Probing quark Orbital Angular Momentum in ep collisions

Shohini Bhattacharya

Los Alamos National Laboratory

April 9, 2024

In Collaboration with:

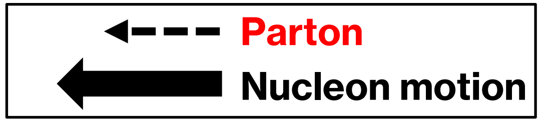
Duxin Zheng (Shandong Institute of Advanced Tech.)

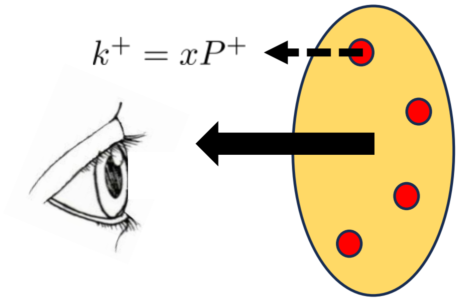
Jian Zhou (Shandong University)

Based on:

arXiv: 2312.01309

Wigner function - The "mother function"

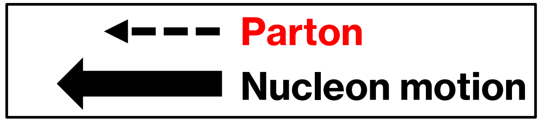


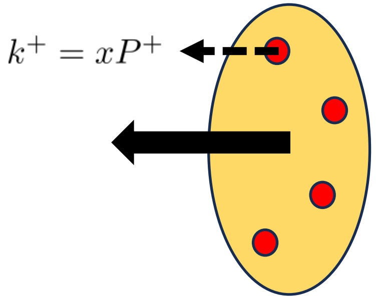


Parton Distribution Functions

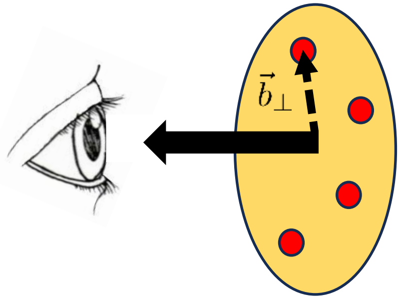
PDFs (x)

Wigner function - The “mother function”





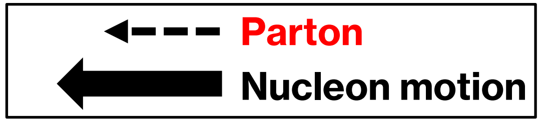
Form Factors



PDFs (x)

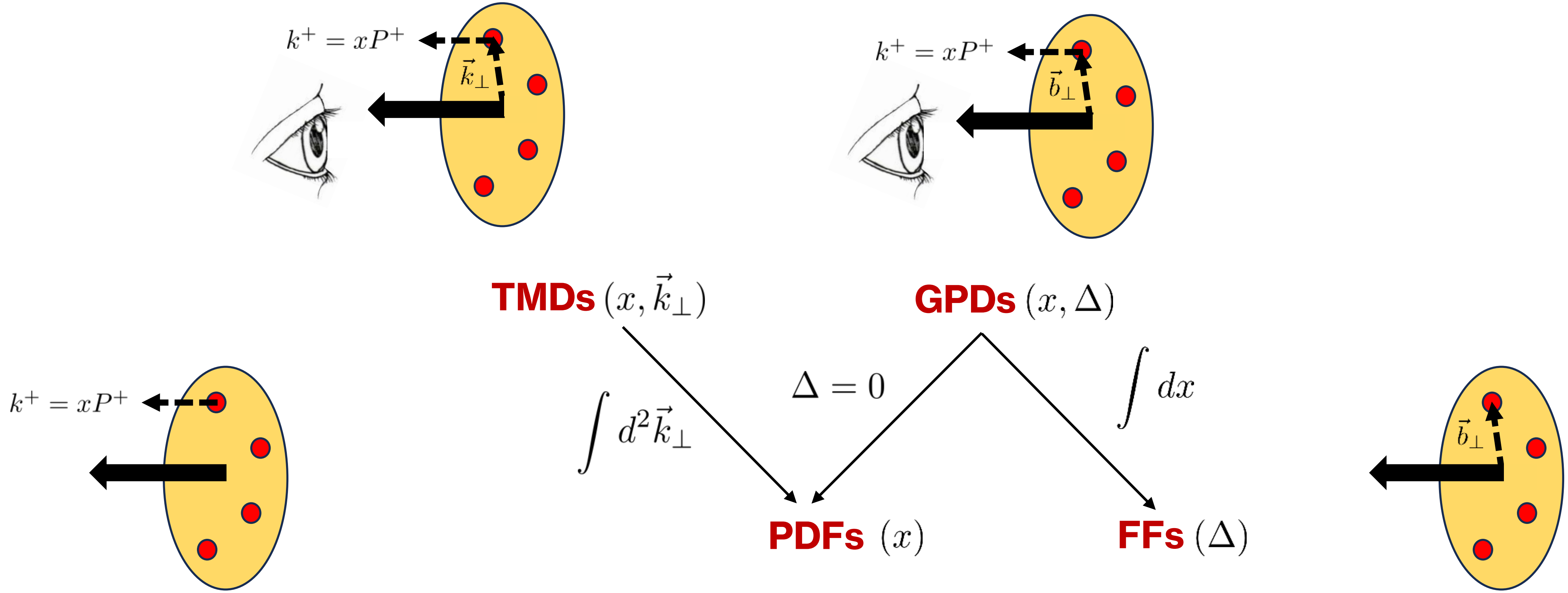
FFs (Δ)

Wigner function - The “mother function”



Transverse Momentum-dependent Distributions

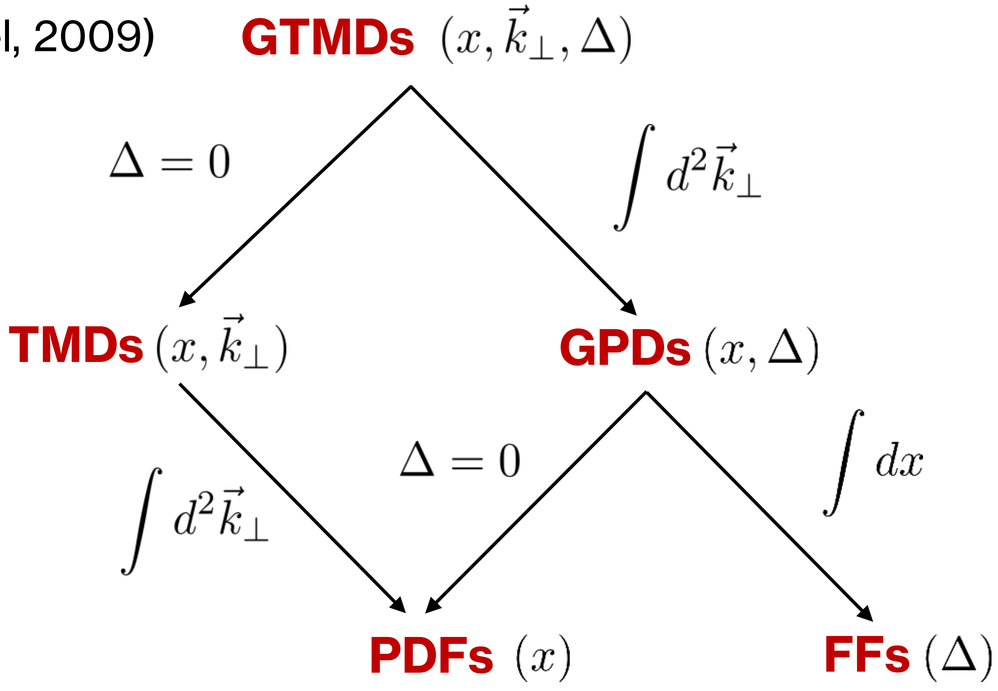
Generalized Parton Distributions



Wigner function - The “mother function”

Generalized Transverse Momentum-dependent Distributions

(Meissner, Metz, Schlegel, 2009)



