Unveiling the 3D Structure of Deuterium: Focusing on the Spin-1 System through Transverse Momentum Distributions

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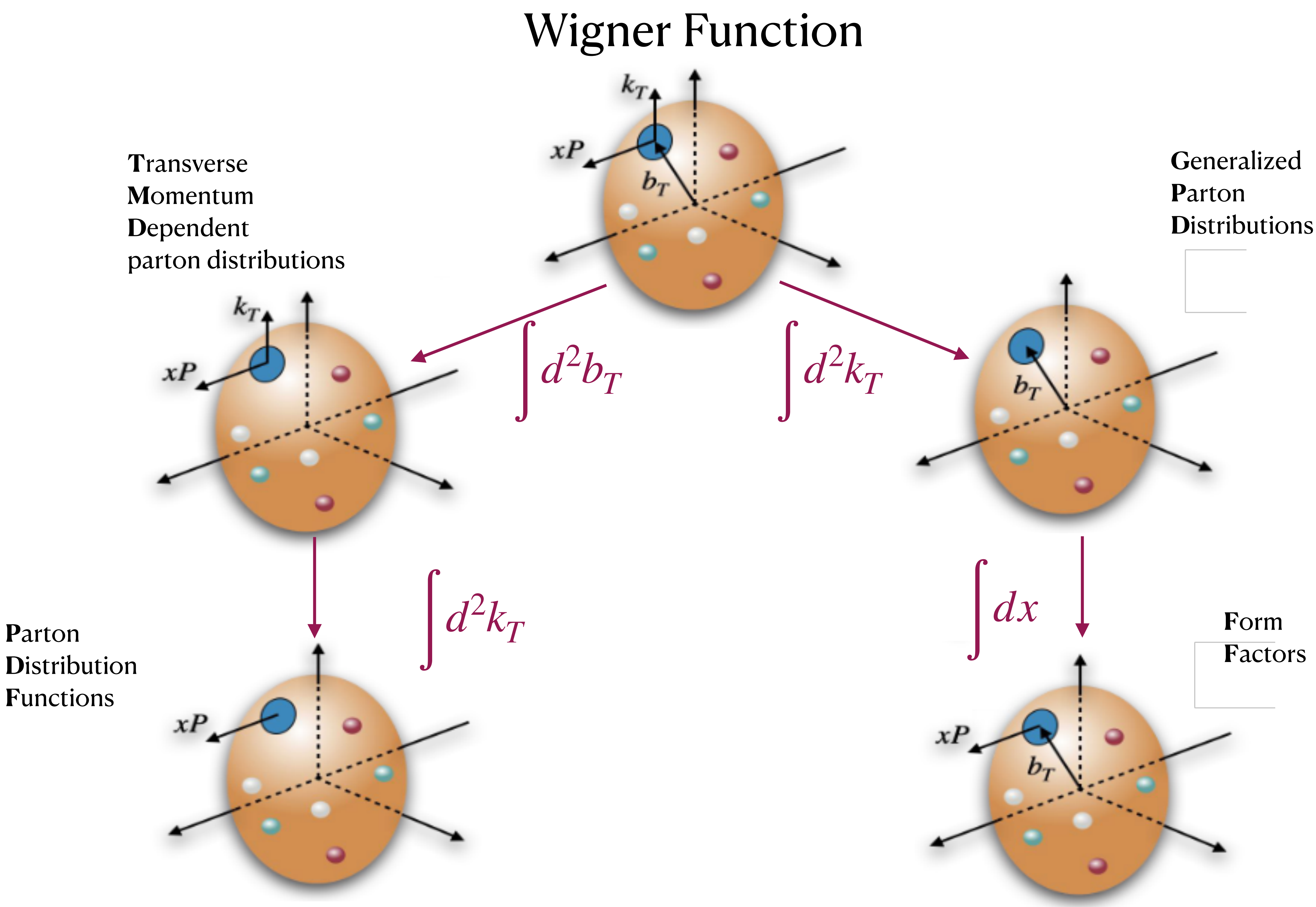
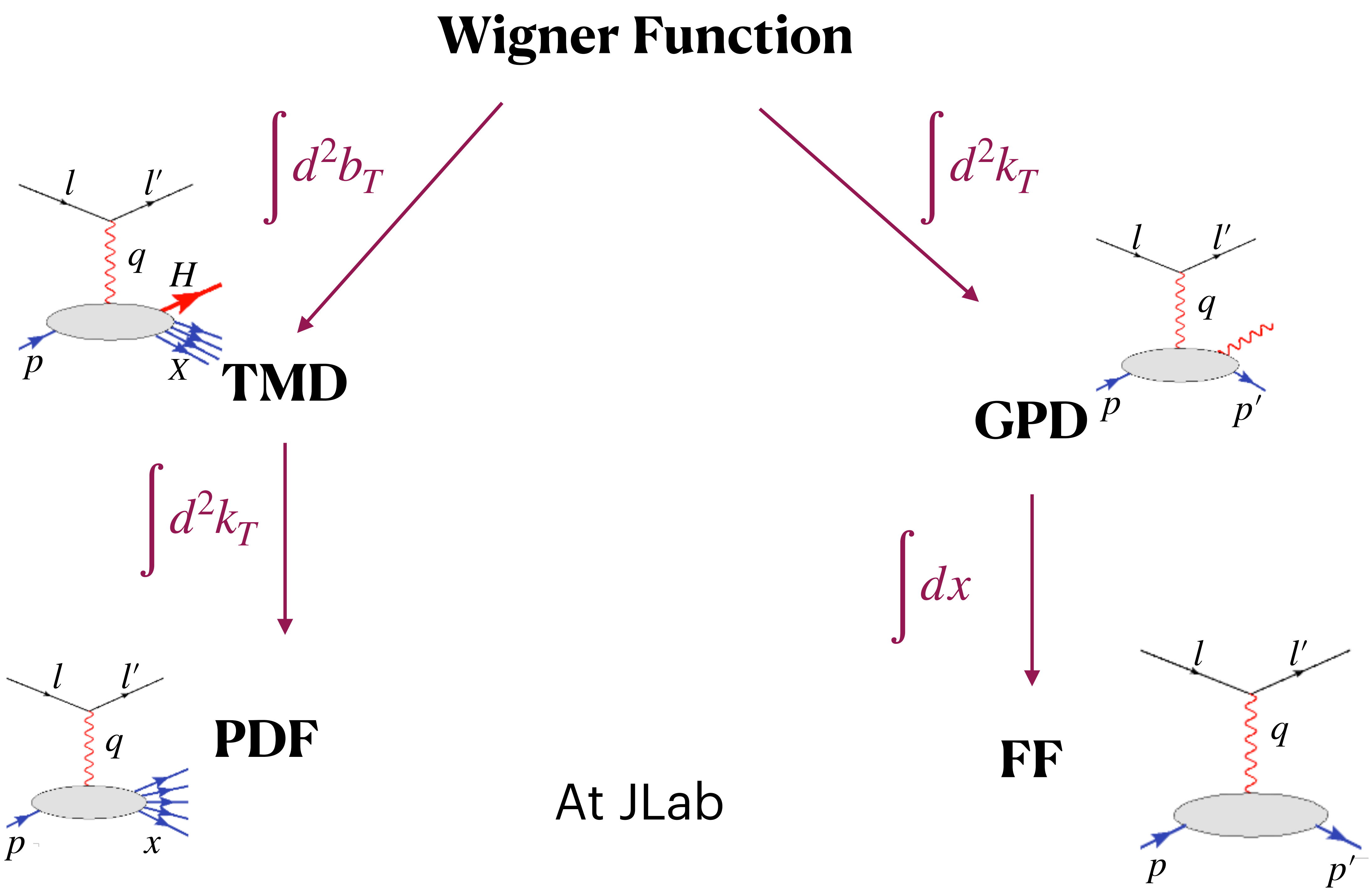
University of New Hampshire
October 14, 2025

Unified View of Nucleon Structure



Unified View of Nucleon Structure

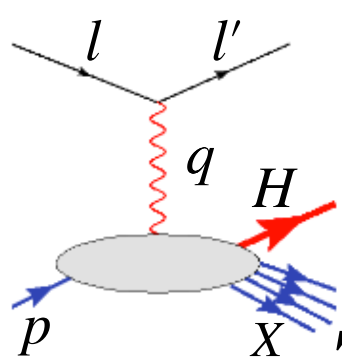


Unified View of Nucleon Structure

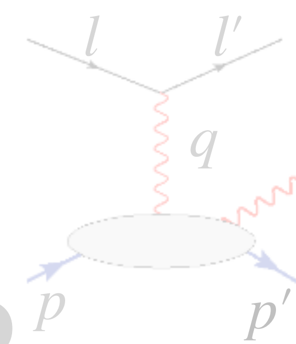
Wigner Function

$\int d^2b_T$

$\int d^2k_T$



TMD



GPD

Today's talk

Describe the distribution of quarks and gluons in a nucleon with respect to x and k_T

