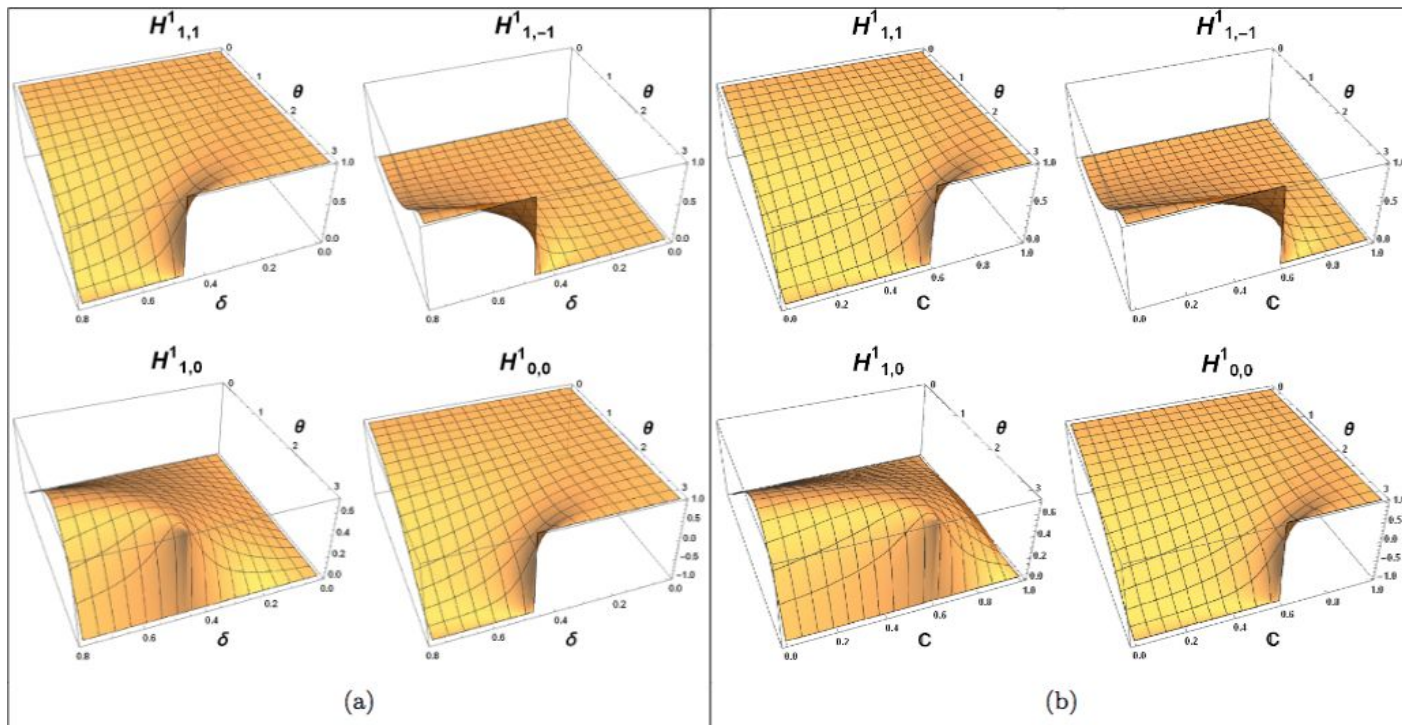
$$H(k, P, \Delta) = (2\pi)^{-4} \int d^4 z e^{izk} \left\langle p \left(P + \frac{1}{2} \Delta \right) \left| \bar{q} \left(-\frac{1}{2} z \right) \Gamma q \left(\frac{1}{2} z \right) \right| p \left(P - \frac{1}{2} \Delta \right) \right\rangle$$



Quantum orientation entanglement analysis of the interpolating helicity states between the instant form dynamics and the light-front dynamics

Deepasika Dayananda and Chueng-Ryong Ji¹

¹*Department of Physics and Astronomy, North Carolina State University, Raleigh, North Carolina 27695-8202, USA*



Interpolating conformal algebra in (1 + 1) dimensions between the instant form and the light-front form of relativistic dynamics

Chueng-Ryong Ji¹ and Hariprashad Ravikumar²

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²*Department of Physics, New Mexico State University, Las Cruces, New Mexico 88003-8001, USA*

TABLE III. 1 + 1 conformal algebra. Note here that the cumbersome superscript (1 + 1) is removed for all generators.

	\mathfrak{K}_0	P_0	D	\mathfrak{K}_3	P_3	K_3
\mathfrak{K}_0	0	$-2iD$	$-i\mathfrak{K}_0$	0	$-2iK_3$	$i\mathfrak{K}_3$
P_0	$2iD$	0	iP_0	$-2iK_3$	0	iP_3
D	$i\mathfrak{K}_0$	$-iP_0$	0	$i\mathfrak{K}_3$	$-iP_3$	0
\mathfrak{K}_3	0	$2iK_3$	$-i\mathfrak{K}_3$	0	$2iD$	$i\mathfrak{K}_0$
P_3	$2iK_3$	0	iP_3	$-2iD$	0	iP_0
K_3	$-i\mathfrak{K}_3$	$-iP_3$	0	$-i\mathfrak{K}_0$	$-iP_0$	0

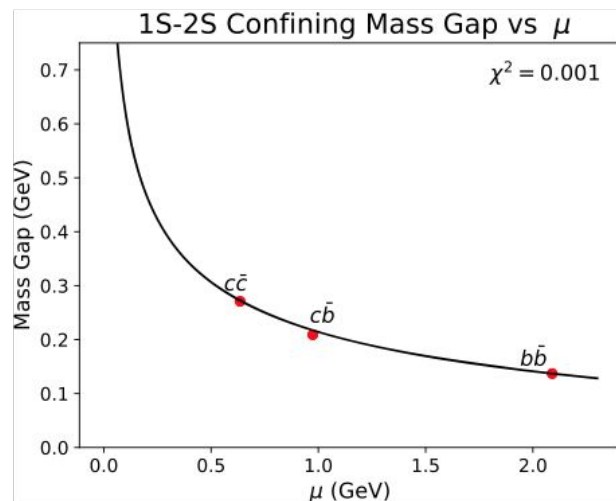
TABLE IV. 1 + 1 conformal algebra in LFD.

	\mathfrak{K}_+	P_+	D_+	\mathfrak{K}_-	P_-	D_-
\mathfrak{K}_+	0	$-2\sqrt{2}iD_+$	$-\sqrt{2}i\mathfrak{K}_+$	0	0	0
P_+	$2\sqrt{2}iD_+$	0	$\sqrt{2}iP_+$	0	0	0
D_+	$\sqrt{2}i\mathfrak{K}_+$	$-\sqrt{2}iP_+$	0	0	0	0
\mathfrak{K}_-	0	0	0	0	$-2\sqrt{2}iD_-$	$-\sqrt{2}i\mathfrak{K}_-$
P_-	0	0	0	$2\sqrt{2}iD_-$	0	$\sqrt{2}iP_-$
D_-	0	0	0	$\sqrt{2}i\mathfrak{K}_-$	$-\sqrt{2}iP_-$	0



The Feynman Path Integral Formulation of Non-Dispersive Airy Wave Packets and their Applications to the Heavy Meson Mass Spectra and Ultra-Cold Neutrons

Paul Ferrante¹ · Connor Donovan¹ · Chueng-Ryong Ji¹



Source	h_1	h_2	h_3	h_4	h_5
Exact	13.73	24.00	32.41	39.85	46.64
WKB Approx. ^a	13.63	23.98	32.40	39.85	46.65

^a These approximations are taken from Sakurai and Napolitano [19]





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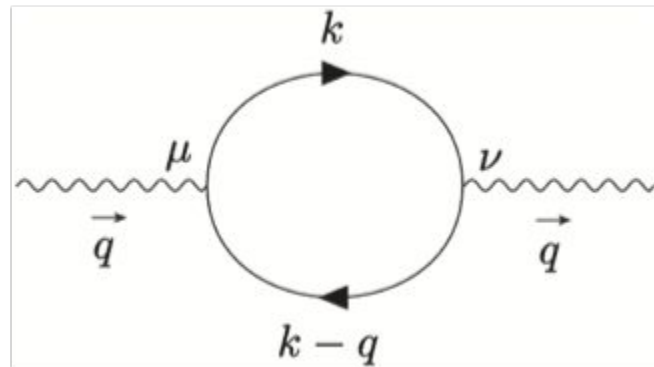
Letter

Axial anomaly and confinement in two-dimensional QED: Singular behavior of vacuum polarization at threshold

Bailing Ma ^a, Chueng-Ryong Ji ^{b,*}

$$D_{\mu\nu}(q) = -\frac{g_{\mu\nu} - q_\mu q_\nu / q^2}{q^2 - e^2 / \pi + i\epsilon}$$

$$D_{\mu\nu}(q) = -\frac{g_{\mu\nu} - q_\mu q_\nu / q^2}{q^2 - \frac{e^2}{\pi} \left[1 - \frac{2\pi m^2}{e^2} \ln \left(\frac{2\pi m^2}{3e^2} \right) \right] + i\epsilon}$$





**(3 + 1)-dimensional scalar field model analysis of beam spin asymmetry
in the electroproduction of a scalar meson off a scalar target**

