Deuteron Tensor Structure

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The 12th Workshop on Hadron Physics and Opportunities Worldwide

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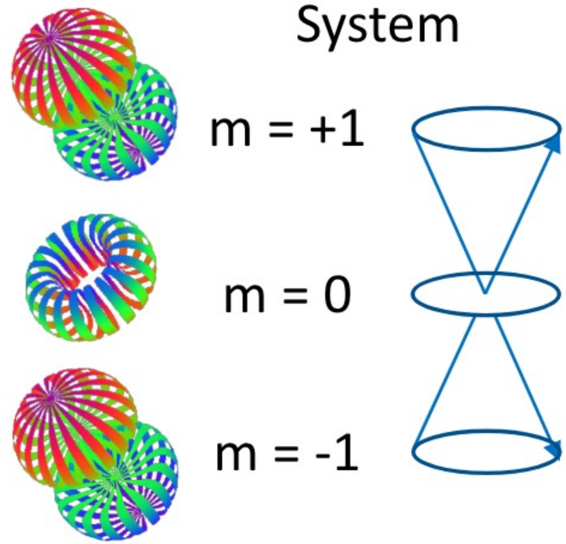
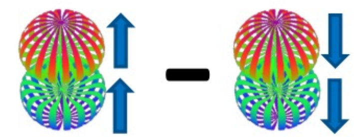
Spin-1 System



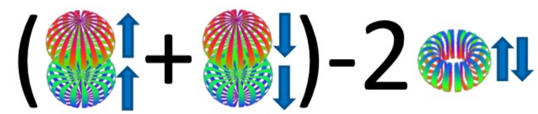
Deuteron in a magnetic field

Vector Polarization:



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

Tensor Polarization:



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

N(m): population density

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

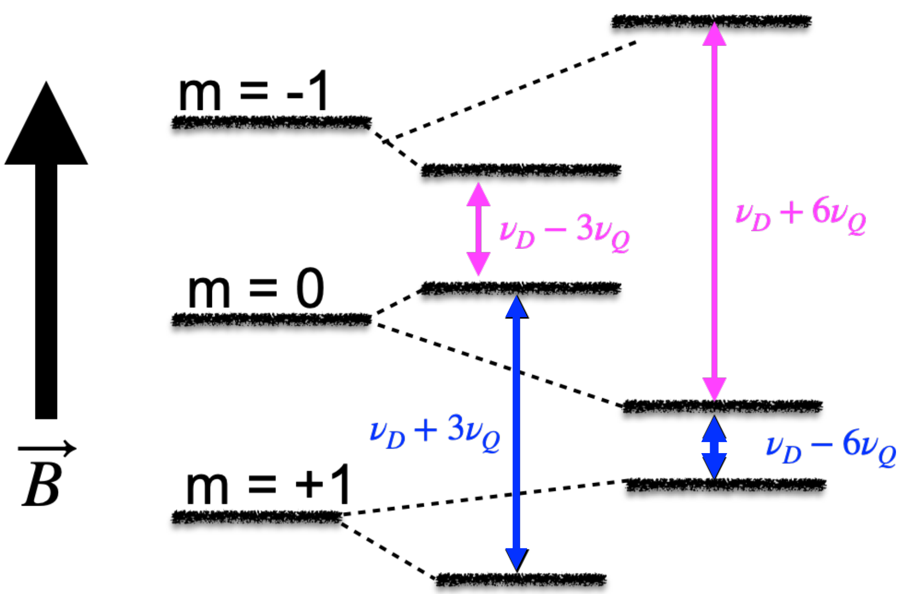
Normalization

Deuteron Polarization

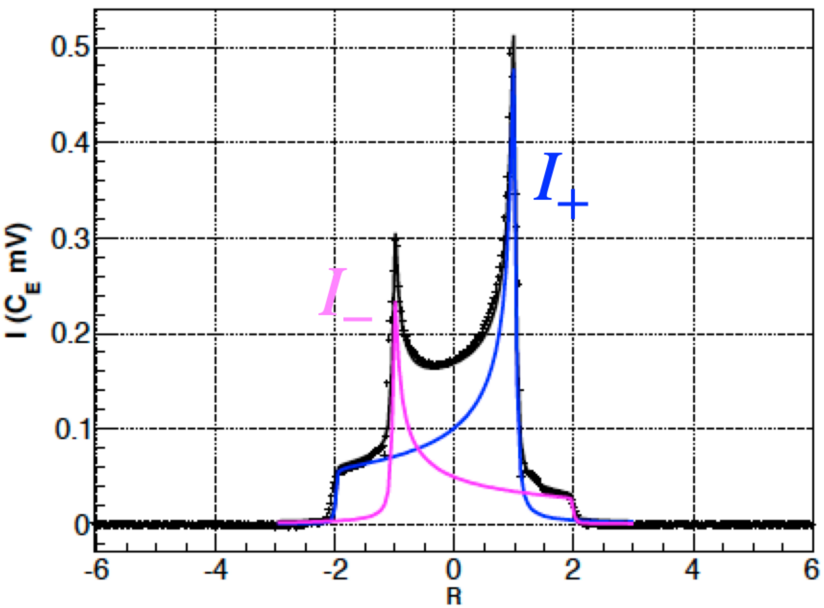
$$E_m = -h\nu_D m + h\nu_Q(\cos^2\theta - 1)(3m^2 - 2)$$

eQ : Electric Quadrupole interaction shifts energy levels
eq : Electric field gradient
θ : angle between *eq* and *B*

$\nu_Q = \frac{e^2qQ}{8h}$: Quadrupole Frequency



Deuteron NMR Line-shape.

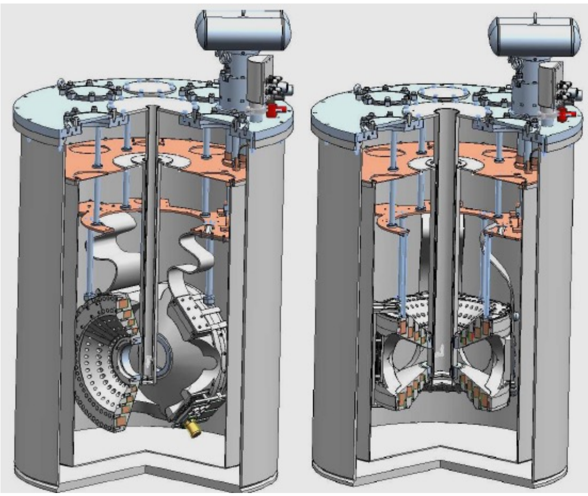


$$R = \frac{\nu - \nu_D}{3\nu_Q}$$

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

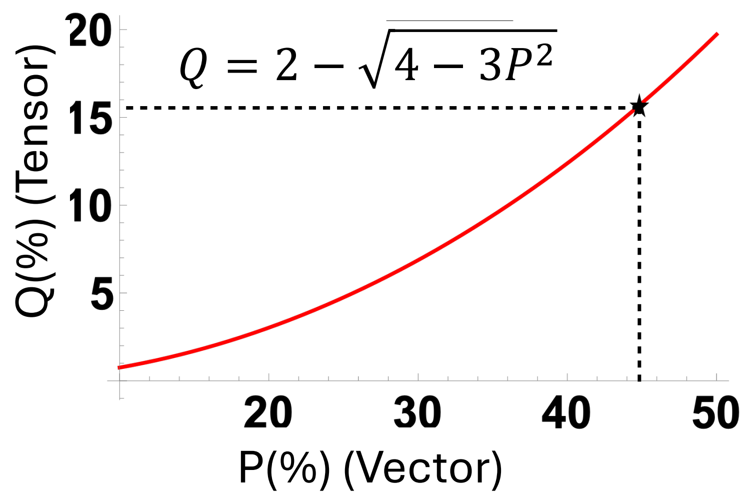
DNP Technique

Dynamic Nuclear Polarization: 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.

