Novel Physics
with
Tensor Polarized Deuteron Targets

PSTP 2013
K. Slifer, UNH
Sept 9, 2013

This Talk

Brief Review of Tensor Polarization

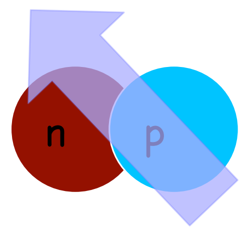
Overview of the Jefferson Lab b1 experiment (E12-13-011)

- All Conventional Models predict b1 small or vanishing at moderate x
- The Large values of b_1 observed at Hermes would indicate exotic effects if confirmed
- RF Hole Burning looks quite promising to reach high values of P_{zz}
- R&D planned to develop this and other techniques

Tensor Polarized Target opens many new avenues of research at JLab

- b_2, b_3, b_4
- A_{xx}
- T_{20}, T_{11}
- Q.E. / x>1
- Semi-Inclusive & Exclusive measurements of the Deuteron Wave Function

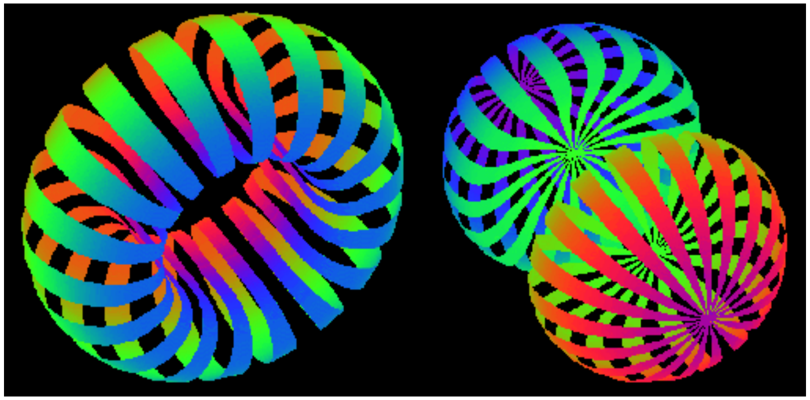
Deuteron



Spin-1 system

Simple testing ground for nuclear physics
Reasonably "easy" to polarize

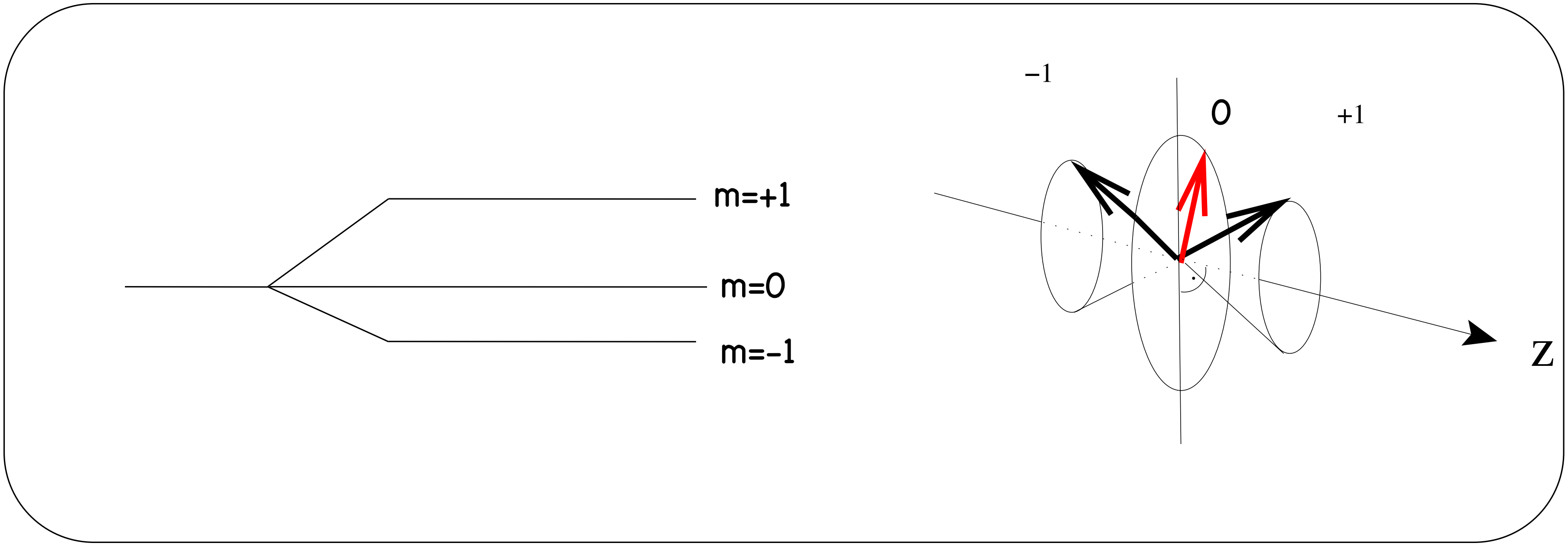
Spatial distribution depends on the spin state



M = 0 M = ±1

Spin-1 System

Spin-1 in B-field leads to 3 Zeeman sublevels



<u>Vector Polarization</u> P_z : $(n^+ - n^-)$ $(-1 < P_z < +1)$

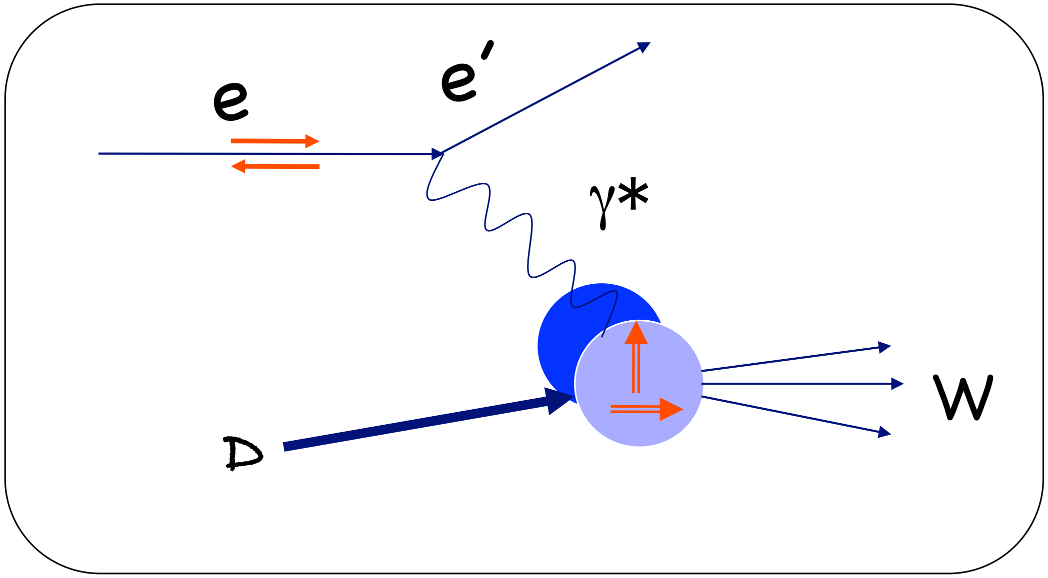
and

<u>Tensor polarization</u> P_{zz} : $(n^+ - n^0) - (n^0 - n^-)$ $(-2 < P_{zz} < +1)$

<u>Normalization</u>

$(n^+ + n^- + n^0) = 1$

Inclusive Scattering



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

Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

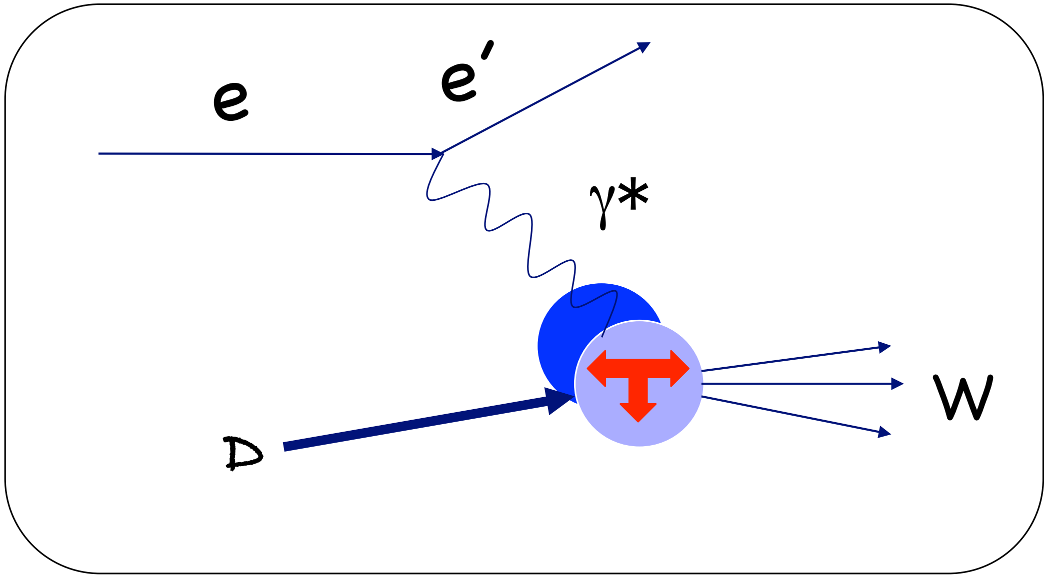
$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu}$$

Unpolarized Scattering

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

Vector Polarization

Inclusive Scattering



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

Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

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

} Tensor Polarization

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

F_1 : quark distributions averaged over target spin states
g_1 : difference of distributions of quarks aligned/anti-aligned with hadron
b_1 : difference of helicity-0/helicity non-zero states of *the deuteron*

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

F_1 : quark distributions averaged over target spin states
g_1 : difference of distributions of quarks aligned/anti-aligned with hadron
b_1 : difference of helicity-0/helicity non-zero states of *the deuteron*

---

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

b_1 Structure Function

Focus on b_1 in this experiment:

Leading twist

Simplest to access experimentally.

Probe the tensor polarization of the sea quarks.

Signature of "exotic" effects in nuclei.
i.e. deviation of deuteron from a simple system of two bound nucleons.

b_1 Structure Function

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

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

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

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

Nice mix of nuclear and quark physics

measured in DIS (so probing quarks), but depends solely on the deuteron spin state

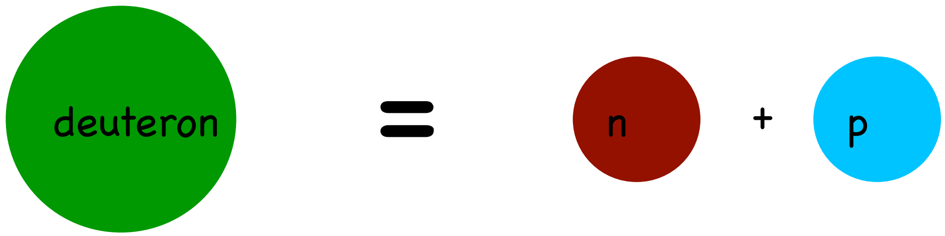
Investigate nuclear effects at the level of partons!

b_1 Structure Function

<u>Hoodbhoy, Jaffe and Manohar (1989)</u>

b_1 vanishes in the absence of nuclear effects

i.e. if...



Proton Neutron in relative S-state

Even accounting for D-State admixture <u>b_1 expected to be vanishingly small</u>

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

Close-Kumano Sum Rule

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

Satisfied for an unpolarized sea.

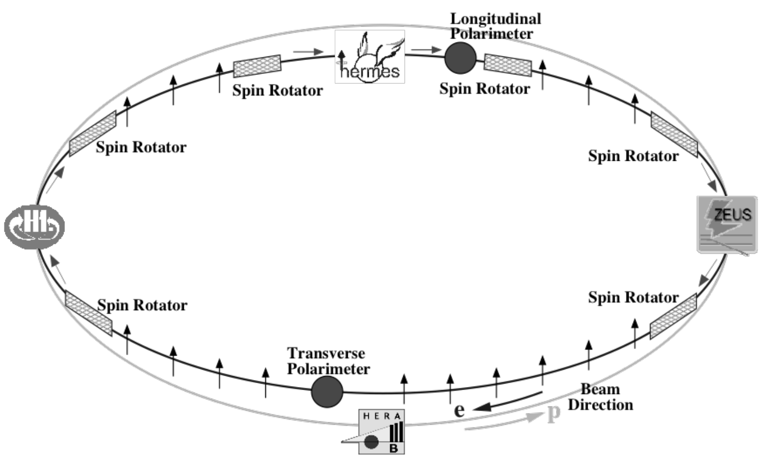
Deviations from zero : good signature of exotic effects in the Deuteron Wave Function.

