Tensor Physics in Motion: Current Activities and Emerging Directions

Nathaly Santiesteban
University of New Hampshire
October 13, 2025

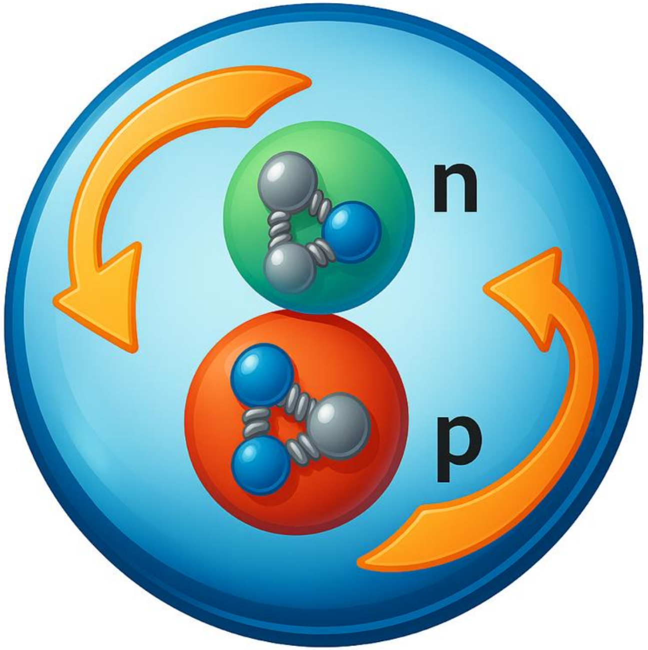
Deuteron
Cross-Section

Vector Contribution
P: Vector Polarization

$$\sigma_D \sim \sigma_U + P \cdot \sigma_V + Q \cdot \sigma_T$$

Unpolarized
Cross-Section

Tensor Contribution
Q: Vector Polarization



The tensor contribution (σ_T) remains one of the least explored contributions in the deuteron cross-section

Tensor Contribution in the Deuteron

Nuclear Structure Insights

- Unique to spin-1 systems
- Reveals the non-central component of the nuclear force
- Tests models of nucleon–nucleon correlations

Toward the Partonic picture

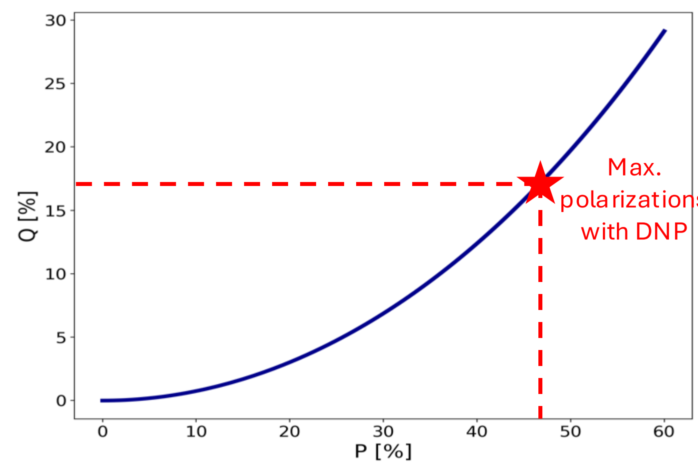
- Probes sub-nucleonic (quark-gluon) structure
- Constrains theoretical frameworks (from nuclear to QCD scales)
- Links hadronic and partonic regimes

These observables enable more refined studies of QCD and provide new insights into deuteron, illuminating the interplay between QCD dynamics and nuclear structure

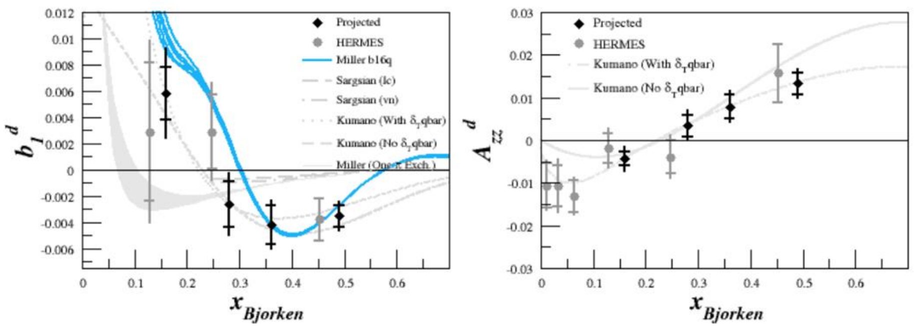
Enhancing Vector Polarization with Dynamic Nuclear Polarization (DNP)

- Common target: deuterated ammonia (ND3)
- DNP enhances the vector polarization to up to P ~ 50%
  Paramagnetic centers in the material induce spin transitions through the application of microwaves to the sample, which is already in a magnetic field at very low temperatures.
- 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)

