Accessing Spin-1 Structure Functions and TMDs of the Deuteron

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On behalf of the SIDIS-Tensor collaboration

University of New Hampshire

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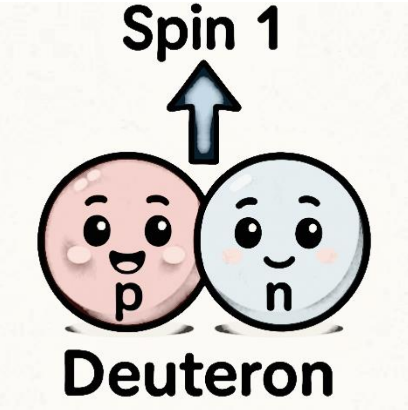
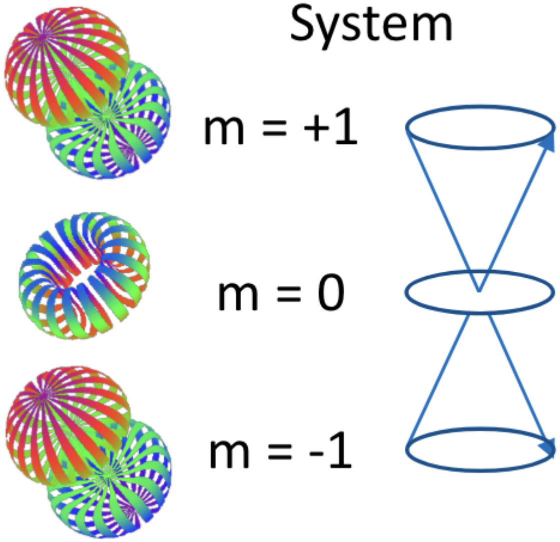
Department of Energy
United States of America

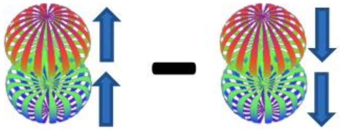


Spin-1 System



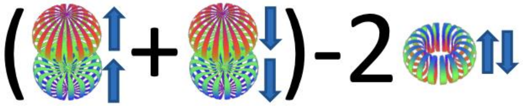
Deuteron in a magnetic field

Vector Polarization:



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

Tensor Polarization:



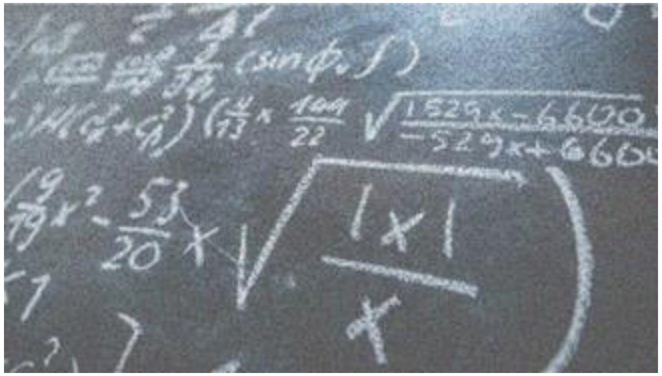
$$Q = N(+1) + N(-1) - 2N(0)$$

N(m): population density

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

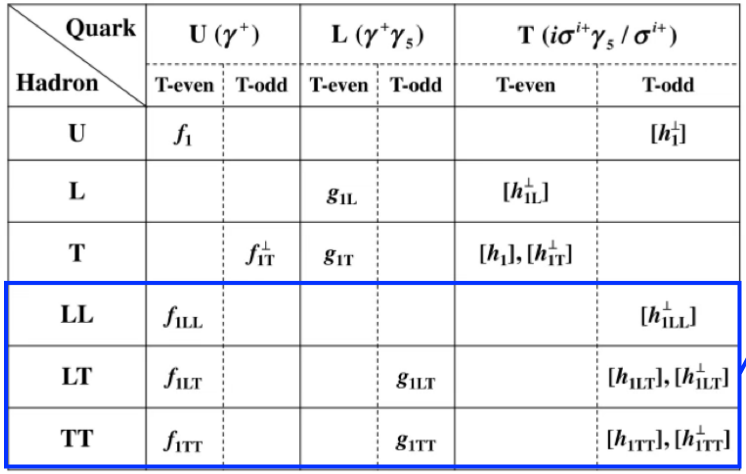
Normalization

Spin-1
Theory developments



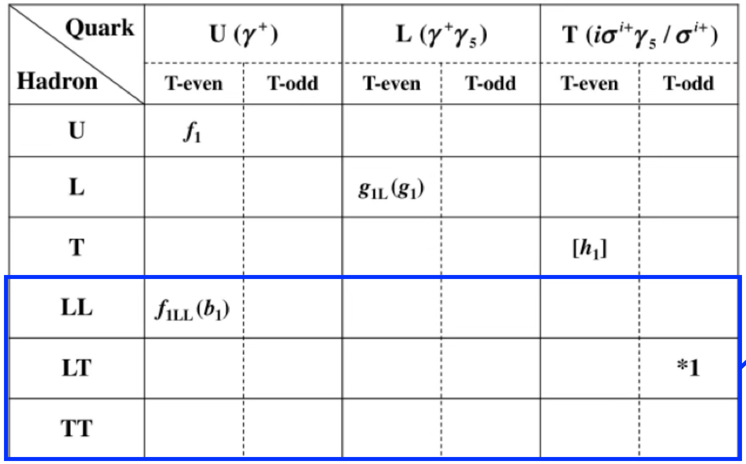
- Leading twist (thesis): arXiv:hep-ph/0212025
- Leading twist: Phys. Rev. D 62 (2000)
- Polarized deuteron DIS with spectator tagging: Phys. Rev. C 102, 065204 (2020)
- Up to twist 4: Phys. Rev. D 103 (2021)
- Formalism and covariant calculations: Phys. Rev. C 96, no.4, 045206 (2017)