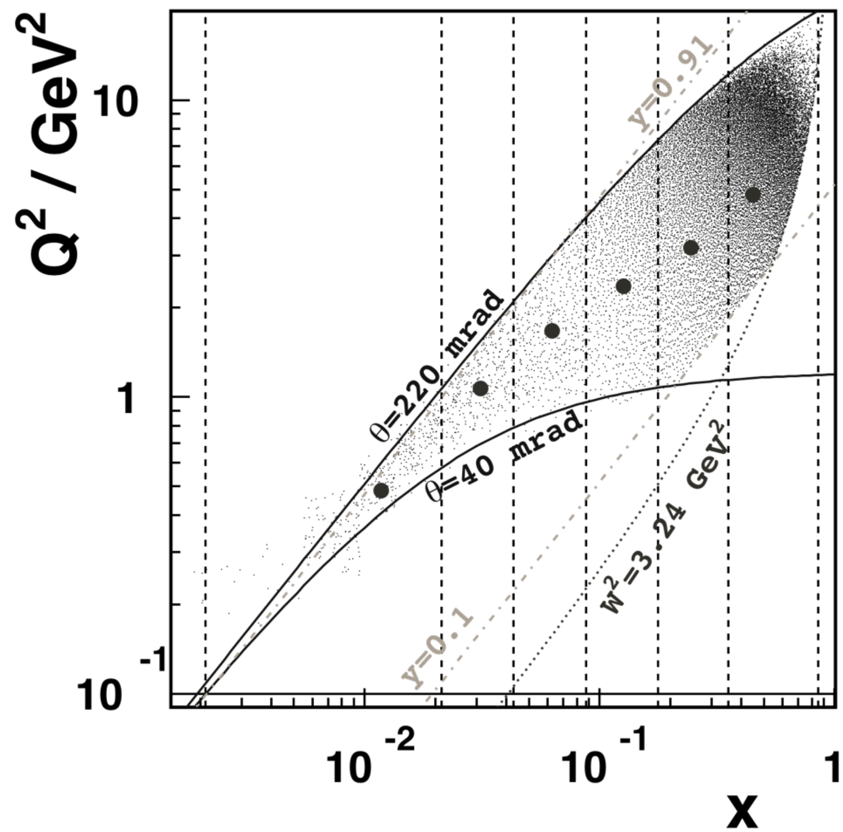
Khan & Hoodbhoy, PRC 44 ,1219 (1991) :
Relativistic convolution model with binding : $-6.7E10^{-4}$

Nikolaeva and Schafer, PLB 398, 245 (1997)

CK Sum Rule may be invalidated by divergence of b2 as $x \rightarrow 0$

Data from HERMES



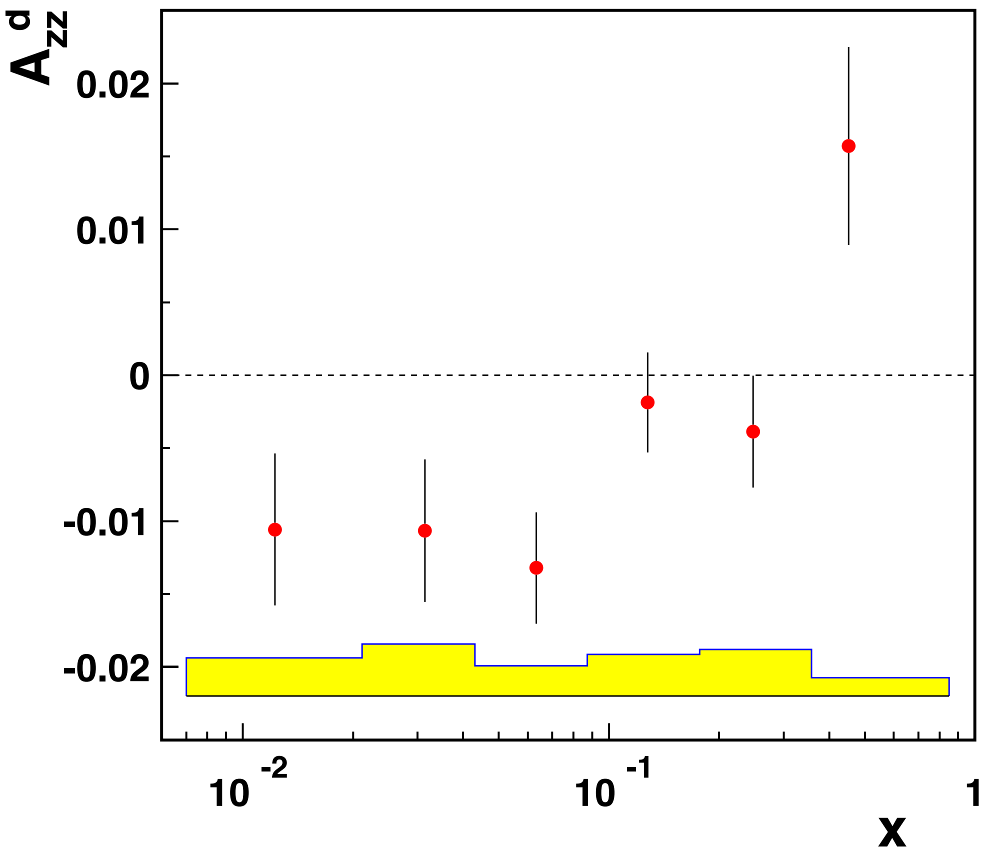


27.6 GeV positrons

Internal gas target

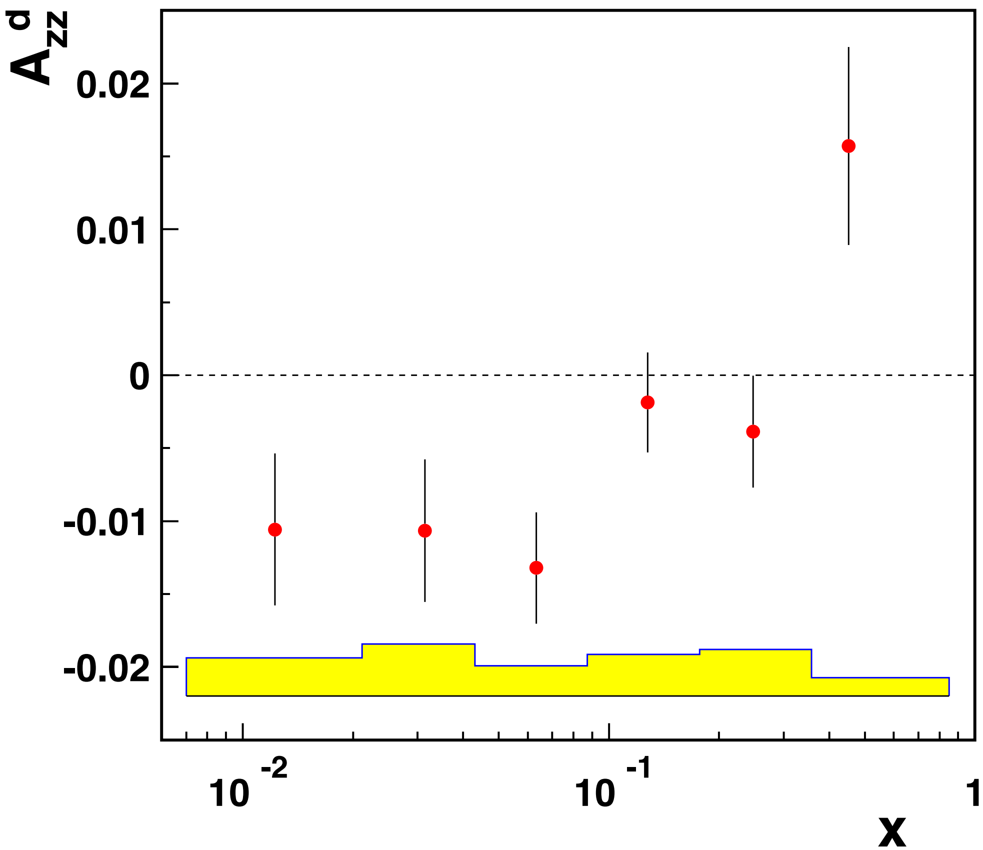
~Pure tensor polarization
with little vector component

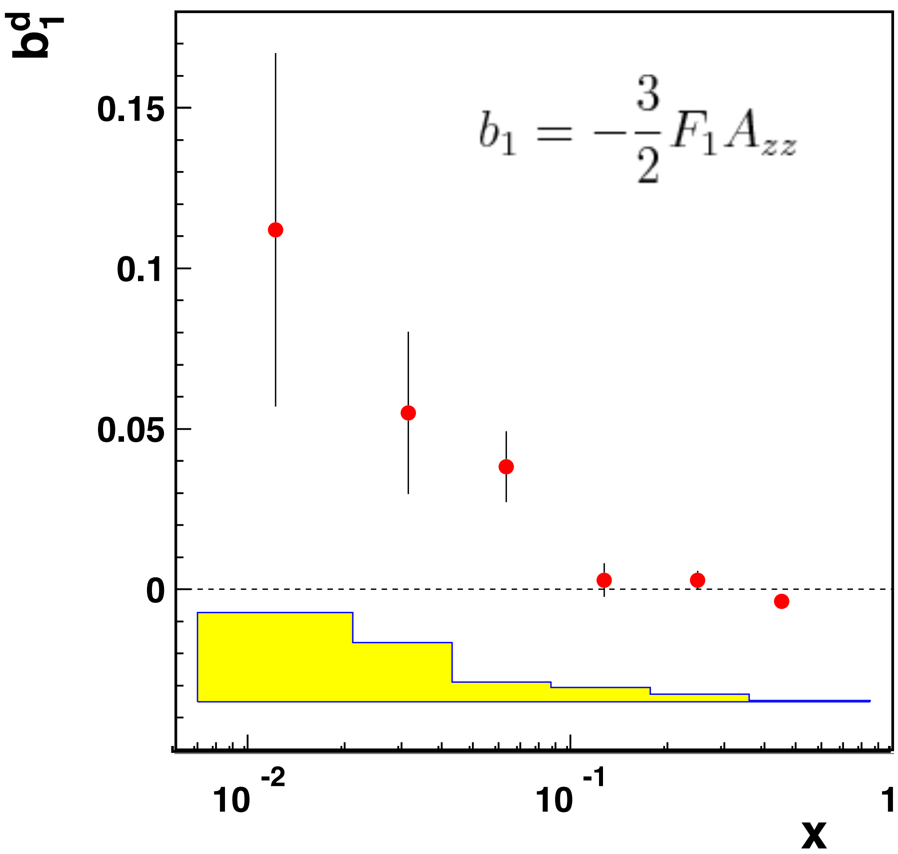
Data from HERMES



PRL **95**, 242001 (2005)

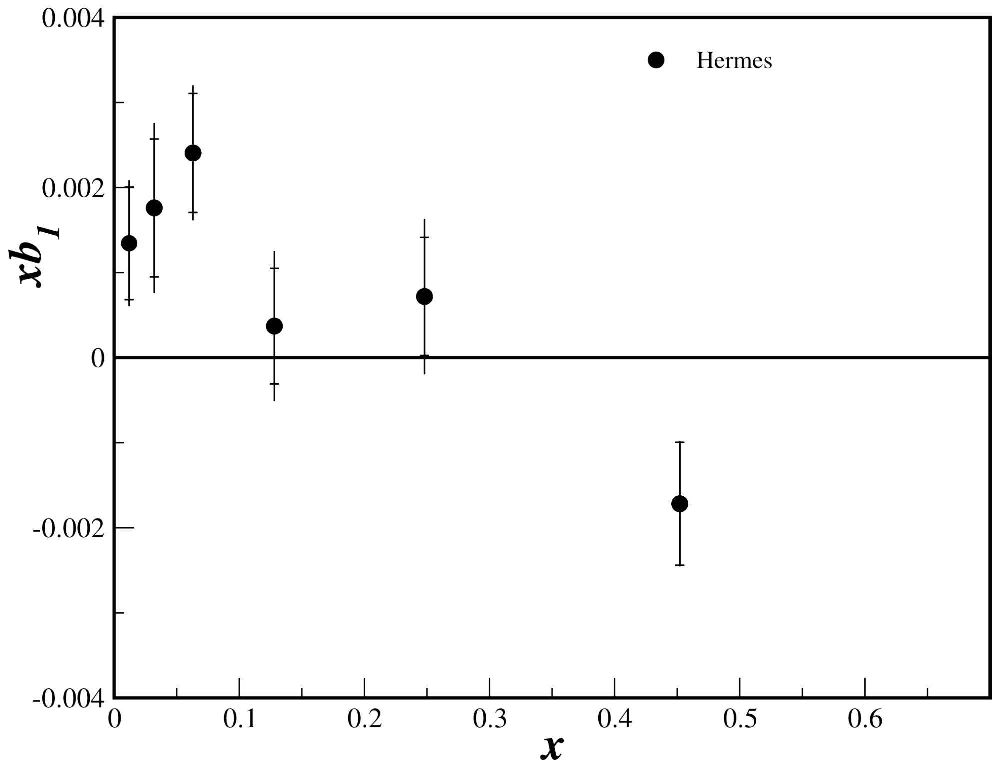
Data from HERMES





PRL **95,** 242001 (2005)

