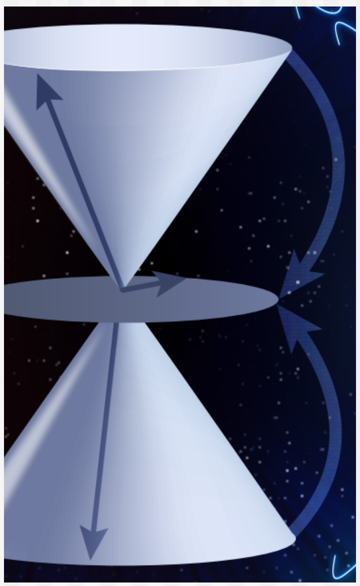
(Tensor) Polarized Deuteron at an EIC



Next Gen. Physics @ JLab12/EIC Workshop

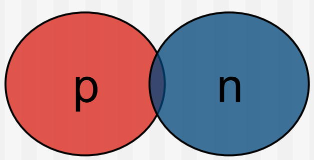
February 12, 2016

Narbe Kalantarians

Hampton University

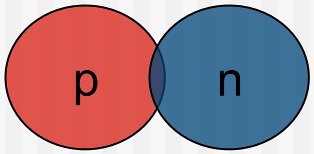
Outline

- Background/Motivation
- Spin-1/Tensor-Polarization Concept
- Physics possibilities with an EIC

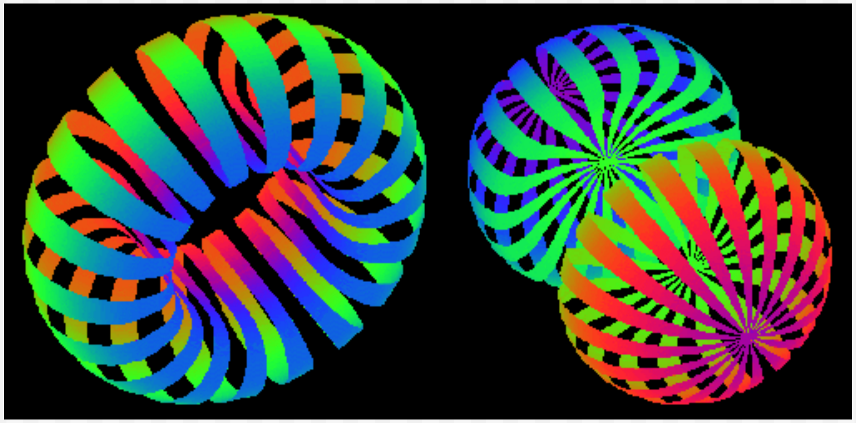


Why Deuteron?

- Relatively simple lab for nuclear physics
- Spin-1 system
- Reasonably "easy" to polarize.



Spatial distribution depends on the spin state



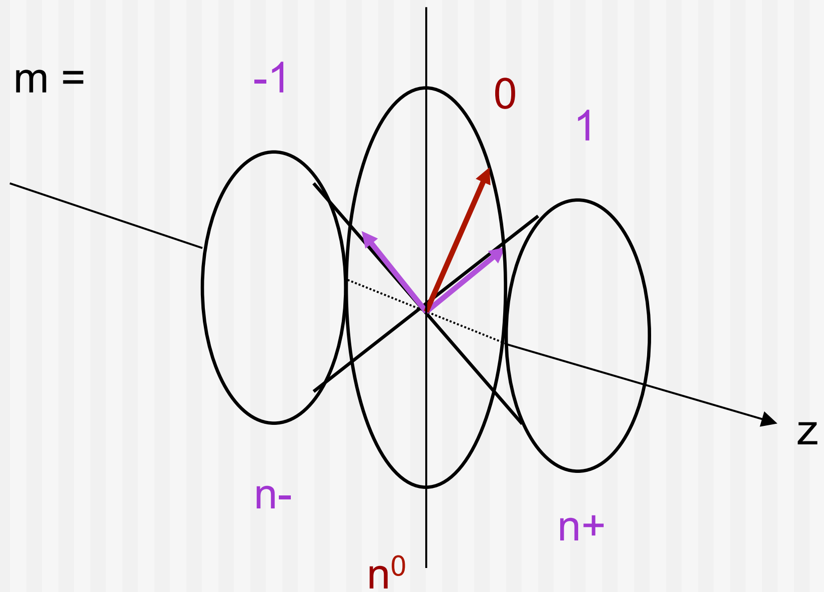
M = 0 M = ±1

J. Carlson, R. Schiavalla
Rev. Mod. Phys. **70** 743 (1998)

J.L. Forrest *et al.*
Phys. Rev. **C54** 646 (1996)

Spin-1

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

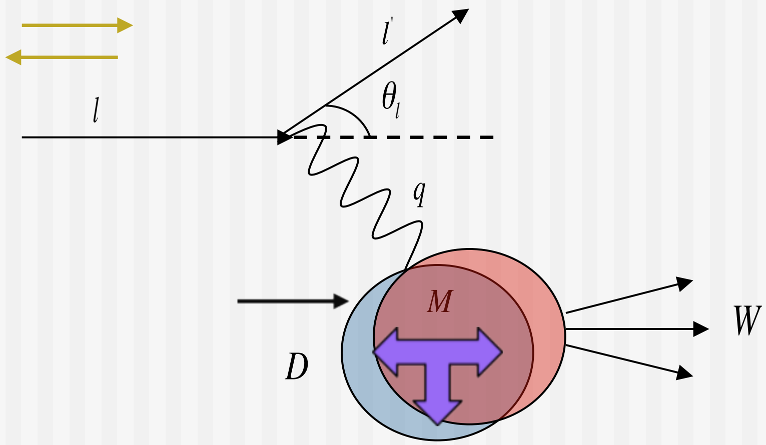


Vector polarization: (n+ - n^-); $-1 < P_z < +1$

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)

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}[\frac{1}{y}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)tan^2(\theta/2)] + \gamma g_1(x,Q^2) + \delta g_2(x,Q^2)$$

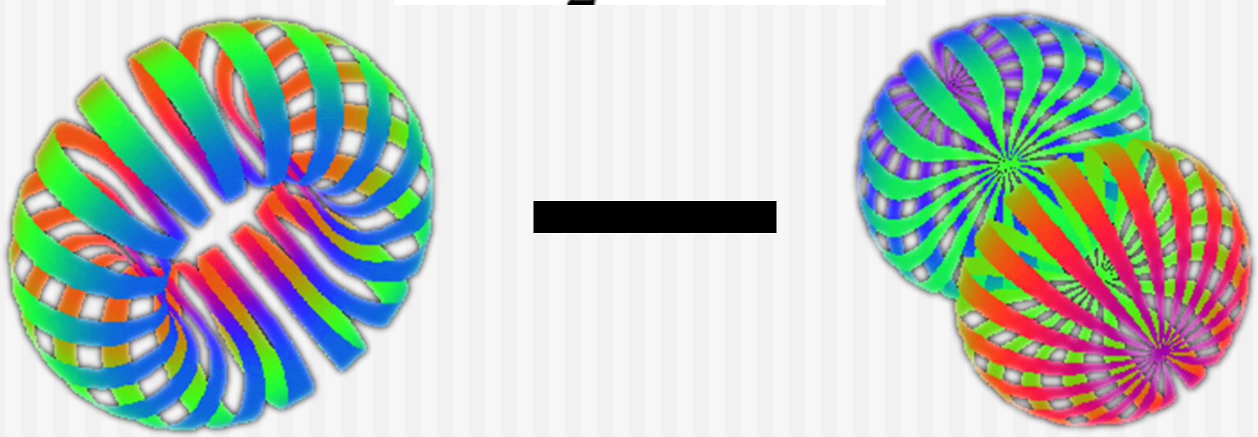
$$+\varsigma b_1(x,Q^2) + \epsilon b_2(x,Q^2) + \zeta b_3(x,Q^2) + \eta b_4(x,Q^2)$$

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

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

$b_1{}^d$

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



- 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.

