Toward Measuring Tensor-Polarized Structure Functions in SIDIS

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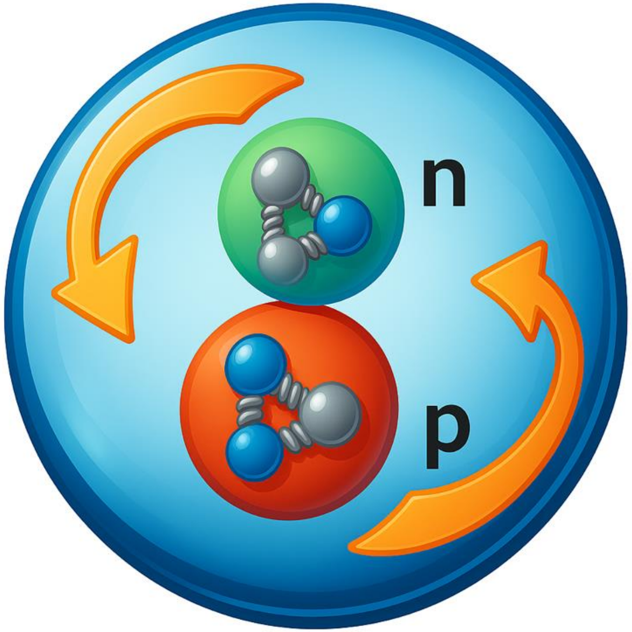
Tensor SIDIS workshop

June 4, 2026

University of New Hampshire



Deuteron
Cross-Section

Vector Contribution
P: Vector Polarization

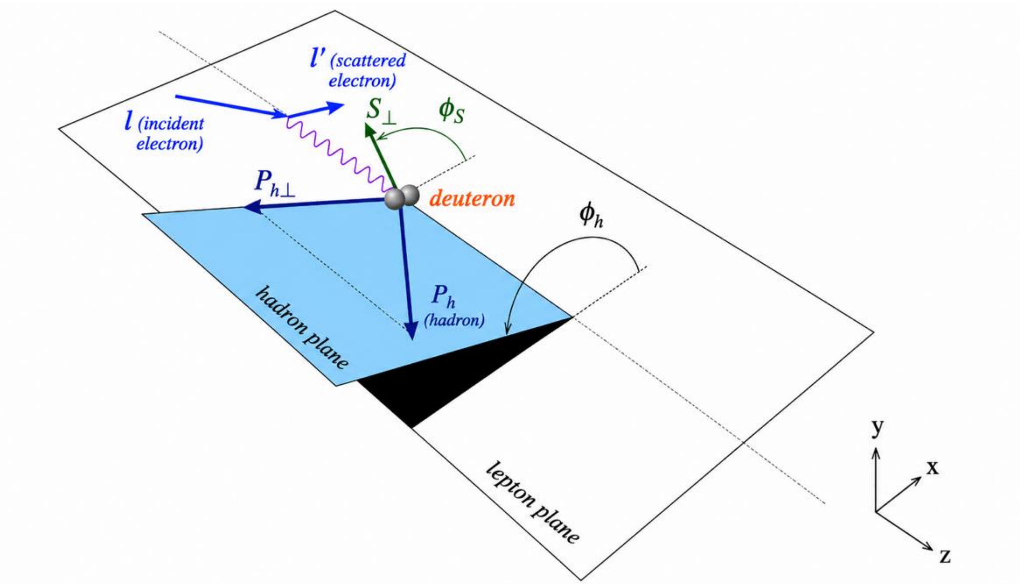
$$\sigma_D \sim \sigma_U + P \cdot \sigma_V + Q \cdot \sigma_T$$