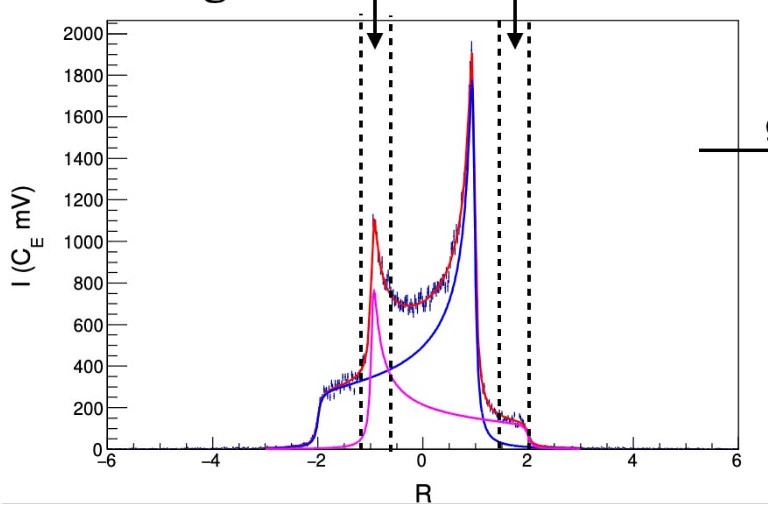
★ Typical average vector polarization in Jefferson lab $P \sim 45\%$ which corresponds to $Q \sim 16\%$

Enhancing tensor polarization

Semi-selective

RF

Starting with:

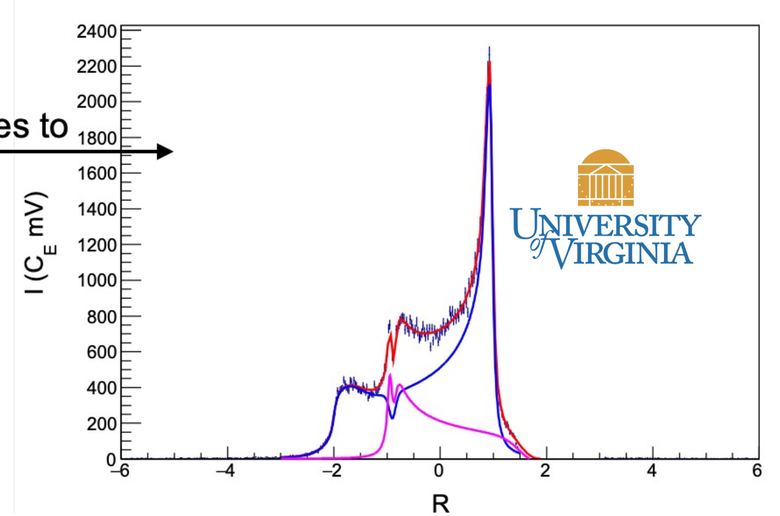


DNP polarized enhanced signal

Q = 19%

goes to

Tensor enhanced signal:



ss-RF enhanced signal

Q = 28.8%

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

- 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.

Quasi-elastic Measurements

Scattering from an unpolarized deuteron target

$$\rho_{unp}(p_m) = u(p_m)^2 + w(p_m)^2$$

$u(p_m)$: S-partial wave of the deuteron
$w(p_m)$: D-partial wave of the deuteron

Scattering from tensor polarized target

$$\rho_{20}(p_m, \theta_N) = \frac{2cos^2(\theta_N) - 1}{2}\left[2\sqrt{2}u(p_m)w(p_m) - w^2(p_m)\right]$$

θ_N: direction of internal momenta with respect to the polarization axis of the deuteron

Measured asymmetry

$$A_d^T = A_{20}(p_m, \theta_N) = \frac{\rho_{20}(p_m, \theta_N)}{\rho_{unp}(p_m)}$$

Experimental Measurement

P: target vector polarization
Q: target tensor polarization

A_D^V : vector analyzing power
A_D^T : vector analyzing power

$$\sigma_{pol}(P,Q) \quad = \sigma_{unpol}\left[1 + PA_D^V + \frac{1}{2}QA_D^T\right]$$

$$\sigma_{pol}(-P,Q) = \sigma_{unpol}\left[1 - PA_z + \frac{1}{2}QA_{zz}\right]$$

$$\sigma_{pol}(P,0). \quad = \sigma_{unpol}[1 + PA_z]$$

$$\sigma_{pol}(-P,0) \quad = \sigma_{unpol}[1 - PA_z]$$

$$A_d^T \;= \frac{2}{Q}\left(\frac{\sigma_{pol}(P,Q) + \sigma_{pol}(-P,Q)}{\sigma_{pol}(P,0) + \sigma_{pol}(-P,0)} - 1\right)$$

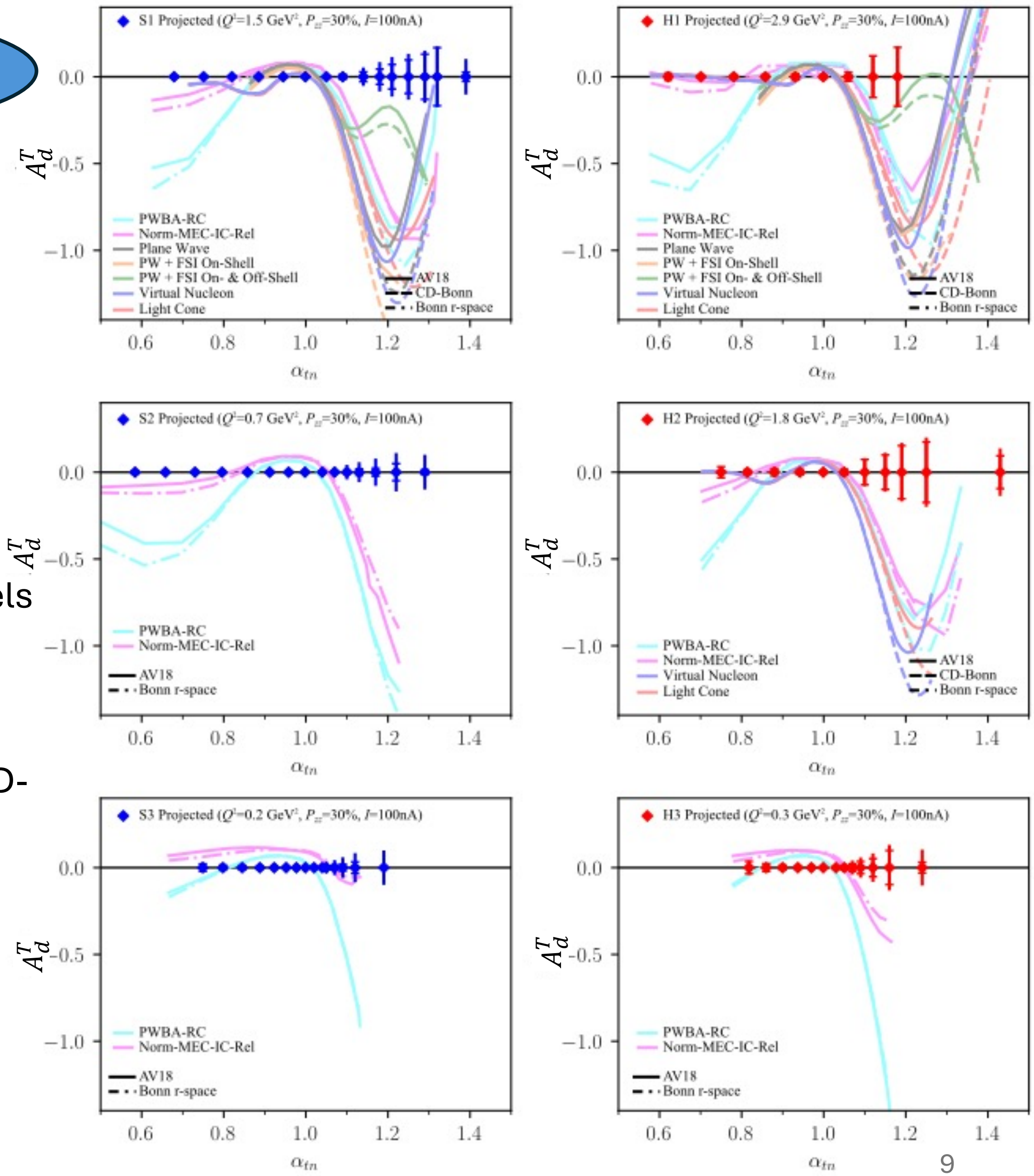
E12-15-006 Approved
Experiment at Jefferson Lab