Andrew Lundeen^{*} and Chueng-Ryong Ji[†]

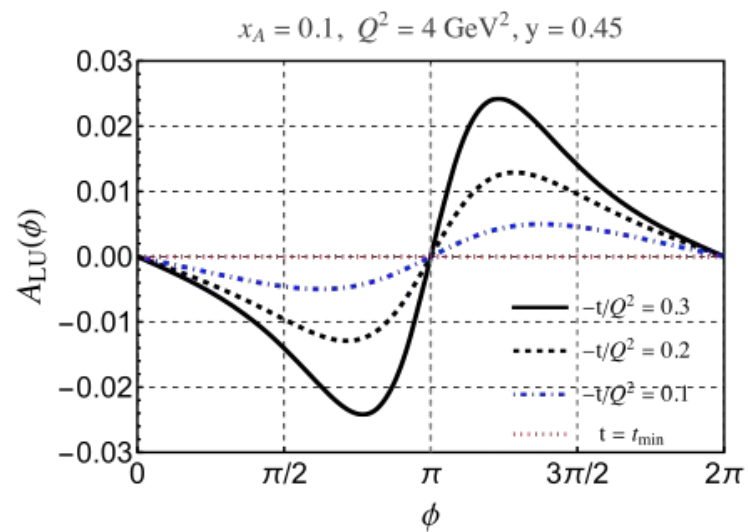
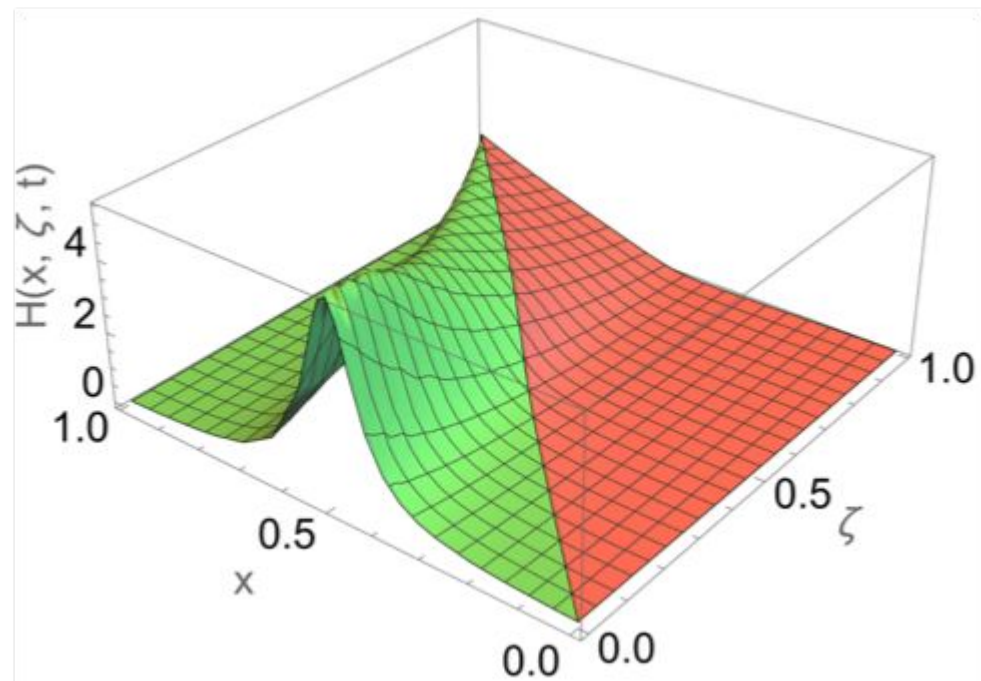
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Ho-Meoyng Choi[§]

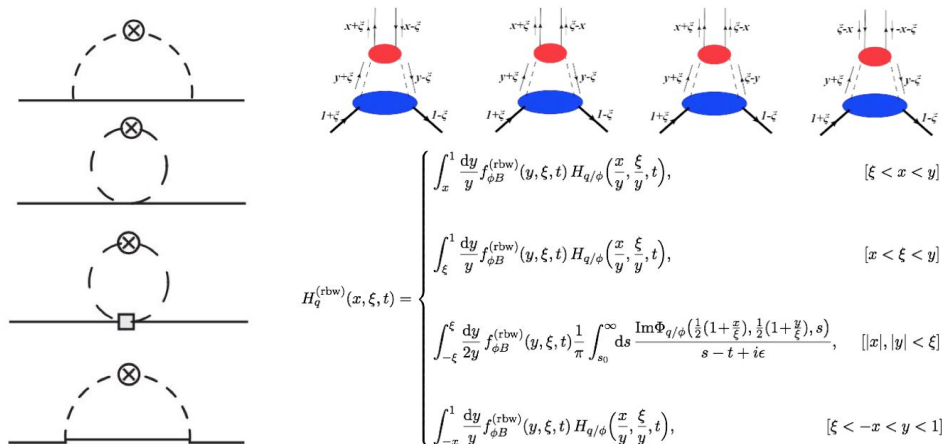
*Department of Physics Education, Teachers College, Kyungpook National University,
Daegu 41566, Korea*



Review

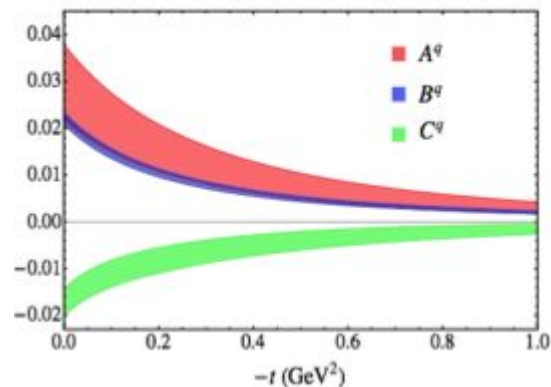
Nonlocal Effective Field Theory and Its Applications

Ping Wang ^{1,2,*} , Zhengyang Gao ^{1,2} , Fangcheng He ³ , Chueng-Ryong Ji ⁴ , Wally Melnitchouk ⁵ 
and Yusupjiang Salamu ⁶






The figure shows four Feynman diagrams on the left, each representing a different nonlocal interaction. The first diagram is a semi-circular loop with a cross in the center. The second is a circular loop with a cross. The third is a circular loop with a square. The fourth is a semi-circular loop with a cross. To the right, four diagrams show the internal structure of the vertices, with red and blue blobs and various momentum labels like $x+\xi$, $x-\xi$, $y+\xi$, $y-\xi$, $I+\xi$, and $I-\xi$.

$$H_q^{(rbw)}(x, \xi, t) = \begin{cases} \int_x^1 \frac{dy}{y} f_{\phi B}^{(rbw)}(y, \xi, t) H_{q/\phi}\left(\frac{x}{y}, \frac{\xi}{y}, t\right), & [\xi < x < y] \\ \int_\xi^1 \frac{dy}{y} f_{\phi B}^{(rbw)}(y, \xi, t) H_{q/\phi}\left(\frac{x}{y}, \frac{\xi}{y}, t\right), & [x < \xi < y] \\ \int_{-\xi}^\xi \frac{dy}{2y} f_{\phi B}^{(rbw)}(y, \xi, t) \frac{1}{\pi} \int_{s_0}^\infty ds \frac{\text{Im}\Phi_{q/\phi}\left(\frac{1}{2}\left(1+\frac{x}{y}\right), \frac{1}{2}\left(1+\frac{y}{x}\right), s\right)}{s-t+i\epsilon}, & [||x|, |y| < \xi] \\ \int_{-x}^1 \frac{dy}{y} f_{\phi B}^{(rbw)}(y, \xi, t) H_{q/\phi}\left(\frac{x}{y}, \frac{\xi}{y}, t\right), & [\xi < -x < y < 1] \end{cases}$$



Structure of the lightest nucleus in the visible Universe

Satvir Kaur ^{1,2,*} Chandan Mondal ^{1,2,†} Xingbo Zhao ^{1,2,3,‡} and Chueng-Ryong Ji ^{4,§}

¹*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

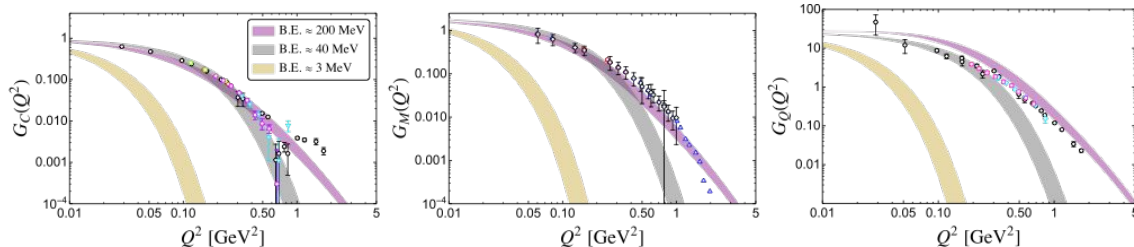
²*University of Chinese Academy of Sciences, Beijing 100049, China*

³*Advanced Energy Science and Technology Guangdong Laboratory, Huizhou, Guangdong 516000, China*

