# Experimental Program at Jefferson Lab to Explore Tensor-TMDs in Deuteron

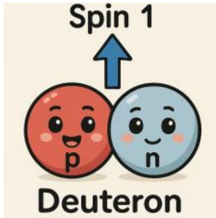
**Nathaly Santiesteban**

On behalf of the SIDIS-Tensor collaboration

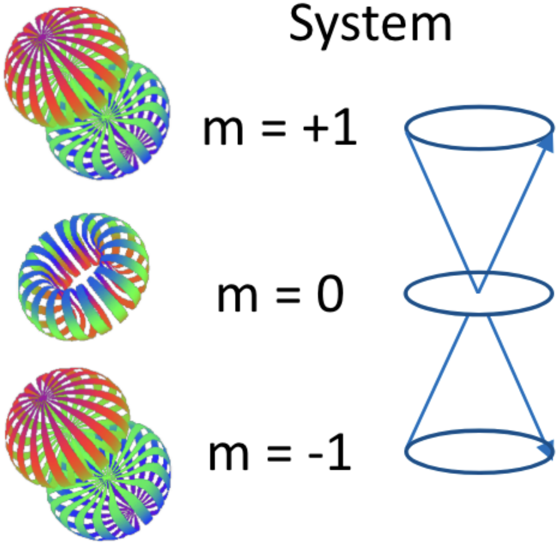
QCD Evolution Workshop

May 20, 2025

University of New Hampshire

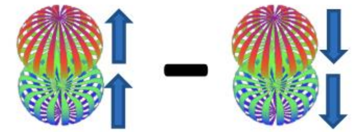



Spin-1
System



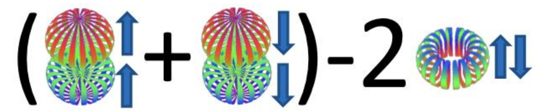

Deuteron in a magnetic field

Vector Polarization:




$$P = N(+1) - N(-1)$$

Tensor Polarization:




$$Q = N(+1) + N(-1) - 2N(0)$$

N($m$): population density

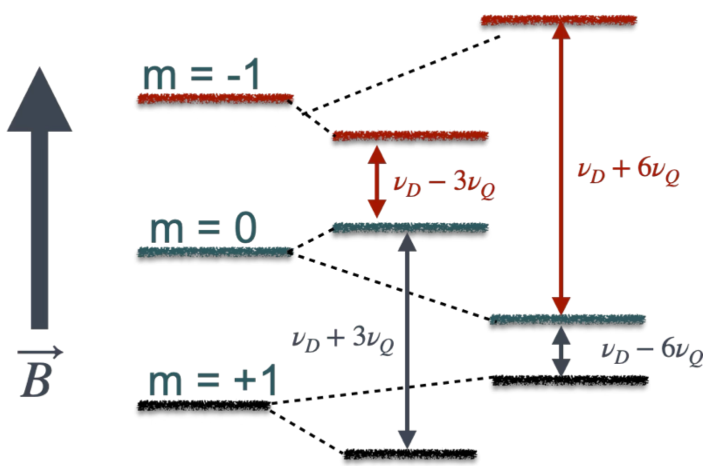
$$N(+1) + N(-1) + N(0) = 1$$

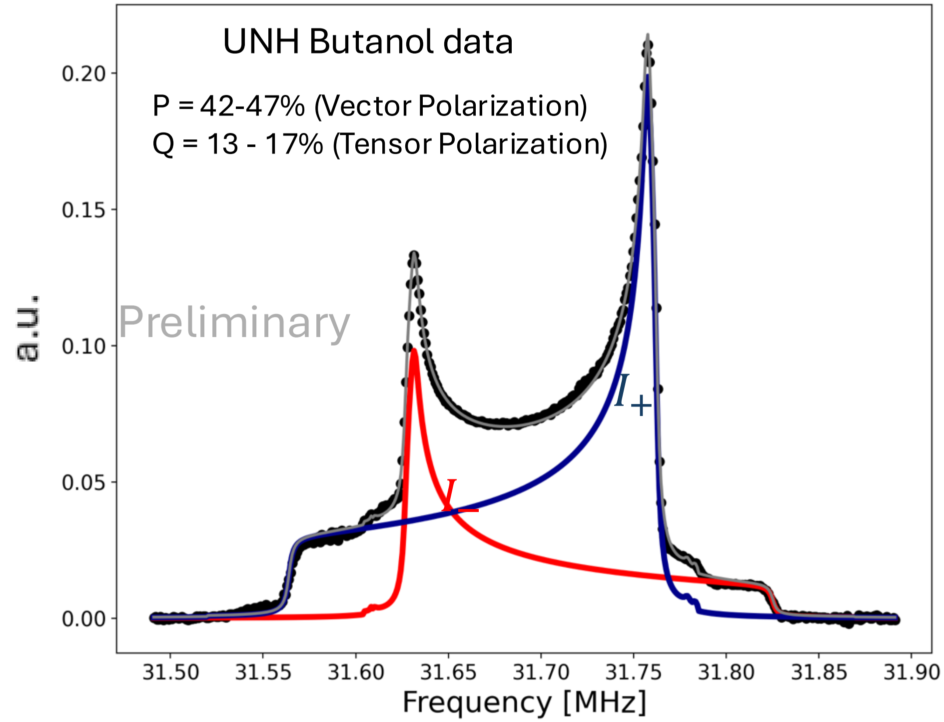
Normalization

# Deuteron Polarization

$$E_m = -h\nu_D m + h\nu_Q(cos^2\theta - 1)(3m^2 - 2)$$

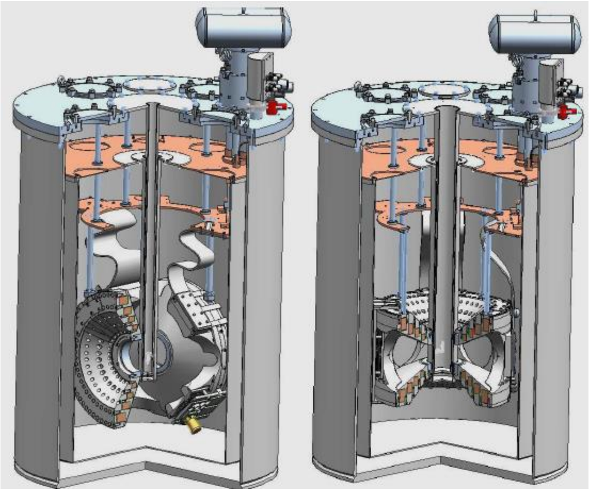
$eQ$: Electric quadrupole interaction (shifts the energy levels)
$eq$: Electric field gradient
$\theta$: angle between $eq$ and $eQ$
$\upsilon_D$: deuteron Larmor frequency



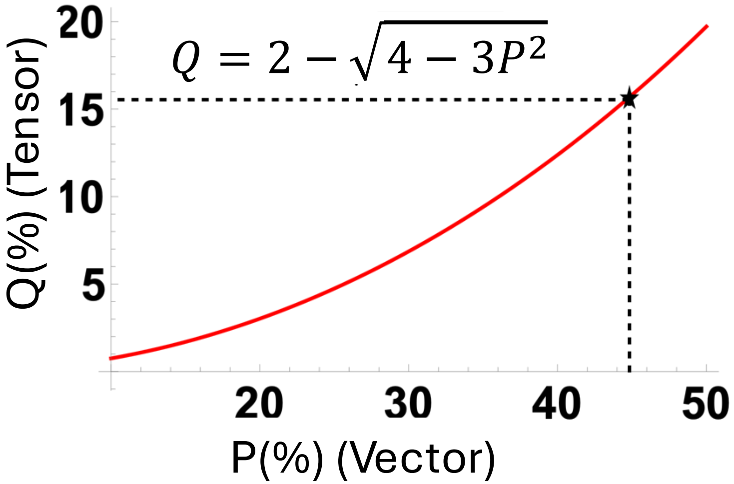
# Enhancing Vector polarization: DNP Technique

