Higher-Twist Effects on Measurements of b_1

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2023-07-10

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The Tensor Experiments

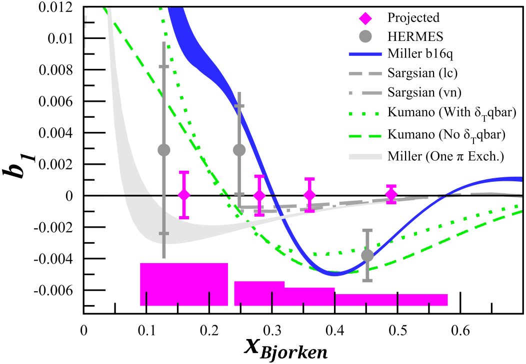
b_1 Experiment

- Intended to improve upon HERMES' 2005 data
- Verifications of zero-crossing
  - Implications for Close-Kumano sum rule
- Tensor physics at quark level
- Better understanding of b_1 allows discrimination of different deuteron components by spin (e.g., quarks vs gluons)

See K. Slifer experimental talk for more info!

E12-13-011

The Deuteron Tensor Structure Function b_1



K. Slifer *et al*, JLab C12-13-011 **Spokespersons:** K. Slifer, O.R. Aramayo, J.P. Chen, N. Kalantrians, D. Keller, E. Long, P. Solvignon

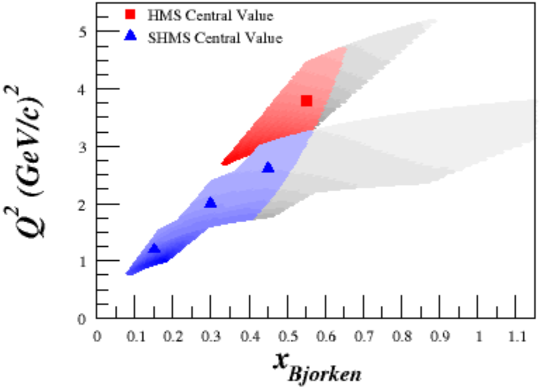
b_1 Kinematics

- Approved for 30 days of physics running + 10.8 days overhead
- 11 GeV beam incident on polarized target
- 9.2% systematic error on A_{zz}
- Foward scattering angles

	x_{Bj}	Q^2 [GeV^2]	E'_0 [GeV]	$\theta_{e'}$ [°]
SHMS	0.15	1.21	6.70	7.35
SHMS	0.30	2.00	7.45	8.96
SHMS	0.452	2.58	7.96	9.85
HMS	0.55	3.81	7.31	12.50

E12-13-011

The Deuteron Tensor Structure Function b_1



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A_{zz} Experiment

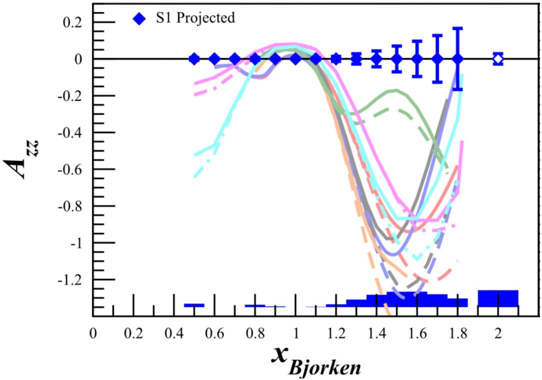
- First-of-its-kind quasielastic A_{zz} measurement
- Implications for SRC physics and deuteron wavefunction
- Widest range of x covered by a single measurement
- Measurement of T_{20} included!

Spokespersons: E. Long, K. Slifer, P. Solvignon, D. Day, D. Keller, D. Higinbotham

See E. Long talk on Thursday for more info!