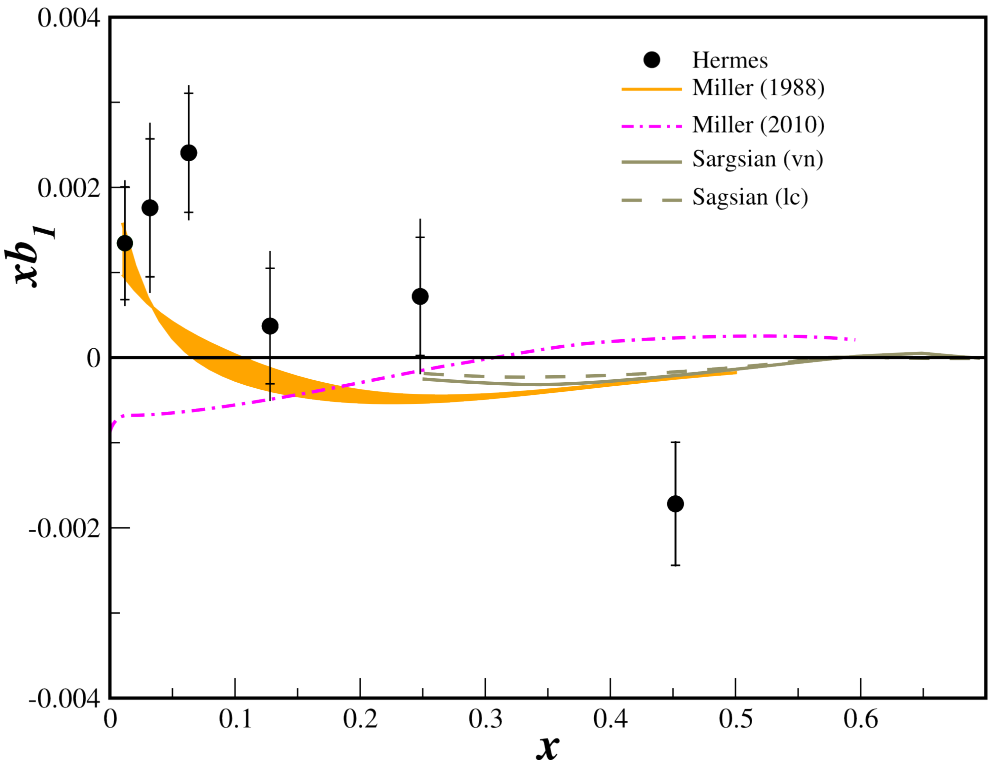
Data from HERMES



PRL **95,** 242001 (2005)

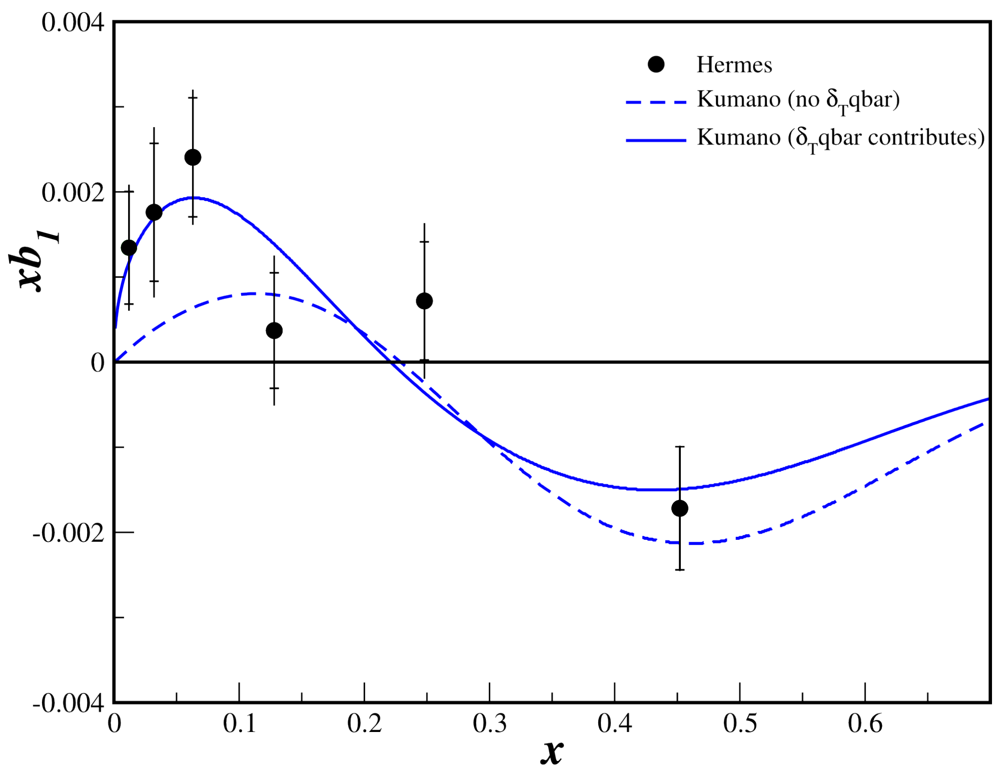
$$b_1 = -\frac{3}{2} F_1 A_{zz}$$

Model Predictions



All Conventional Models predict small or vanishing values of b1 in contrast to the HERMES data

Model Predictions



Kumano Fit to the Data

Requires tensor polarized sea for best fit.

Kumano Fit is constrained to agree with the HERMES data.

No other model shows such large effects.

Jefferson Lab E12-13-011

E. Long, K. Slifer (contact), P. Solvignon
University of New Hampshire

O. Rondon, D. Keller
University of Virginia

J.-P. Chen
Jefferson Lab

N. Kalantarians
Hampton University

A- rating from PAC40

30 production days + 11 overhead

(Conditional on target polarization)

b_1 Collaboration

K. Allada, A. Camsonne, *J.-P. Chen*, A. Deur,
D. Gaskell, M. Jones, C. Keith, C. Keppel, D. Mack,
J. Piece, *P. Solvignon*, S. Wood, J. Zhang
Jefferson Lab

T. Badman, J. Calarco, J. Dawson,
S. Phillips, *E. Long*, *K. Slifer*, R. Zielinski
University of New Hampshire

R. Gilman
Rutgers

J. Dunne, D. Dutta
Mississippi State University

E. Christy, P. Gueye, *N. Kalantarians,*
M. Kohl, P. Monaghan,
Hampton University

H. P .Cheng, H. J. Lu, X. H. Yan
Huangshan University

B. T. Hu, Y. Zhang
Lanzhou University

Caroline Riedl
DESY

O. Rondon Aramayo, D. Crabb, D. B. Day, C. Hanretty,
D. Keller, R. Lindgren, S. Liuti, B. Norum,
Zhihong Ye, X. Zheng
University of Virginia

W. Bertozzi, S. Gilad, J. Huang,
V. Sulkosky
MIT

G. Ron, A. Kelleher
Hebrew University of Jerusalem

K. Adhikari
Old Dominion University

Seonho Choi, Hoyoung Kang,
Hyekoo Kang, Yoomin Oh
Seoul National University

Y. X. Ye, P. J. Zhu
University of Science and Technology of China

Abdellah Ahmidouch
North Carolina A&T State University

Experimental Method

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

$$= \frac{2}{fP_{zz}} \left(\frac{N_{\dagger}}{N_0} - 1 \right)$$

Observable is the Normalized XS Difference

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

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

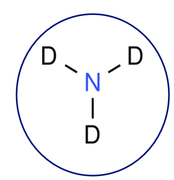
$\sigma_{\dagger}$: Tensor Polarized cross-section

σ_0 : Unpolarized cross-section

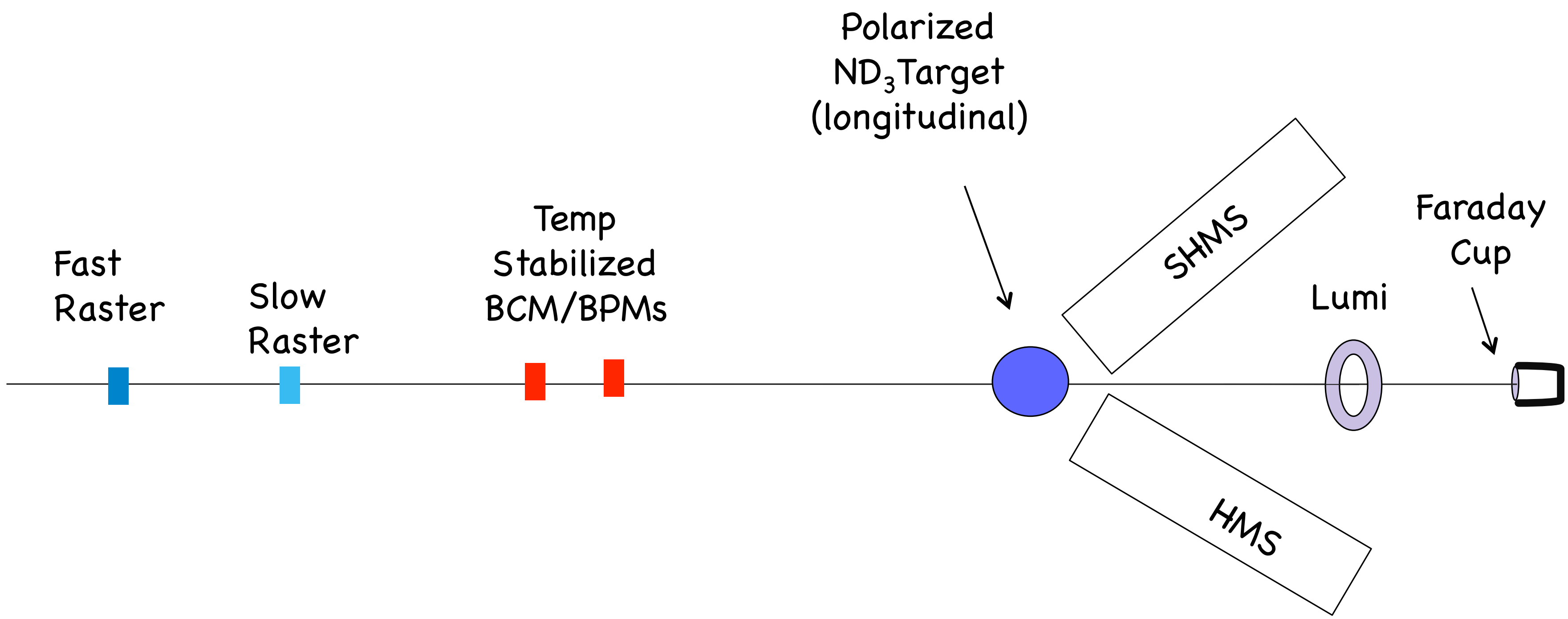
P_{zz} : Tensor Polarizzation

dilution factor

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



Hall C



Unpolarized Beam : 115 nA

UVa/JLab Polarized Target

$\mathcal{L}=10^{35}$

Magnetic Field Held Along Beam Line at all times

Technically Challenging Experiment

I) Systematics

TAC : Important to control measured false asymmetries to better than 6×10^{-4}.

TAC : *"We believe this is possible with a combination of upgrades to Hall C infrastructure and sufficient commitment by the collaboration to control the unusual systematic issues of this experiment."*

II) Development of Large Tensor Polarizations

1) **Incremental** : Higher B field (7.55T, 212 GHz), better fridge, pumps, tempering, FM'ing.

2) **RF Saturation** : Has been demonstrated to produce large P_{zz} (30%).
For full saturation $P_{zz} \approx P_z$, so range of expectation is about 20-50%.

3) **Additional Microwave Source**: No theoretical limit to P_{zz}, but expensive and unproven.

