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

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On behalf of the SIDIS-Tensor collaboration

QCD Evolution Workshop

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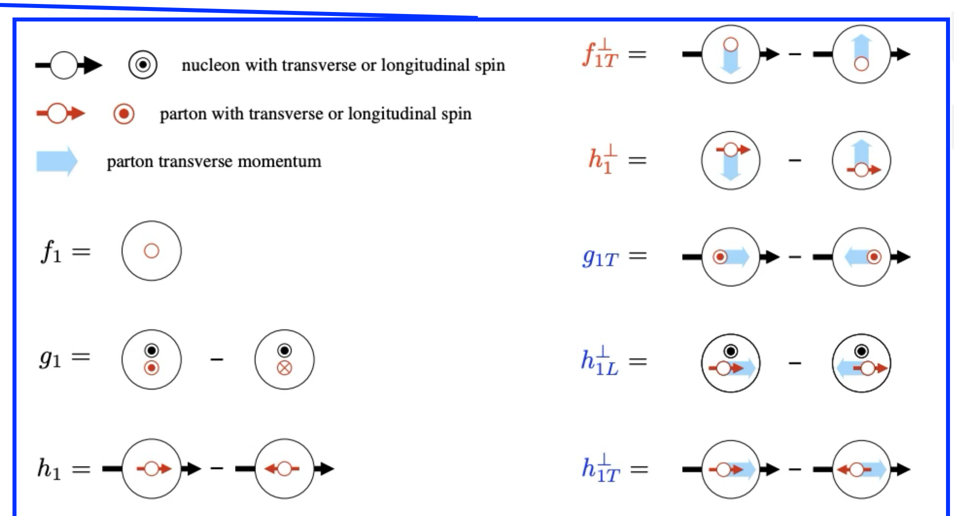
University of New Hampshire

Today’s talk

- Spin-1 TMDs
- Tensor SIDIS with a longitudinal polarized target
- Tensor SIDIS measurements at JLAb with a longitudinal polarized target.
- Status of the tensor target

Spin-½: 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}		$[h_1], [h_{1T}^\perp]$	



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					$[h_1]$	

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

Spin-1

Theory developments

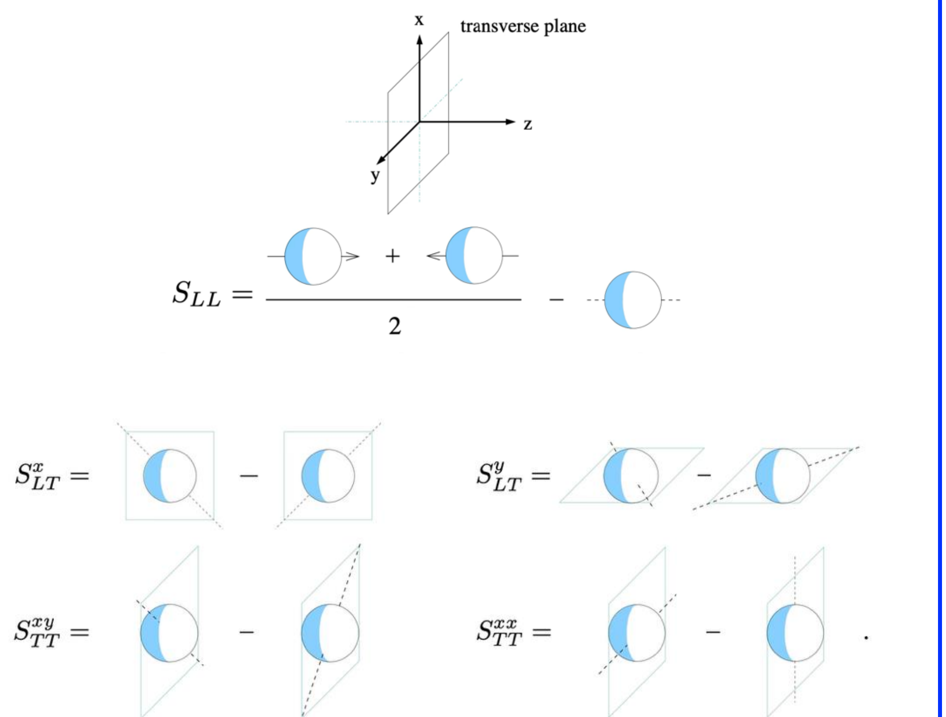
- Leading twist (thesis): arXiv:hep-ph/0212025
- Leading twist: Phys. Rev. D 62 (2000)
- Polarized deuteron DIS with spectator tagging: Phys. Rev. C 102, 065204 (2020)
- Up to twist 4: Phys. Rev. D 103 (2021)
- Formalism and covariant calculations: Phys. Rev. C 96, no.4, 045206 (2017)

Spin-1: Leading twist distribution functions

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						



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

After integration upon p_T

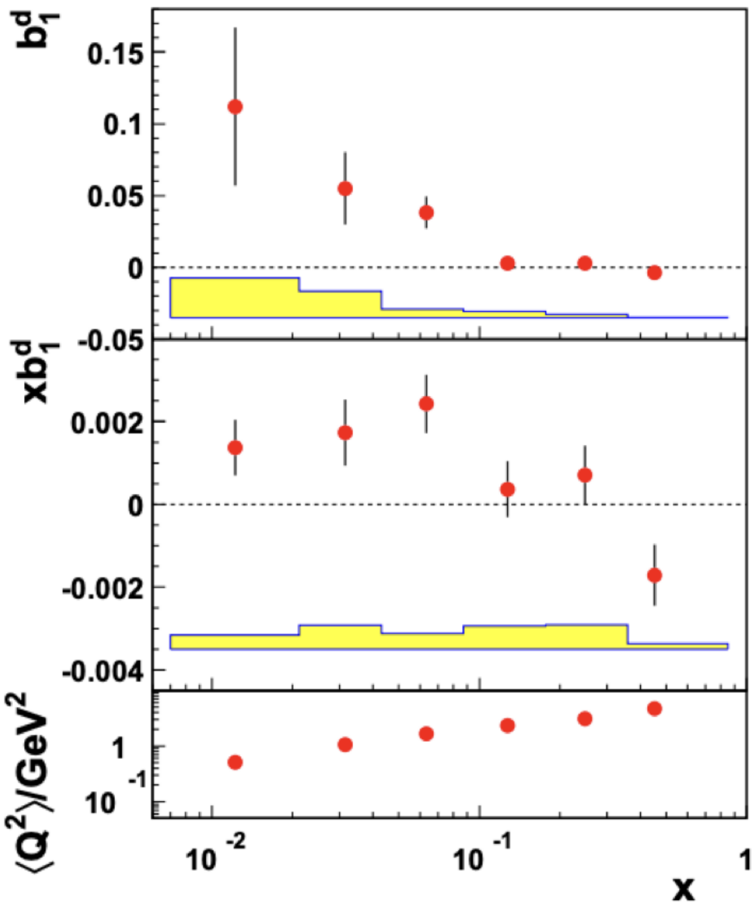
Quark / Hadron	$U(\gamma^+)$		$L(\gamma^+\gamma_5)$		$T(i\sigma^{i+}\gamma_5/\sigma^{i+})$	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					
L			$g_{1L}(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}(b_1)$					
LT						*1
TT						

