Nucleon Spin Results from the JLab Program

Hadronic Physics with
Lepton & Hadron Beams

Newport News, VA
9/5/2017

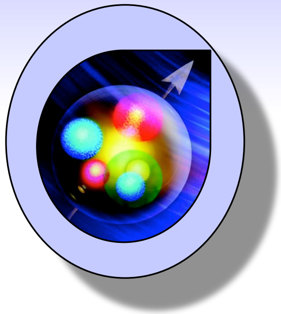
Karl Slifer
University of New Hampshire

This Talk

Brief Review

Inclusive Scattering & Structure Functions

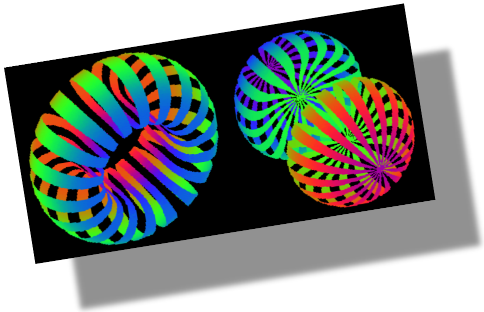
Spin Polarizabilities & Moments.



Spin Results

Halls A,B,C: g2p, sagdh, EG4, SANE

$0.04 < Q^2 < 6$ GeV^2



Tensor Structure Program

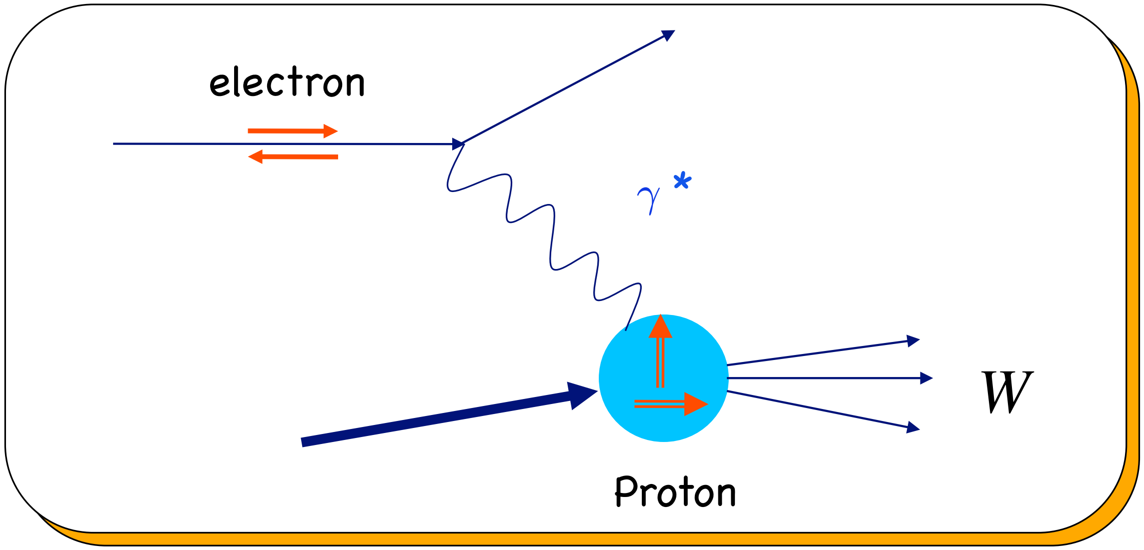
E12-13-011: "The *b_1 experiment*"

E12-15-005: "*A_{zz} for $x>1$*"

LOI-12-16-006: "Nuclear Gluometry"

Technical Developments

Inclusive Scattering



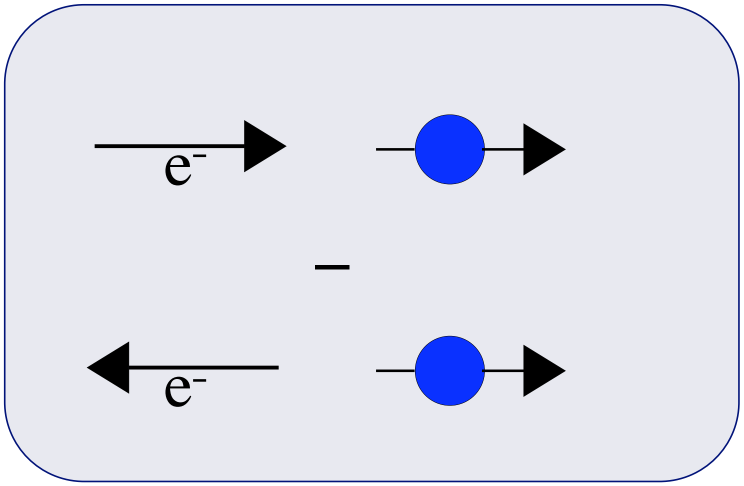
When we add spin degrees of freedom to the target and beam, 2 Additonal SF needed.

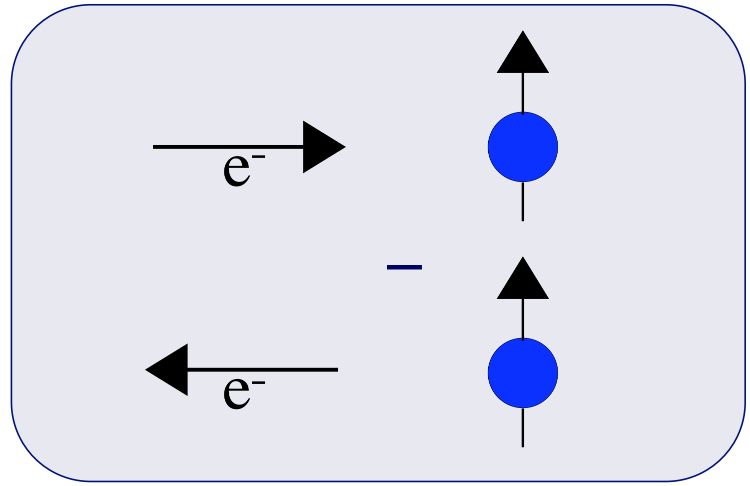
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

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

Inclusive **Polarized** Cross Section

Cross Section Differences





$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2}\frac{E'}{E}\left[(E + E'\cos\theta)\, g_1 - 2Mx g_2\right]$$

$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2}\frac{E'}{E}\sin\theta\left[g_1 + \frac{2ME}{\nu} g_2\right]$$

SSF Moments

Generalized GDH Sum

$$\Gamma_1(Q^2) = \int_0^{x_0} \mathrm{d}x\, g_1(x, Q^2)$$

Burkhardt Cottingham

$$\Gamma_2(Q^2) = \int_0^{x_0} dx \;\; g_2(x, Q^2)$$

Generalized Forward Spin polarizabilities

$$\gamma_0(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 g_{TT}(x, Q^2),$$

$$\delta_{LT}(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 \Big[g_1(x, Q^2) + g_2(x, Q^2) \Big]$$

$$g_{TT} \;=\; g_1 - (4M_N^2 x^2/Q^2) g_2$$

Thanks to these Collaborations

EG4 Proton : M. Ripani(Contact), M. Battaglieri, A. Deur, R. De Vita
H. Kang

EG4 Deuteron : A. Deur(Contact), G. Dodge, K. Slifer
K. Adhikari

g2p : K. Slifer (contact), JP Chen, D. Crabb, A. Camsonne
R. Zielinski, T. Badman

sagdh : JP Chen(contact), A. Deur
Chao Peng

SANE: O. Rondon(contact), M. Jones
W. Armstrong, Anushka Liyanage

E08-027 : Proton g_2 Structure Function

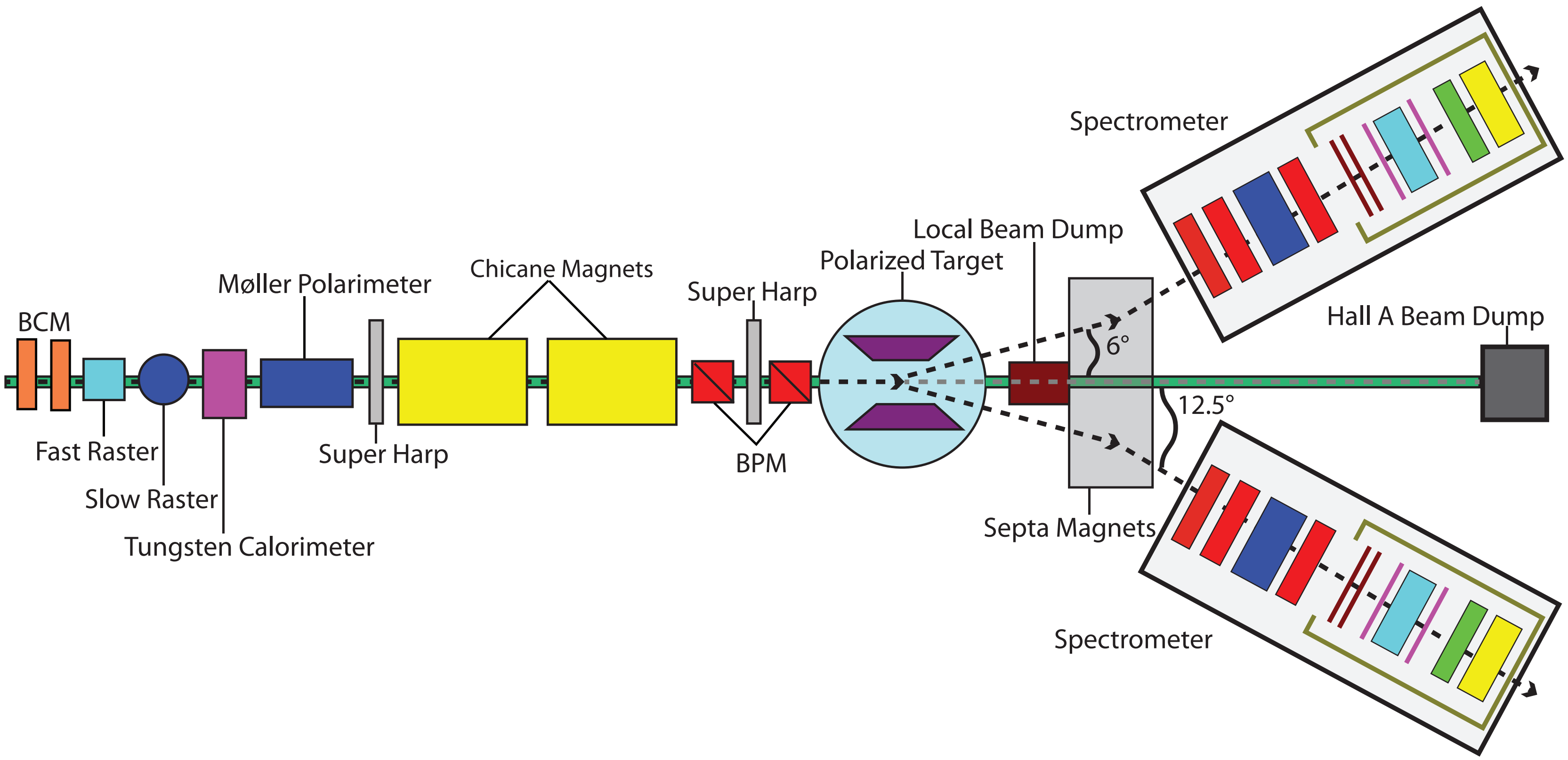
Camsonne, Crabb,

Chen, Slifer

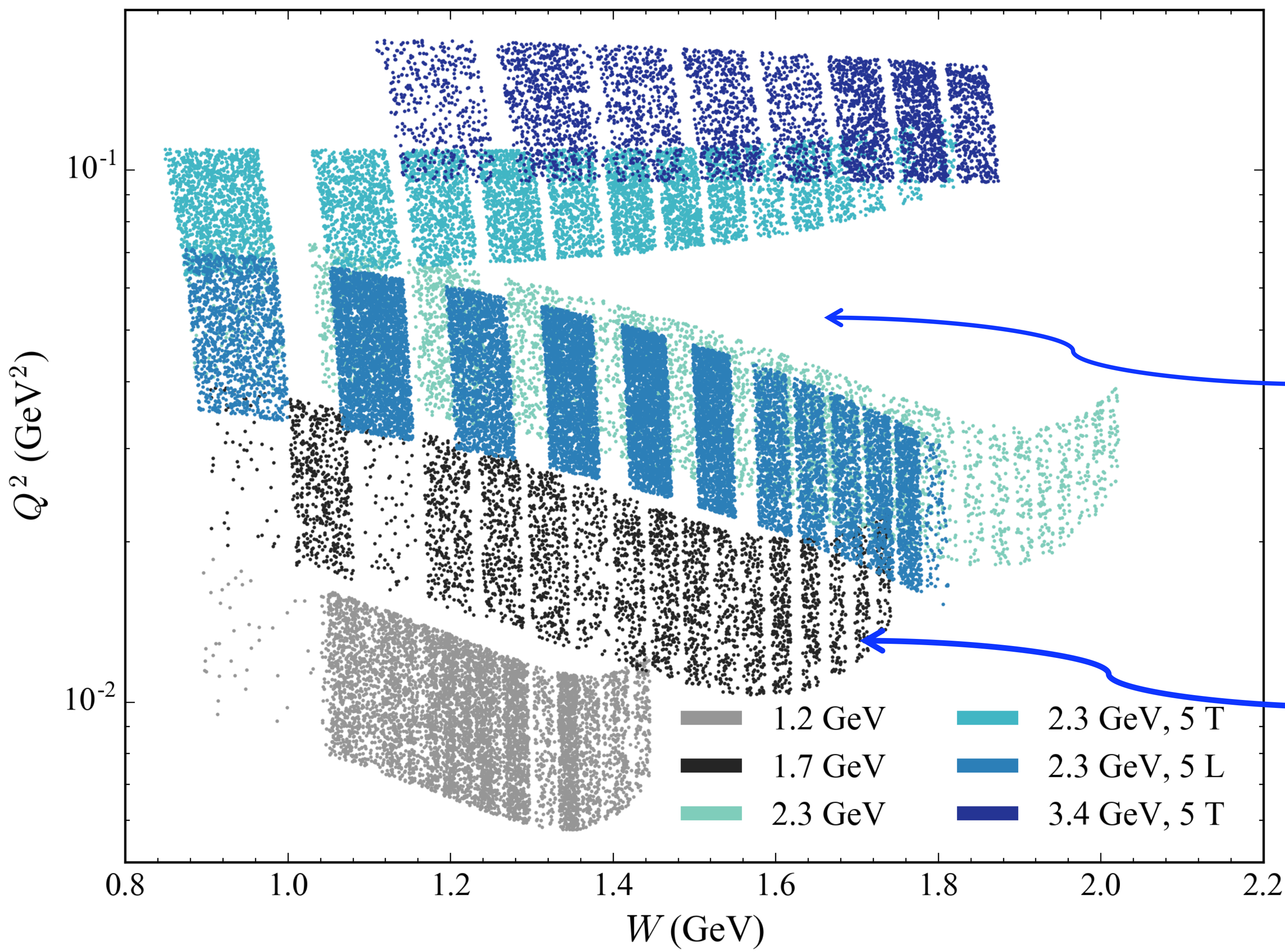
BC Sum Rule : violation suggested for proton at large Q^2, but found satisfied for the neutron & ^{3}He.

Spin Polarizability : Major failure (>8σ) of χPT for neutron δ_{LT}

Hydrogen HFS: Structure dependent corrections



E08-027 : Proton g_2 Structure Function



5T :Large Q^2 data final prepariing for publication

2.5 T Low Q^2 data preliminary finalizing dilution

courtesy R. Zielinski

Largest Installation in Hall A History

Polarized proton target

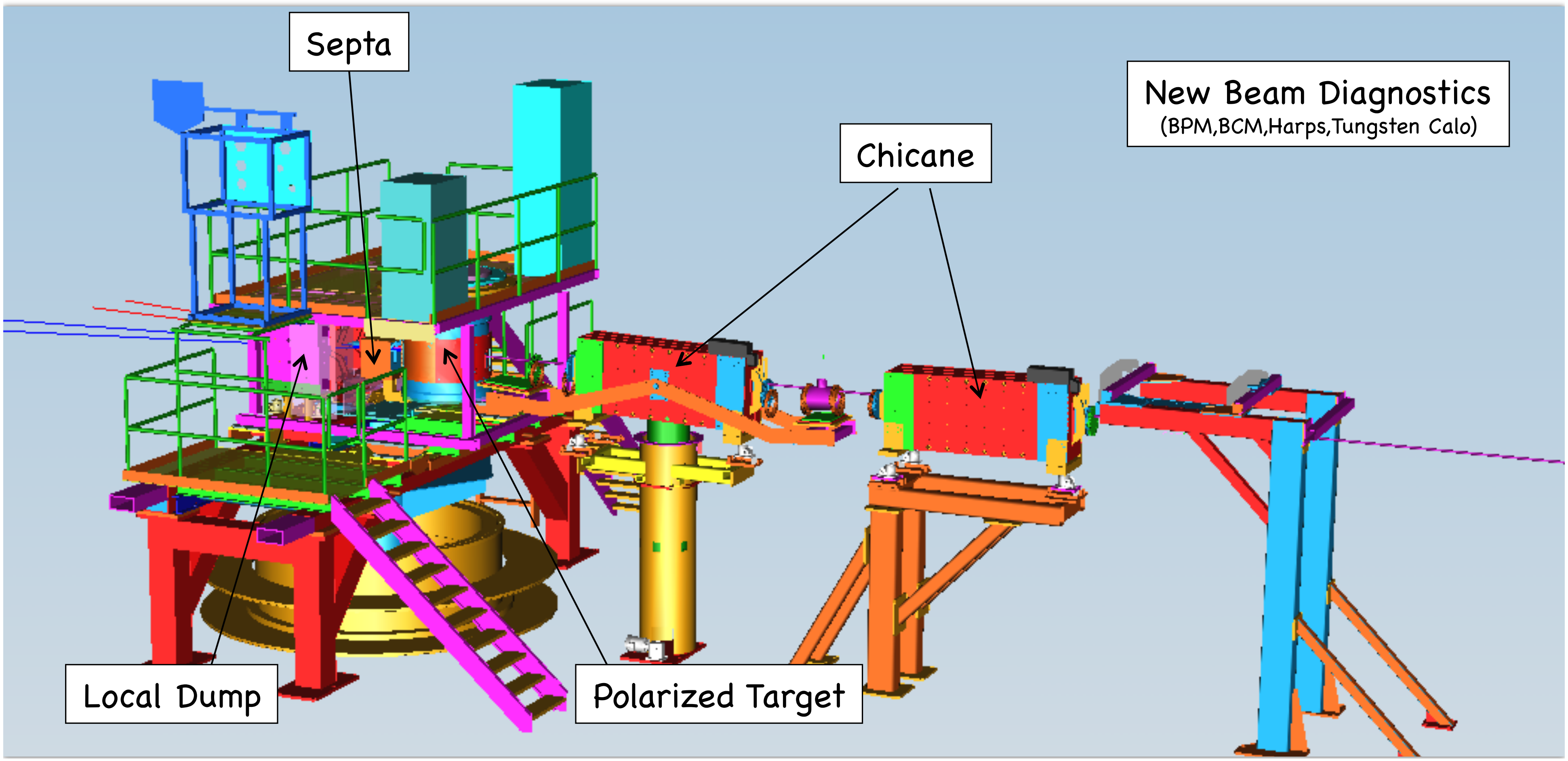
- upstream chicane
- downstream local dump

Low current polarized beam

- Upgrades to existing Beam Diagnostics to work at 85 nA

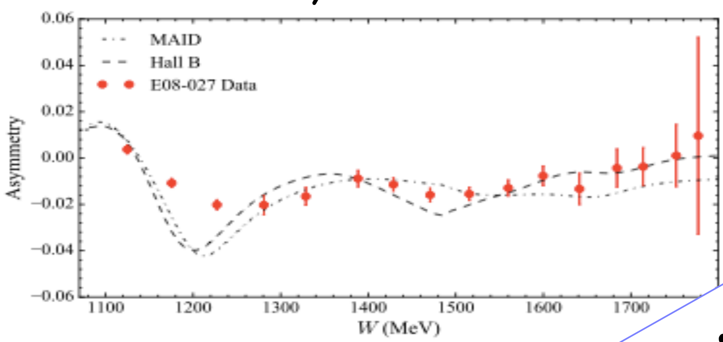
Lowest possible Q^2 in the resonance region

- Septa Magnets to detect forward scattering

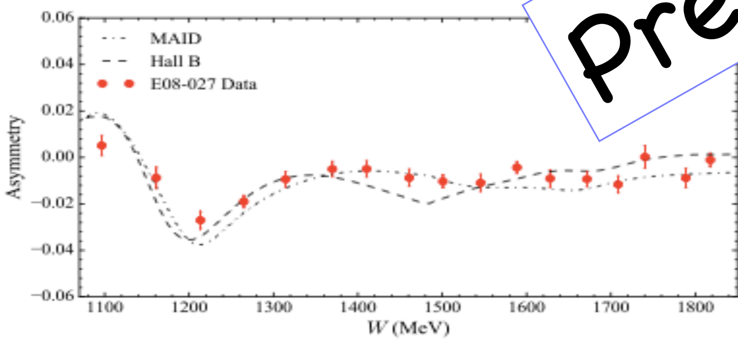


E08-027 Data

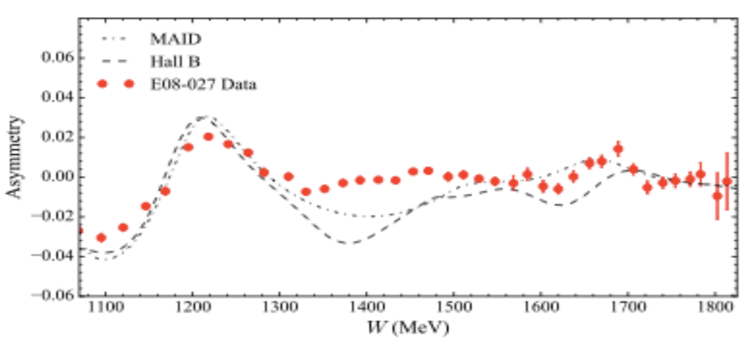
Asymmetries



(a) E_0 = 2254 MeV 5T Transverse



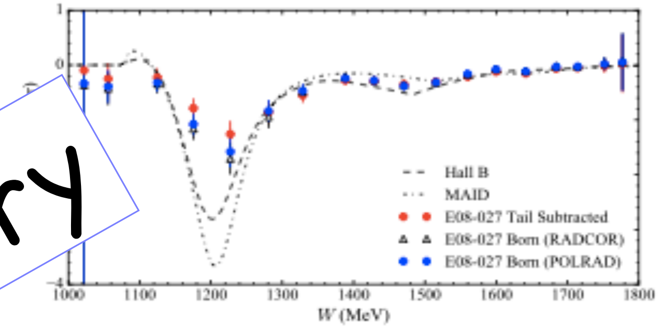
(b) E_0 = 3350 MeV 5T Transverse



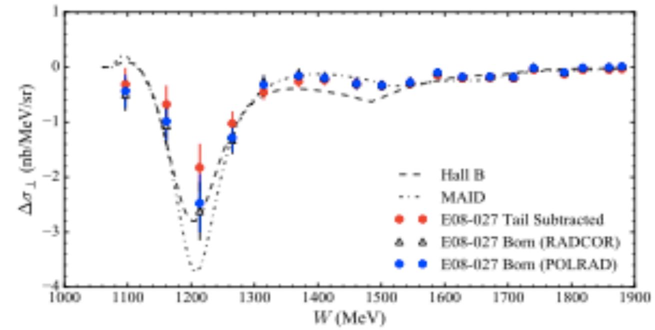
(c) E_0 = 2254 MeV 5T Longitudinal

Figure 8-9: Final asymmetries for the 5 T settings.

