The b_1 experiment
& Experimental Overview

ECT* workshop

Trento, Trentino-Alto
Adige/Südtirol
2023-07-10

Karl Slifer
University of New Hampshire

Tensor Spin Observables

Tensor Structure Functions

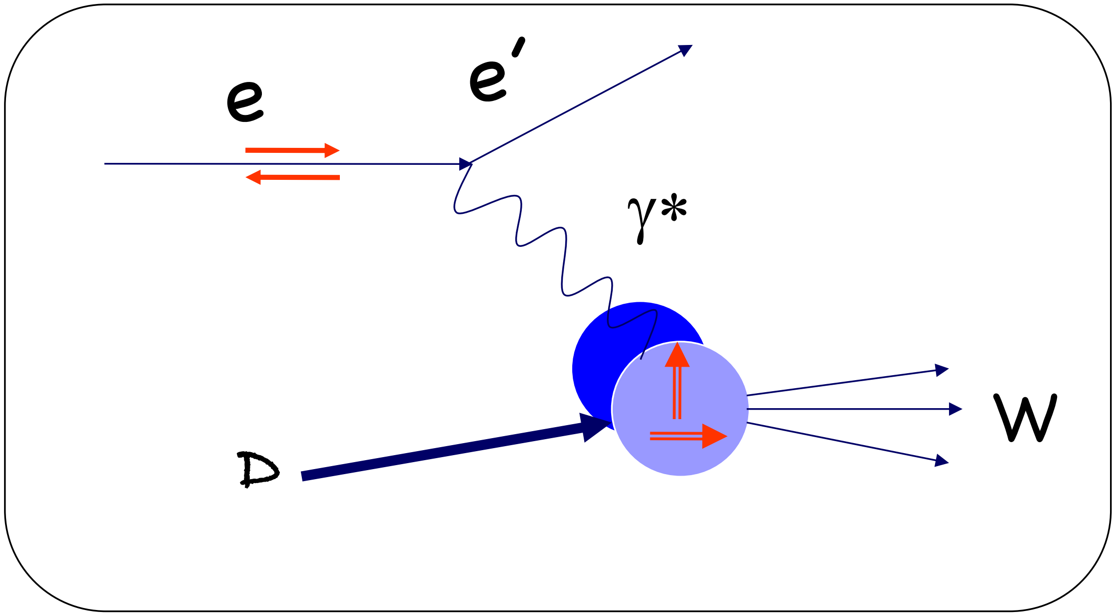
Tensor Asymmetry at high X_b

Experimental status

Target Status

Planned Experiments

Inclusive Scattering



Construct the most general
Tensor W consistent with
Lorentz and gauge invariance

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

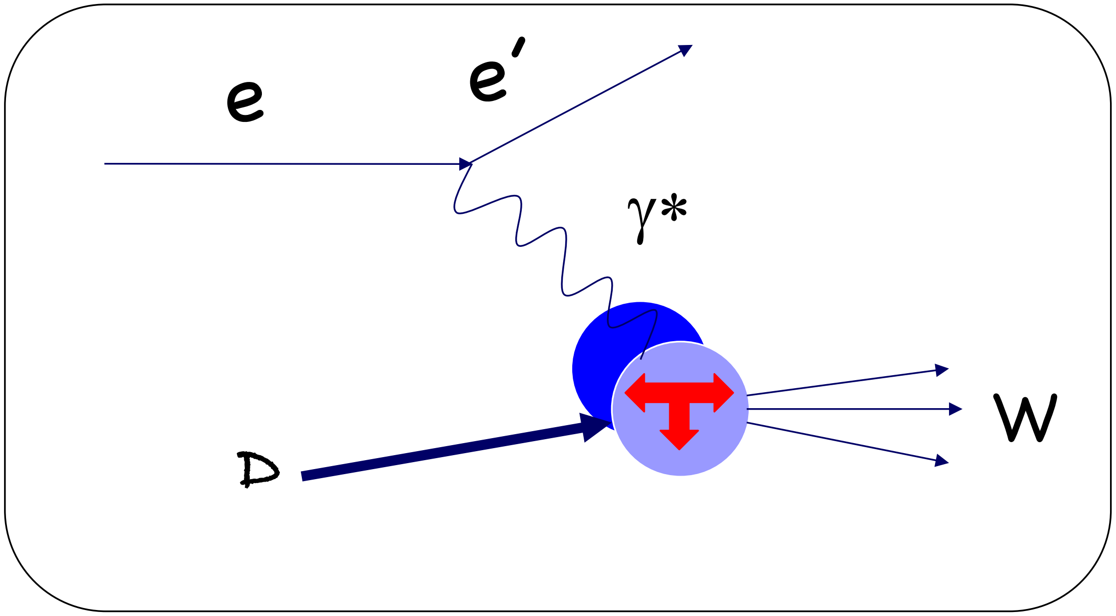
$$W_{\mu\nu} \quad = \quad -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu}$$

Unpolarized Scattering

$$+i\frac{g_1}{\nu}\epsilon_{\mu\nu\lambda\sigma}q^\lambda s^\sigma + i\frac{g_2}{\nu^2}\epsilon_{\mu\nu\lambda\sigma}q^\lambda(p\cdot qs^\sigma - s\cdot qp^\sigma)$$

Vector Polarization

Tensor Structure Functions



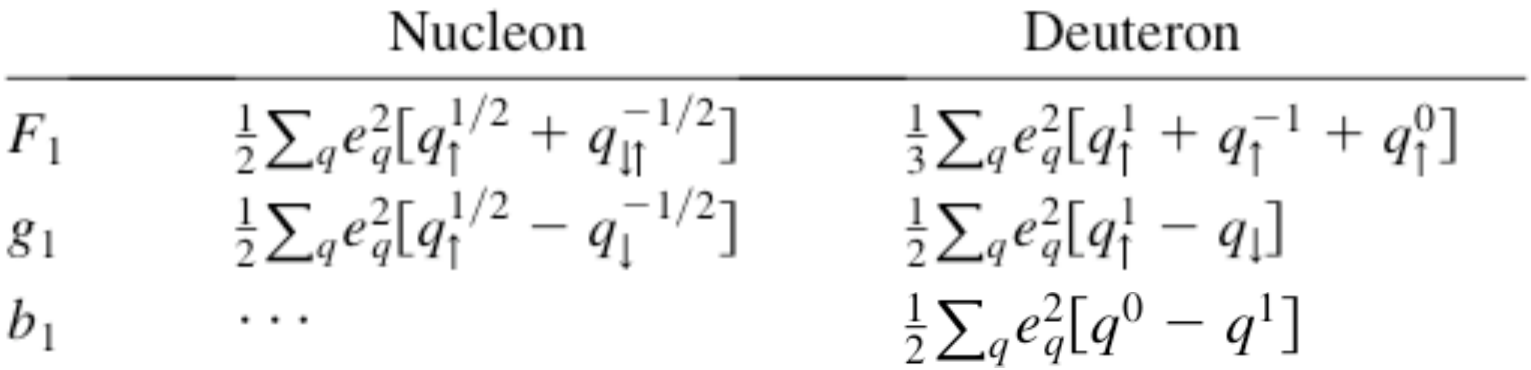
Construct the most general
Tensor W consistent with
Lorentz and gauge invariance

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

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

Caution : There is an alternate similar formulation by Edelmann, Piller, Weise

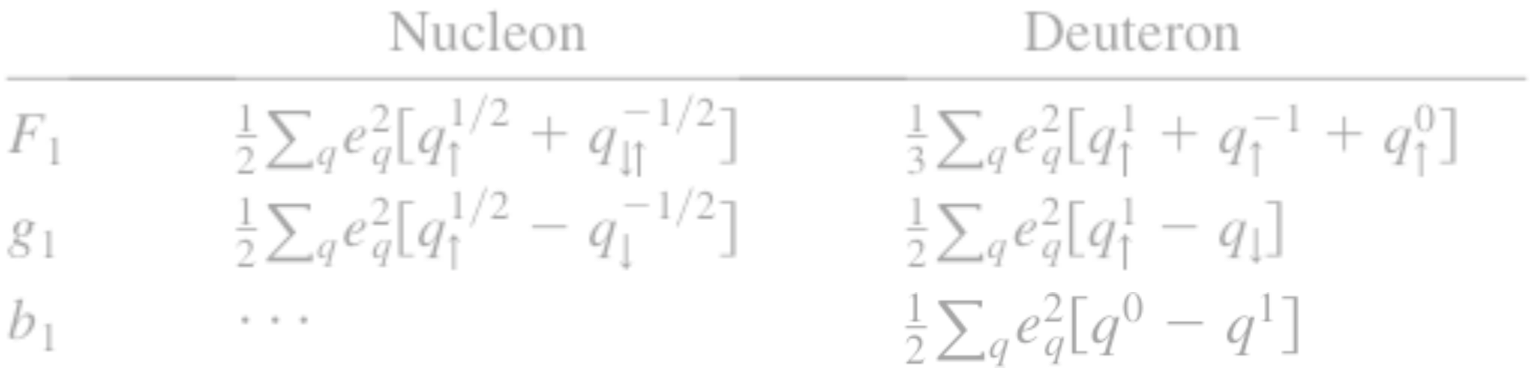
Tensor Structure Functions



	Nucleon	Deuteron
F_1	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^{1/2} + q_{\downarrow\uparrow}^{-1/2}]$	$\frac{1}{3}\sum_q e_q^2[q_\uparrow^1 + q_\uparrow^{-1} + q_\uparrow^0]$
g_1	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^{1/2} - q_\downarrow^{-1/2}]$	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^1 - q_\downarrow]$
b_1	$\cdots$	$\frac{1}{2}\sum_q e_q^2[q^0 - q^1]$

Leading Twist

Tensor Structure Functions



	Nucleon	Deuteron
F_1	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^{1/2} + q_{\downarrow\uparrow}^{-1/2}]$	$\frac{1}{3}\sum_q e_q^2[q_\uparrow^1 + q_\uparrow^{-1} + q_\uparrow^0]$
g_1	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^{1/2} - q_\downarrow^{-1/2}]$	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^1 - q_\downarrow]$
b_1	$\cdots$	$\frac{1}{2}\sum_q e_q^2[q^0 - q^1]$

Leading Twist

b_2 : related to b_1 by A Callan-Gross relation

b_4 : Also Leading Twist, but kinematically suppressed for a longitudinally polarized target.

b_3 : higher twist, like g_2

Parton Distributions

$q^m_{\uparrow\downarrow}$ Probability to scatter from a quark with spin up/down carrying momentum fraction x while the *Deuteron* is in state m

$$
\begin{aligned}
q_1(x) &= q^1_\uparrow(x) + q^1_\downarrow(x) \\
q^0(x) &= q^0_\uparrow(x) + q^0_\downarrow(x)
\end{aligned}
$$

spin averaged parton distributions

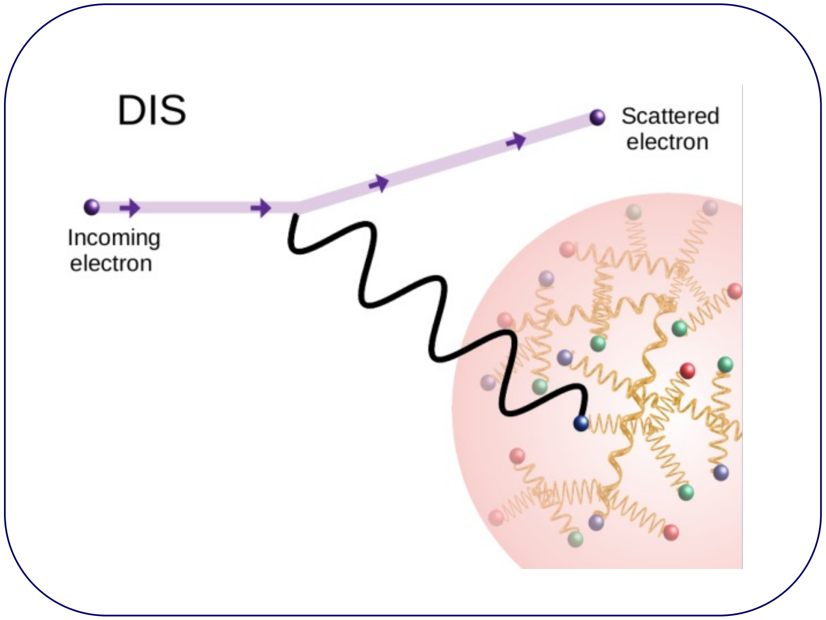
q^0 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state m=0

q^1 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state |m| = 1

b_1 structure function

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

DIS (probing quarks)