⁴*Department of Physics and Astronomy, North Carolina State University,
Raleigh, North Carolina 27695-8202, USA*

$$\left(-\frac{d^2}{d\zeta^2} + \frac{4L^2 - 1}{4\zeta^2} + U_{\perp}(\zeta) \right) \phi(\zeta) = M_{\perp}^2 \phi(\zeta)$$

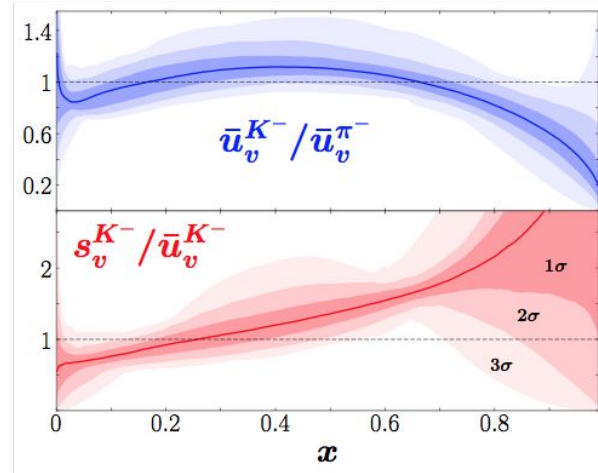
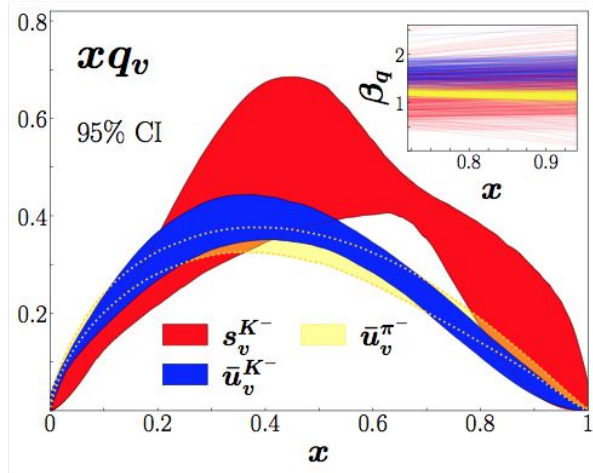
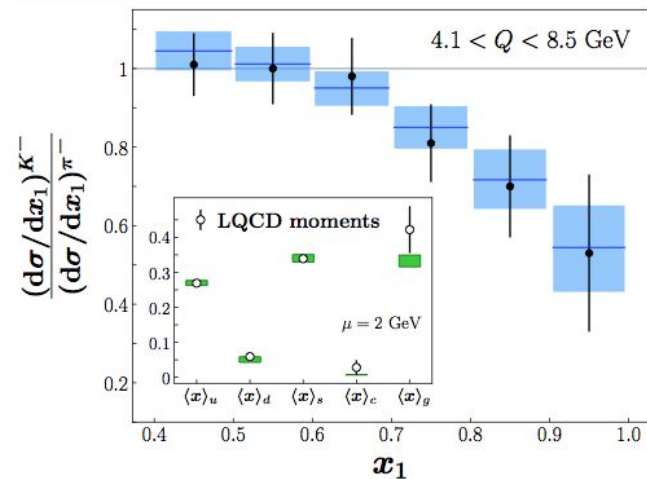
$$\left(\frac{m_c^2}{z(1-z)} + U_{\parallel}(z) \right) \chi(z) = M_{\parallel}^2 \chi(z)$$



First simultaneous global QCD analysis of kaon and pion parton distributions with lattice QCD constraints

P. C. Barry,¹ Chueng-Ryong Ji,² W. Melnitchouk,³ N. Sato,³ and Fernanda Steffens^{4,5}

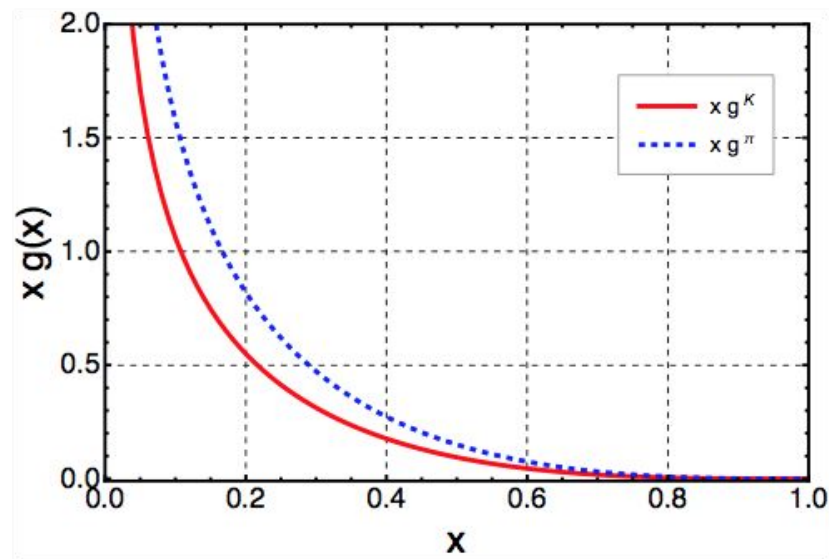
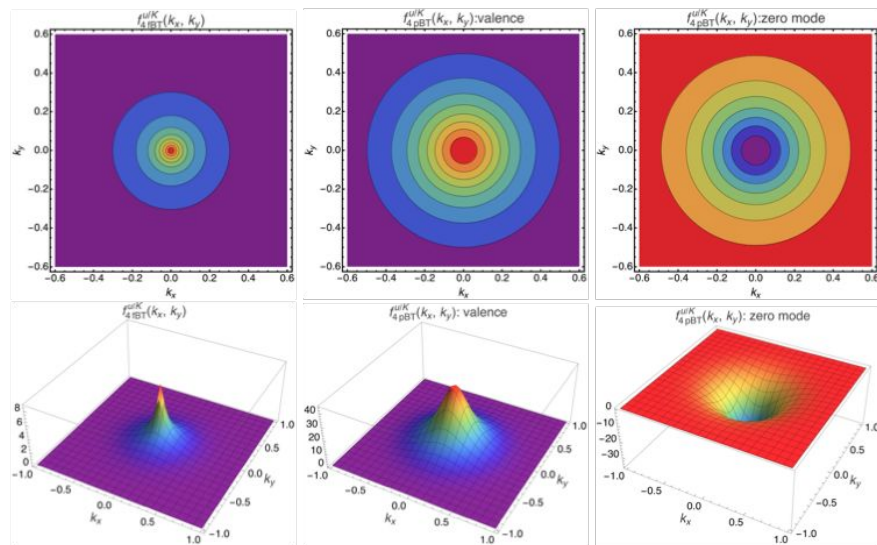
arXiv:2510.11979v1 [hep-ph] 13 Oct 2025



Kaon T-even transverse-momentum-dependent distributions and form factors in a self-consistent light-front quark model

Yongwoo Choi,^{1,2,*} Ahmad Jafar Arifi,^{3,4,†} Ho-Meoyng Choi,^{5,‡} and Chueng-Ryong Ji^{6,§}

arXiv:2512.21642v2 [hep-ph] 25 Feb 2026





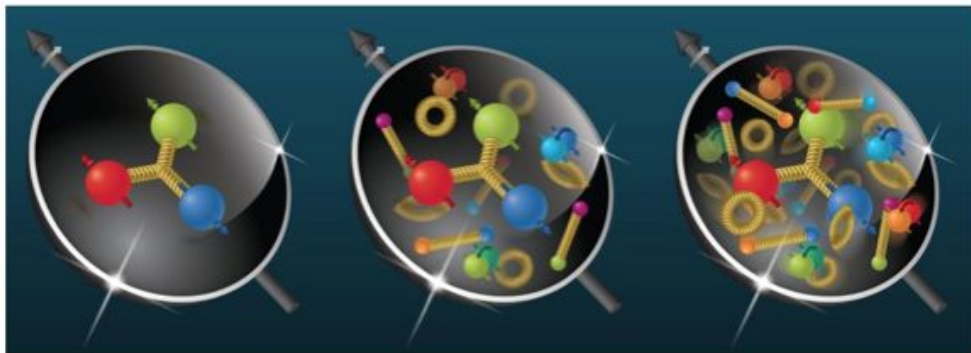
- **May 13 - June 17**
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- KNU
- Yonsei
...
- **June 21 - June 27**
LC2026
@StonyBrook
- **July @ NCSU**
- **August 5-8**
UKC2026
@Orlando

Summer 2026 schedule (9:30am EST) for Group Meetings

Date	Speaker	Informal Topic or Title
5/22/26	Moab Croft	Crash-Course in Geometric Algebra
6/5/26	Moab Croft	Pauli Theory in the Algebra of Physical Space
6/19/26	Moab Croft	Spinor Formalism in the Algebra of Physical Space
7/3/26	Moab Croft	Classical Electromagnetic Field Theory in the Spacetime Algebra
7/17/26	Shubham Sharma	J/ ψ Production and Gluon Helicity Studies at Spin Physics Detector Energies
7/31/26	TBA	TBA
8/14/26	Chueng Ji	Summer Report and Fall Plan

NC STATE
UNIVERSITY

Chueng Ji's Research Group



GROUP PAGE ADMINISTRATOR



Arianna Harris

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Crash-Course in Geometric Algebra

Geometric Algebra will be pedagogically introduced, starting with a 2-dimensional geometric algebra and ending with a projective 3-dimensional geometric algebra. Both the *traditional view* of Geometry and the *mirror view* of Geometry will be presented. It will be seen that rotations and translations are algebraically identical (and in later talks it will be seen that boosts are likewise algebraically identical) and may be applied coordinate-free. The methods of Geometric Algebra are dimension-agnostic and so intuition garnered in a lower-dimensional algebra applies in a higher-dimensional algebra.

