Tensor Polarized Deuteron

QCD Frontier 2013 Meeting

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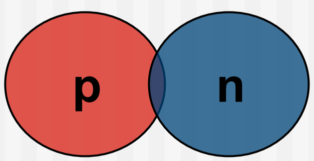
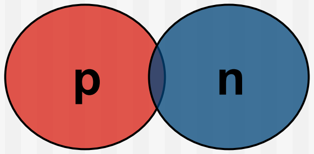
Outline

- Background/Motivation
- Spin-1/Tensor-Polarization Concept
- Previous and planned measurements
- Possible (Spin-1) Physics with an EIC

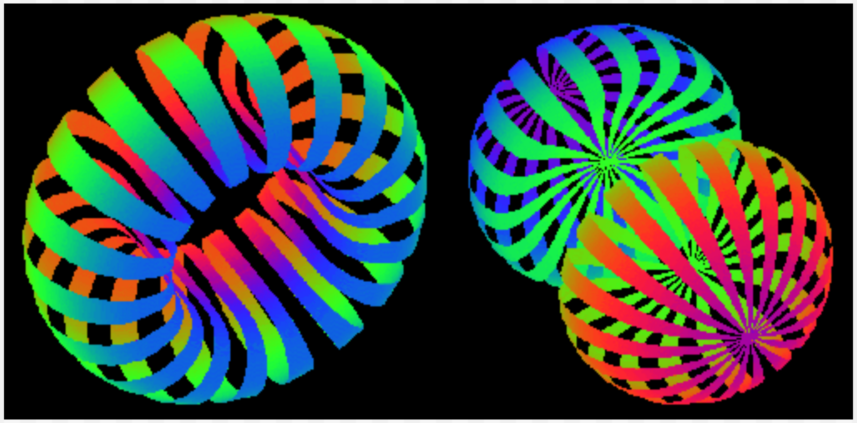


Why Deuteron?

- Spin-1 system
- Simple lab for nuclear physics
- Reasonably “easy” to polarize.



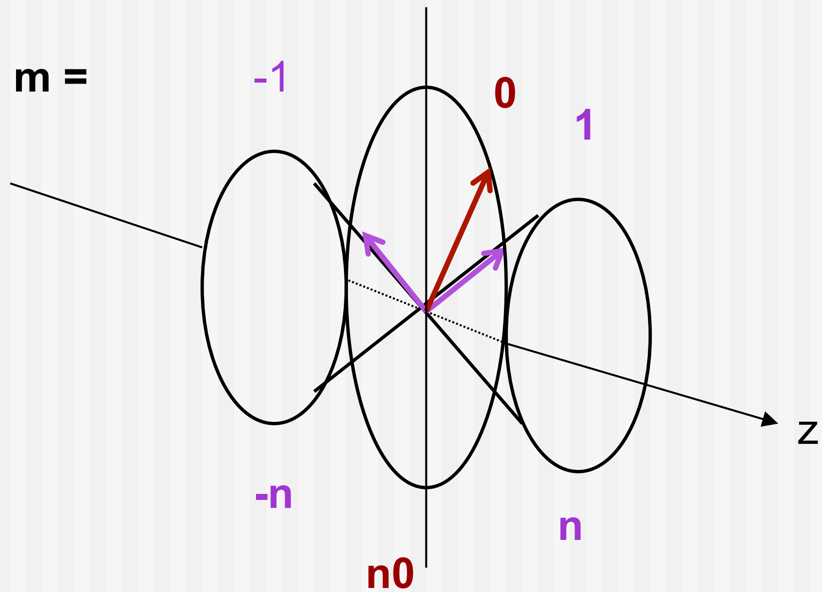
Spatial distribution depends on the spin state



M = 0 **M = ±1**

Spin-1

Spin-1 system in a B-field leads to 3 sublevels via Zeeman interaction.

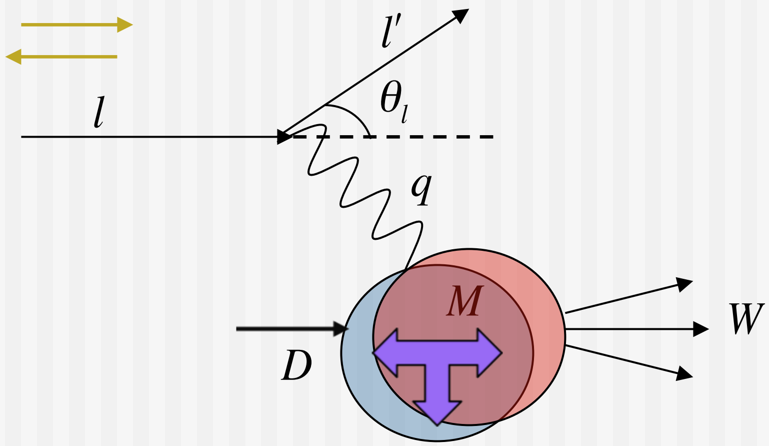


Vector polarization: (n+ - n$^-$); -1 < P_z < +1

Tensor polarization: (n+ - n^0) – (n^0 - n-); -2 < P_{zz} < +1 Normalization: (n$^+$ + n$^-$ +n^0) = 1

Some research has been done with deuteron beams (Thesis: V. Morozov)

Inclusive Scattering with Spin-1



Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2(\theta/2)\right]$$

$$+\gamma g_1(x,Q^2) + \delta g_2(x,Q^2)$$

$$\boxed{+\varsigma b_1(x,Q^2) + \varepsilon b_2(x,Q^2) + \zeta b_3(x,Q^2) + \eta b_4(x,Q^2)}$$

$$b_1, b_2 \sim \frac{1}{P_{zz}^{eff}}$$

Spin-1 => 4 more structure-functions: b_1, b_2, b_3, b_4

Spin-1 Structure Functions

Leading Twist: F_1, g_1, b_1

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

$$q^0 = (q_\uparrow^0 + q_\downarrow^0) = 2q_\uparrow^0$$

$$q^1 = (q_\uparrow^1 + q_\downarrow^1) = (q_\uparrow^1 + q_\uparrow^{-1})$$

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

Spin-1 Structure Functions

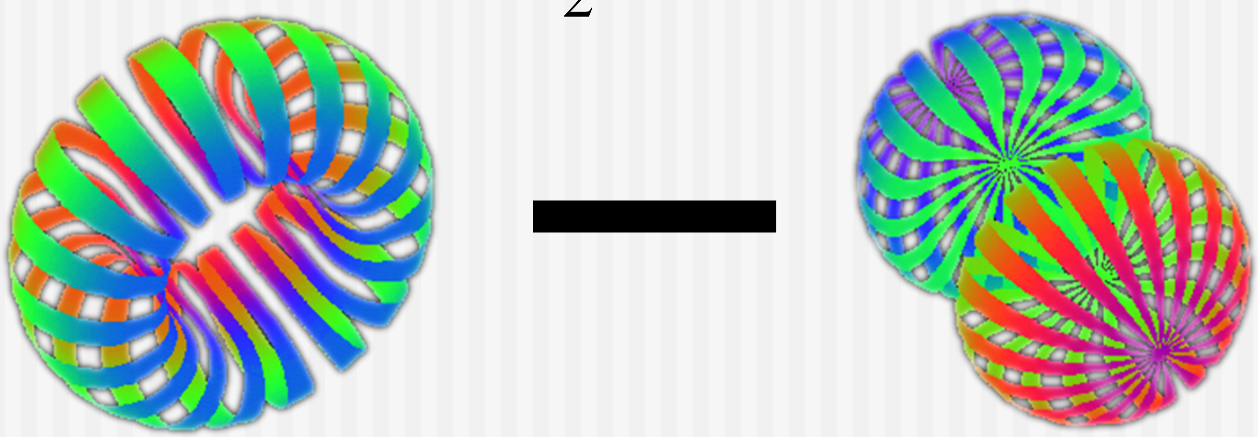
Leading Twist: F_1, g_1, b_1

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

b_2: related to b_1 by relation similar to Callan-Gross.
b_4: kinematically suppressed at longitudinal polarization. Also, leading twist.
b_3: higher twist, similar to g_2.