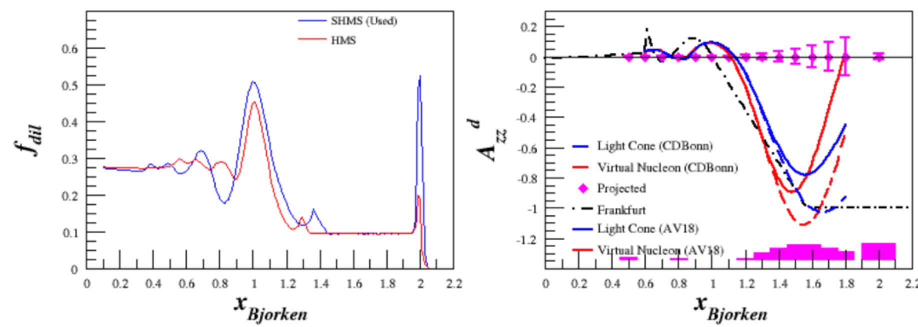


Approved experiments: b_1 and A_{zz}



[The Deuteron Tensor Structure Function b1]()

Scientific Rate: A-
Hall C
Days awarded: 41

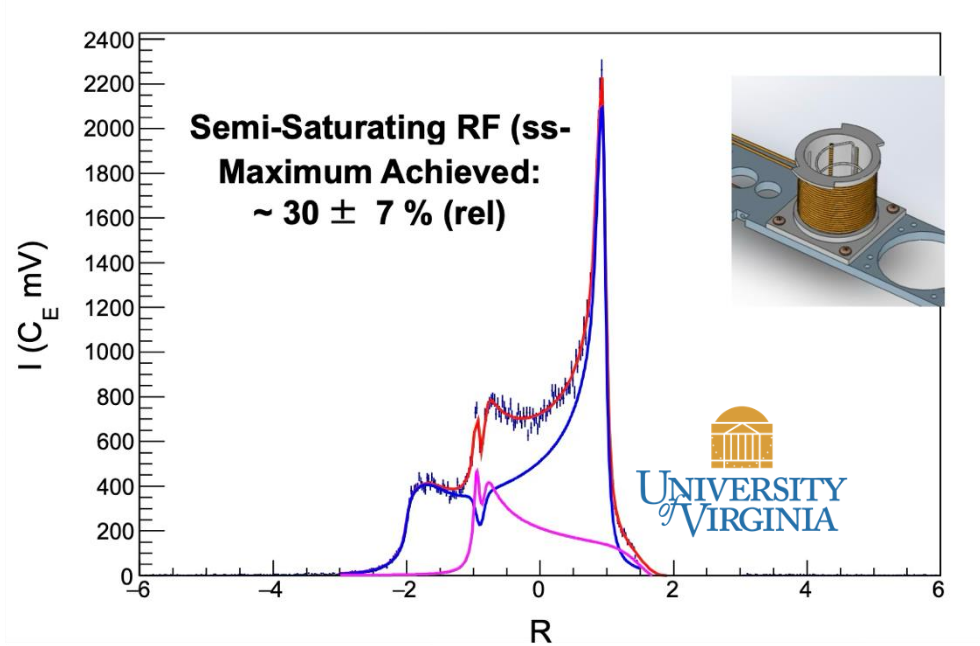


[Measurements of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries]()

Scientific Rate: A-
Hall C
Days awarded: 45

Expected to run with tensor polarizations ~28-30%

Enhancing Tensor Polarization with Semi-Saturating RF



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}.

Summary of Tensor Target Global Status
See next talk: Dustin Keller

Current Target Developments

University of Virginia
Overview talk: Jordan Roberts

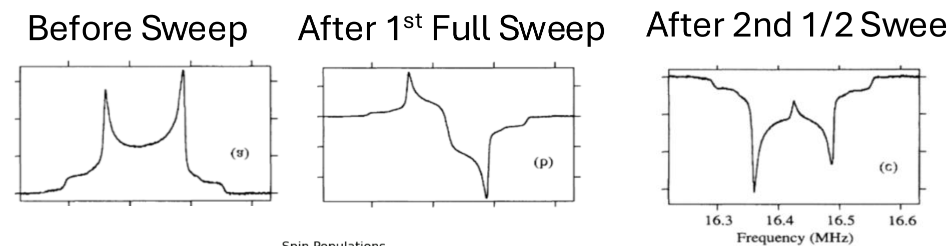
University of New Hampshire
Overview talk: Karl Slifer