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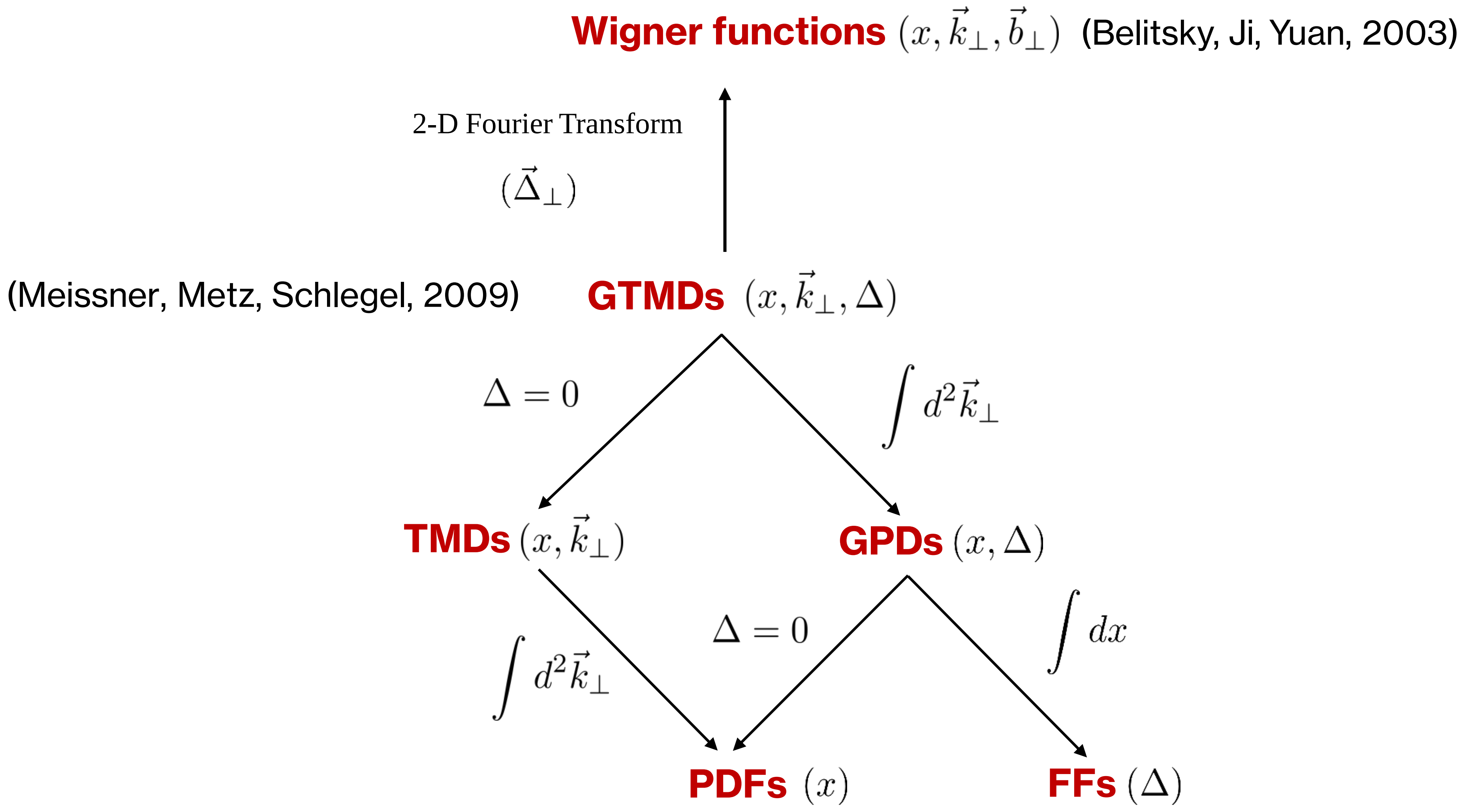
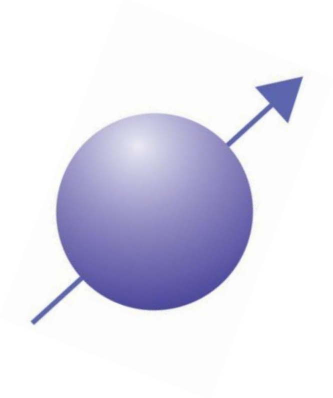


Spin of proton

Jaffe-Manohar spin decomposition

An incomplete story:



$$\frac{1}{2}$$

Spin of proton

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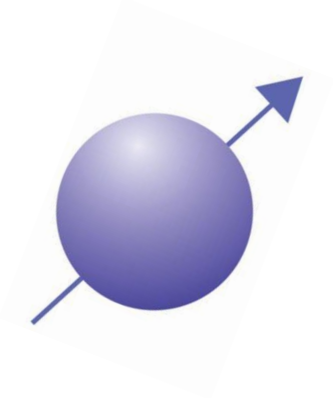


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G$$

Best known

How well do we know?

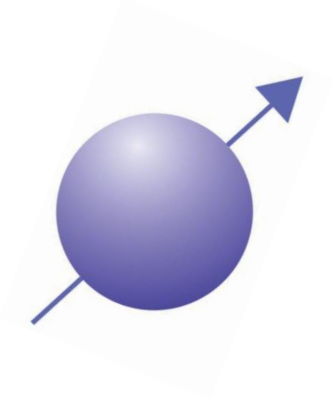
Quark helicity $\sim 30\%$

Gluon helicity $\sim 40\%$

Spin of proton

Jaffe-Manohar spin decomposition

An incomplete story:



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Best known → **Quark helicity** $\sim 30\%$

How well do we know? → **Gluon helicity** $\sim 40\%$

??????? → **OAM of quarks & gluons**

Wigner functions & Orbital Angular Momentum

Wigner functions in Quantum Mechanics

(Wigner, 1932)

- Calculate from wave functions:

$$W(x,k) = \int \frac{dx'}{2\pi} e^{-ikx'} \psi(x + \frac{x'}{2}) \, \psi^*(x - \frac{x'}{2})$$

- Expectation value of observables:

$$\langle \mathcal{O} \rangle = \int dx \int dk \mathcal{O}(x,k) W(x,k)$$

Wigner functions & Orbital Angular Momentum

Wigner functions in Quantum Mechanics (Wigner, 1932)	Wigner functions in parton physics (Belitsky, Ji, Yuan, 2003)
• Calculate from wave functions: $W(x,k) = \int \frac{dx'}{2\pi} e^{-ikx'} \psi(x+\frac{x'}{2})\, \psi^*(x-\frac{x'}{2})$	• Calculate from fourier transform of GTMD correlator: $W^{[\Gamma]}(x, \vec{k}_\perp, \vec{b}_\perp)$
• Expectation value of observables: $\langle \mathcal{O} \rangle = \int dx \int dk \mathcal{O}(x,k) W(x,k)$	• Application: **O**rbital **A**ngular **M**omentum (**OAM**) $L_z^{q,g} = \int dx \int d^2k_\perp d^2b_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z\, W^{q,g}\, (x, \vec{b}_\perp, \vec{k}_\perp)$ (Lorcé, Pasquini, 2011 / Hatta, 2011)

Wigner functions & Orbital Angular Momentum

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Wigner functions in parton physics

(Belitsky, Ji, Yuan, 2003)

- Calculate from fourier transform of GTMD correlator:

$$W^{[\Gamma]}(x, \vec{k}_\perp, \vec{b}_\perp)$$

- Application: Relation between GTMD $F_{1,4}^{q,g}$ & OAM

$$L_z^{q,g} = -\int dx \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{M^2} F_{1,4}^{q,g}(x, k_\perp, \xi = 0, \Delta_\perp = 0)$$

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Wigner functions in parton physics

(Belitsky, Ji, Yuan, 2003)

of GTMD correlator:

Big question:

Experimental observable?