Dynamic Nuclear Polarization (DNP): technique used to enhance vector polarization



**Requirements**

- High magnetic field (at JLab typically 5T)
- Low temperature (~1K)
- Microwaves (induce spin transitions)
- CW NMR
- Irradiated material $ND_3$



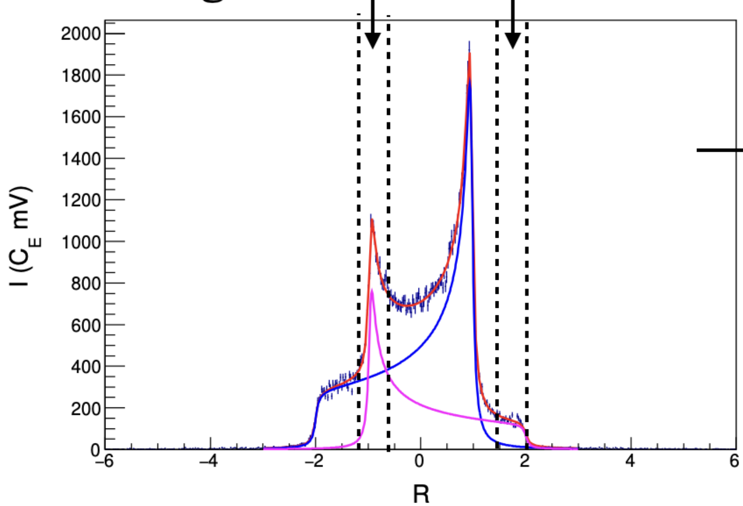

DNP enhancement carries tensor polarization enhancement.

★ Typical average vector polarization in Jefferson lab $P \sim 45\%$ which corresponds to Q$\sim 16\%$

# Enhancing tensor polarization

**Semi-selective RF**

Starting with:

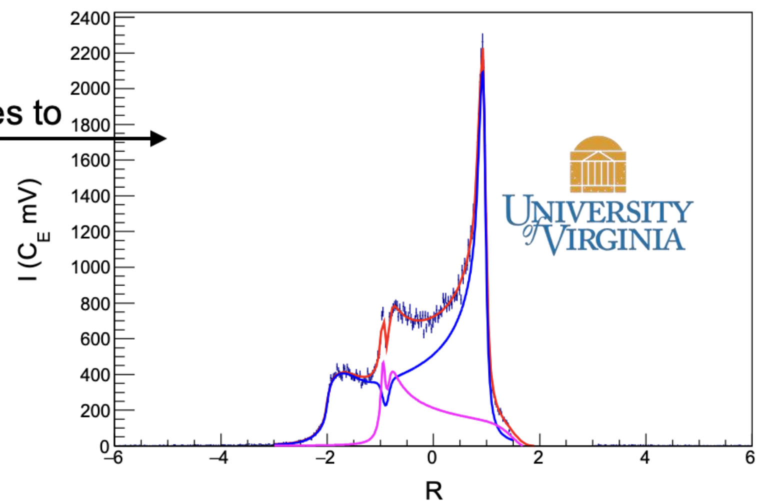



DNP polarized enhanced signal

Q = 19%

goes to

Tensor enhanced signal:




ss-RF enhanced signal

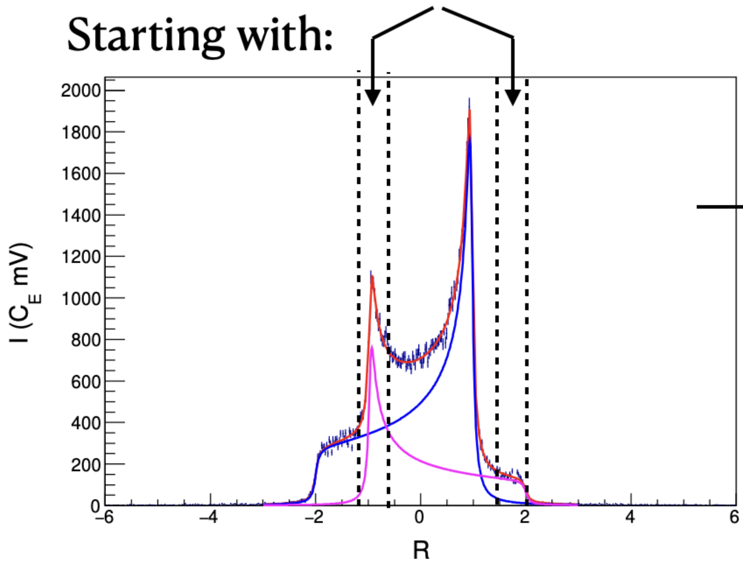
Q = 28.8%

D. Keller Eur. Phys. J. A53 (2017)

# Enhancing tensor polarization

**Semi-selective RF**

Starting with:

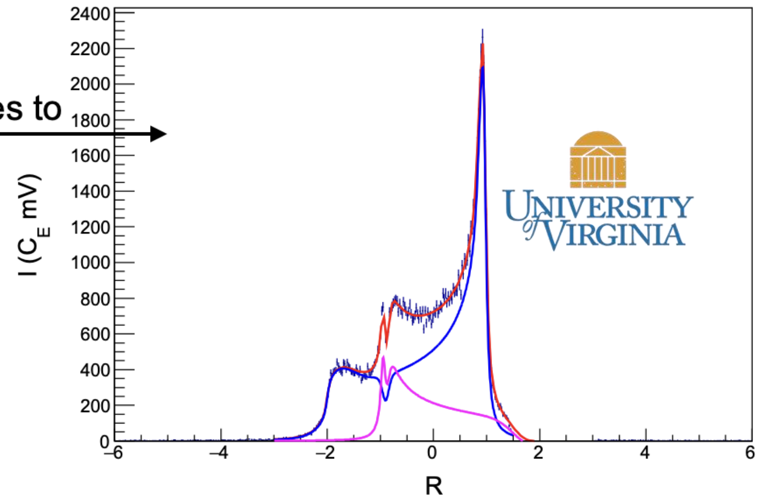



DNP polarized enhanced signal

Q = 19%

goes to

Tensor enhanced signal:



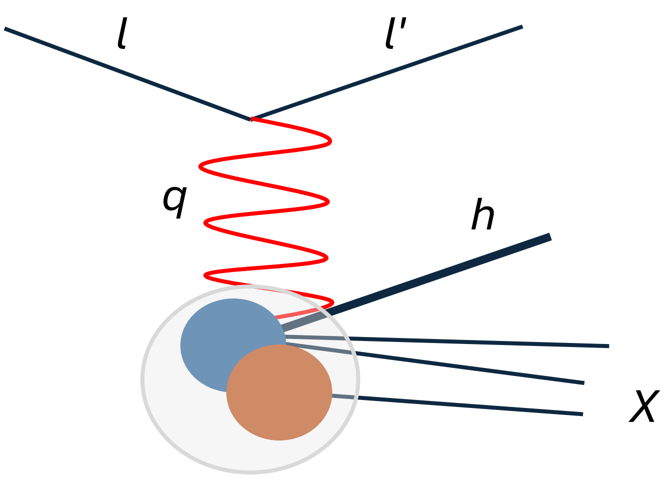

ss-RF enhanced signal

Q = 28.8%

D. Keller [Eur. Phys. J. A53 (2017)]

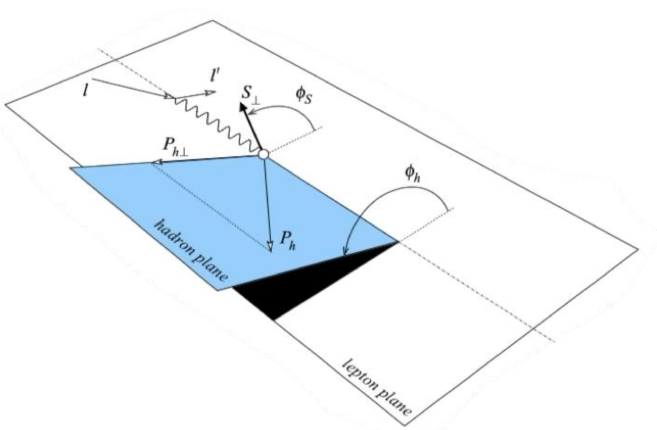
- Low tensor polarization has limited physics experiments.
- New target developments are ongoing, with an enhancement of up to 30%.
- Two experiments to measure tensor observables have been approved.
- Several new experiments are underway.

# Semi-Inclusive Deep Inelastic Scattering

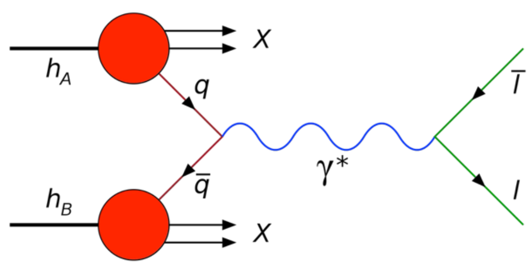


# Accessing TMDs

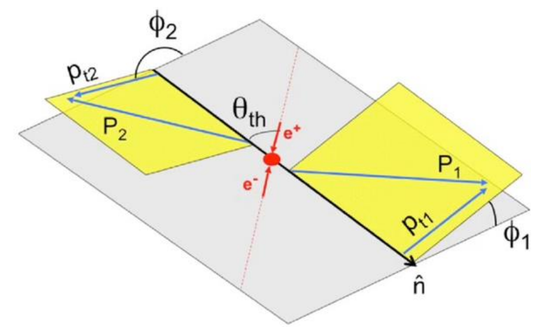
**SIDIS**
JLab, HERMES,
COMPASS




**Drell-Yan**
COMPASS, Fermilab,
RHIC



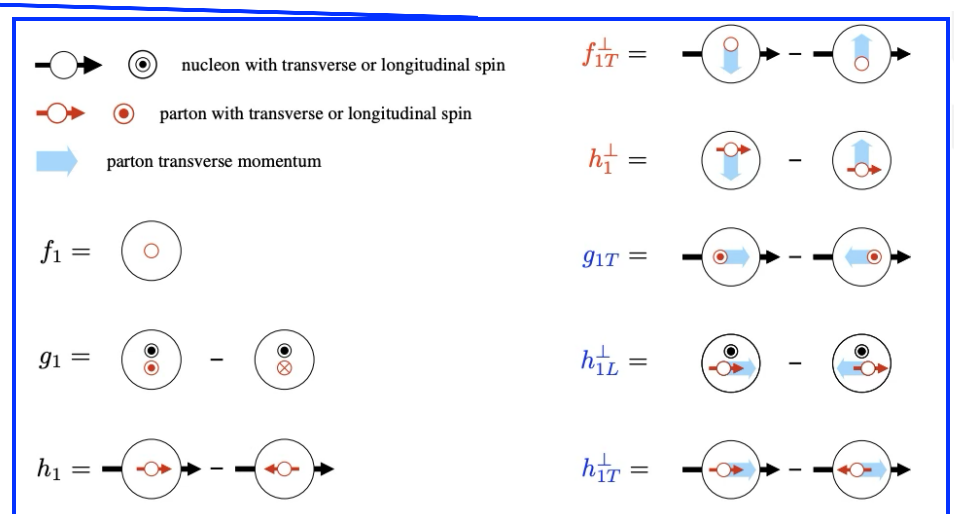

$e^- + e^+ \rightarrow h_1 + h_2 + X$
Belle, BaBar




- Needs two observed momenta.
- Sensitive to:
  - parton model with gluons and sea quarks
  - partons transverse momentum and angular momentum
  - full decomposition of the nucleon spin

# Spin-½: Leading twist distribution functions

| Hadron \ Quark | 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 | | $f_{1T}^\perp$ | $g_{1T}$ | | $[h_1], [h_{1T}^\perp]$ | |



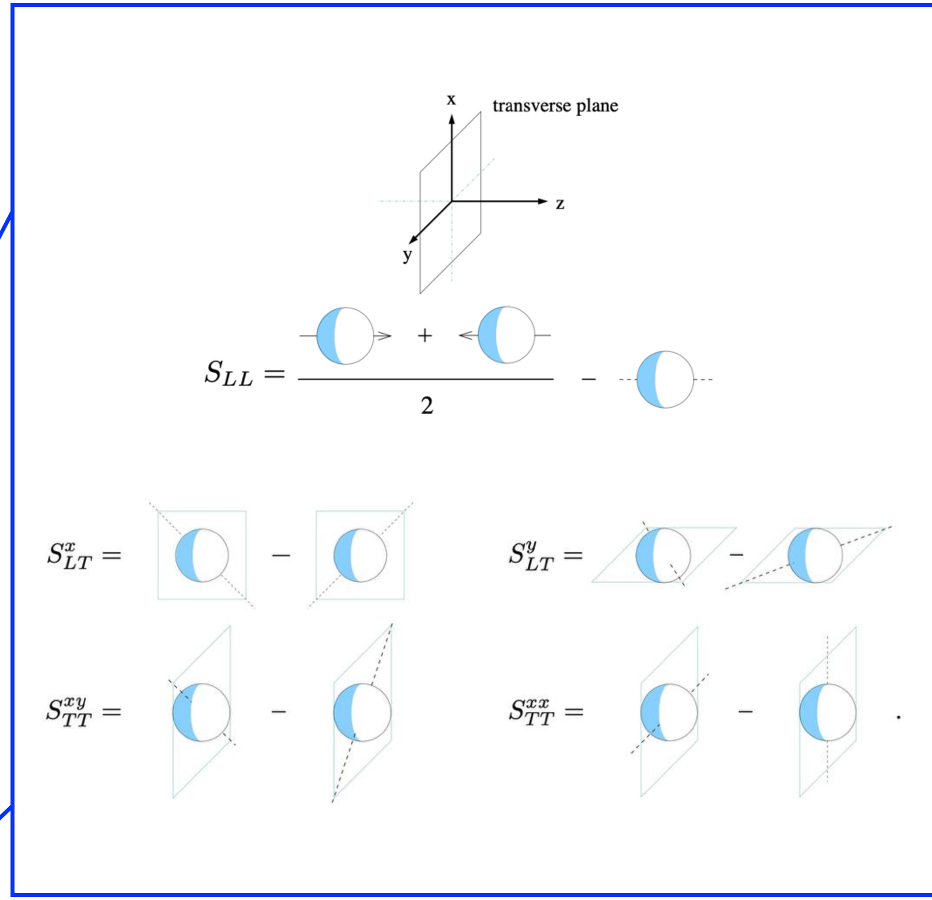

| Hadron \ Quark | U ($\gamma^+$) | | L ($\gamma^+\gamma_5$) | | T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) | |
|---|---|---|---|---|---|---|
| | T-even | T-odd | T-even | T-odd | T-even | T-odd |
| U | $f_1$ | | | | | |
| L | | | $g_{1L}\,(g_1)$ | | | |
| T | | | | | $[h_1]$ | |