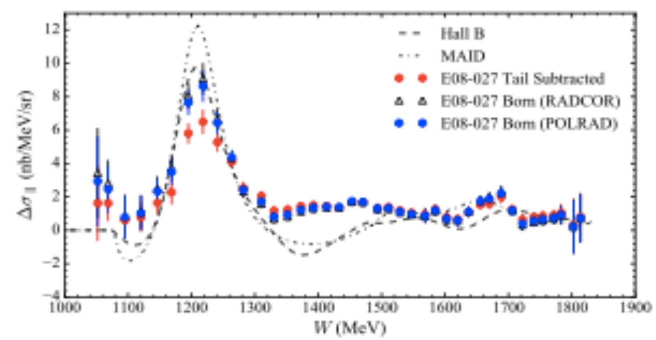
$\Delta\sigma$



(a) E_0 = 2254 MeV 5T Transverse



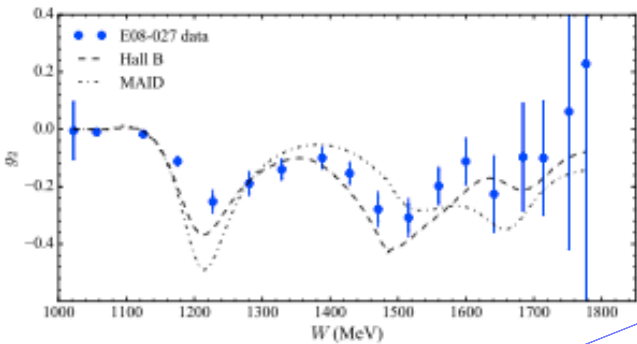
(b) E_0 = 3350 MeV 5T Transverse



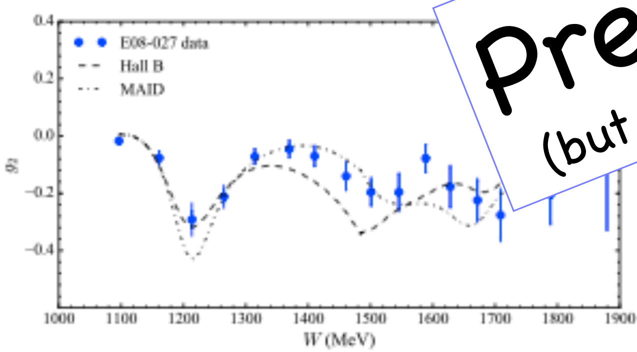
(c) E_0 = 2254 MeV 5T Longitudinal

Figure 8-19: Born polarized cr courtesy R. Zielinski, UNH

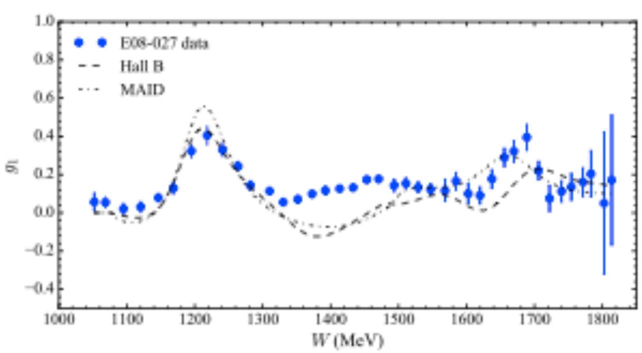
E08-027 Structure Functions (5T data)



(a) E_0 = 2254 MeV 5T Transverse



(b) E_0 = 3350 MeV 5T Transverse

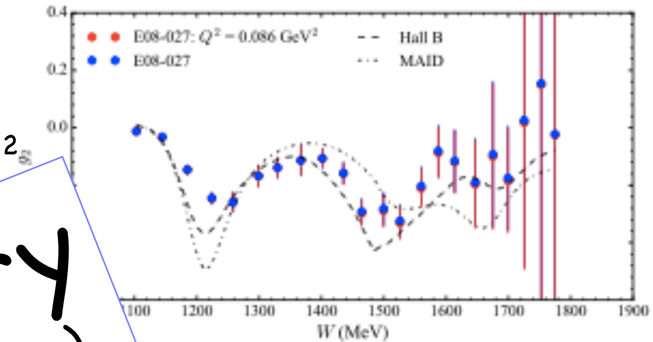


(c) E_0 = 2254 MeV 5T Longitudinal

Figure 8-21: Born spin structure functions for the 5 T kinematic settings.

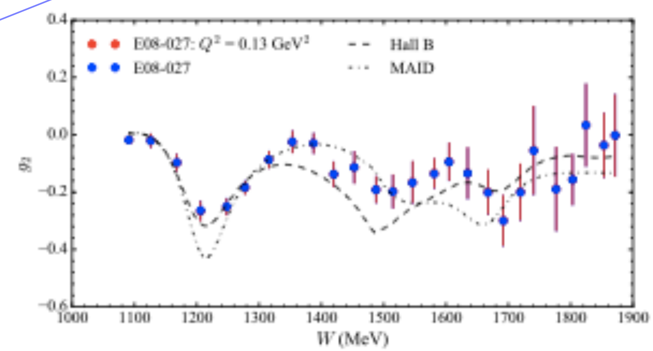
Preliminary
(but analysis complete)

Q^2= 0.08 GeV^2



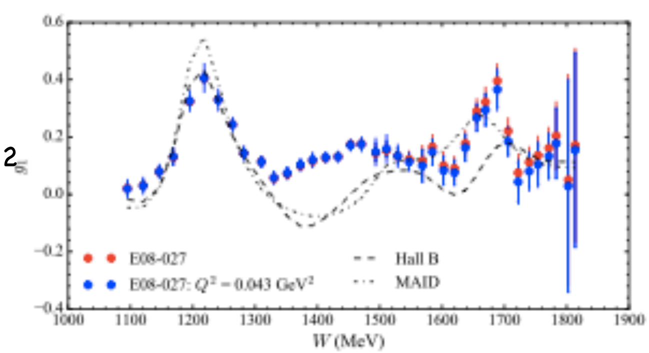
(a) E_0 = 2254 MeV 5T Transverse

Q^2= 0.13 GeV^2



(b) E_0 = 3350 MeV 5T Transverse

Q^2= 0.04 GeV^2

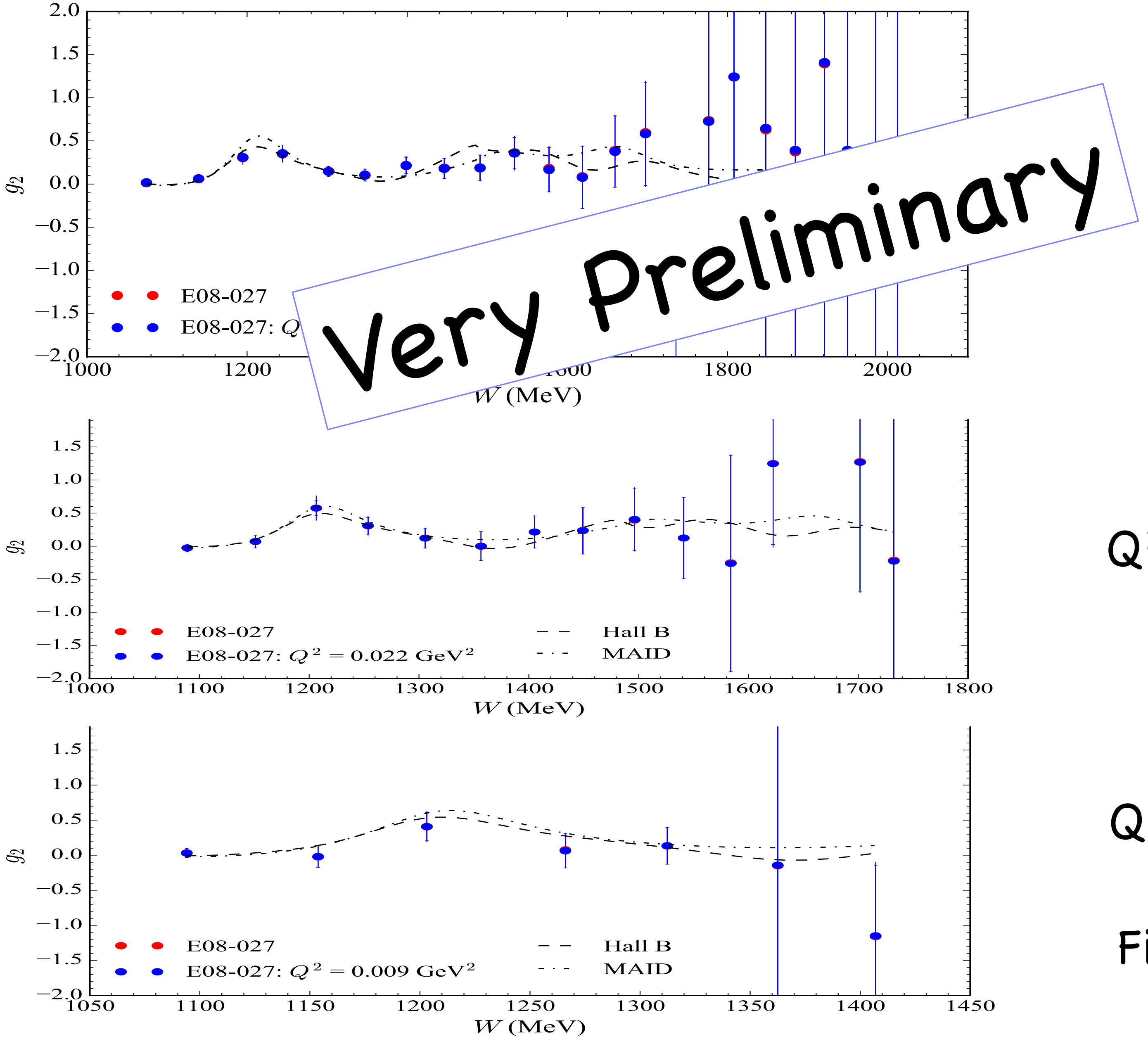


(c) E_0 = 2254 M

Figure 8-24: E08-027 spin structure functi

courtesy R. Zielinski, UNH

g2p 2.5T data



Q^2= 0.05 GeV^2

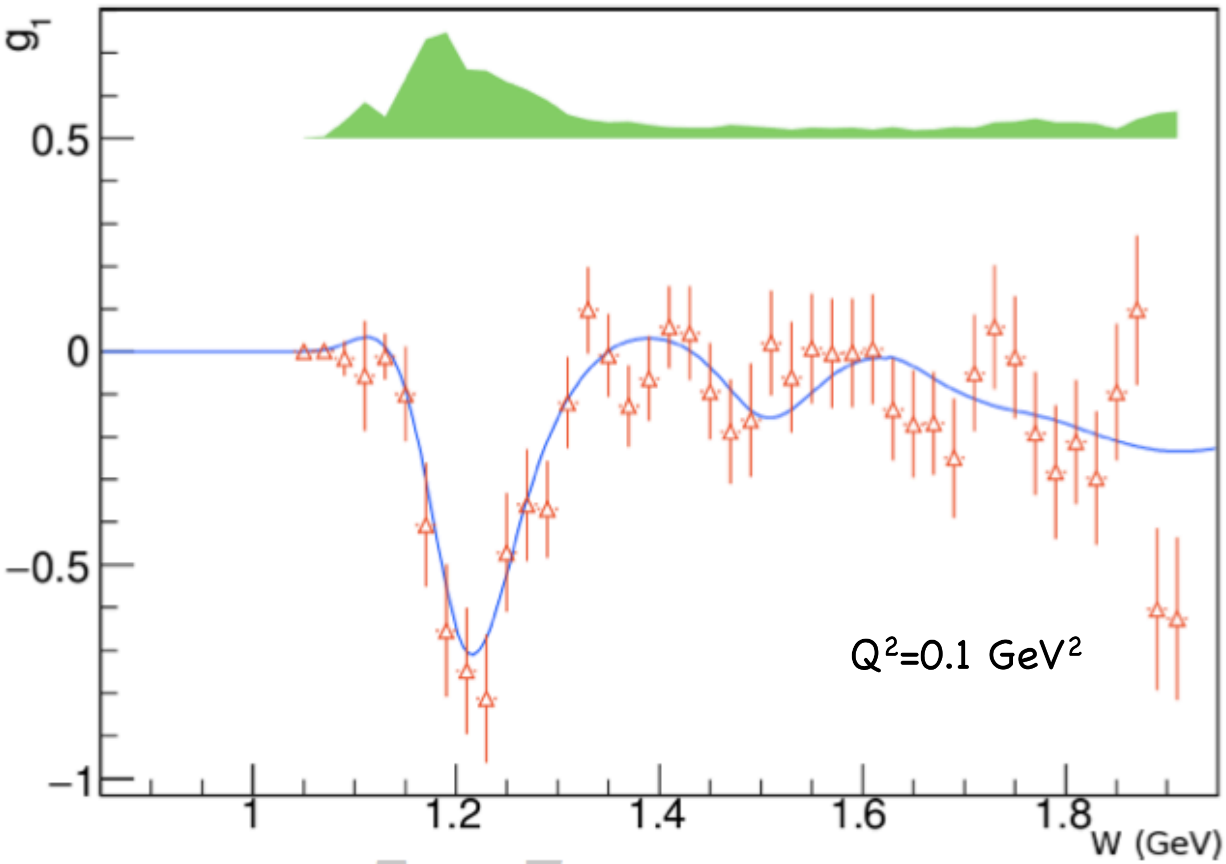
Q^2= 0.02 GeV^2

Q^2= 0.01 GeV^2

Finalizing df/pf/RC

courtesy R. Zielinski, UNH

Deuteron g_1



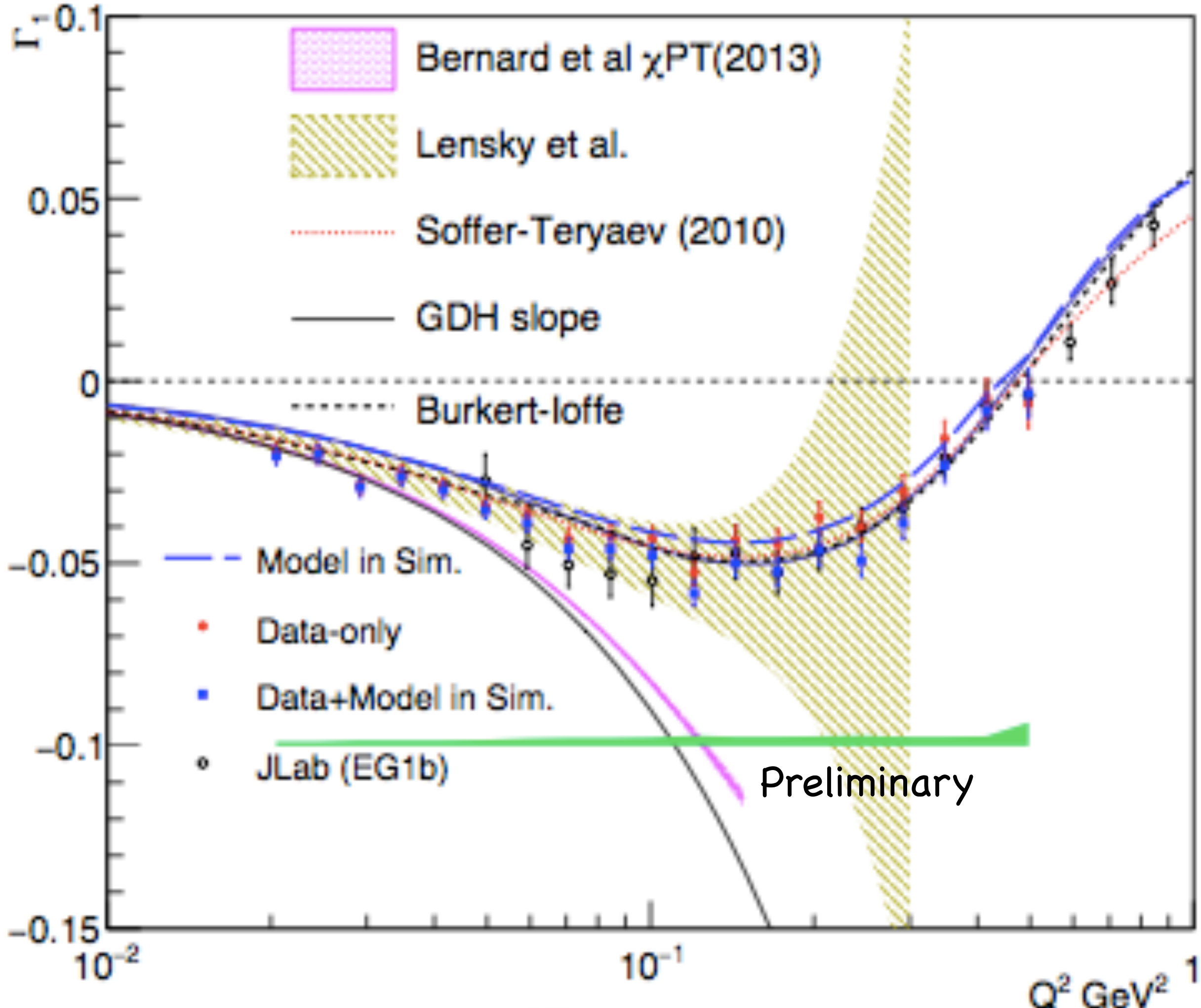
EG4 experiment
$Q^2 > 0.02$ GeV^2

CLAS Note in
final stage of review
publication ready
to submit

courtesy K. Adhikari

1st Moment

Deuteron



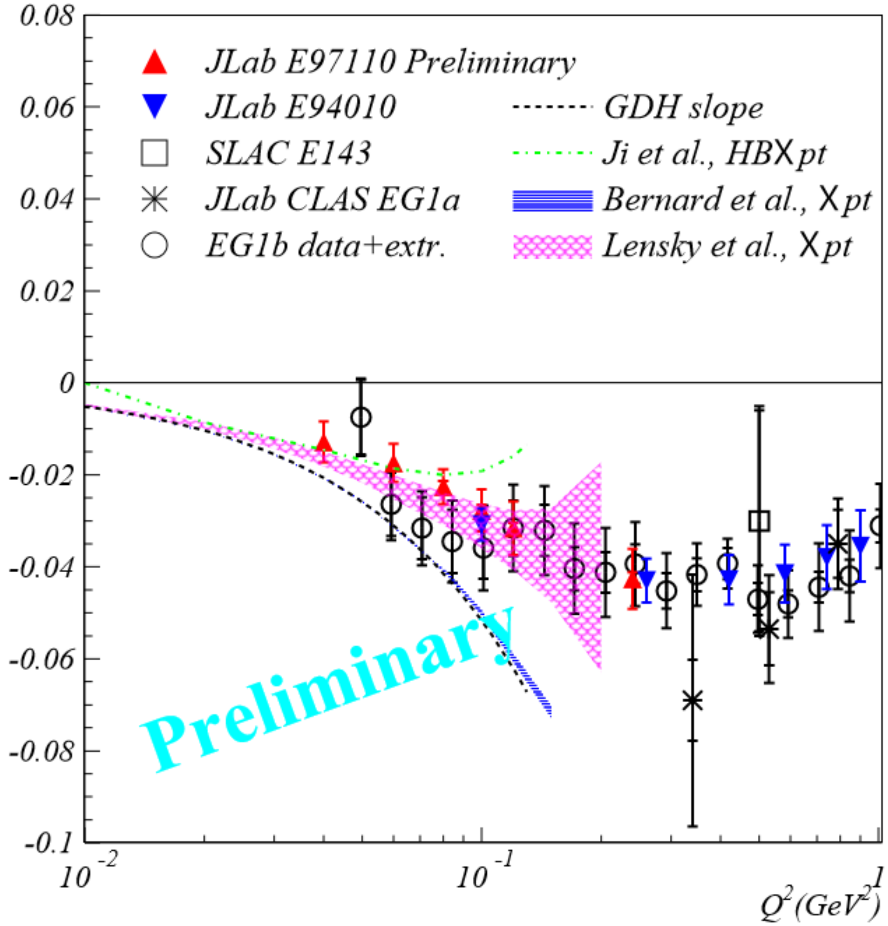
$$\Gamma_1(Q^2) = \int_0^{x_0} \mathrm{d}x\, g_1(x, Q^2)$$

EG4

courtesy K. Adhikari

1st Moment

Neutron (sagdh)



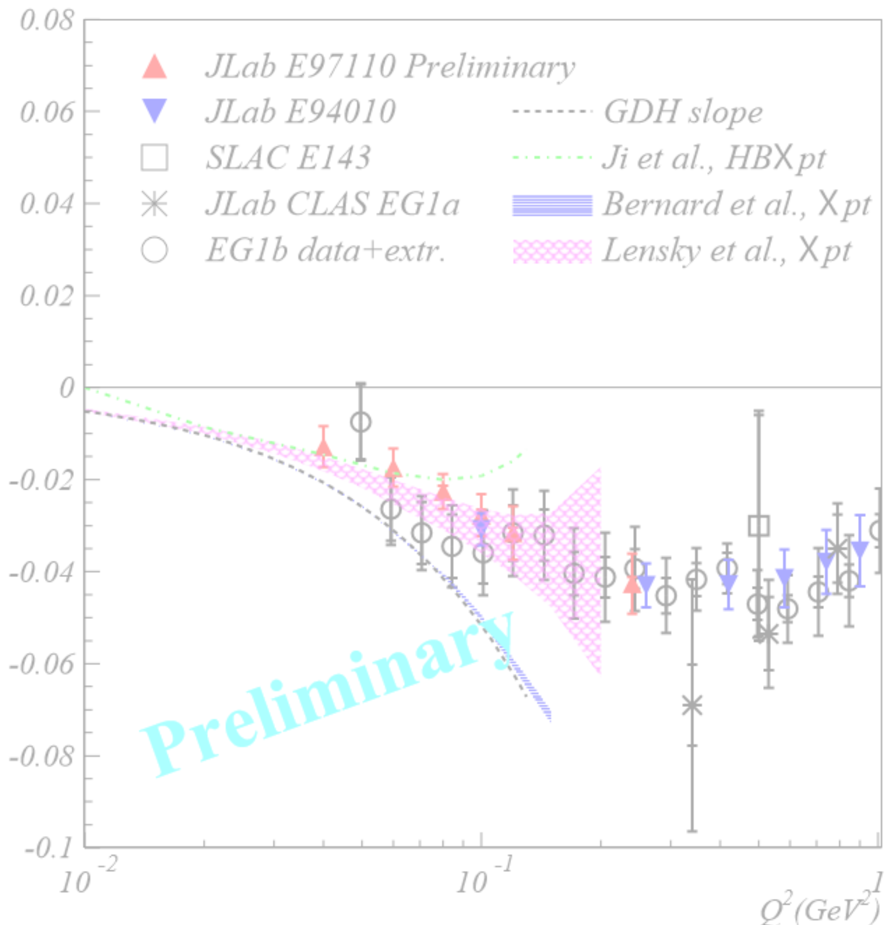
$$\Gamma_1(Q^2) = \int_0^{x_0} \mathrm{d}x\, g_1(x, Q^2)$$

sagdh

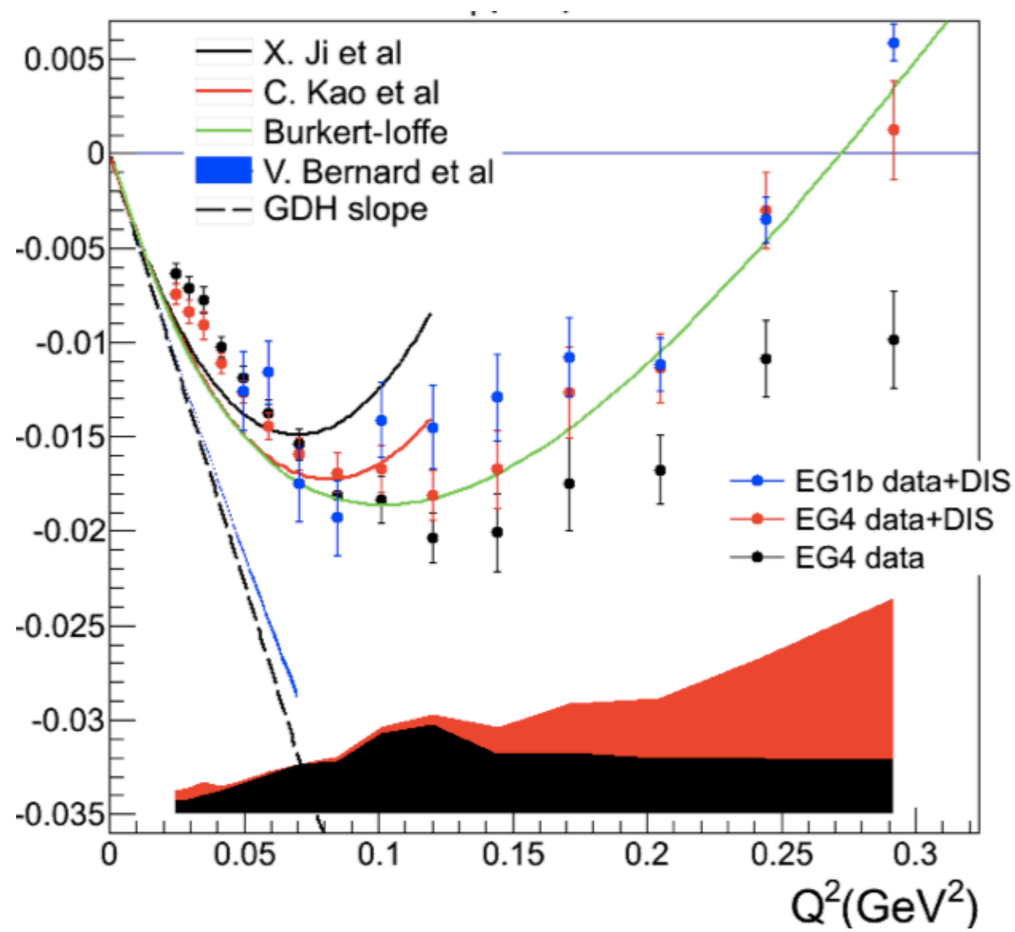
courtesy A. Deur

1st Moment

Neutron



Proton (EG4)

