Spin Results from Jefferson Lab

9th Workshop on Hadron Physics in China and Opportunities

Nanjing, China
7/25/2017

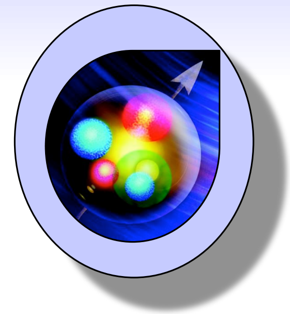
Karl Slifer
University of New Hampshire

This Talk

Brief Review

Inclusive Scattering & Structure Functions

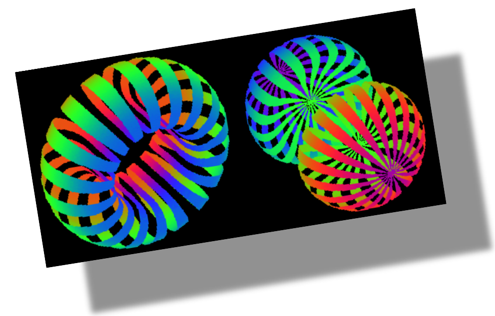
Spin Polarizabilities & Moments.



Jlab Spin Results

Halls A,B & C

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



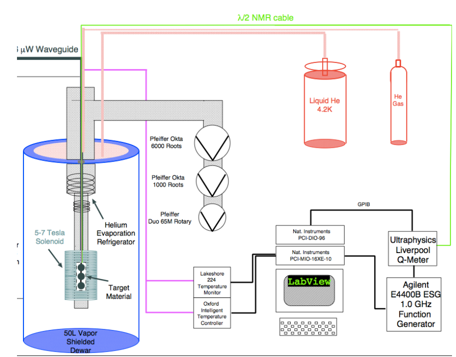
Jlab Tensor Structure Program

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

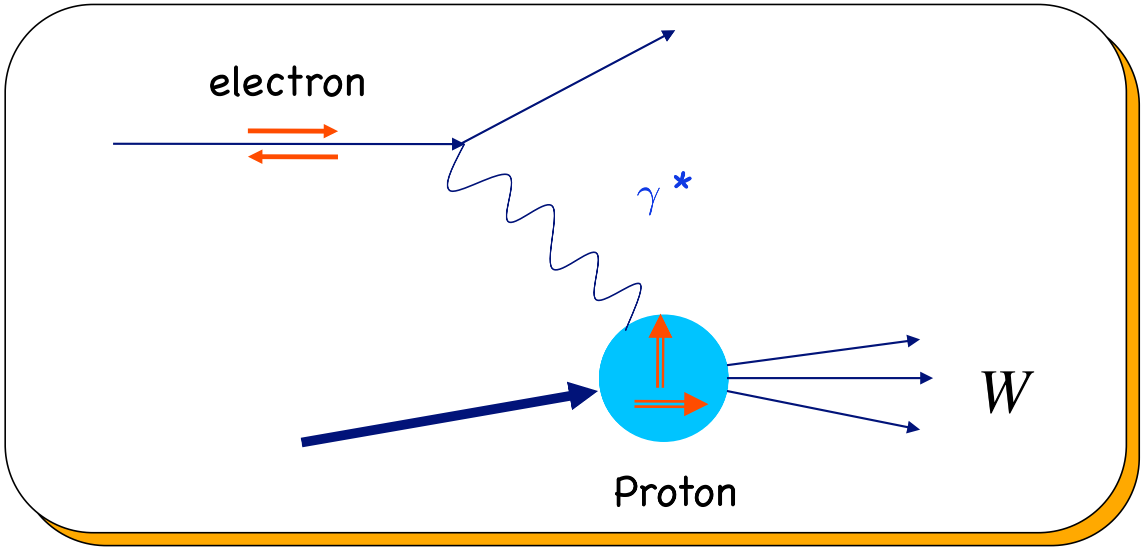
E12-15-005: "*A_{zz} for x>1*"

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

Technical Developments



Inclusive Scattering



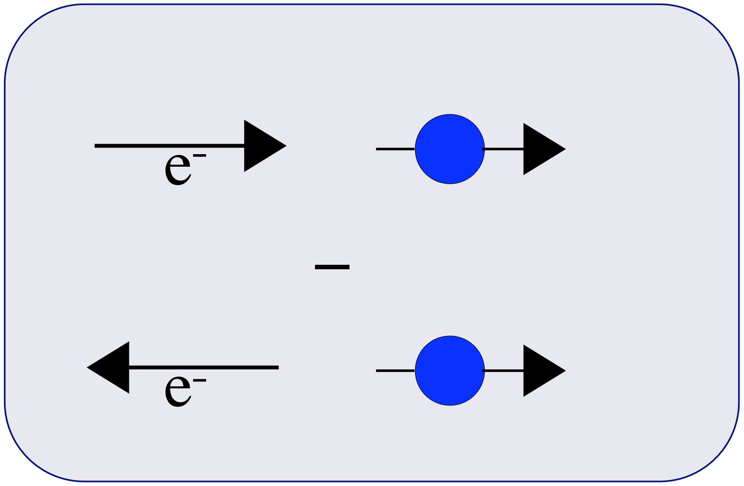
When we add spin degrees of freedom to the target and beam, 2 Additonal SF needed.

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

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

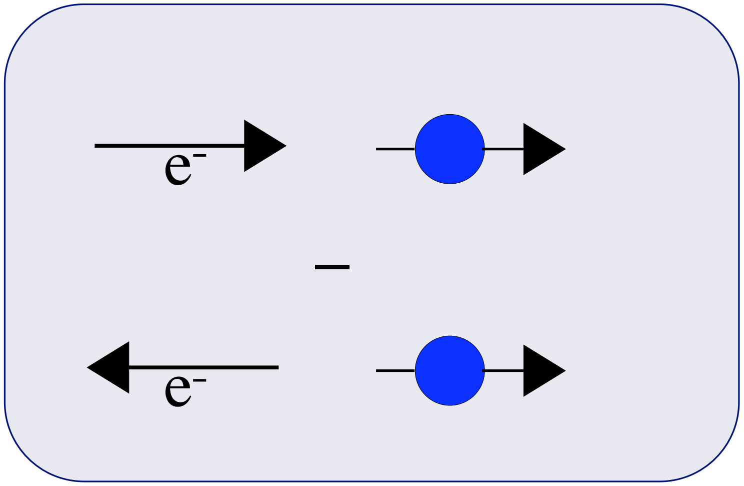
Inclusive **Polarized** Cross Section

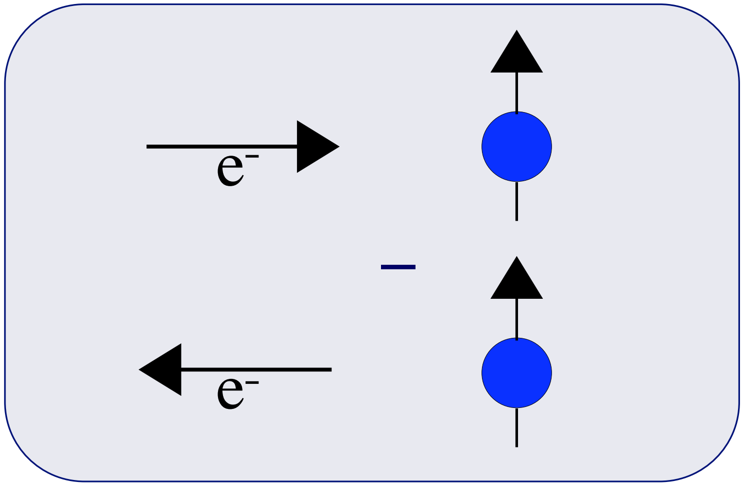
Cross Section Differences



$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2}\frac{E'}{E}\left[(E + E'\cos\theta)\,g_1 - 2Mxg_2\right]$$

