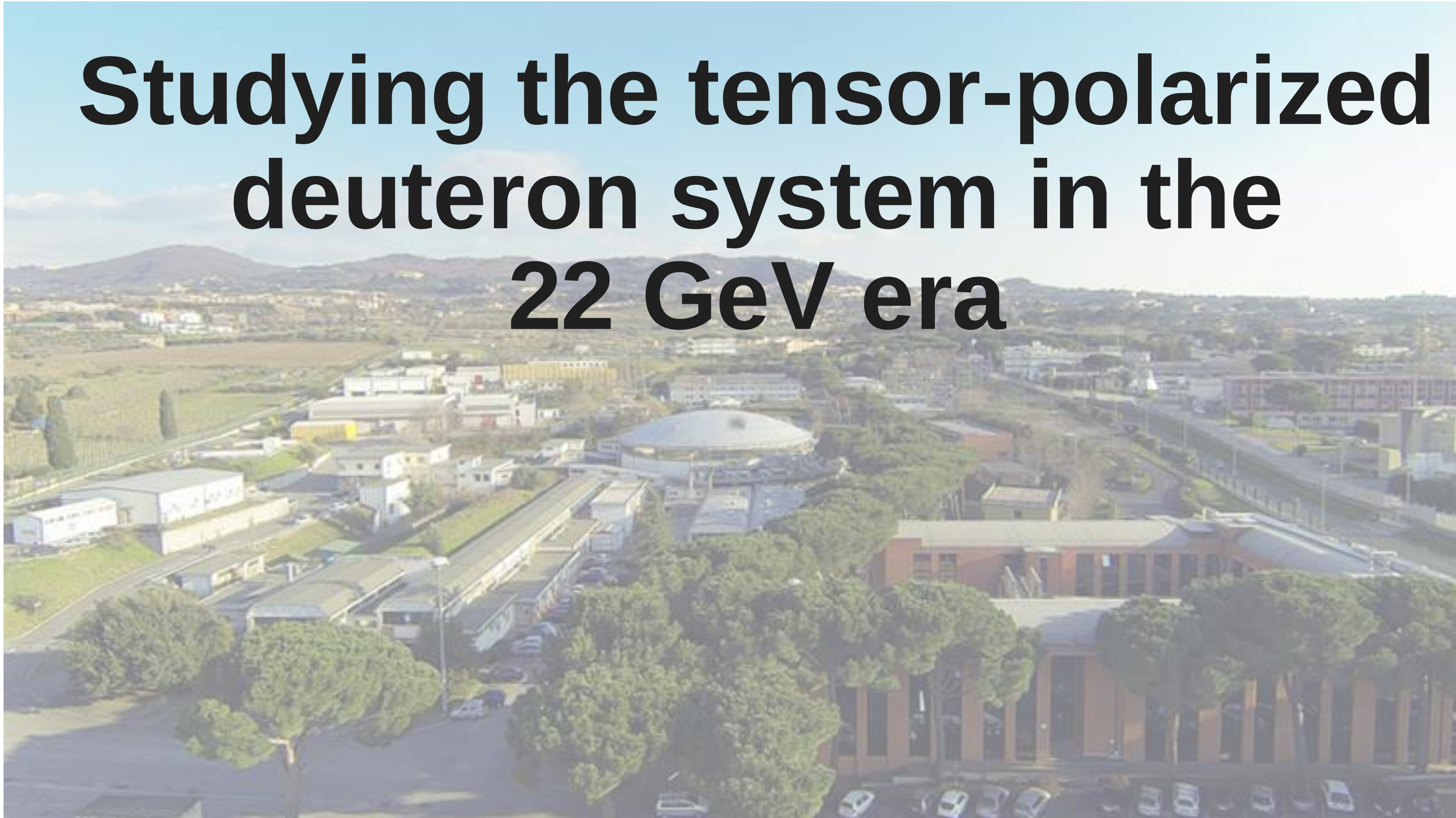
Studying the tensor-polarized deuteron system in the 22 GeV era