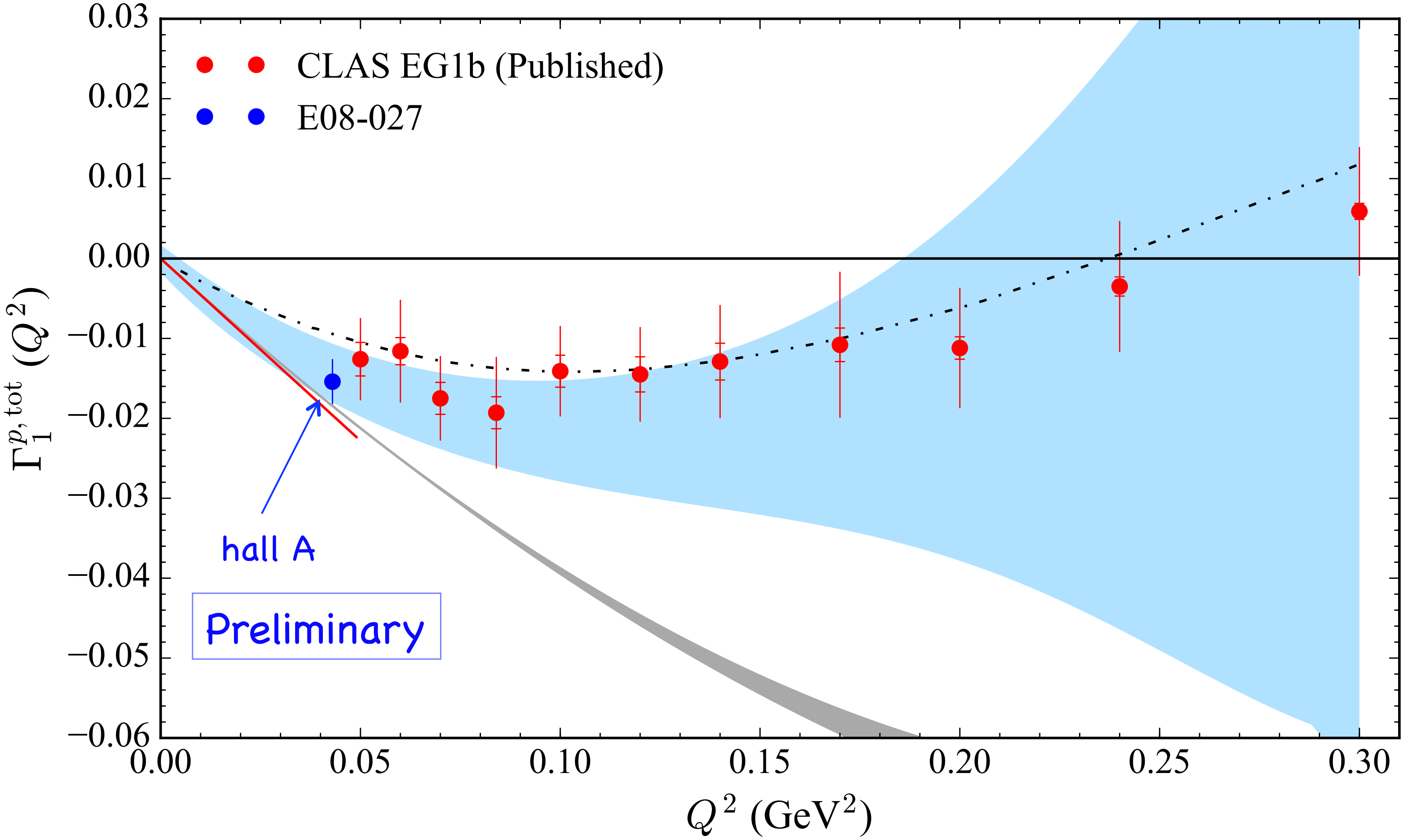


$$\Gamma_1(Q^2) = \int_0^{x_0} \mathrm{d}x\, g_1(x, Q^2)$$

saqdh, EG4

courtesy A. Deur, K. Adhikari

E08-027 Proton 1st Moment



courtesy R. Zielinski, UNH

Spin Polarizabilities

$$\gamma_0(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 g_{TT}(x, Q^2),$$

$$\delta_{LT}(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 \Big[g_1(x, Q^2) + g_2(x, Q^2) \Big]$$

$$g_{TT} = g_1 - (4M_N^2 x^2/Q^2) g_2$$

Good Test of ChPT.

Chpt respects all symmetries of QCD but its Lagrangian is constructed from hadron degrees of freedom

Heavy Baryon χPT : Mainz group (Lensky, Vanderhagen, et al)

Treats the Baryon as a heavy static particle

Relativistic Baryon : (Meissner, Bernard et al)

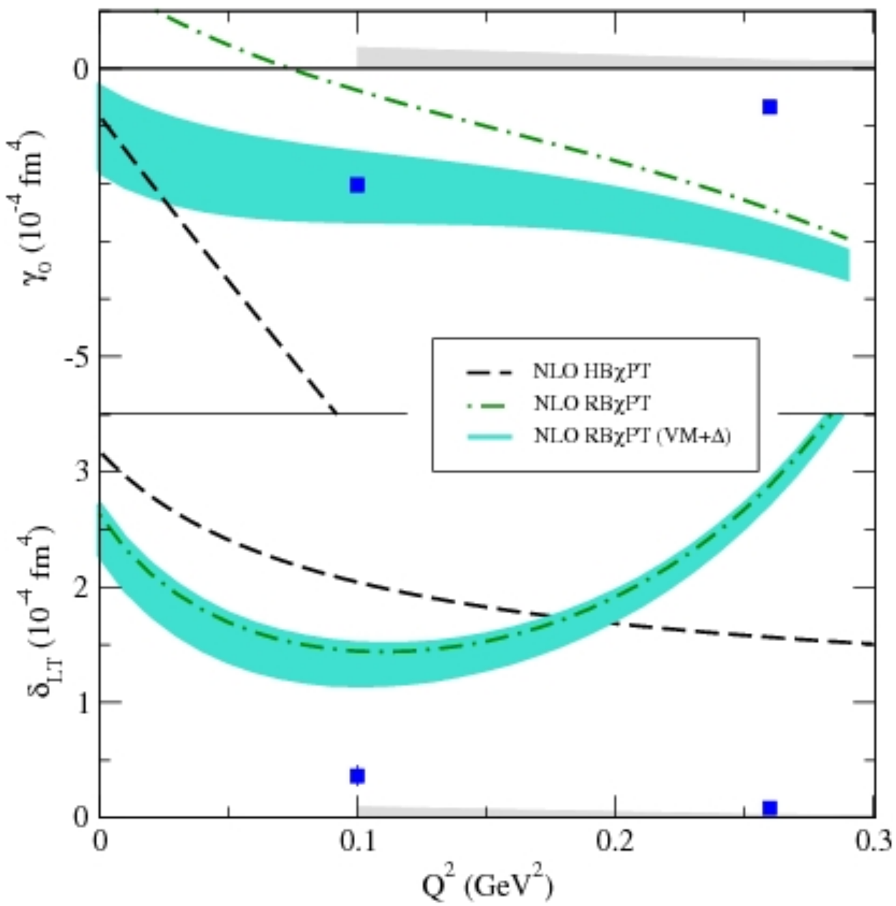
large momentum effects are absorbed in the low energy consts

Resonances are included sytematically through additional low energy constants

δ_{LT} Puzzle

Neutron

PRL 93: 152301 (2004)



$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

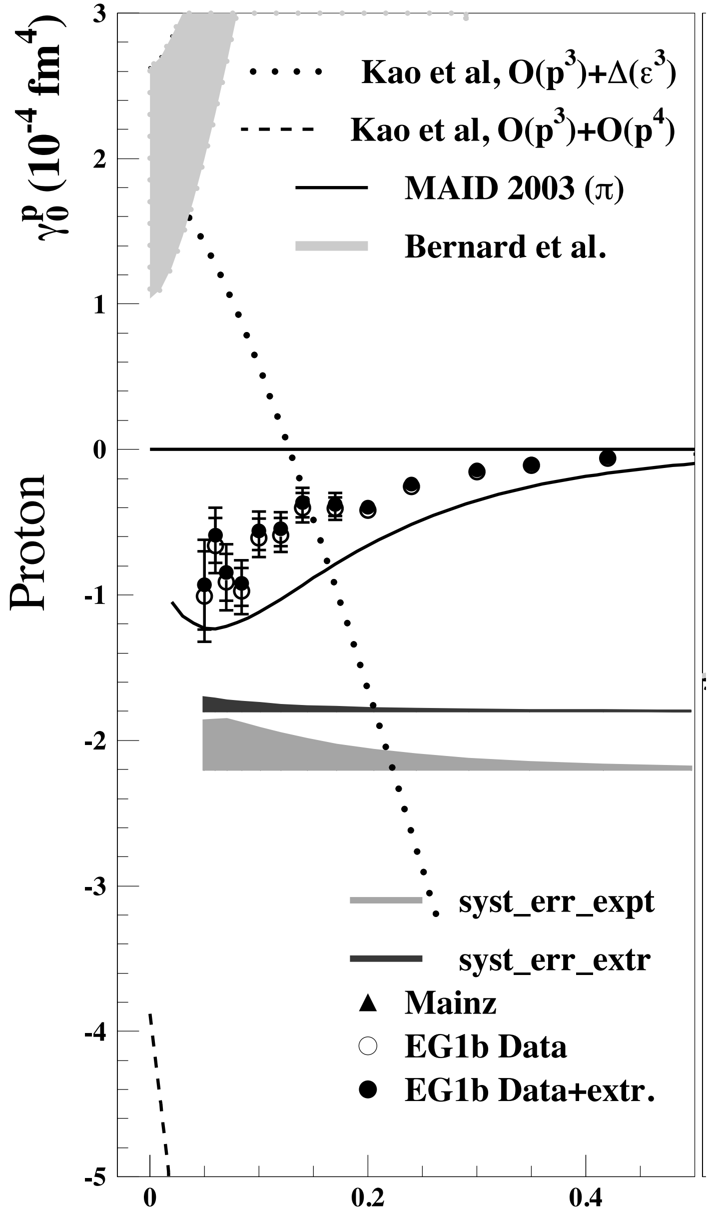
$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]$$

Dramatic Discrepency with χPT

Heavy Baryon χPT Calculation
Kao, Spitzenberg, Vanderhaeghen
PRD 67:016001(2003)

Relativistic Baryon χPT
Bernard, Hemmert, Meissner
PRD 67:076008(2003)

Proton γ_0



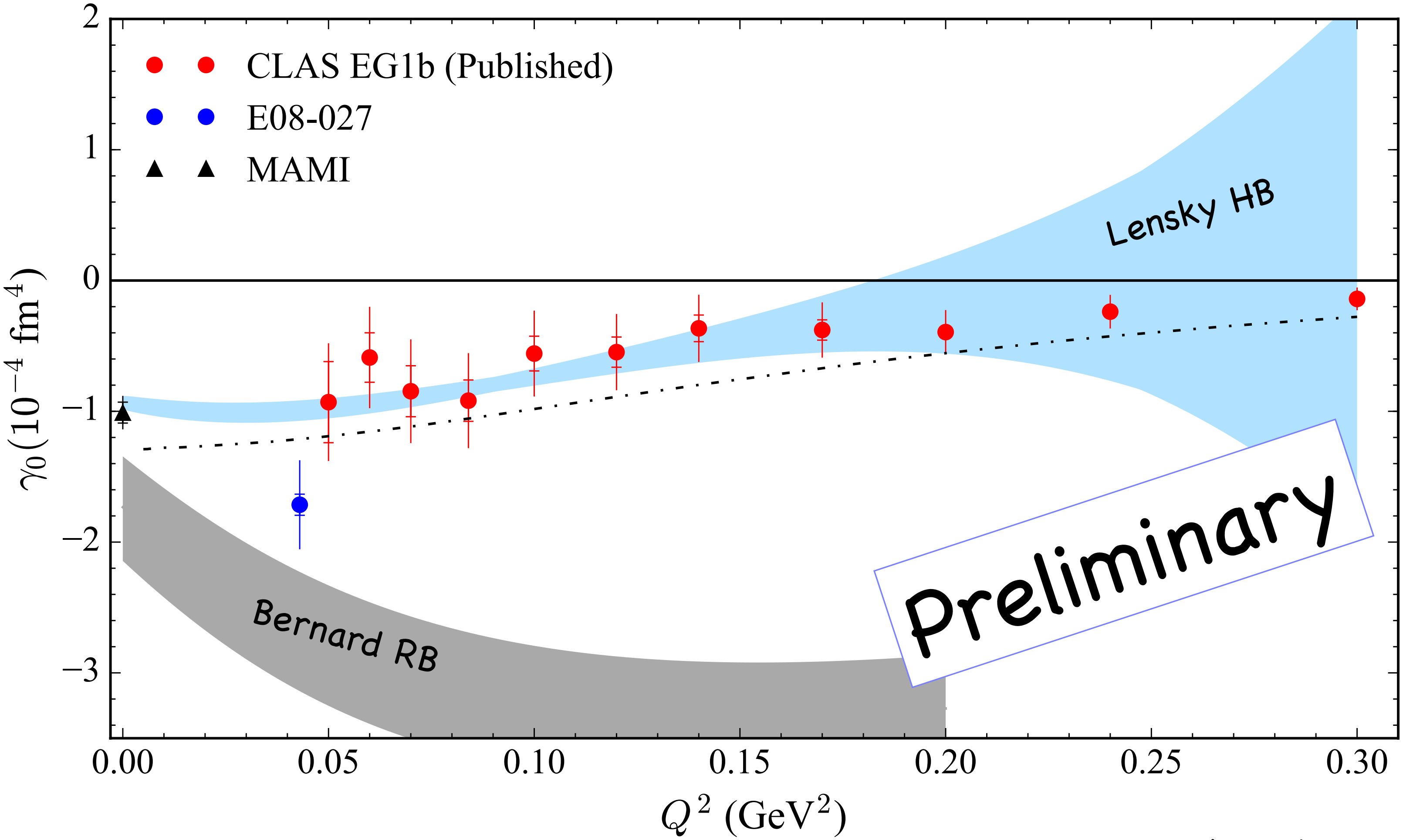
$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

Older Calcs also failed for proton γ_0

PLB 672 12, 2009

published data goes down to about 0.06 GeV^2

Proton γ_0 (latest data)

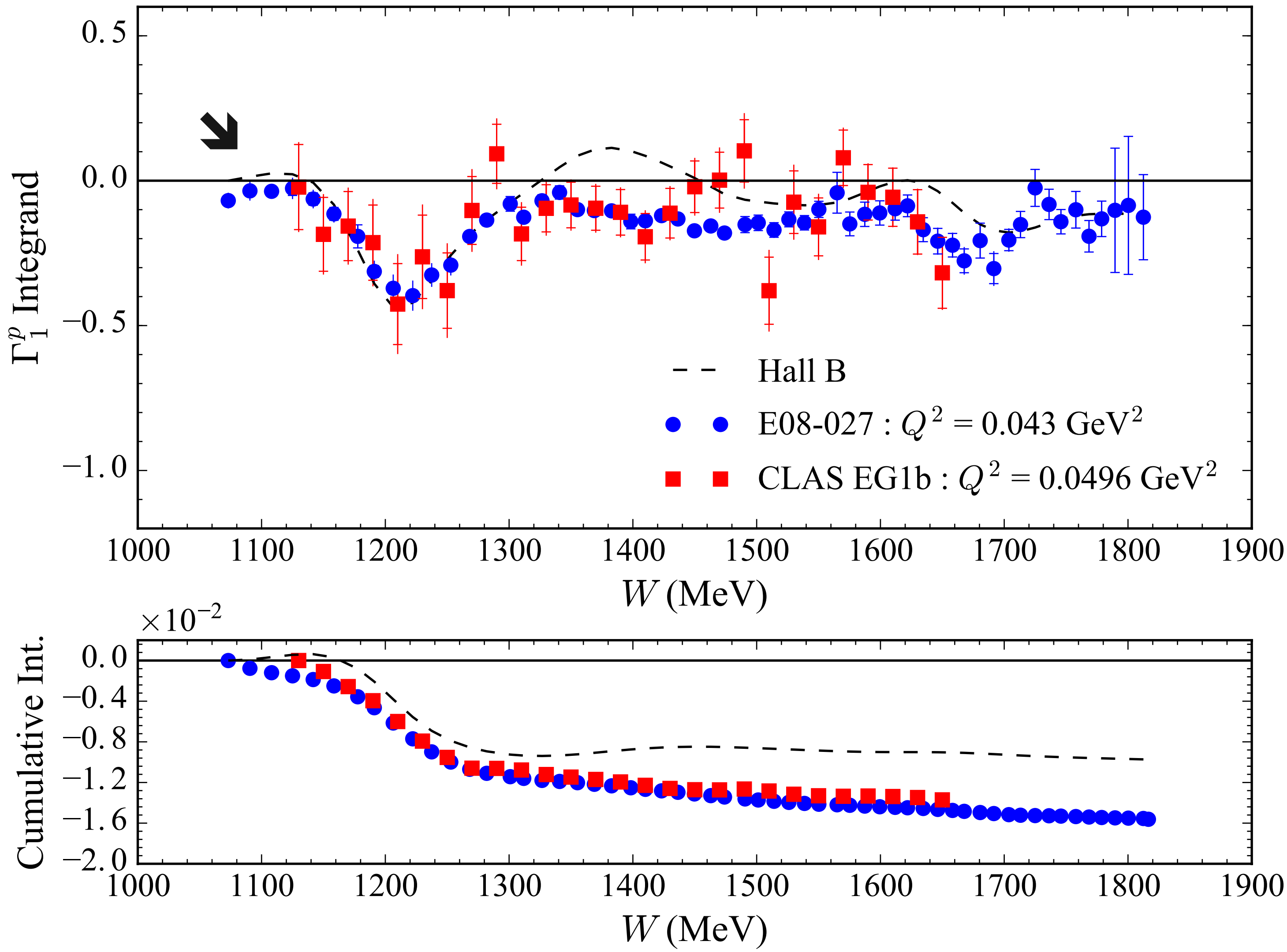


$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2 \left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

decent agreement with HBChpt

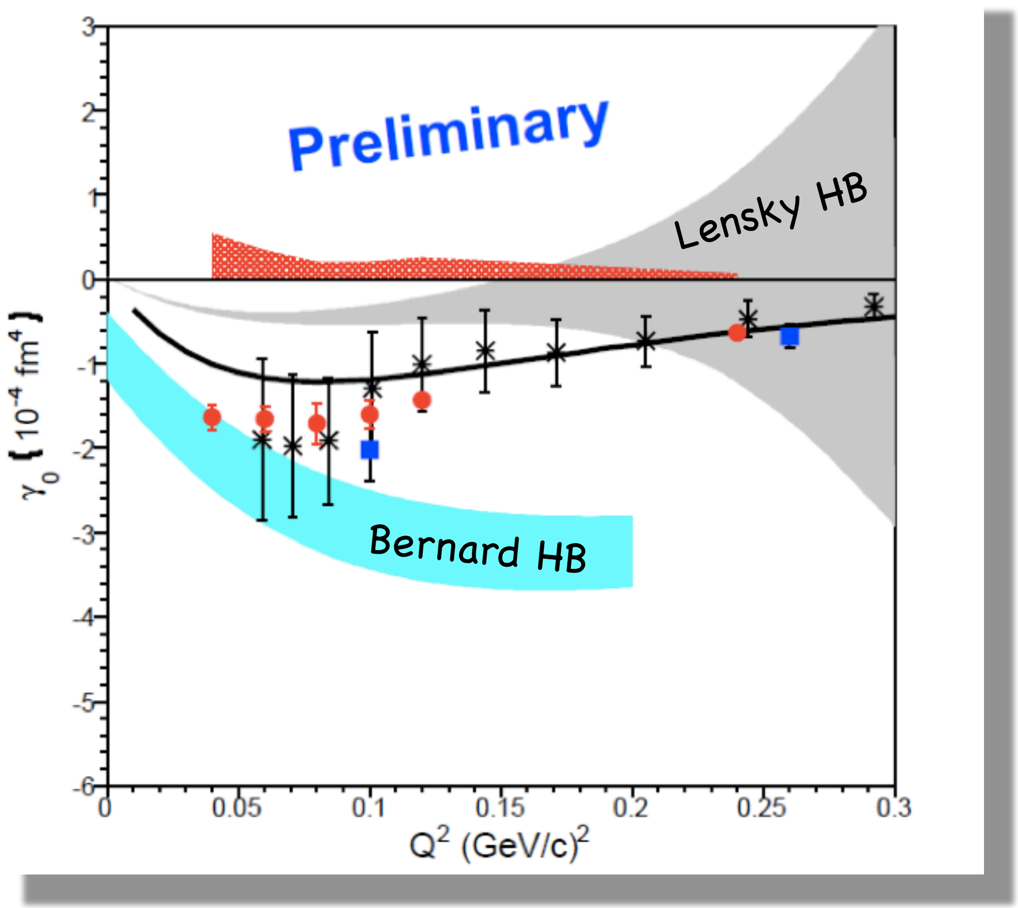
courtesy R. Zielinski, UNH

Proton g1 (E08-027 vs. CLAS)



courtesy R. Zielinski, UNH

Neutron γ_0 (latest data)

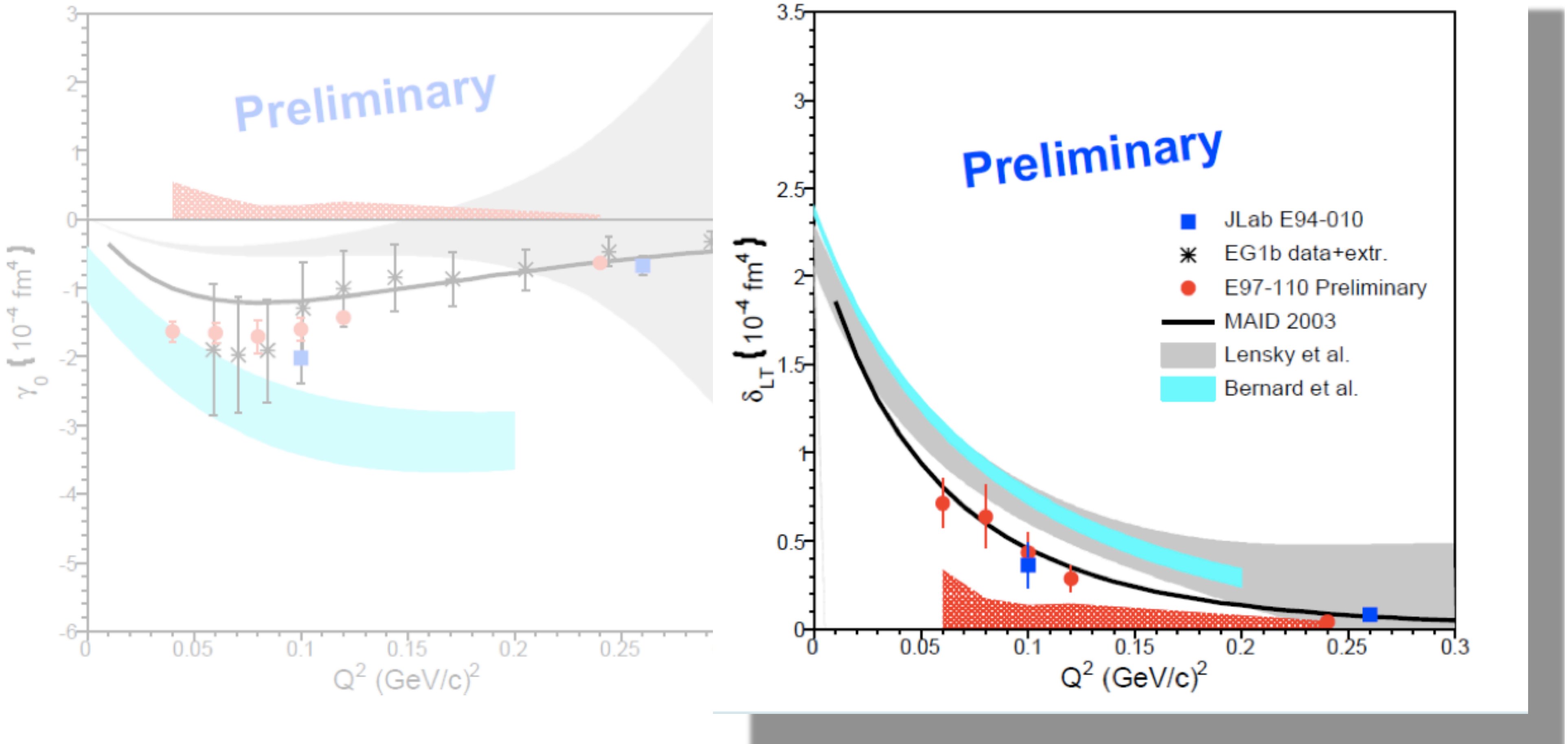


Big disagreement with Lensky et al. for Neutron γ_0

BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202

Neutron δ_{LT} (latest data)

