Probing the Deuteron Tensor Structure with Quasi-Elastic Scattering

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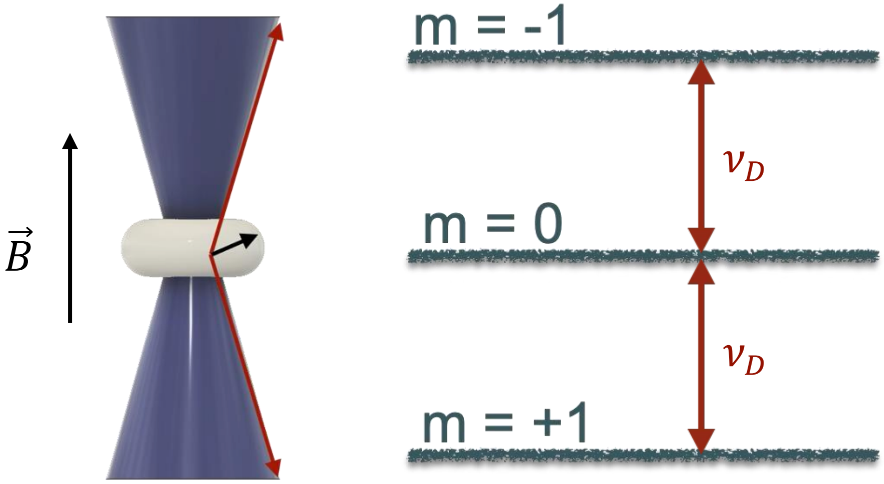
The International Workshop on Quantitative Challenges in Short-Range Correlations (SRC) and the EMC-Effect Research

University of New Hampshire

What do we need? Large tensor polarization

Spin-1 Polarization



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

$$\nu_D = 6.54 \text{ MHz/T}$$

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).

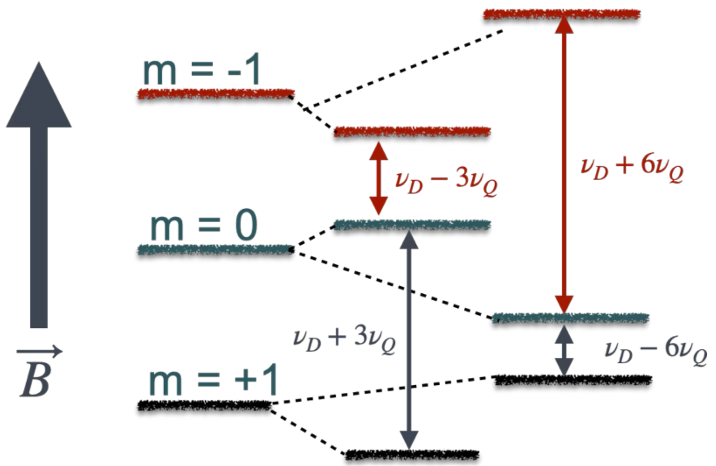
Spin-1 Polarization

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

eQ: Electric quadrupole interaction (shifts the energy levels)

eq: Electric field gradient

θ: angle between eq and eQ



Vector Polarization:

$$P = N_+ - N_-$$

$$-1 < P < +1$$

Tensor Polarization:

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

$$-2 < Q < +1$$

Normalization:

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

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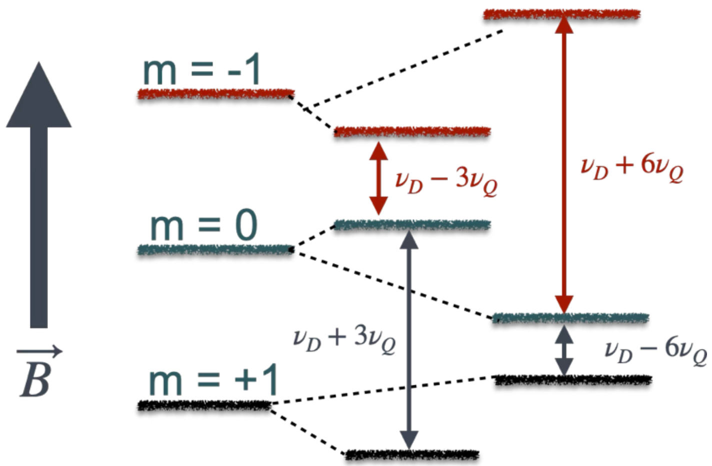