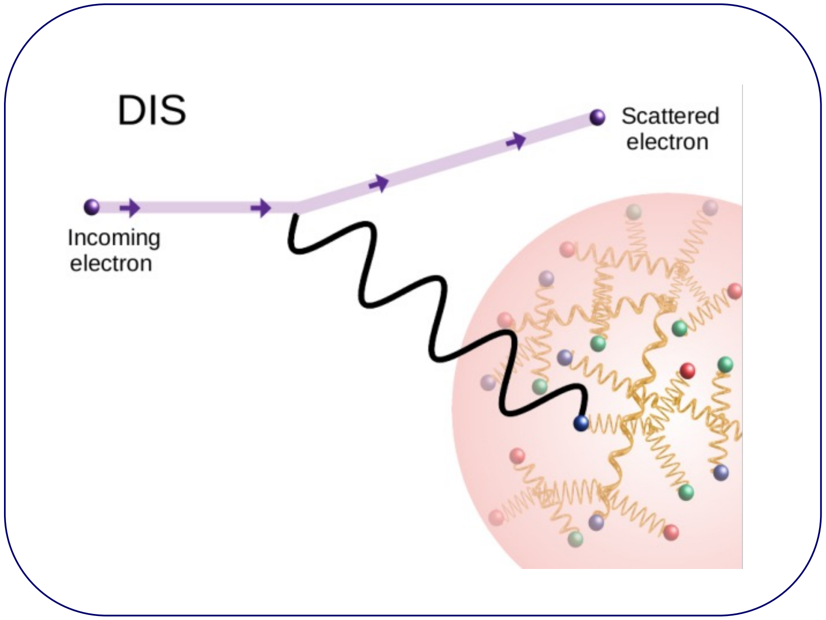


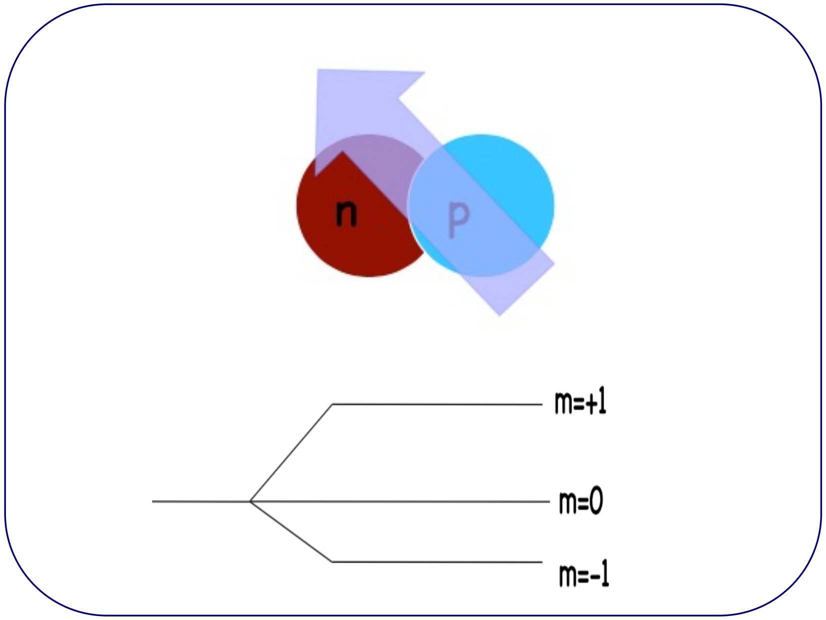
b_1 structure function

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

DIS (probing quarks)

but depends on the Deuteron spin state





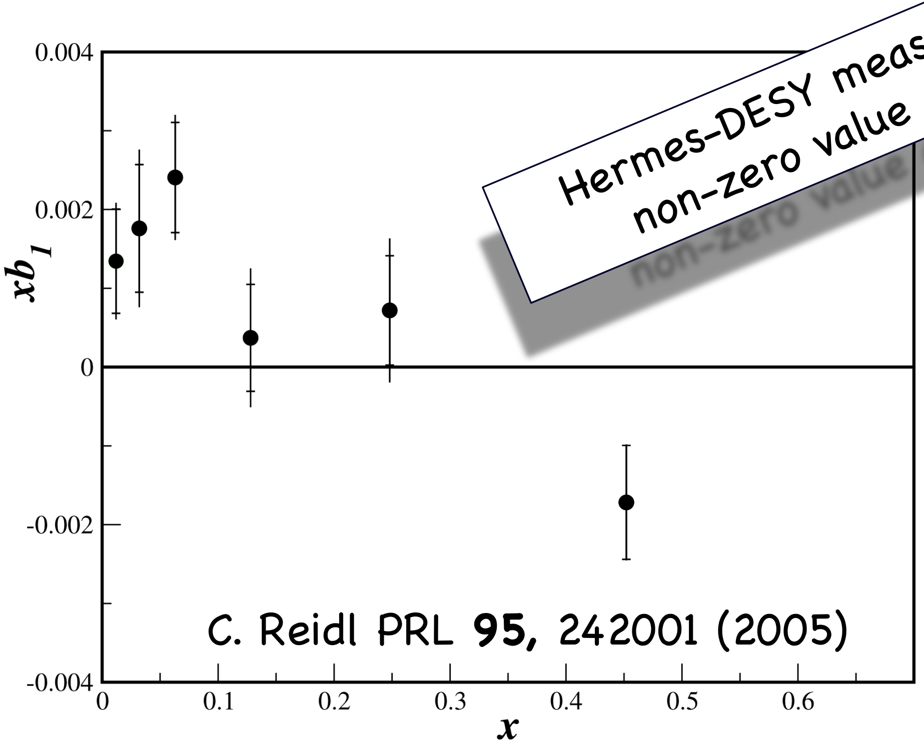
Data from HERMES

Conventional Nuclear Physics predicts b_1 to be vanishingly small at large x

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

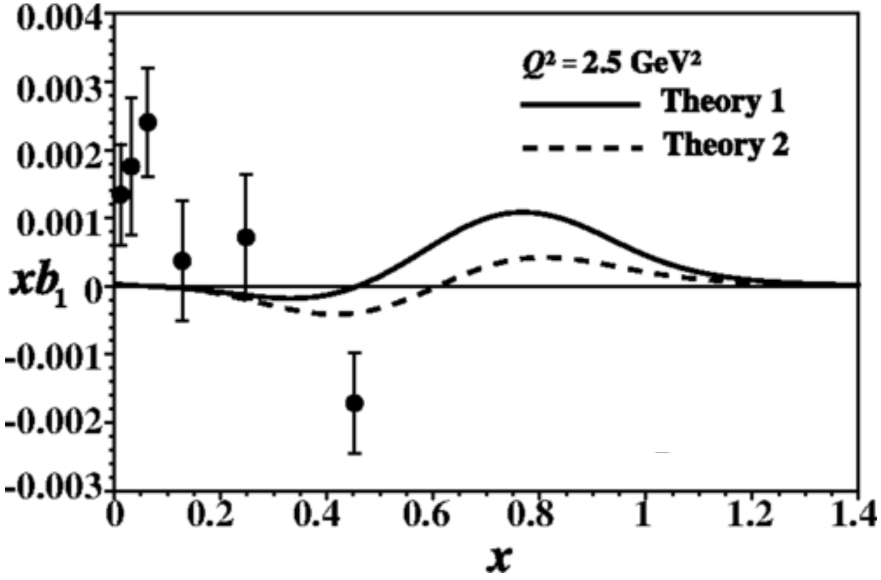
W. Cosyn, Y. Dong, S. Kumano, M. Sargsian PRD95 (2017) 074036
Standard Convolution description



Hermes-DESY measured a large non-zero value at $x \approx 0.45$

C. Reidl PRL **95,** 242001 (2005)

Standard nuclear physics can not explain the large x results

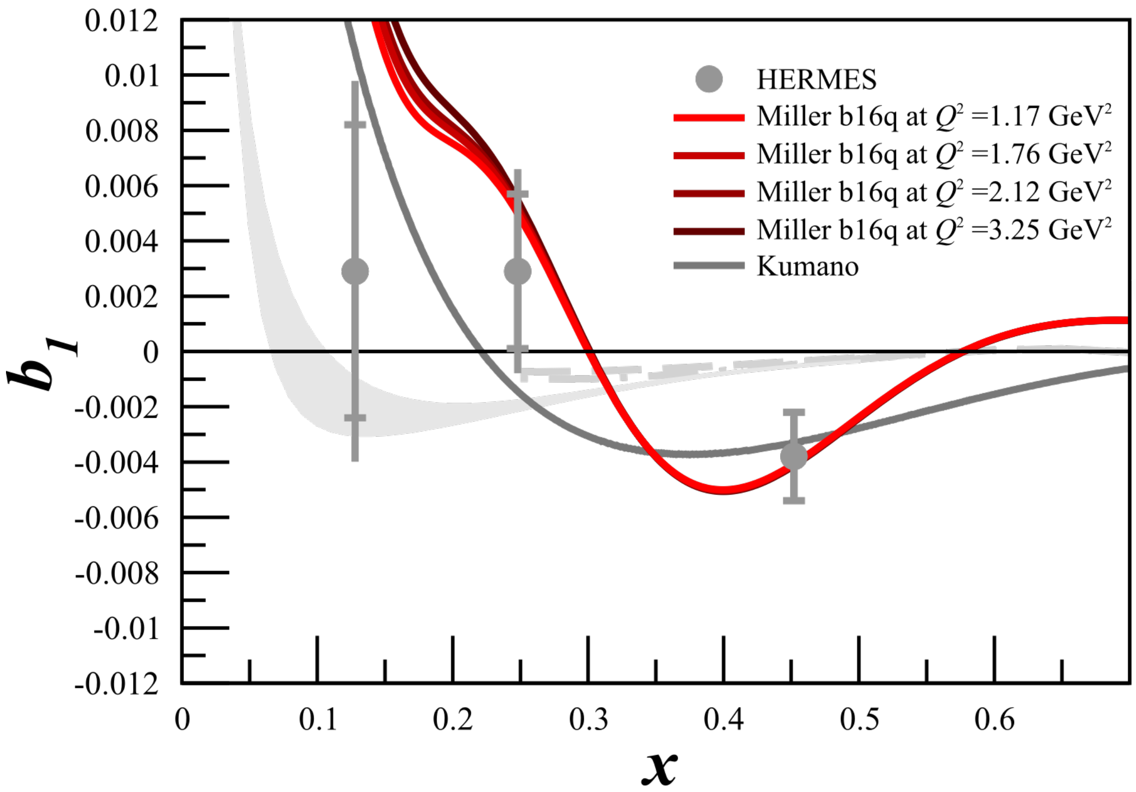


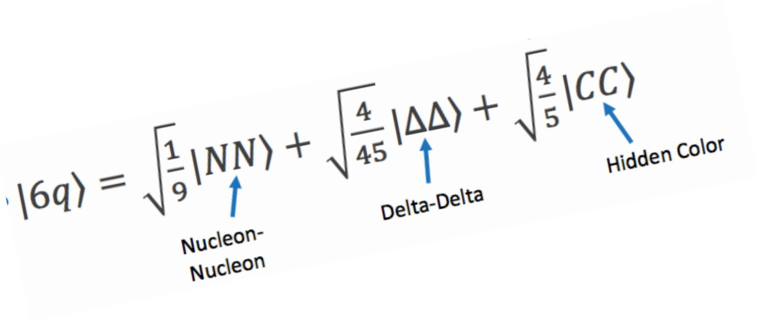
"new mechanism [is needed] to explain large differences between current data and our theoretical results"

