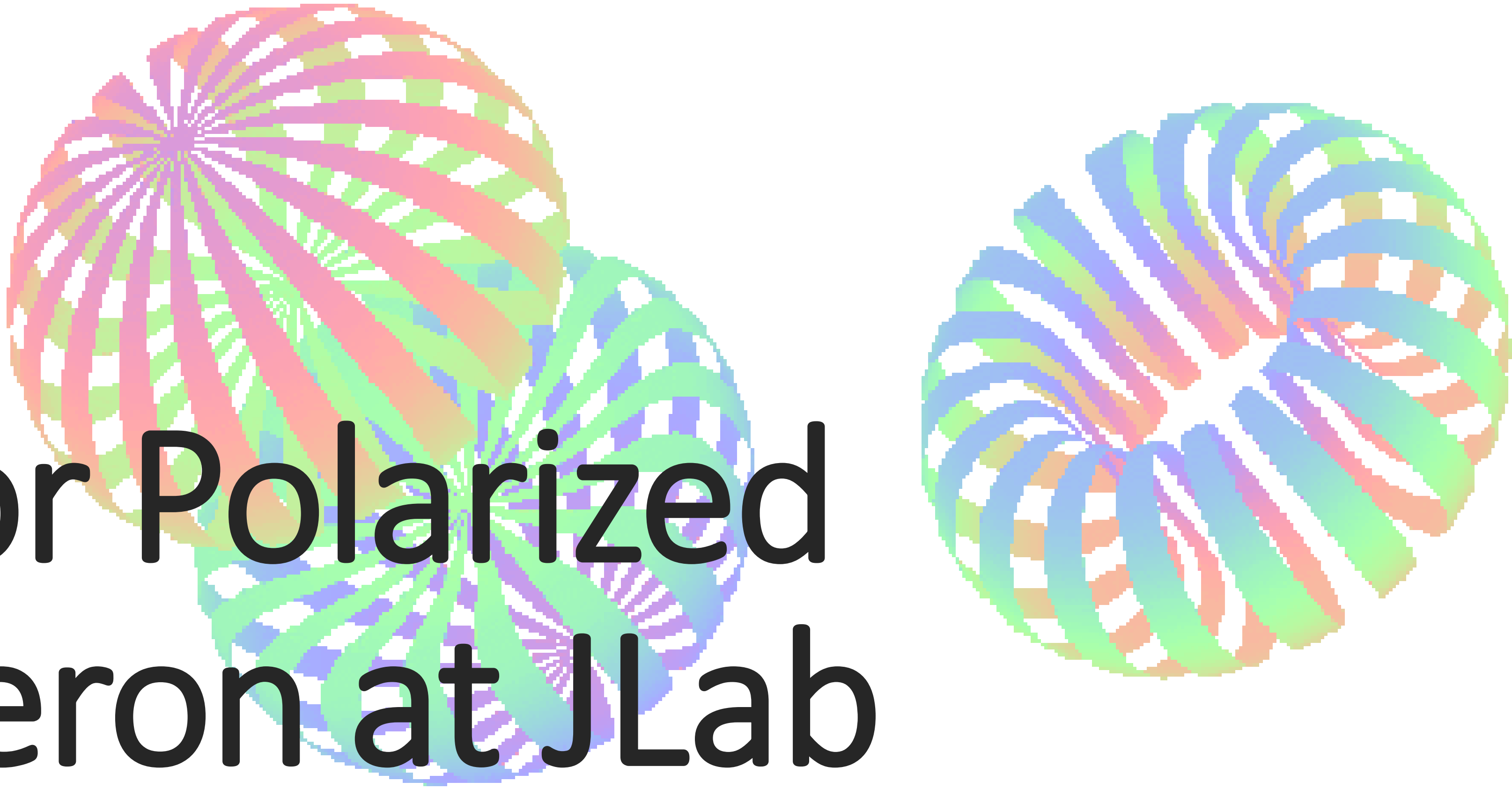


Tensor Polarized Deuteron at JLab

Elena Long

Next Generation Nuclear Physics

With JLab12 and EIC, FIU

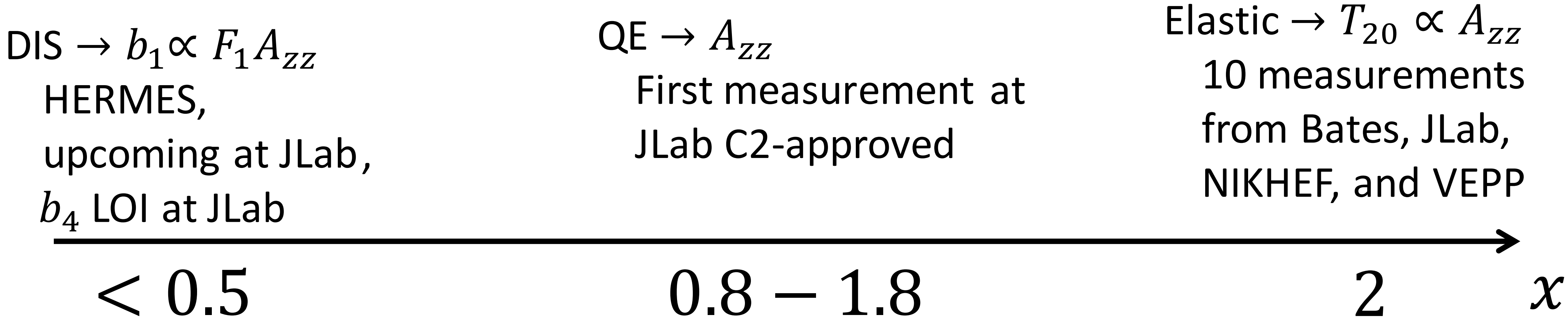
February 12th, 2016

University of New Hampshire

Talk at http://bit.ly/EllieNGNP

Today's Discussion

- Brief Introduction to Tensor Polarization
- Deuteron Structure Function b_1
- Elastic and Quasi-Elastic Tensor Asymmetry A_{zz}
- Exotic Gluonic States from Δ (b_4)
- Future of Tensor Polarization at JLab



DIS → $b_1 \propto F_1 A_{zz}$
HERMES,
upcoming at JLab,
b_4 LOI at JLab

QE → A_{zz}
First measurement at
JLab C2-approved

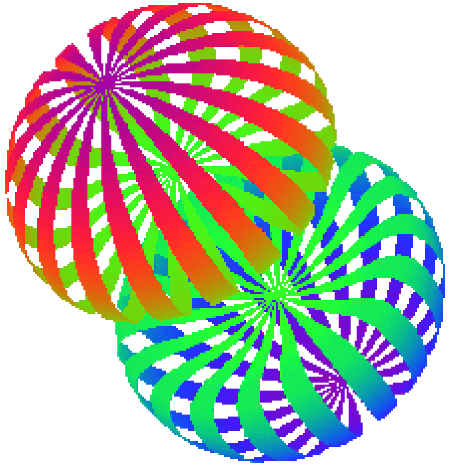
Elastic → $T_{20} \propto A_{zz}$
10 measurements
from Bates, JLab,
NIKHEF, and VEPP

A Brief Introduction to Tensor Polarization

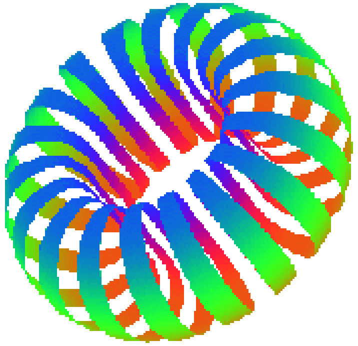
Tensor Polarization

For tensor polarization, need spin-1 particles

Development of a high luminosity, high tensor polarized target has promise as a novel probe of nuclear physics



$m_j = \pm 1$



$m_j = 0$

$(p_+ + p_-) = 1, \quad p_0 = 0, \quad P_{zz} = +1$

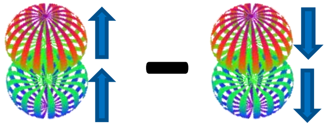
$(p_+ + p_-) = 2/3, \quad p_0 = 1/3, \quad P_{zz} = 0$

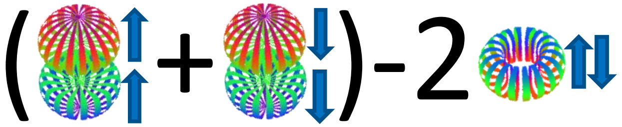
$(p_+ + p_-) = 0.5, \quad p_0 = 0.5, \quad P_{zz} = -1$

$(p_+ + p_-) = 0, \quad p_0 = 1, \quad P_{zz} = -2$

Vector $P_z = p_+ - p_-$

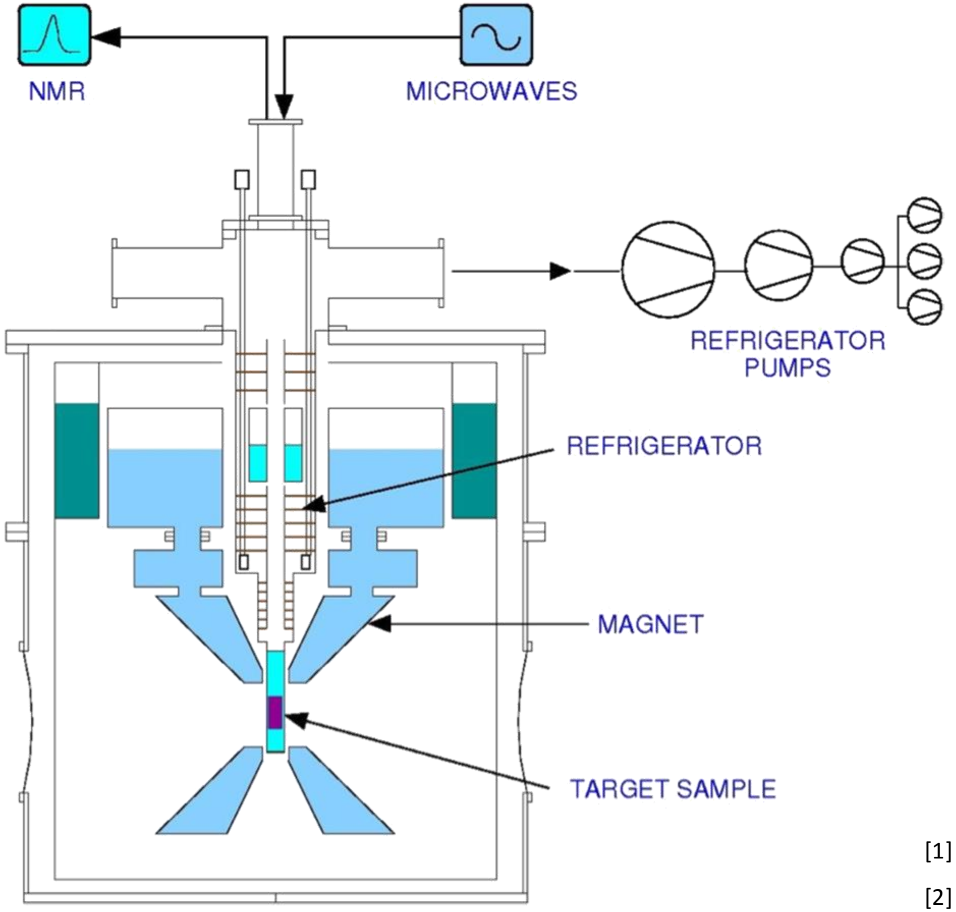
Tensor $P_{zz} = (p_+ + p_-) - 2p_0$





Animations by SC Pieper, *et al*, http://www.phy.anl.gov/theory/movie-run.html

Tensor Polarization Techniques



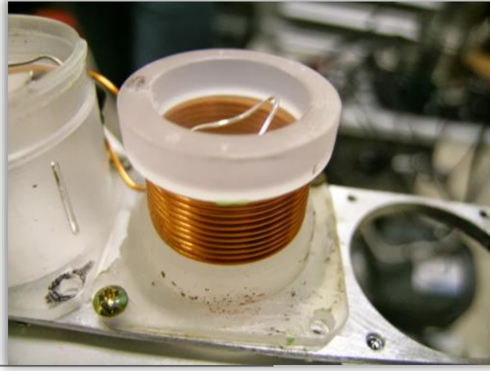
- **Unpolarized Target + Polarimeter**
  - D_2O waterfall[1]
  - Liquid D_2[2]
  - Medium-high luminosity, no polarization enhancement
- **Gas Jet/Storage Cell Target**[3]
  - Low luminosity, very high tensor polarization
- **Solid Polarized DNP Target**[4]
  - High luminosity, polarization enhancement, large dilution at high x

[1] ME Schulze, *et al*, PRL **52** 597 (1984)

[2] D Abbot, *et al*, PRL **84** 5053 (2000)

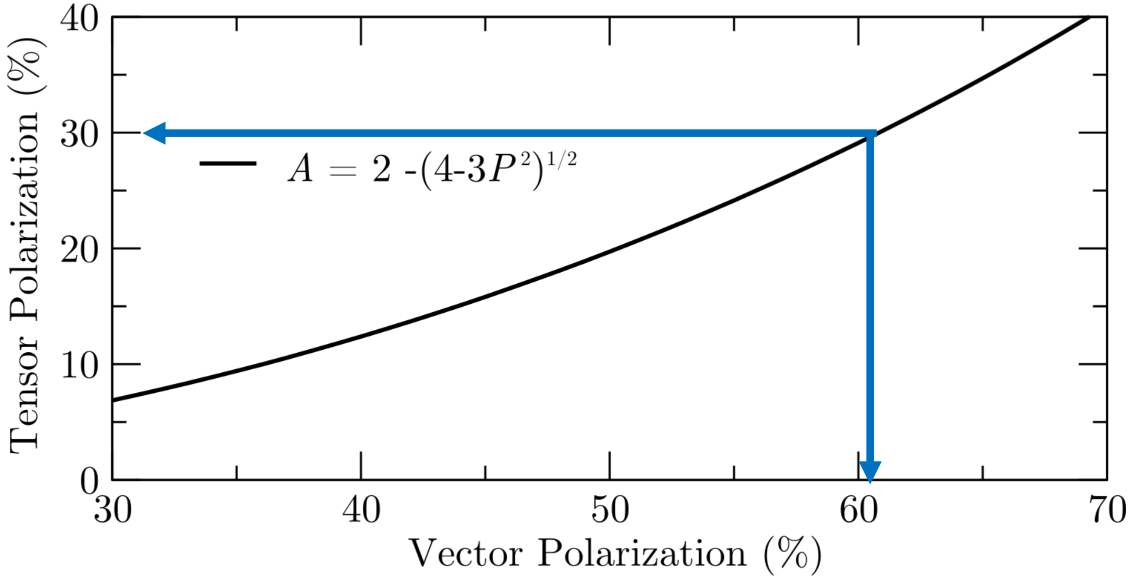
[3] AV Evstugneev, *et al*, NIM A **238** 12 (1985)

[4] B Boden, *et al*, Z. Phys. C **49** 175 (1991)

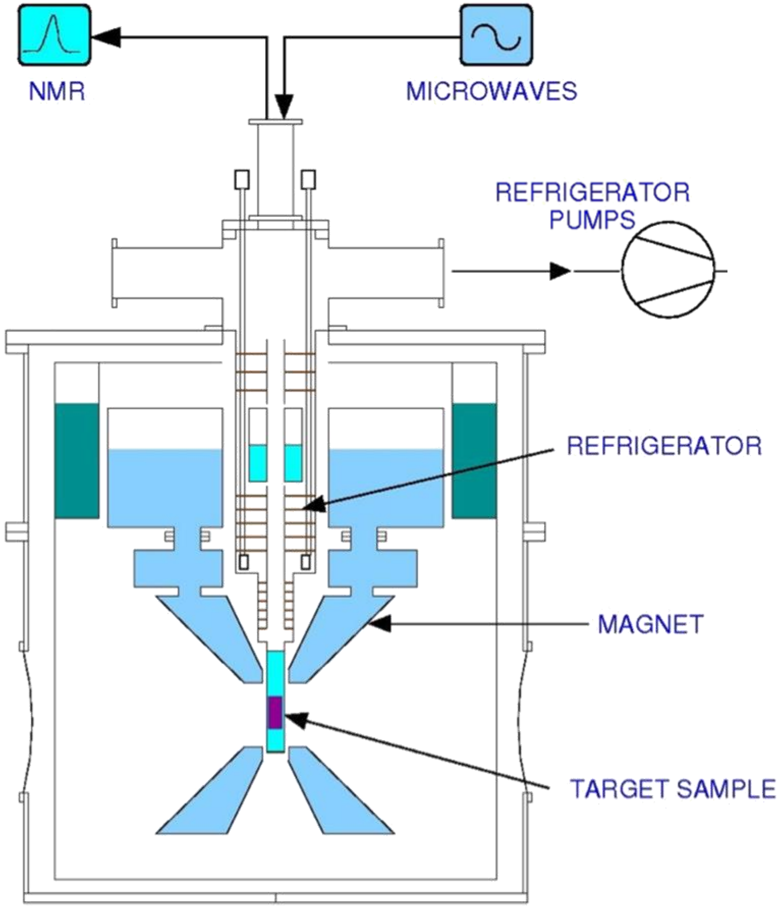


Tensor Structure Function, b_1

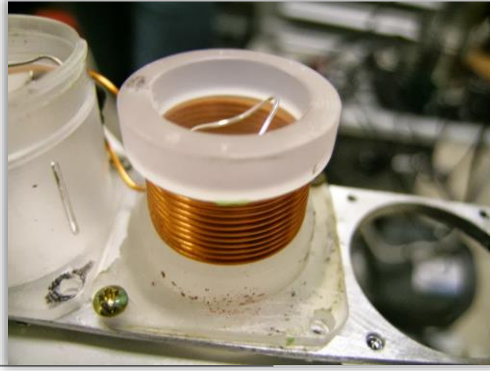
- Dynamic Nuclear Polarization of ND_3
- Approved experiments for $P_{zz} \sim 30\%$
- 5 Tesla at 1 K



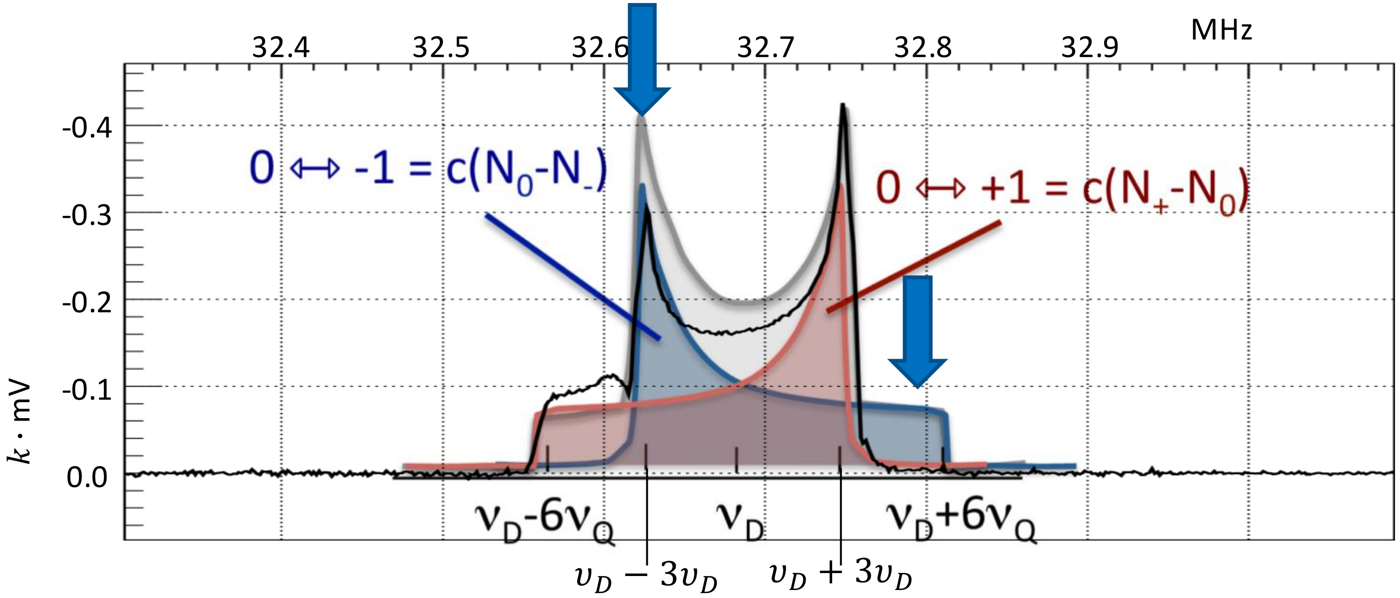
“Brute Force” Tensor Polarization

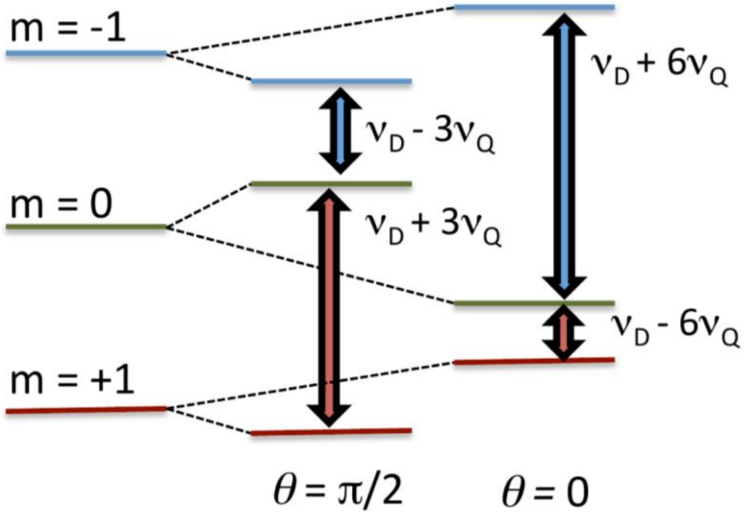


Tensor Structure Function, b_1



“Hole Burning” Tensor Enhancement



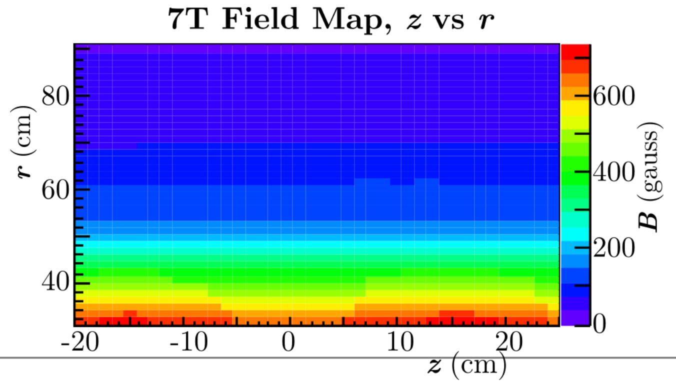


Techniques in R&D:

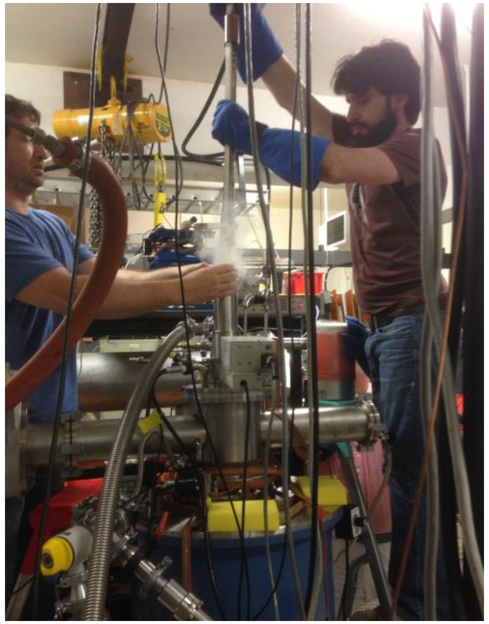
1) Selective Semi-Saturation
2) Time Dependence of Sample Rotation
3) Material Crystallization
4) Alternative Materials

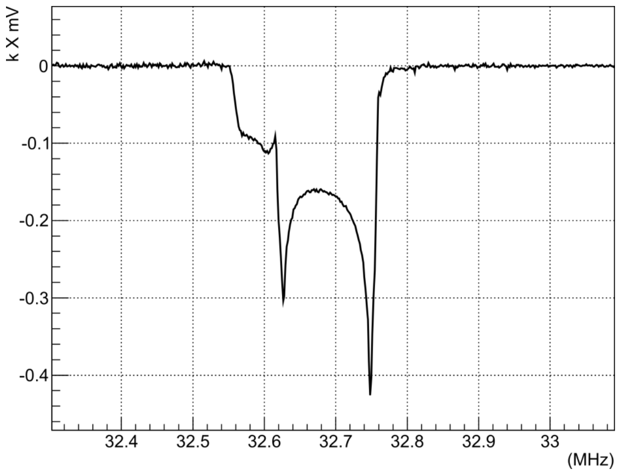
D Keller, HiX Workshop (2014)
UVA Tensor Enhancement on Butanol (2014)

Target Status Update



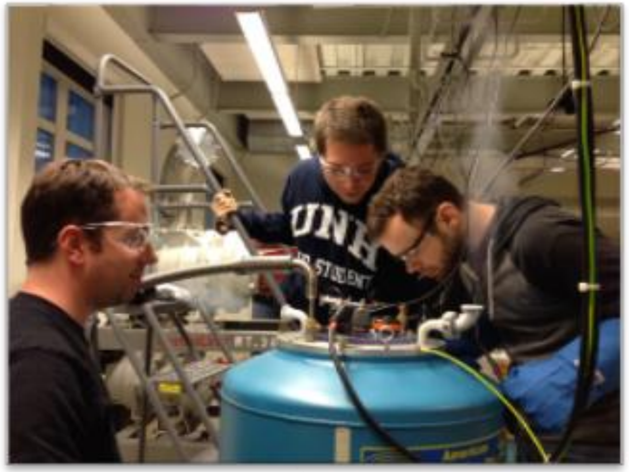
- Results from UVA are promising, preliminary Pzz=30% recently achieved with full analysis in progress

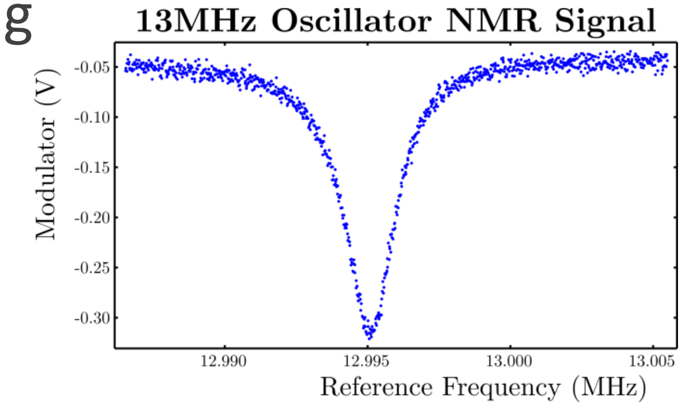


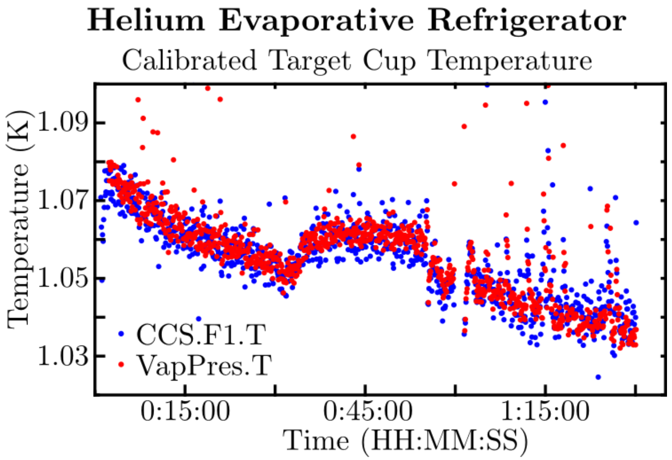


D Keller, PoS(PSTP 2013) 010
D Keller, HiX Workshop (2014)
D Keller, J.Phys.:Conf.Ser. **543**, 012015 (2014)
UVA Tensor Enhancement on Butanol (2014)

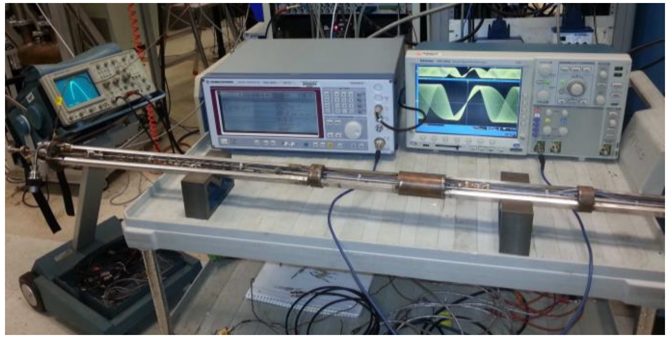
- UNH target lab is nearing complete, successfully tested magnet, NMR, horizontal He fridge