- Application: Relation between GTMD $F_{1,4}^{q,g}$ & OAM

$$L_z^{q,g} = -\int dx \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{M^2} F_{1,4}^{q,g}(x, k_\perp, \xi = 0, \Delta_\perp = 0)$$

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Developments

arXiv: 1612.02438 (2016)

Hunting the Gluon Orbital Angular Momentum at the Electron-Ion Collider

Xiangdong Ji,[1,2] Feng Yuan,[3] and Yong Zhao[1,3]

Developments

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Generalized TMDs and the exclusive double Drell-Yan process

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Exclusive double quarkonium production and generalized TM

Shohini Bhattacharya,[1] Andreas Metz,[1] Vikash Kumar Ojha,[2] Jeng-Yuan Tsai,[1]

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Probing the Weizsäcker-Williams gluon Wigner distribution in *pp* collisions

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arXiv: 1912.08182 (2019)

Probing the gluon Sivers function with an unpolarized target: GTMD distributions and the Odderons

Renaud Boussarie,[1] Yoshitaka Hatta,[1] Lech Szymanowski,[2] and Samuel Wallon[3,4]

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Signature of the gluon orbital angular momentum

Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[1,3,‡]

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Angular correlations in exclusive dijet photoproduction in ultra-peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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arXiv: 1802.10550 (2018)

Exclusive double quarkonium production and generalized TM...

Exclusive double Drell-Yan:

Until now, this has been the sole known process sensitive to quark GTMDs

...tion in pp collisions

...Feng Yuan[5]

...ction of di-pions

Yoshikazu Hagiwara, Cheng Zhang, Jian Zhou, and Ya-jin Zhou

Renaud Boussarie,[1] Yoshitaka Hatta,[1] Lech Szymanowski,[2] and Sa...

arXiv: 2201.08709/2404.04209 (2022/2024)

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Probing quark OAM through double Drell-Yan

Main findings

arXiv: 1702.04387 (2017)

Generalized TMDs and the exclusive double Drell-Yan process

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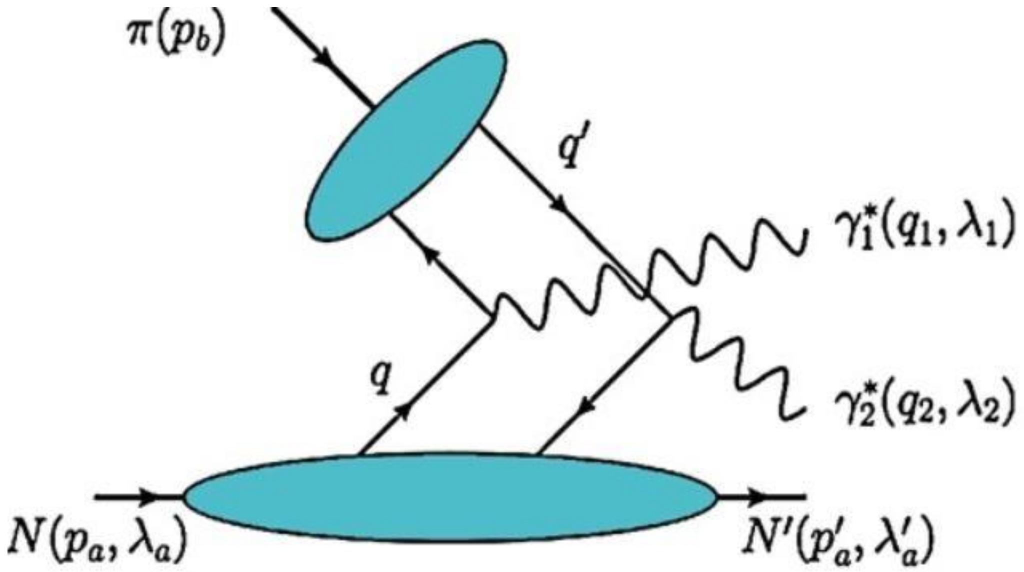


Probing quark OAM through double Drell-Yan

Main findings

Example of an observable sensitive to OAM & spin-orbit correlation :

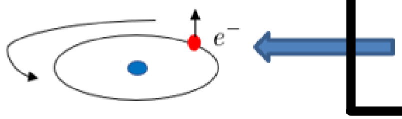
$$\frac{1}{2}(\tau_{XY} - \tau_{YX}) = \frac{4}{M_a^2}(\varepsilon_\perp^{ij}\Delta q_\perp^i \Delta_{a\perp}^j)\,\mathrm{Re.}\Big\{C^{(-)}\big[F_{1,1}\,\phi_\pi\big]C^{(+)}\big[\vec{\beta}_\perp\cdot\vec{k}_{a\perp}\,\boldsymbol{F}^*_{1,4}\,\phi^*_\pi\big] - C^{(+)}\big[G_{1,4}\,\phi_\pi\big]C^{(-)}\big[\vec{\beta}_\perp\cdot\vec{p}_{a\perp}\,\boldsymbol{G}^*_{1,1}\,\phi^*_\pi\big]\Big\}$$

Spin-orbit entanglement in the Color Glass Condensate

Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[3,4,‡]

2404.04208

Recall Spin-Orbit coupling in H atom!



$$G_{1,1}^{q/g} \to L^{q/g}\cdot S^{q/g}$$

Probing quark OAM through double Drell-Yan

Main findings

Challenges:

- Low count rate (Amplitude $\sim \alpha_{em}^2$)

Probing quark OAM through double Drell-Yan

Main findings

Challenges:

- Low count rate (Amplitude $\sim \alpha_{em}^2$)
- Sensitivity to GTMDs only in the ERBL region $-\xi < x < \xi$

OAM density: $$L^{q/g}(x,\boldsymbol{\xi}) = -\int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{M^2} F_{1,4}^{q,g}(x,k_\perp,\boldsymbol{\xi},\Delta_\perp = 0)$$

OAM: $$L^{q/g} = \int dx\, L^{q/g}(x,\boldsymbol{\xi} = \mathbf{0})$$

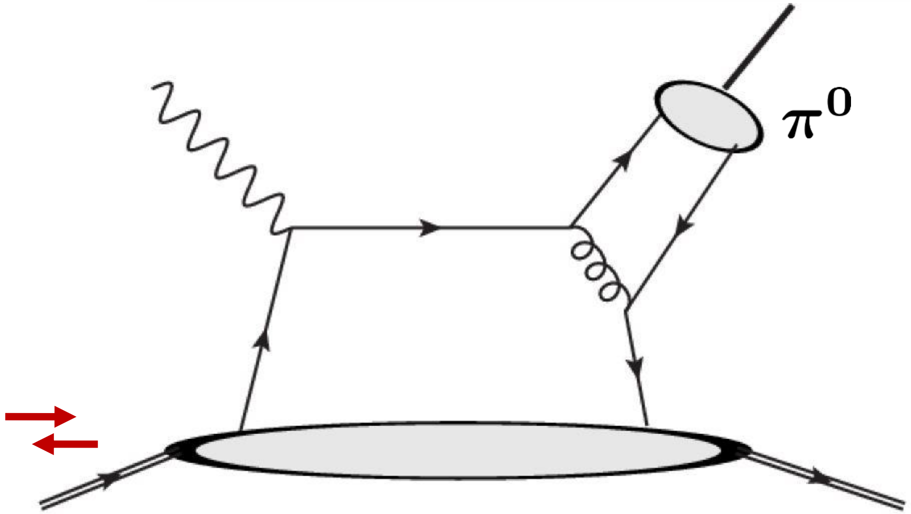
The challenge lies in extrapolating the distribution to the forward limit, where the OAM equation is applicable

Our work

arXiv: 2312.01309 (2023)

Probing quark orbital angular momentum at EIC and EicC

Shohini Bhattacharya,[1] Duxin Zheng,[2] and Jian Zhou[3]

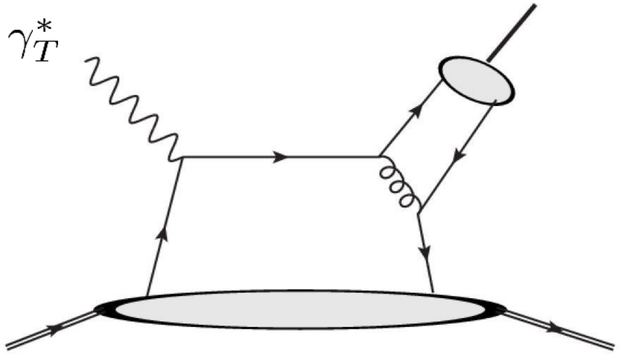


Main Observable:

Longitudinal single-target spin asymmetry

Exclusive π^0 production in ep collisions

Known results



The coupling of twist-2 helicity-flip chiral odd GPDs with the twist-3 distribution amplitude of the neutral pion yields the leading power contribution to the unpolarized cross-section:

$$\frac{d\sigma_T}{dt} = \frac{1}{2\kappa}(\mid M_{0-,++} \mid^2 + 2 \mid M_{0+,++} \mid^2)$$

$$\frac{d\sigma_{TT}}{dt} = -\frac{1}{\kappa} \mid M_{0+,++} \mid^2 \cos(2\phi)$$

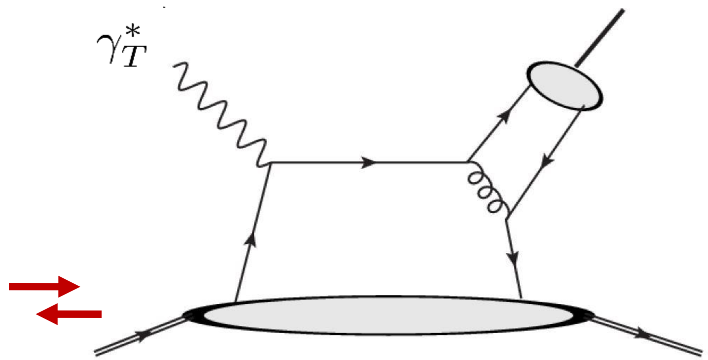
$$M_{0-,++} = \frac{e_0}{Q}\sqrt{1-\xi^2}\langle H_T \rangle$$

$$M_{0+,++} = -\frac{e_0}{Q}\frac{\sqrt{-t'}}{4m}\langle \bar{E}_T \rangle$$

See for example L. Frankfurt, P. Pobylitsa, M. Polyakov, & M. Strikman, 1999

Probing quark OAM through π^0 production in ep collisions

Scattering amplitude



4 leading-order Feynman diagrams

Probing quark OAM through π^0 production in ep collisions

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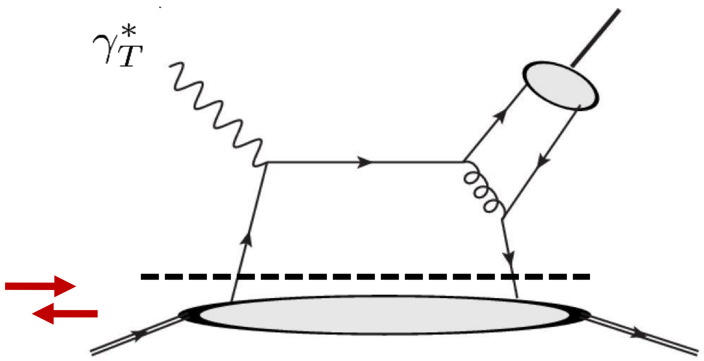


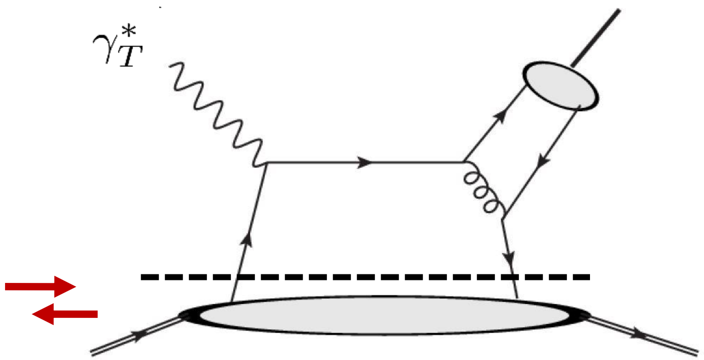
Scattering amplitude:

$$A \propto \int dx \int d^2k_\perp \, H(x,\xi,z,k_\perp,\Delta_\perp)\, f^q(x,\xi,k_\perp,\Delta_\perp) \int dz \phi_\pi(z)$$

- H: Hard part
- f^q: Soft part from proton
- ϕ_π: Pion Distribution Amplitude

Probing quark OAM through π^0 production in ep collisions

Scattering amplitude



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Collinear twist-expansion of hard part:

$$H(k_\perp,\Delta_\perp) = H(k_\perp=0,\Delta_\perp=0) + \frac{\partial H(k_\perp,\Delta_\perp=0)}{\partial k_\perp^\mu}\Big|_{k_\perp=0} k_\perp^\mu + \frac{\partial H(k_\perp=0,\Delta_\perp)}{\partial \Delta_\perp^\mu}\Big|_{\Delta_\perp=0} \Delta_\perp^\mu + \ldots$$

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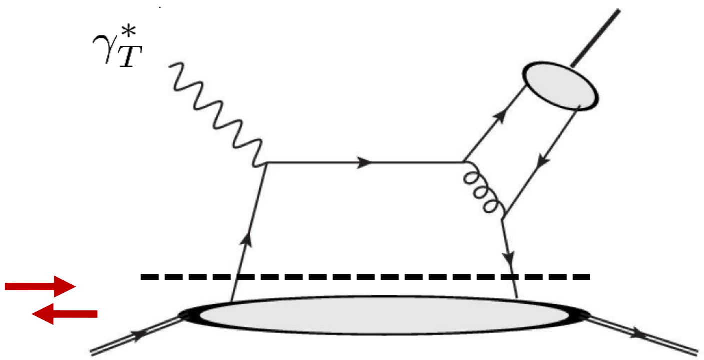

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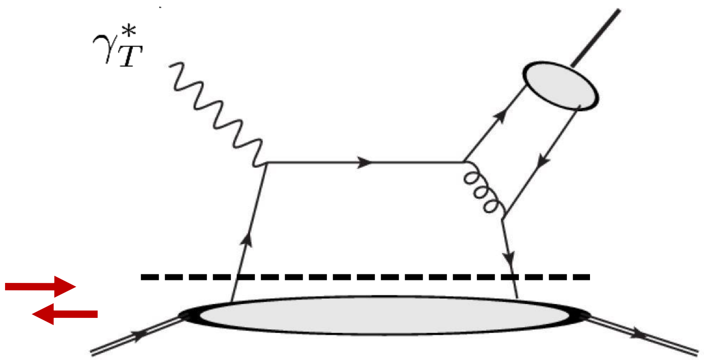
Twist 2 term vanishes

Probing quark OAM through π^0 production in ep collisions

Scattering amplitude



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Use special-propagator technique to ensure electromagnetic gauge invariance

(J. W. Qiu, 1990)

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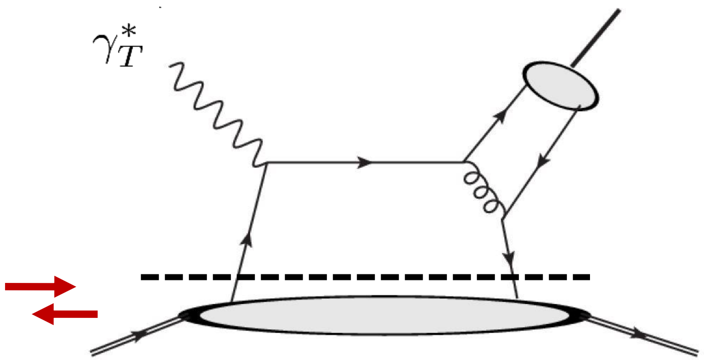

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$$A \propto \int d^2k_\perp k_\perp^2 \, \mathrm{GTMD}$$

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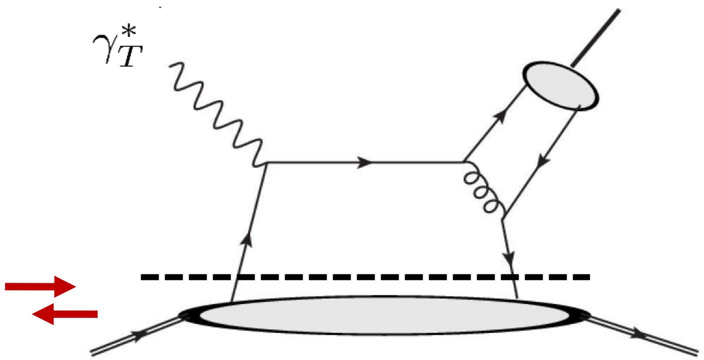