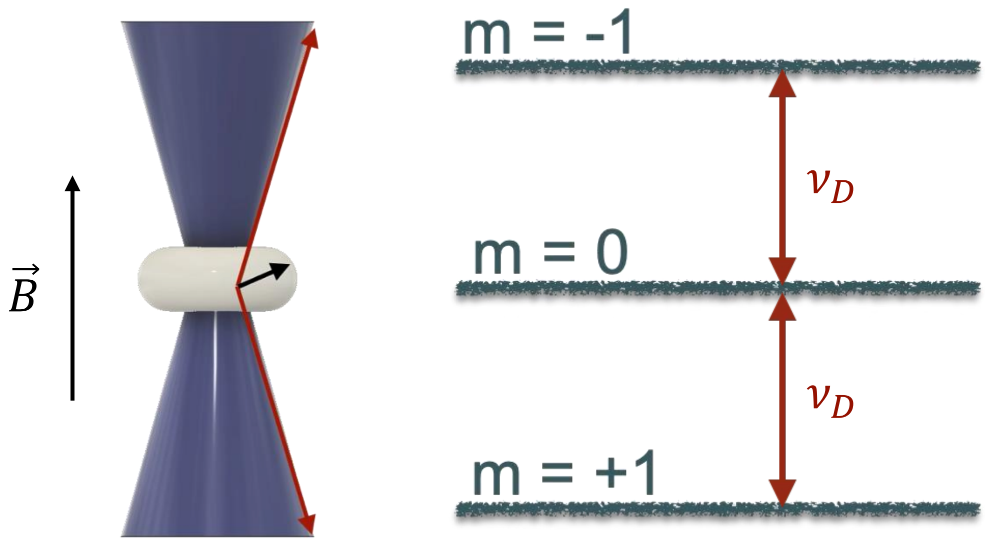


Nathaly Santiesteban

Science at the Luminosity Frontier
Jefferson Lab 22 GeV

University of New Hampshire

Spin-1 polarization



$$\nu_D = \frac{\mu_D B}{h}$$

$\nu_D = 6.54$ MHz/T

Spin-1 in a magnetic field System

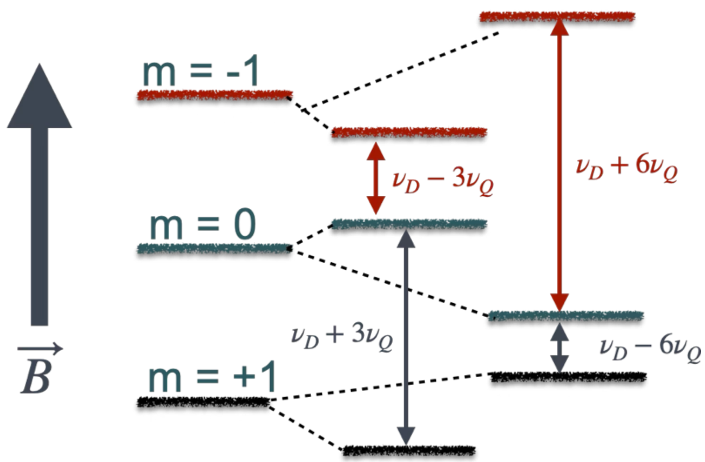
- 3 sub-levels (+1, 0, 1) due to Zeeman interaction.

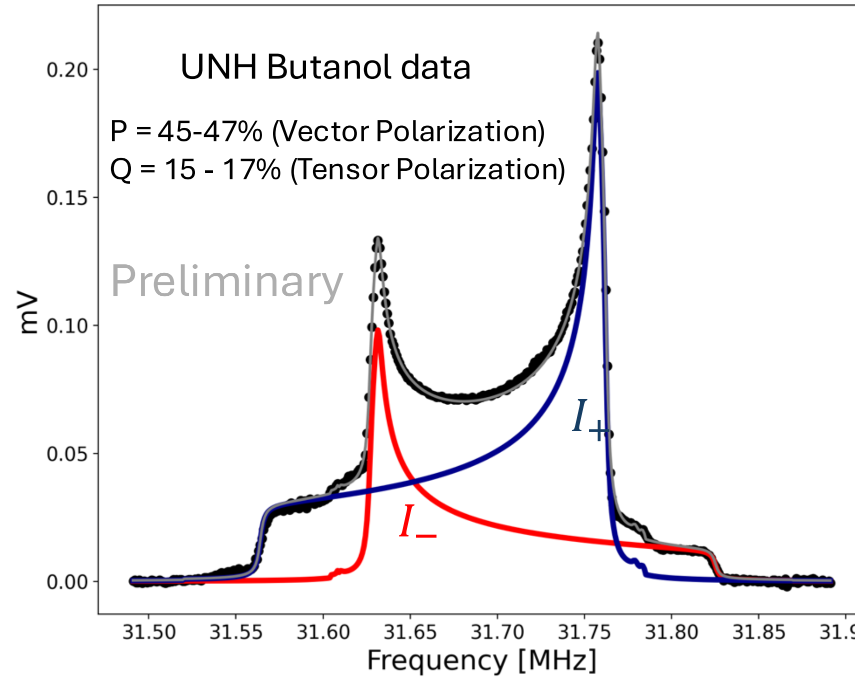
- Two energy transitions I_+(+1⟶0) and I_- (0 ⟶ -1).

Spin-1 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





UNH polarized target group

Enhancing vector polarization with DNP

- At thermal equilibrium (B = 5 T and T = 1 K), the vector polarization in Deuterium is P ~0.1%
- Dynamic Nuclear Polarization (DNP) enhances the vector polarization to up to 50% in deuterated butanol and deuterated ammonia
  Paramagnetic centers in the material, either chemically doped or irradiated, induce spin transitions through the application of microwaves to the sample, which is already in a magnetic field at very low temperatures.

Vector Polarization:

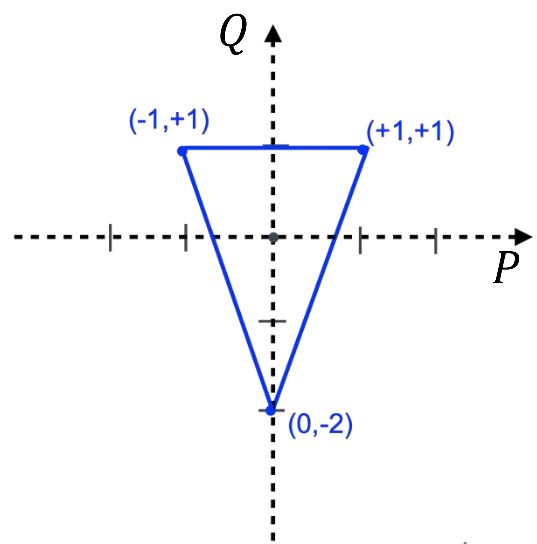
$$P = N_+ - N_-$$
$$-1 < P < +1$$

Tensor Polarization:

$$Q = N_+ + N_- - 2N_0$$
$$-2 < Q < +1$$

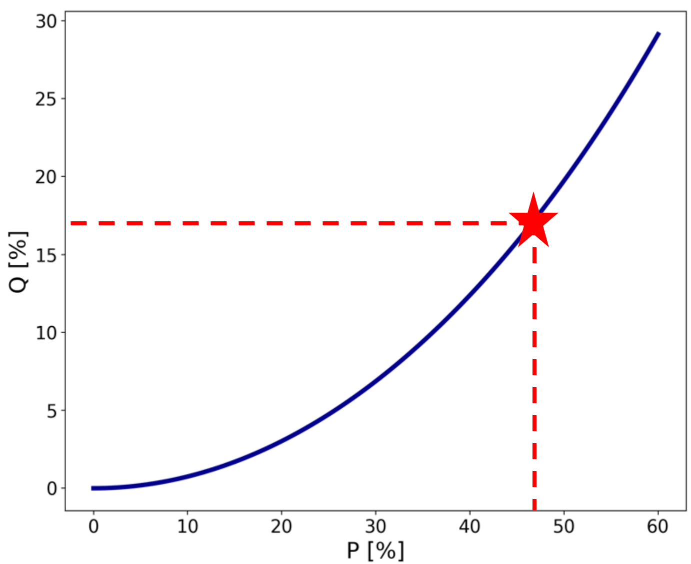
Normalization:

$$1 = N_+ + N_- + N_0$$

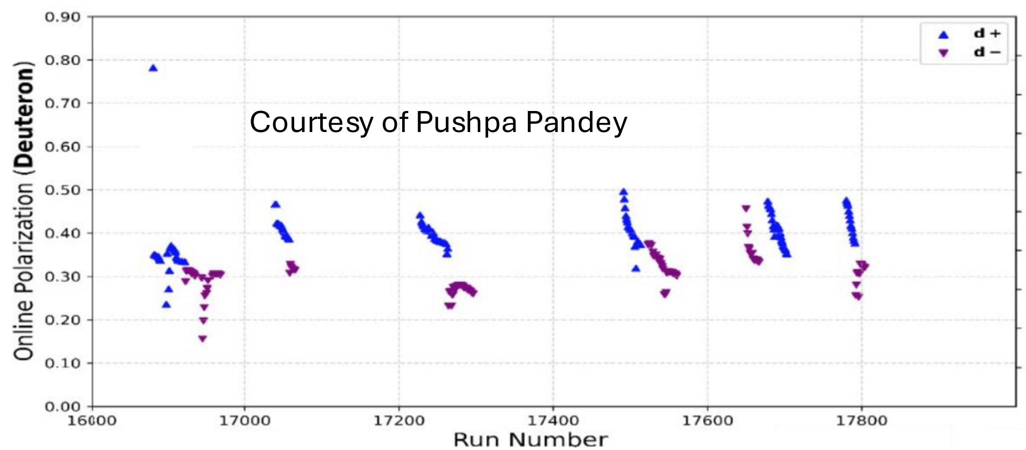


Can we perform an experiment with this technique?

- Target material used in tensor polarized techniques: deuterated ammonia (ND_3)
- After DNP, Vector and tensor polarizations are related as: $Q = 2 - \sqrt{4 - 3P^2}$



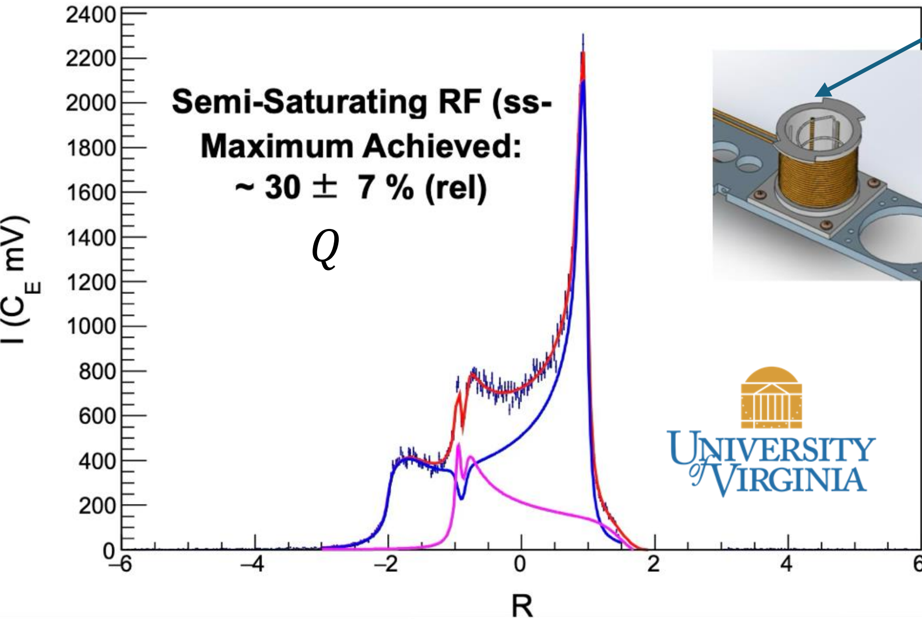
Tensor polarization with DNP is at best 15 – 20% and decays with dose (under electron beam)



