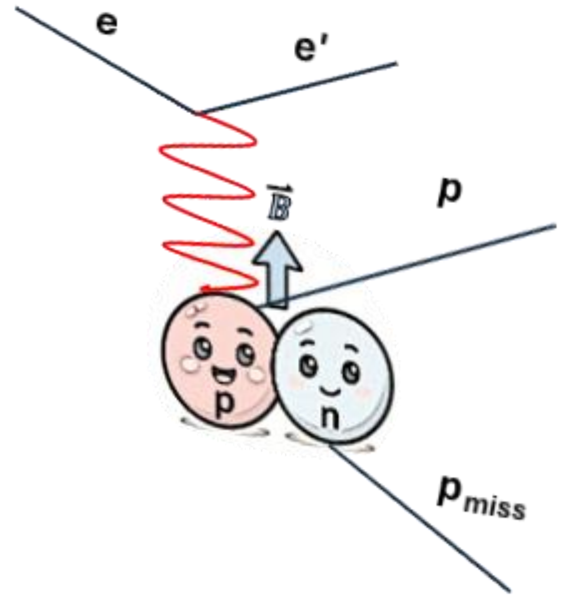
Exclusive electro-disintegration of tensor polarized deuterium

LOI

Nathaly Santiesteban
Hall A/C Collaboration Meeting

June 15, 2025



University of New Hampshire

Exclusive electro-disintegration of tensor polarized deuterium (PAC53)

LOI

E. Long* and S.N. Santiesteban†

University of New Hampshire, Durham, NH, USA

C. Yero*

The Catholic University of America, Washington, DC, USA

M. Jones*

Thomas Jefferson National Accelerator Facilty, Newport News, VA, USA

I.P. Fernando* and M. F. Hossain

University of Virginia, Charlottesville, VA, USA

M. Sargsian and H. Szumila-Vance*

Florida International University, Miami, FL, USA

S. Jeschonnek

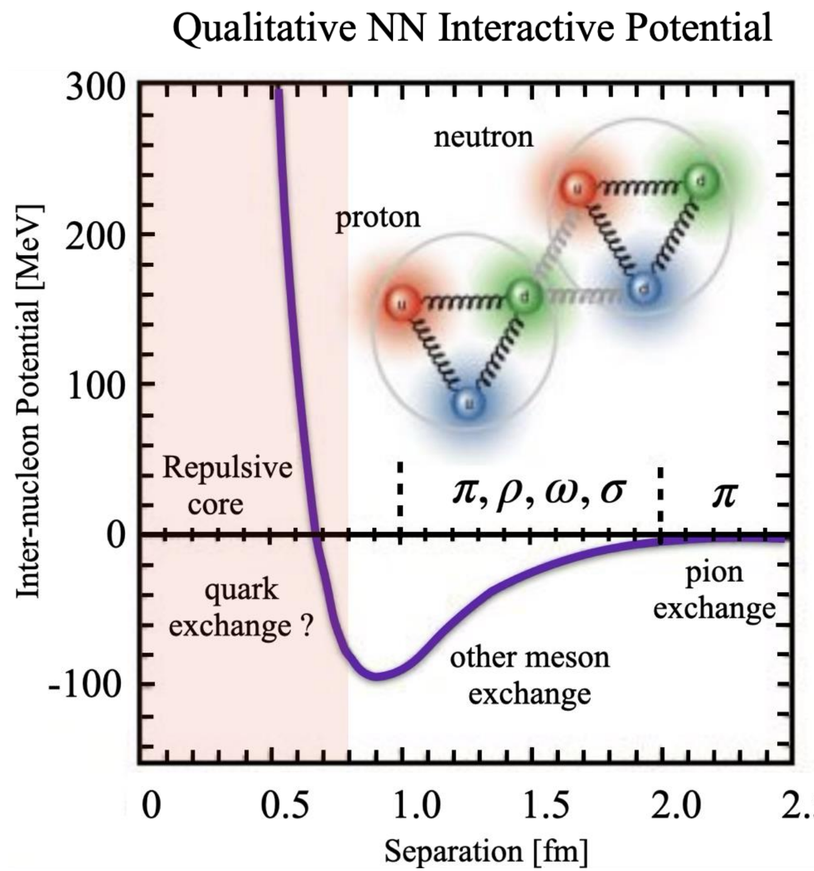
The Ohio State University, Lima, OH, USA

Why study the deuteron ?

- most simple *np* bound state to study *NN* interaction at sub-Fermi scale (repulsive core)

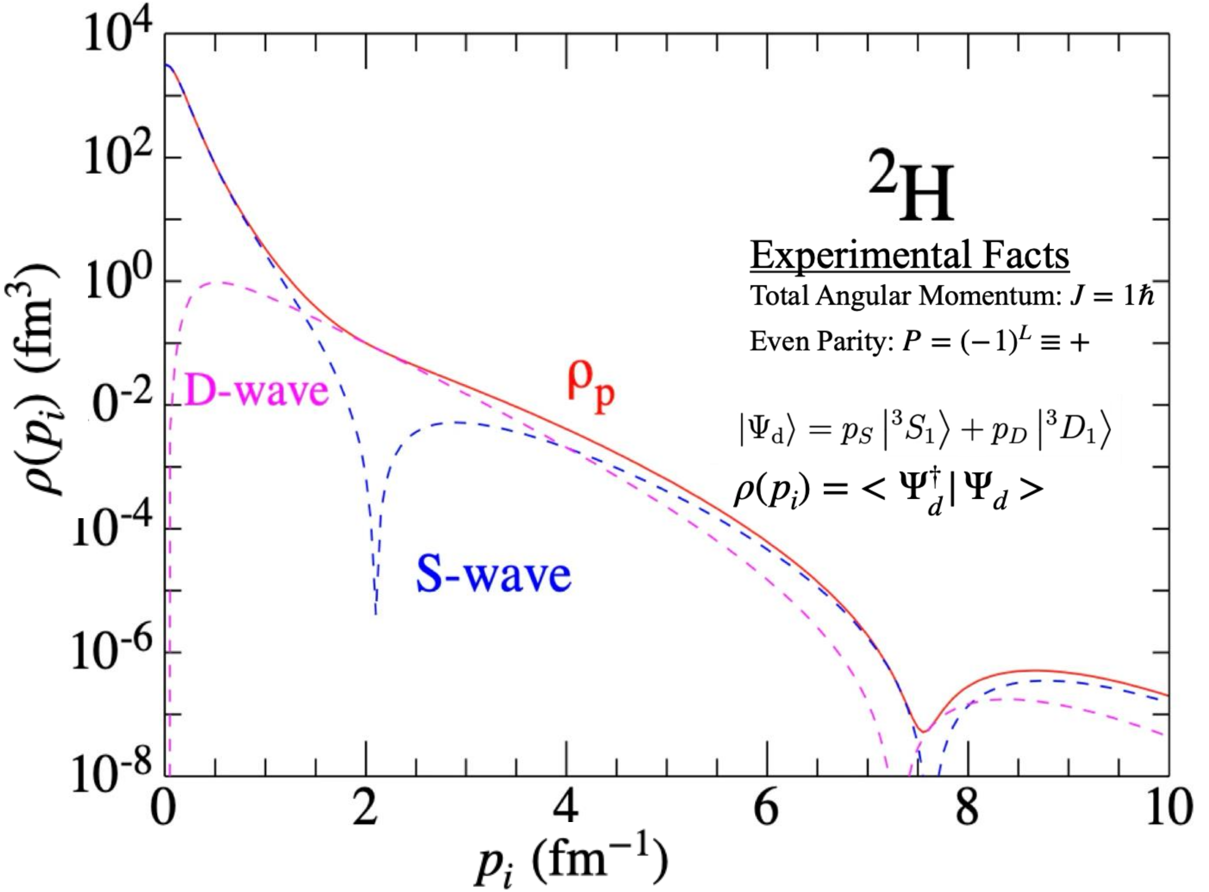
- elementary system for studying short-range correlations (SRC) in A>2 nuclei

- final-state interactions (FSI) reliable and well-understood which is a requirement for directly probing short-range



Deuteron Momentum Distribution

S-wave has node at $2\ \mathrm{fm}^{-1}$ that D-wave fills in to give a broad high-momentum shoulder out to $> 7\ \mathrm{fm}^{-1}$ before the second S-wave and first D-wave node.



