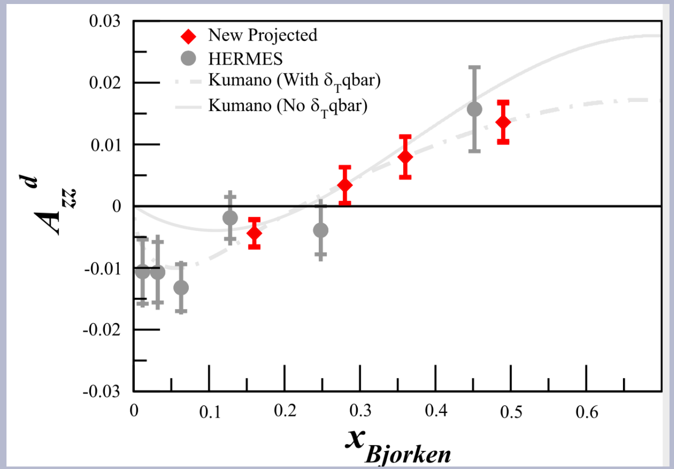
E12-13-011: Deuteron DIS Structure Function b_1

KS, Chen, Long, Kalantarians, Keller, Rondon, Santiesteban, Solvignon



Measurement

$0.15 < x < 0.55$ $1.2 < Q^2 < 3.81$ GeV^2
P_{zz}= 26% with 85nA polarized beam.
36 PAC Days + 12 Days overhead
First tensor poltarg experiment at Jlab

Technical

Fully approved after C_1 Conditional Review in 2022
New tensor polarized ND_3 target
New Jlab based polarizing magnet

Scientific Impact

Depends on partonic distribution & nuclear configuration
Uniquely sensitive to non-nucleonic components of
the Deut wave function: 6 quark & Hidden Color
Gluonic Contributions to Nuclear Structure
Crucial guidance for future Jlab, EIC, FNAL, NICA exps.

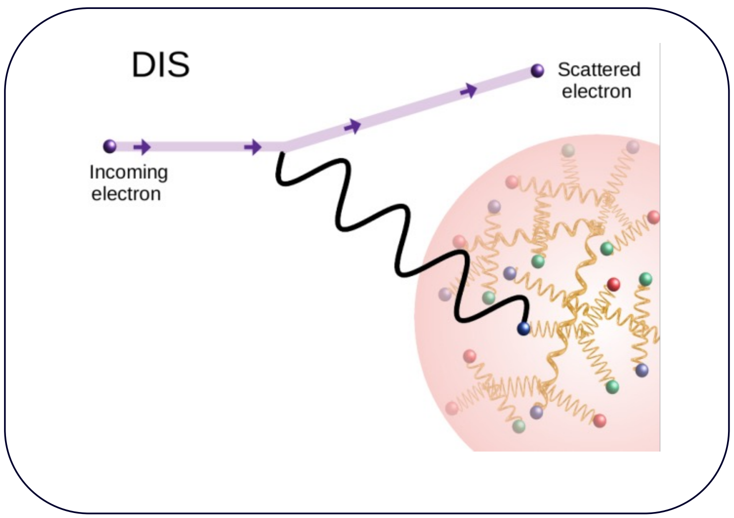
b_1 structure function

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu}$$
$$+i\frac{g_1}{\nu}\epsilon_{\mu\nu\lambda\sigma}q^\lambda s^\sigma + i\frac{g_2}{\nu^2}\epsilon_{\mu\nu\lambda\sigma}q^\lambda(p\cdot q s^\sigma - s\cdot q p^\sigma)$$
$$-b_1 r_{\mu\nu} + \frac{1}{6}b_2(s_{\mu\nu}+t_{\mu\nu}+u_{\mu\nu})$$
$$+\frac{1}{2}b_3(s_{\mu\nu}-u_{\mu\nu}) + \frac{1}{2}b_4(s_{\mu\nu}-t_{\mu\nu})$$

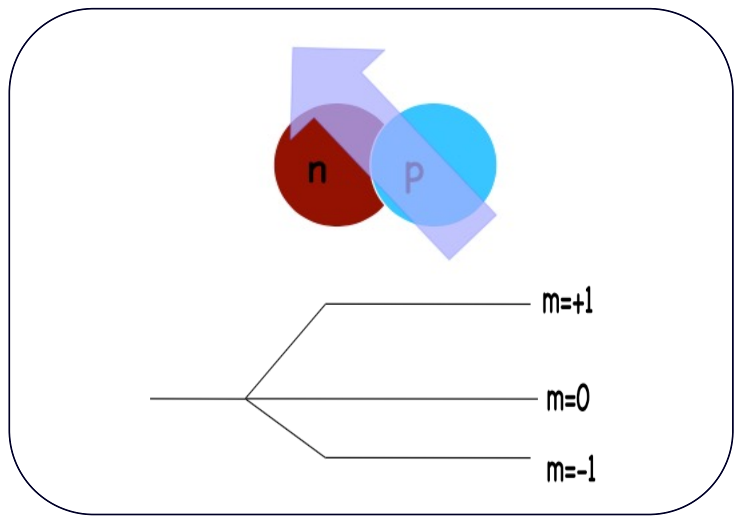
difference of spin averaged parton distributions of a m=0 and m=1 nuclear target