$\int d^2k_T$

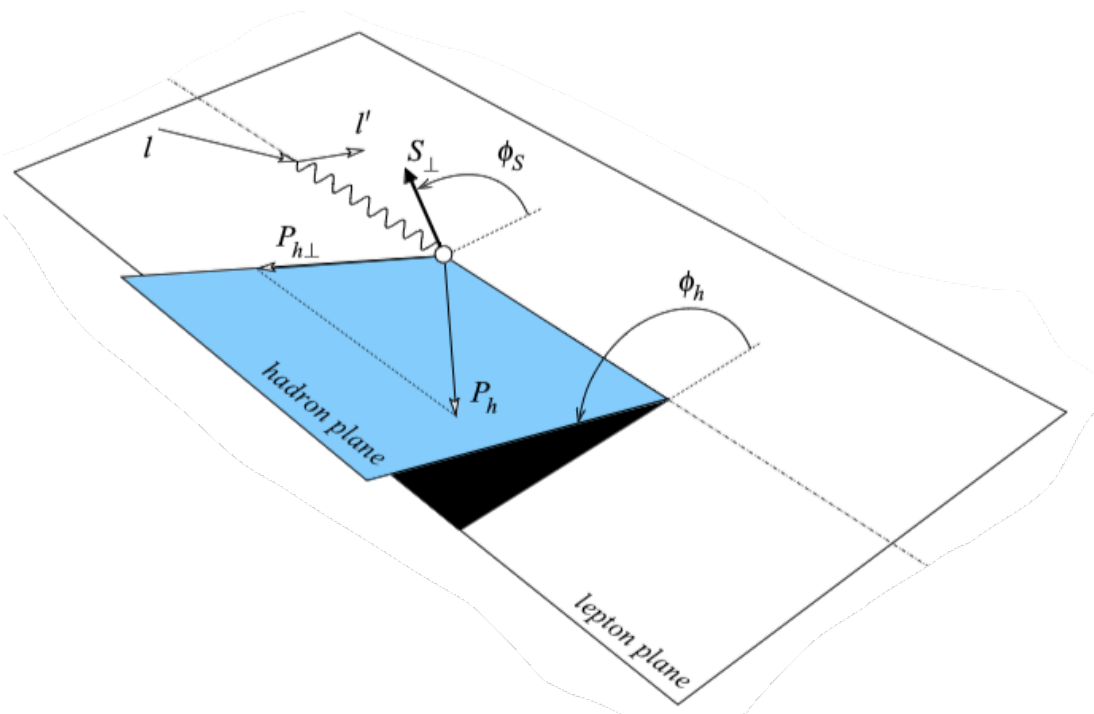
$\int dx$

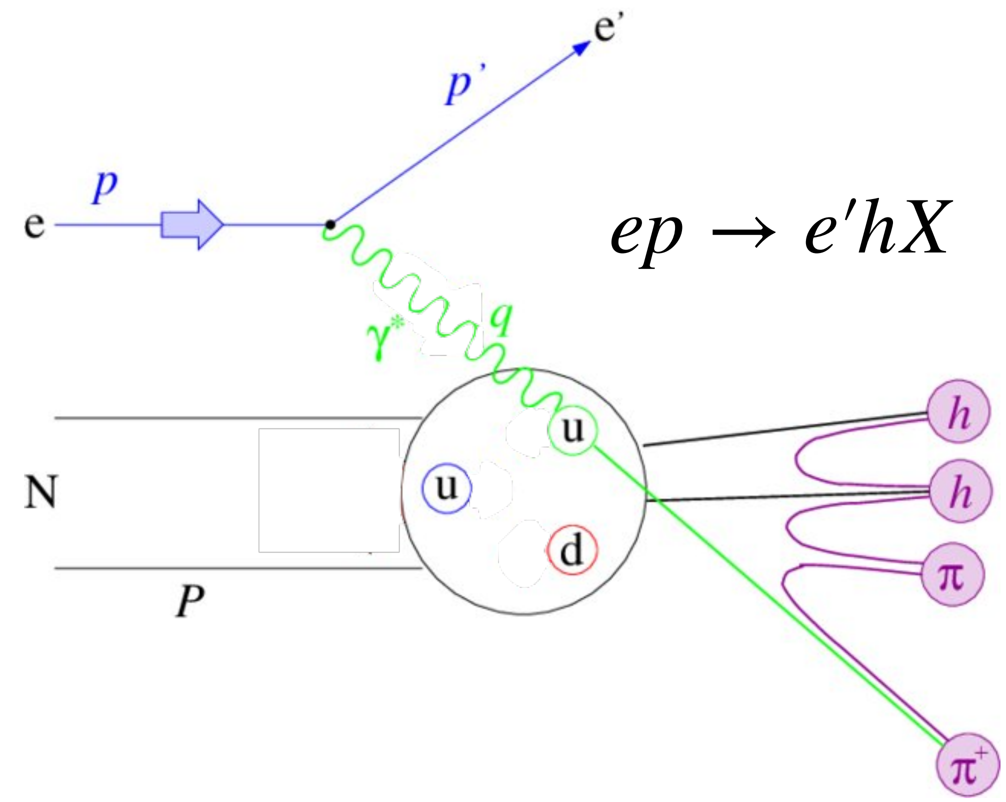
PDF

FF

Accessing TMDs at JLab

SIDIS





$$x \; Q^2 \; \phi_s \; z \; P_{h\perp} \; \phi_h$$

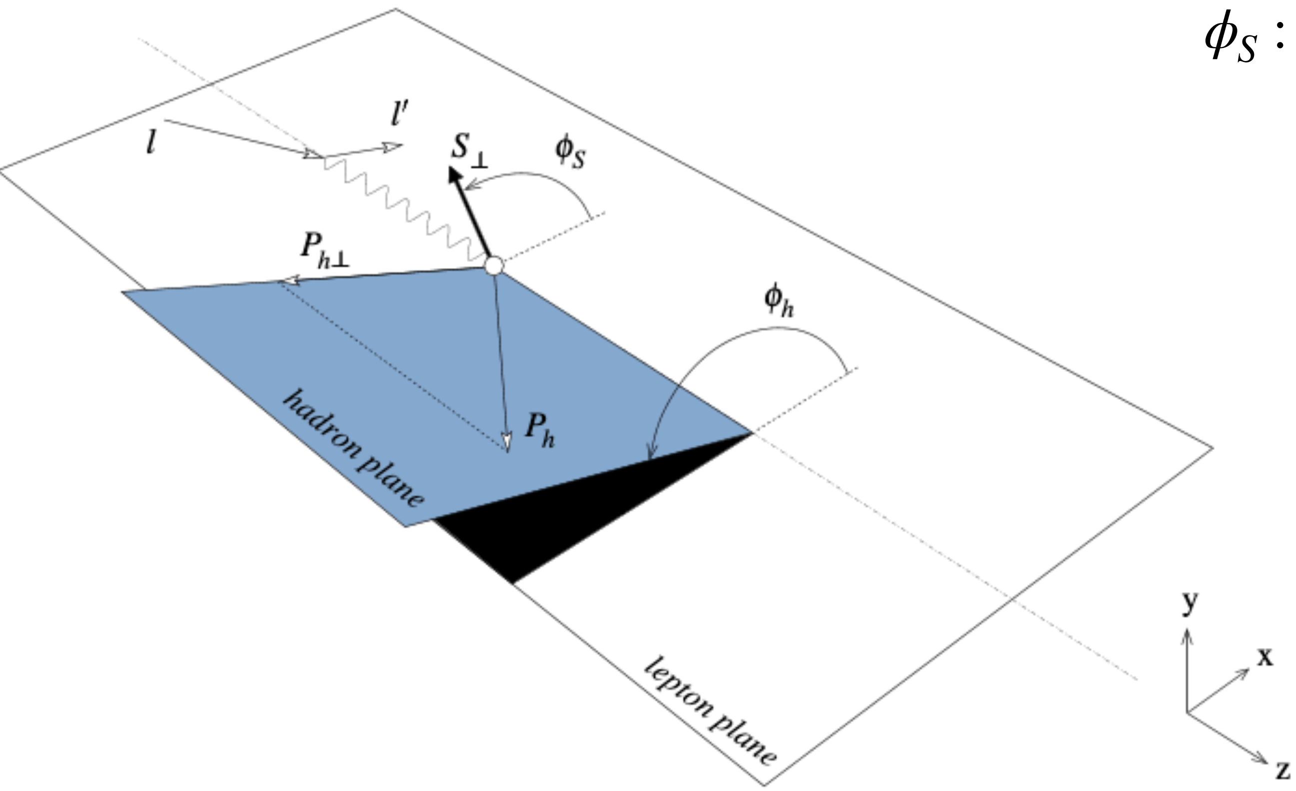
multi-dimensional observables

TMDs are NOT direct physical observables!

SIDIS Kinematics

ϕ_h : Angle between lepton and hadron planes

ϕ_S : Angle between lepton plane and nucleon spin



Momentum transfer: $Q^2 = -(l - l')^2$

Center-of-mass energy: $s = (P + l)^2$

Invariant mass: $W^2 = (P + q)^2$

Missing mass: $W'^2 = (P + q - P_h)^2$

$$y = \frac{P \cdot q}{P \cdot l}$$

$$\cos\phi_h = \frac{\hat{\mathbf{q}} \times \mathbf{l}}{|\hat{\mathbf{q}} \times \mathbf{l}|} \cdot \frac{\hat{\mathbf{q}} \times \mathbf{P}_h}{|\hat{\mathbf{q}} \times \mathbf{P}_h|}$$

$$\sin\phi_h = \frac{(\mathbf{l} \times \mathbf{P}_h) \cdot \hat{\mathbf{q}}}{|\hat{\mathbf{q}} \times \mathbf{l}||\hat{\mathbf{q}} \times \mathbf{P}_h|}$$

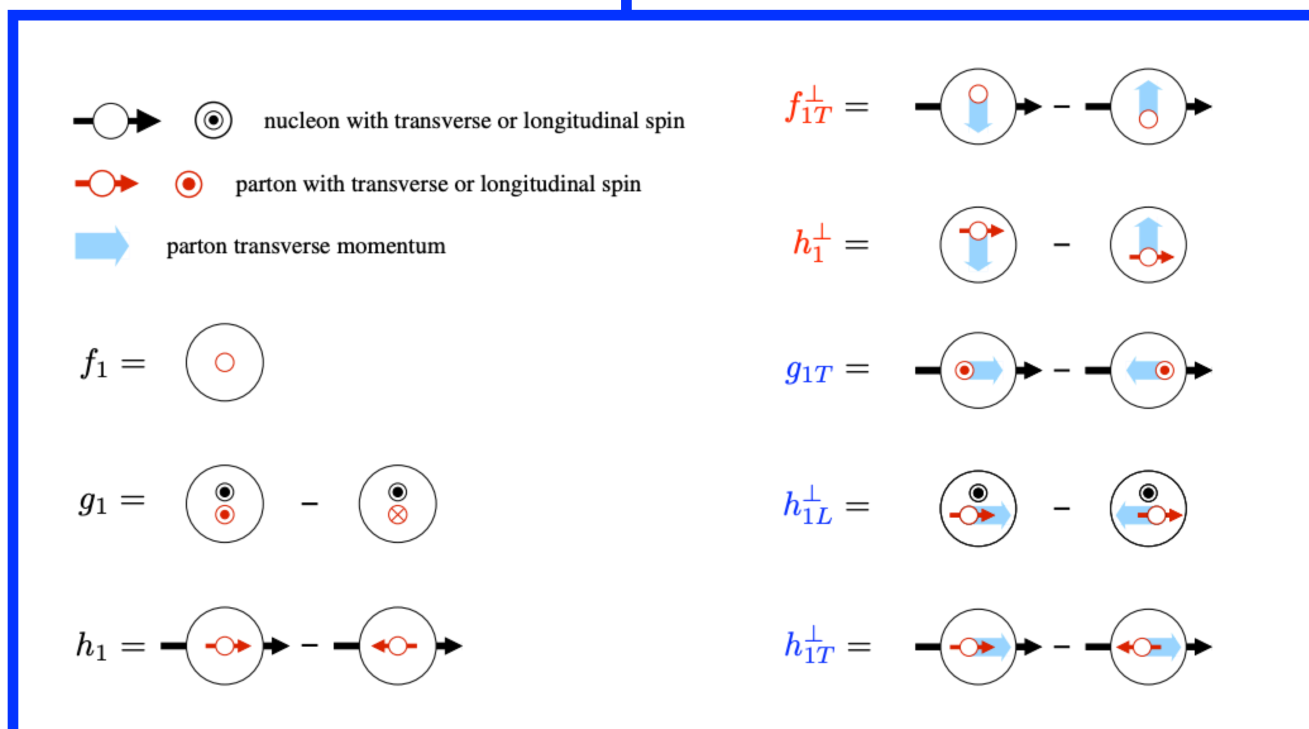
$$x = \frac{Q^2}{2P \cdot q} \qquad z = \frac{P_h \cdot P}{P \cdot q}$$