Need additional techniques to enhance the tensor polarization

Enhanced tensor polarization using ss-RF

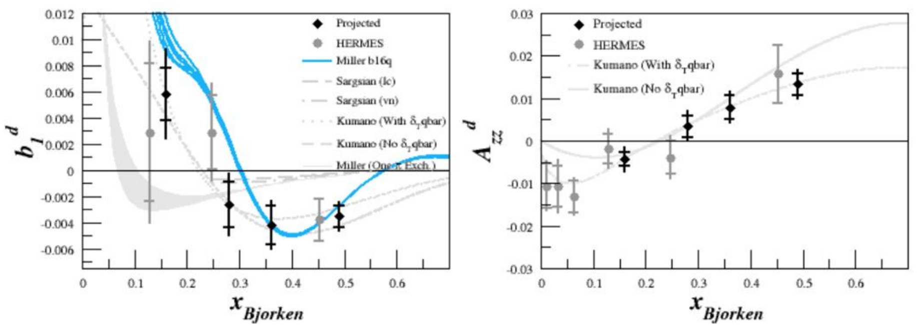
Target cup



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

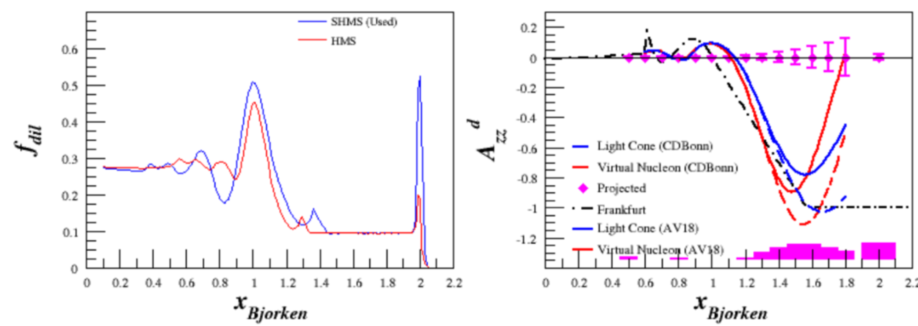
- Use optimized radiofrequency (RF) to manipulate the NMR line of deuteron.
- Technique has been successful with deuterated butanol.
- Work is ongoing to demonstrate its effectiveness in ND3, with the goal of running the approved experiments b_1 and A_{zz}.

Jefferson Lab approved experiments: b_1 and A_{zz}.



[The Deuteron Tensor Structure Function b1]()

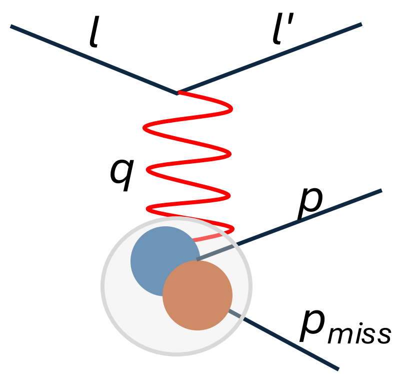
Scientific Rate: A-
Hall C
Days awarded: 41
K. Slifer (contact), J.-P. Chen, D. Keller, E. Long, O. Rondon, N. Santiesteban, P. Solvignon



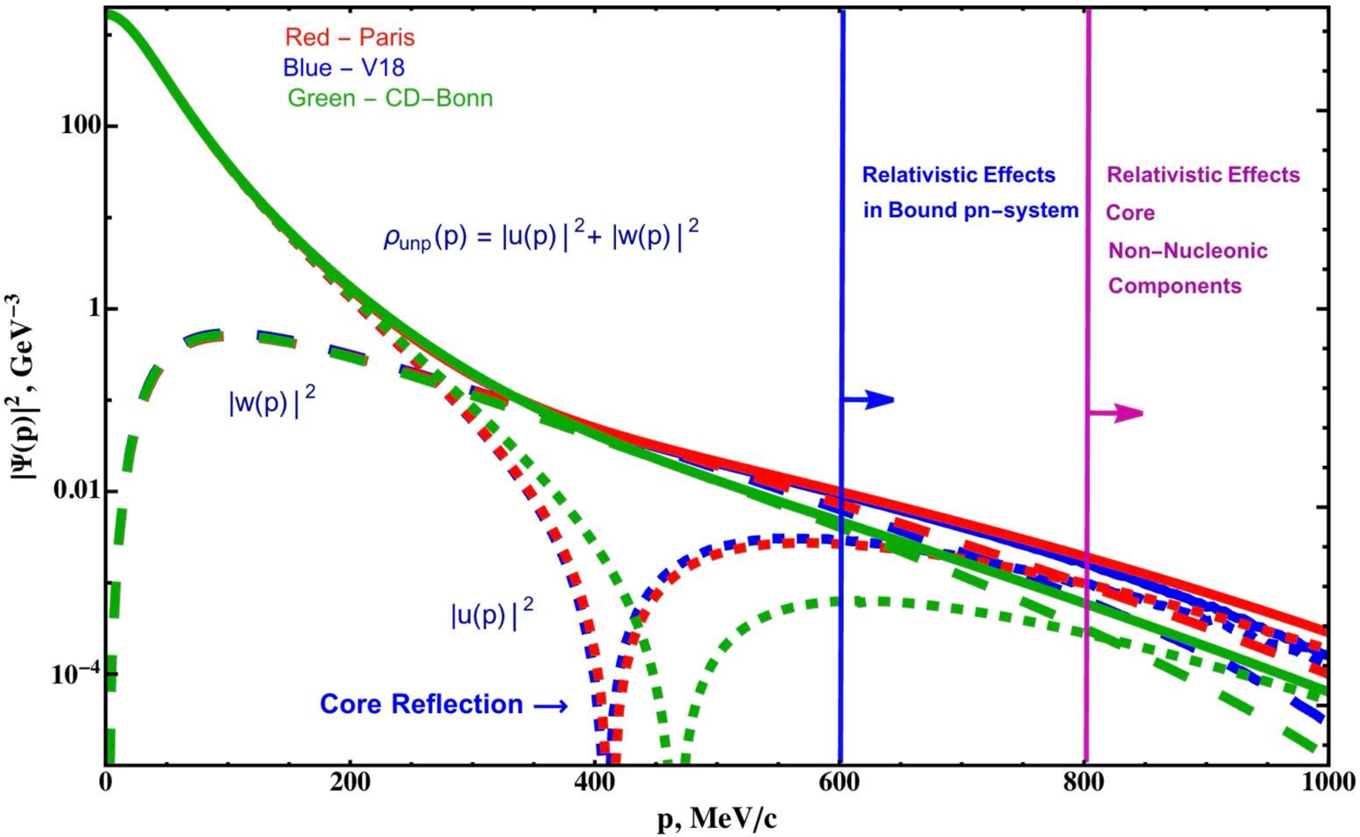
[Measurements of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries]()