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

W. Cosyn, Y. Dong, S. Kumano, M. Sargsian **PRD95 (2017) 074036**

Unique Signal of Hidden Color





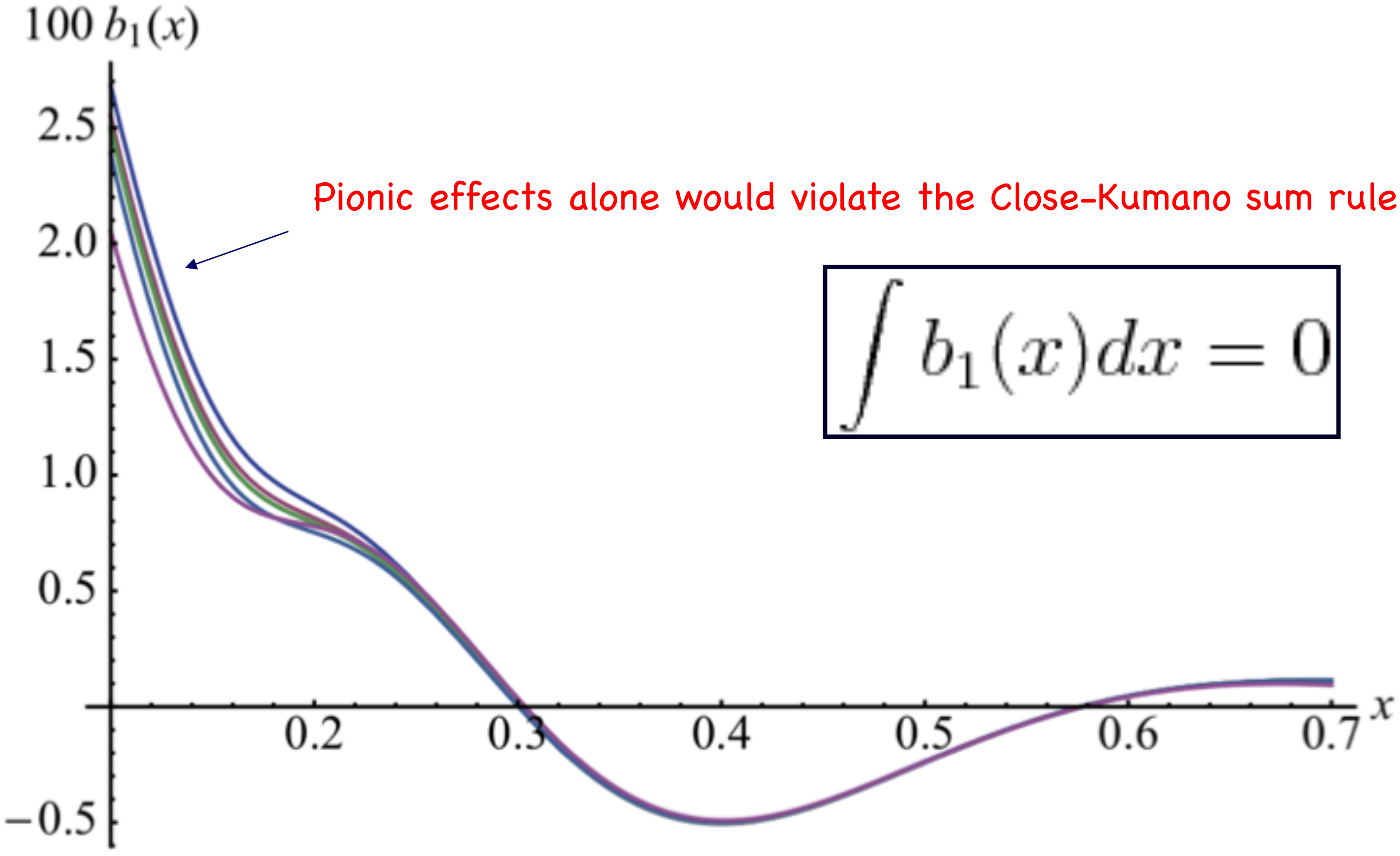
$$|6q\rangle = \sqrt{\frac{1}{9}}\underset{\substack{\uparrow\\ \text{Nucleon-}\\ \text{Nucleon}}}{|NN\rangle} + \sqrt{\frac{4}{45}}\underset{\substack{\uparrow\\ \text{Delta-Delta}}}{|\Delta\Delta\rangle} + \sqrt{\frac{4}{5}}\underset{\substack{\nwarrow\\ \text{Hidden Color}}}{|CC\rangle}$$

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**

6-quark, Hidden Color



Pionic effects alone would violate the Close-Kumano sum rule

$$\boxed{\int b_1(x)dx = 0}$$

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

Gluon Contribution to Tensor Structure

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

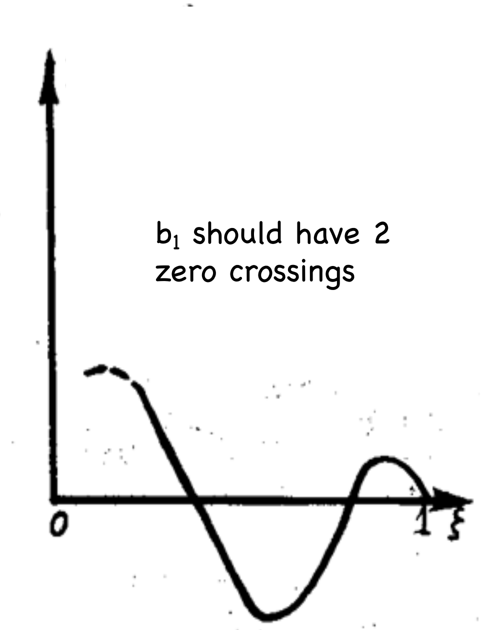
$$\int xb_1(x)dx = 0$$

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!



b$_1$ should have 2 zero crossings

Рис.1

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)

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

b_1/A_{zz} Collaboration

<u>RunGroup Spokespersons</u>

Chen, Day, Higinbothan, Kalantarians, Keller
Long, Rondon, Santiesteban, Slifer, Solvignon*

14 different active institutions
10 identified PhD students (from 3 universities)
2 active post-docs + 2 more expected
Weekly meetings

Join by going to link https://mailman.jlab.org/mailman/listinfo/Tensor

Or just send an email to karl.slifer@unh.edu to be added

Experimental Method

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

Normalized XS Difference

B-Field, density, temp,.... held same in both states

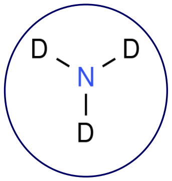
$$b_1 = -\frac{3}{2}F_1^d A_{zz}$$

σ_Q : Tensor Polarized cross-section

σ_0 : Unpolarized cross-section

P_{zz} : Tensor Polarization (or Q)

$f \approx \frac{6}{20}$ dilution factor



Experimental Method

$$A_{zz} = \left[\frac{2}{fP_{zz}}\right]\left[\frac{\sigma(P_z, P_{zz}) + \sigma(-P_z, P_{zz})}{\sigma(P_z, 0) + \sigma(-P_z, 0)} - 1\right]$$