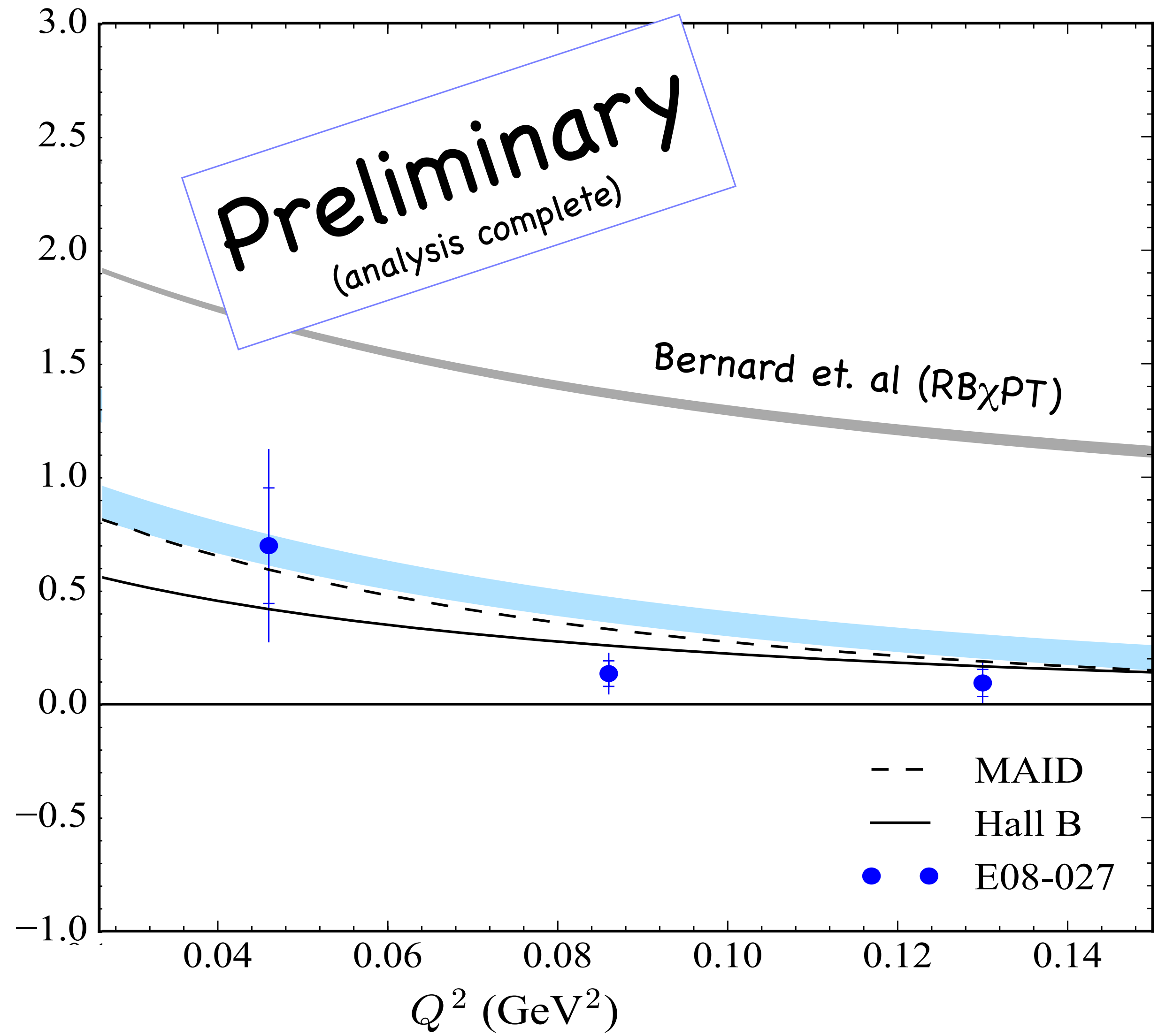


BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202

sagdh

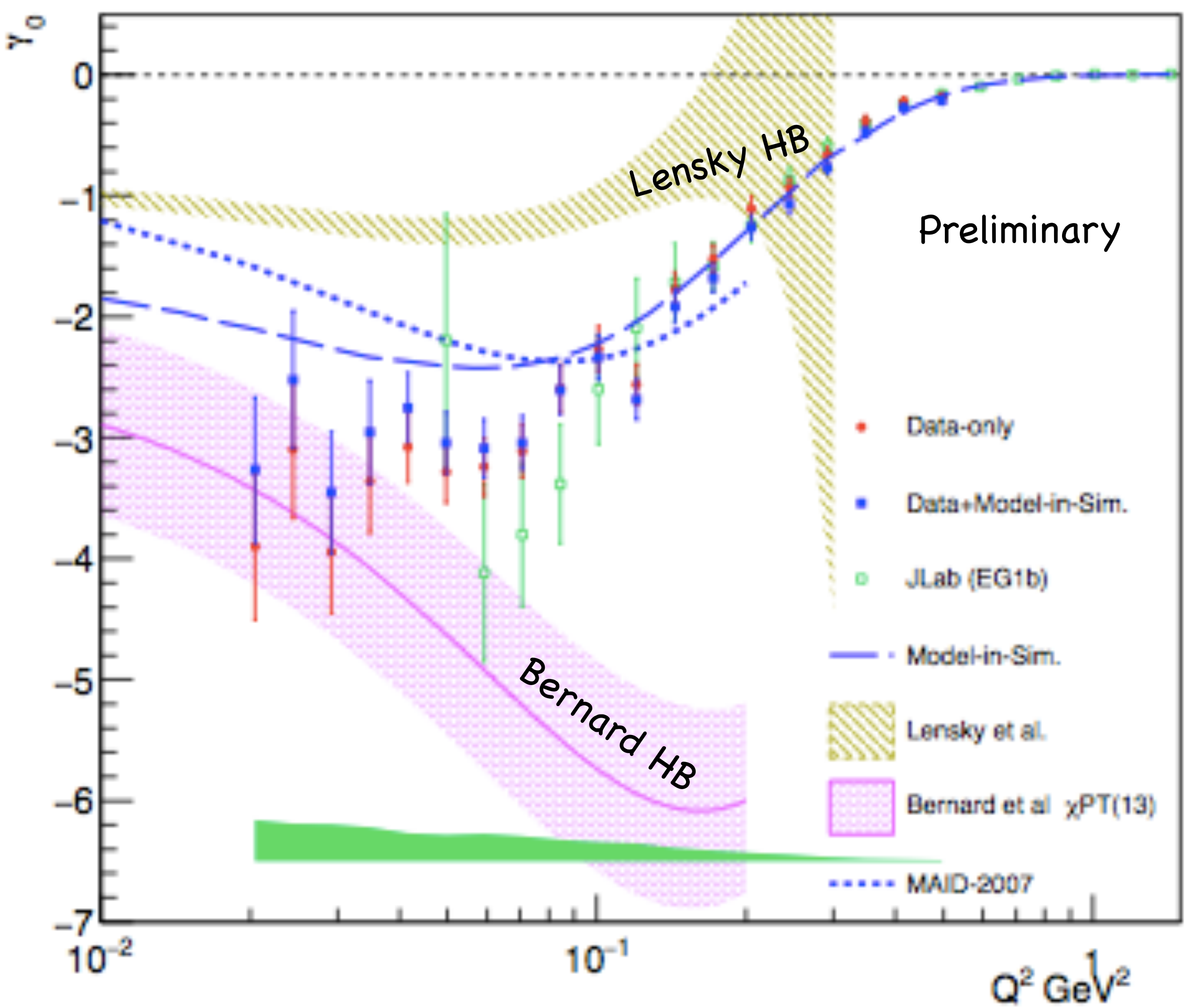
δ_{LT} Proton (brand new data)



Lensky et al (HBχPT)

courtesy R. Zielinski, UNH

Deuteron γ_0



Big disagreement with Lensky et al.

arising from neutron part

(EG4)

χPT Comparison Summary

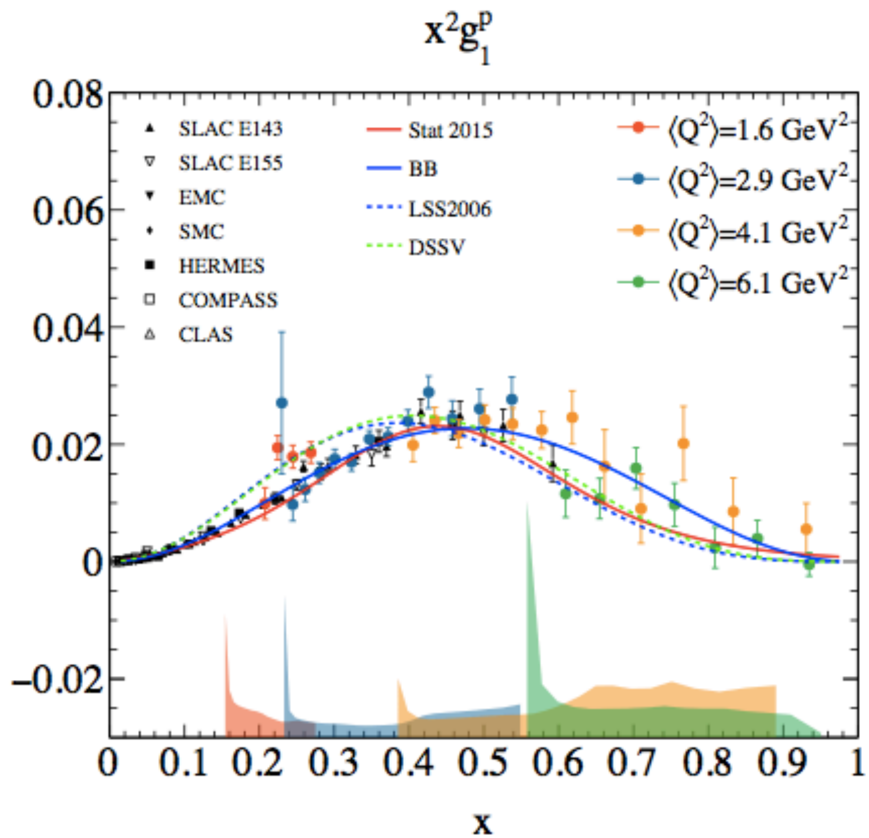
Γ_1 Pretty good agreement with χPT calculations

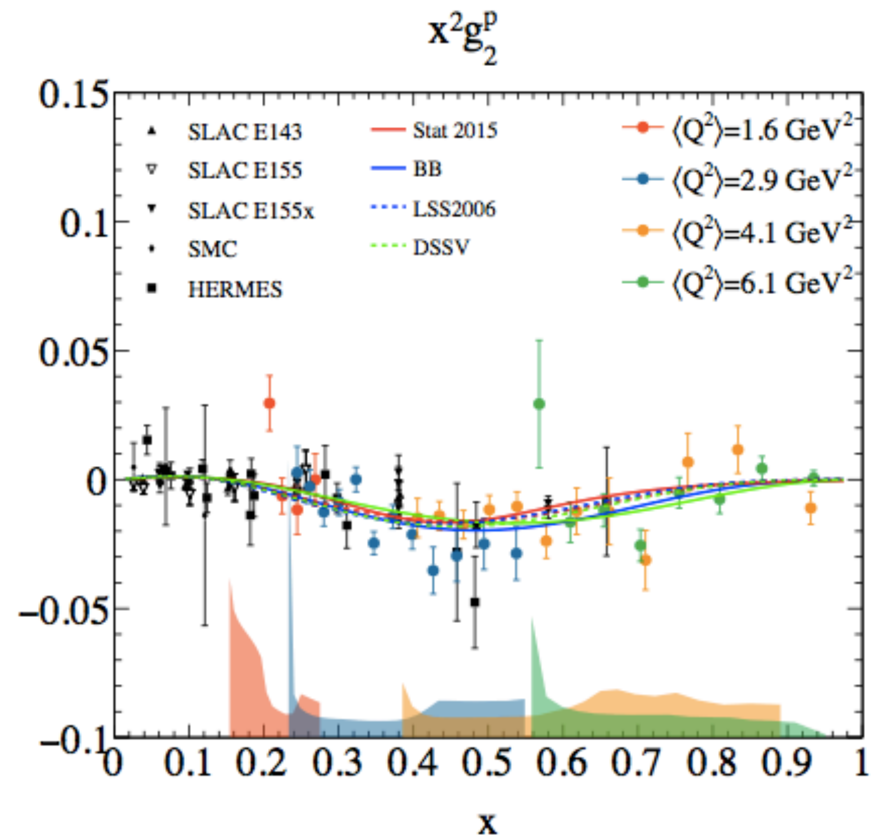
δ_{LT} Good agreement for neutron
Proton data favors HBχPT (Lensky et al)

γ_0 Good agreement for proton for HBχPT (Lensky et al)
but perhaps an issue with the low nu data
needs further comm between HallA/HallB collabs

Neutron (&Deutron) big discrepency with HBχPT

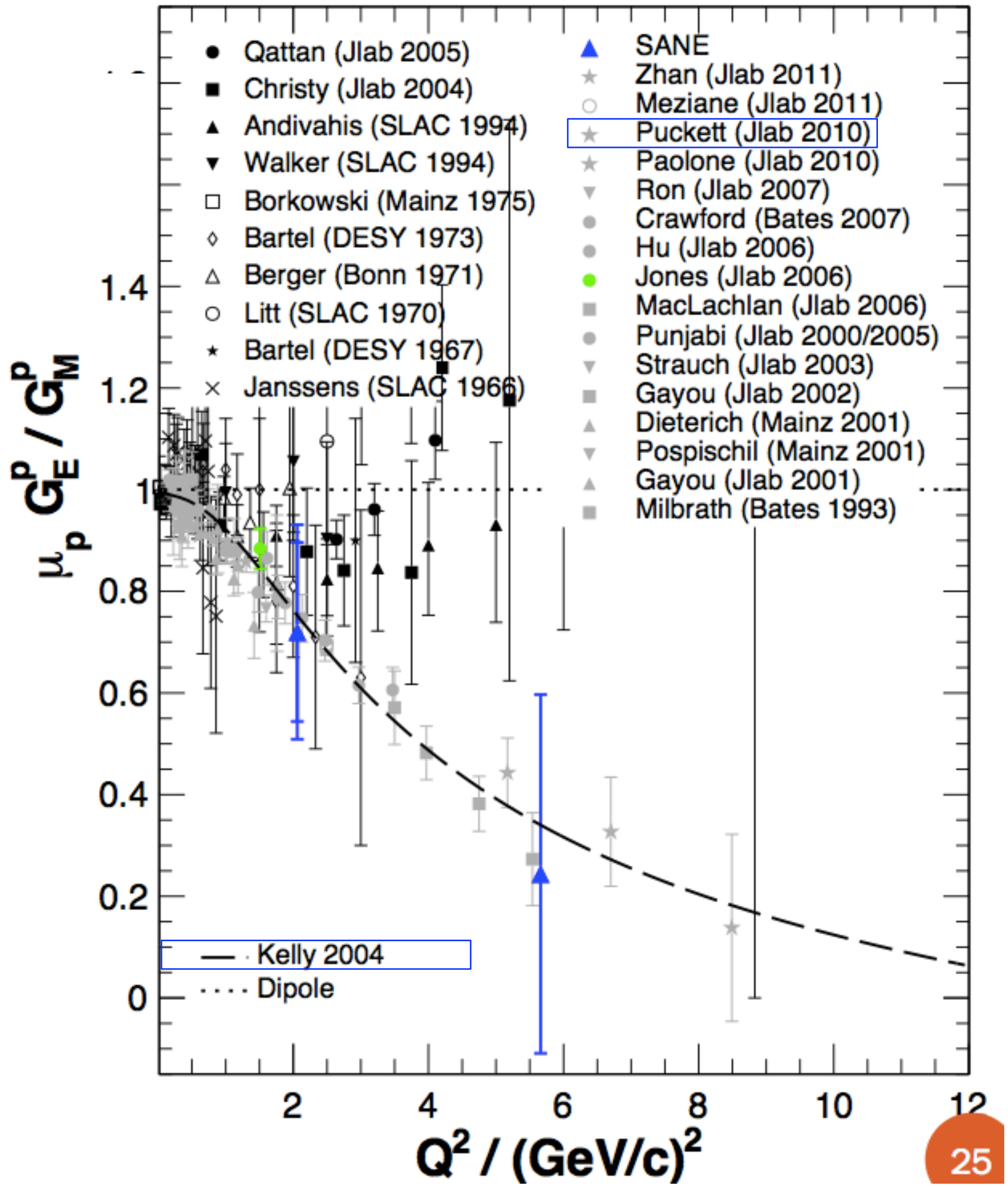
SANE $x^2g_1^p$ and $x^2g_2^p$





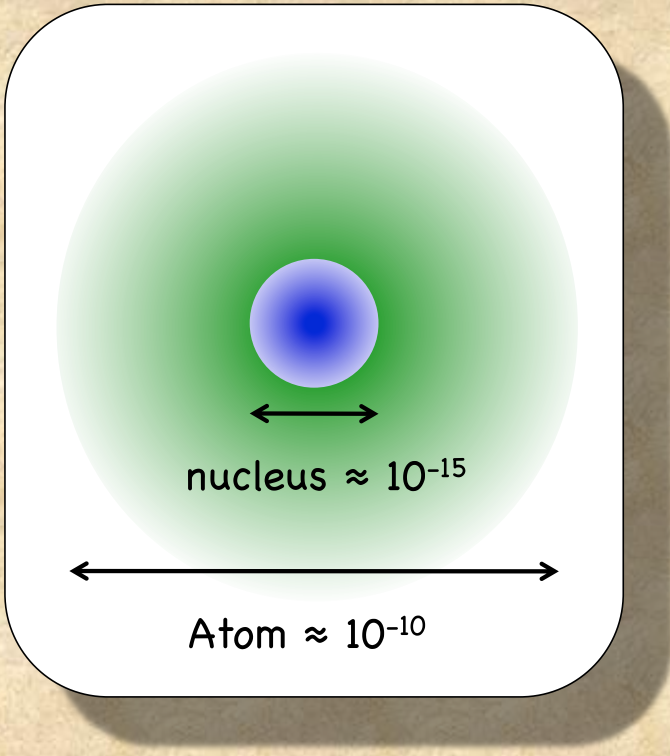
Models are showing g_2^{WW}.

SANE Proton G_E/G_M



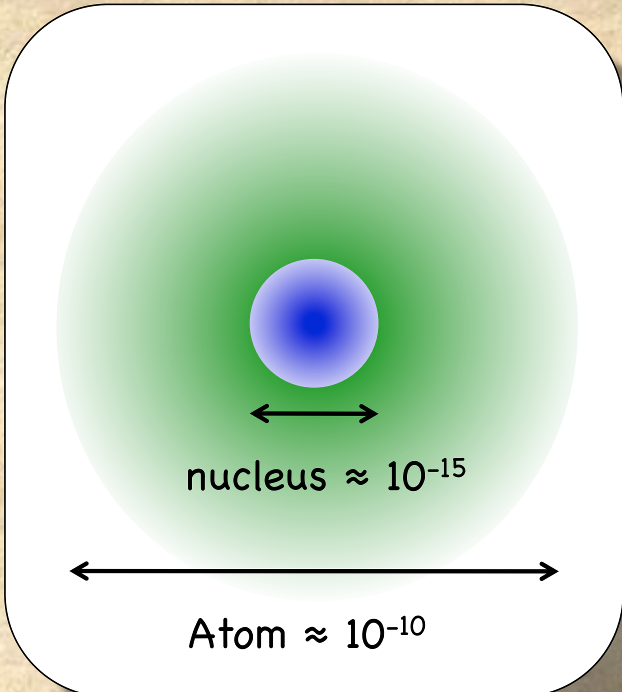
courtesy Anuska Liyanage

Applications to Bound State Q.E.D.



The finite size of the nucleus plays a small but significant role in atomic energy levels.

Applications to Bound State Q.E.D.

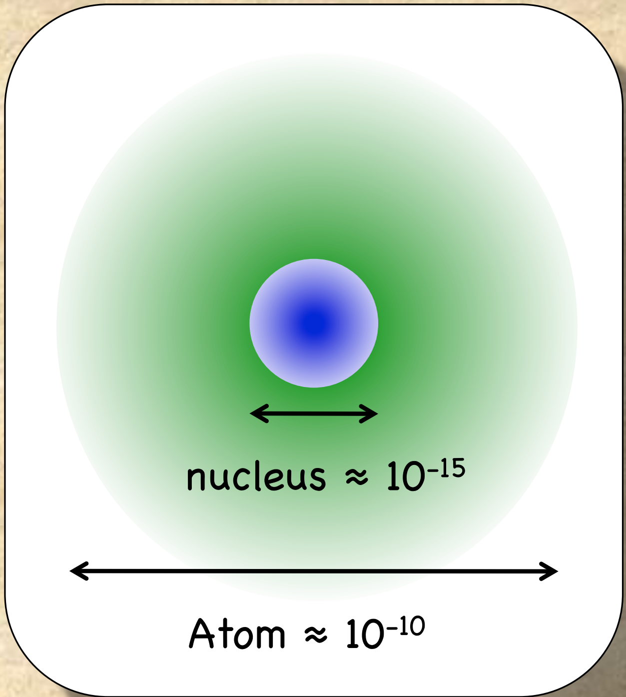


Hydrogen HF Splitting

$$\begin{aligned} \Delta E &= 1420.405\ 751\ 766\ 7(9)\ \ \text{MHz} \\ &= (1+\delta)E_F \end{aligned}$$

The finite size of the nucleus plays a small but significant role in atomic energy levels.

Applications to Bound State Q.E.D.



The finite size of the nucleus plays a small but significant role in atomic energy levels.