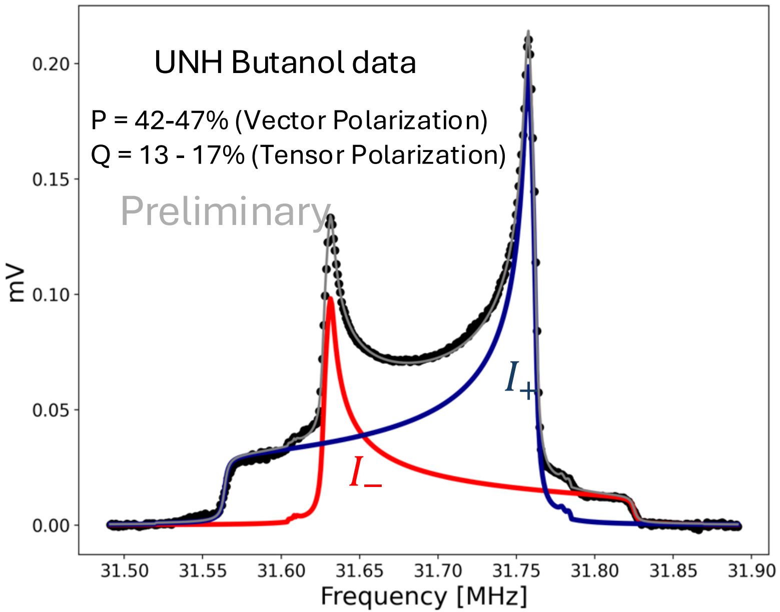

NMR signal

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:

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Tensor Polarization:

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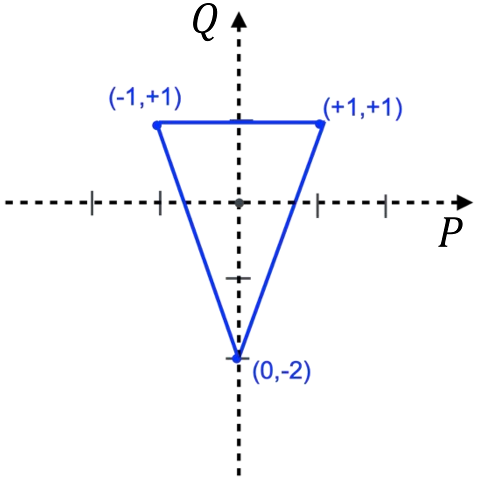
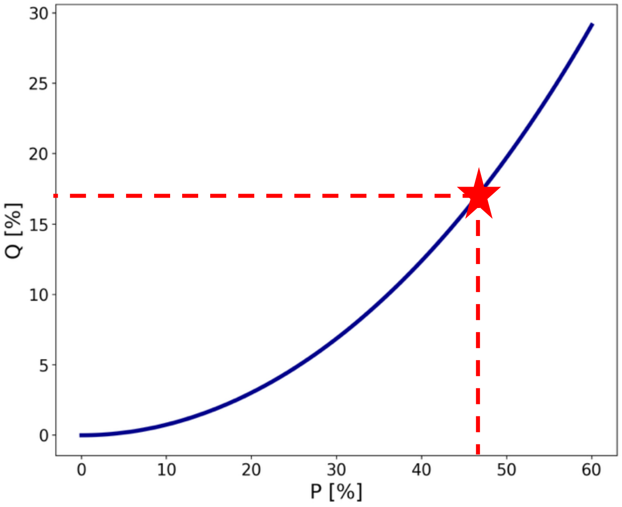
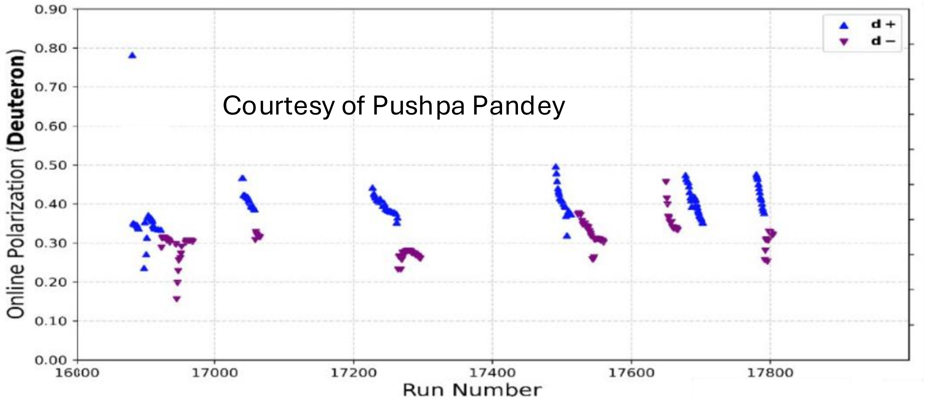


Can we perform an experiment with this technique?