$$\sigma_1 = \sigma(+P_z, P_{zz})$$

$$\sigma_2 = \sigma(-P_z, P_{zz})$$

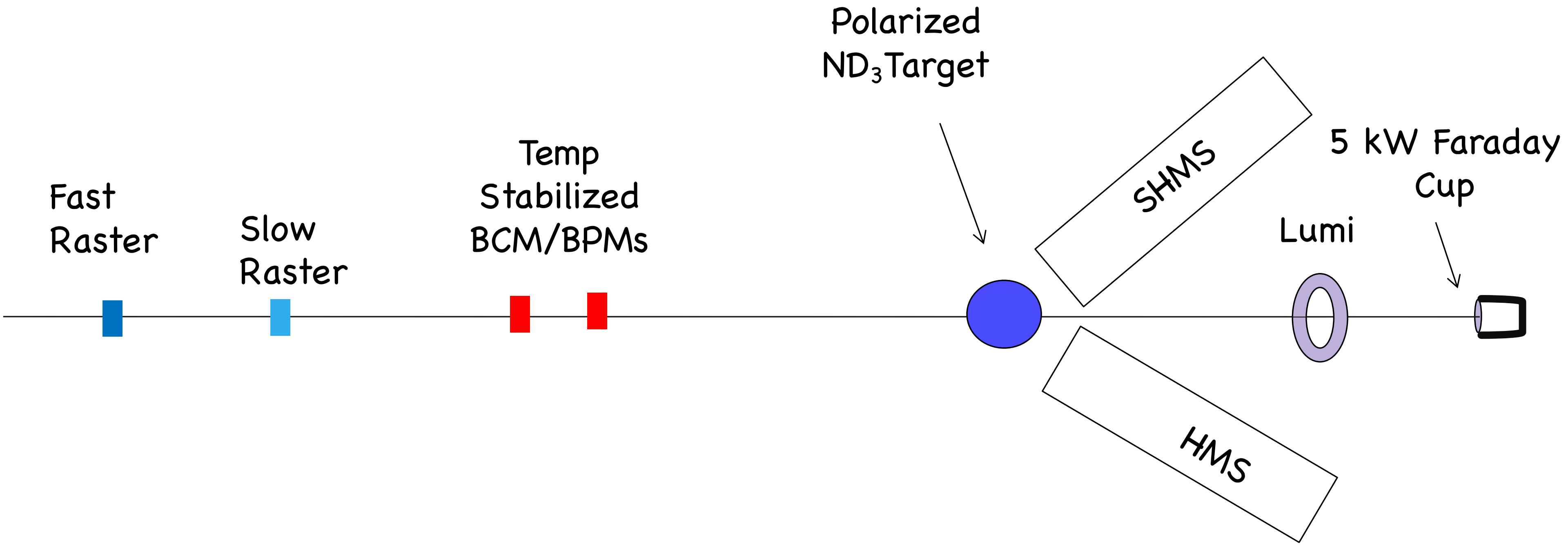
$$\sigma_3 = \sigma(+P_z, 0)$$

$$\sigma_4 = \sigma(-P_z, 0)$$

Suppresses A_V

Rapid tensor spin flips suppress Slow Drift effects

Jlab Hall C

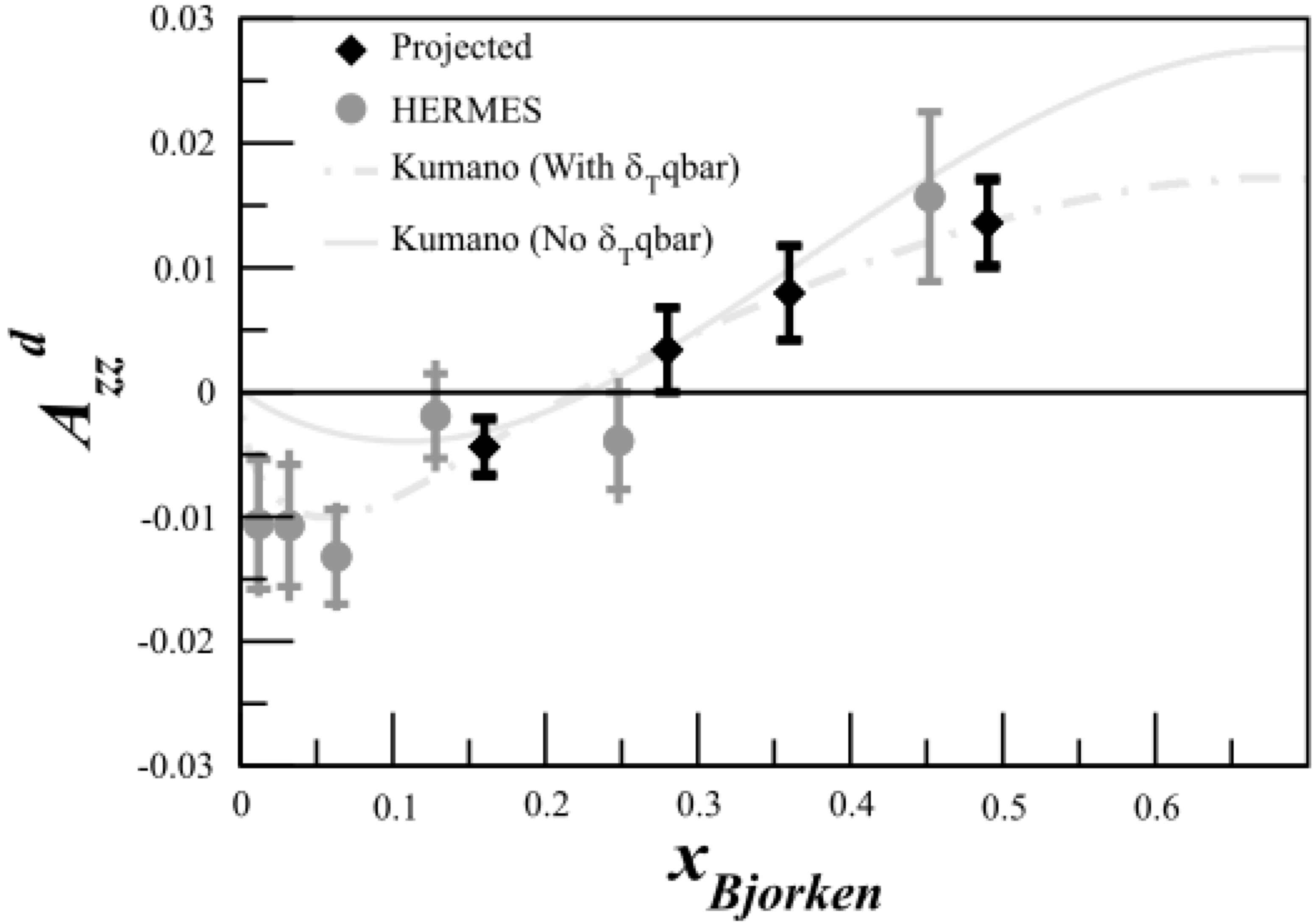


Unpolarized Beam

UVa/JLab Polarized Target
$\mathcal{L}=10^{35}$

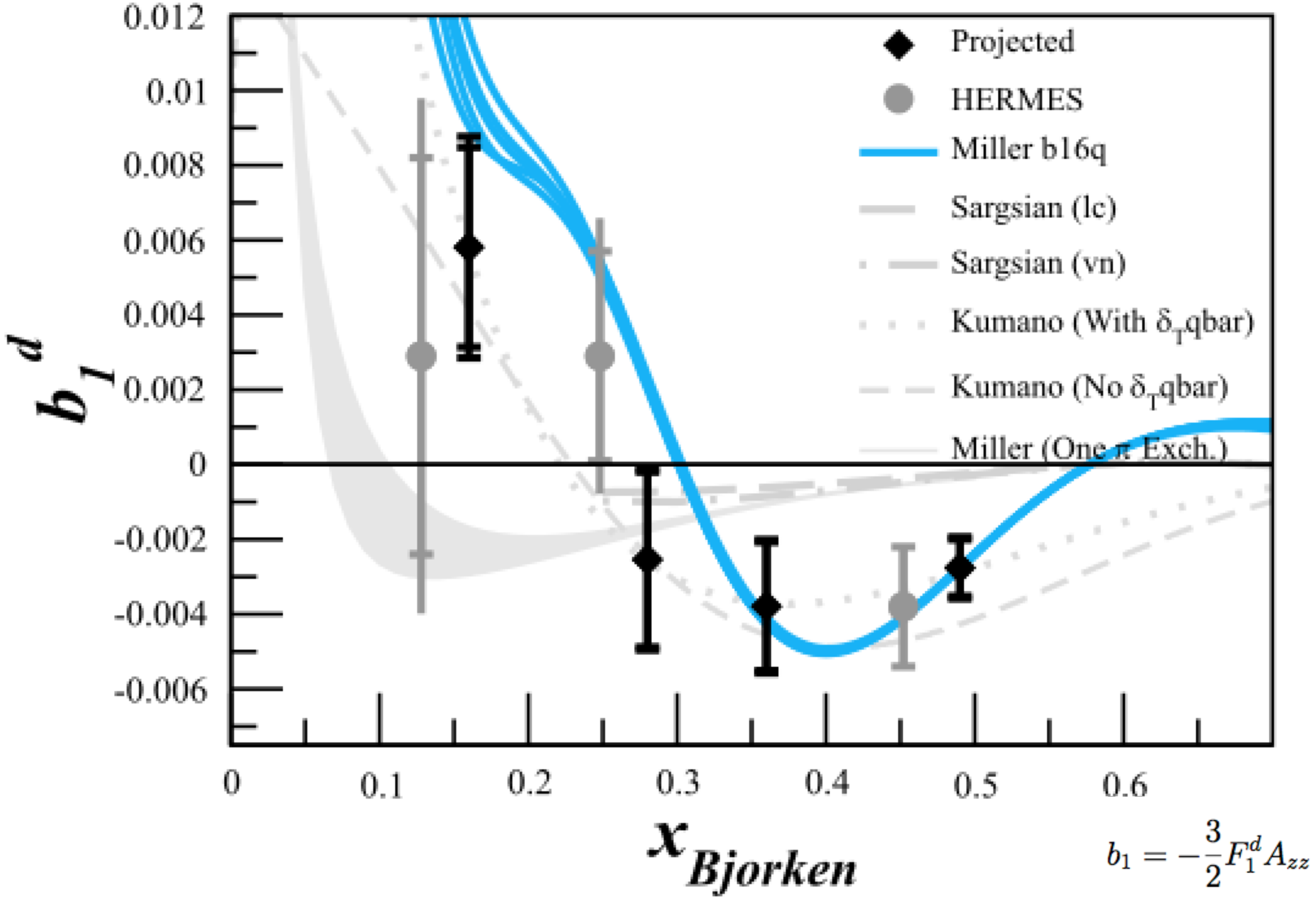
See D. Mack's talk on
Beam Current Monitoring
Conceptual Design

Projected



85 nA, P_{zz}=0.26, 36 PAC days + 12 days overhead

Projected



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

85 nA, P_{zz}=0.26, 36 PAC days + 12 days overhead

New Developments

New Jlab Magnet

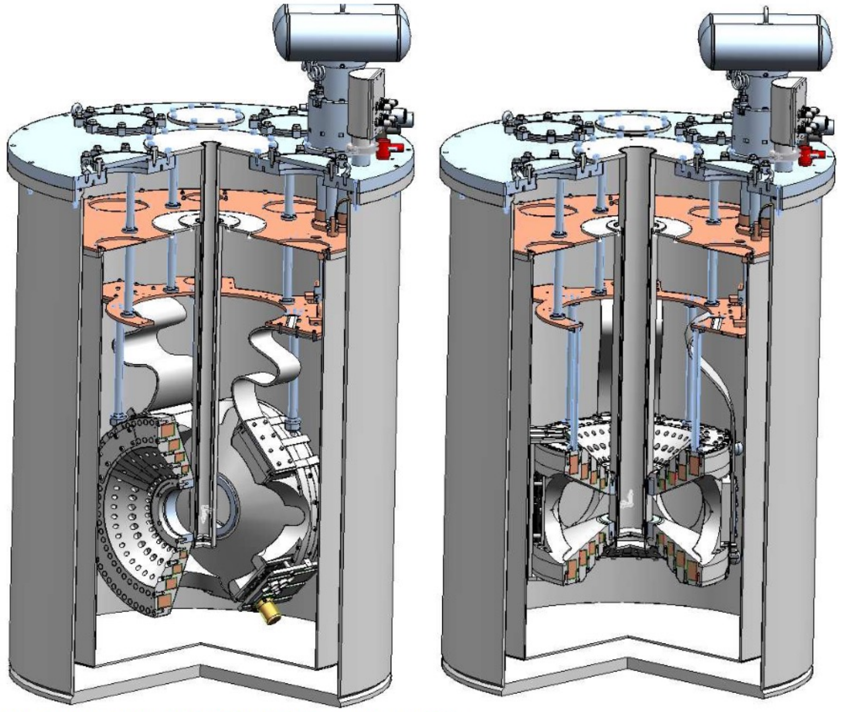


Figure 7: Cut-away of the 2 orientations for the magnet.

The new magnet will provide acceptances:
±35° for longitudinal polarization (30% smaller)
±25° for transverse polarization (67% larger)

Coils cooled by a 4K cryo pulse tube

See J. Maxwell's talk

New Jlab Magnet & NMR System

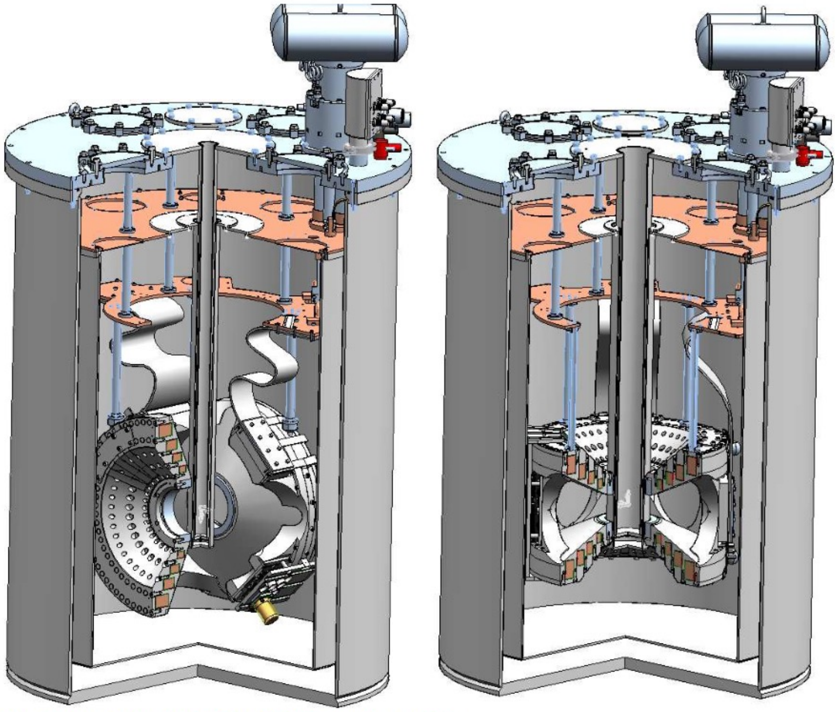
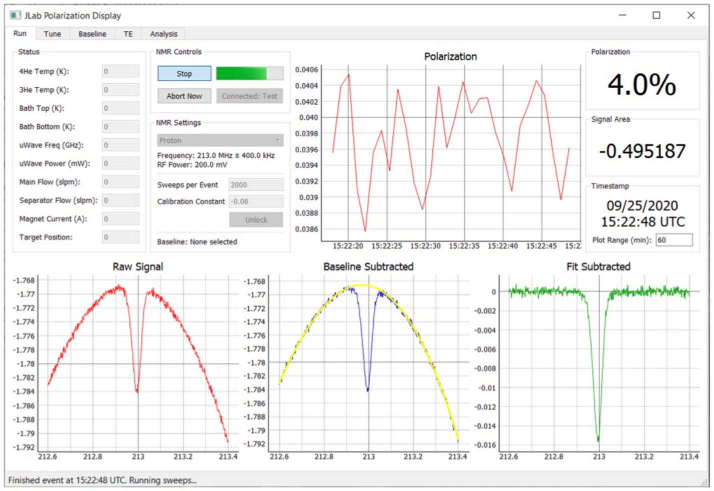


Figure 7: Cut-away of the 2 orientations for the magnet.