4) **Adiabatic Fast Passage** : Potential to reduce flip times, and also attain higher P_{zz}

Polarized Target

Dynamic Polarization of ND_3

5 Tesla

3 cm target length, 2 cm diameter

Longitudinally polarized

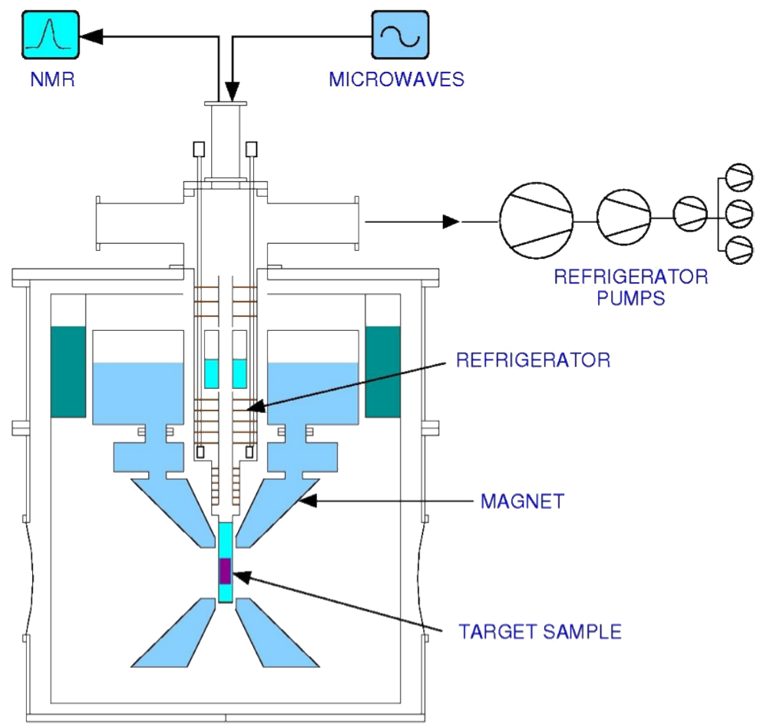


fig. courtesy of C. Keith

<u>Run in Polarized and Unpolarized Mode.</u>

B Field held at const value for both states

LHe level, temp. etc. held const for both states

Polarized Target

Dynamic Polarization of ND_3

5 Tesla

3 cm target length, 2 cm diameter

Longitudinally polarized

See Dustin Keller's Talk

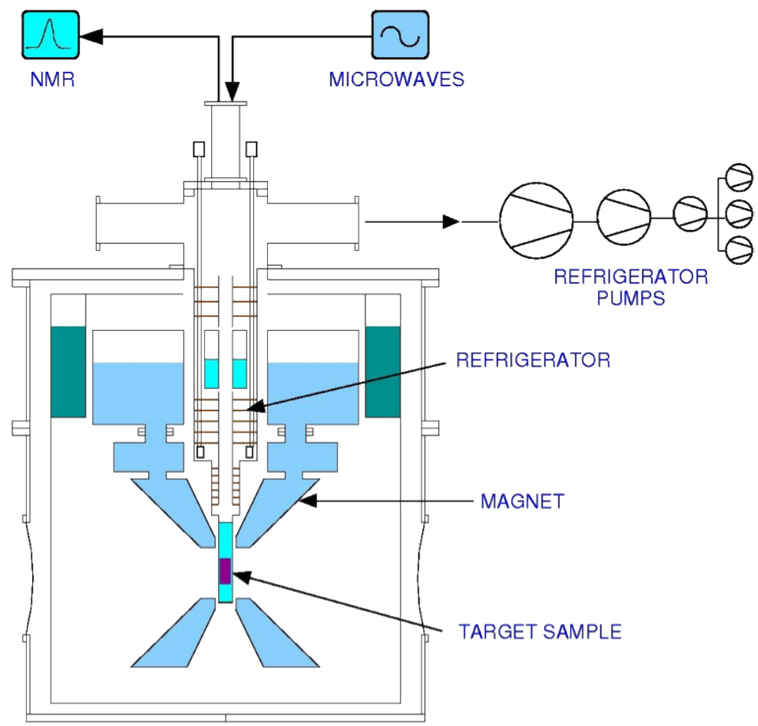


fig. courtesy of C. Keith

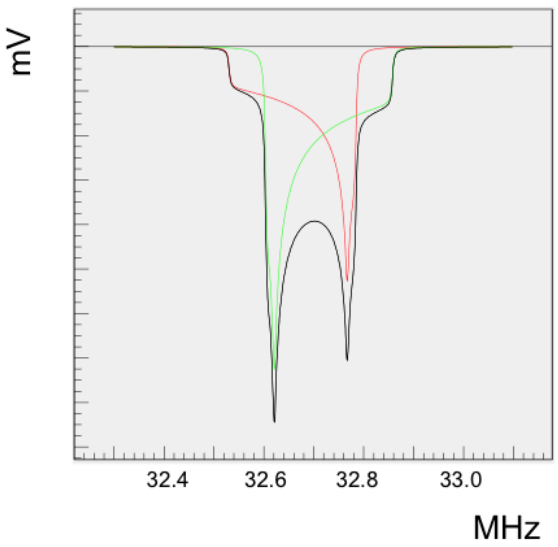
Run in Polarized and Unpolarized Mode.

B Field held at const value for both states

LHe level, temp. etc. held const for both states

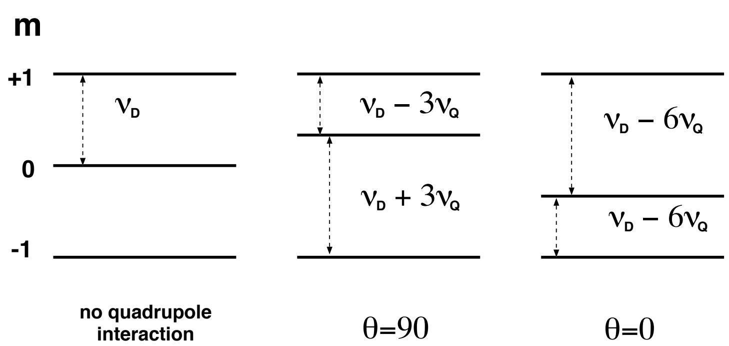
RF Saturation to Enhance P_{zz}

ND_3 Vector polarized



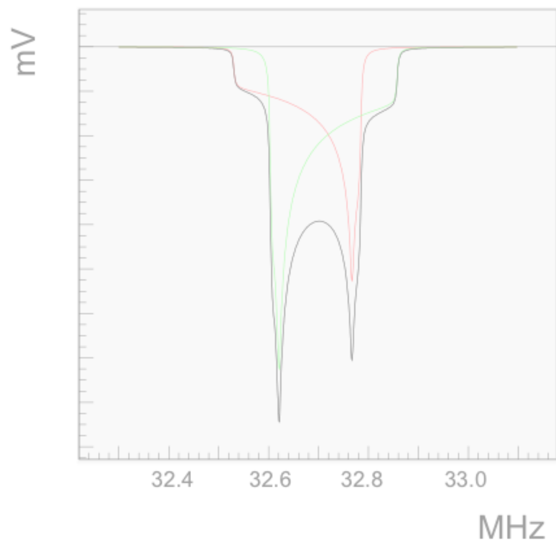
Vector Polarization ∝ Sum of Peak Areas

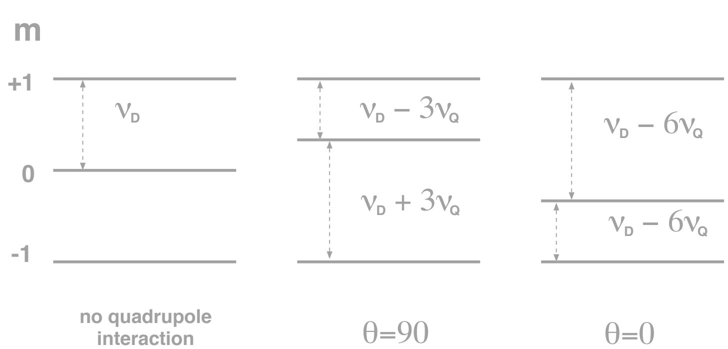
Tensor Polarization ∝ Diff of Peak Areas



RF Saturation to Enhance P_{zz}

ND_3 Vector polarized



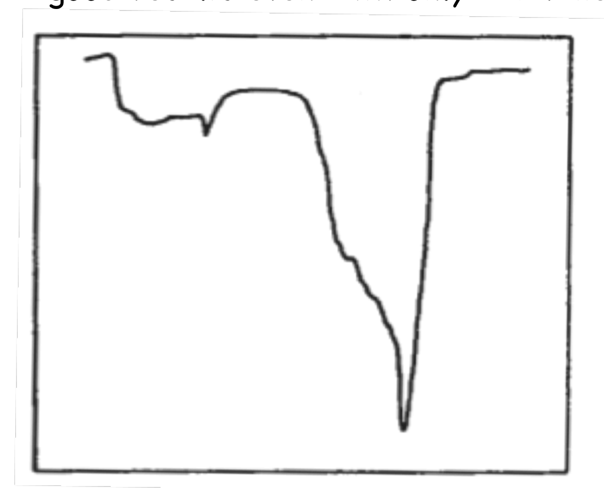


<u>RF Saturate one of the peaks</u>

kill the m=0 <=> m=-1 transition, which enhances the m=1 <=> m=0 transition

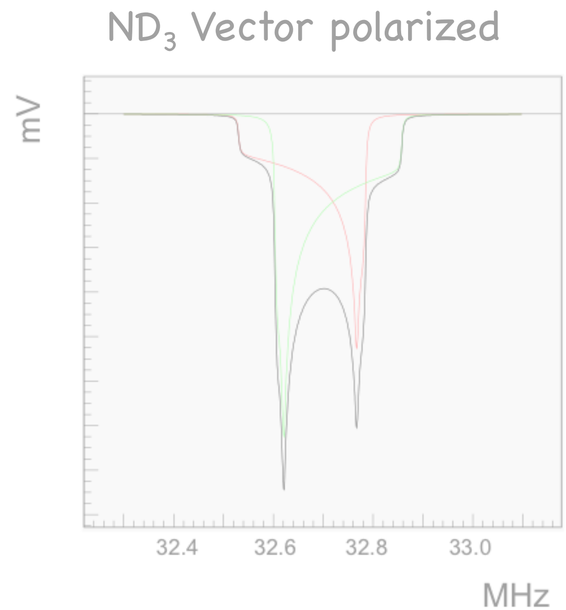
Pzz = 20% for 2.5T at 1K

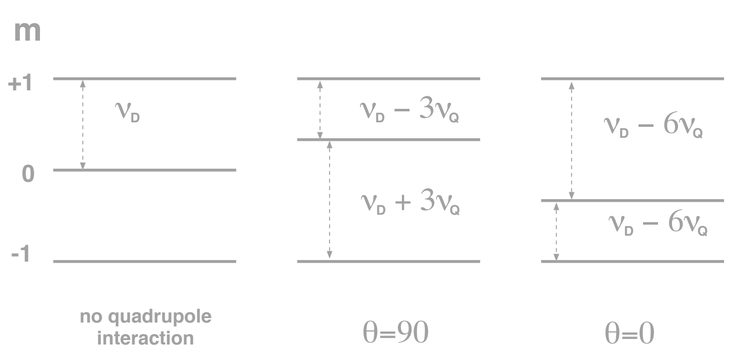
good results even with only 2.5 T field



Meyer and Schilling , 1984 *Proceedings of the 4th Int. Workshopon Polarized Target Materials & Techniques*

RF Saturation to Enhance P_{zz}

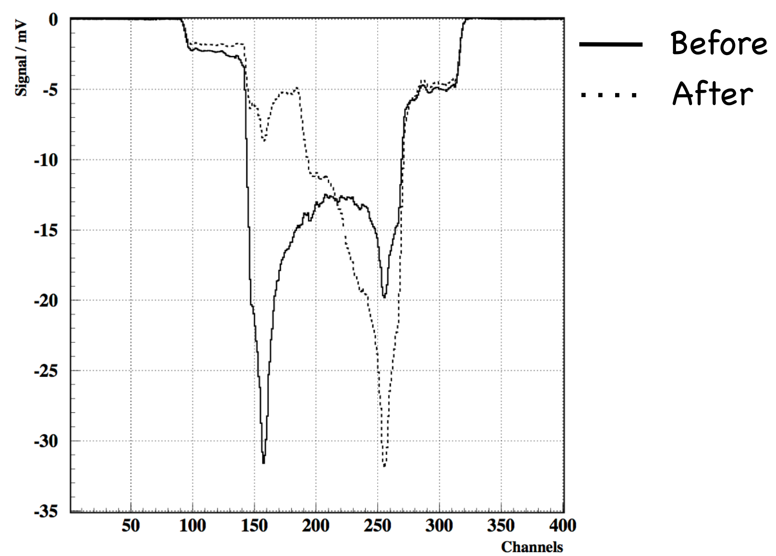




RF Saturate one of the peaks

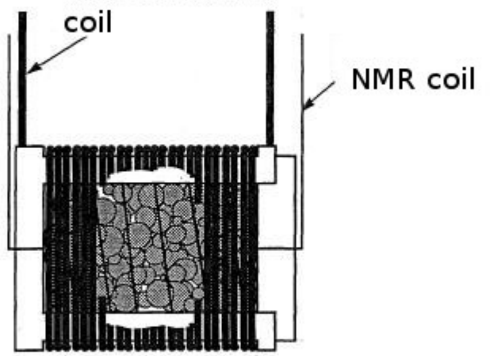
kill the m=0 <=> m=-1 transition, which enhances the m=1 <=> m=0 transition

Pzz = 30% for 5.0 T at 1K



S. Bueltmann, et al (D. Crabb Lab) 1999.

RF Saturation to Enhance P_{zz}



UVa prototype
(D. Keller)

Hardware :

- RF Coil optimized to minimize blockage
- Controllable RF Sweep Generator
- RF Amplifier

For 100% RF Saturation, expect $P_{zz} \approx P_z$

Reasonable expectation range is $20\% < P_{zz} < 45\%$

Groups working on this

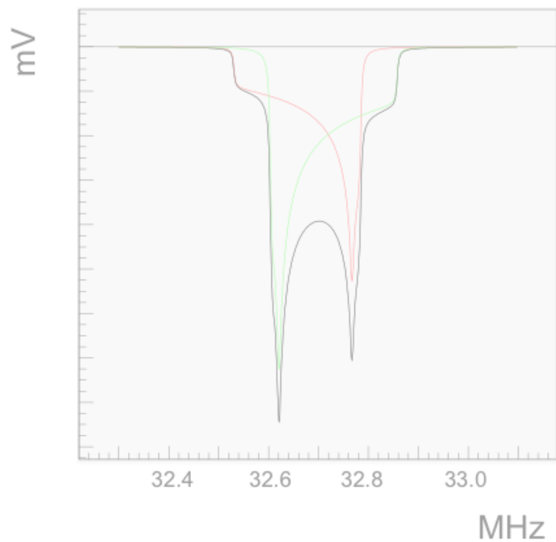
- JLab Target Group
- University of Virginia
- University of N.H.

