

Overview and Plan for 2026

Chueng-Ryong Ji

North Carolina State University

Group Meeting, January 9, 2026

Outline

- **Big Picture**
 - **Topical Collaborations**
- **DOE Renewal Proposal for 2026-2029**
- **Progress Report and Proposed Works**
- **Conclusion and Outlook**
 - **What to think about**
 - **What we need to work on**
- **Plan for group meetings in Spring 2026**

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**?



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Genesis Mission Town Hall

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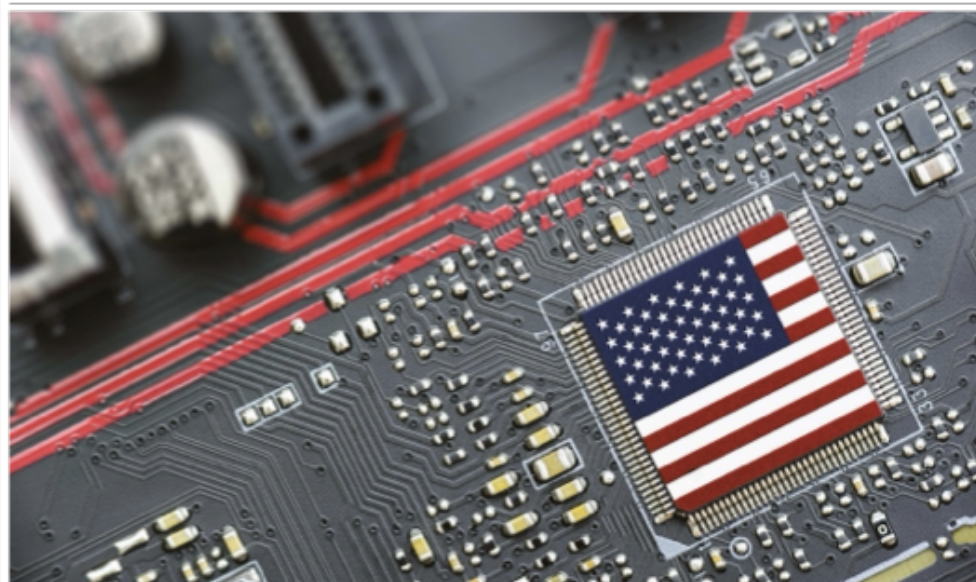
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News in focus



WILLIAM PETERSON/ISTOCK/VALENTI

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

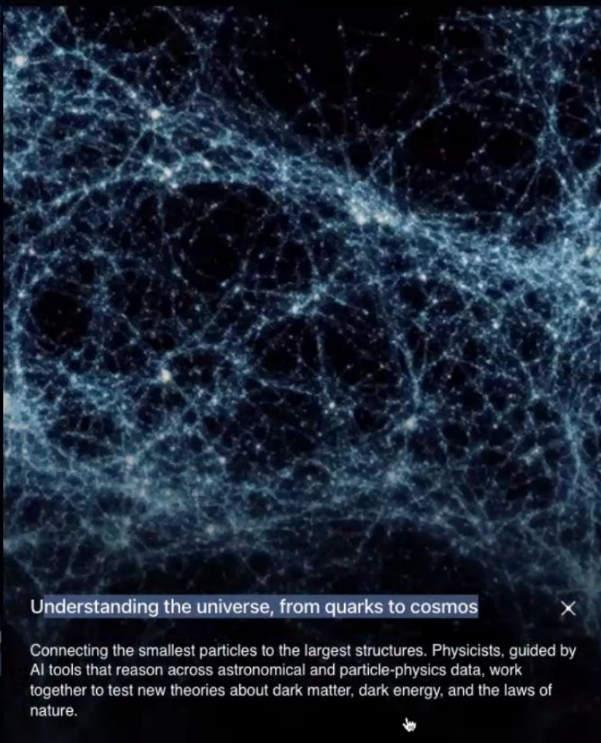
The White House has launched a plan to accelerate research in the United States, by building artificial intelligence (AI) models on the rich scientific data sets held by the country's 17 national laboratories, as well as harnessing their enormous computing resources.

Nature | Vol 648 | 11 December 2025 | 253

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**

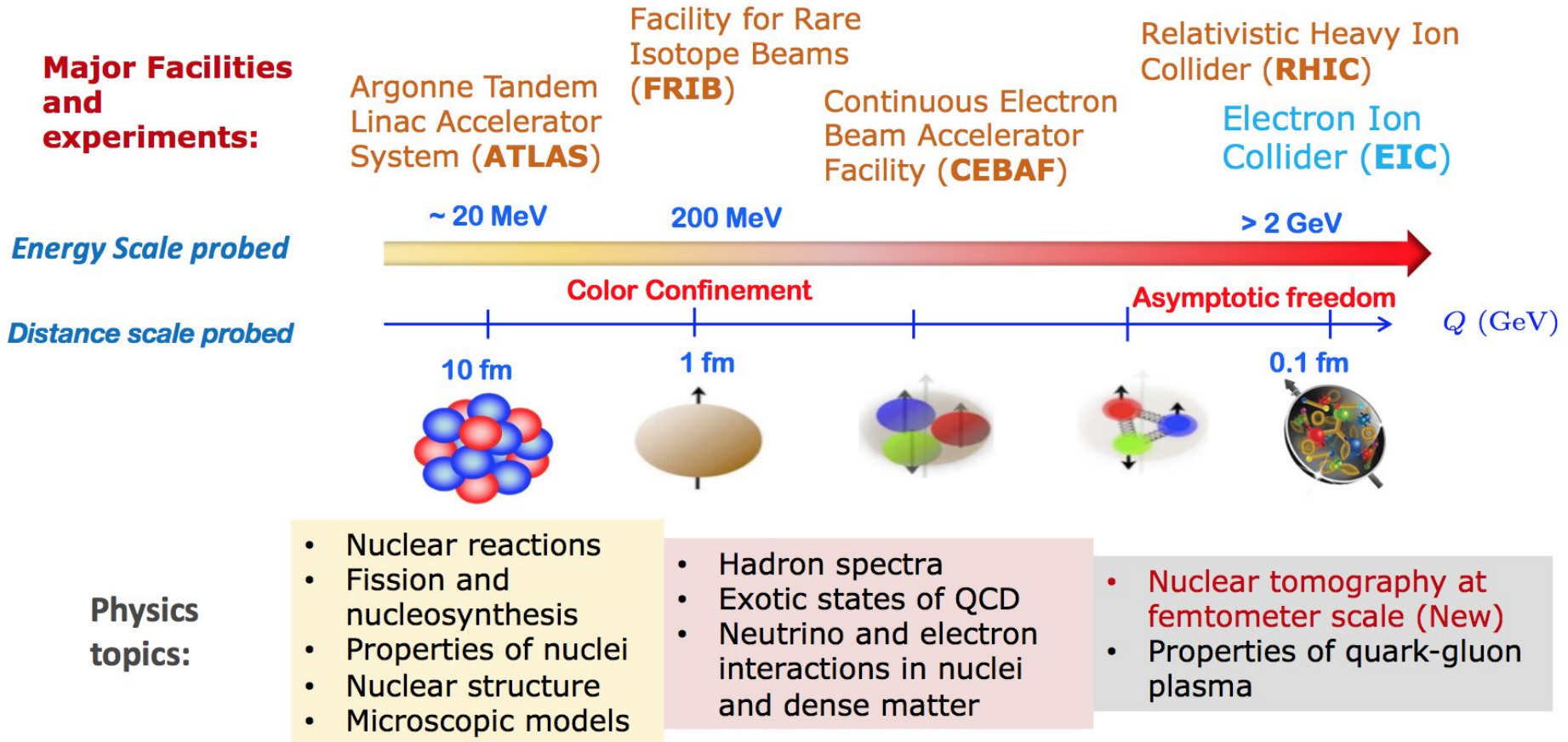
[LHC, RHIC, JLab, JPARC, e^+e^- (Beijing, DAPHNE, KEKB, Novosibirsk), . . . , FAIR]

- **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](#).

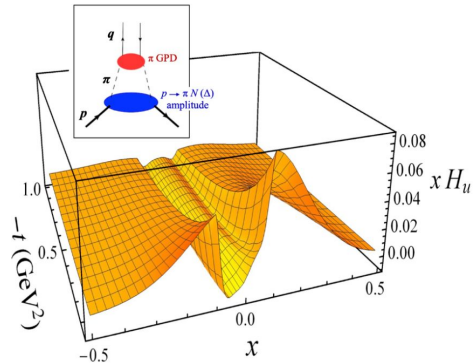


Supported by DOE topical collaboration program (DE-SC0023646)



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

Published: 23 December 2025

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

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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

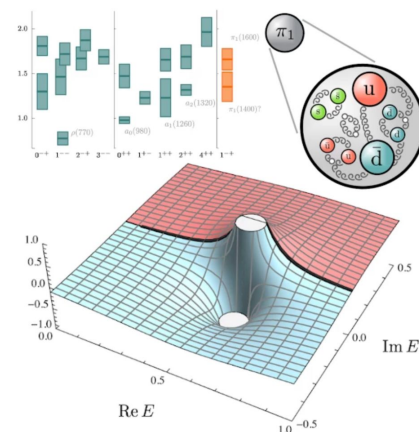
The mission of the Topical Collaboration on Nuclear Theory for New Physics (NTNP) is to address outstanding theoretical questions related to the "targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model" (2015 NSAC Long Range Plan). NTNP 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).

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P. C. Barry, C.-R. Ji, W. Melnitchouk, N. Sato and F. Steffens, “First simultaneous global QCD analysis of kaon and pion parton distributions with lattice QCD constraints,” [arXiv:2510.11979 [hep-ph]].