E12-15-005

Quasi-Elastic and Elastic Deuteron Tensor Asymmetries



E. Long *et al*, JLab C12-15-005

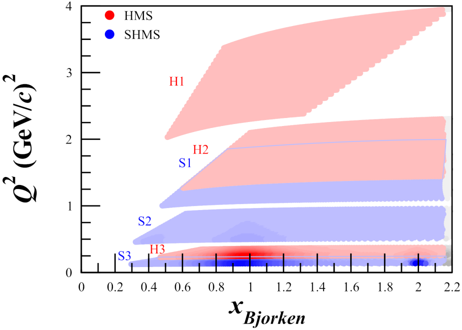
A_{zz} Kinematics

- Approved for 34 days of physics running + 10.3 days overhead
  - 25 days 8.8 GeV beam
  - 8 days 6.6 GeV beam
  - 1 day of 2.2 GeV beam
- 9.2% systematic error on A_{zz}, 7.4% on T_{20}
- Forward scattering angles

	E_0 [GeV]	Q^2 [GeV^2]	E_0' [GeV]	$\theta_{e'}$ [°]
SHMS (S1)	8.8	1.5	8.36	8.2
HMS (H1)	8.8	2.9	7.26	12.2
SHMS (S2)	6.6	0.7	6.35	7.5
HMS (H2)	6.6	1.8	5.96	12.3
SHMS (S3)	2.2	0.2	2.15	10.9
HMS (H3)	2.2	0.3	2.11	14.9

E12-15-005

Quasi-Elastic and Elastic Deuteron Tensor Asymmetries



E. Long *et al*, JLab C12-15-005

Higher Twist Theory and b_1 Extraction

A_{zz} Formulation

$$A_{zz} = 2\frac{[T_{LL}](\Lambda_d = +1)(F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + [T_{LT}\cos\phi_{T_L}](\Lambda_d = +1)\sqrt{2\epsilon(1+\epsilon)}F_{UT_{LT}}^{\cos\phi_{T_L}} + [T_{TT}\cos 2\phi_{T_T}](\Lambda_d = +1)\epsilon F_{UT_{TT}}^{\cos 2\phi_{T_T}}}{F_{UU,T} + \epsilon F_{UU,L}}$$

- Where ϵ and γ are kinematic factors
- T_{LL}, T_{LT} and T_{TT} are tensor polarization factors dependent on P_{zz} as well as scattering & polarization direction

$$F_{UT_{LL},L} = \frac{1}{x_D}\sqrt{\frac{2}{3}}\left[2(1+\gamma^2)x_D b_1 - (1+\gamma^2)^2\left(\frac{1}{3}b_2 + b_3 + b_4\right) - (1+\gamma^2)\left(\frac{1}{3}b_2 - b_4\right) - \left(\frac{1}{3}b_2 - b_3\right)\right],$$

$$F_{UT_{LL},T} = -\frac{1}{x_D}\sqrt{\frac{2}{3}}\left[2(1+\gamma^2)x b_1 - \gamma^2\left(\frac{1}{6}b_2 - \frac{1}{2}b_3\right)\right],$$

$$F_{UT_{LT}}^{\cos\phi_{T_\parallel}} = -\sqrt{\frac{2}{3}}\frac{\gamma}{2x_D}\left[(1+\gamma^2)\left(\frac{1}{3}b_2 - b_4\right) + \left(\frac{2}{3}b_2 - 2b_3\right)\right],$$

$$F_{UT_{TT}}^{\cos(2\phi_{T_\perp})} = -\sqrt{\frac{2}{3}}\frac{\gamma^2}{x_D}\left(\frac{1}{6}b_2 - \frac{1}{2}b_3\right). \qquad (32)$$

W. Cosyn, Y.-B. Dong, S. Kumano and M. Sargsian PRD **95** 074036 (2017)

Top: A_{zz} written as a function of helicity amplitudes with, *Right:* Helicity amplitude definitions

b_1 Extraction from A_{zz}

If polarized along the q-vector...

$$A_{zz}^{pol_q} = 2(1+\gamma^2)(\epsilon-1)b_1 + \frac{1}{3x}\left(\frac{\gamma^2}{2} - \epsilon(1+\gamma^2)^2 - \epsilon(1+\gamma^2) - \epsilon\right)b_2 + \frac{1}{x}\left(\epsilon - \frac{\gamma^2}{2} - \epsilon(1+\gamma^2)^2\right)b_3 - \frac{\epsilon}{x}(1+\gamma^2)\gamma^2 b_4$$

If polarized along the electron beam axis...