***S*- and *D*-waves are not observables**

Objective: First measurement of the tensor asymmetry $\mathrm{A_{node}}$

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

$\mathrm{u(p_m)}$: S-partial wave of the deuteron
$\mathrm{w(p_m)}$: D-partial wave of the deuteron

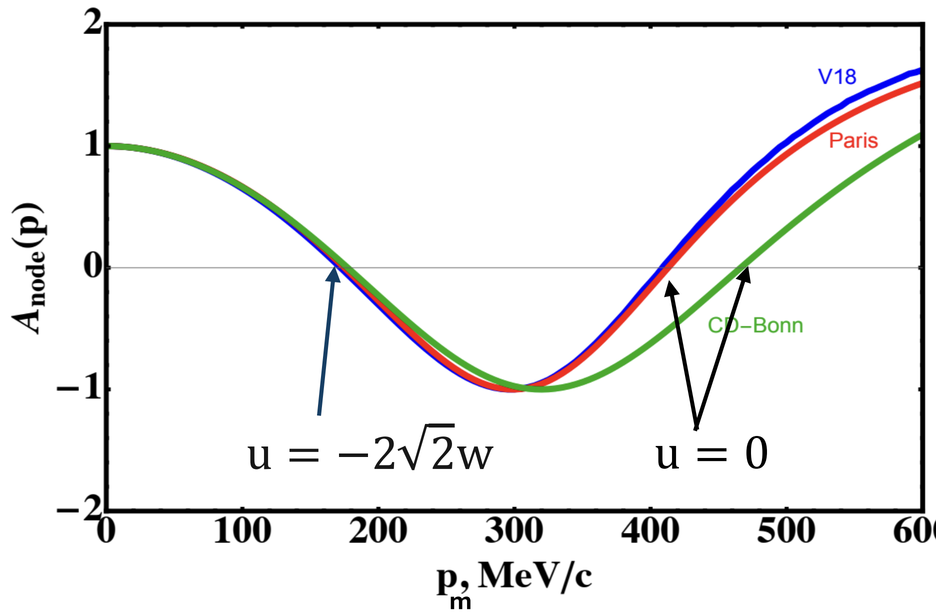
$$\mathrm{A_{node}} = 0, \quad \begin{cases} \mathrm{u(p_m)} = -2\sqrt{2}\mathrm{w(p_m)}, & \mathrm{p_m} \sim 180\ \mathrm{MeV} \\ \mathrm{u(p_m)} = 0, & \mathrm{p_m} \geq 400\ \mathrm{MeV} \end{cases}$$

M. Sargsian 2410.08384 (2024).

Probing the NN core

Objective: First measurement of the tensor asymmetry A_{node}

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



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).

Objective: First measurement of the tensor asymmetry $\mathrm{A}_{\mathrm{node}}$

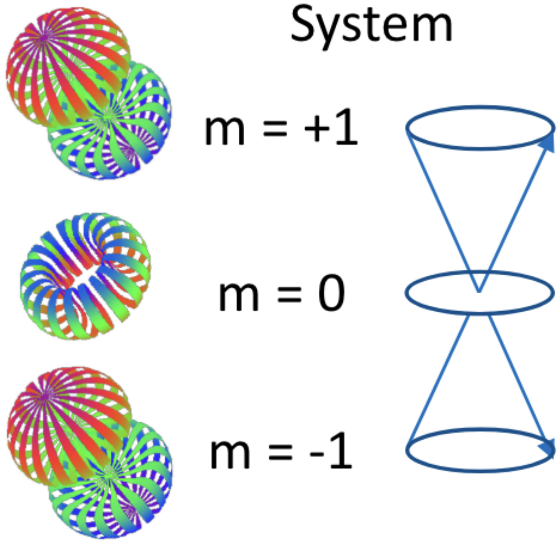
Direct measurement of the repulsive strength of the nuclear core ever done in electro-nuclear processes.

- 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 $\mathrm{p_m} > 300\ \mathrm{MeV}$
- measures the contribution of the S-partial wave of the deuteron with respect to the missing momentum

M. Sargsian 2410.08384 (2024).

Experimental Setup: Tensor polarized target

Spin-1
System



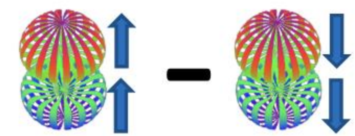
Deuteron in a magnetic field

Normalization

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

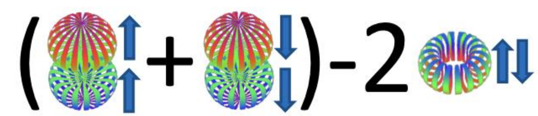
N(m): population density

Vector Polarization:



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

Tensor Polarization:



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

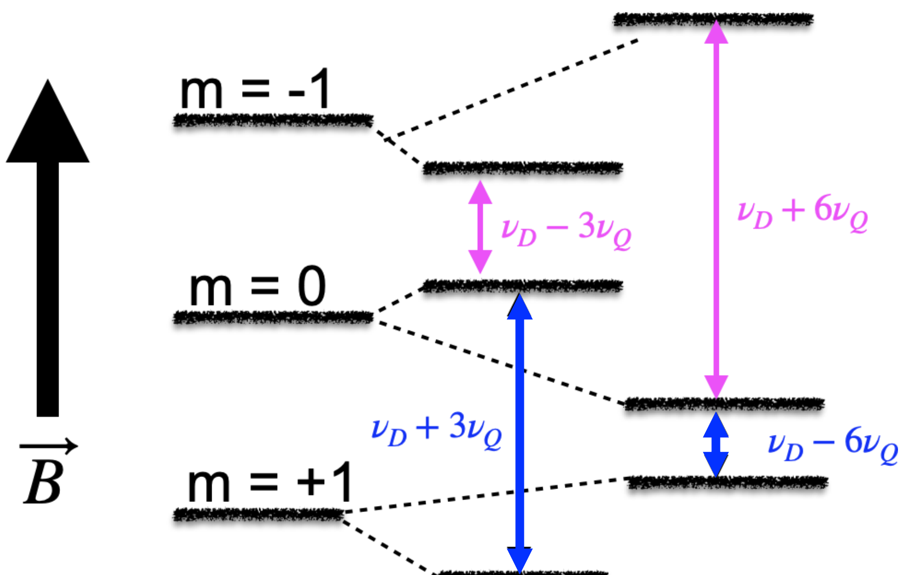
Need as large tensor polarization as possible
Currently assuming 30% tensor polarization