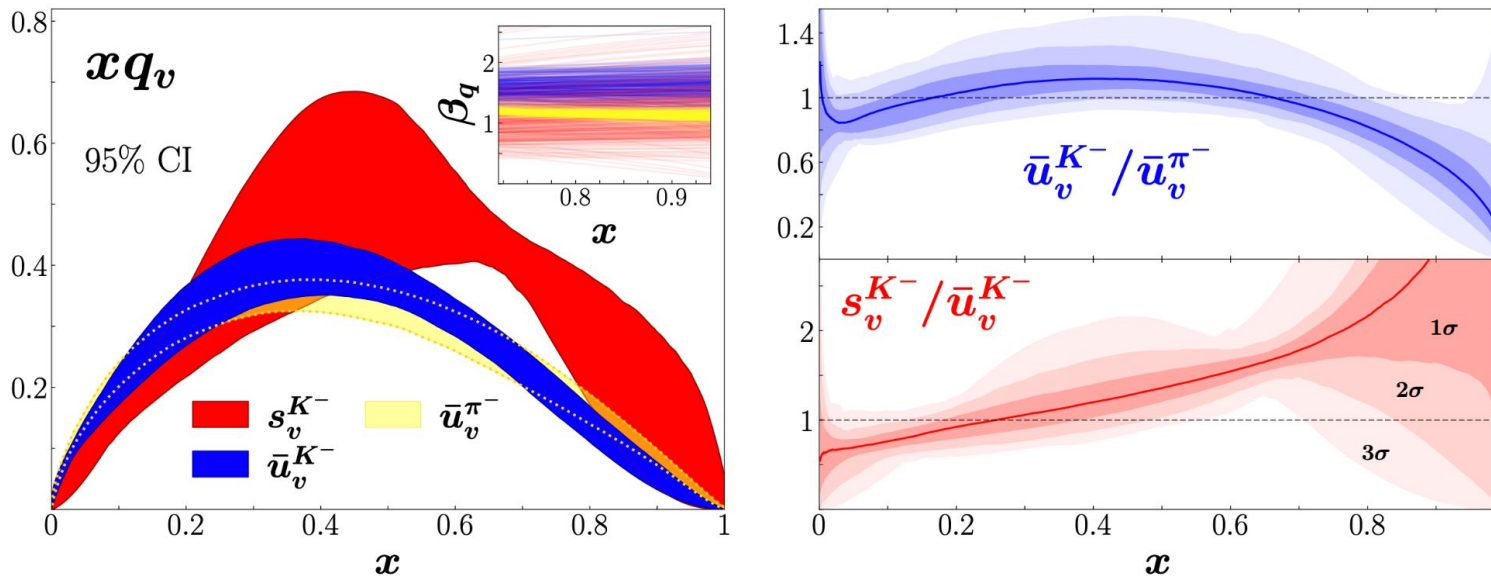


FIG. 1: Left panel: Valence quark PDFs xq_v in the K^- for the s (red) and \bar{u} (blue) quarks, and the \bar{u} in the π^- (yellow), at the input scale $\mu = m_c$ for the 95% CI. The inset shows the effective β_q exponents at large x as replicas. Here, replicas are sample PDFs drawn from the Bayesian posterior. Right panel: Ratios of the $\bar{u}_v^{K^-}$ to $\bar{u}_v^{\pi^-}$ PDFs (upper panel) and $s_v^{K^-}$ to $\bar{u}_v^{K^-}$ PDFs (lower panel) for 1 σ (darkest shading), 2 σ , and 3 σ (lightest shading) CIs.

A. Lundeen, C.-R. Ji, Y. Choi and H. M. Choi, “The (3+1)-dimensional scalar field model analysis of beam spin asymmetry in the electroproduction of a scalar meson off a scalar target,” [arXiv:2510.00369 [hep-ph]].

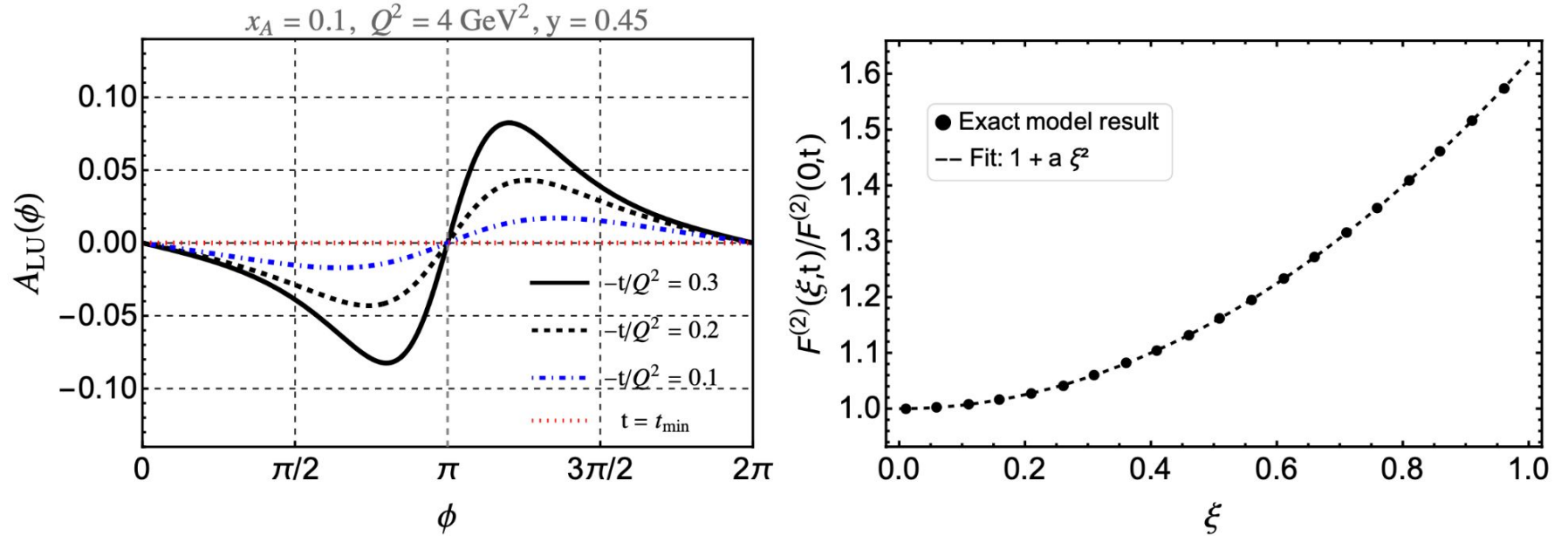
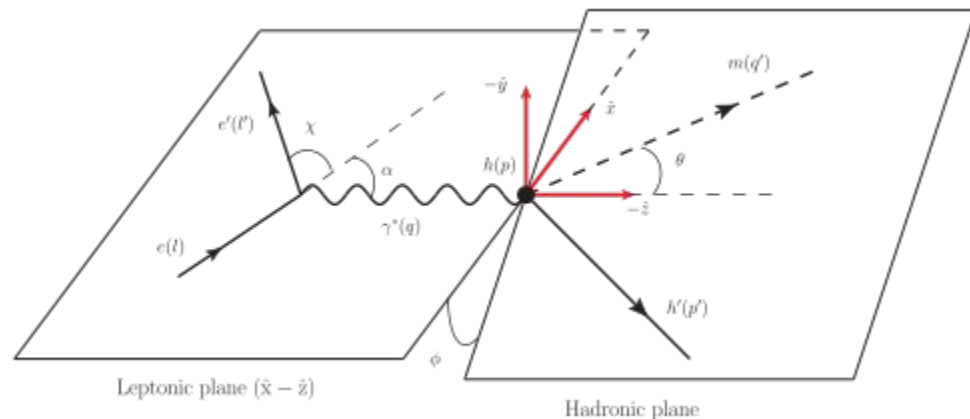
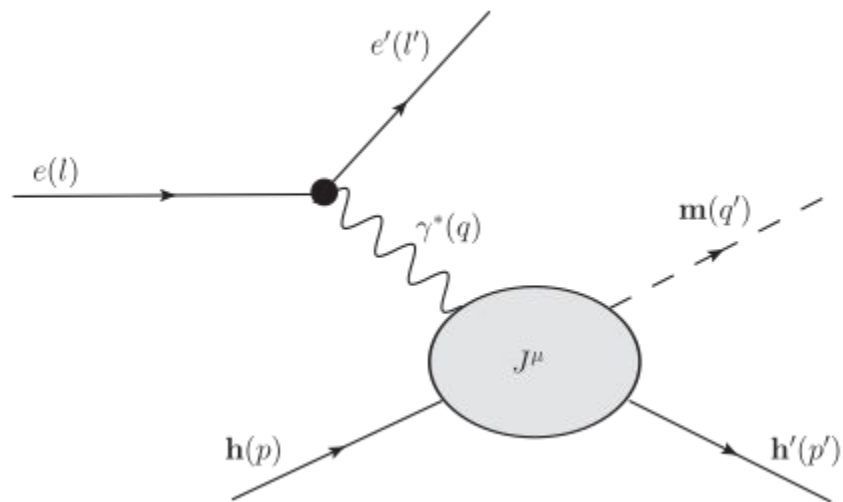