Spin-1: Leading twist distribution functions

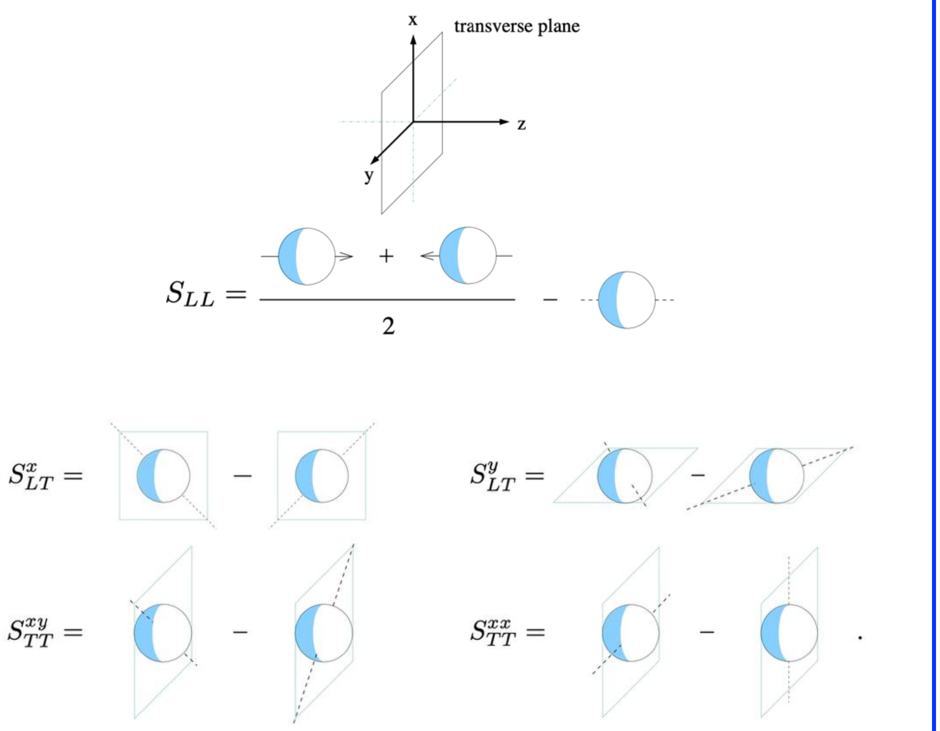


Hadron \ Quark	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		$f_{1T}^\perp$	g_{1T}		$[h_1], [h_{1T}^\perp]$	
LL	f_{1LL}					$[h_{1LL}^\perp]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}],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

After integration upon p_T



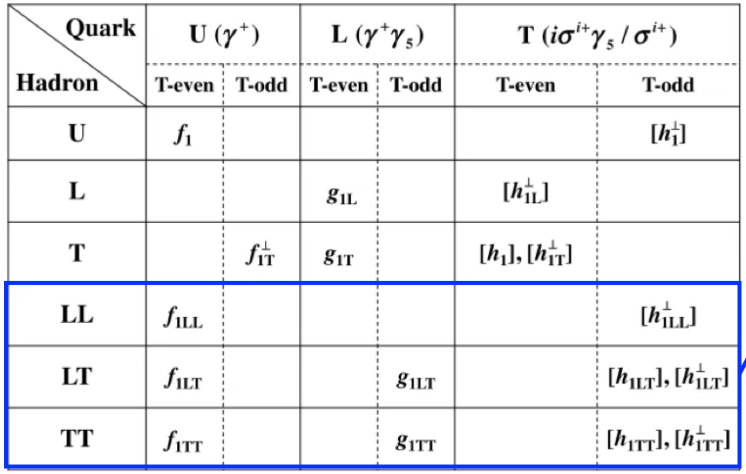
Hadron \ Quark	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					
L			$g_{1L}(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}(b_1)$					
LT						*1
TT						



Arrows represent spin states m = +1 and m = −1 in the direction of the arrow itself, while dashed lines denote spin state m = 0 again in the direction of the line itself

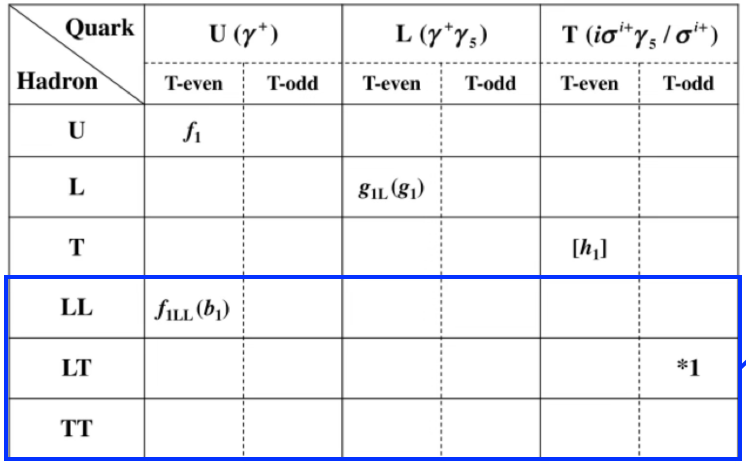
Phys. Rev. D **62**, 114004 (2000)