Hydrogen HF Splitting

$$\begin{aligned}\Delta E &= 1420.405\;751\;766\;7(9) \quad \text{MHz} \\ &= (1+\delta)E_F\end{aligned}$$

$$\delta = (\delta_{QED} + \delta_R + \delta_{small}) + \Delta_S$$

Friar & Sick PLB **579** 285(2003)

Structure dependence of Hydrogen HF Splitting

$$\Delta_S = \Delta_Z + \Delta_{POL}$$

Elastic Scattering

Δ_Z=-41.0±0.5ppm

$$\Delta_Z = -2\alpha m_e r_Z (1 + \delta_Z^{\rm rad})$$

$$r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_p} - 1\right]$$

Structure dependence of Hydrogen HF Splitting

$$\Delta_S = \Delta_Z + \Delta_{POL}$$

Inelastic

Nazaryan,Carlson,Griffieon
PRL **96** 163001 (2006)

Δ_Z=-41.0±0.5ppm

$\Delta_{pol} \approx$ 1.3±0.3 ppm

Elastic piece larger but with similar uncertainty

$$\Delta_{POL} = 0.2265 \quad (\Delta_1 + \Delta_2)\text{ppm}$$

integral of g1 & F1

pretty well determined from F_2,g_1 JLab data

Structure dependence of Hydrogen HF Splitting

$$\Delta_S = \Delta_Z + \Delta_{POL}$$

inelastic

Nazaryan,Carlson,Griffieon
PRL **96** 163001 (2006)

$\Delta_{pol} \approx 1.3 \pm 0.3$ ppm

Elastic piece larger but with similar uncertainty

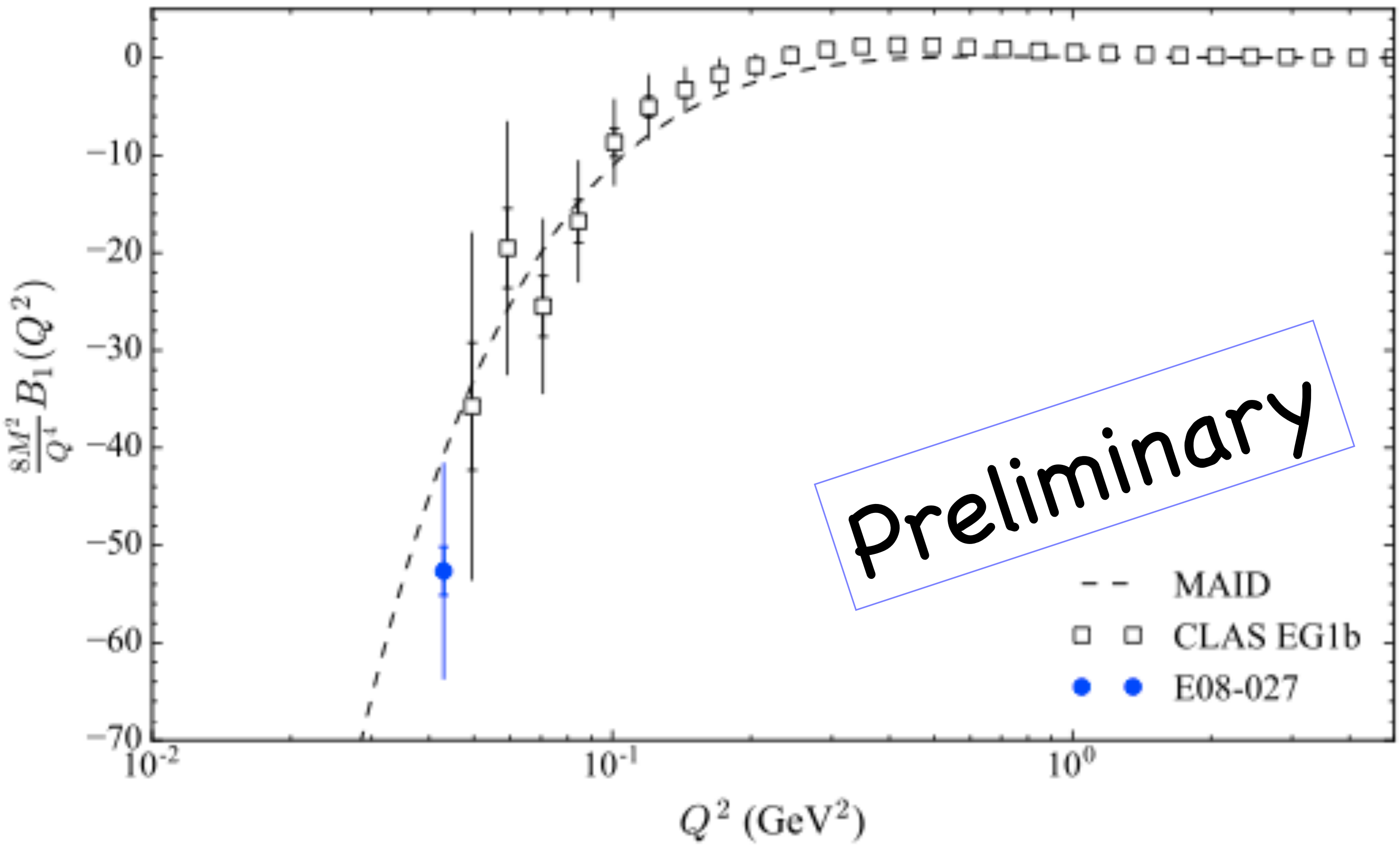
$$\Delta_{POL} = 0.2265 \quad (\Delta_1 + \Delta_2)\text{ppm}$$

$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$$B_2(Q^2) = \int_0^{x_{th}} dx \beta_2(\tau) g_2(x, Q^2)$$

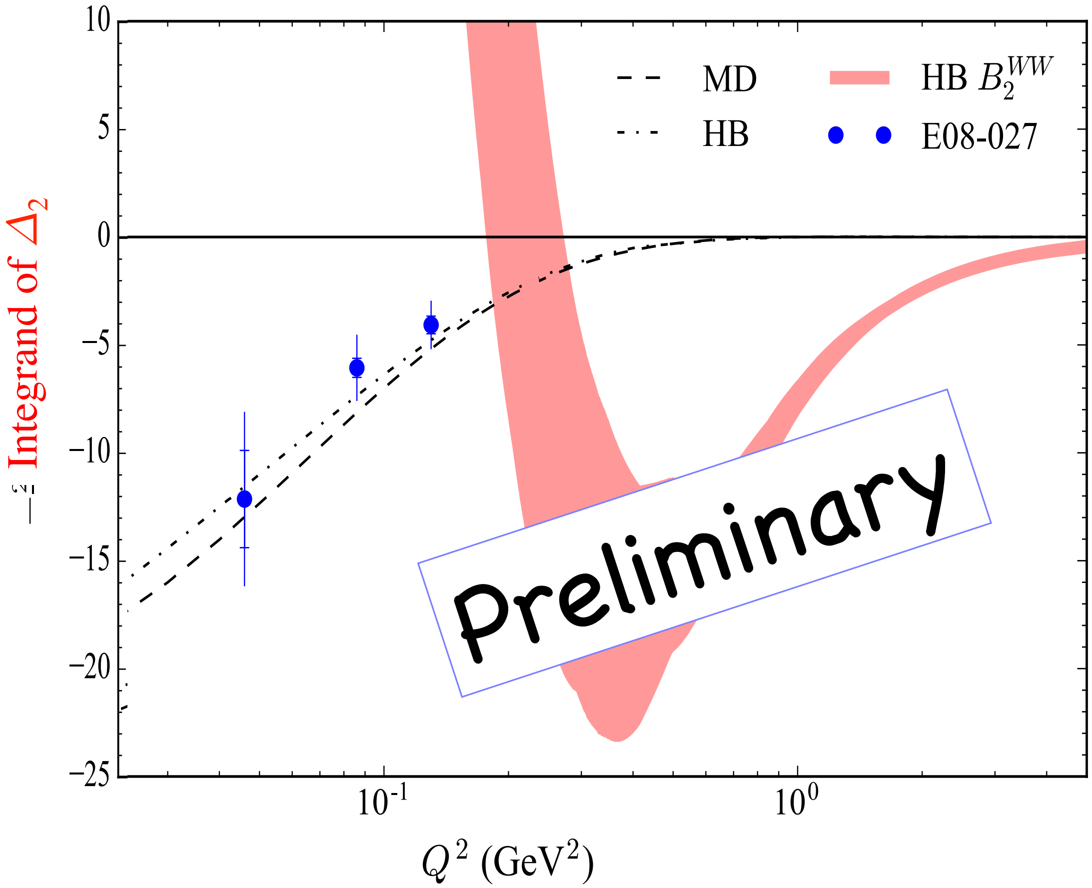
weighted heavily to low Q^2

g1p contribution to the Hyperfine Splitting



courtesy R. Zielinski, UNH

g2 contribution to Hyperfine Structure



$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$= -0.57 \pm 0.57$ CLAS Model

$= \quad -1.98$ MAID Model

$= \quad -1.86$ Simula Model

good agreement with the MAID and (most recent) Hall B predictions
200% difference from Hall B 2007 model

E08-027 provides first real constraint on Δ_2

courtesy R. Zielinski, UNH

Tensor Program

Jefferson Lab

UNIVERSITY OF VIRGINIA 1819

E12-13-011: "The b_1 experiment"

30 Days in Jlab Hall C
A- Physics Rating
Conditional Approval (Target Performance)

Contact : K. Slifer, UNH

E12-15-005: "A_{zz} for $x>1$"

44 Days in Jlab Hall C
A- Physics Rating
Conditional Approval (Target Performance)

Contact : E. Long, UNH

The Deuteron Polarized Tensor Structure Function b_1

JLAB E12-14-011

A^- rating by PAC40

(C1: conditional on target performance)

Spokespersons

Slifer, Solvignon, Long, Chen, Rondon, Kalantarians

b_1 Structure Function

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

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

Investigate nuclear effects at the level of partons!

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

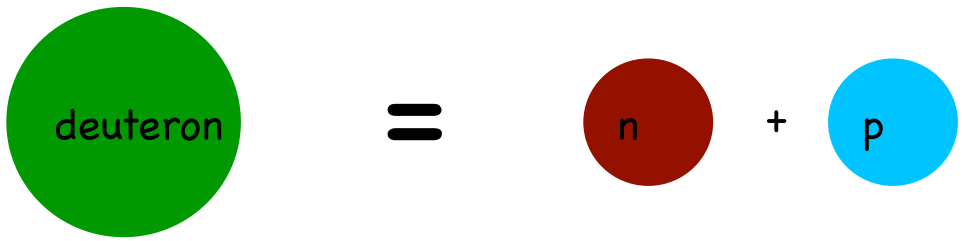
q^1 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state |m| = 1

b_1 Structure Function

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

b_1 vanishes in the absence of nuclear effects

i.e. if...



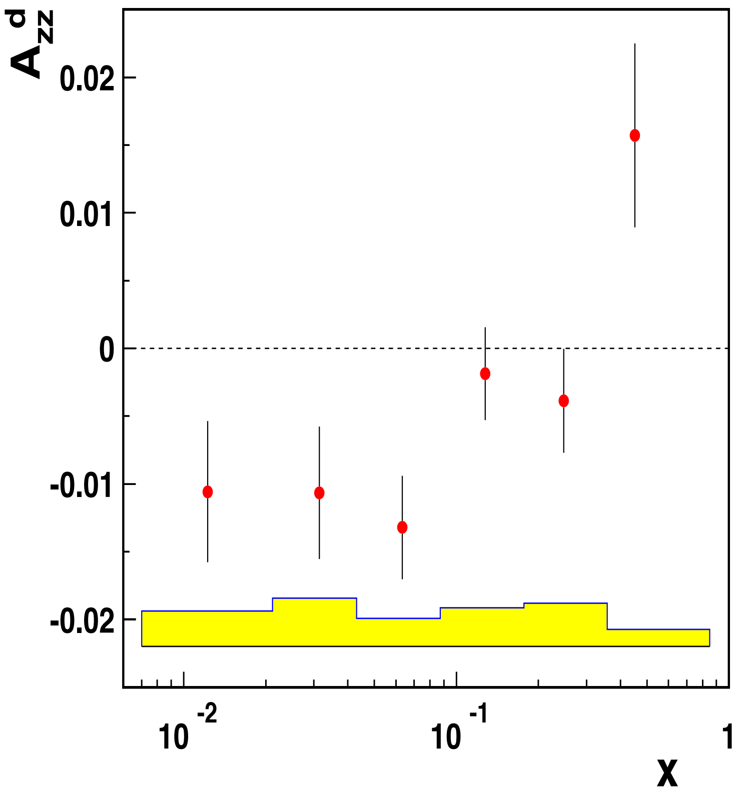
Proton Neutron in relative S-state

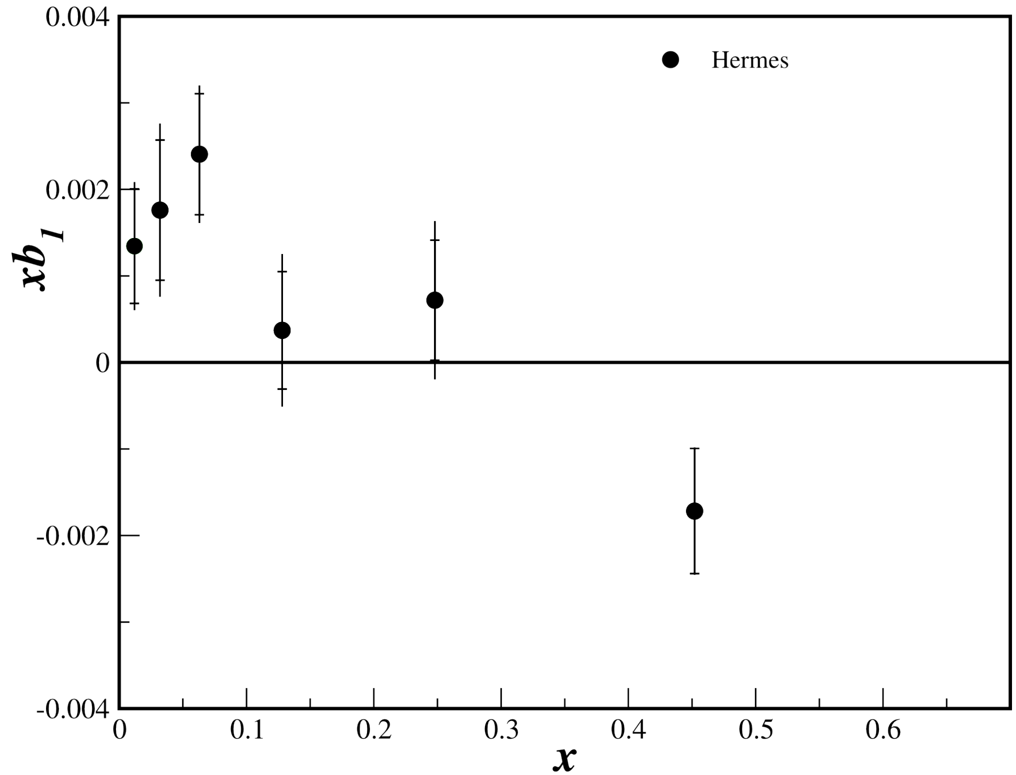
Even accounting for D-State admixture <u>b_1 expected to be vanishingly small</u>

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

Data from HERMES





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

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

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

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

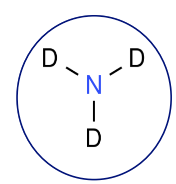
$\sigma_\dagger$: Tensor Polarized cross-section