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

Hoodbhoy, Jaffe & Manohar (1989)
Interpretation in Parton model

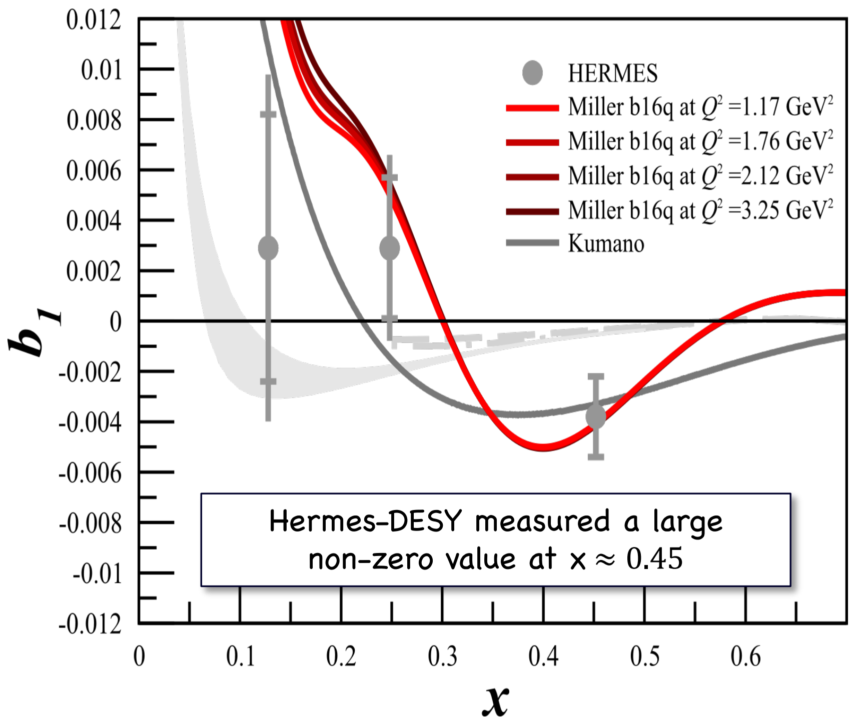


DIS (probing partons)



but depends on the Nuclear Spin State

Conventional Nuclear Physics can not reproduce HERMES Data



Khan & Hoodbhoy, PRC 44 ,1219 (1991) : $b_1 \approx O(10^{-4})$
Relativistic convolution model with binding

Umnikov, PLB 391, 177 (1997) : $b_1 \approx O(10^{-3})$
Relativistic convolution with Bethe-Salpeter formalism

W. Cosyn, Y. Dong, S. Kumano, M. Sargsian PRD95 (2017) 074036
Standard Convolution description

"new mechanism [is needed] to explain large differences between current data and our theoretical results"

"room for more advanced or exotic mechanisms playing an important role"

Cosyn *et. al* **PRD95 (2017) 074036**

G. Miller PRC89 (2014) 045203
Pionic and Hidden-Color, Six-Quark Contributions to the Deuteron b1 Structure Function

6-quark probability needed to (P_{6Q} = 0.0015) is small enough that it does not violate conventional nuclear physics.

Observable: Tensor Asymmetry Azz

$$A_{zz} = \frac{2}{fP_{zz}} \frac{\sigma_Q - \sigma_0}{\sigma_0}$$

$$b_1 = -\frac{3}{2} F_1^d A_{zz}$$

At leading twist

$$\text{sensitivity to slow drifts} \propto \frac{1}{\sqrt{N_{flips}}}$$

<u>New Information</u>

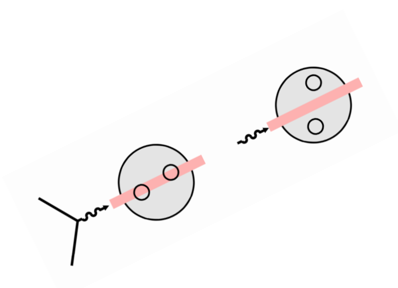
Since the original PAC review we have increased the planned number of polarization state flips from about once per day to about once per hour

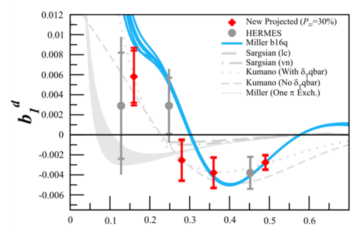
This reduces the sensitivity to slow drifts by about $1/\sqrt{24}$

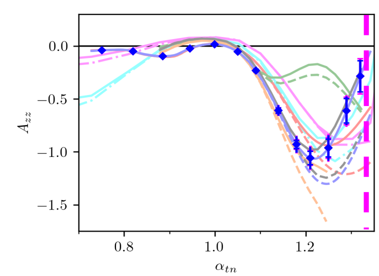
P_{zz} = 26% (originally was 30%)
I = 85 nA (originally was 115nA)
Request for Polarized beam (originally assumed unpol)

Tensor polarization allows control of the nuclear spatial configuration

Measuring A_{zz} over a broad range in x gives access to :







$$
\begin{aligned}
q_{\uparrow}^{1}(x) &= q_{\downarrow}^{-1}(x) \\
q_{\downarrow}^{1}(x) &= q_{\uparrow}^{-1}(x) \\
q_{\uparrow}^{0}(x) &= q_{\downarrow}^{0}(x)
\end{aligned}
$$