Experimental Setup: Tensor polarized target

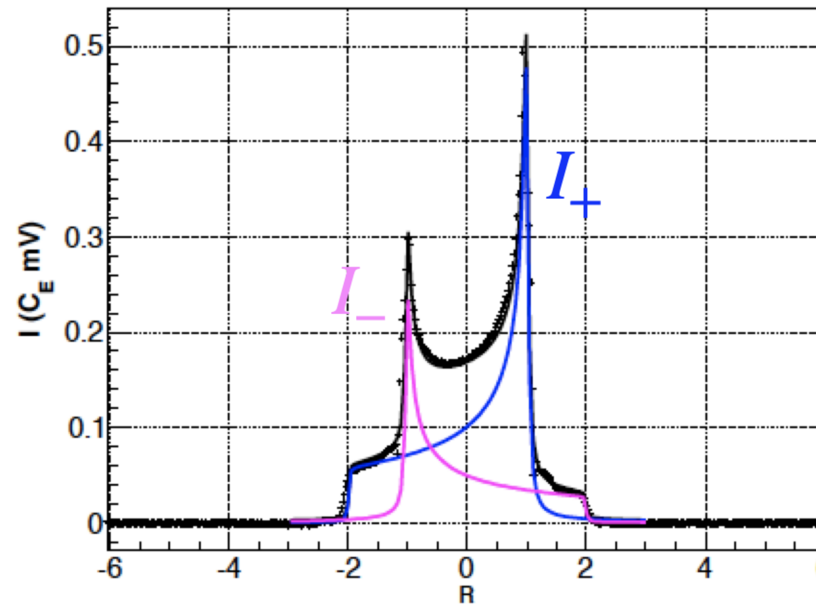
$$E_m = -h\nu_D m + h\nu_Q(cos^2\theta - 1)(3m^2 - 2)$$

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



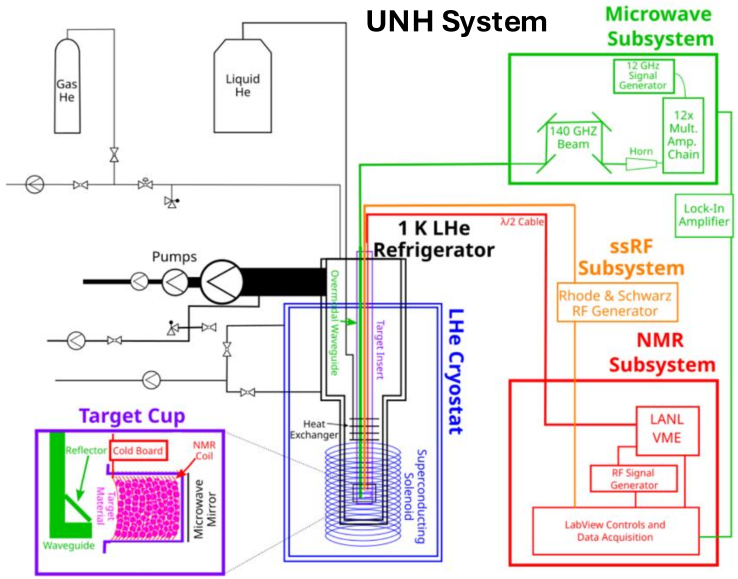
Deuteron NMR Line-shape.



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

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

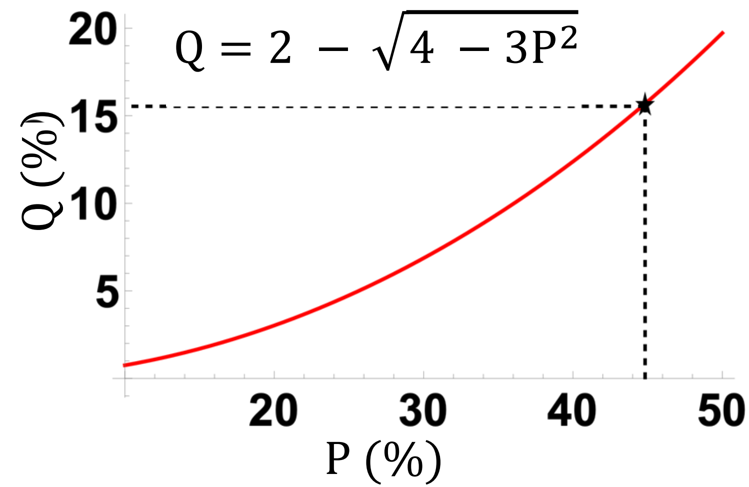
Experimental Setup: Tensor polarized target



Requirements

- High magnetic field (at Jlab typically 5T)
- Low temperature (~1K)
- Microwaves (induce spin transitions)
- CW NMR
- Irradiated material ND_3

Dynamic Nuclear Polarization

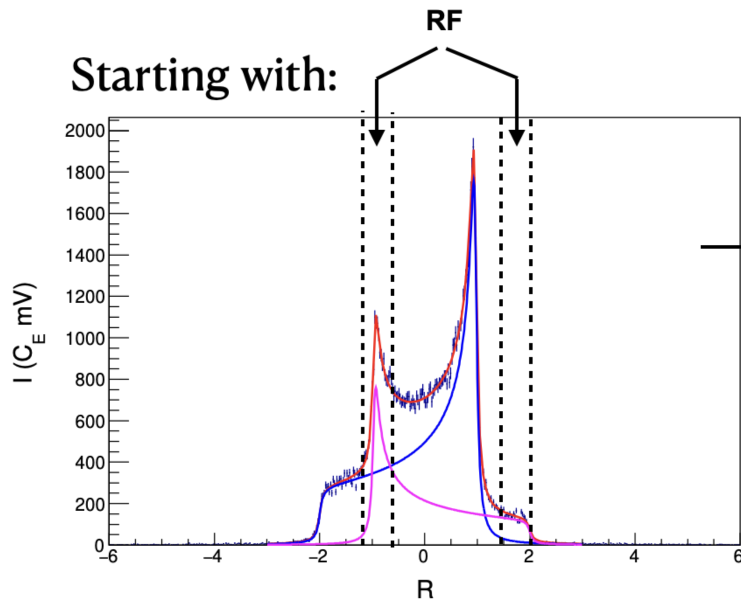


DNP [x] enhancement carries tensor polarization enhancement. Typical average vector polarization in Jefferson lab $P \sim 45\%$ which corresponds to $Q \sim 16\%$

Experimental Setup: Tensor polarized target

Semi-selective RF enhancing

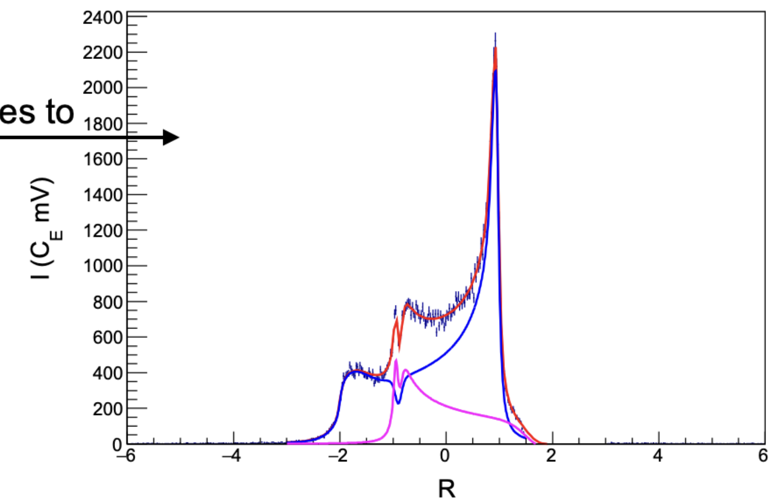
Starting with:



DNP polarized enhanced signal

Q = 19%

Tensor enhanced signal:

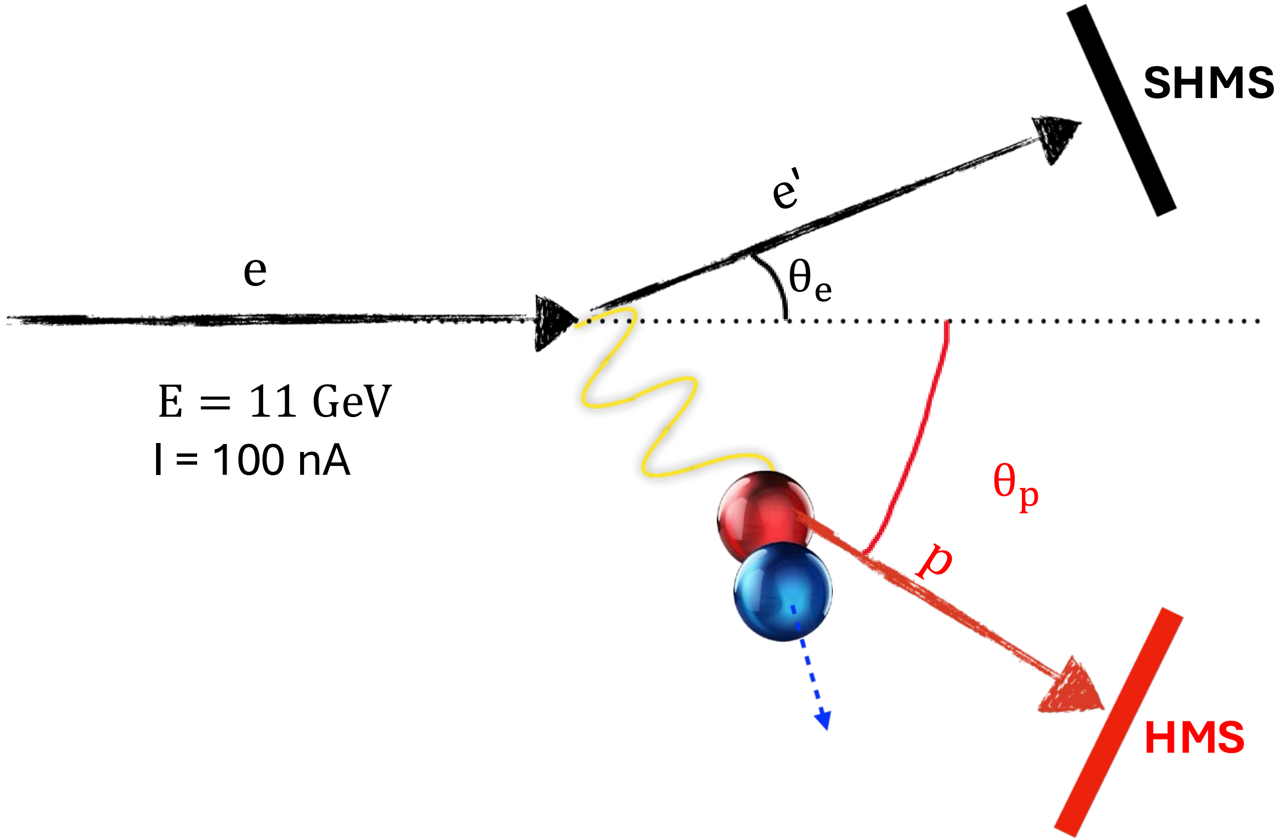


ss-RF enhanced signal

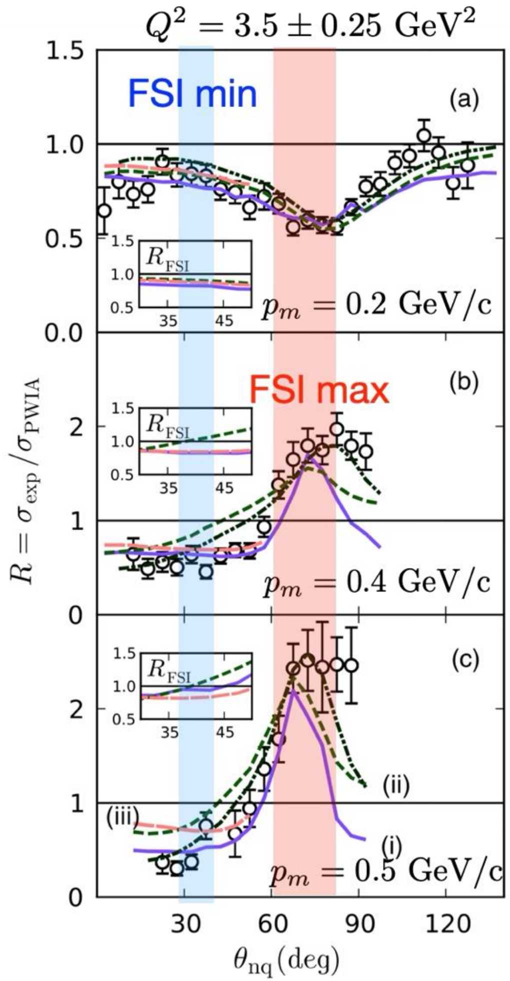
Q = 28.8%

We will use the same technique that the already approved inclusive experiments b_1 and A_{zz} with **two target cups**.

Experimental Setup: Detectors configuration



Experimental Setup: Detectors configuration



controlling final-state interactions (FSI)

CD-Bonn FSI
(Calculations: Misak Sargsian)

Misak M. Sargsian Phys.Rev.C 82014612 (2010)

JVO Model
(Calculations: J.W. Van Orden & S. Jeschonnek)

S.Jeschonnek and J. W. VanOrden Phys.Rev.C80054001 (2009)

Paris FSI
(Calculations: J.M. Laget)

J. Laget Phys.Lett.B60949 (2005)

Paris FSI+MEC+IC
(Calculations: J.M. Laget)

J. Laget Phys.Lett.B60949 (2005)

DATA

FSI strongly anisotropic (angular-dependent):

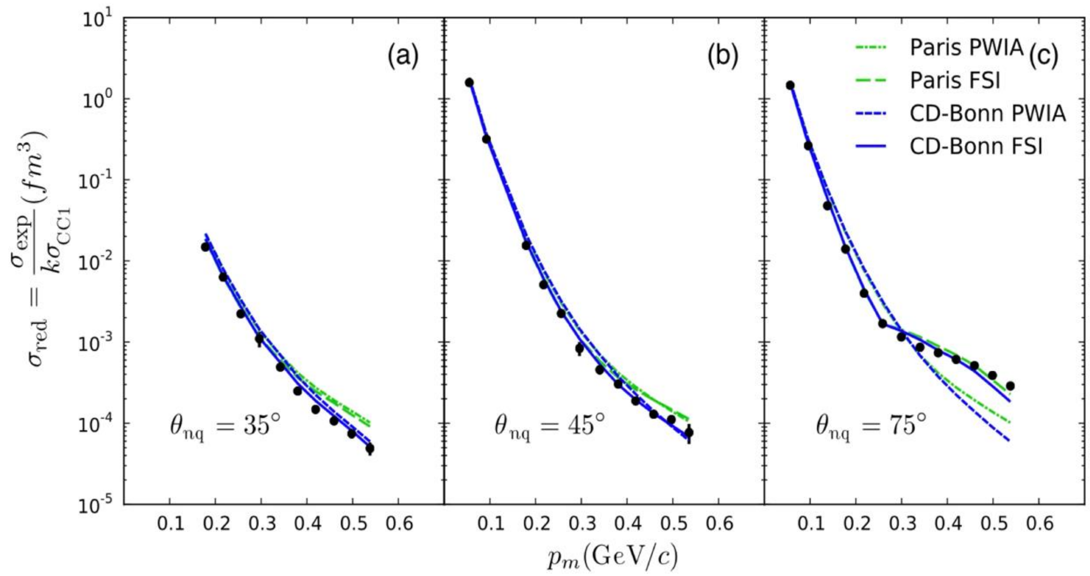
- Sargsian uses GEA, Laget uses fully relativistic
- FSI peak at $\theta_{nq} \sim 70^o$
- minimal FSI at $\theta_{nq} \sim 35^o - 45^o$