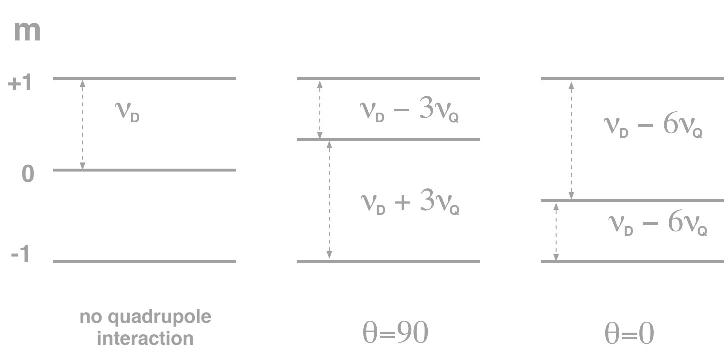
Challenge is to fit the NMR lineshape

- Research project for PhD student or Post-doc
- D. Keller (UVa) initial studies

RF Saturation to Enhance P_{zz}

ND_3 Vector polarized

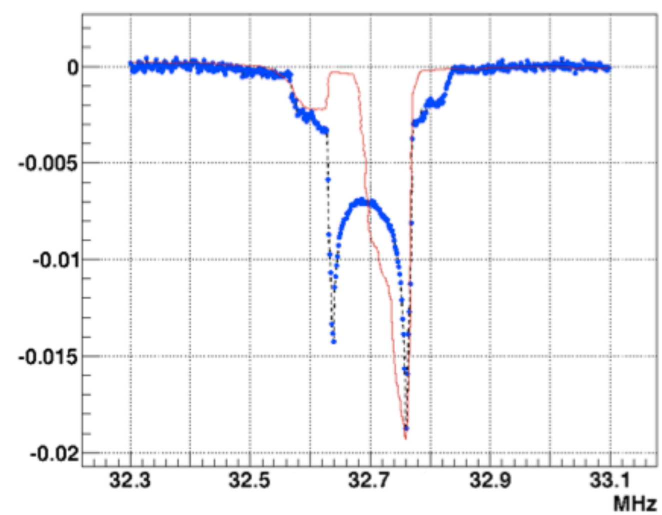




RF Saturate one of the peaks

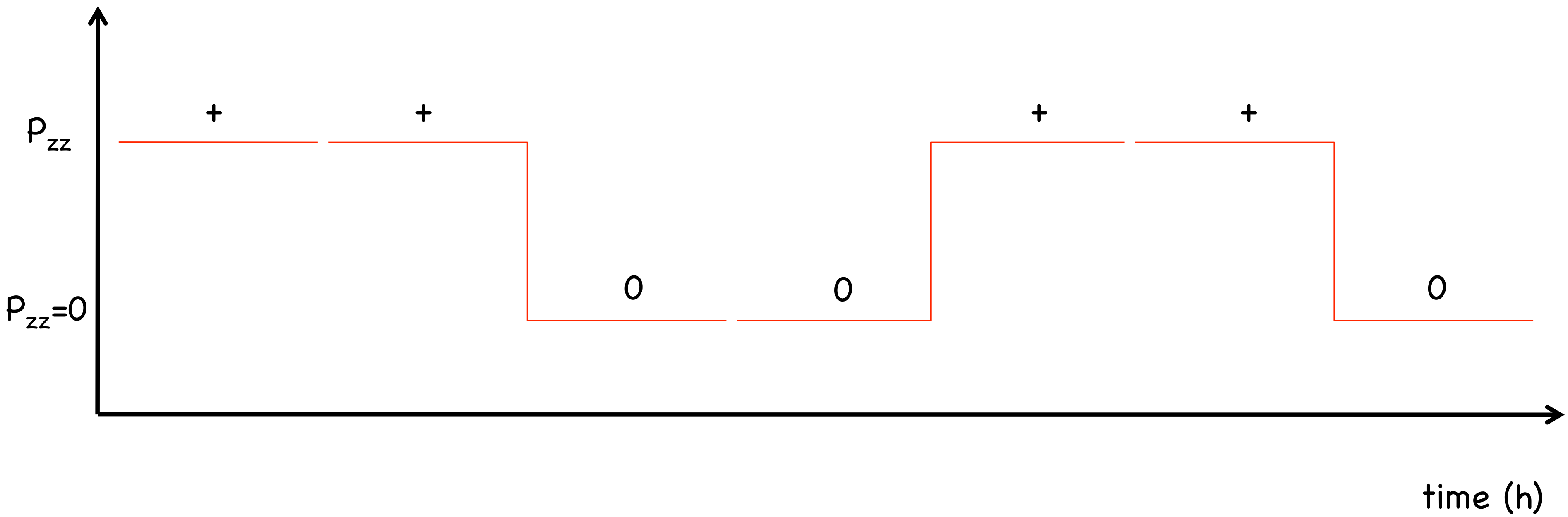
kill the m=0 <=> m=-1 transition, which enhances the m=1 <=> m=0 transition

2013 : See Dustin Keller Talk



Before
After

Polarization Cycle

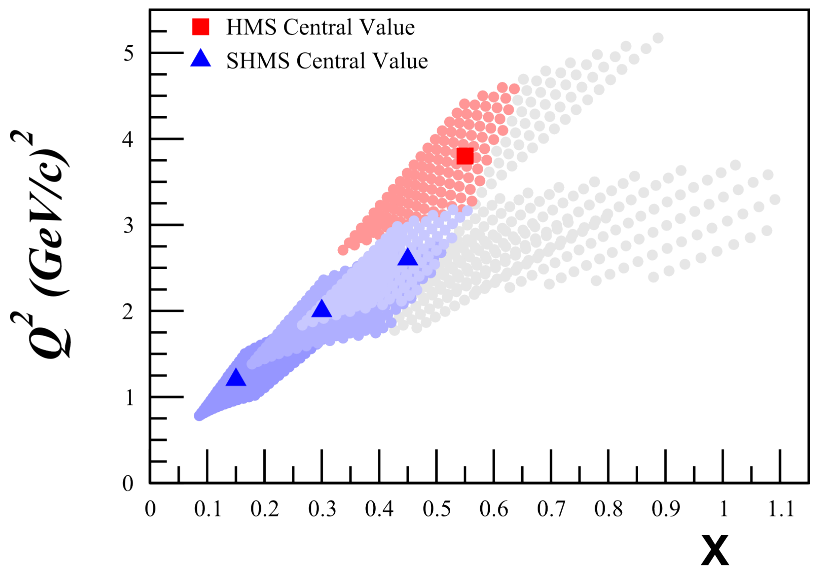


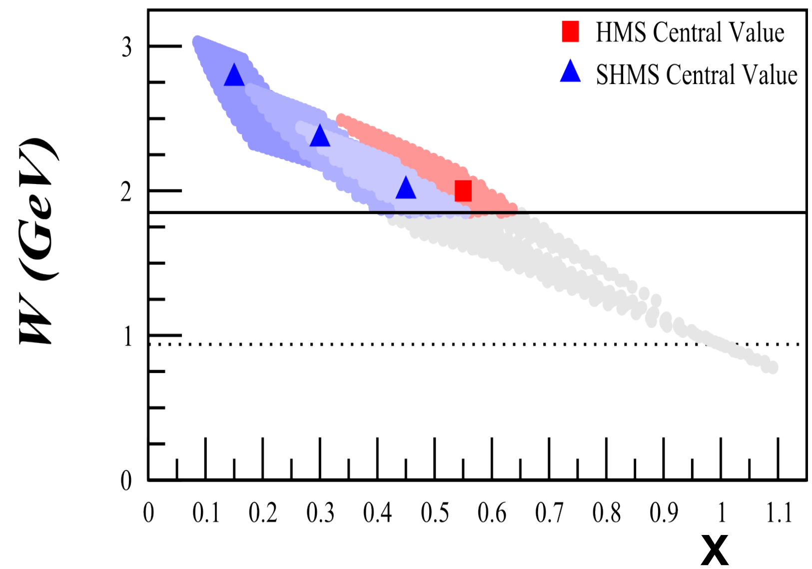
Each Pol/unpol cycle is an independent measurement of A_{zz}

Annealing and target motion only at start of new cycle
Any issues from annealing, bead dropping will be isolated to a single cycle