Trento Conventions
Phys. Rev. D70, 117504 (2004)

Leading twist distribution functions

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		$f_{1T}^\perp$	g_{1T}		$[h_1], [h_{1T}^\perp]$	

Spin 1/2



After integrating over the transverse momentum:

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					
L			$g_{1L}\,(g_1)$			
T					$[h_1]$	

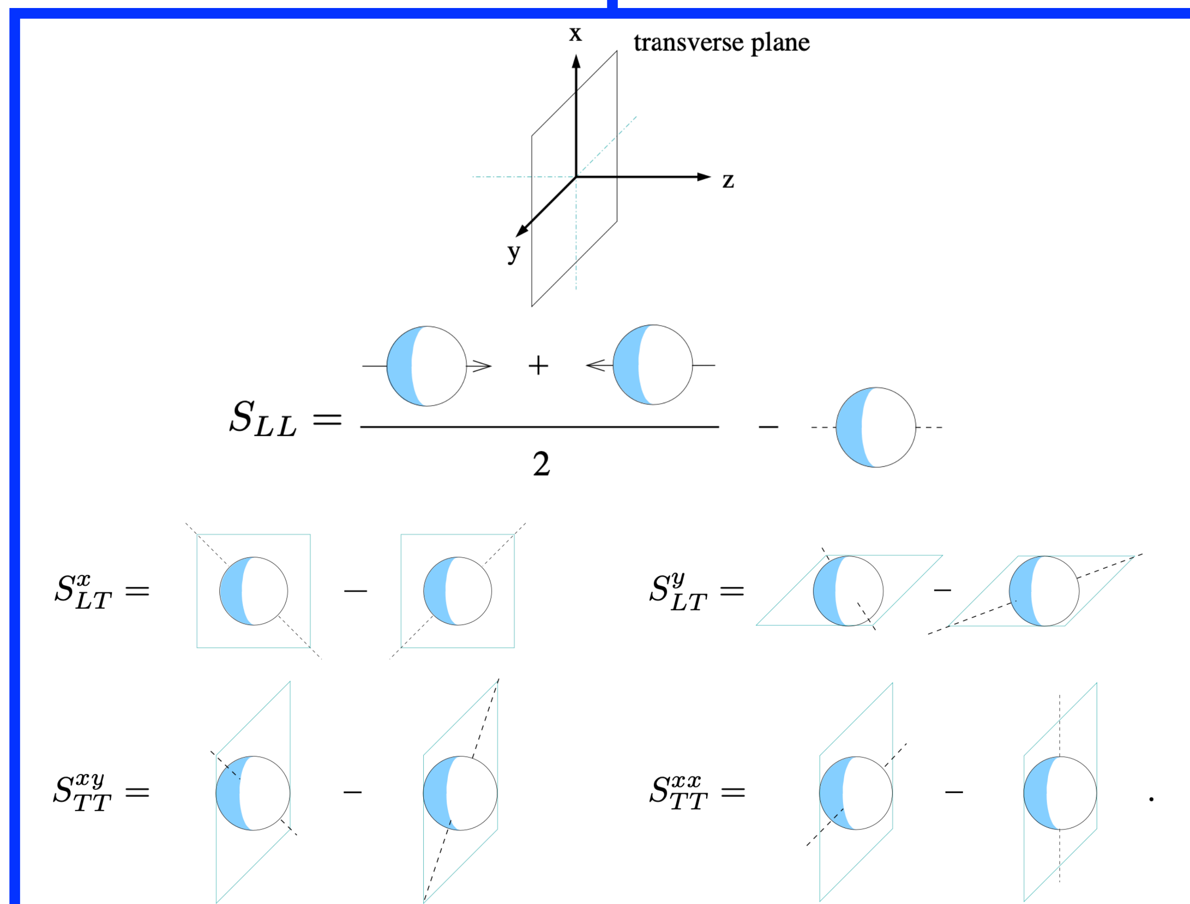
Phys. Rev. D 62 (2000)

Leading twist distribution functions

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
LL	f_{1LL}					$[h_{1LL}^{\perp}]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}], [h_{1LT}^{\perp}]$
TT	f_{1TT}			g_{1TT}		$[h_{1TT}], [h_{1TT}^{\perp}]$

Add 10 leading functions completely unexplored

Spin 1

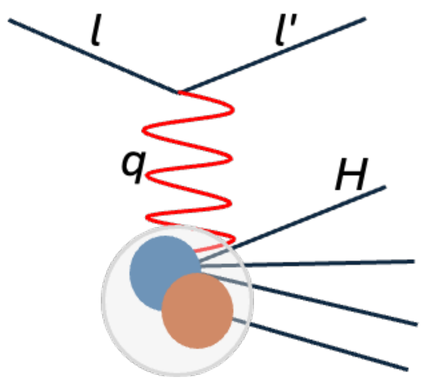


After integrating over the transverse momentum:

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
LL	$f_{1LL}(b_1)$					
LT						*1
TT						

Phys. Rev. D 62 (2000)

This talk: Longitudinally Polarized Target



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

vector

$$+\,S_{\parallel}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+\,S_{\parallel}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

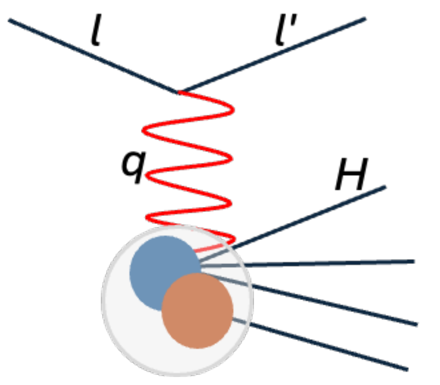
tensor

$$+\,T_{\parallel\parallel}\Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{U(LL)}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]\Big\}.$$

J. Zhao et al., arXiv:2508.06134 (2025).

This talk: Longitudinally Polarized Target



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

vector

$$+\,S_{\parallel}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

*Vector Polarization

$$+\,S_{\parallel}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

tensor

$$+\,T_{\parallel\parallel}\Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{U(LL)}^{\cos\phi_h}$$

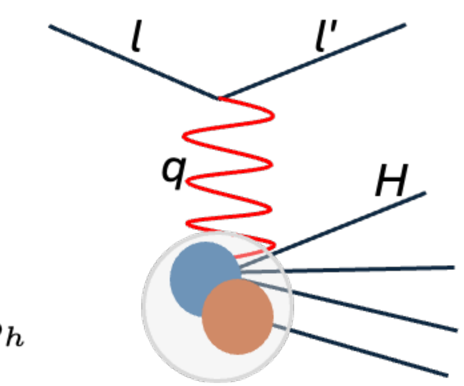
*Tensor Polarization

$$+\,\varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]\Big\}.$$

* Along the q-vector

J. Zhao et al., arXiv:2508.06134 (2025).

This talk: Longitudinally Polarized Target



$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)
&\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}
\end{aligned}
$$

vector

$$
+S_{\parallel}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]
$$

Electron helicity

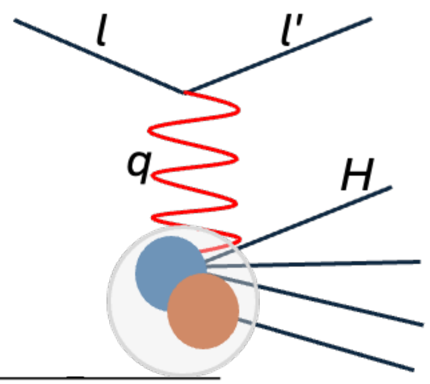
$$
+S_{\parallel}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]
$$

tensor

$$
\begin{aligned}
&+T_{\parallel\parallel}\Big[F_{U(LL),T}+\varepsilon F_{U(LL),L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{U(LL)}^{\cos\phi_h} \\
&+\varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]\Big\}.
\end{aligned}
$$

J. Zhao et al., arXiv:2508.06134 (2025).

This talk: Longitudinally Polarized Target



$$\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} =$$

tensor

$$+\, T_{\parallel\parallel} \Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{U(LL)}^{\cos\phi_h}$$

$$+\, \varepsilon \cos(2\phi_h)\, F_{U(LL)}^{\cos 2\phi_h} + \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{L(LL)}^{\sin\phi_h} \Big] \Big\}.$$