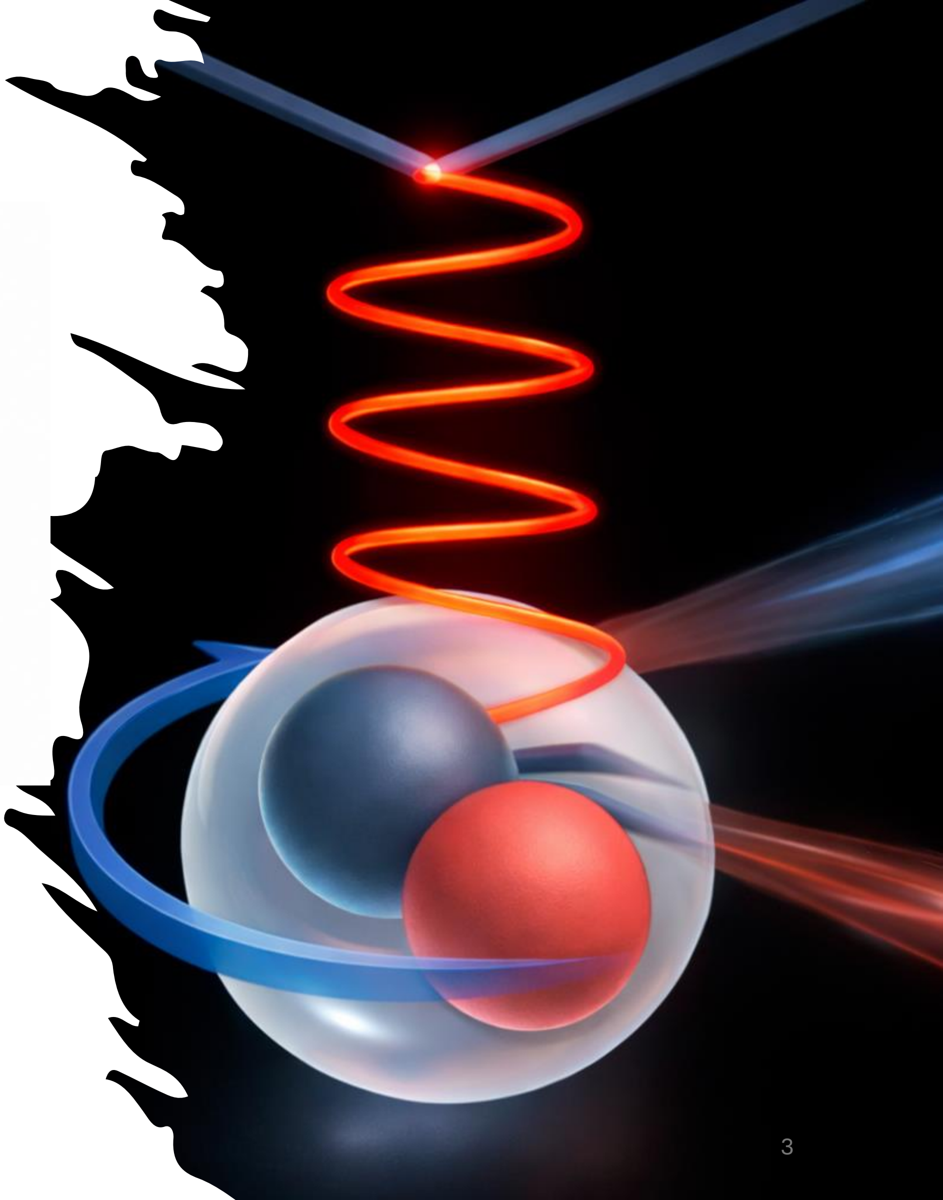
Unpolarized
Cross-Section

Tensor Contribution
Q: Vector Polarization

The tensor contribution (σ_T) remains one of the least explored contributions in the deuteron cross-section

$$e(l) + d(P) \rightarrow e'(l') + h(P_h) + X$$





Electron side

x_{Bj} and Q^2 set the DIS kinematics

Hadron side

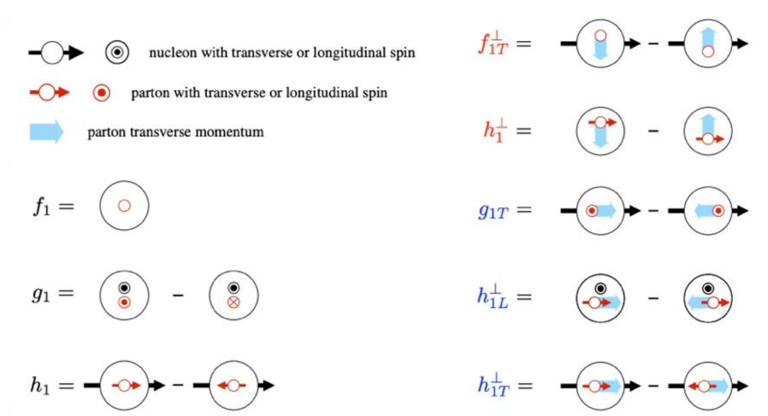
z, P_h, and hadron angle select the final state h

X contains the remaining fragments

Leading twist distribution functions

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
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:

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
U	f_1					
L			$g_{1L}(g_1)$			
T					$[h_1]$	

Phys. Rev. D 62 (2000)

Leading twist distribution functions

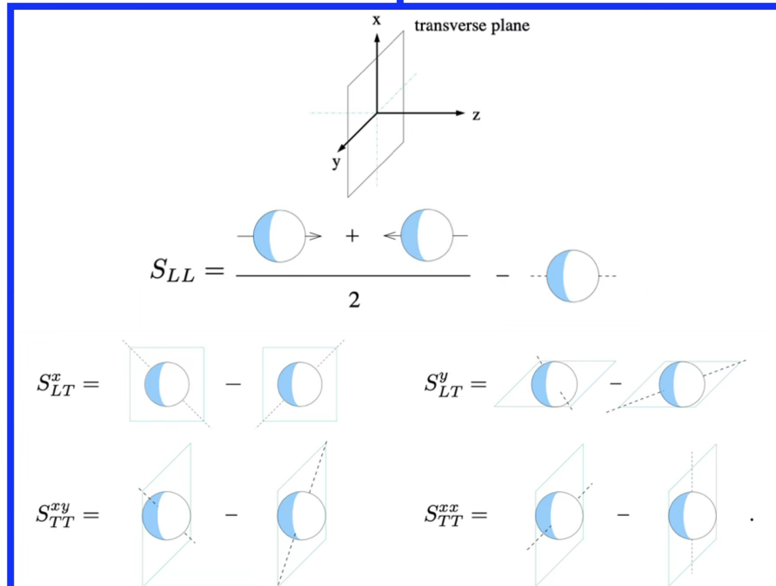
Hadron \ Quark	U (γ^+) T-even	U (γ^+) T-odd	L ($\gamma^+\gamma_5$) T-even	L ($\gamma^+\gamma_5$) T-odd	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-even	T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) T-odd
LL	f_{1LL}					$[h_{1LL}^{\perp}]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}]$, $[h_{1LT}^{\perp}]$
TT	f_{1TT}		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