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

After integration upon p_T



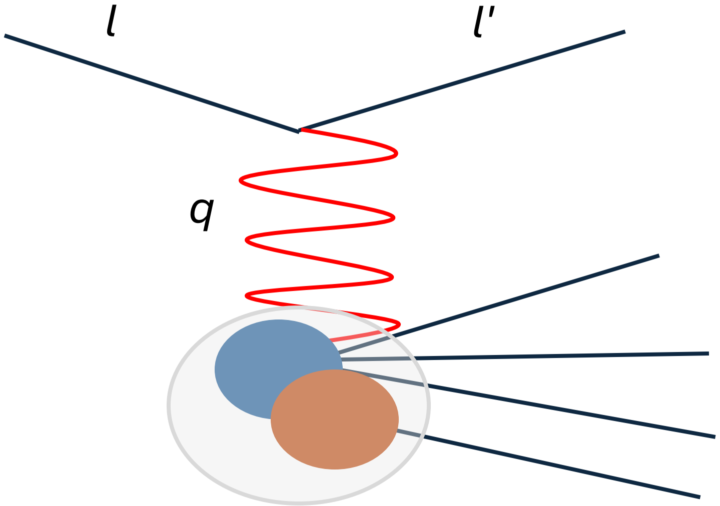
Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					
L			$g_{1L}(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}(b_1)$					
LT						*1
TT						

- 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.

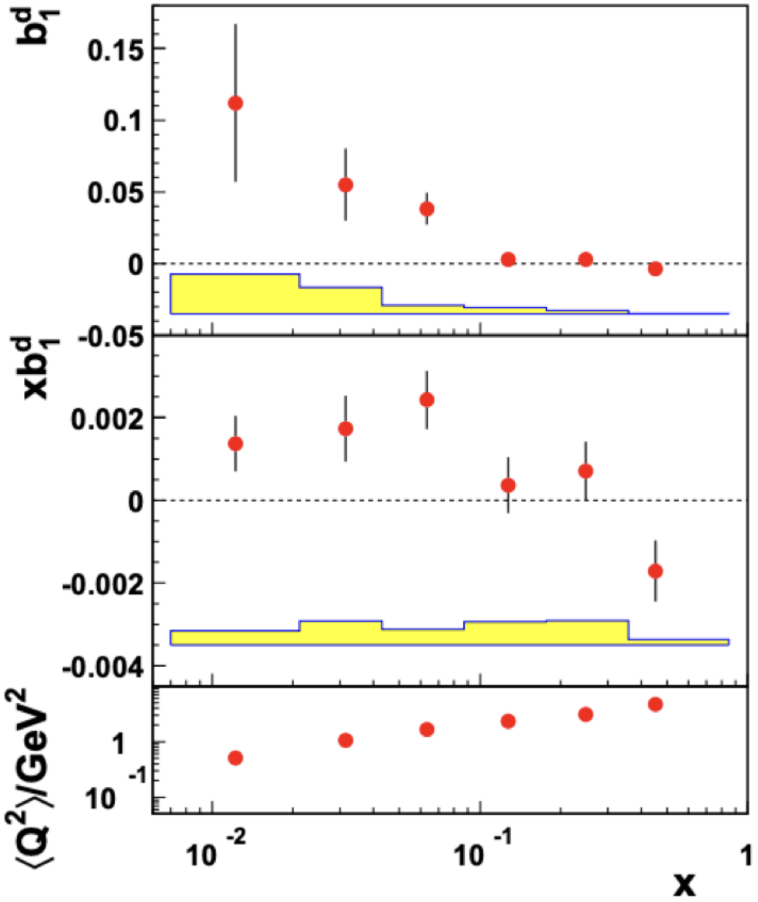
Phys. Rev. D **62**, 114004 (2000)

Deep Inelastic Scattering



b_1 measurements (HERMES data and Future Jefferson Lab experiment)

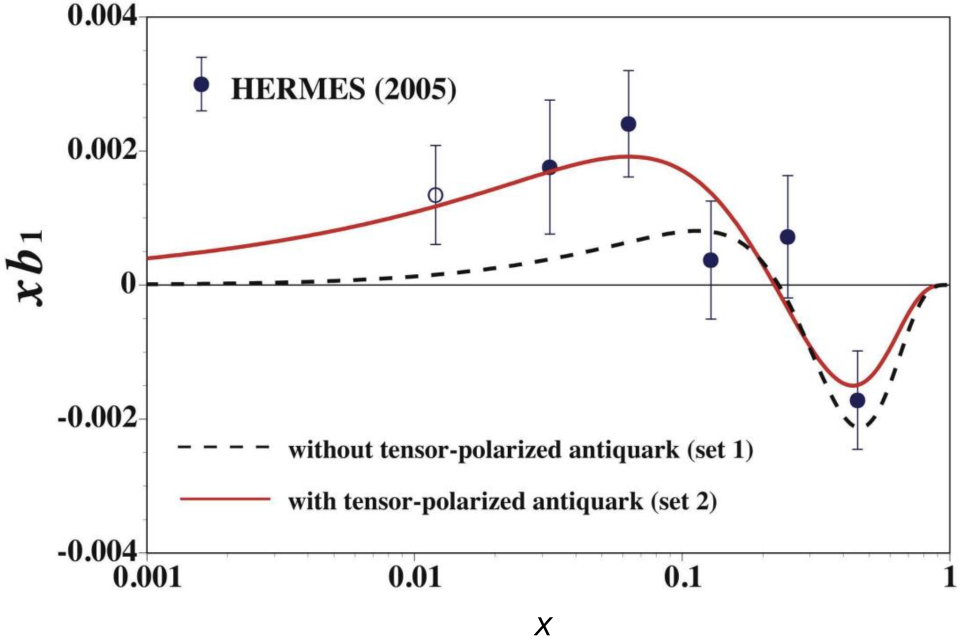
HERMES Experiment: First Measurement of b_1