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



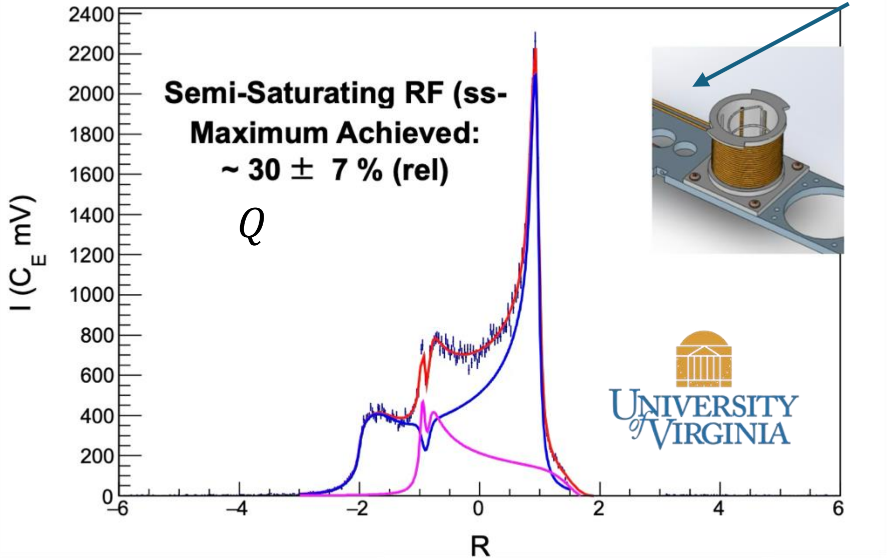
Tensor polarization with DNP is at best 15 – 20% and decays with dose (under electron beam)



Need additional techniques to enhance the tensor polarization

Enhanced tensor polarization using ss-RF

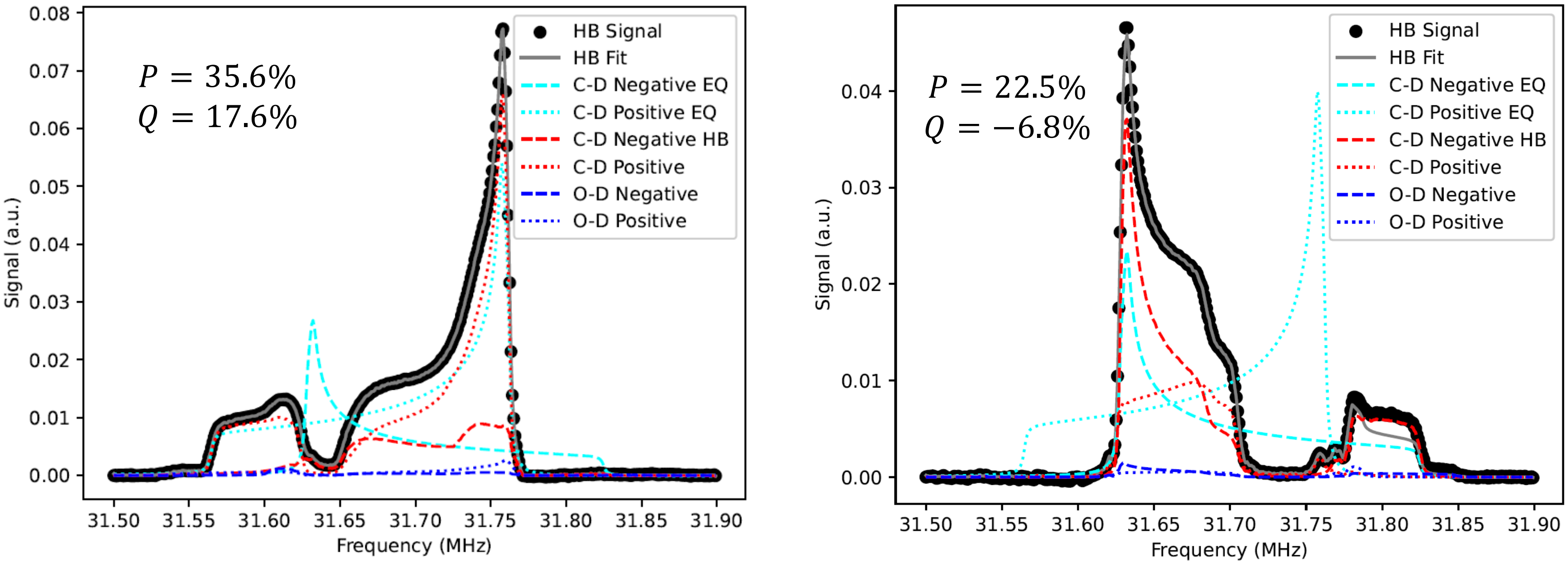
Target cup



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}.

Enhanced tensor polarization using ss-RF



M. McClellan, PhD Thesis (2026)

What do we measure?