See talks:
Md Forhad Hossain, Devin Say, Ian Cruz Sujan Subedi, Shane Clements

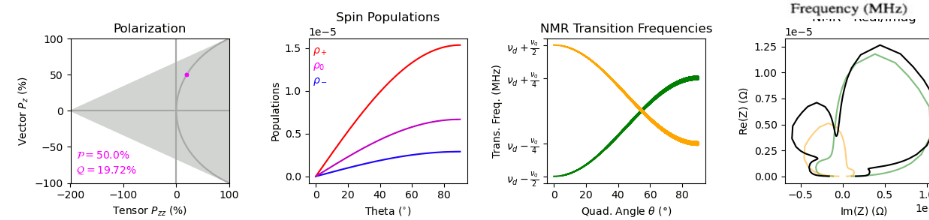
See talks:
Michael McClellan, Chhetra Lama

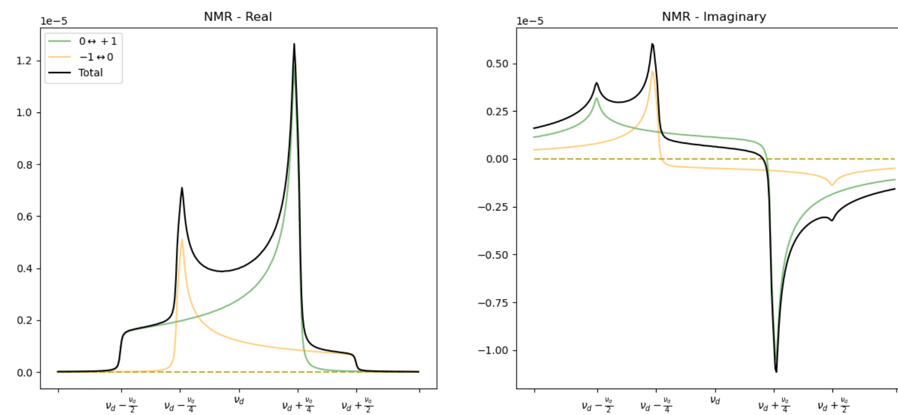
Simulation of the NMR Lineshape at UNH

Hautle et al, PRB **46**, 6596 (1992)
AFP Data on d-Butanol:



Current Status:
Able to simulate
- ✓ Arbitrary P and Q
- ✓ ssRF with arbitrary power, width, and shape (shown in gray)
- ✓ AFP
- ✓ Noise + Q-curve





Ongoing Work:
- ❑ Rewriting code to run on GPUs
- ❑ Dynamic simulation with full DNP rates + time-dependent spin diffusion + time-dependent ssRF

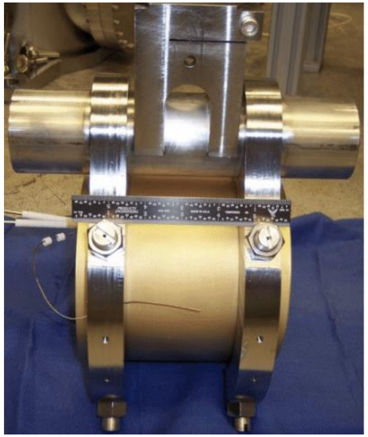
Expected Completion: December '25

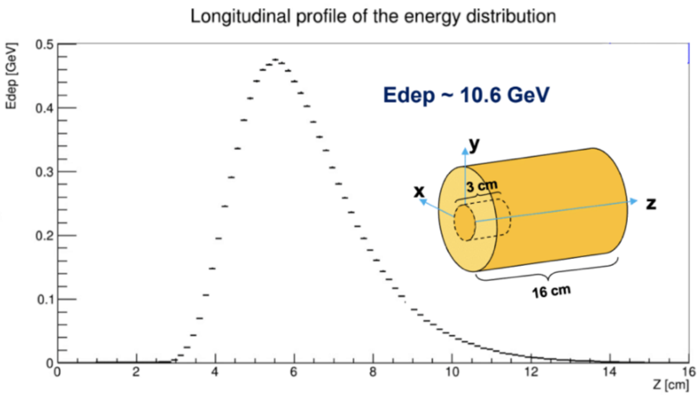
Developed by Elena Long

Faraday Cup for b_1 and A_{zz}

The tensor-polarized target experiments require monitoring relative changes in the beam current at the 0.01% level on an hourly basis.

The current plan is to re-purpose and commission the W–Cu calorimeter previously used in Hall C.