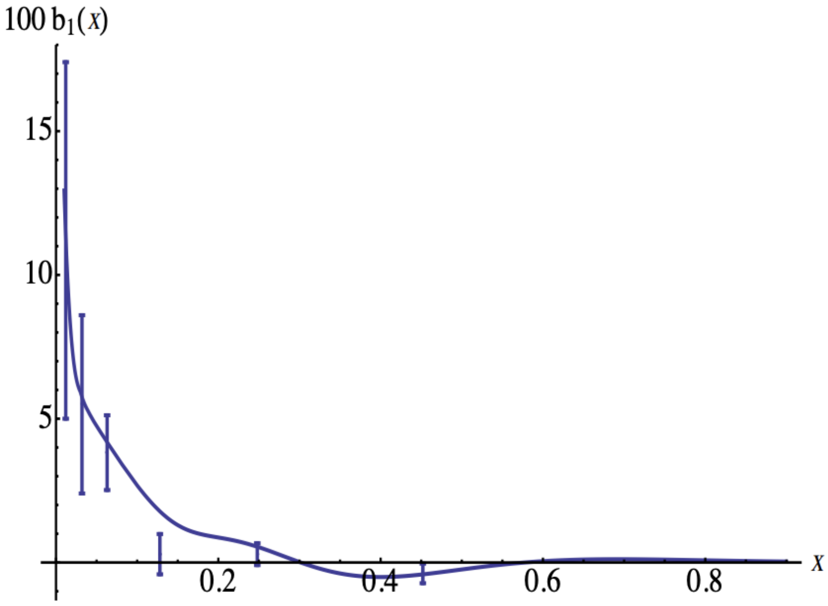


- 27.6 GeV/c positron beam of Hera
- $0.5 \text{ GeV}^2/c^2 < Q^2 < 5 \text{ GeV}^2/c^2$
- $0.01 < x < 0.45$
- Positrons in the momentum range of 2.5 GeV /c to 27 GeV/c
- The average target vector $\mathcal{P}$ and tensor $\mathcal{Q}$ polarizations are typically more than 80%
- Polarized gas target (integrated luminosity 42 pb^{-1})
- *The rise of b_1 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.*

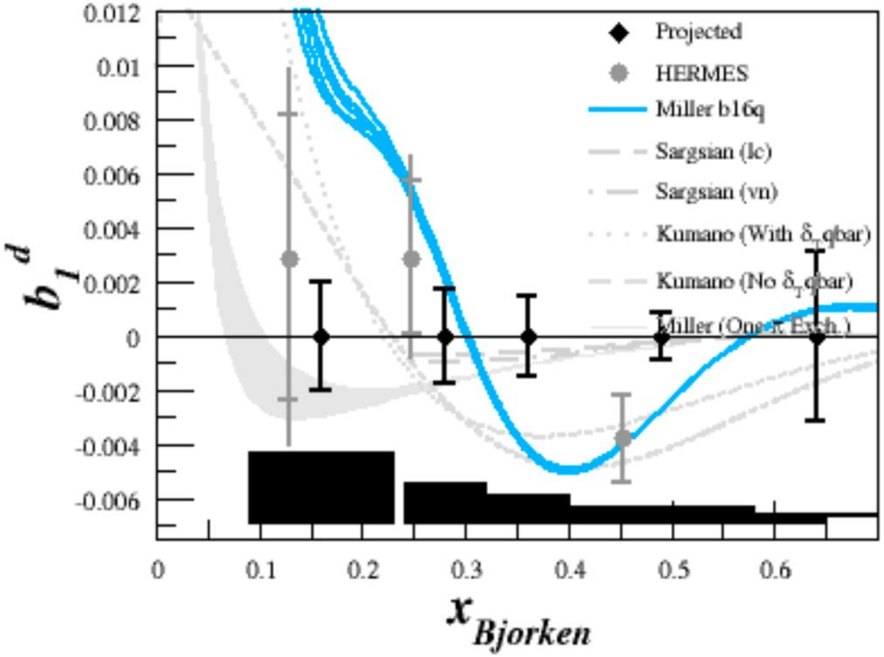
Phys. Rev. D 82, 017501 (2010)