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

$$\mathit{\Gamma}_1(Q^2) = \int_0^{x_0} \mathrm{d}x \, g_1(x, Q^2)$$

Burkhardt Cottingham

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

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

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

g2p : K. Slifer (contact), JP Chen, D. Crabb, A. Camsonne

sagdh : JP Chen(contact), A. Deur

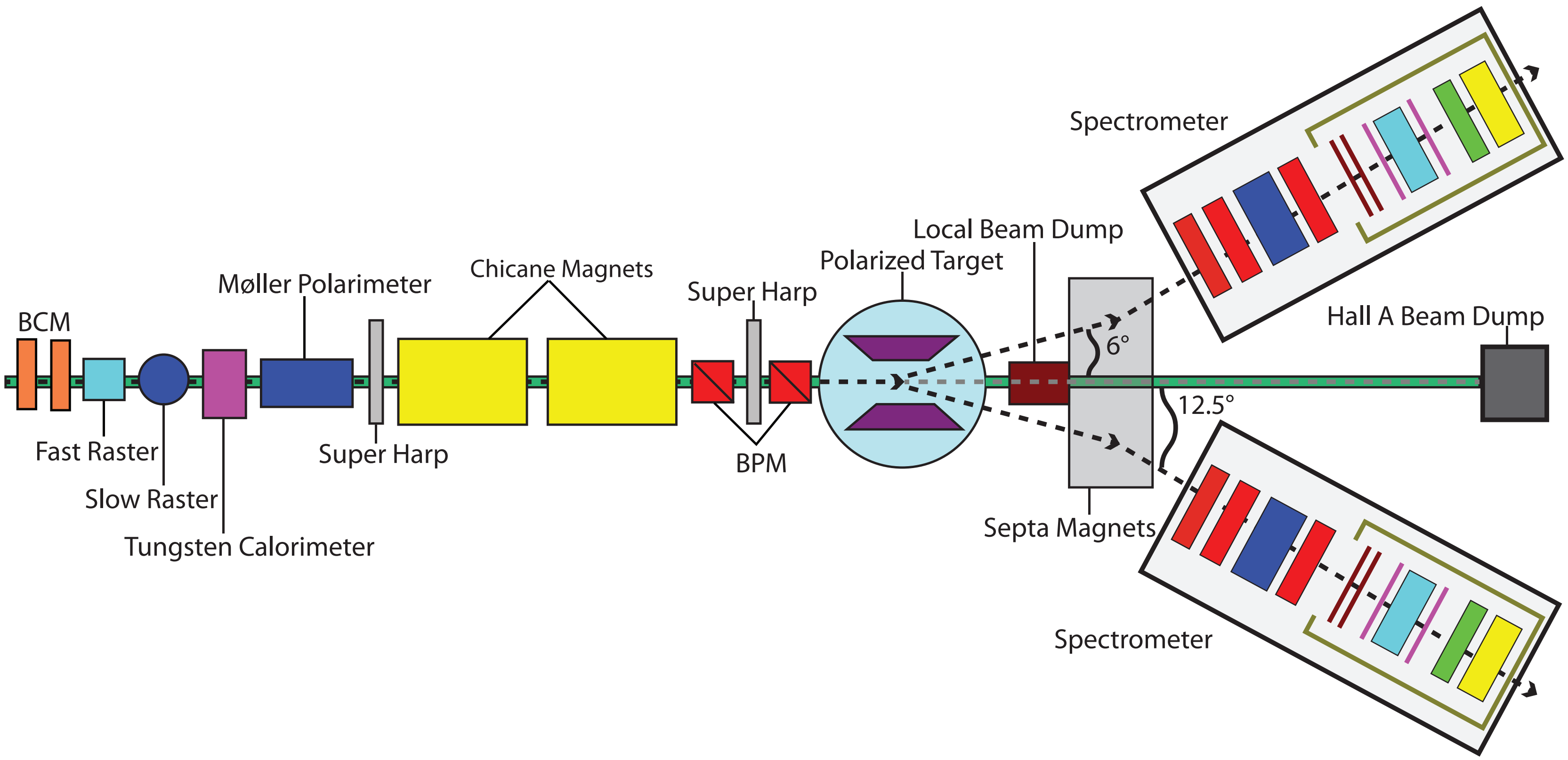
E08-027 : Proton g_2 Structure Function

Camsonne, Crabb,

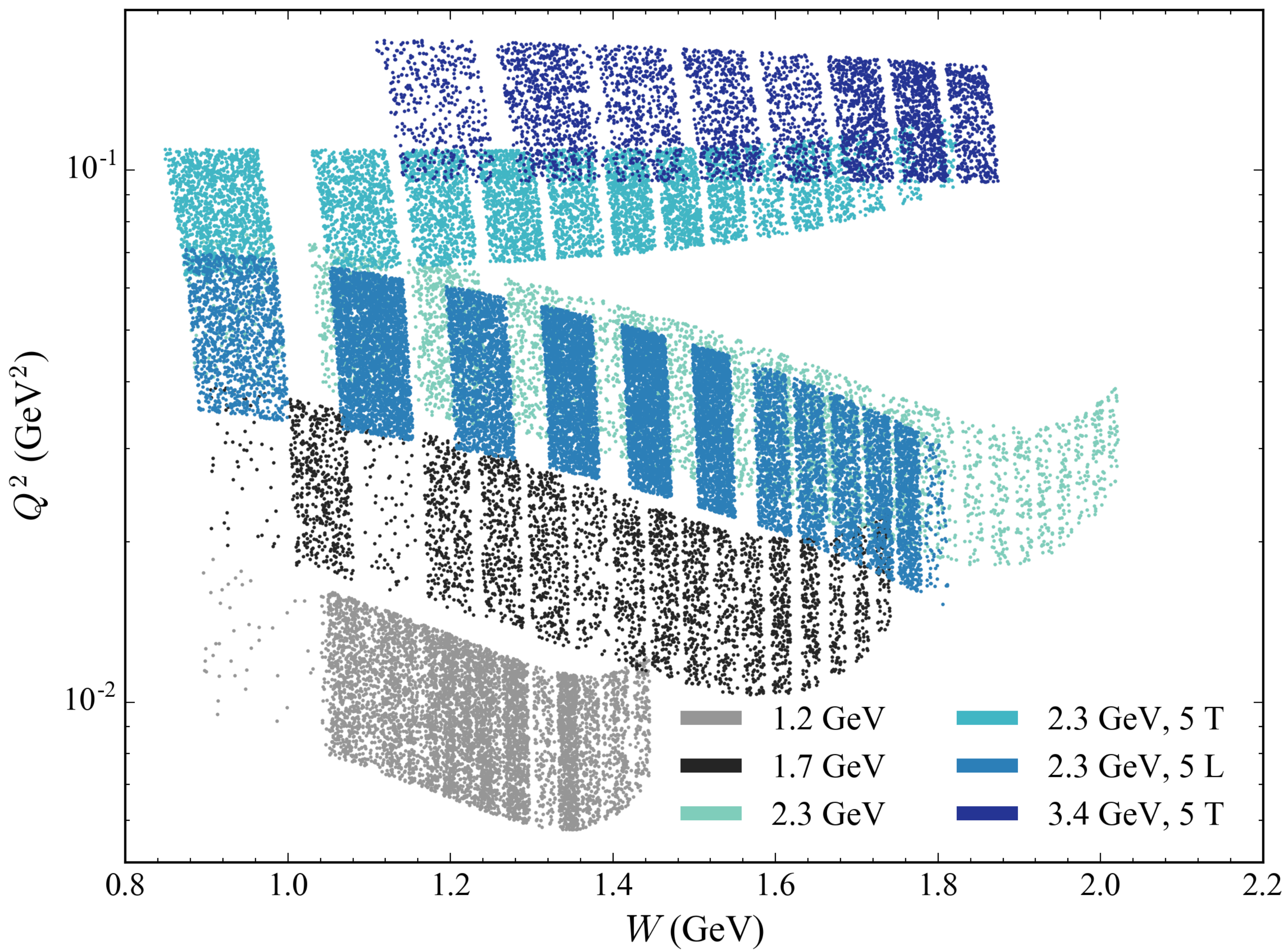
Chen, Slifer

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}



E08-027 : Proton g_2 Structure Function



Large Q^2 data final prepariing for publication

Low Q^2 data preliminary finalizing dilution

Largest Installation in Hall A History

Polarized proton target

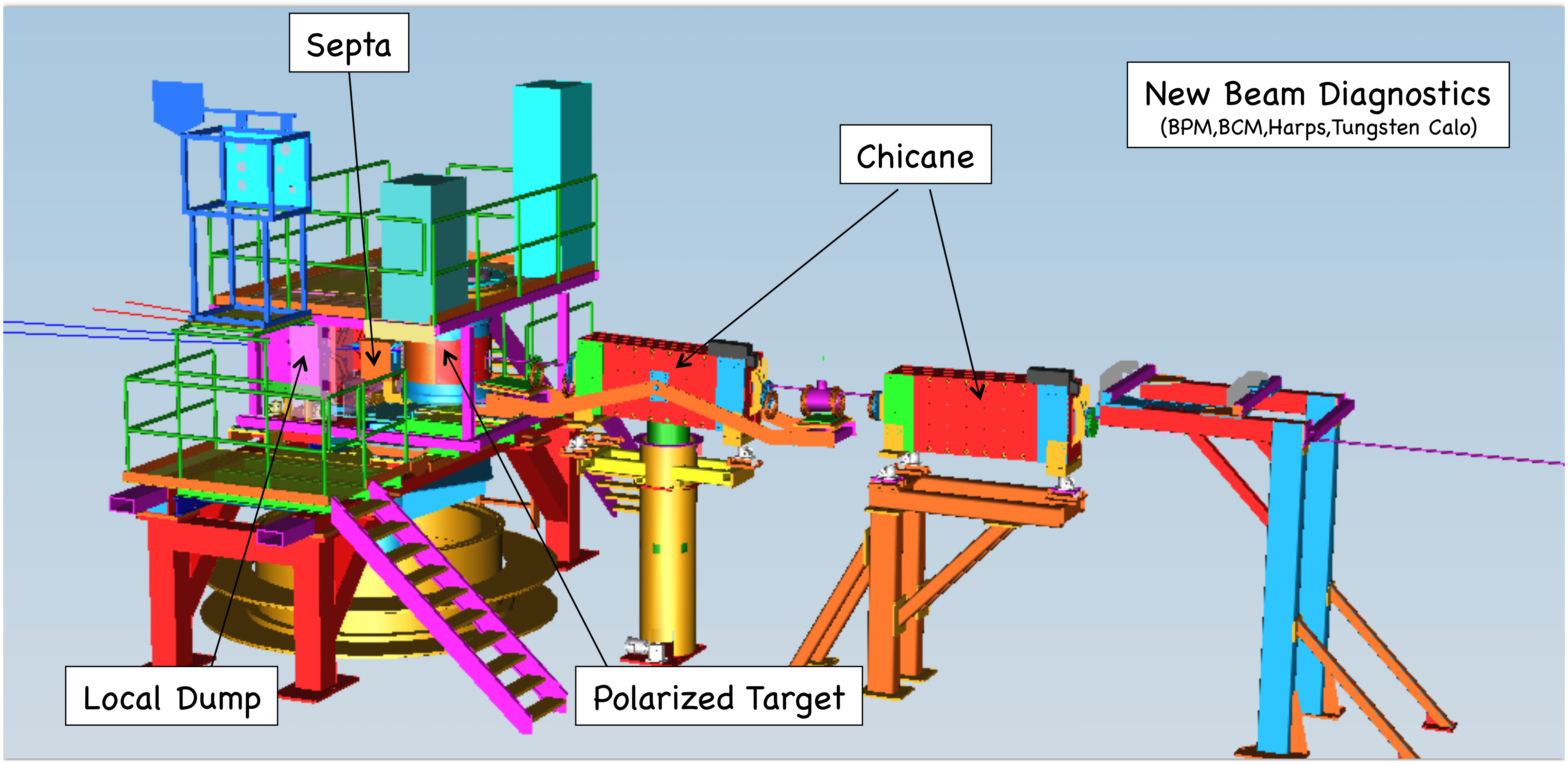
- upstream chicane
- downstream local dump

Low current polarized beam

- Upgrades to existing Beam Diagnostics to work at 85 nA

Lowest possible Q^2 in the resonance region

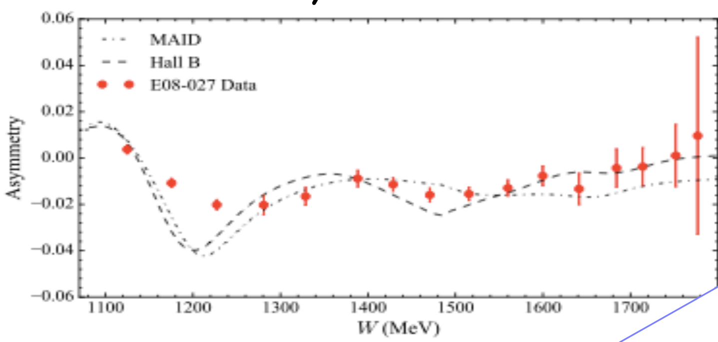
- Septa Magnets to detect forward scattering



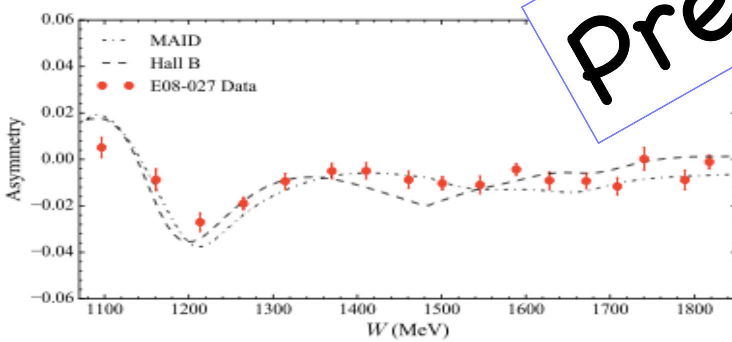
E08-027 Data

Preliminary

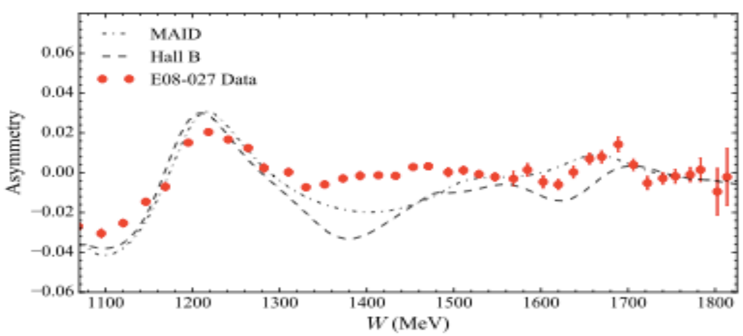
Asymmetries



(a) E_0 = 2254 MeV 5T Transverse



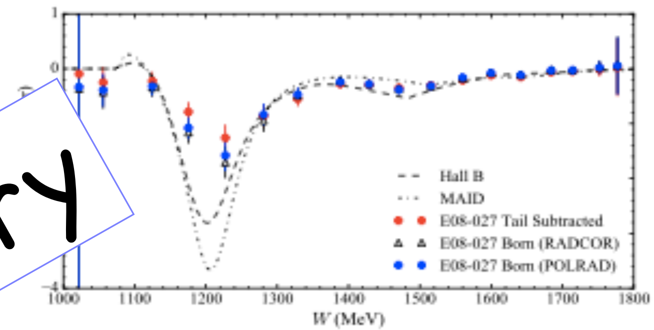
(b) E_0 = 3350 MeV 5T Transverse



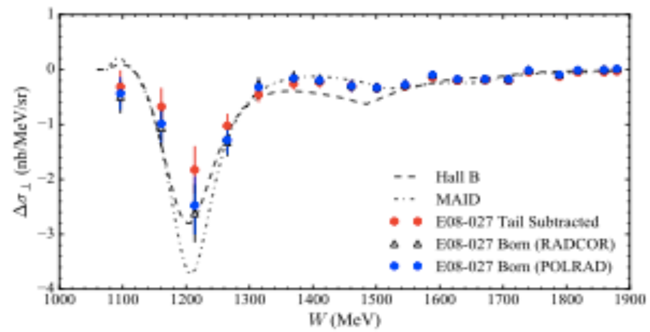
(c) E_0 = 2254 MeV 5T Longitudinal

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

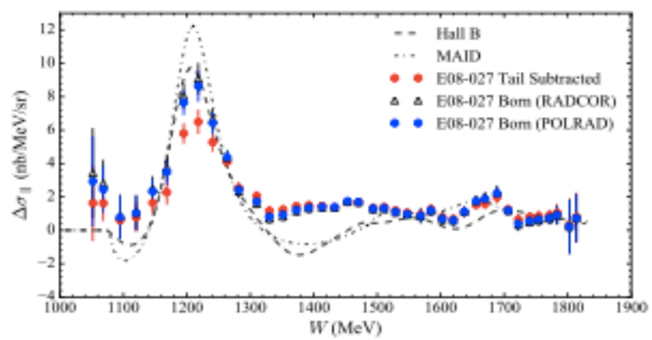
Δσ



(a) E_0 = 2254 MeV 5T Transverse



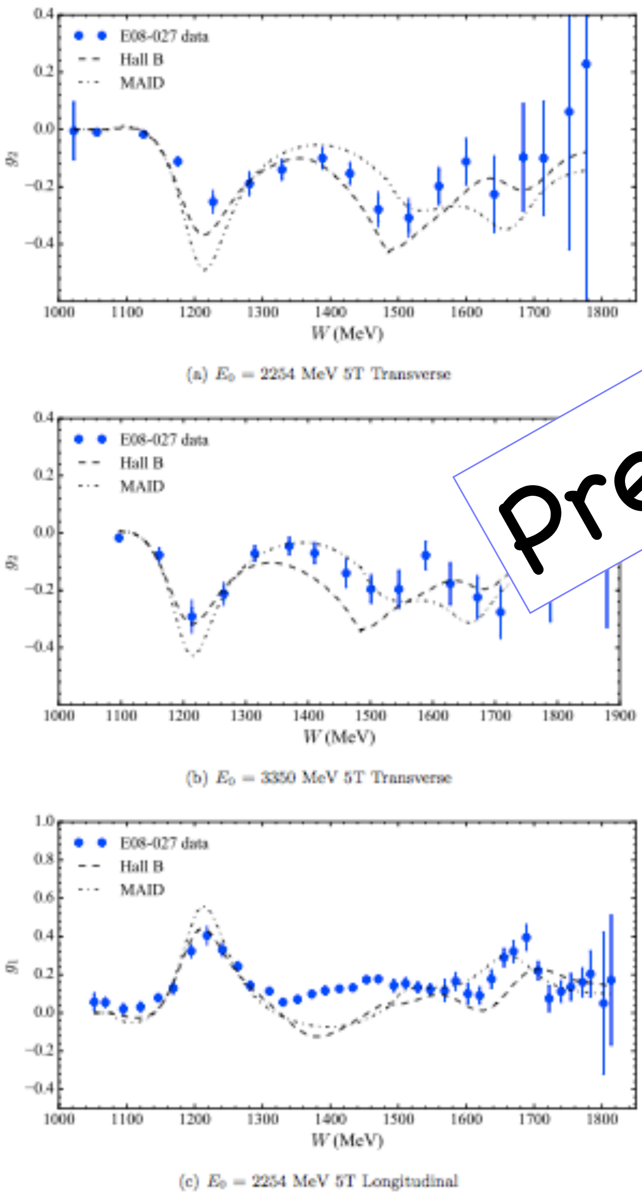
(b) E_0 = 3350 MeV 5T Transverse



(c) E_0 = 2254 MeV 5T Longitudinal

Figure 8-19: Born polarized cross section differences for the 5 T kinematic settings.