JLab Polarization Display

Status

4He Temp (K): 0
3He Temp (K): 0
Bath Top (K): 0
Bath Bottom (K): 0
uWave Freq (GHz): 0
uWave Power (mW): 0
Main Flow (slpm): 0
Separator Flow (slpm): 0
Magnet Current (A): 0
Target Position: 0

NMR Controls

NMR Settings

Proton
Frequency: 213.0 MHz ± 400.0 kHz
RF Power: 200.0 mV
Sweeps per Event 2000
Calibration Constant -0.08

Baseline: None selected

Polarization: 4.0%

Signal Area: -0.495187

Timestamp: 09/25/2020 15:22:48 UTC

Plot Range (min): 60

Finished event at 15:22:48 UTC. Running sweeps...

The new magnet will provide acceptances:

±35° for longitudinal polarization (30% smaller)

±25° for transverse polarization (67% larger)

Coils cooled by a 4K cryo pulse tube

See J. Maxwell's talk

Tensor Enhancement

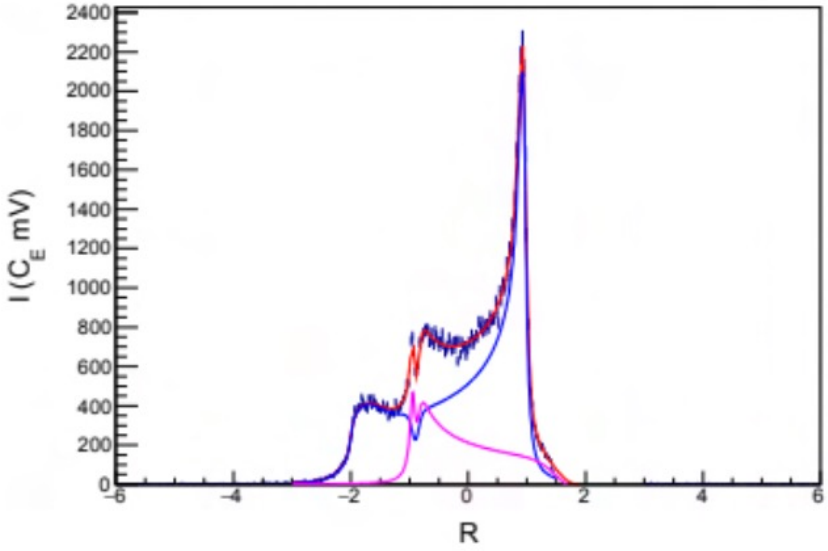
In 2014, tensor polarization P_{zz} of 10-20% was typical

$$P_{ZZ} = 2 - \sqrt{4 - 3P_Z^2}$$

Now SS-RF techniques can be used to reliably achieve tensor polarizations of about 30%

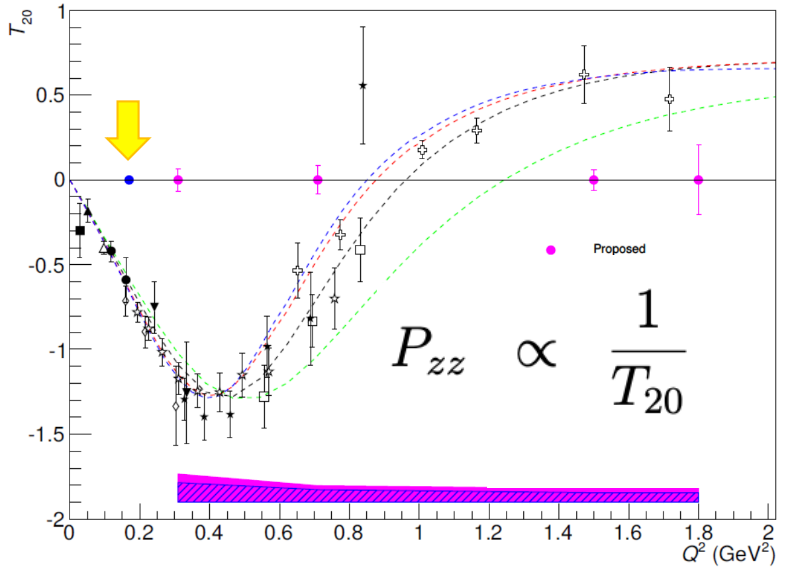
See talks of D. Keller/I. Fernando/D. Seay

Polarization Uncertainty



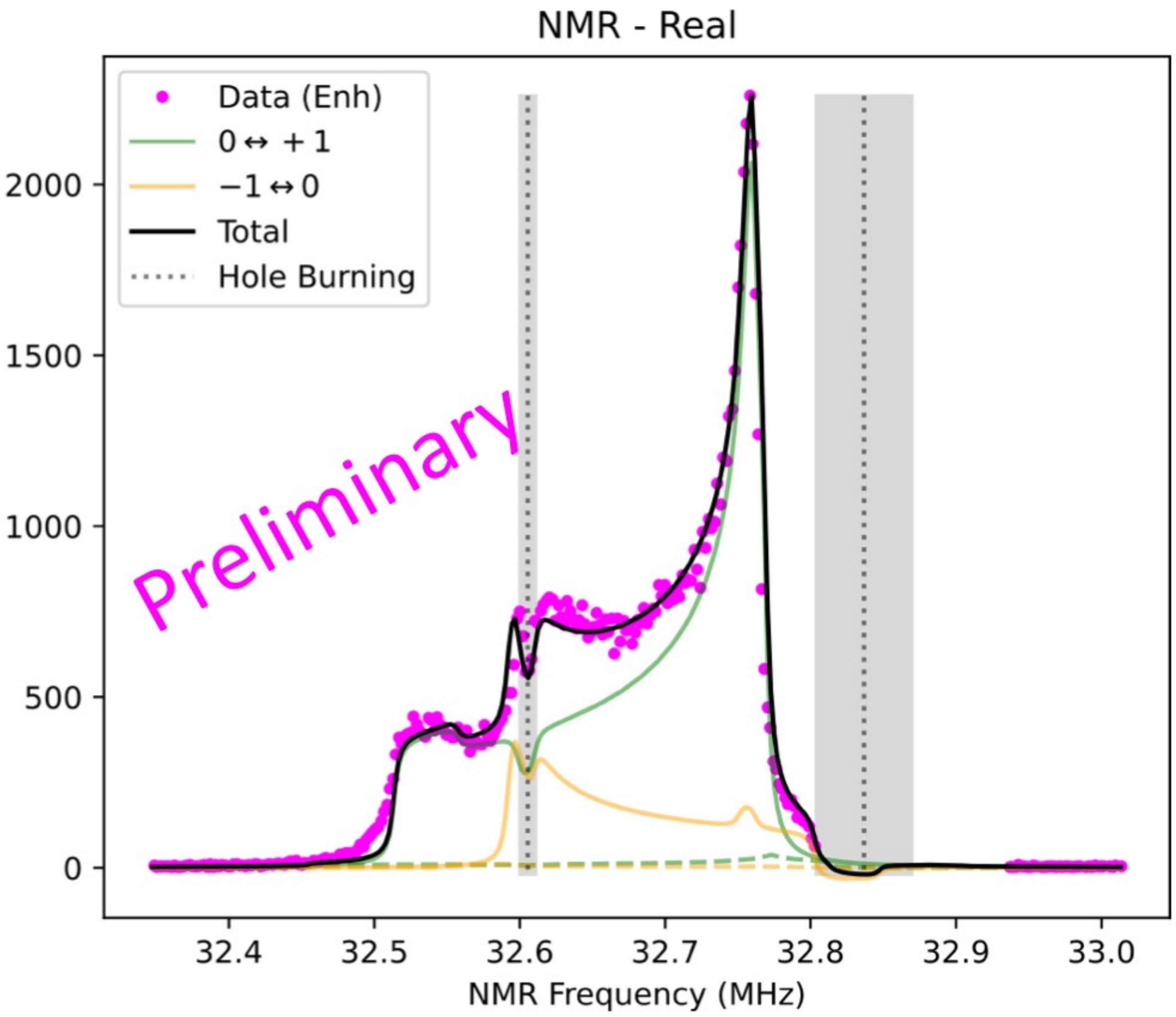
P_{zz} can be extracted from NMR Lineshape with about 9% relative error

See D. Keller, Elena Long, Michael McClellan



P_{zz} can be extracted from T_{20} with about 8.6% relative error

Line Shape Analysis



See E. Long and Michael McClellan

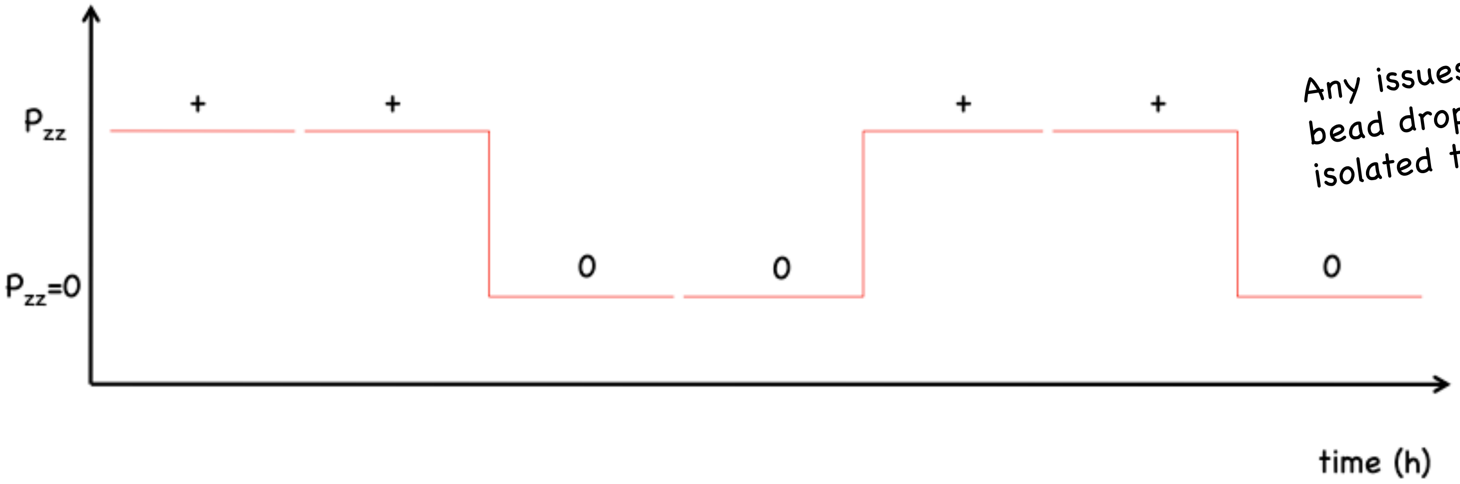
Switching Tensor Spin State

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

In the proposals we planned to transition between tensor enhanced state to unpolarized every 12 hours via DNP