$D \rightarrow w(k)$

$$
A_{zz} \propto \frac{\frac{1}{2}w^2(k) + u(k)w(k)\sqrt{2}}{u^2(k) + w^2(k)}
$$

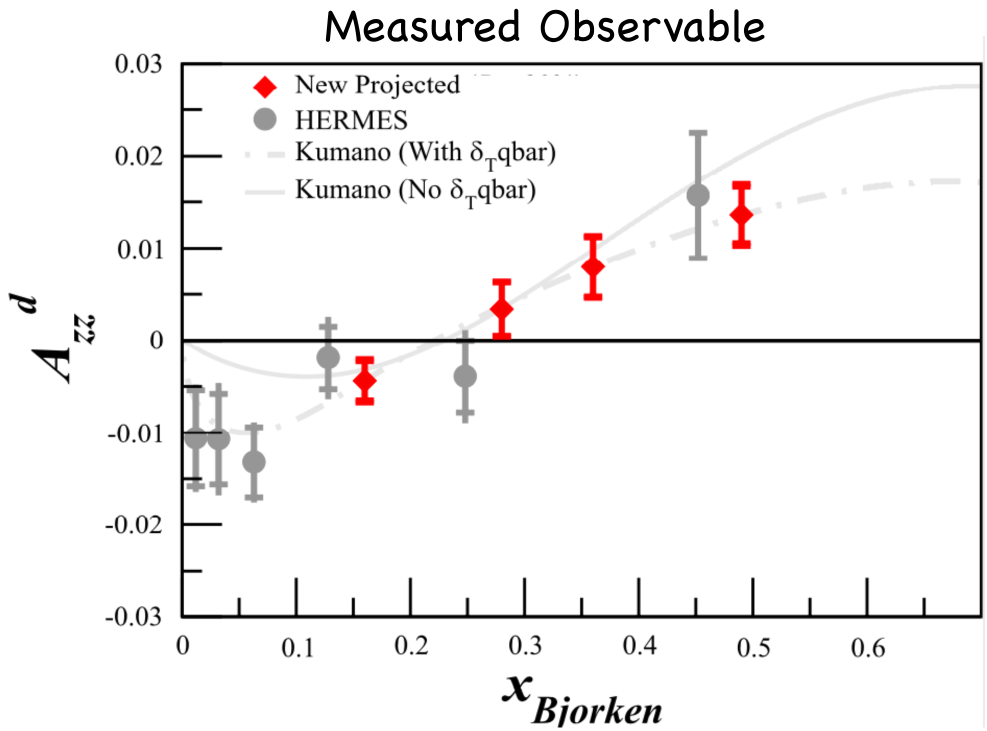
Nuclear shadowing
at low X

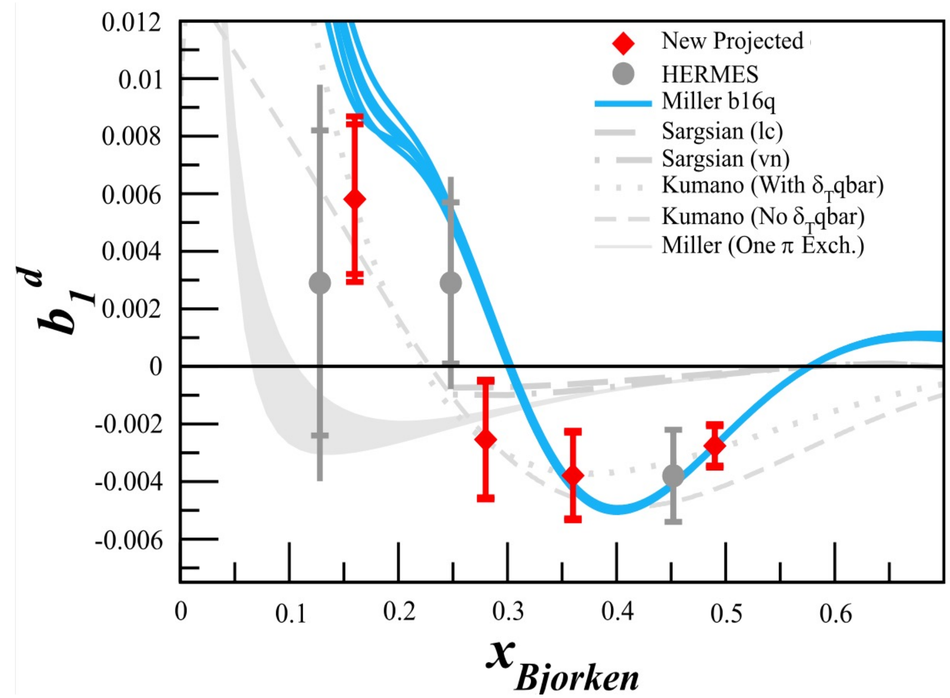
Tensor structure functions &
momentum distributions in nucleus
Hidden color

S/D Wave components
SRCs at large x

X_B

Projected Results





$$b_1 = -\frac{3}{2} F_1^d A_{zz}$$

<u>Projections based on</u>

P_{zz} = 26%

I = 85 nA

36 PAC Days + 12 Days overhead

There is an active theoretical discourse about these questions, with several new results appearing in the last years, and the experiment is supported by a coherent community, closely connected to the physics of the EMC effect and other topics in nuclear physics. The experiment is therefore very well motivated.