Scientific Rate: A-
Hall C
Days awarded: 45
E. Long (contact), S. Santiesteban, K. Slifer, D. Day, D. Keller, D. Higinbotham

Exclusive electro-disintegration of tensor polarized deuterium



W. Boeglin, I.P. Fernando, M. Jones E. Long, S. N. Santiesteban,
M. Sargsian, H. Szumila-Vance, C. Yero



Momentum distributions for S (dotted) and D (dashed) partial waves
Total contribution to unpolarized deuteron momentum distribution (solid)

Courtesy of M. Sargsian

Probing the NN core

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

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

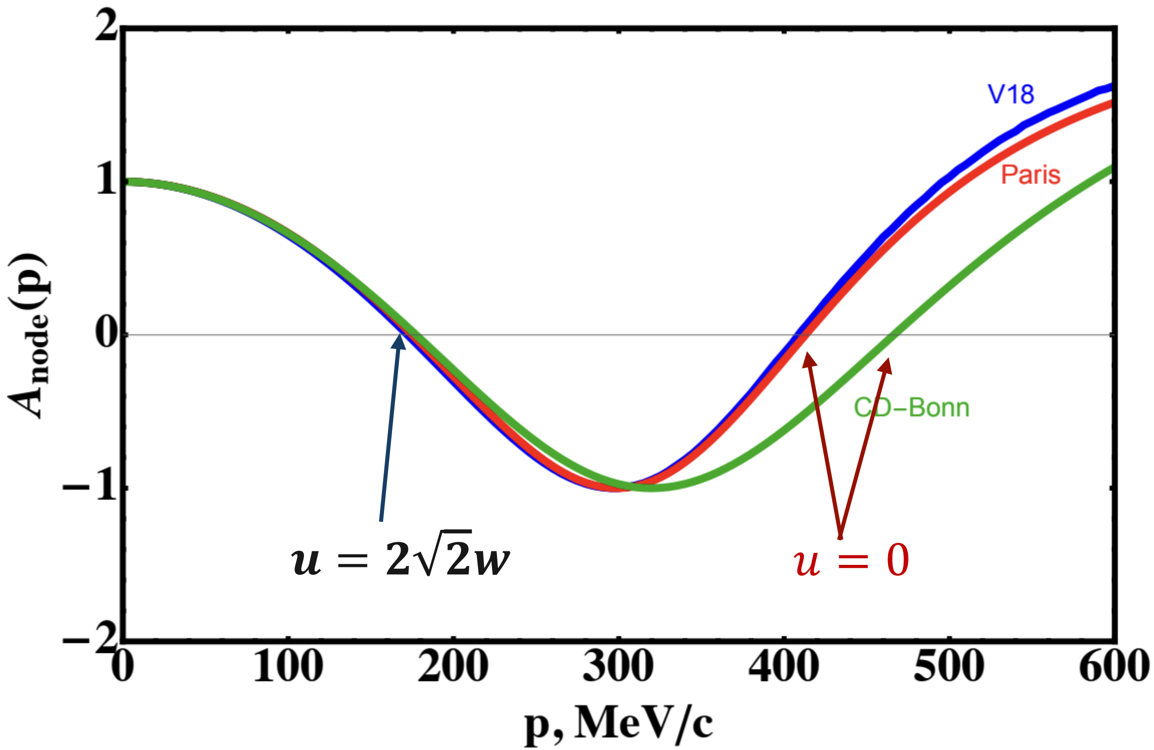
$$\rho_{20}(p_m) = \frac{3cos^2(\theta_N)\ -1}{2}\left[2\sqrt{2}u(p_m)w(p_m) - w(p_m)^2|\right]$$