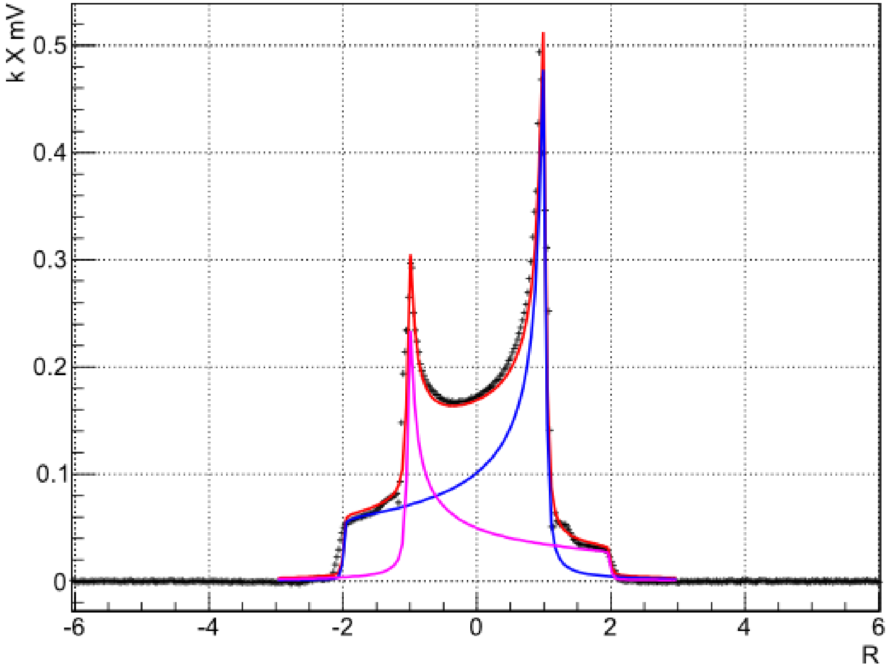


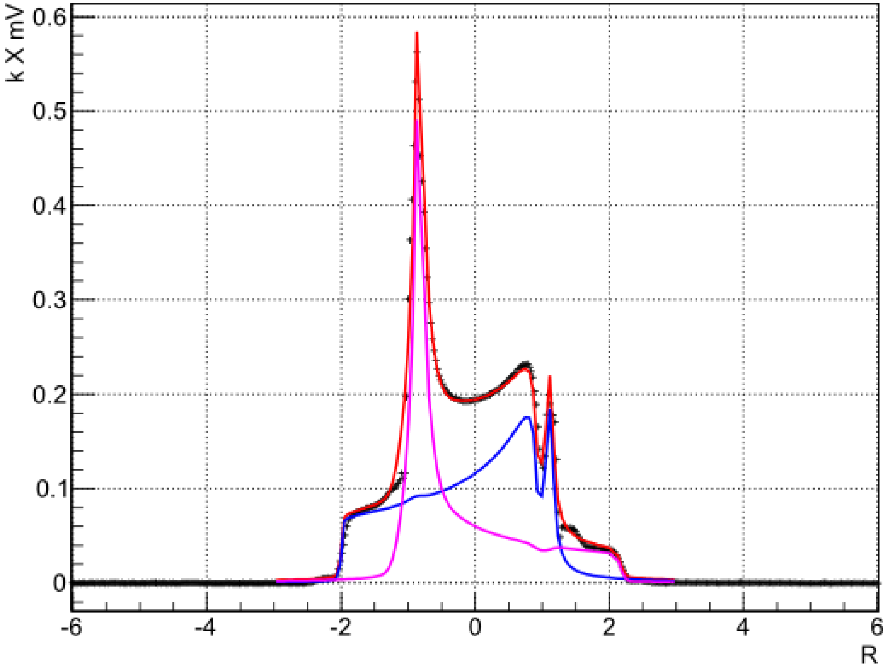
D Keller, PoS(PSTP 2013) 010
D Keller, HiX Workshop (2014)
D Keller, J.Phys.:Conf.Ser. **543**, 012015 (2014)
UVA Tensor Enhancement on Butanol (2014)



Target Status Update

Progress made on measuring P_{zz} through NMR line-shape analysis





C12-13-011: The Deuteron Tensor Structure Function b_1

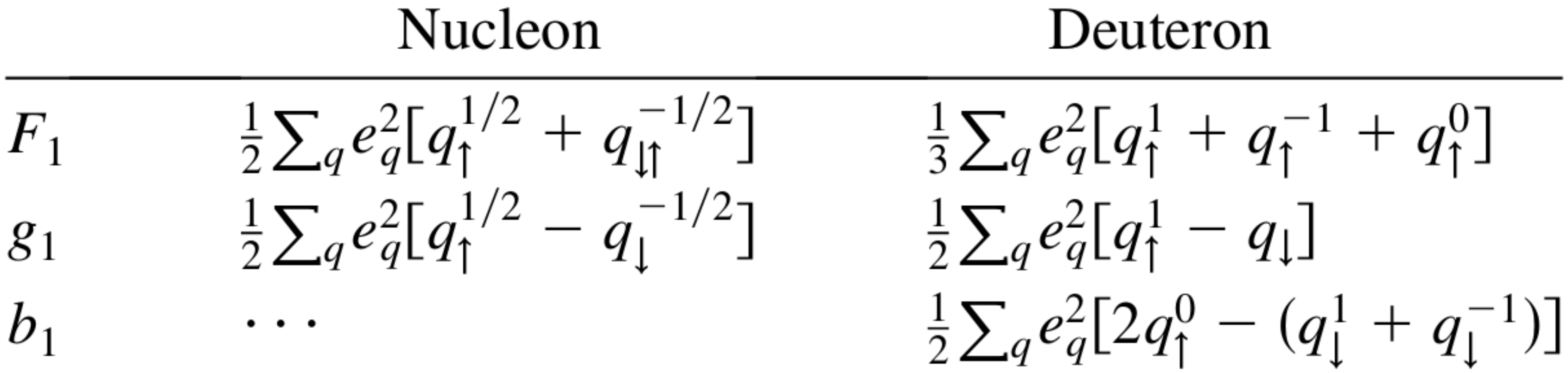
Spokespeople:

K. Slifer*, O.R. Aramayo, J.P. Chen, N. Kalatarians, D. Keller, E. Long, P. Solvignon

C1-Approved, A- Physics Rating

DIS Tensor Observables

$W_{\mu\nu} = -\alpha F_1 + \beta F_2$	Scattering on Unpolarized Targets
$+i\gamma g_1 + i\delta g_2$	Scattering on Vector Polarized Targets
$-\varepsilon b_1 + \zeta b_2 + \eta b_3 + \kappa b_4$	Scattering on Tensor-Polarized Targets



	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	$\cdots$	$\frac{1}{2}\sum_q e_q^2[2q_\uparrow^0 - (q_\downarrow^1 + q_\downarrow^{-1})]$

P Hoodbhoy *et al*, Nucl. Phys. **B312,** 571 (1989)

A Airapetian, *et al*, PRL **95** 242001 (2005)

Tensor Structure Function, b_1

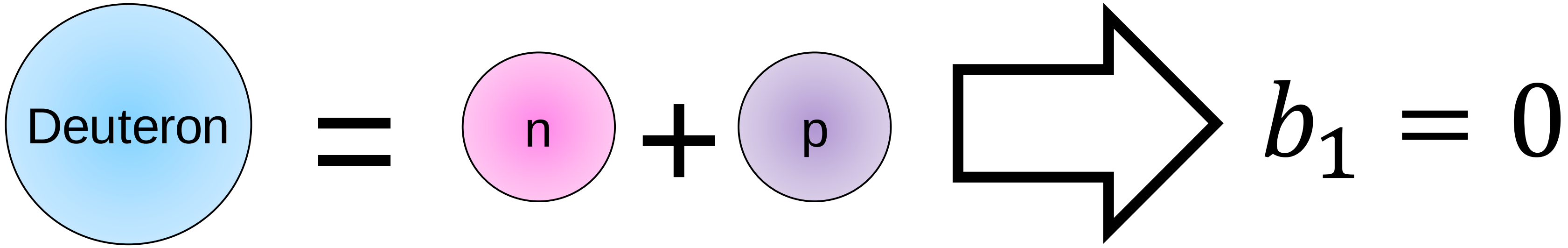
b_1 → Leading twist

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

b_1 is the measure of quark distributions when the nucleus is in a particular spin state

<u>Looks at nuclear effects at the resolution of quarks!</u>

If there are no nuclear effects, then b_1 vanishes.



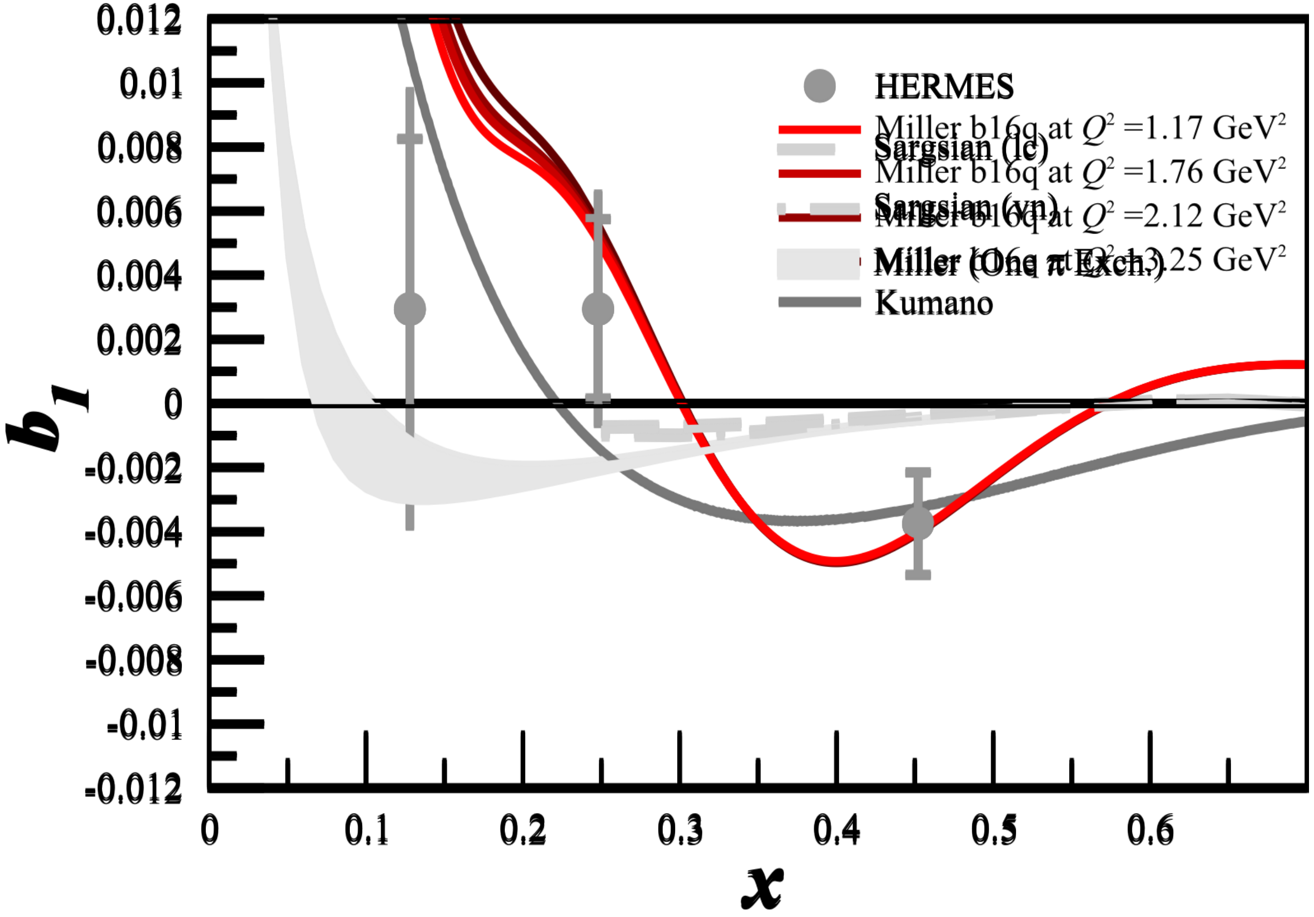
Even with D-state admixture, it's expected to be vanishingly small

Khan & Hoodbhoy, PRC **44** 1219 (1991)
Umnikov, Phys. Lett. B **391** 177 (1997)

Tensor Structure Function, b_1

All conventional **models predict small or vanishing values of b_1** in contrast with the HERMES data

Any measurement of a $b_1<0$ indicates exotic physics



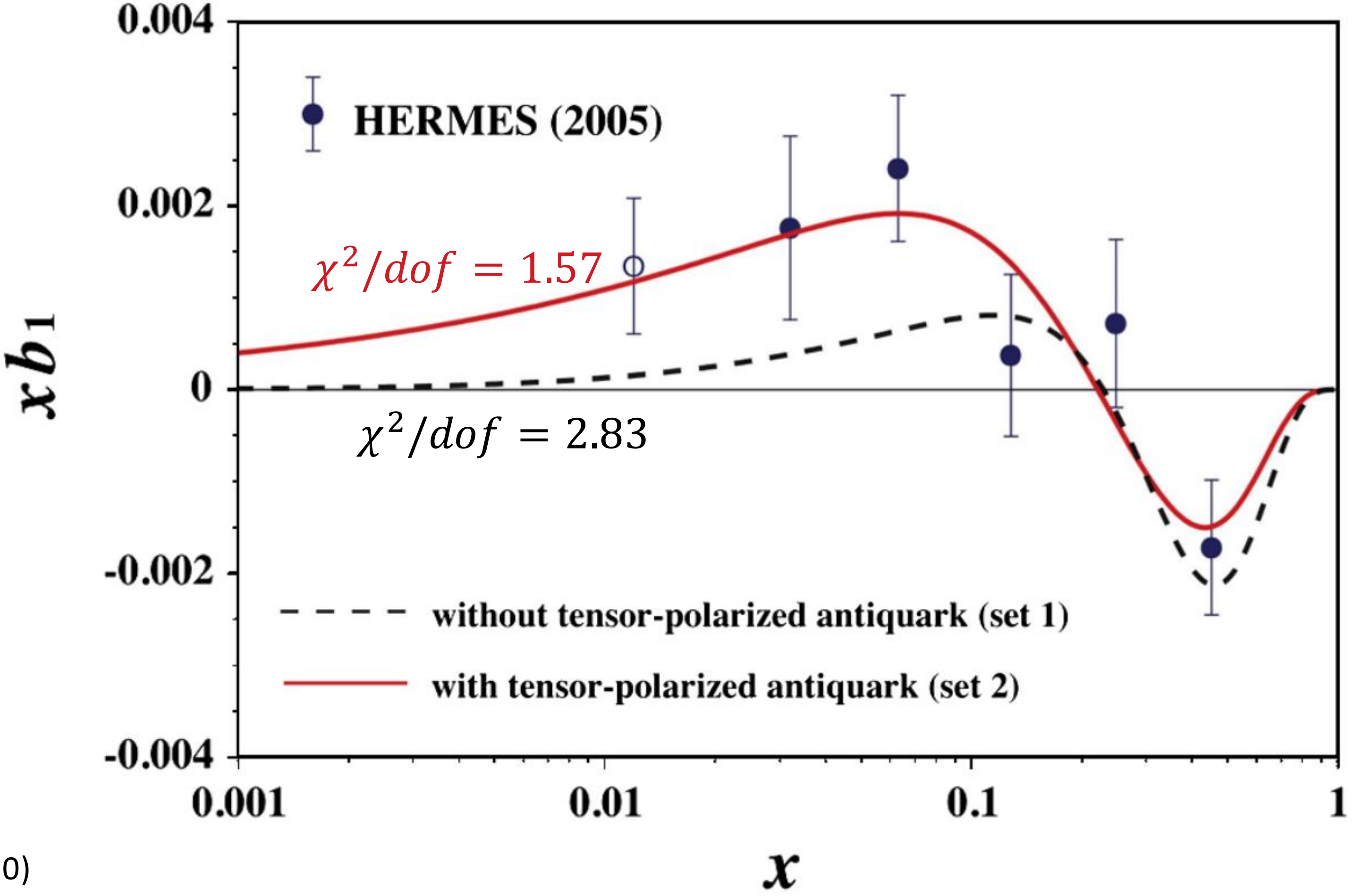
K Slifer *et al*, JLab E12-13-011

Close-Kumano Sum Rule

- $\int b_1(x)dx = 0$
  - Related to the electric quadrupole structure
  - Vanishes in any model with an unpolarized sea
- $b_1 = \underset{\text{Quarks}}{\boxed{\frac{1}{36}\delta_T w[5\{u_v + d_v\}]}} + \underset{\text{Sea Strange and Anti-Quarks}}{\boxed{4\alpha_{\bar{q}}\left[2\bar{u} + 2\bar{d} + s + \bar{s}\right]}}$
- Looked at difference between $\alpha_{\bar{q}} = 0$ and floating $\alpha_{\bar{q}}$
  - $\alpha_{\bar{q}} \sim$ Tensor polarization of sea
- $\alpha_{\bar{q}} = 3.20 \pm 0.212$ improved χ^2, indicating significant tensor polarization in antiquark distributions

S Kumano, PRD **82** 017501 (2010)

Close-Kumano Sum Rule



S Kumano, PRD **82** 017501 (2010)

6-Quark, Hidden Color

- Deuteron wave function can be expressed as
  - $|6q\rangle = \sqrt{\frac{1}{9}}|NN\rangle + \sqrt{\frac{4}{45}}|\Delta\Delta\rangle + \sqrt{\frac{4}{5}}|CC\rangle$

Nucleon-Nucleon

Delta-Delta

Hidden Color

- Early hidden color calculations gave small results, but author noted "as experimental techniques have improved dramatically, the meaning of small has changed."

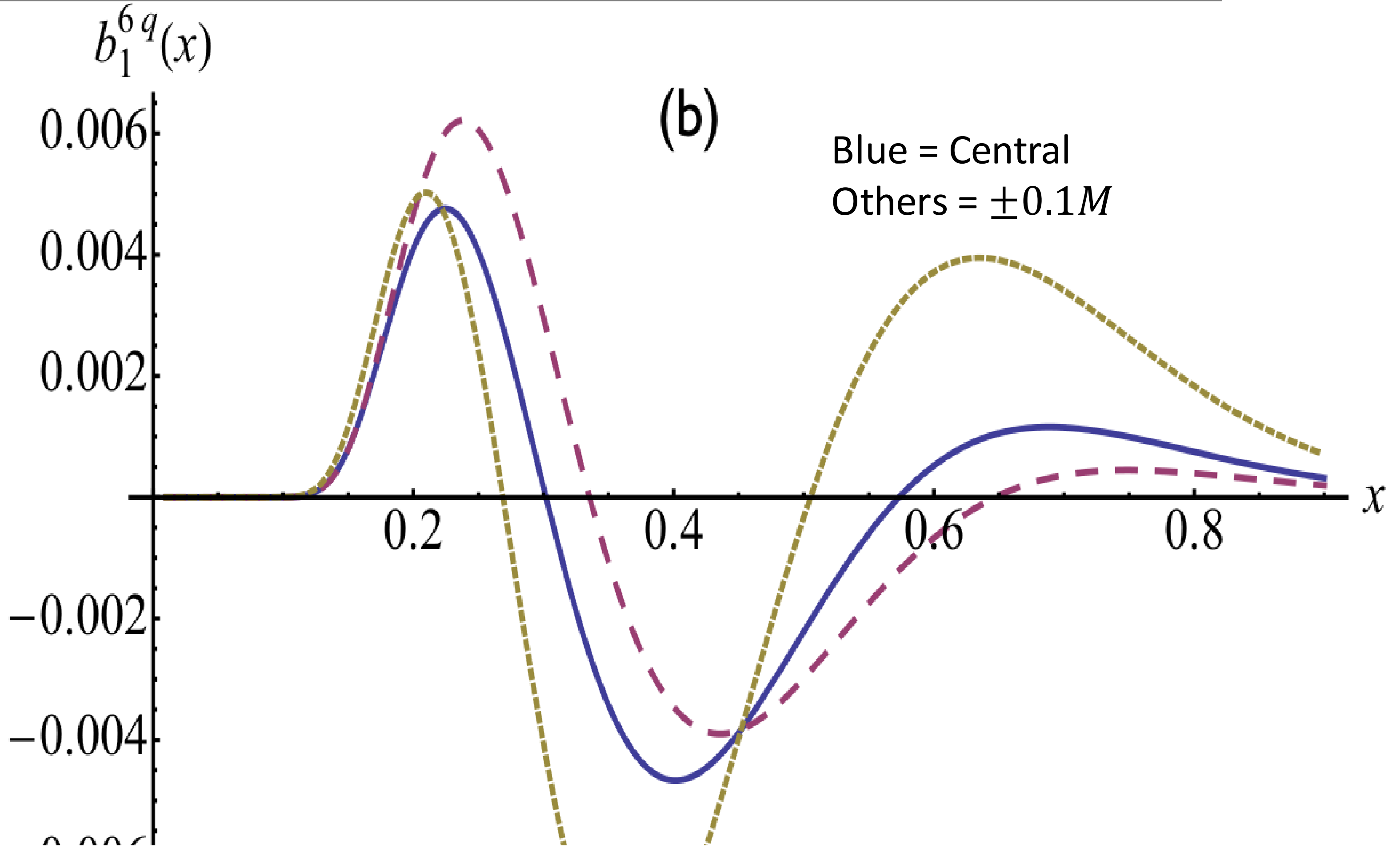
Probability of Hidden-Color Effects

- Even though experimental upper limit of $P_{6q} < 1.5\%$, a much smaller value (0.15%) can have a significant effect on b_1

G Miller, PRC **89** 045203 (2014)

6-Quark, Hidden Color

- 6-quark, hidden color states predict large negative b_1 at large x
- Using central values R=1.2 fm, m=338 MeV

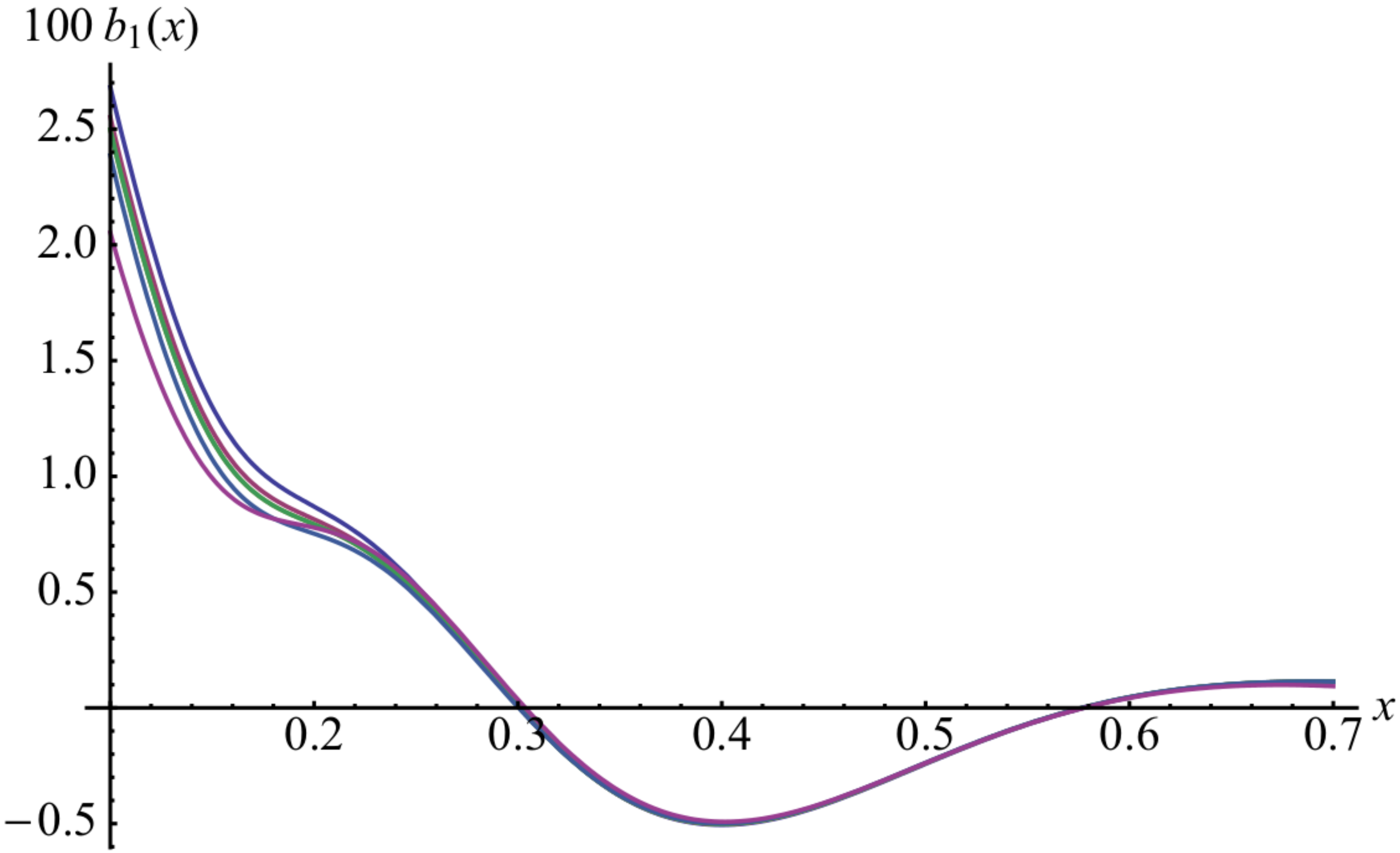


Blue = Central
Others = $\pm 0.1M$

G Miller, PRC **89** 045203 (2014)

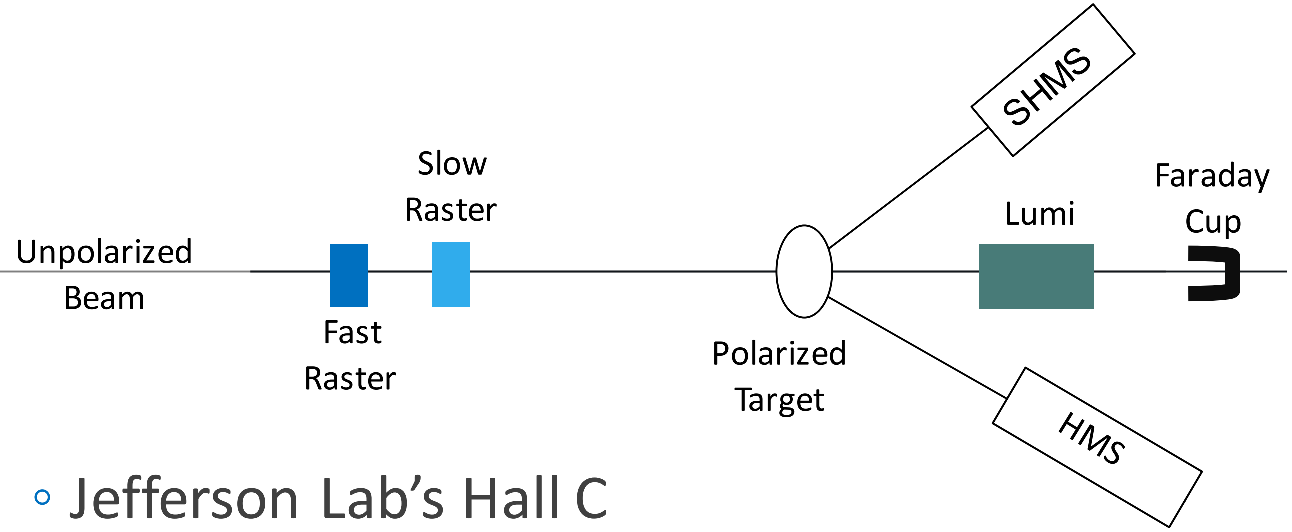
6-Quark, Hidden Color

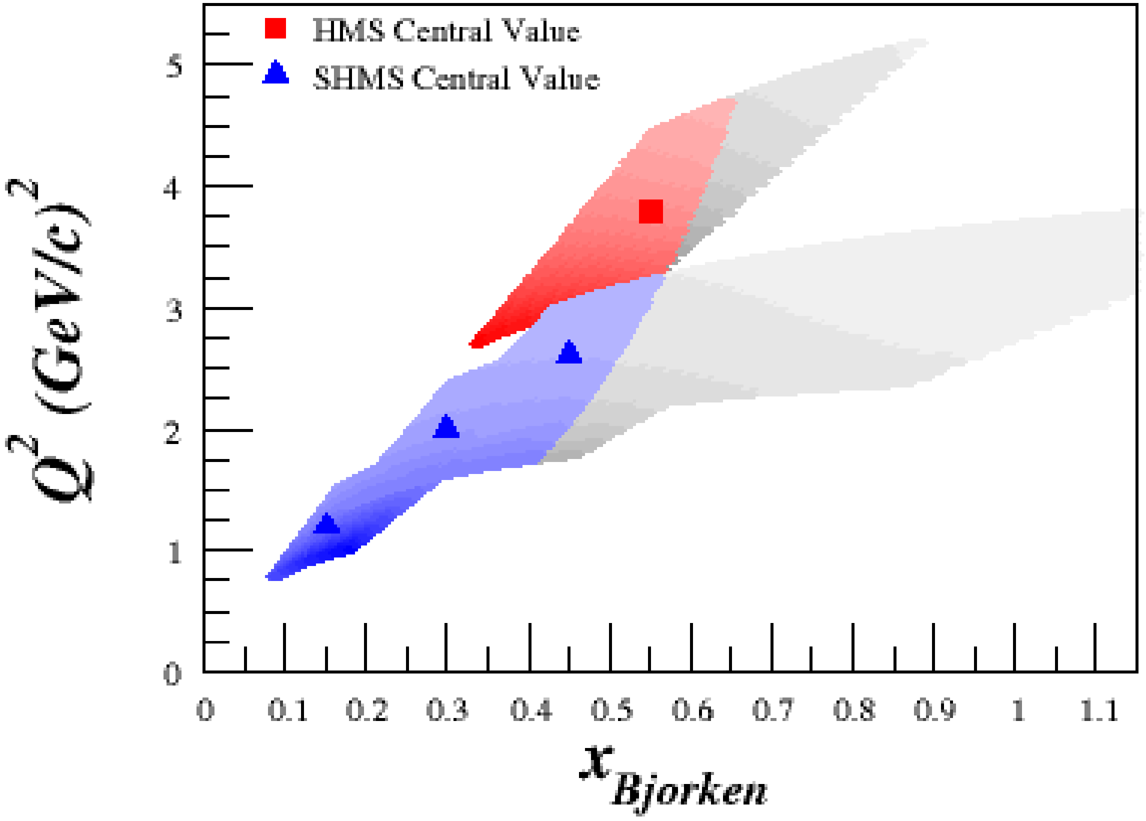
- First theory to reproduce anomalous HERMES result
- $b_1^{\pi} + b_1^{6q}$ predictions made for upcoming JLab b_1 measurement



G Miller, PRC **89** 045203 (2014)

b_1 Kinematics





- Jefferson Lab's Hall C
- Unpolarized beam, tensor polarized target (longitudinal alignment)

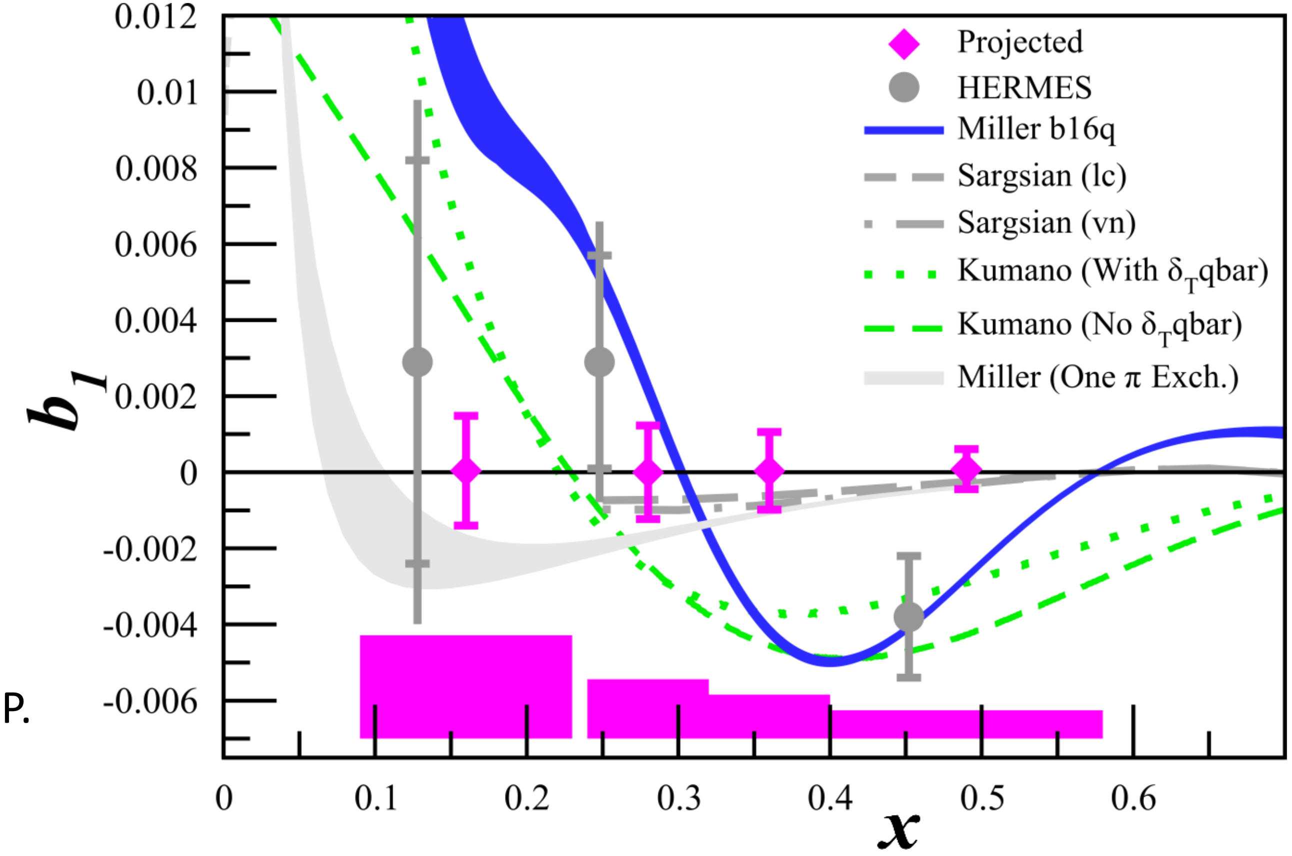
Det.	x	Q^2 (GeV^2)	W (GeV)	$E_{e'}$ (GeV)	$\theta_{e'}$ (deg)	Rate (kHz)	Time (Day)
SHMS	0.15	1.21	2.78	6.70	7.4	1.66	6
SHMS	0.30	2.00	2.36	7.45	9.0	0.79	9
SHMS	0.45	2.58	2.0	7.96	9.9	0.38	15
HMS	0.55	3.81	2.0	7.31	12.5	0.11	30

Tensor Structure Function, b_1

Measuring b_1 will give insight into:

- Close-Kumano sum rule[1]
- 6-quark hidden color[2]
- OAM and spin crisis[3]
- Pionic effects[2,4]
- Polarized sea quarks[4]

Approved JLab Experiment C12-13-011
Spokespersons: K. Slifer, E. Long, D. Keller, P. Solvignon, J.P. Chen, O.R. Aramayo, N. Kalantarians



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[1] FE Close, S Kumano, Phys. Rev. **D42,** 2377 (1990)

[2] G Miller, Phys. Rev. **C89,** 045203 (2014)

[3] SK Taneja *et al*, Phys. Rev. **D86,** 036008 (2012)

[4] S Kumano, Phys. Rev. **D82,** 017501 (2010)

PR12-15-005: Quasi-Elastic and Elastic Deuteron Tensor Asymmetry A_{zz}

Spokespeople:

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

C2-Approved

Deuteron Wavefunction

Is the deuteron wavefunction hard or soft?