b_1^d

$$b_1^d \approx \frac{1}{2}\left(q^0 - q^1\right)$$



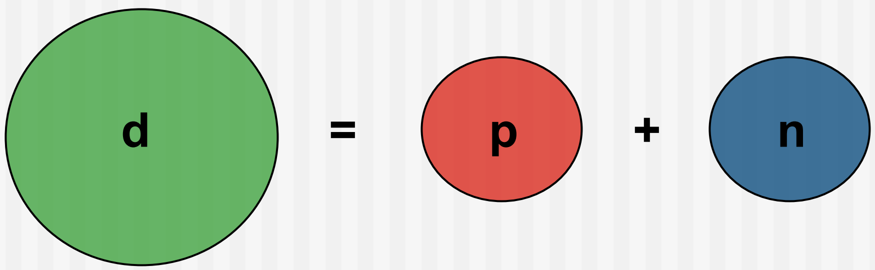
- Deuteron essentially combination of nuclear and quark physics.
- Measured via DIS, but dependent on deuteron spin-state.
- Allows for investigation of nuclear effects at parton level.

b_1^d

Hoodbhoy,Jaffe, Manohar (1989)

b_1 vanishes in the absence of nuclear effects.

i.e., if



p,n in relative S-state

D-state has component with nuclear spin 1 from orbital angular momentum 1, but total nucleon spin 0. But even accounting for this, expected to be very small.

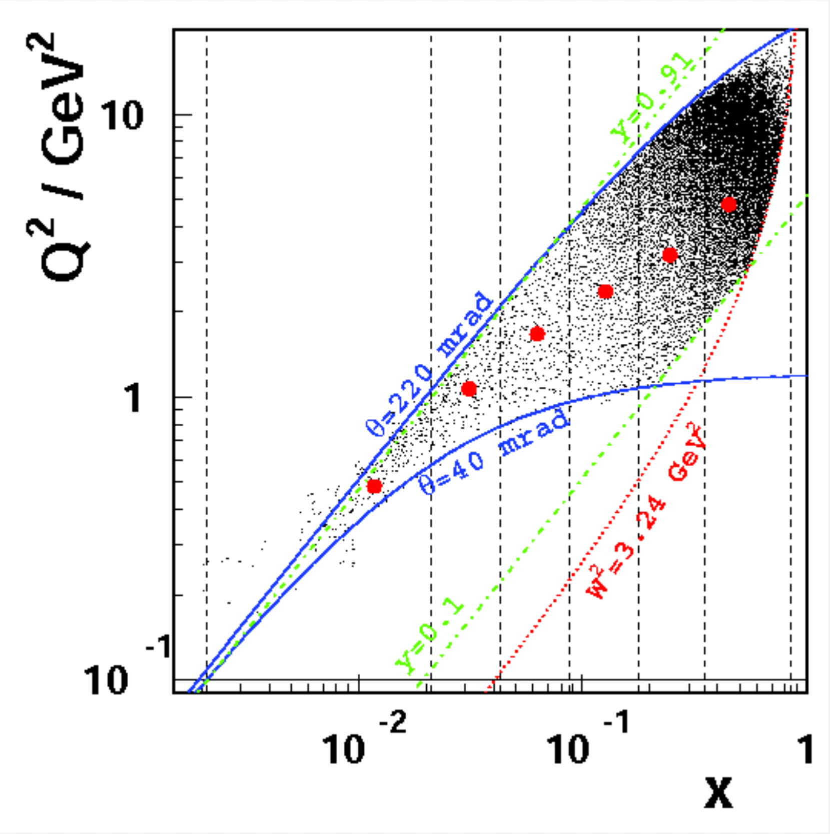
Khan & Hoodbhoy, PRC **44** ,1219 (1991) : **$b_1 \approx O(10^{-4})$**

Relativistic convolution model with binding

Umnikov, **PLB** 391, 177 (1997) : **$b_1 \approx O(10^{-3})$**

Relativistic convolution with Bethe-Salpeter formalism

HERMES Measurement:kinematics

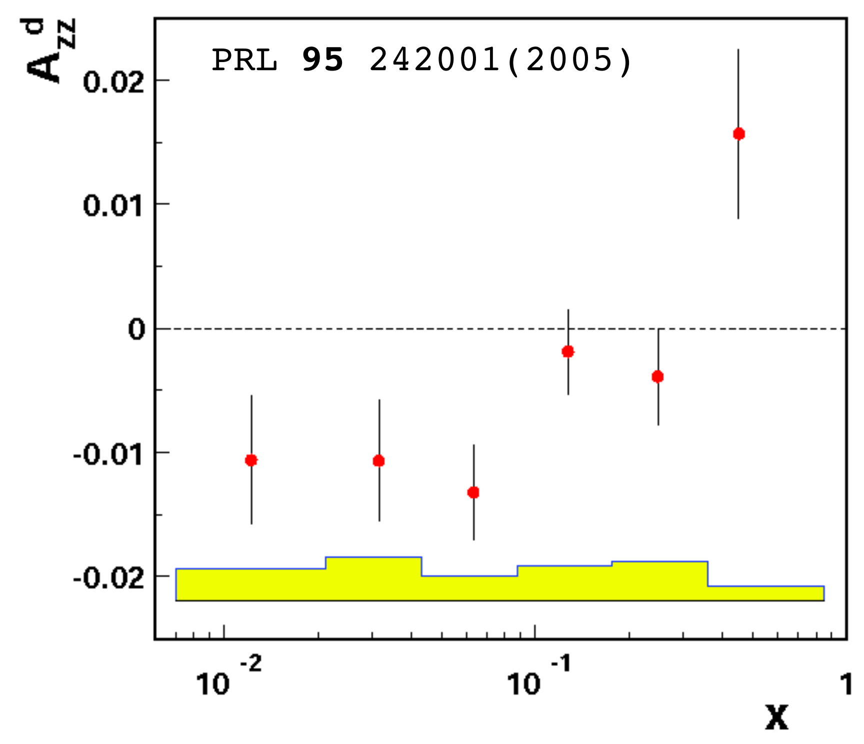


- 27.6 GeV longitudinally polarized positron beam
- Internal tensor polarized d_2 gas target; P_{zz}~0.8 (negligible P_z), dilution~0.9.
- 1 month of data taking.

$$0.01 < x < 0.45$$

$$0.5 < Q^2 < 5\ GeV^2$$

HERMES Measurement: A_{zz}^{d}

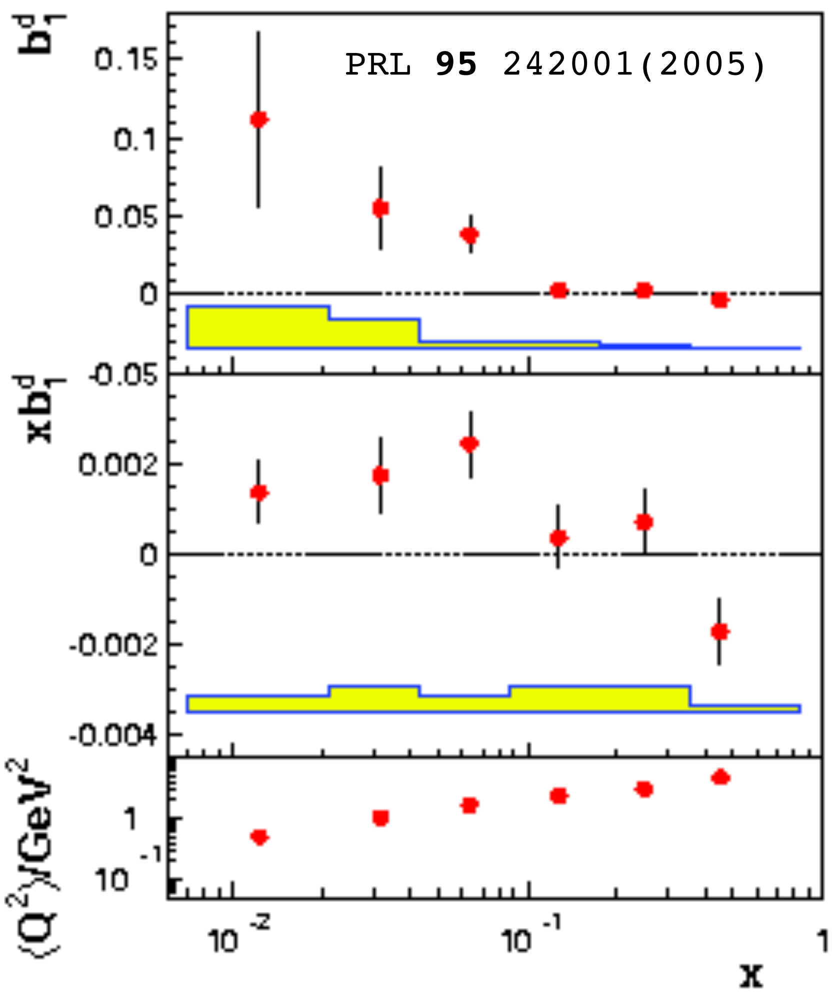


Tensor spin asymmetry

$$A_{zz} = \frac{1}{P_{zz}} \frac{2\sigma^{1} - 2\sigma^{0}}{3\sigma^{U}}$$

HERMES result was about 2σ from 0.