Pauli Theory in the Algebra of Physical Space

Pauli theory is naturally encoded within the geometry of 3-dimensional Euclidean space. Pauli spinors are the rotations that take some *reference axis* to a fermion's *spin axis*. This naturally promotes an interpretation of Pauli spinors as a superposition of the transformations that *could* take place rather than a superposition of fermionic eigenspins. Considering time-evolution naturally leads to the *Schrödinger-Pauli equation*, demonstrating the Schrödinger equation is simply the equation for a fermion in a spin eigenstate. The spin density element is then recovered as the application of Pauli spinors to a *reference lightray*, and the outcomes of the Stern-Gerlach experiment are trivially the results of geometric lightray-overlap.

Spinor Formalism in the Algebra of Physical Space

Relativistic mechanics can be described via the dynamics of Lorentz (Dirac-Hestenes) spinors, which are simply the standard Lorentz transformations that take a fermion from rest to some observed momentum. It will be shown how this formalism is equivalent to traditional Dirac theory. Finally, *lightray spinor structure* will be demonstrated as a general geometric property of 3-dimensional space; its uses in the Constructive Standard Model will be presented.

Classical Electromagnetic Field Theory in the Spacetime Algebra

The Spacetime Algebra will be presented, and with it classical electromagnetic theory. The electromagnetic field bivector and electromagnetic potential will be given, after which the Lorentz force law, the Maxwell equation, the canonical stress-energy vector, and the symmetric stress-energy vector will be derived from the Principle of Least Action. These derivations demonstrate the equivalency between the Geometric Algebra formalism and the traditional tensorial methods and highlight the coordinate-free simplicity of the former.

Big Picture

11 Science Questions for the 21st Century

Genesis Mission

US Long Range Plan for Nuclear Science

5 Topical Collaboration Projects

Eleven Science Questions for the 21st Century

- What is **Dark Matter**?
- What is the nature of **Dark Energy**?
- How did the **Universe** begin?
- Did Einstein have the last word on **Gravity**?
- What are the masses of the **Neutrinos**, and how have they shaped the evolution of the Universe?
- How do **Cosmic Accelerators** work and what are they accelerating?
- Are **Protons** unstable?
- What are the new states of matter at exceedingly **High Density and Temperature**?
- Are there **Additional Space-Time Dimensions**?
- How were the elements from **Iron to Uranium** made?
- Is a new theory of **Matter and Light** needed at the **Highest Energies**?

Quantum Scales of Galaxies from Self-interacting Ultralight Dark Matter

Jae-Weon Lee ^{1,*} , Chueng-Ryong Ji ^{2,*} 

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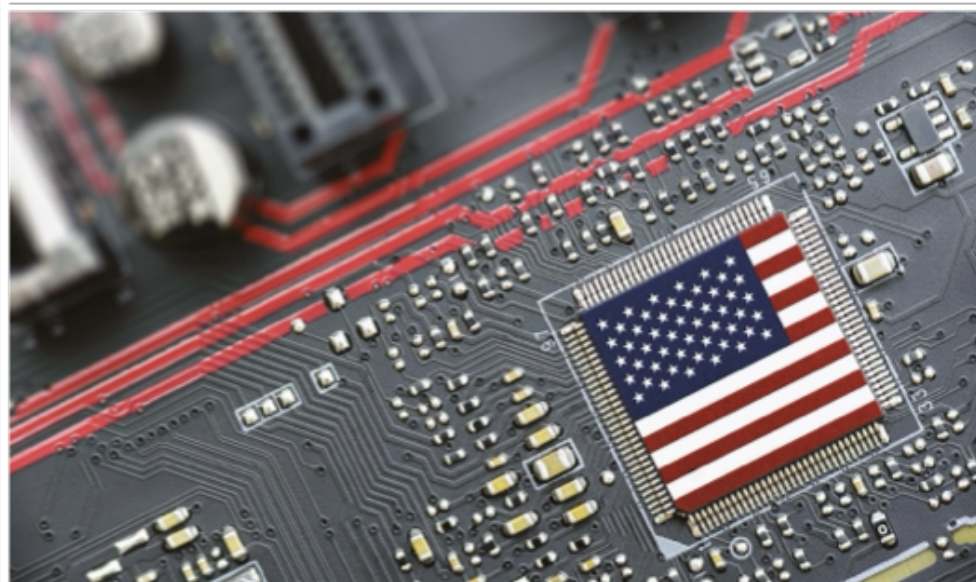
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News in focus



WILLIAM PETERSON/ISTOCK/VALENTY

The Genesis Mission aims to provide researchers with the computing power and data sets necessary to train artificial-intelligence models.

TRUMP'S AI 'GENESIS MISSION': WHAT ARE THE RISKS AND OPPORTUNITIES?

National laboratories have been told to broaden access to their data sets to accelerate research as part of the federal government's AI platform. But who stands to benefit?

By Elizabeth Gibney, Alexandra Witze
& Jenna Ahart

The White House has launched a plan to accelerate research in the United States, by building artificial intelligence (AI) models on the rich scientific data sets held by the country's 17 national laboratories, as well as harnessing their enormous computing resources.



U.S. DEPARTMENT of ENERGY

Office of Science (SC), Office of Critical Minerals and Energy Innovation (CMEI), Office of Environmental Management (EM), Office of Electricity (OE), Hydrocarbons and Geothermal Energy Office (HGEO), and Office of Nuclear Energy (NE)



Genesis Mission

The Genesis Mission: Transforming Science and Energy with AI

**Notice of Request for Application (RFA) Number:
DE-FOA-0003612**

**RFA Type: Initial
Assistance Listings: 81.049**

RFA Issue Date:	March 17, 2026
Submission Deadline for FY26 Phase I Applications:	April 28, 2026, at 11:59 PM Eastern
Submission Deadline for FY26 Phase II Letters of Intent:	April 28, 2026, at 5 PM Eastern
Submission Deadline for FY26 Phase II Applications:	May 19, 2026, at 11:59 PM Eastern
Submission Deadline for Phase II Applications resulting from FY26 Phase I Awards:	December 17, 2026, at 11:59 PM Eastern

Contents

- Reenvisioning Advanced Manufacturing and Industrial Productivity..... 1
- Reimagining Construction and Operation of Buildings2
- Scaling the Biotechnology Revolution.....3
- Securing America’s Critical Minerals Supply..... 4
- Delivering Nuclear Energy that is Faster, Safer, Cheaper 5
- Accelerating Delivery of Fusion Energy6
- Transforming Nuclear Cleanup and Restoration.....7
- Discovering Quantum Algorithms with AI..... 8
- Realizing Quantum Systems for Discovery9
- Recentering Microelectronics in America.....10
- Securing U.S. Leadership in Data Centers 11
- Accelerating Materials Discovery, Production, and Qualification for Strategic Deterrence12
- Achieving AI-Driven Autonomous Laboratories.....13
- Designing Materials with Predictable Functionality.....14
- Enhancing Particle Accelerators for Discovery 15
- Unifying Physics from Quarks to the Cosmos.....16
- Predicting U.S. Water for Energy17
- Scaling the Grid to Power the American Economy.....18
- Unleashing Subsurface Strategic Energy Assets.....19
- Accelerating Nuclear Threat Assessment, Preparedness, and Response 20
- Harnessing America’s Historic Nuclear Data and Research21
- Increasing Experimental Capacity at Nuclear Research Facilities22
- Integrating Design and Production Operations for Nuclear Deterrence.....23
- Safeguarding Nuclear Materials from Proliferation Threats24
- Streamlining Production, Removing Red Tape, and Ensuring Safety in the Nuclear Enterprise25
- Strengthening Deterrence Through Attribution of Nuclear and Radiological Signatures.....26

Unifying Physics from Quarks to the Cosmos

Challenge: The universe obeys only one set of rules, and scientists have hundreds of experiments targeting parts of that one set. Experiments range over distance scale (31 orders of magnitude), cost (\$100k to \$B), duration (fractions of a second to decades), and human investment (few to thousands). We need a way to integrate the disparate experimental results with theoretical knowledge to accelerate discovery.

AI Solution: High-energy physics and nuclear physics form a unique foundation to build AI reasoning models at unprecedented scale. Developing AI that simultaneously learns from particle collisions, nuclear decays, and cosmological surveys will require breakthroughs in multi-modal learning and the ability to derive insights rather than merely recognize patterns. An AI that internalizes the Standard Model could accelerate analysis by orders of magnitude, identify anomalies pointing to new physics, and propose theoretical extensions consistent with all data—a leap from pattern matching to physics reasoning.