$$\begin{aligned} A_{zz}^{pol_e} = {} & 2(1+\gamma^2)(\epsilon-1)\left(\frac{1}{4}+\frac{3}{4}\cos(2\theta_q)\right)b_1 + \\ & \left[\frac{1}{3x}\left(\frac{\gamma^2}{2} - \epsilon(1+\gamma^2)^2 - \epsilon(1+\gamma^2) - \epsilon\right)\left(\frac{1}{4}+\frac{3}{4}\cos(2\theta_q)\right)\right]b_2 + \\ & \left[\frac{1}{x}\left(\epsilon - \frac{\gamma^2}{2} - \epsilon(1+\gamma^2)^2\right)\left(\frac{1}{4}+\frac{3}{4}\cos(2\theta_q)\right)\right]b_3 + \\ & \left[\frac{3}{4}\sin(2\theta_q)\sqrt{2\epsilon(1+\epsilon)}\frac{\gamma}{x} + \frac{3}{4}(1-\cos(2\theta_q))\frac{\epsilon\gamma^2}{2x}\right]b_3 + \\ & \left[\frac{3}{4}\sin(2\theta_q)\sqrt{2\epsilon(1+\epsilon)}\frac{\gamma}{2x}(1+\gamma^2) - \frac{\epsilon}{x}(1+\gamma^2)\gamma^2)\left(\frac{1}{4}+\frac{3}{4}\cos(2\theta_q)\right)\right]b_4 \end{aligned}$$

b_1 Extraction from A_{zz}

If polarized along the q-vector...

$$A_{zz}^{pol_q} = C_{b_1}(\epsilon, \gamma, x, \theta_q = 0) b_1 + C_{b_2}(\epsilon, \gamma, x, \theta_q = 0) b_2 + C_{b_3}(\epsilon, \gamma, x, \theta_q = 0) b_3 + C_{b_4}(\epsilon, \gamma, x, \theta_q = 0) b_4$$

If polarized along the electron beam axis...

$$A_{zz}^{pol_e} = C_{b_1}(\epsilon, \gamma, x, \theta_q) b_1 + C_{b_2}(\epsilon, \gamma, x, \theta_q) b_2 + C_{b_3}(\epsilon, \gamma, x, \theta_q) b_3 + C_{b_4}(\epsilon, \gamma, x, \theta_q) b_4$$

b_1 Extraction from A_{zz}

If polarized along the q-vector. . .

$$A_{zz}^{pol_q} = C_{b_1}(\epsilon, \gamma, x, \theta_q = 0) b_1 + C_{b_2}(\epsilon, \gamma, x, \theta_q = 0) b_2 + C_{b_3}(\epsilon, \gamma, x, \theta_q = 0) b_3 + C_{b_4}(\epsilon, \gamma, x, \theta_q = 0) b_4$$

If polarized along the electron beam axis. . .

$$A_{zz}^{pol_e} = C_{b_1}(\epsilon, \gamma, x, \theta_q) b_1 + C_{b_2}(\epsilon, \gamma, x, \theta_q) b_2 + C_{b_3}(\epsilon, \gamma, x, \theta_q) b_3 + C_{b_4}(\epsilon, \gamma, x, \theta_q) b_4$$

Why do we care?

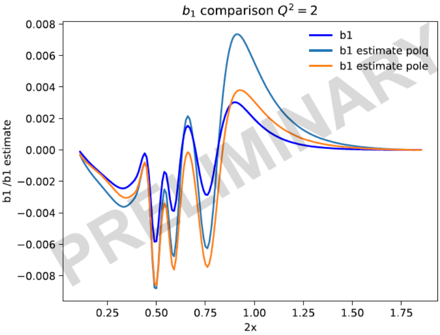
Does polarizing along the q-vector provide a significantly cleaner extraction of b_1? (Enough to justify the labor and expense of putting in a chicane in the Hall C beamline?)