Inclusive Measurement

First Azz measurement in the QE region.

- Differentiate light cone and VN models [1]
- Probe final state interaction models [2]
- can be used to separate between soft and hard wavefunctions (AV18 and CD-Bonn).

Long, Day, Higinbotham Keller, Santiesteban, Solvignon , Slifer



New Ideas: Exclusive measurement

$$\rho_{node}(p_m) = \rho_{unp}(p_m) + \frac{2\rho_{20}}{3cos^2(\theta_N) - 1} = u^2(p_m) + 2\sqrt{2}u(p_m)w(p_m)$$

We could measure Courtesy of Sargsian (2024)

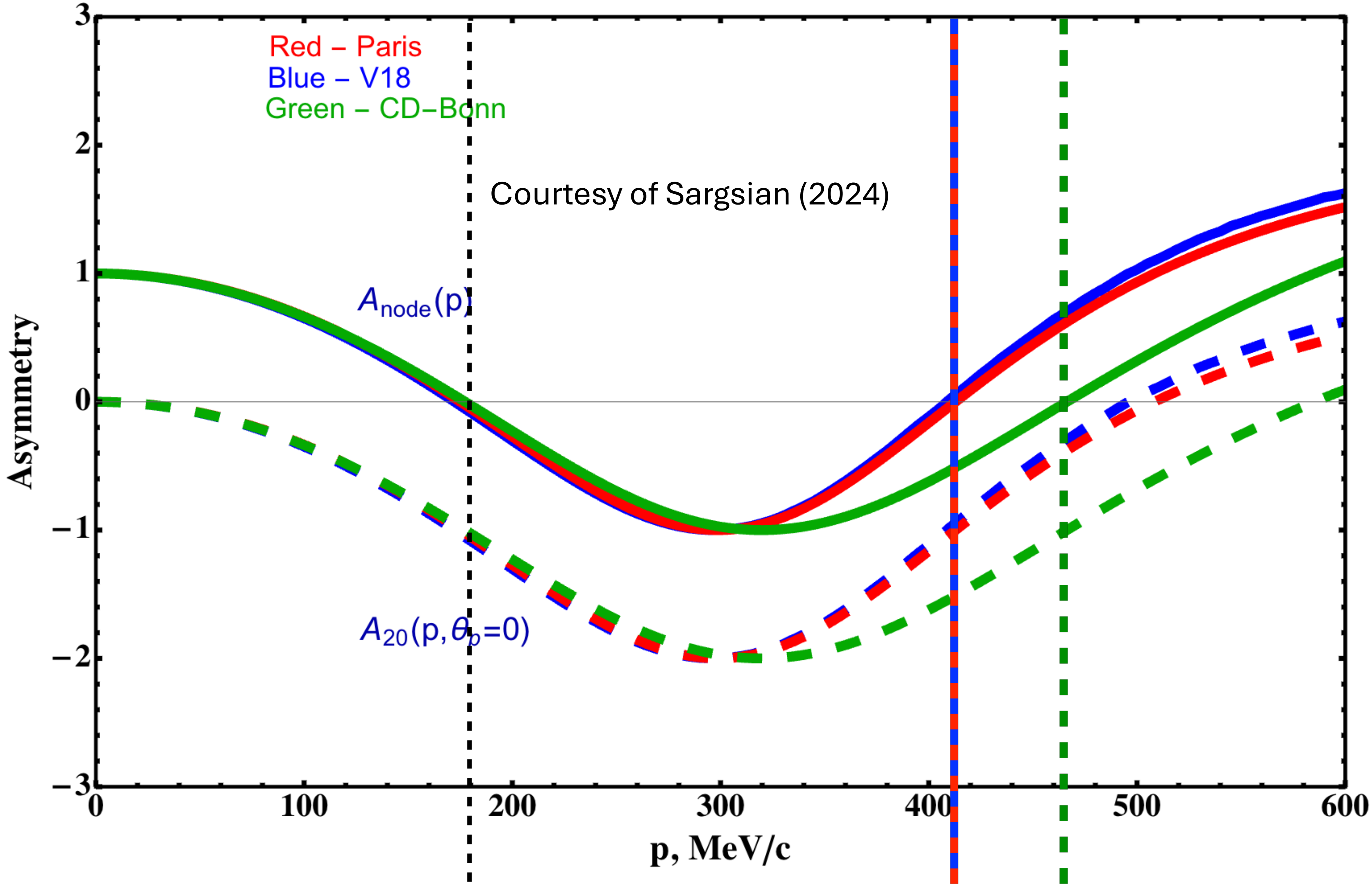
$$A_{node}(p_m) \equiv \frac{\rho_{node}}{\rho_{unp}} = 1 + \frac{2A_{20}(p_m, \theta_N)}{3cos^2(\theta_N) - 1} = \frac{u^2(p_m) + 2\sqrt{2}u(p_m)w(p_m)}{u(p_m)^2 + w(p_m)^2}$$

$$A_{node} = \begin{cases} u(p_m) = -2\sqrt{2}w(p_m) & \mapsto p_m \sim 180MeV \\ u(p_m) = 0 & \mapsto p_m > 400MeV \end{cases} = 0$$

Most direct measurement of the repulsive strength of the nuclear core ever done in electro-nuclear processes.