Full cross-section:

Unpolarized Tensor

$$\frac{d^6\sigma_p}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} = \sigma_u \left[\boxed{1} + \boxed{PA_d^V} + \boxed{\frac{1}{2}QA_d^T} \right]$$

Vector

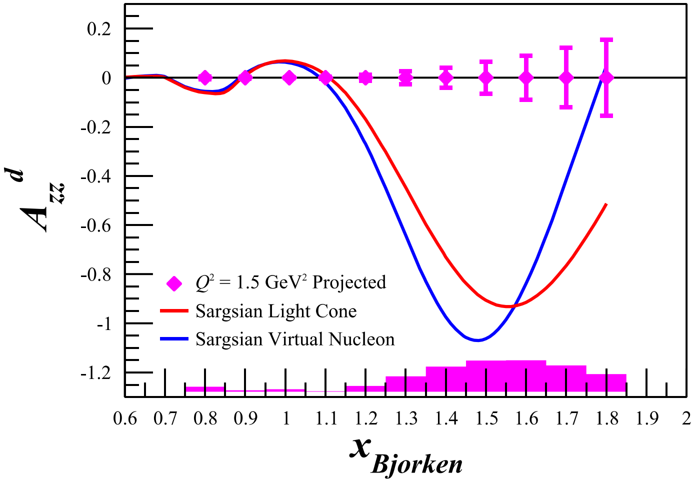
Tensor asymmetry:

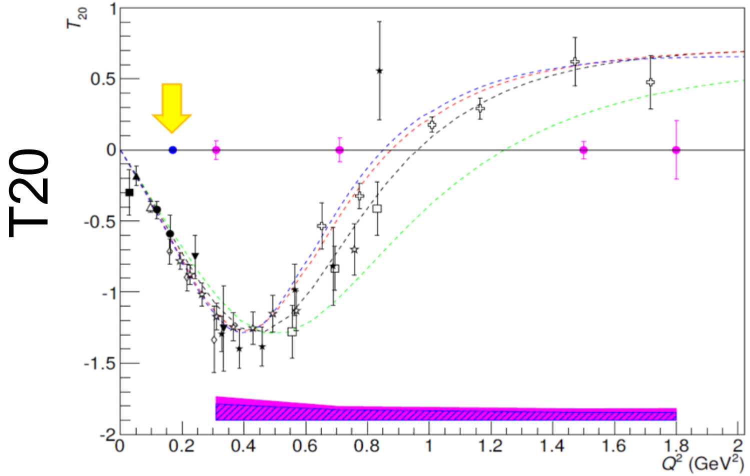
$$A_d^T = \frac{2}{Q}\left(\frac{\sigma(P,Q)+\sigma(-P,Q)}{\sigma(P,0)+\sigma(-P,0)} - 1\right)$$

Four target configurations

Assuming most factors will cancel in the cross-section ratios:

$$A_d^T = \frac{2}{fQ}\frac{N_p - N_u}{N_u}$$





Inclusive measurement

Very Large Tensor Asymmetries predicted

Sensitive to the S/D-wave ratio in the deuteron wave function

4σ discrim between hard/soft wave functions

$6\ \sigma$ discrim between relativistic models

What else can we measure?

Our asymmetry:

$$A_{node} = \left(1 - \frac{4}{(3\cos^2\theta_N - 1)Q}\right) + \frac{4}{(3\cos^2\theta_N - 1)Q}\left(\frac{\sigma(P,Q) + \sigma(-P,Q)}{\sigma(P,0) + \sigma(-P,0)}\right)$$