SS-RF allows transition from tensor enhanced to unpolarized several times per hour reducing our sensitivity to slow drifts

Switching Tensor Spin State



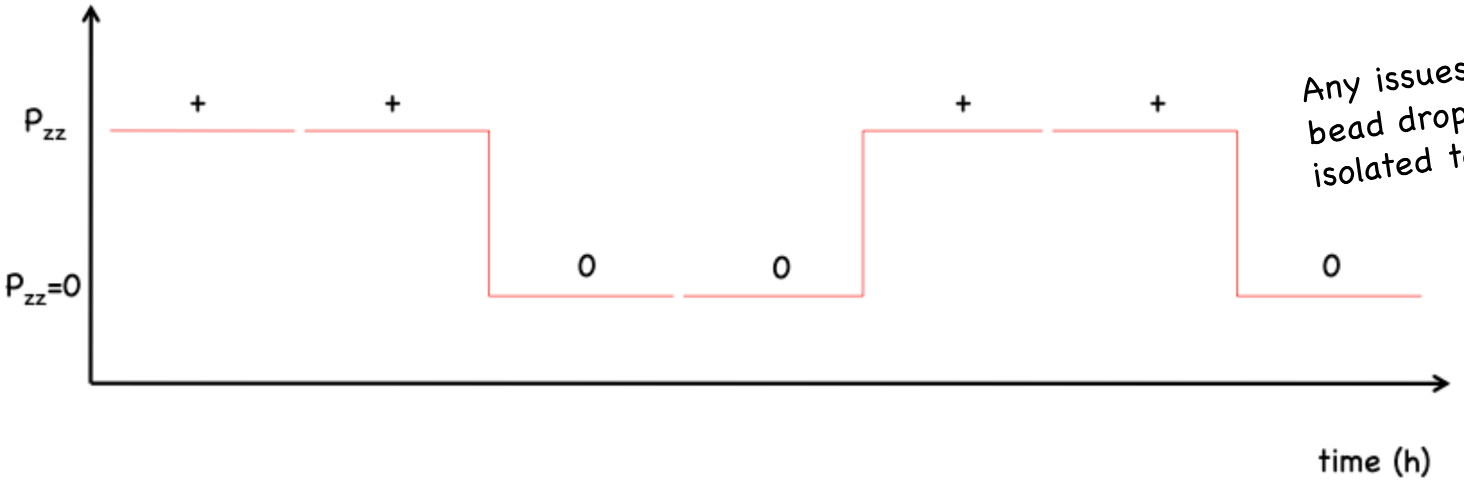
Any issues from bead dropping,etc is isolated to a single cycle

Proposal Assumption: Switching from unpolarized state to tensor state requires a DNP spin up.
So we would do this only once per day

We now know we can do this switch very rapidly via RF by filling/emptying the m=0 state
So we now plan to do this a few times per hour
Switching from Tensor enhanced to unpolarized requires a few seconds
Switching from unpolarized back to Tensor enhanced requires a few minutes.

See talks of D. Keller/I. Fernando/D. Seay

Switching Tensor Spin State



Any issues from bead dropping,etc is isolated to a single cycle

Proposal Assumption: Switching from unpolarized state to tensor state requires a DNP spin up.
So we would do this only once per day

We can now match the PAC conditions even for significantly lower current and P_{zz}
eg.: I=85 nA, P_{zz}=0.26 gives smaller total uncertainty than PAC approved conditions

polarized requires a few seconds

switching from unpolarized back to Tensor enhanced requires a few minutes.

This significantly reduces our sensitivity due to slow instrumental drifts

$$\text{Systematic} \propto \frac{1}{\sqrt{N}}$$

polarization state pairs

Jlab Schedule

August 2022 : Conditional Status Removed, Full Approval

July 2023 : Jeopardy Review of b_1/A_{zz}

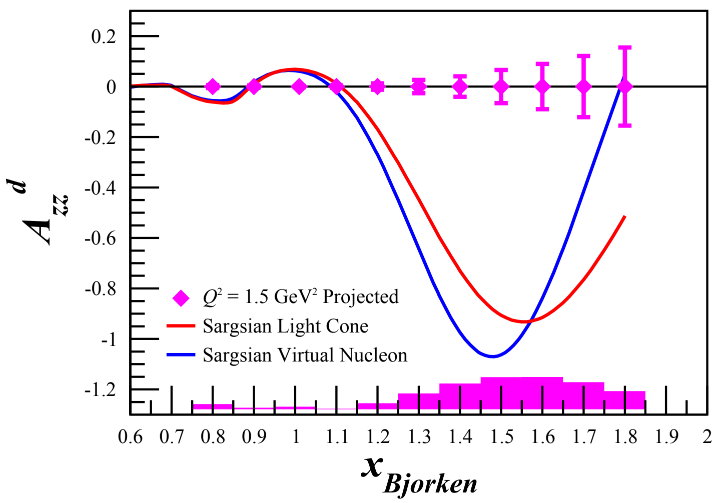
2024 : Experimental Readiness Review ??

>2025 : Run in Hall C

More details on the Jlab Schedule
in Doug Higinbothan's talk

E12-15-005

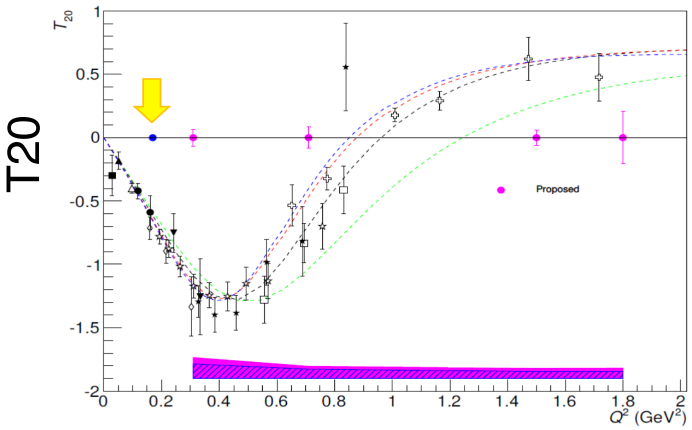
A_{zz} in the x>1 Region



Very Large Tensor Asymmetries predicted

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

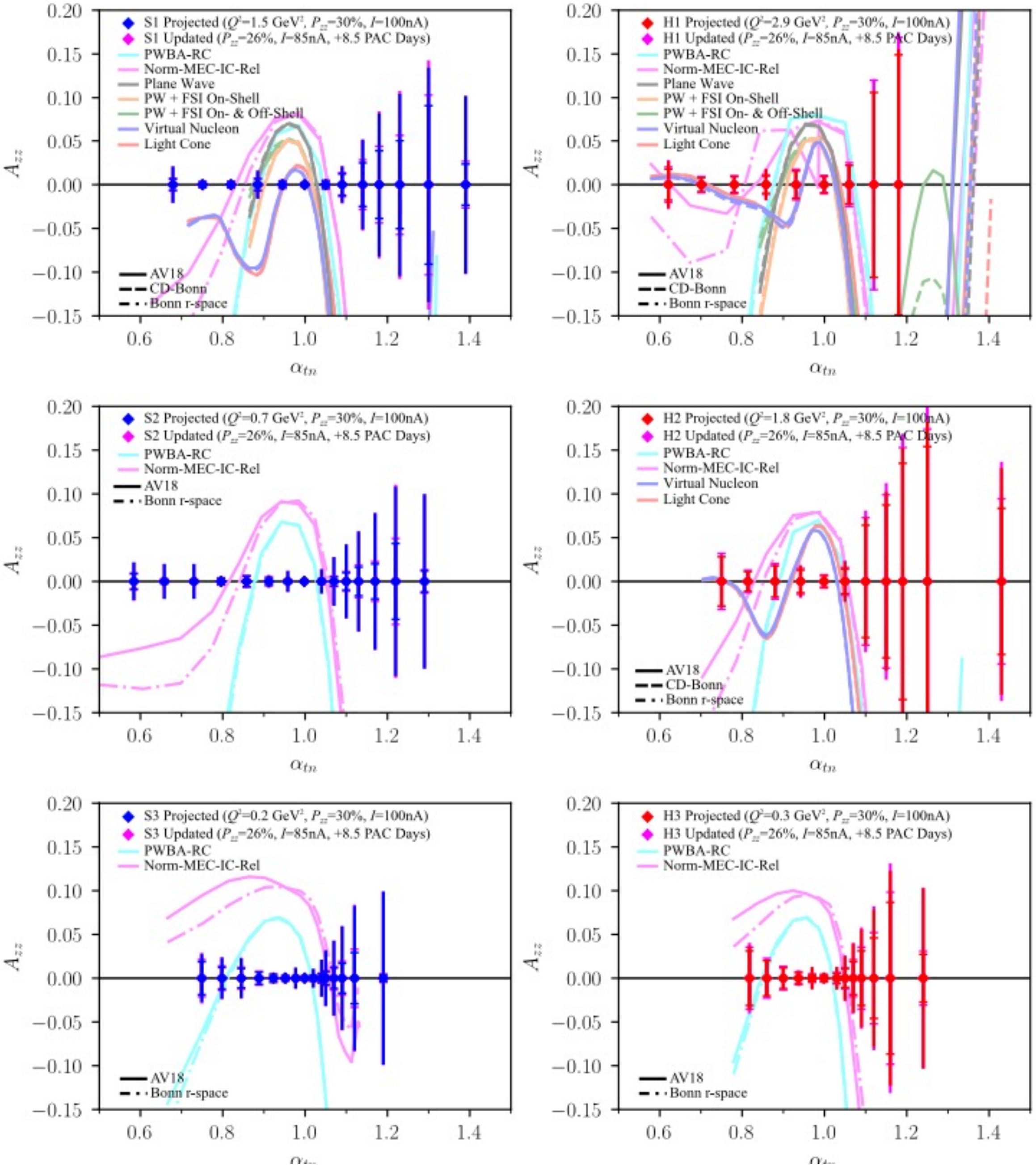
4σ discrim between hard/soft wave functions
6σ discrim between relativistic models



"further explores the nature of short-range pn correlations, the discovery of which was one of the most important results of the 6 GeV nuclear program."