Add 10 leading functions completely unexplored

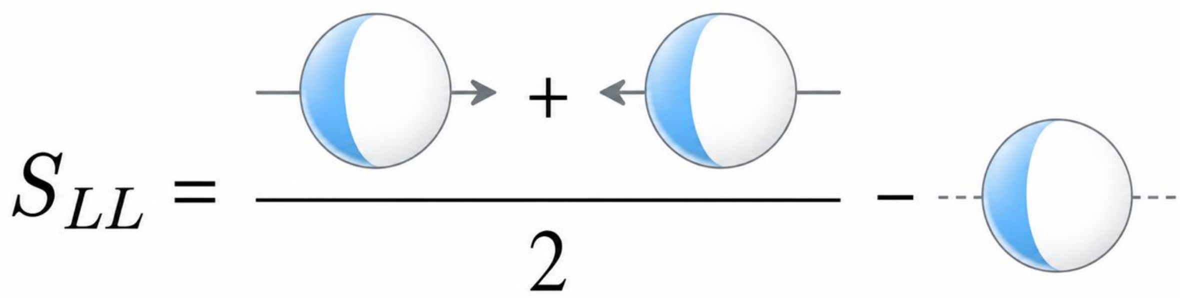
After integrating over the transverse momentum:

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

Spin 1



Phys. Rev. D 62 (2000)



TMD description

LL	
TMDs (leading twist)	SIDIS structure functions
$f_{1LL}(x, k_T)$	$F_{U(LL),T} \leftrightarrow f_{1LL}$
$[h_{1LL}^{\perp}(x, k_T)]$	$F_{U(LL)}^{\cos 2\phi_h} \leftrightarrow h_{1LL}^{\perp}$

$$\int d^2 k_T$$

Collinear limit

LL

$$f_{1LL}(x)\ (b_1)$$
$$\equiv b_1(x)$$

What is the best way to introduce these functions to the broader community and demonstrate the impact that their measurement will have?

Longitudinally Polarized Target

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

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

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

---

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

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

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

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

Here the polarization is measured along the q-vector

Longitudinally Polarized Target

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

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

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

For each angular modulation, the tensor-polarized structure function is the analogue of the unpolarized structure function, with the same kinematic weight and angular dependence.

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).

Unpolarized $F_{UU,T}$ and F_1

$$F^h_{UU,T}(x,z,Q^2) = \sum_q e_q^2 \left[q(x,Q^2)\, D^h_q(z,Q^2) + \bar{q}(x,Q^2)\, D^h_{\bar{q}}(z,Q^2) \right]$$

carries the hadron-production weight
through fragmentation functions

$$F_1(x,Q^2) = \frac{1}{2} \sum_q e_q^2 \left[q(x,Q^2) + \bar{q}(x,Q^2) \right]$$

unpolarized inclusive DIS structure function:
spin-averaged quark response

b_1 is the tensor analogue of F_1

For a spin-1 target, b_1 measures tensor-polarized parton structure.

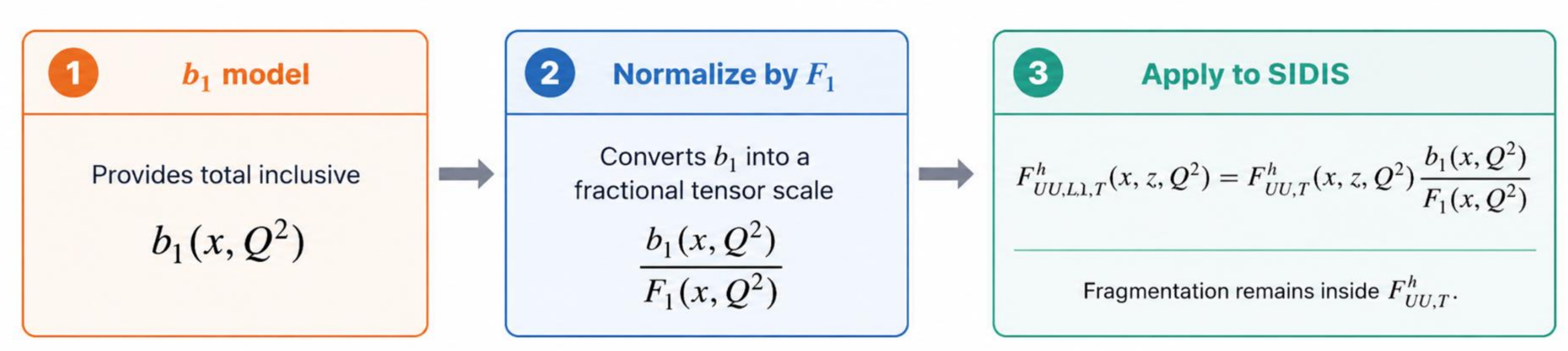
$$b_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left[\delta_T q(x, Q^2) + \delta_T \bar{q}(x, Q^2)\right]$$