E08-027 Structure Functions

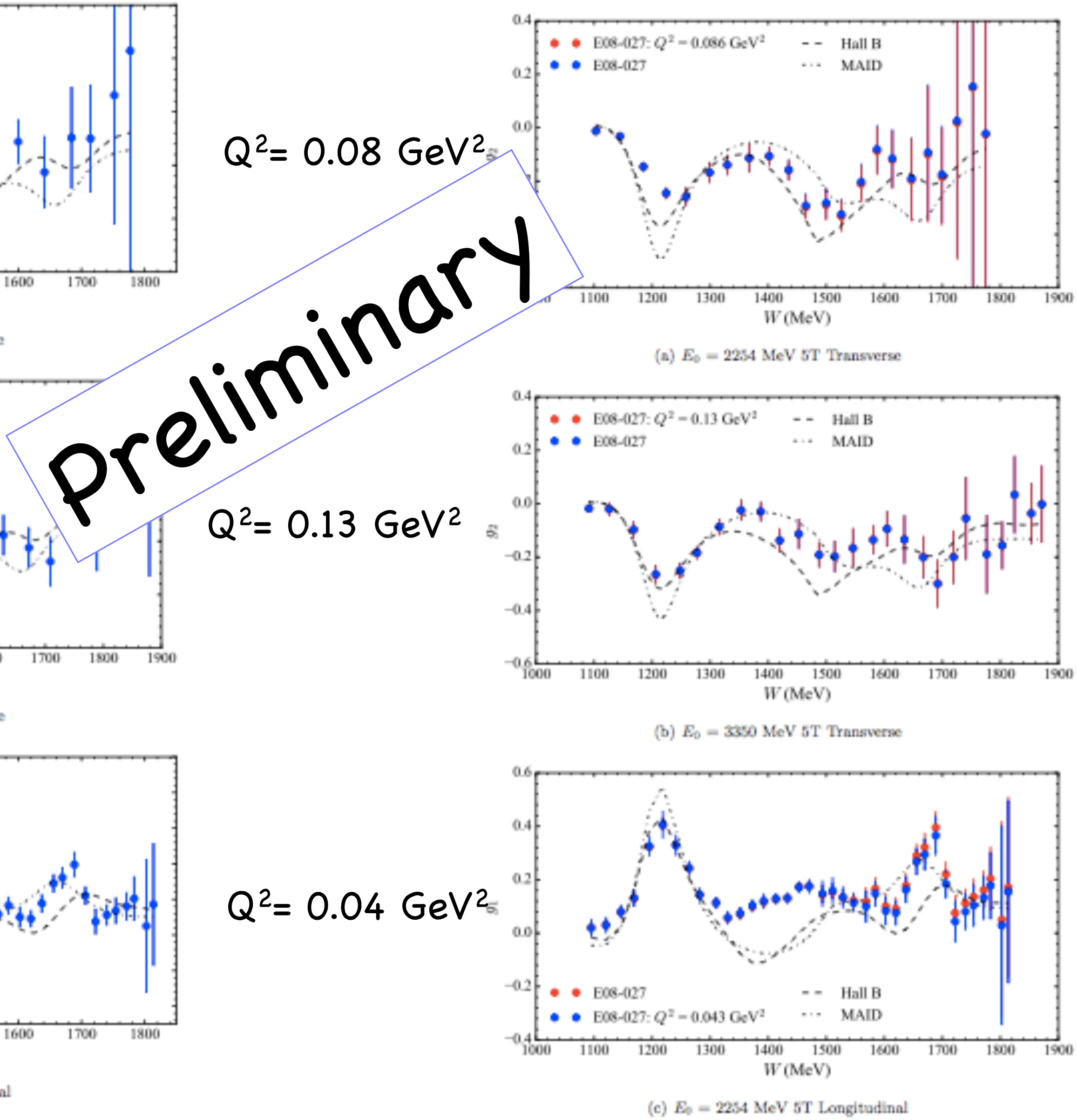


(a) $E_0 = 2254$ MeV 5T Transverse

(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.



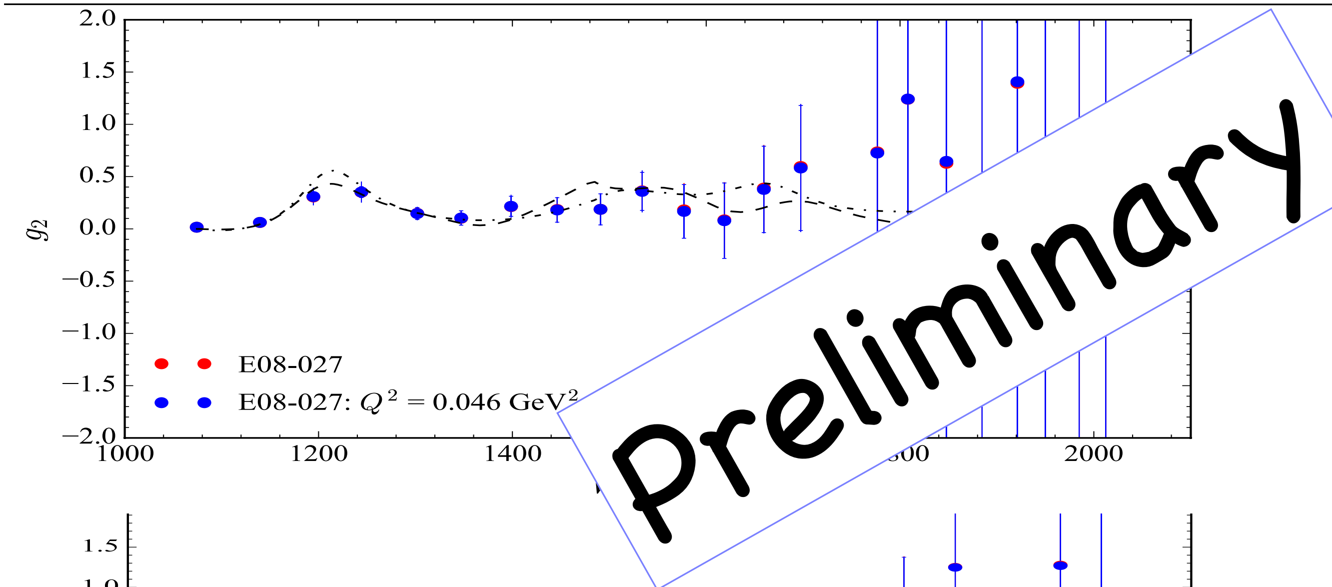
(a) $E_0 = 2254$ MeV 5T Transverse

(b) $E_0 = 3350$ MeV 5T Transverse

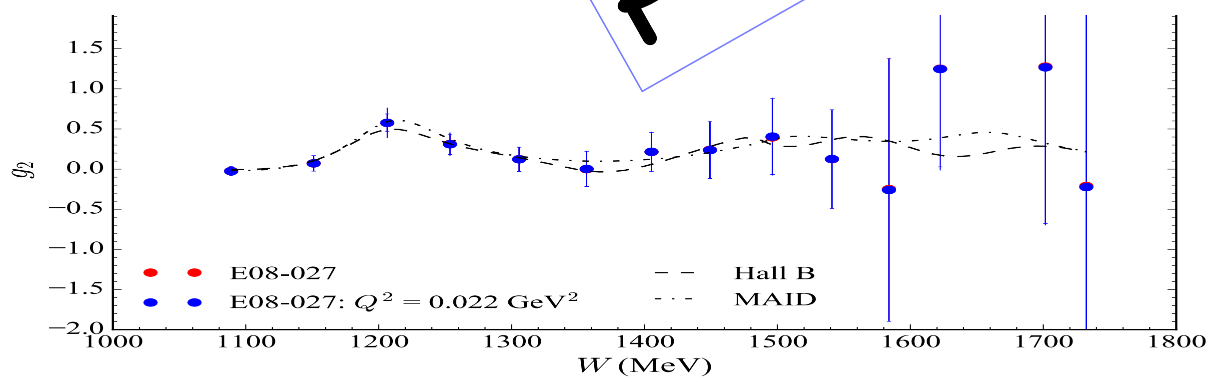
(c) $E_0 = 2254$ MeV 5T Longitudinal

Figure 8-24: E08-027 spin structure functions evolved to a constant momentum transfer.