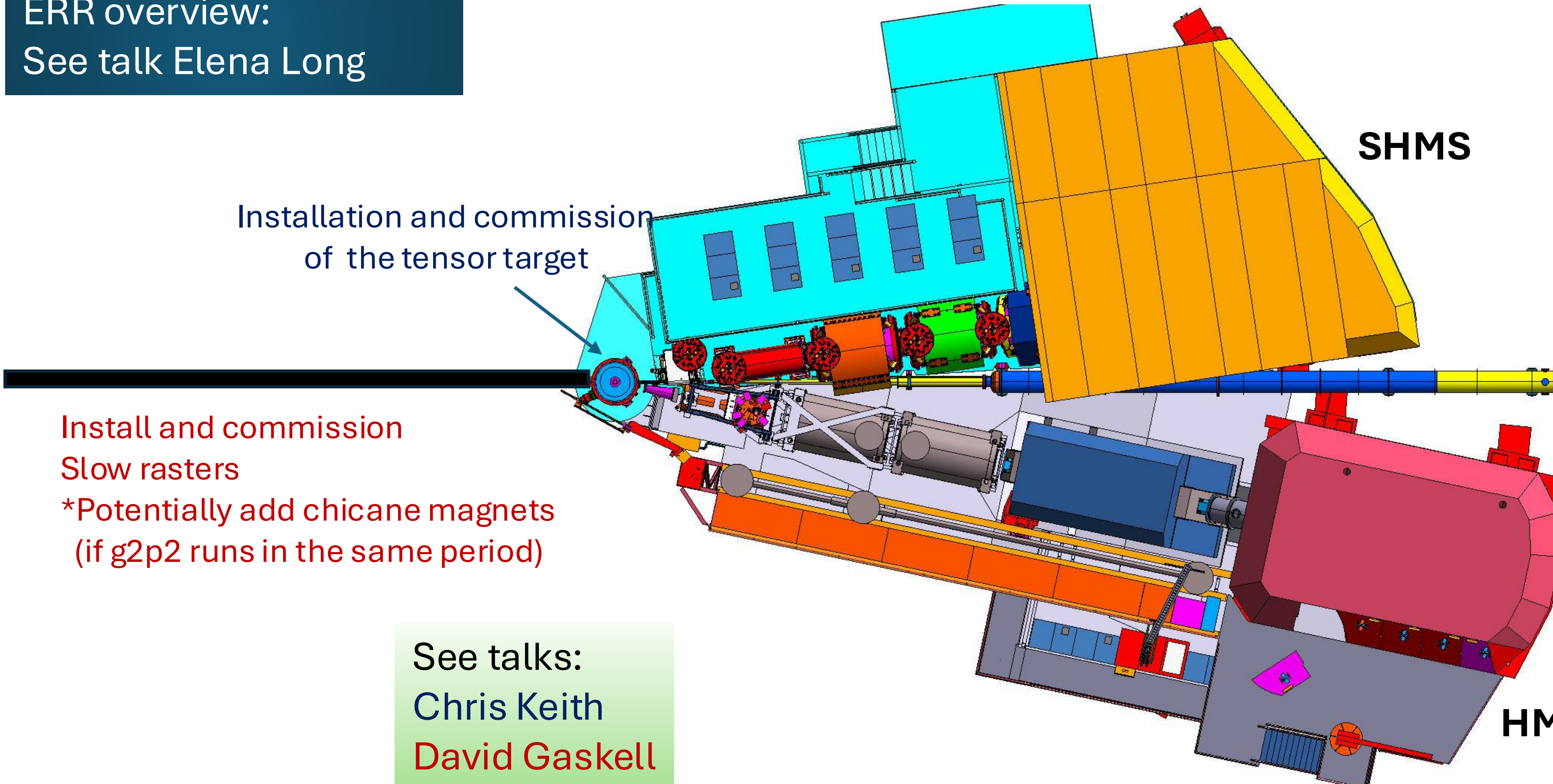




Courtesy of Hector Chinchay

See talks:
Dave Mack and Hector Chinchay

ERR overview:
See talk Elena Long



Installation and commission
of the tensor target

Install and commission
Slow rasters
*Potentially add chicane magnets
(if g2p2 runs in the same period)

See talks:
Chris Keith
David Gaskell
Hanjie Liu

Prepare electronics and trigger

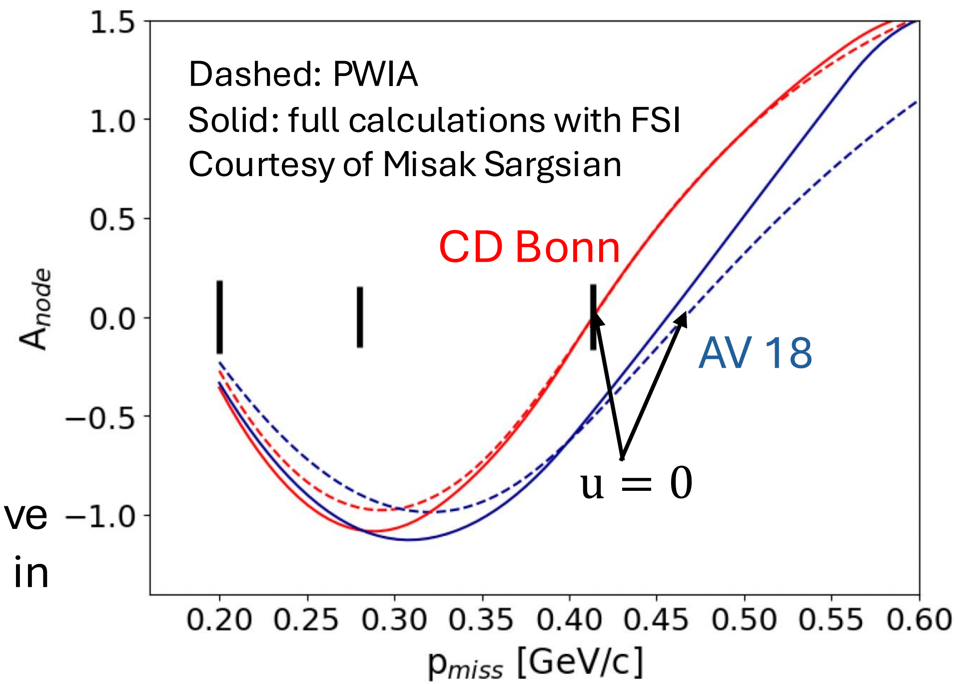
Beyond the scope of the b_1 and A_{zz} experiments