HERMES Measurement: b_1^d



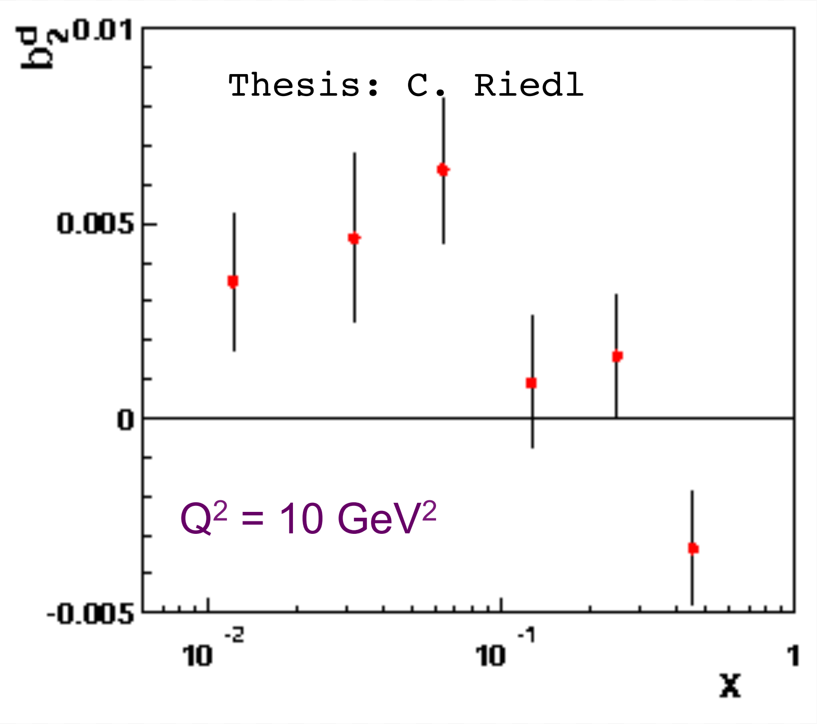
$$b_1 = -\frac{3}{2} F_1 A_{zz}$$

Rising of b_1 as x->0 can be related to same mechanism responsible for nuclear shadowing.

Ashman, *et al.* PLB 206 364(1988)

Can also be described in models involving double-scattering of leptons (first from proton, then neutron).

HERMES Measurement: b_2^d



b_2 related to b_1 via Callan-Gross-type relation.

$$b_2 = 2xb_1\left(\frac{1+R}{1+\gamma^2}\right)$$

$$R = (1+\gamma^2)\frac{F_2}{2xF_1} - 1$$

HERMES Close-Kumano Sum Rule

F.E.Close,S.Kumano, PRD**42** 2377(1990)

If sea quark and antiquark tensor polarization vanishes
i.e.

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

HERMES measurement:

$$\int_{0.02}^{0.85} b_1(x)dx = 0.0105 \pm 0.0034 \pm 0.0035$$

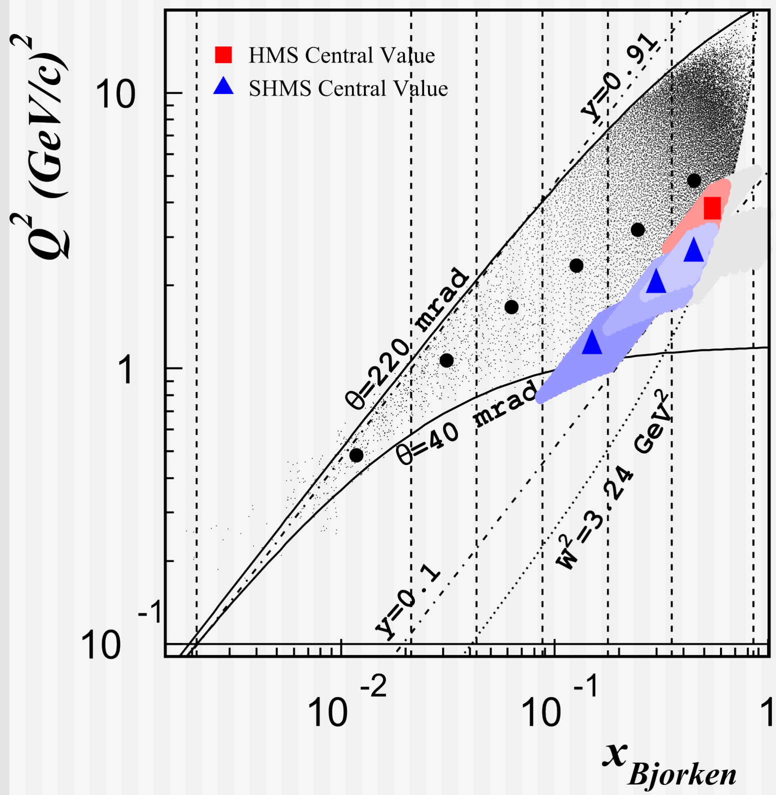
2σ result, over measured range

$$\int_{0.02}^{0.85} b_1(x)dx = 0.0035 \pm 0.0010 \pm 0.0018$$

1.7σ result, with $Q^2 > 1\text{GeV}^2$

PRL **95** 242001(2005)

Proposal To Determine b_1^d at JLab



- Measurement at Jlab 12GeV could be complementary to HERMES.
- Advantage would be higher luminosity: $\sim10^{35}cm^{-2}s^{-1}$ compared to $\sim10^{31}cm^{-2}s^{-1}$.
- Some research has been done tensor polarizing solid deuteron (ND_3) target via NMR*: $P_{zz}\sim0.2$, dilution~0.24,0.36.
- Submitted at PAC 40; Conditionally approved.

Experimental Method

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

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

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

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

σ_0 : Unpolarized cross-section

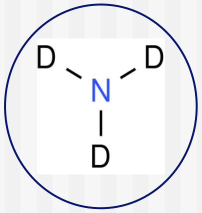
P_{zz} : Tensor Polarization

Observable is the Normalized XS Difference

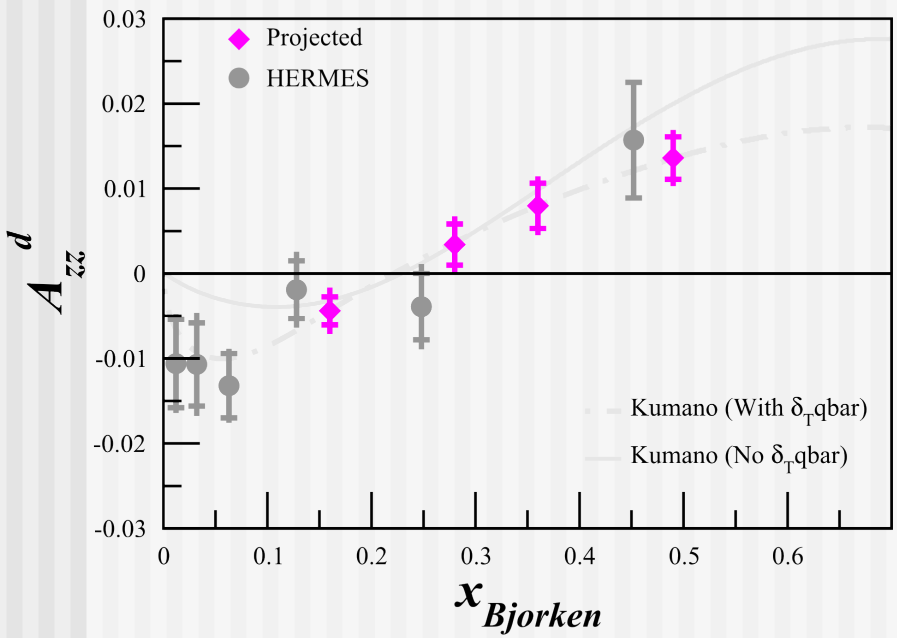
B-Field, density, temp, etc. held same in both states