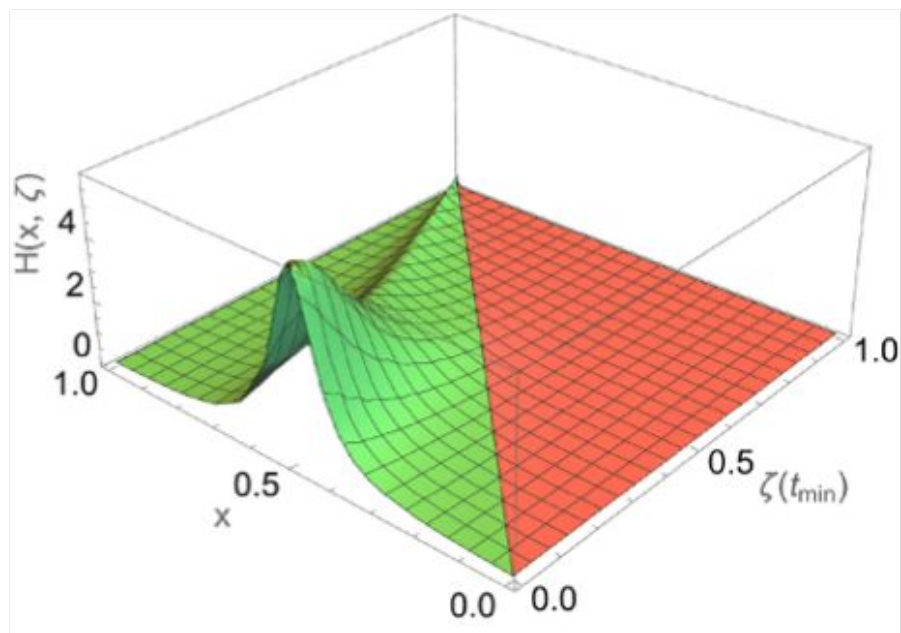
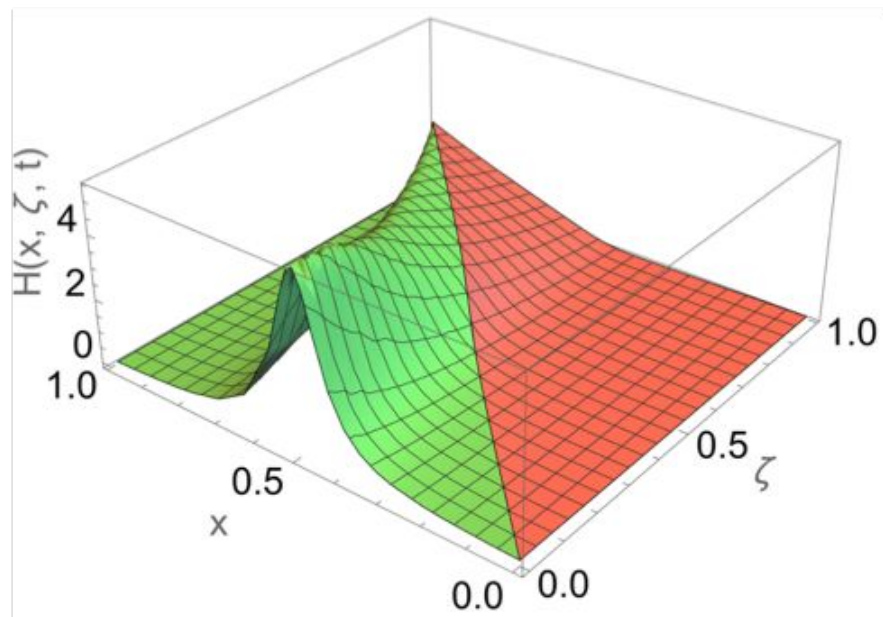
FIG. 2: Left panel: Azimuthal angle ϕ dependence of the beam spin asymmetry for various t values (in GeV^2) at fixed $x_A = 0.1$, $Q^2 = 4\text{GeV}^2$, and $y = 0.45$. Right panel: the normalized second Mellin moment ($n = 2$) at fixed $t = 0$ as a function of the symmetric skewness variable ξ .

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

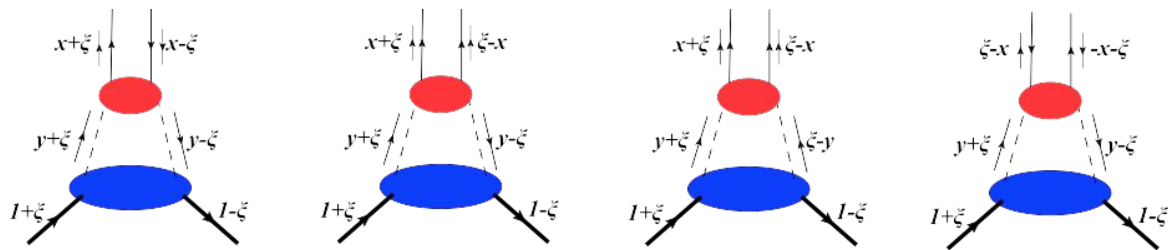
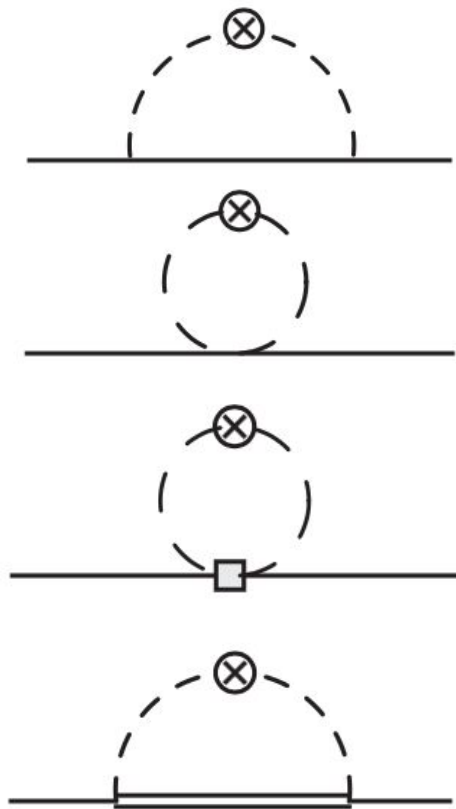
A. Lundeen, C.-R. Ji, Y. Choi and H. M. Choi,



S	$0 < k^+ < -q^+$	$-q^+ < k^+ < \Delta^+$	$\Delta^+ < k^+ < p^+$
	(a)	(b)	(c)
U	$0 < k^+ < q^{++}$	$q^{++} < k^+ < \Delta^+$	$\Delta^+ < k^+ < p^+$
	(e)	(f)	(g)
C	$0 < k^+ < q^{++}$	$q^{++} < k^+ < p^+ + q^+$	$p^+ + q^+ < k^+ < p^+$
	(i)	(j)	(k)
		(l)	

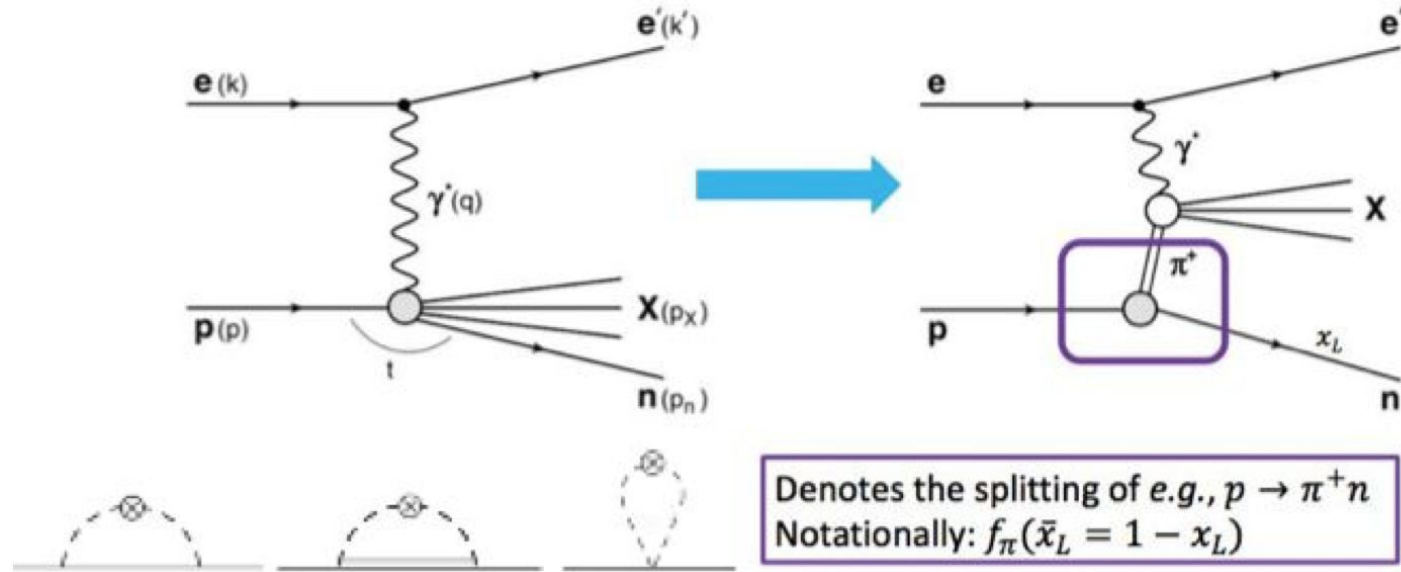


P. Wang, Z. Gao, F. He, C.-R. Ji, W. Melnitchouk and Y. Salamu, “Nonlocal effective field theory and its applications,” [arXiv:2509.25657 [hep-ph]].