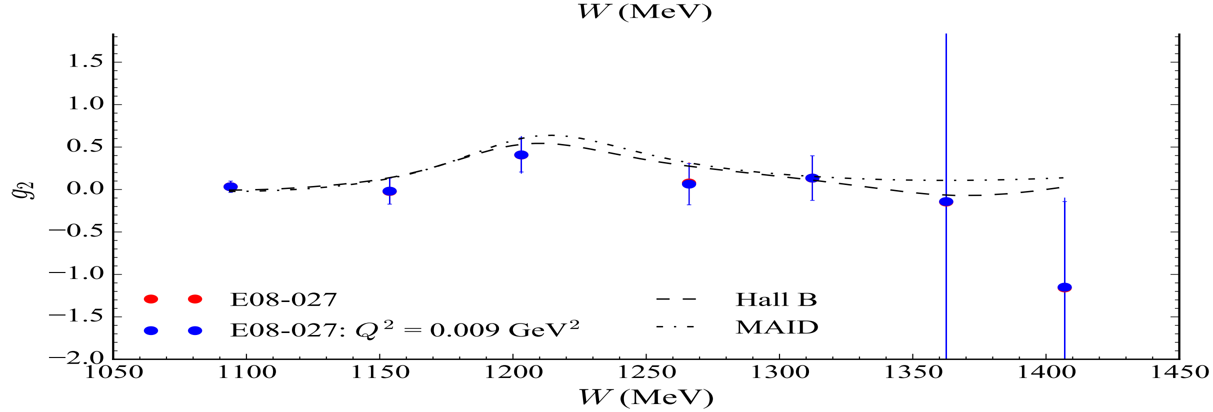
g2p Low Q^2 data



$Q^2 = 0.05$ GeV^2



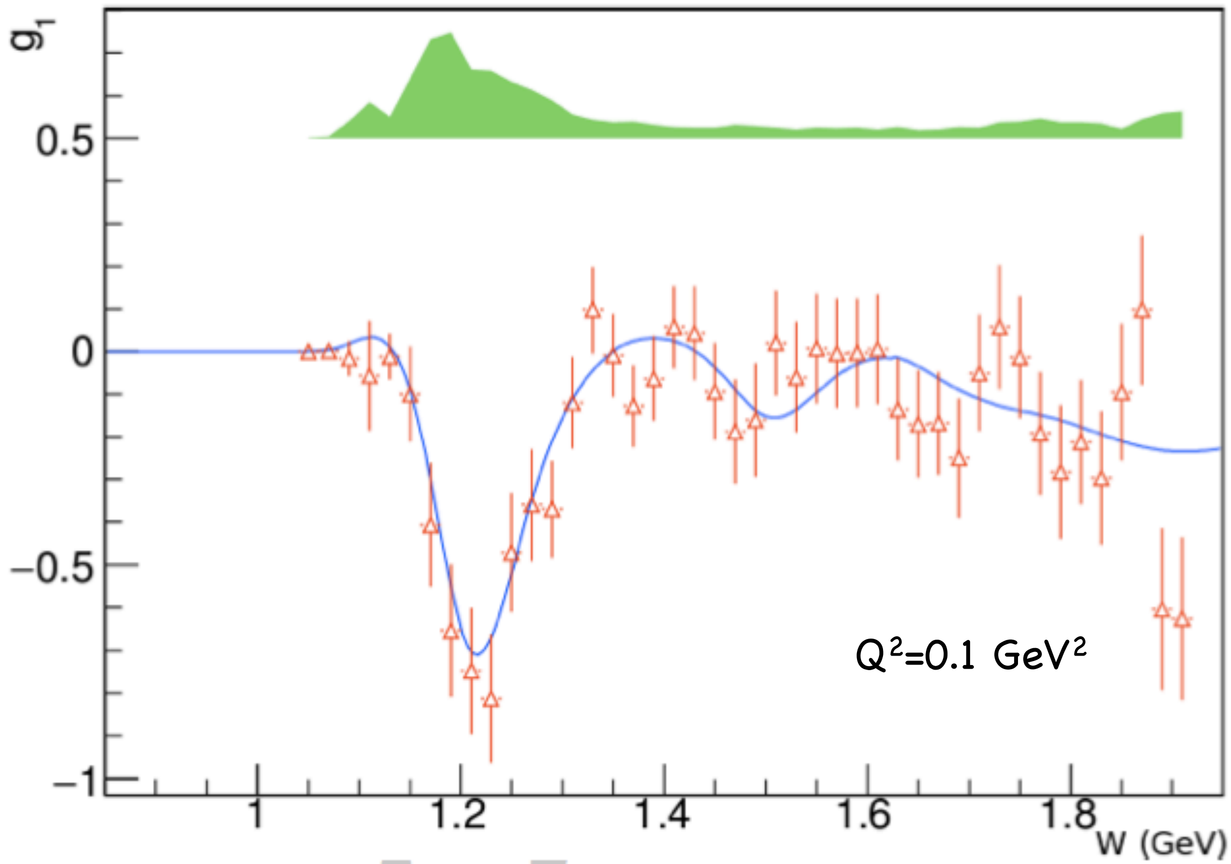
$Q^2 = 0.02$ GeV^2



$Q^2 = 0.01$ GeV^2

Acceptance/Dilution preliminary

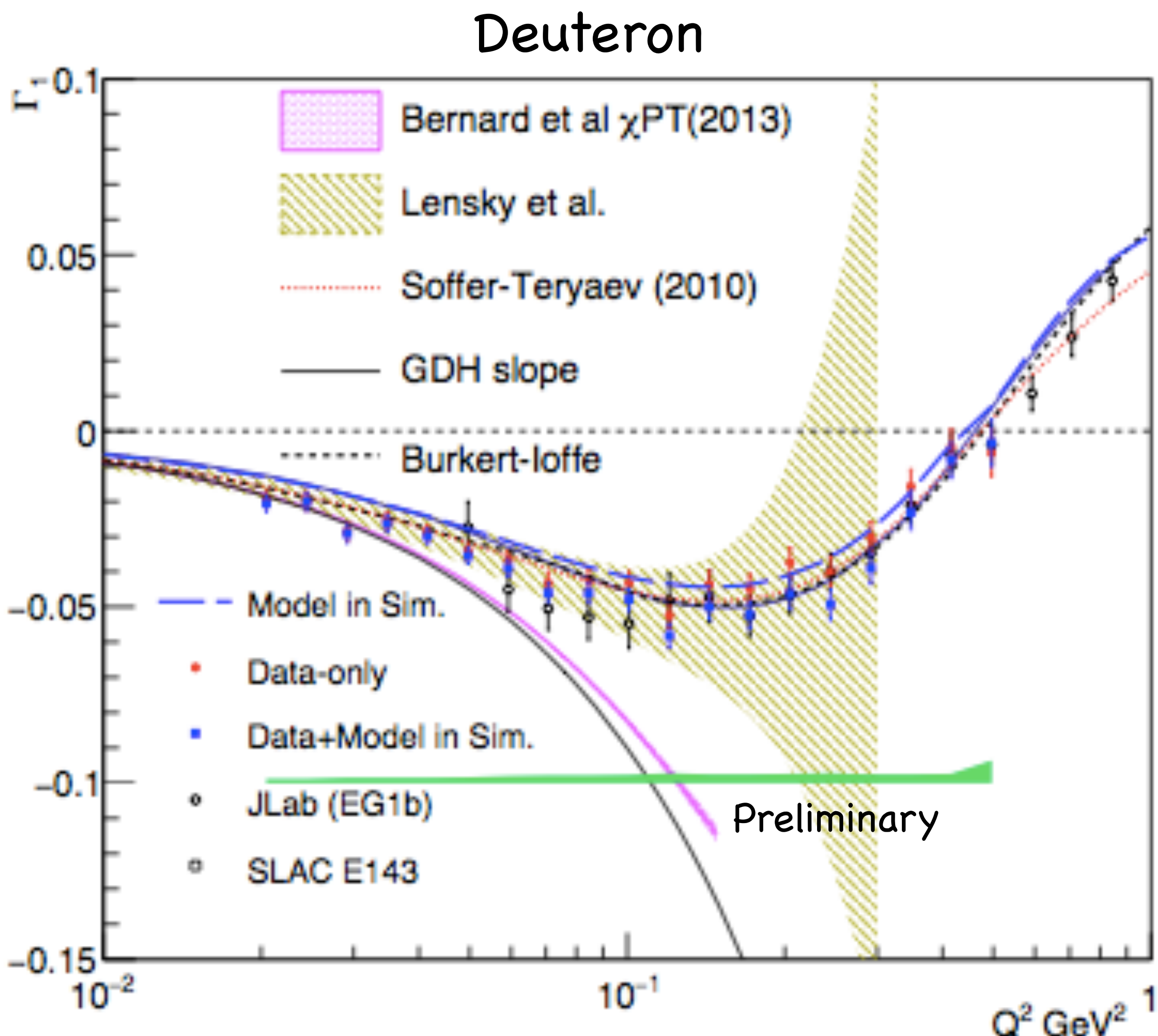
Deuteron g_1



EG4 experiment
Q^2>0.02 GeV^2

CLAS Note in review
publication ready to submit

1^{st} Moment

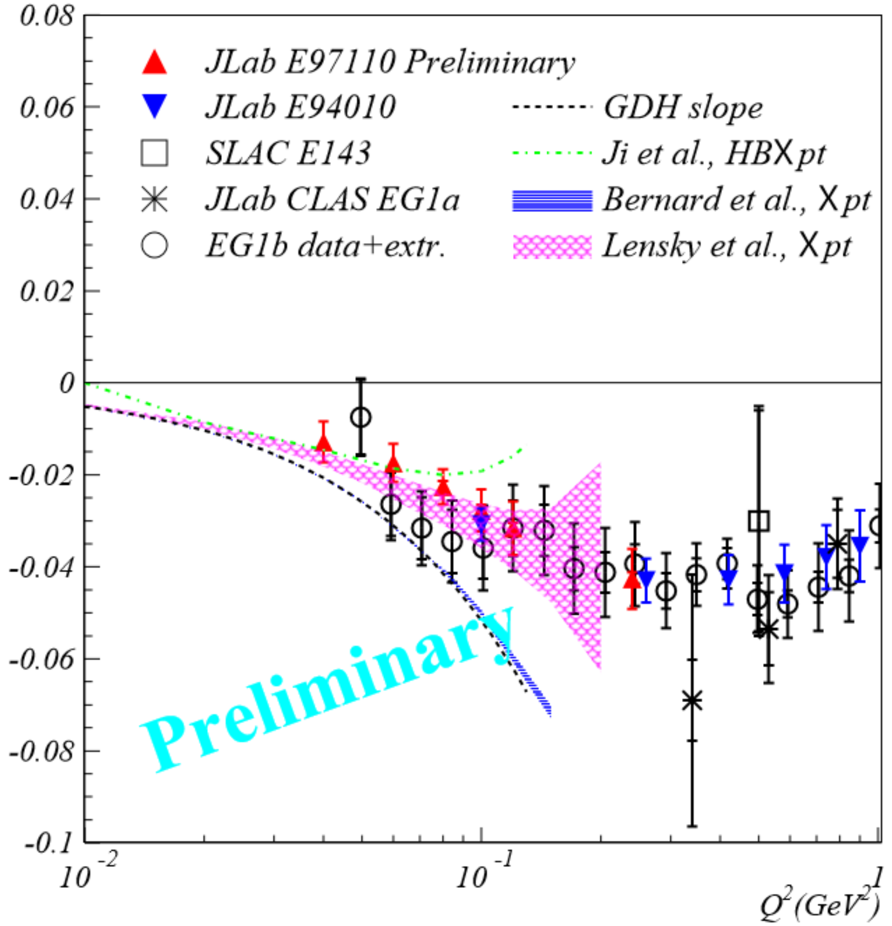


$$\Gamma_1(Q^2) = \int_0^{x_0} \mathrm{d}x\, g_1(x, Q^2)$$

EG4

1^{st} Moment

Neutron

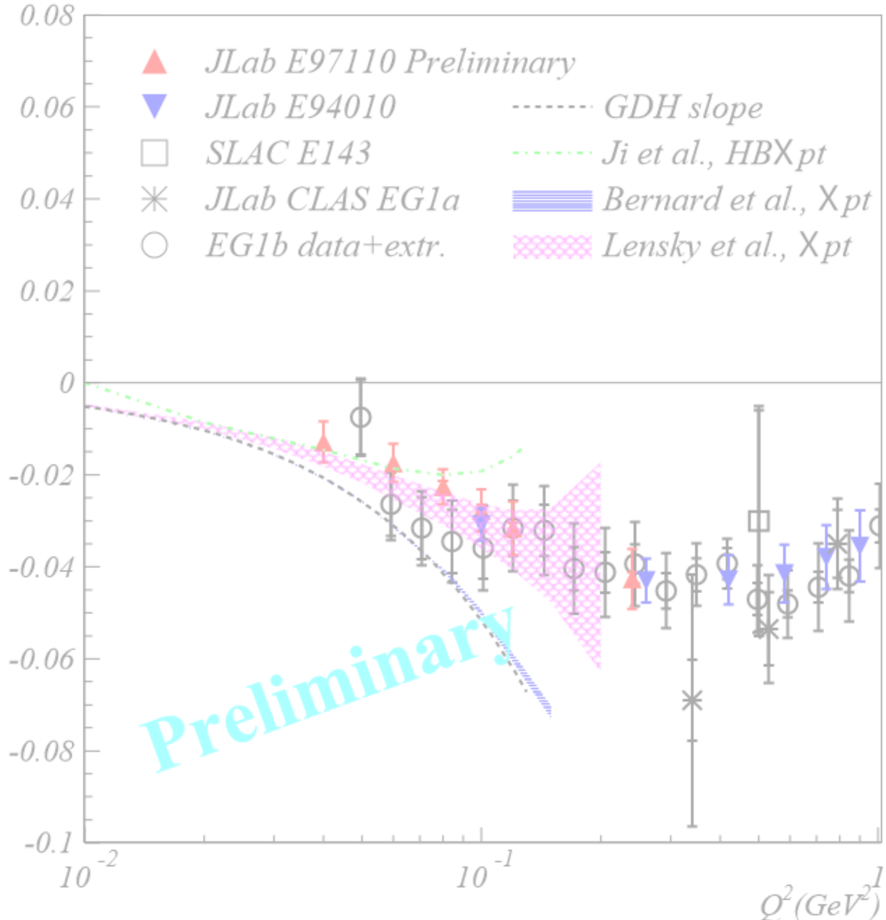


$$\Gamma_1(Q^2) = \int_0^{x_0} \mathrm{d}x\, g_1(x, Q^2)$$

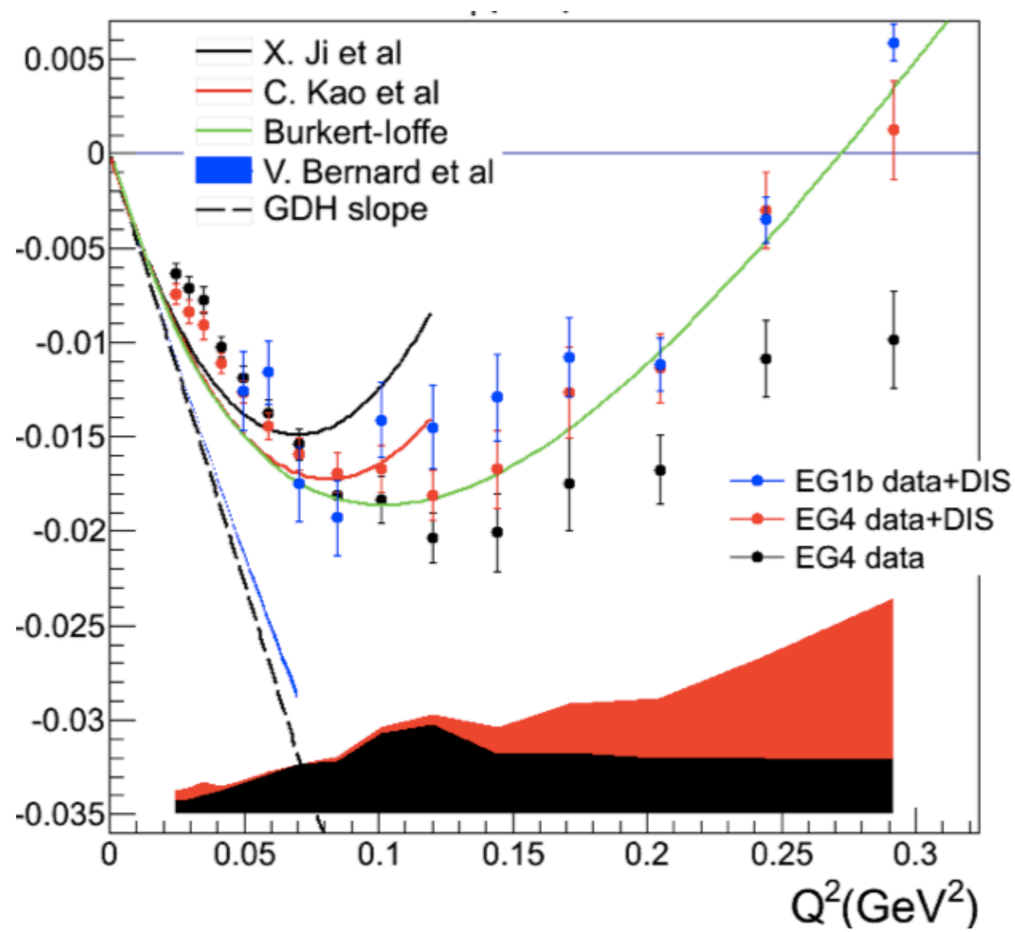
sagdh, EG4

1st Moment

Neutron



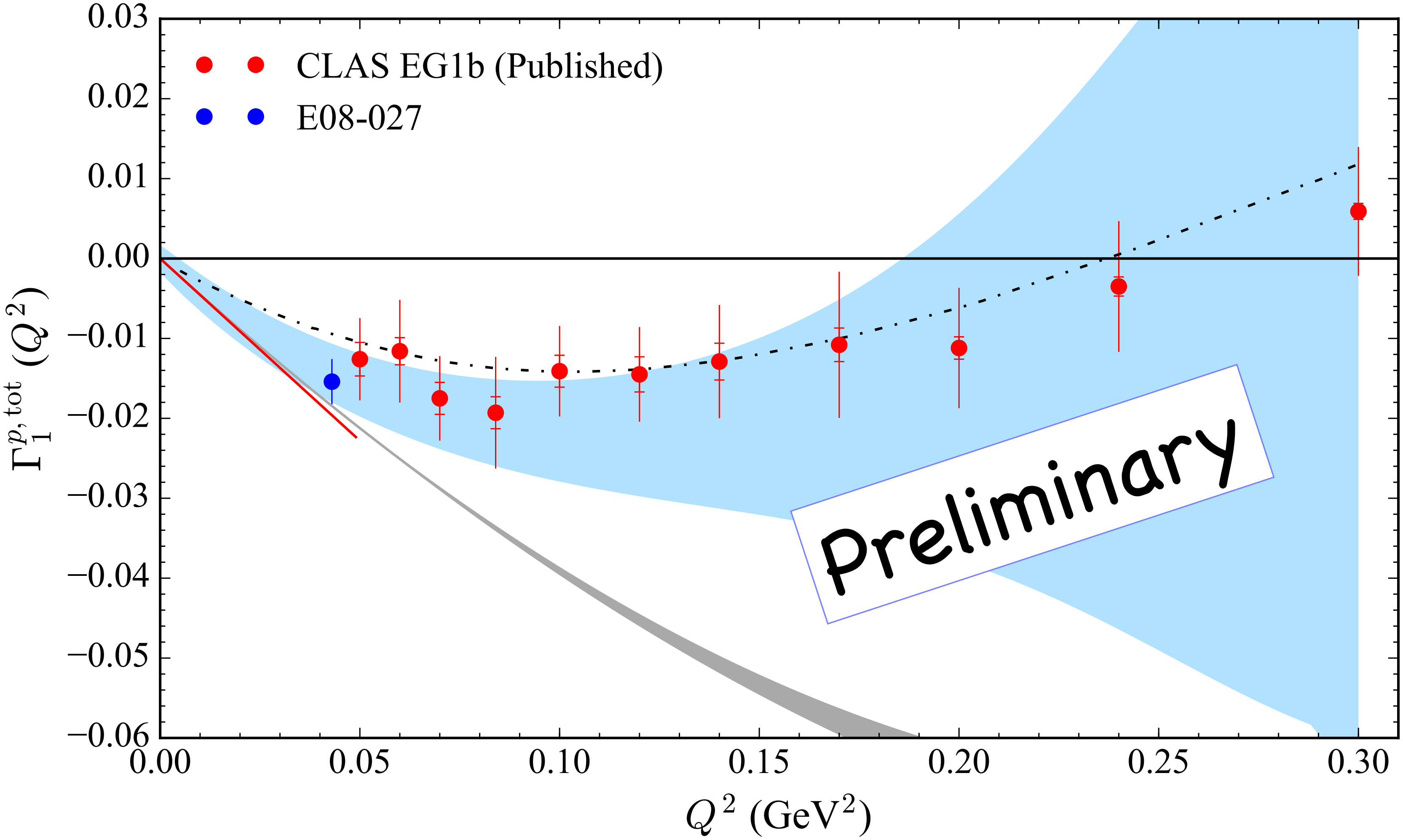
Proton



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

sagdh, EG4

E08-027 Proton 1st Moment



Spin Polarizabilities