Doubled the number of cycles for lowest x, to better match statistics

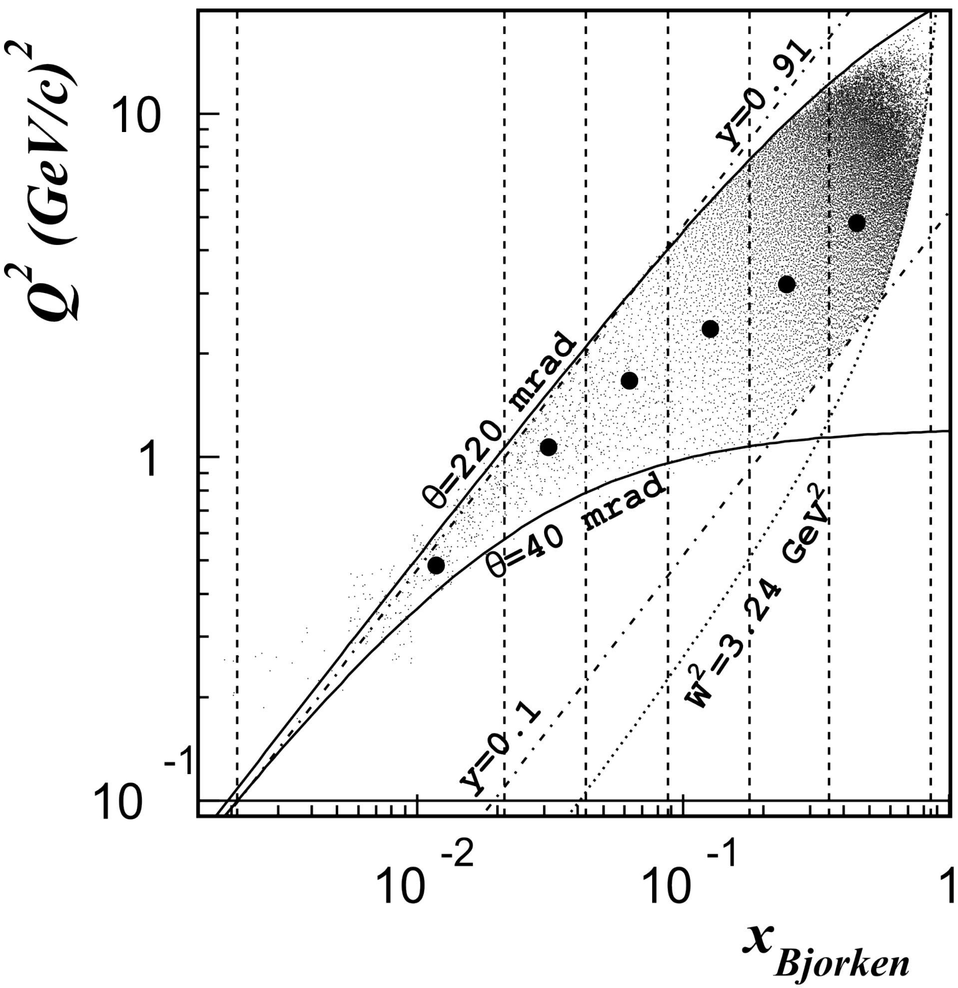
Kinematics



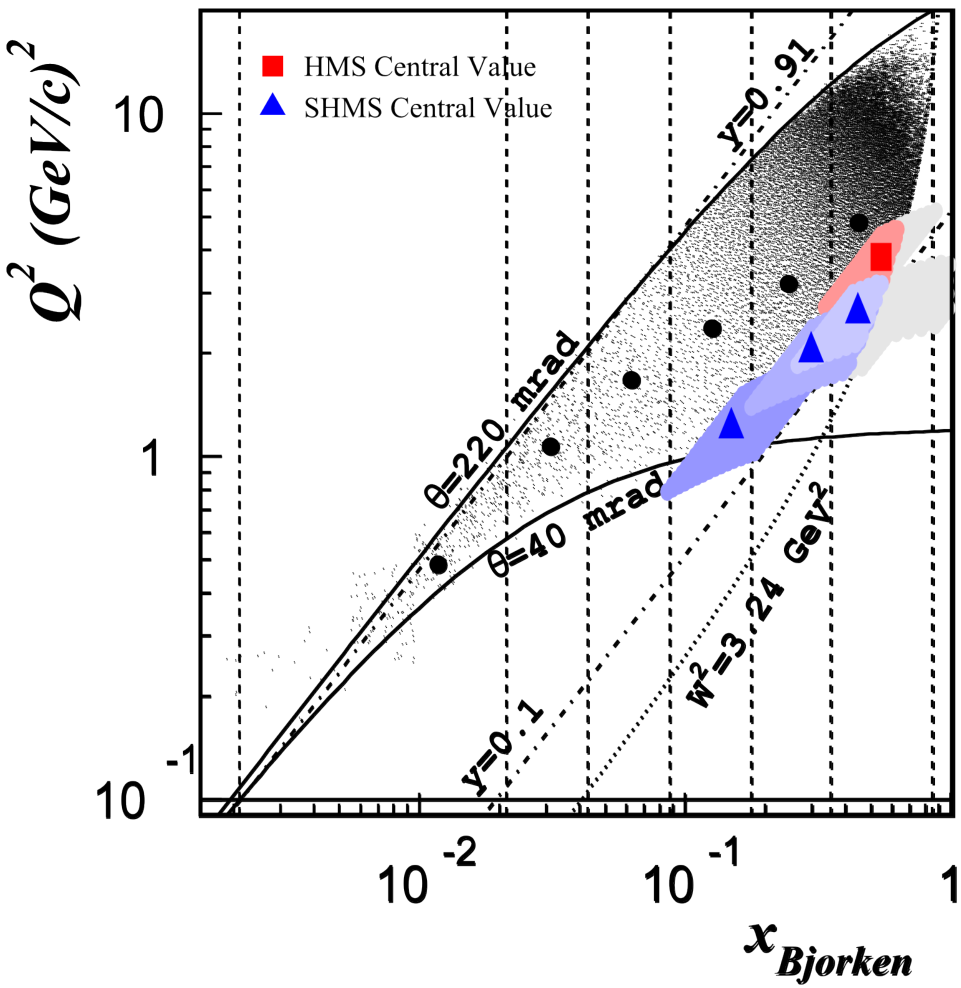


Detector	x	Q^2 (GeV^2)	W (GeV)	$E_{e'}$ (GeV)	$\theta_{e'}$ (deg.)	θ_q (deg.)	Rates (kHz)	Time (Days)
SHMS	0.15	1.21	2.78	6.70	7.35	11.13	1.66	6
SHMS	0.30	2.00	2.36	7.45	8.96	17.66	0.79	9
SHMS	0.45	2.58	2.00	7.96	9.85	23.31	0.38	15
HMS	0.55	3.81	2.00	7.31	12.50	22.26	0.11	30

Comparison to Hermes



Comparison to Hermes



Systematics

$\delta\xi$ {

Charge Determination

< 2 x 10^{-4}, mitigated by thermal isolation of BCMs and addition of 1 kW Faraday cup

Luminosity

< 1 x 10^{-4}, monitored by Hall C lumi

Target dilution and length step like changes observable in polarimetry

< 1 x 10^{-4}

Beam Position Drift effect on Acceptance

< 1 x 10^{-4} (we can control the beam to 0.1 mm, raster over 2cm diameter)

}

Effect of using polarized beam

< 2.2 x 10^{-5}, using parity feedback

Impact on the observable

$$\delta A_{zz} = \pm \frac{2}{f P_{zz} \sqrt{N_{cycles}}} \delta\xi$$

Dedicated team to systematics/false asyms

similar manpower requirement to g2p exp. where we had several teams completely separate from the polarized target effort.

Systematics

False Asymmetries from Time Dependent Drifts

Spec. $\langle x \rangle$	Hours	Stat. Err ($\times 10^{-3}$)	Cycles	False Asymmetries δA_{zz} ($\times 10^{-3}$)
0.15	144	2.6	12	4.3
0.30	216	3.0	9	4.9
0.45	360	3.7	15	3.8
0.55	720	4.1	36	2.4

Normalization Factors

Source	Relative Uncertainty
Polarimetry	8.0%
Dilution/Packing Fraction	4.0%
Radiative Corrections	1.5%
Charge Determination	1.0%
Detector Resolution and Efficiency	1.0%
Total	9.2%

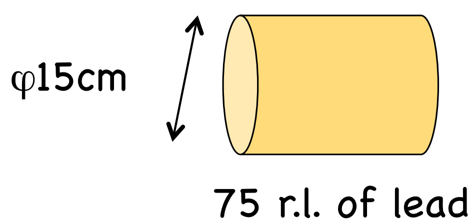
Hall Upgrades

Point of contact : D. Mack

Improve Thermal Isolation of BCMs

Historically temperature stability of the BCMs has been good
(10^{-4} stability of CC over months)
Further reduce sensitivity to Hall ambient temperatures with oil bath

Low Power Faraday Cup similar to Hall B's

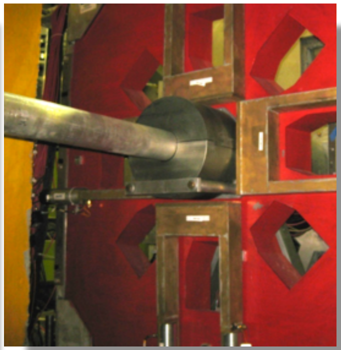


Total power 1.1 kW
Air cooled

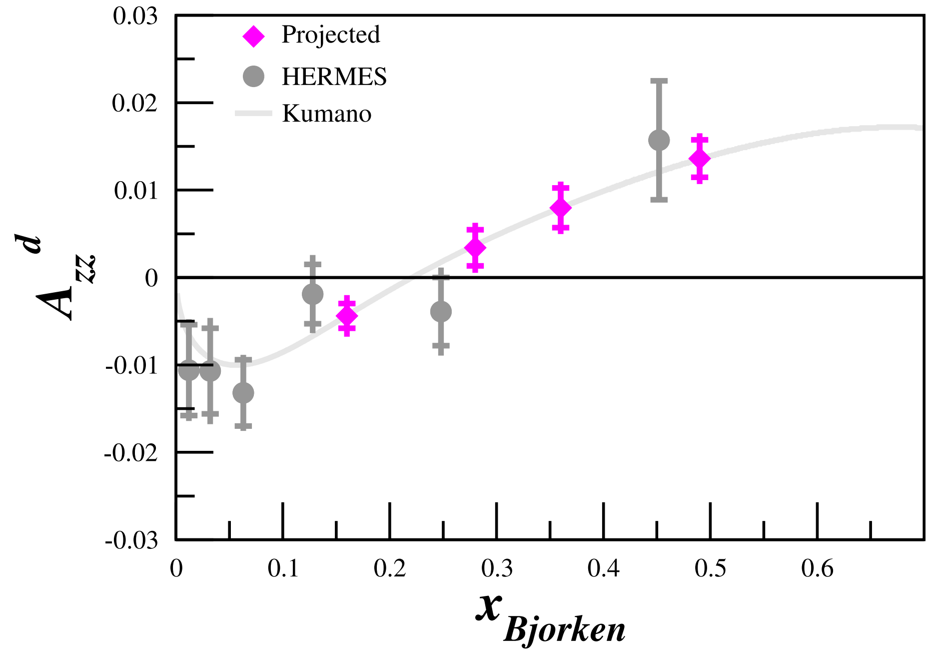
Luminosity Monitors

Existing lumis in counting mode with slow lock on beam position and angle at the target.