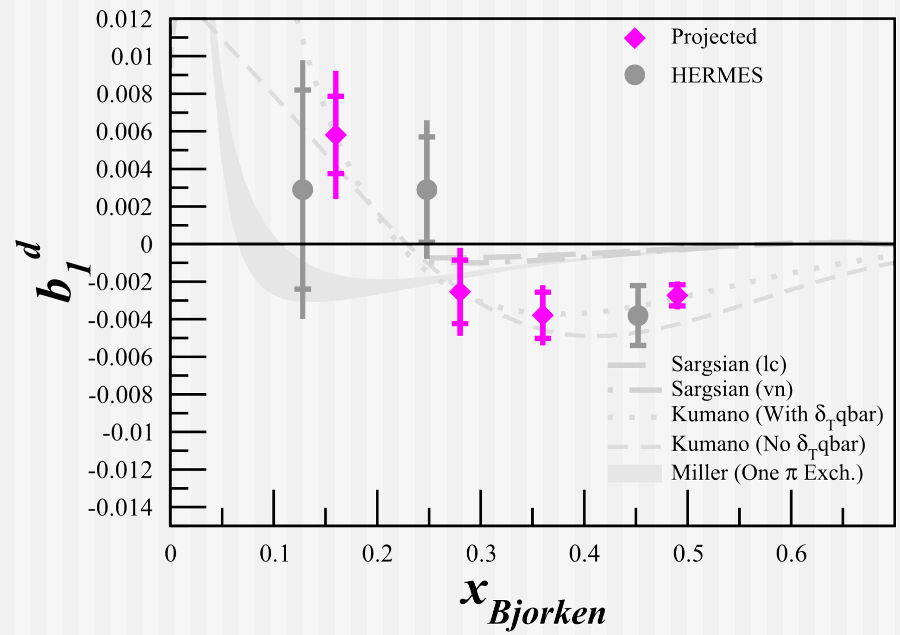
dilution factor

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



Projected Results: P_{ZZ} near 30%





RF saturation has demonstrated P_{zz} enhancement to ~30%

*Crabb *et al.* $P_{zz} = 2 - \left(4 - 3P_z^2\right)^{1/2}$

false asymmetries suppressed by $1/P_{zz}$

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

Tens. Pol. Scattering at low *x*

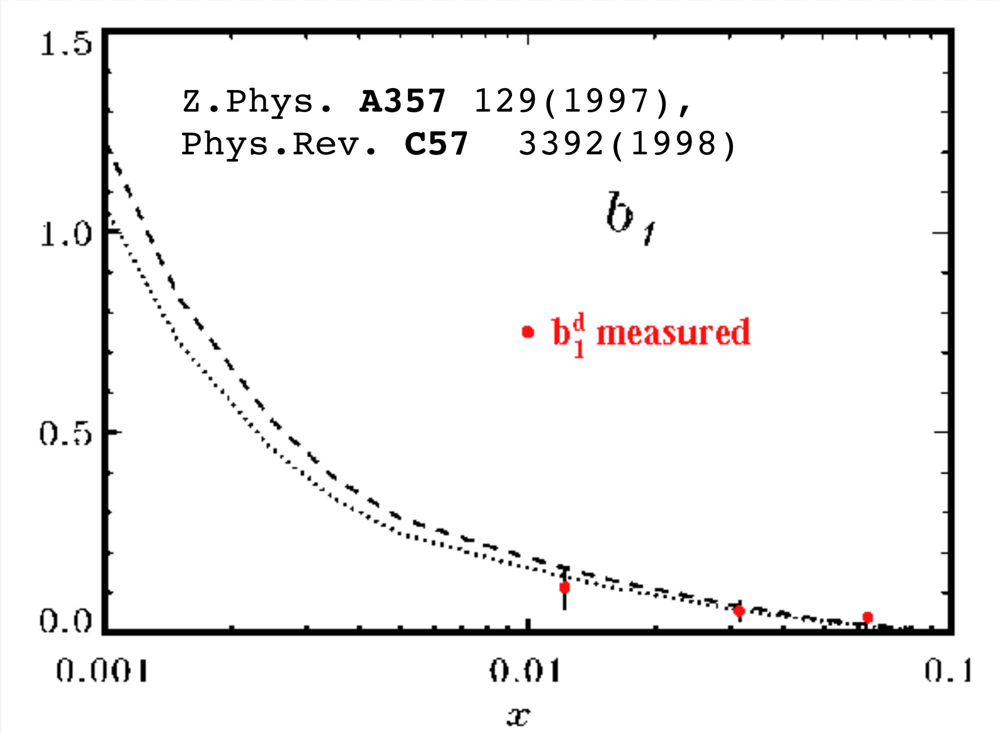
Possibilities

- Small *x* aspect of tensor pol. (deuteron) could access anti-shadowing and 2 nucleon scattering.
- Could also provide complementary information for OAM.
- A good starting point would be to extract b_1^d with an EIC.

Issues to Address:

- How well can polarization, beam stability be understood and controlled?
- Need to do simulation studies.

b_1^d Predictions



Bonn OBE

Paris

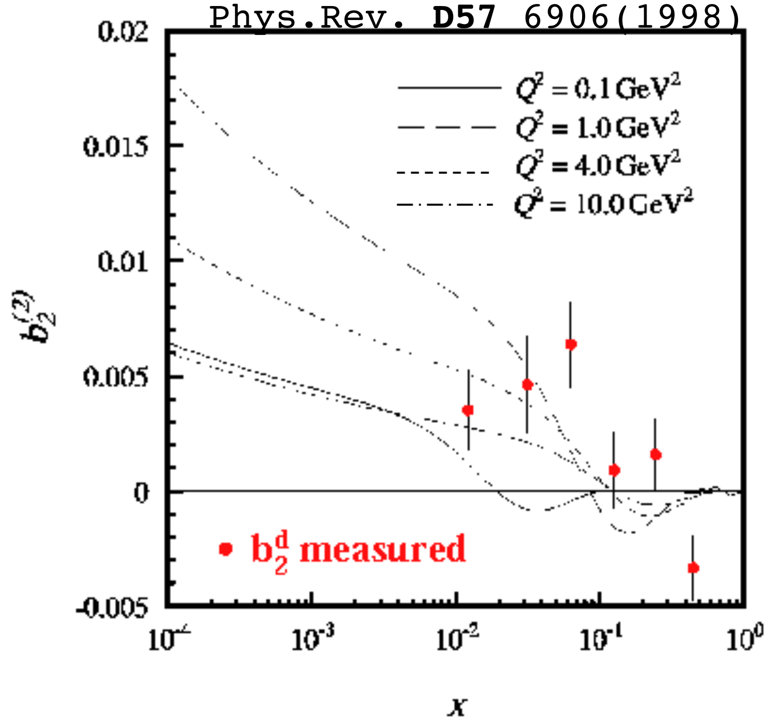
- Both models predict b_1 (rapidly) increasing as x->0.
- Errors for (HERMES) data shown are statistical only.