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

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

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

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

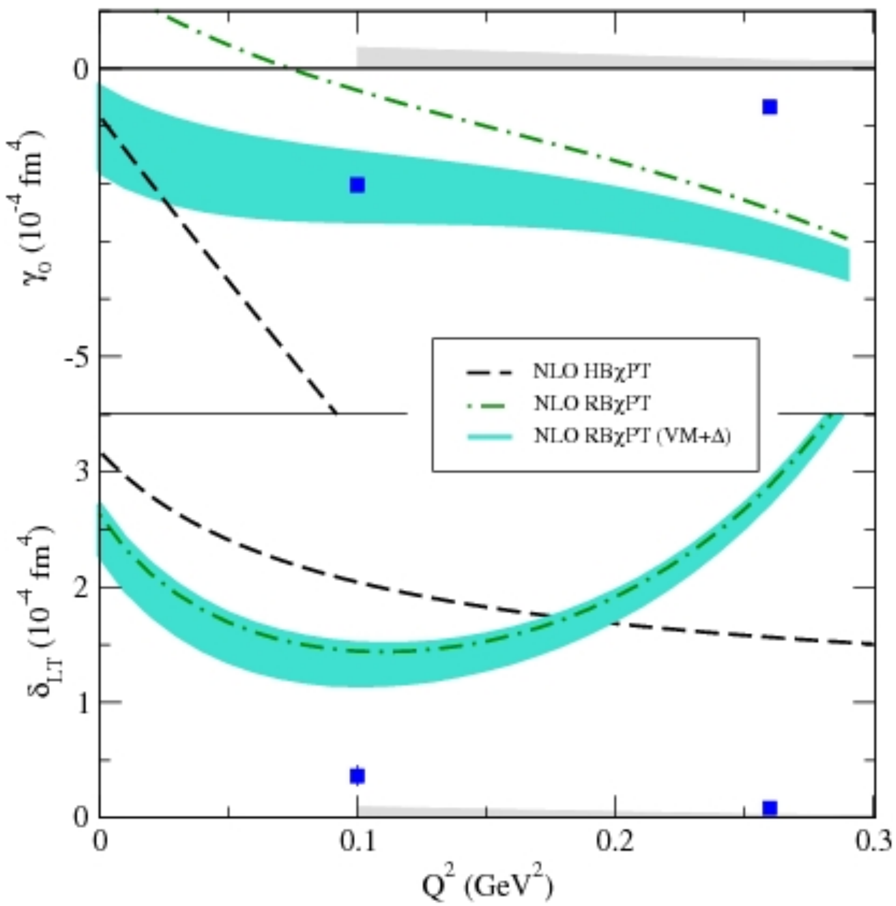
Relativistic Baryon : (Meissner, Bernard et al)
large momentum effects are absorbed in the low energy consts

Resonances are included sytematically through additional low energy constants

δ_{LT} Puzzle

Neutron

PRL 93: 152301 (2004)



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

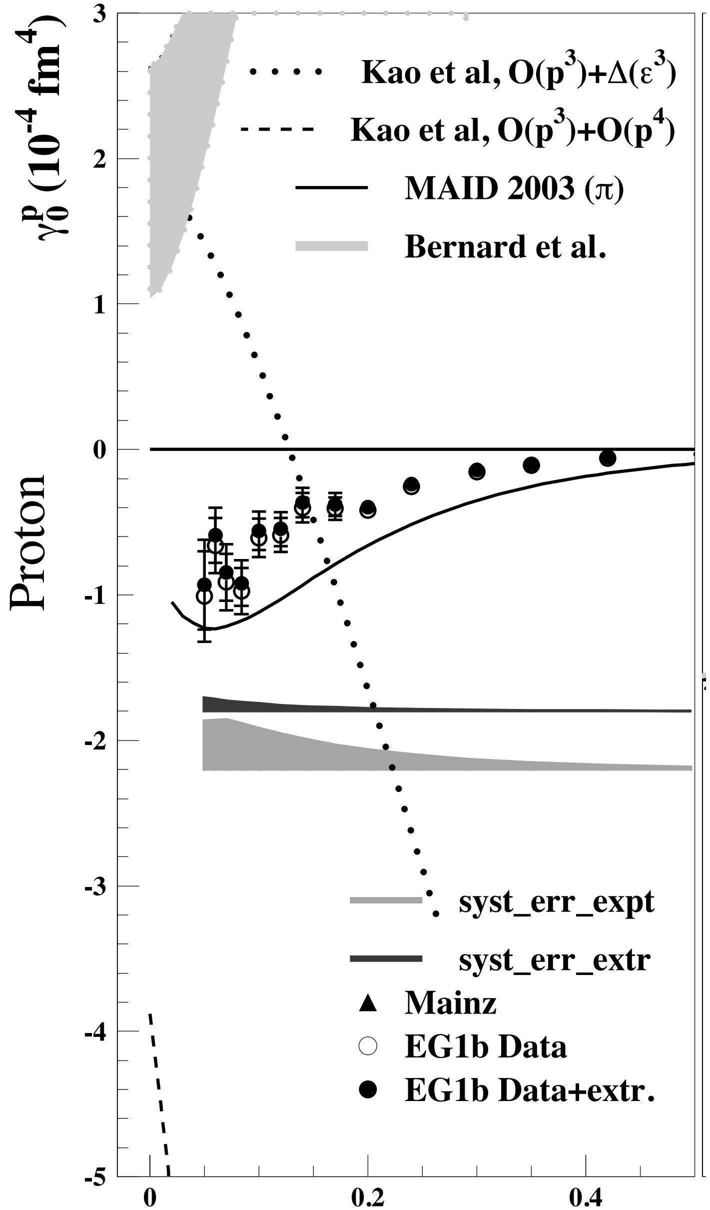
$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\,[g_1 + g_2]$$

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



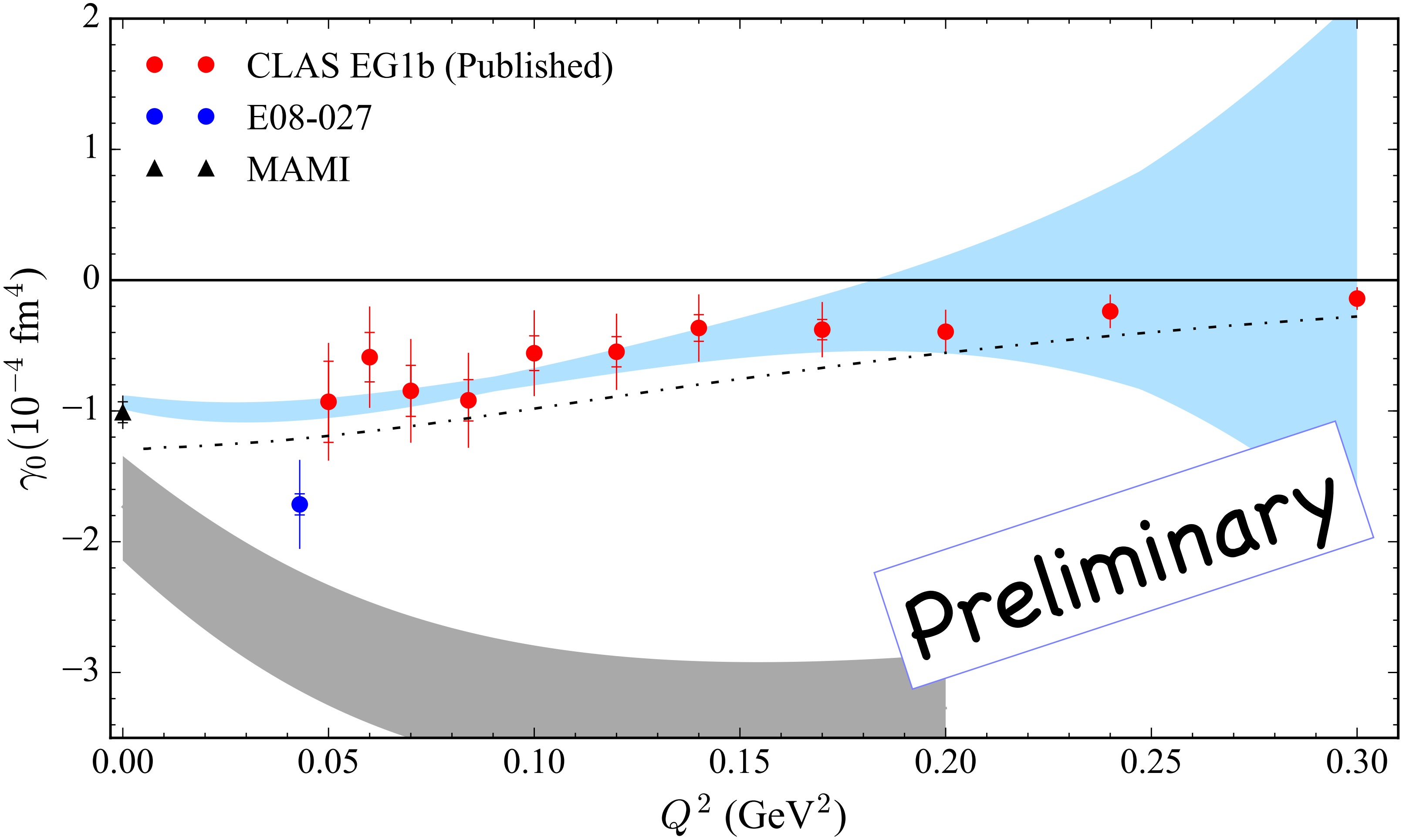
$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