σ_0 : Unpolarized cross-section

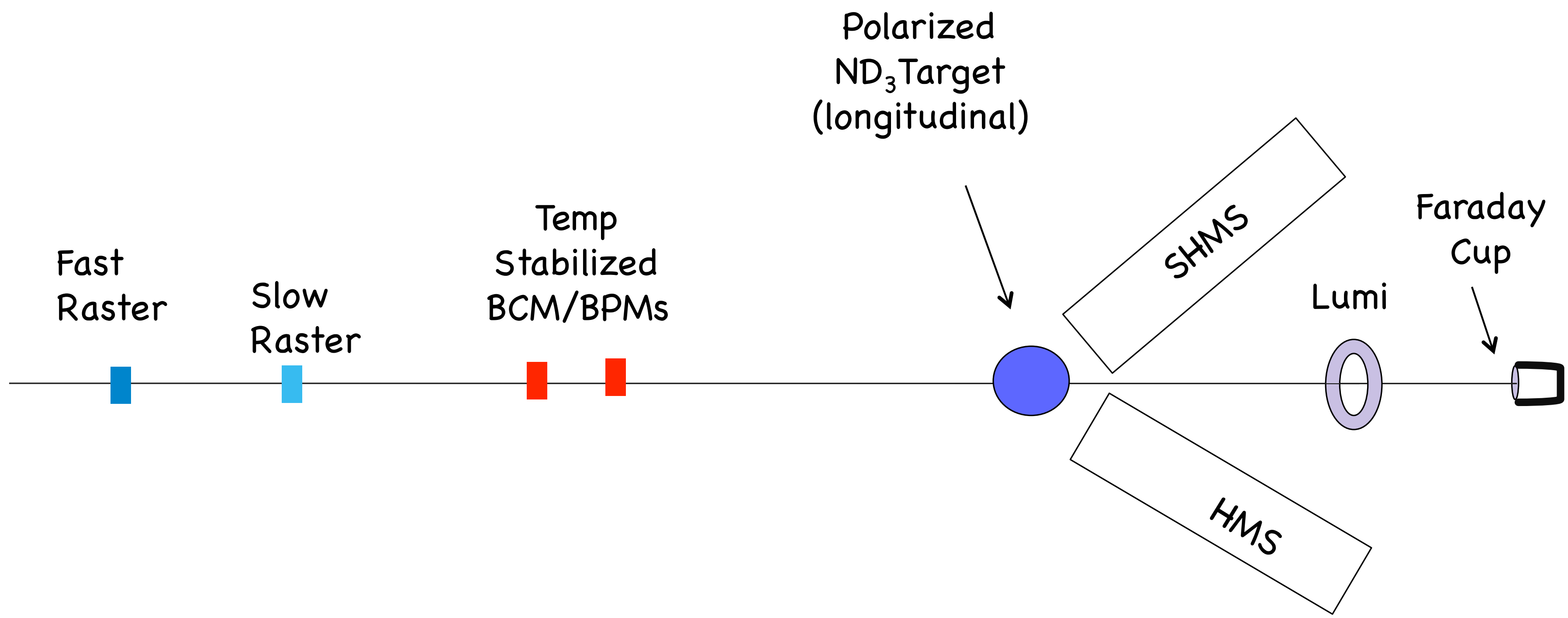
P_{zz} : Tensor Polarizzation

dilution factor

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



Jlab Hall C

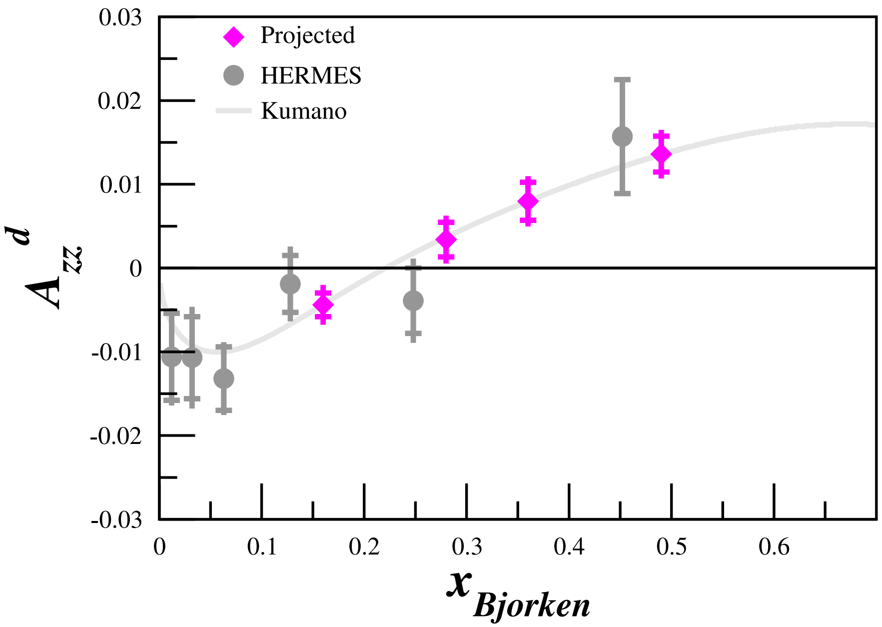


Unpolarized Beam
UVa/JLab Polarized Target

Magnetic Field Held Along Beam Line at all times

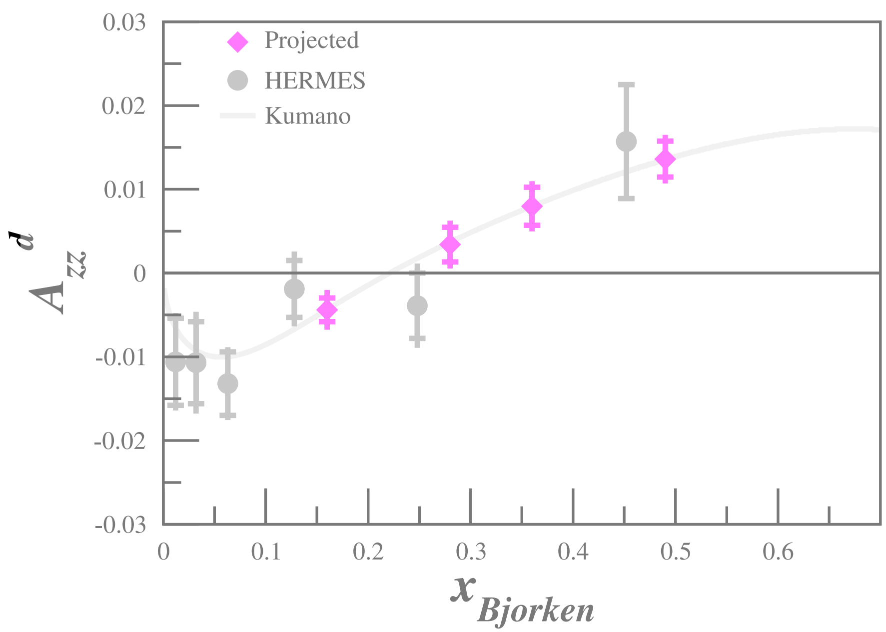
$\mathcal{L}=10^{35}$

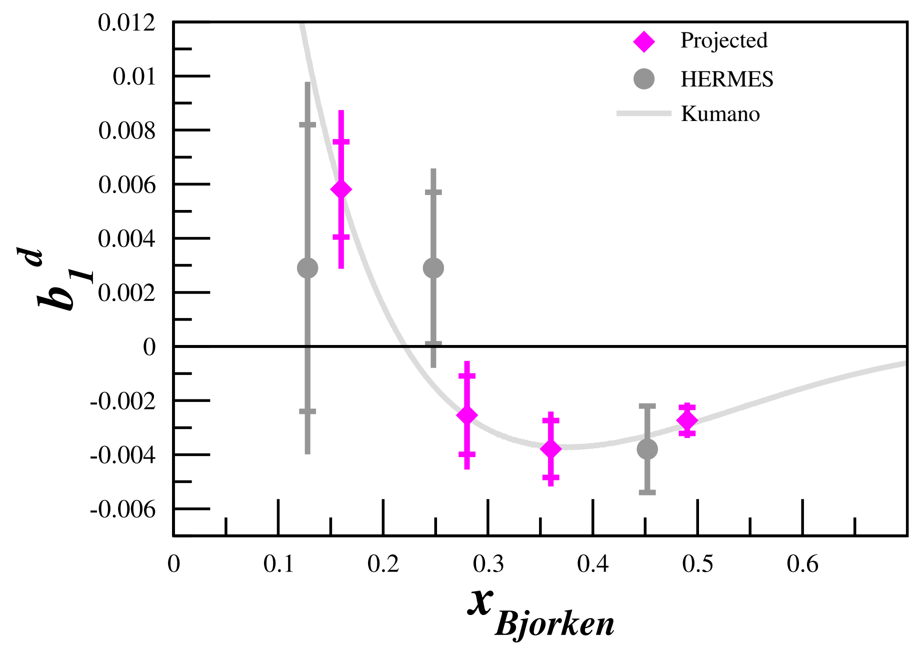
Projected Results for P_{zz} = 35%



30 Days in Jlab Hall C

Projected Results for P_{zz} = 35%

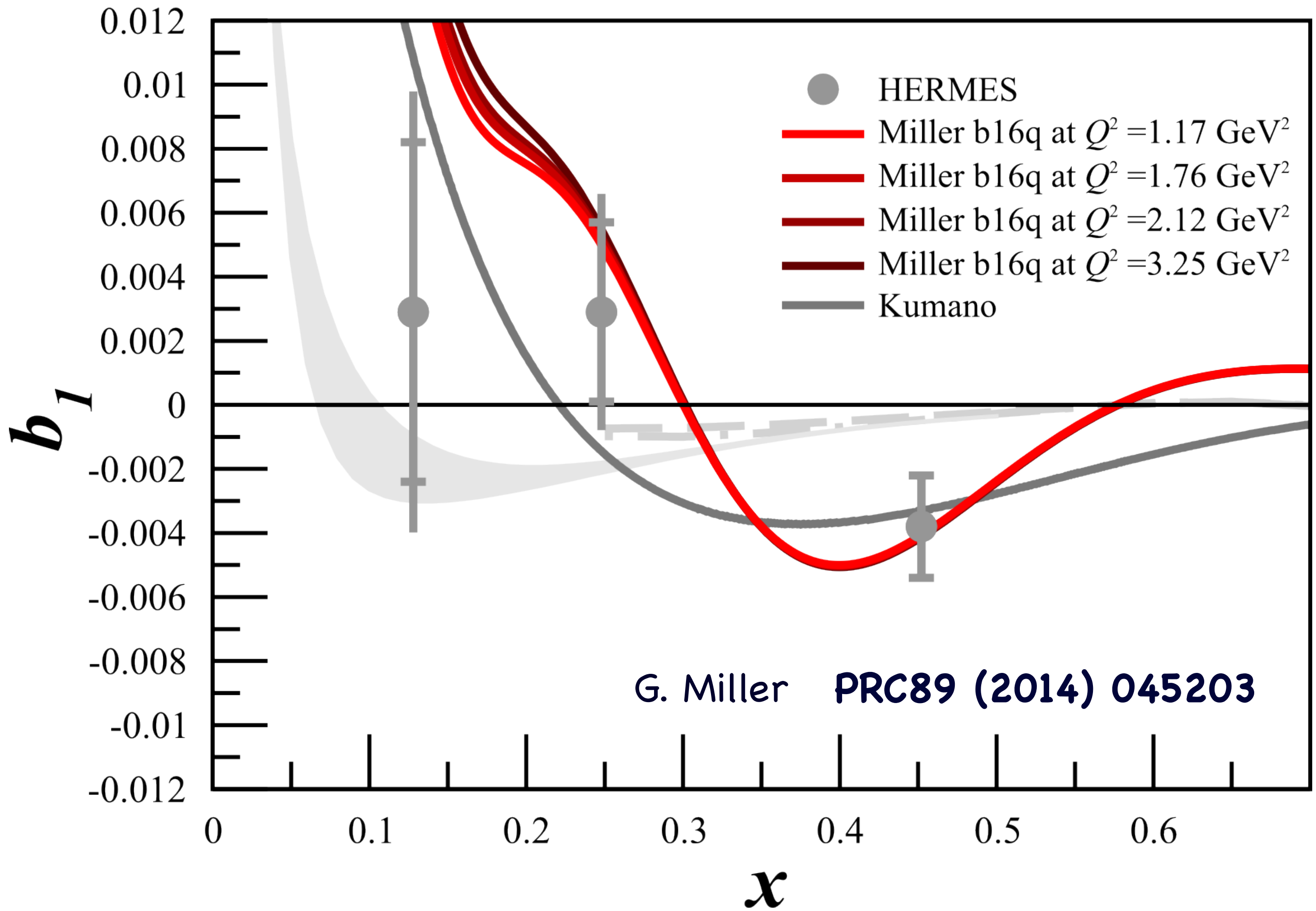




30 Days in Jlab Hall C

verification of zero crossing
essential for satisfaction of CK Sum

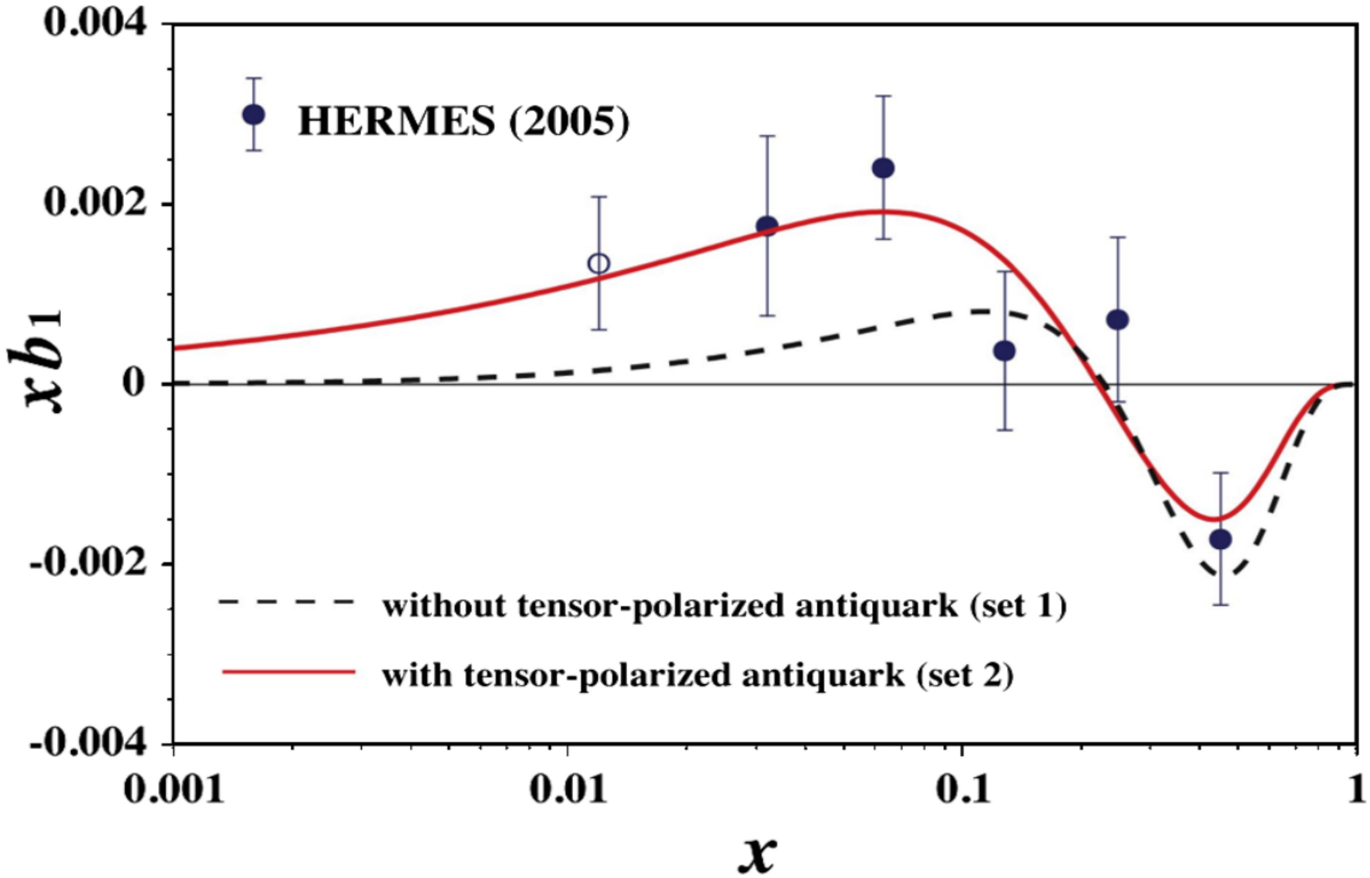
Unique Signal of Hidden Color



no conventional nuclear mechanism can reproduce the Hermes data,

but that the 6-quark probability needed to do so (P_{6Q} = 0.0015) is small enough that it does not violate conventional nuclear physics.

Tensor polarization of the sea



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

Fit improves when tensor polarization of the antiquark distributions is included

Close-Kumano Sum Rule

$$\int b_1(x)dx = \frac{1}{9}\Theta Q_s$$

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

if the sea quark tensor polarization vanishes

Close-Kumano Sum Rule

$$\int b_1(x)dx = \frac{1}{9}\Theta Q_s$$

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

if the sea quark tensor polarization vanishes

Hermes result

$$\int_{0.0002}^{0.85} b_1(x)dx = 0.0105 \pm 0.0034 \pm 0.0035$$

2.2 σ difference from zero

Gluon Contribution to Tensor Structure

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

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

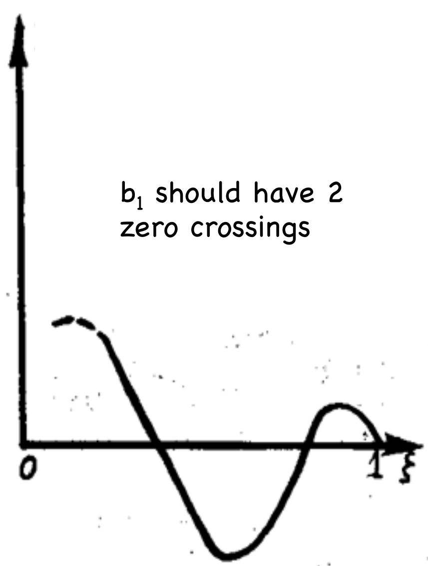


Рис.1

Efremov and Teryaev (1982, 1999)

Gluons (spin 1) contribute to both moments

Quarks satisfy the first moment, but

Gluons may have a non-zero first moment!

2nd moment more likely to be satisfied experimentally since the collective glue is suppressed compared to the sea

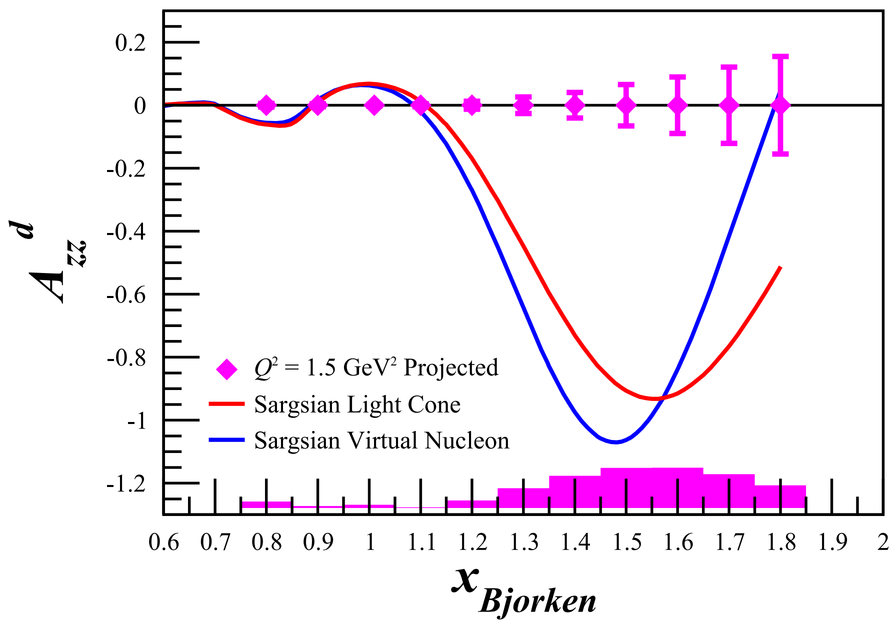
Study of b_1 allows to discriminate between deuteron components with different spins (quarks vs gluons)

Efremov, Teryaev, JINR PreprintR2-81-857(1981), Yad. Phys. 36, 950 (1982)
A.V. Efremov, O. V. Teryaev JINR-E2-94-95 (1999)
Jaffe, Manohar Phys.Lett. B223 (1989) 218

E12-15-005

A_{zz} in the x>1 Region

Ellie Long, Slifer, Solvignon,
Day, Higinbothan, Keller

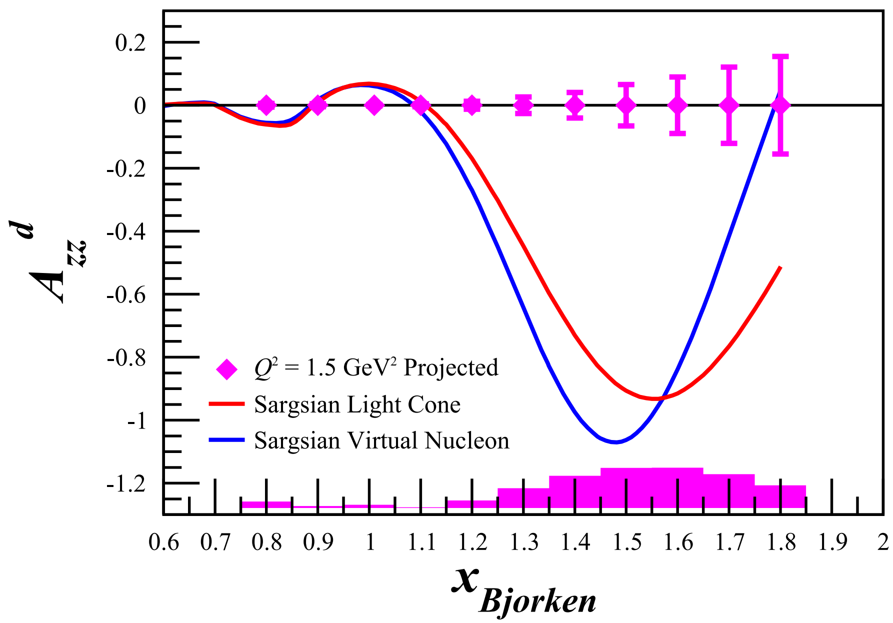


Very Large Tensor Asymmetries predicted

E12-15-005

A_{zz} in the x>1 Region

Ellie Long, Slifer, Solvignon,
Day, Higinbothan, Keller



Very Large Tensor Asymmetries predicted

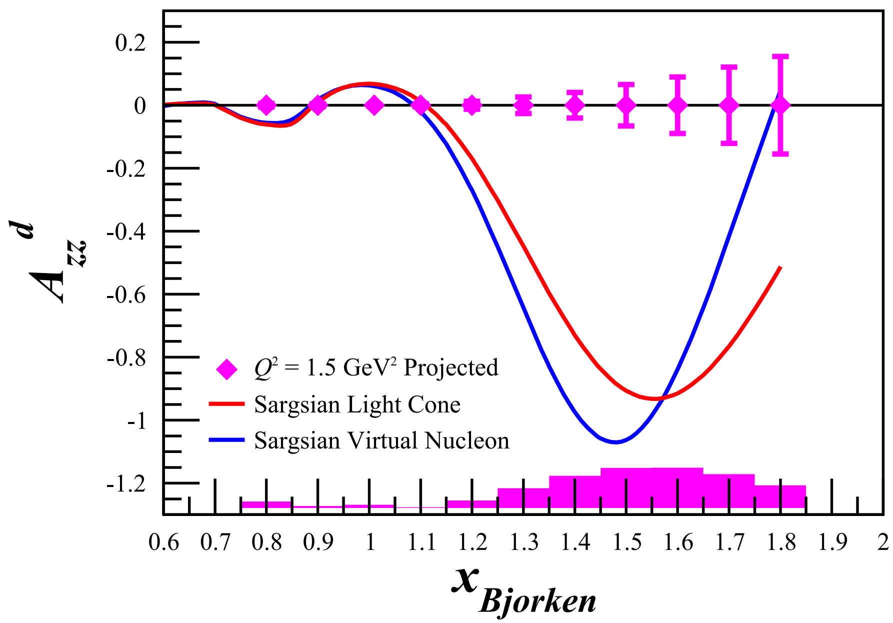
Sensitive to the S/D-wave ratio in the deuteron wave function

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

E12-15-005

A_{zz} in the x>1 Region

Ellie Long, Slifer, Solvignon, Day, Higinbothan, Keller



Very Large Tensor Asymmetries predicted

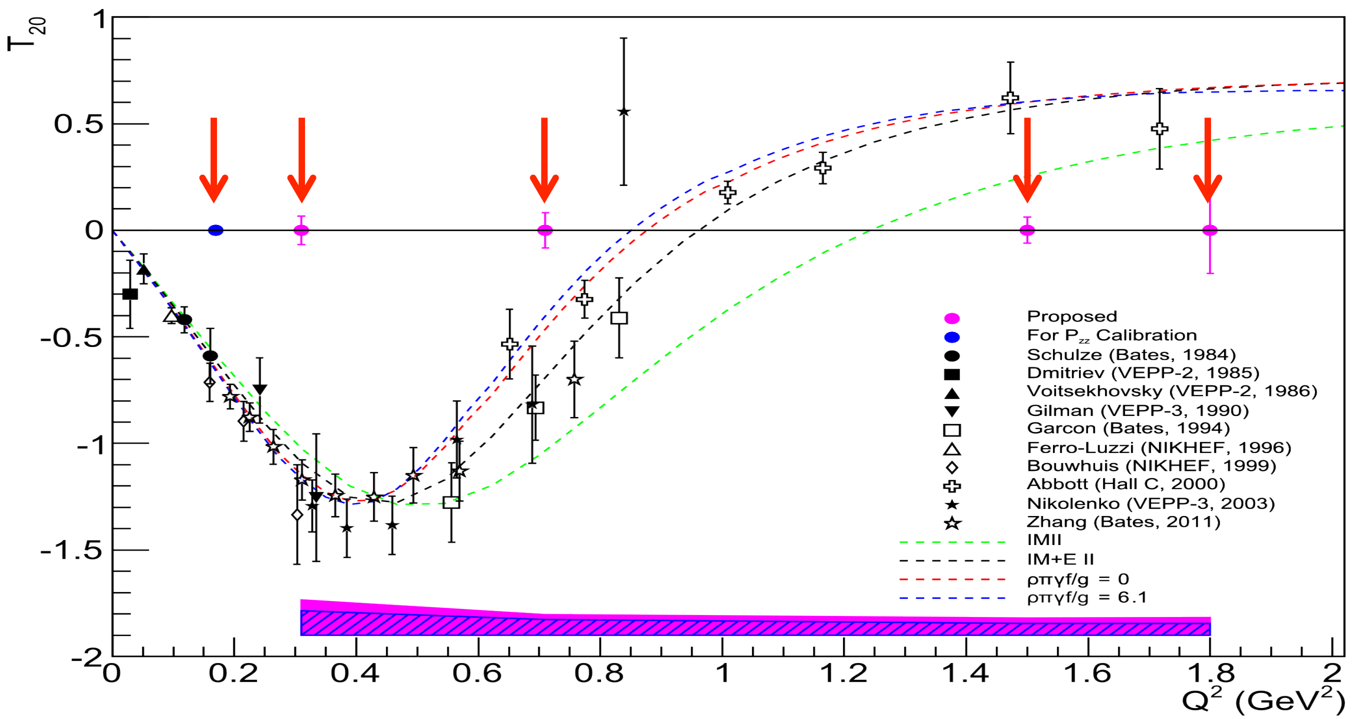
Sensitive to the S/D-wave ratio in the deuteron wave function

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

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

PAC44 Theory Report

A_{zz} experiment



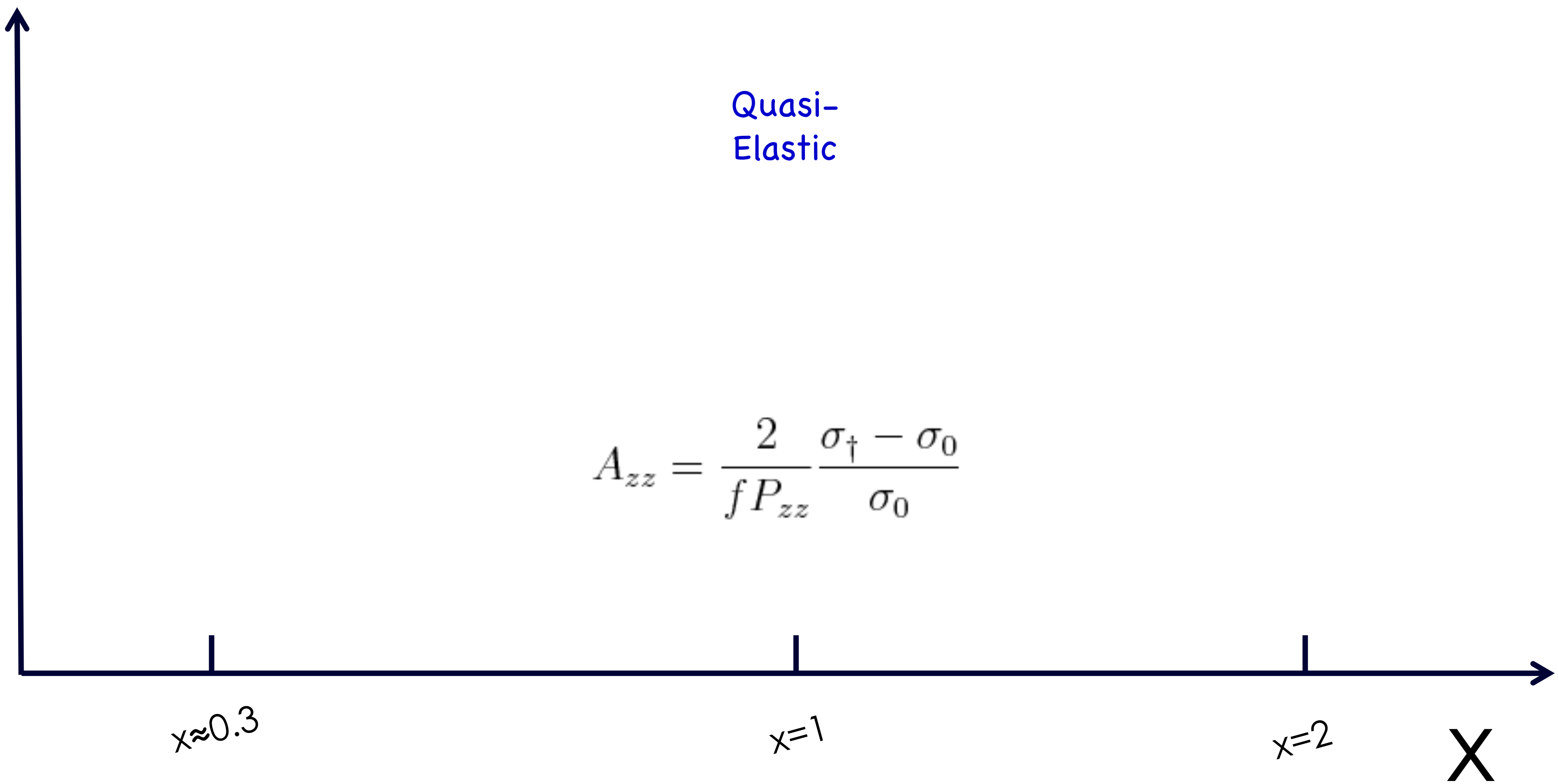
We simultaneously measure nuclear elastic

-> T_{20} over huge Q^2 range

-> measure T_{20} at largest Q^2 yet

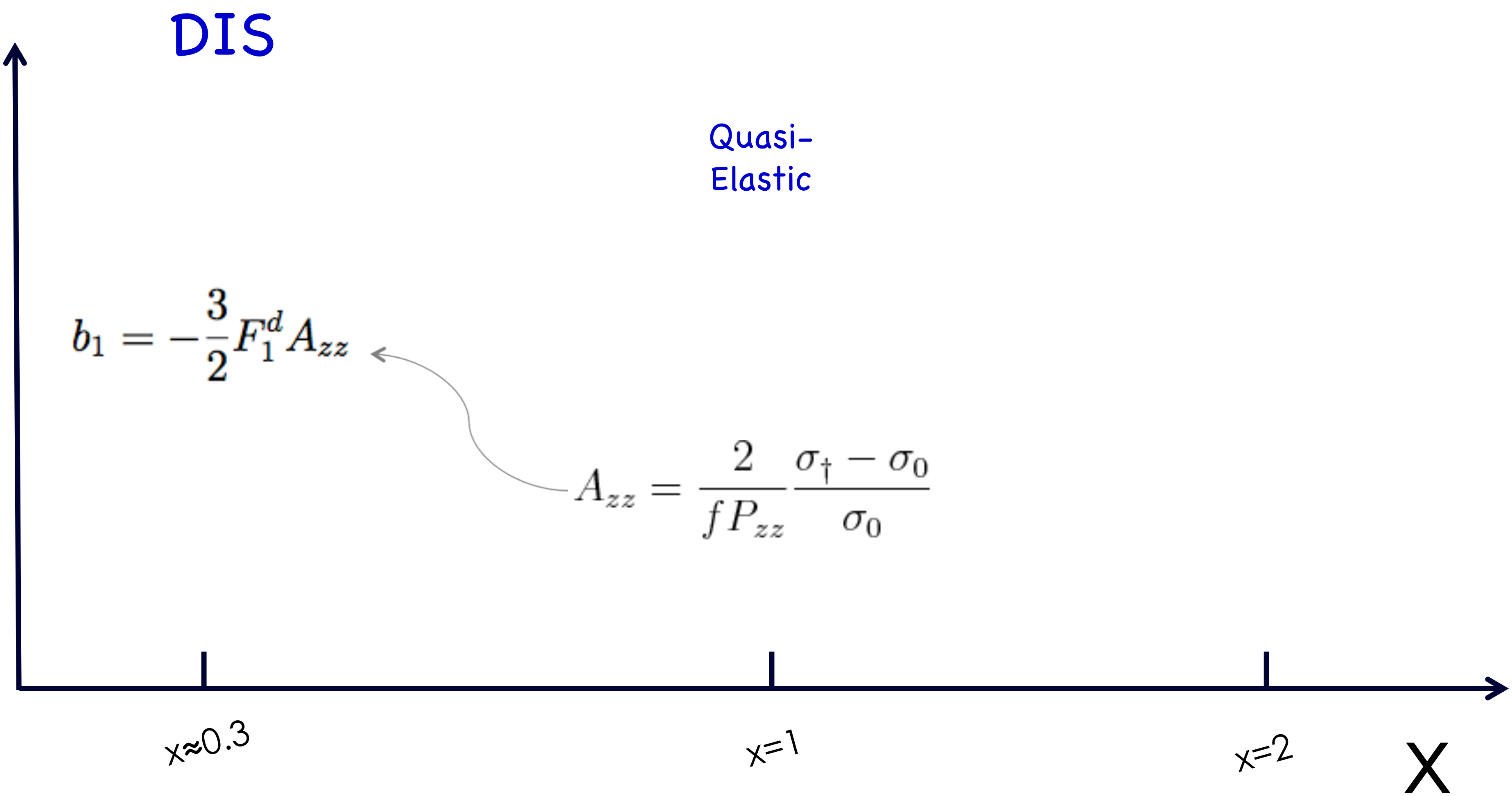
-> will use to cross-check Pzz

Tensor Spin Observables



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

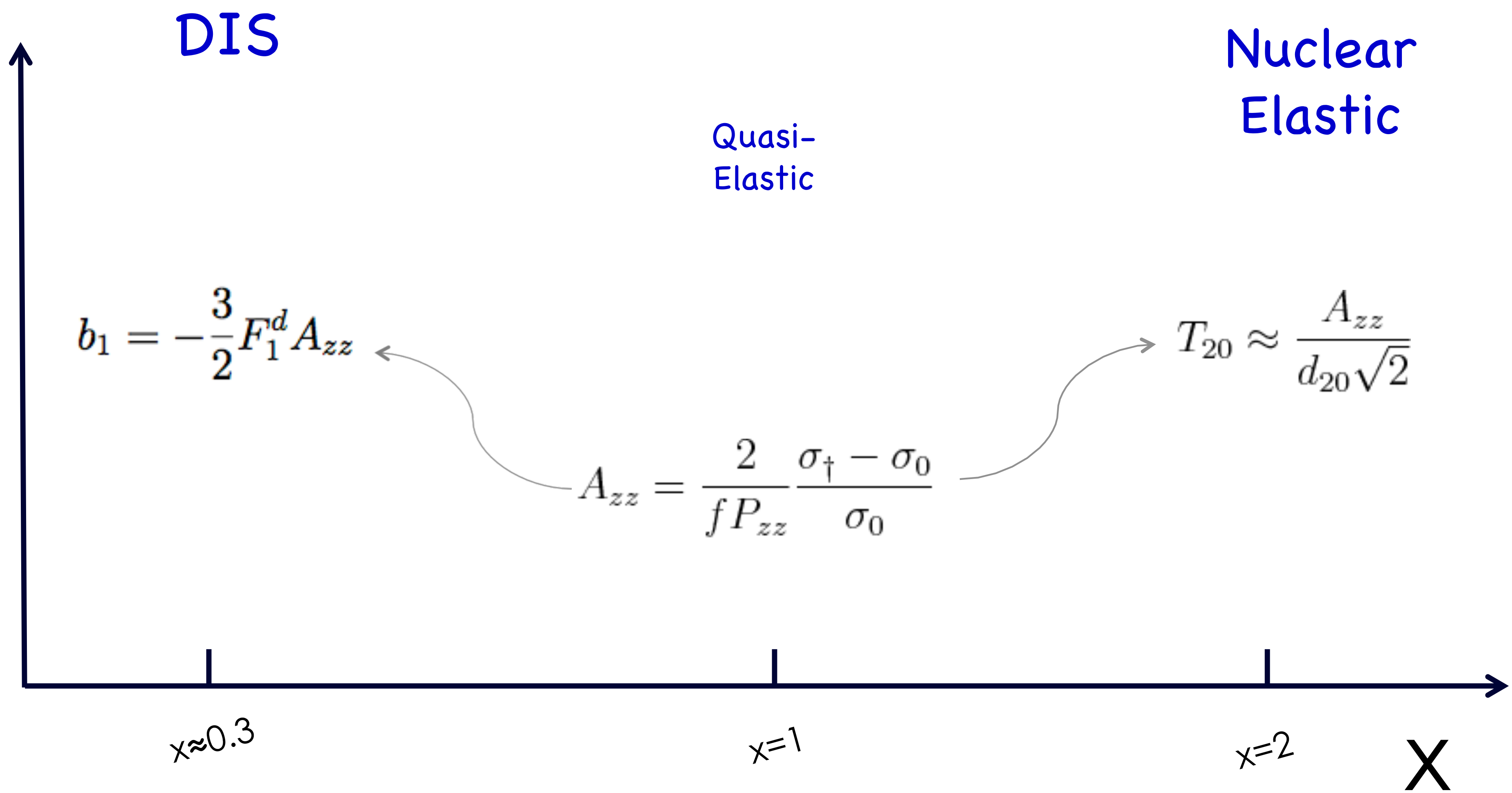
Tensor Spin Observables



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

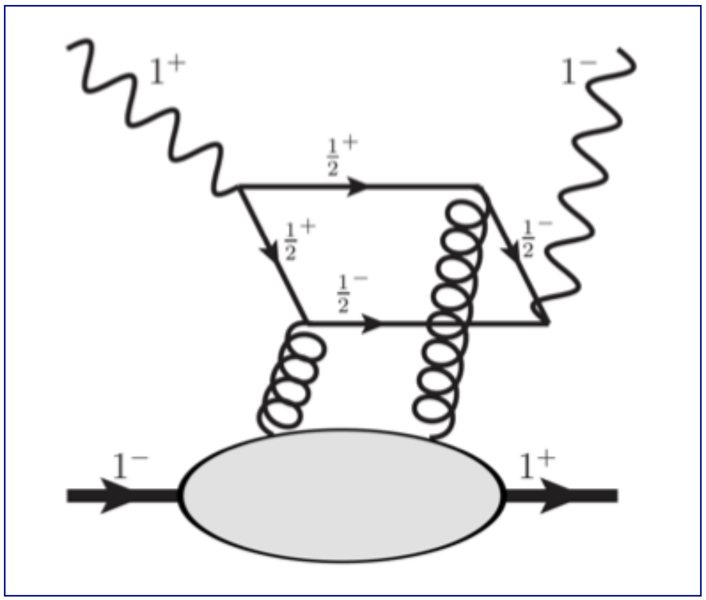
$$A_{zz} = \frac{2}{f P_{zz}} \frac{\sigma_\dagger - \sigma_0}{\sigma_0}$$