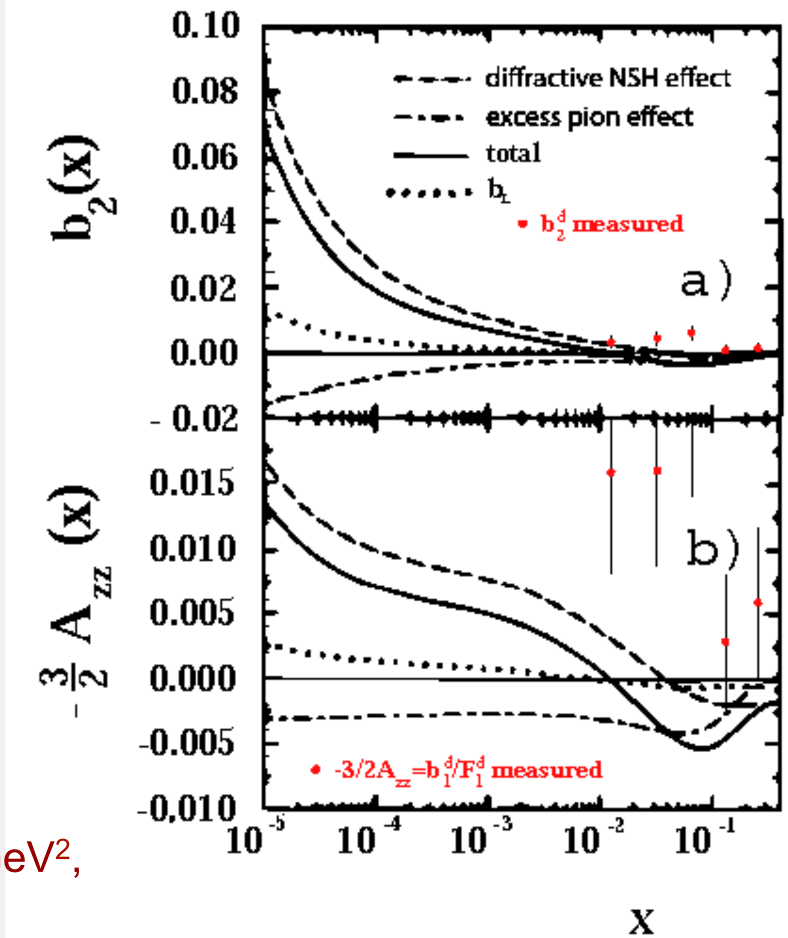
L. Frankfurt, V. Guzey, M. Strikman
Mod. Phys.Lett. **A21**(2006) 23-40

Predictions for b_2^d, A_{zz}^d

Phys.Lett. **B398** 245(1997)

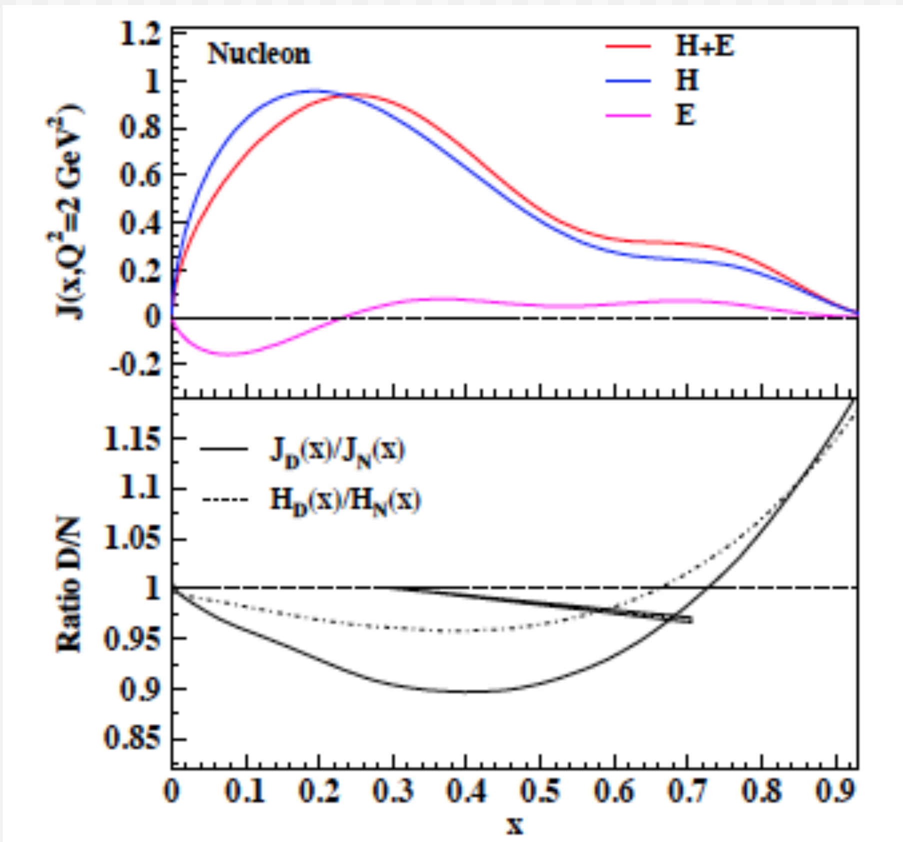
Phys.Rev. **D57** 6906(1998)





- Disentangling possible at lower x .
- (HERMES)Results shown are for Q^2=10 GeV^2, errors are statistical.

OAM Sum Rule



- OAM obtained from A_{UT} (vector pol.)
- Small, hatched area, for ratio, experimental (1109.6197[hep-ph])
- b_1^d adds complementary information.
- Further development in progress.

$$b_1^d \equiv H_5(x,0,0)$$

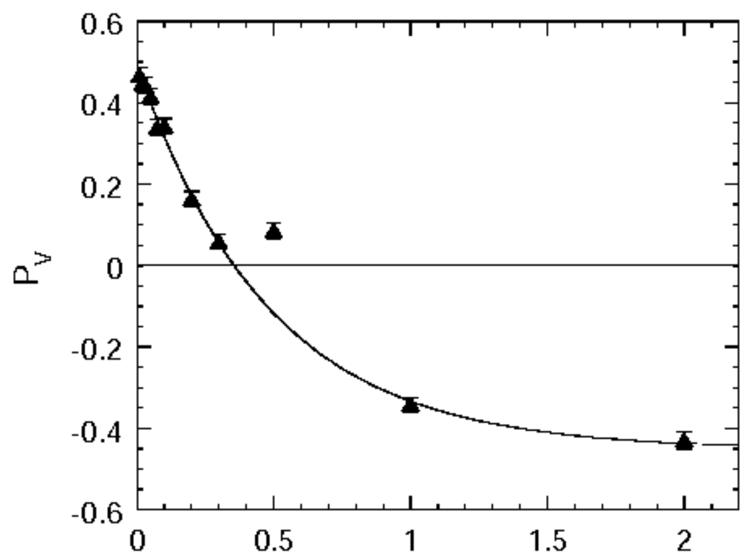
S. K. Taneja, K. Kathuria, S. Liuti, G. R. Goldstein Phys.Rev. D. **86** 036008

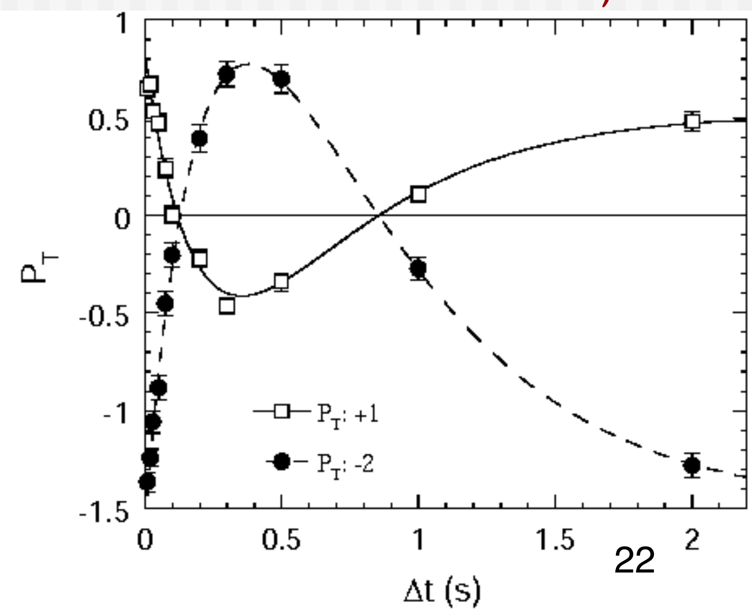
Deuteron Beam Polarization Studies

- Studied deuteron spin manipulation with a 270 MeV vertically polarized beam stored in IUCF storage ring. Similar study done at COSY.
- Beam Fast RF cycled through 4 vertical polarization states (to reduce systematic errors).
- Spin-1 linear combination: Flip by bunches or extract at experiment.
- Simulation in progress for MEIC (figure-8) concept.