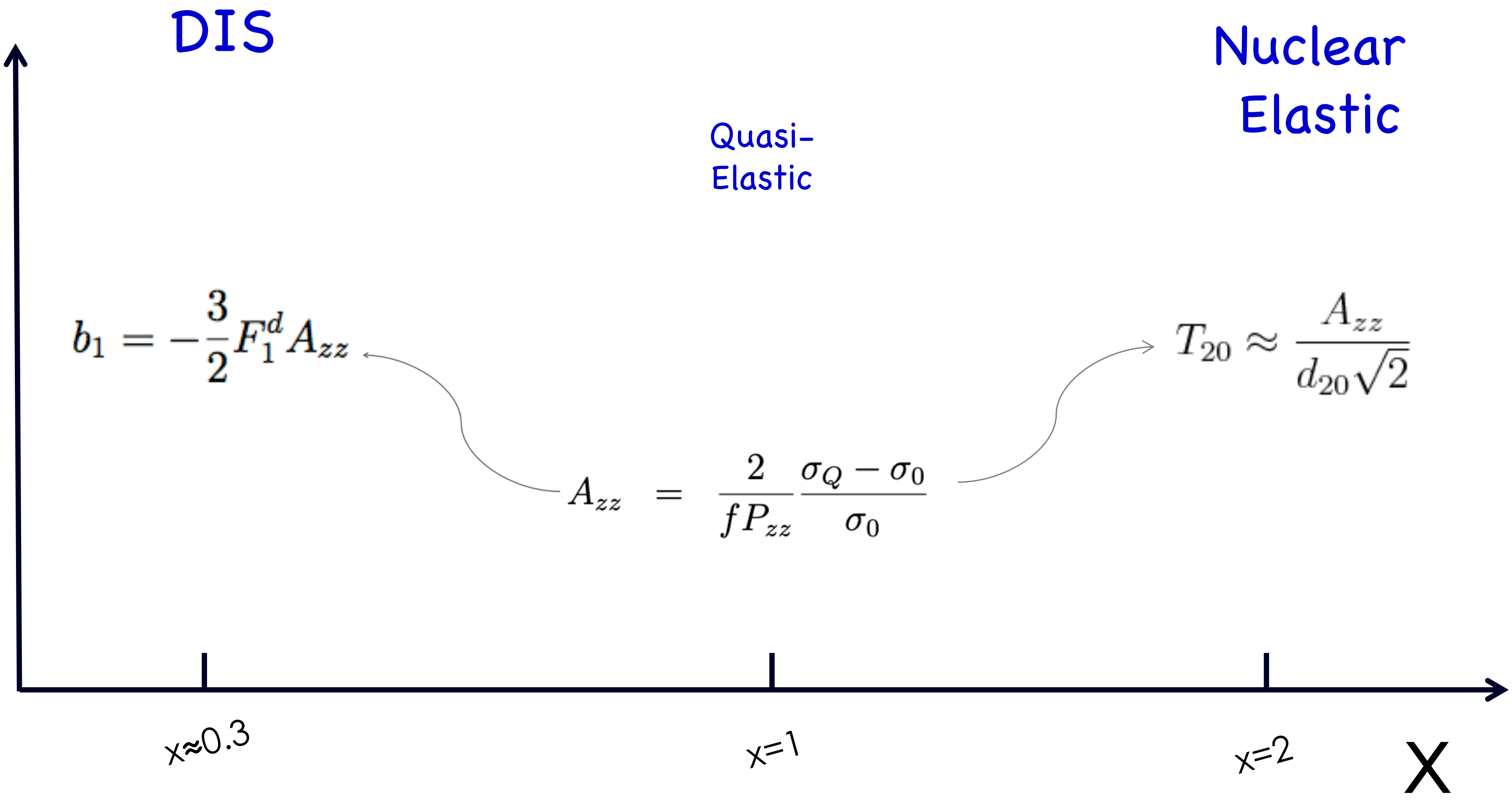
PAC44 Theory Report

E12-15-005



See E. Long's talk

Tensor Spin Observables



DIS

Quasi-Elastic

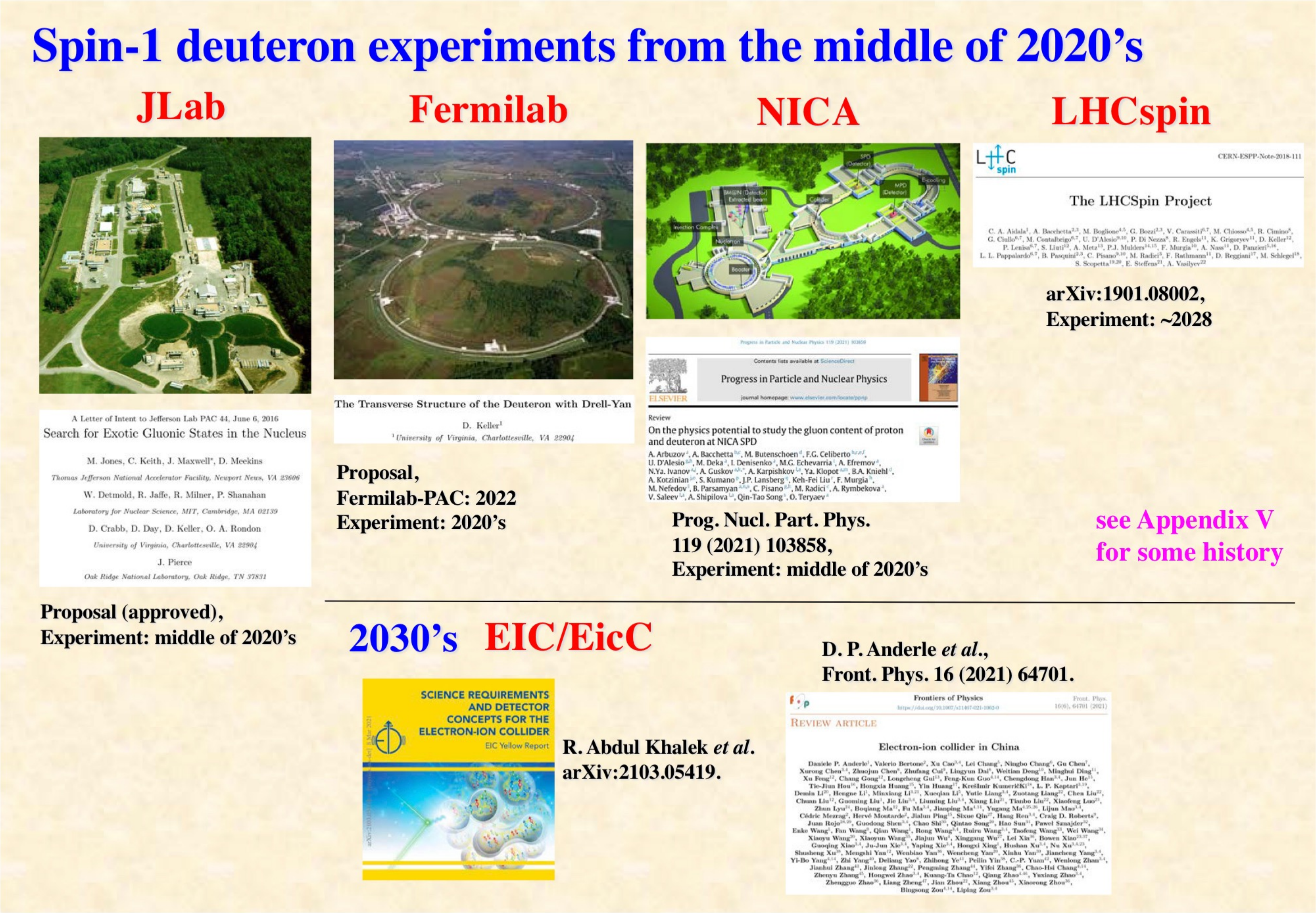
Nuclear Elastic

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

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

$$T_{20} \approx \frac{A_{zz}}{d_{20}\sqrt{2}}$$

Future



Spin-1 deuteron experiments from the middle of 2020's

JLab

A Letter of Intent to Jefferson Lab PAC 44, June 6, 2016

Search for Exotic Gluonic States in the Nucleus

M. Jones, C. Keith, J. Maxwell*, D. Meekins

Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

W. Detmold, R. Jaffe, R. Milner, P. Shanahan

Laboratory for Nuclear Science, MIT, Cambridge, MA 02139

D. Crabb, D. Day, D. Keller, O. A. Rondon

University of Virginia, Charlottesville, VA 22904

J. Pierce

Oak Ridge National Laboratory, Oak Ridge, TN 37831

Proposal (approved),
Experiment: middle of 2020's

Fermilab

The Transverse Structure of the Deuteron with Drell-Yan

D. Keller[1]

[1] *University of Virginia, Charlottesville, VA 22904*

Proposal,
Fermilab-PAC: 2022
Experiment: 2020's

NICA

Progress in Particle and Nuclear Physics 119 (2021) 103858

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

Review

On the physics potential to study the gluon content of proton and deuteron at NICA SPD

A. Arbuzov, A. Bacchetta, M. Butenschoen, F.G. Celiberto, U. D'Alesio, M. Deka, I. Denisenko, M.G. Echevarria, A. Efremov, N.Ya. Ivanov, A. Guskov, A. Karpishkov, Ya. Klopot, B.A. Kniehl, A. Kotzinian, S. Kumano, J.P. Lansberg, Keh-Fei Liu, F. Murgia, M. Nefedov, B. Parsamyan, C. Pisano, M. Radici, A. Rymbekova, V. Saleev, A. Shipilova, Qin-Tao Song, O. Teryaev

Prog. Nucl. Part. Phys.
119 (2021) 103858,
Experiment: middle of 2020's

LHCspin

CERN-ESPP-Note-2018-111

The LHCSpin Project

C. A. Aidala^{1}, A. Bacchetta^{2,3}, M. Boglione^{4,5}, G. Bozzi^{2,3}, V. Carassiti^{6,7}, M. Chiosso^{4,5}, R. Cimino^{8}, G. Ciullo^{6,7}, M. Contalbrigo^{6,7}, U. D'Alesio^{9,10}, P. Di Nezza^{8}, R. Engels^{11}, K. Grigoryev^{11}, D. Keller^{12}, P. Lenisa^{6,7}, S. Liuti^{12}, A. Metz^{13}, P.J. Mulders^{14,15}, F. Murgia^{10}, A. Nass^{11}, D. Panzieri^{5,16}, L. L. Pappalardo^{6,7}, B. Pasquini^{2,3}, C. Pisano^{9,10}, M. Radici^{3}, F. Rathmann^{11}, D. Reggiani^{17}, M. Schlegel^{18}, S. Scopetta^{19,20}, E. Steffens^{21}, A. Vasilyev^{22}

arXiv:1901.08002,
Experiment: ~2028

see Appendix V
for some history

2030's EIC/EicC

SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report

R. Abdul Khalek *et al*.
arXiv:2103.05419.

D. P. Anderle *et al*.,
Front. Phys. 16 (2021) 64701.

Frontiers of Physics

https://doi.org/10.1007/s11467-021-1062-0

Front. Phys. 16(6), 64701 (2021)

REVIEW ARTICLE

Electron-ion collider in China

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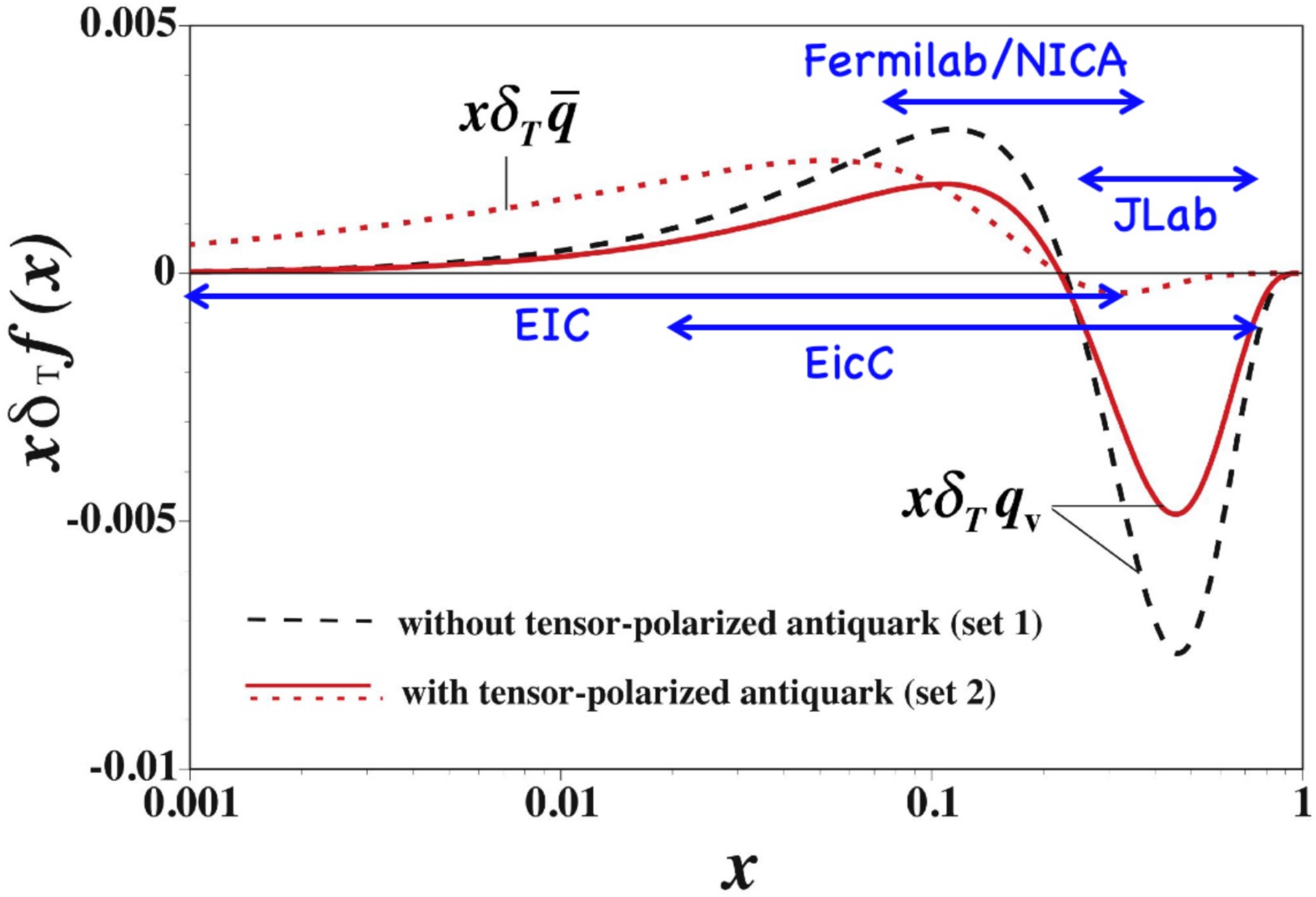
See talk of Kumano