Older Calcs also failed for proton γ_0

PLB 672 12, 2009

published data goes down to about 0.06 GeV^2

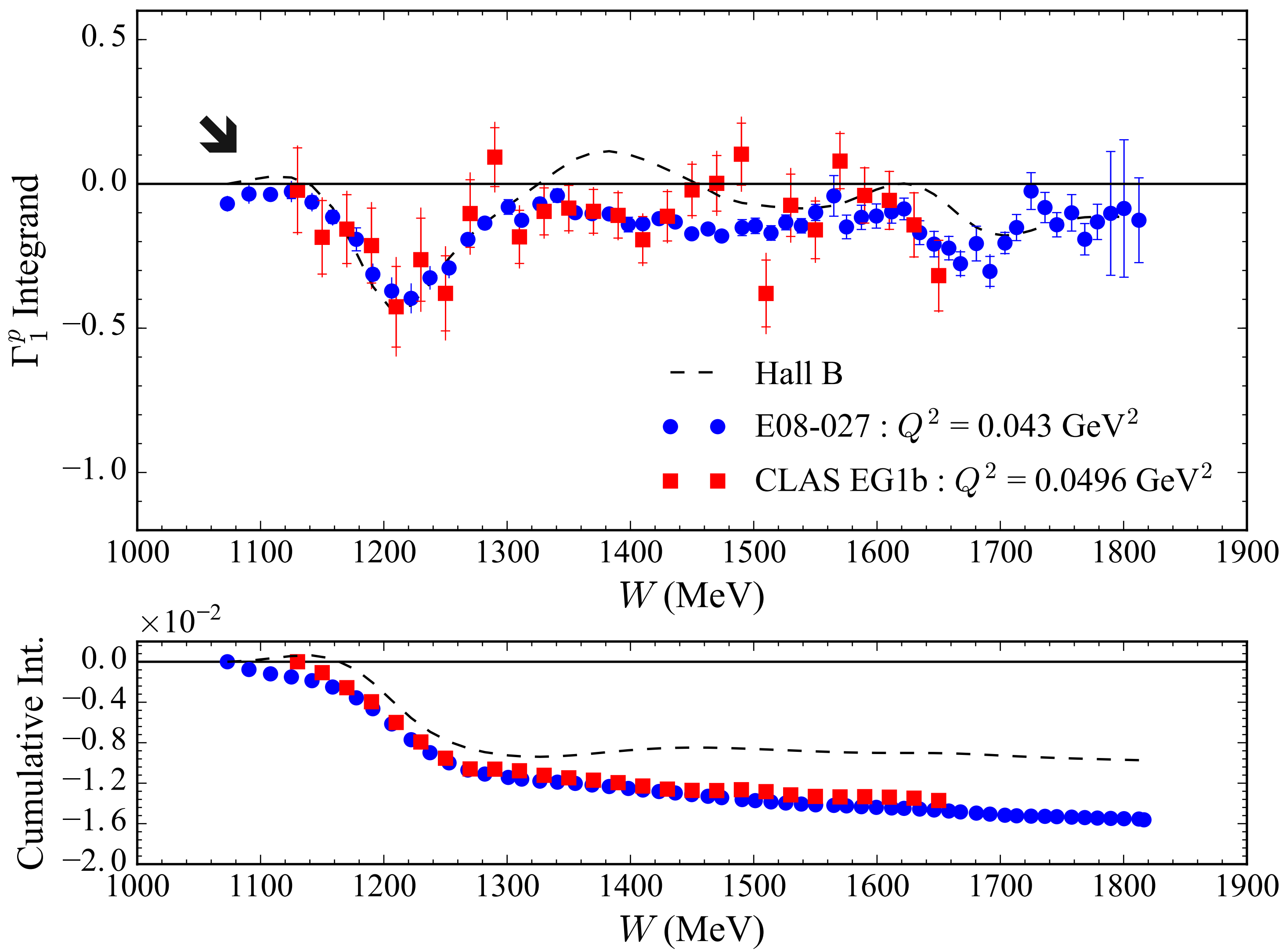
Proton γ_0 (latest data)



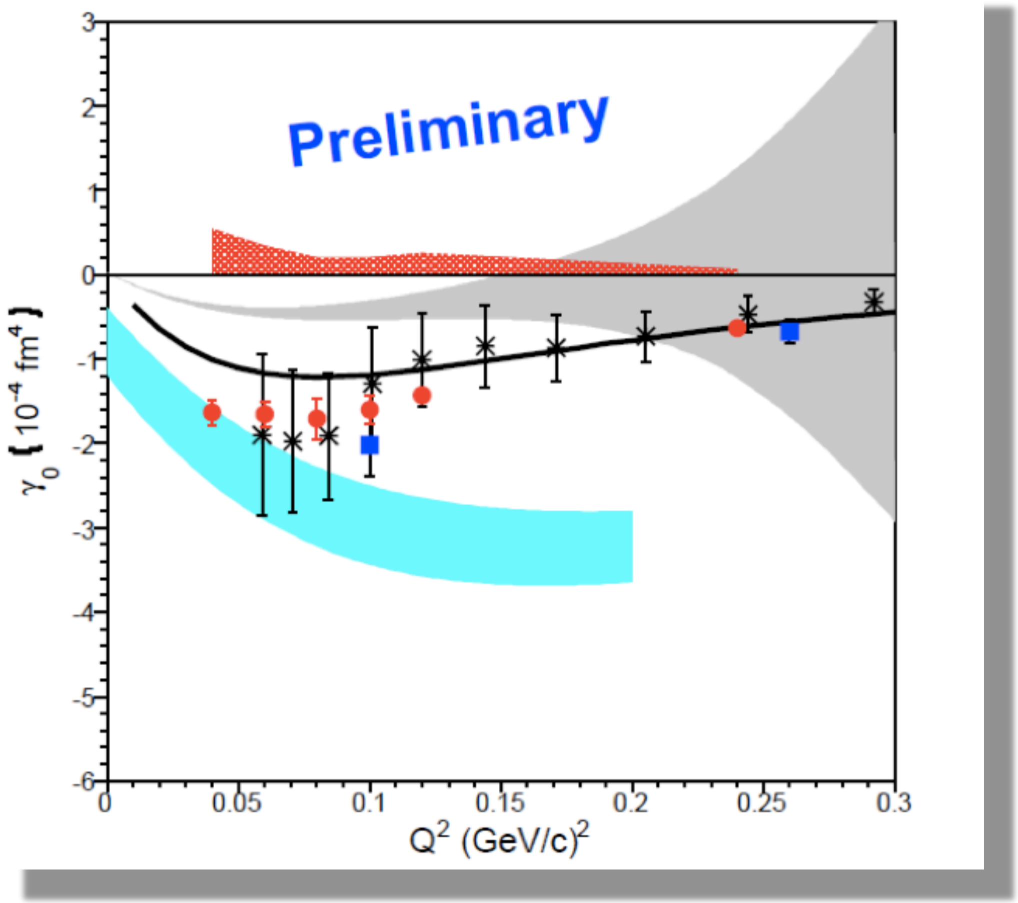
$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

decent agreement
with HBChpt

Proton g1 (E08-027 vs. CLAS)



Neutron γ_0 (latest data)

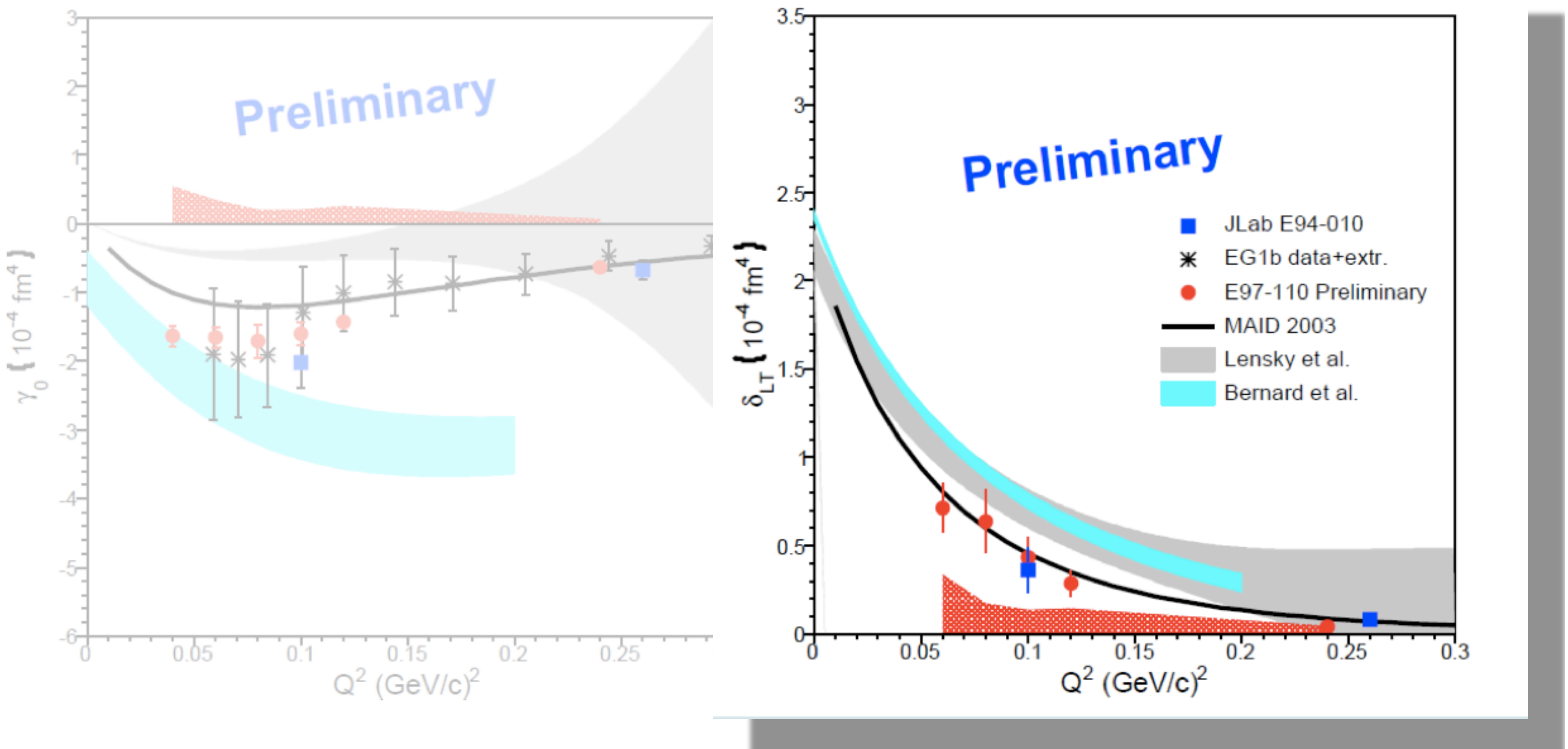


Big disagreement with Lensky et al.

BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202

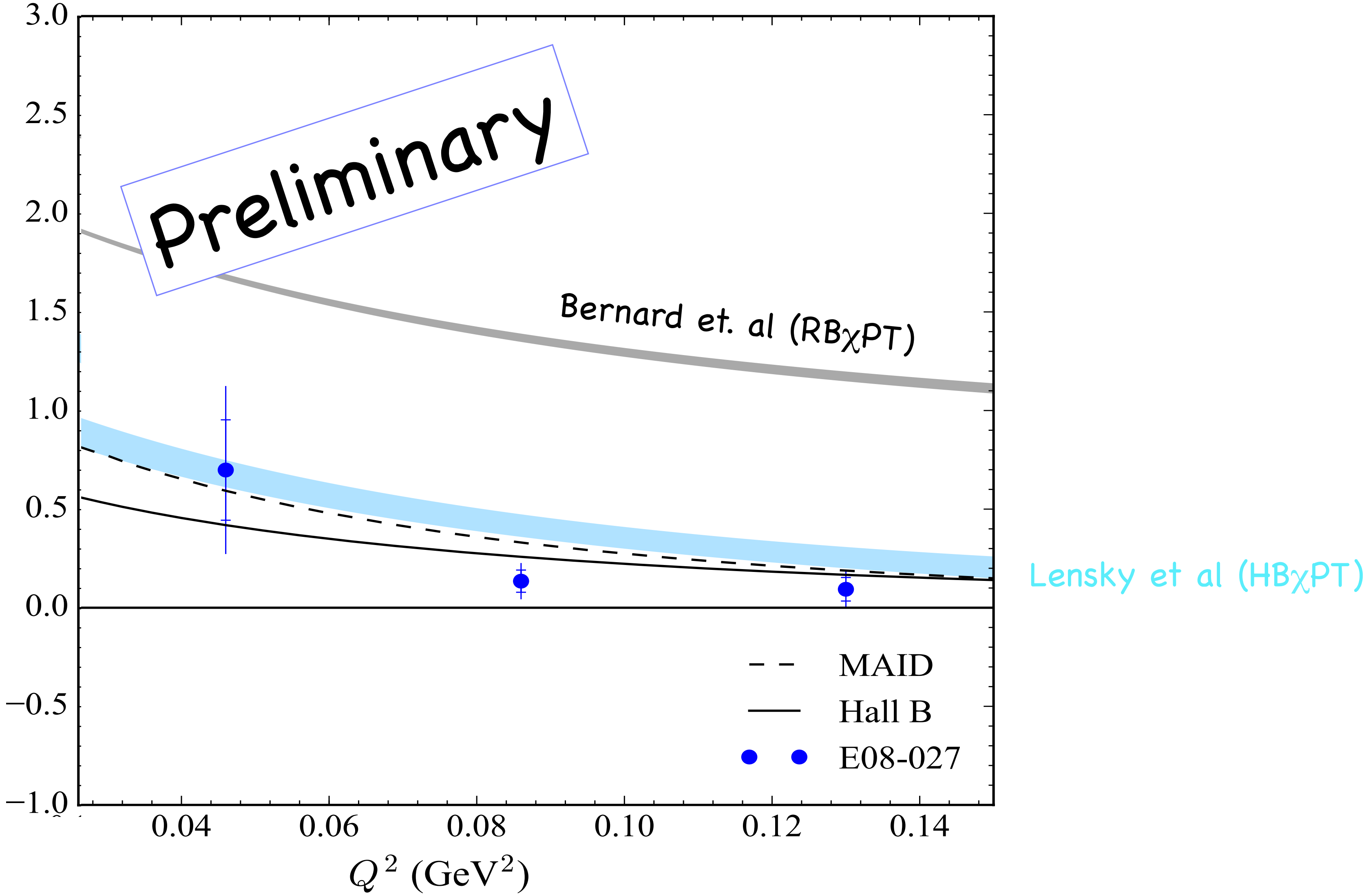
Neutron δ_{LT} (latest data)