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

Convolution with Chiral Effective Theory



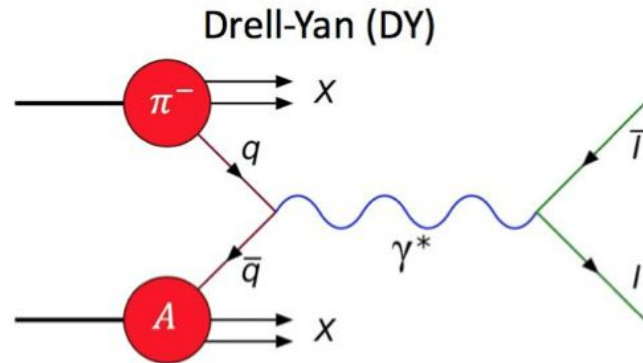
$$(\bar{d} - \bar{u})(x) = \frac{2}{3} \int_x^1 \frac{dy}{y} f_\pi(y) \bar{q}^\pi(x/y)$$

pion light-cone momentum distribution in nucleon

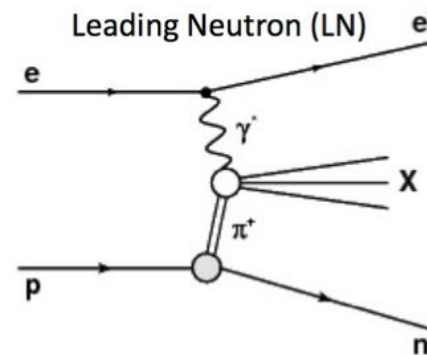
Pion Properties

- Lightest bound state composed of quarks, antiquarks, and gluons
- Masses: $m_{\pi^\pm} = 139.57 \text{ MeV}$, $m_{\pi^0} = 134.977 \text{ MeV}$
- Lifetimes: $\tau_{\pi^\pm} = 2.603 \times 10^{-8} \text{ s}$, $\tau_{\pi^0} = 8.52 \times 10^{-17} \text{ s}$

Charged pions decay via weak interaction



Neutral pions decay via electromagnetic interaction, *i.e.* $\pi^0 \rightarrow \gamma\gamma$



Datasets vs. Kinematics

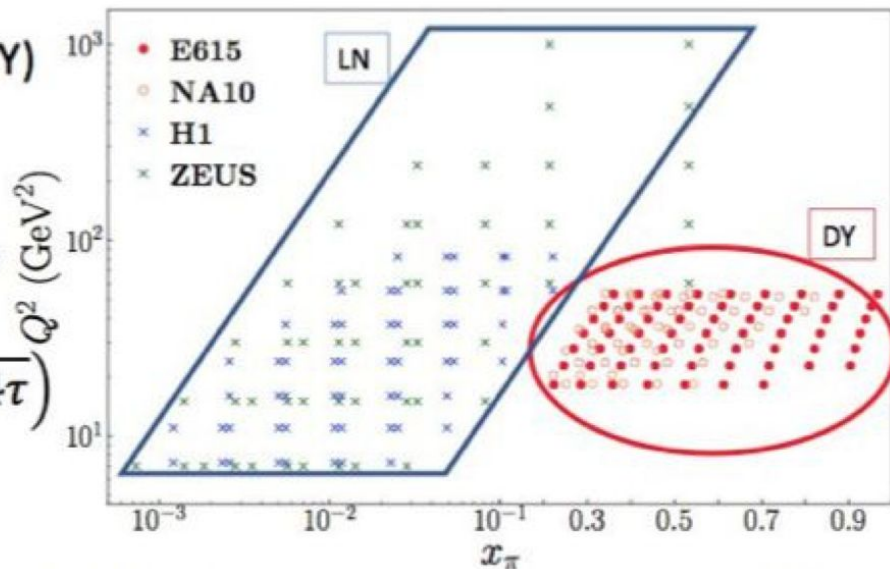
- Large x_π -- Drell-Yan (DY)
- Small x_π -- Leading Neutron (LN)
- Not much data overlap

- In DY:

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

- In LN:

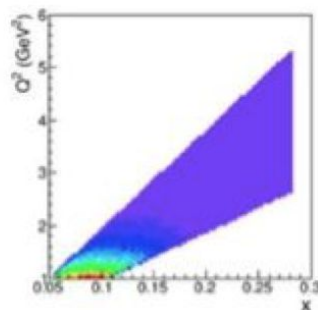
$$x_\pi = x_B / \bar{x}_L$$

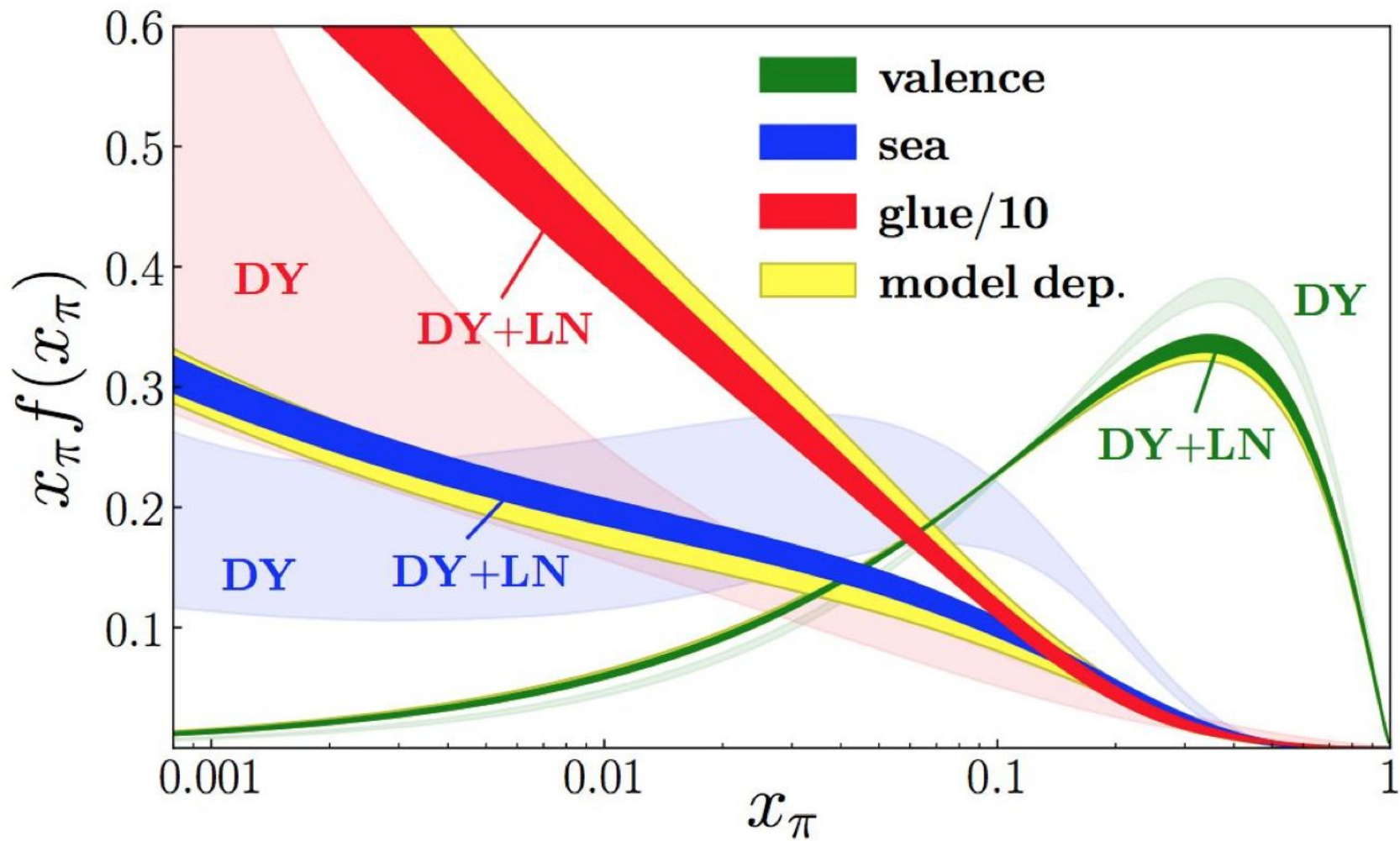


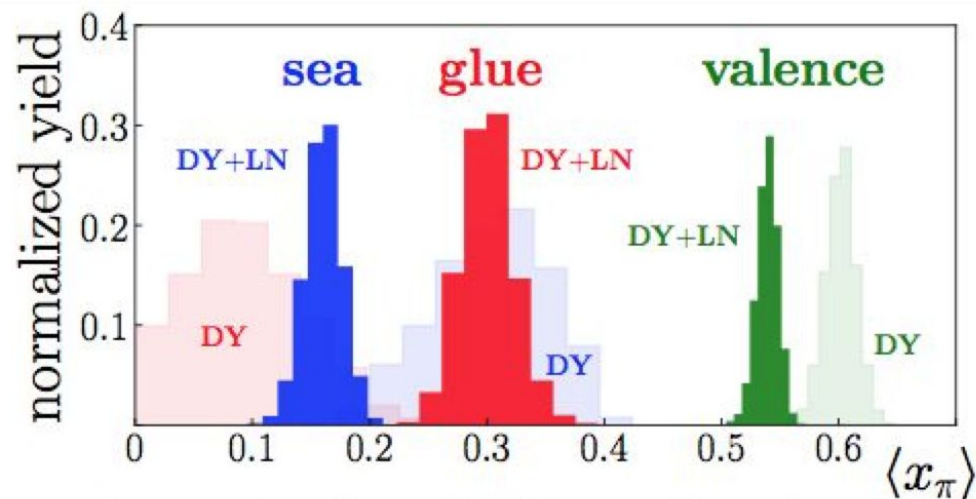
- JLab can reach much smaller Q^2 and larger x range than in the HERA

EIC Impact on Pion PDFs

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







- Constraints from HERA significantly increase $\langle x_\pi^g \rangle$.
The role of the glue is more important than suggested by DY alone
- In contrast, the strength of the sea is reduced
- Due to momentum sum rule $\langle x_\pi^{\text{valence}} \rangle$ decreases

Featured in Physics

First Monte Carlo Global QCD Analysis of Pion Parton Distributions

P. C. Barry, N. Sato, W. Melnitchouk, and Chueng-Ryong Ji (Jefferson Lab Angular Momentum (JAM) Collaboration)

Phys. Rev. Lett. **121**, 152001 (2018) – Published 10 October 2018

Physics

Synopsis: [More Gluons in the Pion](#)

<https://journals.aps.org/collections/50-years-QCD>



Teaser: A combined analysis of collider data finds that the gluon contribution to the pion is three times larger than earlier estimates.