Scattering amplitude:

$$A \propto \int dx \int \boldsymbol{d^2k_\perp}\, H(x,\xi,z,k_\perp,\Delta_\perp)\, \boldsymbol{f^q}(x,\xi,k_\perp,\Delta_\perp) \int dz \phi_\pi(z)$$

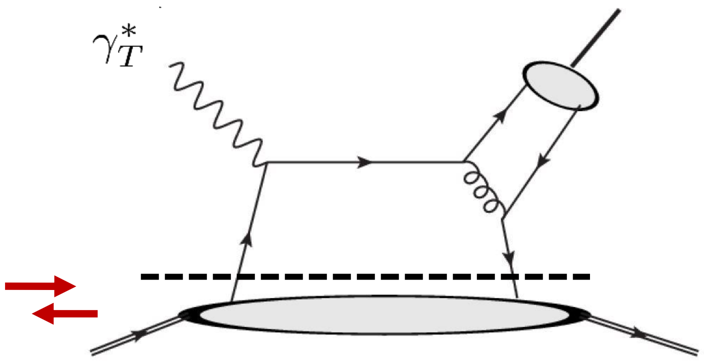
Collinear twist-expansion of hard part:

$$H(k_\perp,\Delta_\perp) = H(k_\perp=0,\Delta_\perp=0) + \frac{\partial H(k_\perp,\Delta_\perp=0)}{\partial k_\perp^\mu}\bigg|_{k_\perp=0} k_\perp^\mu + \frac{\partial H(k_\perp=0,\Delta_\perp)}{\partial \Delta_\perp^\mu}\bigg|_{\Delta_\perp=0} \boldsymbol{\Delta_\perp^\mu} + \ldots$$

$$A \propto \mathbf{GPD}$$

Probing quark OAM through π^0 production in ep collisions

Scattering amplitude



Scattering amplitude:

$$A \propto \int dx \int d^2k_\perp \, H(x,\xi,z,k_\perp,\Delta_\perp)\, f^q(x,\xi,k_\perp,\Delta_\perp) \int dz \phi_\pi(z)$$

Collinear twist-expansion of hard part:

Consequently, the scattering amplitudes are a convolution of moments of GTMDs and GPDs and are of twist-3 nature

Probing quark OAM through π^0 production in ep collisions

Angular correlations

Scattering amplitudes depend on different angular correlations:

$$\mathcal{M}_1 = \frac{g_s^2 e f_\pi}{2\sqrt{2}} \frac{(N_c^2-1)2\xi}{N_c^2\sqrt{1-\xi^2}} \delta_{\lambda\lambda'} \frac{\boldsymbol{\epsilon}_\perp \times \boldsymbol{\Delta}_\perp}{Q^2} \{\mathcal{F}_{1,1} + \mathcal{G}_{1,1}\}$$

$$\mathcal{M}_2 = \frac{g_s^2 e f_\pi}{2\sqrt{2}} \frac{(N_c^2-1)2\xi}{N_c^2\sqrt{1-\xi^2}} \delta_{\lambda,-\lambda'} \frac{M\boldsymbol{\epsilon}_\perp \cdot \boldsymbol{S}_\perp}{Q^2} \{\mathcal{F}_{1,2} + \mathcal{G}_{1,2}\} \qquad S_\perp^\mu = (0^+, 0^-, -i, \lambda)$$

$$\mathcal{M}_4 = \frac{i g_s^2 e f_\pi}{2\sqrt{2}} \frac{(N_c^2-1)2\xi}{N_c^2\sqrt{1-\xi^2}} \lambda\delta_{\lambda\lambda'} \frac{\boldsymbol{\epsilon}_\perp \cdot \boldsymbol{\Delta}_\perp}{Q^2} \{\mathcal{F}_{1,4} + \mathcal{G}_{1,4}\}$$

Probing quark OAM through π^0 production

Compton Form Factors:

Angular correlations

Scattering amplitudes depend on different angular correlations:

$$\mathcal{M}_1 = \frac{g_s^2 e f_\pi}{2\sqrt{2}} \frac{(N_c^2-1)2\xi}{N_c^2\sqrt{1-\xi^2}} \delta_{\lambda\lambda'} \frac{\epsilon_\perp \times \Delta_\perp}{Q^2} \{\mathcal{F}_{1,1} + \mathcal{G}_{1,1}\}$$

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$$\mathcal{F}_{1,1} = \int_{-1}^{1} dx \frac{x^2 \int d^2k_\perp F_{1,1}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (8)$$

$$\mathcal{G}_{1,1} = \int_{-1}^{1} dx \int_0^1 dz \frac{\phi_\pi(z)(x^2+2x^2z+\xi^2)}{z^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int d^2k_\perp \frac{k_\perp^2}{M^2} G_{1,1}^{u+d}(x,\xi,\Delta_\perp,k_\perp), \quad (9)$$

$$\mathcal{F}_{1,2} = \int_{-1}^{1} dx x \frac{\xi(1-\xi^2)\int d^2k_\perp k_\perp^2 F_{1,2}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{M^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (10)$$

$$\mathcal{G}_{1,2} = \int_{-1}^{1} dx \int_0^1 dz \frac{\phi_\pi(z)(x^2+2x^2z+\xi^2)(1-\xi^2)}{z^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int d^2k_\perp \frac{k_\perp^2}{M^2} G_{1,2}^{u+d}(x,\xi,\Delta_\perp,k_\perp), \quad (11)$$

$$\mathcal{F}_{1,4} = \int_{-1}^{1} dx \frac{x\xi \int d^2k_\perp k_\perp^2 F_{1,4}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{M^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (12)$$

$$\mathcal{G}_{1,4} = \int_{-1}^{1} dx \int_0^1 dz \frac{x(4\xi^2 z+\xi^2-2x^2z+x^2)}{z^2\xi(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2}\phi_\pi(z) \times \int d^2k_\perp G_{1,4}^{u+d}(x,\xi,\Delta_\perp,k_\perp). \quad (13)$$

Probing quark OAM through π^0 production in ep collisions

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$$\mathcal{M}_4 = \frac{i g_s^2 e f_\pi}{2\sqrt{2}} \frac{(N_c^2-1)2\xi}{N_c^2\sqrt{1-\xi^2}} \lambda\delta_{\lambda\lambda'} \frac{\epsilon_\perp \cdot \Delta_\perp}{Q^2} \{\mathcal{F}_{1,4} + \mathcal{G}_{1,4}\}$$

Sensitivity to quark OAM

$$\mathcal{F}_{1,1} = \int_{-1}^{1} dx \frac{x^2 \int d^2k_\perp F_{1,1}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (8)$$

$$\mathcal{G}_{1,1} = \int_{-1}^{1} dx \int_0^1 dz \frac{\phi_\pi(z)(x^2+2x^2z+\xi^2)}{z^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int d^2k_\perp \frac{k_\perp^2}{M^2} G_{1,1}^{u+d}(x,\xi,\Delta_\perp,k_\perp), \quad (9)$$

$$\mathcal{F}_{1,2} = \int_{-1}^{1} dx\, x \frac{\xi(1-\xi^2)\int d^2k_\perp k_\perp^2 F_{1,2}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{M^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (10)$$

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$$\mathcal{F}_{1,4} = \int_{-1}^{1} dx \frac{x\xi \int d^2k_\perp k_\perp^2 F_{1,4}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{M^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}, \quad (12)$$

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Probing quark OAM through π^0 production in ep collisions

Cross section

$$\frac{d\sigma}{dtdQ^2dx_Bd\phi} = \frac{(N_c^2-1)^2\alpha_{em}^2\alpha_s^2 f_\pi^2\xi^3\Delta_\perp^2}{2N_c^4(1-\xi^2)Q^{10}(1+\xi)}\left[1+(1-y)^2\right]$$

$$\times\left\{\left[|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2+2\frac{M^2}{\Delta_\perp^2}|\mathcal{F}_{1,2}+\mathcal{G}_{1,2}|^2\right]+\cos(2\phi)a\left[-|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2\right]\right.$$

$$\left.+\lambda\sin(2\phi)\,2a\,\mathrm{Re}\left[(i\mathcal{F}_{1,4}+i\mathcal{G}_{1,4})\left(\mathcal{F}_{1,1}^*+\mathcal{G}_{1,1}^*\right)\right]\right\}$$