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

$$A_{node} = \frac{u(p_m)^2 + 2\sqrt{2}u(p_m)w(p_m)}{|u(p_m)|^2 + |w(p_m)|^2}$$

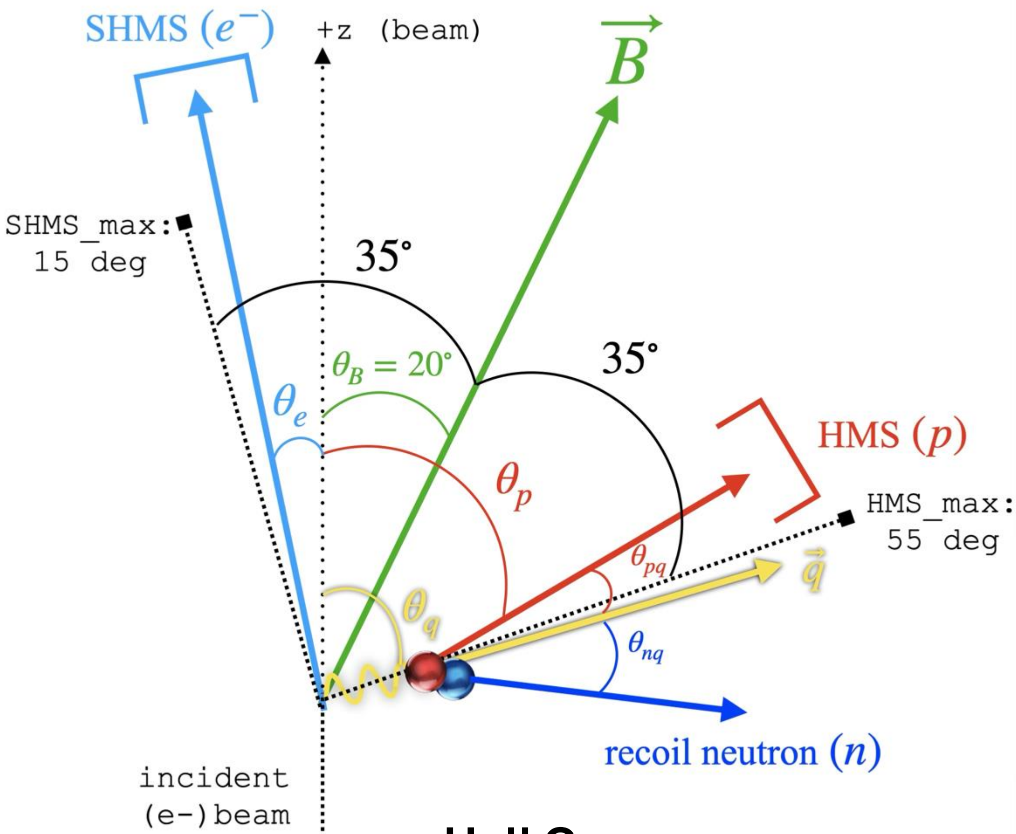
$$A_{node}(p) = 0 \begin{cases} u(p) = -2\sqrt{2}w(p) \longrightarrow & p \sim 180MeV \\ u(p) = 0 \longrightarrow & p \geq 400MeV \end{cases}$$

M. Sargsian 2410.08384 (2024).



The node is a signature of nuclear repulsive core: In the PWIA approximation, if deuteron consisted of only the S-state, then in this case the node is like a hole in the momentum space through which the probe-electron will pass without interaction.

M. Sargsian 2410.08384 (2024).



Hall C

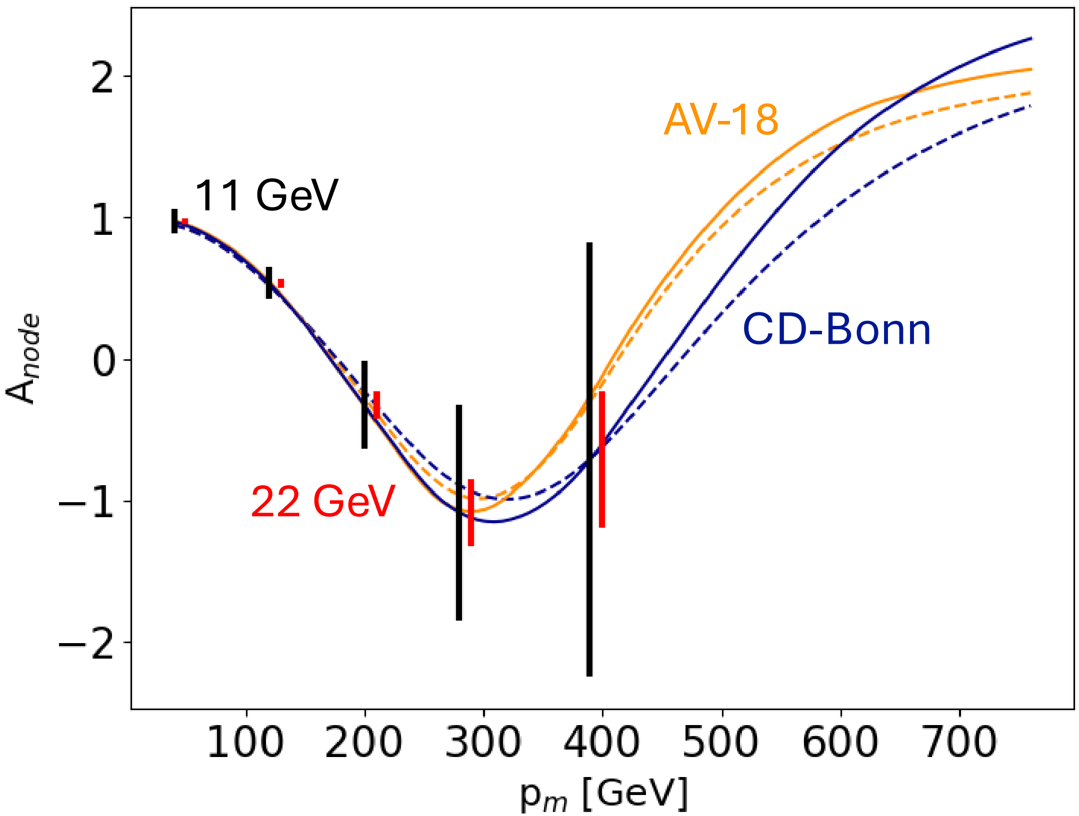
At 11 GeV:

Looking at forward kinematics to minimize FSI ($0 < \theta_{nq} < 35$).
In short, this implies $\theta_p > 50\ deg$

We currently are limited by the acceptance of the target magnet (± 35 deg).

We can rotate the magnet maximum 20 deg: Proton side up to 50 deg.