Once this pioneering experiment has been performed, a measurement of the x dependence of b_1 at fixed Q^2, and/or the Q^2 dependence at fixed x (even if over a more limited kinematic range than the one here) should be considered as a next step.

JLAB Theory Report 2023

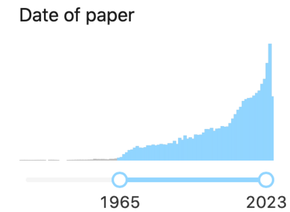
I remain strongly supportive of these tensor measurements. The measurement of the b1 structure function remains as a very powerful, possibly unique, probe of exotic (non nucleon-nucleon) components of the deuteron wave function. Theoretical calculations, performed after my paper, have again found that nucleon-nucleon components alone cannot reproduce the previously measured data points.

G. Miller 2023

From the late 2020's to the beginning of 2030's, the b1 and tensor-polarized parton distribution functions will be investigated at other accelerator facilities, such as Fermilab, NICA, LHCspin, EIC, and EicC by using polarized deuteron targets and polarized deuteron beams. The JLab b1 experiment should play the leading role in these experimental projects, and we believe that the JLab experiment will create a new unique field in hadron physics.

S. Kumano 2023

Brief Sample of Recent Theoretical Developments



QCD hidden-color hexadiquark in the core of nuclei

Jennifer Rittenhouse West [a,b,c,*], Stanley J. Brodsky [c], Guy F. de Téramond [d], Alfred S. Goldhaber [e], Iván Schmidt [f]

A New Structure in the Deuteron

Misak M. Sargsian and Frank Vera
Florida International University, Miami, Florida 33199,USA
(Dated: August 22, 2022)

PHYSICAL REVIEW D **95**, 074036 (201

Tensor-polarized structure function b_1 in the sta... description of the deuteron

W. Cosyn,[1] Yu-Bing Dong,[2,3] S. Kumano,[4,5] and

Deep-inelastic electron-deuteron scattering with spectator nucleon tagging at the electron-ion collider. Extracting free nucleon structure

Alexander Jentsch,[1] Zhoudunming Tu,[1,2] and Christian Weiss[3]

On the physics potential to study the gluon... deuteron at NICA SPD

A. Arbuzov et al.
Progress in Particle and Nuclear Physics **119** 103858 (2021)

PHYSICAL REVIEW C **95**, 044001 (2017)

Factorization breaking of A_d^T for polarized deuteron targets in a relativistic framework

Sabine Jeschonnek[1] and J. W. Van Orden[2,3]

Twist-2 relation and sum rule for tensor-polarized parton distribution functions of spin-1 hadrons

S. Kumano and Qin-Tao Song
J. High Energ. Phys. **2021** 141 (2021)

Transverse Angular Momentum Sum Rule
O. Alkassasbeh, M. Engelhardt, S. Liuti and A. Rajan (2022)

...eron polarizations in the proton-deuteron Drell-Yan process for ...ng the gluon transversity

...ano and Qin-Tao Song
...ev. D **101** 09401...

PHYSICAL REVIEW D **106**, 114013 (2022)

Spatial densities of momentum and forces in spin-one hadrons

Adam Freese[1,*] and Wim Cosyn[2,3,†]
[1]Department of Physics, University of Washington, Seattle, Washington 98195, USA
[2]Department of Physics, Florida International University, Miami, Florida 33199, USA
[3]Department of Physics and Astronomy, Ghent University, B9000 Gent, Belgium

Transversity generalized parton distributions for the...

W. Cosyn and B. Pire

Equation-of-motion and Lorentz-invariance relations for tensor-polarized parton distribution functions of spin-1 hadrons

S. Kumano [a,b], Qin-Tao Song [c,d,*]

Exposing novel quark and gluon effects in nuclei

I C Cloët, R Dupré, S Riordan, W Armstrong, J Arrington, W Cosyn, N Fomin, A Freese, S Fucini, D Gaskell, C E... Keppel, G A Miller, E Pace, S Platchkov, P E Reimer, S Scopetta, A W Thomas, and P Zurita
J. Phys. G: Nucl. Part. Phys. **46** 093001 (2019)

The energy-momentum tensor of spin-1 hadrons: formalism

Wim Cosyn, Sabrina Cotogno, Adam Freese, and Cédric Lorcé
Eur. Phys. J. C **79** 476 (2019)