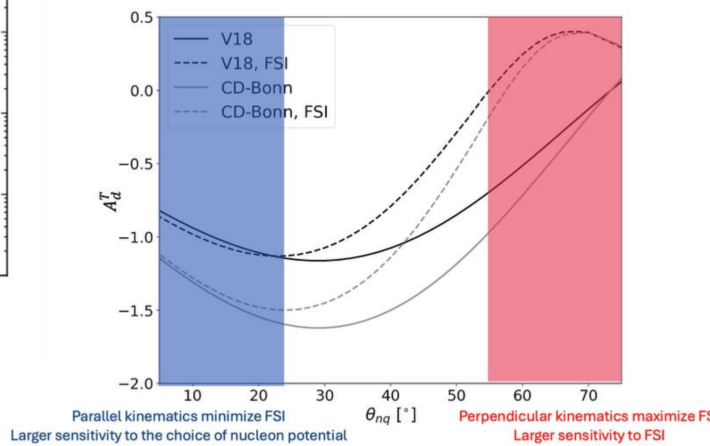
Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)

Experimental Setup: Detectors configuration

controlling final-state interactions (FSI)

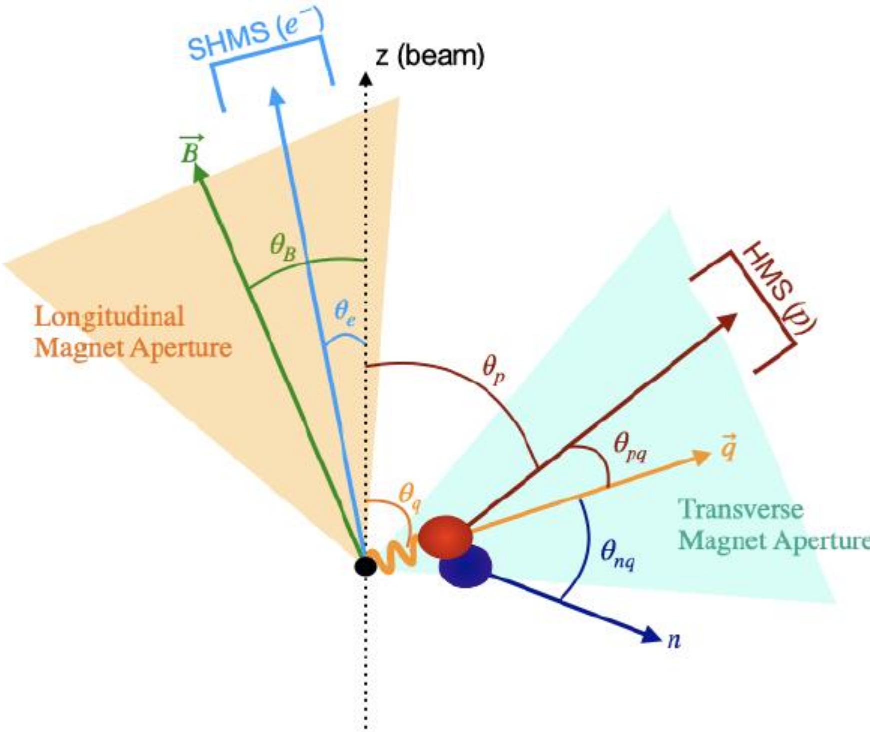
Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)





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

Experimental Setup: Detectors configuration

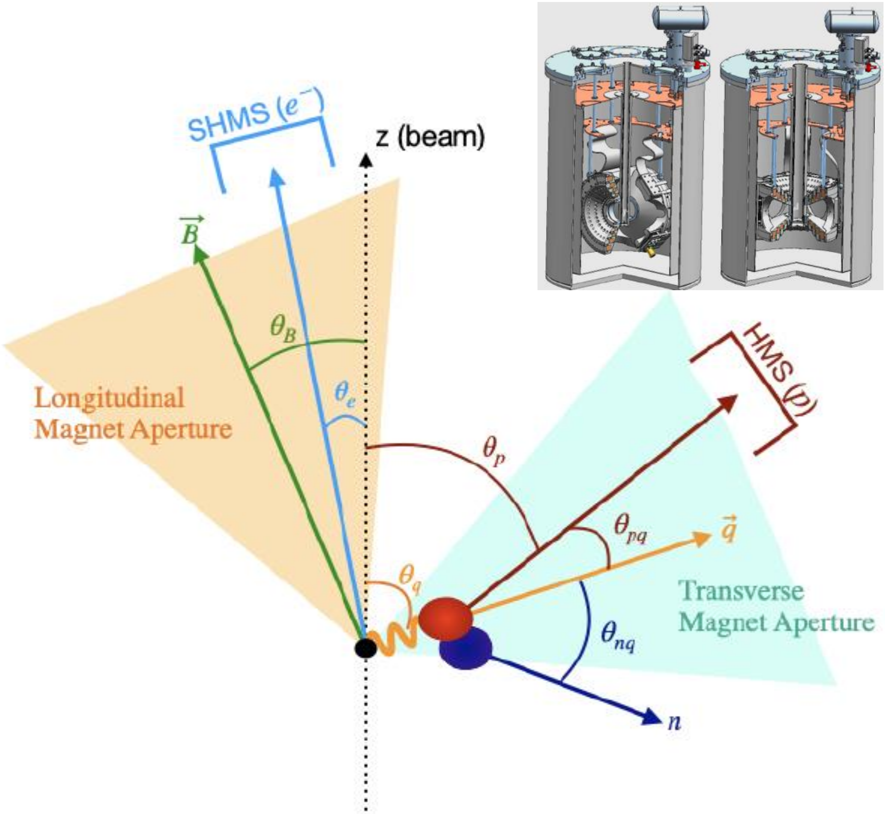


controlling final-state interactions (FSI)

Meaning: $\theta_p > 50^o$

	k_f (GeV/c)	θ_e (deg)	p_f (GeV/c)	θ_p (deg)	P_{miss} (MeV/c)	Q^2 (GeV/c)^2
central setting	10.46	6.54°	1.06	69.83°	–	–
kinematic coverage	10.1–10.8	5–8	0.95–1.2	65–75	100-500	1–2

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.