•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**, 114004 (2000)

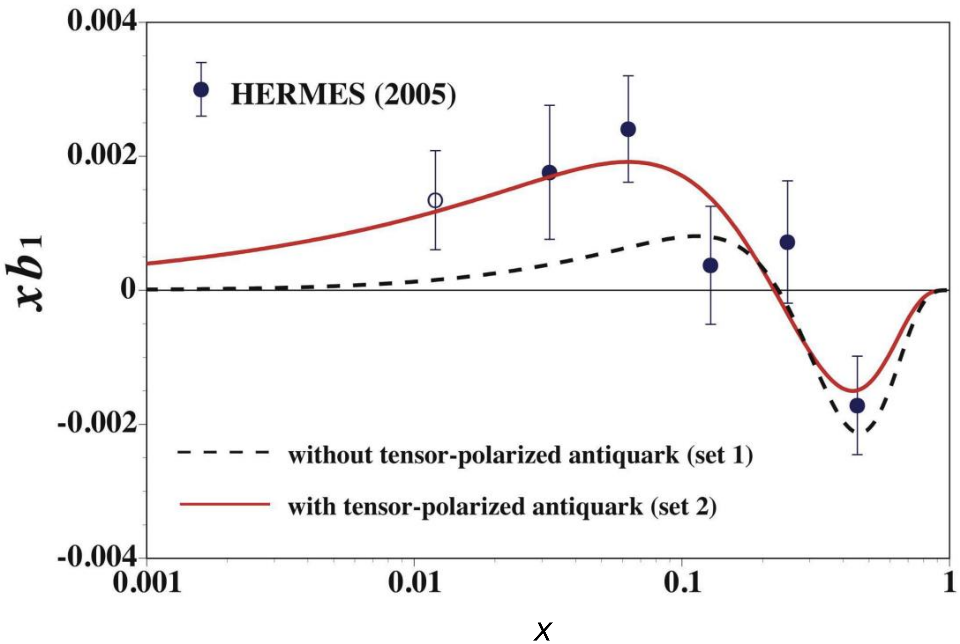
HERMES Experiment: First Measurement of b_1

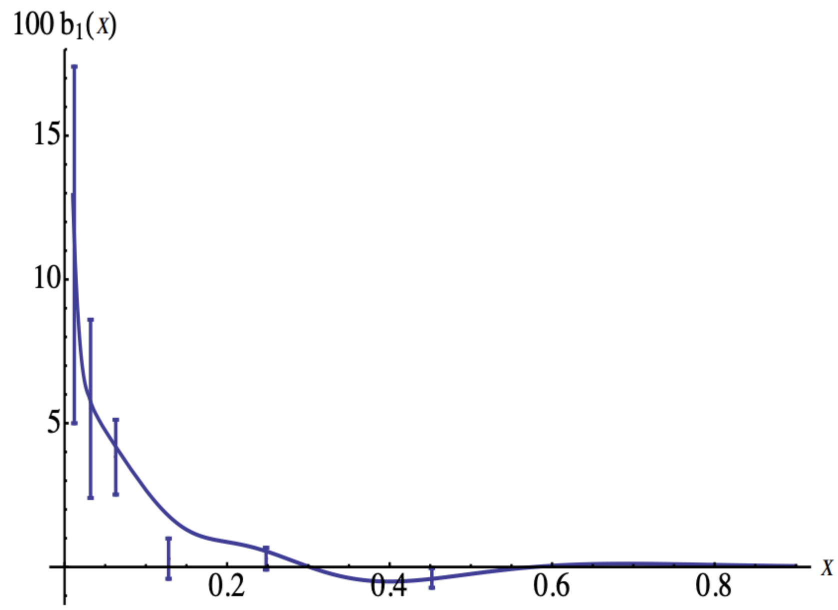


- 27.6 GeV/c positron beam of Hera
- 0.5 GeV^2/c^2 < Q^2 < 5 GeV^2/c^2
- 0.01 < x < 0.45
- Positrons in the momentum range of 2.5 GeV /c to 27 GeV/c
- The average target vector $\mathcal{P}$ and tensor $\mathcal{Q}$ polarizations are typically more than 80%
- Polarized gas target (integrated luminosity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

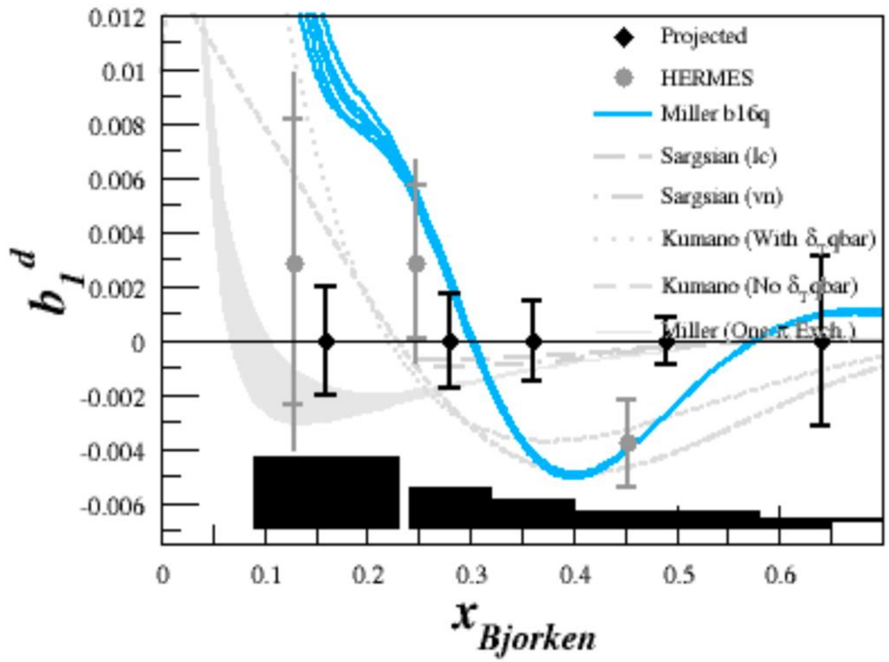
Phys. Rev. D 82, 017501 (2010)