New thermally stabilized lumi



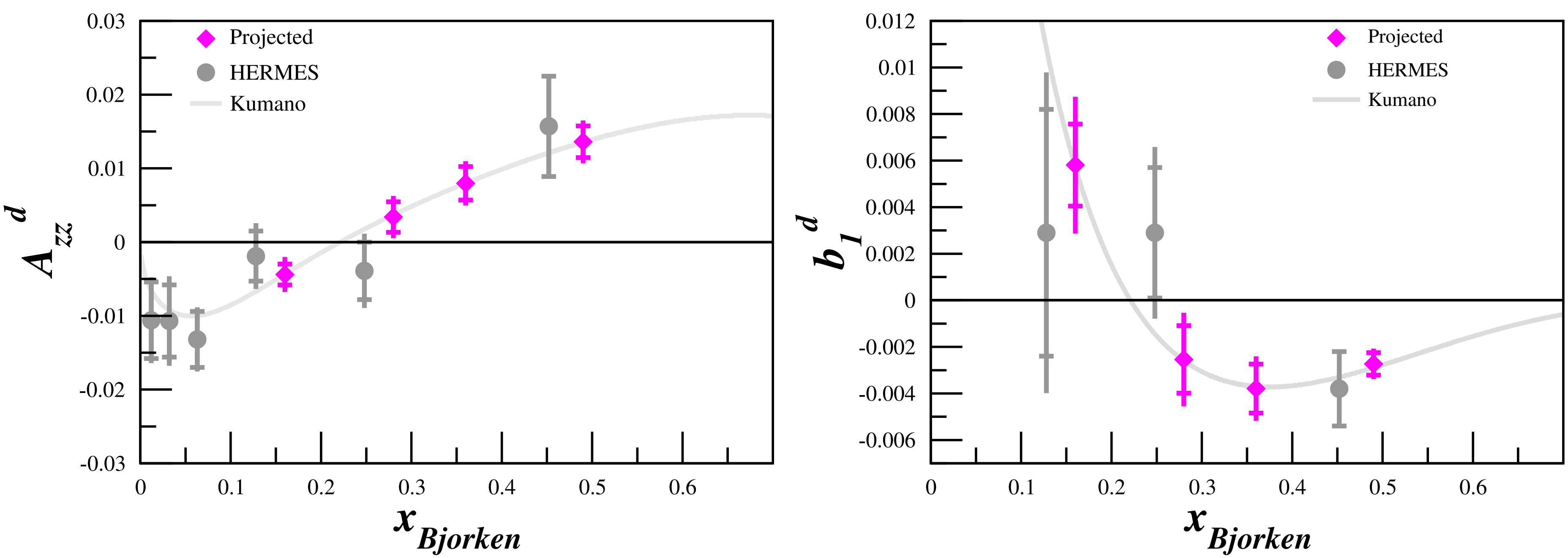
Projected Results



30 Days in Jlab Hall C

P_{zz}=35%

Projected Results



30 Days in Jlab Hall C

P_{zz}=35%

Tensor Target opens new possibilities

Few Examples

Tensor Structure function b_2, $b_{3,}$ b_4

Azimuthal Asymmetries b_4

Elastic e-D scattering

T_{20}

T_{11}

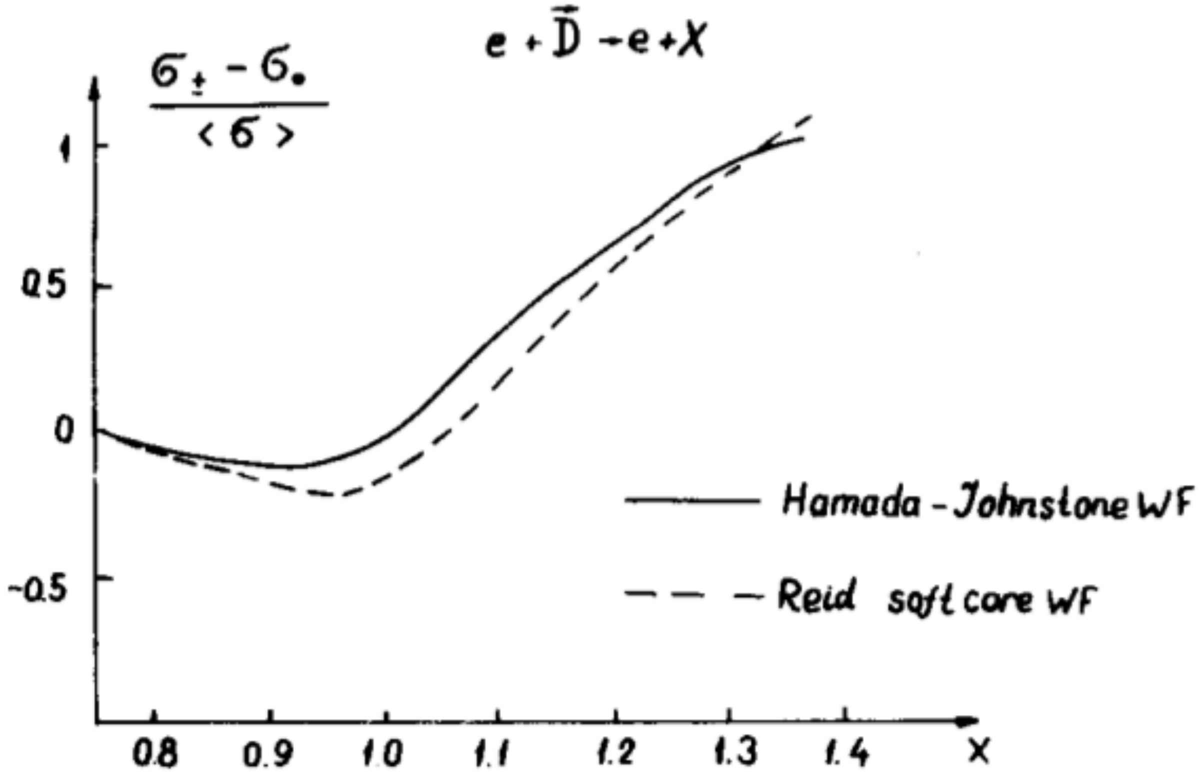
D(e,e'p) Cross Section on Tensor Polarized Deuterium.
H. Anklin, W. Boeglin et al., PR97-102, PAC13 rated A

X>1 Scattering, connection to SRCs : M. Sargian et al.

D-Wave Components of Deuteron Wave function : S. Luiti et al.

Tensor Target opens new possibilities

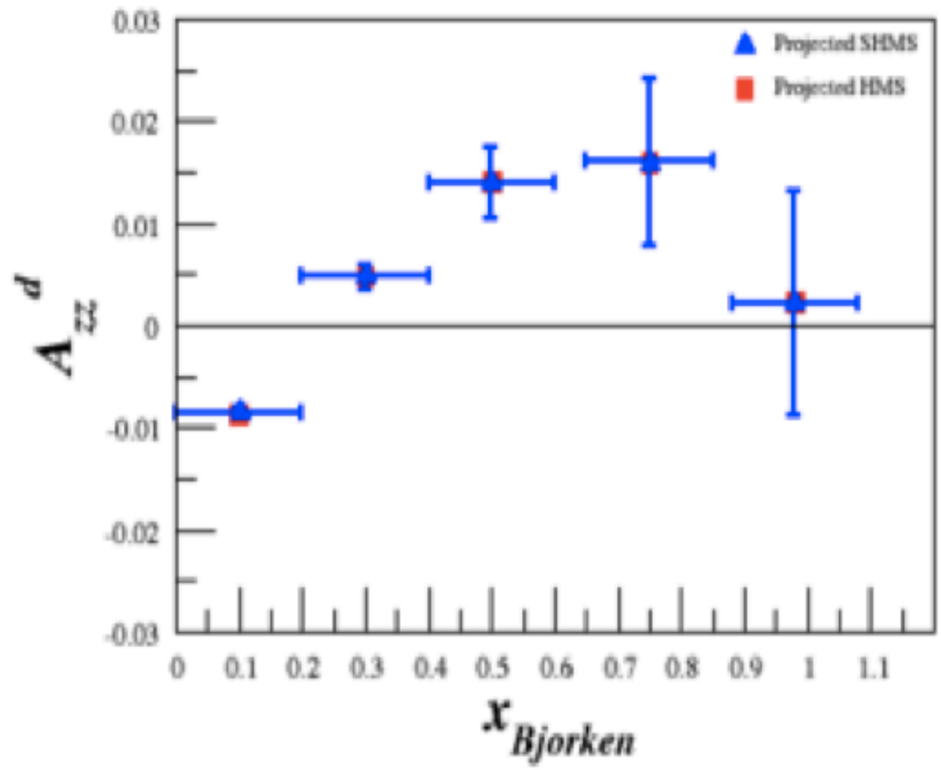
Very Large Tensor Asymmetries expected in x>1 region

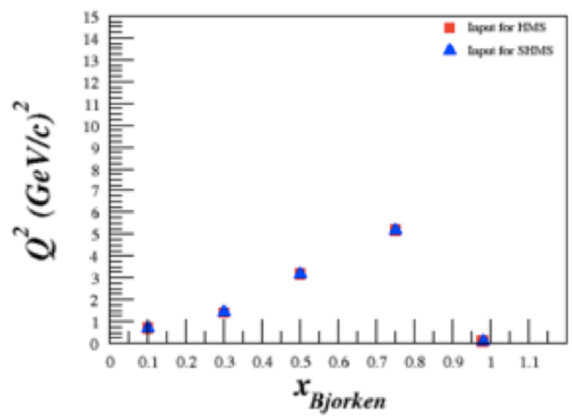


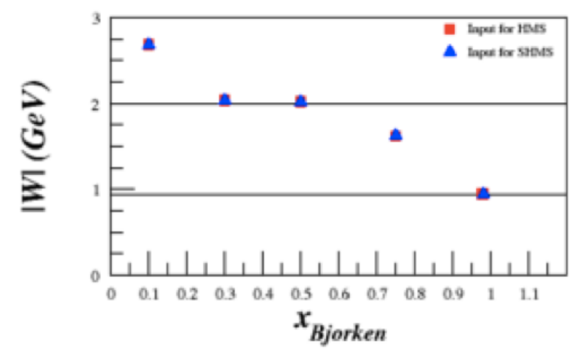
Frankfurt and Strikman: Phys Rep 160, (1988) 235

Tensor Target opens new possibilities

Quasi-Elastic and x>1







Summary

b1 Experiment approved at last PAC

A- rating, with condition (c1) on target polarization.

30 days of 11 GeV beam + 10.8 overhead days.

All Conventional Models predict b1 small or vanishing at moderate x

The Large values of b_1 observed at Hermes would indicate exotic effects if confirmed

RF Hole Burning looks quite promising to reach high values of P_{zz}

See Dustin's Talk

Need R&D to develop this and other techniques

Tensor Polarized Target opens many new avenues of research at Jlab

BACKUPS

Incremental Improvements to Pzz

Crabb Lab (1999)

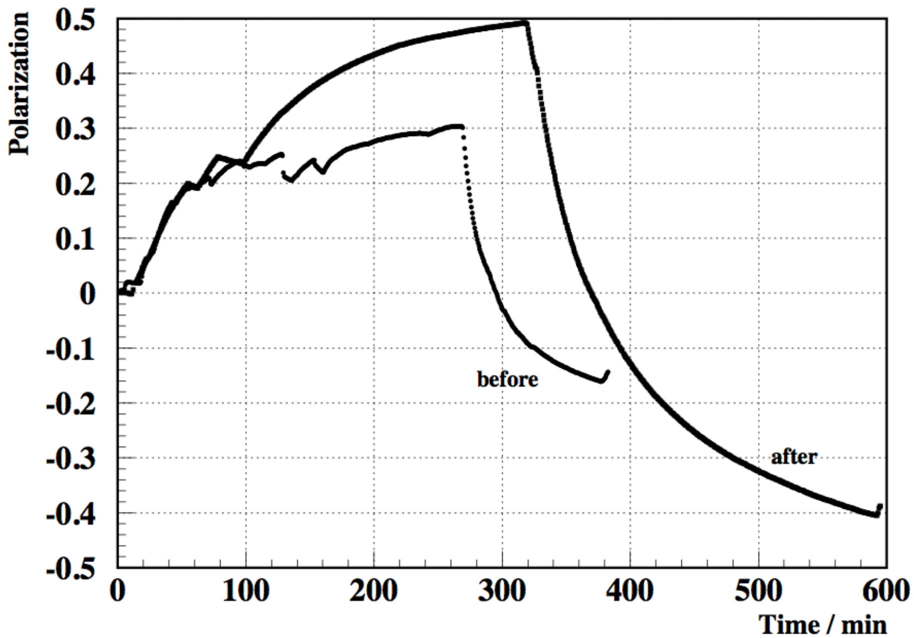
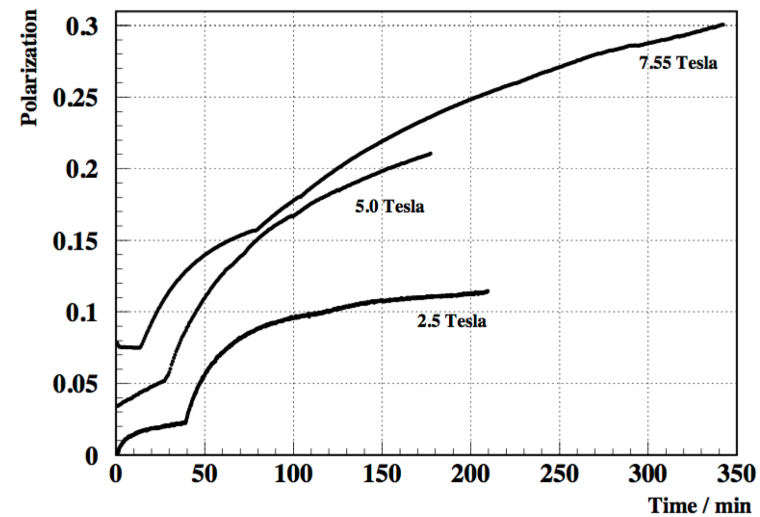


Figure 4: ND_3 polarization, before and after tempering.



Improvement of LiD polarization with holding field

S. Bültmann et al. / Nuclear Instruments and Methods in Physics Research A 425 (1999) 23–36 25

Table 1
Naive dilution factor, *f*, and polarizations of ^{2}H and ^{6}Li obtained at different magnetic fields, *B*, and temperatures, *T*

Material	Dopant	*f*	P_2	P_6	*B*/*T*	*T*/*K*	Ref.
$^{14}ND_3$	Irradiation	0.30	0.49		2.5	0.20	[12]
$^{15}ND_3$	Irradiation	0.29	0.42		5.0	1.05	[5]
$C_4D_{10}O$	EDBA-Cr(V)	0.24	0.50		2.5	0.30	[13]
^6LiD	Irradiation	0.50		0.71	6.5	0.25	[10]
				0.64	4.9	0.25	[10]
				0.40	2.5	0.25	[10]

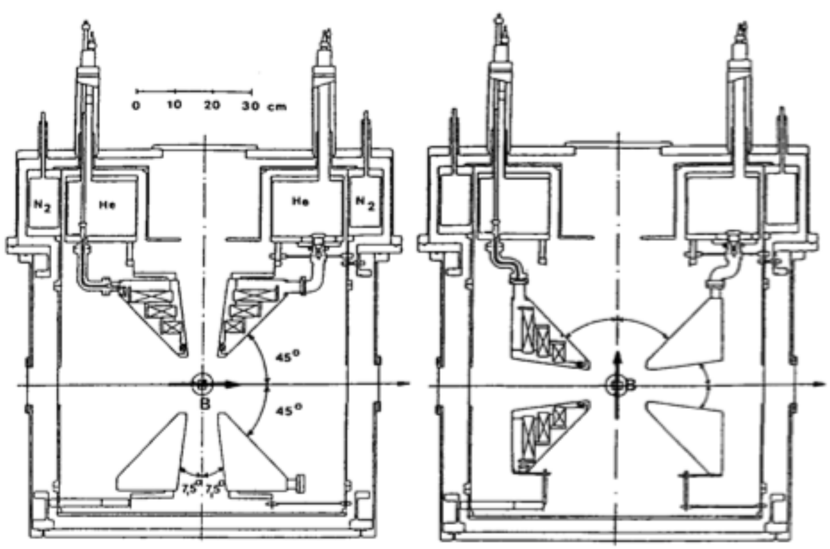
Tensor Polarization

Elastic electron deuteron scattering on a tensor polarized solid ND_3 target

Z. Phys. C – Particles and Fields 49, 175-185 (1991)

Bonn electron accelerator

Polarized ND3



Similar DNP Target

but brute force enhancement of Pzz using a $^3He/^4He$ Fridge

Large Average P_{zz} in electron beam

$$\langle P_z \rangle^c = (-53.2 \pm 4.5)\%$$
$$\langle P_{zz} \rangle = 0.225 \pm 0.036$$

It is a unique opportunity at JLab to develop this new field of spin physics.