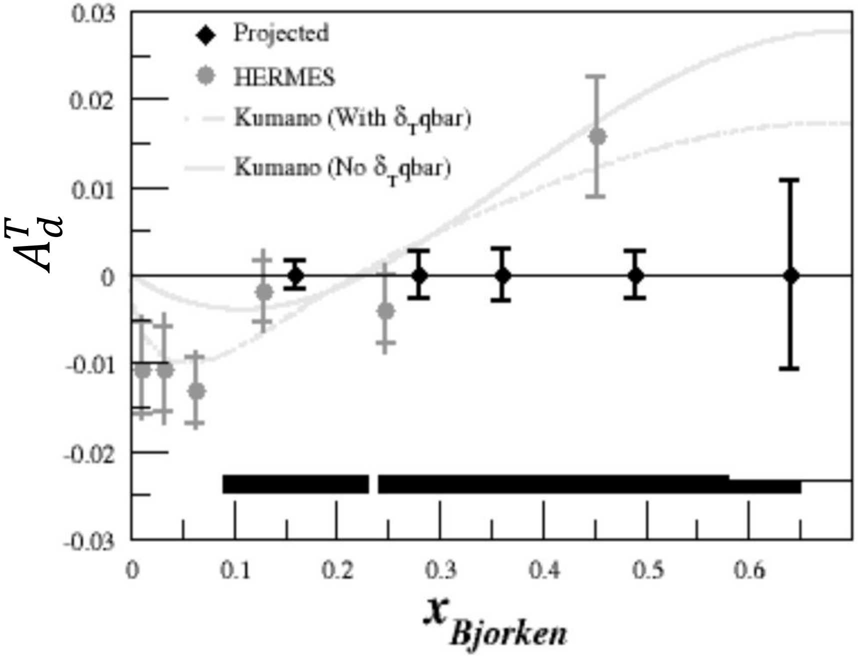
Hidden-color model: six-quark configurations (with ~ 0.15% probability to exist in the deuteron) proposed and found to give substantial contributions for values of $x > 0.2$.

Phys. Rev. C 89, 045203 (2014)

E12-13-011Approved Experiment at Jefferson Lab

Inclusive Measurement





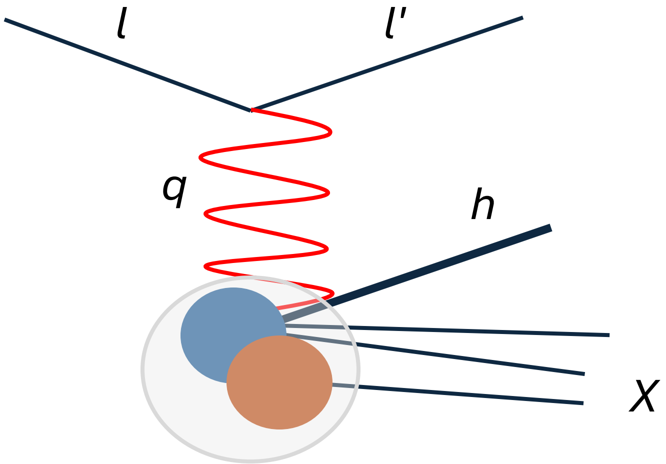
0.16 < x < 0.49

0.8 5 GeV^2/c^2 < Q^2 < 5.0 5 GeV^2/c^2

Incident beam (electrons): E= 11 GeV

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

Semi–Inclusive Deep Inelastic Scattering



Future measurements at Jefferson Lab

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

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

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

tensor

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

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

, $S_{\|}$ is the vector polarization, and $T_{\|\|}$ 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

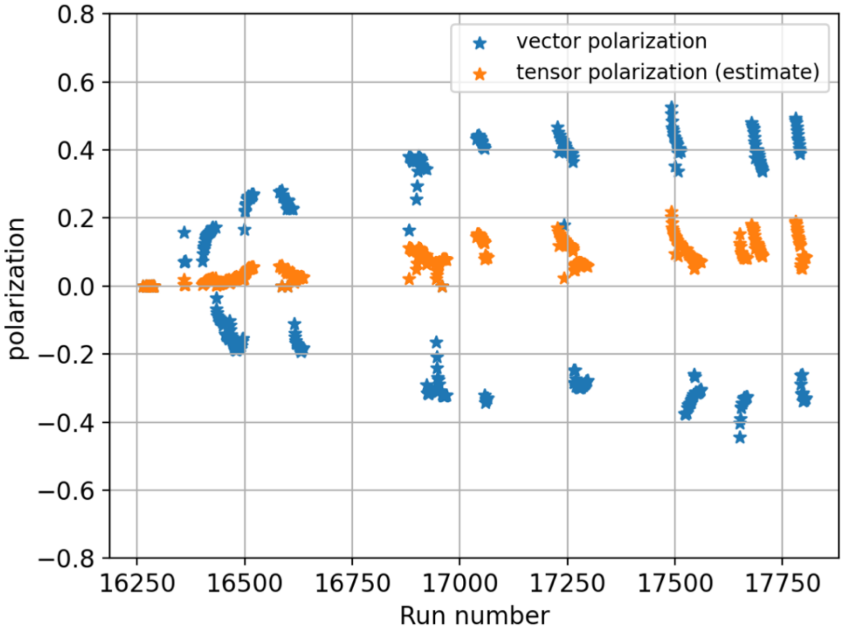
Experimental Measurements

Step 1: Exploratory measurement with CLAS12 data

Approved analysis with Run Group C of already taken data of ND_3

Run Group C at CLAS12:

- 8 experiments using the CLAS12 to study the multidimensional partonic structure of nucleons
- Longitudinally polarized electrons are scattered from polarized 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.