5 structure functions analogous to the unpolarized

J. Zhao et al., arXiv:2508.06134 (2025).

Tensor-polarized structure functions

tensor

$$+T_{\|\|\|}\Big[F_{U(LL),T}+\varepsilon F_{U(LL),L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{U(LL)}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]\Big\}.$$

$$F_{U(LL),T}=\mathcal{C}\big[f_{1LL}D_1\big],$$

$$F_{U(LL),L}=0,$$

$$F_{U(LL)}^{\cos\phi_h}=\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh_{LL}\,H_1^{\perp}+\frac{M_h}{M}\,f_{1LL}\frac{\tilde{D}^{\perp}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf_{LL}^{\perp}D_1+\frac{M_h}{M}\,h_{1LL}^{\perp}\frac{\tilde{H}}{z}\right)\right],$$

$$F_{U(LL)}^{\cos 2\phi_h}=\mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{MM_h}h_{1LL}^{\perp}H_1^{\perp}\right],$$

$$F_{L(LL)}^{\sin\phi_h}=\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_{LL}\,H_1^{\perp}+\frac{M_h}{M}\,f_{1LL}\frac{\tilde{G}^{\perp}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_{LL}^{\perp}D_1+\frac{M_h}{M}\,h_{1LL}^{\perp}\frac{\tilde{E}}{z}\right)\right].$$

Tensor-polarized structure functions

tensor	$+T_{\parallel\parallel}\Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{U(LL)}^{\cos\phi_h}$
	$+\,\varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]\Big\}.$

$$F_{U(LL),T} = \mathcal{C}\big[f_{1LL}D_1\big],$$

$$F_{U(LL),L} = 0,$$

$$F_{U(LL)}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\bigg[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\bigg(xh_{LL}\,H_1^{\perp} + \frac{M_h}{M}f_{1LL}\frac{\tilde{D}^{\perp}}{z}\bigg) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\bigg(xf_{LL}^{\perp}D_1 + \frac{M_h}{M}h_{1LL}^{\perp}\frac{\tilde{H}}{z}\bigg)\bigg],$$

$$F_{U(LL)}^{\cos 2\phi_h} = \mathcal{C}\bigg[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{MM_h}h_{1LL}^{\perp}H_1^{\perp}\bigg],$$

$$F_{L(LL)}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\bigg[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\bigg(xe_{LL}\,H_1^{\perp} + \frac{M_h}{M}f_{1LL}\frac{\tilde{G}^{\perp}}{z}\bigg) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\bigg(xg_{LL}^{\perp}D_1 + \frac{M_h}{M}h_{1LL}^{\perp}\frac{\tilde{E}}{z}\bigg)\bigg].$$

Hadron \ Quark	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5\,/\,\sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
LL	f_{1LL}					$[h_{1LL}^{\perp}]$

Leading twist

Let's start simple:

tensor $\quad + T_{\parallel\parallel}\left[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{U(LL)}^{\cos\phi_h} \right.$

$$\left. + \varepsilon\cos(2\phi_h)\, F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{L(LL)}^{\sin\phi_h} \right]\Bigg\}.$$

$$F_{U(LL),T} = \mathcal{C}\left[f_{1LL} D_1\right],$$

How do we approach this structure function?

1. Understand the size of these contribution to propose dedicated experiments

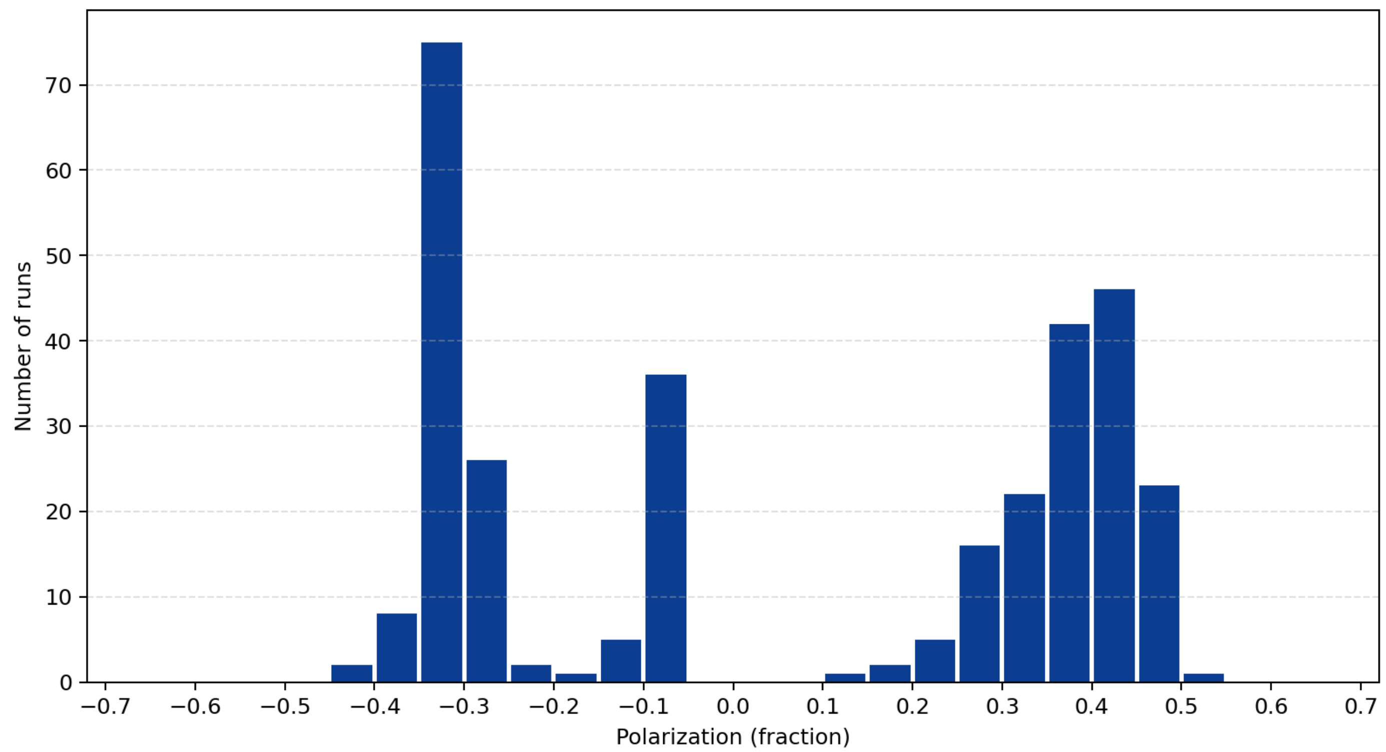
"Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12"

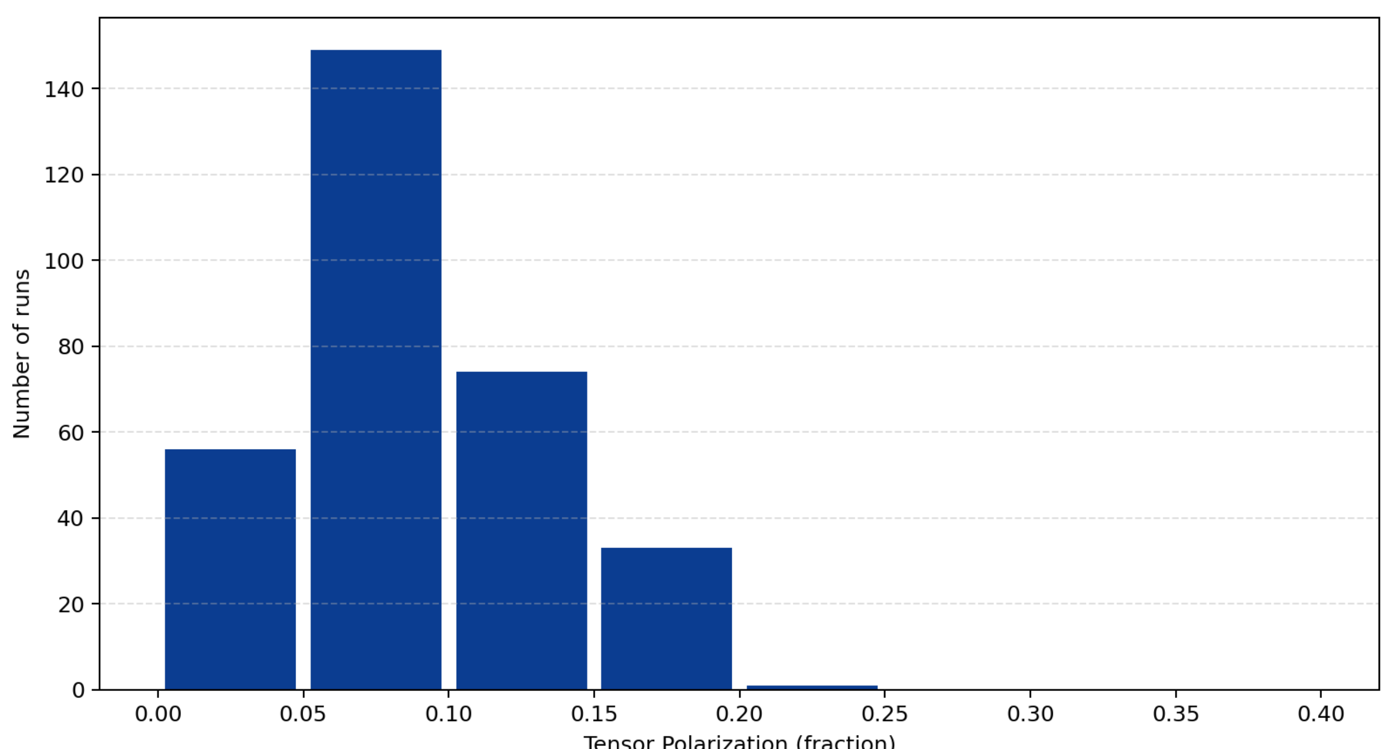
CLAS12 Approved Analysis (CAA approved in Fall 2024)

