U.S. DEPARTMENT OF ENERGY | Office of Science

University of New Hampshire

Tensor Structure Functions of the Deuteron in SIDIS Experiments

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DIS 2026
33rd International Workshop on Deep Inelastic Scattering Related Subjects

Advisor: Nathaly Santiesteban

Bologna, Italy, May 4-8, 2026

Motivation: Why Deuteron?

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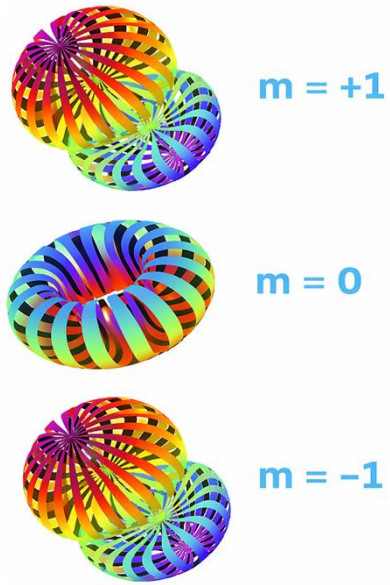
Deuteron in a magnetic field



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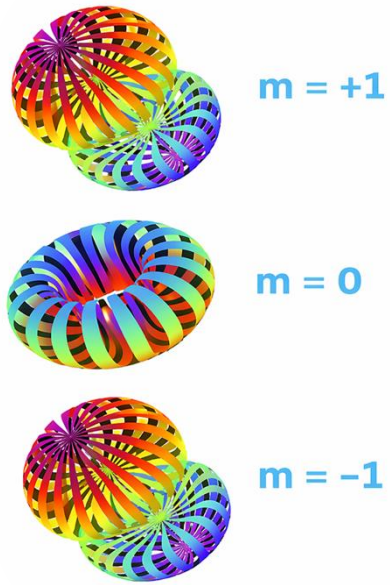

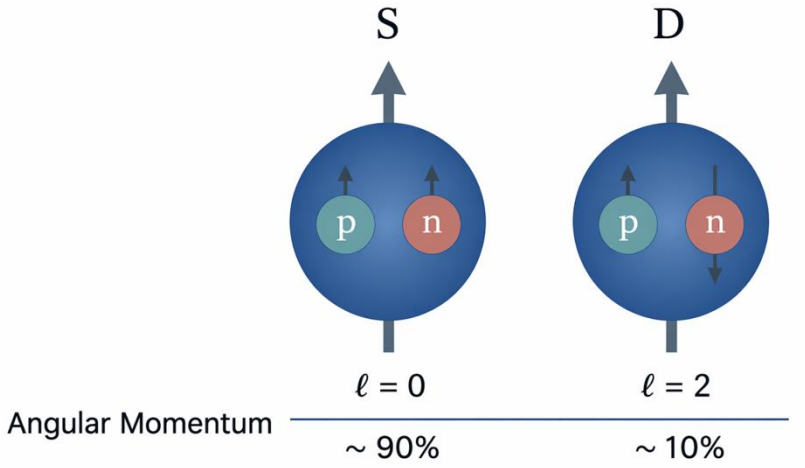

Target Tensor polarization of deuteron

- **Spin-1/2 system splits into 2 energy levels in magnetic field (Zeeman effect)**
  - m = +1/2 and -1/2 energy states with population n_+ and n_-
  - Vector polarization $(S_{||}) = (n_+ - n_-)/(n_+ + n_-)$

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  - Vector polarization $(S_{||}) = (n_+ - n_-)/(n_+ + n_0 + n_-)$
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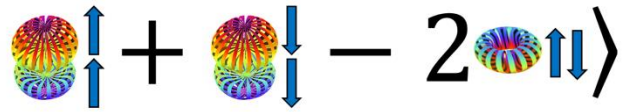
$$T = \langle \quad + \quad - 2 \quad \rangle$$



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$$T = \langle \uparrow\uparrow + \downarrow\downarrow - 2\,\uparrow\downarrow \rangle$$

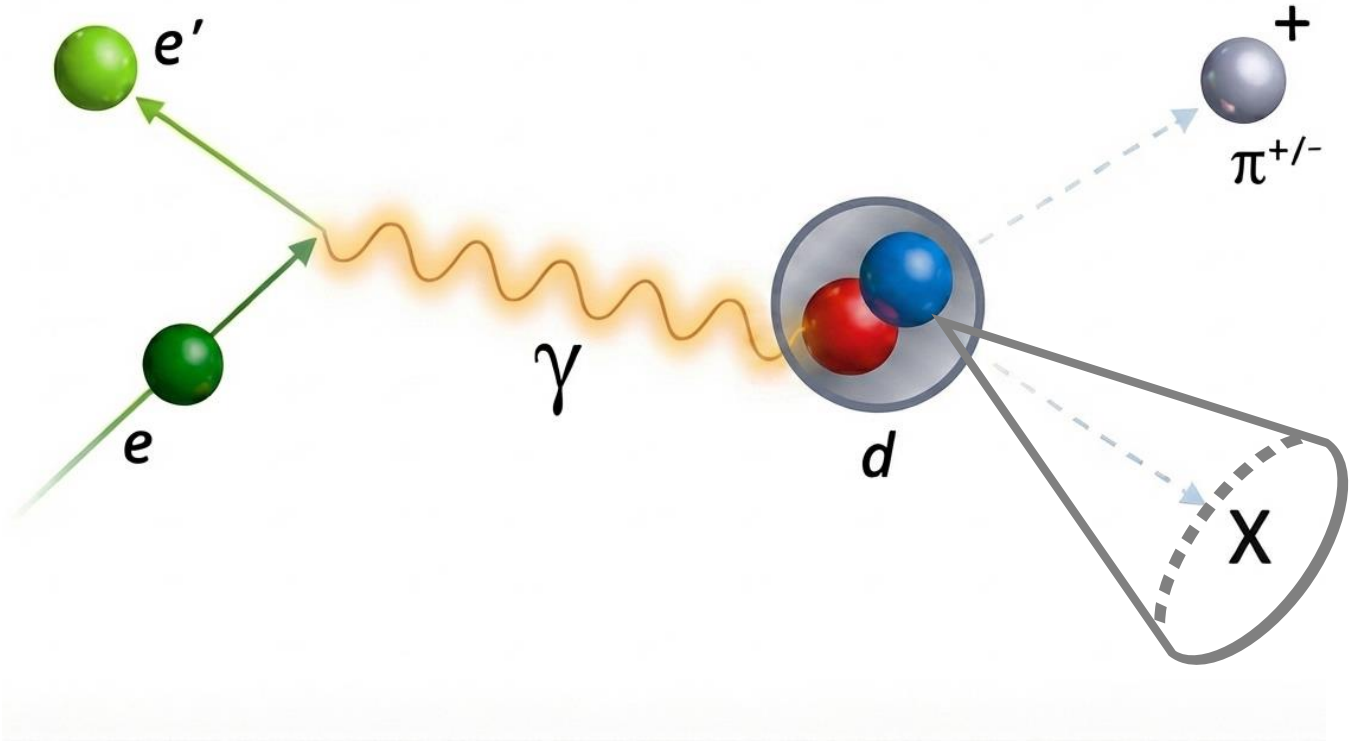
The spin system follows the Boltzmann distribution at thermal equilibrium, then

$$T_{||\,||} = 2 - \sqrt{4 - 3S_{||}^2}$$

SIDIS (Semi-Inclusive Deep Inelastic Scattering)

An electron with momentum l scatters off a deuteron target. In the final state, the scattered electron with momentum l' is measured together with one hadron h (π^+/π^-) with momentum P_h.

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



SIDIS is a way to access TMDs.