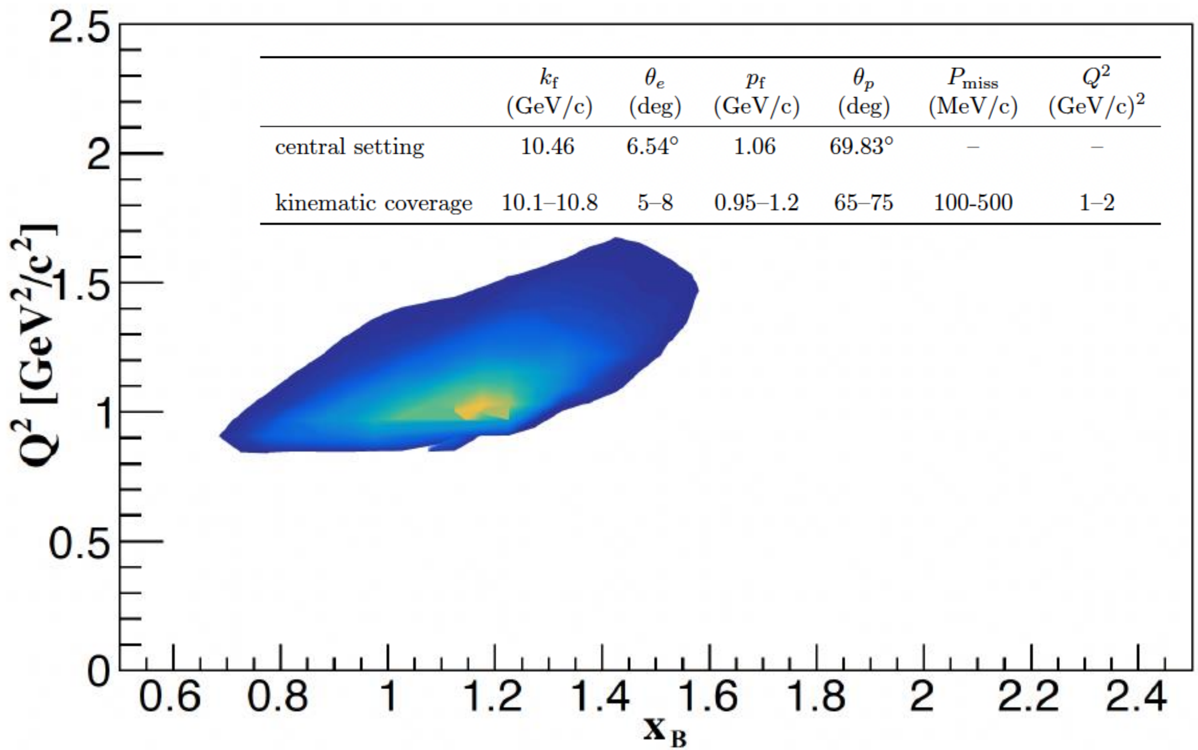
Two possible avenues:

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

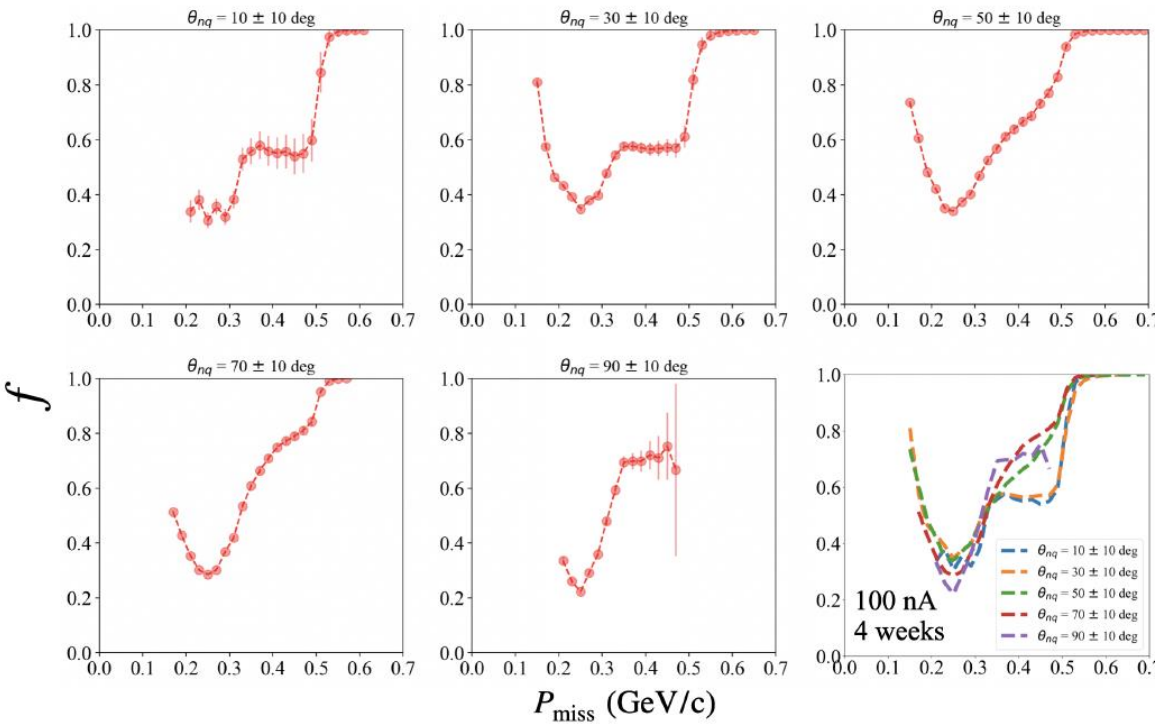
Experimental Setup: Kinematics Settings



	k_f (GeV/c)	θ_e (deg)	p_f (GeV/c)	θ_p (deg)	P_{miss} (MeV/c)	Q^2 (GeV/c)^2
central setting	10.46	6.54°	1.06	69.83°	–	–
kinematic coverage	10.1–10.8	5–8	0.95–1.2	65–75	100-500	1–2

Target material: $\mathrm{ND_3}$ in a He bath

Dilution factor: $$f = \frac{N_D \sigma_D}{N_D \sigma_D + N_N \sigma_N + \sum_A N_A \sigma_A}$$



What do we measure?

Full cross-section:

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

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:

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

What do we measure?

Our asymmetry:

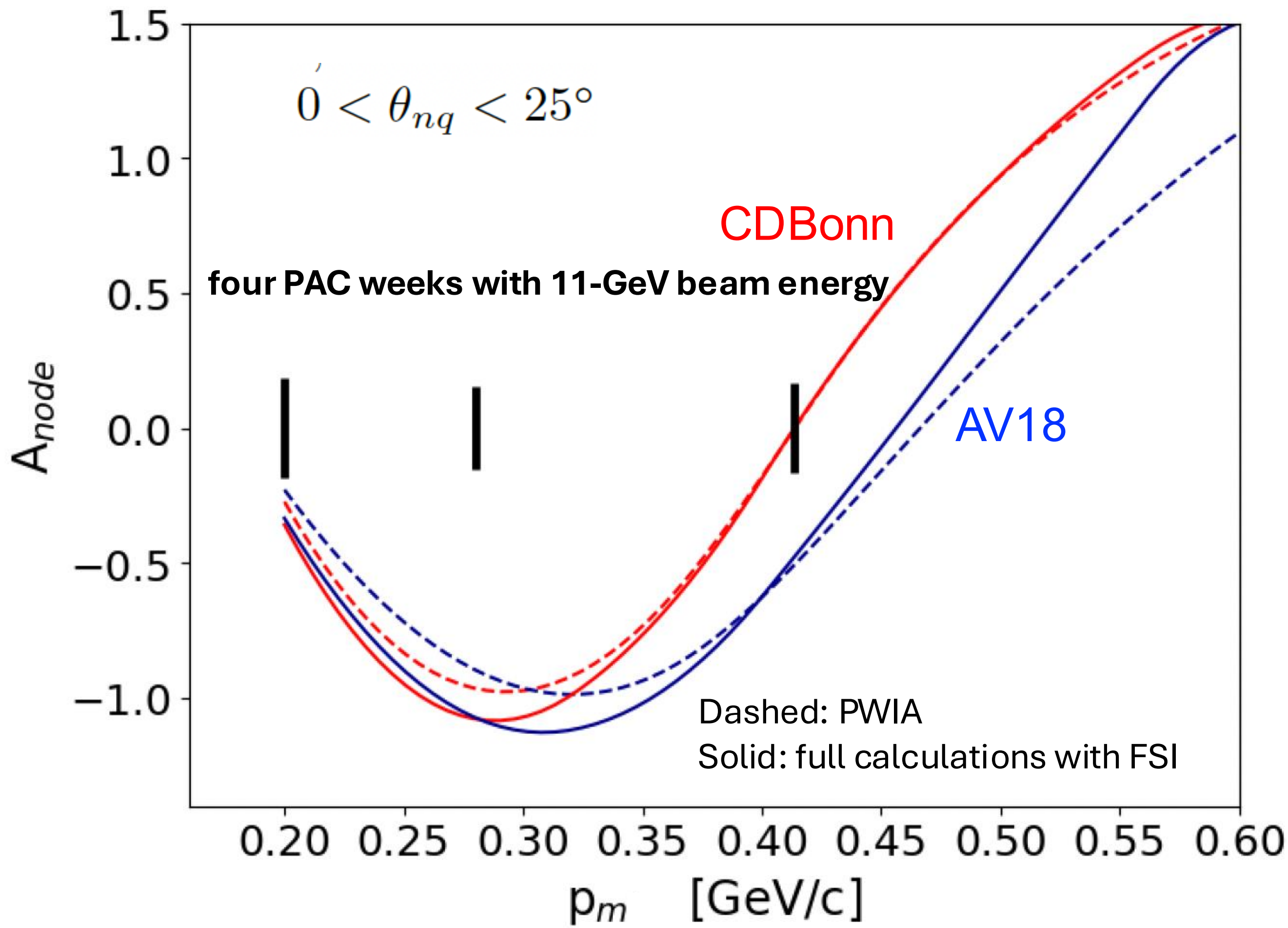
$$A_{node} = \left(1 - \frac{4}{(3\cos^2\theta_N - 1)Q}\right) + \frac{4}{(3\cos^2\theta_N - 1)Q}\left(\frac{\sigma(P,Q) + \sigma(-P,Q)}{\sigma(P,0) + \sigma(-P,0)}\right)$$