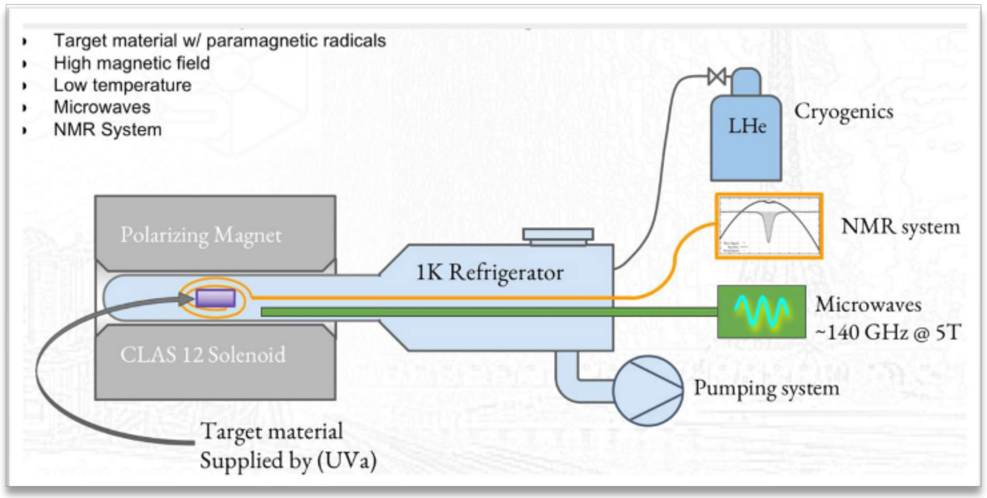
Data: Polarized Deuterium (ND_3 via DNP). Q_{max}~20%

Goal: understand the size of the tensor contribution to the SIDIS processes ($eD \rightarrow e'\pi^{\pm}X$)

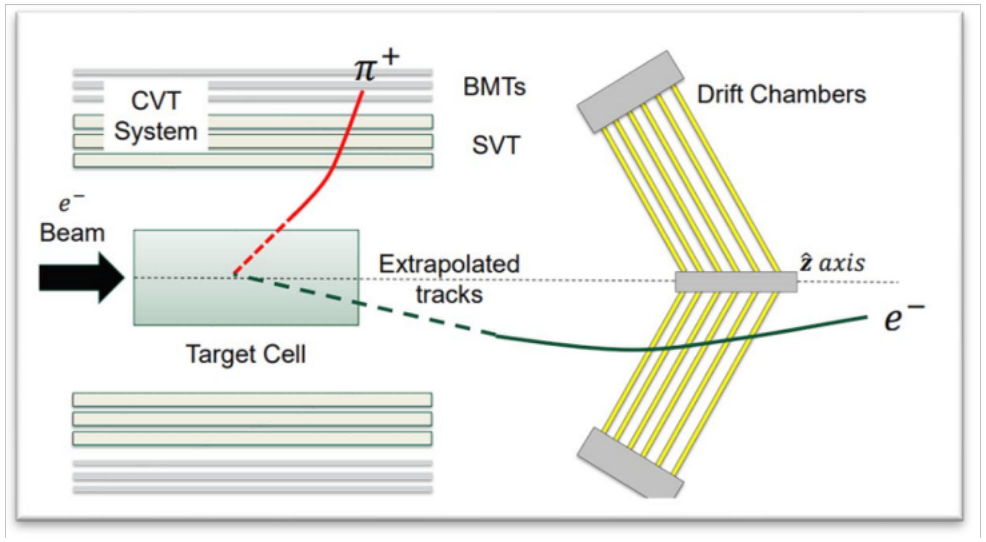
Run group C data
(ND_3 via DNP)



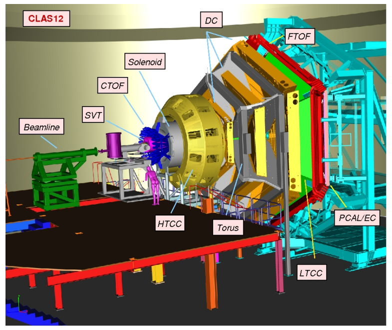




Courtesy of Gregory Matousek



Although small, the tensor polarization is non-negligible.



General Idea

Assuming vector + and - are about the same size:

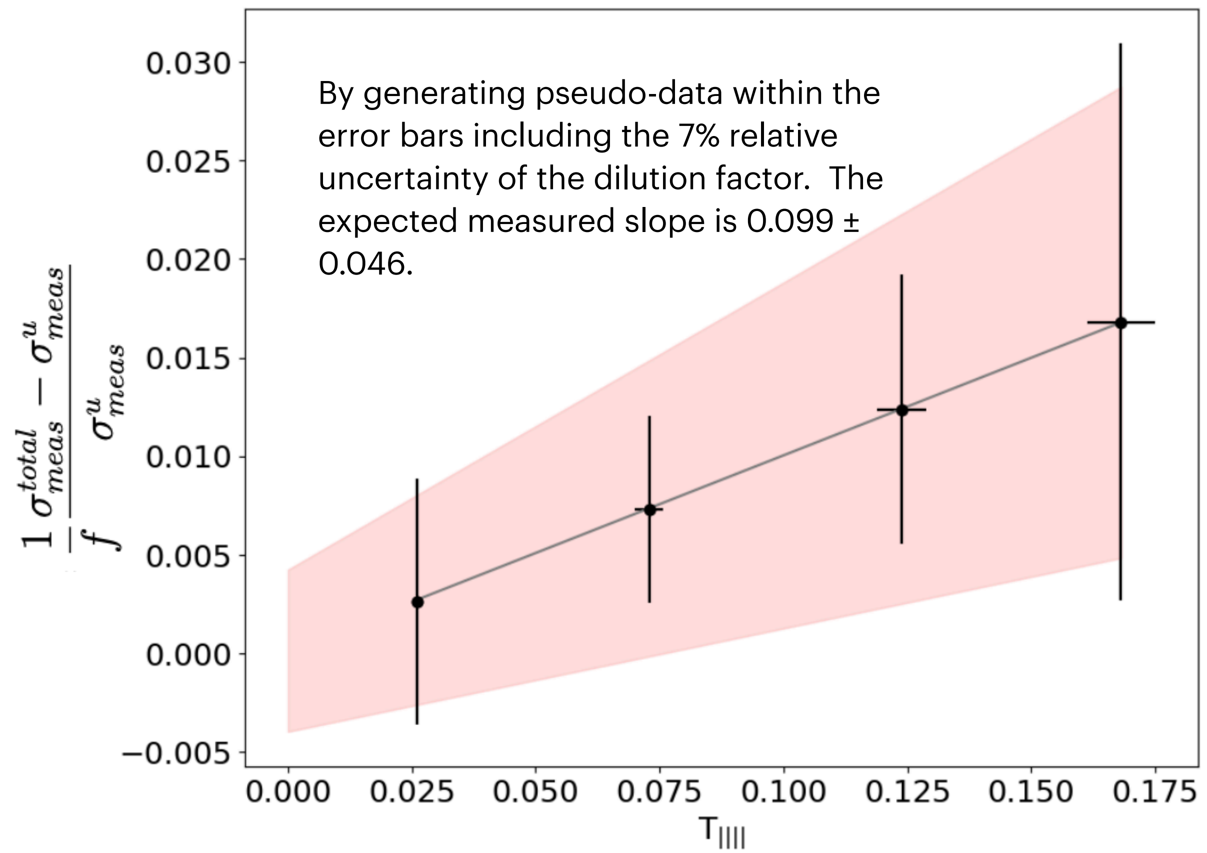
$$\sigma^{+}_{meas} = \frac{1}{2}\left(\sigma^{D}_{u} + S^{+}_{\|}\sigma_S + T_{\|\|}\sigma_T + \sum_i \sigma^i\right)$$

$$\sigma^{-}_{meas} = \frac{1}{2}\left(\sigma^{D}_{u} + S^{-}_{\|}\sigma_S + T_{\|\|}\sigma_T + \sum_i \sigma^i\right)$$

$$\sigma^{total}_{meas} = \sigma^{+}_{meas} + \sigma^{-}_{meas} = \sigma^{D}_{u} + T_{\|\|}\sigma_T + \sum_i \sigma^i$$

Subtracting the unpolarized cross-section and rearranging terms:

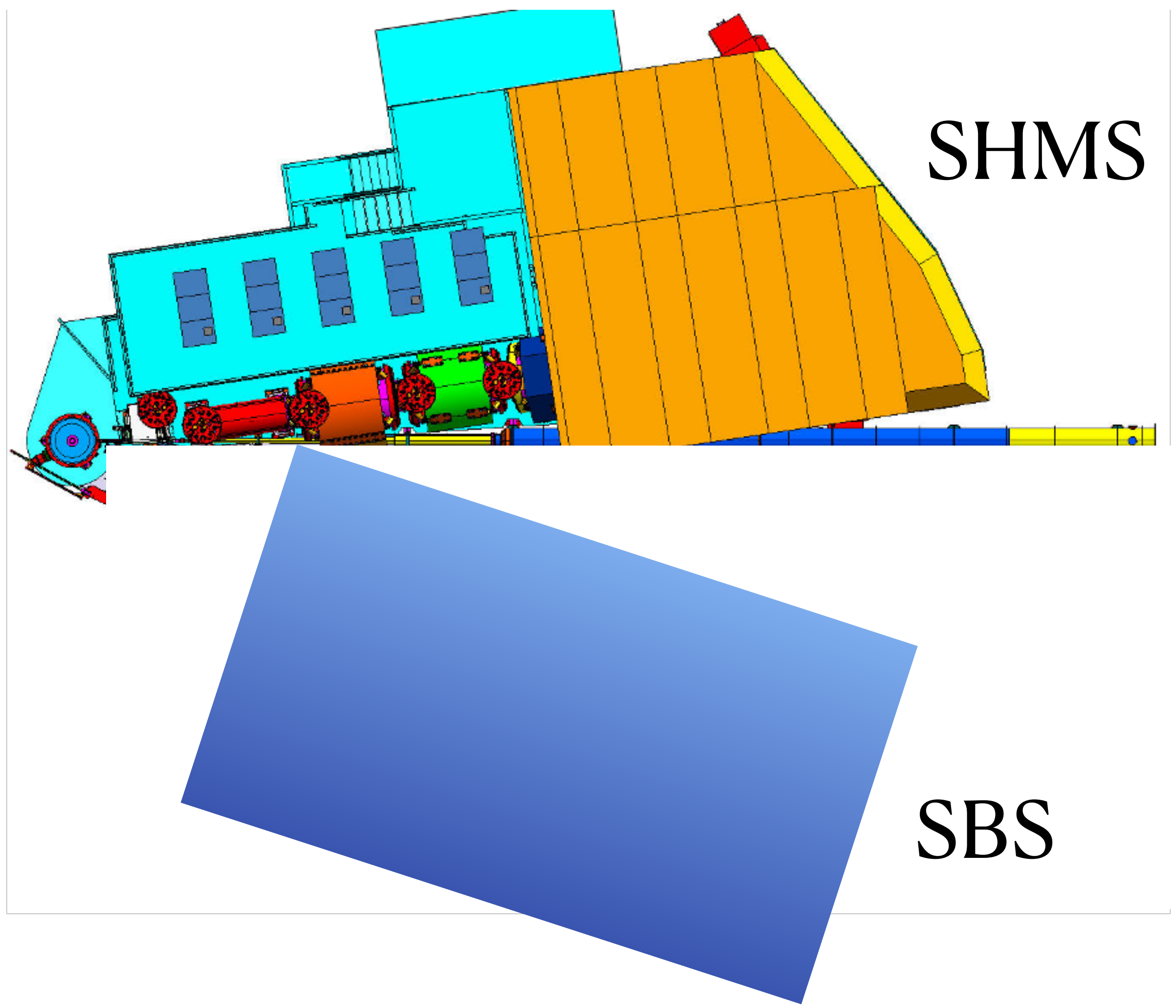
$$T_{\|\|}\frac{\sigma_T}{\sigma^D_u} = \frac{1}{f}\frac{\sigma^{total}_{meas} - \sigma^{u}_{meas}}{\sigma^{u}_{meas}}$$