$0 < \theta_{nq} < 35$



11 GeV

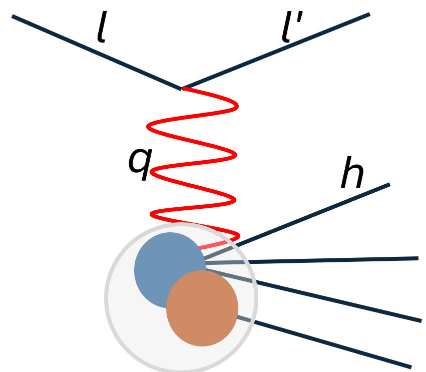
$E'_p = 1.65\ GeV, \theta'_p = 53\ deg$
$E'_e = 9.5\ GeV, \quad \theta'_e = 8.46\ deg$

22 GeV

$E'_p = 1.65\ GeV, \quad \theta'_p = 55\ deg$
$E'_e = 21.01\ GeV, \quad \theta'_e = 4.12\ deg$

Probably a good idea to optimize SoLID for electrons and potentially use other detector to measure the protons.

TMD Study with SIDIS on tensor polarized deuteron

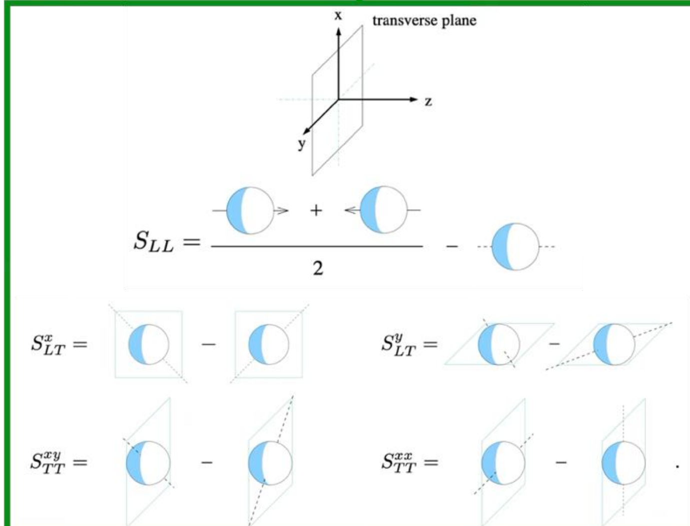


A. Bacchetta, J.P. Chen, I. Fernando, D. Keller, E. Long, J. Poudel,
D. Ruth (contact), N. Santiesteban, K. Slifer,

Leading twist distribution functions

Never Measured!

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 integrating over the transverse momentum:

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						

The tensor structure of the spin-1 deuteron will unlock new and fascinating possibilities for further understanding the parton structure in light nuclei.

A. Bacchetta Phys. Rev. D 62 (2000)

Longitudinally polarized target

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

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

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

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

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

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

Courtesy of A. Bacchetta (private communication) 2023.

Tensor-polarized structure functions

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

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

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

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

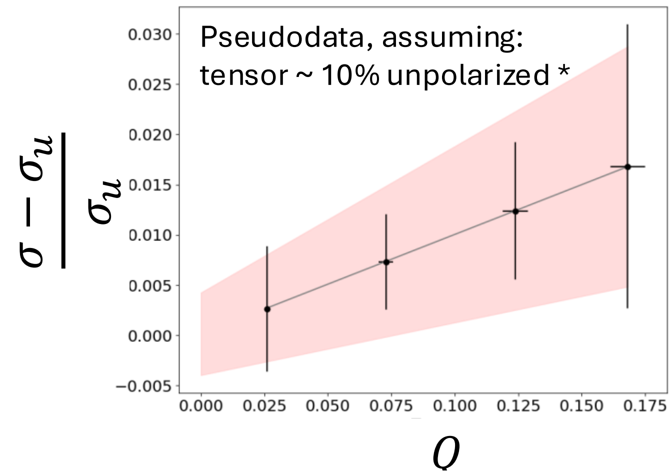
$$F_{L(LL)}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e_{LL}\, H_1^{\perp} + \frac{M_h}{M}\, f_{1LL}\,\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g_{LL}^{\perp} D_1 + \frac{M_h}{M}\,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

Spin-1 leading twist

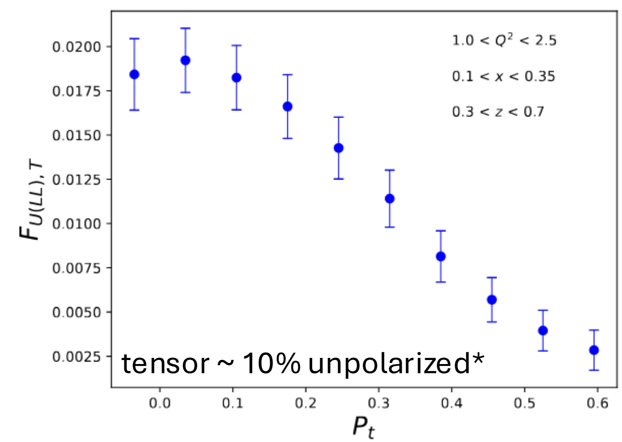
Courtesy of A. Bacchetta (private communication) 2023.