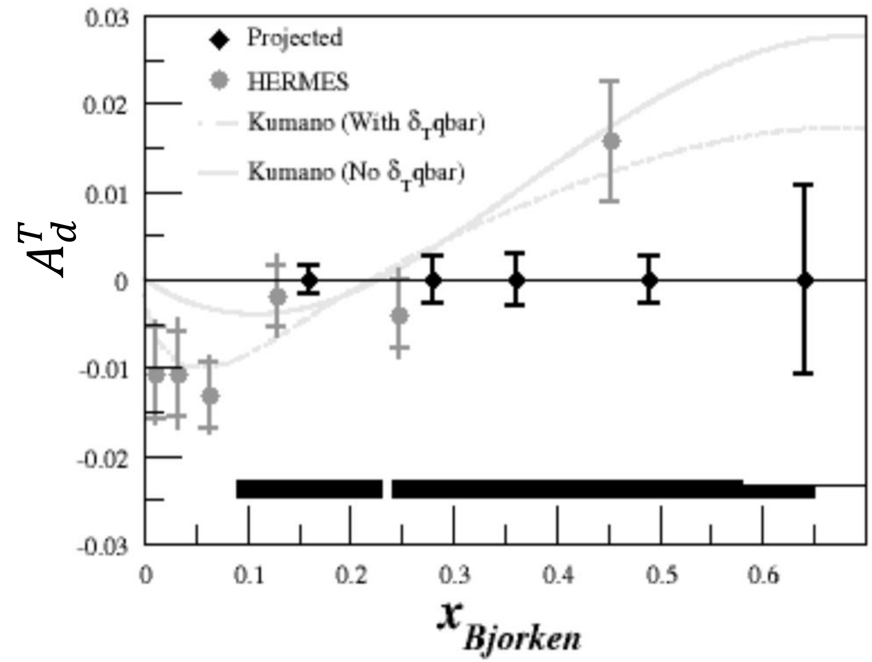
Hidden-color model: six-quark configurations (with ~ 0.15% probability to exist in the deuteron) proposed and found to give substantial contributions for values of $x > 0.2$.

Phys. Rev. C 89, 045203 (2014)

E12-13-011Approved Experiment at Jefferson Lab

Inclusive Measurement





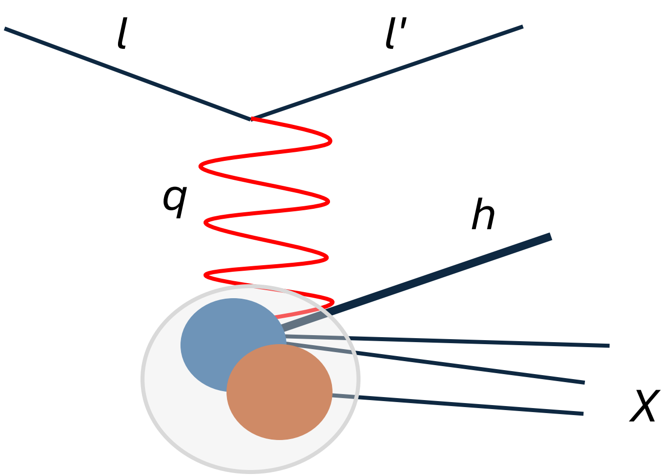
0.16 < x < 0.49

0.8 5 GeV²/c² < Q^2 < 5.0 5 GeV²/c²

Incident beam (electrons): E= 11 GeV

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

Semi-Inclusive Deep Inelastic Scattering



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

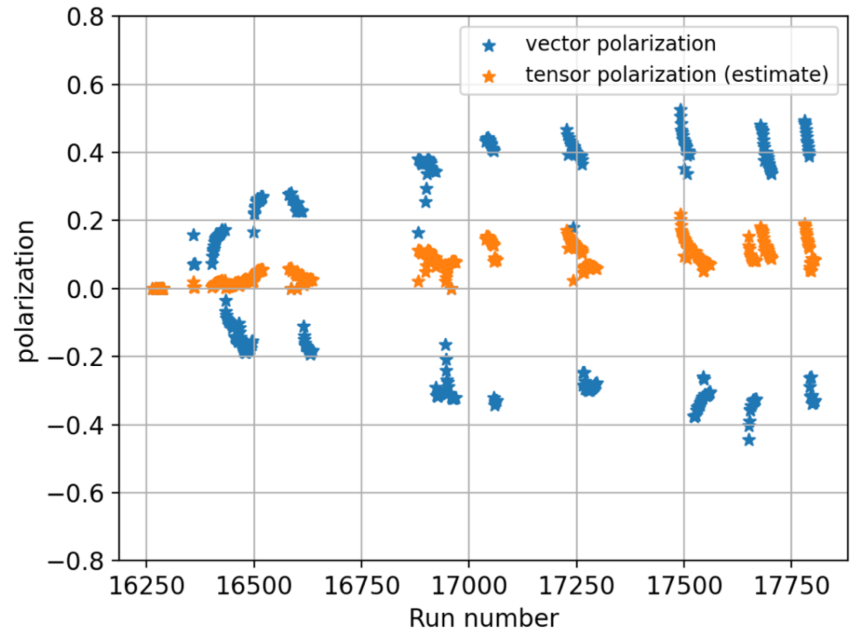
Eur. Phys. J. A (2025) **61**: 81

Experimental Measurements

Step 1: Exploratory measurement with CLAS12 data

Run Group C at CLAS12:

- 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

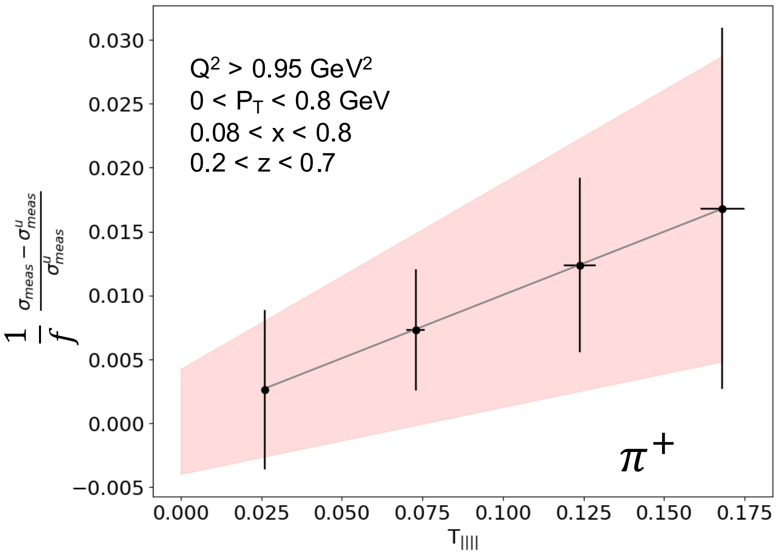
$$\sigma_{meas}^{total} = \sigma_u^D + \mathcal{P}\sigma_v + \mathcal{Q}\sigma_T + \sum \sigma_i$$

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

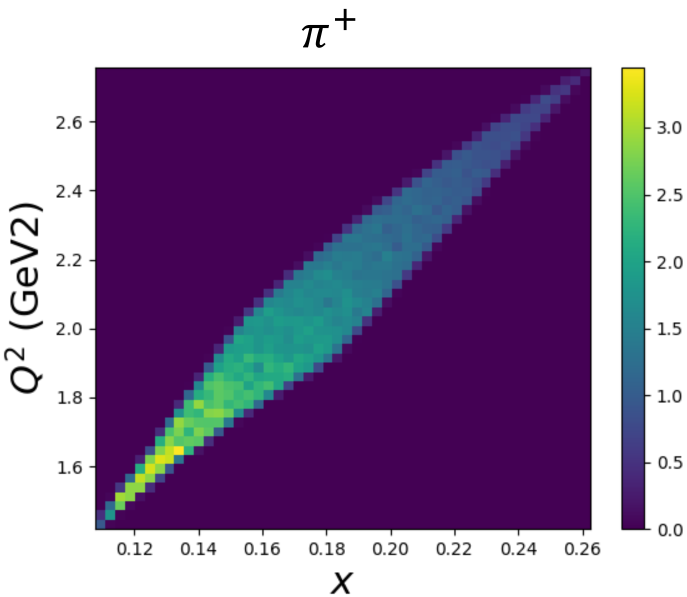


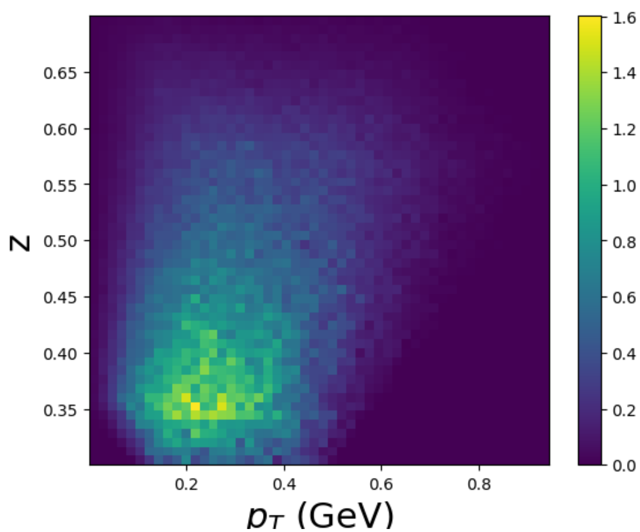
- This measurement will help to understand the tensor contribution.
- Currently assuming 10% of the unpolarized contribution as the inclusive measurement.
- Our predictions imply a 60% uncertainty.
- **Crucial to propose new experiments.**