$$\delta_T q = q^0 - \frac{1}{2}\left(q^{+1} + q^{-1}\right)$$

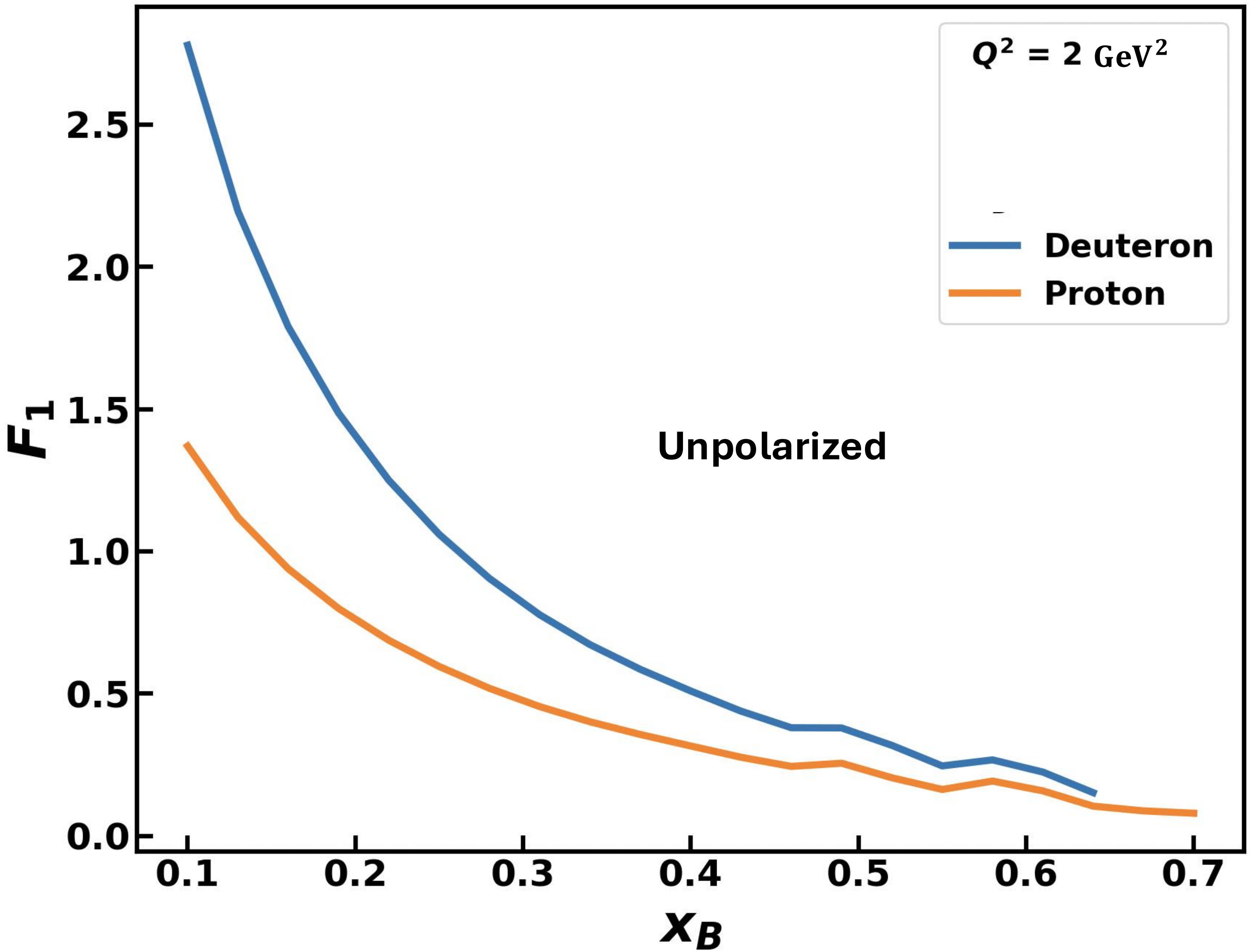
b_1 is signed. It may be positive, negative, or pass through zero.