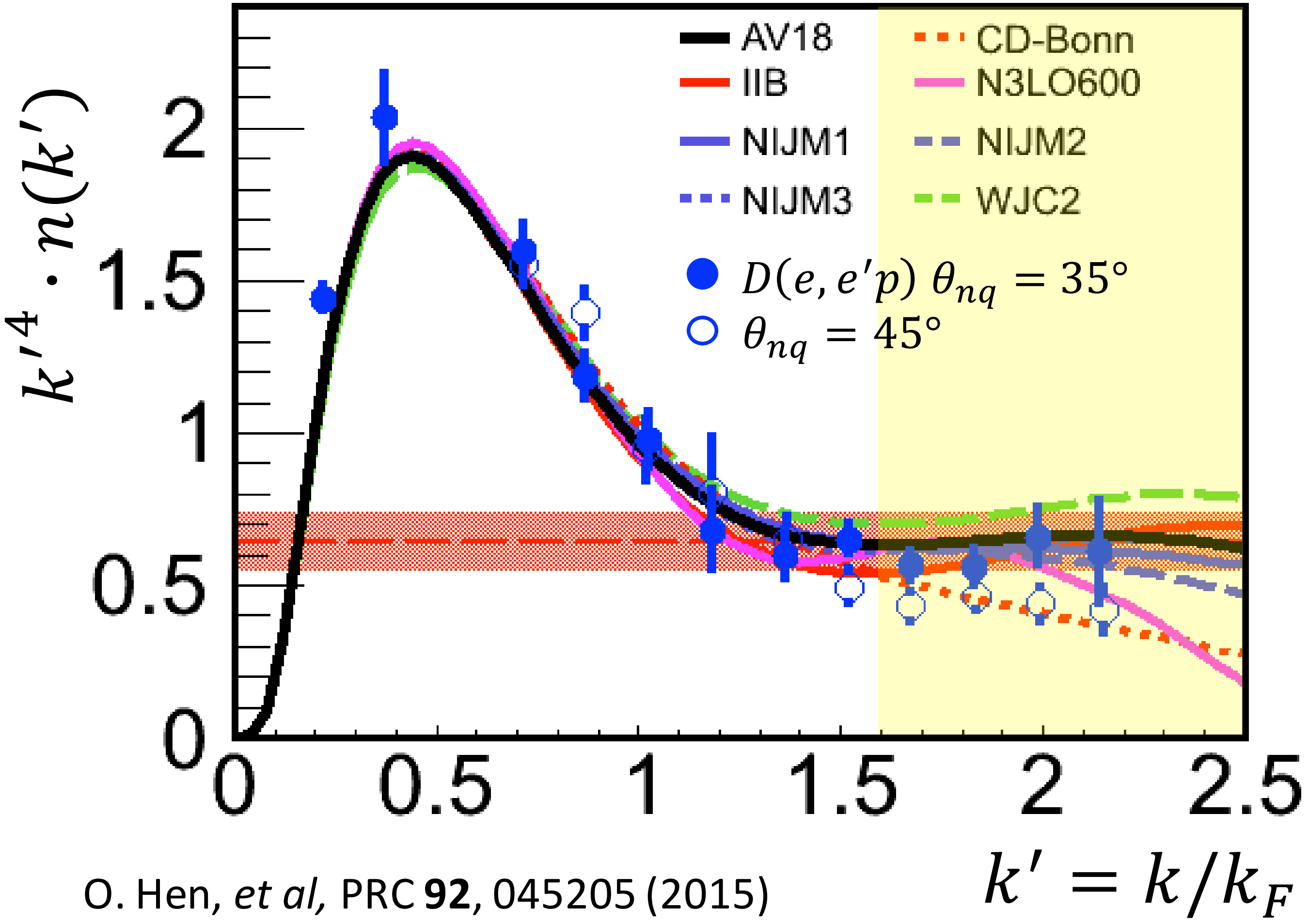
- AV18 is an example of a moderate-hard WF
- CDBonn is an example of a soft WF

Unpolarized deuterons need to be probed at $k > 400\ \mathrm{MeV}$ to distinguish between hard and soft WFs

- Not practical

Currently no unambiguous experimental evidence for which is more valid

Tensor polarization enhances the *D*-state, allowing hard and soft WFs to be distinguished at lower momenta



O. Hen, *et al*, PRC **92**, 045205 (2015)

Deuteron Wavefunction

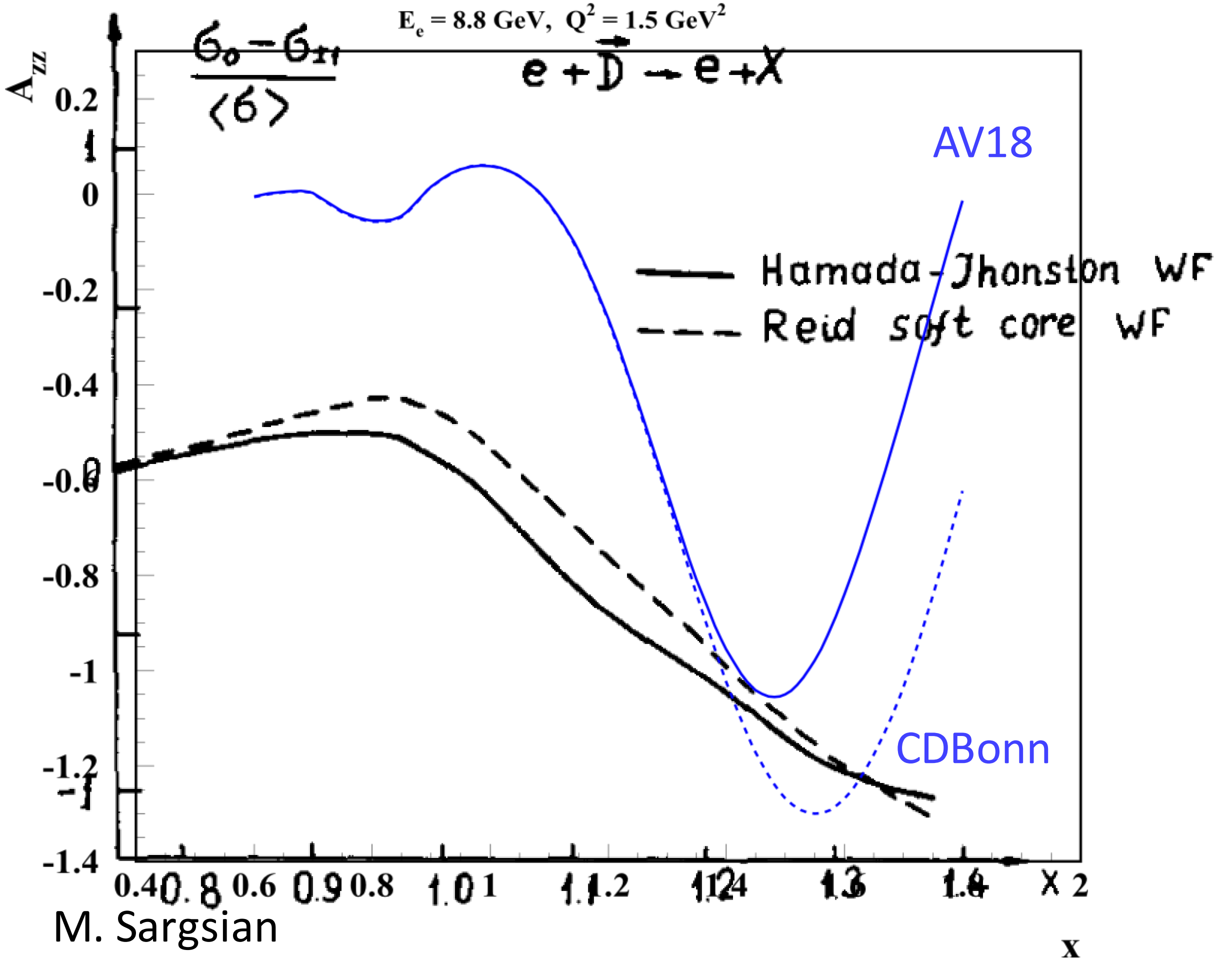
First calculated in the ‘70s, A_{zz} can be used in to discriminate between hard and soft wavefunctions

$$A_{zz} = \frac{2}{f P_{zz}} \left(\frac{\sigma_p - \sigma_u}{\sigma_u} \right)$$

In the impulse approximation, A_{zz} is directly related to the *S*- and *D*-states

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

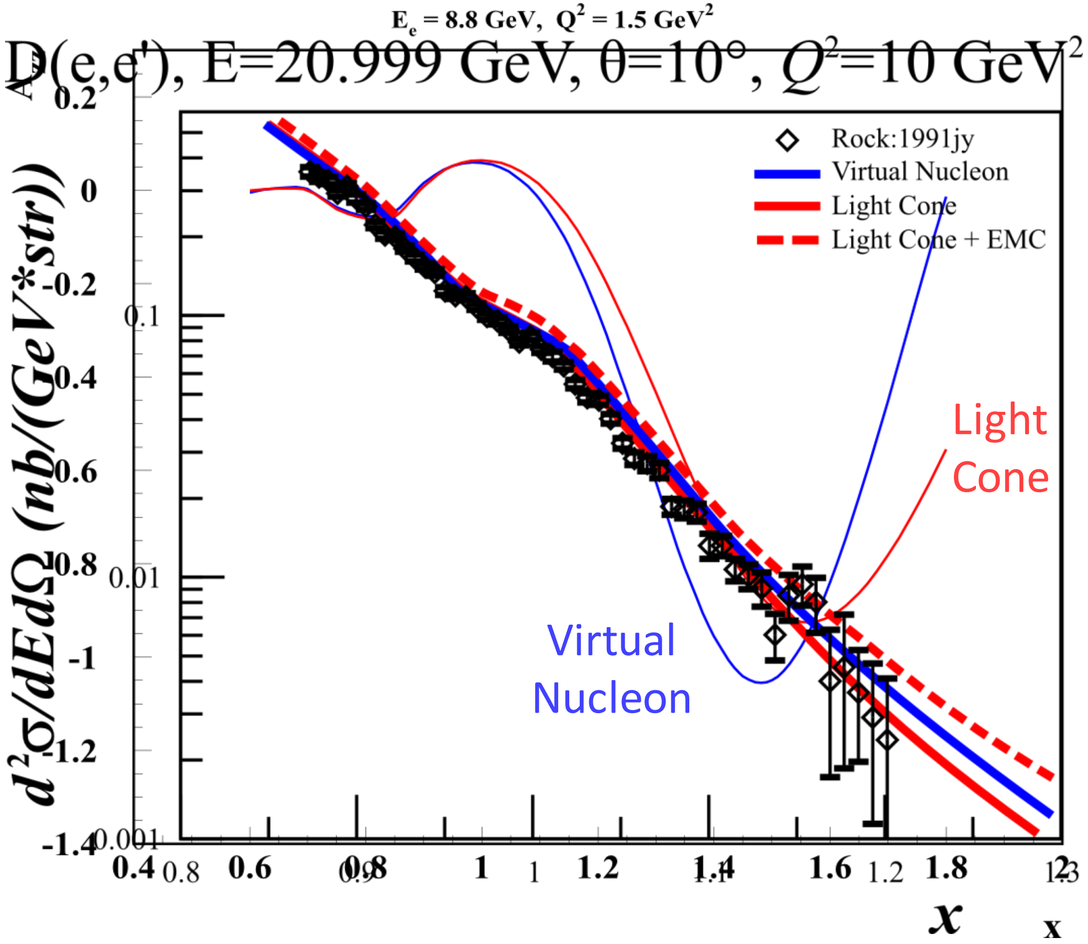
Modern calculations indicate a large separation of hard and soft WFs begins just above the quasi-elastic peak at $x > 1.3$



L.L. Frankfurt, M.I. Strikman, Phys. Rept. **76** 215 (1981)

M. Sargsian

Relativistic *NN* Bound System



Relativistic calculations needed to understand underlying physics in short-range correlations at high momenta

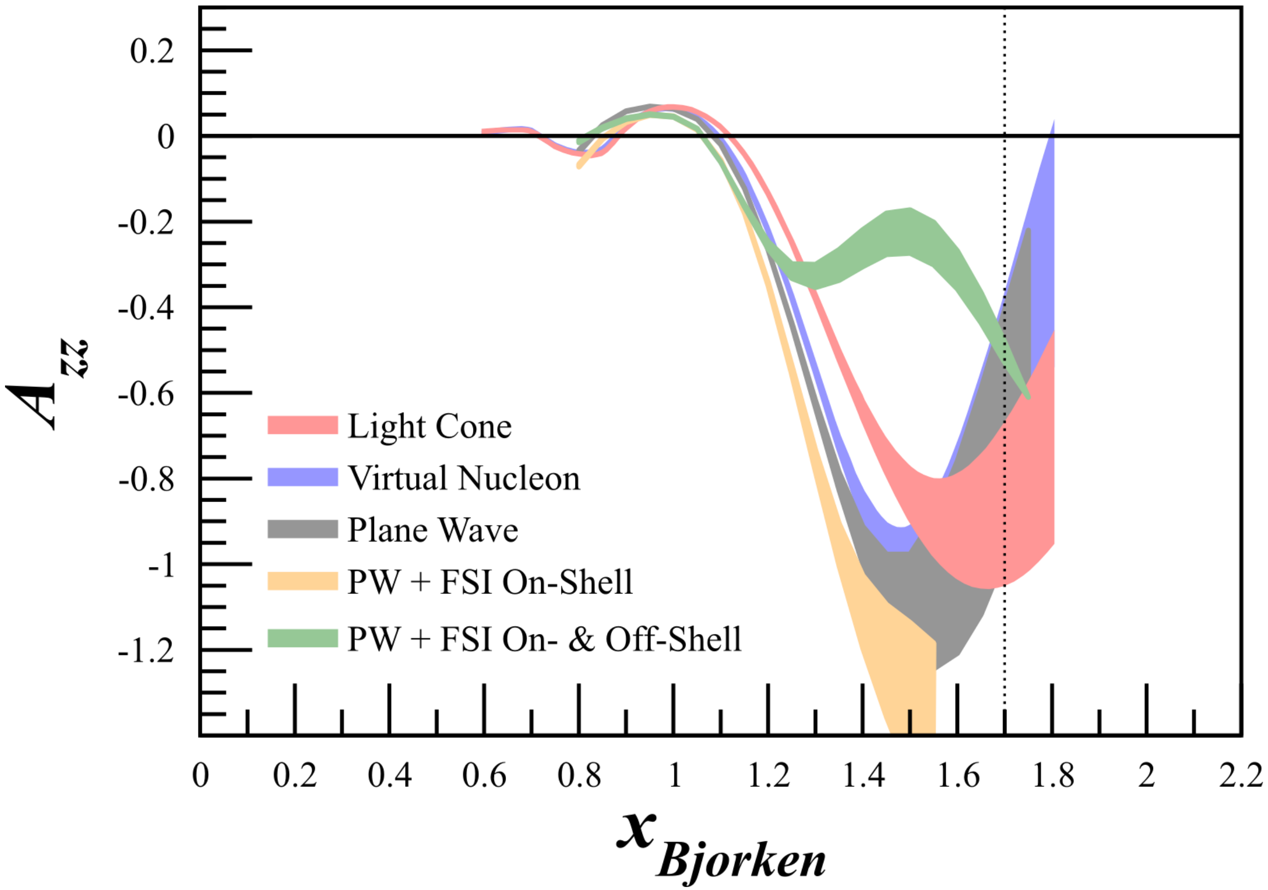
Light Cone (LC) and Virtual Nucleon (VN) calculations are often used

Large momenta ($> 500\ \mathrm{MeV}/c$) needed to discriminate with unpolarized deuterons

With tensor polarized A_{zz} significant difference at much lower momenta ($> 300\ \mathrm{MeV}/c$) and $x > 1.1$

M Sargsian, Tensor Spin Observables Workshop (2014)

First Measurement of Quasi-Elastic A_{zz}



Sensitive to effects that are very difficult to measure with unpolarized deuterons

Huge 10-100% asymmetry

Measuring A_{zz} over a range in x and Q^2 provides insight to

- Nature of *NN* Forces
- Hard/Soft Wavefunctions
- Relativistic *NN* Dynamics
- On-Shell/Off-Shell Effect FSI

Decades of theoretical interest that we can only now probe with a high-luminosity tensor-polarized target

Importance ranges from understanding short-range correlations to the equations of state of neutron stars

Elastic T_{20} - Calibration & Measurement

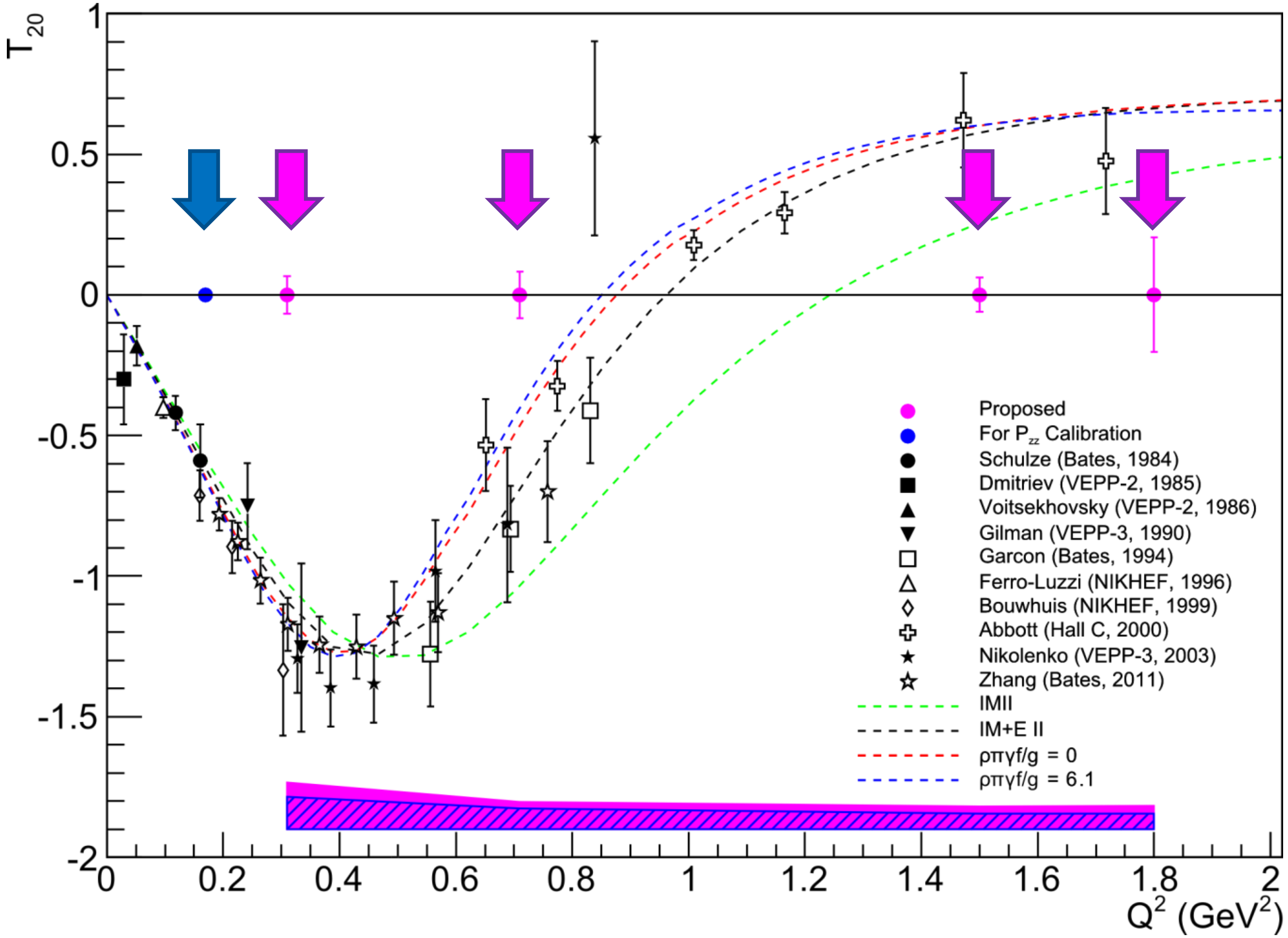
Simultaneous measurement of the elastic tensor analyzing power T_{20}

At low Q^2,

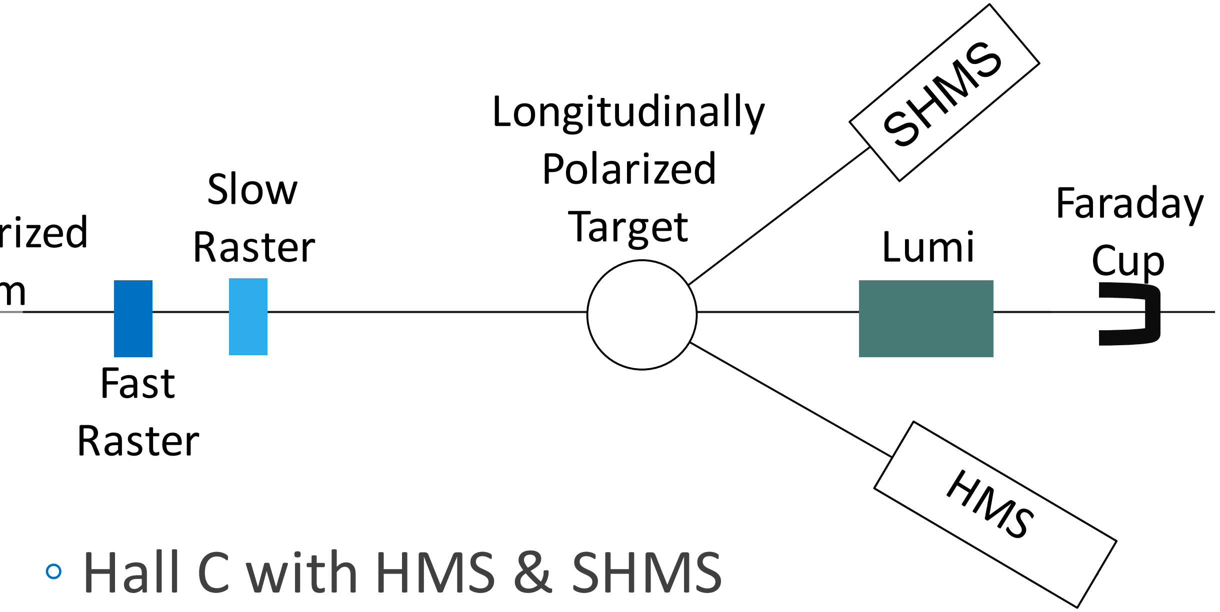
- T_{20} well known
- P_{zz} can be extracted from T_{20}
- Completely independent P_{zz} measurement from NMR line-shape P_{zz}

T_{20} in the largest and highest Q^2 range ever done in a single experiment

- Import cross-check of Hall C high Q^2 data



Kinematics


Unpolarized Beam

Fast Raster

Slow Raster

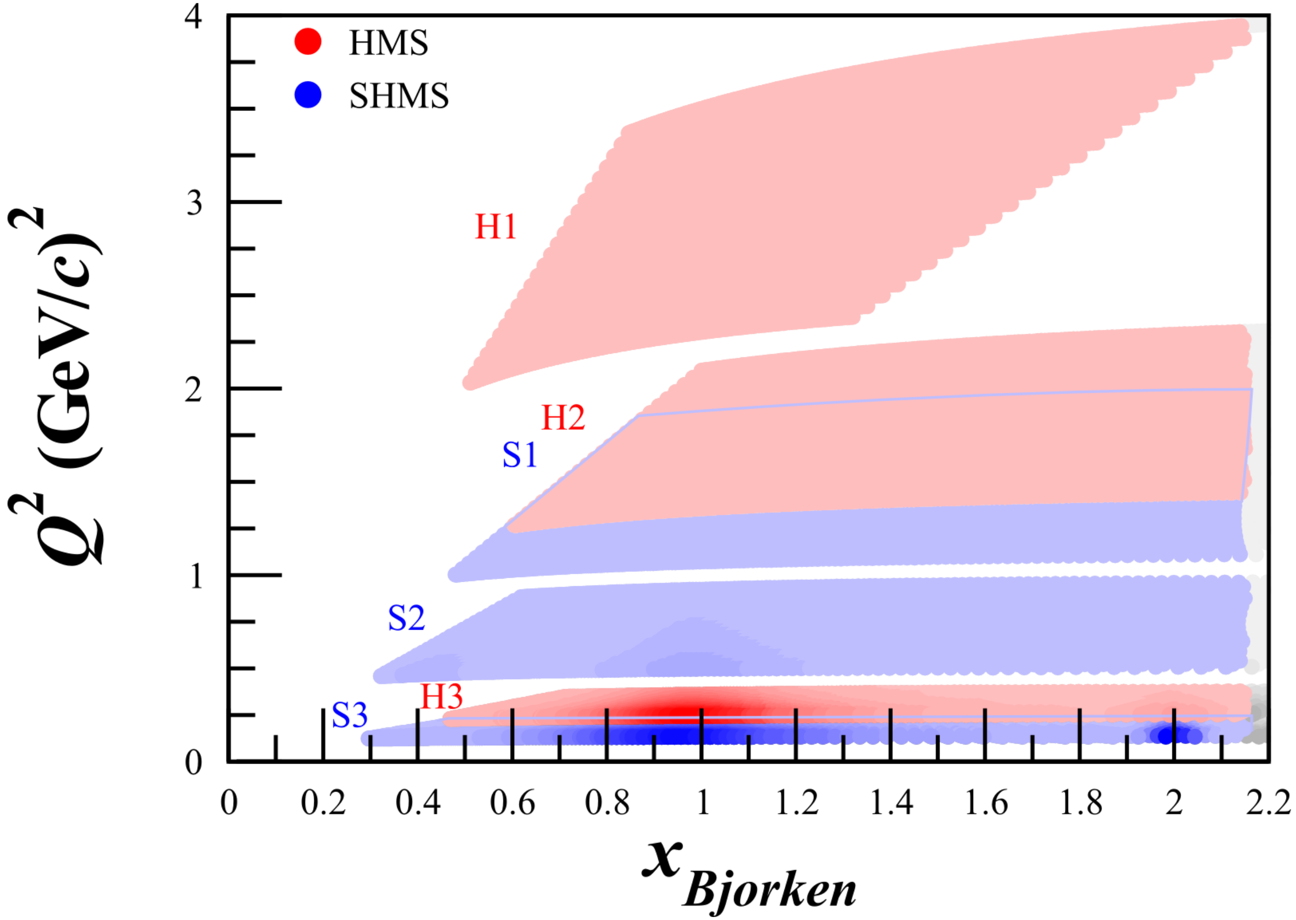
Longitudinally Polarized Target

SHMS

HMS

Lumi

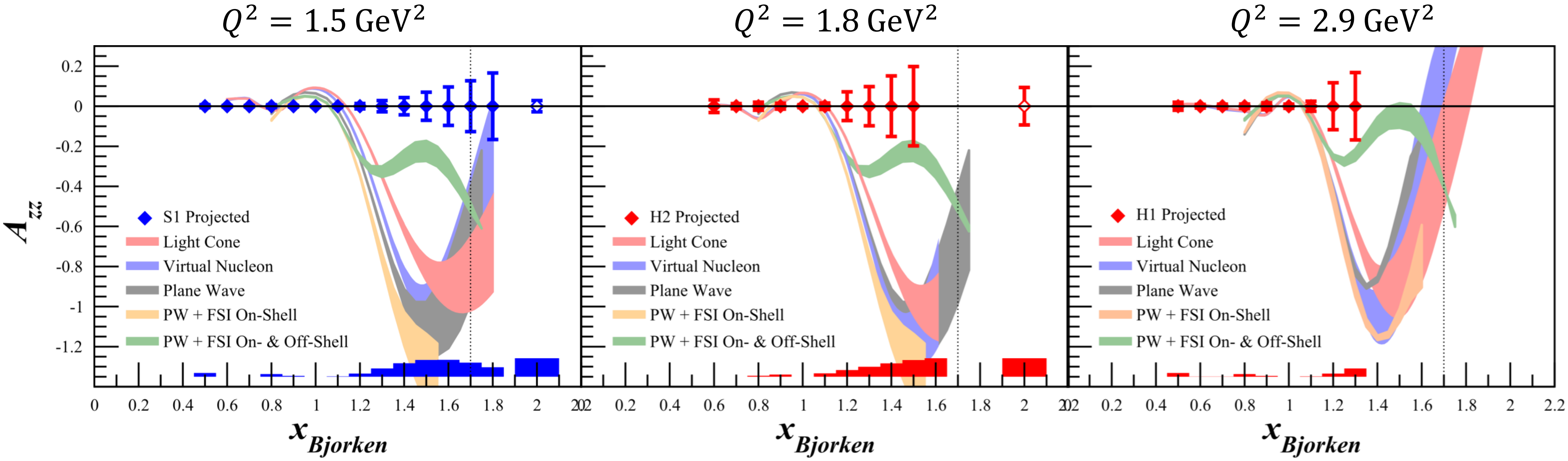
Faraday Cup



- Hall C with HMS & SHMS
- Identical equipment and technique as b_1 (E12-13-011)