Justification: DOE uniquely possesses the confluence of world-class scientific talent, stewardship of cutting-edge facilities, unparalleled access to experimental data, and a critical national mission to effectively address this challenge. These facilities, alongside a broad portfolio of programs that explore the fundamental constituents and forces of the universe and delve into the nature of atomic nuclei, underscore DOE's singular ability to conduct large-scale, long-term, and high-impact scientific research.

National Impact: The acceleration of discovery, particularly in areas involving vast datasets from cutting-edge experiments, means we could reach breakthroughs much faster than previously possible, impacting our technological capabilities and quality of life in unforeseen ways. Questions such as why is there more matter than antimatter, what is the nature of dark matter, and how do protons generate mass and spin address the nature of reality, and answering questions through advanced AI could have profound shifts in our philosophical and scientific understanding of the cosmos and our place within it.

Focus Areas for FY 2026:

A. Foundation Models of Particle Interactions and Cosmic Physics (HEP, NP):

Develop and curate the essential data of nuclear and particle experimental efforts, critical to train foundation models of particle interactions and cosmology to accelerate new breakthroughs in our understanding of the universe. Data and models may include the future Electron-Ion Collider, cosmic observations, underground and accelerator-based experiments as well as synthesizing different modalities of data from across multiple large-scale sky surveys to understand nuclear astrophysics, dark energy, dark matter, and the physics of the early Universe. Successful scope will seamlessly span experimental and theoretical inputs across the pinch points of analysis pipelines from detector-level through to final scientific artifacts, along with the output of advanced theoretical calculations. Discovery science potential will be maximized by addressing such technical challenges as sparse-data domains and real-time data acquisition of high-dimensional petabyte-scale datasets with associated scalability challenges and interpreting the experimental signals using theoretical knowledge.

B. AI Accelerated DUNE Science (HEP)

Develop AI methods that significantly speed up and enhance the DUNE science program, reducing the time needed for the collaboration to publish neutrino oscillation measurements, significantly improving the sensitivity to neutrinos from core-collapse supernova, and developing new flagship measurements that will enhance the DUNE science goals.

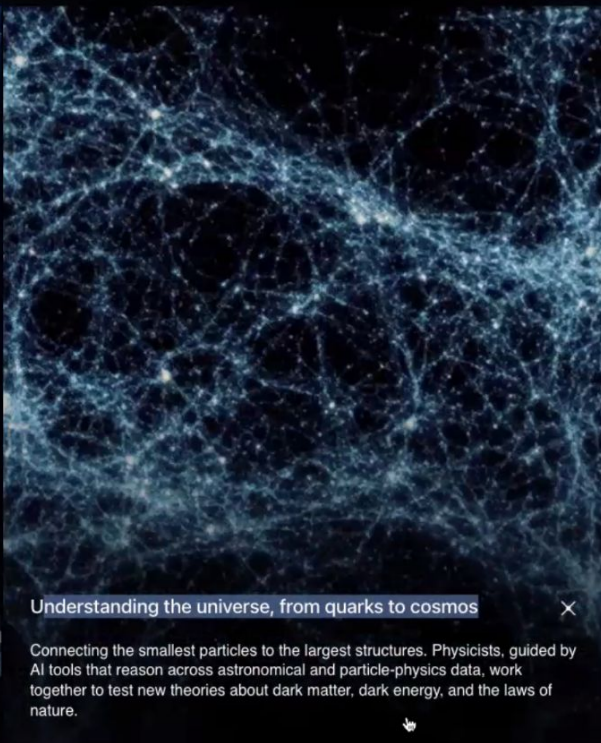
C. Expedited Discovery from High Complexity and Petabyte-Scale Datasets (HEP, NP)

Partner domain expertise with data science and industry to develop AI methods and techniques capable of drawing robust scientific insight from increasingly complex and/or petabyte-scale datasets. Enable deeper insights by directly connecting datasets with theoretical parameters for uncertainty-aware reasoning to leverage the high-dimensionality of particle physics datasets. Scope will address the critical slowdown problem in Lattice QCD, automate big-data analysis, achieve new levels of experimental precision and theoretical calculation, and significantly improve understanding of the universe and particle interactions. AI-assisted design to maximize experimental sensitivity to fundamental parameters of interest or that significantly reduces costs of proposed or current projects and can be implemented in the next three to five years, is also of interest.

Discovery Science



Seeing molecules in action



Understanding the universe, from quarks to cosmos



Connecting the smallest particles to the largest structures. Physicists, guided by AI tools that reason across astronomical and particle-physics data, work together to test new theories about dark matter, dark energy, and the laws of nature.



Discovering new quantum algorithms



Nuclear Science

[Today and for the Next Decade]

General goal (from U.S. Long Range Plan):
Explain the origin, evolution, and structure of the visible matter of the universe—the matter that makes up stars, planets, and human life itself.

Frontiers:

- **Quantum Chromodynamics (QCD) and Hadrons**

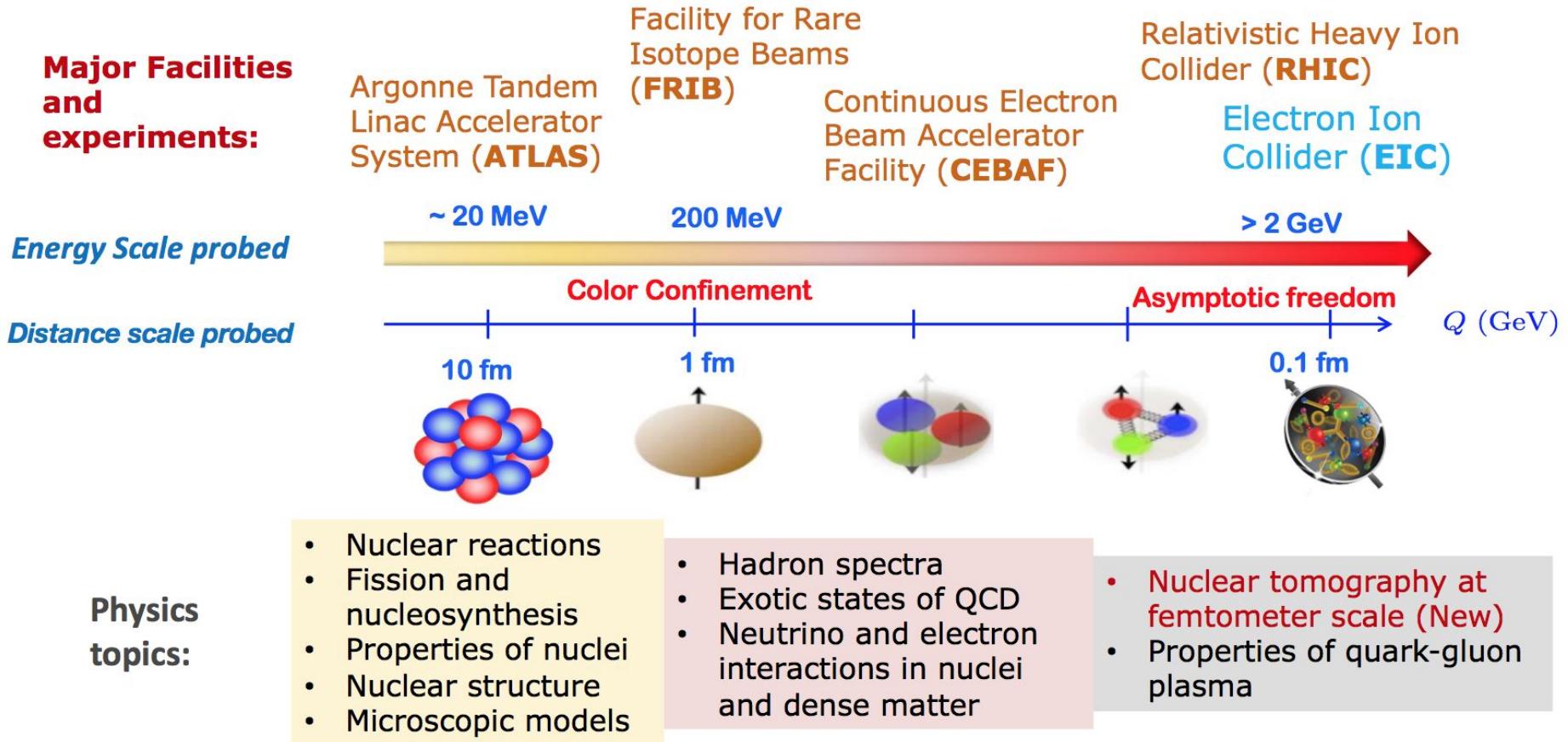
[LHC, RHIC, JLab, JPARC, e^+e^- (Beijing, DAPHNE, KEKB, Novosibirsk), . . . , FAIR]

- **Fundamental Symmetries and Neutrinos**

[neutrinos, double-beta decay, low-energy Standard Model studies, edm's, . . .]

- **Physics of Nuclei and Nuclear Astrophysics**

2022 FOA physics topics in the context of NP program



QGT Collaboration:

3-dimensional imaging of the internal structure of nucleons and nuclei

Heavy-Flavor Theory (HEFTY) for QCD Matter :

Developing framework for Heavy quarks in QCD by employing Lattice QCD computation and rigorous statistical data analysis based on effective field theory

Saturated Glue Topical Collaboration (SURGE):

Establishing an end-to-end framework for small-x observables by employing Lattice QCD and light-cone method

Nuclear Theory for New Physics (NTNP):

Precision study of neutron and nuclear decays, neutrino interactions, and electric dipole moments to uncover fundamental laws of physics

Exotic Hadron Spectroscopy(ExoHad):

Explore all aspects of exotic hadron physics, through the numerical computations of Lattice QCD and extraction of experimental data for a robust determination of the presence and properties of exotic hadron states.