SIDIS Kinematics

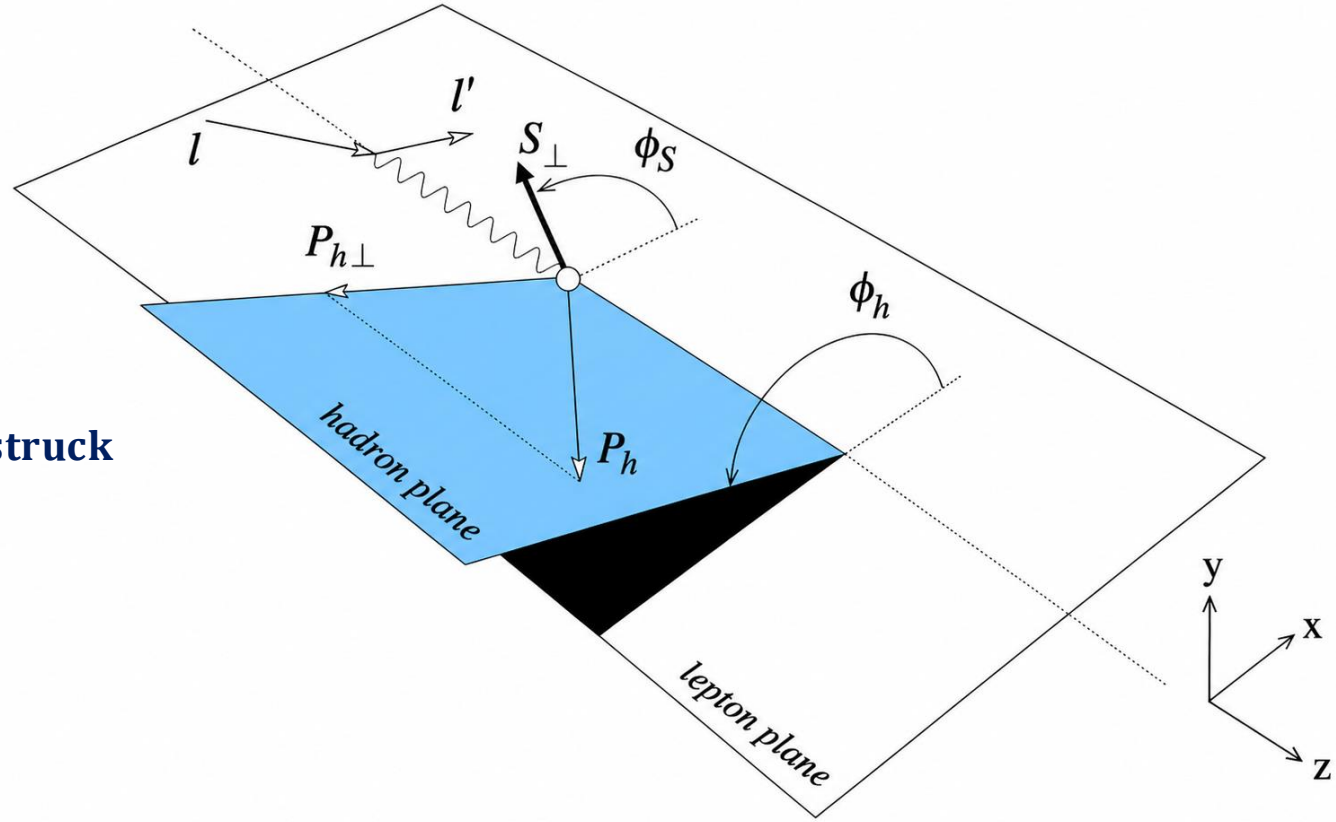
$Q^2 = -q^2$ **Squared four − momentum transfer; measures the resolution scale of the interaction**

$x_B = \frac{Q^2}{2M\nu}$ **Bjorken − x: scaling variable; represents the fraction of the nucleon momentum carried by the struck quark**

$y = \frac{P.q}{P.l}$ **Fractional energy loss of the lepton**

$z = \frac{P_h.P}{q.P}$ **Fraction of the photon energy transferred to the produced hadron**

$P_{h\perp}$: **Transverse momentum of the produced hadron**



$x_B, Q^2, \phi_S, z, P_{h\perp}, \phi_h$
multidimensional observables

Tensor TMDs

Considering longitudinal polarization only, we could express the differential cross-section for SIDIS as:

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

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

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

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

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

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

Courtesy of A. Bacchetta (2023)

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

$$F_{U(LL)}^{\cos 2\phi_h} = C\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k_T})(\hat{\mathbf{h}}\cdot\mathbf{p_T}) - \mathbf{k_T}\cdot\mathbf{p_T}}{MM_h}\,h_{1LL}^{\perp}\,H_1^{\perp}\right]$$

In this exploratory analysis, we will attempt to access the $F_{U(LL),T}$ and $F_{U(LL)}^{cos2\boldsymbol{\Phi}_h}$ structure functions, which provide access to the f_{1LL} and $h_{1LL}^{\perp}$ TMDs

Courtesy of A. Bacchetta (2023)

Leading twist distribution functions

Quark / Hadron	$U\ (\gamma^+)$		$L\ (\gamma^+\gamma_5)$		$T\ (i\sigma^{i+}\gamma_5/\sigma^{i+})$	
	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}		$[h_1]$, $[h_{1T}^\perp]$	
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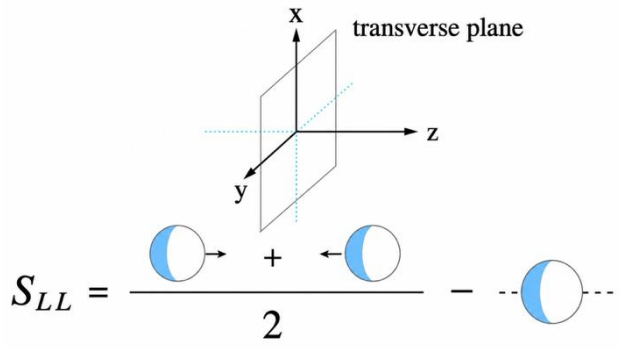

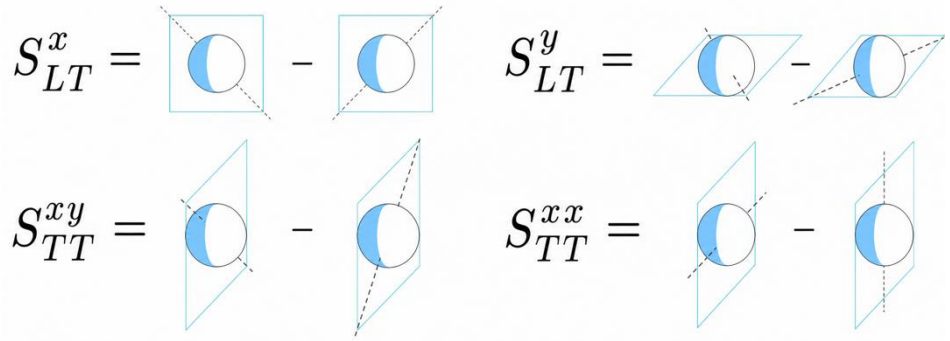

A. Bacchetta and P.J. Mulders, PRD 62 (2000)
S. Kumano and Q. Song, PRD 103 (2021)

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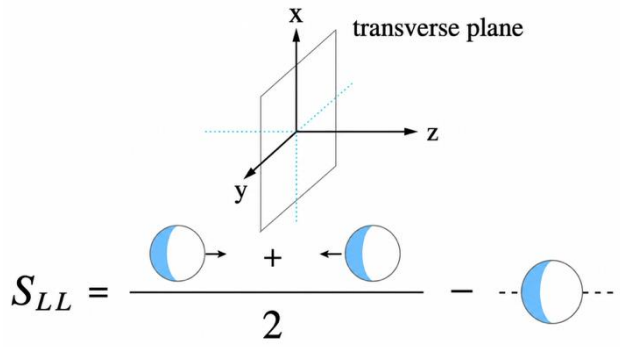
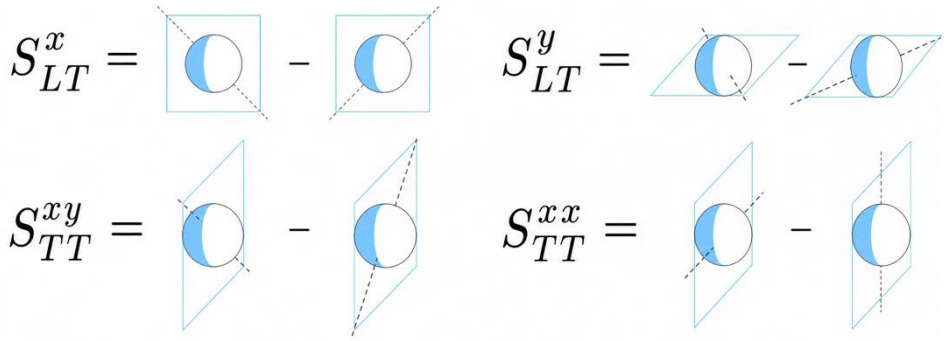
Never Measured!