		E_0 (GeV)	Q^2 (GeV^2)	E' (GeV)	$\theta_{e'}$ (°)	Rates (kHz)	PAC Time (Days)
SHMS	(S1)	8.8	1.5	8.36	8.2	0.38	25
HMS	(H1)	8.8	2.9	7.26	12.2	0.04	25
SHMS	(S2)	6.6	0.7	6.35	7.5	3.57	8
HMS	(H2)	6.6	1.8	5.96	12.3	0.09	8
SHMS	(S3)	2.2	0.2	2.15	10.9	10.5	1
HMS	(H3)	2.2	0.3	2.11	14.9	3.23	1

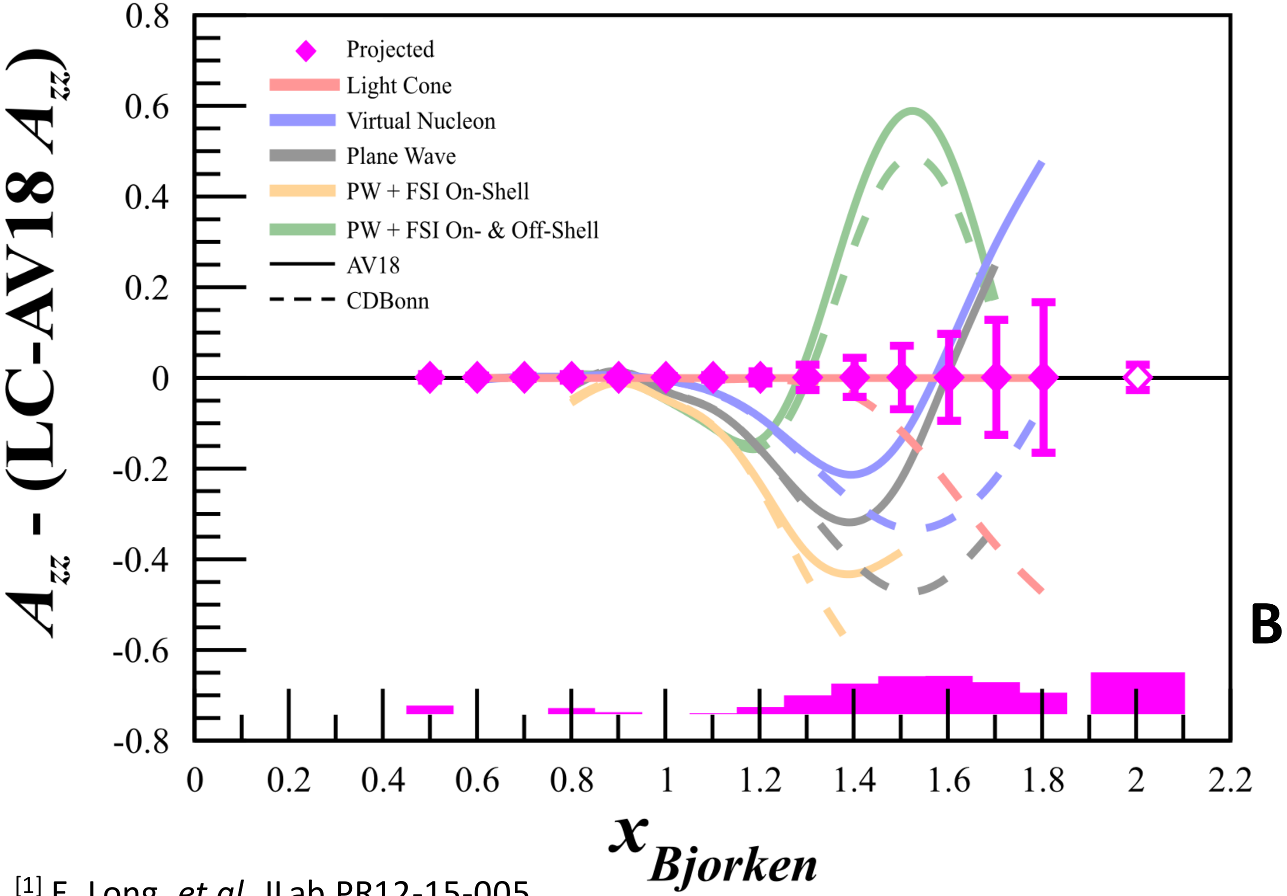
A_{zz} for $Q^2 > 1\,\mathrm{GeV}^2$ with $P_{zz} = 30\%$



Solid = Quasi-elastic
Open = Elastic

LL Frankfurt, *et al*, PRC **48** 2451 (1993)

A_{zz} Summary



First measurement of QE A_{zz} will give insight into:

- Relativistic LC and VN models[1,2]
- Hard or soft NN potentials[4]
- SRCs & pn dominance[3]
- Final state interaction models[5]

Bonus: T_{20} for largest Q^2 range ever measured in a single experiment, region of systematic discrepancy, highest Q^2 measured

[1] E. Long, *et al*, JLab PR12-15-005

[2] Sargsian, Strikman, J. Phys.: Conf. Ser. **543**, 012099 (2014)

[3] J Arrington *et al*, Prog. Part. Nucl. Phys. **67**, 898 (2012)

[4] L Frankfurt, M Strikman, Phys. Rept. **160**, 235

[5] W Cosyn, M Sargsian, arXiv:1407.1653

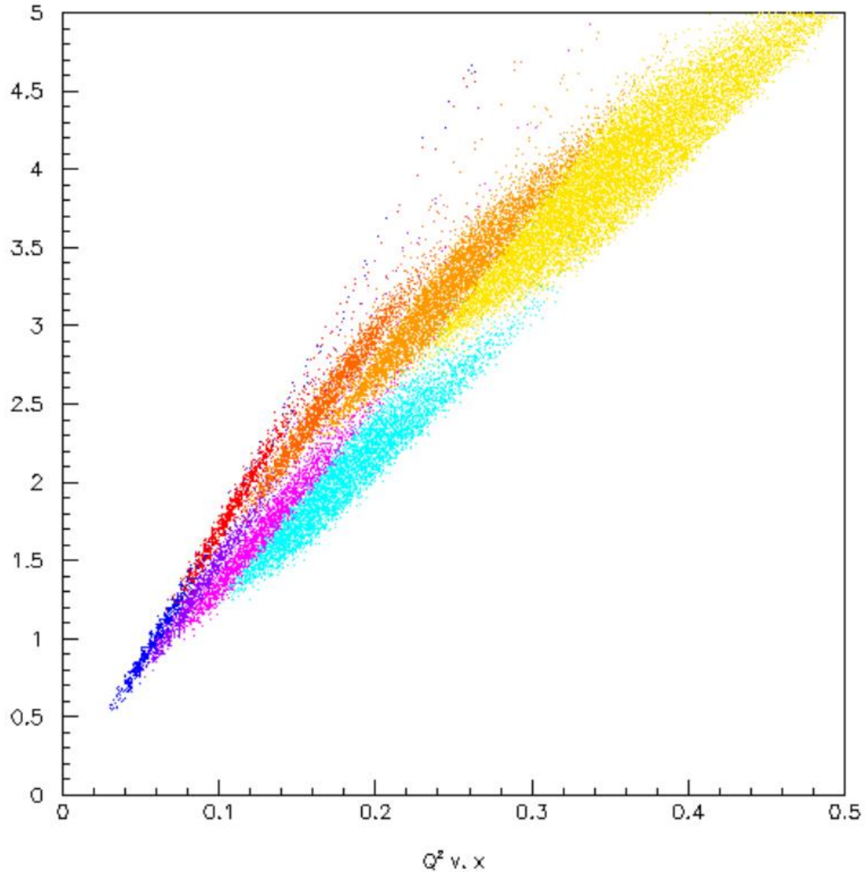
LOI12-14-001: Search for Exotic Gluonic States in the Nucleus

Authors:

J. Maxwell*, W. Detmold, R. Jaffe, R. Milner, D. Crabb, D. Day, D. Keller, O.A. Rondon, M. Jones, C. Keith, J. Pierce

Tensor Structure Function, b_4 (or Δ)

- Hadronic double helicity flip structure function, $\Delta(x, Q^2) = b_4$
- Unpolarized electron beam on transversely-aligned tensor polarized target
- Insensitive to bound nucleons or pions
- Any non-zero value indicates exotic gluonic components
- Encouraged for full proposal submission



R Jaffe, A Manohar, Phys. Lett. B **223,**218 (1989)

J. Maxwell, *et al*, JLab LOI-14-001

J. Phys.: Conf. Ser. 543 011001-012015 (2014)
http://iopscience.iop.org/1742-6596/543/1

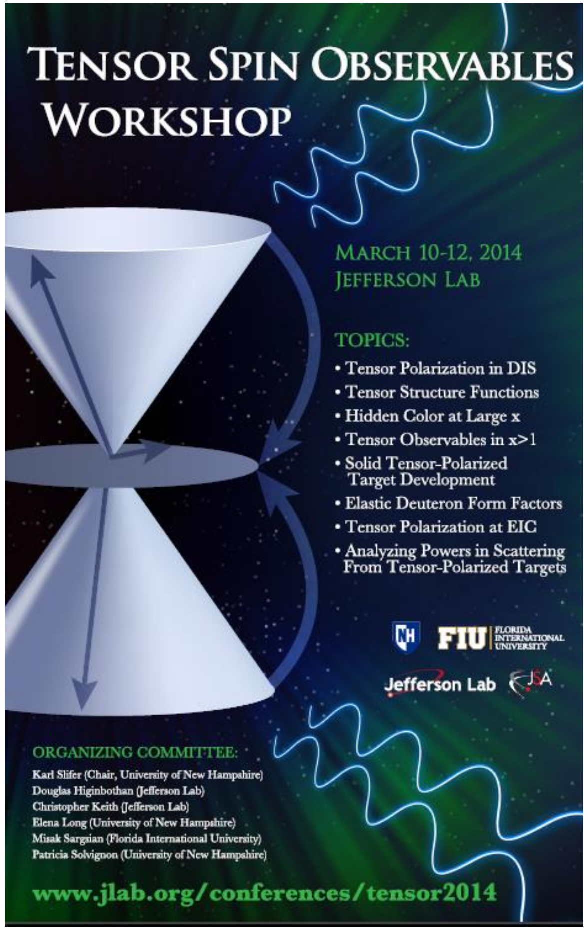
The Future of Tensor Polarization

Growing tensor program:

- DIS b_1 already approved (C12-13-011)
- QE and Elastic A_{zz} C2-approved (PR12-15-005)
- Exotic gluon states through Δ (LOI12-14-001)

Physics accessible with a tensor polarized target:

- Orbital Angular Momentum & Spin Crisis
- Gravitomagnetic Form Factors
- Pionic Effects
- Polarized Sea Quarks
- Tensor polarized antiquarks
- Linking traditional nuclear physics and quark-gluon picture
- Final State Interactions
- Gluonic Effects
- New tensor structure functions → b_2, b_3
- Tensor DVCS → Test sum rules, new helicity term
- Tensor Drell-Yan → 60 new structure functions
- …and more!



TENSOR SPIN OBSERVABLES WORKSHOP

MARCH 10-12, 2014
JEFFERSON LAB

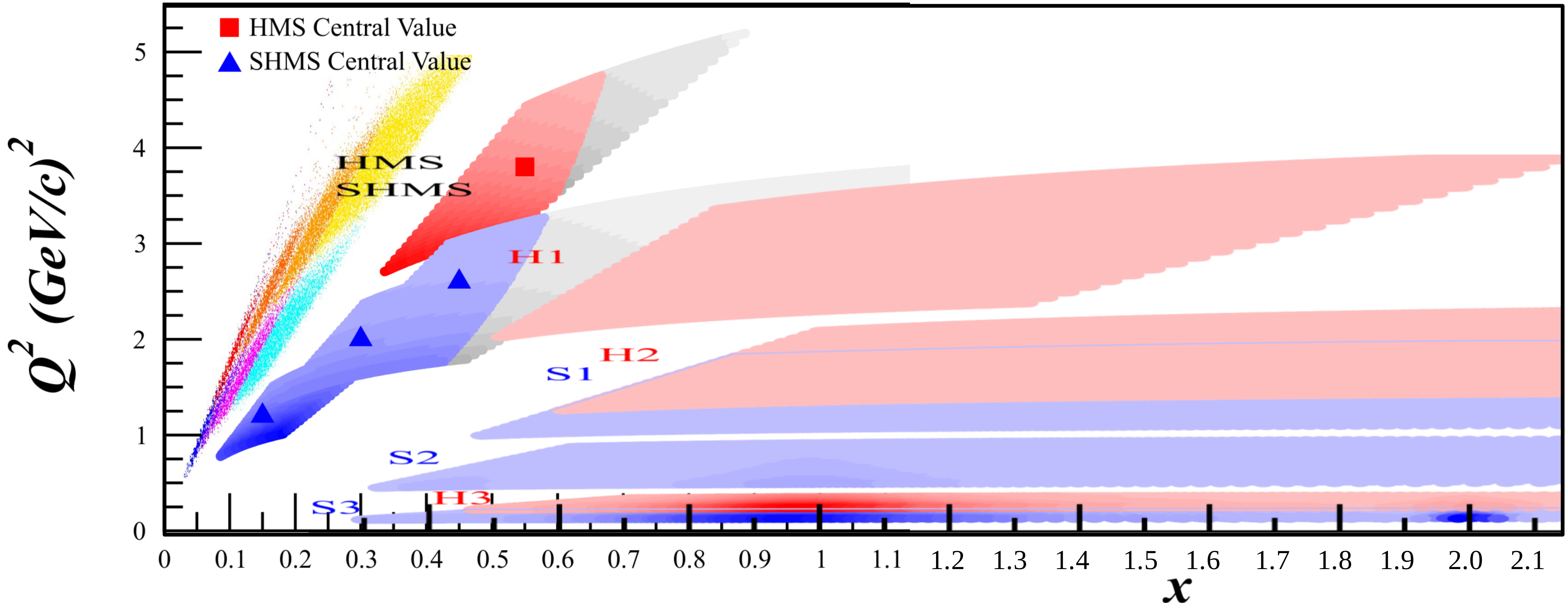
TOPICS:

- Tensor Polarization in DIS
- Tensor Structure Functions
- Hidden Color at Large x
- Tensor Observables in x>1
- Solid Tensor-Polarized Target Development
- Elastic Deuteron Form Factors
- Tensor Polarization at EIC
- Analyzing Powers in Scattering From Tensor-Polarized Targets

ORGANIZING COMMITTEE:
Karl Slifer (Chair, University of New Hampshire)
Douglas Higinbothan (Jefferson Lab)
Christopher Keith (Jefferson Lab)
Elena Long (University of New Hampshire)
Misak Sargsian (Florida International University)
Patricia Solvignon (University of New Hampshire)

www.jlab.org/conferences/tensor2014

JLab12 Tensor Program (So far…)

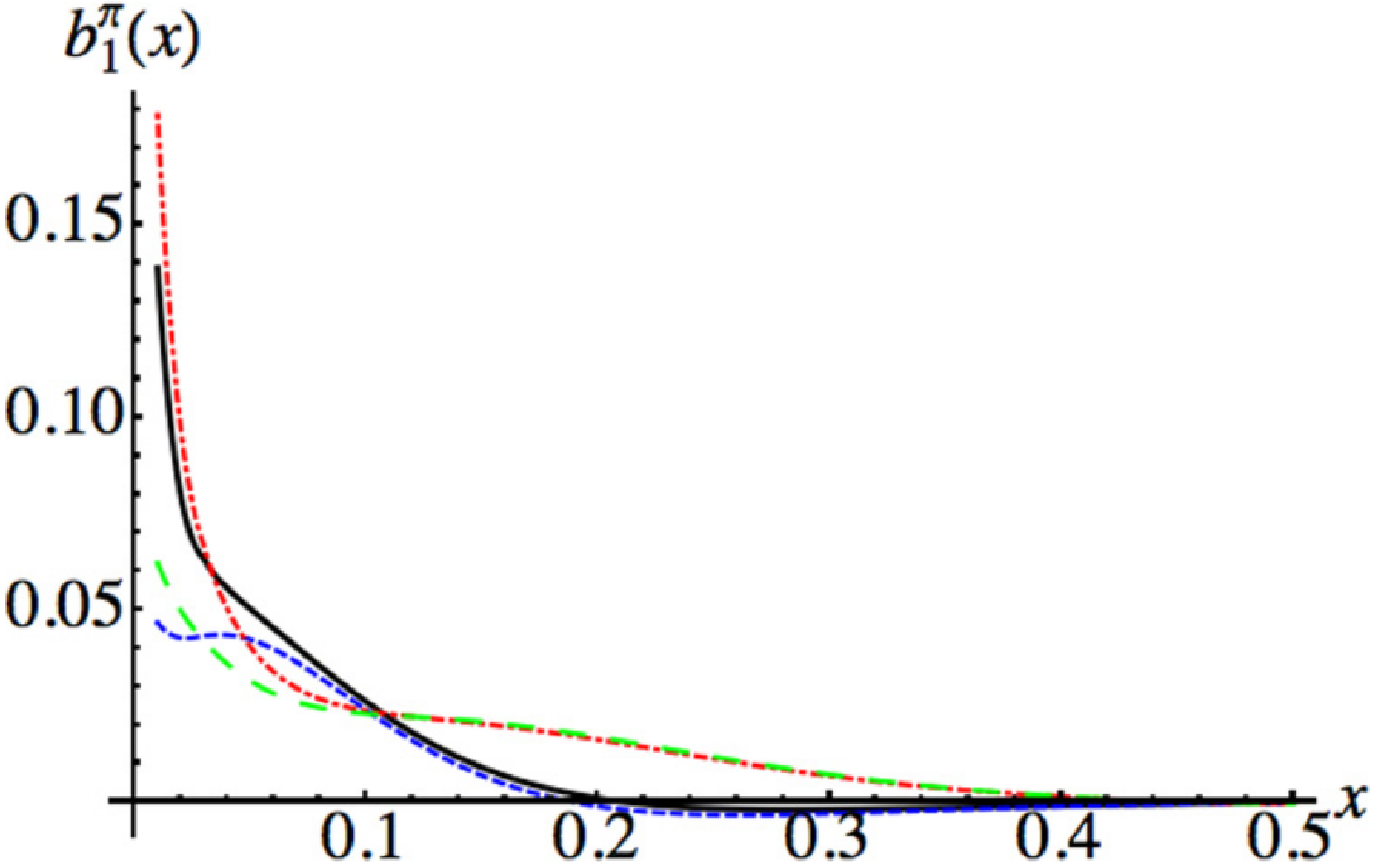


Thank you

Backup Slides

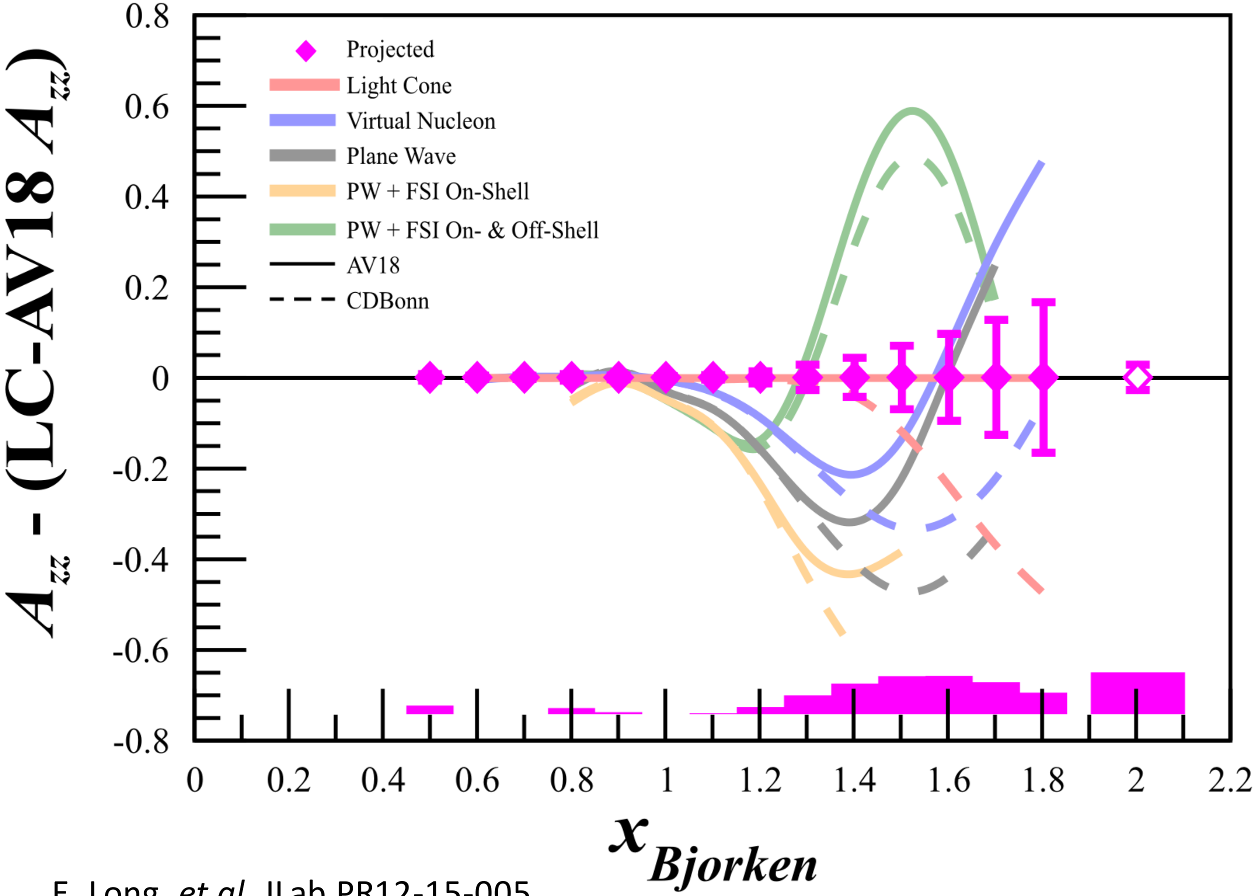
6-Quark, Hidden Color

- Pionic effects alone would violate Close-Kumano Sum Rule $\int b_1(x)dx = 0$



G Miller, PRC **89** 045203 (2014)

Summary



E. Long, *et al*, JLab PR12-15-005

Sargsian, Strikman, J. Phys.: Conf. Ser. **543**, 012099 (2014)

> **“The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range *pn* correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program.”**
>
> -JLab PAC42 & PAC43 Theory TACs
>
> (C. Weiss, R. Schiavilla, J.W. Van Orden)

Deuteron

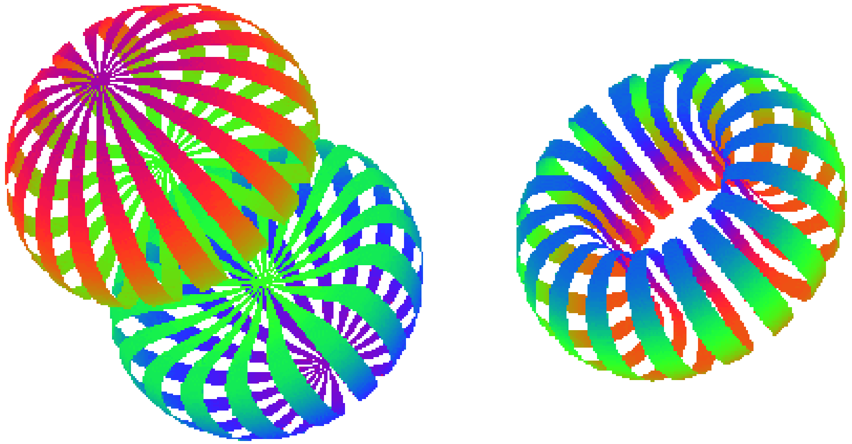
Simplest composite nuclear system

However, understanding of deuteron at short distances remains unsatisfying

- A well-constrained theoretical model is necessary for understanding tensor interactions underlying short-range correlations and *pn*-dominance

Short-range deuteron structure can be probed using choice in kinematics ($x > 1$) and by enhancing the *D*-state through tensor polarization

- This proposal uses a combination of both techniques



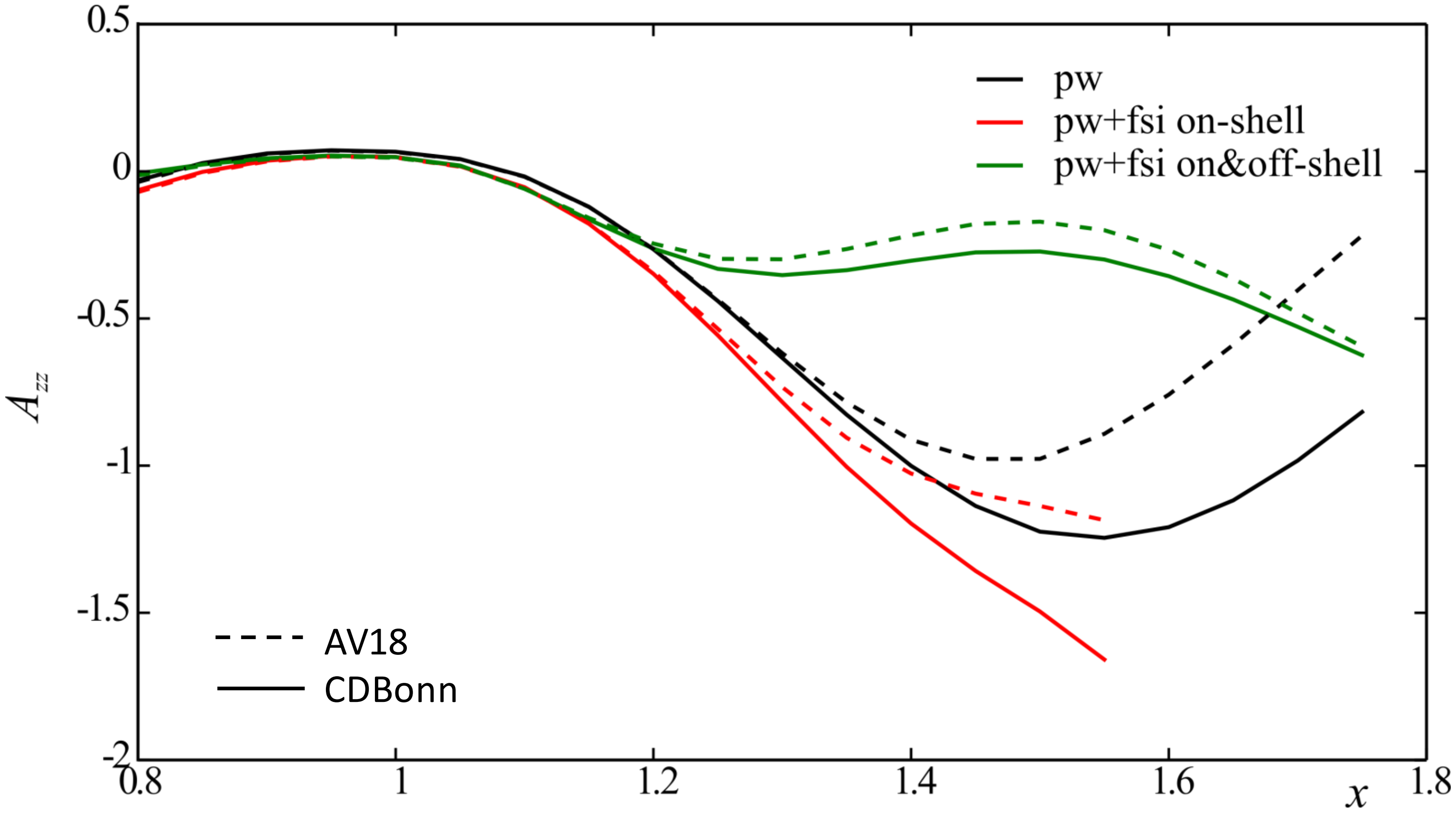
J Forest, *et al*, PRC **54** 646 (1996)