Courtesy: P Pandey

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

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

Simplified version:

Unpolarized

Tensor

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

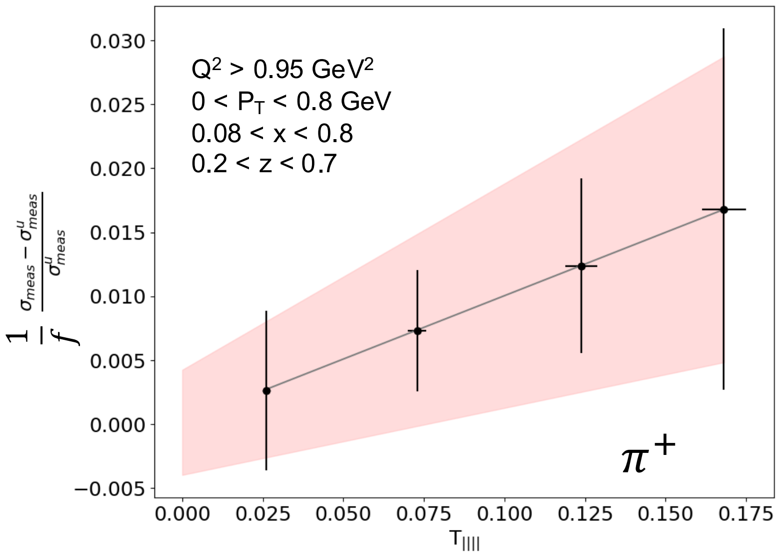
Vector

Other Nuclei
(N, He, etc)

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 σ_i



- 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.**

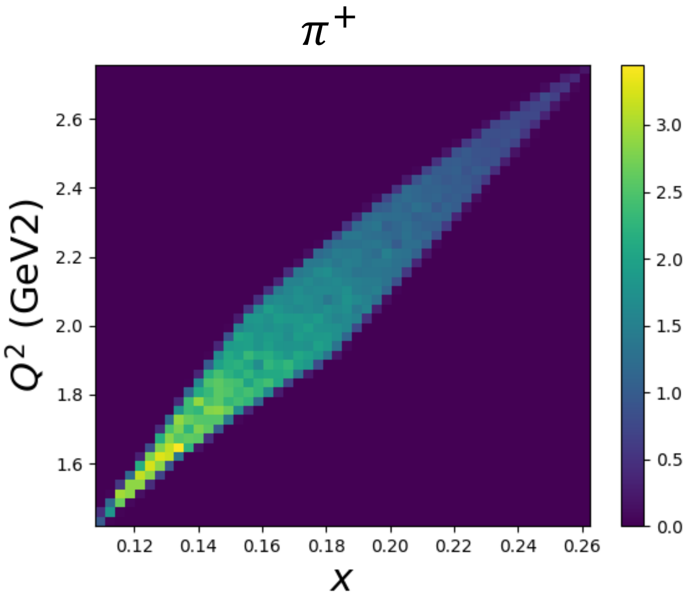
CAA: Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12