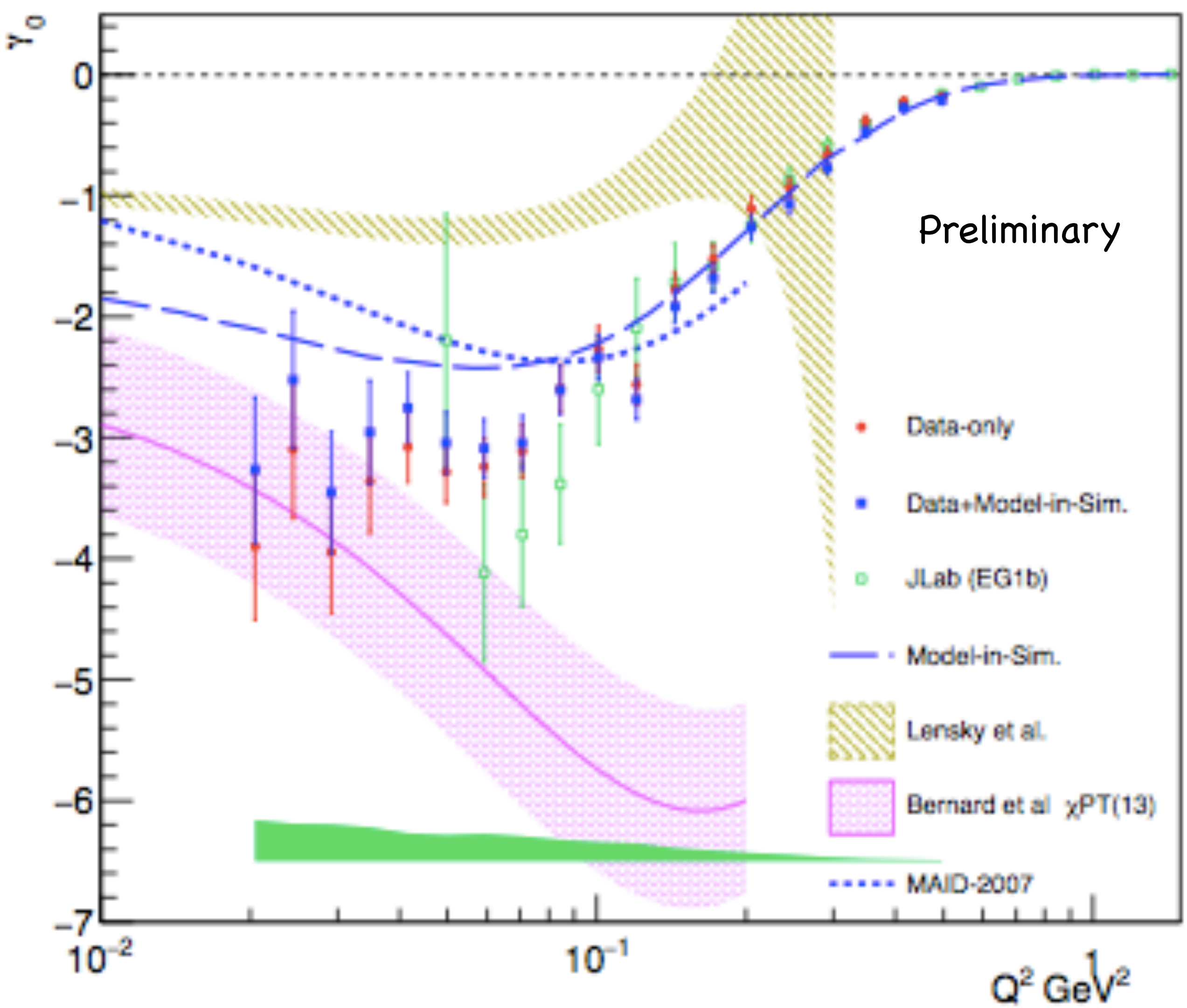
BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202

δ_{LT} Proton (brand new data)



Deuteron γ_0



Big disagreement with Lensky et al.

arising from proton part

(EG4)

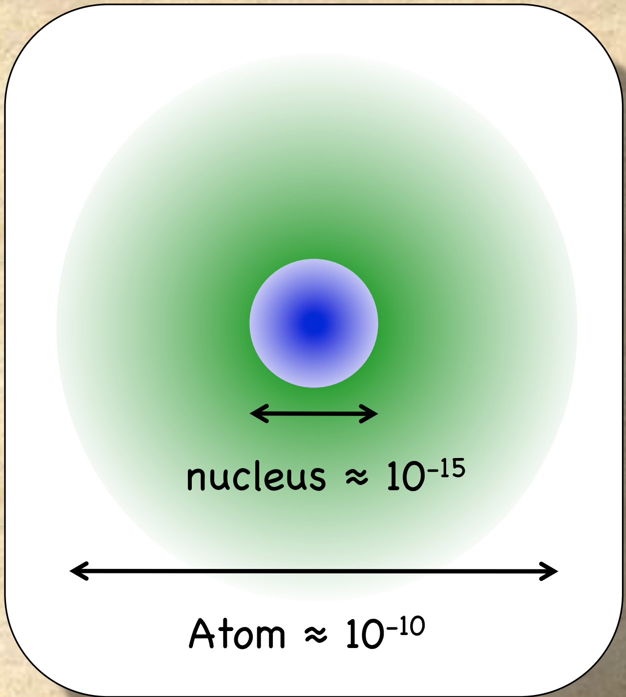
ChPT Comparison Summary

1^{st} moments: Pretty good agreement with chPT calculations

δ_{LT} : Good agreement for neutron
Proton data favors HBχPT

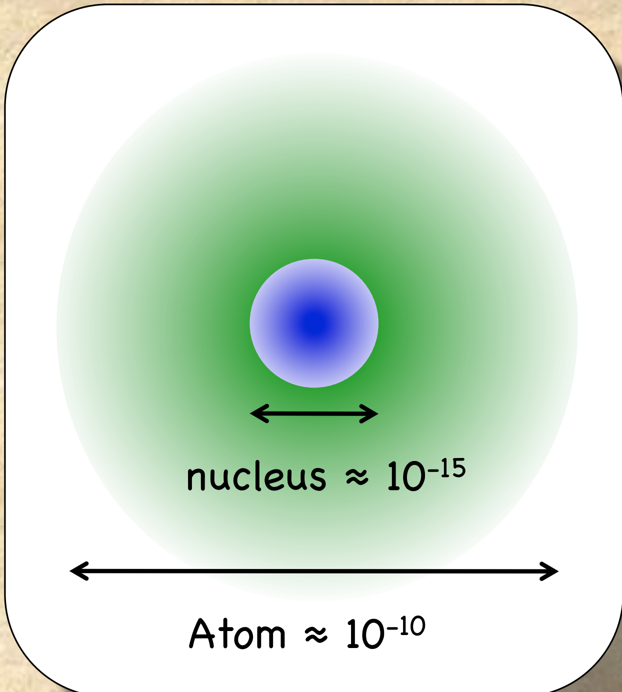
γ_0 : Good agreement for proton
Neutron (&Deutron) big discrepency with HBχPT

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.

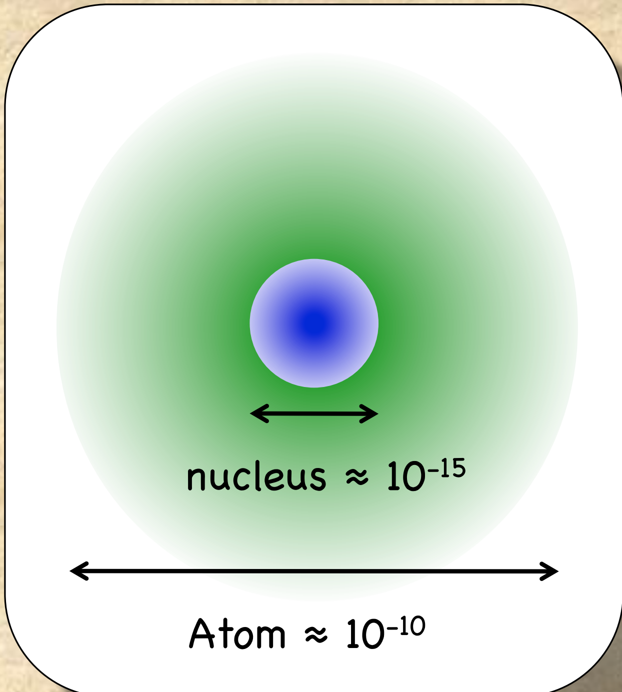


Hydrogen HF Splitting

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

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

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

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

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

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

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

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

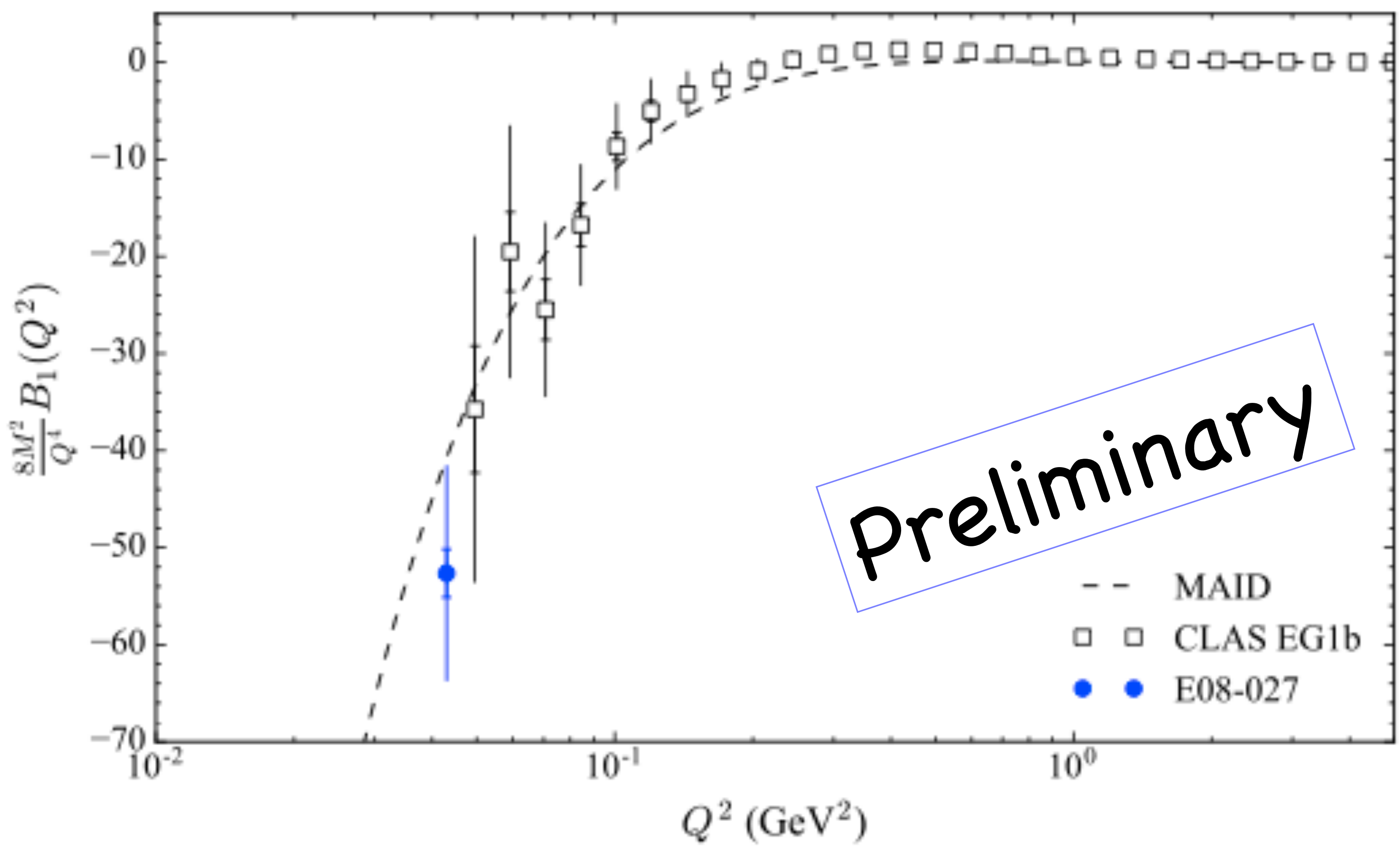
$$\Delta_{POL} = 0.2265 \quad (\Delta_1 + \Delta_2)\text{ppm}$$