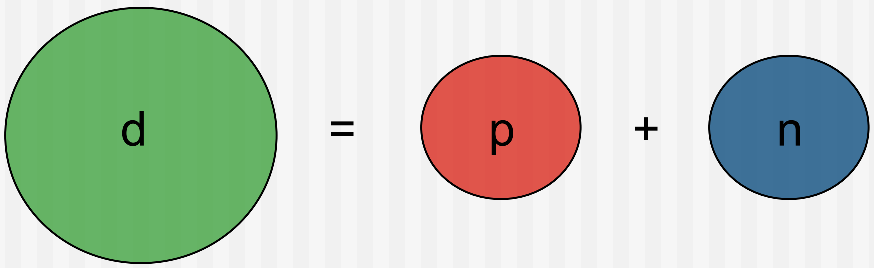
b_1^d

Hoodbhoy,Jaffe, Manohar (1989)

b_1 vanishes in the absence of nuclear effects.

Details in S. Kumano's Talk

i.e., if



p,n in relative S-state

Even accounting for D-state admixture, b_1^d 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

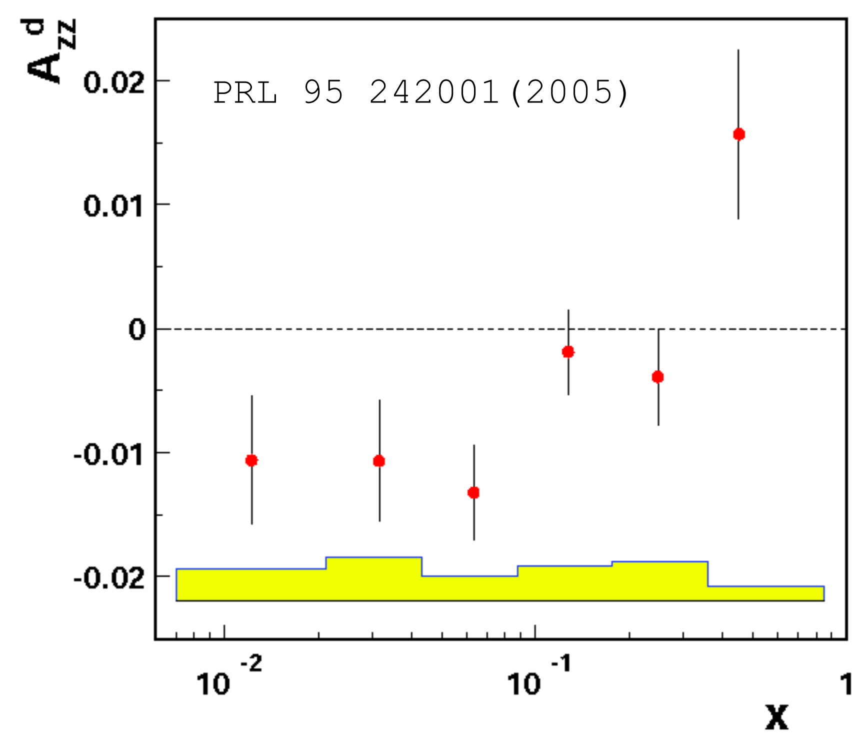
Experimental Method

Observable is the Normalized XS Difference: HERMES

$$\sigma_{meas} = \sigma_U[1 - P_B P_Z A_{\parallel} + \frac{1}{2} P_{ZZ} A_{ZZ}]$$

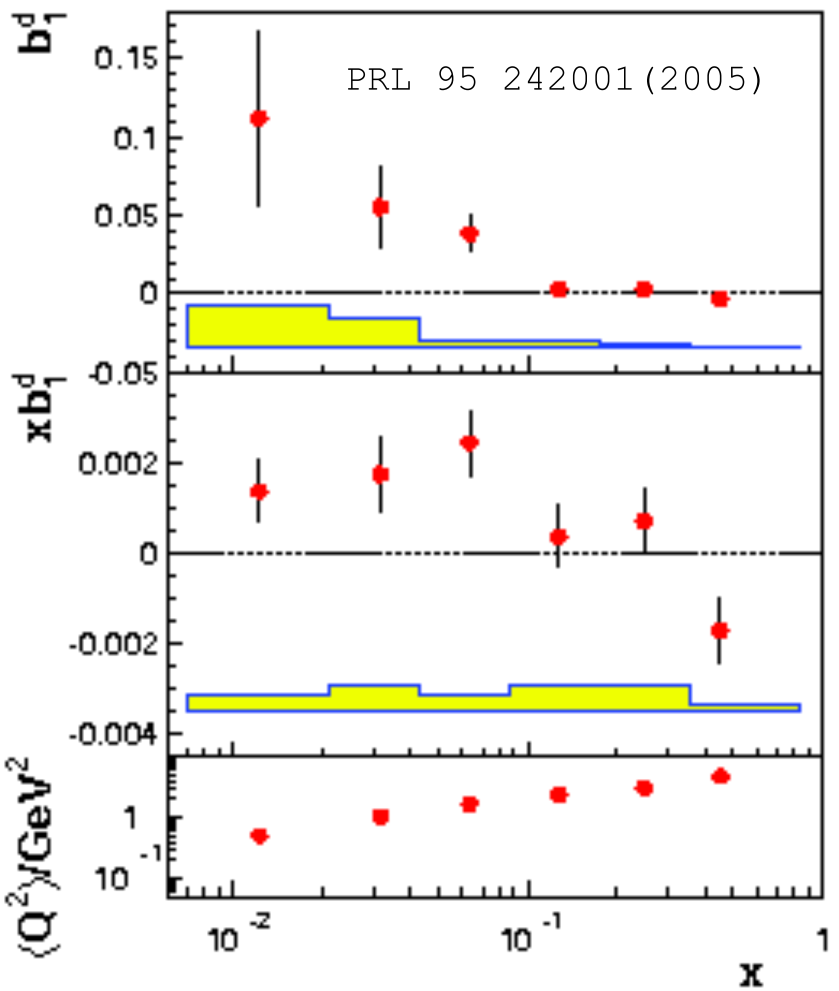
$$A_{ZZ} = \frac{1}{P_{ZZ}} \frac{2\sigma^1 - 2\sigma^0}{3\sigma^U}$$