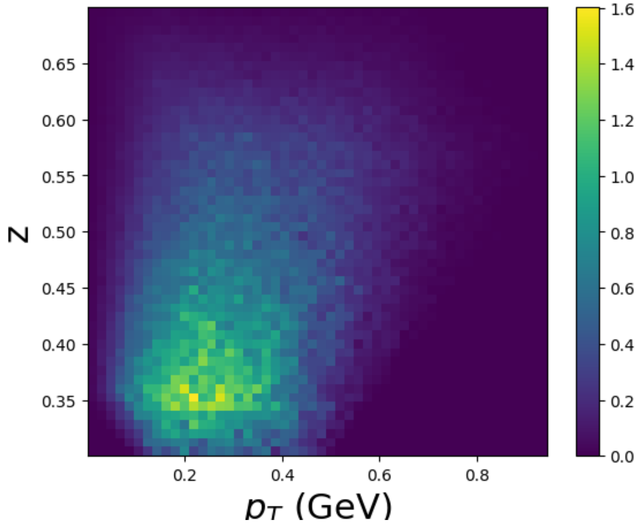
Experimental Measurements

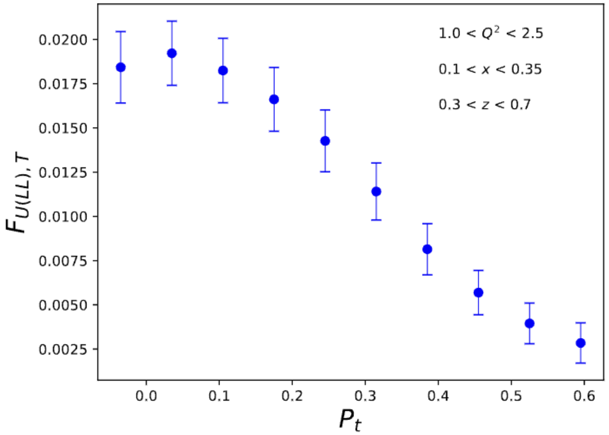
Step 2:
Dedicated Measurement

Letter of Intent (LOI) submitted to PAC 52 in
Jefferson Lab

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





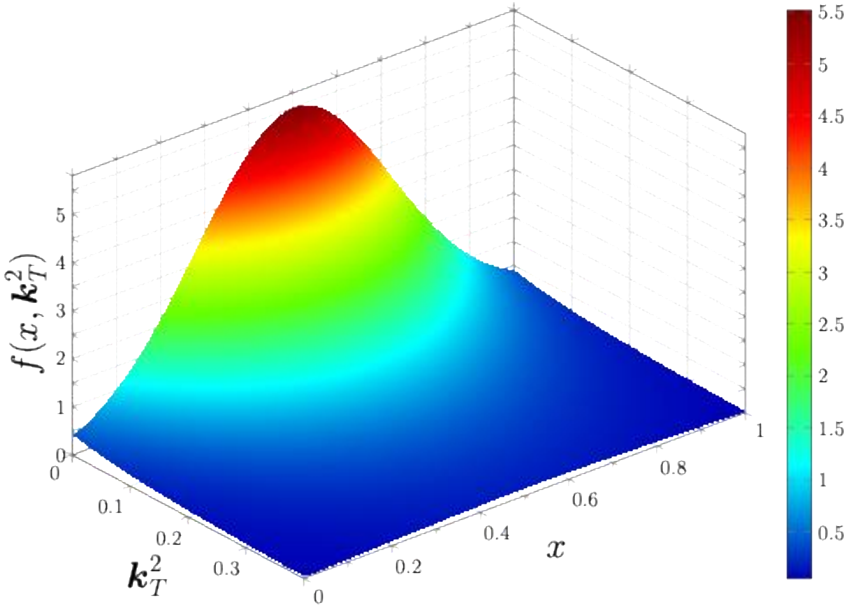


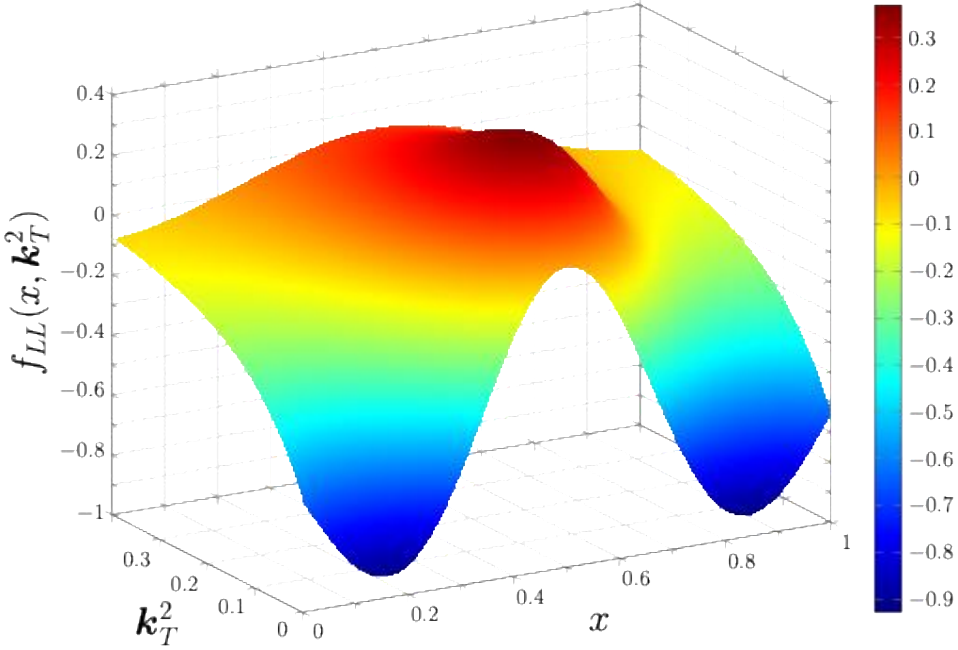
	θ (deg.)	ϕ (deg.)	P (GeV)
Electron	10.3 - 12.4	-2.87 - 2.87	4.0 - 5.4
Hadron	5.0 - 15.0	167 - 193	2.0 - 4.0

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

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

Currently incorporating covariant calculations





Spin-one ρ particle
Next: Deuteron

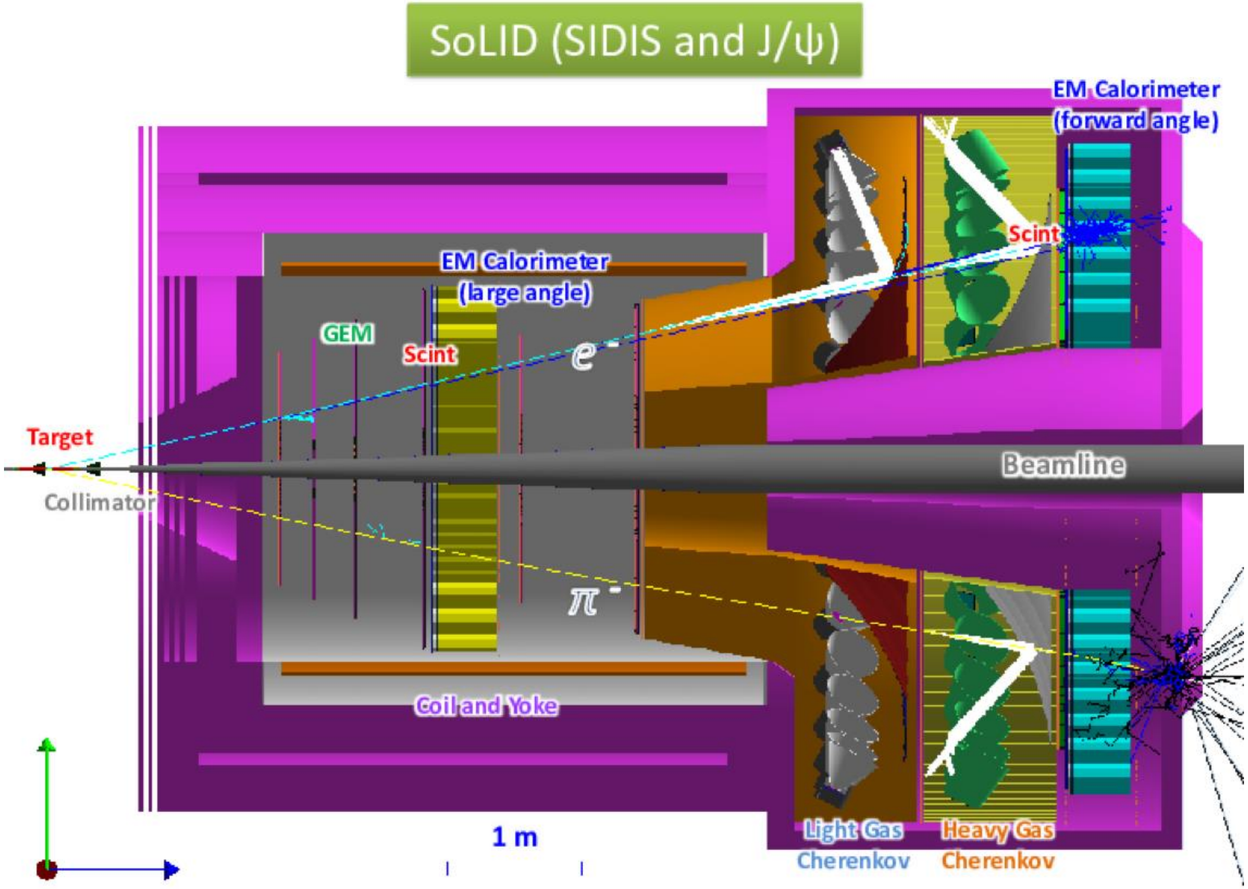
Tensor polarized TMDs may have surprising features