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T					$[h_1]$	
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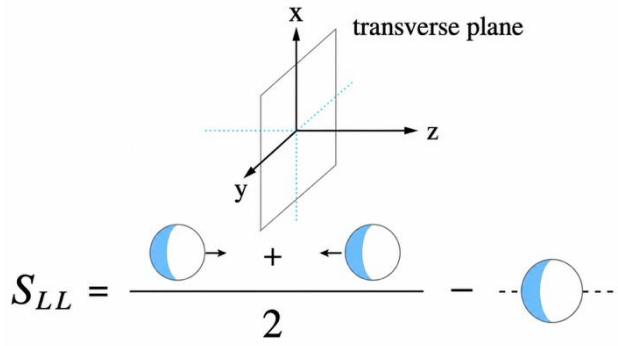
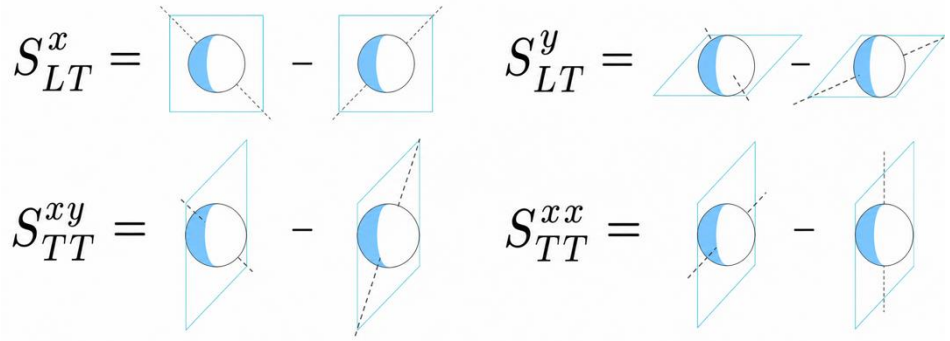
LT						$*1$
TT						





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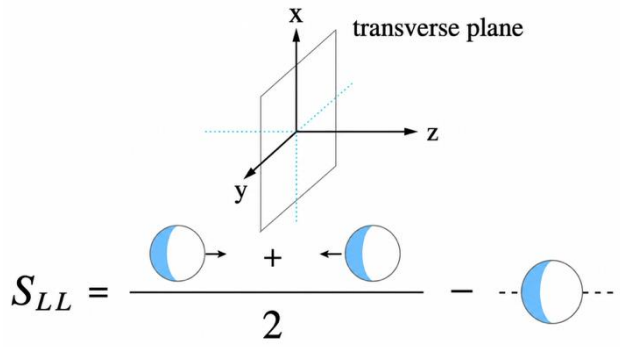
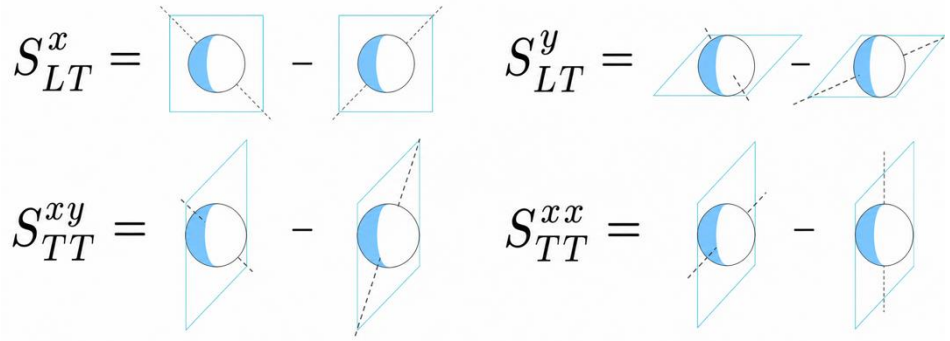
b1 measured at HERMES. Phys.Rev.Lett.95 (2005)





The spin deuteron's tensor structure will open up exciting new opportunities to deepen our understanding of partonic structure in light nuclei.

A. Bacchetta and P.J. Mulders, PRD 62 (2000)
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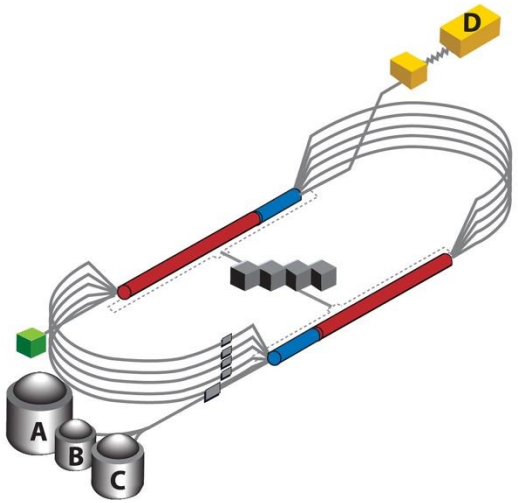
Where to measure out SIDIS processes?

Jefferson Lab Accelerator Facility, Newport News, Virginia, USA.

Jefferson Lab is a U.S. Department of Energy Office of Science national laboratory.

Continuous Electron Beam Accelerator Facility (CEBAF) is a unique accelerator used to conduct investigations in the field of nuclear physics.



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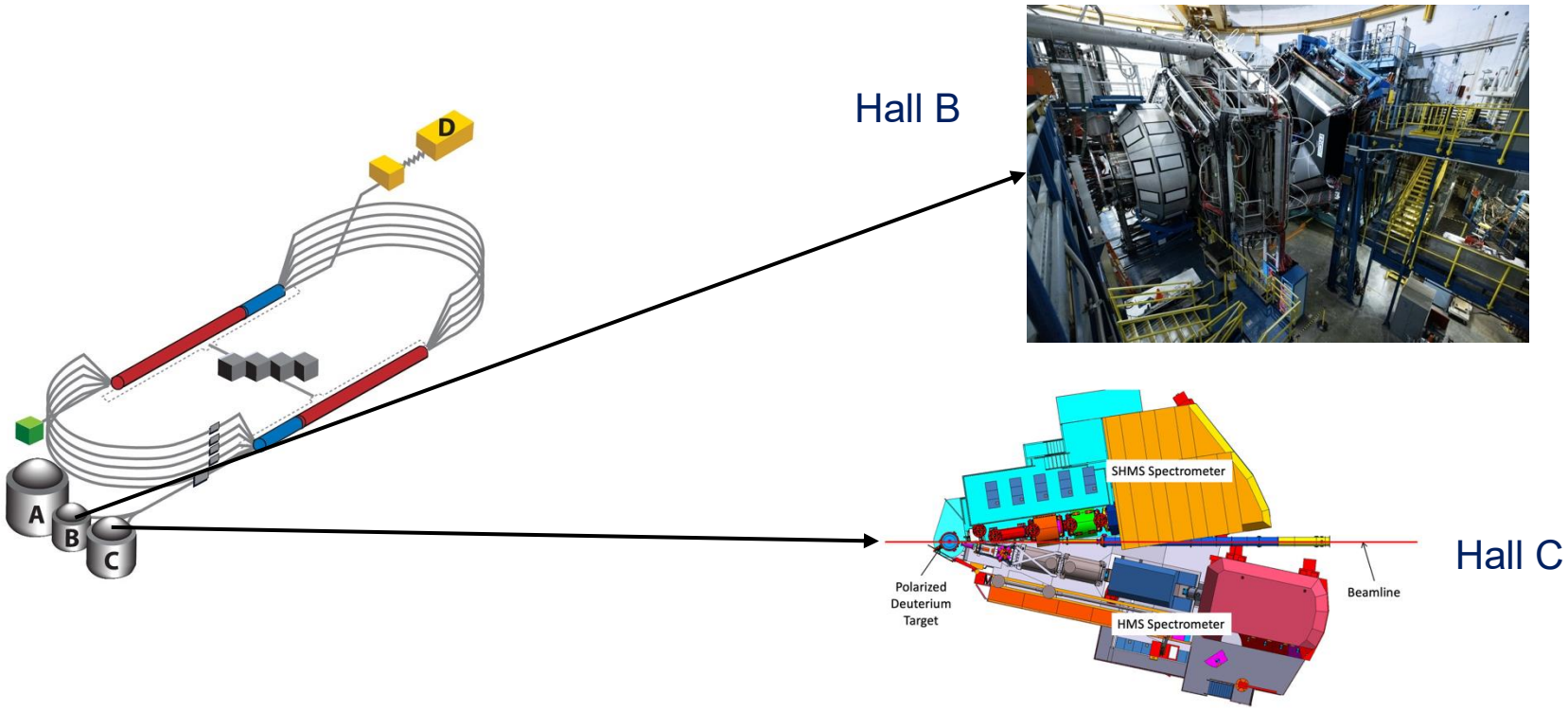
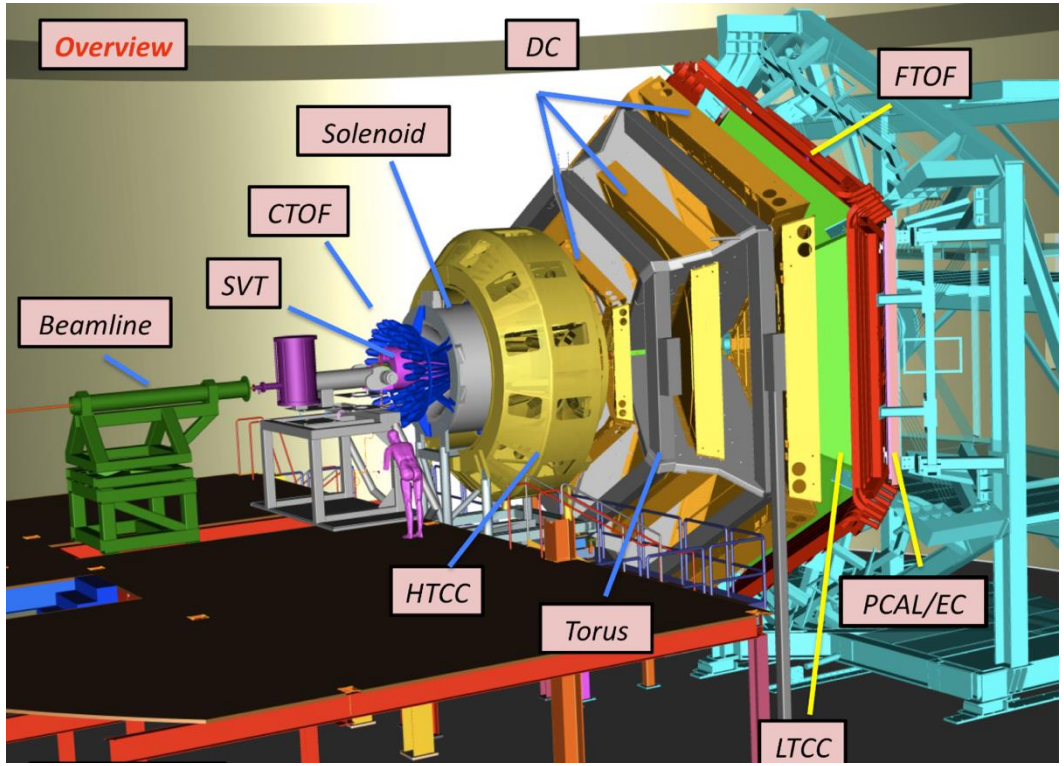