Final State Interactions

To determine nucleonic components of the deuteron WF, FSI must be understood

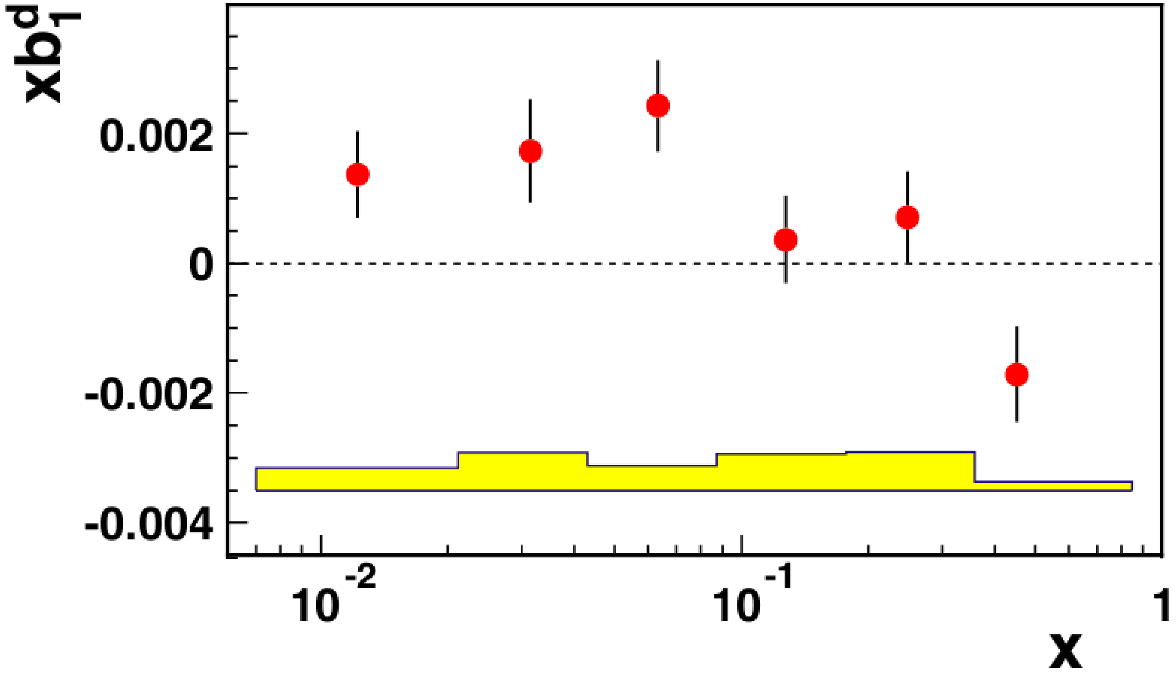
Minimum and maximum effects from FSI have been calculated by W. Cosyn

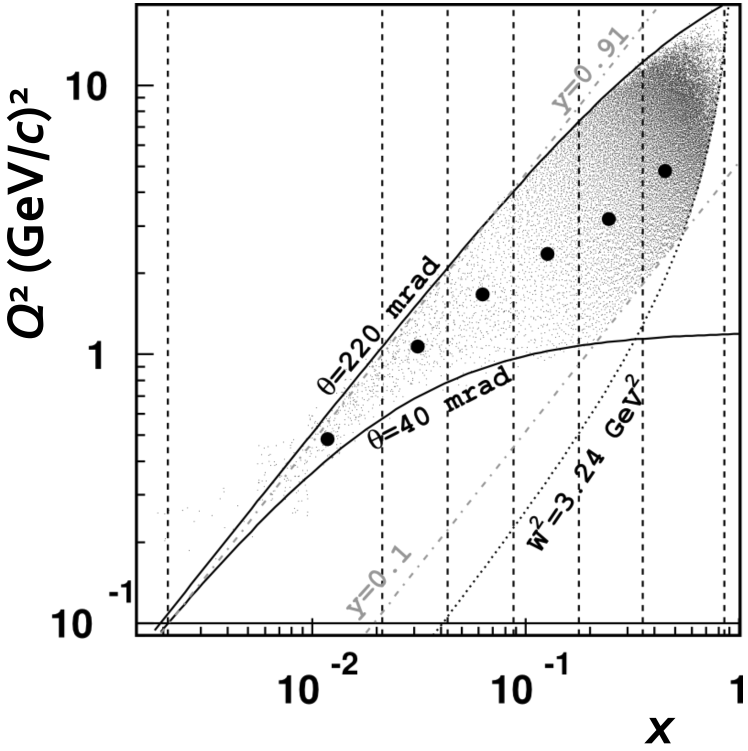
Even with FSI, large discrepancy based on WF input



DIS Tensor Observables

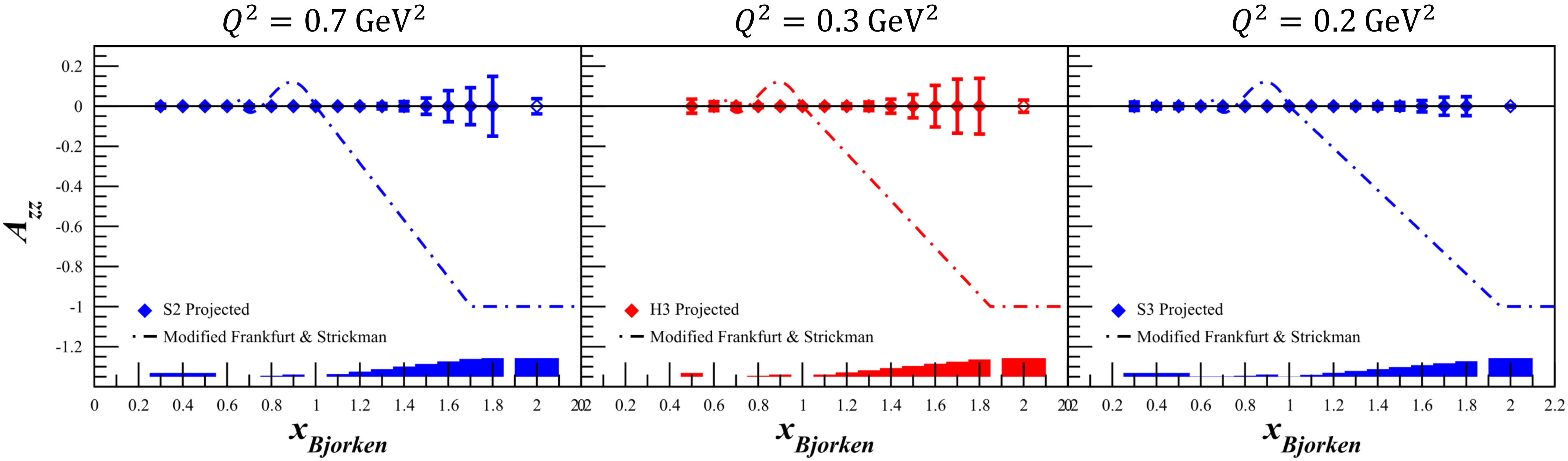
- HERMES b_1 -- First tensor structure function measurement





A Airapetian, *et al*, PRL **95** 242001 (2005)

A_{zz} for $Q^2 < 1\ \mathrm{GeV}^2$ with $P_{zz} = 30\%$

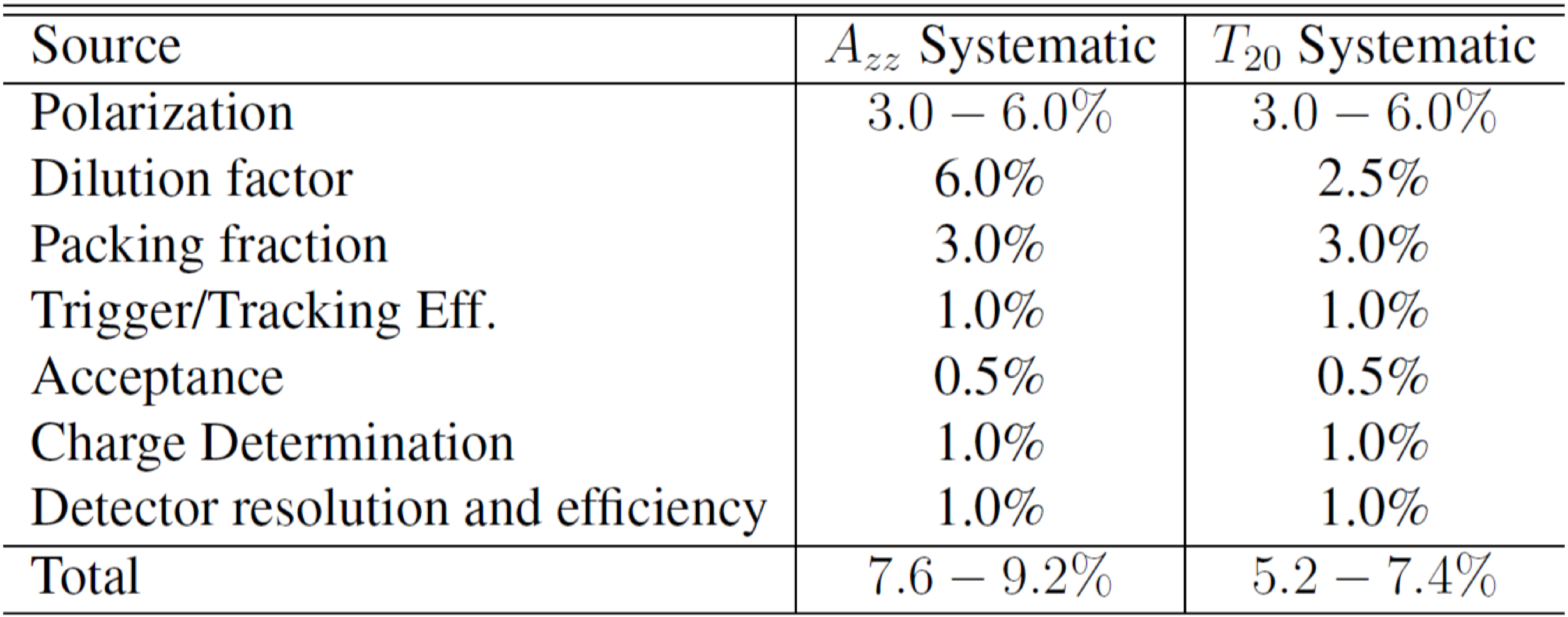


Solid = Quasi-elastic
Open = Elastic

* More calculation coming soon…

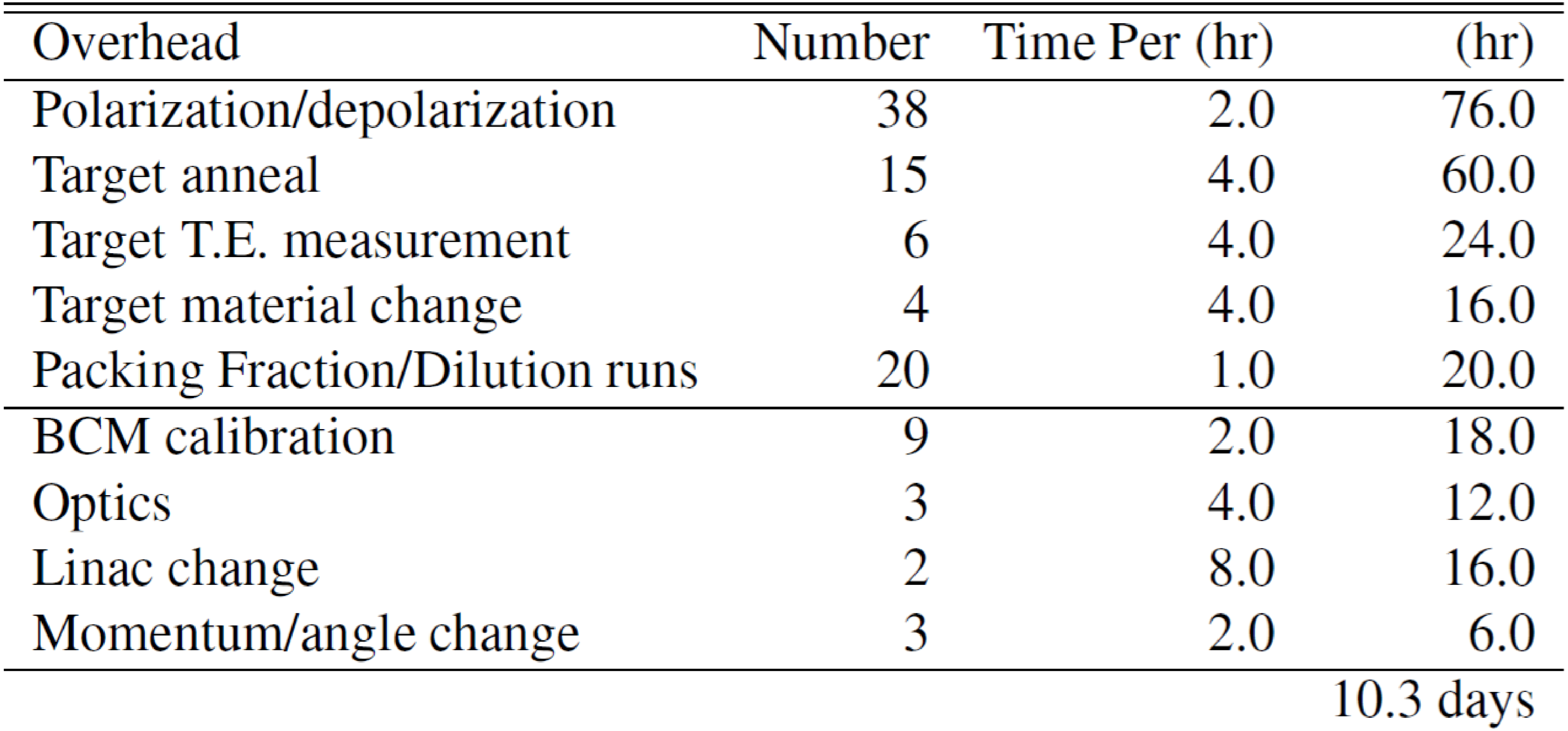
More than 10x less sensitive to systematics than b_1

Systematics



Source	A_{zz} Systematic	T_{20} Systematic
Polarization	$3.0-6.0\%$	$3.0-6.0\%$
Dilution factor	6.0%	2.5%
Packing fraction	3.0%	3.0%
Trigger/Tracking Eff.	1.0%	1.0%
Acceptance	0.5%	0.5%
Charge Determination	1.0%	1.0%
Detector resolution and efficiency	1.0%	1.0%
Total	$7.6-9.2\%$	$5.2-7.4\%$

Overhead



Overhead	Number	Time Per (hr)	(hr)
Polarization/depolarization	38	2.0	76.0
Target anneal	15	4.0	60.0
Target T.E. measurement	6	4.0	24.0
Target material change	4	4.0	16.0
Packing Fraction/Dilution runs	20	1.0	20.0
BCM calibration	9	2.0	18.0
Optics	3	4.0	12.0
Linac change	2	8.0	16.0
Momentum/angle change	3	2.0	6.0
			10.3 days

Challenges and Opportunities

- Tensor polarized target in development with dedication from multiple labs
- Stray SHMS fields will have negligible effect on target
- Data recoverable in rare event of target material shifting

- Very large A_{zz} asymmetry (10-120%)
- Identical equipment and technique as b_1
- More than an order of magnitude less dependent on systematics than b_1
  - Perfect testing ground for fully understanding and controlling systematics

Theoretical Interest

"A measurement of Azz will provide important information on whether the deuteron wavefunction is hard or soft, as well as on relativistic effects. These are important for the progress of our understanding of the short-range dynamics of nuclear interactions, which have relevance ranging from short-range correlations in nuclei to the equations of state of neutron stars."

- M. Sargsian

"A_{zz} is a unique method to measure the ratio of *S*- and *D*-waves in the deuteron at short distances and hence test the spin structure of short-range correlations. It is also the most sensitive observable to test different approaches to the description of relativistic dynamics."

– M. Strikman

"What interests me most in this proposal is that it can teach us about the nature of the nucleon-nucleon force at short distances and with an observable sensitive to non-nucleonic contributions there is also room for surprising results. Additionally, on the theory side, this measurement would also provide an incentive for additional calculations and studies on top of the testing of various existing models, which is always a good thing."

-W. Cosyn

"Previous low Q^2 measurements seemed to indicate that the asymmetries are far less sensitive to reaction mechanisms than the cross sections; so while the new calculations are not yet available, it is clear that the asymmetries will produce unique constraints on our understanding of the deuteron."

- W. Van Orden

"This proposal really challenges theorists to better understand the meaning of nuclear wave functions in a situation that demands a relativistic treatment. I plan on working to understand this reaction during the upcoming summer."

- G. A. Miller

Tensor Structure Function, b_1

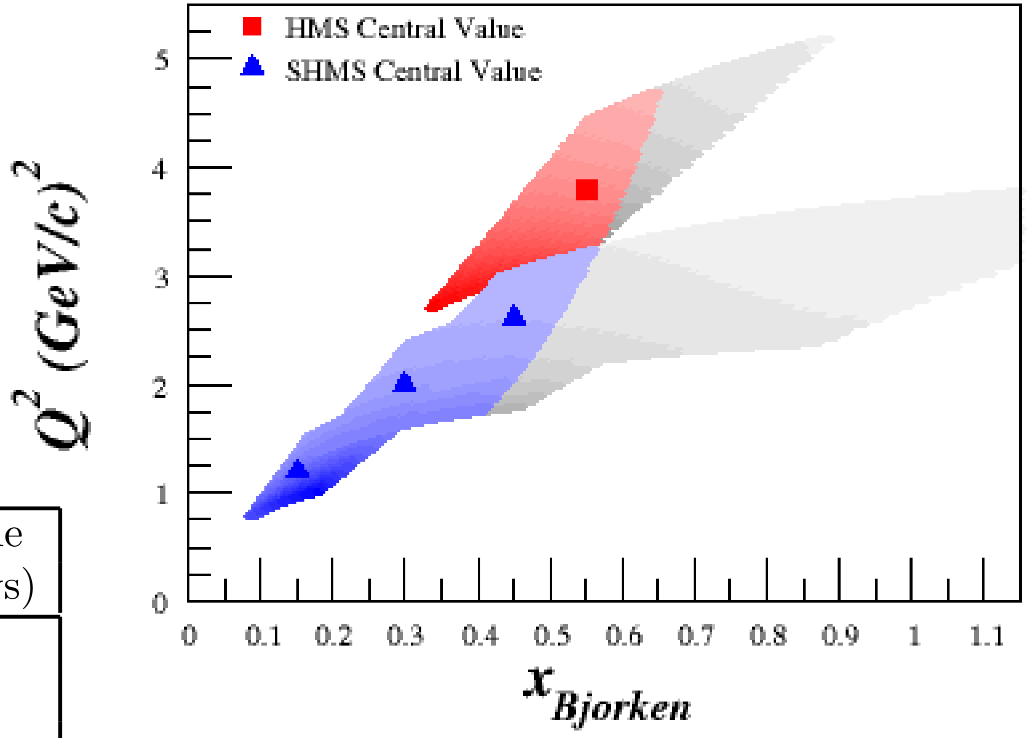
Measured by ratio method

$$\frac{N_{Pol}}{N_u} - 1 = f\frac{1}{2}A_{zz}P_{zz}$$

$$A_{zz} = \frac{2}{f \cdot P_{zz}}\left(\frac{N_{Pol}}{N_u} - 1\right)$$

$$b_1 = -\frac{3F_1}{f \cdot P_{zz}}\left(\frac{N_{Pol}}{N_u} - 1\right) = -\frac{3}{2}F_1 A_{zz}$$

Detector	x	Q^2 (GeV^2)	W (GeV)	$E_{e'}$ (GeV)	$\theta_{e'}$ (deg.)	θ_q (deg.)	Rates (kHz)	Time (Days)
SHMS	0.15	1.21	2.78	6.70	7.35	11.13	1.66	6
SHMS	0.30	2.00	2.36	7.45	8.96	17.66	0.79	9
SHMS	0.45	2.58	2.00	7.96	9.85	23.31	0.38	15
HMS	0.55	3.81	2.00	7.31	12.50	22.26	0.11	30

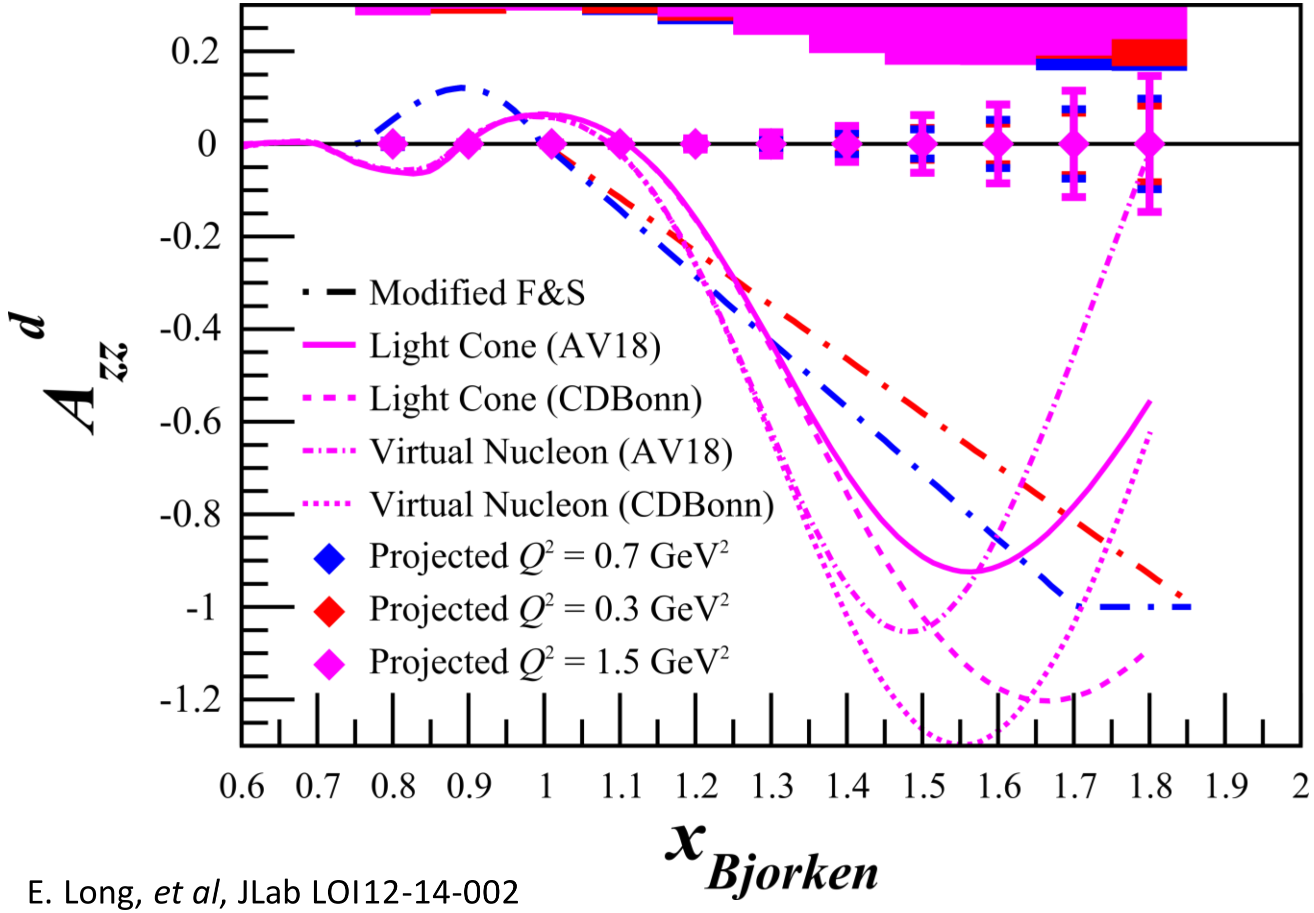


OAM and Angular Momentum Sum Rule

- Deuteron angular momentum dominated by the GPD H
  - $J_q = \frac{1}{2}\int dx x H_2^q(x, 0{,}0)$
  - DVCS (A_{UT}) on tensor-polarized deuterons would be an ideal observable to test this sum rule
- Sum rule can calculate normal nuclear effects with high precision, giving $H_2 \approx H + E$
- Any measured deviation might shed light on elusive gluon angular momentum components
- Measurement of $b_1 = H_5(x, 0{,}0)$ will provide necessary information for assumptions in the above sum rule and relates to gravitomagnetic form factors
  - $\int dx x H_5(x, \xi, t) = -\frac{t}{8M_D^2}\mathcal{G}_6(t) + \frac{1}{2}\mathcal{G}_7(t)$

SK Taneja, *et al*, PRD **86** 036008 (2012)

Quasi-Elastic A_{zz}



E. Long, *et al*, JLab LOI12-14-002

Sargsian, Strikman, J. Phys.: Conf. Ser. **543**, 012099 (2014)

Encouraged for full submission by PAC42

"The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range *pn* correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program."

-JLab PAC42 Theory Advisory Committee

Elastic Tensor Observables

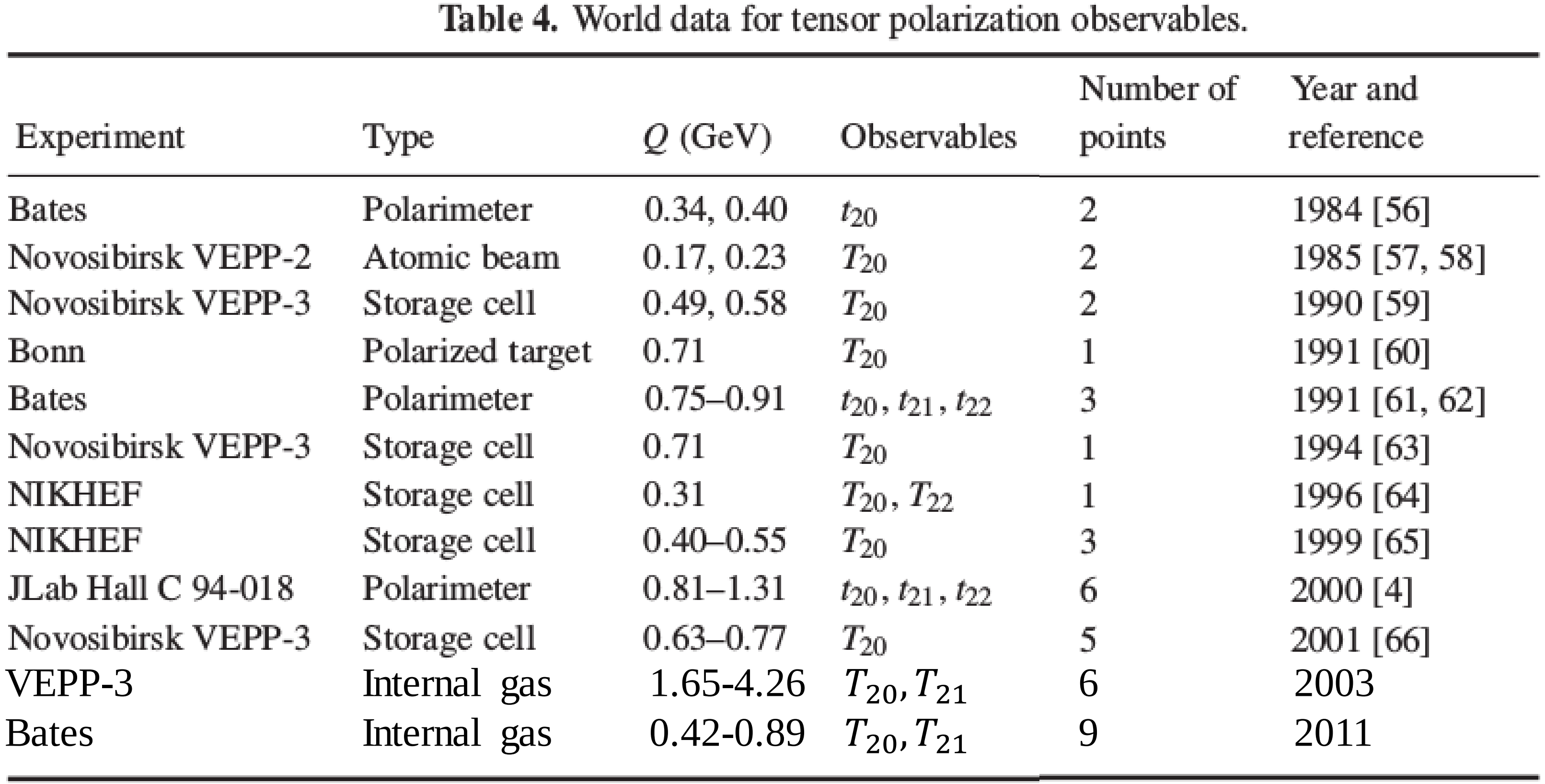


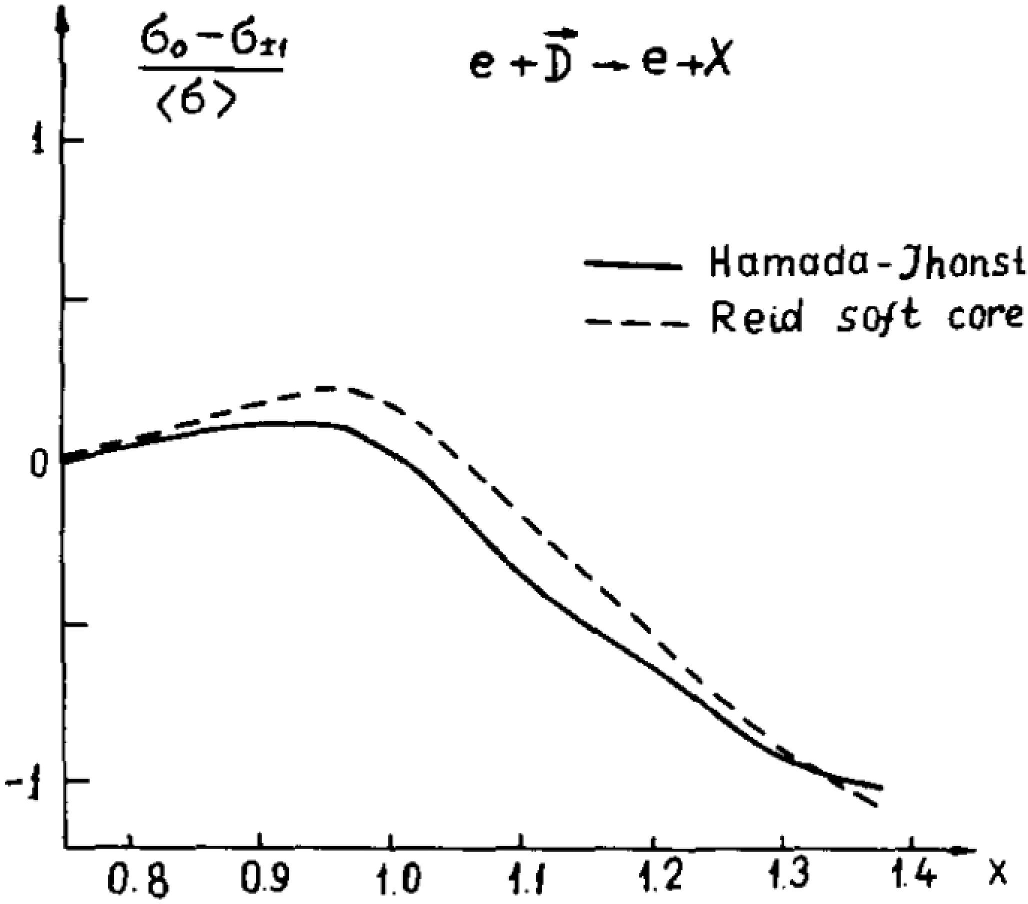
Table 4. World data for tensor polarization observables.