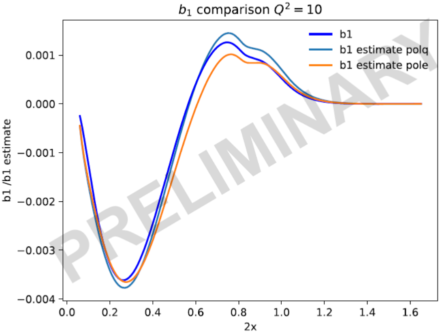
(Calculations courtesy of W. Cosyn group)

b_2, b_3 & b_4 Contamination

Sanity Check: Low-High Q^2 Comparison

Data courtesy of W. Cosyn group, with Paris SLAC

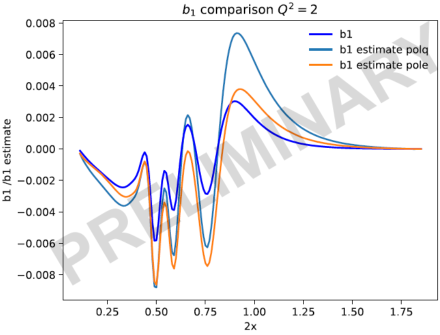


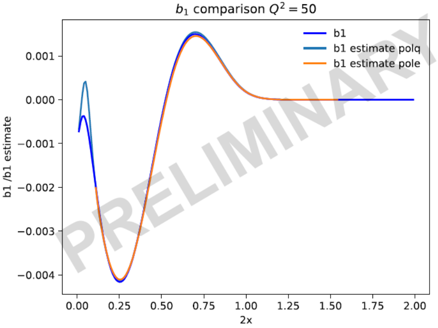


Higher twist effects should become less and less as $Q^2 \to \infty$

Sanity Check: Low-High Q^2 Comparison

Data courtesy of W. Cosyn group, with Paris SLAC



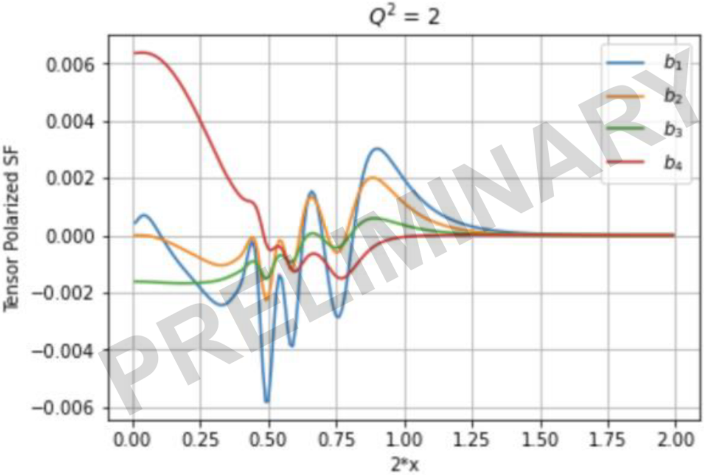


Higher twist effects should become less and less as $Q^2 \to \infty$

...And that is apparent from the calculations at $Q^2 \geq 10$ GeV

Tensor Structure Functions

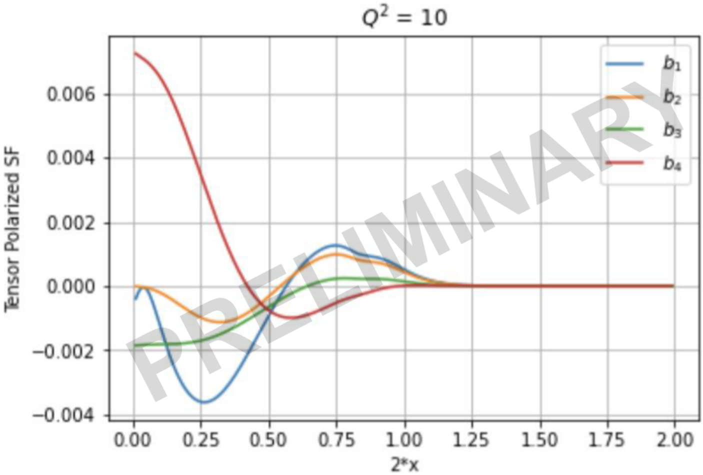
Data courtesy of W. Cosyn group, with Paris SLAC



- At b_1 expt. kinematics, b_{1-4} are similar magnitude
- b_{2-4} as yet unmeasured