- has large sensitivity to the position of these nodes
- has sensitivity to the choice of the potential used in calculating the deuteron wave function at $p_m > 300\ MeV$
- measures the contribution of the S-partial wave of the deuteron with respect to the missing momentum

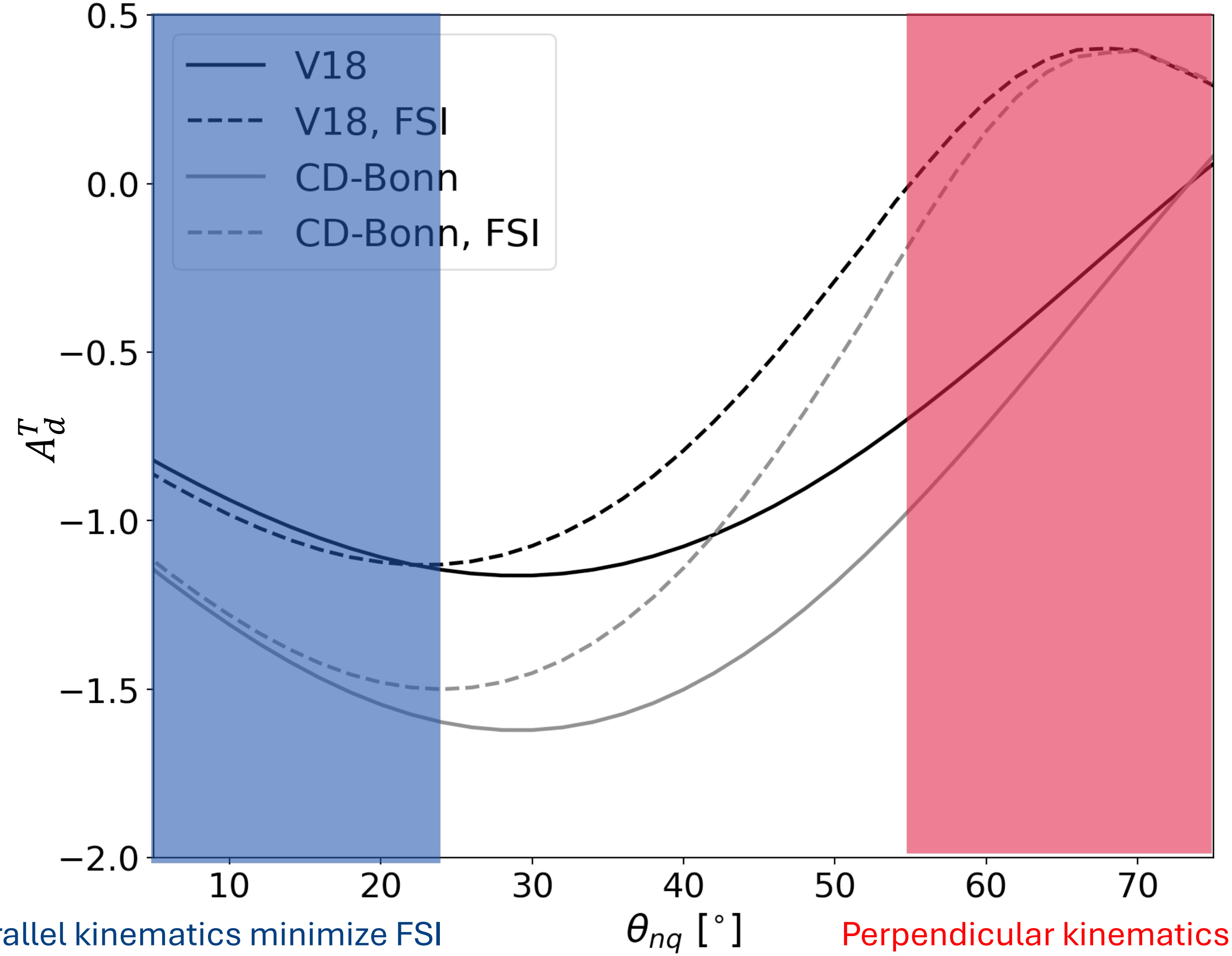
Our observable



$u(p_m) = -2\sqrt{2}w(p_m)$

$u(p_m) = 0$

PWIA vs FSI

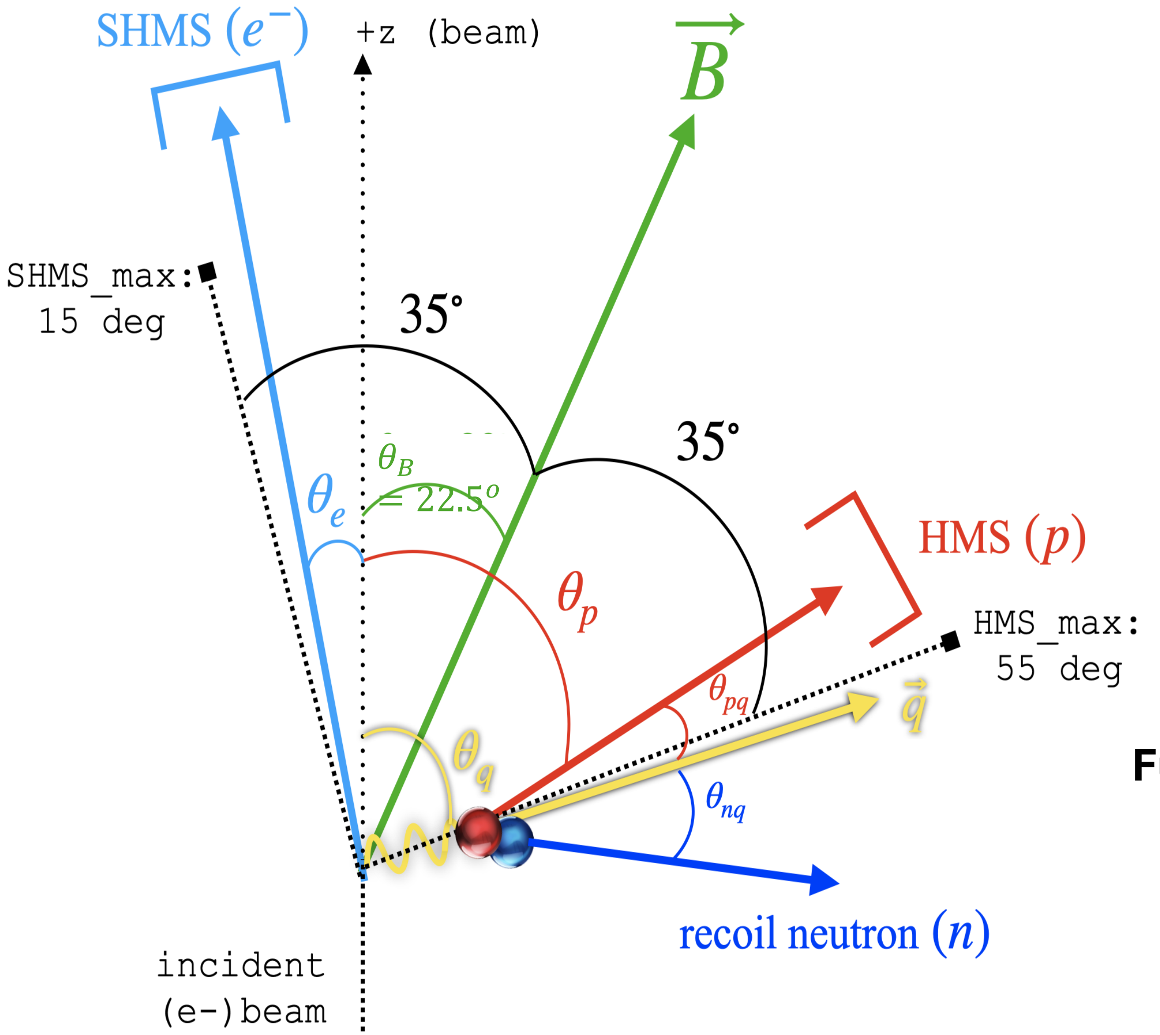


Parallel kinematics minimize FSI
Larger sensitivity to the choice of nucleon potential