Experiment	Type	Q (GeV)	Observables	Number of points	Year and reference
Bates	Polarimeter	0.34, 0.40	t_{20}	2	1984 [56]
Novosibirsk VEPP-2	Atomic beam	0.17, 0.23	T_{20}	2	1985 [57, 58]
Novosibirsk VEPP-3	Storage cell	0.49, 0.58	T_{20}	2	1990 [59]
Bonn	Polarized target	0.71	T_{20}	1	1991 [60]
Bates	Polarimeter	0.75–0.91	t_{20}, t_{21}, t_{22}	3	1991 [61, 62]
Novosibirsk VEPP-3	Storage cell	0.71	T_{20}	1	1994 [63]
NIKHEF	Storage cell	0.31	T_{20}, T_{22}	1	1996 [64]
NIKHEF	Storage cell	0.40–0.55	T_{20}	3	1999 [65]
JLab Hall C 94-018	Polarimeter	0.81–1.31	t_{20}, t_{21}, t_{22}	6	2000 [4]
Novosibirsk VEPP-3	Storage cell	0.63–0.77	T_{20}	5	2001 [66]
VEPP-3	Internal gas	1.65-4.26	T_{20}, T_{21}	6	2003
Bates	Internal gas	0.42-0.89	T_{20}, T_{21}	9	2011

R Gilman, F Gross, J. Phys. G **28** R37 (2002)

Frankfurt and Strikman Light Cone Calculations

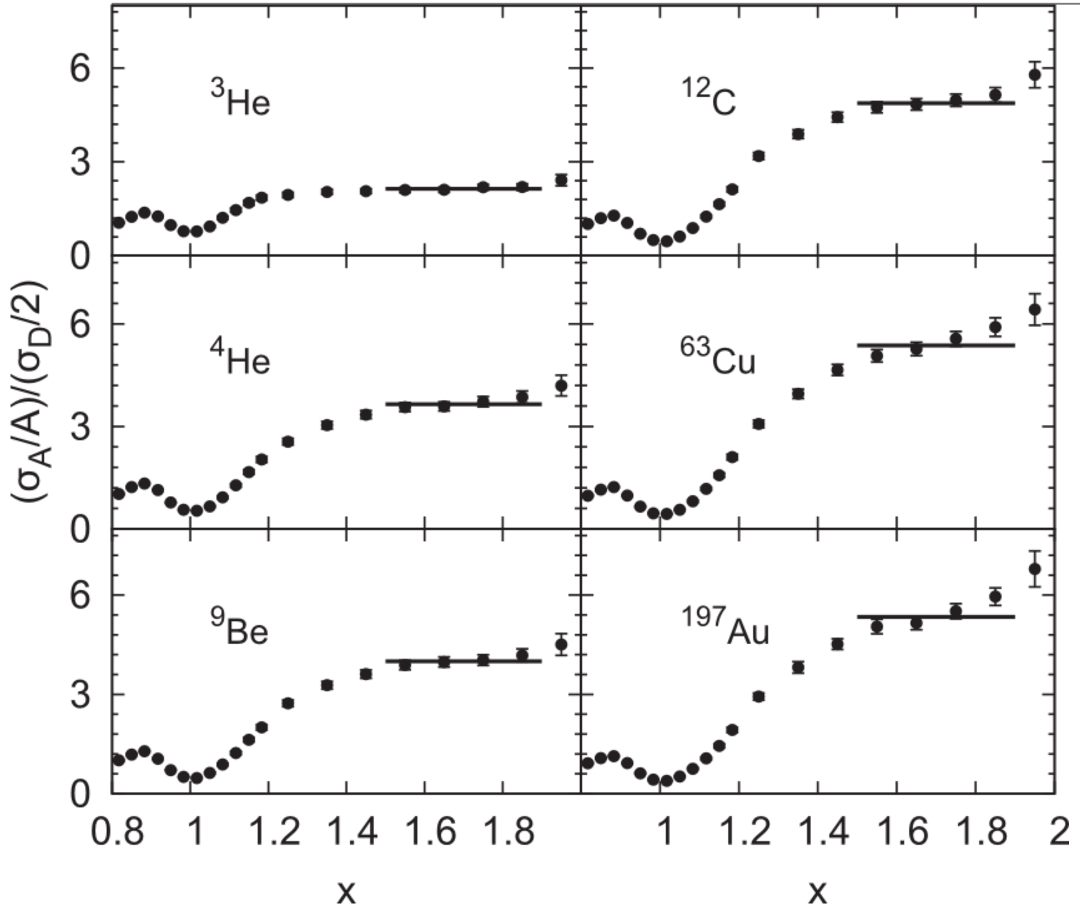
- $A_{zz} = \left(3\,\frac{\frac{1}{2}k_\perp^2 - k_z^2}{k^2}\right)\frac{\frac{1}{2}w^2(k) - u(k)w(k)\sqrt{2}}{u^2(k)+w^2(k)}$
  - $u(k)$ is the momentum-dependent S state
  - $w(k)$ is the momentum-dependent D state
- Recent study indicates dependence on choice of NN potential



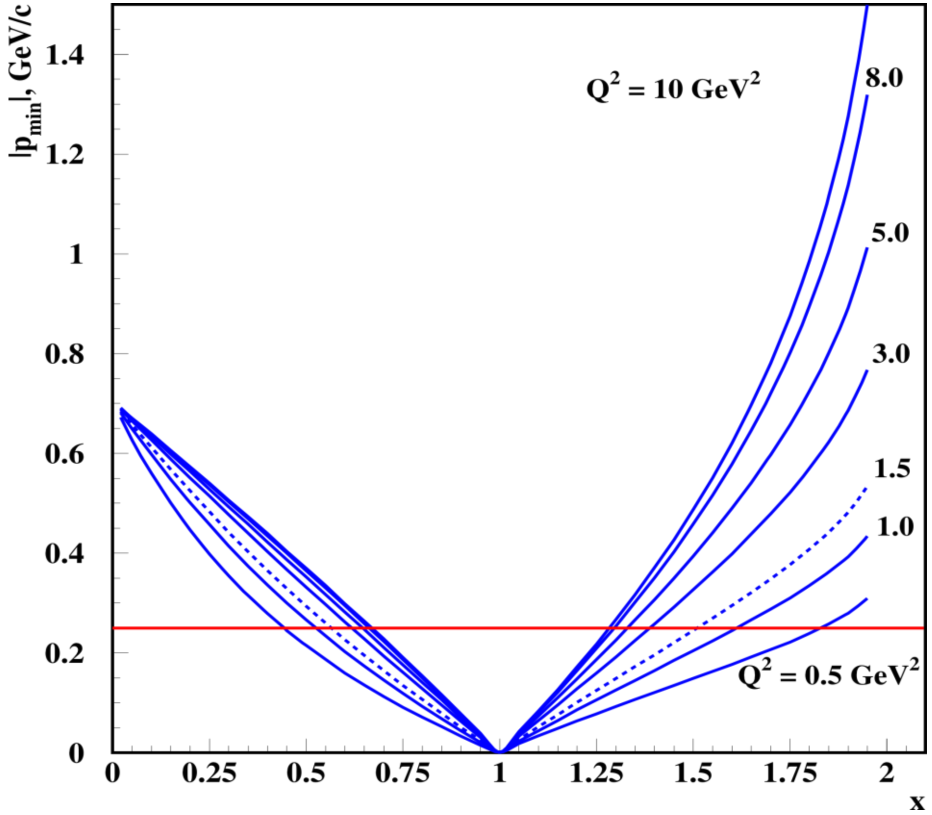
L.L. Frankfurt, M.I. Strikman, Phys. Rept. **76** (1981) 215

Connection to Short Range Correlations

Short range correlations caused by tensor force – why not probe it through tensor polarization?



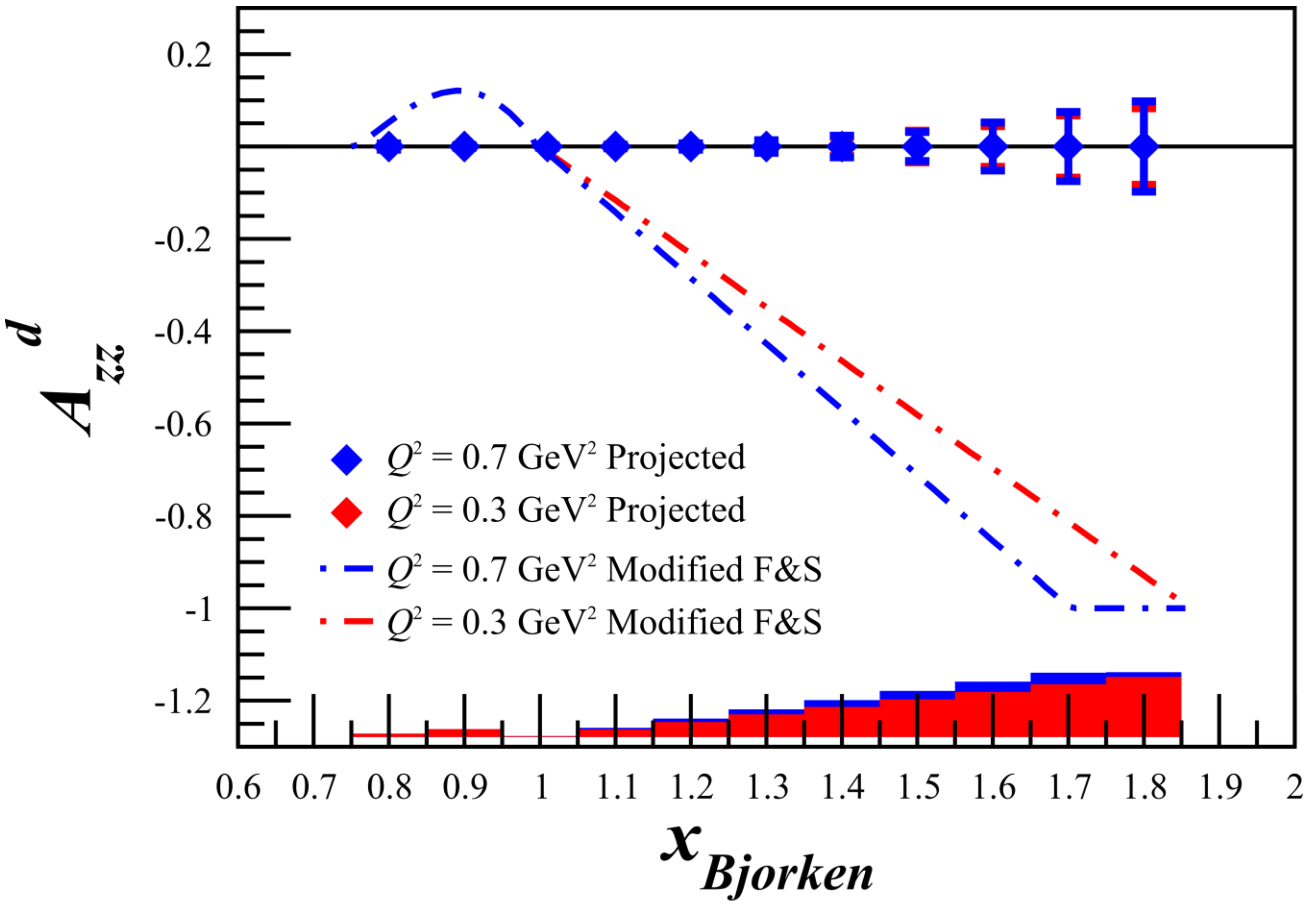
N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092505

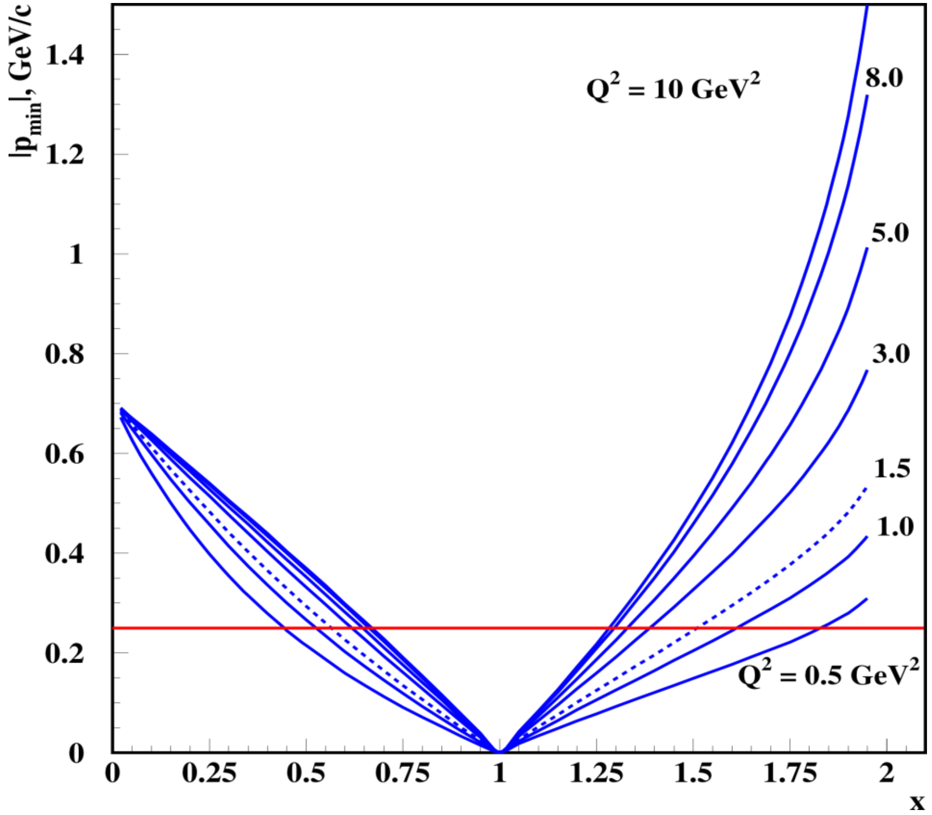


L.L. Frankfurt et al., Int. J. Mod. Phys. A23 (2008) 2991-3055

Connection to Short Range Correlations

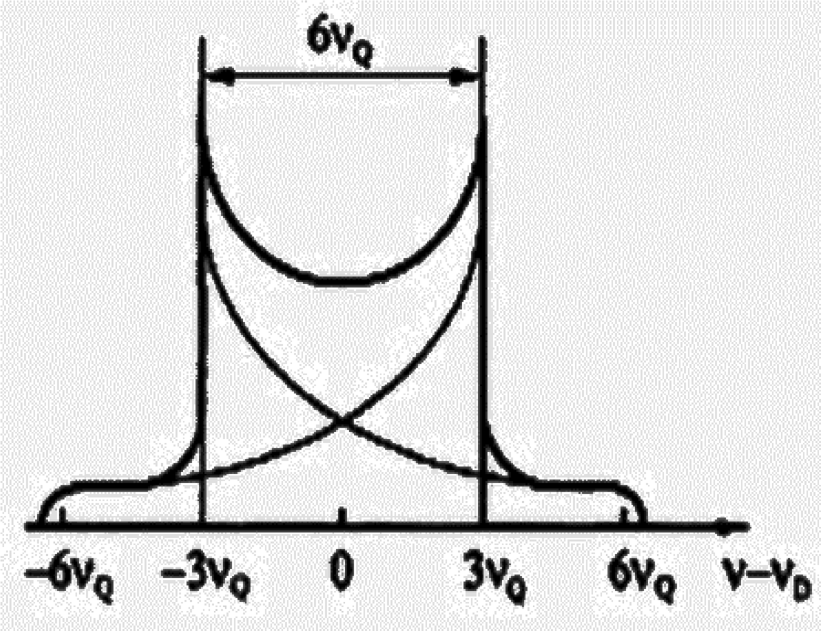
Short range correlations caused by tensor force – why not probe it through tensor polarization?





L.L. Frankfurt et al., Int. J. Mod. Phys. A23 (2008) 2991-3055

Tensor Polarization Measurement



Vector optimize with microwaves

Fit peaks with convolution

Tensor optimize with RF

Measure change in peaks using Riemann Sum segments

$$P_{zz}^{HB} \approx \frac{A^{NMR}}{A^{I}} \left(P_{zz}^{I} + r_0 (P^{I} - P_{zz}^{I}) \right)$$

Ratio of instantaneous to initial NMR signal area

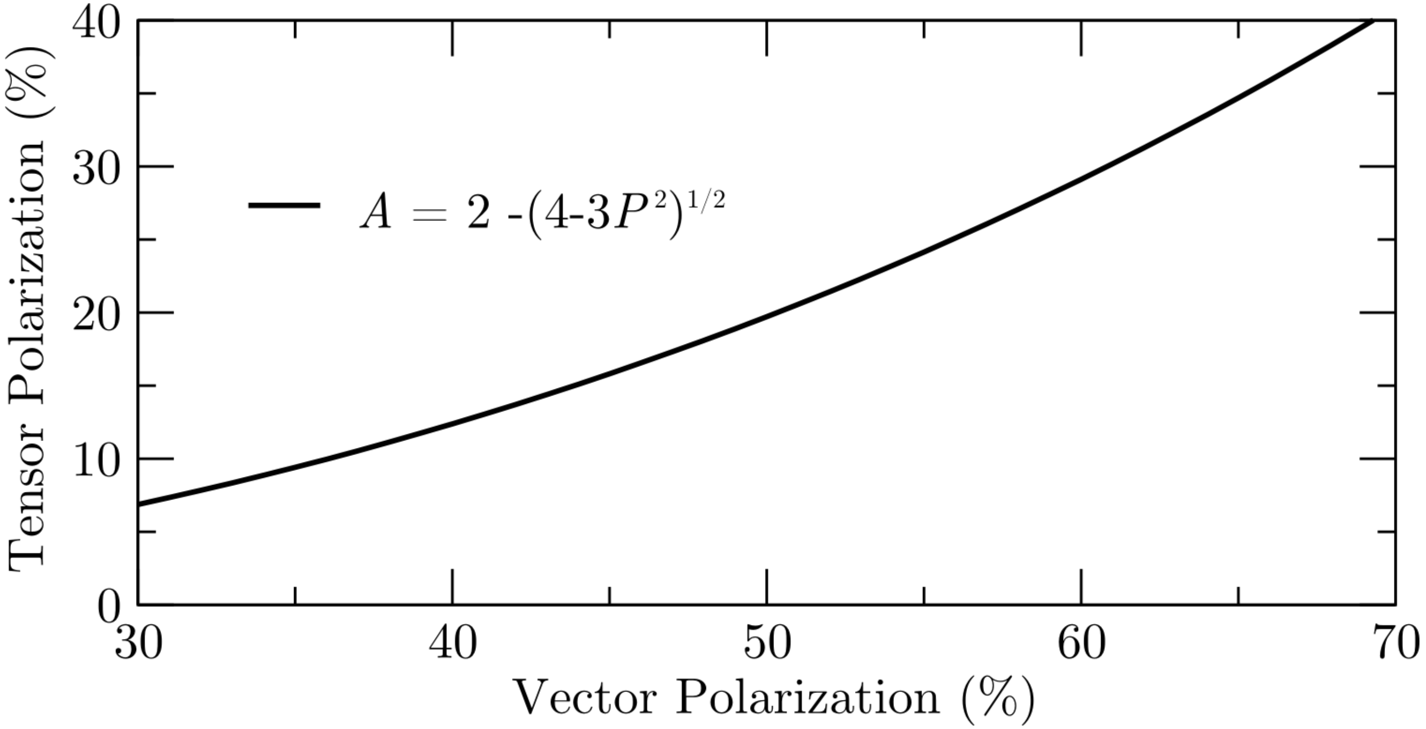
Percentage of initial peak shifted any time (from reduced side)

Available tensor enhancement

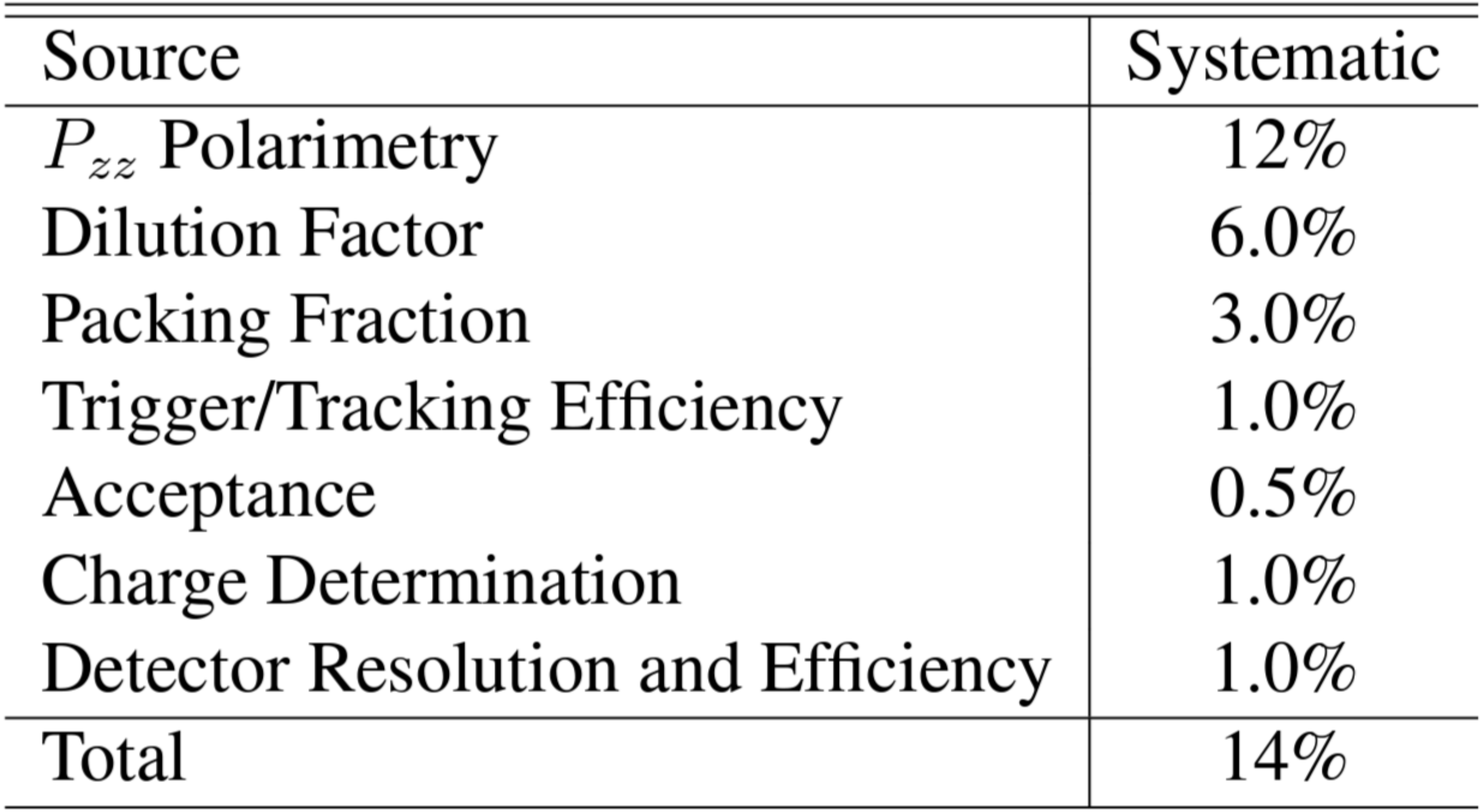
Brute Force Tensor Polarization

When vector polarizing deuterium, some amount of tensor polarization occurs

Higher vector polarization → Higher tensor polarization



Systematics Estimate for A_{zz}



Source	Systematic
P_{zz} Polarimetry	12%
Dilution Factor	6.0%
Packing Fraction	3.0%
Trigger/Tracking Efficiency	1.0%
Acceptance	0.5%
Charge Determination	1.0%
Detector Resolution and Efficiency	1.0%
Total	14%

Interest from Theorists

M. Strikman and M. Sargsian have already been involved in providing A_{zz} calculations

"This is an important measurement. Accessing the large x region will provide insights on the partonic structure of the D-wave dominated deuteron tensor structure function, b_1. This process should be calculated more thoroughly." – S. Liuti

"This measurement was a highlighted need early at Jlab. A new measurement at higher Q^2 would be very interesting. In principle such could test my model. I could calculate the influence of my 6-quark configurations on elastic scattering." – G. Miller

"I hope to do some calculations soon and could easily do them for the kinematics in your proposal." – W. Cosyn

W. Van Orden has agreed to look into tensor polarization observables at low Q^2 using a variety of NN potentials

Rates for D(e,e’)X

Assumptions:

$$P_{zz} = 30\%$$
$$p_f = 65\%$$
$$z_{\rm tgt} = 3\ \rm cm$$

P.E. Bosted, V. Mamyan, arXiv:1203.2262
M. Sargsian, Private Communication
N. Fomin, et al., Phys. Rev. Lett. 108 (2012) 092502
N. Fomin, et al., Phys. Rev. Lett. 105 (2010) 212502

$$R_{\rm Pol} = \mathcal{A}\left[\mathcal{L}_{\rm He}\sigma^u_{\rm He} + \mathcal{L}_{\rm N}\sigma^u_{\rm N} + \mathcal{L}_{\rm D}\sigma^u_{\rm D}\left(1 + \tfrac{1}{2}P_{zz}A_{zz}\right)\right]$$

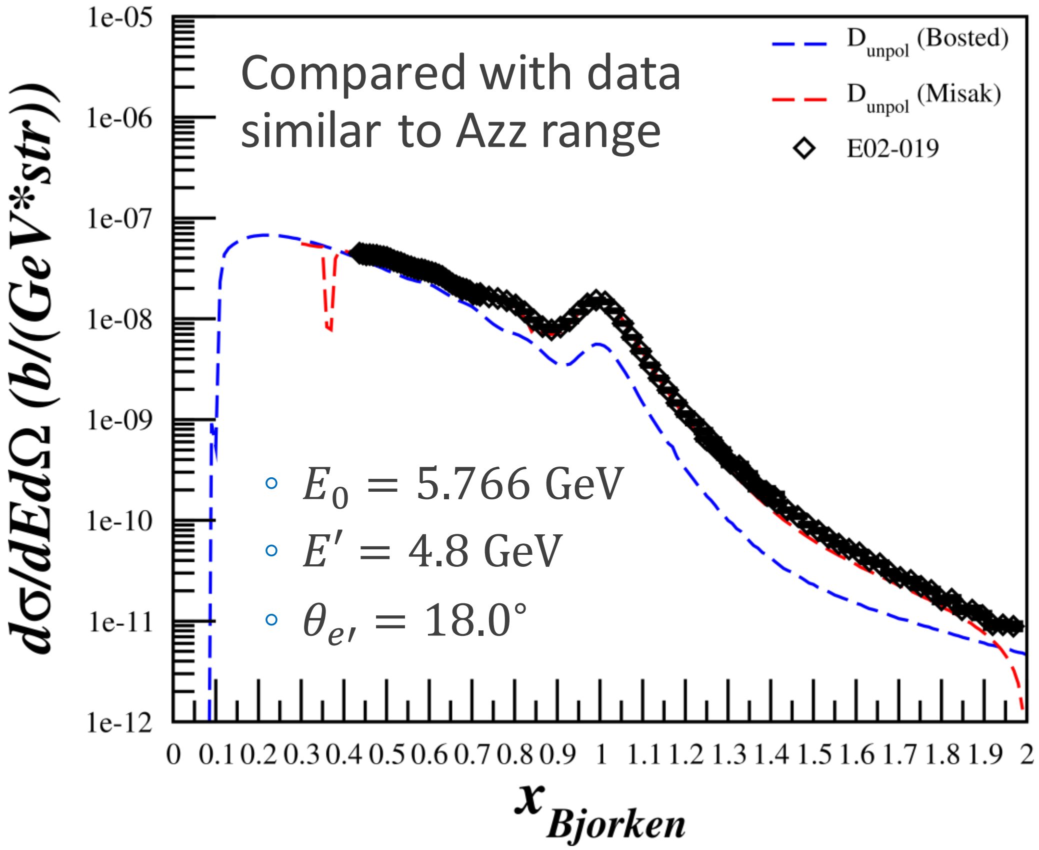
$$R_{\rm Unpol} = \mathcal{A}[\mathcal{L}_{\rm He}\sigma^u_{\rm He} + \mathcal{L}_{\rm N}\sigma^u_{\rm N} + \mathcal{L}_{\rm D}\sigma^u_{\rm D}]$$

$$N = Rt$$

$$A_{zz} = \frac{2}{f_{dil}P_{zz}}\left(\frac{N_{\rm Pol}}{N_{\rm Unpol}} - 1\right)$$

$$\delta A^{\rm stat}_{zz} = \frac{2}{f_{dil}P_{zz}}\sqrt{\left(\frac{1}{N_{\rm Unpol}}\sqrt{N_{\rm Pol}}\right)^2 + \left(\frac{N_{\rm Pol}}{N^2_{\rm Unpol}}\sqrt{N_{\rm Unpol}}\right)^2}$$

- Used combination of P. Bosted and M. Sargsian code to calculate unpolarized cross sections



Compared with data similar to Azz range

- $E_0 = 5.766$ GeV
- $E' = 4.8$ GeV
- $\theta_{e'} = 18.0°$

E. Long, Technical Note, JLAB-TN-13-029

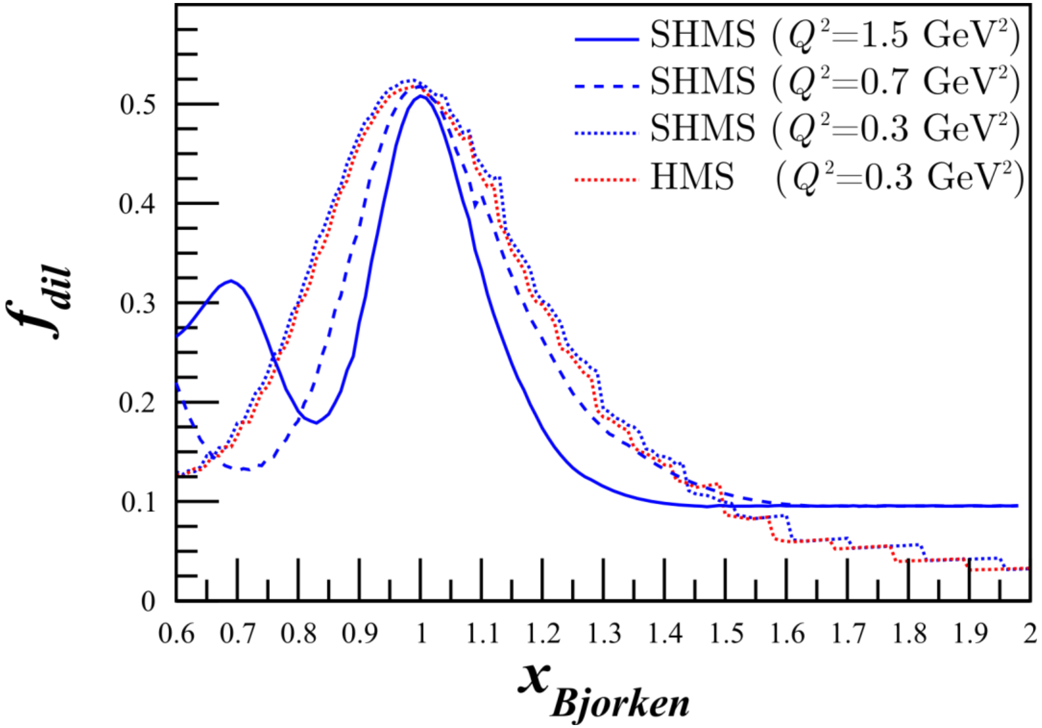
Dilution Factor

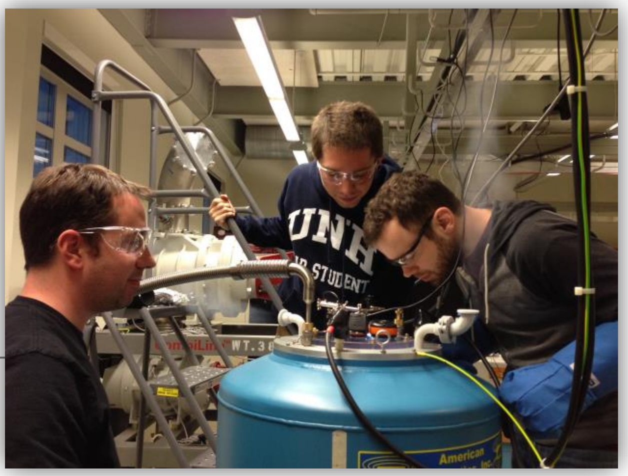
"…the background from interaction with nuclei increases as $\alpha(x)$ increases. For example, for a $D^{12}C$ target the ratio of the cross sections σ_A for A=^{12}C and A=D is of the order of 40 for $x \sim 1.3$ and increases with x."