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

Relating to the tensor asymmetry

$$A_{node} = 1 + \frac{2}{(3\cos^2\theta_N - 1)} A_d^T$$

Probing the NN core

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

unpolarized

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

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

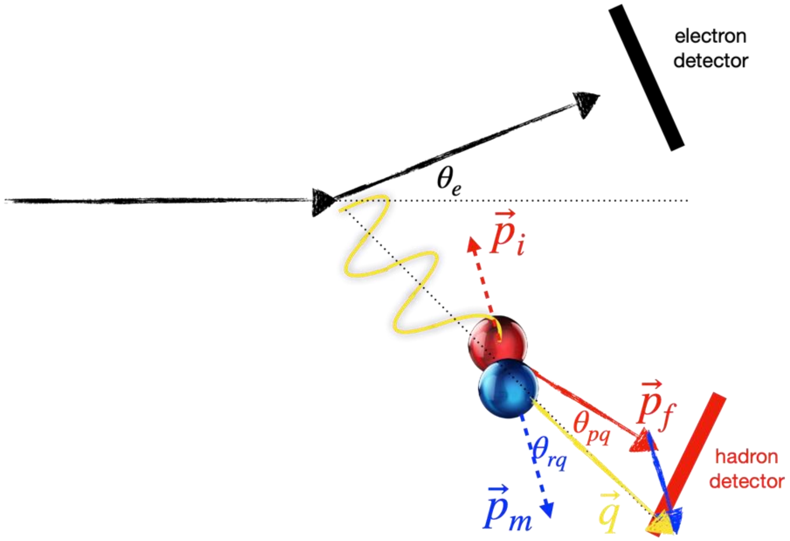
Tensor polarized

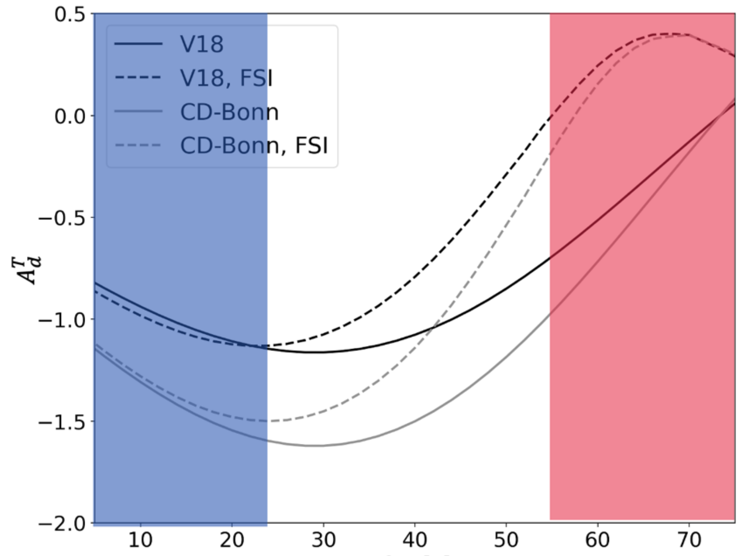
θ_N : direction of internal momenta with respect to the polarization axis of the deuteron

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

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

M. Sargsian 2410.08384 (2024).



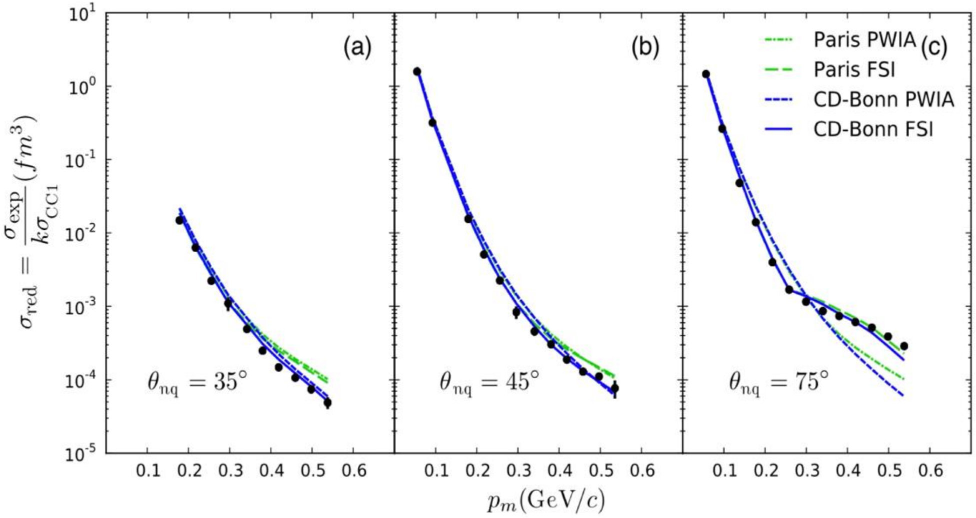


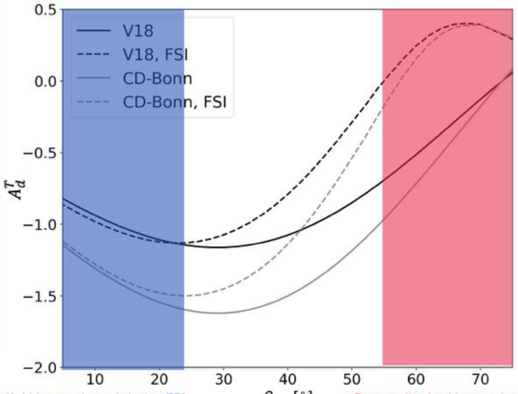
Our experiment needs to look for kinematics where the final state interactions are minimal

Experimental Setup: Detectors configuration

controlling final-state interactions (FSI)

Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)