Perpendicular kinematics maximize FSI
Larger sensitivity to FSI

θ_{nq}: angle between the virtual photon and the recoiling neutron

Possible Experimental setup at Hall C



Challenge: Find the kinematic region that will allow the measurement in a reasonable amount of time with the target magnet limitations

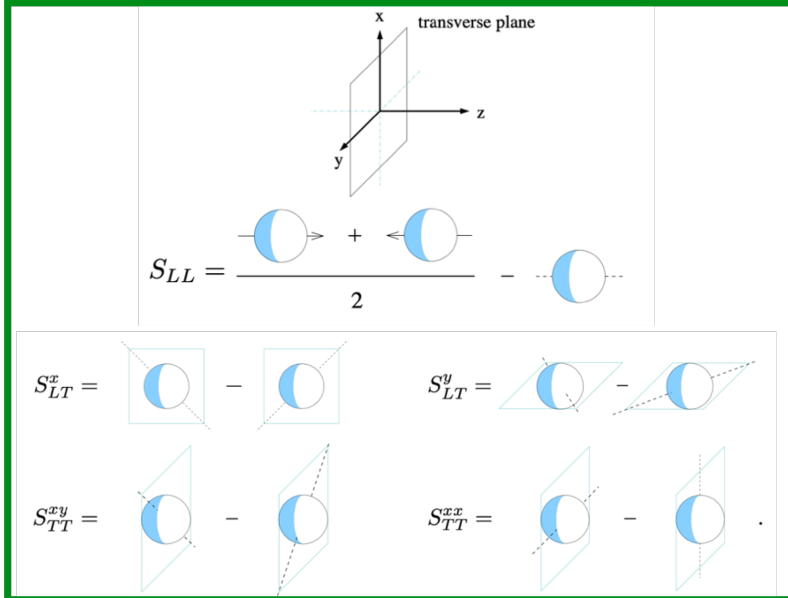
Full proposal: PAC-53, 2025

Santiesteban, Yero, Sargsian, Boeglin, Szumila-Vance, Jones, Fernando, Long

Semi-Inclusive Deep Inelastic Scattering

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 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					$[h_1]$	
LL	$f_{1LL}(b_1)$					
LT						*1
TT						

Phys. Rev. D 62 (2000)

Leading twist distribution functions

Quark / Hadron	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
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}		$[h_{1TT}], [h_{1TT}^\perp]$

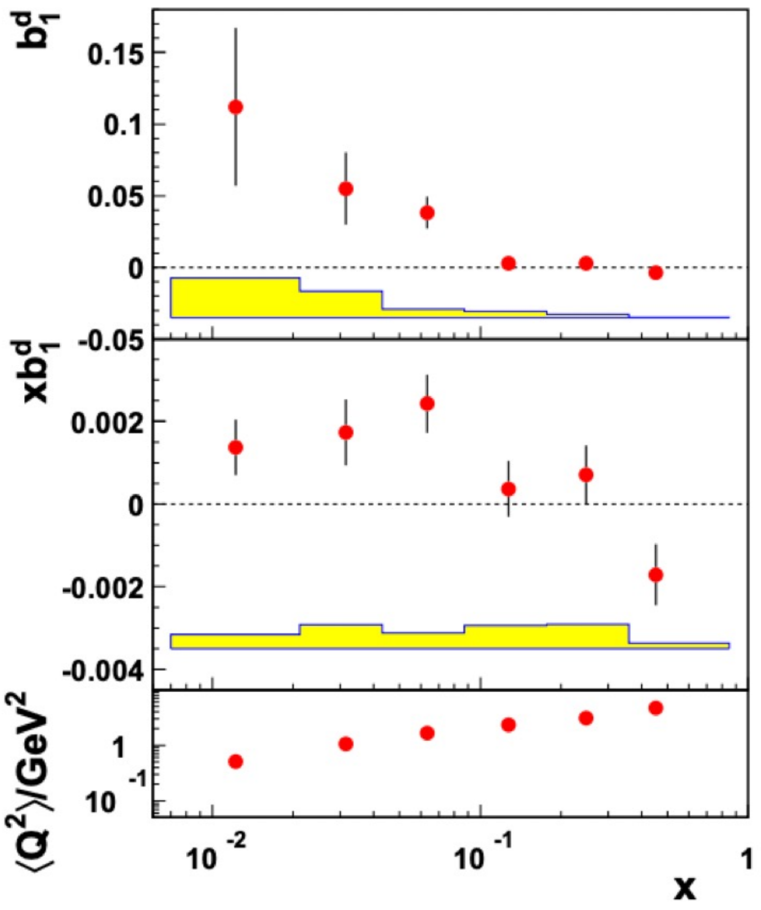
After integrating over the transverse momentum:

Quark / Hadron	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
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.

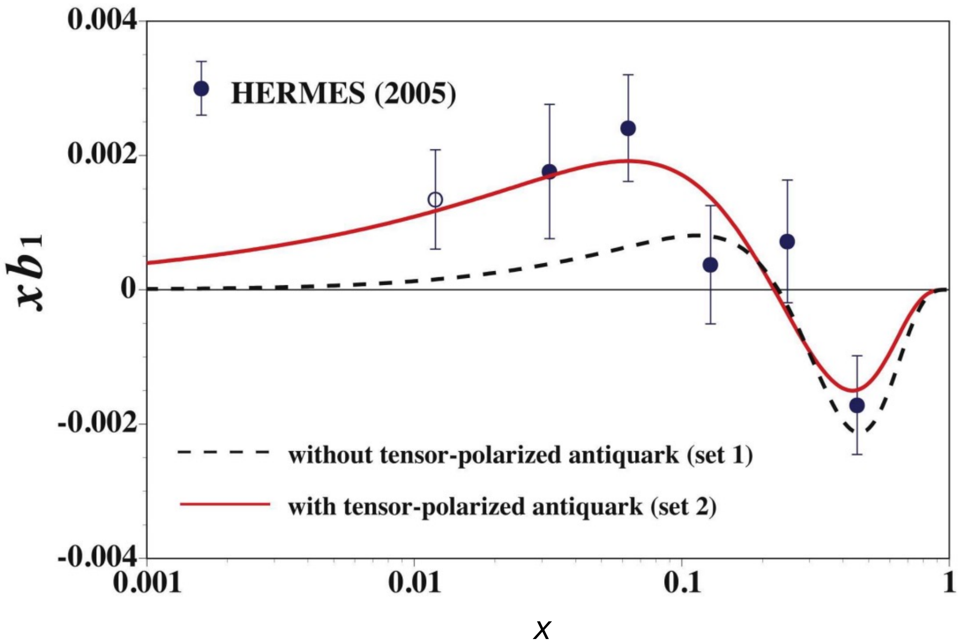
Hermes Experiment: First Measurement of b_1