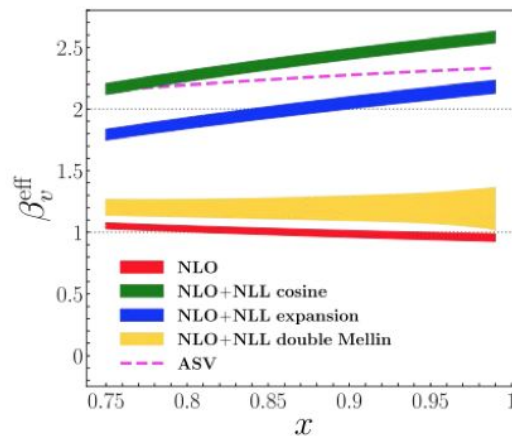
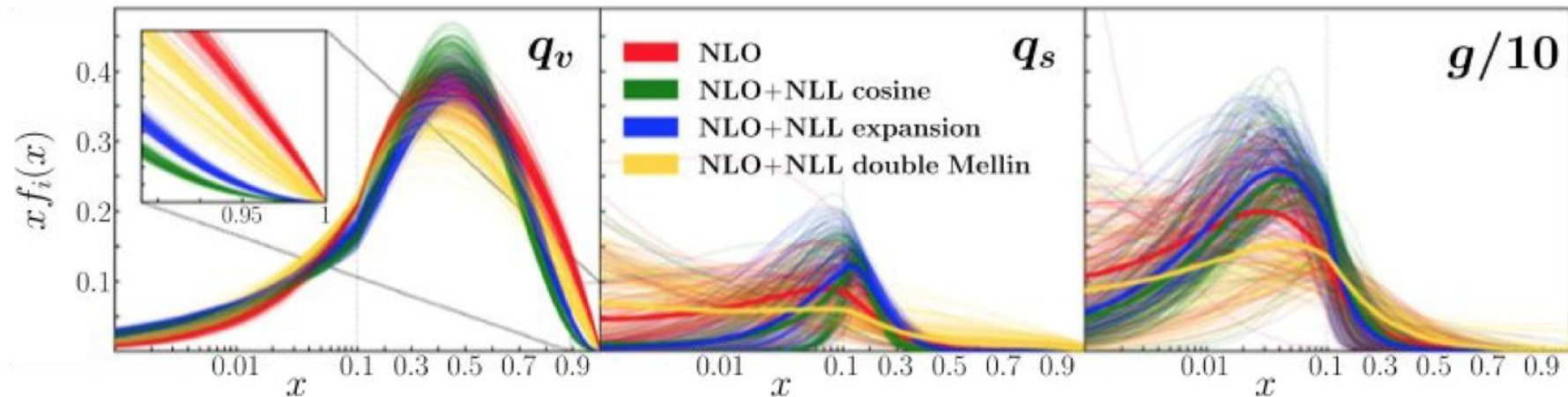
physicsworld

PARTICLE AND NUCLEAR RESEARCH UPDATE

Gluons account for much more pion momentum than previously thought

19 Oct 2018

$$f_i(x, \mu_0; \mathbf{a}_i) = N_i x^{\alpha_i} (1-x)^{\beta_i} (1 + \gamma_i x^2)$$

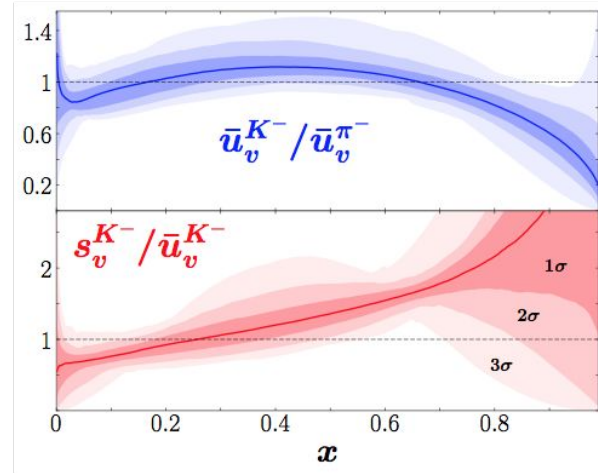
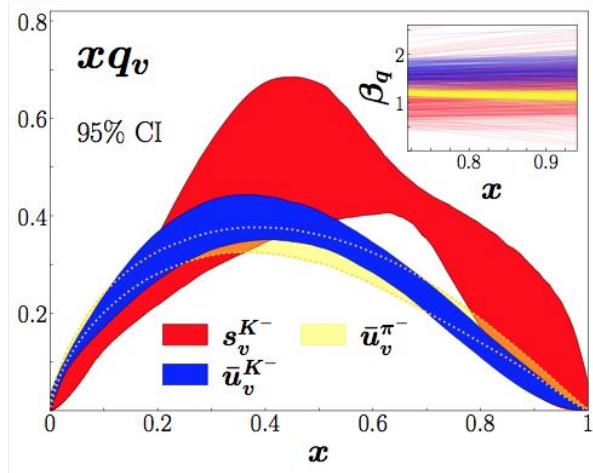
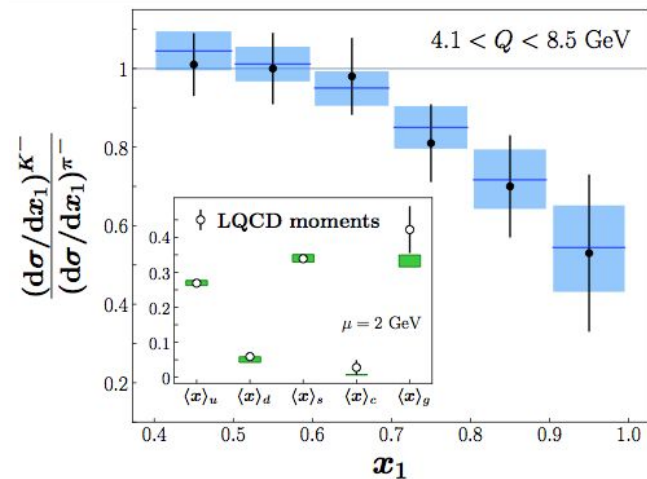


Resummation method	$\langle x \rangle_v$	$\langle x \rangle_s$	$\langle x \rangle_g$
NLO	0.53(2)	0.14(4)	0.34(6)
NLO + NLL cosine	0.47(2)	0.14(5)	0.39(6)
NLO + NLL expansion	0.46(2)	0.16(5)	0.38(6)
NLO + NLL double Mellin	0.46(3)	0.15(7)	0.40(5)

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

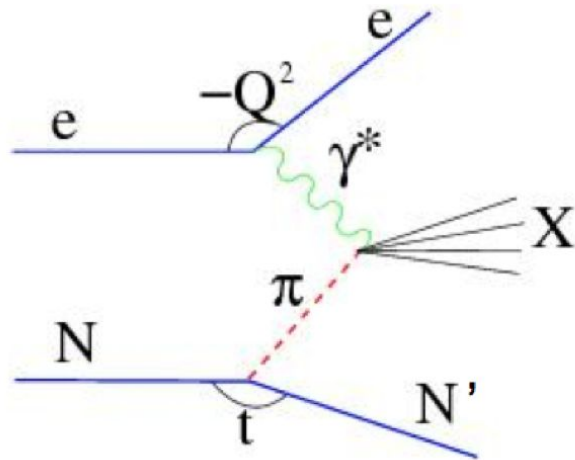
P. C. Barry,¹ Chueng-Ryong Ji,² W. Melnitchouk,³ N. Sato,³ and Fernanda Steffens^{4,5}

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



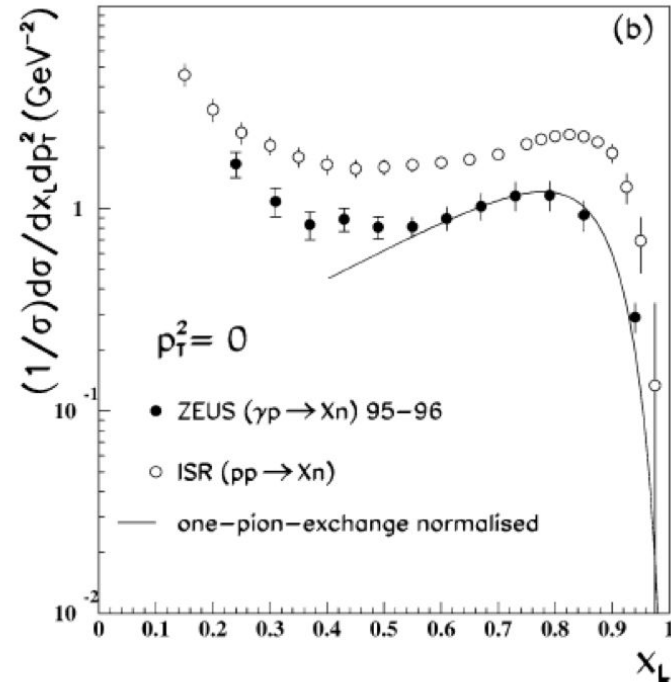
Measurement of Tagged Deep Inelastic Scattering (TDIS)

C.Keppel (Contact person)



$$e + p(\text{or } n) \rightarrow e' + p + X$$

$$e + D \rightarrow e' + p + p + X$$



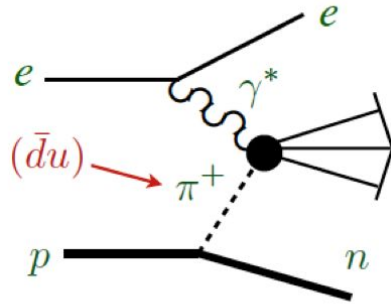
Leading neutron production in e^+p collisions at HERA

ZEUS Collaboration, NPB 637 (2002) 3–56

Flavor asymmetry

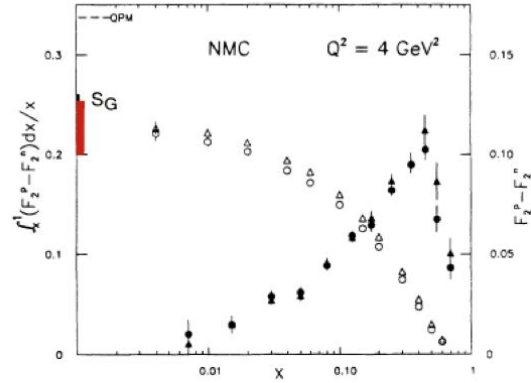
- Large flavor asymmetry in proton sea suggests important role of chiral symmetry in high-energy reactions