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

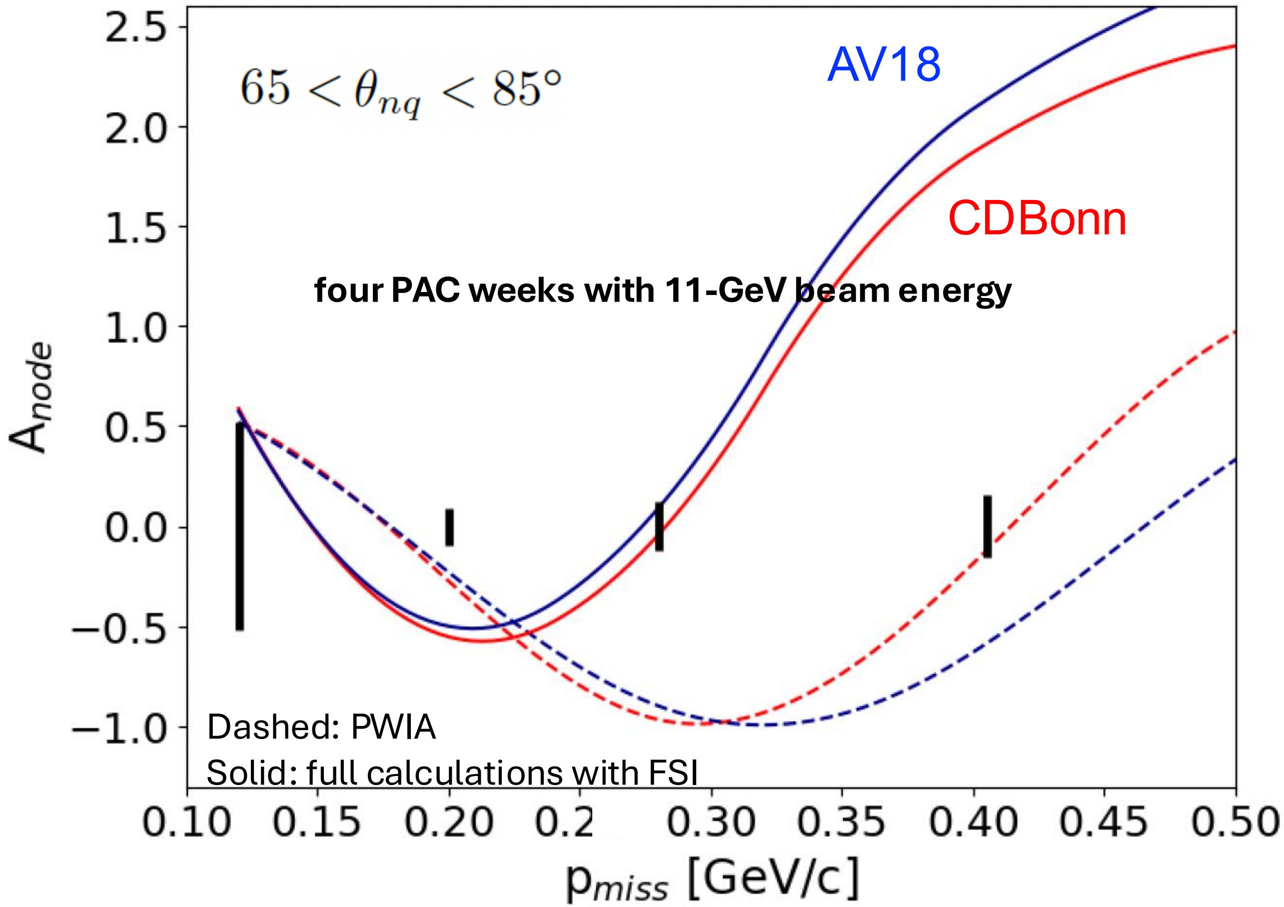
Relating to the tensor asymmetry

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

Expected measurement



Expected measurement

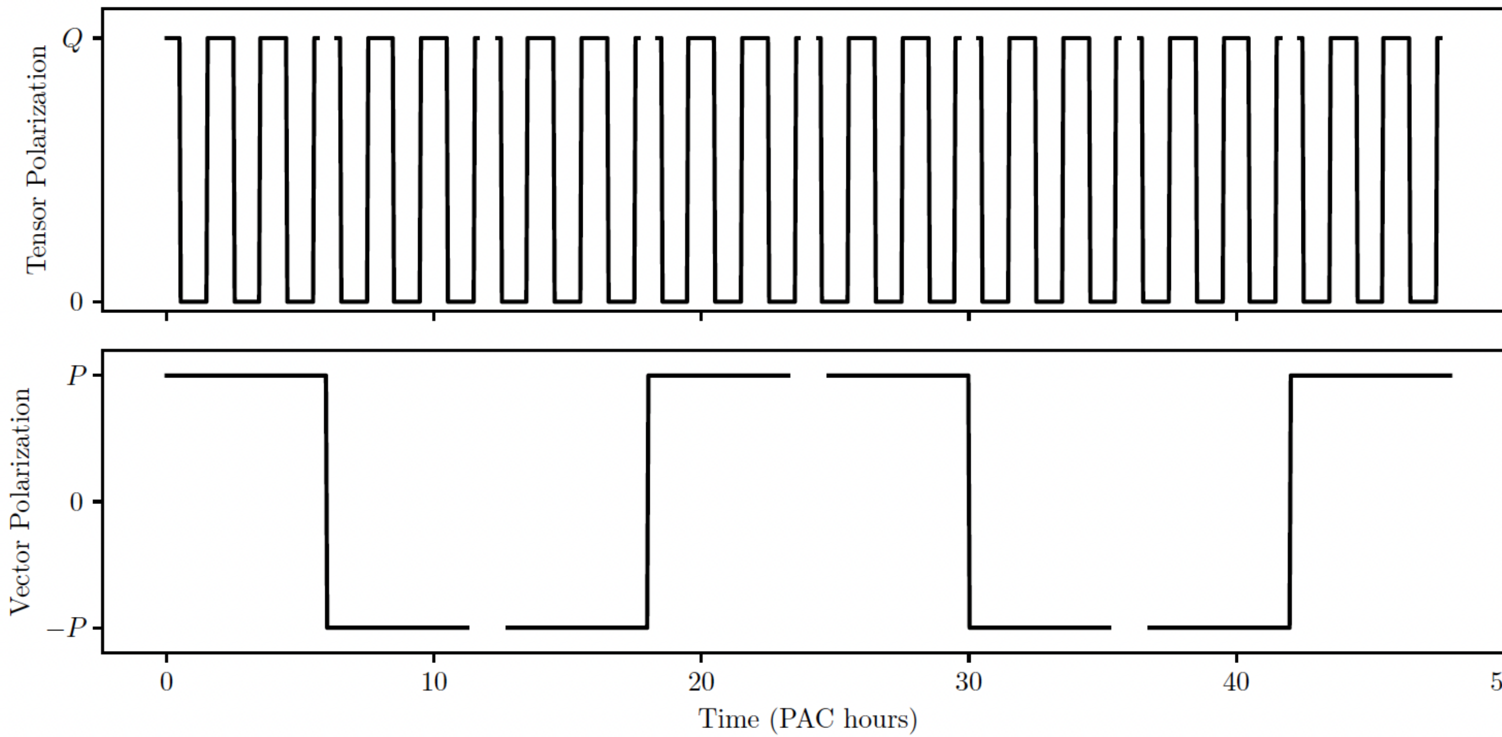


Major source of uncertainties

Source	(%)
Polarization	7
Dilution and Packing fraction	6
Radiative corrections	3
Charge determination	1
Trigger/tracking Efficiency	1
Acceptance	0.5

Based on previous experiments.

Need to fully understand overhead conditions



Theory Support

Professor Misak Sargsian has been collaborating with our team for over a year. His recent publications reflect the impact of this experiment to his work.

M. Sargsian 2410.08384 (2024).

Professor Sabine Jeschonnek will help us to motivate studies to measure vector-polarized asymmetries of deuterons at the same kinematics to disentangle the effects of final state interactions and ground state properties. This observable is non-zero only with FSI, and when measured out-of-plane. Thus, it is more sensitive to details of the FSI.

Executive Summary

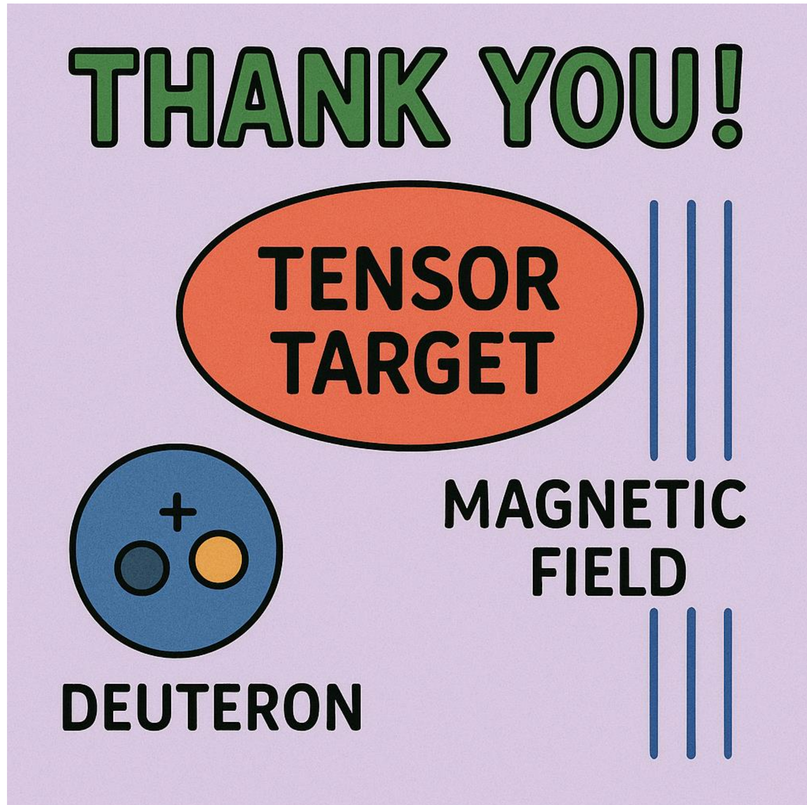
The deuteron, the most fundamental nuclear system, possesses a wave function primarily dominated by the proton-neutron (pn) component. Consequently, it serves as a valuable tool for investigating diverse aspects of the pn strong interaction. One such area is the study of the pn system at short distances, which offers insights into fundamental questions of nuclear dynamics. These include the relativistic description of nuclear structure, the dynamics of the repulsive core in nucleon-nucleon (NN) interactions, the significance of non-nucleonic degrees of freedom, and the transitions between hadrons and quarks at very short distances. Employing a tensor-polarized deuteron target in electroproduction reactions unlocks new possibilities for exploring various phenomena in short-range hadronic and nuclear physics. Furthermore, proton-neutron (pn) potentials, including AV18 and CD-Bonn, exhibit significant discrepancies in their predictions at high momentum, corresponding to short internucleon distances. Theoretical investigations indicate that these differences could be discerned and quantified through specialized electrodisintegration experiments employing a tensor-polarized target.