Supported by DOE topical collaboration program (DE-SC0023646)



Quark-Gluon Tomography collaboration

This collaborative effort supported by US Department of Energy (DOE) aims to delve into the intricate realm of “3D quark-gluon structure of hadrons: mass, spin, and tomography.” The collaboration is built upon three foundational pillars: theory, lattice QCD, and phenomenology. The interplay among these pillars will foster a robust synergy, ultimately yielding fresh perspectives and profound insights into the overarching questions in the field.

Recent events

- 3rd QGT Collaboration All-Hands Meeting JLab, September 19-20, 2025 [link](#)

Recent press & highlights

- [Quantum calculations provide a sharper image of subatomic stress](#)

see more [here](#).

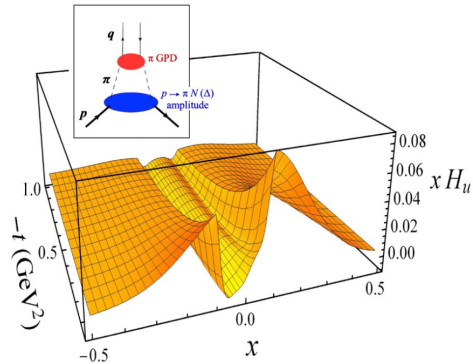


Supported by DOE topical collaboration program (DE-SC0023646)



Nucleon GPDs in nonlocal chiral effective theory

Representation of the convolution formula and the three-dimensional distribution of u quarks as a function of x and t for fixed skewness $\xi = 0.1$.



The Science

Generalized parton distributions (GPDs) are powerful tools for investigating nucleon structure, providing three-dimensional images of the nucleon's internal quark and gluon substructure. The



Review

Nucleon form factors and parton distributions in nonlocal chiral effective theory

P. Wang ^{a,b,*}, Fangcheng He ^c, Chueng-Ryong Ji ^d, W. Melnitchouk ^e



Review

Nonlocal Effective Field Theory and Its Applications

Ping Wang ^{1,2,*}, Zhengyang Gao ^{1,2}, Fangcheng He ³, Chueng-Ryong Ji ⁴, Wally Melnitchouk ⁵ and Yusupujiang Salamu ⁶

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Topical Collaboration on Heavy-Flavor TheorY (HEFTY) for QCD Matter

Search

SURGE Collaboration

The Saturated Glue (SURGE) Collaboration is a Topical Collaboration in Nuclear Theory, funded by the US Department of Energy, Office of Science, Office of Nuclear Physics for the period 2023-2027.



Nuclear Theory for New Physics

- [About Us](#)
- [Funding Acknowledgement](#)

About Us

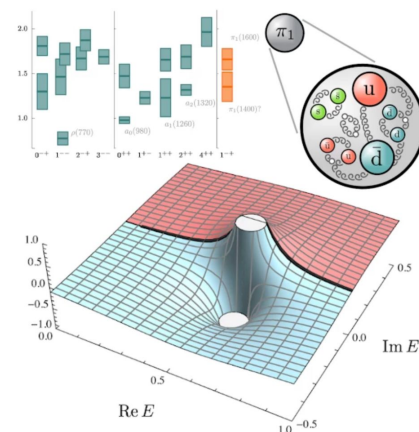
The mission of the Topical Collaboration on Nuclear Theory for New Physics (NTNP) is to address outstanding theoretical questions related to the "targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model" (2015 NSAC Long Range Plan). NTNP researchers will focus on three main topics: (i) precision calculations of β decays of neutron and nuclei, which probe possible new physics in the weak charged current at levels inaccessible by high-energy colliders; (ii) calculations of Electric Dipole Moments (EDMs) of neutral diamagnetic atoms, which provide a unique window into the breaking of CP (Charge-Parity) symmetry and the origin of the matter-antimatter asymmetry in the universe; and (iii) precise calculations of neutrino-nucleus scattering processes, a key ingredient entering the measurement of CP-violation in neutrino oscillations at long-baseline experiments. The NTNP collaboration will provide robust predictions for these processes, with controlled theoretical uncertainties, which is a prerequisite to turn experimental measurements into discovery tools.

Funding Acknowledgement

We are funded in part through [The Department of Energy, Office of Science, Office of Nuclear Physics](#) and the [Office of High Energy Physics](#)



The Exo(tic) Had(ron) Collaboration started in 2023 to explore all aspects of exotic hadron physics, from predictions within lattice QCD, through reliable extraction of their existence and properties from experimental data, to descriptions of their structure within phenomenological models.



DOE Renewal Proposal 2026-2029

Nuclear Theory at North Carolina State University

This proposal covers work by Ji, Ünsal, and Schäfer.

This proposal seeks funding for theoretical structure studies of the QCD vacuum, hadrons, finite nuclei, and dense nuclear matter. The central questions we address

How do quarks and gluons make up protons, neutrons, and, ultimately, atomic nuclei?

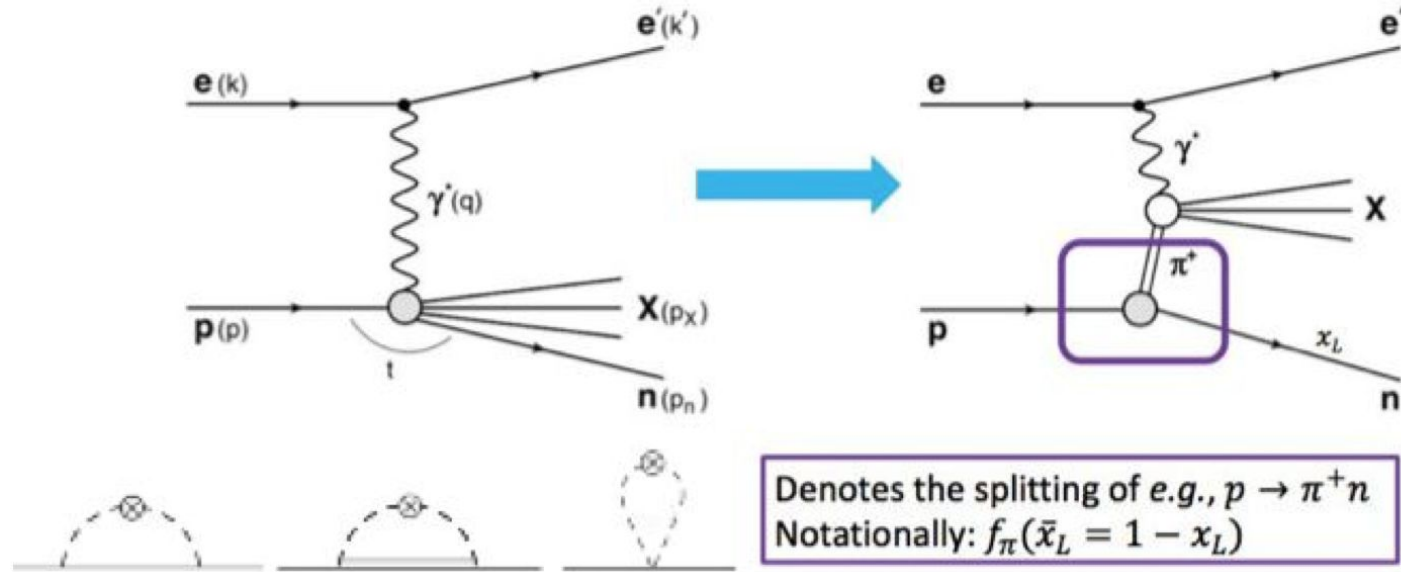
is among the main questions listed in the NSAC long range plan “A New Era of Discovery”, and it drives the experimental program at the large facilities in the US, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab (JLab), the Facility for Rare Isotope Beams (FRIB), as well as a future Electron Ion Collider (EIC).