LOI: Exclusive Electro-Disintegration of Tensor Polarized Deuterium

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

$$A_{\mathrm{node}} = 0,$$

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



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

See Carlos Yero's talk (Tomorrow)

TMD Studies with SIDIS with a Tensor 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

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

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

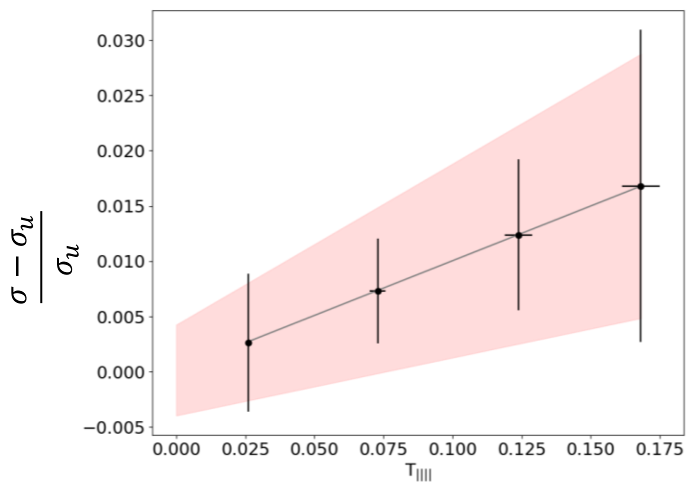
Longitudinally Polarized Target

Courtesy of A. Bacchetta (2023).

tensor

Completely unexplored

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



"Spin-1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12" CLAS12 Approved Analysis (CAA, Fall 2024)

Data (RG-C): Polarized deuterium target (ND_3 via DNP), with maximum tensor polarization $Q_{\max} \approx 20\%$

Goal: To quantify the tensor contribution to Semi-Inclusive Deep Inelastic Scattering (SIDIS) processes($eD \to e'\pi^{\pm}X$)

See talks: Mohammad Farooq and Hector Chinchay

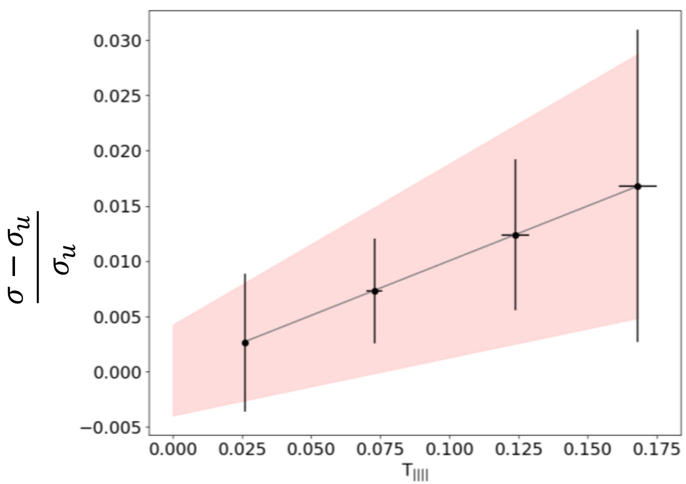
More about RG-C: Sebastian Kuhn's talk

tensor

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

Completely unexplored

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



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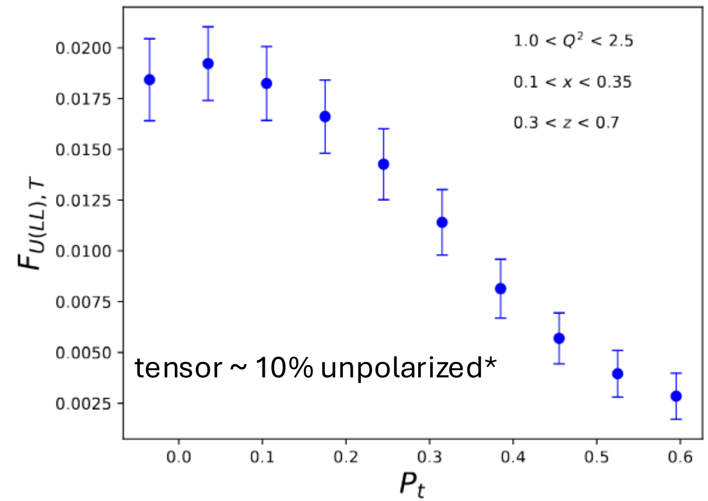