Phys. Rev. D 62 (2000)

# Spin-1: 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 | | $f_{1T}^\perp$ | $g_{1T}$ | | $[h_1]$, $[h_{1T}^\perp]$ | |
| LL | $f_{1LL}$ | | | | | $[h_{1LL}^\perp]$ |
| LT | $f_{1LT}$ | | | $g_{1LT}$ | | $[h_{1LT}]$, $[h_{1LT}^\perp]$ |
| TT | $f_{1TT}$ | | | $g_{1TT}$ | | $[h_{1TT}]$, $[h_{1TT}^\perp]$ |

| 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 | $f_1$ | | | | | |
| L | | | $g_{1L}$ ($g_1$) | | | |
| T | | | | | $[h_1]$ | |
| LL | $f_{1LL}$ ($b_1$) | | | | | |
| LT | | | | | | *1 |
| TT | | | | | | |




[Phys. Rev. D 62 (2000)]

# Spin-1: 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 | | $f_{1T}^\perp$ | $g_{1T}$ | | $[h_1], [h_{1T}^\perp]$ | |
| LL | $f_{1LL}$ | | | | | $[h_{1LL}^\perp]$ |
| LT | $f_{1LT}$ | | | $g_{1LT}$ | | $[h_{1LT}], [h_{1LT}^\perp]$ |
| TT | $f_{1TT}$ | | | $g_{1TT}$ | | $[h_{1TT}], [h_{1TT}^\perp]$ |

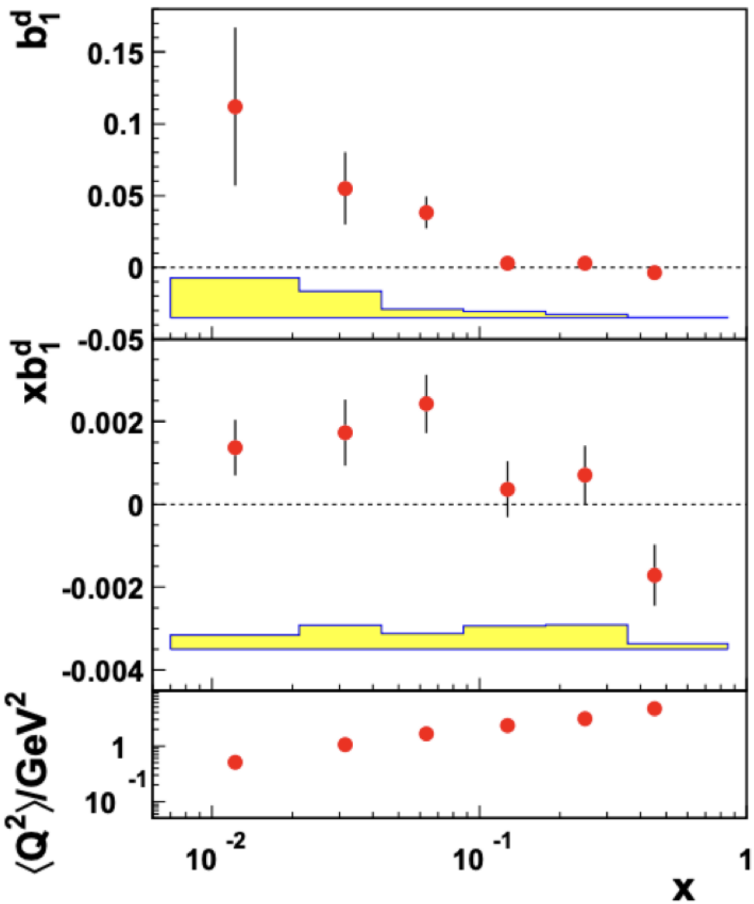
| Quark / Hadron | U ($\gamma^+$) | | L ($\gamma^+\gamma_5$) | | T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$) | |
|---|---|---|---|---|---|---|
| | T-even | T-odd | T-even | T-odd | T-even | T-odd |
| U | $f_1$ | | | | | |
| L | | | $g_{1L}$ ($g_1$) | | | |
| T | | | | | $[h_1]$ | |
| LL | $f_{1LL}$ ($b_1$) | | | | | |
| LT | | | | | | *1 |
| TT | | | | | | |

- Only $b_1$ has been measured by Hermes Phys.Rev.Lett. 95 (2005).
- A new measurement of $b_1$ will be done at JLab (E12-13-011).

SIDIS spin-1 measurements open the door to a complete new set of observables that can tell us about color degrees of freedom and beyond standard hadron physics.

Phys. Rev. D 62 (2000)

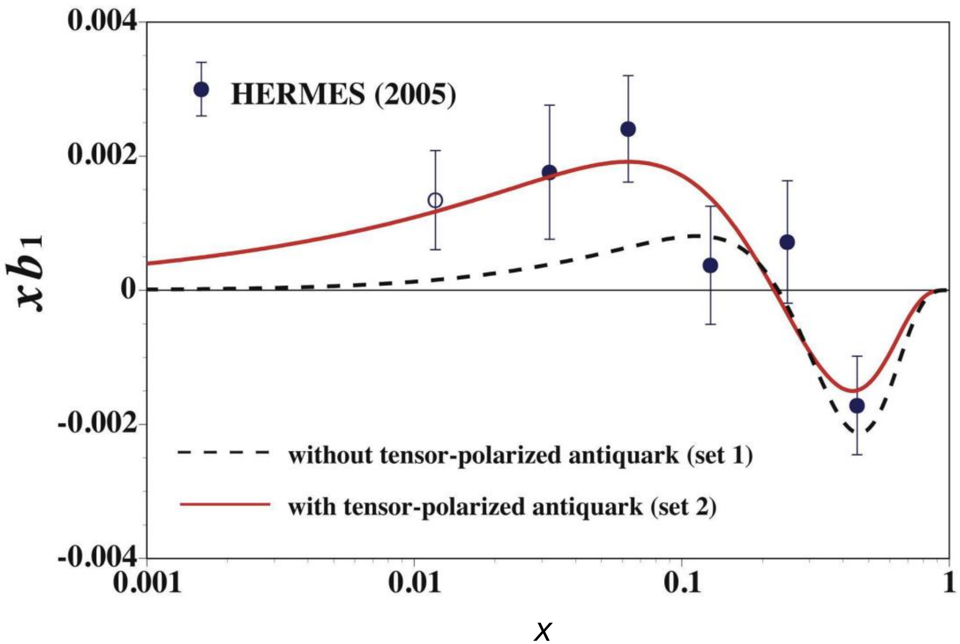
# HERMES Experiment: First Measurement of $b_1$