→ Sullivan process in DIS



Sullivan, PRD 5, 1732 (1972)

$$\bar{d} > \bar{u}$$



$$\int_0^1 \frac{dx}{x} (F_2^p - F_2^n) = \frac{1}{3} - \frac{2}{3} \int_0^1 dx (\bar{d} - \bar{u})$$

$$= 0.235(26)$$

NMC, PRD 50, 1 (1994)

Flavor asymmetry

- Pion cloud corrections to electromagnetic N coupling

→ N rainbow (c), π rainbow (d),
Kroll-Ruderman (e),
 π bubble (f), π tadpole (g)

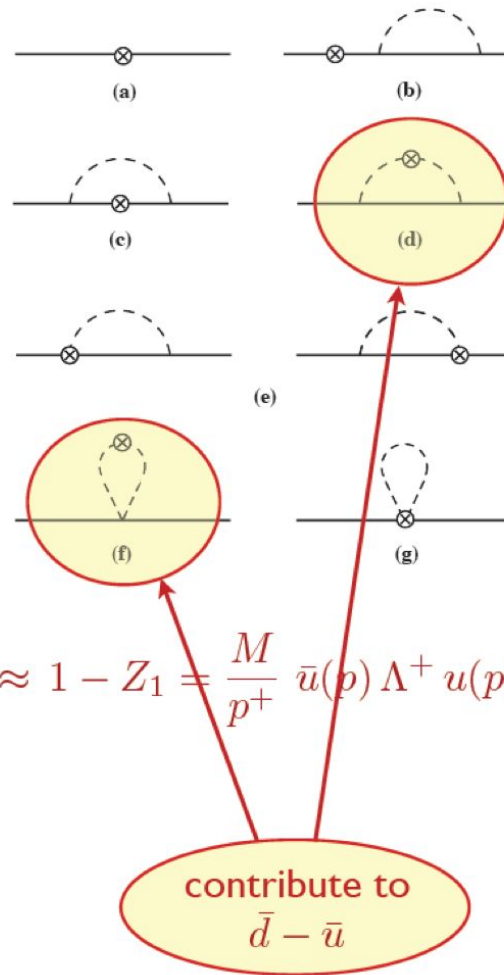
- Vertex renormalization

$$(Z_1^{-1} - 1) \bar{u}(p) \gamma^\mu u(p) = \bar{u}(p) \Lambda^\mu u(p)$$

→ taking “+” components: $Z_1^{-1} - 1 \approx 1 - Z_1 = \frac{M}{p^+} \bar{u}(p) \Lambda^+ u(p)$

→ e.g. for N rainbow contribution,

$$\Lambda_\mu^N = -\frac{\partial \hat{\Sigma}}{\partial p^\mu}$$



Connection with QCD

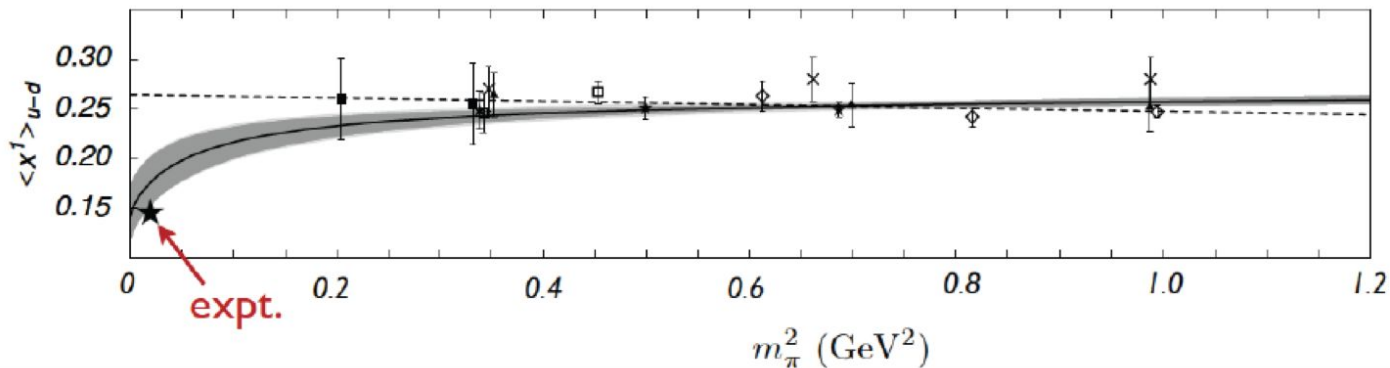
$$\blacksquare (\bar{d} - \bar{u})(x) = \frac{2}{3} \int_x^1 \frac{dy}{y} f_\pi(y) \bar{q}^\pi(x/y) \quad \boxed{f_\pi(y) = \frac{3g_{\pi NN}^2}{16\pi^2} y \int dt \frac{-t \mathcal{F}_{\pi NN}^2(t)}{(t - m_\pi^2)^2}}$$

→ *model-independent leading nonanalytic (LNA) behavior consistent with Chiral Symmetry of QCD.*

$$\begin{aligned} \langle x^0 \rangle_{\bar{d}-\bar{u}} &\equiv \int_0^1 dx (\bar{d} - \bar{u}) & \boxed{m_\pi^2 f_\pi^2 = -2m_q \langle \bar{q}q \rangle} \\ &= \frac{2}{3} \int_0^1 dy f_\pi(y) = \frac{2g_A^2}{(4\pi f_\pi)^2} m_\pi^2 \log(m_\pi^2/\mu^2) + \text{analytic terms} \end{aligned}$$

Nonanalytic behavior vital for chiral extrapolation of lattice data

Thomas, Melnitchouk, Steffens PRL 85, 2892 (2000)



LNA of $\bar{D} - \bar{U} \equiv \int_0^1 dx (\bar{d} - \bar{u})$

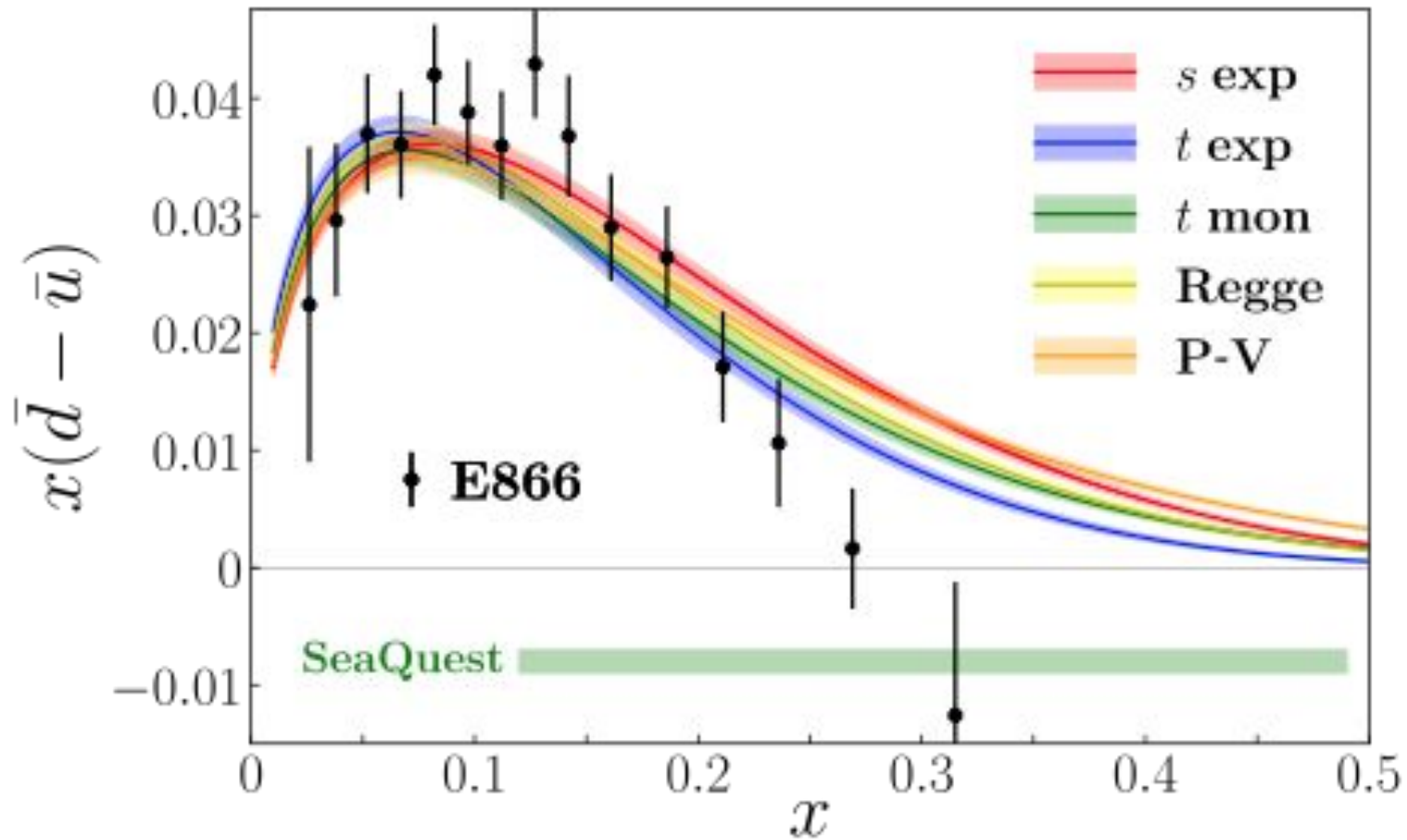


C.Ji, W.Melnitchouk, A.W.Thomas,
Phys.Rev.D 88 (2013) 7, 076005

$$\begin{aligned}
 (\bar{D} - \bar{U})_{LNA} &= \frac{3g_A^2 + 1}{2(4\pi f_\pi)^2} m_\pi^2 \log m_\pi^2 \\
 &= \frac{4g_A^2 + (1 - g_A^2)}{2(4\pi f_\pi)^2} m_\pi^2 \log m_\pi^2
 \end{aligned}$$