↑

$$a=\frac{2(1-y)}{1+(1-y)^2}$$

Probing quark OAM through π^0 production in ep collisions

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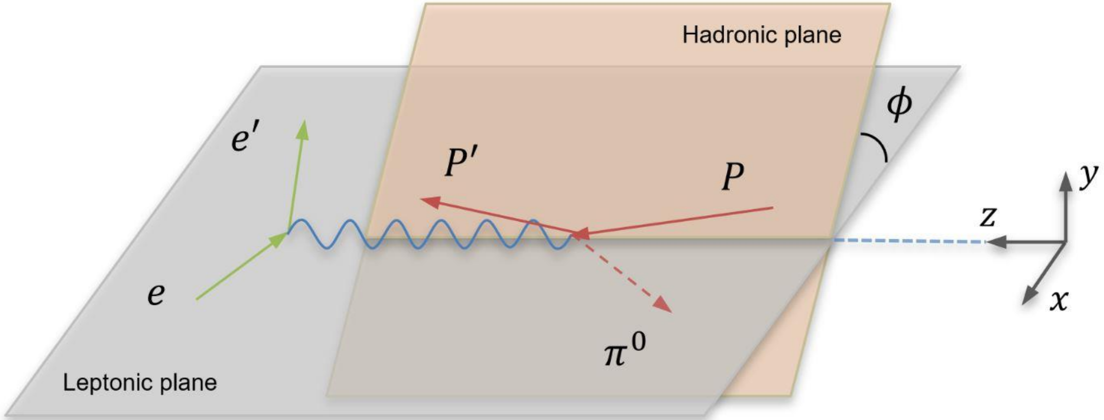
Distinguished experimental signature of quark OAM

$$\phi = \phi_{l_\perp} - \phi_{\Delta_\perp}$$



Probing quark OAM through π^0 production in ep collisions

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$$\times \left\{ \left[|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2 + |\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2 + 2\frac{M^2}{\Delta_\perp^2}|\mathcal{F}_{1,2}+\mathcal{G}_{1,2}|^2 \right] + \cos(2\phi) a \left[-|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2 + |\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2 \right] \right.$$

$$\left. + \lambda \sin(2\phi)\, 2a\, \mathrm{Re}\left[(i\mathcal{F}_{1,4}+i\mathcal{G}_{1,4})\left(\mathcal{F}_{1,1}^* + \mathcal{G}_{1,1}^*\right)\right] \right\}$$

Surprise!

- Probe quark Sivers function through an unpolarized target

$$\mathrm{Im}\left[F_{1,2}\right]\Big|_{\Delta=0} = -f_{1T}^{\perp}$$

(Similar to the gluon GTMD $F_{1,2}$, as discussed in Boussarie, Hatta, Szymanowski, Wallon, 2019)

Probing quark OAM through π^0 production in ep collisions

Cross section

$$\frac{d\sigma}{dtdQ^2dx_Bd\phi} = \frac{(N_c^2-1)^2\alpha_{em}^2\alpha_s^2 f_\pi^2\xi^3\Delta_\perp^2}{2N_c^4(1-\xi^2)Q^{10}(1+\xi)}\left[1+(1-y)^2\right]$$

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$$\left.+\lambda\sin(2\phi)\,2a\,\mathrm{Re}\left[(i\mathcal{F}_{1,4}+i\mathcal{G}_{1,4})\left(\mathcal{F}_{1,1}^*+\mathcal{G}_{1,1}^*\right)\right]\right\}$$

Surprise!

- Probe quark Sivers function through an unpolarized target $\quad \mathrm{Im}\left[\boldsymbol{F_{1,2}}\right]\Big|_{\Delta=0} = -\boldsymbol{f_{1T}^{\perp}}$

- Probe quark worm-gear function through an unpolarized target $\quad \mathrm{Re}\left[\boldsymbol{G_{1,2}}\right]\Big|_{\Delta=0} = \boldsymbol{g_{1T}}$

Probing quark OAM through π^0 production in ep collisions

Cross section

$$\frac{d\sigma}{dt\,dQ^2\,dx_B\,d\phi} = \frac{(N_c^2-1)^2\alpha_{em}^2\alpha_s^2 f_\pi^2\xi^3\boldsymbol{\Delta_\perp^2}}{2N_c^4(1-\xi^2)Q^{10}(1+\xi)}\left[1+(1-y)^2\right]$$

$$\times\left\{\left[|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2+2\frac{M^2}{\boldsymbol{\Delta_\perp^2}}|\boldsymbol{\mathcal{F}_{1,2}}+\boldsymbol{\mathcal{G}_{1,2}}|^2\right]+\cos(2\phi)a\left[-|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2\right]\right.$$

$$\left.+\lambda\sin(2\phi)\,2a\,\mathrm{Re}\left[(i\mathcal{F}_{1,4}+i\mathcal{G}_{1,4})\left(\mathcal{F}_{1,1}^*+\mathcal{G}_{1,1}^*\right)\right]\right\}$$

Helicity flip terms persist even when $\Delta_\perp\to 0$

Probing quark OAM through π^0 production in ep collisions

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Since both unpolarized and polarized cross sections contribute at twist-3,
the magnitudes of the asymmetries are not power-suppressed

Probing quark OAM through π^0 production in ep collisions

Model input for numerical estimations

Ingredients for non-perturbative functions:

- Model $(H^q,\ \tilde{H}^q)$ according to the Double distribution approach (see Radyushkin, 9805342)

Example:

$$H^q(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\, \delta(\beta+\xi\alpha-x) \times \frac{3}{4}|\beta|^{-0.9t} \frac{\left[(1-|\beta|)^2-\alpha^2\right]}{(1-|\beta|)^3} q(|\beta|)$$

JAM 2022 PDFs

Probing quark OAM through π^0 production in ep collisions

Model input for numerical estimations

Ingredients for non-perturbative functions:

- Model $(H^q, \tilde{H}^q)$ according to the Double distribution approach (see Radyushkin, 9805342)

- Model for OAM:

    1. "OAM density": (Hatta, Yoshida, 1207.5332)

$$L^q_{can}(\boldsymbol{x}) = x\int_x^1 \frac{dx'}{x'} q(x') - x\int_x^1 \frac{dx'}{x'^2} \Delta q(x') + \text{ genuine twist-three}$$

Probing quark OAM through π^0 production in ep collisions

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$$L^q_{can}(x) \overset{\text{WW approx}}{=} x\int_x^1 \frac{dx'}{x'}q(x') - x\int_x^1 \frac{dx'}{x'^2}\Delta q(x') + \text{genuine twist-three}$$

Probing quark OAM through π^0 production in ep collisions

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2. Use the Double distribution approach to construct $xL^q(x,\boldsymbol{\xi})e^{\boldsymbol{t}/\Lambda}$ from $xL^q(x)$

Probing quark OAM through π^0 production in ep collisions

Model input for numerical estimations

Ingredients for non-perturbative functions:

- Pion distribution amplitude:

Asymptotic form $$\phi_\pi(z) = 6z(1-z)$$

Probing quark OAM through π^0 production in ep collisions

Model input for numerical estimations

End-point singularity & discontinuity:

$$\mathcal{F}_{1,4} = \int_{-1}^{1} dx \frac{x\xi \int d^2k_\perp k_\perp^2 F_{1,4}^{u+d}(x,\xi,\Delta_\perp,k_\perp)}{M^2(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2} \times \int_0^1 dz \frac{\phi_\pi(z)(1+z^2-z)}{z^2(1-z)^2}$$