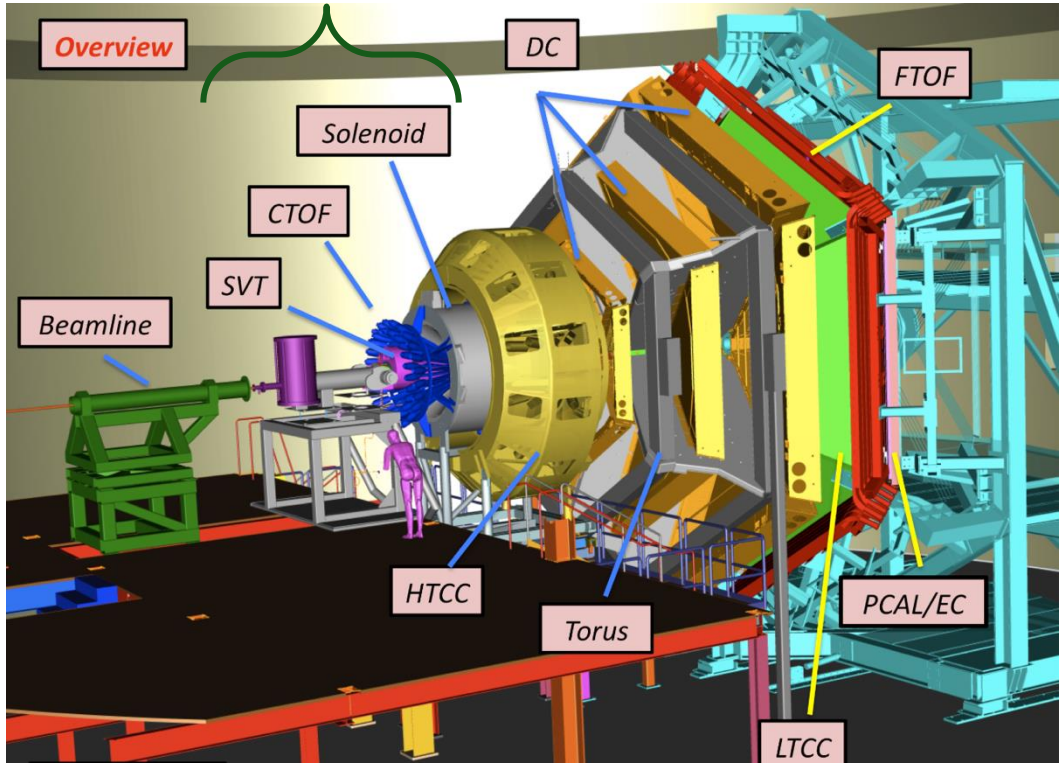
Part I: Estimate the size of the tensor contribution



CLAS12 detector

Part I: Estimate the size of the tensor contribution

Central Detector (CD)



CLAS12 detector

SVT: Silicon Vertex Tracker
CTOF: Central Time of Flight

Part I: Estimate the size of the tensor contribution

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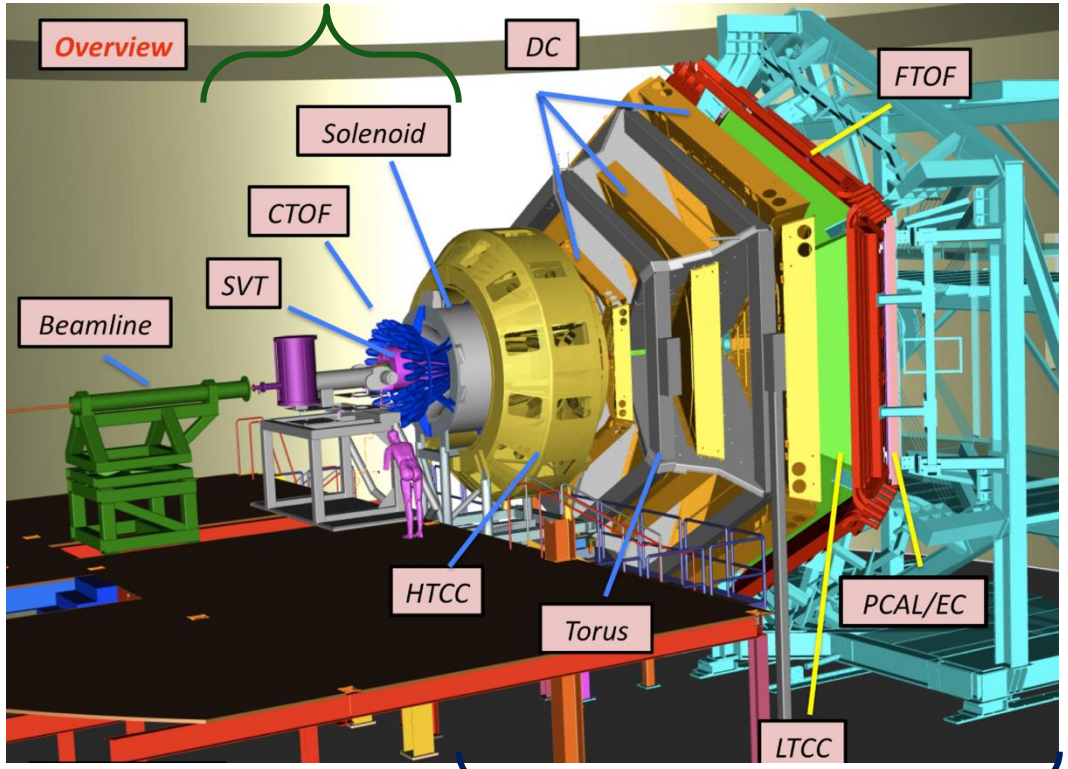

Forward Detector (FD)

CLAS12 detector

SVT: Silicon Vertex Tracker
CTOF: Central Time of Flight

HTCC: High Threshold Cherenkov Counter
DC: Drift Chamber
LTCC: Low Threshold Cherenkov
FTOF: Forward Time of Flight
PCAL/EC: Pre-Shower/Electromagnetic calorimeter