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



$$P_{ZZ} = \frac{(n^+ + n^-) - 2n^0}{n^+ + n^- + n^0}, -2 < P_{ZZ} < 1$$

HERMES Measurement: b_1^d



$$b_1 = -\frac{3}{2} F_1 A_{ZZ} \qquad A_{ZZ} = \frac{1}{P_{ZZ}} \frac{2\sigma^1 - 2\sigma^0}{3\sigma^U}$$

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

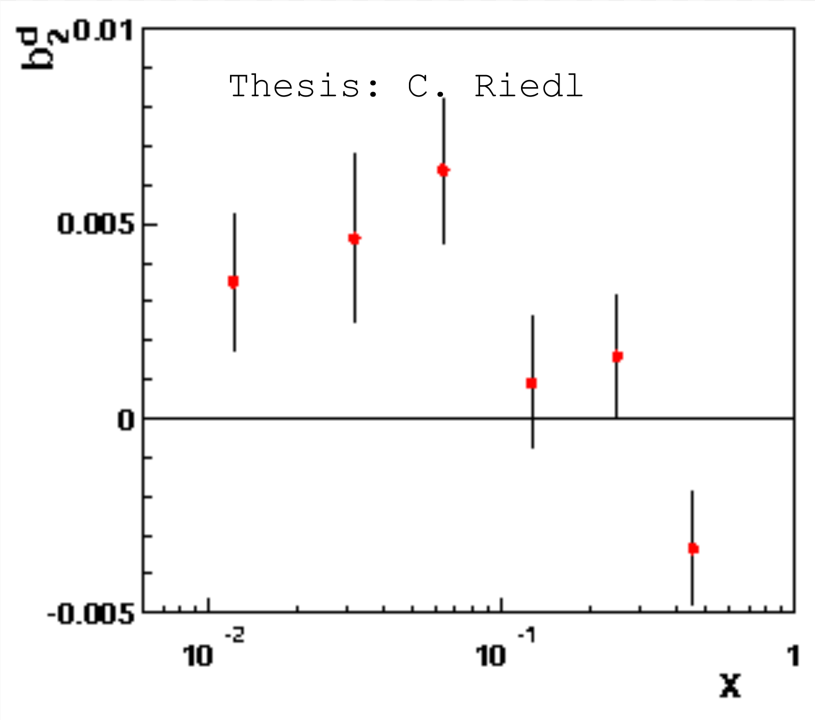
Ashman, *et al.* PLB 206 364(1988)

Can also be described in models involving double-scattering of leptons

HERMES Details in C. Riedl's thesis.

Proposed measurements at JLab12 (E. Long's talk).

HERMES Measurement: b_2^d



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

$$b_2 = 2xb_1 \frac{1+R}{1+\gamma^2}$$

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

HERMES Close-Kumano Sum Rule

F.E.Close,S.Kumano, PRD42 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 $Q^2 > 1 GeV^2$

PRL 95 242001(2005)

Physics @ EIC w/ (Tens.) Pol. Deuteron Beam

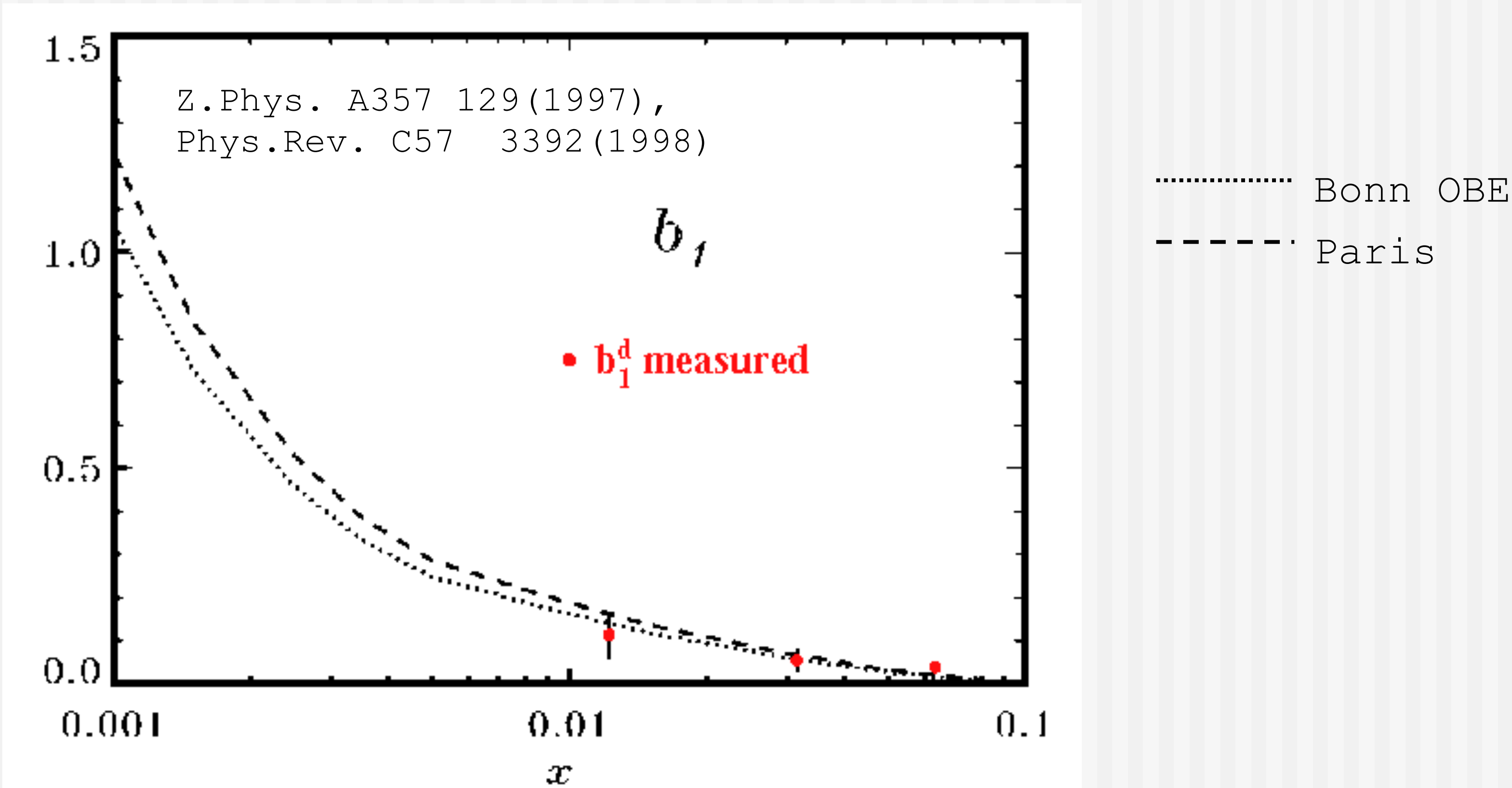
Possibilities

- A_{ZZ}, b_1^d, …. not very easy: susceptible to backgrounds(A_{PV}) and FSIs.
- With spectator (nucleon) tagging, can access angular modulations, as well as minimizing FSIs.
- With exclusive channels (DVCS); can access information for sum rules, enhance b_1.