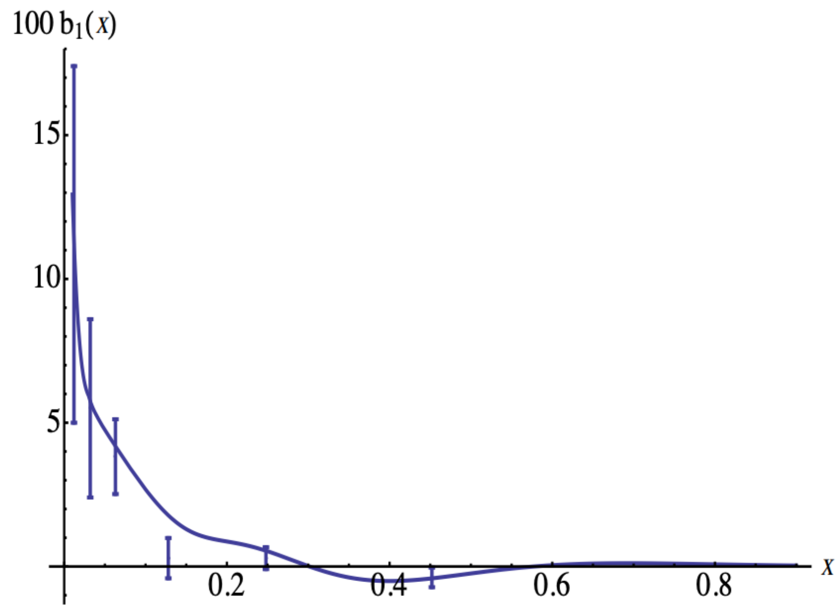


- 0.5 GeV^2 < Q < 5 GeV^2
- 0.01 < x < 0.45
- Positrons in the momentum range of 2.5 GeV to 27 GeV
- The average target vector P and tensor Q polarizations are typically more than 80%
- Polarized gas target (integrated luminosity 42 pb^{-1})
- *The rise of for decreasing values of x can be interpreted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

Phys.Rev.Lett. 95 (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.*

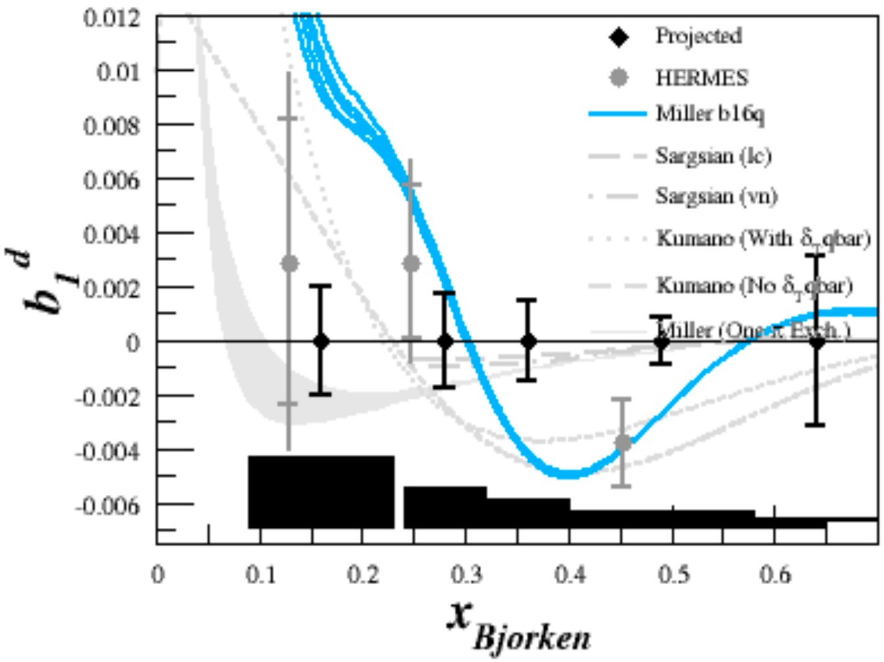
Phys. Rev. D 82, 017501 (2010)

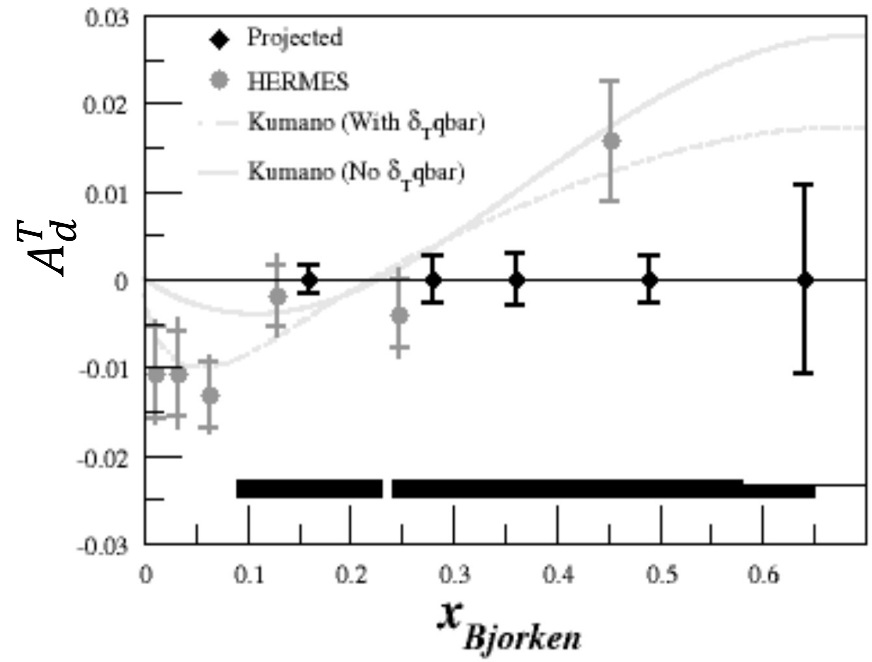
Hidden-color model: six-quark configurations (with ~ 0.15% probability to exist in the deuteron) proposed and found to give substantial contributions for values of $x > 0.2$.

Phys. Rev. C 89, 045203 (2014)

E12-13-011Approved
Experiment at Jefferson Lab

Inclusive Measurement





0.16 < x < 0.49
0.8 < 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)

Explicit cross-sections weren't completely estimated for all processes. A theory effort is currently being done.

Longitudinally polarized target

To be published

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right) & \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
\text{vector} \qquad & + S_{\parallel}\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
& + S_{\parallel}\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
\text{tensor} \qquad & + T_{\parallel\parallel}\Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{U(LL)}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]\Big\}.
\end{aligned}
$$

Courtesy of A. Bacchetta (private communication) 2023.