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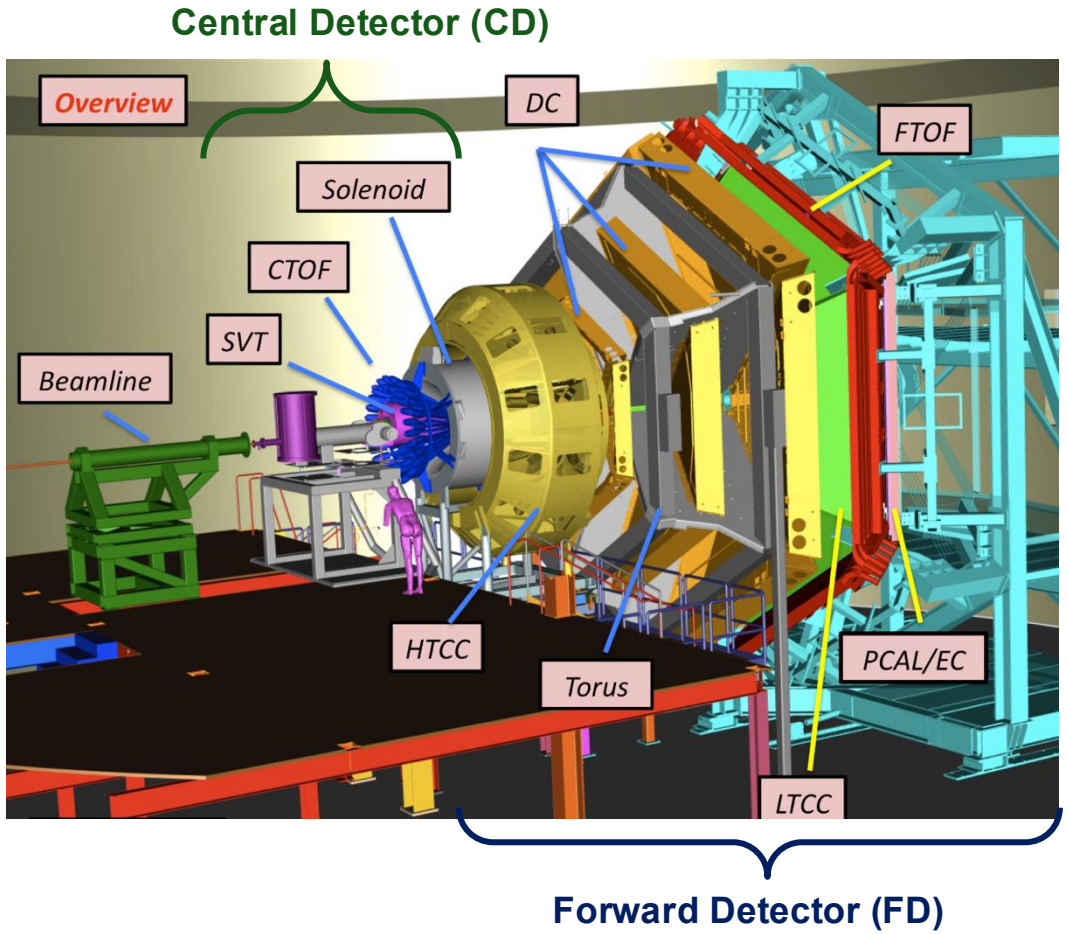

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Goal: Use existing data to estimate the size of the tensor contribution. The data used in this analysis is from the CLAS12 Run Group C (RG-C), which took data on longitudinally vector polarized deuteron target with polarized electron beams during 2022 and 2023.

Number of vector polarization runs and estimated tensor polarization

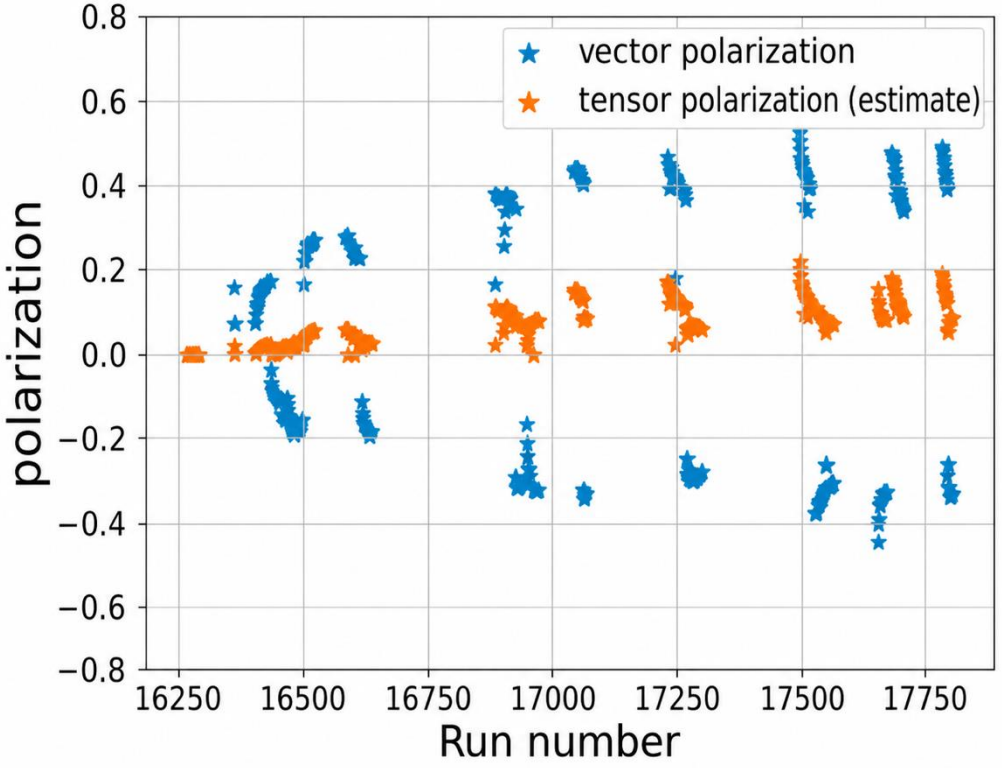


Figure 1: Vector polarization ($+S_{||}$ and $-S_{||}$) (blue) of the ND_3 target during the RG-C experiment. Estimated tensor polarization ($T_{||}$) of ND_3 target based on the vector polarization numbers.

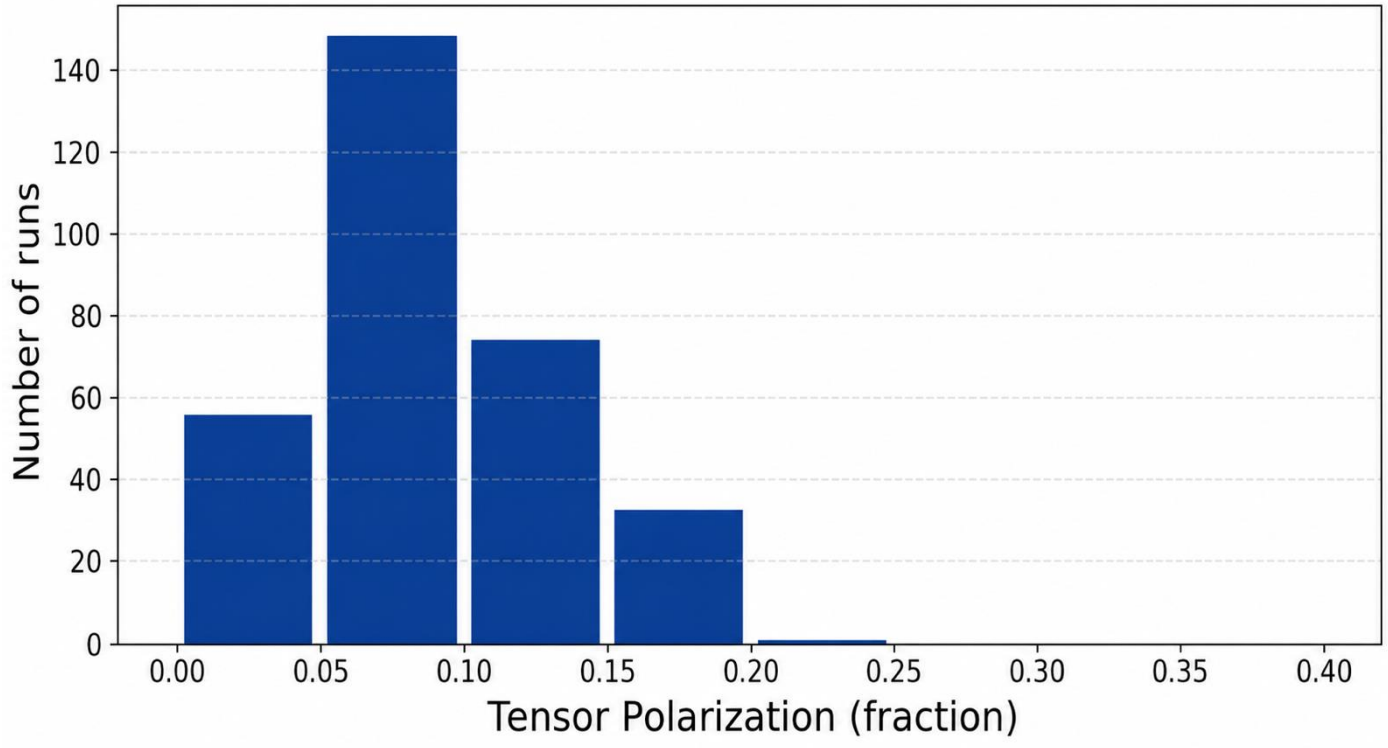


Figure 2: NMR measurements from Jefferson Lab and University of Virginia.