Issues to Address:

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

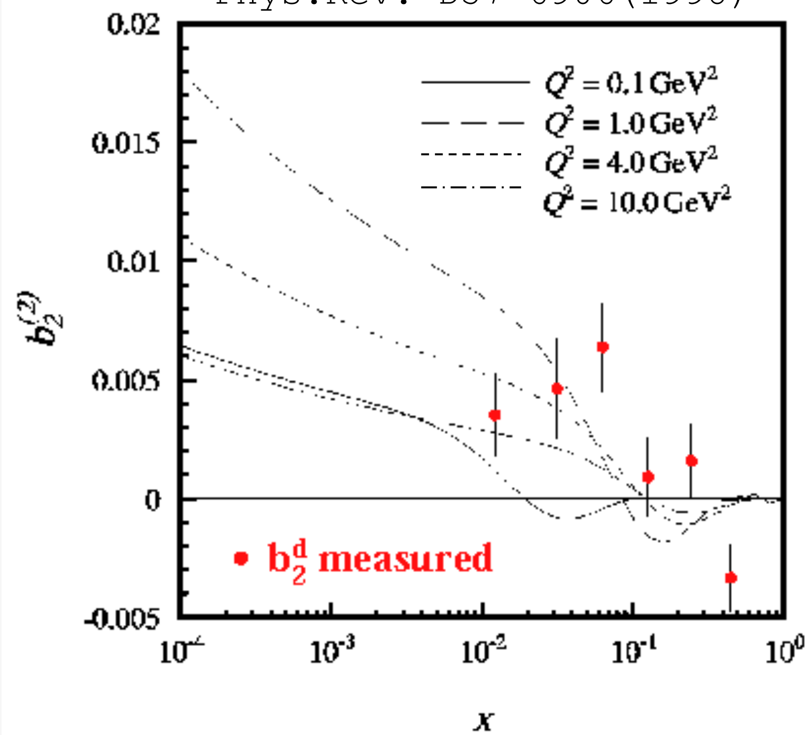
b_1^d Predictions



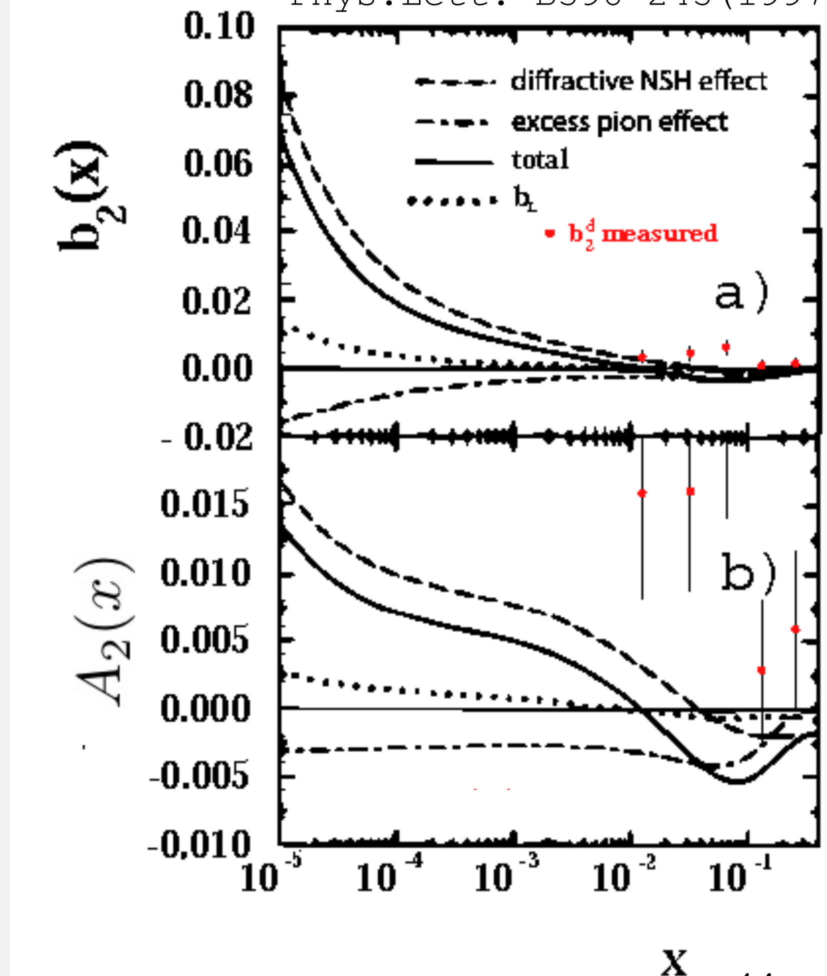
- Both models predict b_1 (rapidly) increasing as x->0: Double-scattering
- Errors for (HERMES) data shown are statistical only.

Predictions for b_2^d, $A_{2(zz)}^d$

Phys.Rev. D57 6906(1998)



Phys.Lett. B398 245(1997)