Tensor Structure Functions

Data courtesy of W. Cosyn group, with Paris SLAC

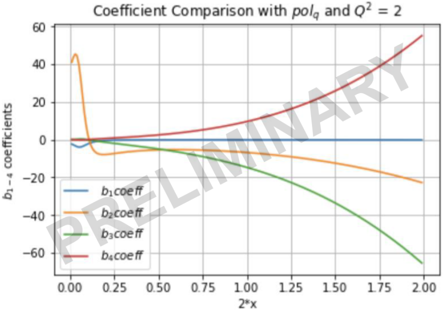


- At b_1 expt. kinematics, b_{1-4} are similar magnitude
- b_{2-4} as yet unmeasured
- Effect of resonances changes at higher Q^2

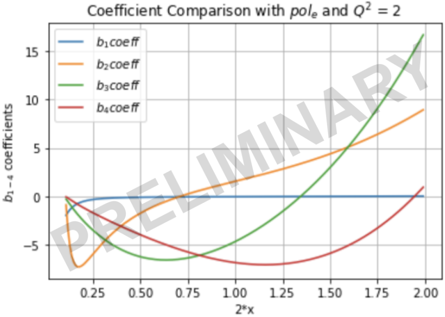
Coefficients $C_{b_{1-4}}$

Data courtesy of W. Cosyn group, with Paris SLAC

Q-Vector Polarization



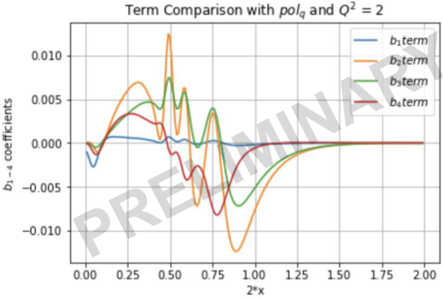
e^- Direction Polarization



Full b_{1-4} Terms

Data courtesy of W. Cosyn group, with Paris SLAC

Q-Vector Polarization



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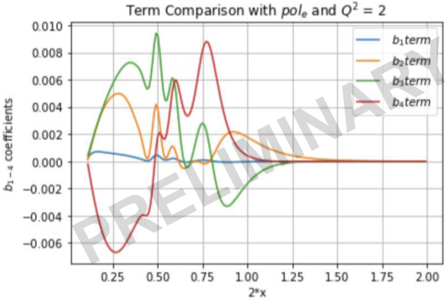

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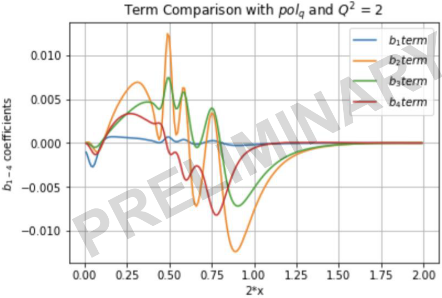

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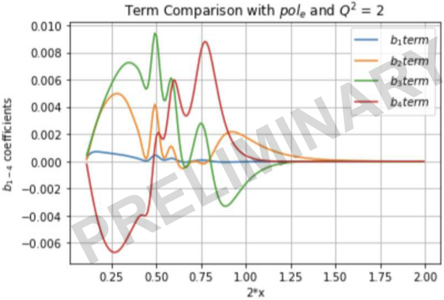


b_{2-4} contributions to b_1 measurement exist regardless of polarization direction choice.

Summary

Professors

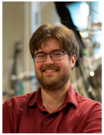
Karl Slifer

Elena Long

Nathaly Santiesteban

Postdocs

Allison Zec



David Ruth

Graduate Students

Michael McClellan

Anchit Arora

Zoe Wolters

Thank you to the UNH PolTarg Group and our collaborators at FIU!

- Tensor experiment program progressing
- b_1 experiment between conditional removal and jeopardy

- Studies of higher-twist effects have preliminary results
- No results suggest need to polarize along Q-vector
- UNH companion studies forthcoming!

Trans & Nonbinary Physicists

TRANS & NON-BINARY PHYSICISTS

The Trans and Nonbinary Physicists Discord server is an online community for transgender and nonbinary physicists — from enthusiasts to professors! — to socialize, network, and support one another. All are welcome, and so far we have over 200 members from across the world!

Follow

@transphysicists

on twitter!

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Questions, comments, concerns, observations?