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

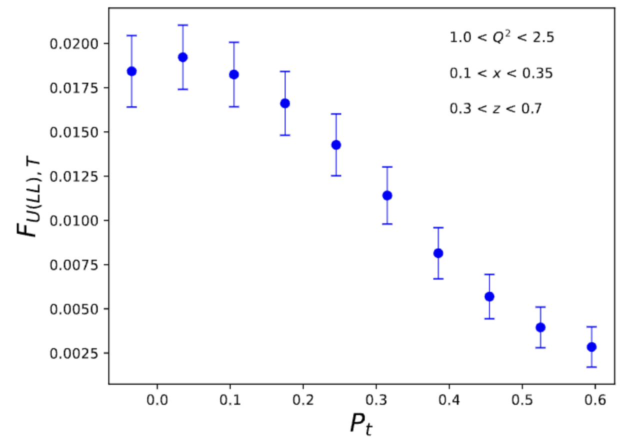
Experimental Measurements

Step 2: Dedicated measurement with CLAS12 data





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

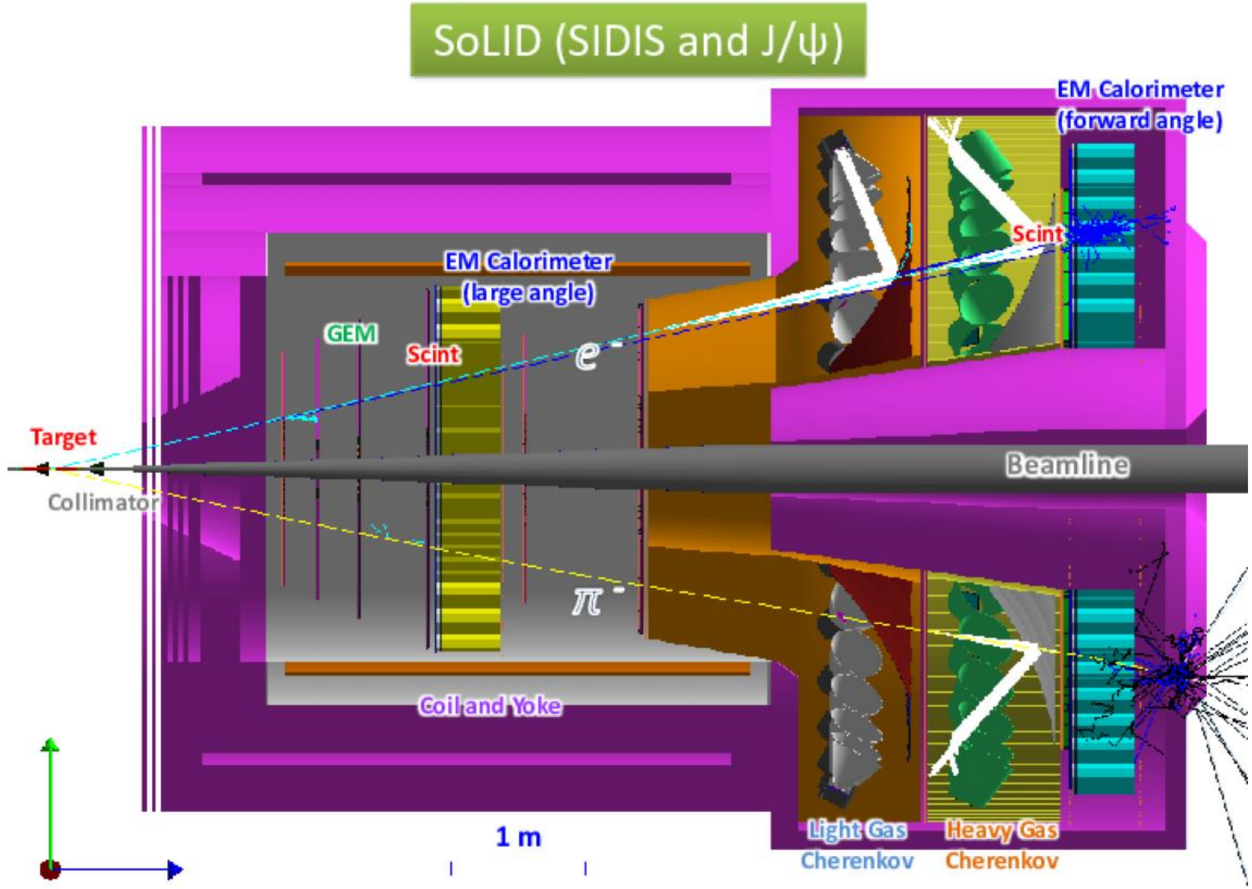
The kinematic ranges assumed for the chosen momentum setting in SHMS (electron) and SBS (hadron)