" Spin-1 TMDs and Structure Functions of the Deuteron" LOI12-24-002 PAC 52, 2024

Goal: Dedicated Measurement in Hall C ($eD \to e'\pi^{\pm}X$)

See Nathaly Santiesteban's talk (Tomorrow)

The prospective (tentative) plan with transversely tensor polarized ND_3 target

A slide from Ishara Fernando and Dustin Keller

- Proposals for JLab PAC (2026)

$$F_{U(TT),T}^{\cos(2\phi_h-2\phi_{LT})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2} f_{1TT} D_1\right]$$

$$F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2} g_{1TT} D_1\right]$$

$$F_{U(TT)}^{\cos(2\phi_{TT})} = \mathcal{C}\left[\frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{MM_h} h_{1TT} H_1^{\perp}\right]$$

First Generation Tensor Experiments

Using lower temps and lower intensity: 1K and 5T

To run sequentially after the data taking for $F_{U,(LL)}$

Exploring
(needs to be discussed with JLab Target group

- Proposals (2027<)

  * An addition to RGH (Hall B) program: Gluon Transversity in SIDIS

  Note: Complementary to the measurement with DY (FNAL)
  [Stage 1 Approval (March 2025) https://pac.fnal.gov/wp-content/uploads/2025/04/PAC_Report_March_2025_Public.pdf

  Needs to be discussed with RGH

  * Hall A (SoLID)

  With high statistics

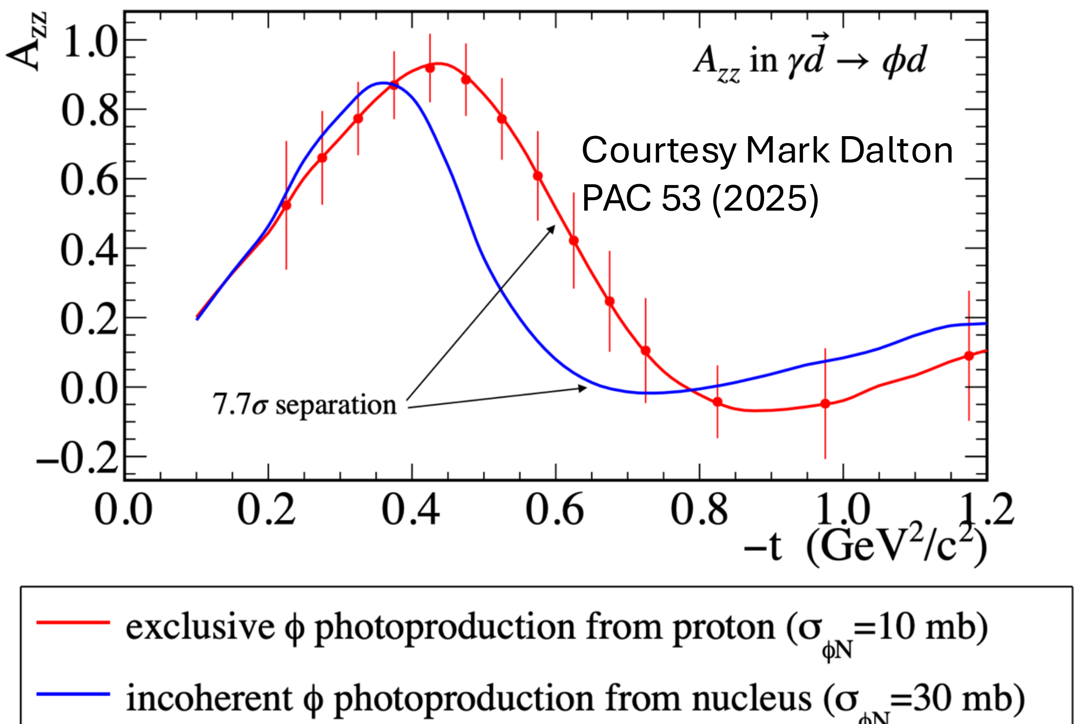
  Needs to be discussed with SoLID Collaboration

$$F_{U(TT),T}^{\cos(2\phi_h-2\phi_{LT})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2} f_{1TT} D_1\right] \qquad F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2} g_{1TT} D_1\right]$$

See Ishara Fernando's talk (Tomorrow)

High Precision Measurement of Phi-Nucleon Cross-Section and Tensor Asymmetry with a Tensor Polarized Deuteron Target

Approved experiment PAC 53 (2025)