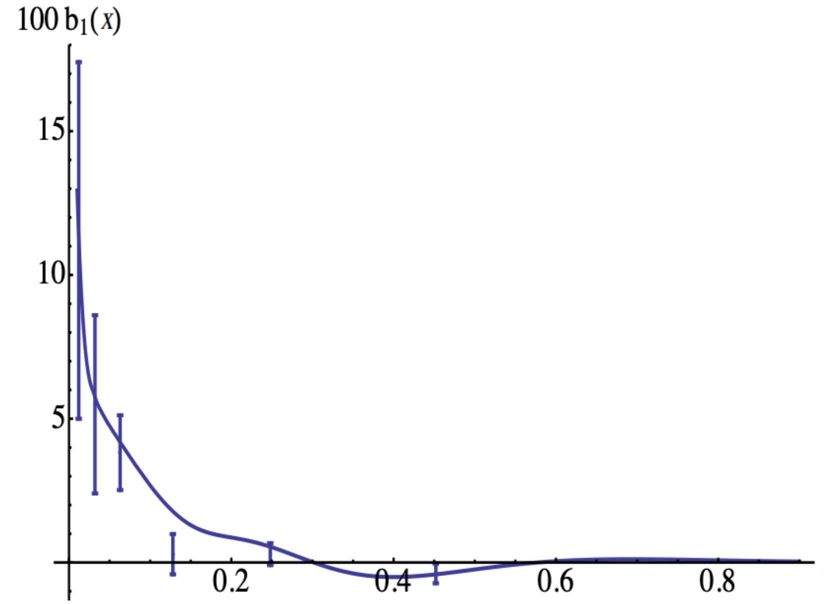



- $0.5\ GeV^2 < Q < 5\ GeV^2$
- $0.01 < x < 0.45$
- Positrons in the momentum range of 2.5 GeV to 27 GeV
- The average target vector $P$ and tensor $Q$ polarizations are typically more than 80%
- Polarized gas target (integrated luminosity 42 $pb^{-1}$ )
- *The rise of  for decreasing values of x can be interpreted to originate from the same mechanism that leads to nuclear shadowing in unpolarized scattering.*

[Phys. Rev. Lett. 95, 242001(2005)]

# Theory predictions of $b_1$




*We found that a significant antiquark tensor polarization exists if the overall tensor polarization vanishes for the valence quarks although such a result could depend on the assumed functional form.* ***Further experimental measurements are needed for $b_1$ such as at JLab*** *as well as Drell-Yan measurements with tensor-polarized deuteron at hadron facilities, J-PARC and GSI-FAIR.*

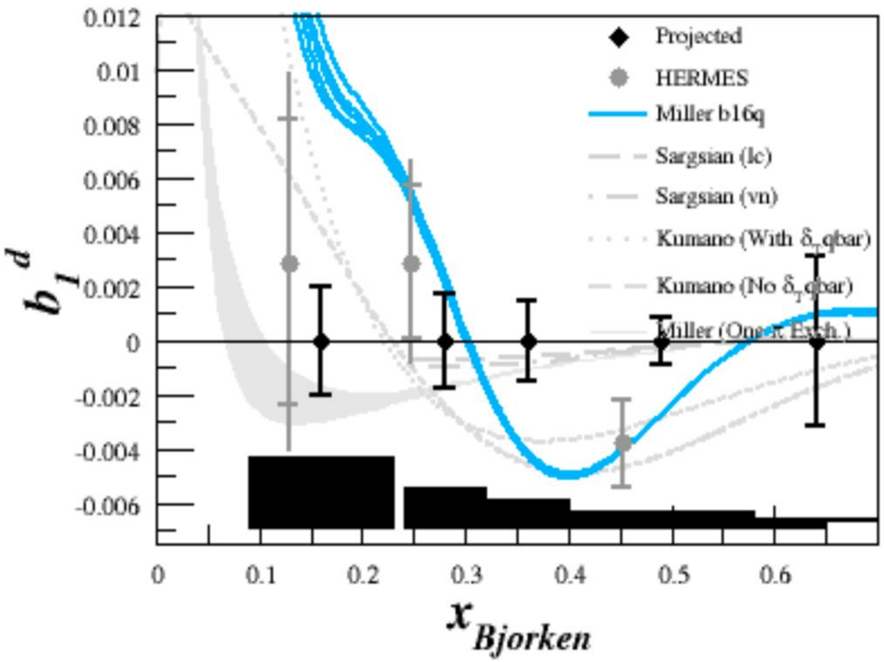
[Phys. Rev. D 82, 017501 (2010)](Phys. Rev. D 82, 017501 (2010))

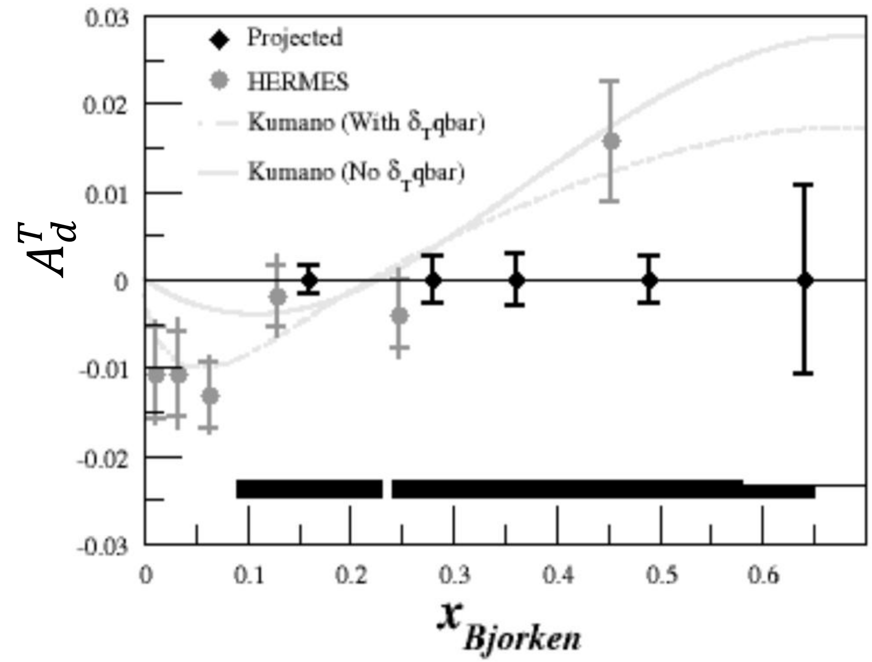
*Hidden-color model: six-quark configurations (with ~ 0.15% probability to exist in the deuteron) proposed and found to give substantial contributions for values of $x > 0.2$.*

Phys. Rev. C 89, 045203 (2014)

E12-13-011Approved
Experiment at Jefferson Lab

## Inclusive Measurement




$0.16 < x < 0.49$
$0.8 < Q^2 < 5.0$ GeV$^2$
Incident beam 11 GeV

**Slifer**, Chen, Kalantarians, Keller, Long,
Rondon, Santiesteban, Solvignon

# SIDIS processes with a Spin-1 target

Theory developments

- Leading twist: A. Bacchetta (thesis) arXiv:hep-ph/0212025
- Leading twist: Phys. Rev. D 62 (2000)
- Phys. Rev. C 102, 065204 (2020)
- Up to twist 4: Phys. Rev. D 103 (2021)
- Formalism and covariant calculations: Phys. Rev. C 96, no.4, 045206 (2017)

# 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

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

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

, $S_{\parallel}$ is the vector polarization, and $T_{\parallel\parallel}$ is the tensor polarization of target in parallel to the virtual photon direction which are related with $\mathcal{P}$ and $\mathcal{Q}$ along the direction of electron beam

Courtesy of A. Bacchetta (2023).