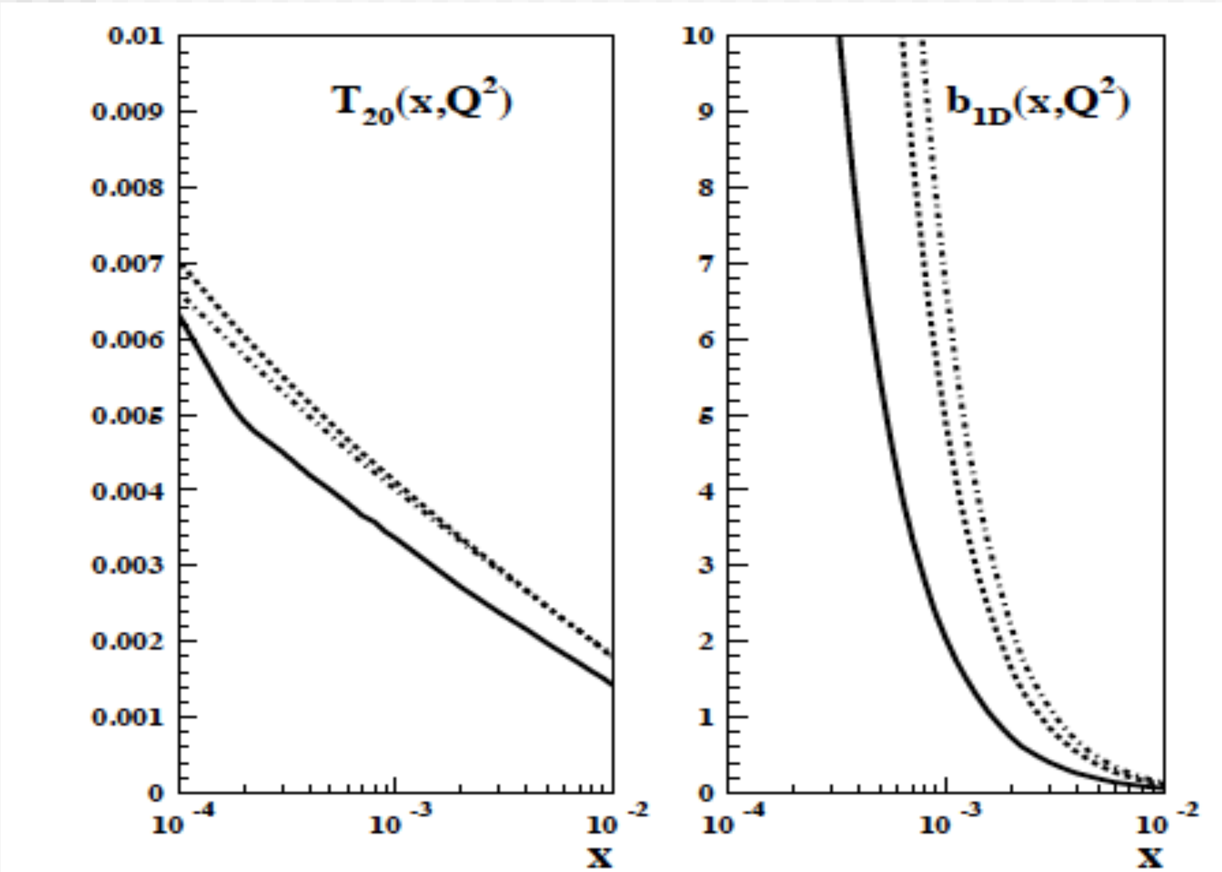


- Disentangling possible at lower *x* .
- (HERMES) errors are statistical here; $Q^2 = 10GeV^2$

$$A_2(x, Q^2) = \frac{b_2(x, Q^2)}{F_2(x, Q^2)}$$

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

$$T_{20} = \frac{2\sigma^+ - 2\sigma^0}{2\sigma^+ - \sigma^0}$$

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

Exclusive

H_5 ➔ b_1

Liuti, Kathuria, J.Phys.Conf.Ser. 543 (2014)
Taneja,Kathuria,Liuti,Goldstein, PRD86 (2012)

$$H_5(x,\xi,t) = \frac{1}{2}\left(2f_{00}^{11} - f_{++}^{11} - f_{--}^{11}\right)$$

$$= \int_x^2 dz f_D^{l=2}(z) H\left(\frac{x}{z},\frac{\xi}{z},t\right) + c_E \frac{\sqrt{t_0 - t}}{2M} E\left(\frac{x}{z},\frac{\xi}{z},t\right)$$

GPD E makes b_1 increase!

b_1 in forward limit

$$b_1^d = H_5(x,0,0)$$

(S. Liuti's talk).

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Cross Section Calculation w/ Tagging

**Carried out by W. Cosyn, M. Sargisian, and C. Weiss (very much in progress)

- Cross-section for pol. Deuteron, w/ tagged nucleon -> 16 SFs sensitive to tensor pol.
- These all go like the deuteron S-D-wave interference and D-wave density so will be small.
- All have their own modulation with azimuthal angles like sin or cos($n\Phi_h$-Φ_{offset}) -with 2 different offset angles.
- There is a 4Φ_h modulation that does not appear in the unpolarized or vector-polarized part of the cross section.
- Integrated over all tagged nucleons (inclusive) 4 of the structure functions survive, which can be related to SSFs b_{1-4}.

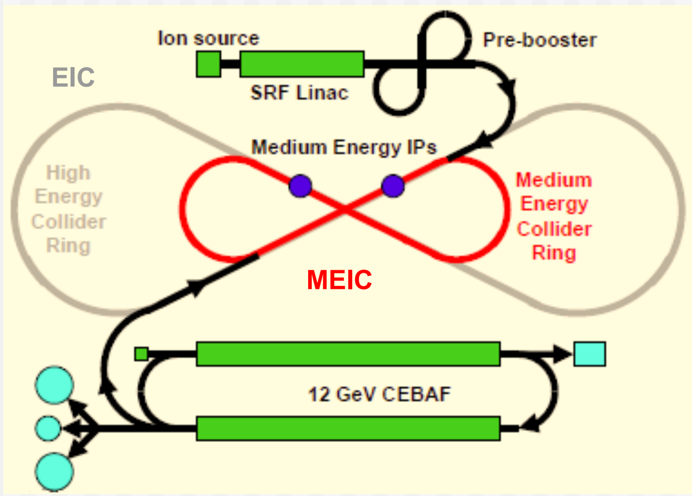
The (M)EIC at JLab (*nka* JLEIC)

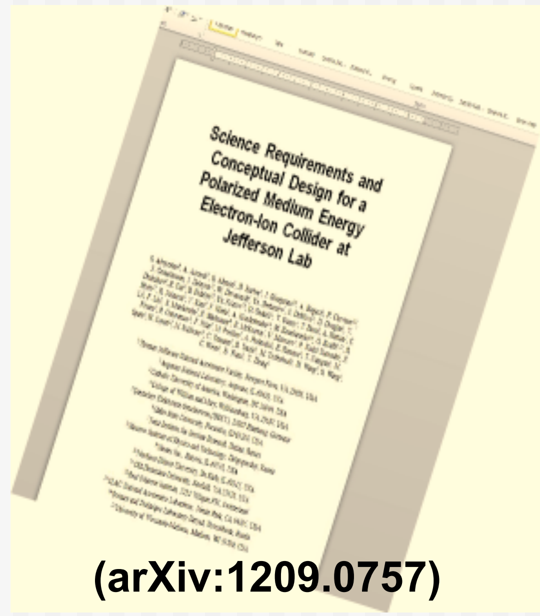
See P. Nadel-Turonski's Talk

- **12 GeV CEBAF is a full-energy lepton injector**
  - **Parallel running with fixed target possible**
- **Both the MEIC and CEBAF have a ~1.4 km circumference**
- **MEIC can store 20-100 GeV protons, or heavy ions up to 40 GeV/A.**
- **The stage II EIC will increase the energy to 250 GeV for protons and 20 GeV for electrons.**
- **Two detectors**
  - ***IP2 could host ePHENIX***