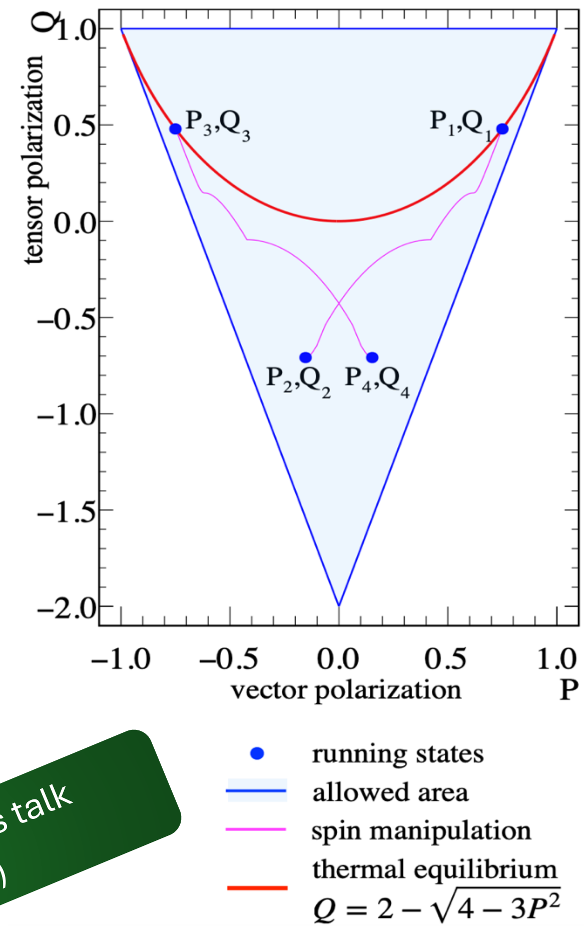
- Uses the approved polarized target from the Real Gamma GDH (REGGE) setup.
- Based on the FROST target design successfully operated in Hall B and at other facilities (CERN, Mainz, KEK, JINR).
- Dynamically polarized 10 cm target optimized to reduce tagger accidentals.
- Utilizes Hall D solenoid field with internal superconducting coils to achieve 2.5 T and maintain<100 ppm gradient.

Using the frozen spin mode allows manipulations that take the spin states of the deuterium out of thermal equilibrium. This allows negative Q.

Dalton et al. Eur. Phys. J. A (2025)

- Equipped with a ^{3}He–^{4}He dilution refrigerator (50 mK base temperature; 300 mK with microwaves).

- Supports continuous polarization and frozen-spin operation modes.



See Mark Dalton's talk
(Tomorrow)

ORNL → UT DNP System

Ongoing Development of Innovative Target Systems for Gluex

- Modify ORNL DNP apparatus for UT lab operation
  - Demonstrate and maximize polarization in a variety of nuclei and proteins
  - Detailed measurements of nuclear spin-relaxation times at ultra-low temperatures
  - Design and construction of superconducting shim coils
  - Demonstration and characterization of negative tensor polarization using AFP

Initial UT cooldown reached 31.8 mK (Oct 6, 2025)

Training platform for both undergraduate and graduate students to support experiments at multiple facilities

Courtesy Nadia Fomin

See Vicente Corral Arreola's (Tomorrow)

ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE
BRUNO KESSLER

Tensor spin observables

Jul 10 – 14, 2023
ECT*
Europe/Rome timezone

Enter your search term

~30 contributions

Main goal after the collaboration Meeting

Jeopardy Prep

- Pac talks : focus on target and theory developments andaccomplishments.
- Address Bacchetta's list of questions
- Connect to EIC and other new proposals
  - Foundational to the EIC program
- Azz relation to SRCs

- Emphasize Active Theorists:
  - Sabina Jeschonnek , Wim Cosyn, Jennifer Rittenhouse-West
  - Simonetta Liuti, Christian Weiss
  - Misak Sargsian, Mark Strikman,
  - Shunzo Kumano,
  - Golak+Polyzou, Hiller, Chabyzeav,
  - Robert Jaffe, Chueng-Ryong Ji, Leonard Gamberg, Stan Brodsky
  - Vladimir Pascalutsa,
  - More...

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- •Emphasize Ac
  - •Sabina ... ller Rittenhouse-West
  - •Simonet
  - •Misak Sa ... n,
  - •Shunzo Ku
  - •Golak+Polyz ... ler, Chabyzeav,
  - •Robert Jaffe, Chueng-Ryong Ji, Leonard Gamberg, Stan Brodsky
  - •Vladimir Pascalutsa,
  - •More...