* This 10% estimate comes from the HERMES measurement of b1 (the collinear structure function), which is the only available data to date. Phys.Rev.Lett.95 (2005)

CAA: arXiv:2502.20044, 2025

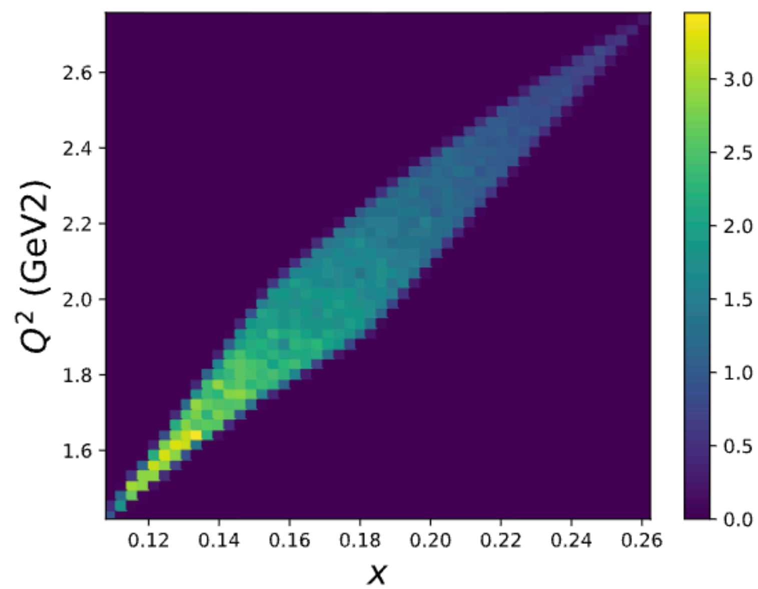
2. Dedicated experiment

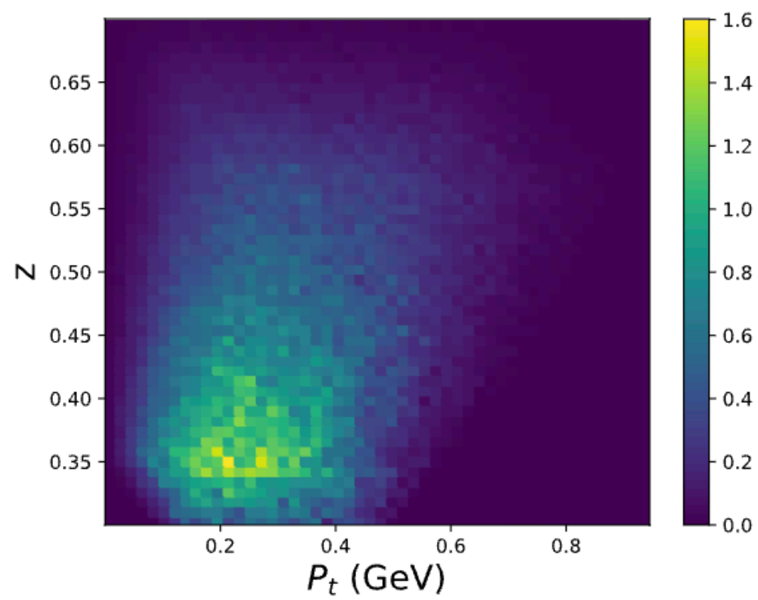


"*Spin-1 TMDs and Structure Functions of the Deuteron*"
at Hall C

Letter of Intent (LOI12-24-002 PAC 52, 2024)

Goal: Dedicated Measurement in Hall C ($eD \to e'\pi^{\pm}X$)





Kinematic Settings

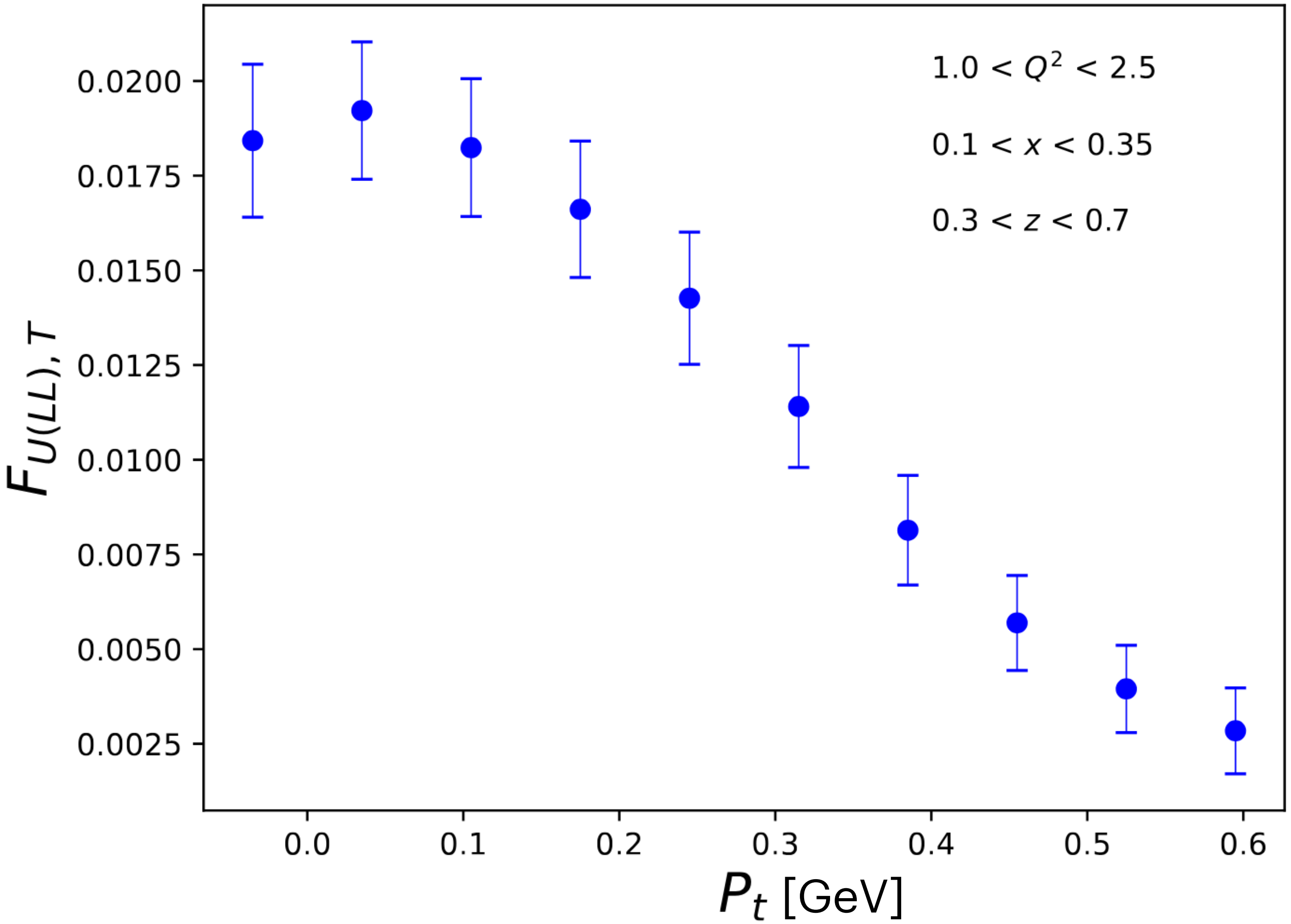
	θ (deg.)	ϕ (deg.)	P (GeV)
Electron	10.3 - 12.4	-2.87 - 2.87	4.0 - 5.4
Hadron	5.0 - 15.0	167 - 193	2.0 - 4.0

A longitudinally tensor polarized deuteron target

The Super BigBite (SBS) Spectrometer, which will be used to measure the produced hadron

The Super High Momentum Spectrometer (SHMS) will be used to measure the scattered electron