Collaboration Status

<u>Collaboration</u>

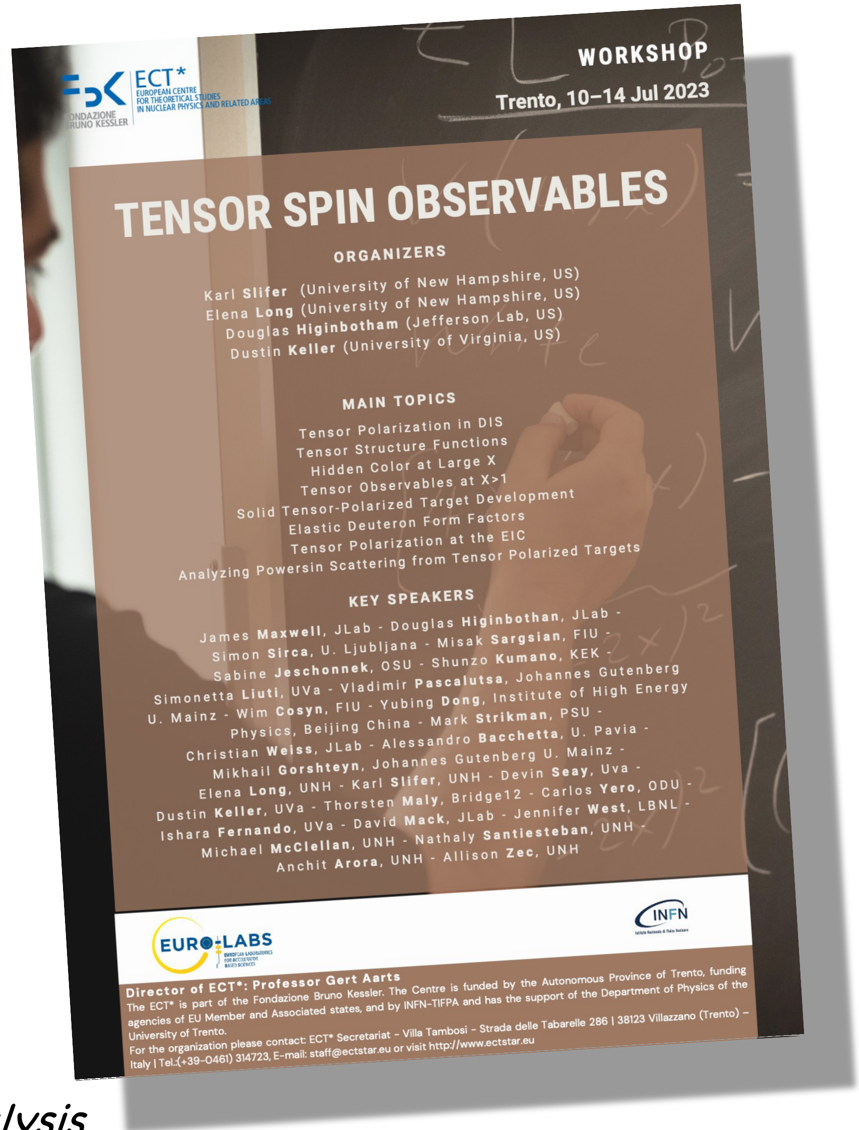
- 50 active members of b_1/Azz collaboration
- 14 Institutions
- 10 PhD students from 3 different universities
- 2 Active Post-Docs.
- 2 more committed to the experimental run
- In-line with previous poltarg efforts

<u>Activities</u>

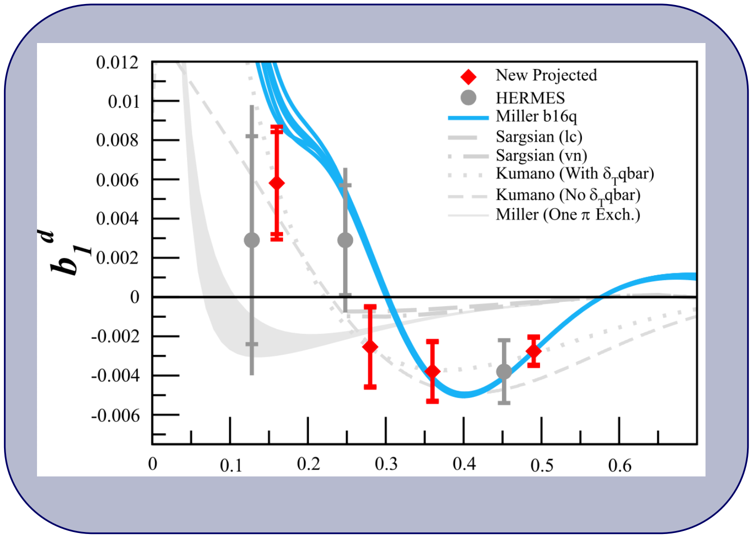
- Active Group meets weekly
- Preparing for ERR
- Tensor Workshop at ECT*
- Active Polarized target development
  - UVa target group
  - UNH target group
  - Jlab target group

<u>2022 Conditional Review → Full Approval</u>

"the UVa and UNH groups have made substantial strides beyond previous work, particularly in the analysis of the deuteron lineshape following RF manipulation."



Summary



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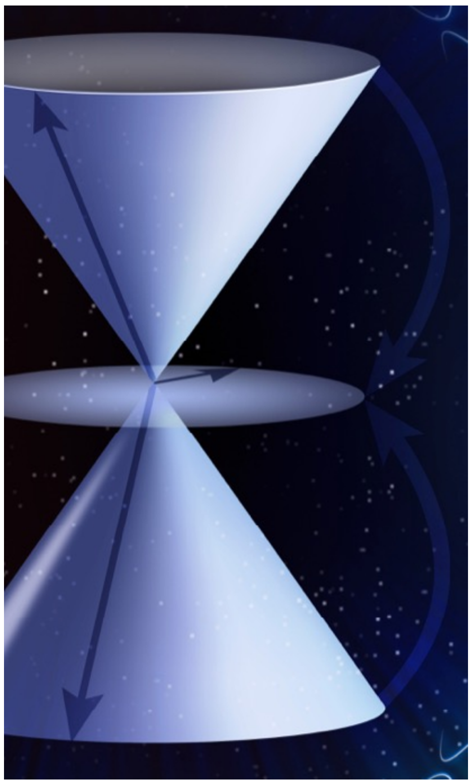