$$(P_V, P_T) = (1,1), (-1,1), (0,1), (0,-2)$$

Thesis: V. Morozov)



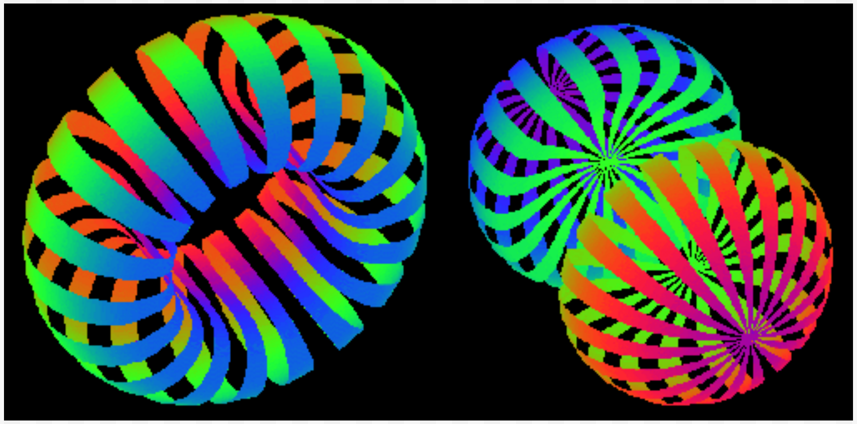


Summary

- Tensor Polarized deuteron provides Spin-1 quark/nuclear system.
- Spin-1 produces 4 new SSFs.
- HERMES measurement, complementary proposal at Jlab.
- Access to lower *x*, with tensor polarized deuteron, could open new physics capabilities.
- Study underway for polarized deuteron beam for MEIC.
- Physics needs some considerable development.

*Many thanks to C. Weiss, V. Morozov, S. Liuti

Support Slides



Spin-1 Structure Functions

	Nucleon	Deuteron
b_1	...	$\frac{1}{2}\sum_q e_q^2\left[2q_\uparrow^0 - (q_\uparrow^1 + q_\downarrow^{-1})\right]$

From reflection-symmetry

$$q_\uparrow^m = q_\downarrow^{-m}$$

b_1 d.n.e for spin-1/2 and vanishes in absence of nuclear effects.
In relative S-state b_1 describes difference between helicity-0 and averaged nonzero.

$$q^0 = (q_\uparrow^0 + q_\downarrow^0) = 2q_\uparrow^0$$

$$q^1 = (q_\uparrow^1 + q_\downarrow^1) = (q_\uparrow^1 + q_\uparrow^{-1})$$

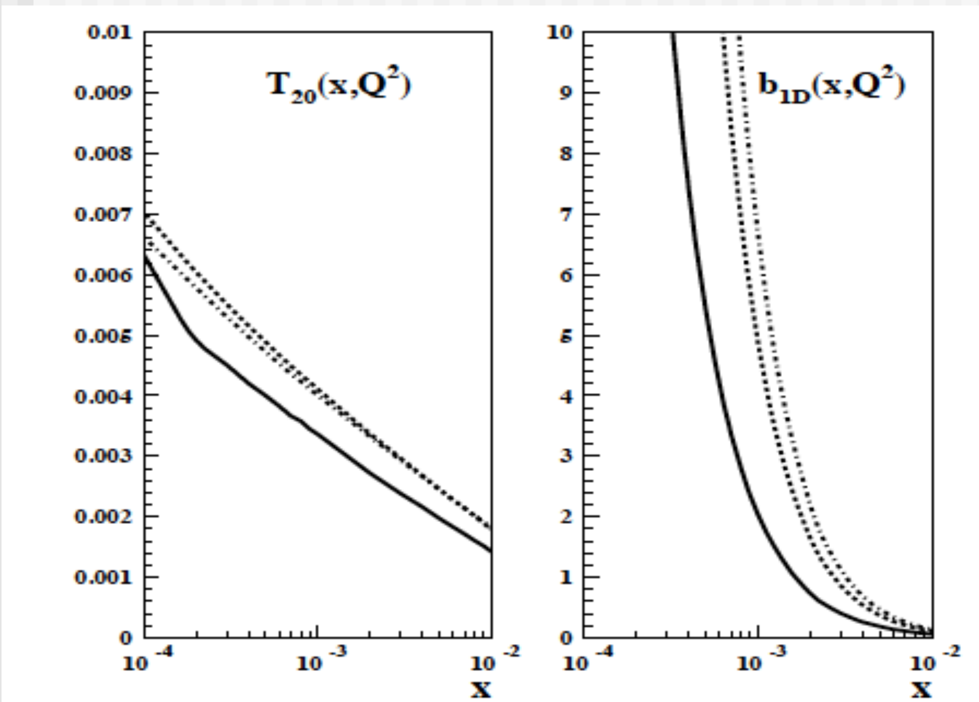
b_1 depends only spin-averaged distributions

$$\frac{1}{2}\sum_q e_q^2\left[q^0 - q^1\right]$$

Hoodbhoy,Jaffe, Manohar (1989)

Tens. Pol. Scattering at low *x*

L. Frankfurt, V. Guzey, M. Strikman
Mod. Phys.Lett. **A21**(2006) 23-40



Solid curve: Q^2 2 GeV^2
Dashed: 5 GeV^2
Dotted: 10 GeV^2

$$T_{20} = 2\left(\frac{\sigma^+ - \sigma^0}{\sigma^+ + \sigma^0}\right)$$

$$b_1^d(x,Q^2) = -\frac{F_2^d(x,Q^2)}{2x} T_{20}(x,Q^2)$$

b_1 Collaboration

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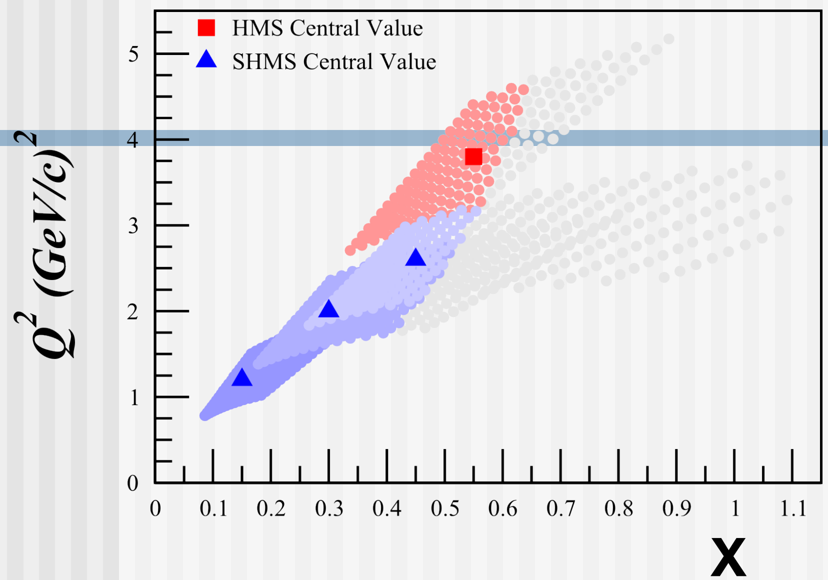
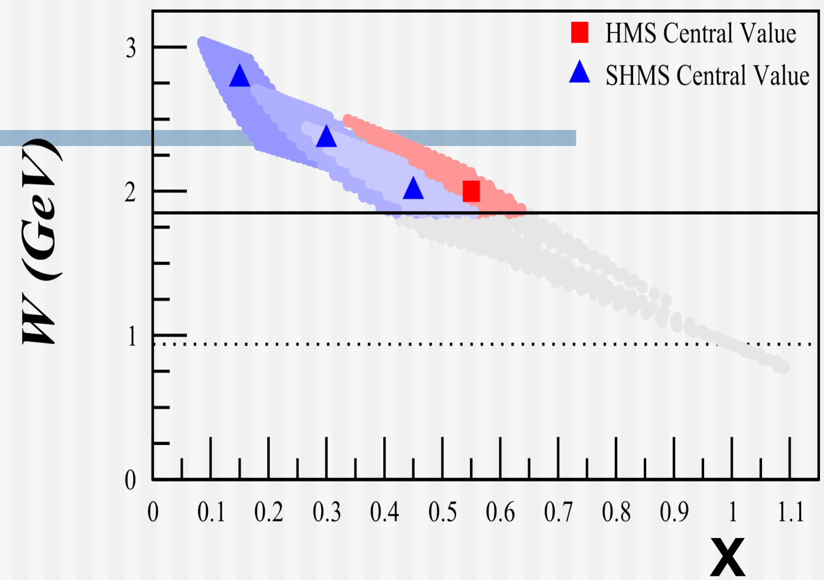
UIUC