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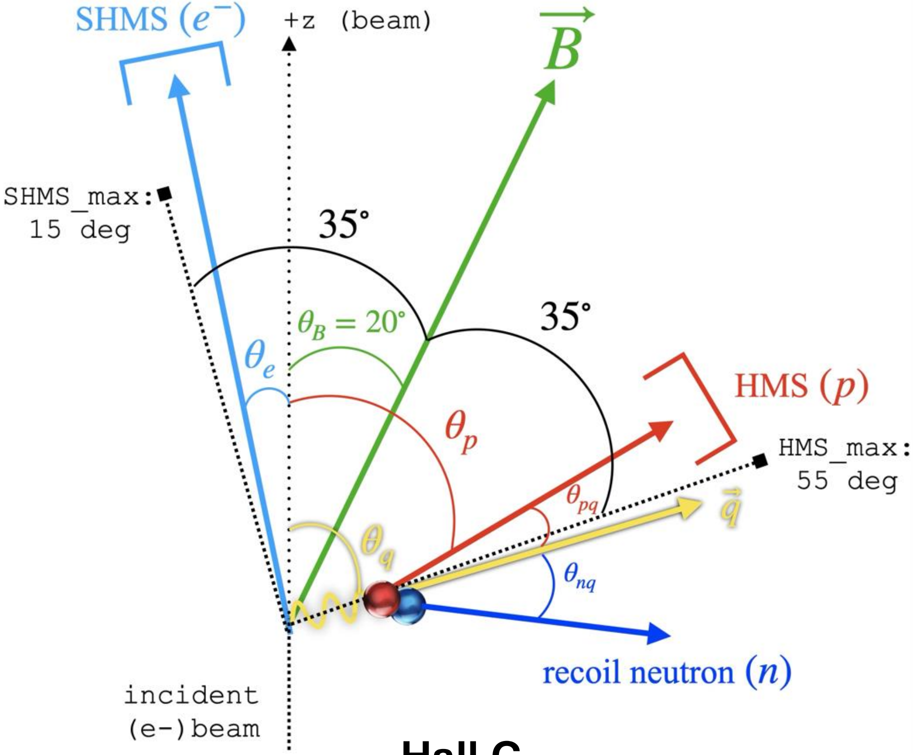


Hall C

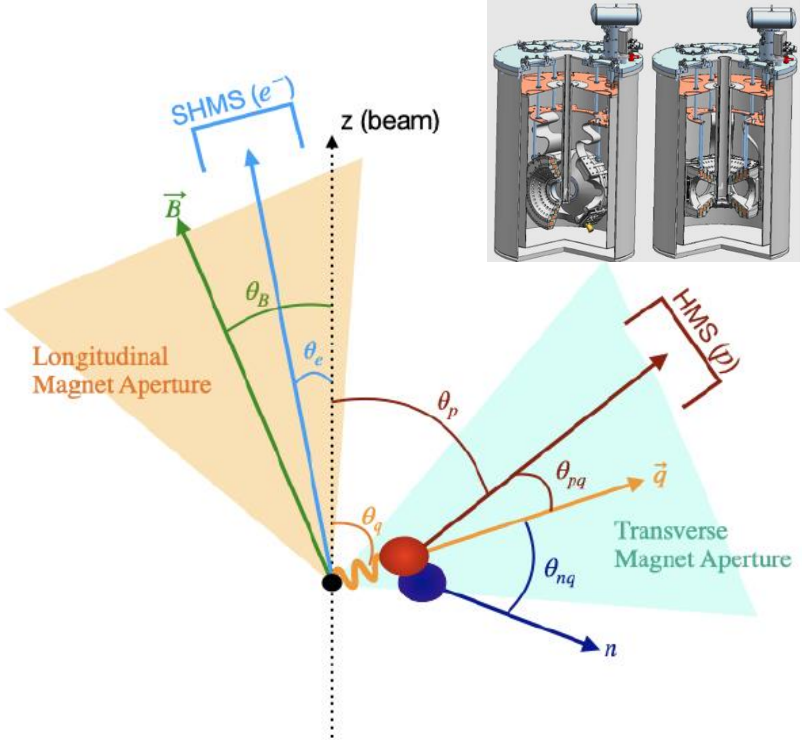
At 11 GeV:

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.

Experimental Setup: Detectors configuration



Challenge: find the appropriate magnet for the target. The current magnet in the longitudinal configuration has an aperture of 35^o and in the transverse configuration an aperture of 25^o.