Developments

Fully approved after C_1 Conditional Review in 2022
Engaged community
ECT* Tensor Spin Workshop

Scientific Impact

"*powerful, possibly unique, probe of exotic Components of the deuteron wave function*"

"*will create a new unique field in hadron physics.*"

Critical first data for many many experiments to follow (see backups)

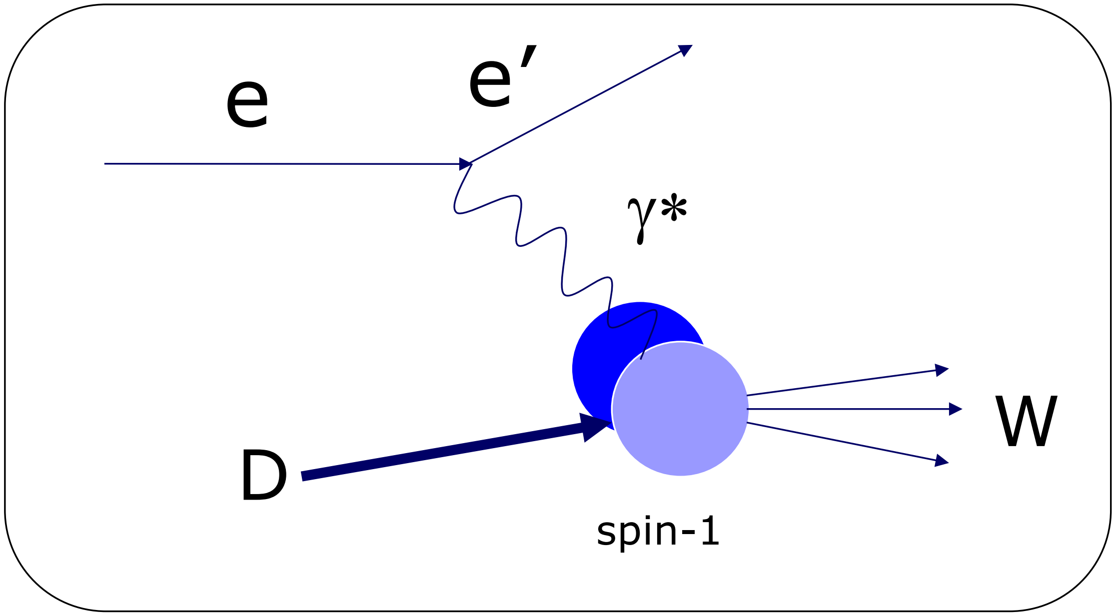
Backups

Expected/Planned Future Experiments

1. Vector and tensor polarized Deuterons at the EIC, and this community's engagement is essential to advocate for and plan for the necessary EIC facility upgrade.
2. 2 LOIs for tensor polarized target in SoLiD (**Slifer, Long**)
3. LOI to measure higher twist Delta structure function (**Maxwell, Milner....)**
4. Exclusive measurements (planned as a followup) to allow tagged selection of highly tensor polarized states (and large asymmetries). (**Carlos Yeros, Nataly Santiesteban, Mark Jones**)
5. Measurements of the higher twist tensor structure functions which are as yet unexplored (b3, b4)
6. Measurements of tensor polarized Drell Yan transversity at FermiLab (**Dustin Keller, Ishara Fernandez**)
7. Nica Spin
8. The b1 effort and collaboration will set a critical foundation for 2^{nd}generation JLab experiments that are in various stages of planning:
    1. Exclusive tensor polarized d(e,e')p,
    2. f_{1LL} in SIDIS,
    3. Tensor polarized DVCS,
    4. SIDIS Transversity, photon tensor polarization observables.

All of these efforts will look to this pioneering experimental run to learn what is possible and what is challenging.

Tensor Structure Functions



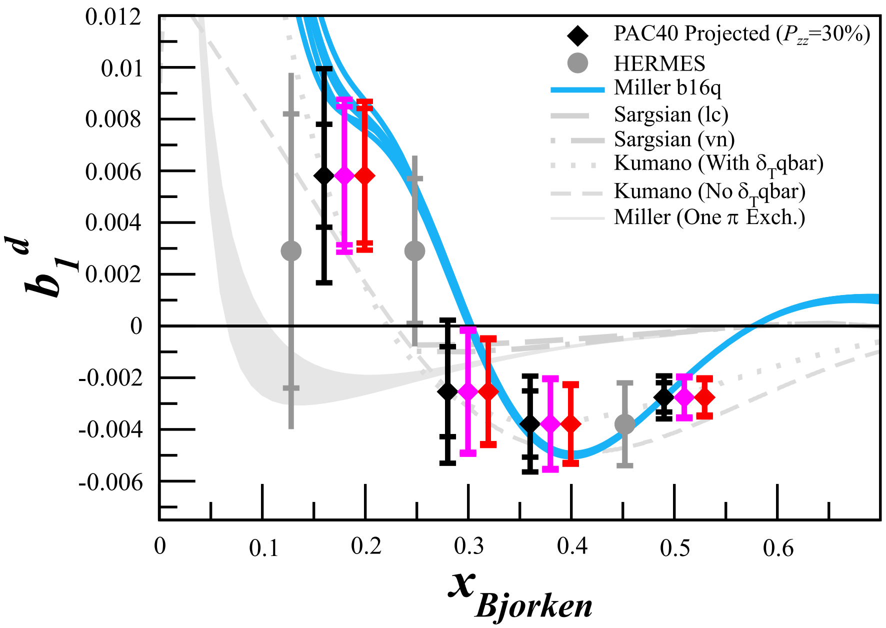
Most general Tensor consistent with Lorentz & gauge invariance