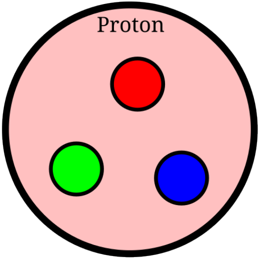
Backup Slides

Deuteron Tensor Polarization and Properties

Protons & Deuterons

Proton

Spin-$\frac{1}{2}$ System



Three valence quarks + gluons and sea quarks

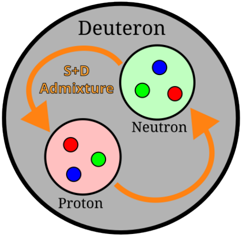
No nucleon-nucleon interactions

$m = \pm\frac{1}{2}$

S. Kumano, IOP Proc. Tens. Pol. Targ. (2014)

Deuteron

Spin-1 System



Proton-Neutron bound state

Simplest nuclear system: nucleon interaction effects

$m = \pm 1, 0$

Quasielastic Tensor Asymmetry

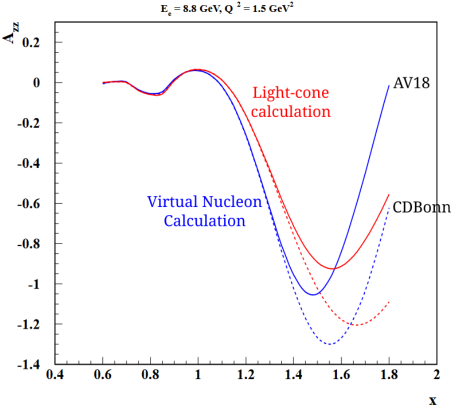
For $0.8 \leq x \leq 1.8$

σ_p =polarized cross section
σ_0 =unpolarized cross section

$$A_{zz} = \frac{2}{fP_{zz}} \left(\frac{\sigma_p}{\sigma_0} - 1 \right) \qquad (1)$$

- **Currently no quasielastic tensor asymmetry measurements!**
- Asymmetry in $1.0 < x < 1.8$ range predicted as high as 100%
- Difficult to measure with just vector polarized deuterons

M. Sargsian, M. Strikman arXiv:1409.6056
E. Long *et al*, JLab C12-15-005



Above: Two theory models: AV18 (solid) and CDBonn (dashed) for two different calculation frameworks predicting the quasielastic value of A_{zz}.

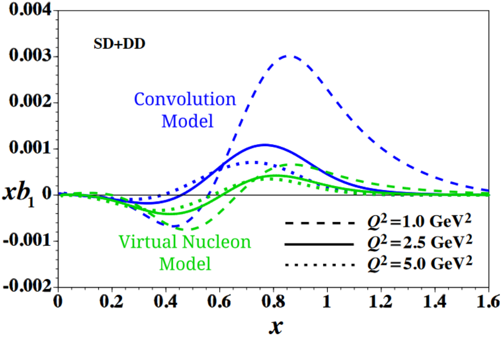
Deep Inelastic Tensor Structure Functions

$$
\begin{aligned}
W_{\mu\nu} = & -\alpha F_1 + \beta F_2 && \text{Unpolarized structure functions} \\
& + i\gamma g_1 + i\delta g_2 && \text{Vector polarized structure functions} \\
& - \epsilon \boxed{b_1} + \zeta b_2 + \eta b_3 + \kappa b_4 && \text{Tensor polarized structure functions}
\end{aligned} \qquad (2)
$$

For $x \leq 0.5$

$$
b_1 = -\frac{3}{2} F_1 A_{zz} \qquad (3)
$$

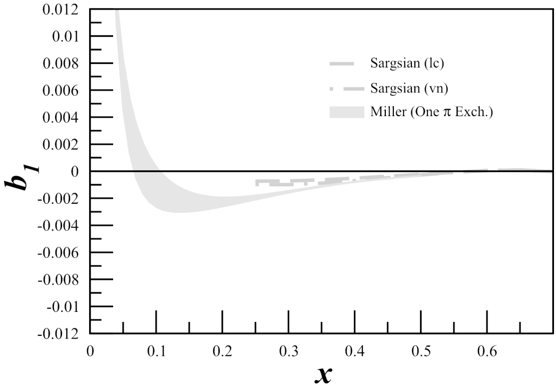
- Callan-Gross relation with $b_2 = 2xb_1$
- b_1 sole tensor structure function that has been measured