Using $F_{U(LL),T}$ in SIDIS

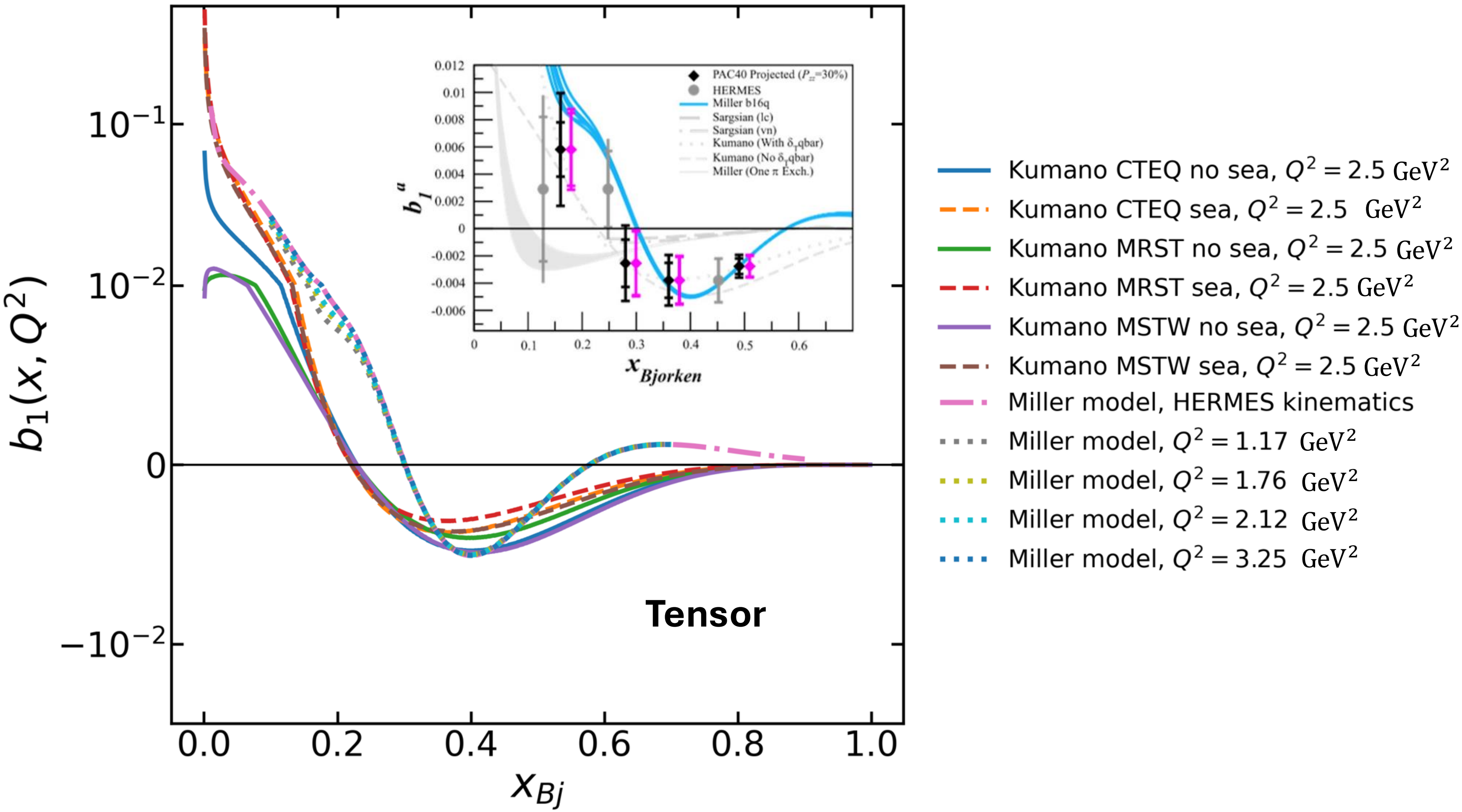
$$F^h_{U(LL),T}(x, z, Q^2) = F^h_{UU,T}(x, z, Q^2)\,\frac{b_1(x, Q^2)}{F_1(x, Q^2)}$$