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

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 :

Systematics

$\delta\xi$ (bracketing the following four items):

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

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

Target dilution and length step like changes observable in polarimetry
< 1×10^{-4}

Beam Position Drift effect on Acceptance
< 1×10^{-4} (we can control the beam to 0.1 mm, raster over 2cm diameter)

Effect of using polarized beam
< 2.2×10^{-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%

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. Sargsian et al.

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

Polarized Target

Dynamic Polarization of ND_3

5 Tesla or 7.5 Tesla

3 cm target length, 2 cm diameter

Longitudinally polarized

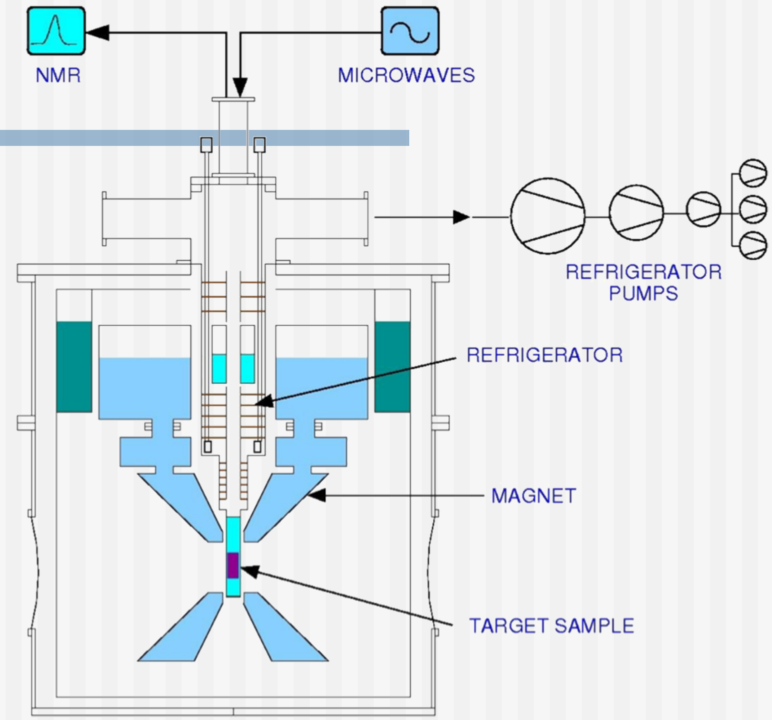


fig. courtesy of C. Keith

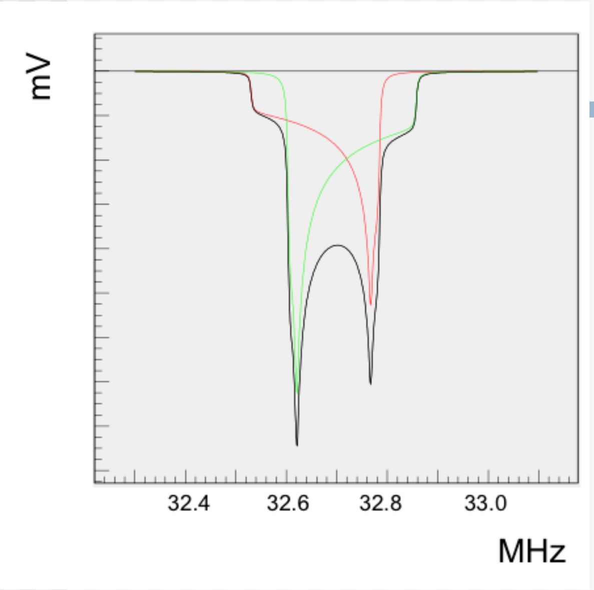
Run in Polarized and Unpolarized Mode.

B Field held at const value for both states

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

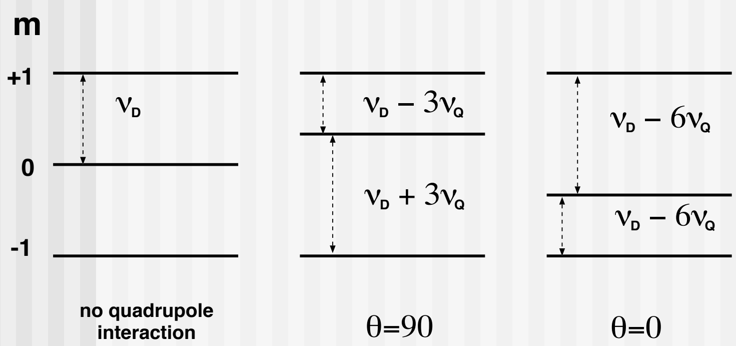
RF Saturation to Enhance P_{zz}

ND_3 Vector polarized



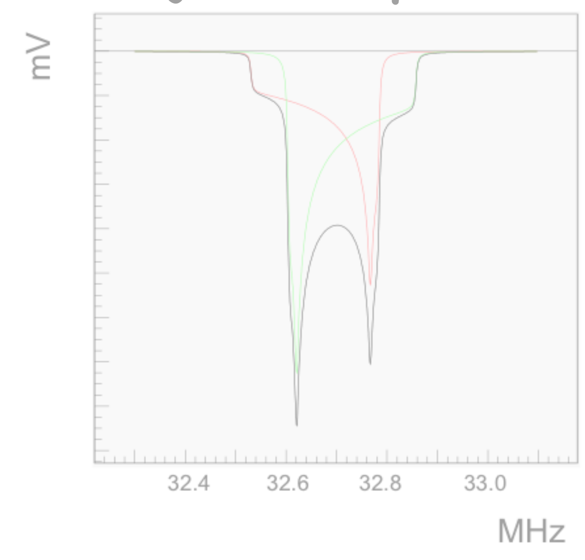
Vector Polarization ∞ Sum of Peak Areas

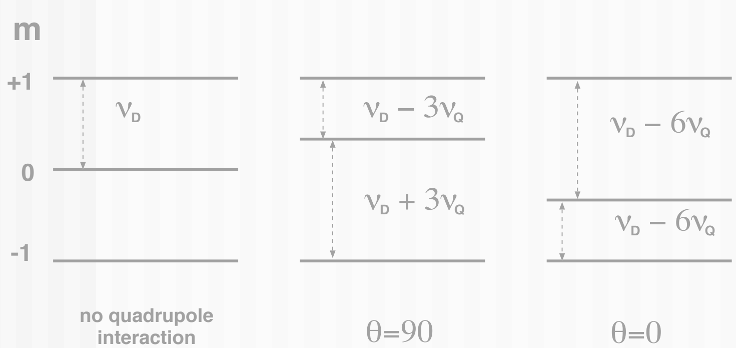
Tensor Polarization ∞ Diff of Peak Areas