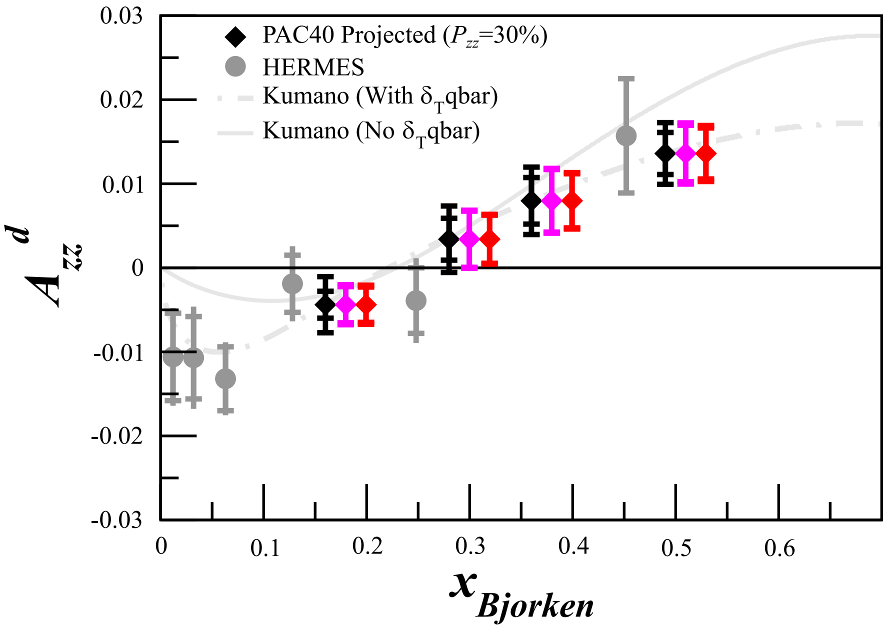
Hoodbhoy, Jaffe, Manohar (1989)
Frankfurt & Strikman (1983)
Efremov and Teryaev (1982, 1999)

$$
\begin{aligned}
W_{\mu\nu} \;=\; & -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu} \\
& + i\frac{g_1}{\nu}\epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i\frac{g_2}{\nu^2}\epsilon_{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s^\sigma - s\cdot q p^\sigma) \\
& - b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\
& + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu})
\end{aligned}
$$

Projected Results for Q = 26%

◆ PAC40 Projected (P_{zz}=30%, I=115nA)
◆ New Projected (P_{zz}=26%, I=85nA)
◆ New Projected w/ additional 6.5 PAC Days (P_{zz}=26%, I=85nA)





Backups

	$\overline{x}$	$\overline{Q^2}$ (GeV^2)	$\overline{W}$ (GeV)	P_0 (GeV)	θ (deg.)	Rates (kHz)	time (days)
SHMS	0.15	1.21	2.78	6.70	7.35	1.66	6
SHMS	0.30	2.00	2.36	7.45	8.96	0.79	14.65
SHMS	0.452	2.58	2.00	7.96	9.85	0.38	15
HMS	0.55	3.81	2.00	7.31	12.50	0.11	35.65

Overhead	PAC Time
Vector Polarization/Depolarization	7 days, 6 hours
Target T.E. Measurements	22.5 hours
Packing Fraction/Dilution Runs	22.5 hours
BCM Calibration Runs	18 hours
Optics Runs	16 hours
Target Anneals	15 hours
Tensor Pol. Spin Flips	9.5 hours
Target Cup Changes	5 hours
Target Material Changes	4 hours
LINAC Changes	4 hours
Momentum/Angle Changes	3 hours
	11.7 days

Parton Model Interpretation

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

difference of spin avergaged parton distributions of a m=0 and m=1 target

where:

$$\begin{aligned} q^0(x) &= q^0_\uparrow(x) + q^0_\downarrow(x) = 2q^0_\uparrow \\ q^1(x) &= q^1_\uparrow(x) + q^1_\downarrow(x) \end{aligned}$$

Mirror symmetry along z-axis reveals

$$\begin{aligned} q^1_\uparrow(x) &= q^{-1}_\downarrow(x) \\ q^1_\downarrow(x) &= q^{-1}_\uparrow(x) \\ q^0_\uparrow(x) &= q^0_\downarrow(x) \end{aligned}$$

Summary of Conditional Review

1. *What technique(s) will be used to produce "a tensor polarization of 30% under standard experimental conditions".*

2. *How will the tensor polarization be measured and with what uncertainty? What crosschecks or auxiliary measurements can be made to validate the results? Will this uncertainty be sufficient to achieve meaningful physics results?*

3. *What assumptions are made regarding the vector polarization of the target? How is the tensor polarization expected to respond as the vector polarization decays in beam?*

4. *What is the current experimental situation? What is the maximum tensor polarization that has been achieved under the anticipated polarizing conditions of 5 T and 1 K?*

The collaboration presented our response to this charge and in consequence, the C1 conditional status was removed and full approval granted by Jefferson Lab in August 2022 to both E12-13-011 and E12-15-005

the UVa and UNH groups have made substantial strides beyond previous work, particularly in the analysis of the deuteron lineshape following RF manipulation.