# Tensor-polarized structure functions

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

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

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

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

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

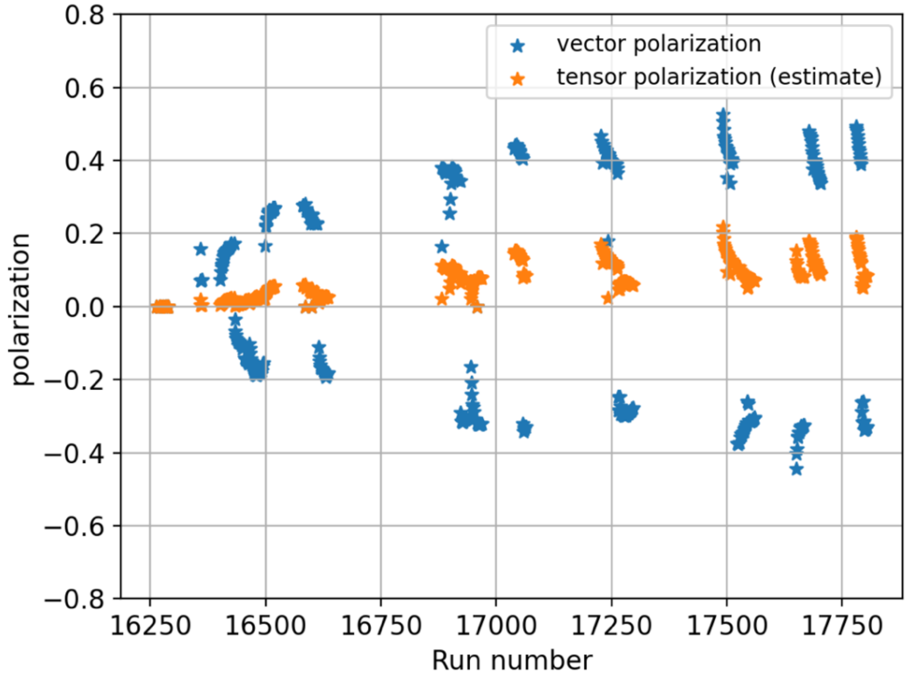
Spin-1 leading twist

Eur. Phys. J. A (2025) **61**: 81

# Experimental Measurements

## Step 1: Exploratory measurement with CLAS12 data

**Run Group C at CLAS12:** eight experiments using the CLAS12 detector in Hall B to study the multidimensional partonic structure of nucleons. Longitudinally polarized electrons are scattered from polarized $NH_3$ and $ND_3$ targets, dynamically polarized via DNP at 1 K in a 5 T magnetic field. While the $ND_3$ target is not optimized for tensor polarization, the DNP process induces a measurable tensor component, allowing for estimates of tensor structure function contributions relevant to the dedicated tensor measurements.




CAA: Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12

**Step 1:** Exploratory measurement with CLAS12 data (data mining)

Simplified version:

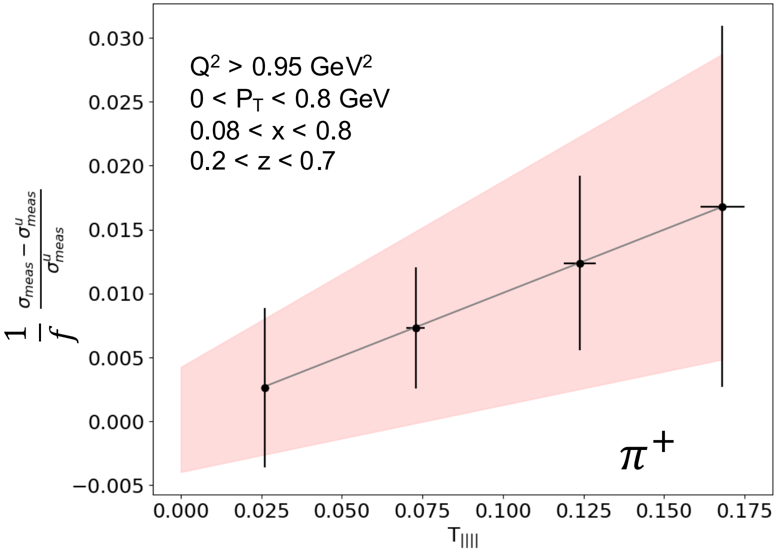
$$\sigma_{meas}^{total} = \sigma_u^D + P\sigma_v + Q\sigma_T + \sum \sigma_i$$

Summing over positive and negative vector polarization:

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

$f$: Dilution factor due to all other nuclei in the target sample $\sigma_i$

**CAA**: Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12
Data: Run Group C

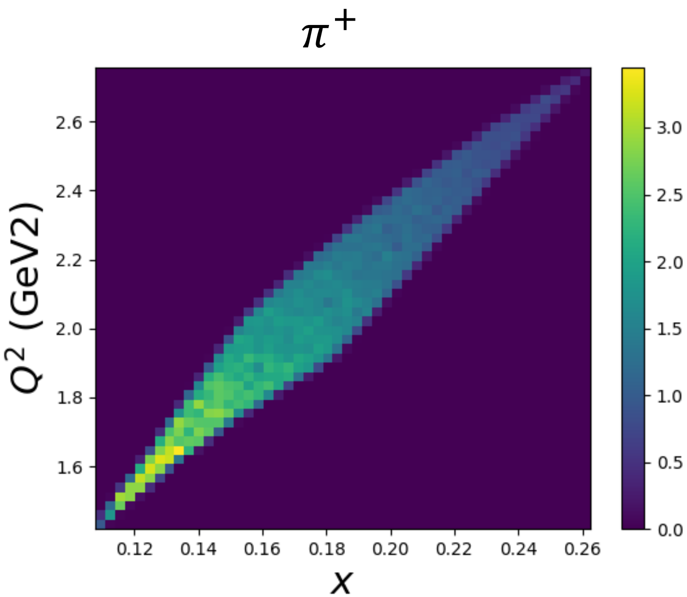


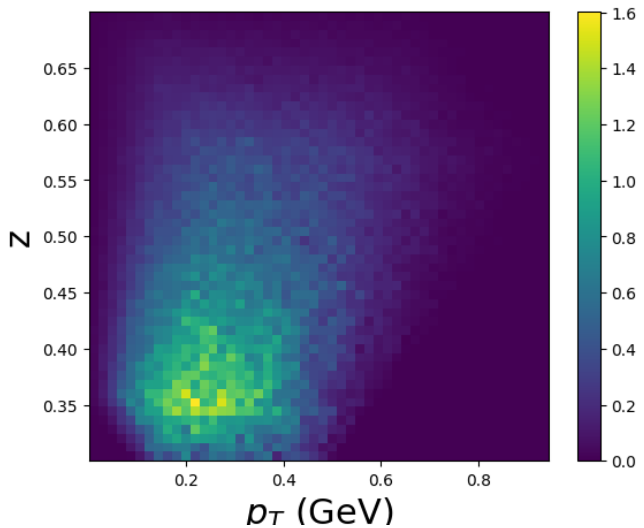

- This measurement will help to understand the tensor contribution.
- Currently assuming 10% of the unpolarized contribution as the inclusive measurement.
- Our predictions imply a 60% uncertainty.
- **Crucial to propose new experiments.**