RF Saturation to Enhance P_{zz}

ND$_3$ Vector polarized



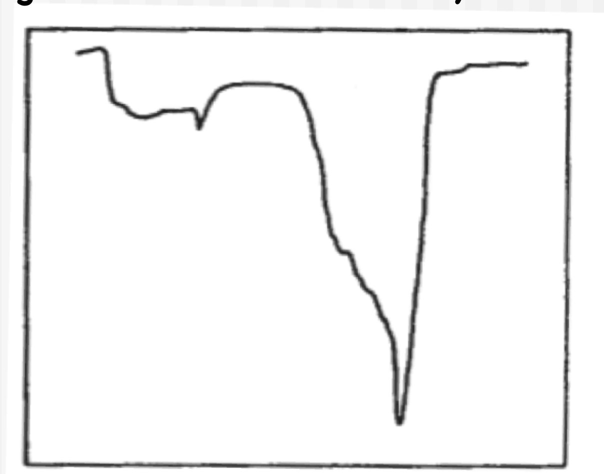


RF Saturate one of the peaks

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

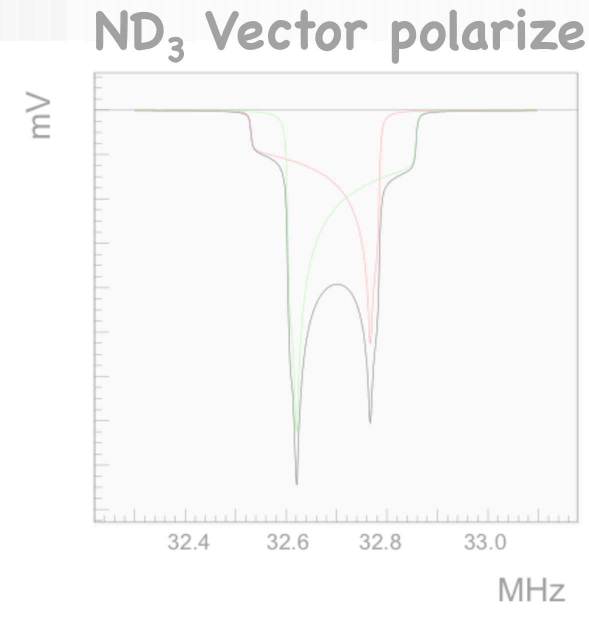
Pzz = 20% for 2.5T at 1K

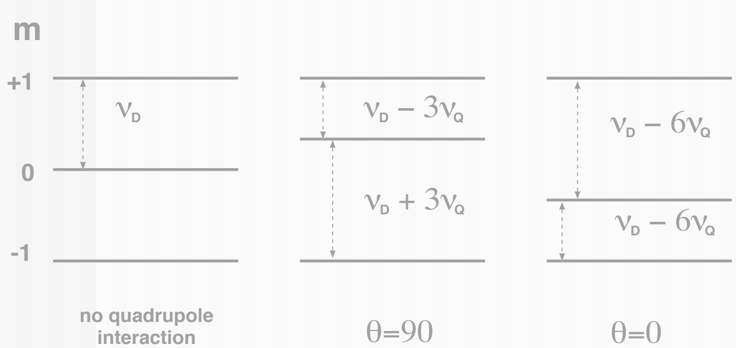
good results even with only 2.5 T field



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

RF Saturation to Enhance P_{zz}

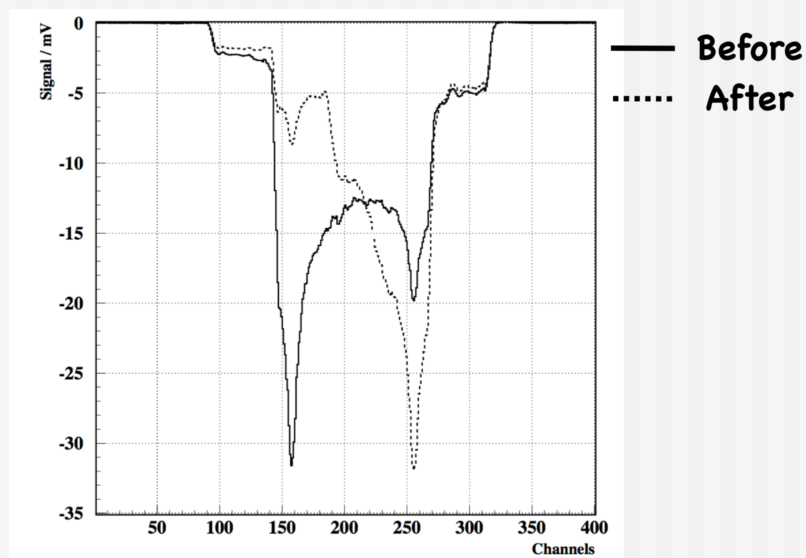




RF Saturate one of the peaks

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

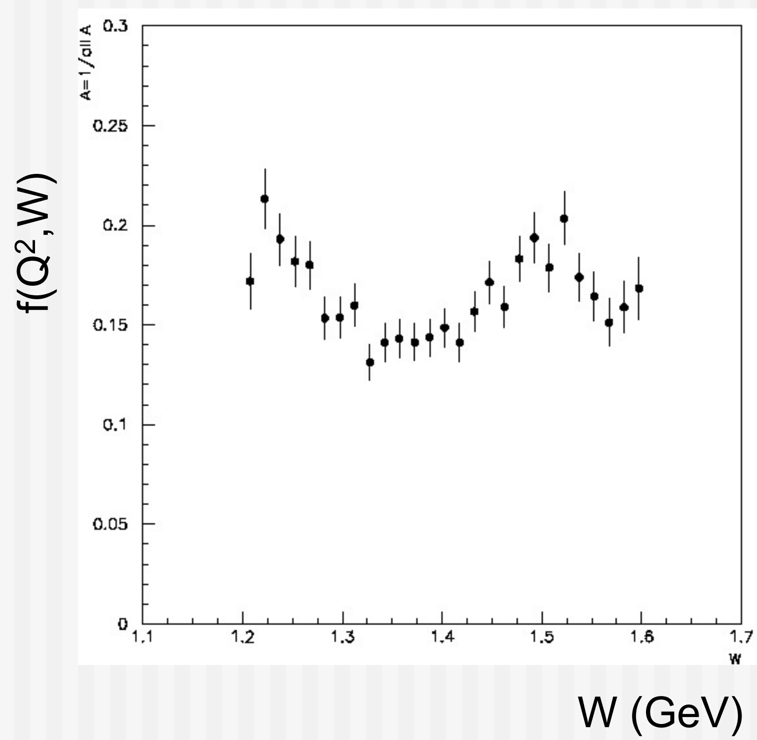
Pzz = 30% for 5.0 T at 1K

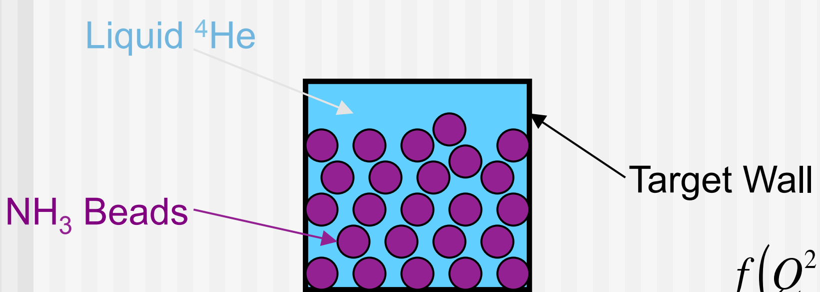


S. Bueltmann, et al (D. Crabb Lab) 1999.

Packing-Fractions & Dilution-Factors

- Packing Fraction essentially amount of material in target cup. This is a number.
- Dilution Factor (*f*) ratio of rates of free polarizable nucleons (proton) to all nucleons composing the target sample (nitrogen, NMR coils, …). This is kinematics dependant.
- Need Packing Fraction and Dilution Factor for each target load used during running of experiment.





$$f\left(Q^2,W\right)=\frac{N_1\sigma_1\left(Q^2,W\right)}{N_{14}\sigma_{14}(Q^2,W)+N_1\sigma_1\left(Q^2,W\right)+\sum N_A\sigma_A\left(Q^2,W\right)}$$