Tensor-polarized structure functions

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

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

To be published

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

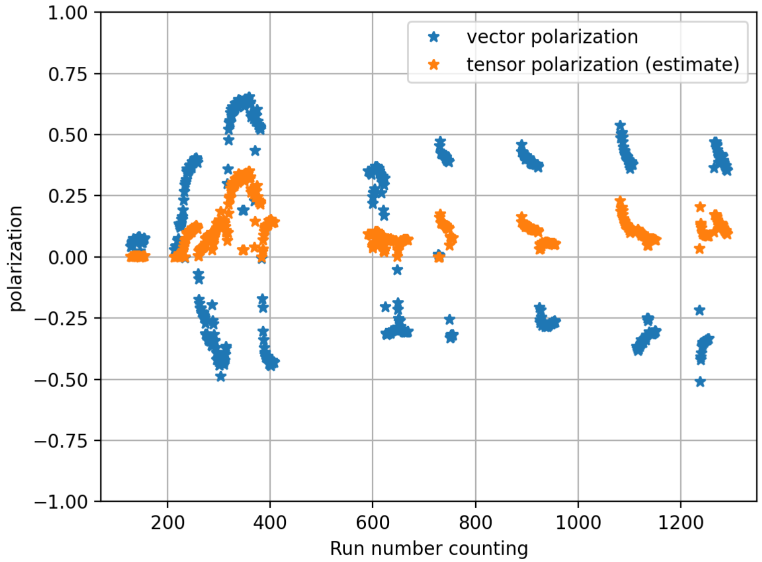
$$F_{U(LL)}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h}\, h_{1LL}^{\perp} H_1^{\perp}\right],$$

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

Spin-1 leading twist

Courtesy of A. Bacchetta (private communication) 2023.

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



Simplified version:

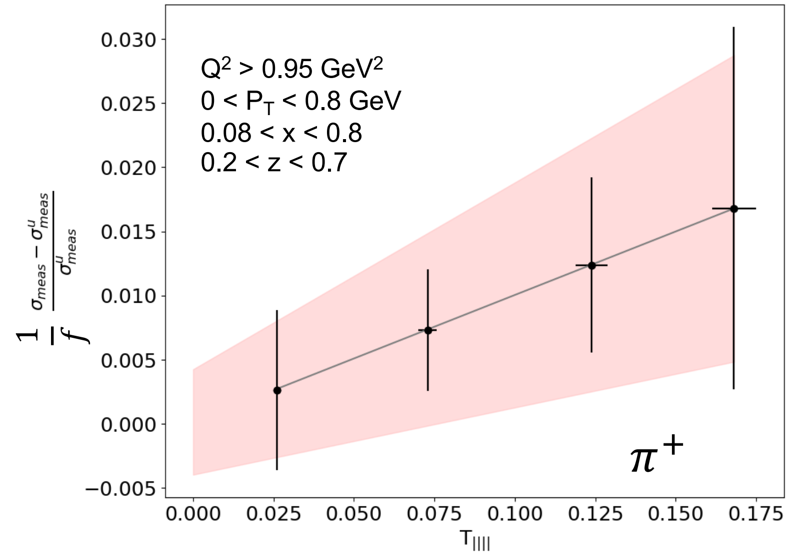
$$\sigma_{meas}^{total} = \sigma_u^D + P\sigma_v + Q\sigma_T + \sum \sigma_i$$

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 σ_i

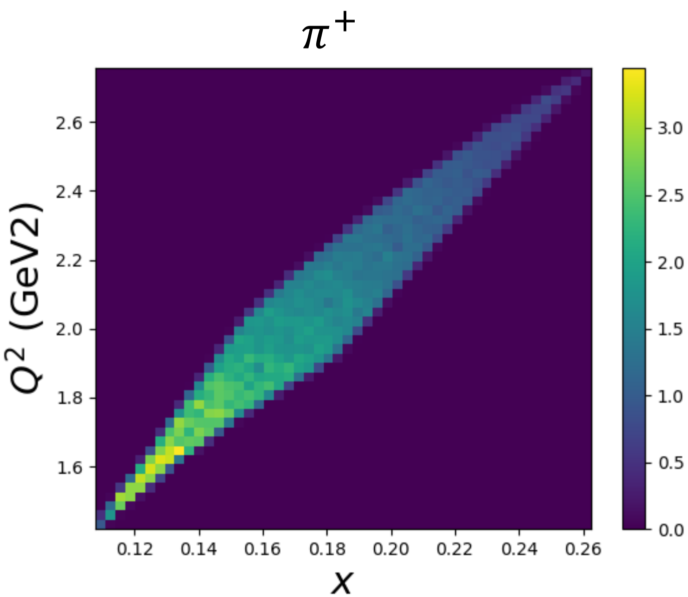
CAA: Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12
Data: Run Group C

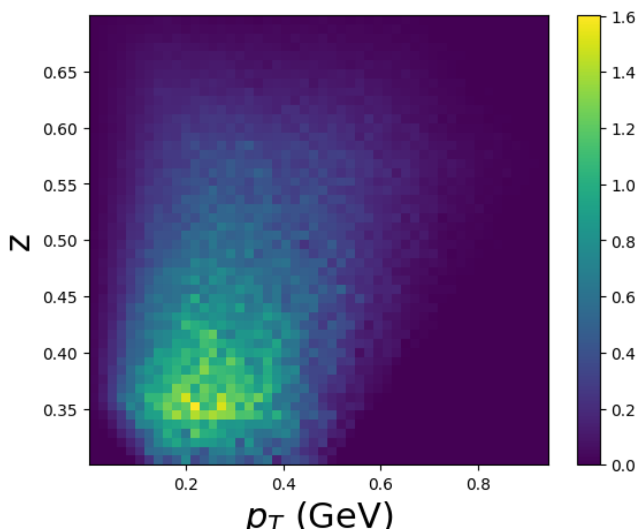


- This measurement will help to understand the tensor contribution.
- Currently assuming 10% of the unpolarized contribution as the inclusive measurement.
- Our predictions imply a 60% uncertainty.
- Crucial to propose new experiments.

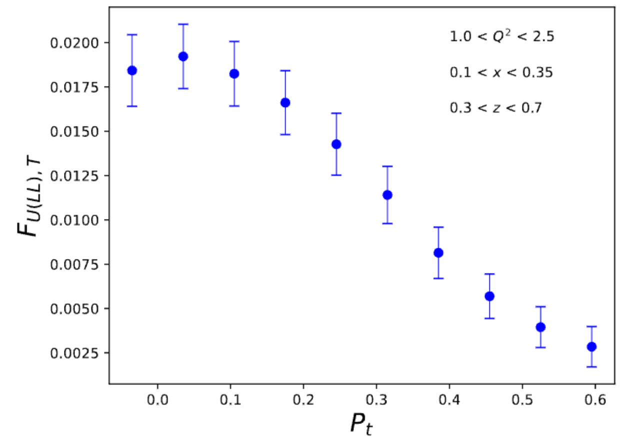
Poudel, Santiesteban, Chen, Slifer, Ruth, Fernando, Keller, Long, Bacchetta