"CLAS12 Target Wiki." https://clasweb.jlab.org/wiki/index.php/RGC_Target_Polarization_Analysis
"Run Group C Data." https://clasweb.jlab.org/wiki/index.php/RGC_data.

Current estimate of tensor polarized and unpolarized cross-section of deuterium

Assuming that the positive and negative vector polarizations are the same:

$$S_{\parallel}^{+} = -S_{\parallel}^{-}$$

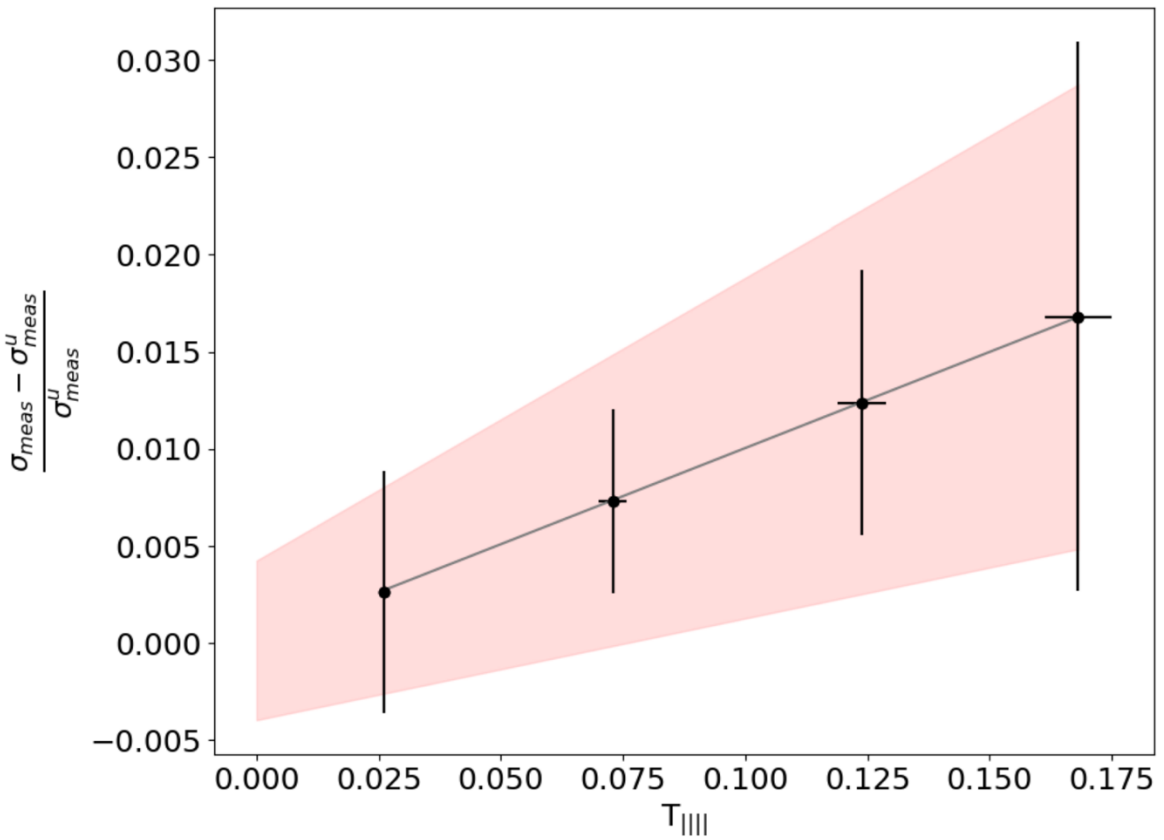


Figure 3: Measured quantity with respect to the tensor polarization.

Current estimate of tensor polarized and unpolarized cross-section of deuterium

Assuming that the positive and negative vector polarizations are the same:

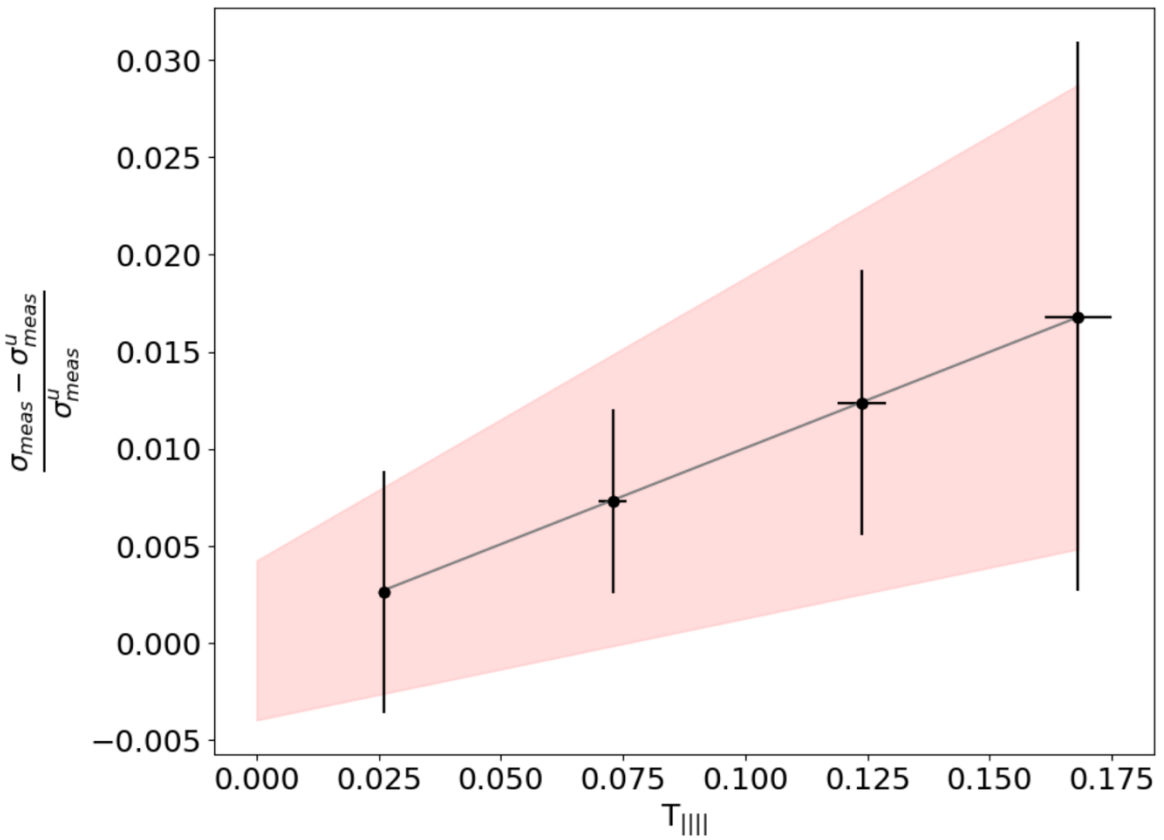
$$S_{\parallel}^{+} = -S_{\parallel}^{-}$$

Measured cross section for the two vector-polarization states:

$$\sigma_{meas}^{+} = \frac{1}{2}\left(\sigma_u^D + S_{\parallel}^{+}\sigma_S + T_{|||}\sigma_T + \sum_i \sigma^i\right)$$

$$\sigma_{meas}^{-} = \frac{1}{2}\left(\sigma_u^D + S_{\parallel}^{-}\sigma_S + T_{|||}\sigma_T + \sum_i \sigma^i\right)$$