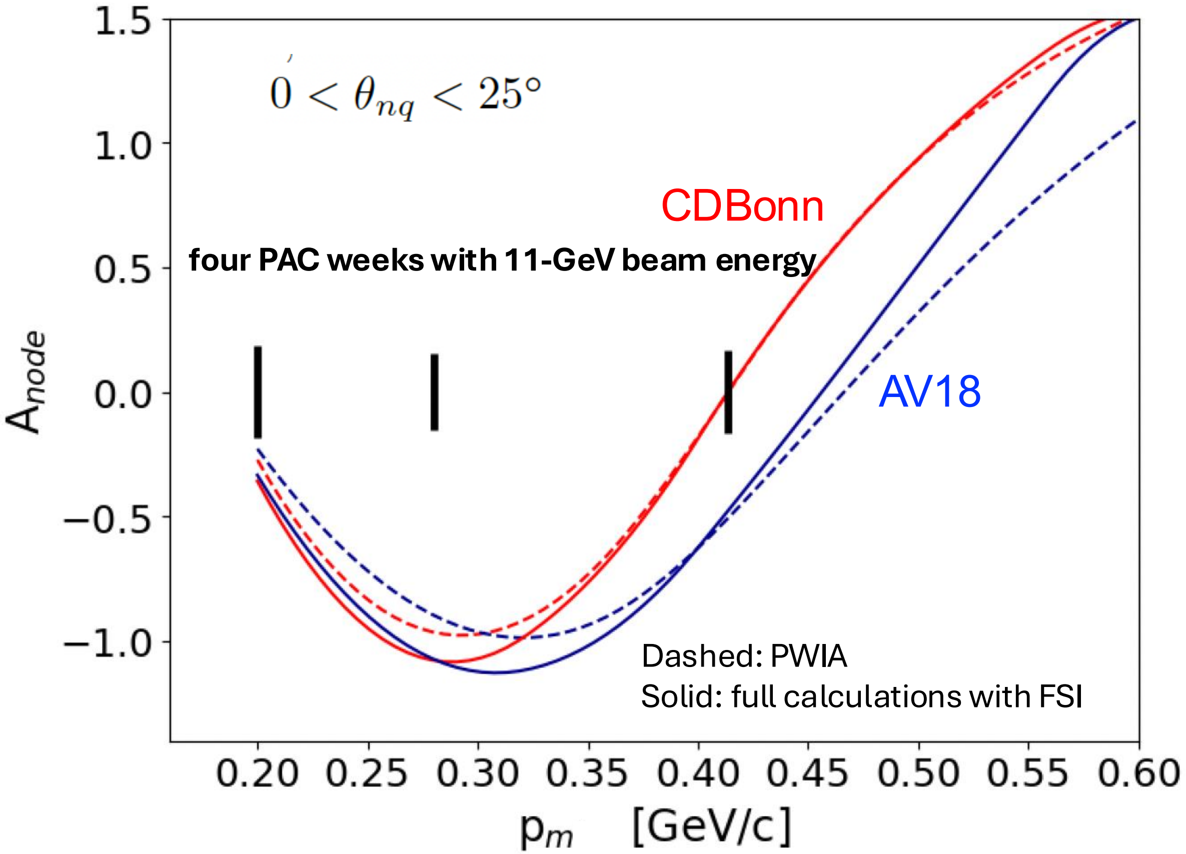
Two possible avenues:

i) use the current target, rotate it, and angle $\theta_B = 20^o$ towards the SHMS and use the longitudinal aperture for
the electrons and the perpendicular aperture for the protons

ii) design and acquire a completely new magnet.

A full study of the magnet needs must be performed before a full proposal

Expected measurement



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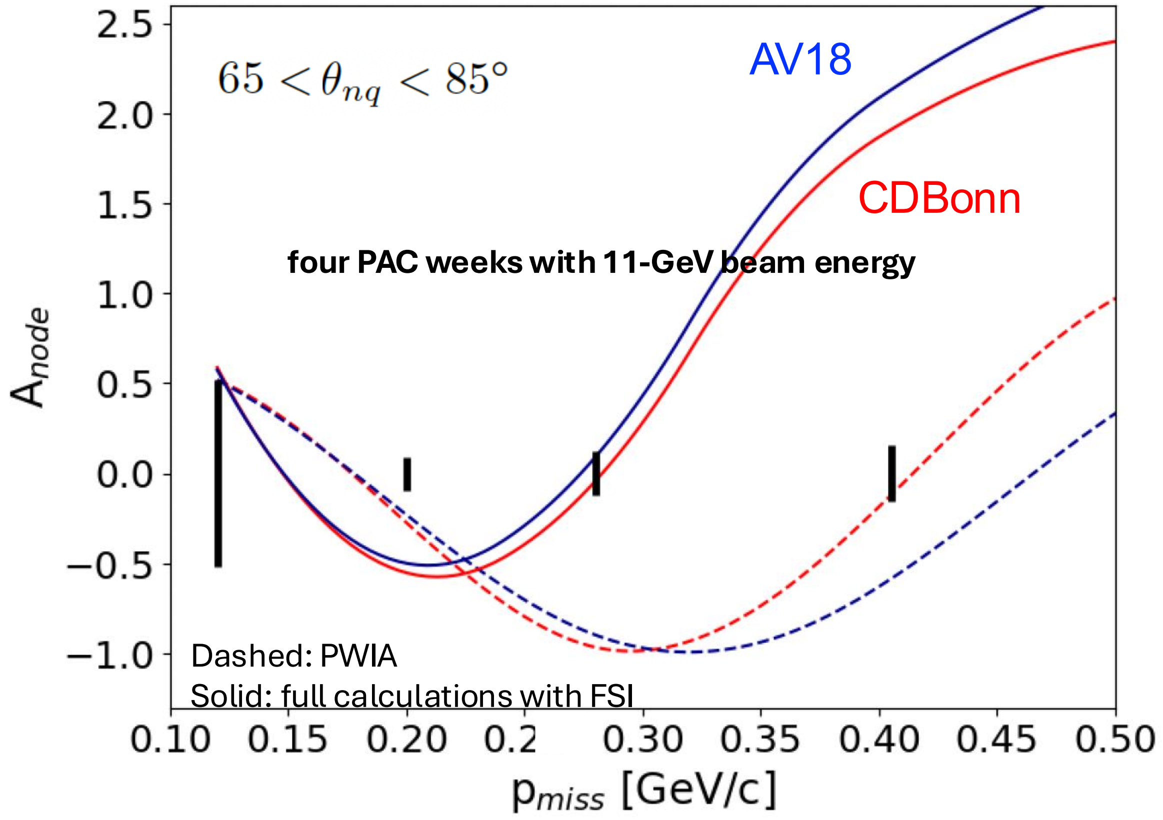