CAA: Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12

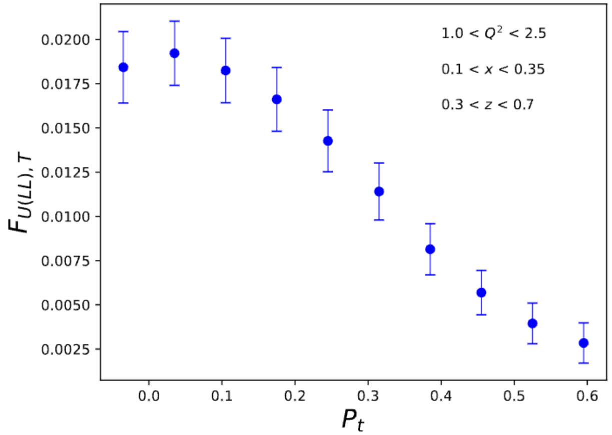
# Experimental Measurements

## Step 2: Dedicated measurement with CLAS12 data




## **LOI:** Spin-1 TMDs and Structure Functions of the Deuteron




| | $\theta$ (deg.) | $\phi$ (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 |

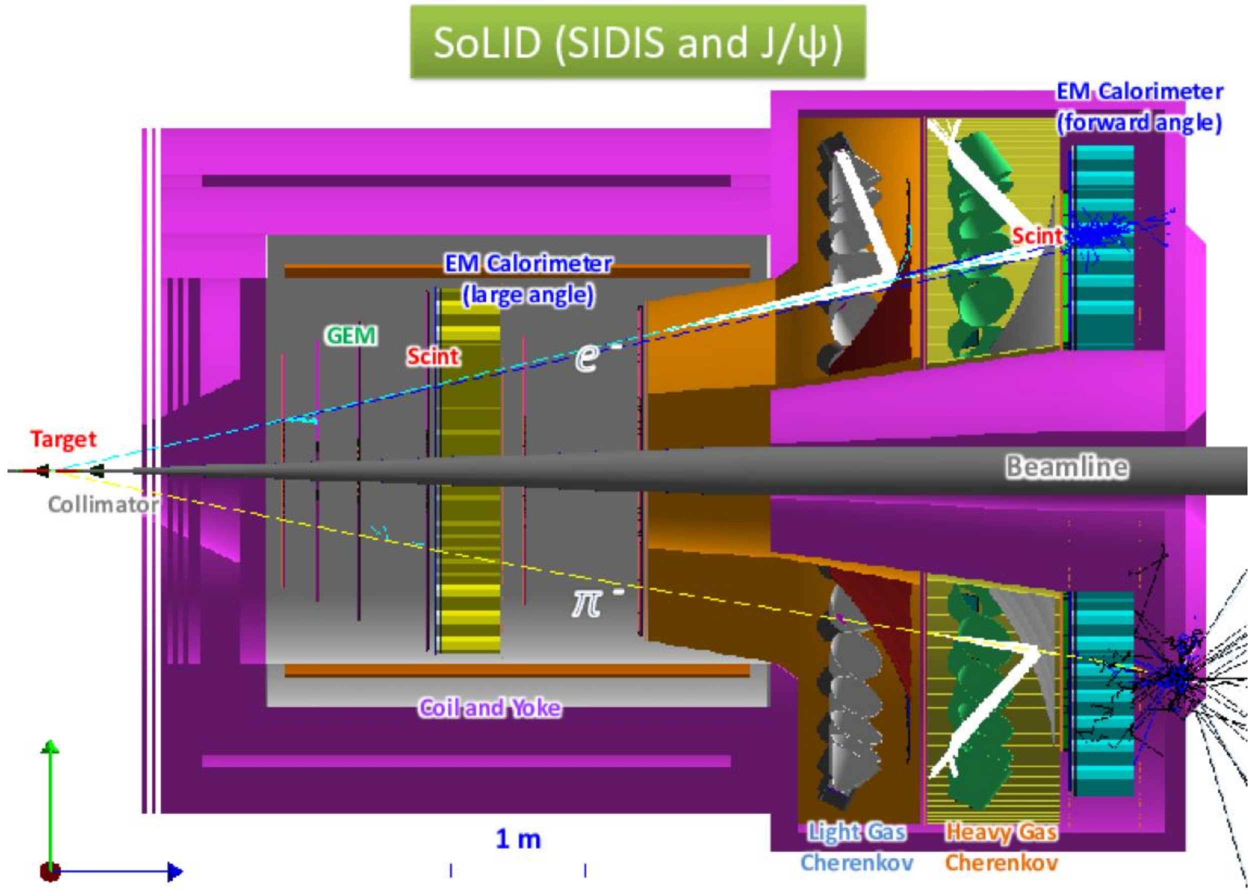
The kinematic ranges assumed for the chosen momentum setting in SHMS (electron) and SBS (hadron)

**Ruth**, Santiesteban, Chen, Slifer, Poudel, Fernando, Keller, Long, Bacchetta

# Experimental Measurements

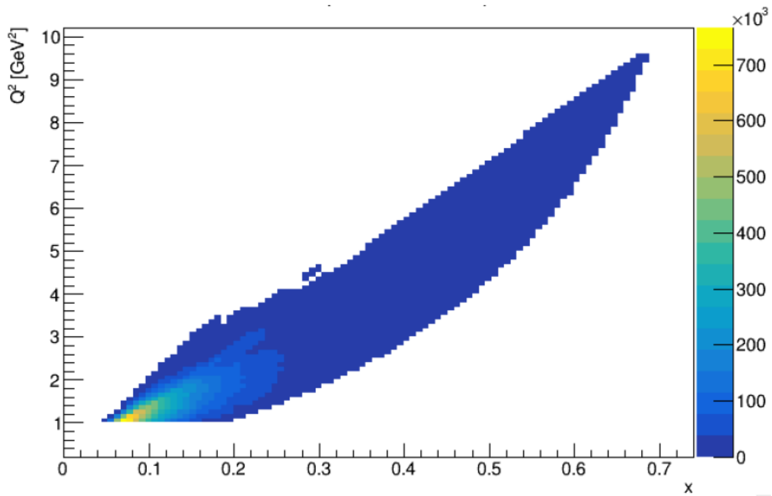
**Step 3:** Future program at SoLID

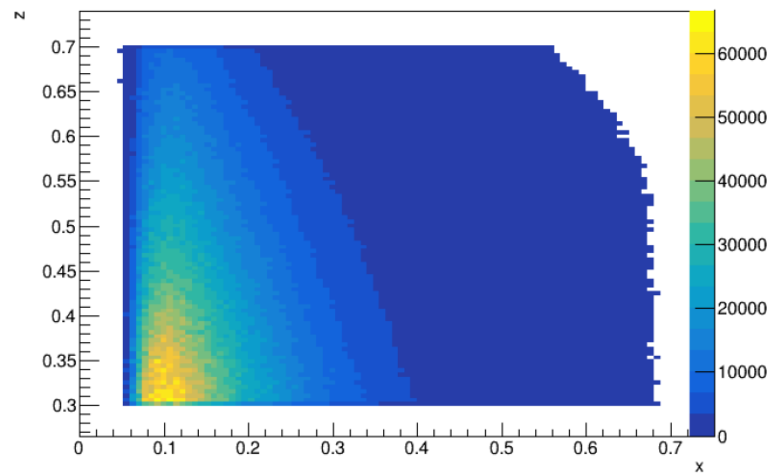
0.3 < z < 0.7
$Q^2$ > 1.0 GeV
W > 2.3 GeV
W’ > 1.6 GeV