S. Kumano (KEK)

I'm glad to hear that b1 is not forgotten in all the excitement about other spin dependent effects.

Robert Jaffe (MIT)

I am particularly interested in signatures of novel QCD effects in the deuteron. The tensor charge could be sensitive to hidden color (non-nucleonic) degrees of freedom at large x. It is also interest- ing that antishadowing in DIS in nuclei is not universal but depends on the quark flavor and spin. One can use counting rules from PQCD to predict the $x \to 1$ dependence of the tensor structure function.

Stanley Brodsky (SLAC)

I am certainly interested in the experimental development to find the novel QCD phenomena from the hidden color component of deuteron.

Chueng-Ryong Ji (NCSU)

Surely this is of real interest to the spin community!

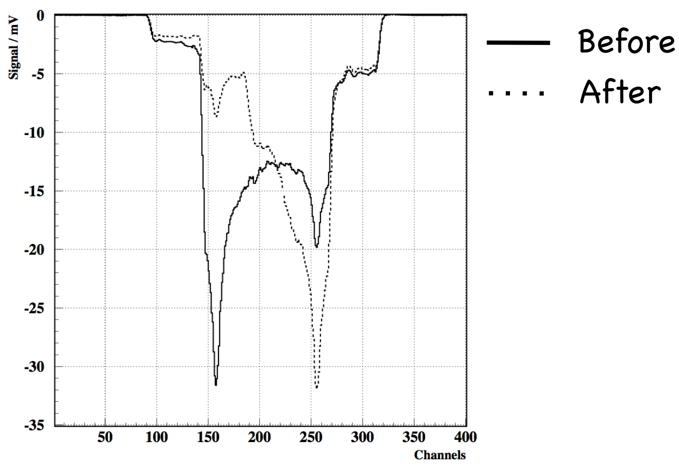
Leonard Gamberg (Penn State Berks)

I find the proposal well written, well justified, sound, and exciting.

Alessandro Bacchetta (Universita di

Enhanced Pzz

Pzz = 30% for 5.0 T at 1K



S. Bueltmann, et al (D. Crabb Lab) 1999.

Initial Studies on characterizing the NMR lineshape of a tensor enhanced sample

Vector Polarizatior ∞ Sum of Peak Areas

Tensor Polarizatior ∞ Diff of Peak Areas

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

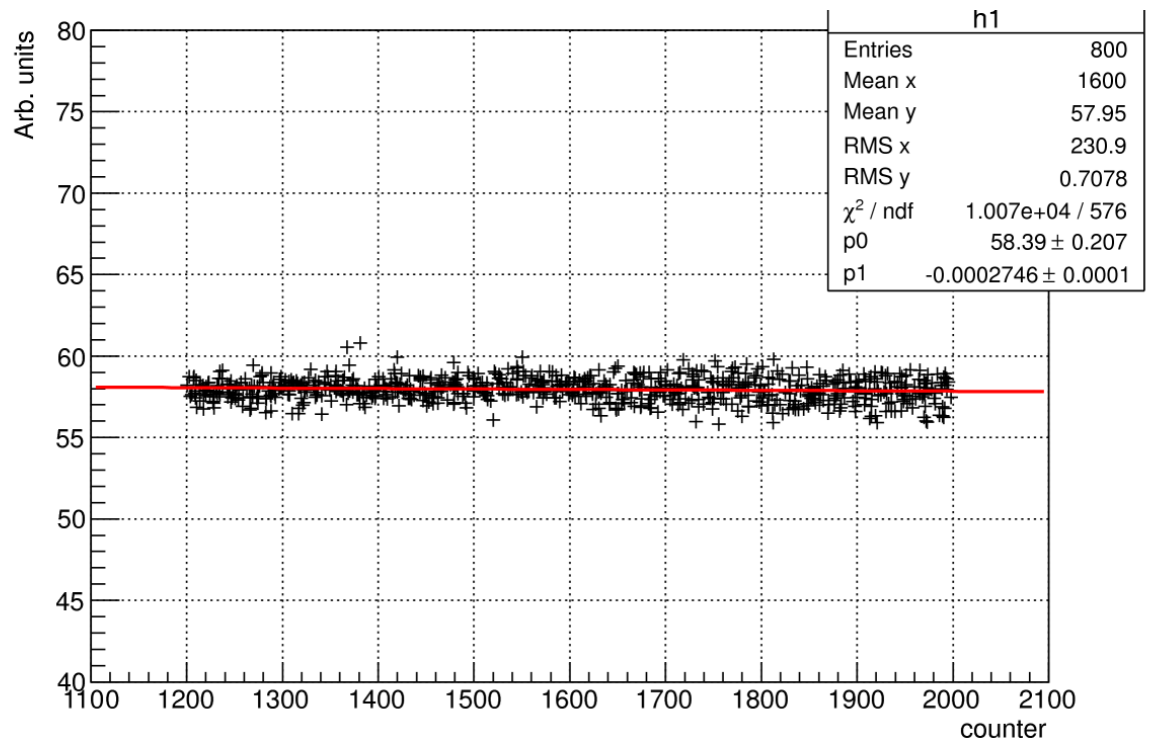
Ratio of instantaneos to initial NMR signal area

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

Available tensor enhancement

Systematics

E06-010 HRS Pion Yield

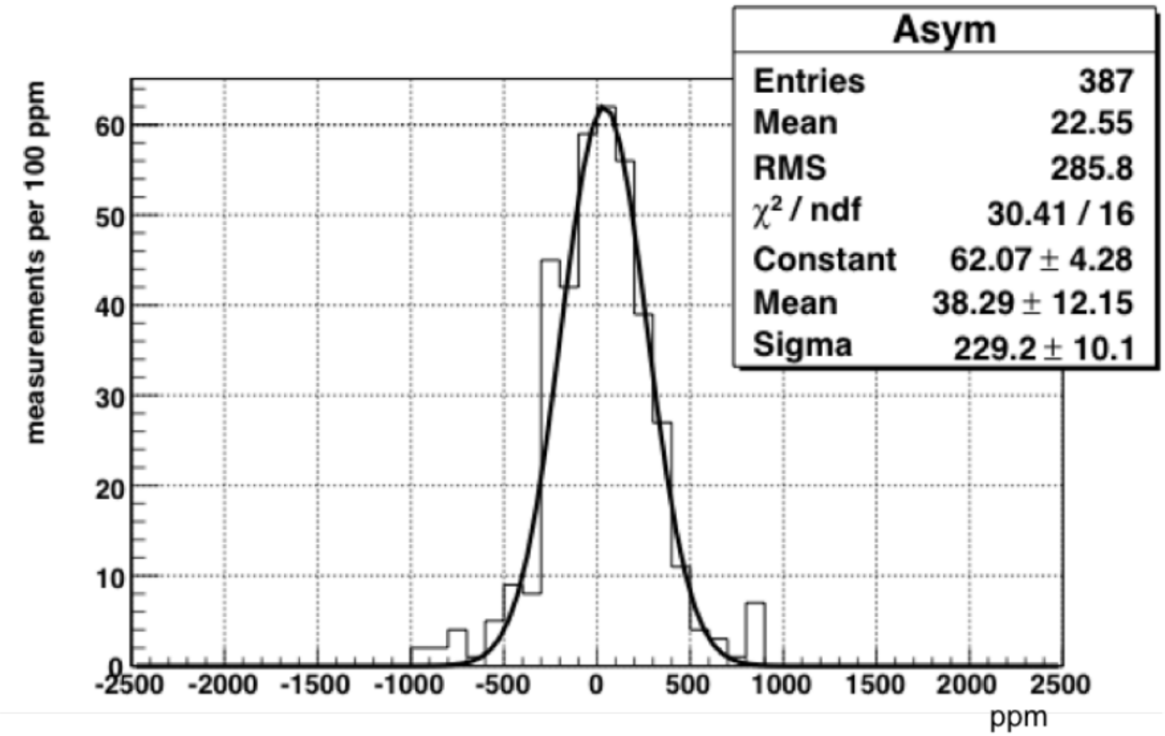


Yield depends on Detector performance, acceptance, charge, ...

Yield drifted 0.355% over 15 days of continuous running.
the slope implies 1.2 x 10^{-4} drift over a 12 hour cycle.

Beam Charge Asymmetry

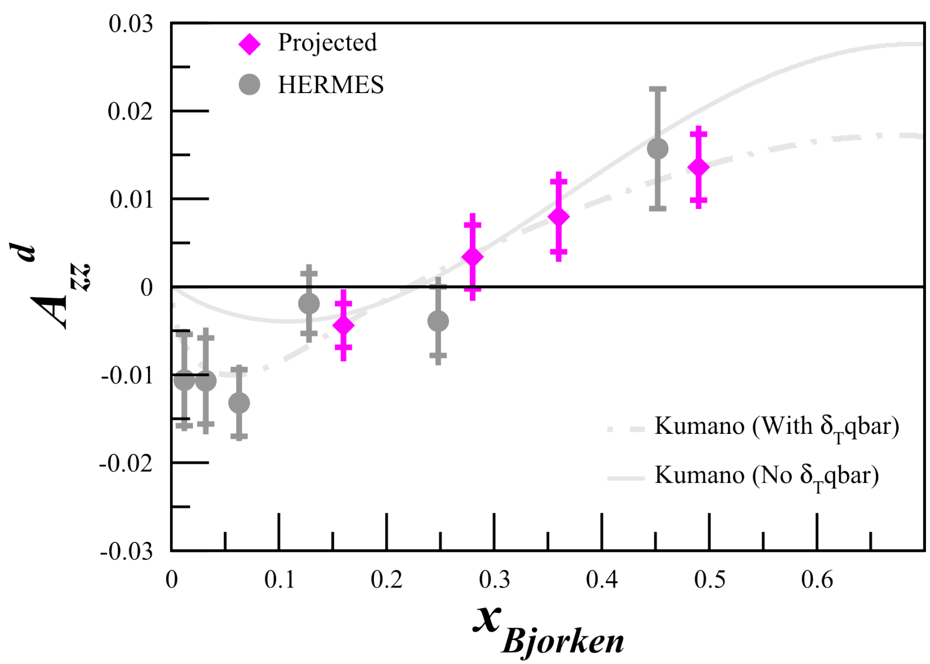
E06-010 Charge Asymmetry

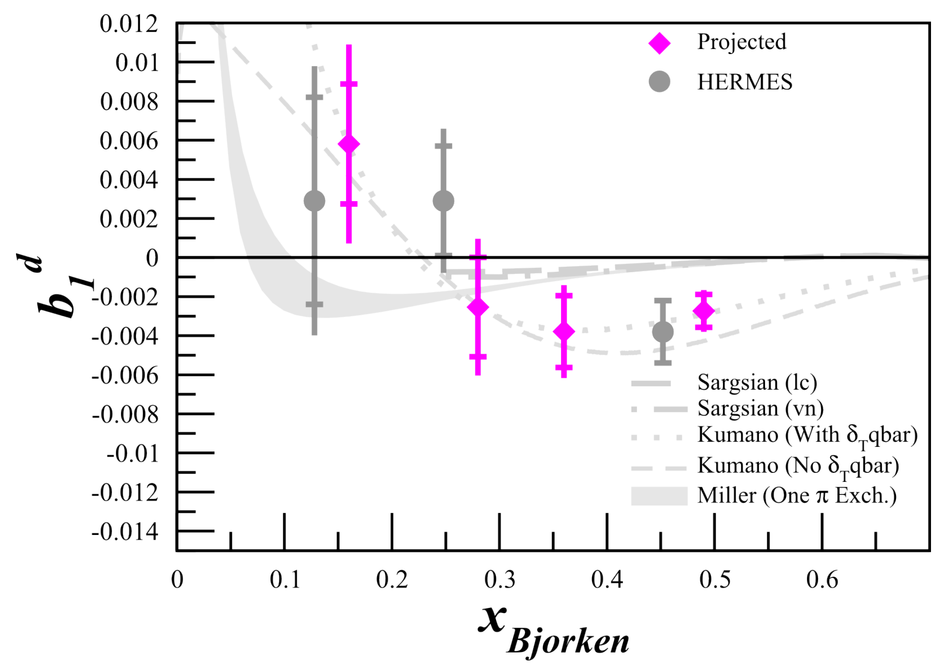


Beam Asymmetry $3.8x10^{-5}$ with width of $2.3x10^{-4}$ over 15 days

similar results found during g2p at low current.

Projected Results P_{zz}=20%





Without P_{zz} enhancing techniques