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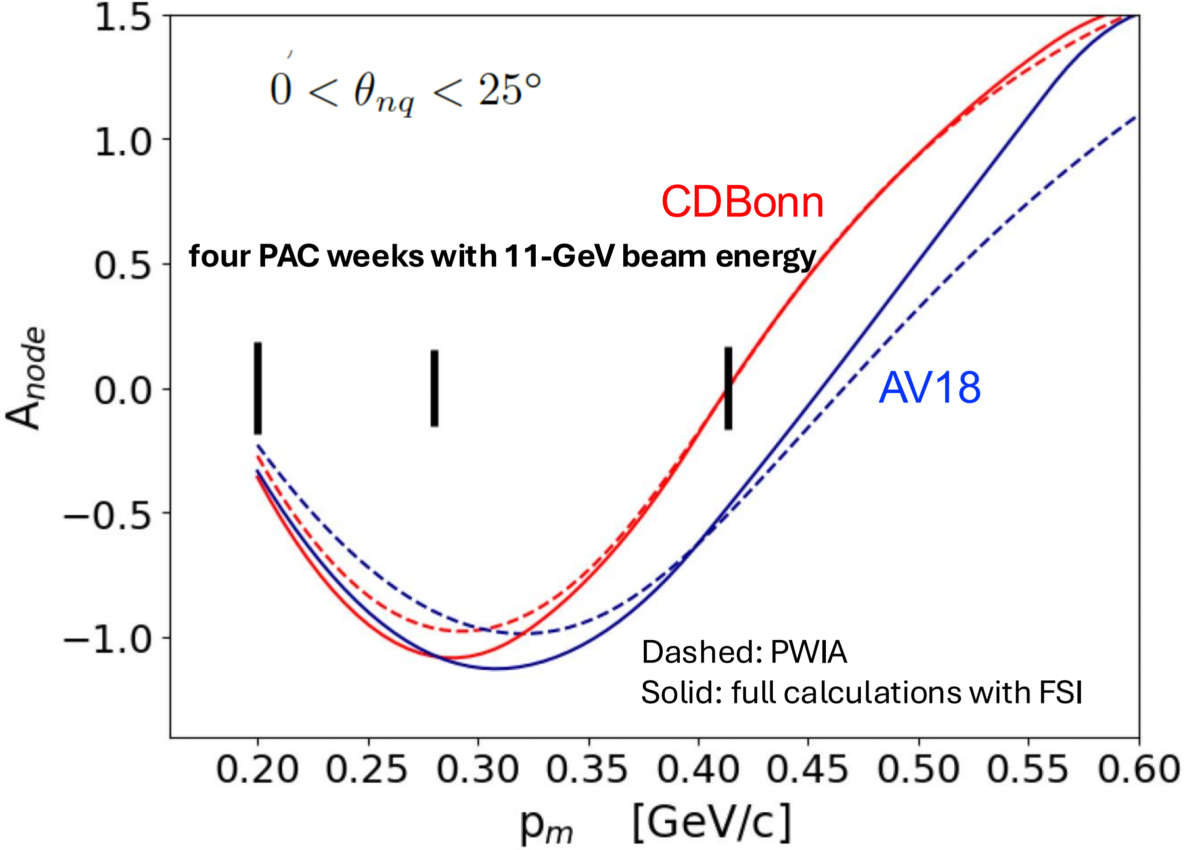

Remarks

- Large tensor polarization is the key enabling technology for this measurement.

- Quasi-elastic tensor observables provide direct sensitivity to the deuteron’s short-range structure and NN dynamics.

- A dedicated magnet/acceptance study is the critical next step toward a full experimental proposal.

Thank You!