- L.L. Frankfurt, M.I. Strikman, Phys. Rept. **160** (1988) 235

$$f_{dil} = \frac{\mathcal{L}_{\mathrm{D}}\sigma_{\mathrm{D}}}{\mathcal{L}_{\mathrm{N}}\sigma_{\mathrm{N}} + \mathcal{L}_{\mathrm{He}}\sigma_{\mathrm{He}} + \mathcal{L}_{\mathrm{D}}\sigma_{\mathrm{D}} + \sum \mathcal{L}_{\mathrm{A}}\sigma_{\mathrm{A}}}$$

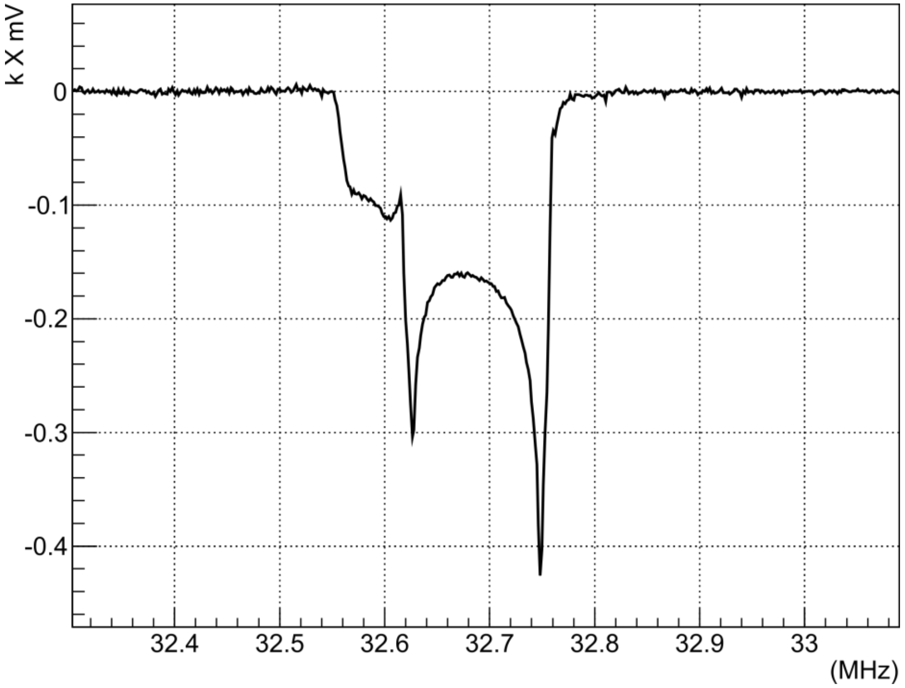
With the 12 GeV upgrade and the new SHMS, this measurement becomes possible even with the low dilution factor at high x





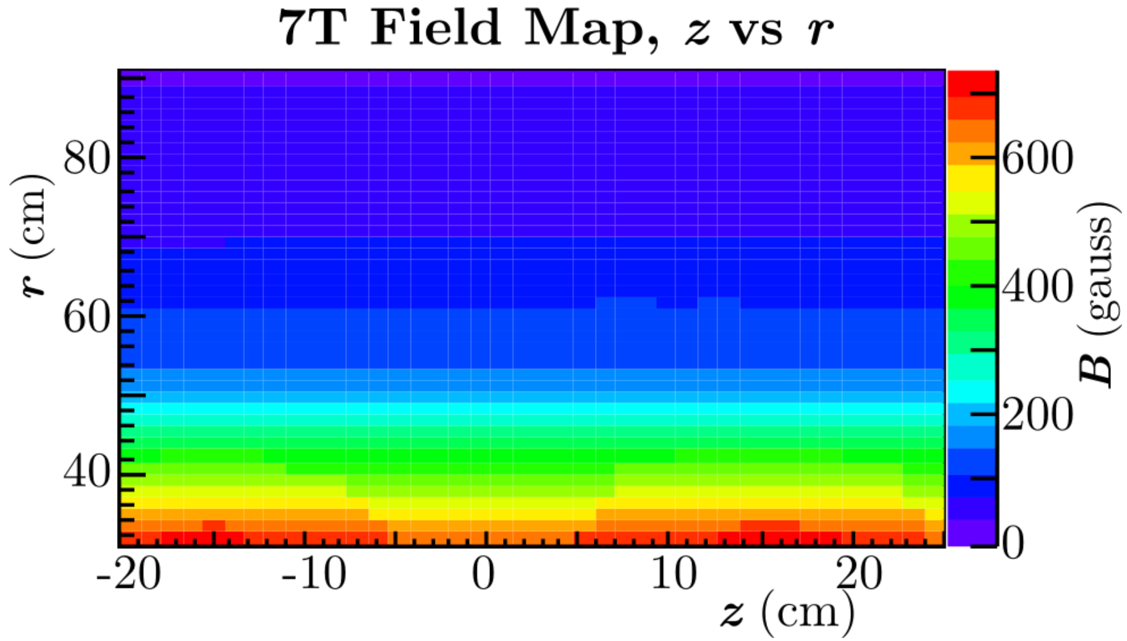
Target Development in Progress

- UVa Target Lab has successfully polarized deuterated butanol in April



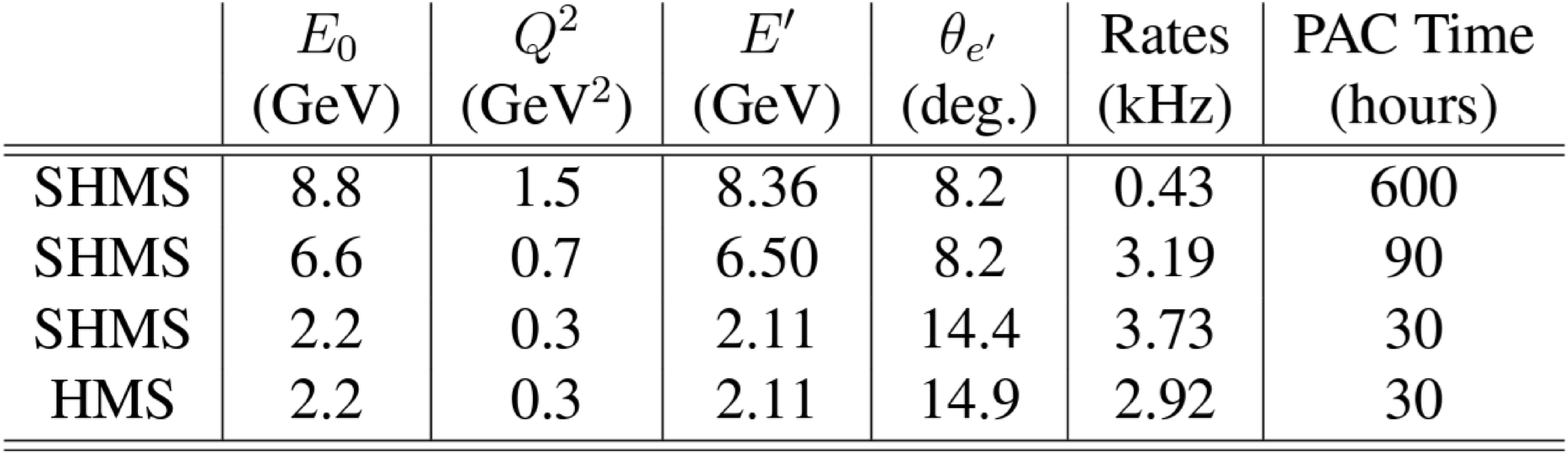
Courtesy of D. Keller

- UNH Target Lab is ramping up, first cool-down in January, successfully reached 7T



Experimental Details

- D(e,e’)X with 90nA beam current
- Same equipment as C1-approved b_1 (E12-13-011) experiment



	E_0 (GeV)	Q^2 (GeV^2)	E' (GeV)	$\theta_{e'}$ (deg.)	Rates (kHz)	PAC Time (hours)
SHMS	8.8	1.5	8.36	8.2	0.43	600
SHMS	6.6	0.7	6.50	8.2	3.19	90
SHMS	2.2	0.3	2.11	14.4	3.73	30
HMS	2.2	0.3	2.11	14.9	2.92	30

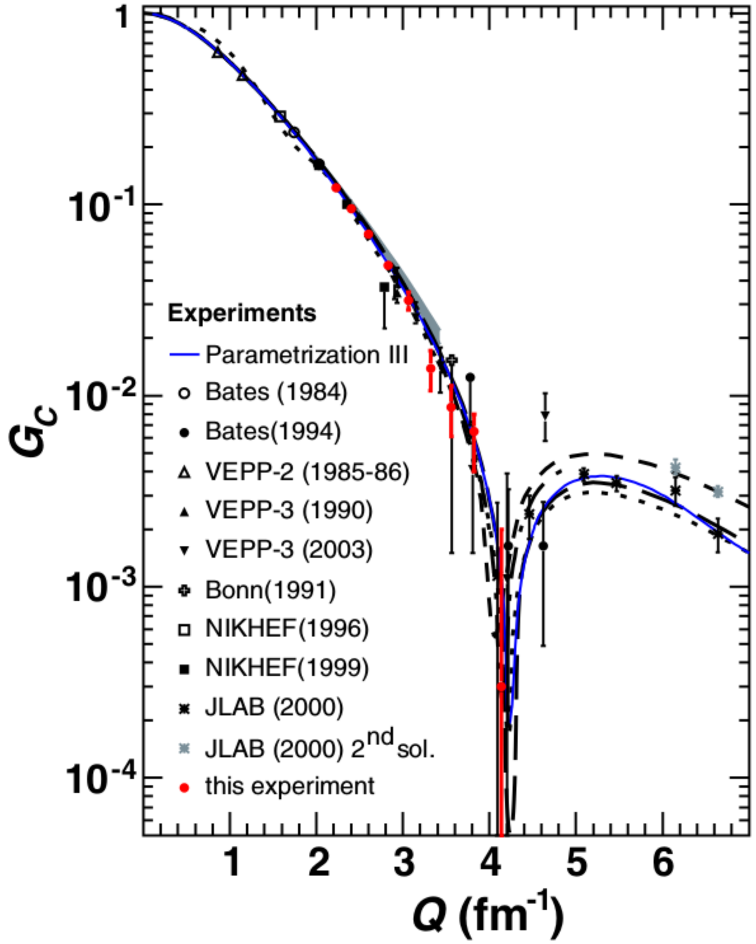
Elastic Tensor Observables

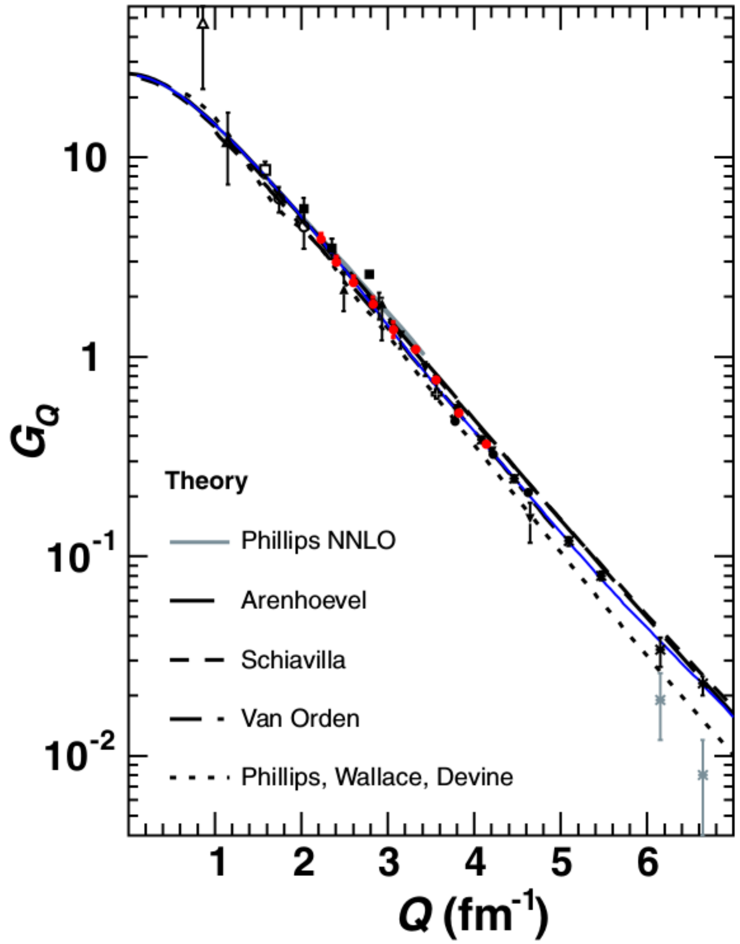
$Q = 7\ \text{fm}^{-1} \rightarrow Q^2 = 1.9\ \text{GeV}^2$

$$A = G_C^2 + \frac{2}{3}\eta G_M^2 + \frac{8}{9}\eta^2 G_Q^2$$

$$B = \frac{4}{3}\eta(1+\eta)G_M^2$$

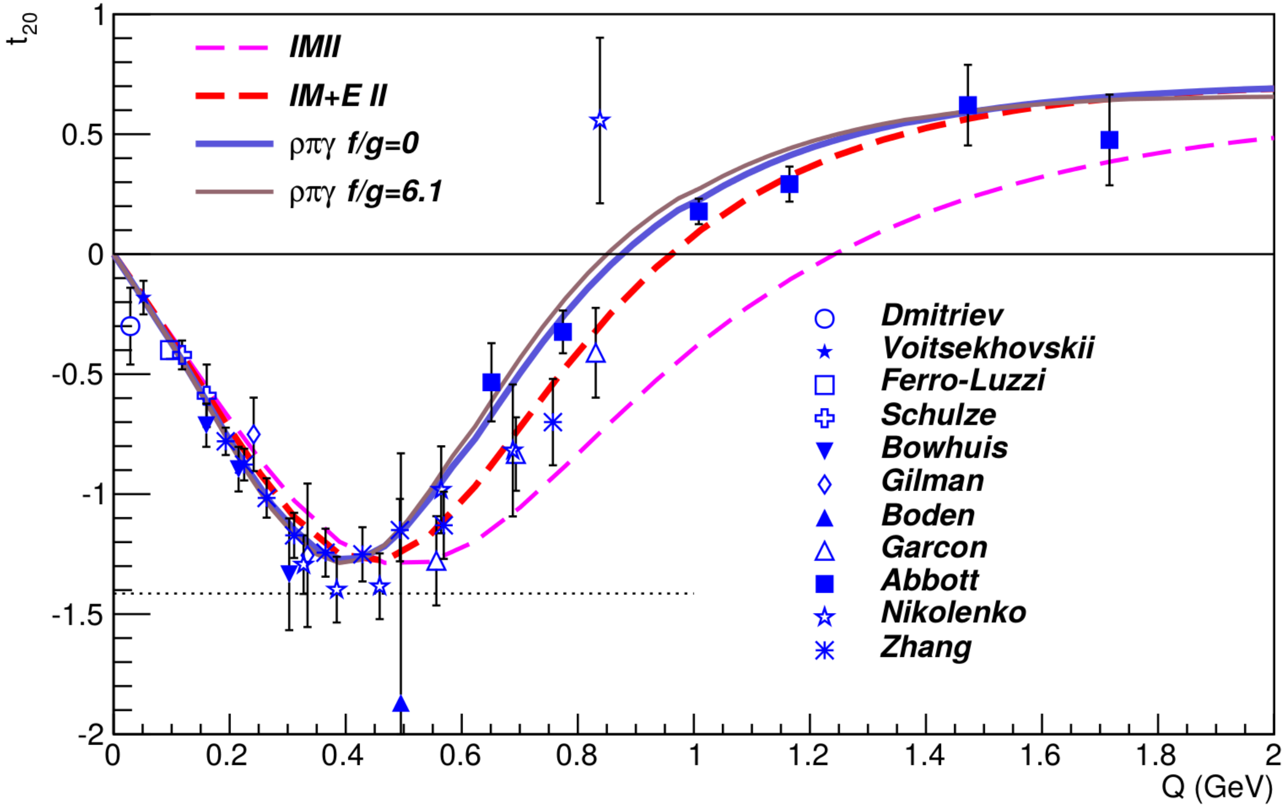
$$T_{20} = -\frac{\frac{8}{9}\eta^2 G_C^2 + \frac{8}{3}\eta G_C G_Q}{\sqrt{2}\left[A + B\tan^2\left(\frac{\theta}{2}\right)\right]} + \frac{\frac{2}{3}\eta G_M^2\left[\frac{1}{2} + (1+\eta)\tan^2(\theta/2)\right]}{\sqrt{2}\left[A + B\tan^2\left(\frac{\theta}{2}\right)\right]}$$



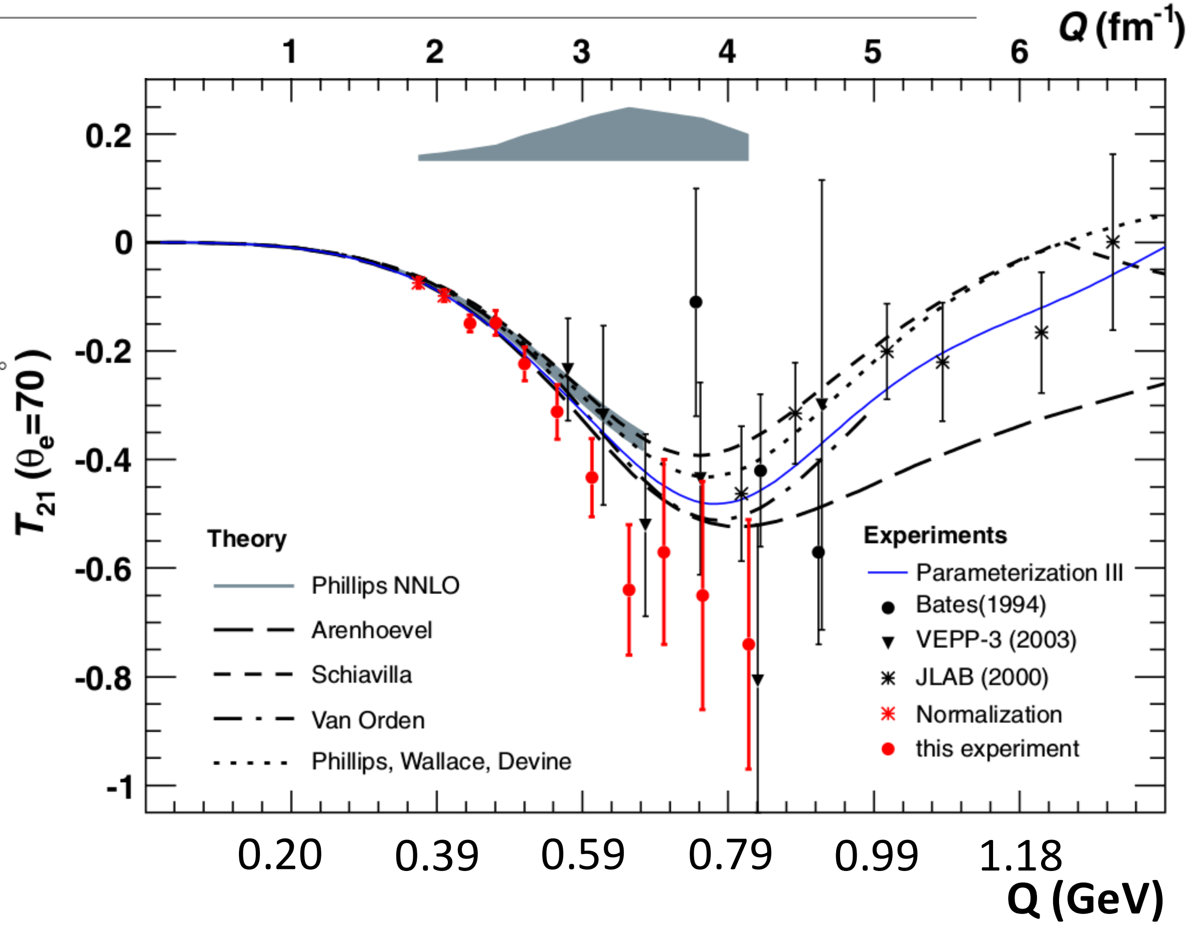


RJ Holt, R Gilman, Rep. Prog. Phys. **75** 086301 (2012)

Elastic Tensor Observables

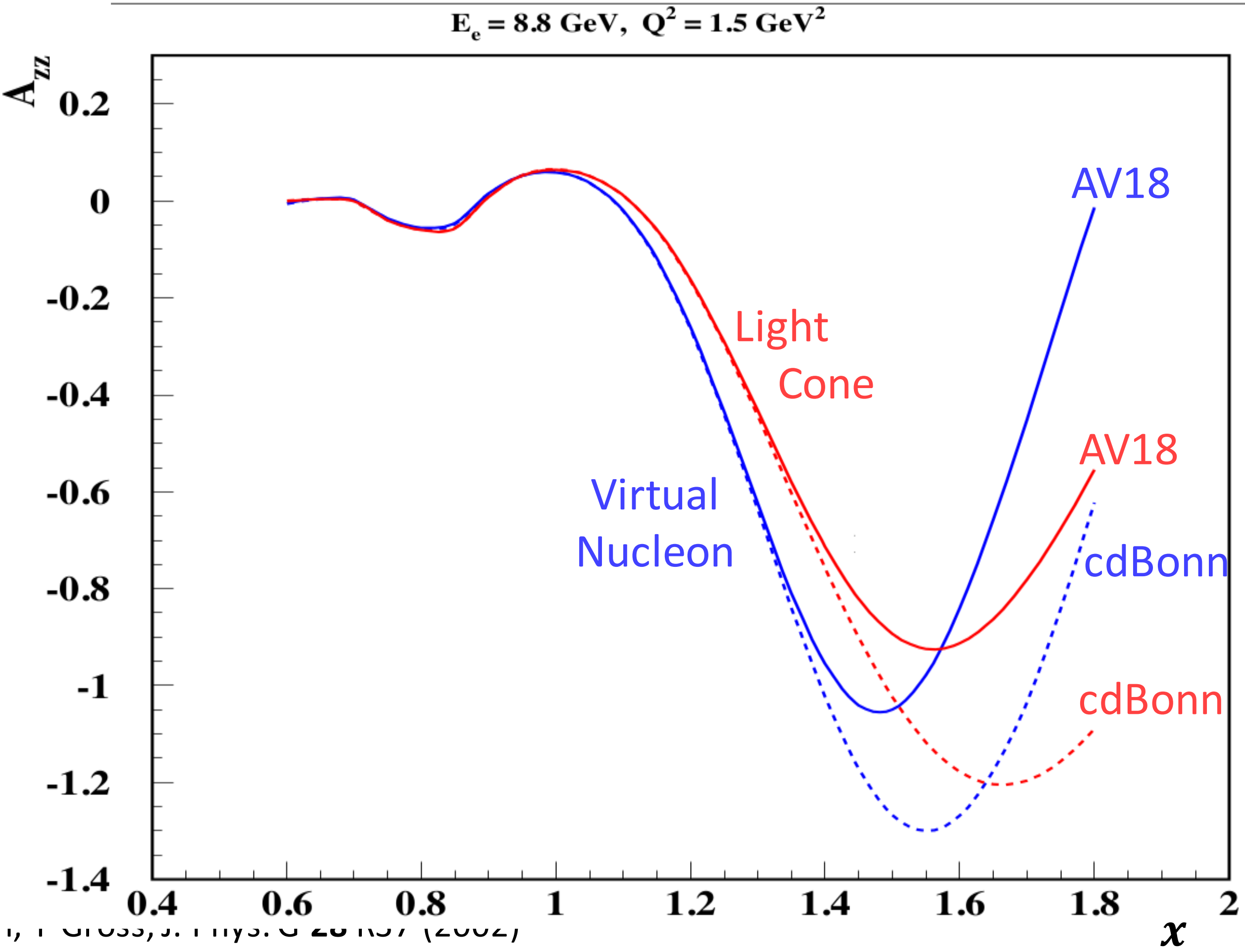


RJ Holt, R Gilman, Rep. Prog. Phys. **75** 086301 (2012)



C Zhang, *et al*, PRL **107** 252501 (2011)

Quasi-Elastic A_{zz}



R Gilman, F Gross, J. Phys. G 28 R37 (2002)

- Repeat same experiment, only look at A_{zz} in the quasi-elastic region
  - DIS → $b_1 \propto F_1 A_{zz}$; QE → A_{zz}; Elastic → $T_{20} \propto A_{zz}$
- Can give insight to short range deuteron structure

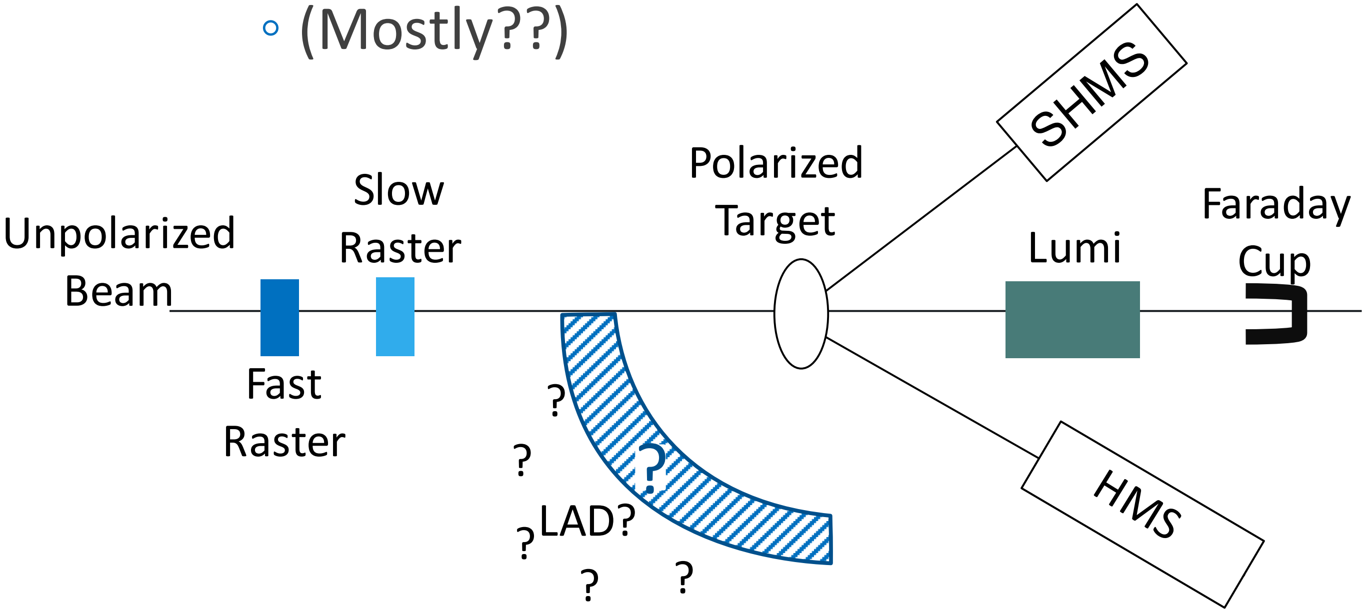
$$A_{zz} = \frac{2}{f \cdot P_{zz}} \left(\frac{N_{Pol}}{N_u} - 1 \right)$$

$$A_{zz} \propto \frac{\frac{1}{2} w^2 - uw\sqrt{2}}{u^2 + w^2}$$

M Sargsian, M Strikman, J. Phys.: Conf. Ser. **543**, 012099 (2014)
L. Frankfurt, M. Strikman, Phys. Rept. **160** 235 (1988)

Quasi-Elastic A_{zz} Experimental Set-Up

- Hall C
- Identical equipment as b_1 (E12-13-011)
- (Mostly??)