Courtesy of Ian Cloët

Experimental Measurements

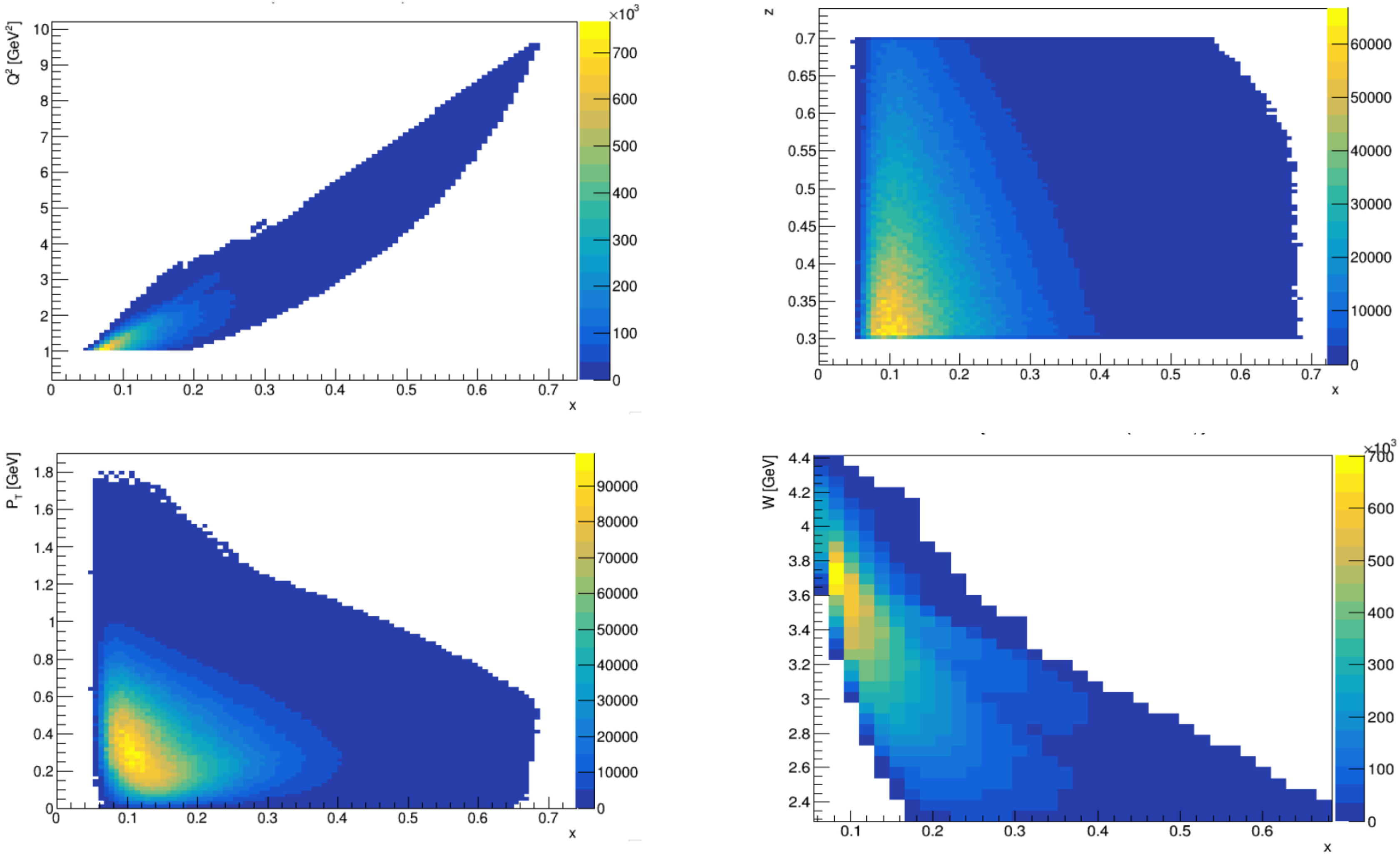
Step 3:
Future program at SoliD

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



Unpolarized rates for π^-

1 week of running



Assuming:

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

Our path for the Spin-1 SIDIS program

Exploratory Measurement CLAS12 → Dedicated Measurement Hall C → Full Program SOLID

- Exploratory measurement Use Hall B data (Run group C ~ 12% tensor polarization) to estimate the rates and possible sensitivity to structure functions shape/structure.
- Dedicated 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!