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



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Tensor contribution of the cross section is related with unpolarized contribution:

$$T_{|||}\frac{\sigma_T}{\sigma_u^D} = \frac{1}{f}\frac{\sigma_{meas}^{total} - \sigma_{meas}^{u}}{\sigma_{meas}^{u}}$$

f: dilution factor

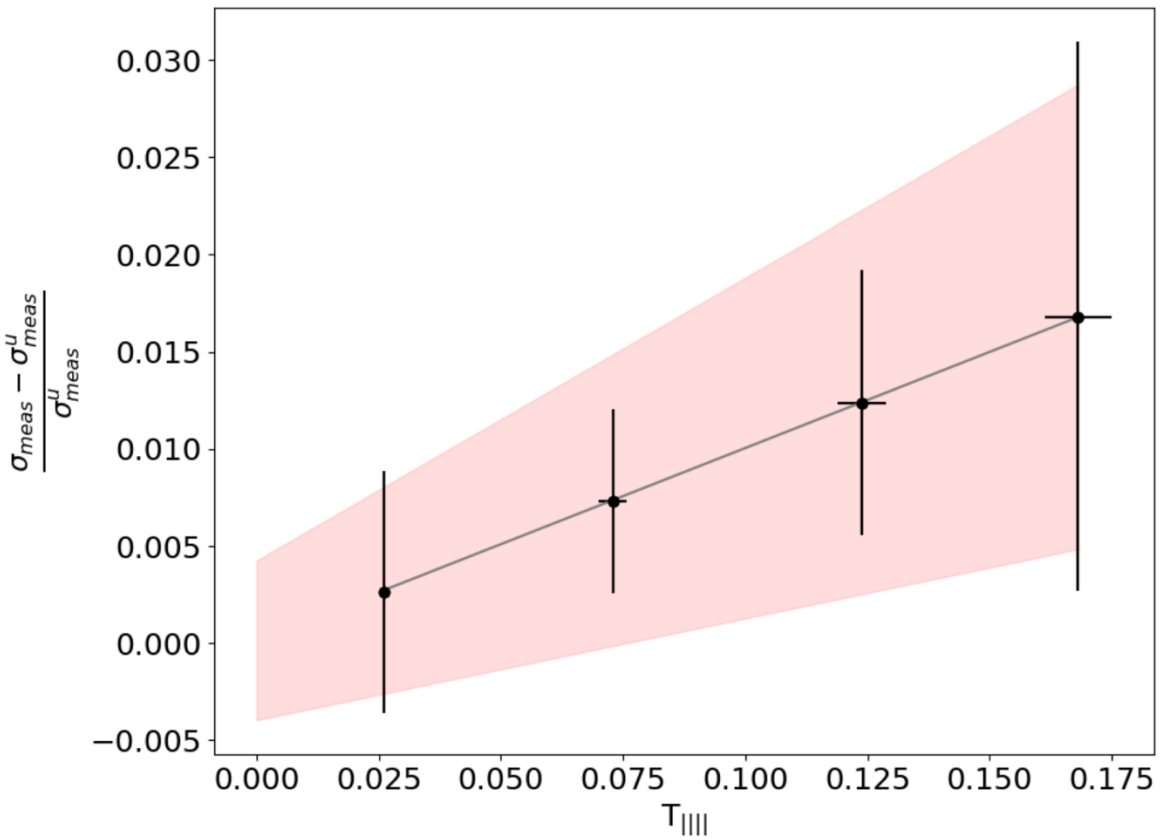
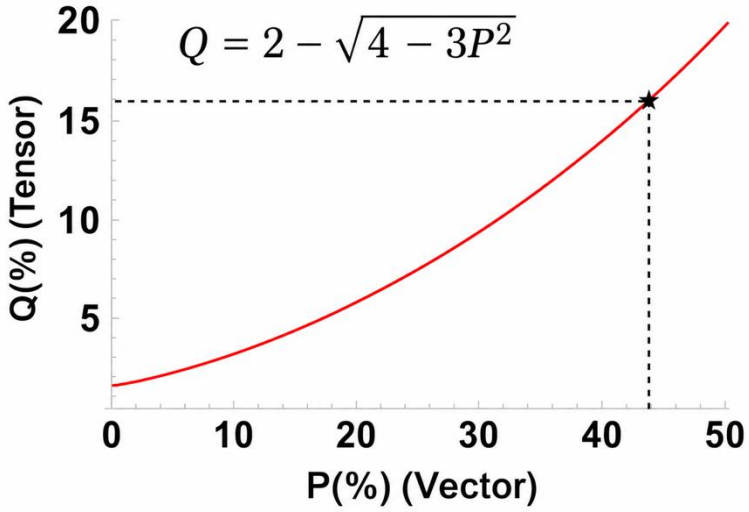


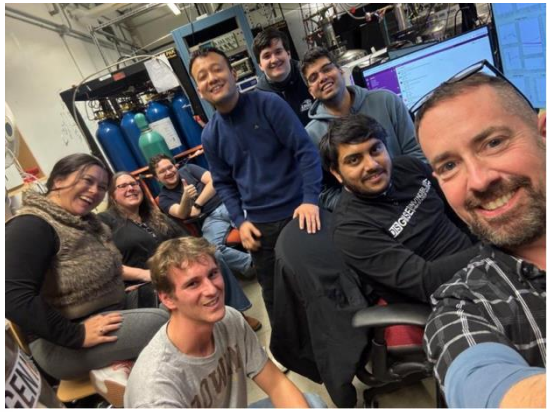
Figure 3: Measured quantity with respect to the tensor polarization.

Tensor Polarization Enhancement

UNH Target System : Using high magnetic fields, low temperatures and microwaves for enhancement of vector and tensor polarization via Dynamic Nuclear Polarization (DNP) .

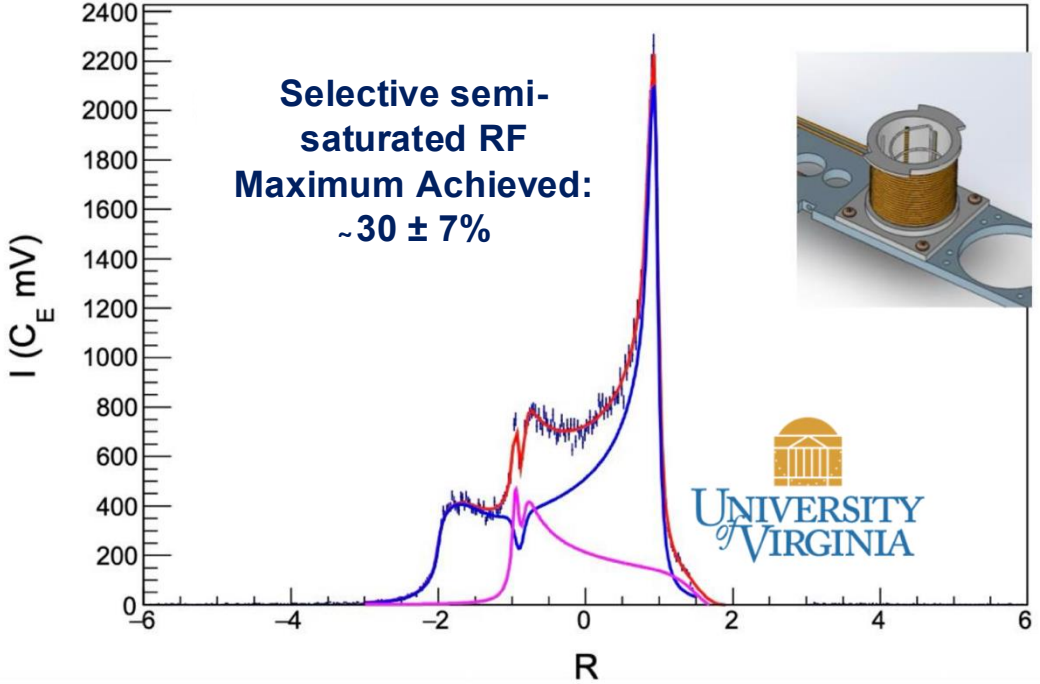
Tensor polarization with DNP reaches at best 15 – 20% and decays with dose (under electron beam).