MEIC – design goals

P. Nadel-Turonski EICAC 2014





Spin control for all light ions

- Figure-8 layout
- Vector- and tensor polarized deuterium

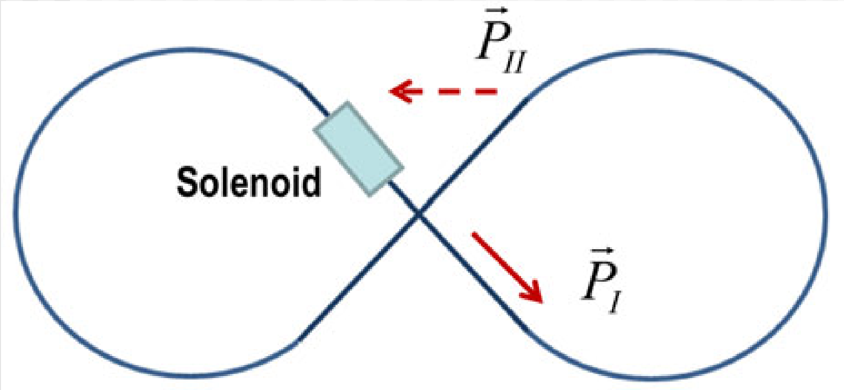
Full-acceptance detector

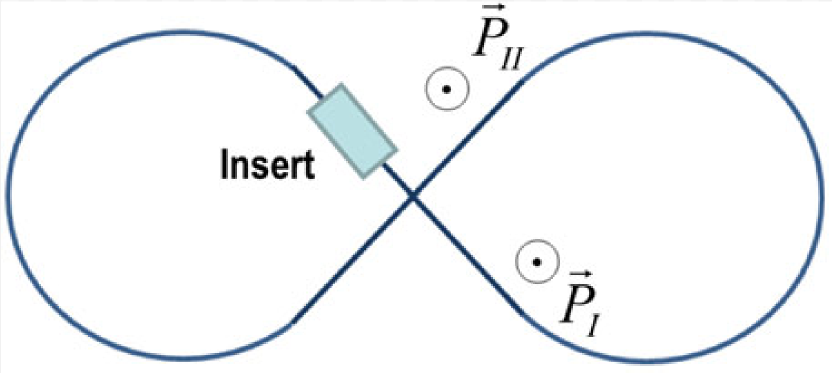
- Ring designed around detector requirements
- Detection of all fragments – nuclear and partonic

Stable concept – detailed design report released August 2012

Polarized Deuterons in Figure-8

Longitudinal **Transverse** **(arXiv:1209.0757)**





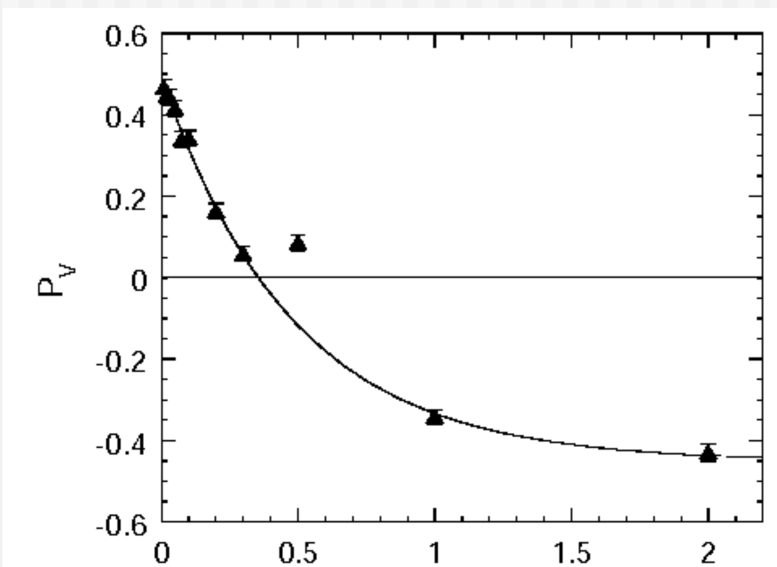
- Maintaining pol. deuteron difficult with present tech., due to small magnetic moment.
- Figure-8 design allows one to control the stable spin orientation with a small spin rotation around a certain axis using magnetic inserts.
- Deuteron pol. is then stable and points along the rotation axis at the insert's location.
- Simulations in progress for MEIC (figure-8) concept.

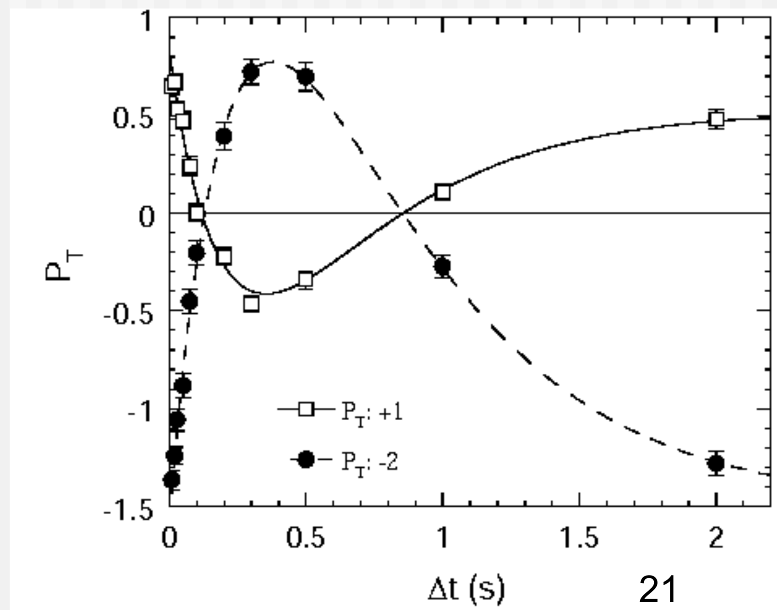
Deuteron Beam Polarization Studies

- 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.

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

Thesis: V. Morozov



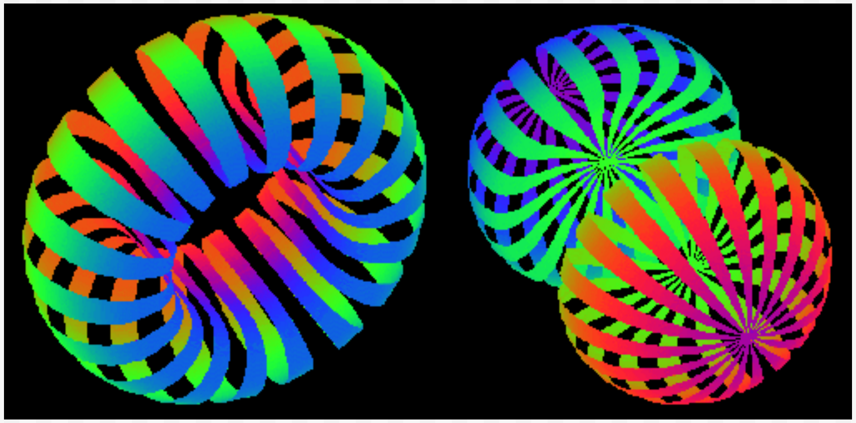


Summary

- (Tensor) Polarized deuteron provides Spin-1 quark/nuclear system.
- Spin-1 introduces new observables of interests.
- HERMES measurement, complementary proposals at Jlab12.
- Access to lower *x,* with tensor polarized deuteron, could open new physics capabilities.
- Study underway for polarized deuteron beam for MEIC –(others interested welcome to join!).

*Many thanks to W. Cosyn, V. Morozov, S. Liuti, P. Nadel-Turonski C. Weiss

Support Slides



Spin-1 Structure Functions

Leading Twist: F_1, g_1, b_1

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

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

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

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

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

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.