We will measure the tensor asymmetry $A_{node} = 1 + \frac{2A_d^T}{(3\cos^2\theta_N - 1)}$. A_{node} is sensitive to the U-wave, specifically to the place where it vanishes, since $A_{node} \sim U^2 + 2\sqrt{2}UW$, it will allow us to access two nodes: i) $U = -2\sqrt{2}W$ and ii) $U = 0$. This measurement will provide a novel test of our understanding of the S-wave, and will help us to evaluate the NN potentials in a region of significant disagreement.

In this Letter of Intent (LOI), we propose to measure the exclusive tensor-polarized electrodisintegration of the deuteron in Hall C. An 11-GeV electron beam will be incident on a solid tensor-polarized ammonia (ND_3) target. The scattered electrons will be detected by the Super High Momentum Spectrometer (SHMS) in coincidence with the knocked-out protons detected by the High Momentum Spectrometer (HMS), and the recoil ("missing") neutrons will be reconstructed from momentum conservation. We will focus in the kinematic region that covers $1 < Q^2 < 2$ GeV^2/c^2, missing momentum $0.1 < P_{\text{miss}} < 0.5$ GeV/c, and recoil angle $0 < \theta_{nq} < 90°$.

Although the differences between the two NN potentials might seem small, both parameterizations predict significantly different strengths for high momenta above 400 MeV/c. The strong predominance of pn short-range correlations (SRCs), which are associated with the tensor component of NN interaction inside SRCs, has increased the motivation to understand the momentum distributions. The high-momentum part of the nuclear wave function where the tensor interaction predominates could have a substantial impact on the dynamics of asymmetric nuclei and have important consequences for the understanding of superdense nuclear matter and neutron stars.

We will request a total of four PAC weeks with 11-GeV beam energy. This work will complement and contribute to Jefferson Lab's larger tensor effort, which continues to draw interest from the theoretical spin, polarized target, and experimental spin groups.


THANK YOU!
TENSOR
TARGET
MAGNETIC
FIELD
DEUTERON