“on-shell”
contribution

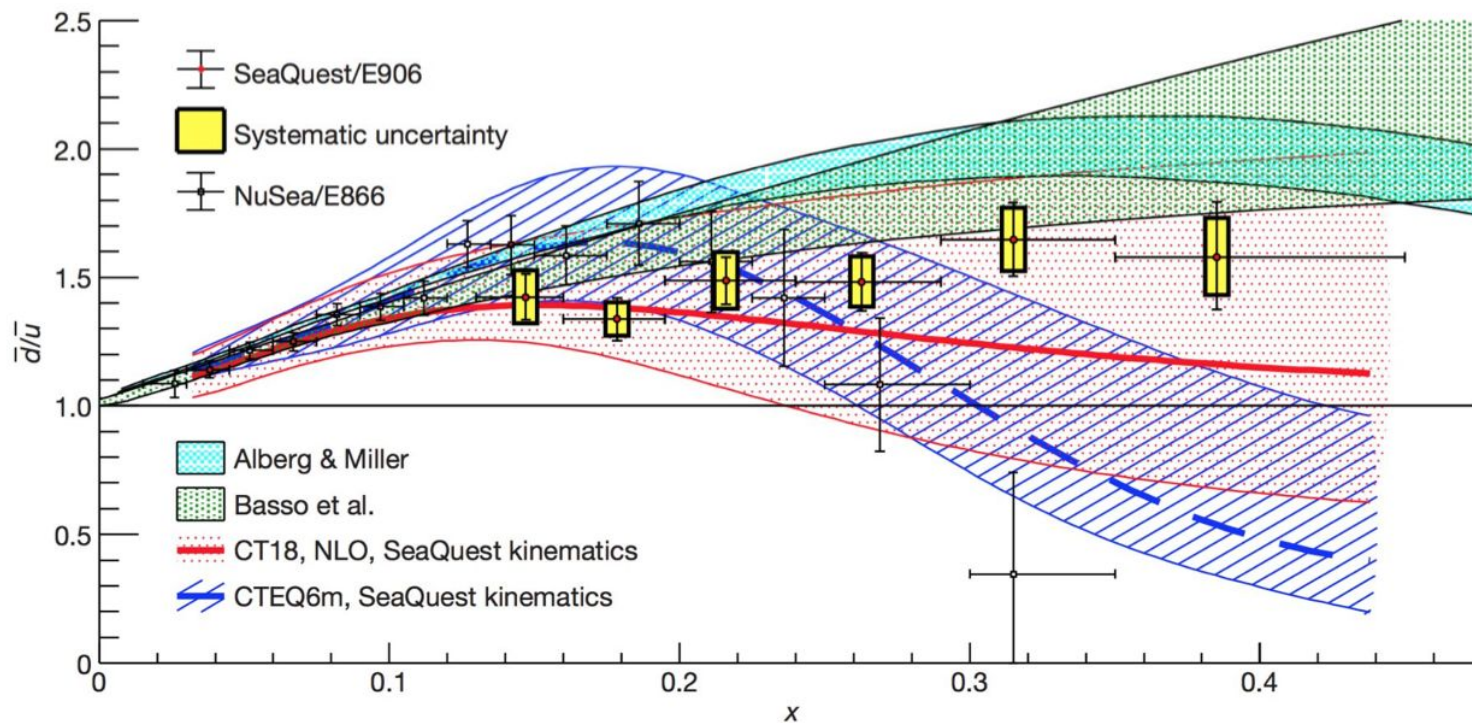
δ -function
contribution



P. Barry, N. Sato, W. Melnitchouk, C.Ji, PRL121, 152001(2018)

Article

The asymmetry of antimatter in the proton



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

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

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

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

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

Glimpse of Link between QCD and LFQM

B.Ma and C. Ji, PRD104, 036004 (2021) ; INPC2025

Large N_c QCD in 1+1 dim. ('tHooft Model)

$$\mathcal{L} = -\frac{1}{4} F_{\hat{\mu}\hat{\nu}}^a F^{\hat{\mu}\hat{\nu}a} + \bar{\psi}(i\gamma^{\hat{\mu}} D_{\hat{\mu}} - m)\psi$$

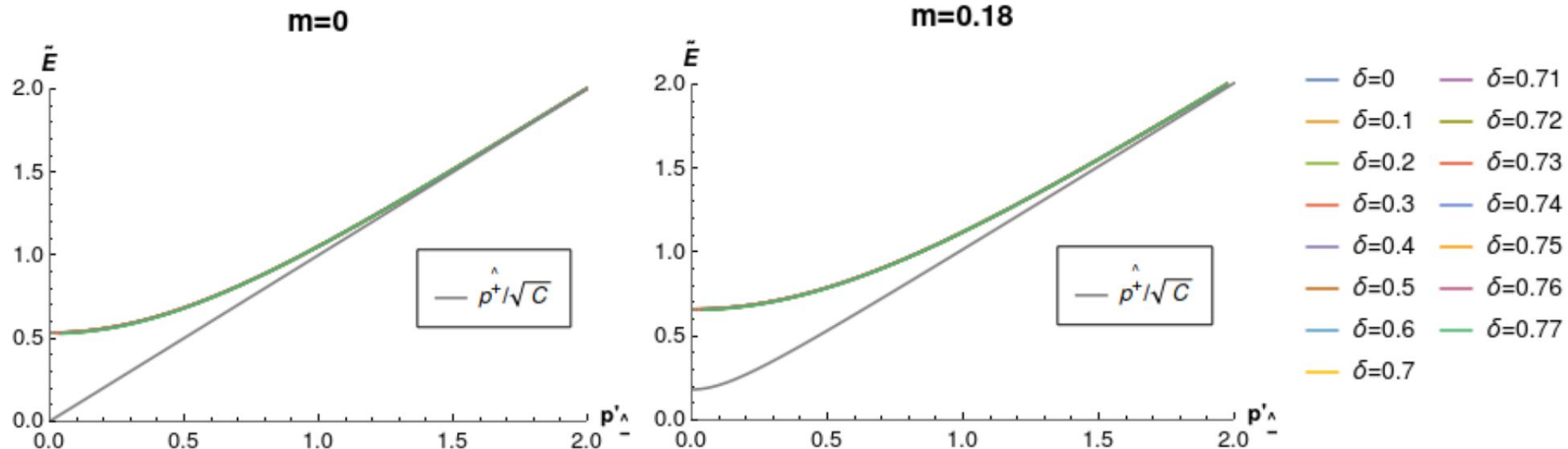
$$D_{\hat{\mu}} = \partial_{\hat{\mu}} - igA_{\hat{\mu}}^a t_a$$

$$F_{\hat{\mu}\hat{\nu}}^a = \partial_{\hat{\mu}} A_{\hat{\nu}}^a - \partial_{\hat{\nu}} A_{\hat{\mu}}^a + gf^{abc} A_{\hat{\mu}}^b A_{\hat{\nu}}^c$$

'tHooft Coupling $\lambda = \frac{g^2(N_c - 1/N_c)}{4\pi}$ and mass m

$$g \rightarrow 0, N_c \rightarrow \infty; \lambda \rightarrow \text{finite}$$

Mass Gap Solutions



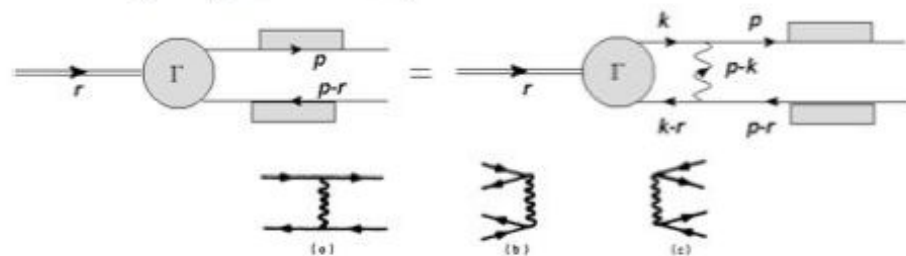
$$\tilde{E}(0) = \frac{F(0)E(0)}{\sqrt{C}} = M(0)$$

m	0	0.045	0.18	0.749	1.00	2.11	4.23
$M(0)$	0.532778	0.563644	0.659112	1.10105	1.31167	2.30969	4.34358
$F(0)$	-0.495173	-0.584175	-0.987673	4.11079	2.17976	1.22134	1.05526

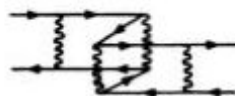
$$m \lesssim 0.56$$

BOUND-STATE EQUATION

$$\Gamma(r, p) = \frac{i\lambda}{2\pi} \int \frac{dk_{\perp} dk_{\parallel}}{(p_{\perp} - k_{\perp})^2} S(p) \gamma^{\dagger} \Gamma(r, k) \gamma^{\dagger} S(p - r)$$



$$\begin{aligned} & \left[-r_{\parallel} + \frac{-S p_{\parallel} + E(p_{\parallel})}{C} + \frac{S(p_{\parallel} - r_{\parallel}) + E(p_{\parallel} - r_{\parallel})}{C} \right] \hat{\phi}_{+}(r_{\perp}, p_{\perp}) \\ &= \lambda \int \frac{dk_{\perp}}{(p_{\perp} - k_{\perp})^2} \left[C(p_{\perp}, k_{\perp}, r_{\perp}) \hat{\phi}_{+}(r_{\perp}, k_{\perp}) - S(p_{\perp}, k_{\perp}, r_{\perp}) \hat{\phi}_{-}(r_{\perp}, k_{\perp}) \right], \\ & \left[r_{\parallel} + \frac{-S(p_{\parallel} - r_{\parallel}) + E(p_{\parallel} - r_{\parallel})}{C} + \frac{S p_{\parallel} + E(p_{\parallel})}{C} \right] \hat{\phi}_{-}(r_{\perp}, p_{\perp}) \\ &= \lambda \int \frac{dk_{\perp}}{(p_{\perp} - k_{\perp})^2} \left[C(p_{\perp}, k_{\perp}, r_{\perp}) \hat{\phi}_{-}(r_{\perp}, k_{\perp}) - S(p_{\perp}, k_{\perp}, r_{\perp}) \hat{\phi}_{+}(r_{\perp}, k_{\perp}) \right]. \end{aligned}$$