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

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

b_1 depends on spin-averaged distributions

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

Hoodbhoy, Jaffe, Manohar (1989)

Spin-1 Structure Functions

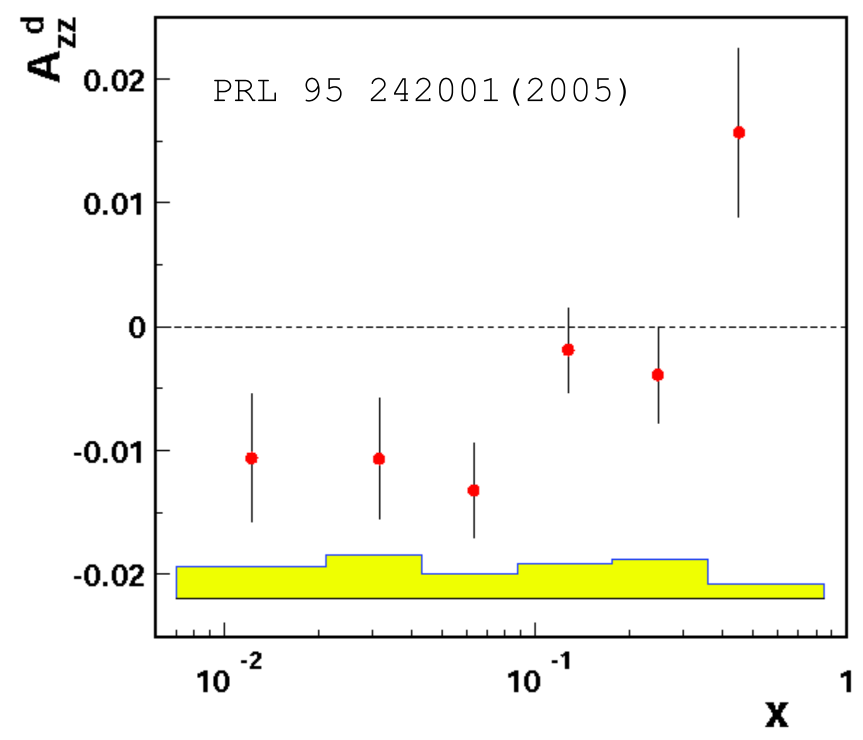
Leading Twist: F_1, g_1, b_1

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

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.

HERMES Measurement: A_{zz}^{d}

**HERMES result was about 2σ from 0.



$$0.01 < x < 0.45$$

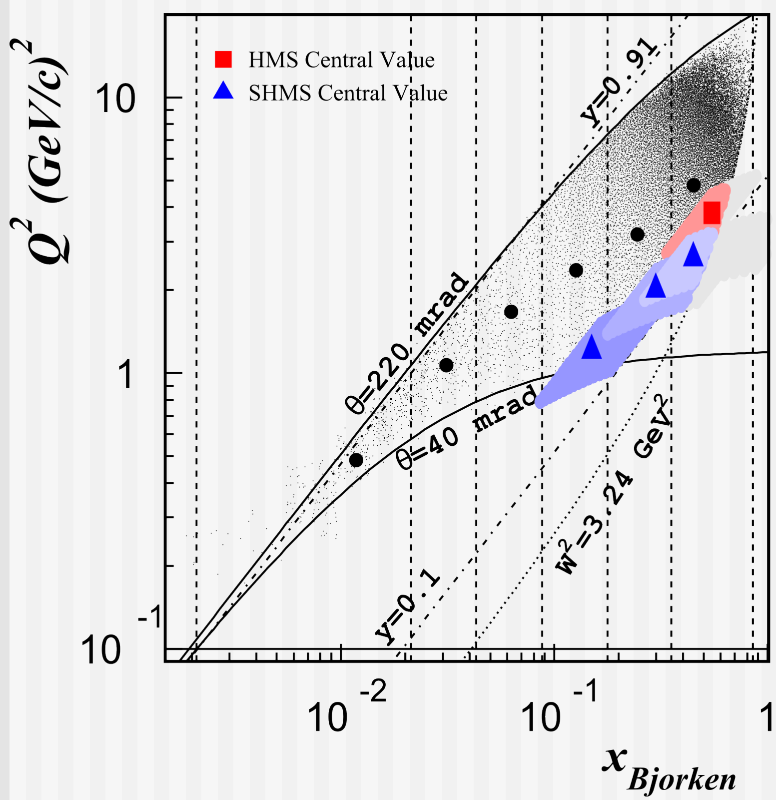
$$0.5 < Q^2 < 5GeV^2$$

- 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.

Tensor spin asymmetry

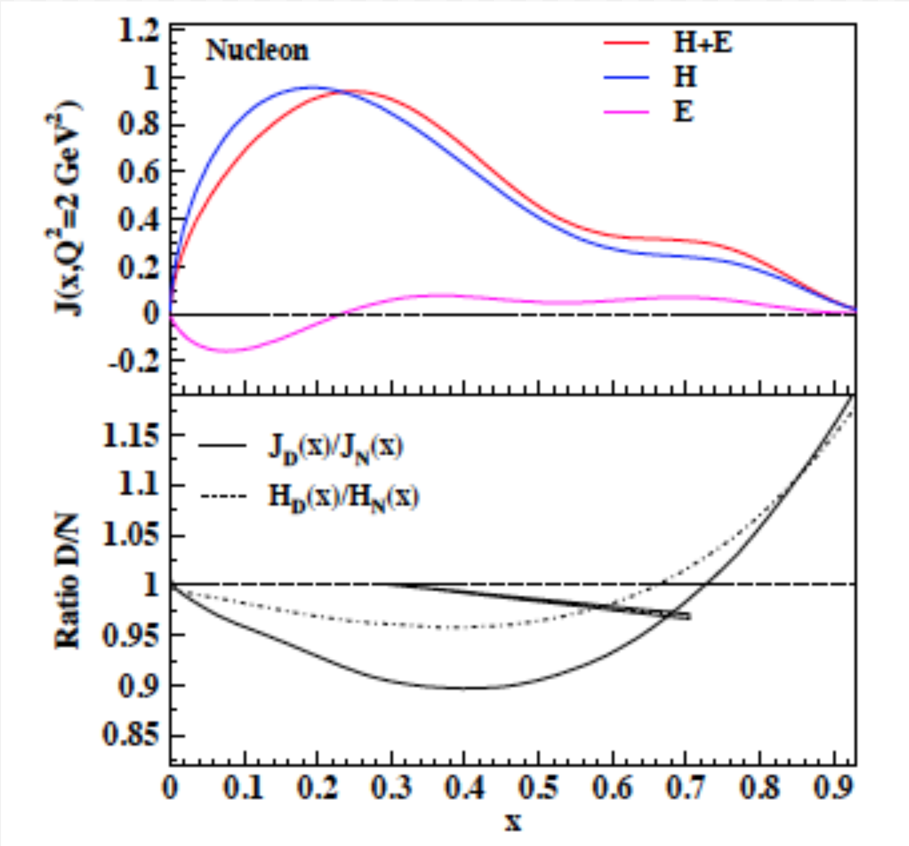
$$A_{ZZ} = \frac{1}{P_{ZZ}} \frac{2\sigma^1 - 2\sigma^0}{3\sigma^U}$$

Proposal To Determine b_1^d at JLab



- Measurement at Jlab 12GeV could be complementary to HERMES.
- Advantage would be higher luminosity: $\sim 10^{35} cm^{-2} s^{-1}$ compared to $\sim 10^{31} cm^{-2} s^{-1}$.
- Some research has been done tensor polarizing solid deuteron (ND_3) target via NMR*: P_{zz}~0.2, dilution~0.24,0.36.
- Submitted at PAC 40; Conditionally approved.