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

Experimental Measurements

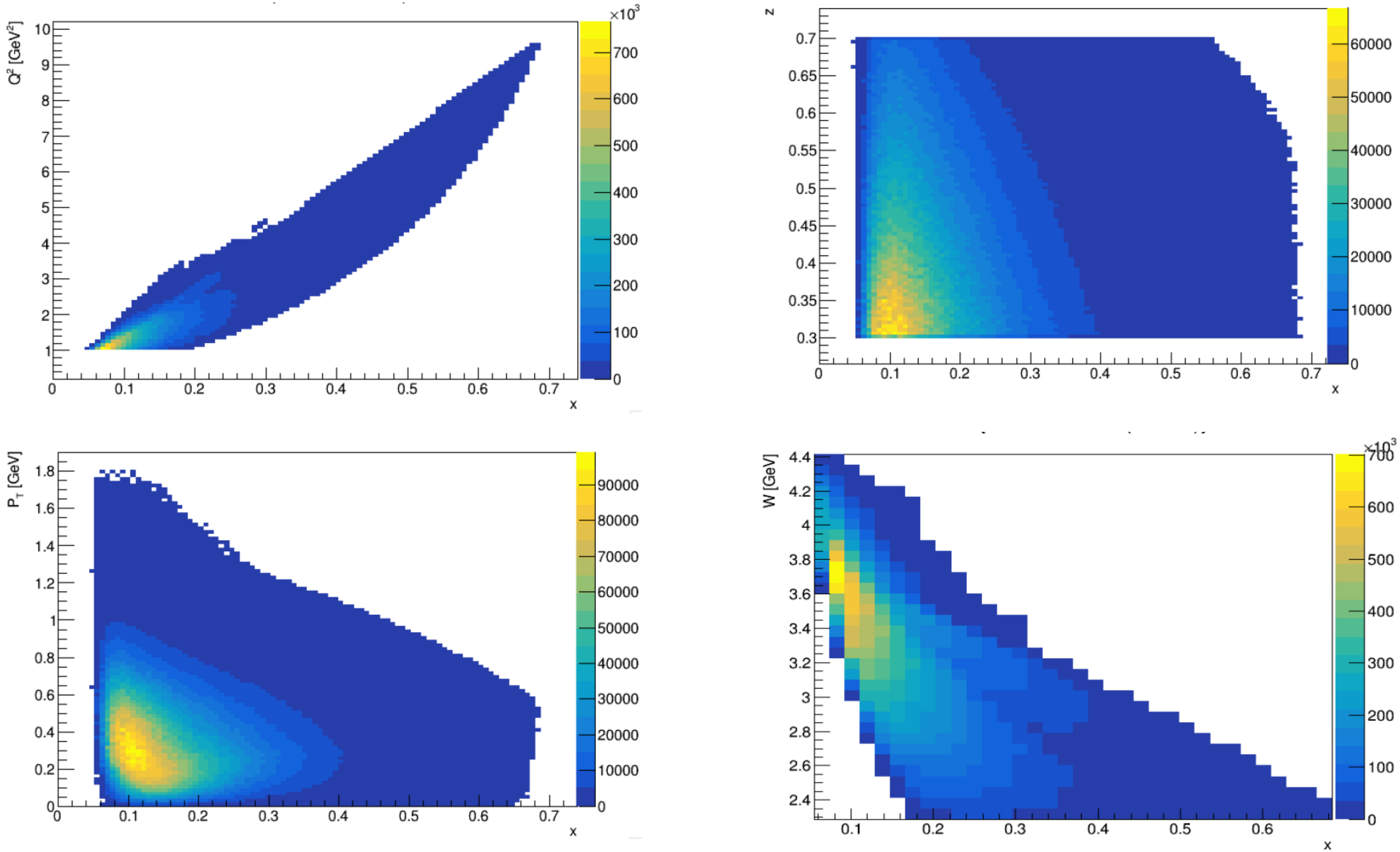
Step 3: Future program at SoLID

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



Unpolarized rates for π^-

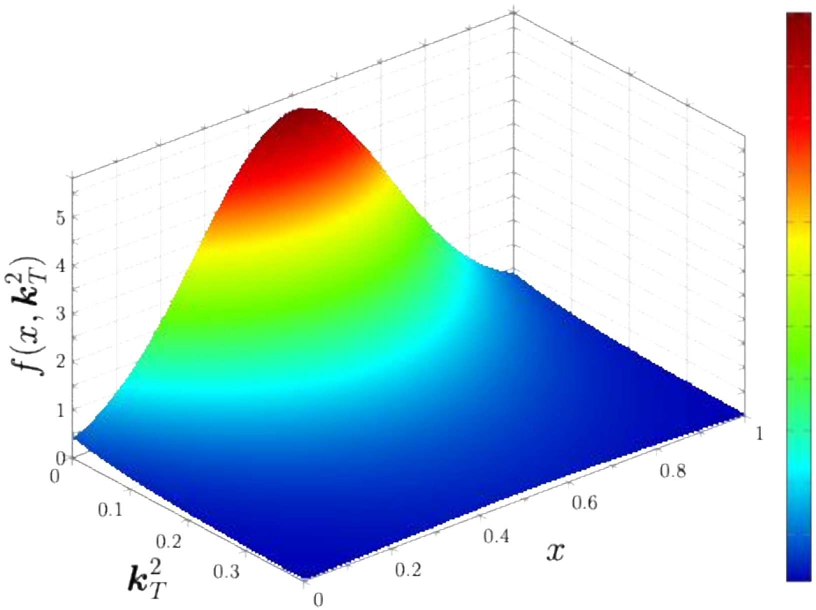
1 week of running

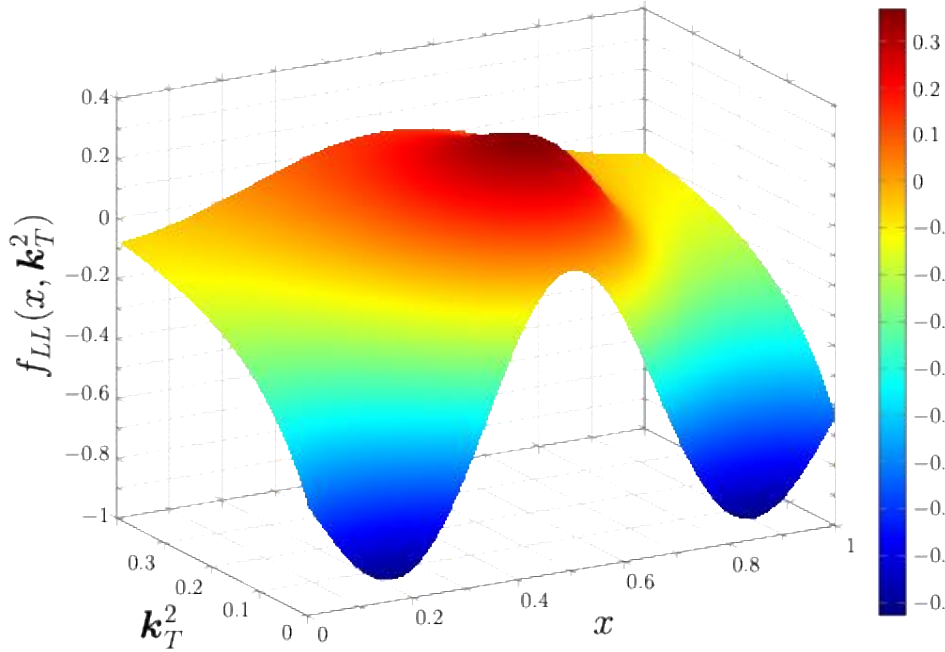


Assuming:

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

Currently incorporating covariant calculations





Spin-one ρ particle
Next: Deuteron

Tensor polarized TMDs may have surprising features

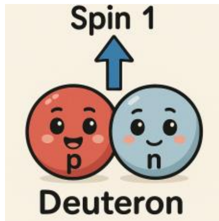
Courtesy of Ian Cloët

Our path for the Spin-1 SIDIS program

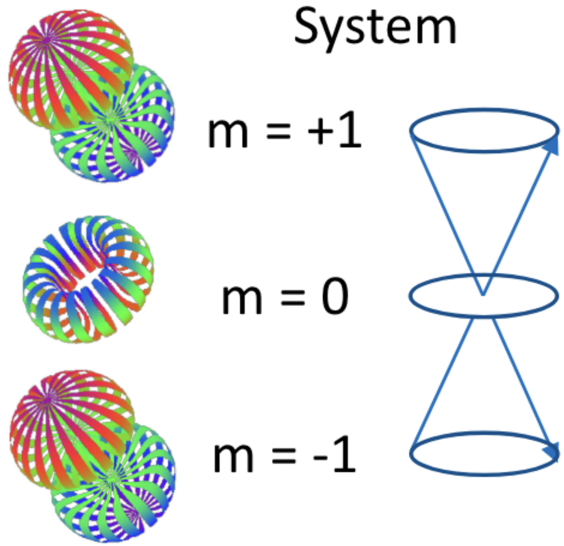
•Exploratory measurement Use Hall B data (Run group C ~ 12% tensor polarization) to estimate the rates and possible sensitivity to structure functions shape/structure.
•Dedicated measurement: Propose a run in the short term (probably around the time of the already approved tensor experiments) to map 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

Status of the polarized target

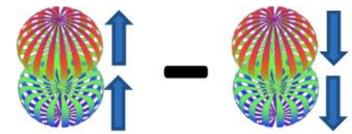


Spin-1
System



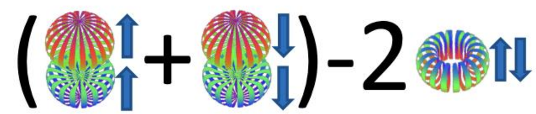
Deuteron in a magnetic field

Vector Polarization:



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

Tensor Polarization:



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

N(m): population density

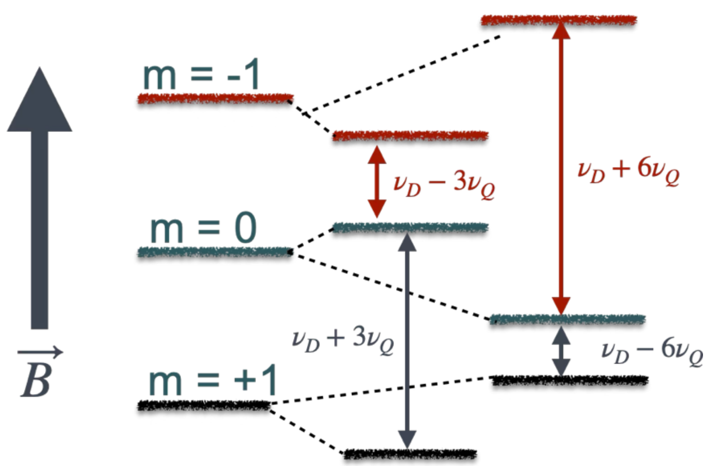
$$N(+1) + N(-1) + N(0) = 1$$

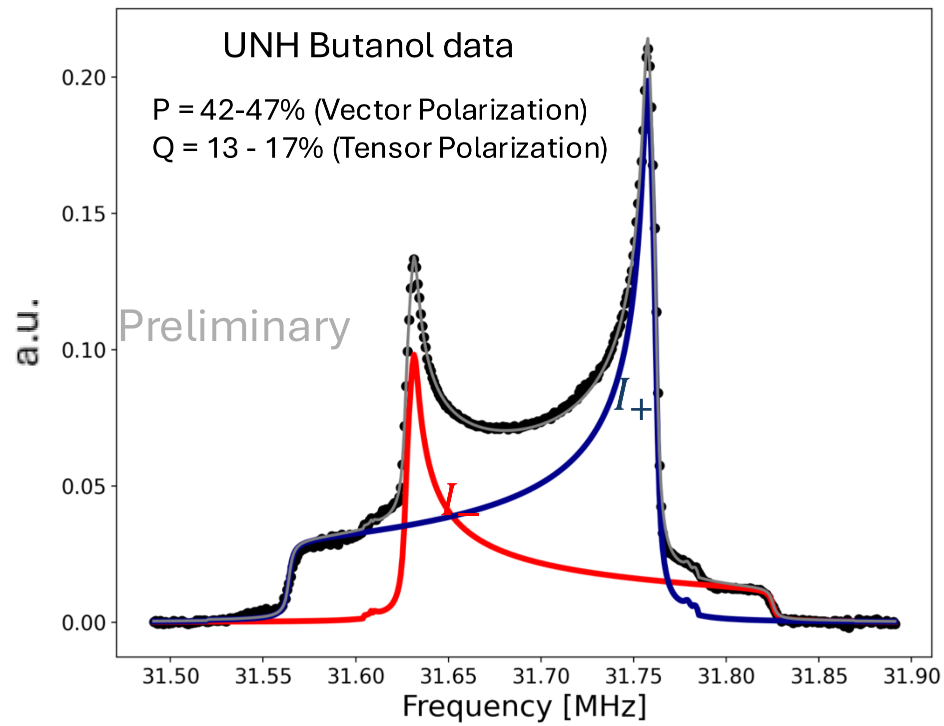
Normalization

Deuteron Polarization

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

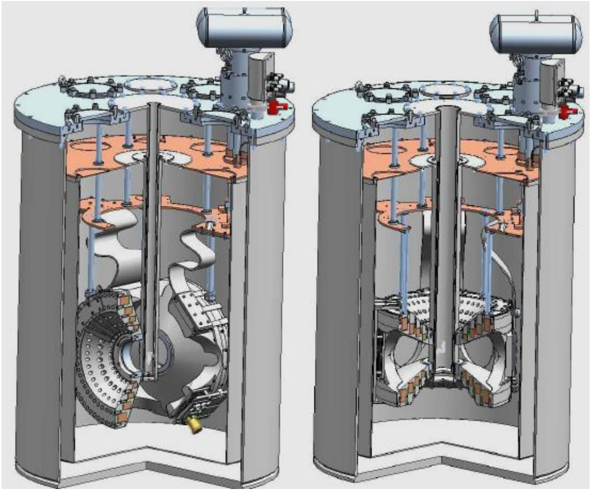
eQ: Electric quadrupole interaction (shifts the energy levels)
eq: Electric field gradient
θ: angle between eq and eQ
υ_D: deuteron Larmor frequency





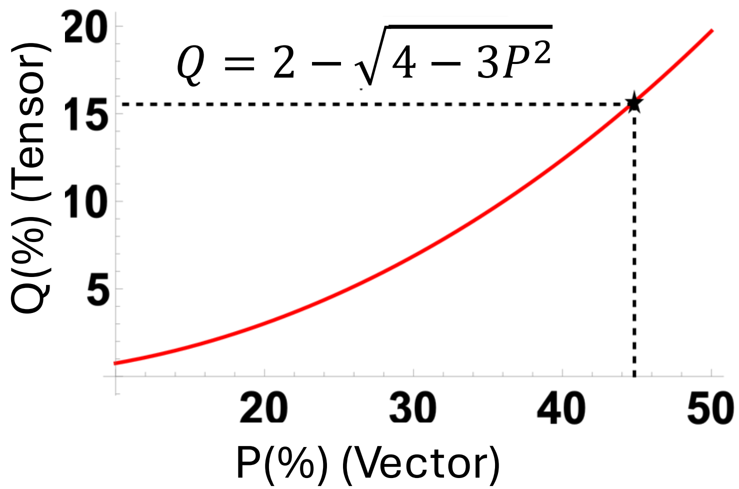
Enhancing Vector polarization: DNP Technique