LFD

$$\left[\mathcal{M}^2 - \frac{m^2 - 2\lambda}{x} - \frac{m^2 - 2\lambda}{1-x} \right] \phi(x) = -2\lambda \int_0^1 \frac{dy}{(x-y)^2} \phi(y)$$

Bakamjian-Thomas Construction

B.Bakamjian and L.H.Thomas, Phys.Rev.92,1300(1953)

B.Keister and W.Polyzou, Adv.Nucl.Phys.20,225(1991)

$$[P^i, K^j] = i\delta_{ij}H$$

$$\{H, \mathbf{P}, \mathbf{J}, \mathbf{K}\} \Rightarrow \{M, \mathbf{P}, \mathbf{j}_c, \mathbf{X}_c\} \Rightarrow \{M_0, \mathbf{P}_0, \mathbf{j}_{c0}, \mathbf{X}_{c0}\} \Rightarrow \{M, \mathbf{P}_0, \mathbf{j}_{c0}, \mathbf{X}_{c0}\}$$

$$H = \sqrt{M^2 + \mathbf{P}^2};$$

$$\mathbf{K} = -\frac{1}{2}\{H, \mathbf{X}_c\}_+ - \frac{\mathbf{P} \times \mathbf{j}_c}{H + M};$$

$$\mathbf{J} = \mathbf{X}_c \times \mathbf{P} + \mathbf{j}_c.$$

$$P_0^\mu := P_1^\mu \otimes I_2 + I_1 \otimes P_2^\mu;$$

$$\mathbf{K}_0 := \mathbf{K}_1 \otimes I_2 + I_1 \otimes \mathbf{K}_2;$$

$$\mathbf{J}_0 := \mathbf{J}_1 \otimes I_2 + I_1 \otimes \mathbf{J}_2.$$

$$M := M_0 + V$$

$$[V, \{\mathbf{P}_0, \mathbf{j}_{c0}, \mathbf{X}_{c0}\}] = 0$$

Light-Front Quark Model(LFQM)

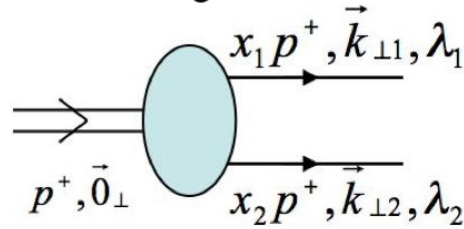
$$|Meson\rangle = \psi_{q\bar{q}} |q\bar{q}\rangle + \psi_{qqg} |qqg\rangle + \dots$$

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

where

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

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



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

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

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

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

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

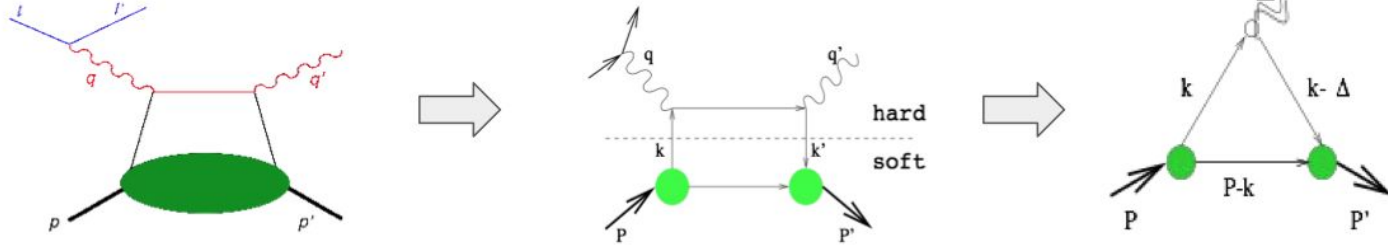
$$1^{-}(\rho, K^*, \omega, \phi, \dots)$$

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)

H.-M. Choi and C. Ji, PRD110, 014006 (2024)



$$\langle P | J^+ | P \rangle = 2P^+ \int dx \int \frac{d^2 \mathbf{k}_\perp}{16\pi^3} |\phi(x, \mathbf{k}_\perp)|^2$$

$$f_1^q(x, \mathbf{k}_\perp) = \frac{1}{16\pi^3} |\phi(x, \mathbf{k}_\perp)|^2 \quad \int dx \int d^2 \mathbf{k}_\perp f_1^q(x, \mathbf{k}_\perp) = \int dx f_1^q(x) = 1$$

$$\langle P | J^\perp | P \rangle = \int dx \int \frac{d^2 \mathbf{k}_\perp}{16\pi^3} |\phi(x, \mathbf{k}_\perp)|^2 \left(-\frac{2\mathbf{k}_\perp}{x} \right)$$

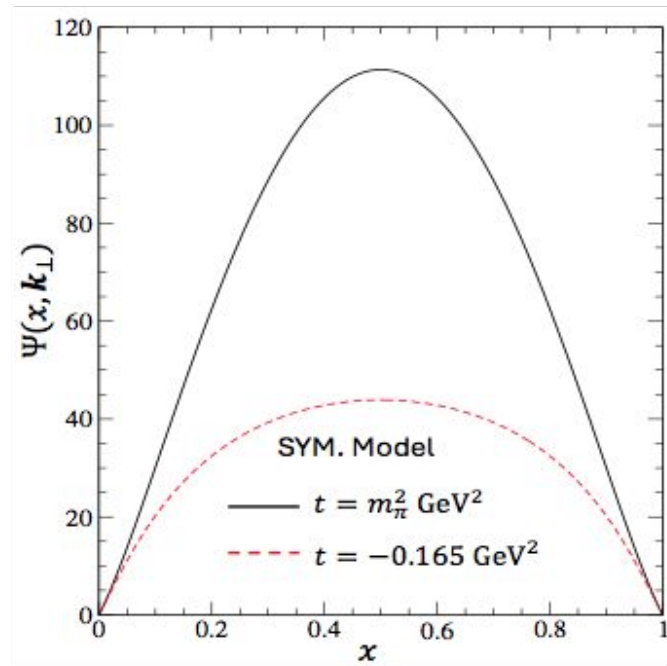
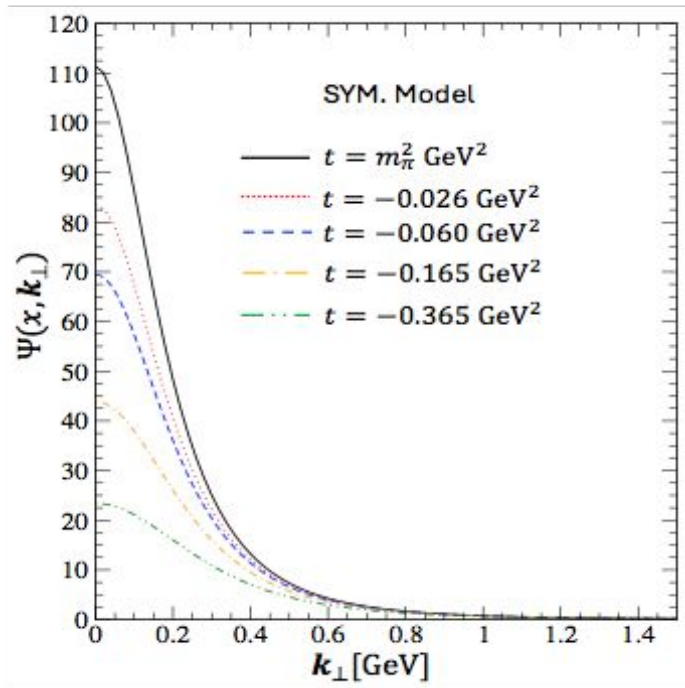
$$2\mathbf{k}_\perp f_3^q(x, \mathbf{k}_\perp) = \frac{1}{16\pi^3} |\phi(x, \mathbf{k}_\perp)|^2 \left(-\frac{2\mathbf{k}_\perp}{x} \right) \quad x f_3^q(x, \mathbf{k}_\perp) = -f_1^q(x, \mathbf{k}_\perp)$$

$$f(x) = \int d^2 p_T f(x, p_T) \quad 2 \int dx f_4^q(x) = \int dx f_1^q(x) = 1$$

Off-shell pion properties: electromagnetic form factors and light-front wave functions

Jurandi Leão,^{1,2} J. P. B. C. de Melo,¹ T. Frederico,³ Ho-Meoyng Choi,⁴ and Chueng-Ryong Ji⁵

PHYSICAL REVIEW D **110**, 074035 (2024)



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 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 with transition form factor**
- **Conformal Symmetry in 1+1D and 3+1D**
- **Orientation entanglement interpolating IFD and LFD**
- **Orientation entanglement in Quantum Computing**
- **Wigner Function in QCD**
- **Energy-Momentum Tensor in LFD**

Spring 2026 schedule (9:30am EST)

Date	Speaker	Informal Topic or Title
1/9/26	Chueng Ji	Overview and Plan for Spring 2026
1/16/26	David Brown	Dirac-Bergmann Algorithm in Classical Mechanics Lecture 1
1/23/26	David Brown	Dirac-Bergmann Algorithm in Classical Mechanics Lecture 2
2/6/26		
2/13/26		
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		
3/13/26	Deepasika Dayananda	Interpolating Relativistic Spacetimes and Quantum Fields between IFD and LFD
3/20/26	Deepasika Dayananda	PhD Defense
3/27/26		
4/3/26	Satyajit Puhan	
4/10/26	Sangwoo Ha	Peer Instruction in Physics Education
4/17/26	Daniel Piasecki	Koopman-von Neumann Classical Spinors