Tensor Spin Observables



LOI-12-16-006

See R. Milner @ Spin2016
"State and Future of Spin Physics"



James Maxwell (contact), R. Milner

"Nuclear Gluonometry"

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

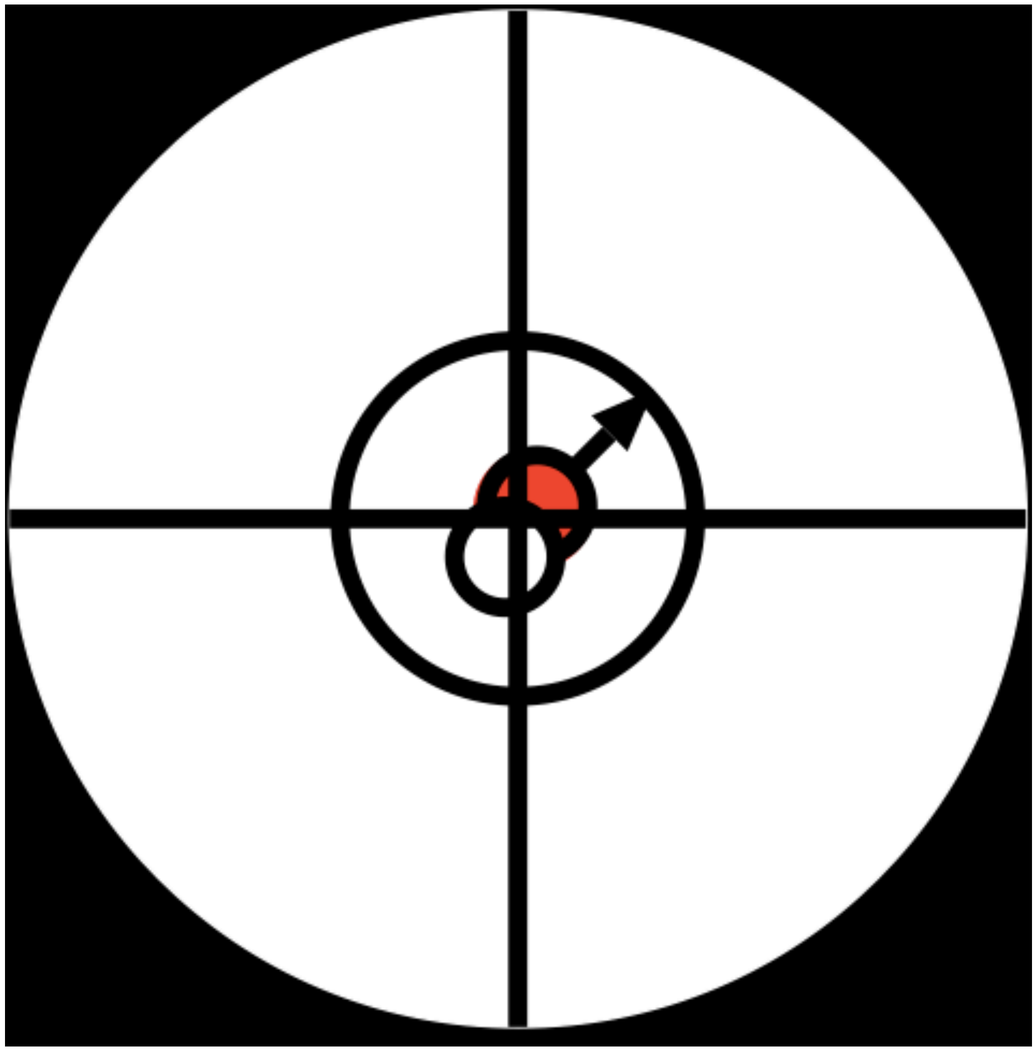
Non-zero value would be a clear signature of exotic gluon states in the nucleus

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

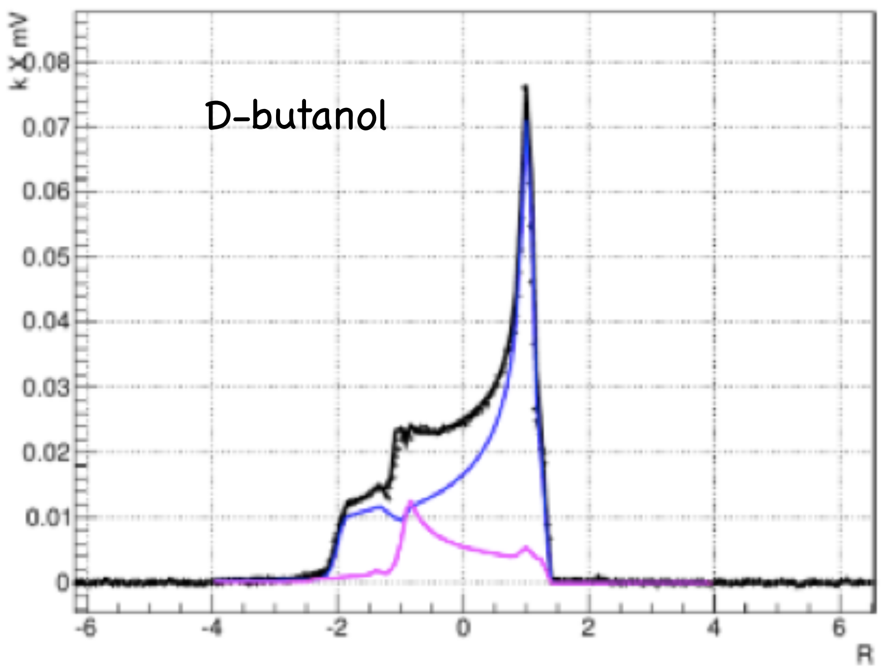
$\Delta(x,Q^2)$ double helicity flip structure function

Encouraged for full submission by PAC44

Technical Developments



Tensor Polarized Target



MC overlap with d-but. NMR experimental points (Pn=51→45,Qn:20→31%)

Significant progress at UVa

Enhancing P_{zz} via semi-selective saturation

understanding the NMR lineshape

D Keller, Eur.Phys.J.A., in review (2016)
D Keller, PoS, PSTP2015:014 (2016)
D Keller, J.Phys.Conf.Ser., **543**(1):012015 (2014)
D Keller, Int.J.Mod.Phys.Conf.Ser., **40**(1):1660105 (2016)
D Keller, EJPA, **53**:155 (2017)

Promising, but need to confirm in ND_3

T_{20} measurement at Higs to verify NMR analysis

Eur. Phys. J. A (2017) **53**: 155
DOI 10.1140/epja/i2017-12344-0

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Modeling alignment enhancement for solid polarized targets

D. Keller[a]

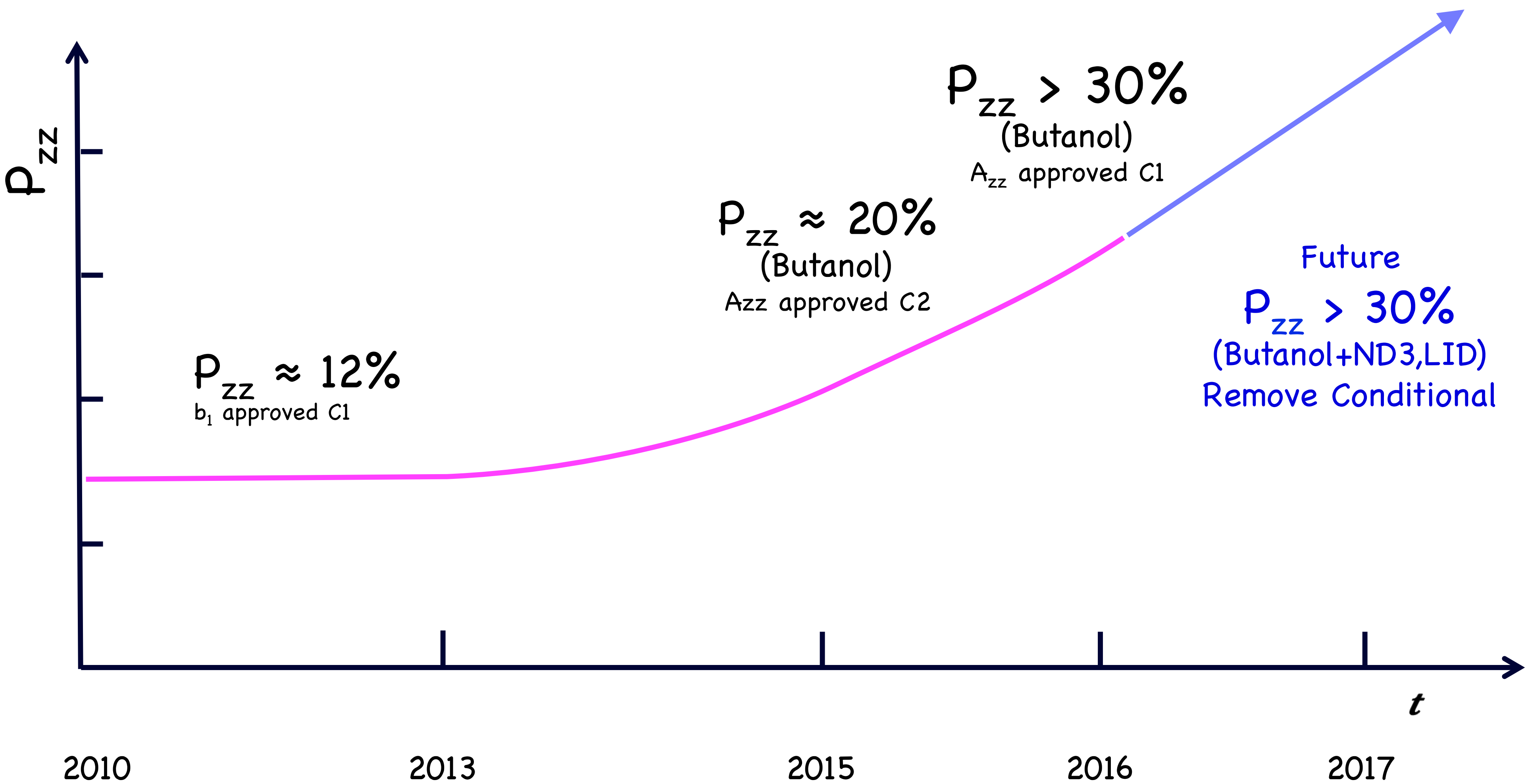
University of Virginia, Charlottesville, VA 22901, USA

Received: 1 May 2017 / Revised: 16 June 2017
Published online: 26 July 2017 – © Società Italiana di Fisica [illegible]
Communicated by M. Anselmino

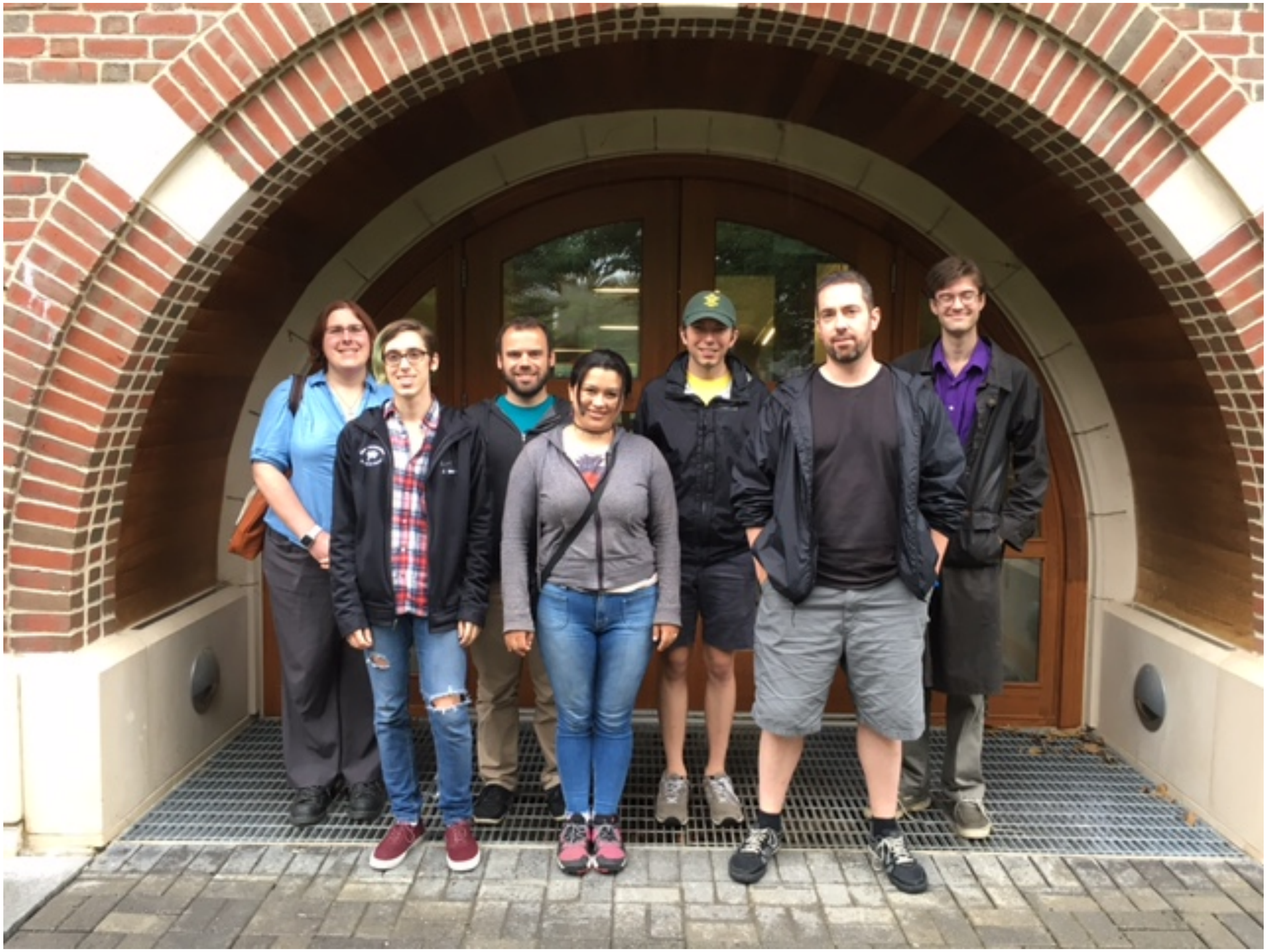
New Publication on tensor polarized target lineshape

Abstract. A model of dyn[illegible] [illegible]frequency (RF) irradiation produced perpendicular to th[illegible] [illegible]pin-1 system required for tensor-polarized fixed-target expe[illegible] [illegible] produced close to the Larmor frequency of the nucleus and [illegible] [illegible]nance linewidth to be much smaller than the nuclear magnetic resonance [illegible] equations are solved numerically to study a semi-saturated steady-state resulting from [illegible] sources of irradiation: microwave from the DNP process and the additional RF used to manipulate the tensor polarization. The steady-state condition and continuous-wave NMR lineshape are found that optimize the spin-1 alignment in the polycrystalline materials used as solid polarized targets in charged-beam nuclear and particle physics experiments.

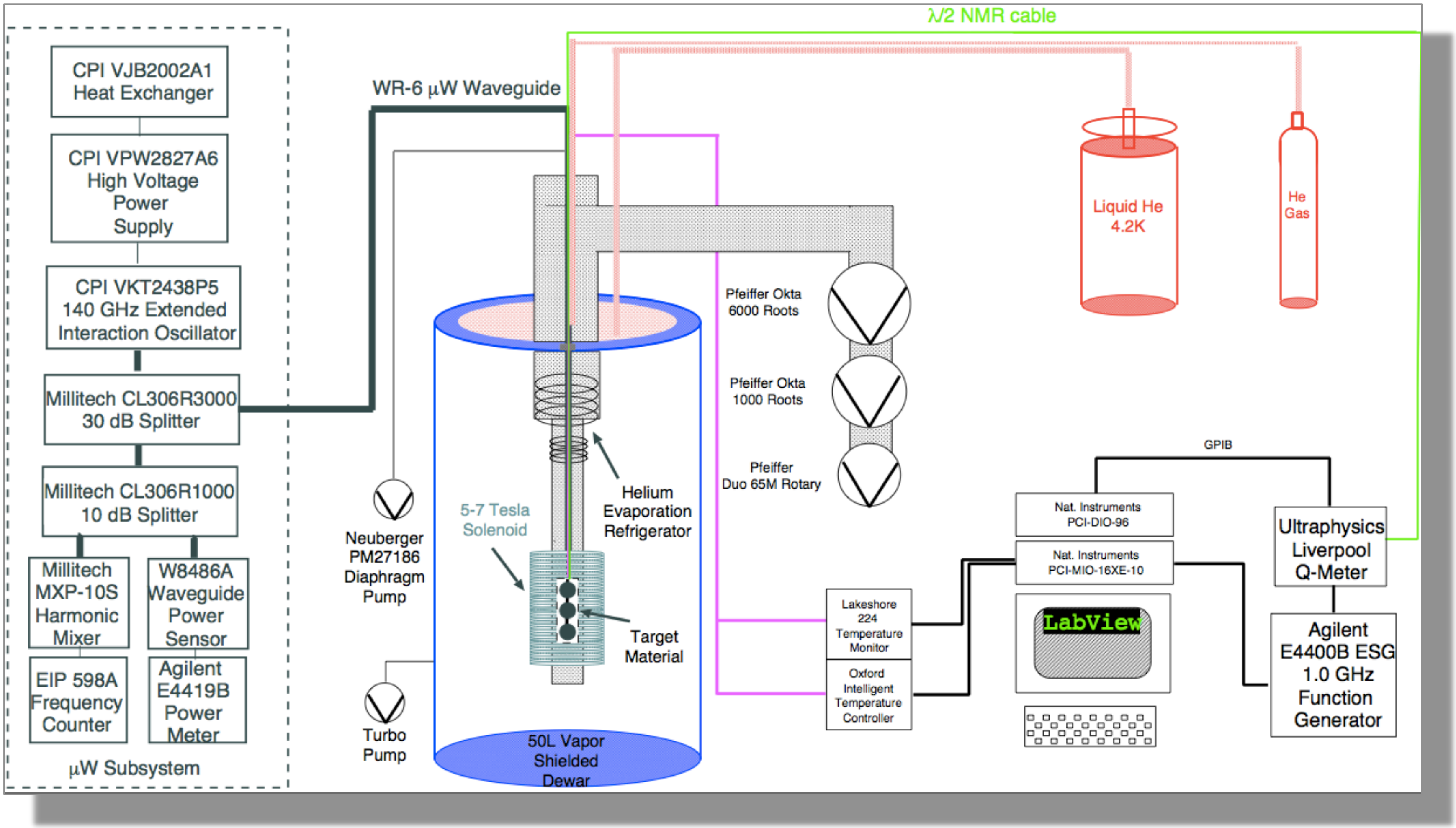
Tensor Polarization progress



UNH Polarized Target Lab



UNH Polarized Target Lab



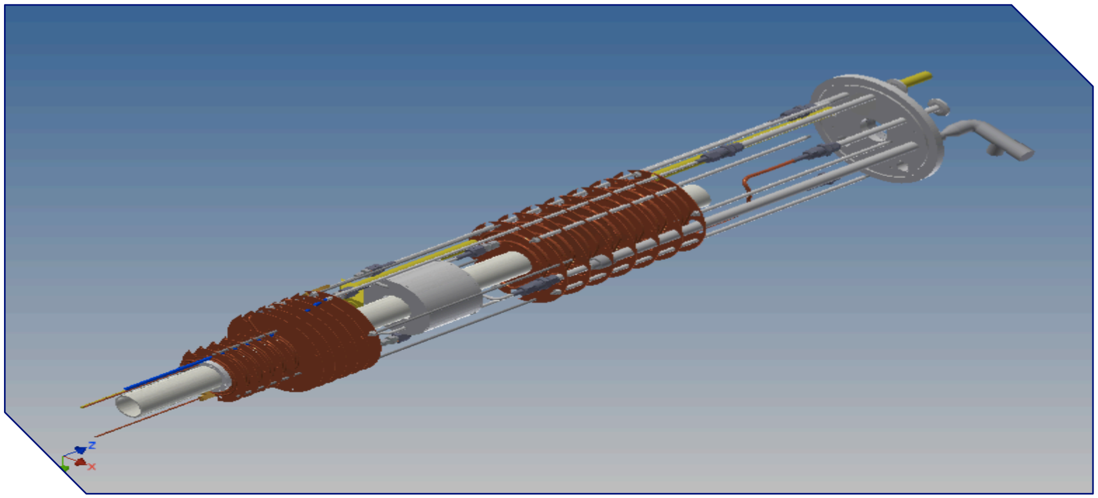
Microwave subsystem focus for the fall/spring