Current estimate



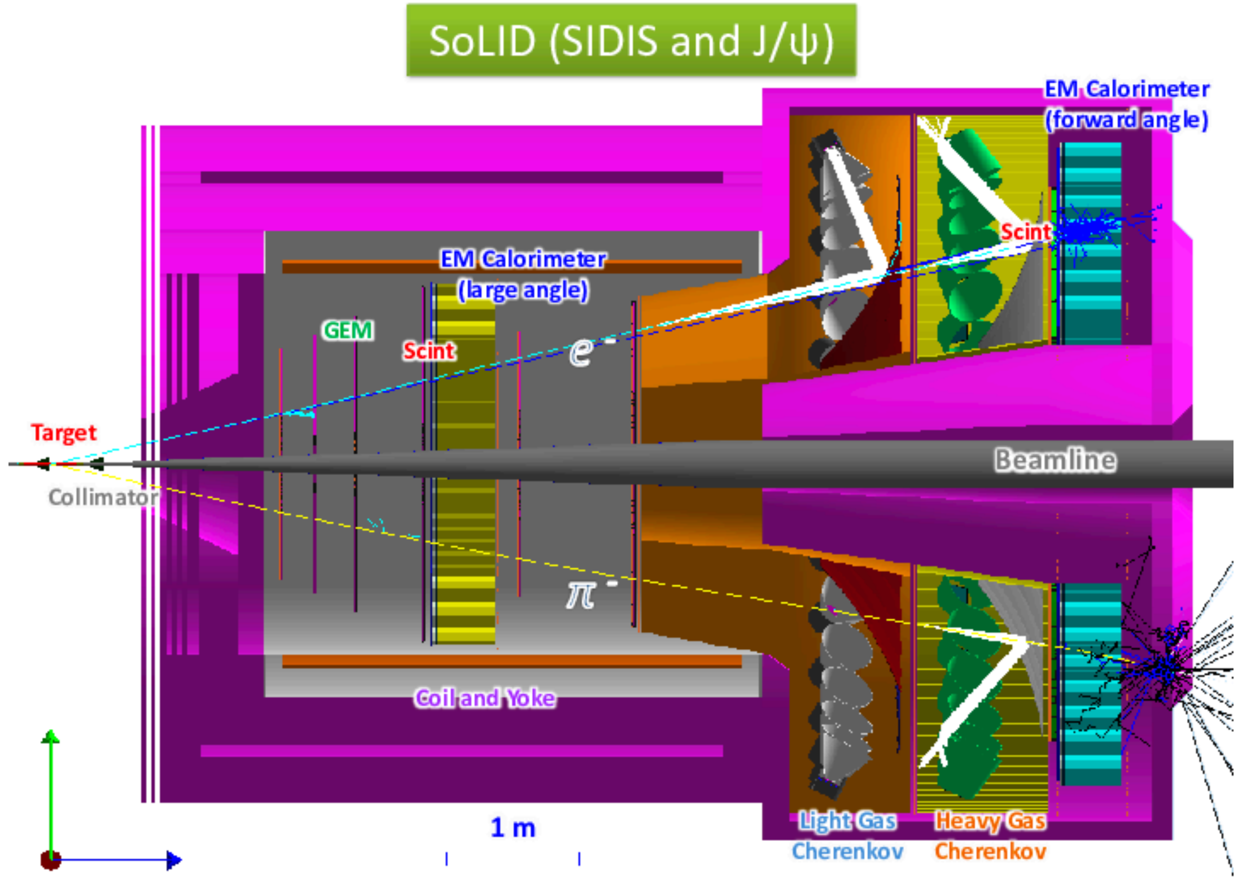
This 10% estimate comes from the HERMES measurement of b1 (the collinear structure function), which is the only available data to date. Phys.Rev.Lett.95 (2005)

This estimate was done using the event generator for SoLID: https://github.com/TianboLiu/LiuSIDIS

Current plans:

- Perform full simulation (Jan Vanek)
- Full proposal (2026)

3. Full mapping in SoLID



"Future Proposals"

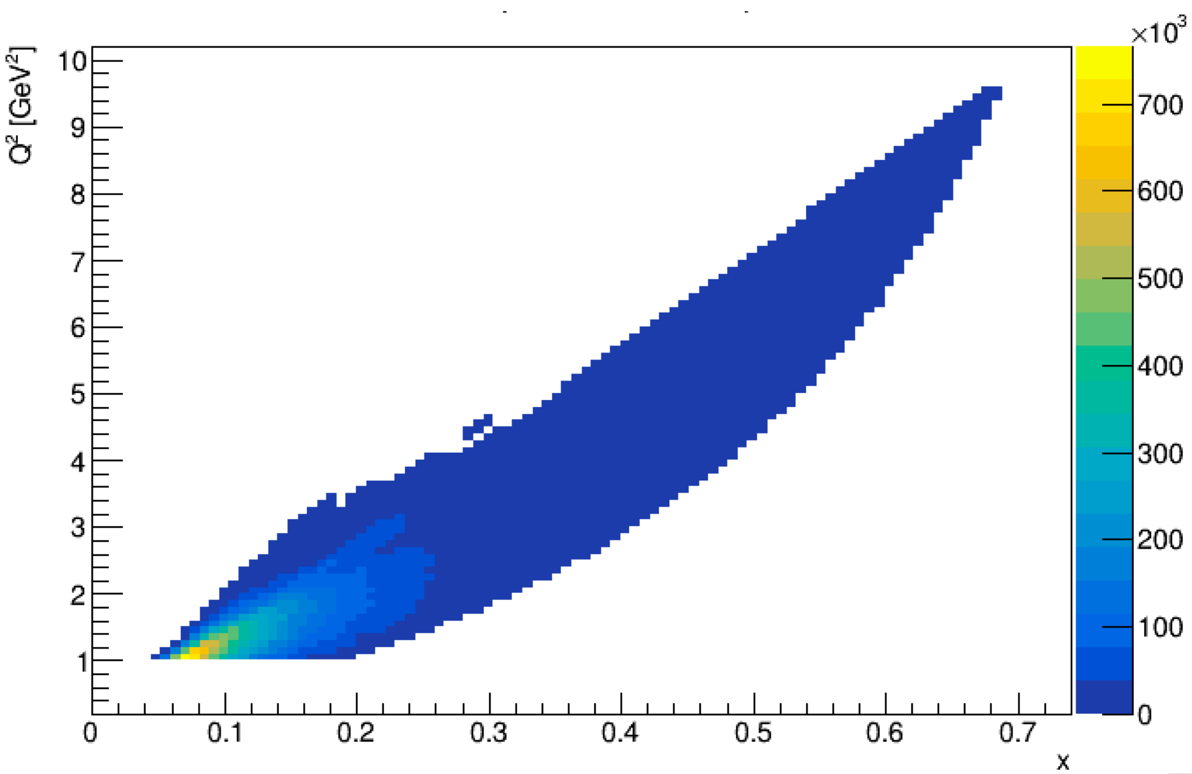
$0.3 < z < 0.7$

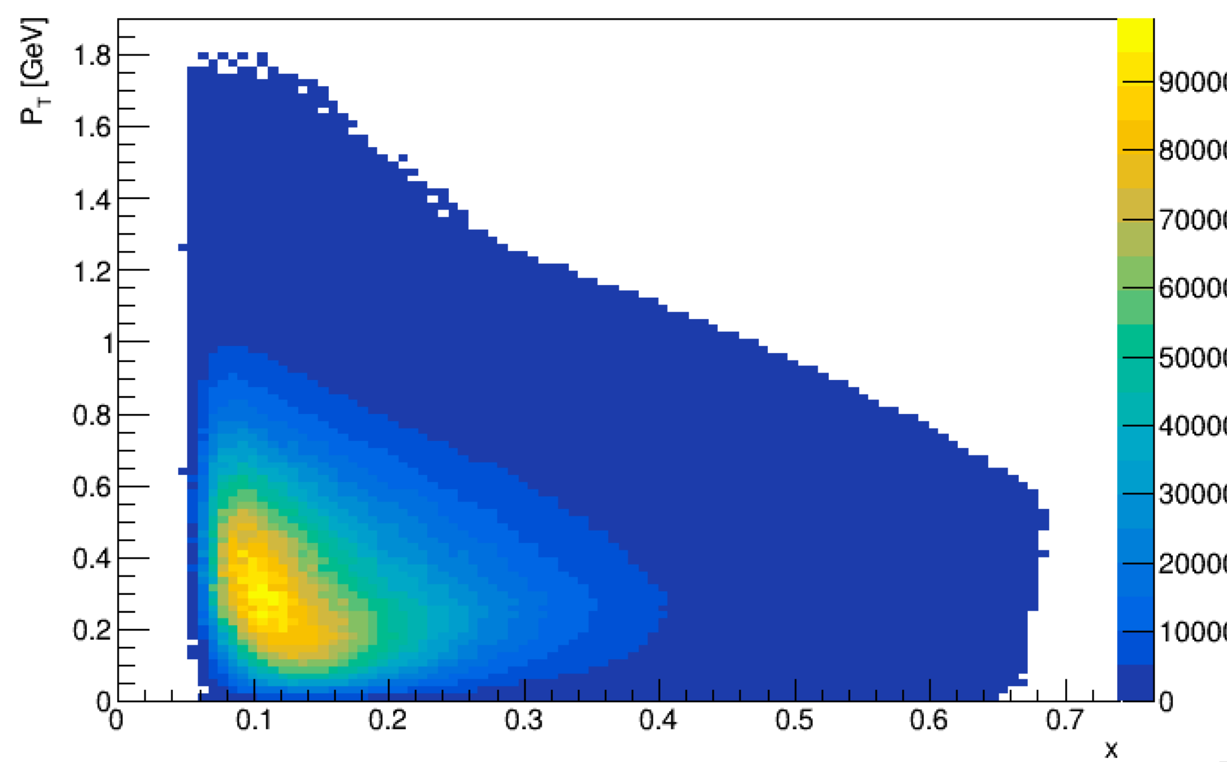
$Q^2 > 1.0\ \mathrm{GeV}^2$

$W > 2.3$ GeV

$W' > 1.6$ GeV

Unpolarized rates for π^-





“Future Proposals"