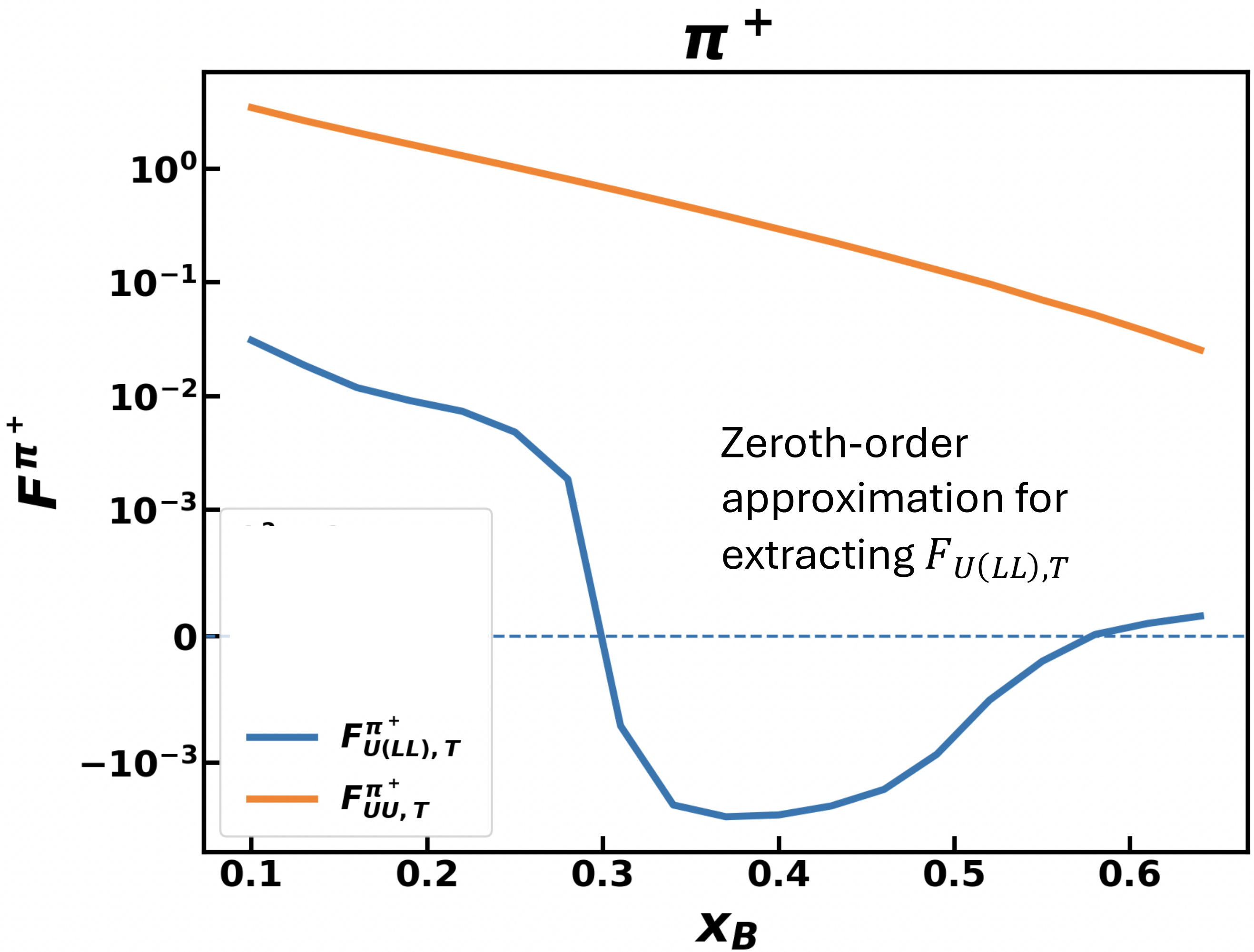
A negative tensor contribution is physically allowed because it only tells us whether tensor polarization increases or decreases the unpolarized cross section. It is not a standalone measurable rate.



$Q^2 = 2$ GeV^2
Deuteron
Proton
Unpolarized
F_1
x_B
0.0
0.5
1.0
1.5
2.0
2.5
0.1
0.2
0.3
0.4
0.5
0.6
0.7



$b_1(x, Q^2)$
10^{-1}
10^{-2}
0
-10^{-2}
0.0
0.2
0.4
0.6
0.8
1.0
x_{Bj}
Tensor
PAC40 Projected (P_{zz}=30%)
HERMES
Miller b16q
Sargsian (lc)
Sargsian (vn)
Kumano (With $\delta_T$qbar)
Kumano (No $\delta_T$qbar)
Miller (One π Exch.)
b_1^a
$x_{Bjorken}$
Kumano CTEQ no sea, $Q^2 = 2.5$ GeV^2
Kumano CTEQ sea, $Q^2 = 2.5$ GeV^2
Kumano MRST no sea, $Q^2 = 2.5$ GeV^2
Kumano MRST sea, $Q^2 = 2.5$ GeV^2
Kumano MSTW no sea, $Q^2 = 2.5$ GeV^2
Kumano MSTW sea, $Q^2 = 2.5$ GeV^2
Miller model, HERMES kinematics
Miller model, $Q^2 = 1.17$ GeV^2
Miller model, $Q^2 = 1.76$ GeV^2
Miller model, $Q^2 = 2.12$ GeV^2
Miller model, $Q^2 = 3.25$ GeV^2


π^+
10^0
10^{-1}
10^{-2}
10^{-3}
0
-10^{-3}
F^{π^+}
0.1
0.2
0.3
0.4
0.5
0.6
x_B
$F^{\pi^+}_{U(LL),T}$
$F^{\pi^+}_{UU,T}$
Zeroth-order approximation for extracting $F_{U(LL),T}$

A key next step is to develop theory predictions for tensor structure functions to motivate future tensor-polarized measurements.

Extracting tensor observables

The cross-section of deuteron can be written in terms of different asymmetries:

$$\sigma = \sigma_U \left[1 + \mathcal{P} A^V + Q A^T + \lambda_e \left(A^e + \mathcal{P} A^{eV} + Q A^{eT}\right)\right]$$

σ_U : unpolarized cross-section	$\mathcal{P}$: vector polarization	Q : tensor polarization
λ_e : beam helicity	A^V : vector asymmetry	A^T : tensor asymmetry
A^e : beam asymmetry	A^{eV} : beam-vector asymmetry	A^{eT} : beam-tensor asymmetry

H. Arenhovel, W. Leidemann, E.L. Tomusiak. Phys. A 331, 123–138 (1988)

Extracting tensor observables

Tensor asymmetry:

$$A^T \sim \frac{1}{\sigma_U} \left[F_{U(LL),T} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h \, F_{U(LL)}^{\cos\phi_h} + \epsilon \cos(2\phi_h) \, F_{U(LL)}^{\cos 2\phi_h} \right]$$