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



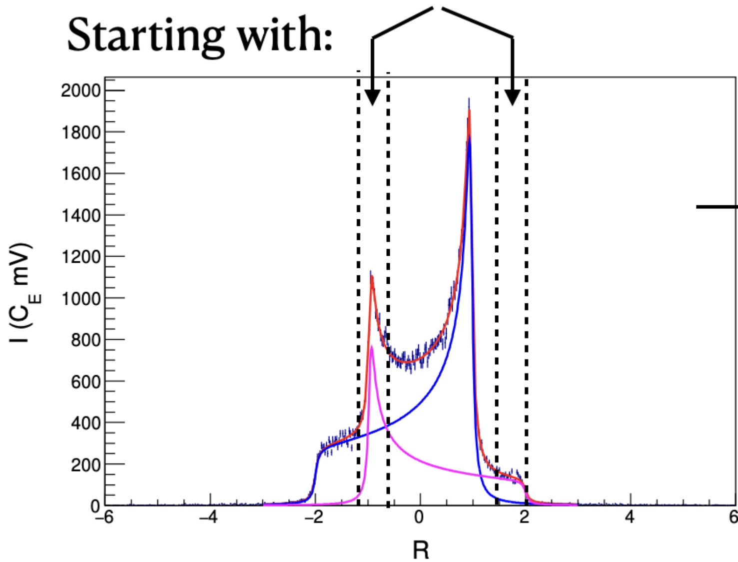
DNP enhancement carries tensor polarization enhancement.

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

Enhancing tensor polarization

Semi-selective RF

Starting with:

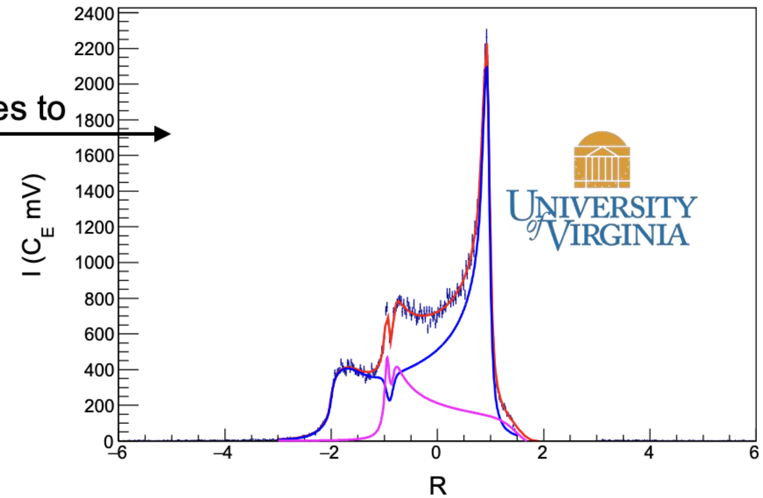


DNP polarized enhanced signal

Q = 19%

goes to

Tensor enhanced signal:

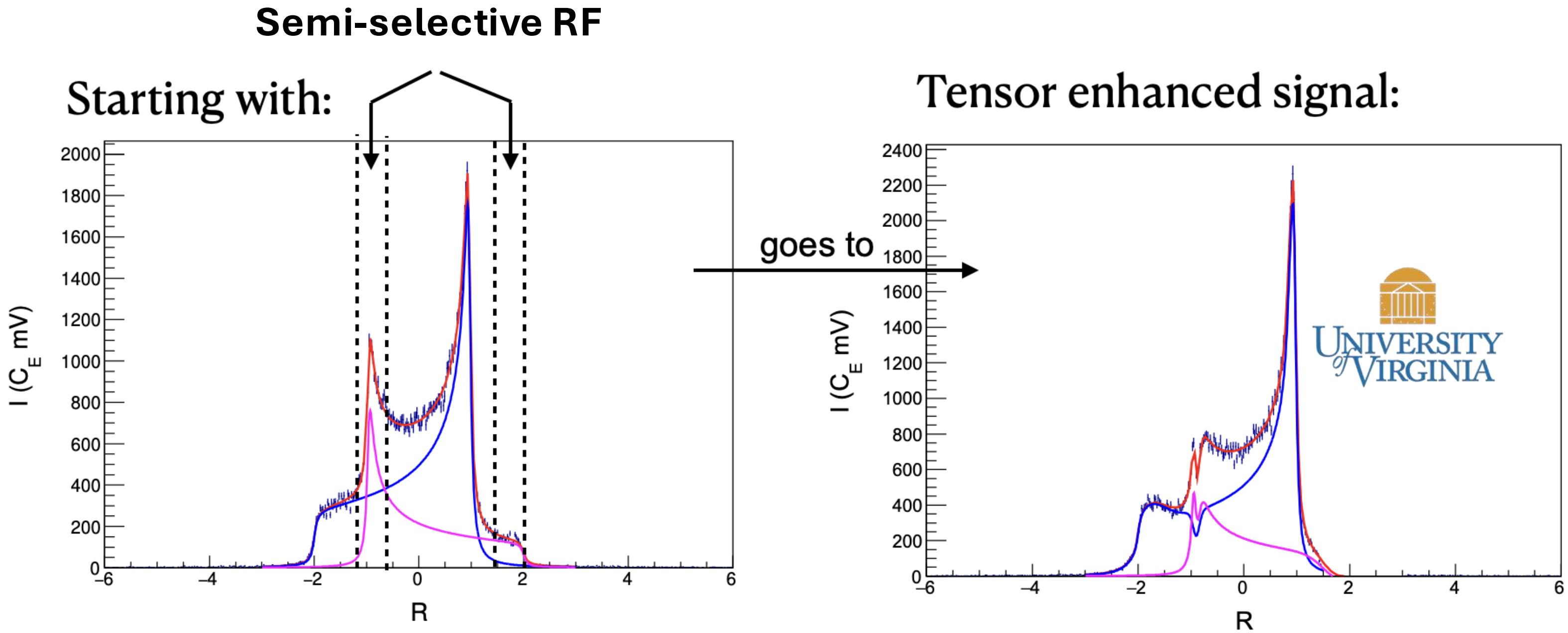


ss-RF enhanced signal

Q = 28.8%

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

Enhancing tensor polarization



DNP polarized enhanced signal

Q = 19%

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.

Unlocking Spin-1 Structure: Key Questions & Future Directions

- How can we extract/interpret TMDs from the experiment?
  - How spin-1 will be different from spin-1/2?
  - What is QCD Evolution of Spin-1 TMDs?
  - What role do higher-twist or higher-order corrections play in the TMD description of the deuteron?

Join our efforts!

Thank you!