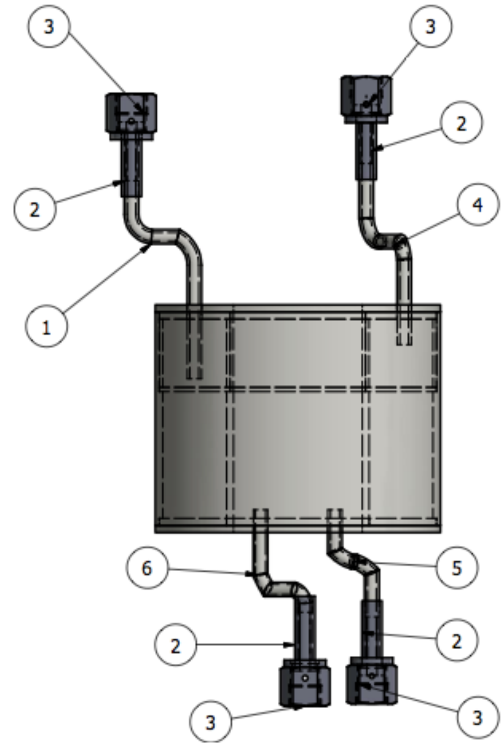
We've run at 1K/7Tesla

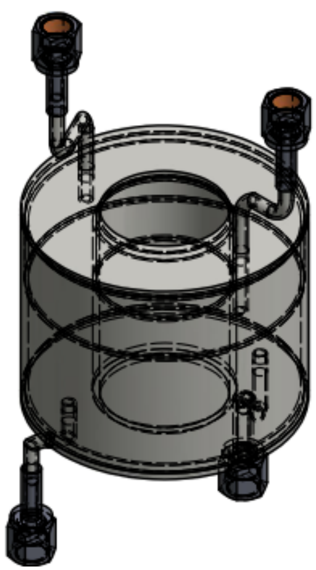
Constructing New 1 K Fridge almost complete

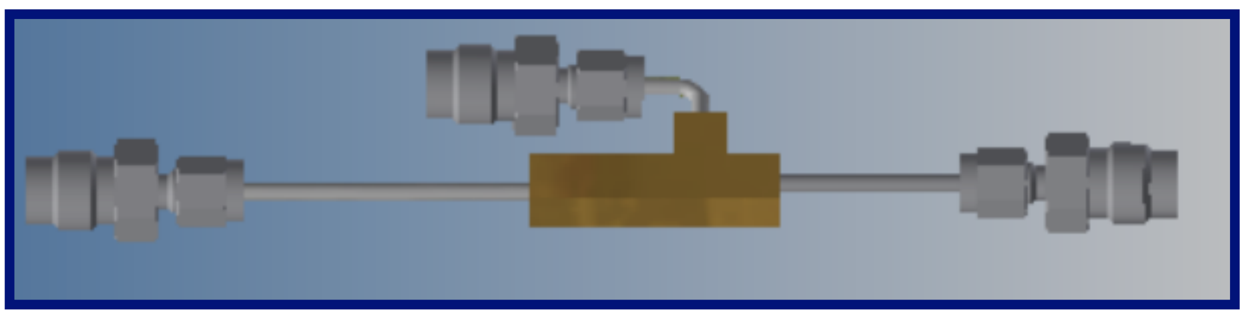
- ✓ NMR
- ✓ Cryogenic/thermometry
- ✓ DAQ
- ✓ UHV

UNH : New 1 K Helium Evaporation Fridge





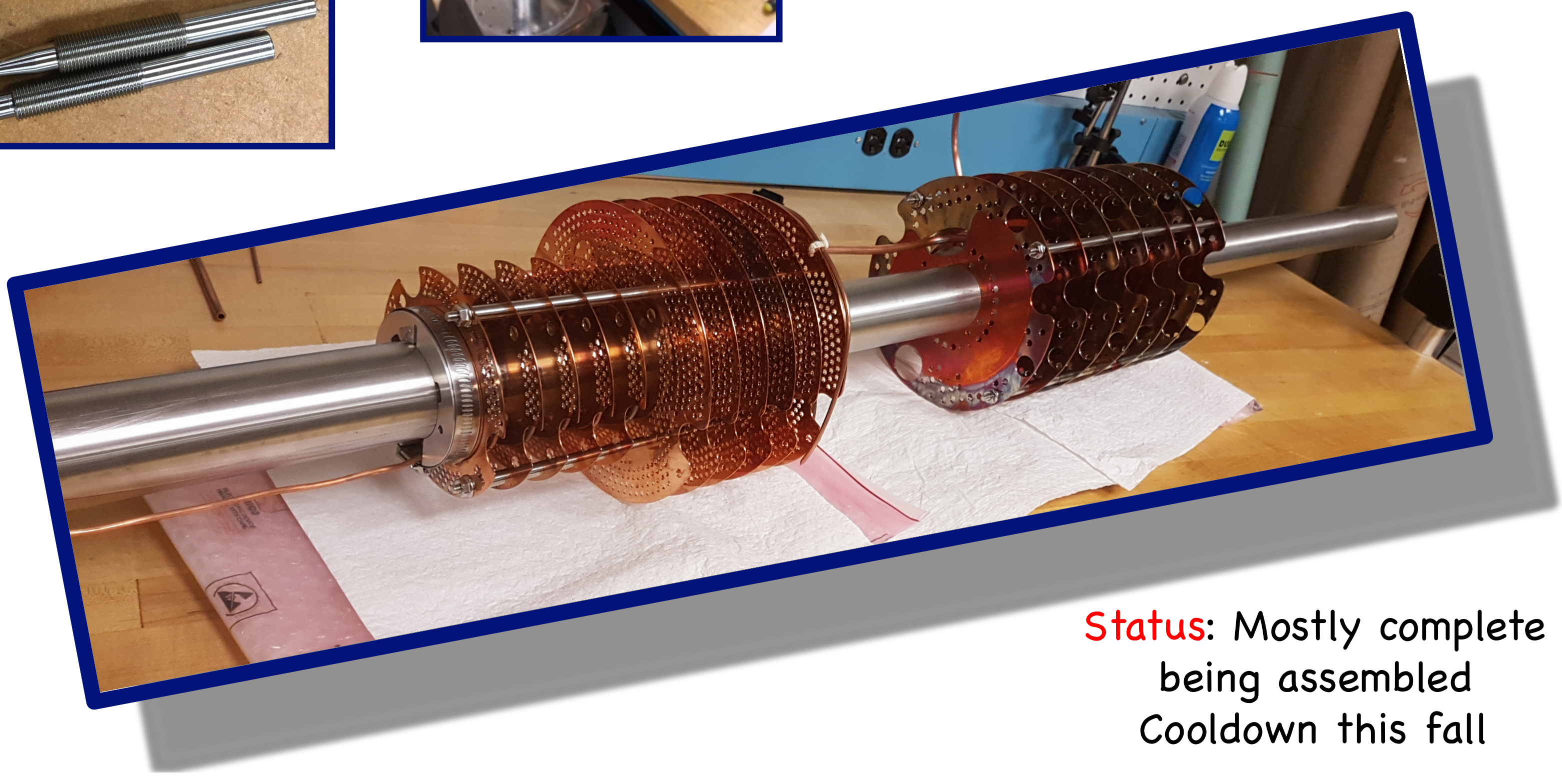




g2p fridge design (C. Keith/Jlab) mods by Nathaly S./UNH

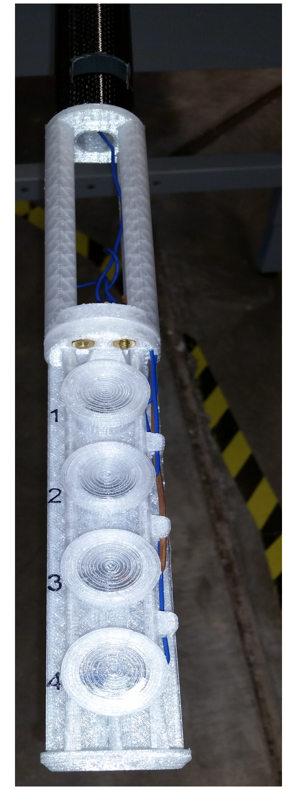
UNH: New 1 K Helium Evaporation Fridge

UNH
Shop
&
Lesker
for
machining
welding



Status: Mostly complete
being assembled
Cooldown this fall

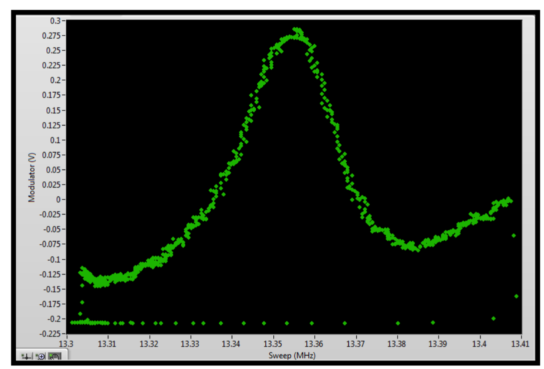
UNH Polarized Target Lab



New Faculty hire : Prof. Elena Long

University made a significant investment in polarized target infrastructure

We should be fully operational by spring



Summary

Spin Polarizabilities

δ_{LT} puzzle and χPT calculations : progress is being made.
but stil large discrepencies data/calcs

New low Q^2 data should help clarify. g2p, Eg4, sagdh and SANE publications in prep.

First measurement of g2p contribution to Hydrogen Hyperfine Splitting.

Tensor Program

E12-13-001: Tensor Polarized Structure function b1 of the Deuteron

E12-14-002: Tensor Asymmetry A_{zz} for x>1

LOI12-14-001: Tensor Structure Function Δ

Significant progress has been made to develop the targets.

High tensor polarizations demonstrated at Uva
UNH target lab goal to be fully operational in Spring.

Moments

Spin polarizabilities

$$\gamma_0(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 g_{TT}(x, Q^2),$$

$$\delta_{LT}(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 \Big[g_1(x, Q^2) + g_2(x, Q^2)\Big],$$

color polarizability

$$\bar{d}_2(Q^2) = \int_0^{x_0} \mathrm{d}x\, x^2 \Big[2g_1(x, Q^2) + 3g_2(x, Q^2)\Big],$$

Generalized GDH

$$I_A(Q^2) = \frac{2M_N^2}{Q^2} \int_0^{x_0} \mathrm{d}x\, g_{TT}(x, Q^2),$$

$$\Gamma_1(Q^2) = \int_0^{x_0} \mathrm{d}x\, g_1(x, Q^2),$$

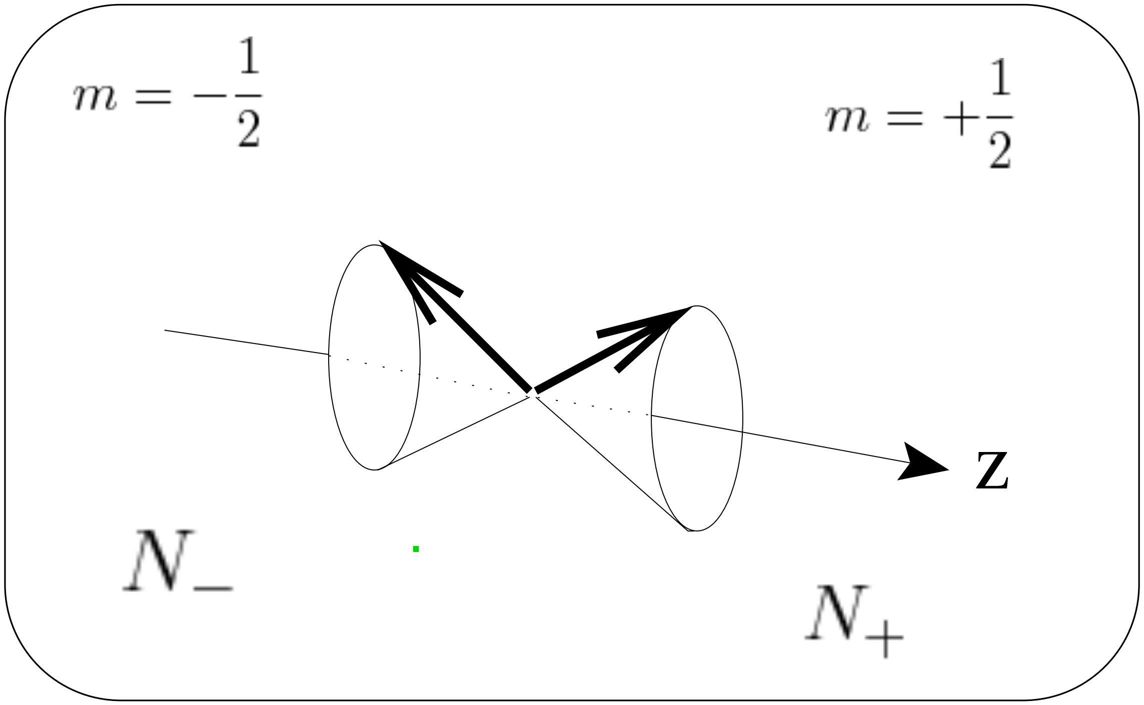
Burkhardt Cottingham

$$\Gamma_2(Q^2) = \int_0^{x_0} dx\ g_2(x, Q^2)$$

$$g_{TT} = g_1 - (4M_N^2 x^2/Q^2) g_2$$

Spin-1/2

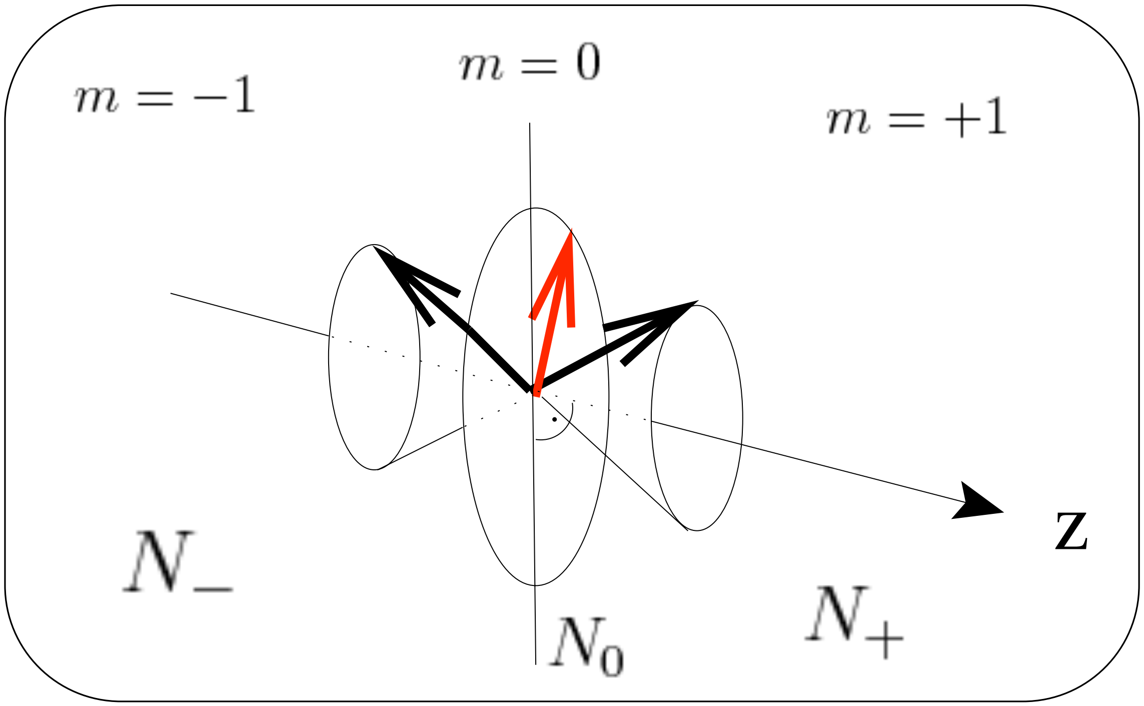
Spin-1/2 system in B-field leads to 2 sublevels due to Zeeman interaction



$$P_z = \frac{N_+ - N_-}{N_+ + N_-}$$

$-1 < P_z < +1$

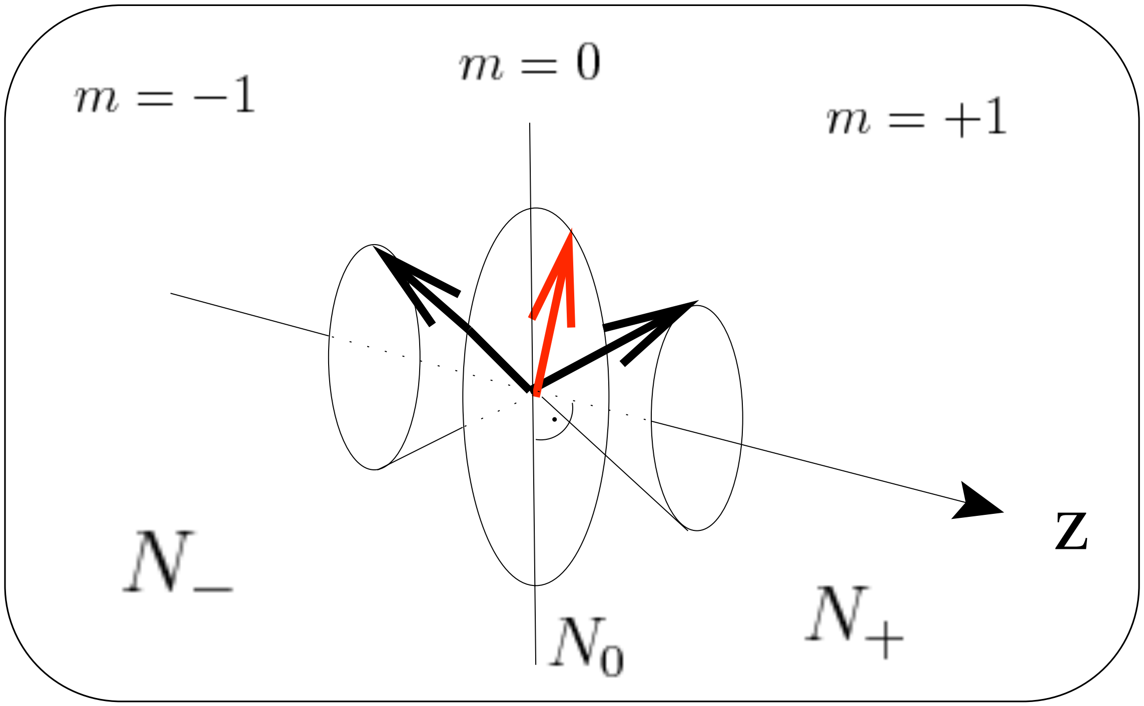
Spin-1



$$P_z = \frac{N_+ - N_-}{N_+ + N_-}$$

$$P_{zz} = \frac{(N_+ - N_0) - (N_0 - N_-)}{N_+ + N_0 + N_-} = \frac{(N_+ + N_-) - 2N_0}{N_+ + N_0 + N_-}$$

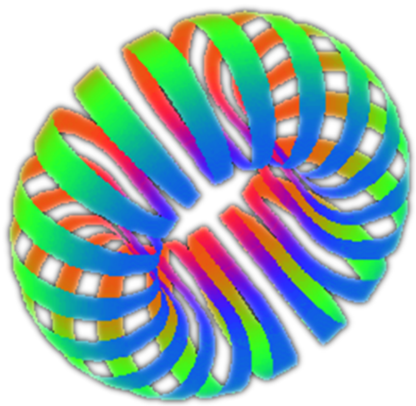
Spin-1



$$P_{zz} = \frac{(N_+ - N_0) - (N_0 - N_-)}{N_+ + N_0 + N_-} = \frac{(N_+ + N_-) - 2N_0}{N_+ + N_0 + N_-}$$

$-2 < P_{zz} < +1$

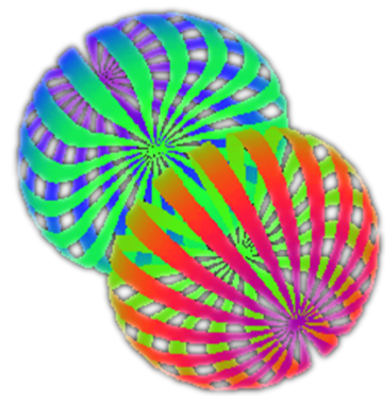
Spin-1



$P_{zz} = -2$

Pure Tensor Polarization

All spins in the m=0 level



$P_{zz} = +1$

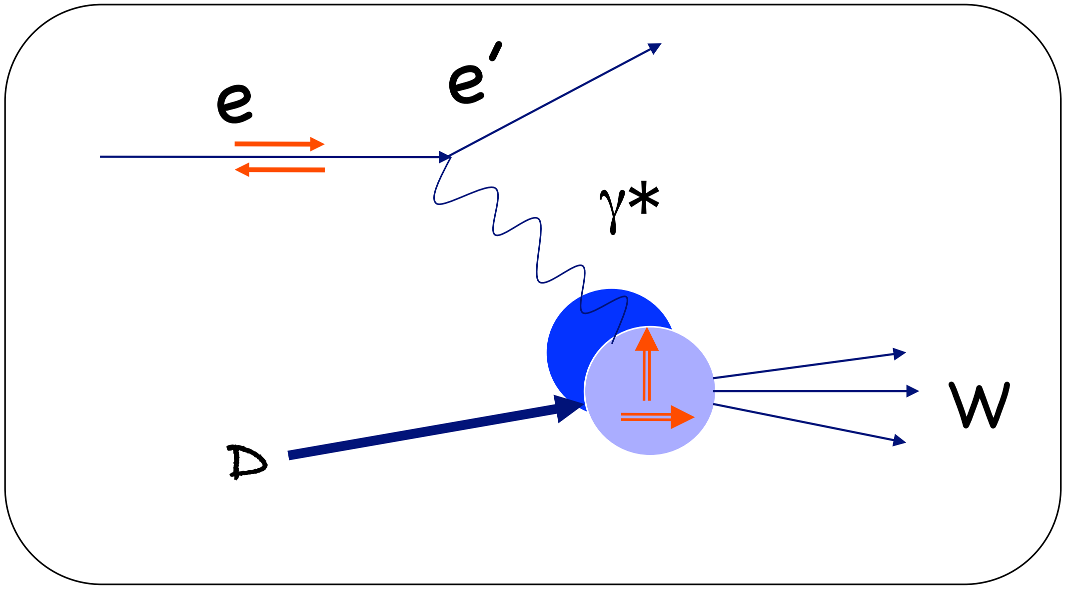
Pure Vector Polarization

m=0 level depopulated

$$P_{zz} = \frac{(N_+ - N_0) - (N_0 - N_-)}{N_+ + N_0 + N_-} = \frac{(N_+ + N_-) - 2N_0}{N_+ + N_0 + N_-}$$

$$-2 < P_{zz} < +1$$

Inclusive Scattering



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

Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

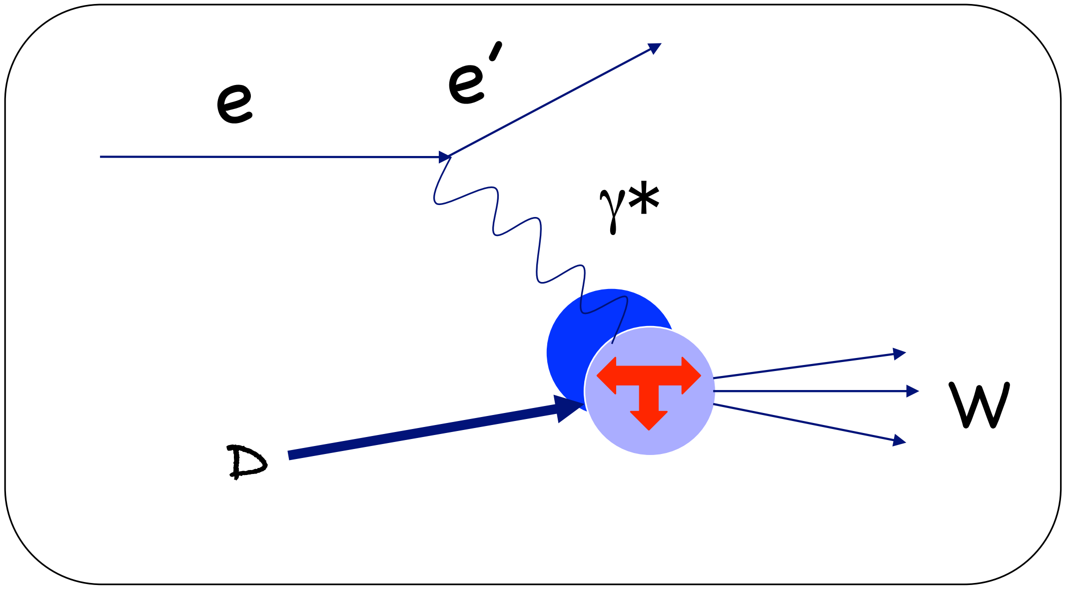
$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu}$$

Unpolarized Scattering

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

Vector Polarization

Tensor Structure Functions



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

Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

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

} Tensor Polarization

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

Tensor Structure Functions

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

Leading Twist

Tensor Structure Functions

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

Leading Twist

b_2 : related to b_1 by A Callan-Gross relation

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

b_3 : higher twist, like g_2

Parton Distributions

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

Parton distributions

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

$$q_1(x) = q^1_\uparrow(x) + q^1_\downarrow(x)$$

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

spin averaged parton distributions

Parton distributions

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

$$q_1(x) = q^1_\uparrow(x) + q^1_\downarrow(x)$$

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

spin averaged parton distributions

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

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