Our approach to study this structure functions

1. *“Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12”*
   CLAS12 Approved Analysis (CAAFall 2024)
   Data: Polarized Deuterium (ND_3via DNP). Q_{max}~20%
   Goal: understand the size of the tensor contribution to the SIDIS processes ($eD \rightarrow e'\pi^{\pm}X$)



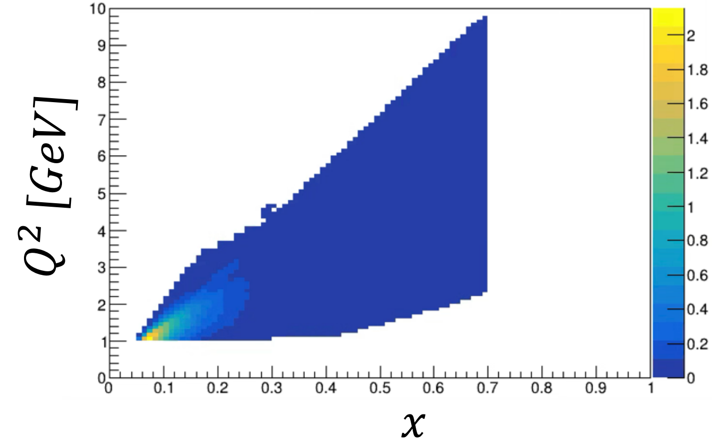
2. " Spin-1 TMDs and Structure Functions of the Deuteron”
   Letter of Intent (LOI12-24-002 PAC 52, 2024)
   Goal: Dedicated Measurement in Hall C ($eD \rightarrow e'\pi^{\pm}X$)

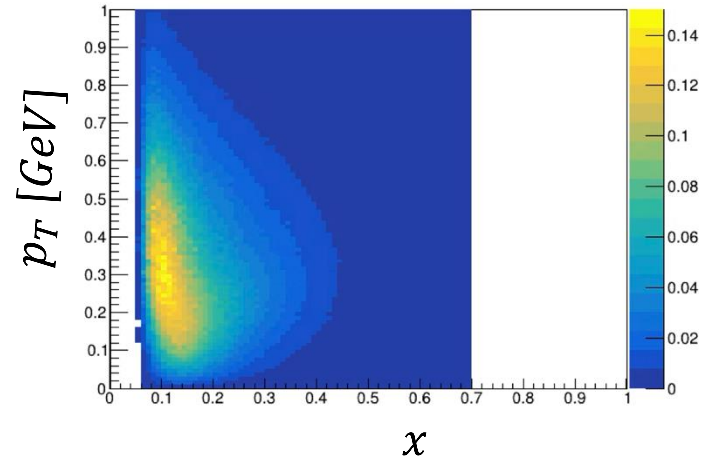


* This 10% estimate comes from the HERMES measurement of b1b_1b1 (the collinear structure function), which is the only available data to date.

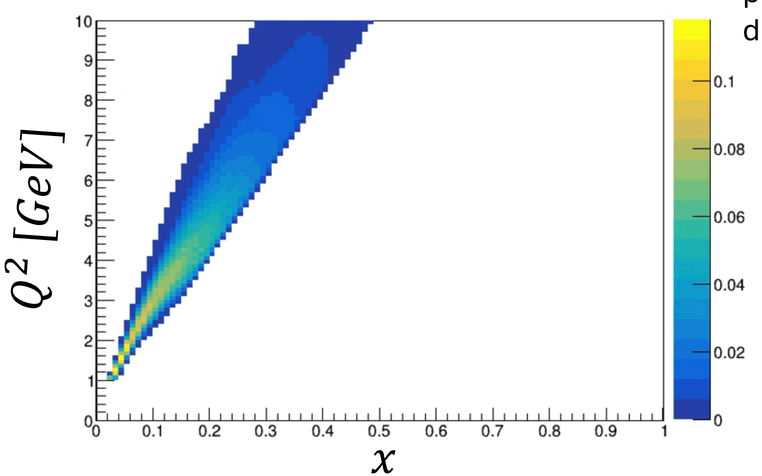
- 0.3 < z < 0.7
- Q2 > 1.0 GeV2
- W > 2.3 GeV
- W’ > 1.6 GeV

3. Full program in SoLID at 11 GeV

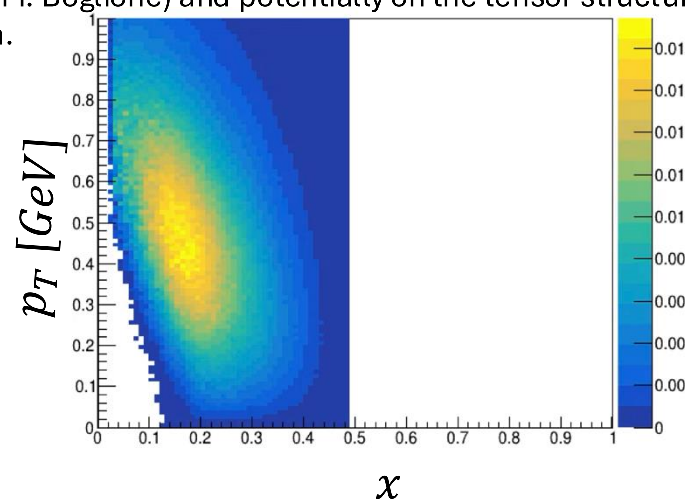




4. Full program in SoLID at 22 GeV



JLab22 can have a considerable impact on our understanding of TMD physics (M. Boglione) and potentially on the tensor structure of the spin-1 deuteron.



Remarks

- The tensor component of spin-1 objects, such as the deuteron, holds the key to new and exciting insights into the parton structure of nuclear matter.
- QE measurements will benefit from the 22-GeV upgrade, provided that the same Q^2 is maintained.
- JLab's 11-GeV and 22-GeV configurations will complement each other to provide a more complete description of TMDs, as discussed over the course of this week.
- SoLID appears to be an excellent place to conduct such measurements. Very likely, this set of experiments and possible additional measurements will benefit from a run group program.