Jeopardy successfully approved

EPJ A

2024 Impact factor **2.8**

Hadrons and Nuclei

Topical Collections

Tensor Spin Observables

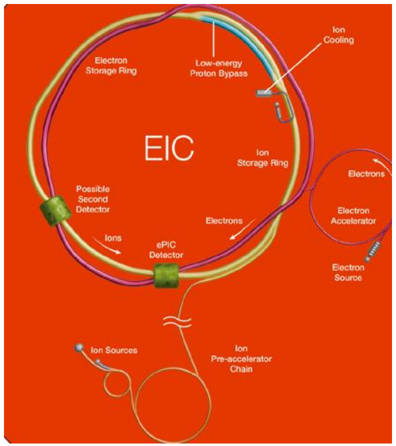
Wim Cosyn, Douglas Higinbotham, Dustin Keller, Elena Long, Patrizia Rossi, Nathaly Santiesteban and Karl J. Slifer (Guest editors)

Cosyn, et al. DOI: 10.1140/epja/s10050-025-01511-x
Puhan, et al. DOI: 10.1140/epja/s10050-025-01527-3
Maly, et al. DOI: 10.1140/epja/s10050-025-01483-y
Kumano DOI: 10.1140/epja/s10050-024-01411-6
Dalton, et al. DOI 10.1140/epja/s10050-025-01580-y
Poudel, et al. DOI 10.1140/epja/s10050-025-01558-w
McClellan, et al. DOI 10.1140/epja/s10050-025-01644-z

12 papers submitted
~7 papers approved
~5 papers in revision

Making the Case for a Tensor Polarized Beam in the EIC

$$\sigma = \sum_{\lambda,\lambda'} \rho_{\lambda\lambda'} \langle d, \lambda' | \ldots | d, \lambda \rangle$$



$$F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h\sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LU}^{\sin\phi_h}$$

$$\begin{aligned} F_S = S_L & \left[\sqrt{2\epsilon(1+\epsilon)} \sin\phi_h F_{US_L}^{\sin\phi_h} + \epsilon \sin 2\phi_h F_{US_L}^{\sin 2\phi_h}\right] \\ & + S_L h \left[\sqrt{1-\epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_h F_{LS_L}^{\cos\phi_h}\right] \\ & + S_\perp \left[\sin(\phi_h - \phi_S) \left(F_{US_T,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h-\phi_S)}\right) + \epsilon \sin(\phi_h + \phi_S) F_{US_T}^{\sin(\phi_h+\phi_S)}\right. \\ & \left. + \epsilon \sin(3\phi_h - \phi_S) F_{US_T}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \left(\sin\phi_S F_{US_T}^{\sin\phi_S} + \sin(2\phi_h - \phi_S) F_{US_T}^{\sin(2\phi_h-\phi_S)}\right)\right] \\ & + S_\perp h \left[\sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LS_T}^{\cos(\phi_h-\phi_S)} + \right. \\ & \left. \sqrt{2\epsilon(1-\epsilon)} \left(\cos\phi_S F_{LS_T}^{\cos\phi_S} + \cos(2\phi_h - \phi_S) F_{LS_T}^{\cos(2\phi_h-\phi_S)}\right)\right], \end{aligned}$$

Here $\phi_h \equiv \phi_p$

$$\begin{aligned} F_T = T_{LL} & \left[F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h}\right] \\ & + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\ & + T_{L\perp}[\cdots] + T_{L\perp} h [\cdots] \\ & + T_{\perp\perp} \left[\cos(2\phi_h - 2\phi_{T_\perp}) \left(F_{UT_{TT},T}^{\cos(2\phi_h-2\phi_{T_\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h-2\phi_{T_\perp})}\right)\right. \\ & + \epsilon \cos 2\phi_{T_\perp} F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(4\phi_h-2\phi_{T_\perp})} \\ & \left. + \sqrt{2\epsilon(1+\epsilon)} \left(\cos(\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(\phi_h-2\phi_{T_\perp})} + \cos(3\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(3\phi_h-2\phi_{T_\perp})}\right)\right] \\ & + T_{\perp\perp} h [\cdots] \end{aligned}$$

Cosyn, Weiss, PRC102 (2020) 065204 + in preparation (2023)

Invariant formulation, suitable for collider and fixed-target

General result, valid for any spin-1 target

Deuteron polarization

Spin-1 density matrix $\rho_{\lambda'\lambda}(S, T)$

3 vector, 5 tensor parameters

Fixed by beam polarization measurements

Polarized cross section

Average with deuteron spin density matrix

U + S + T structures

U + S cross section has same form and ϕ_p-dep as for spin-1/2 target

Bacchetta et al 2007

T cross section has 23 new structures, some with ϕ_p-dep unique to T polarization

Integration over tagged proton momentum: Recover inclusive tensor-polarized structures $b_1 \ldots b_4$

See Jan Vanek's talk (Tomorrow)

Courtesy of W. Cosyn (2023).

Tensor Deuteron: Driving Exciting Times Ahead for Jefferson Lab and the Nuclear Physics Community

- Large number of young scientists in the program
- Growing number of experiments
- Numerous opportunities

Mailing list: https://mailman.jlab.org/mailman/listinfo/Tensor

Meetings: Friday every two weeks at 1 pm