Contents

I. Introduction	1
A. Overview	1
II. Hadronic Physics and QCD in Light-Front Dynamics with an Emphasis on Hadron Phenomenology at JLab and future EIC	1
A. Background/Introduction	1
B. Progress Report	2
1. Global QCD Analysis of Pion and Kaon Parton Distributions	2
2. Theoretical Simulation of Beam Spin Asymmetry	3
3. Chiral Effective Theory and Light-Front Quark Model Phenomenology	4
C. Proposed Work	4
1. Impact Study for future JLab, EIC and AMBER	4
2. Deeply Virtual Compton Scattering Analysis	5
3. Hadron Phenomenology with Nonlocal Chiral Effective Theory	6
4. Light-Front Quark Model Phenomenology	7
D. Milestones	8

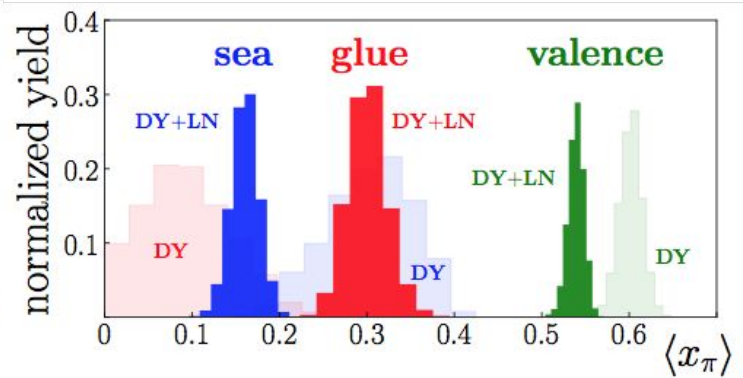
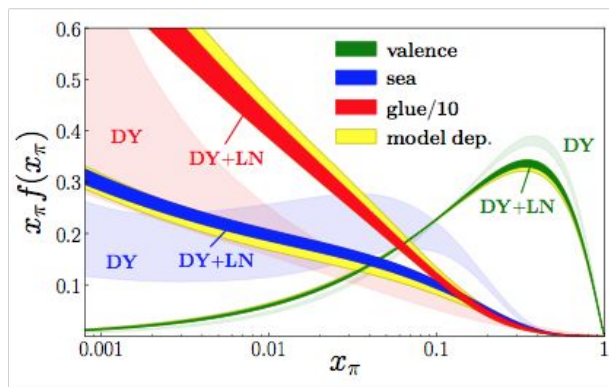
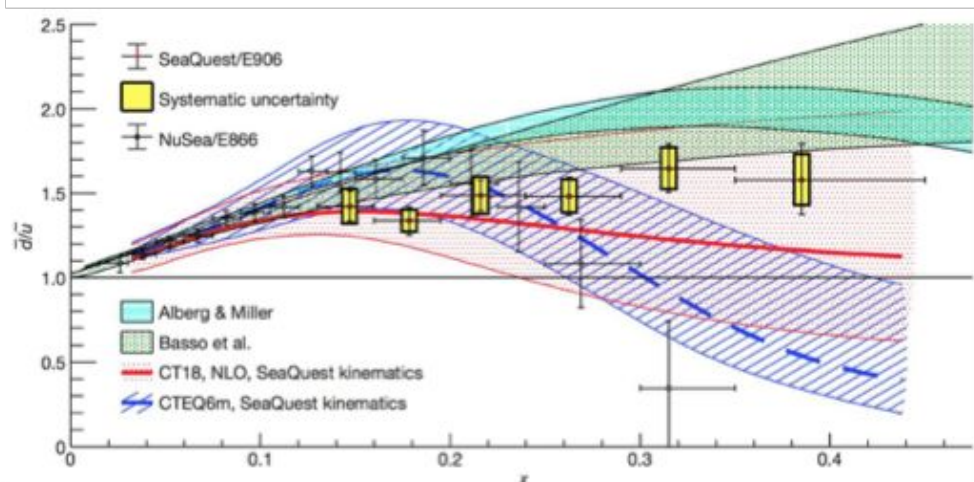
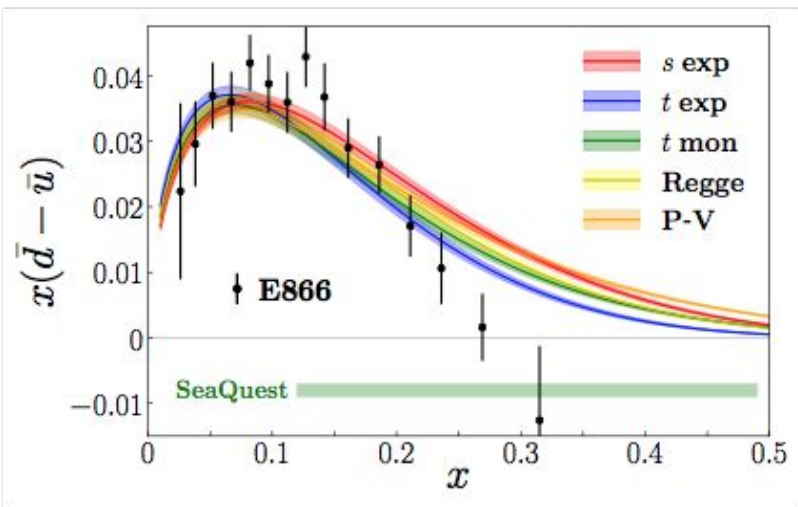
III. Phase structure and transport properties of hot and dense matter	8
A. Background/Introduction	8
B. Progress Report	9
1. Fluctuations in Fluid Dynamics	9
2. Kinetic theory for cold gases and the quark gluon plasma	10
C. Proposed Work	11
1. Relativistic stochastic fluid dynamics	11
2. Fluctuation Dynamics in Heavy Ion Collisions	12
3. Stochastic effective actions	13
4. Critical Dynamics in the Unitary Fermi Gas	13
D. Milestones	14
IV. Quantum Field Theory and Non-perturbative QCD	14
A. Background/Introduction	14
B. Progress Report	15
1. Phases of theories with \mathbb{Z}_N 1-form symmetry	15
2. Semi-classics and relation between confinement mechanisms	15
3. Self-dual monopole loops, instantons and confinement	16
4. Refined instanton analysis of the 2D $\mathbb{C}\mathbb{P}^{N-1}$ model:	16
C. Proposed work	16
1. The Internal Structure of Instantons and their Role in Confinement	16
2. Non-Perturbative Aspects of Self-Dual Yang-Mills Theory and QCD	17
3. A new expansion parameter for Yang-Mills theory and QCD	18
4. Exact WKB and Higher-Genus P/NP Relations	19
D. Milestones	20

Convolution with Chiral Effective Theory



$$(\bar{d} - \bar{u})(x) = \frac{2}{3} \int_x^1 \frac{dy}{y} f_\pi(y) \bar{q}^\pi(x/y)$$

pion light-cone momentum distribution in nucleon



Datasets vs. Kinematics

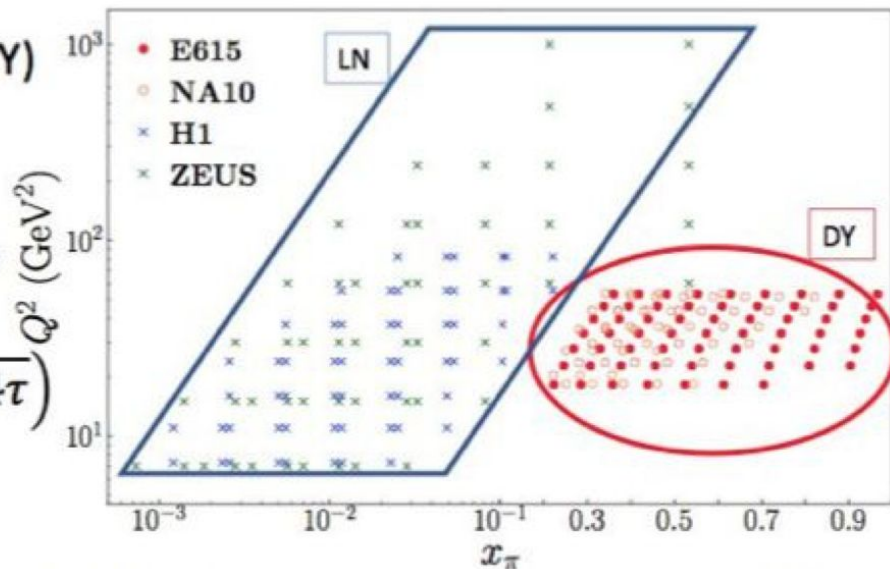
- Large x_π -- Drell-Yan (DY)
- Small x_π -- Leading Neutron (LN)
- Not much data overlap

- In DY:

$$x_\pi = \frac{1}{2} \left(x_F + \sqrt{x_F^2 + 4\tau} \right)$$

- In LN:

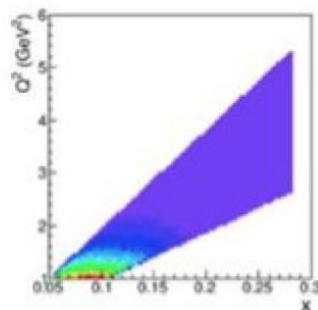
$$x_\pi = x_B / \bar{x}_L$$



- JLab can reach much smaller Q^2 and larger x range than in the HERA

EIC Impact on Pion PDFs

- $s = 5400 \text{ GeV}^2$, 1.2% systematic uncertainty, integrated $\mathcal{L} = 100\text{fb}^{-1}$



Theoretical inputs

- The valence quark GPD in pion

Valence PDF in pion

M. Aicher, A. Schafer and W. Vogelsang,
PRL105(2018)

Pion form factor

$$H_{\pi}^q(x, t) = q_v^{\pi}(x) F_{\pi}(t),$$

Parameterization

$$F_{\pi}(t) = \frac{1}{1 - t/\Lambda_{\pi}^2}.$$

M. Diehl, T. Feldmann, R. Jakob and P. Kroll, EPJC39 (2015)

Profile function

$$\begin{aligned}
 H_{q/\pi}(x, \xi, t) &= \int_{-1}^1 d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(x - \beta - \xi\alpha) h_b(\beta, \alpha) H_{q/\pi}(\beta, 0, t) \\
 &\quad + \frac{\xi}{|\xi|} D_{q/\pi}\left(\frac{x}{\xi}, t\right) \theta(\xi - |x|)
 \end{aligned}$$

$$h_b(\beta, \alpha) = \frac{\Gamma(2b+2)}{2^{2b+1}\Gamma^2(b+1)} \frac{[(1-|\beta|)^2 - \alpha^2]^b}{(1-|\beta|)^{2b+1}}$$

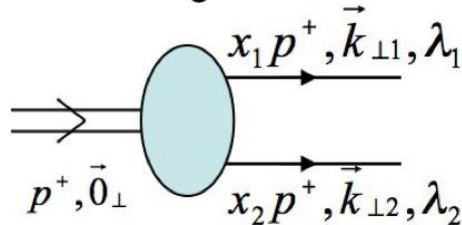
$$D_{q/\pi}(z, t) = \frac{15}{4} z(1-z^2) D_{q/\pi}(t)$$

A. V. Radyushkin, *Phys. Lett. B* **449**, 81 (1999).
 I. V. Musatov and A. V. Radyushkin, *Phys. Rev. D* **61**,
 074027 (2000).