Step 2: Dedicated experiment in Hall C at Jefferson Lab





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



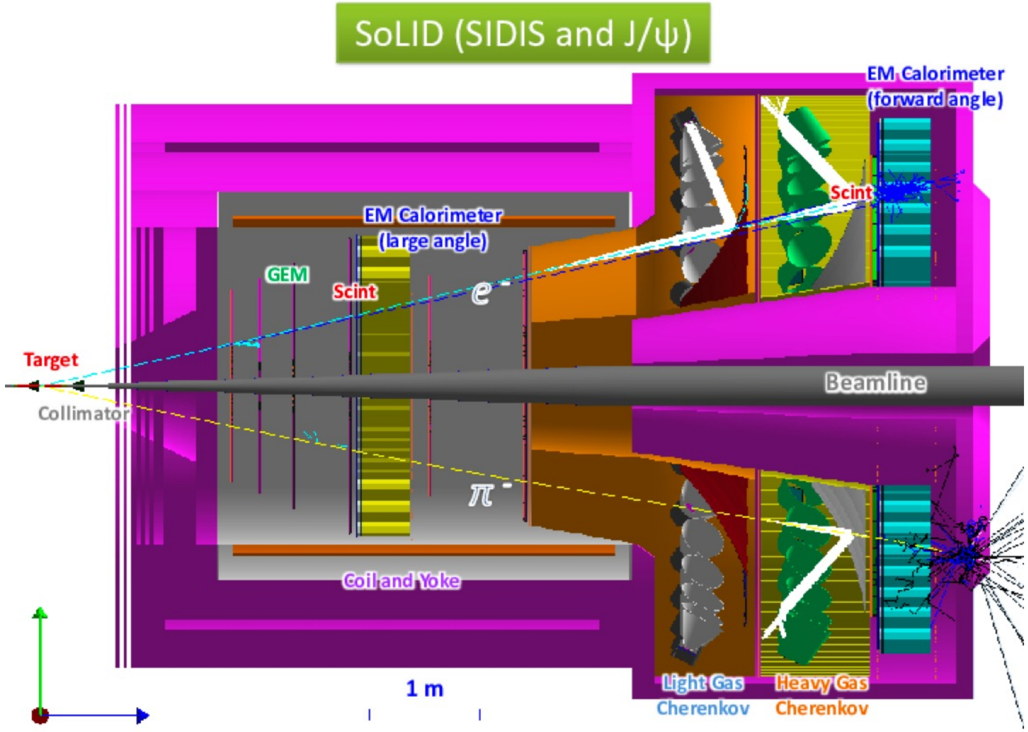
	θ (deg.)	ϕ (deg.)	P (GeV)
Electron	10.3 - 12.4	-2.87 - 2.87	4.0 - 5.4
Hadron	5.0 - 15.0	167 - 193	2.0 - 4.0

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

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

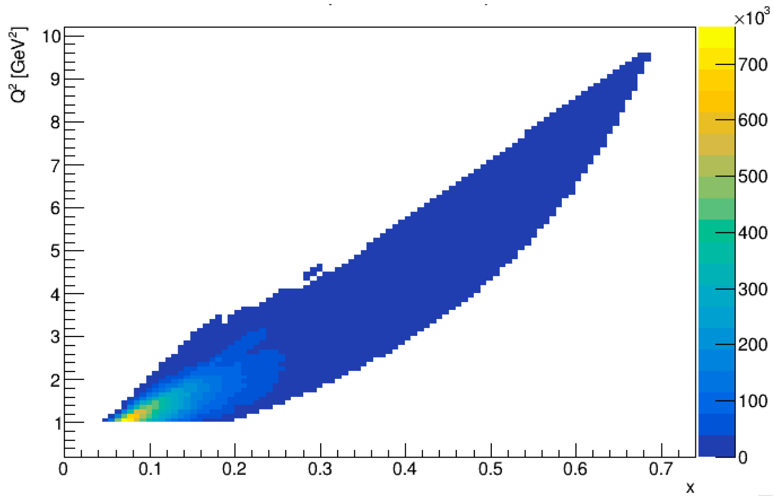
Step 3: Future program at SoLID

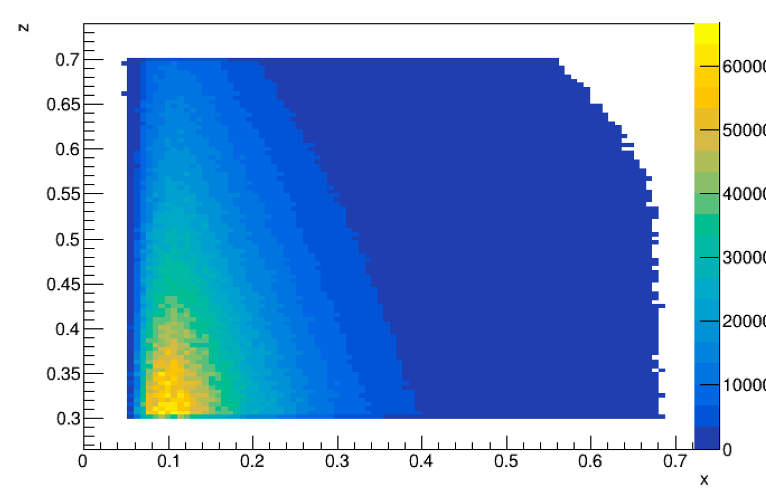
$0.3 < z < 0.7$
$Q^2 > 1.0$ GeV
$W > 2.3$ GeV
$W' > 1.6$ GeV

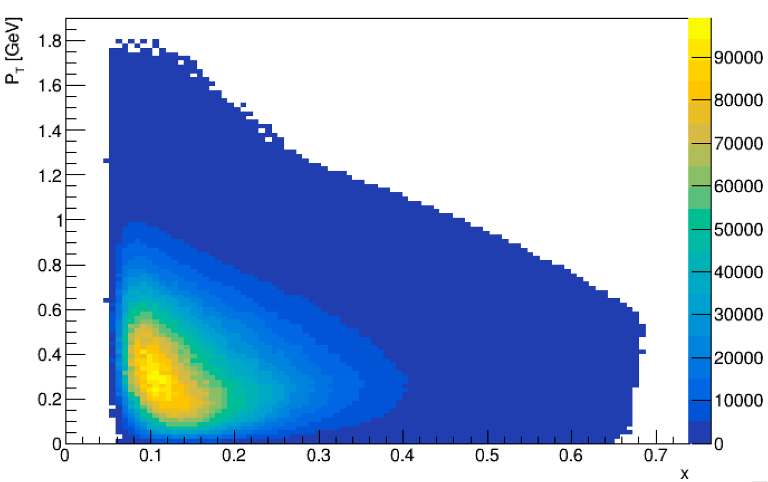


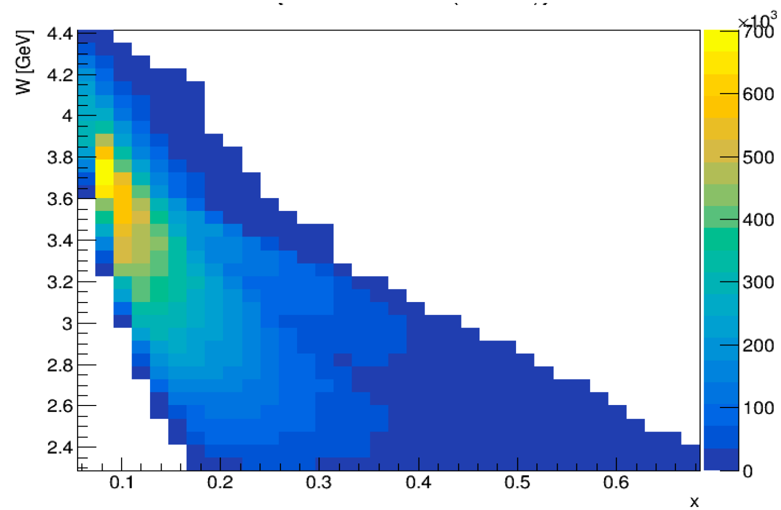
Unpolarized rates for π^-

1 week of running









Assuming:

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

New Ideas: 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!