Gluon Contribution to Tensor Structure

$$\int b_1(x)dx = 0$$

$$\int x b_1(x)dx = 0$$

Efremov and Teryaev (1982, 1999)

Gluons (spin 1) contribute to both moments

Quarks satisfy the first moment, but

Gluons may have a non-zero first moment!

2^{nd} moment more likely to be satisfied experimentally since the collective glue is suppessed compared to the sea

Study of b_1 allows to discriminate between deuteron components with different spins (quarks vs gluons)

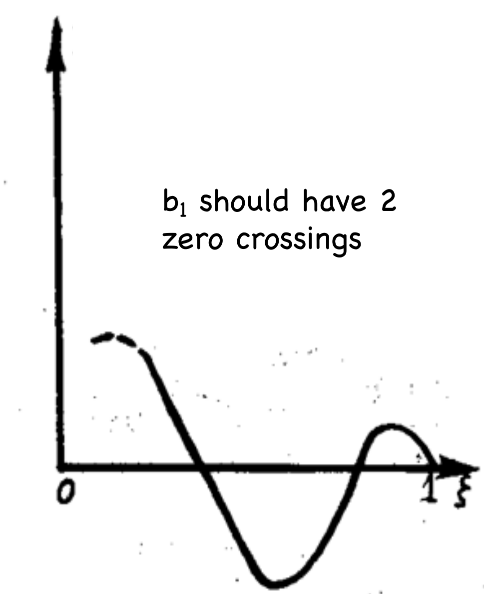
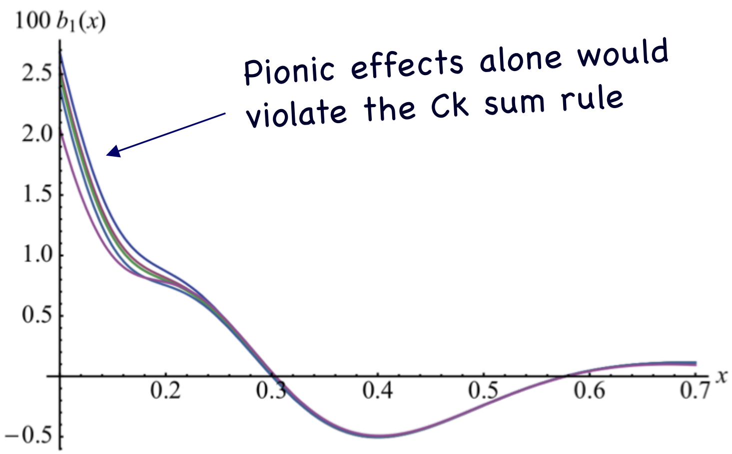
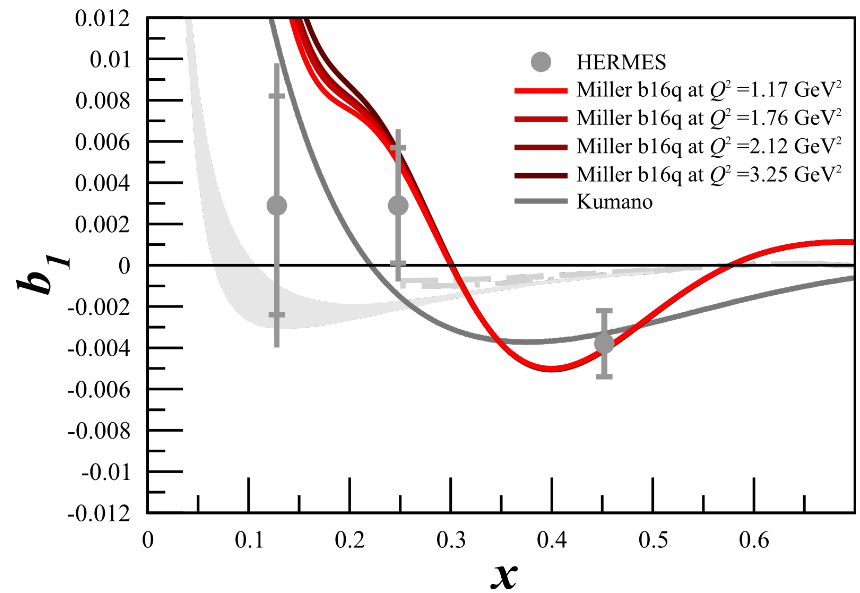


Рис.1

Efremov, Teryaev, JINR PreprintR2-81-857(1981), Yad. Phys. 36, 950 (1982)
A.V. Efremov, O. V. Teryaev JINR-E2-94-95 (1999)
Jaffe, Manohar Phys.Lett. B223 (1989) 218

Unique Signal of Hidden Color





no conventional nuclear mechanism can reproduce the Hermes data,

but the 6-quark probability needed to do so (P_{6Q}= 0.0015) is small enough that it does not violate conventional nuclear physics.

G. Miller **PRC89 (2014) 045203**