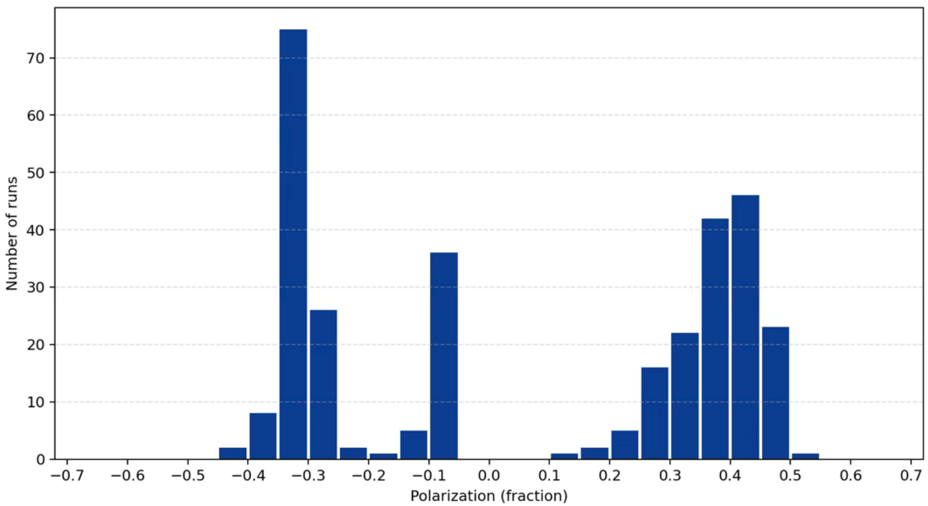
Azimuthal angle dependence provides a way to separate
and extract the different tensor structure functions.

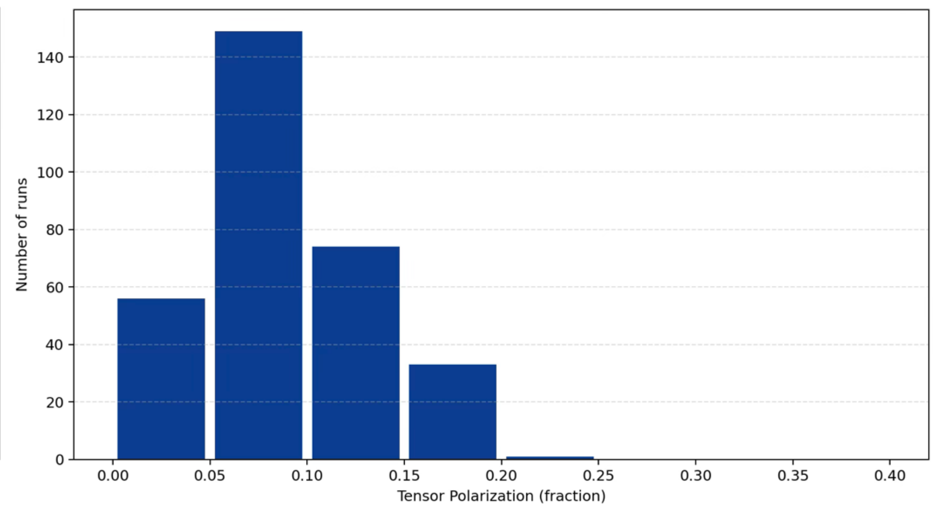
Extracting experimentally:

$$A^T \sim \left[\frac{1}{fQ} \right] \left[\frac{\sigma(\mathcal{P}, Q) + \sigma(-\mathcal{P}, Q)}{\sigma(\mathcal{P}, 0) + \sigma(-\mathcal{P}, 0)} - 1 \right]$$

What corrections should be included to account for these assumptions?

RGC: Extracting tensor observables





Courtesy of Jefferson Lab and UVA target groups.

This data was not optimized for tensor measurements.
Can we extract tensor observables from it?

General Idea

Assuming vector + and - are about the same size:

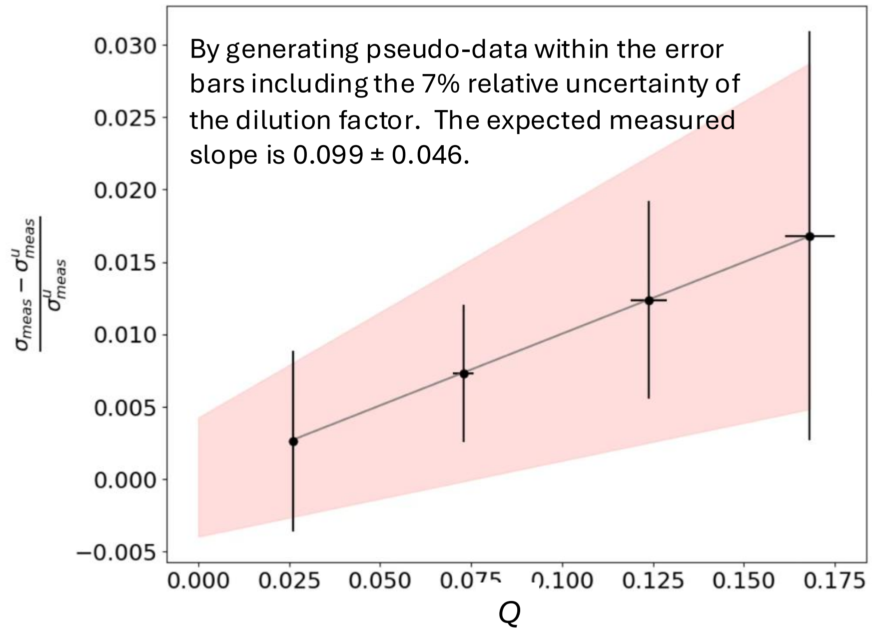
$$\sigma_{\text{meas}}^{+} \sim \frac{1}{2}\left(\sigma_U + P\,\sigma_V + Q\,\sigma_T + \sum_i \sigma_i\right)$$

$$\sigma_{\text{meas}}^{-} \sim \frac{1}{2}\left(\sigma_U - P\,\sigma_V + Q\,\sigma_T + \sum_i \sigma_i\right)$$

$$\sigma_{\text{meas}}^{\text{total}} \sim \sigma_{\text{meas}}^{+} + \sigma_{\text{meas}}^{-} \sim \sigma_U + Q\,\sigma_T + \sum_i \sigma_i$$

Subtracting the unpolarized cross-section and rearranging terms:

$$Q\,\frac{\sigma_T}{\sigma_U} \sim \frac{1}{f}\,\frac{\sigma_{\text{meas}}^{\text{total}} - \sigma_{\text{meas}}^{U}}{\sigma_{\text{meas}}^{U}}$$



* With a 10% estimate for the tensor contribution compared with the unpolarized

CAA: arXiv:2502.20044, 2025

General Idea

Assuming vector + and - are about the same size:

$$\sigma^{+}_{\text{meas}} \sim \frac{1}{2}\left(\sigma_U + P\,\sigma_V + Q\,\sigma_T + \sum_i \sigma_i\right)$$

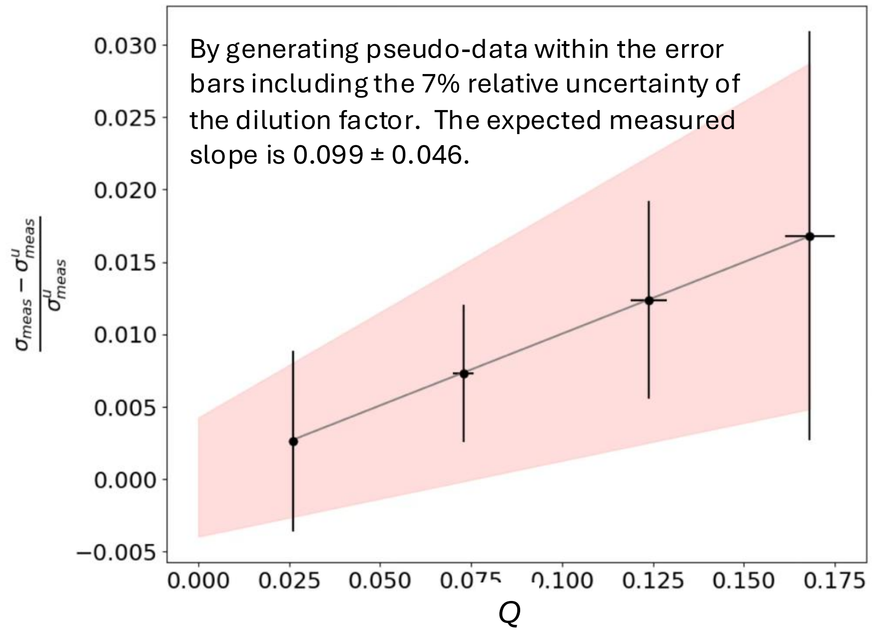
$$\sigma^{-}_{\text{meas}} \sim \frac{1}{2}\left(\sigma_U - P\,\sigma_V + Q\,\sigma_T + \sum_i \sigma_i\right)$$

$$\sigma^{\text{total}}_{\text{meas}} \sim \sigma^{+}_{\text{meas}} + \sigma^{-}_{\text{meas}} \sim \sigma_U + Q\,\sigma_T + \sum_i \sigma_i$$

Subtracting the unpolarized cross-section and rearranging terms:

$$Q\,\frac{\sigma_T}{\sigma_U} \sim \frac{1}{f}\,\frac{\sigma^{\text{total}}_{\text{meas}} - \sigma^{U}_{\text{meas}}}{\sigma^{U}_{\text{meas}}}$$

CAA: arXiv:2502.20044, 2025



Any recommendations?

Remarks

- We are building and growing a strong program at Jefferson Lab.
- This is the right time to share suggestions and requests with our experimental group.
- Motivating future experiments will require as much theory input as possible.
- Broad feedback from the community will be very valuable.

Thank You!