Model-dependent method:

$$\int_{\langle p_\perp^2\rangle/Q^2}^{1-\langle p_\perp^2\rangle/Q^2} dz$$

S. V. Goloskokov and P. Kroll, 2005

Probing quark OAM through π^0 production in ep collisions

Model input for numerical estimations

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Model-dependent method:

$$\int_{\langle p_\perp^2\rangle/Q^2}^{1-\langle p_\perp^2\rangle/Q^2} dz$$

S. V. Goloskokov and P. Kroll, 2005

$$\frac{1}{(x-\xi+i\epsilon)^2} \to \frac{1}{(x-\xi-\langle p_\perp^2\rangle/Q^2+i\epsilon)^2}$$

I. V. Anikin, O. V. Teryaev, 2003

Probing quark OAM through π^0 production in ep collisions

Numerical results

Kinematics:

	$Q^2(\mathrm{GeV}^2)$	$\sqrt{s}_{ep}(\mathrm{GeV})$
EIC	10	100
EicC	3	16

Probing quark OAM through π^0 production in ep collisions

Numerical results

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	$Q^2(\mathrm{GeV}^2)$	$\sqrt{s_{ep}}(\mathrm{GeV})$
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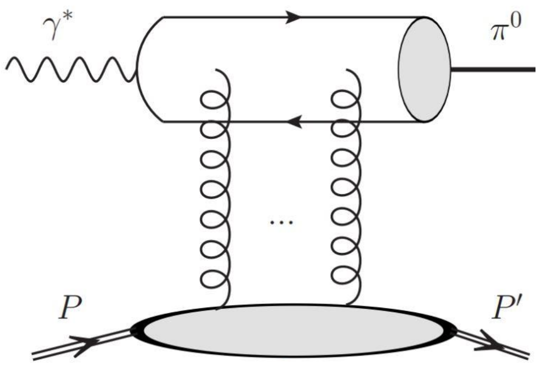
- We focus on large skewness (ξ) region to suppress gluon contribution



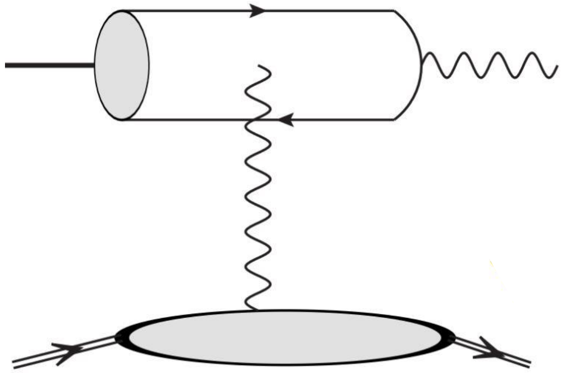
Probing quark OAM through π^0 production in ep collisions

Numerical results

Kinematics:

	$Q^2(\mathrm{GeV}^2)$	$\sqrt{s_{ep}}(\mathrm{GeV})$
EIC	10	100
EicC	3	16

- We focus on large skewness (ξ) region to suppress gluon contribution
- We focus on large momentum transfer (t) region to suppress contribution from Primakoff process



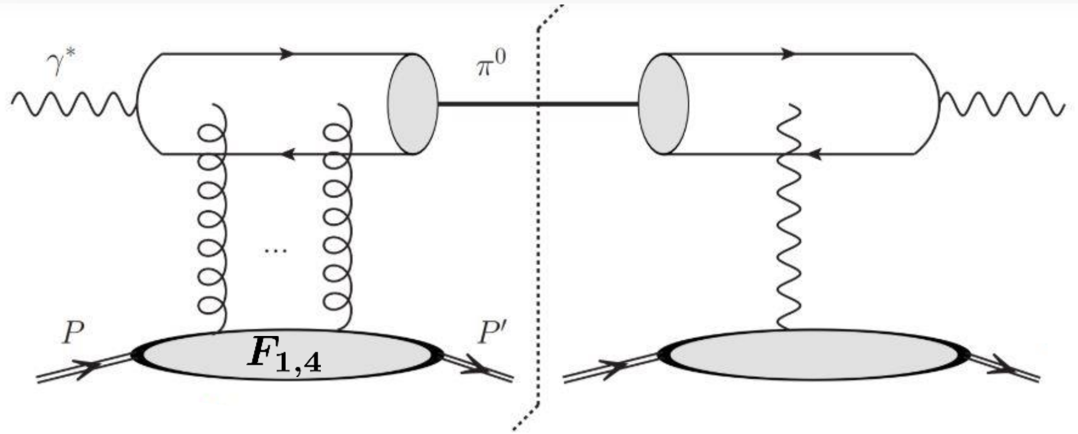
$$\propto \frac{1}{t}$$

Probing quark OAM through π^0 production in ep collisions

Remark:

Accessing the gluon GTMD $F_{1,4}$ in exclusive π^0 production in ep collisions

Shohini Bhattacharya,[1] Duxin Zheng,[2] and Jian Zhou[3]



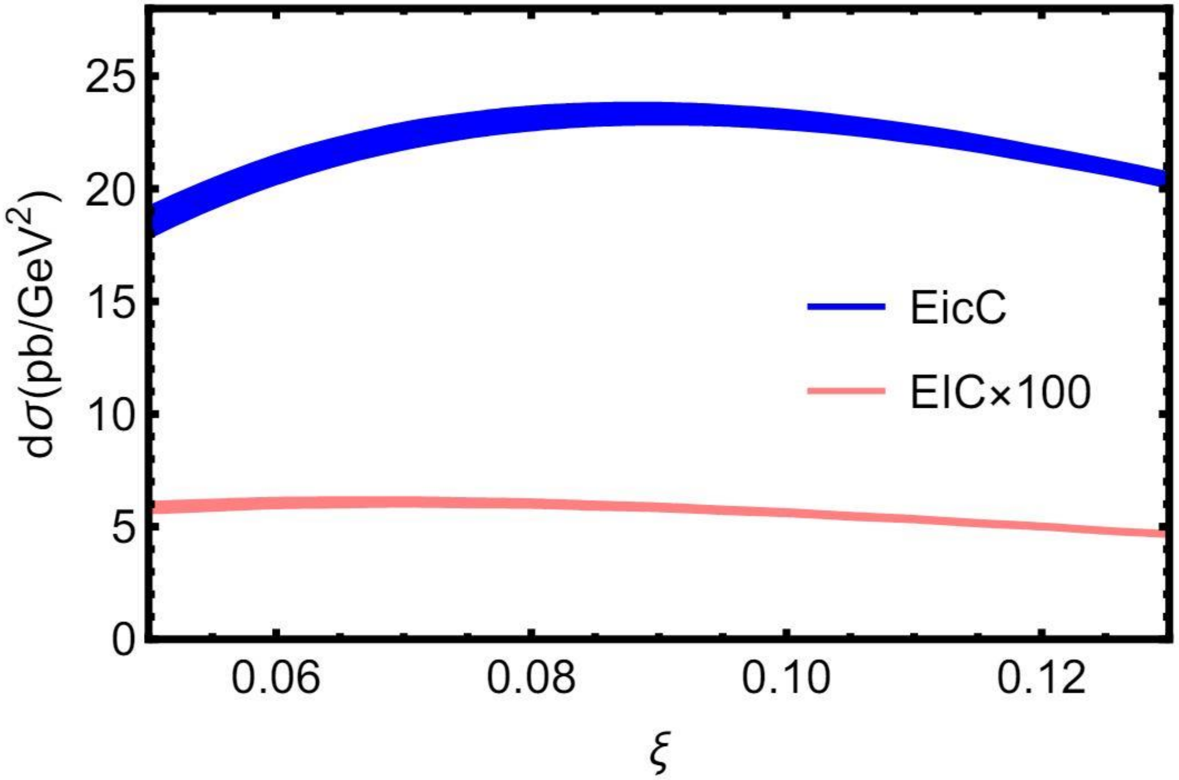
$$\frac{d\Delta\sigma}{dt dQ^2 dx_B d\phi} = -\sin(2\phi)\frac{\alpha_{em}^3 \alpha_s f_\pi^2 (1-y)\xi x_B \mathcal{F}(t)}{3Q^8 N_c}\left[\int_0^1 dz \frac{\phi_\pi(z)}{z(1-z)}\right]^2 \mathrm{Im}\left[\int_{-1}^1 dx \frac{F_{1,4}^{(1)}(x,\xi,\Delta_\perp)/M^2}{(x+\xi-i\epsilon)^2(x-\xi+i\epsilon)^2}\right]$$