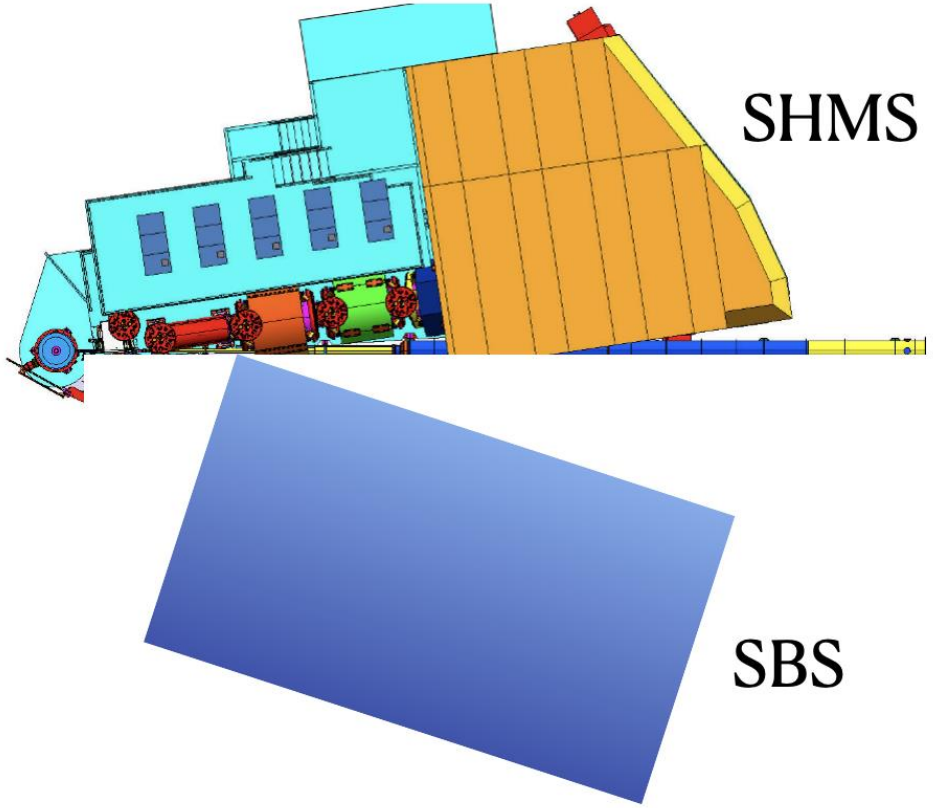


UNH Target Group

Tensor enhancement via DNP + selective semi-saturating RF (ss-RF) at **UVA**



Part II: Dedicated experiment



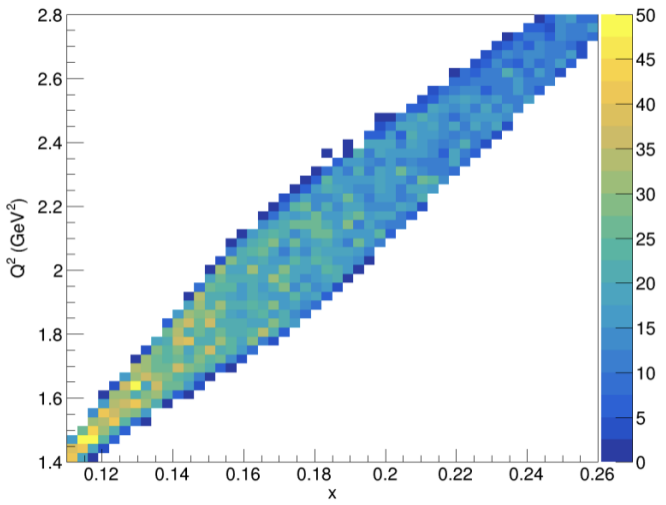
"Spin-1 TMDs and Structure Functions of the Deuteron" at Hall C

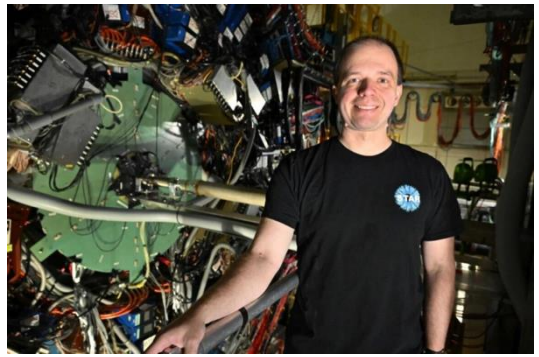
Letter of Intent (LOI12-24-002 PAC 52, 2024)

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

Current efforts: Simulations in SIMC (Monte Carlo simulation package)

- SIDIS kinematics studies are being used to simulate the experiment and evaluate its expected measurements.
- The Hall C simulation packages are based on the unpolarized cross section to estimate the number of events that can be measured.
- Scale unpolarized rates 10% to estimate tensor contributions (estimate based on results from HERMES).





Courtesy of Jan Vanek

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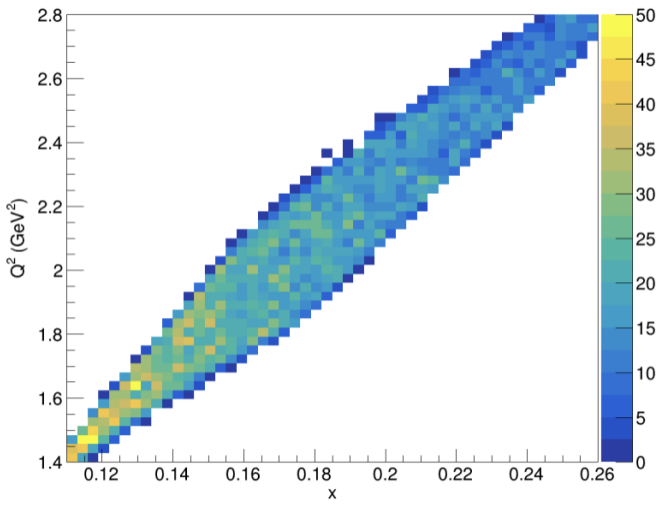
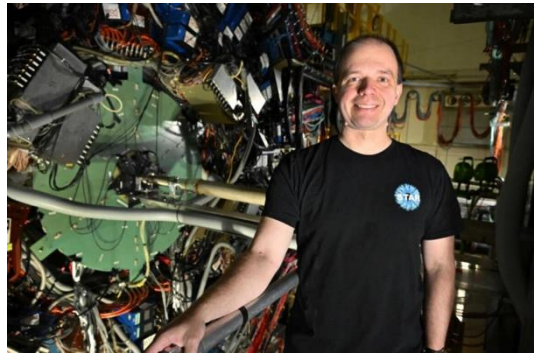
- SIDIS kinematics studies are being used to simulate the experiment and evaluate its expected measurements.
- The Hall C simulation packages are based on the unpolarized cross section to estimate the number of events that can be measured.
- Scale unpolarized rates 10% to estimate tensor contributions (estimate based on results from HERMES).
- Verify/determine optimal experiment setup based on expected kinematics of scattered electrons and hadrons



	θ(deg.)	ϕ(deg.)	P(GeV)
Electron	10.3 – 12.4	-2.87 – 2.87	4.0 – 5.4
Hadron	10.0 – 20.0	167 – 193	2.0 – 4.0

The kinematic ranges assumed for the chosen momentum setting in SHMS (electron) and SBS (hadron)

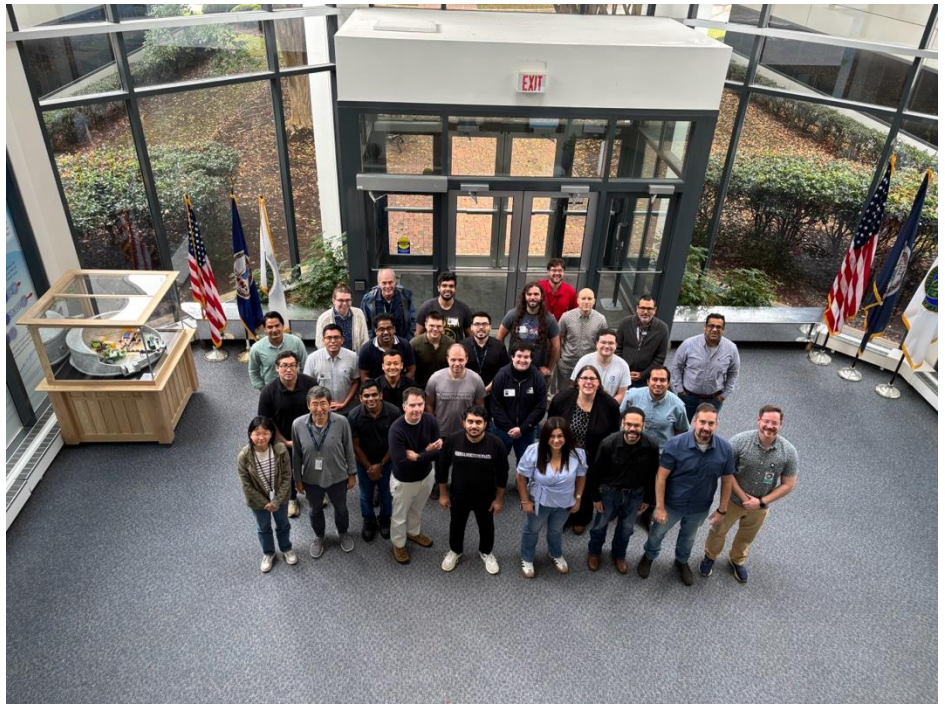


Courtesy of Jan Vanek

Remarks and future work!

- Continue with the analysis of CLAS data.
  - ✓ This analysis will enable the extraction of tensor structure functions of the deuteron, first ever via SIDIS analysis.
- Development of full simulation for the Hall C experiment
- Present the proposal to the PAC (Program Advisory Committee) in Jefferson Lab.
- We are organizing a **Tensor SIDIS Workshop (Jun 3 – 5, 2026 at Jefferson Lab)** to inspire model development for our observables.

  indico page: https://indico.jlab.org/event/1070/



b1/Azz Tensor Collaboration 2025