Light-Front Quark Model(LFQM)

$$|Meson\rangle = \psi_{q\bar{q}} |q\bar{q}\rangle + \psi_{qqg} |qqg\rangle + \dots$$

$$\approx \Psi_{Q\bar{Q}} |Q\bar{Q}\rangle,$$



$$P^- = p_Q^- + p_{\bar{Q}}^-$$

$$M_0^2 = \frac{m_Q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_{\bar{Q}}^2 + \mathbf{k}_\perp^2}{1-x}$$

where

$$|Q\rangle = \psi_q^Q |q\rangle + \psi_{qg}^Q |qg\rangle + \dots$$

$$|\bar{Q}\rangle = \psi_q^{\bar{Q}} |\bar{q}\rangle + \psi_{qg}^{\bar{Q}} |\bar{q}g\rangle + \dots$$

Noninteracting "on-mass" shell Q & \bar{Q} representation

$$\Psi_{Q\bar{Q}}(x_i, \vec{k}_\perp i, \lambda_i) = \Phi(x_i, \vec{k}_\perp i) \chi(x_i, \vec{k}_\perp i, \lambda_i)$$

Radial

Spin-Orbit

The interaction between $Q\bar{Q}$

includes Coulomb, Confinement,
Spin-Spin, Spin-Orbit interactions.

$$M := M_0 + V_{Q\bar{Q}}$$

Interaction independent
Melosh transformation

$$J^{PC} = 0^{++}(f_0, a_0, \dots)$$

$$0^{-+}(\pi, K, \eta, \eta', \dots)$$

$$1^{-}(\rho, K^*, \omega, \phi, \dots)$$

PRD59, 074015(99); PLB460, 461(99) by HMC and CRJ;

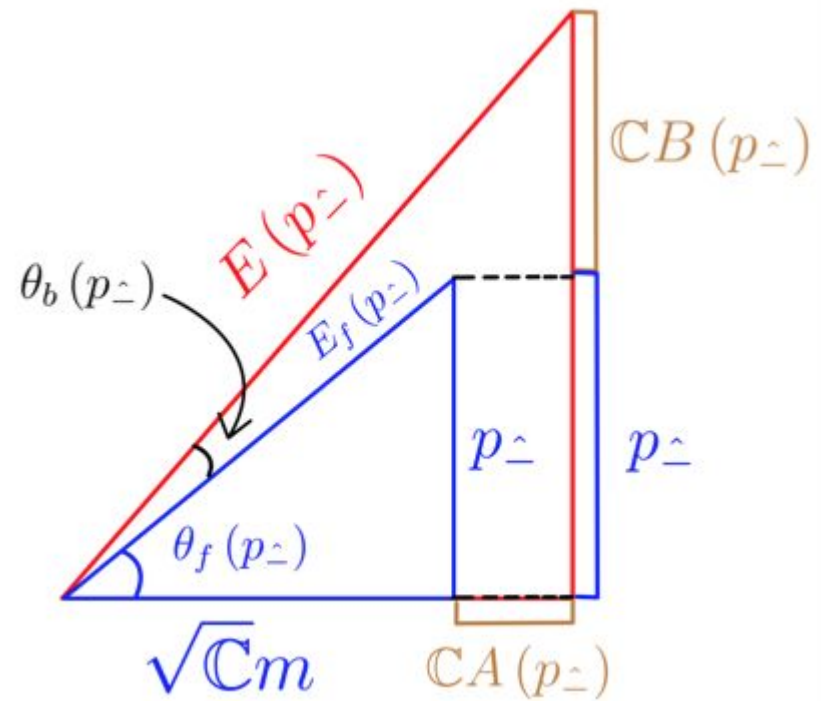
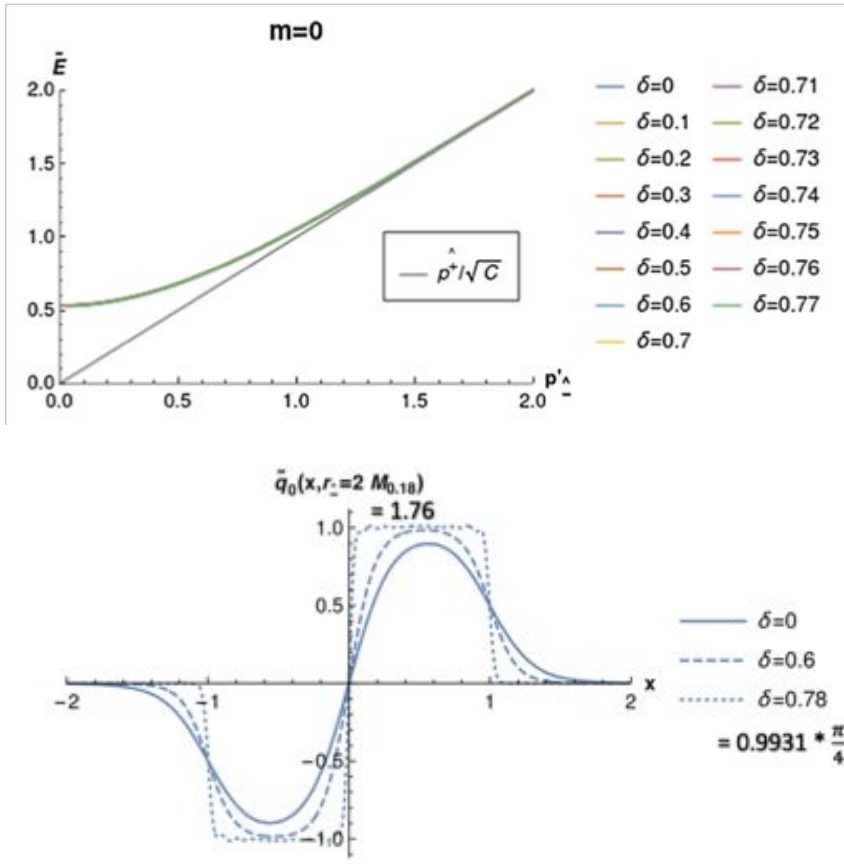
PRC92, 055203(2015) by HMC, CRI, Z. Li, and H. Rvu

PRD106, 014009(2022) by A. J. Arifi, HMC, and CRJ

HMC and CRJ, PRD110, 014006(2024)

H.J. Melosh: PRD 9, 1095(1974)

QCD Link to the Light-Front Quark Model



Conclusions and Outlook

- **Meson structure studies of LFQM provide useful tools to study the nucleon structures via the convolution with the splitting functions computed by the Chiral EFT.**
- **Analysis of LNA behaviors in Chiral EFT provides a useful link to QCD.**
- **Link between QCD and LFQM seems also feasible as exemplified by the mass gap solution in the 't Hooft model interpolation between IFD and LFD.**
- **Convoluting Chiral EFT with LFQM appears useful for the preparation of a comprehensive analysis of potential impacts for hadron structure studies envisioned in future facilities including JLab, EIC and AMBER.**

What to think about

- **EIC physics intermediates between Hot and Cold QCD**
- **AI appears powerful tool in most areas of science.**
- **Data analyses and Impact studies are more extensively called for: Hadron structure studies via SIDIS (TMDs, GPDs, TDAs).**
- **Theoretical Simulation vs. Experiments, Lattice, etc.**
- **QCD vacuum approach and parton approach need to be linked together.**
- **Fundamental understanding of spacetime interpolating IFD and LFD.**
- **LFD may fit well with the Quantum Computing with less Qubits.**

What do we need to work on?

- **LFQM of Baryons: quark-diquark vs. 3 quarks**
- **Convolution of the nucleon-meson splitting functions in the chiral effective theory with the LFQM of mesons**
- **Theoretical simulations: CFFs, GPDs, gravitational FFs**
- **Impact studies for JLab-TDIS, EIC and Amber**
- **Timelike region study of mass gap equation/solution**
- **Fundamental structure studies of hadrons**
- **Wigner Function in QCD**
- **Energy-Momentum Tensor**
- **Orientation entanglement in Quantum Computing**
- **Interpolation of 3+1D QCD between IFD and LFD**

$q\bar{q} \rightarrow gg$ {Lowest Order}