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.

$$b_1^d = H_5(x, 0, 0)$$

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

(S. Liuti's talk).

MEIC accelerator parameters

		50 × 5 GeV^2		100 × 5 GeV^2	
		Proton	Electron	Proton	Electron
Beam energy	GeV	50	5	100	5
Collision frequency	MHz	748.5	748.5	748.5	748.5
Particles per bunch	10^{10}	*0.21*	*2.2*	*0.42*	*2.5*
Beam Current	A	*0.25*	*2.6*	*0.5*	*3*
Polarization	%	~80	>70	~80	>70
Energy spread	10^{-4}	~3	7.1	~3	7.1
RMS bunch length	mm	10	7.5	10	7.5
Horizontal emittance, normalized	µm rad	*0.3*	54	*0.4*	54
Vertical emittance, normalized	µm rad	*0.06*	5.4	*0.04*	5.4
Horizontal and vertical β*	cm	10 and 2	10 and 2	10 and 2	10 and 2
Vertical beam-beam tune shift		*0.015*	*0.014*	*0.014*	*0.03*
Laslett tune shift		*0.053*	*<0.0005*	*0.03*	*<0.001*
Distance from IP to 1st quad	m	7 (downstream) 3.5 (upstream)	3	7 (downstream) 3.5 (upstream)	3
Luminosity per IP*	$cm^{-2}s^{-1}$	**2.4 x 10^{33}**		**8.3 x 10^{33}**	

*** includes space-charge effects and assumes conventional electron cooling**

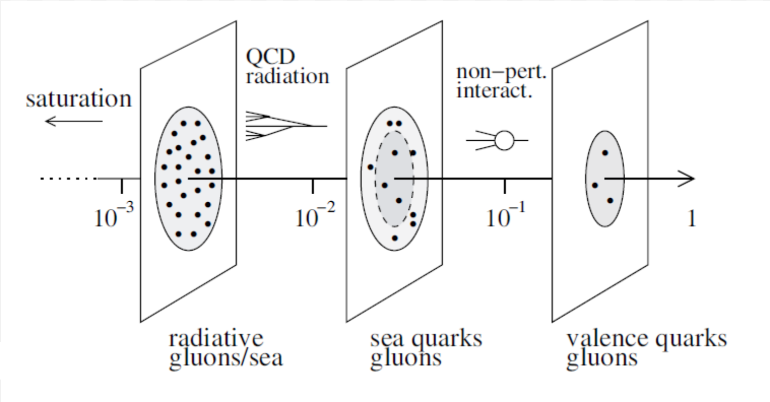
Red indicates parameters specific to the full-acceptance detector

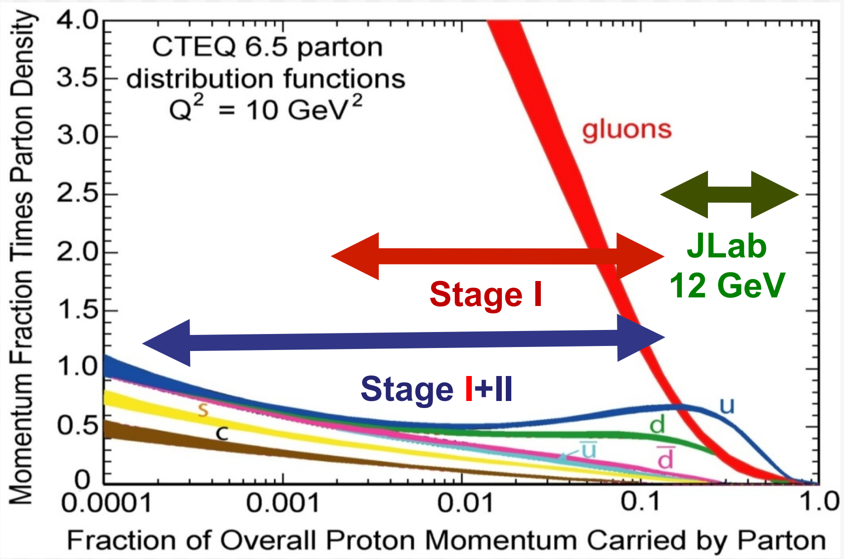
EIC Staging

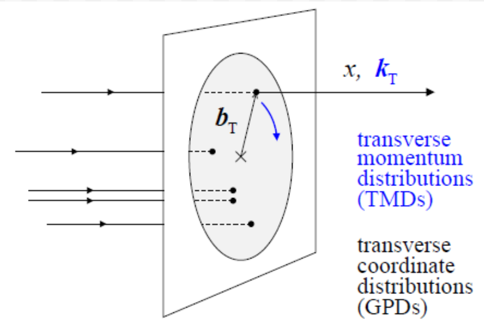
Already the first stage of an EIC gives access to sea quarks and gluons

Need polarization and good acceptance to detect spectators & fragments

An EIC aims to study the sea quark and gluon-dominated matter.



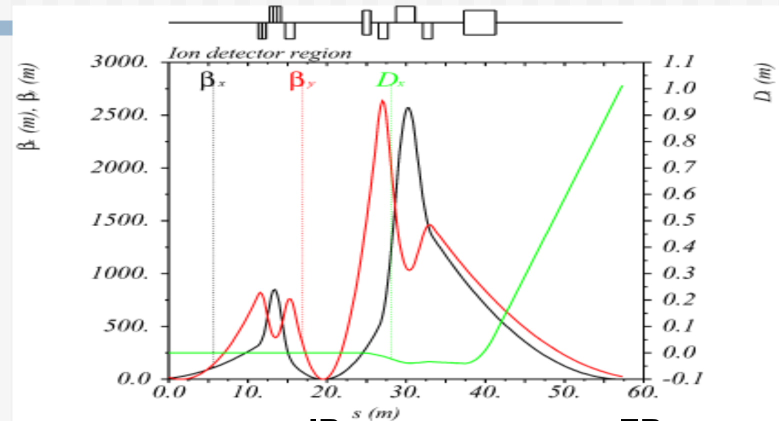




MEIC – full-acceptance detector

Design goals:

1. Detection/identification of complete final state
2. Spectator p_T resolution << Fermi momentum
3. Low-Q^2 electron tagger for photoproduction



(from GEANT4, top view)