W. Cosyn, Y. Dong, S. Kumano, M. Sargsian *et al*, PRD **95** 074036 (2017)

Current b_1 Data

In traditional deuteron state models b_1 is predicted to be small



K. Slifer *et al*, JLab C12-13-011

Current b_1 Data

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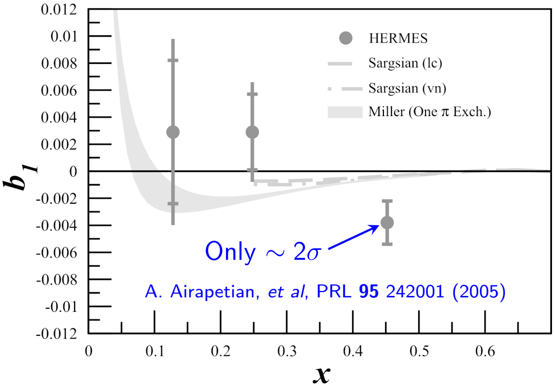
…but the HERMES experiment measured something different!



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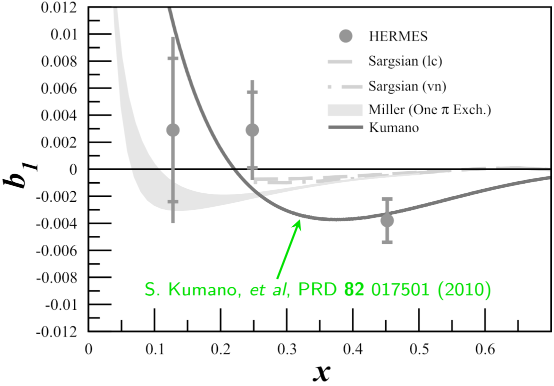
It could be explained by tensor-polarized anti-quark effects



K. Slifer *et al*, JLab C12-13-011

Current b_1 Data

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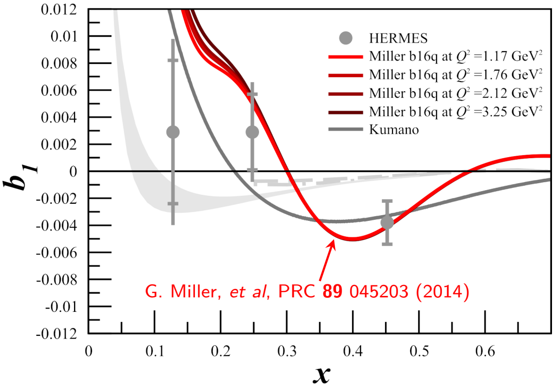
...but the HERMES experiment measured something different!

It could be explained by tensor-polarized anti-quark effects

...or by six-quark hidden color effects.



K. Slifer *et al*, JLab C12-13-011

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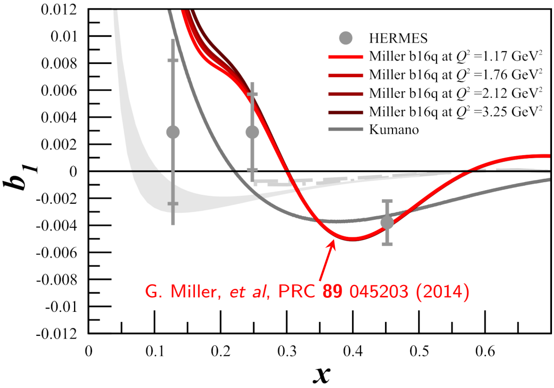


Measuring $b_1 < 0$ indicates exotic physics in the tensor structure of the deuteron! So can we improve on HERMES' error bar?