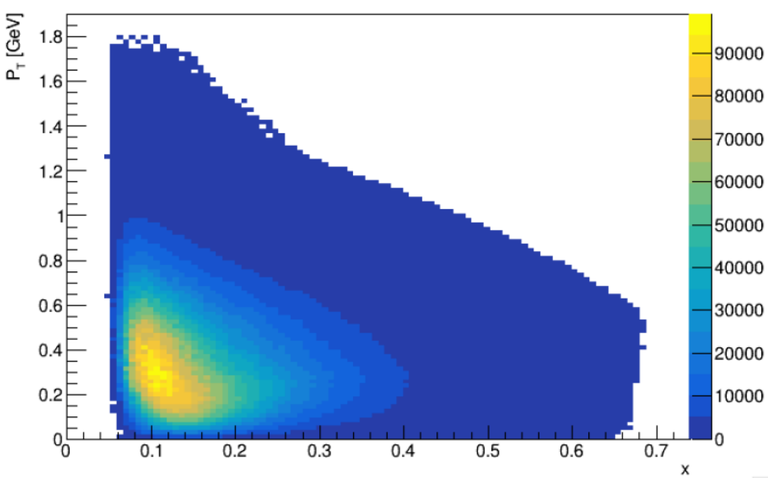


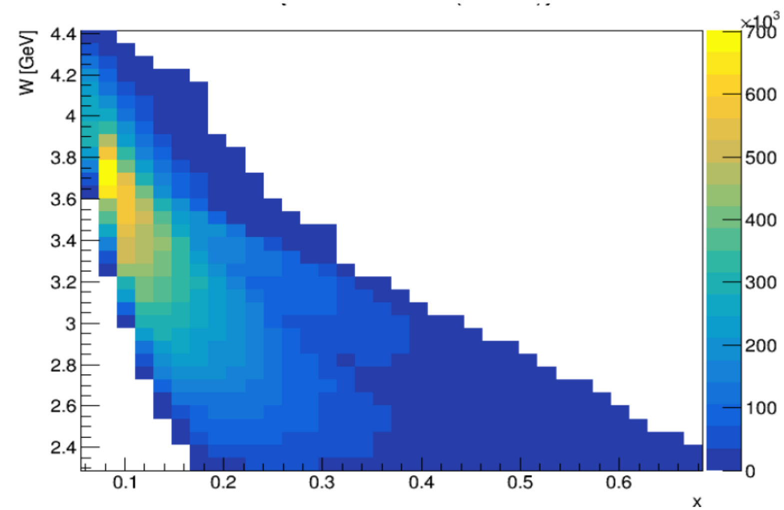
Unpolarized rates for $\pi^-$

1 week of running



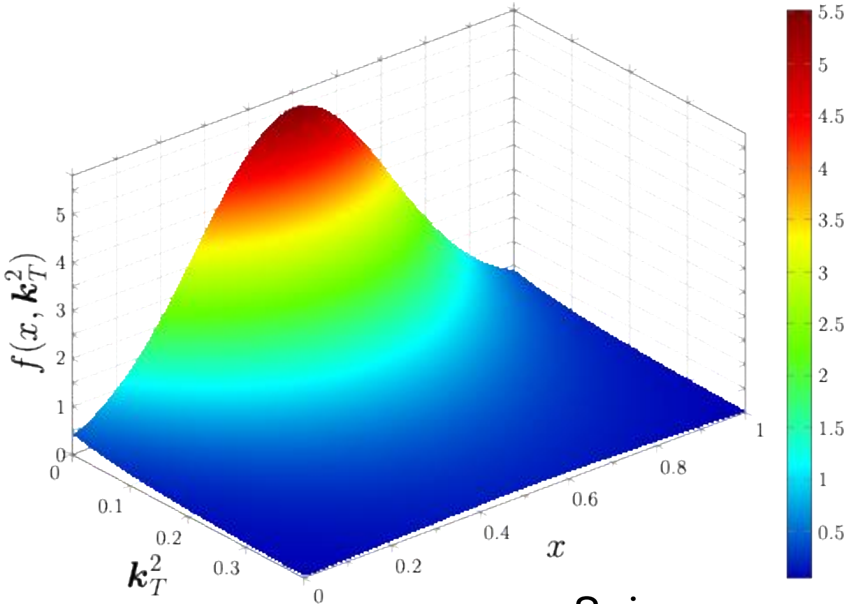



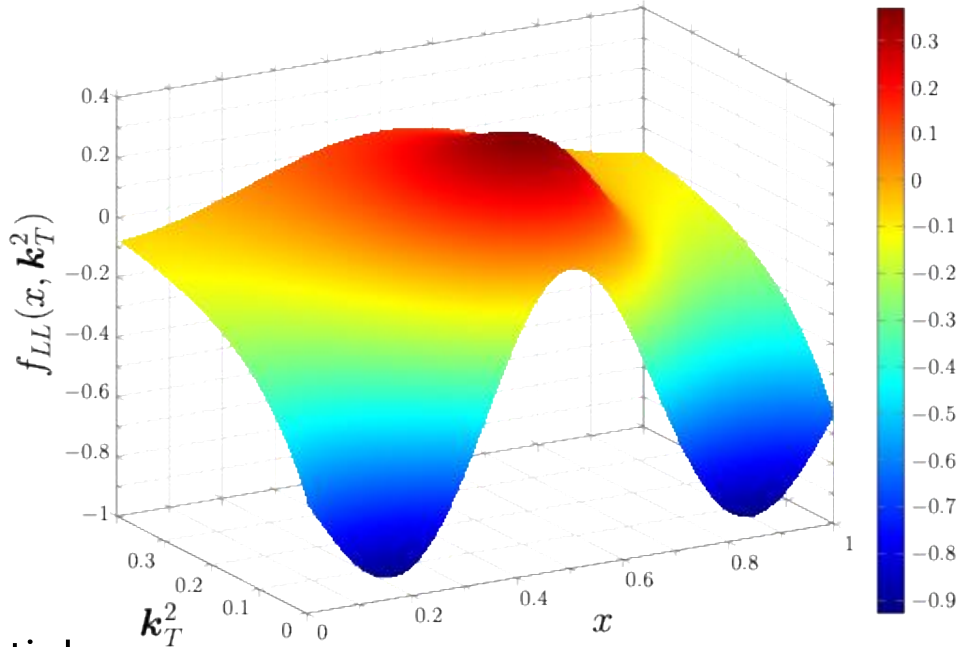




Assuming:

- Luminosity $10^{35}$ $cm^2/s$
- Pure D-> 1n + 1p

# Currently incorporating covariant calculations




Spin-one $\rho$ particle

Tensor polarized TMDs may have surprising features

Courtesy of Ian Cloët

# Our path for the Spin-1 SIDIS program


- No predictions: Use Hall B data (Run group C ~ 12% tensor polarization) to estimate the rates and possible sensitivity to structure functions shape/structure.
- Exploratory measurement: Propose a run in the short term (probably around the time of the already approved tensor experiments) to map the longitudinal distributions with better precision.
- Continue target development and plan for all possible configurations of polarization and higher polarizations.
- Formalize a plan to measure the distributions with the SoLID detector.

Santiesteban, Chen, Ruth, Poudel, Slifer, Fernando,
Keller, Long, Bacchetta

# Thank you!