Future

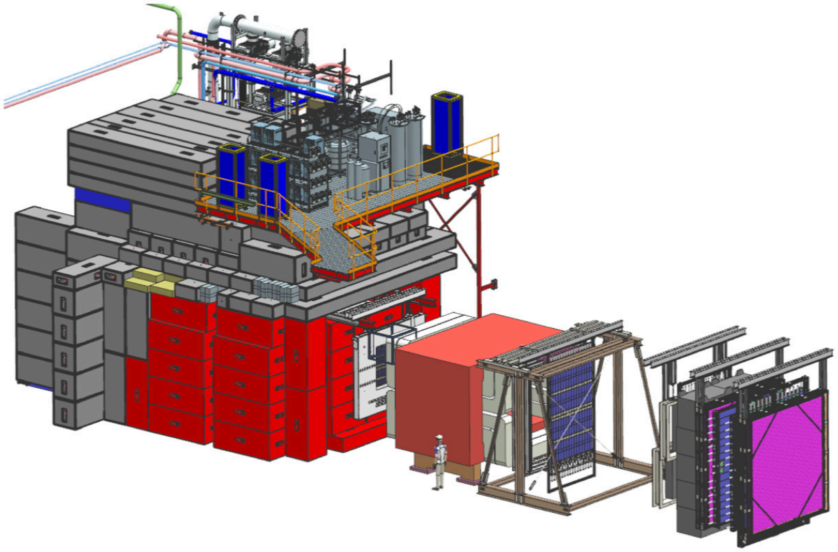


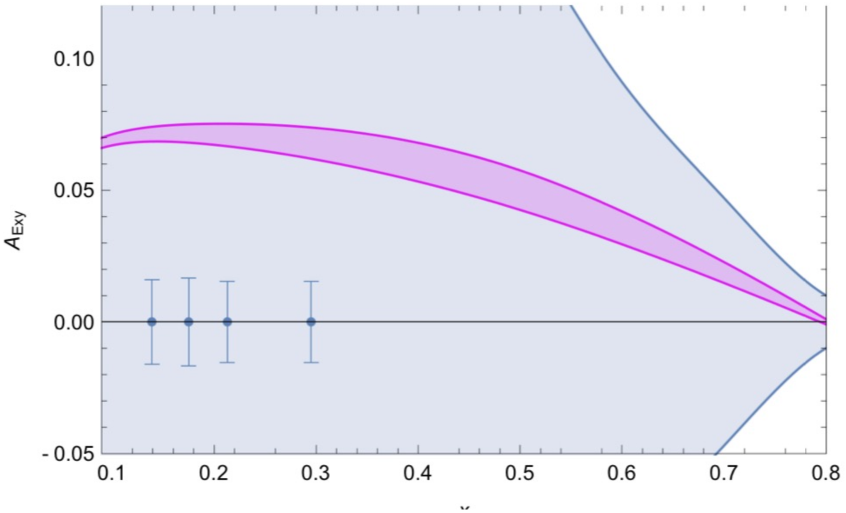
Tensor Experiments planned at Jlab, Fermilab, NICA, EIC, EICC, LHC spin
See talks of Kumano, Keller, Ishara, Long, Maxwell, Yeros

Deuteron Transversity TMDs

D. Keller et al (SpinQuest collab)

Exotic glue contributions to the nucleus not associated with individual nucleons





Linear polarized gluon asymmetry

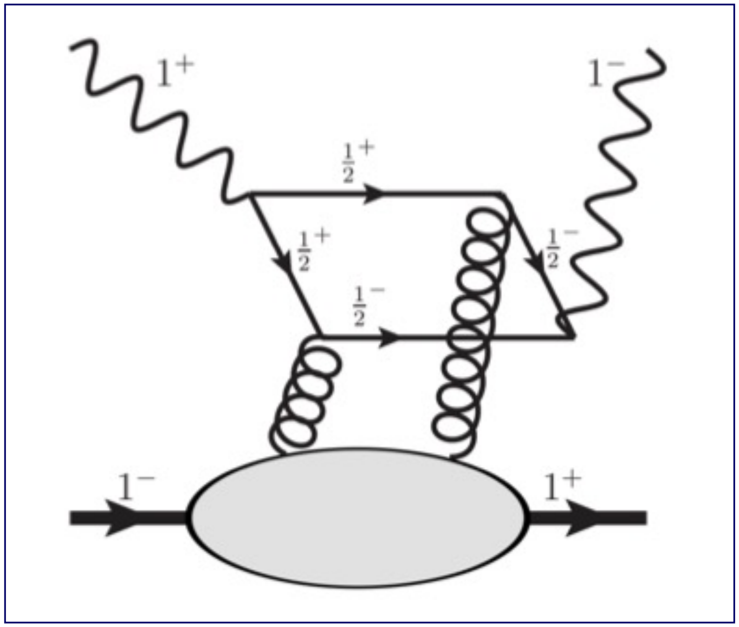
120 GeV proton Beam
Tensor ND3 target
SpinQuest Target and NM4 detector

See talk of Keller, Fernando

Jlab LOI-12-16-006

James Maxwell (contact), R. Milner, …

"Nuclear Gluonometry"



Look for novel gluonic components in nuclei that are not present in nucleons

Non-zero value would be a clear signature of exotic gluon states in the nucleus

Deep inelastic scattering experiment:
- Unpolarized electrons
- Polarized $^{14}NH_3$ Target
- Target spin aligned transverse to beam

$\Delta(x,Q^2)$ double helicity flip structure function

Encouraged for full submission by PAC44

Summary

Tensor Spin Observables have been of high interest for >40 years

Only now can we start to measure them

Jlab experiments will give first data in next few years

But there are many more planned Experiments

Exciting time for Spin Physics and Polarized Targets!!

Backups

Figure of Merit

$$\mathrm{FOM} \propto I * P_{zz}^2 \qquad \text{(Stat. Error)}$$

PAC Conditional

$I = 115\,\mathrm{nA}$
$P_{zz} = 0.30$

$t = 720$ hrs (physics)
$t_O = 172$ hrs (overhead)
$N = 30$ (#tensor flips)

$\varepsilon = 720/(720+172) = 0.81$ (efficiency)

$I * (P_{zz})^2 * \varepsilon = 8.4$

Now

$I = 85\,\mathrm{nA}$
$P_{zz} = 0.26$

$t = 720$ hrs (physics)
$t_O = 281$ hrs (overhead)
$N = 720$ (#tensor flips)

$\varepsilon = 720/(720+285) = 0.72$ (efficiency)

$I * (P_{zz})^2 * \varepsilon = 7.4$

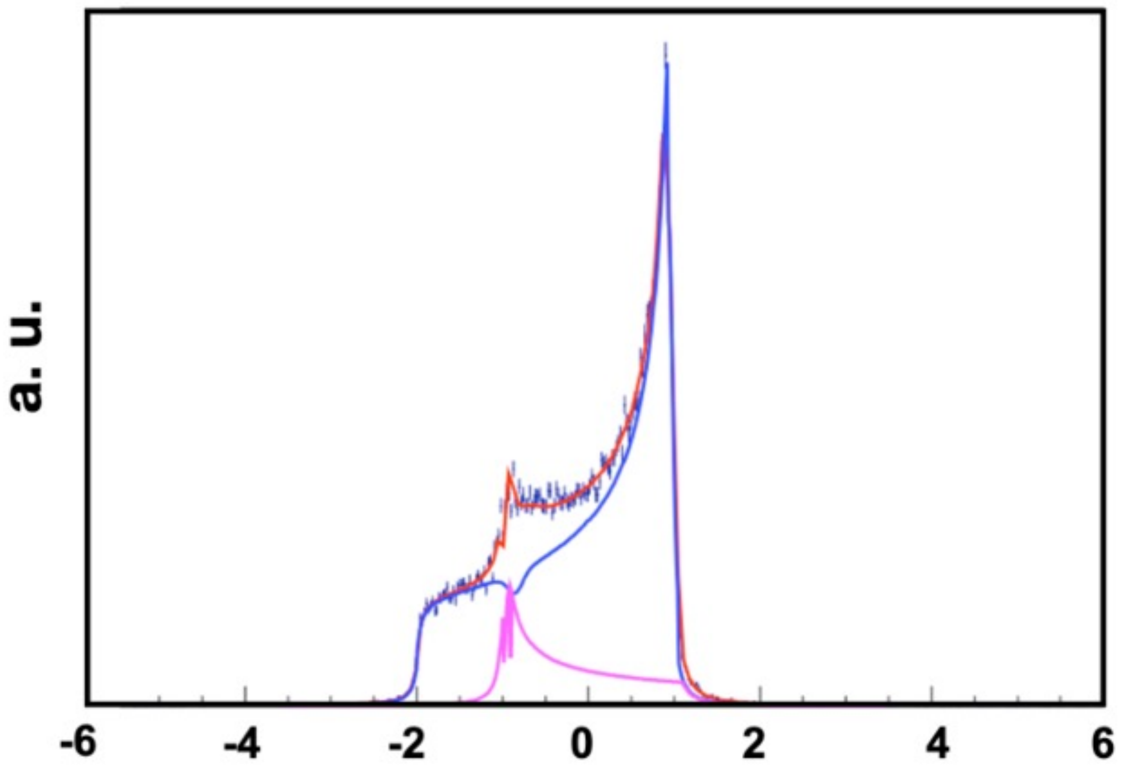
Holding everything consistent with the PAC conditions, the statistical FOM takes a 12% relative hit due to the new overhead

Tensor Enhancement

$P_{zz} \cong$ 30% via SS-RF (with 7% relative uncertainty)

$P_{zz} \cong$ 32% via SS-RF + AFP (with 8.5% relative uncertainty)

$P_{zz} \cong$ 36% via SS-RF + Rotation (with 9.5% relative uncertainty)



Tensor Enhanced NMR Signal & Lineshape Fit

[1] D. Keller, et al., NIM A **981**, 164504 (2020)
[2] D. Keller, Eur. Phys. J. A **53**, 155 (2017)

Full Details in D. Keller's presentation