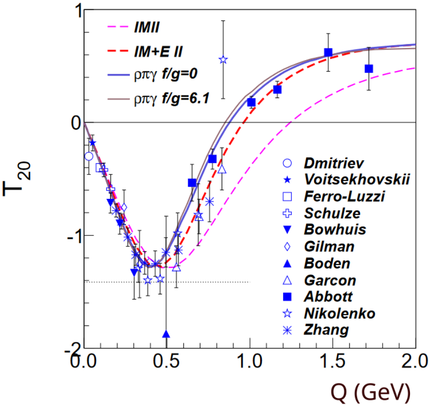
Elastic Tensor Analyzing Power

For $\mathbf{1.5 \leq x \leq 2.0}$

$$T_{20} \approx \frac{A_{zz}}{\sqrt{2}d_{20}} \quad (4)$$

- Third of three elastic scattering functions of deuteron
- Extracted by measuring A_{zz} near elastic peak
- Current data doesn't constrain models well at high x

M. Kohl Nucl Phys A **805** (2008)



Above: T_{20} with current measurements and theoretical models.

R. Holt, R. Gilman Rept.Prog.Phys. **75** (2012)

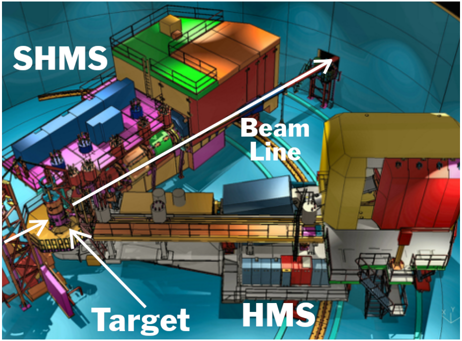
JLab & Hall C

JLab

- 12 GeV CEBAF accelerator
- 4 experimental halls running simultaneously
- Beam current up to 200 μA

Hall C

- Two spectrometers
  - HMS (up to 7.3 GeV momentum)
    - Scattering angle 10°$\leq \theta' \leq$85°
  - SHMS (up to 11 GeV momentum)
    - Scattering angle 5.5°$\leq \theta' \leq$40°
- High-rate detector package



BACKUP: Tensor Polarization & DNP

Tensor Polarization

"Typical" vector polarization:

$$P_z = N_+ - N_- \tag{5}$$

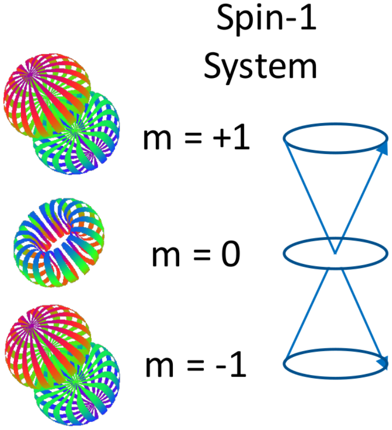
where $-1 \leq P_z \leq 1$
... but with an m=0 state we have tensor polarization:

$$P_{zz} = (N_+ + N_-) - 2N_0 \tag{6}$$

where $-2 \leq P_{zz} \leq 1$

Goal

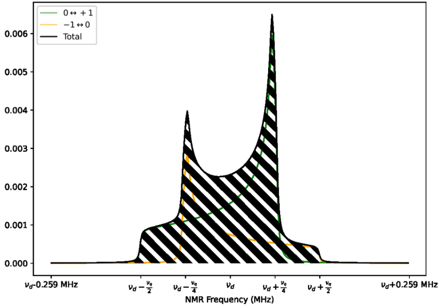
Create target with high tensor polarization for high-luminosity experiments



Measuring Tensor Polarization

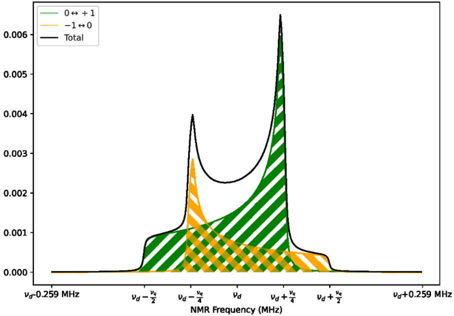
Vector Polarization Measurement

$$P_z = C(I_+ + I_-) \tag{7}$$



Tensor Polarization Measurement

$$P_{zz} = C(I_+ - I_-) \tag{8}$$



where C is a dimensionless calibration constant, $I_+ = n_+ - n_0$, and $I_- = n_0 - n_-$

D. Keller NIM A **981** (2020) 164504