0.3 < z < 0.7

$Q^2 > 1.0$ GeV^2

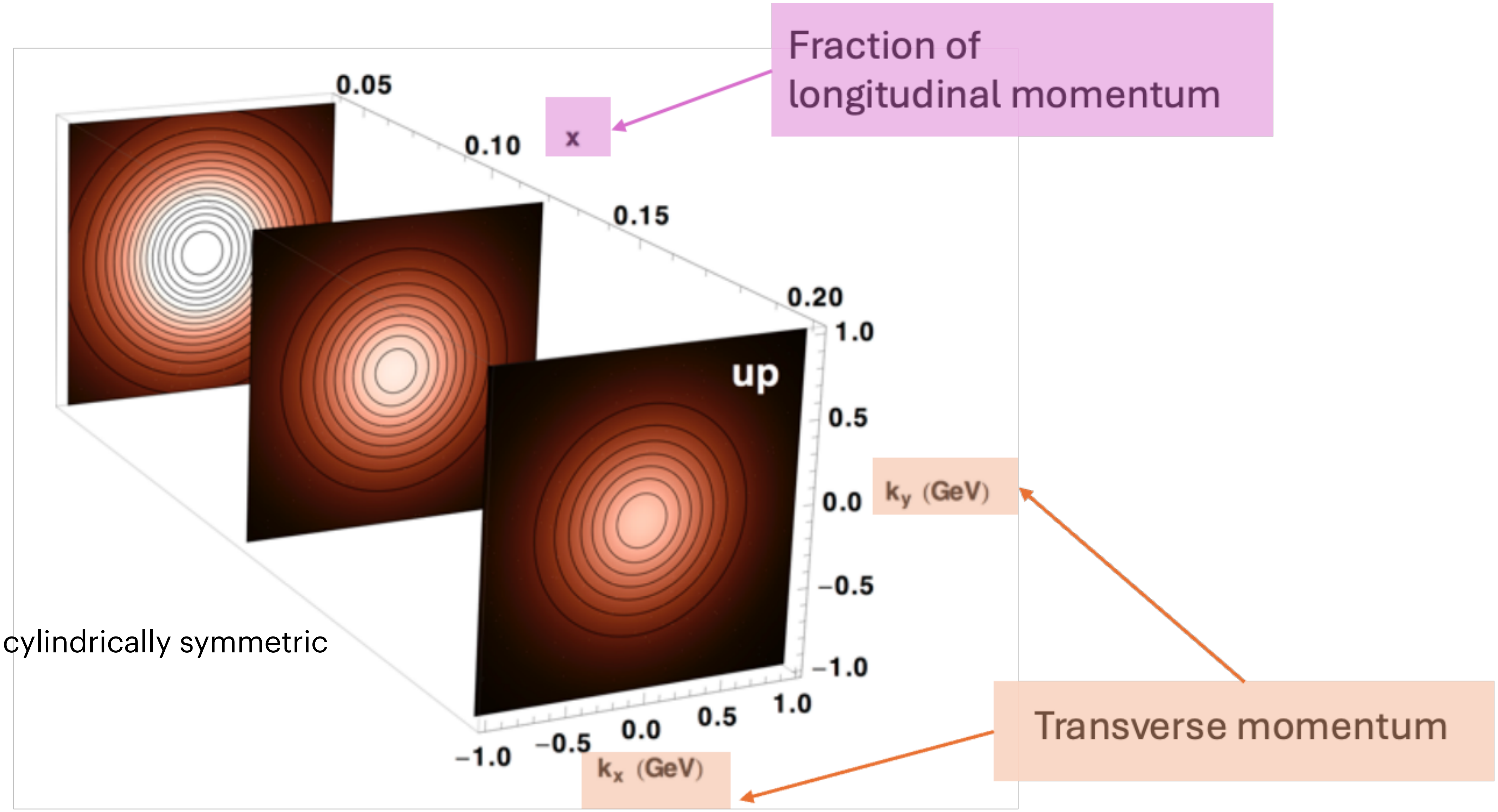
W > 2.3 GeV

W′ > 1.6 GeV

E= 11 GeV

Transverse Momentum Distributions (TMDs)

3D structure of the nucleon



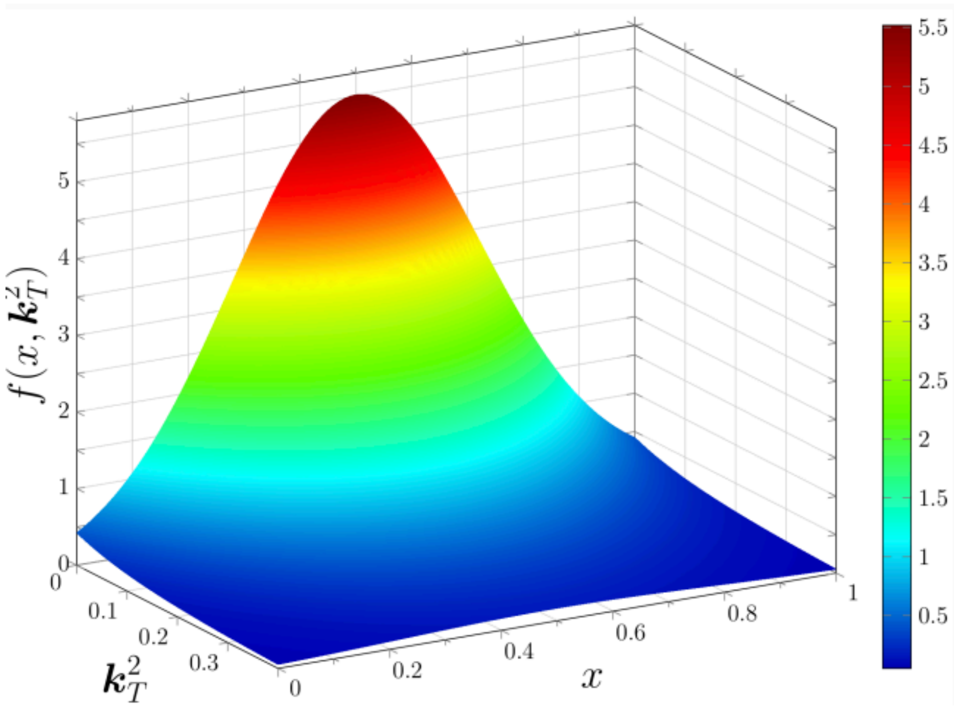
Unpolarized TMD: cylindrically symmetric

Courtesy of Alessandro Bacchetta

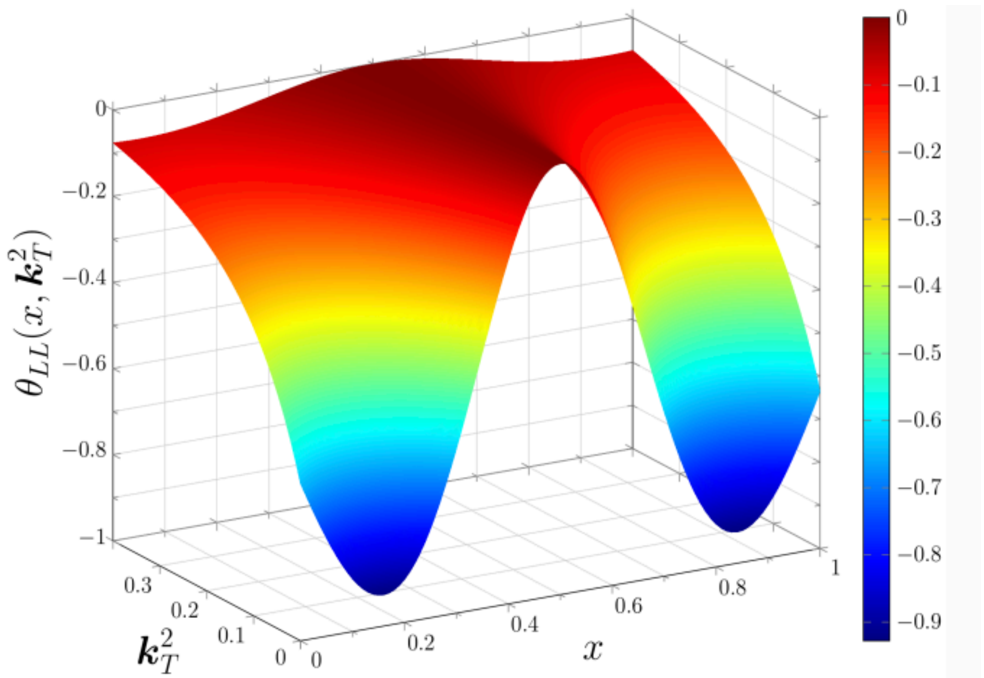
Work in Progress

Theory predictions for the spin-1 tensor st

ρ predictions



Unpolarized



Tensor

Maybe cylindrical is not a right approximation

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Experimental

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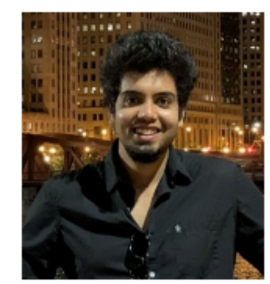

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Polarimetry

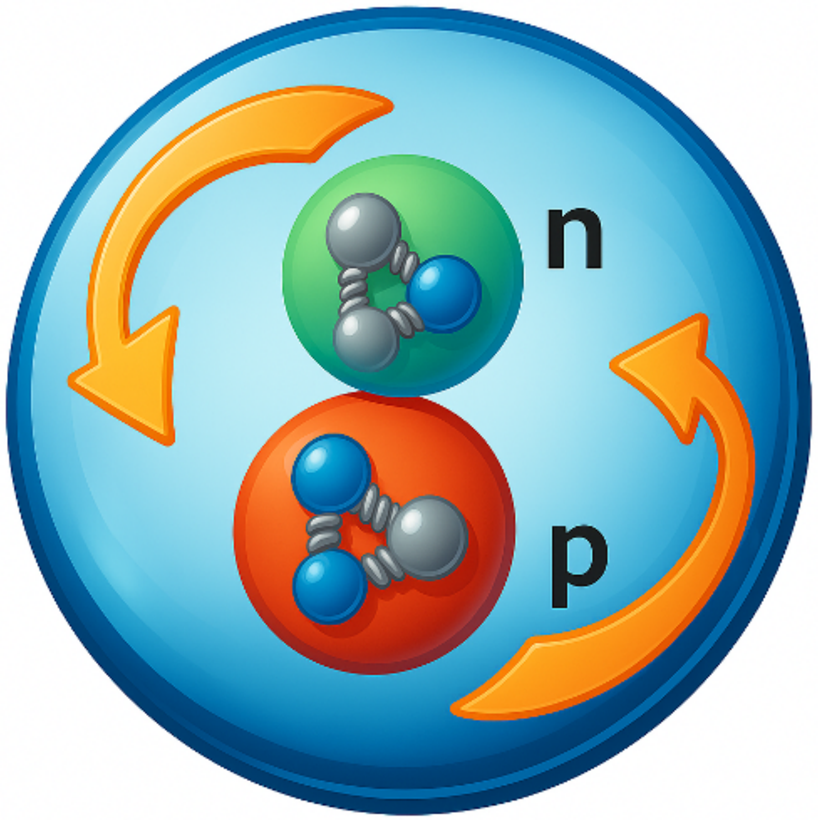
QE

DIS

SIDIS

Summary

- SIDIS spin 1 measurements open the door to a complete new set of observables.
- Theory efforts are being made to provide predictions.



These observables enable more refined studies of QCD and provide new insights into deuteron, illuminating the interplay between QCD dynamics and nuclear structure