The same azimuthal asymmetry, precisely mirroring what we observe in this study, emerges from the interference between the Primakoff process and the contribution from the gluon GTMD

Probing quark OAM through π^0 production in ep collisions

Numerical results

Unpolarized cross section



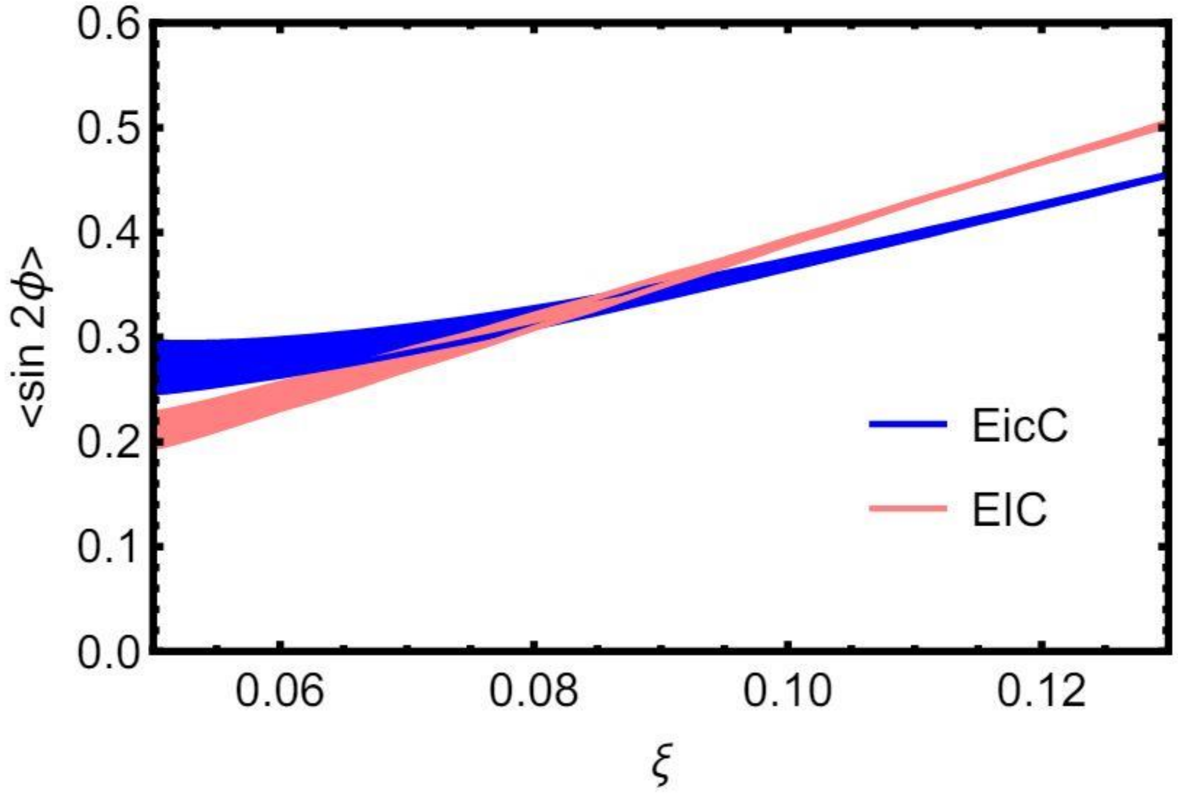
Findings:

- The unpolarized cross section exhibits a notable magnitude at EicC energy
- Relatively small at EIC energy

Probing quark OAM through π^0 production in ep collisions

Numerical results

Asymmetry



$$\langle \sin(2\phi) \rangle = \frac{\int \frac{d\Delta\sigma}{d\mathcal{P}.\mathcal{S}.} \sin(2\phi)\ d\mathcal{P}.\mathcal{S}.}{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} d\mathcal{P}.\mathcal{S}.}$$

Findings:

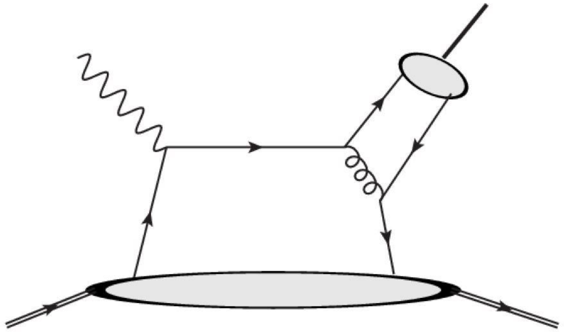
The asymmetries are substantial for both EIC & EicC kinematics

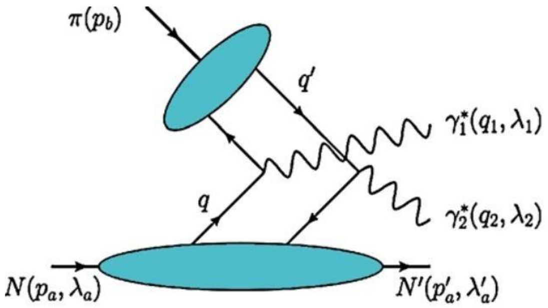
Summary

- Generalized TMDs/Wigner functions are the holy grail of spin physics

Summary

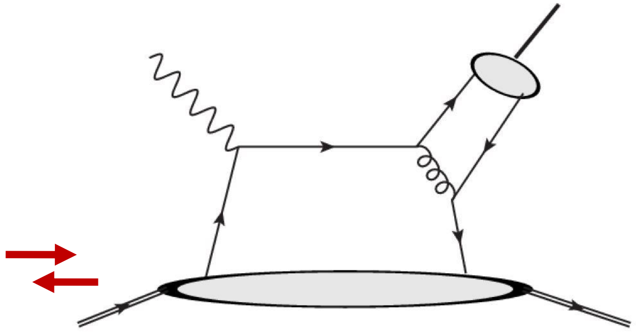
- Generalized TMDs/Wigner functions are the holy grail of spin physics
- Probe **quark OAM** via exclusive π^0 production in ep collisions
- Circumvent challenges associated with double Drell-Yan process:

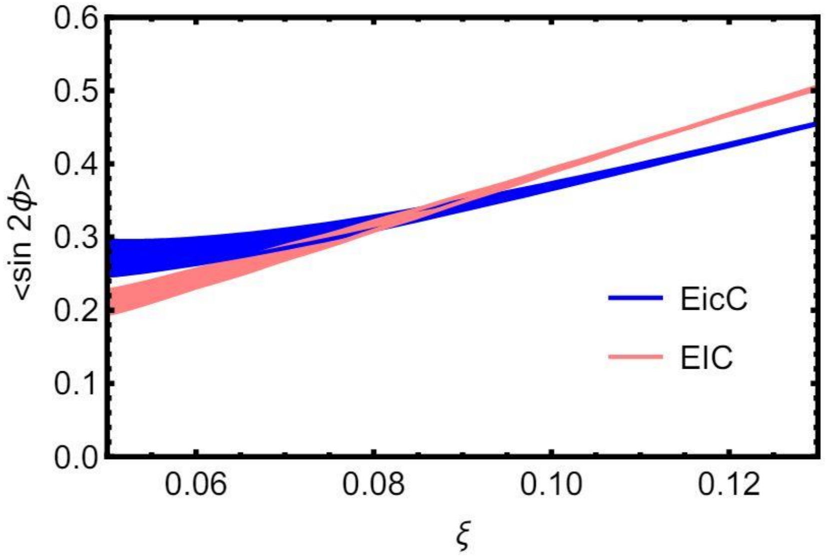




Summary

- Generalized TMDs/Wigner functions are the holy grail of spin physics
- Probe **quark OAM** via exclusive π^0 production in ep collisions
- Circumvent challenges associated with double Drell-Yan process





- Longitudinal single-target spin asymmetry is not power suppressed
- Asymmetry is substantial & thus exclusive π^0 production in ep collisions maybe a promising route to constrain quark OAM