Unpolarized Beam

Fast Raster

Slow Raster

Polarized Target

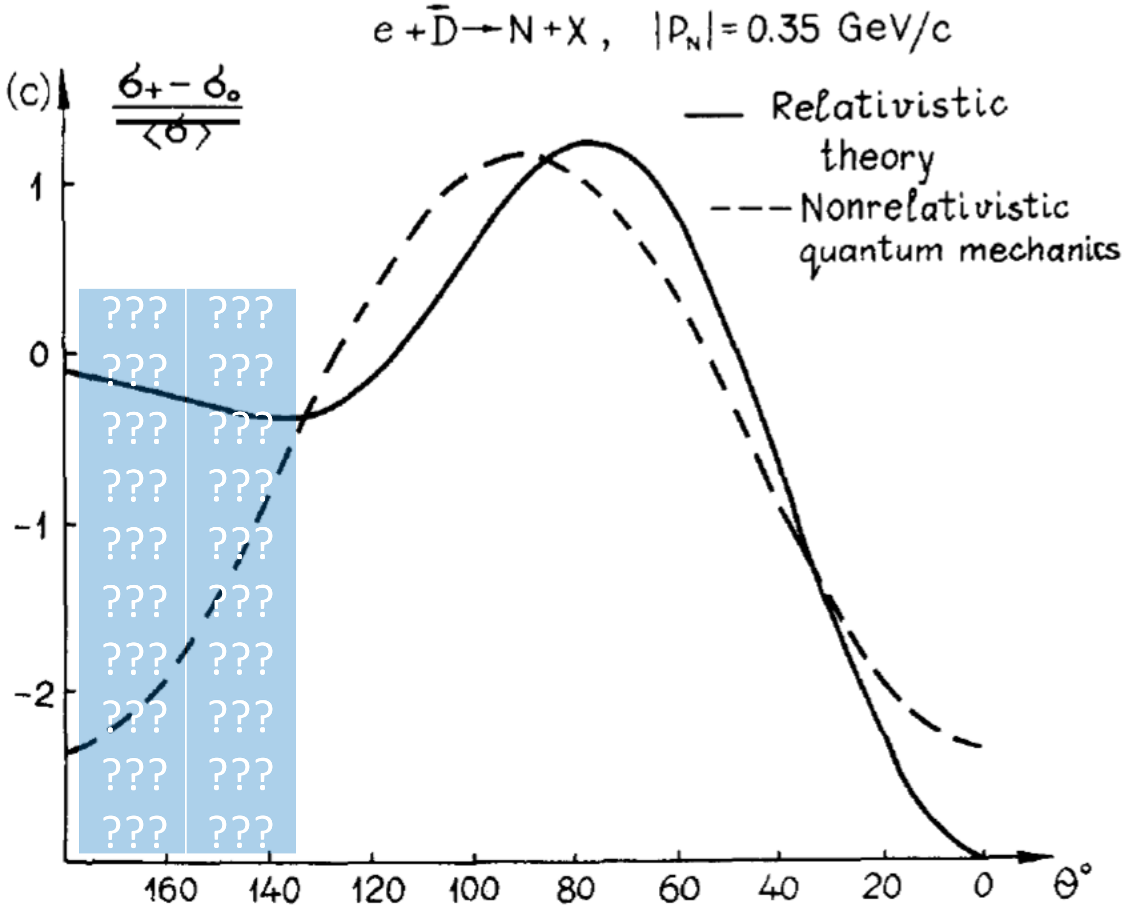
SHMS

HMS

Lumi

Faraday Cup

LAD?



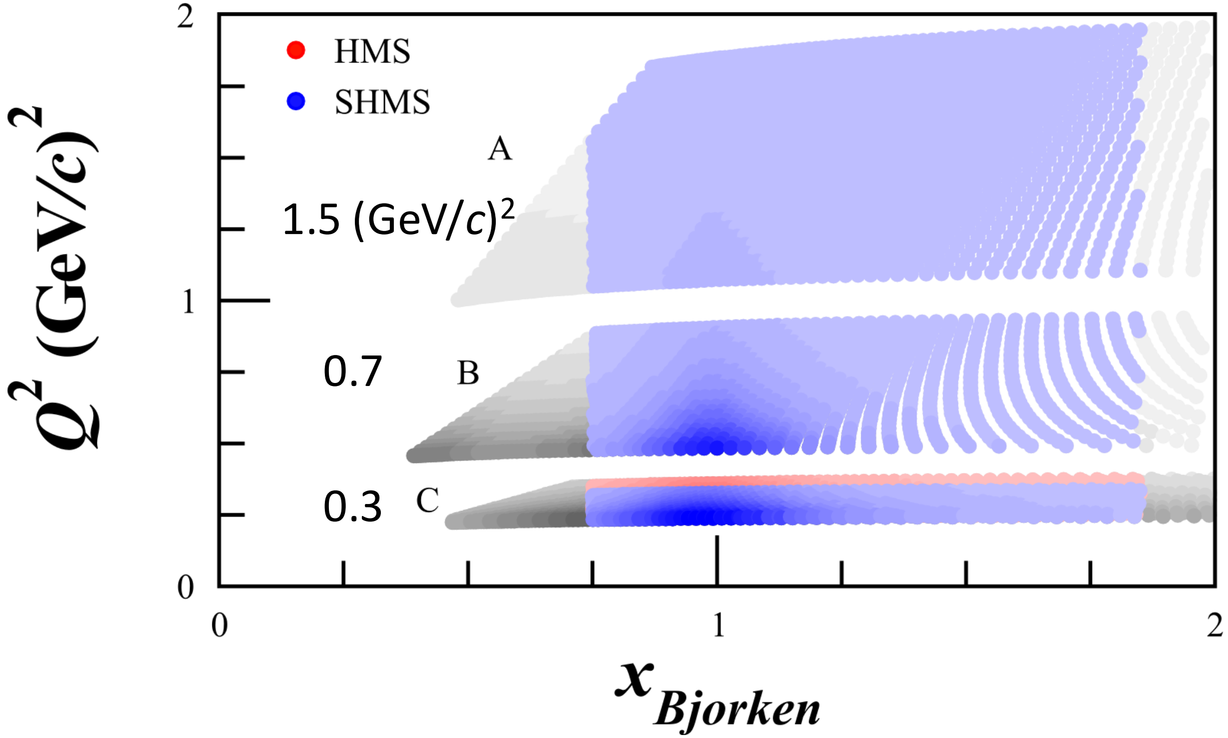
L. Frankfurt, M. Strikman, Phys. Rept. **160** 235 (1988)

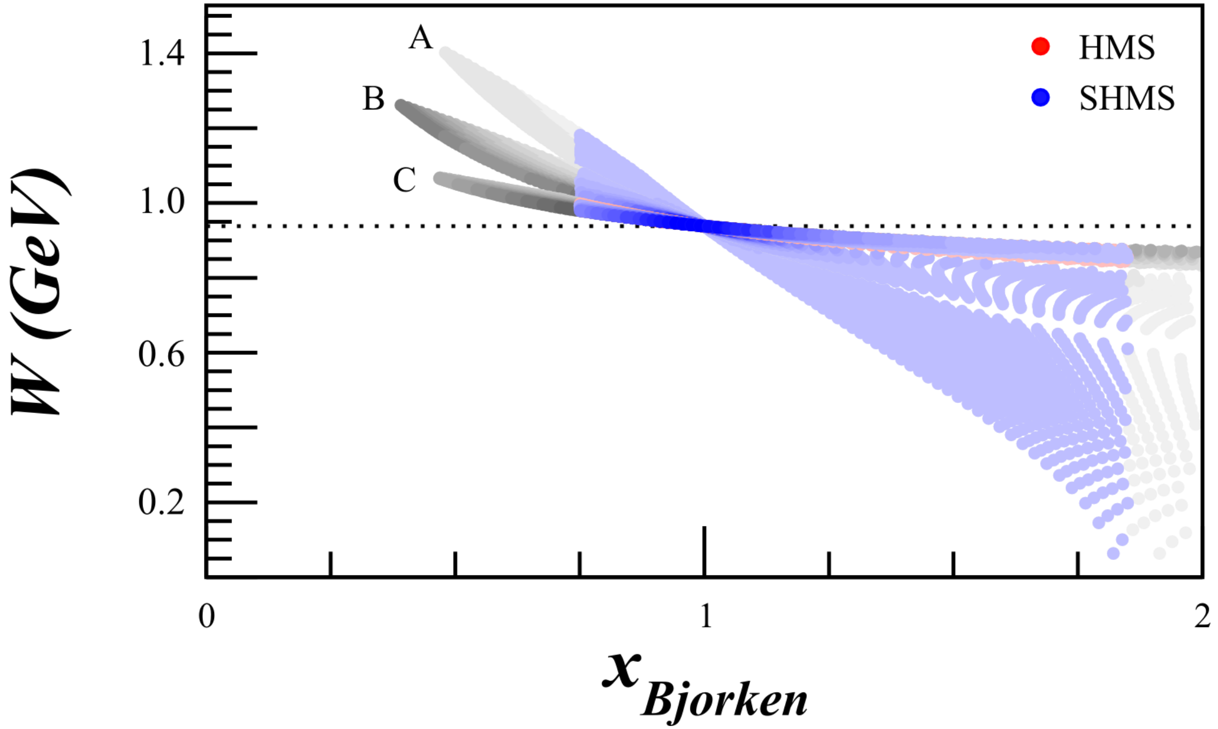
Kinematics

$I = 90$ nA

$\mathcal{L}_D = 1.3 \times 10^{35}\ \mathrm{cm^{-1}s^{-1}}$

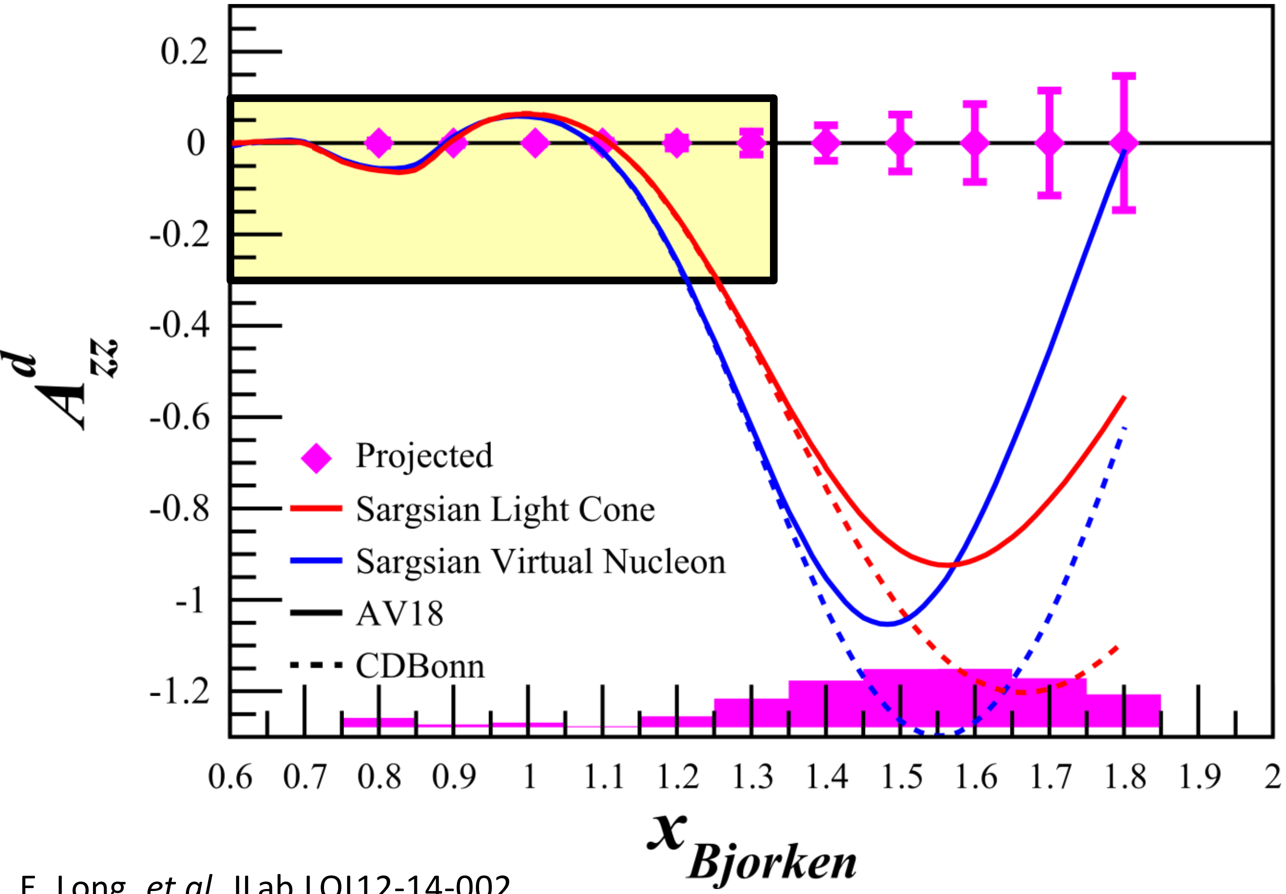
		E_0 (GeV)	Q^2 (GeV^2)	E' (GeV)	$\theta_{e'}$ (°)	Rates (kHz)	PAC Time (Days)
A	SHMS	8.8	1.5	8.36	8.2	0.43	25
B	SHMS	6.6	0.7	6.50	8.2	3.19	3.75
C	SHMS	2.2	0.3	2.11	14.4	3.73	1.25
	HMS	2.2	0.3	2.11	14.9	2.92	1.25

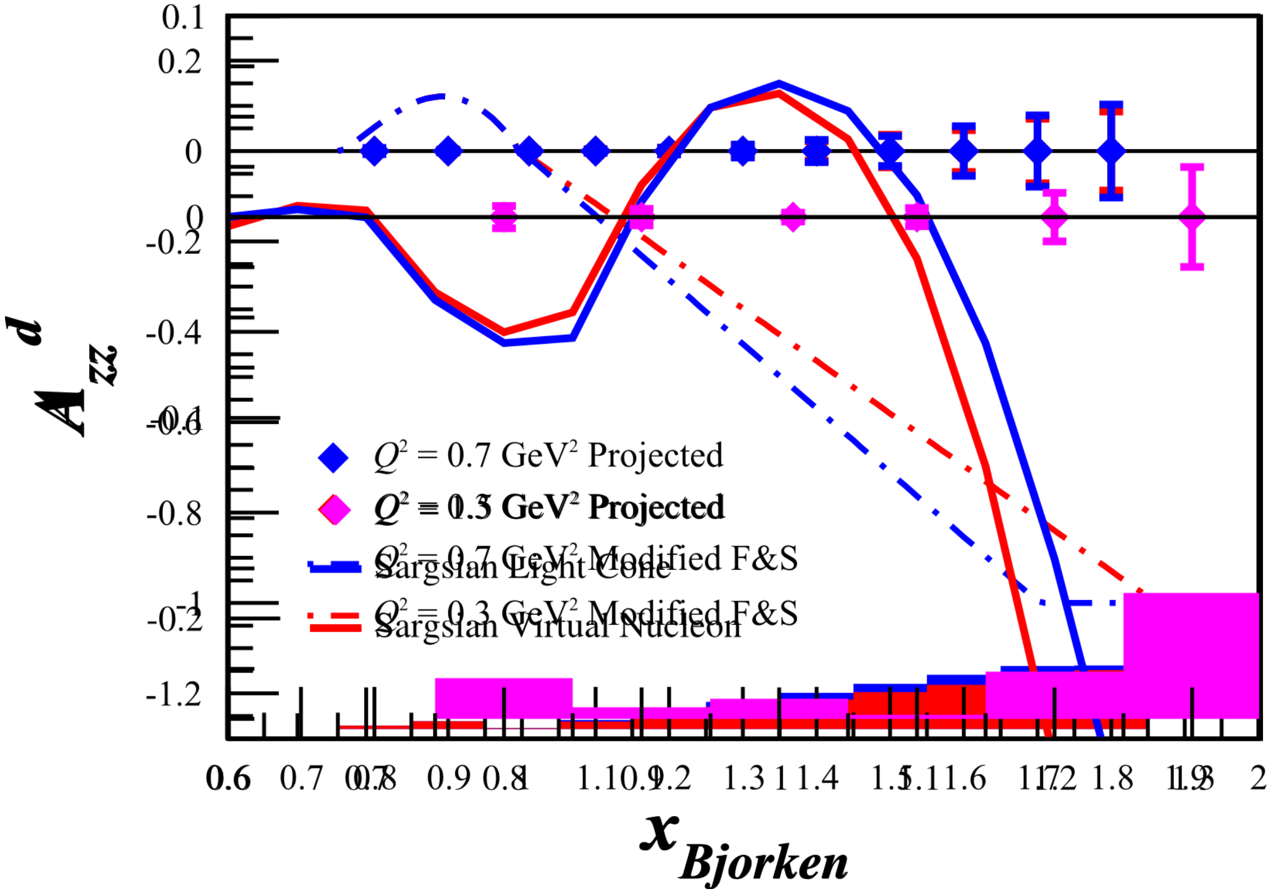




E. Long, *et al*, JLab LOI12-14-002

Quasi-Elastic A_{zz}

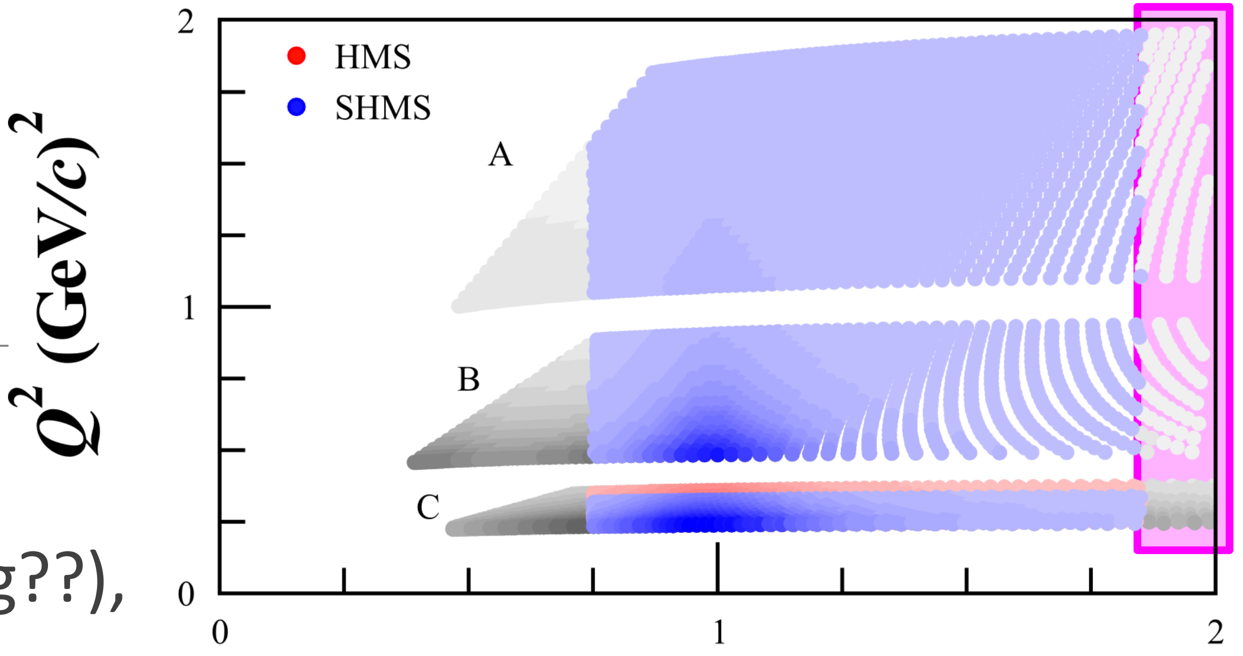


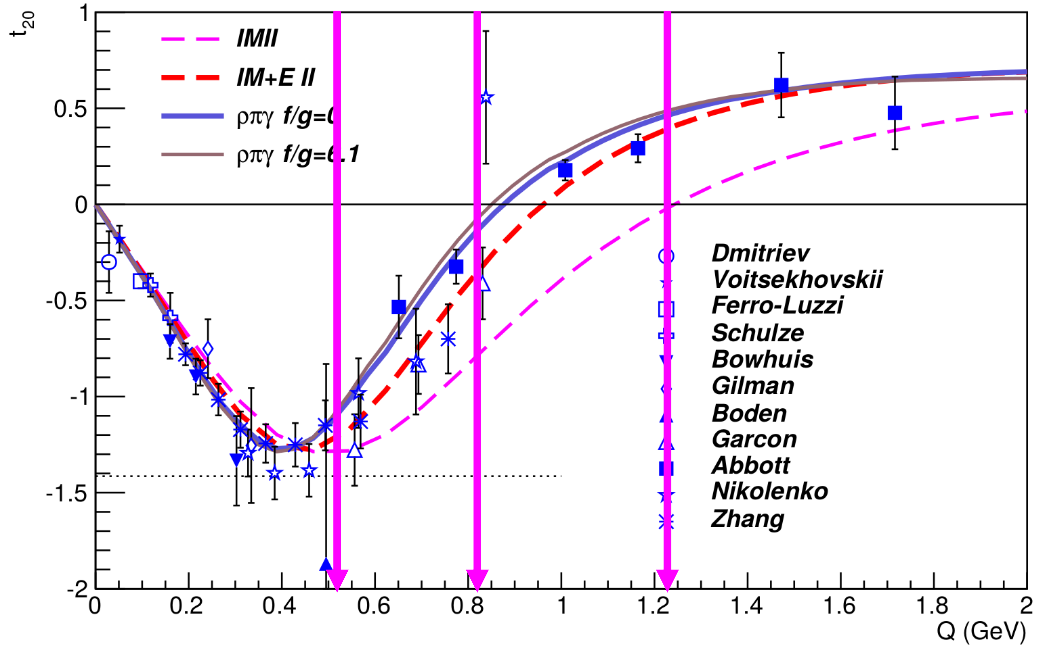


E. Long, *et al*, JLab LOI12-14-002

Quasi-Elastic A_{zz}

- Very large asymmetry
- Identical equipment as b_1 (?? + tagging??), less dependent on systematics
- Direct access to the tensor component of the deuteron, which is necessary to understand SRC
- Potential for parasitic T_{20} measurement
  - Can also be used to calibrate target polarization at low Q^2

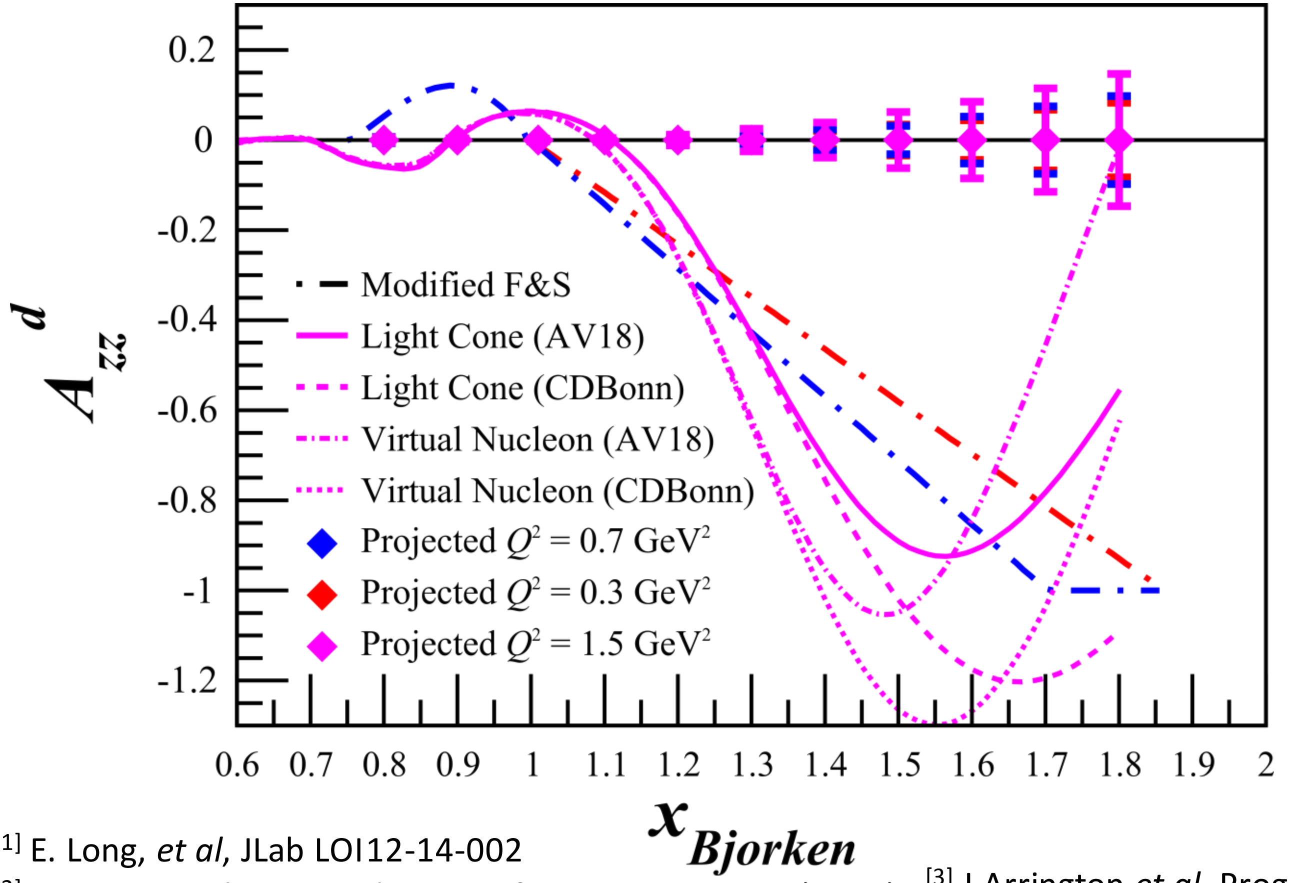




E. Long, *et al*, JLab LOI12-14-002

RJ Holt, R Gilman, Rep. Prog. Phys. **75** 086301 (2012)

Quasi-Elastic A_{zz}



First measurement of quasi-elastic A_{zz} will give insight into:

- SRCs & pn dominance[3]
- Differentiate light cone and VN models[1,2]
- Better understanding of deuteron wf[4]
- Final state interaction models[5]

[1] E. Long, *et al*, JLab LOI12-14-002

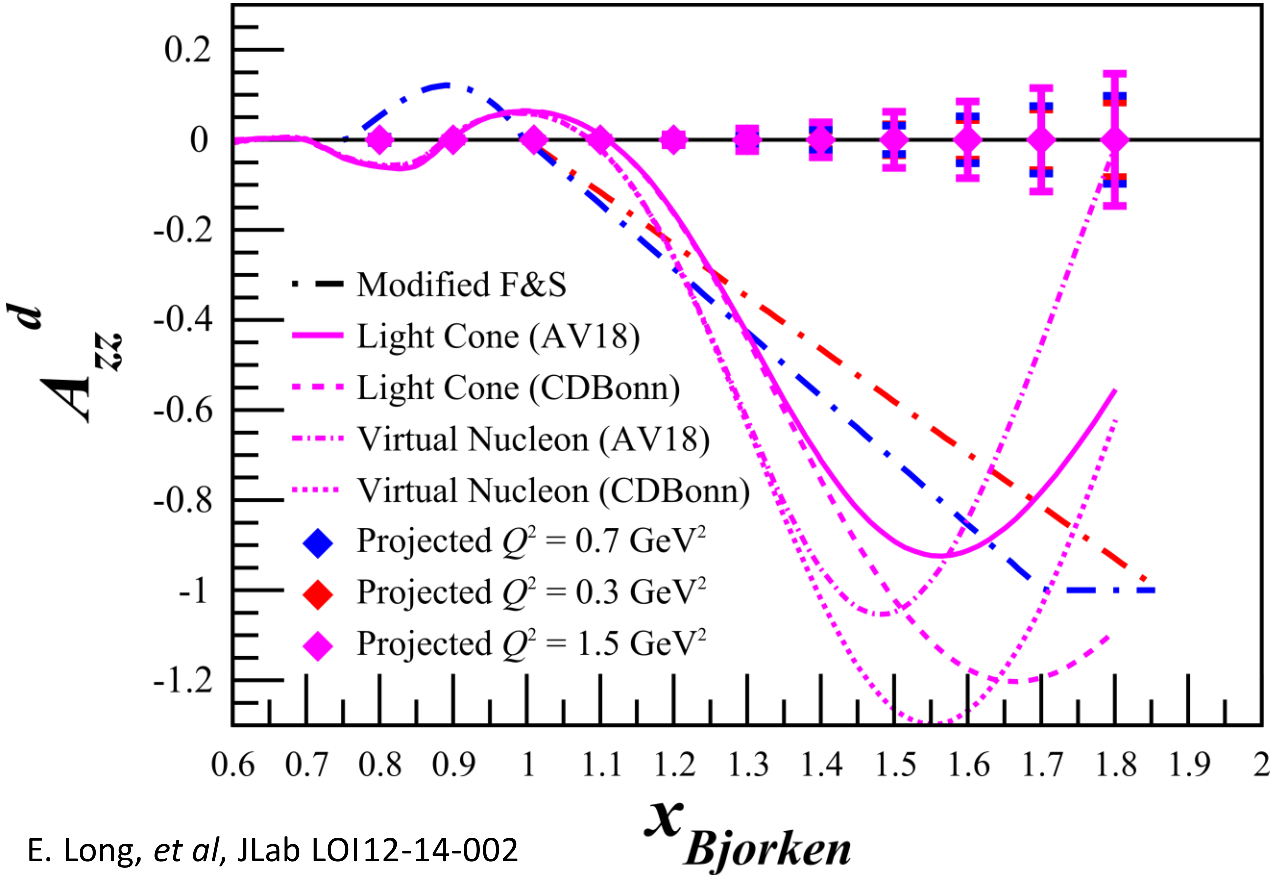
[2] Sargsian, Strikman, J. Phys.: Conf. Ser. **543**, 012099 (2014)

[3] J Arrington *et al*, Prog. Part. Nucl. Phys. **67,** 898 (2012)

[4] L Frankfurt, M Strikman, Phys. Rept. **160,** 235

[5] W Cosyn, M Sargsian, arXiv:1407.1653

Quasi-Elastic A_{zz}



E. Long, *et al*, JLab LOI12-14-002

Sargsian, Strikman, J. Phys.: Conf. Ser. **543**, 012099 (2014)

Encouraged for full submission by PAC42

“The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range *pn* correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program.”

-JLab PAC42 Theory Advisory Committee