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

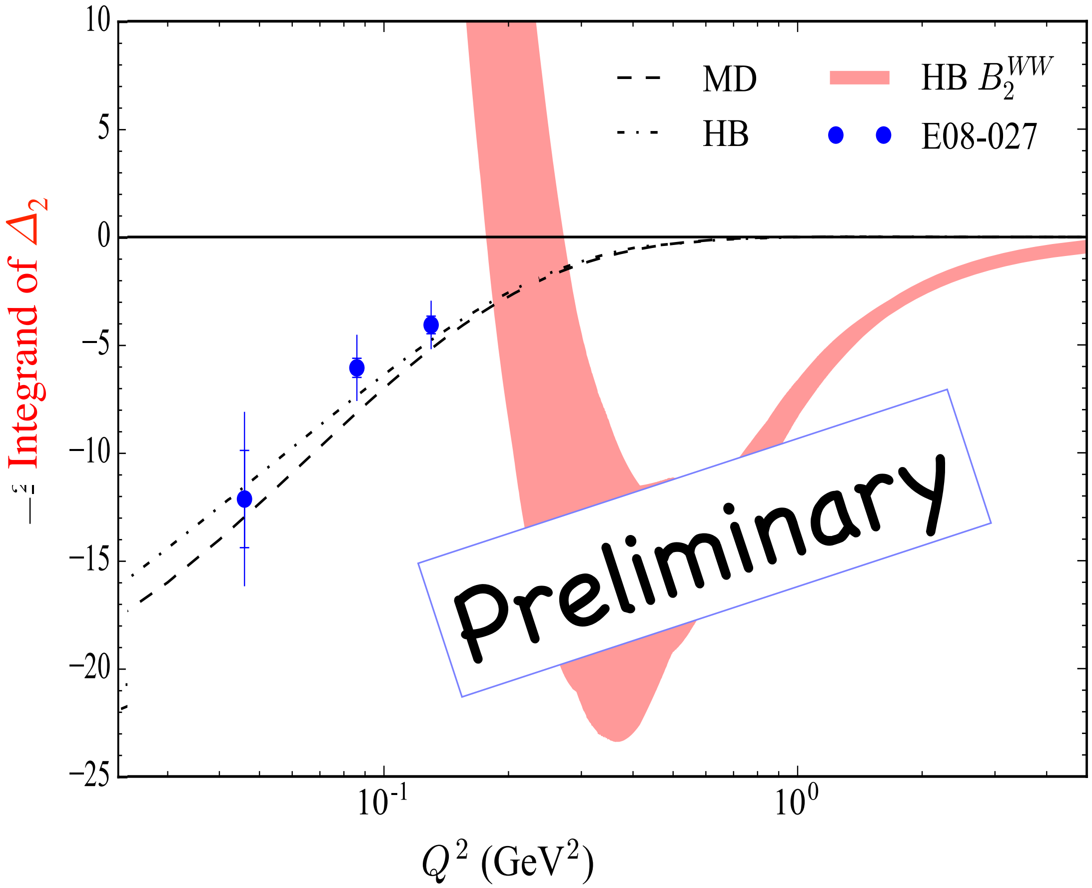
$$B_2(Q^2) = \int_0^{x_{th}} dx \beta_2(\tau) g_2(x, Q^2)$$

weighted heavily to low Q^2

g1p contribution to the Hyperfine Splitting



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

Tensor Program

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

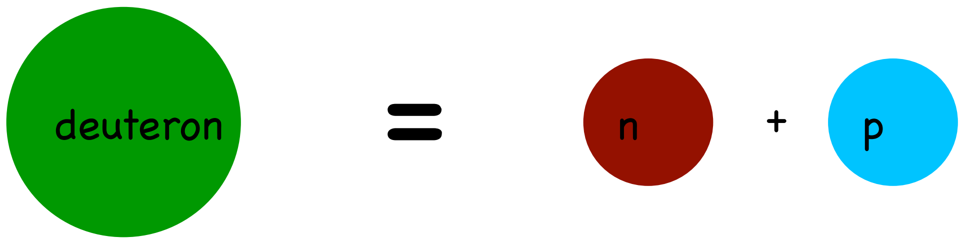
q^1 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state |m| = 1

b_1 Structure Function

Hoodbhoy, Jaffe and Manohar (1989)

b_1 vanishes in the absence of nuclear effects

i.e. if...



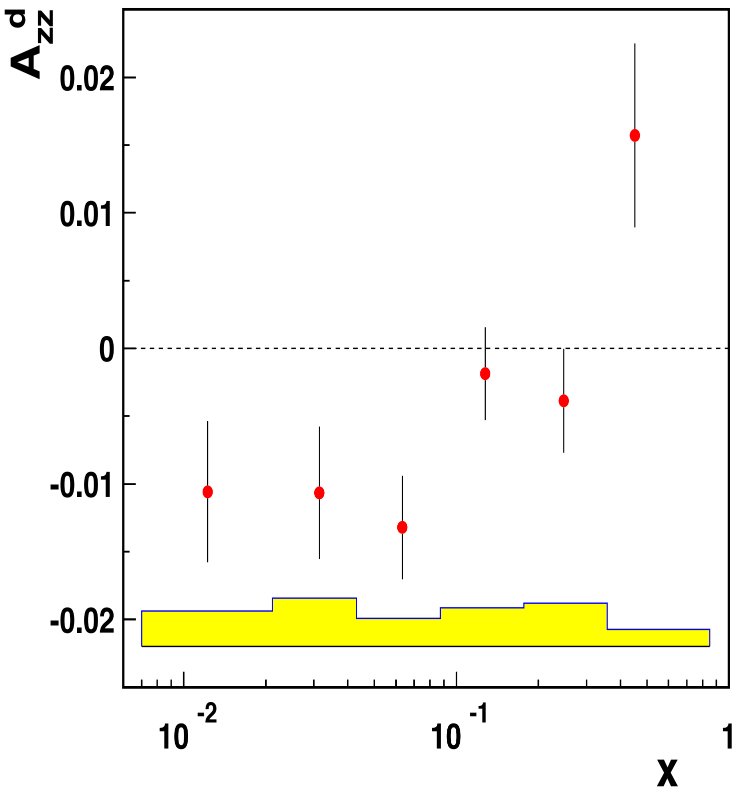
Proton Neutron in relative S-state

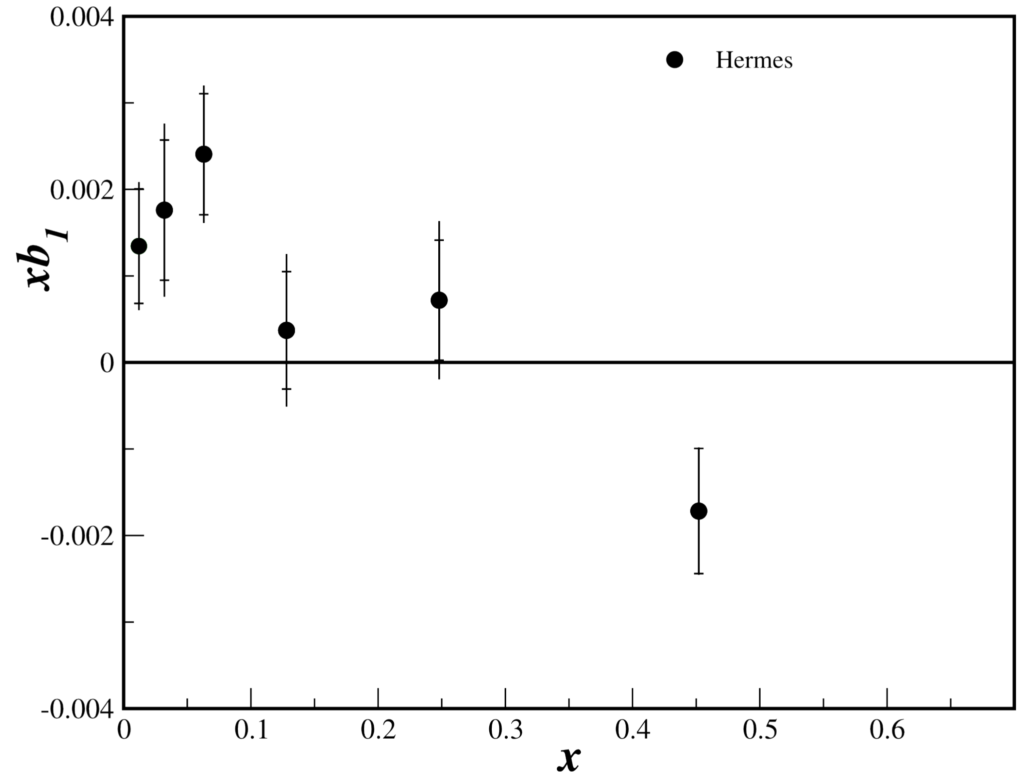
Even accounting for D-State admixture b_1 expected to be vanishingly small

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

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

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

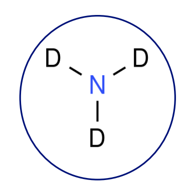
$\sigma_{\dagger}$: Tensor Polarized cross-section

σ_0 : Unpolarized cross-section

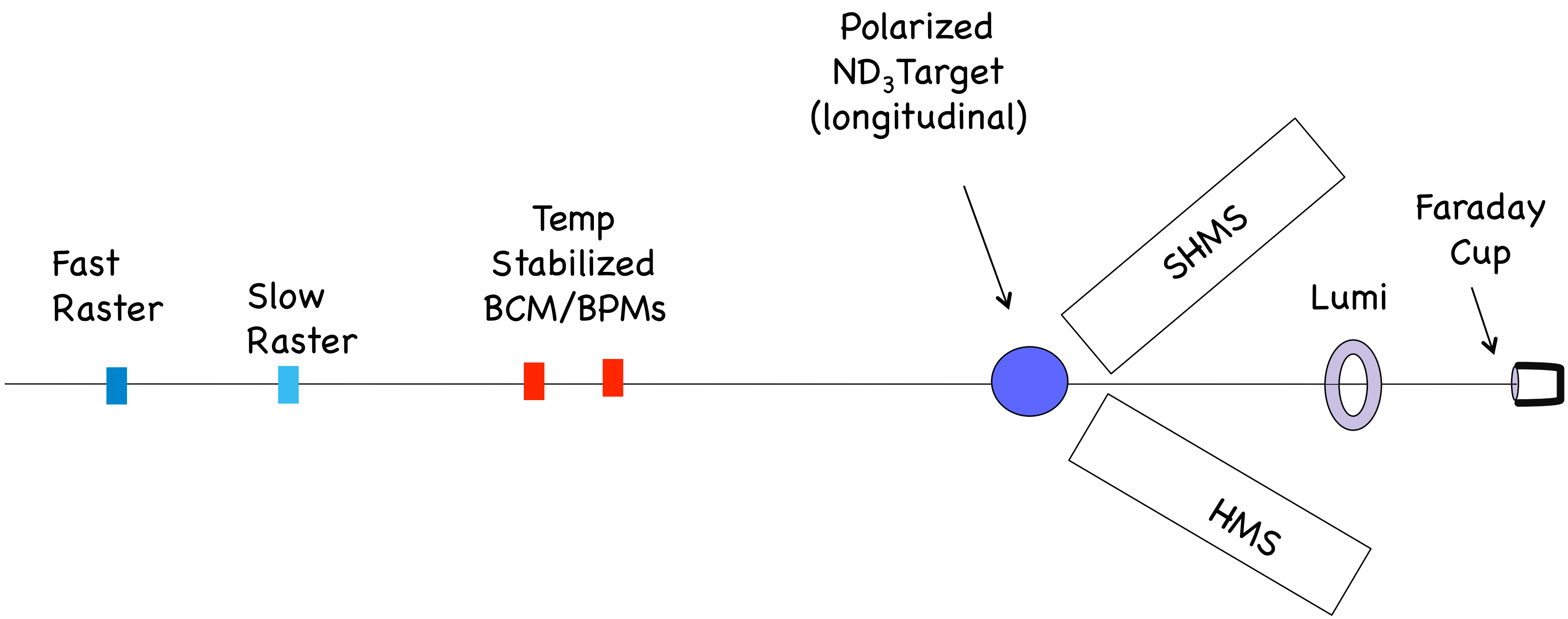
P_{zz} : Tensor Polarizzation

dilution factor

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



Jlab Hall C

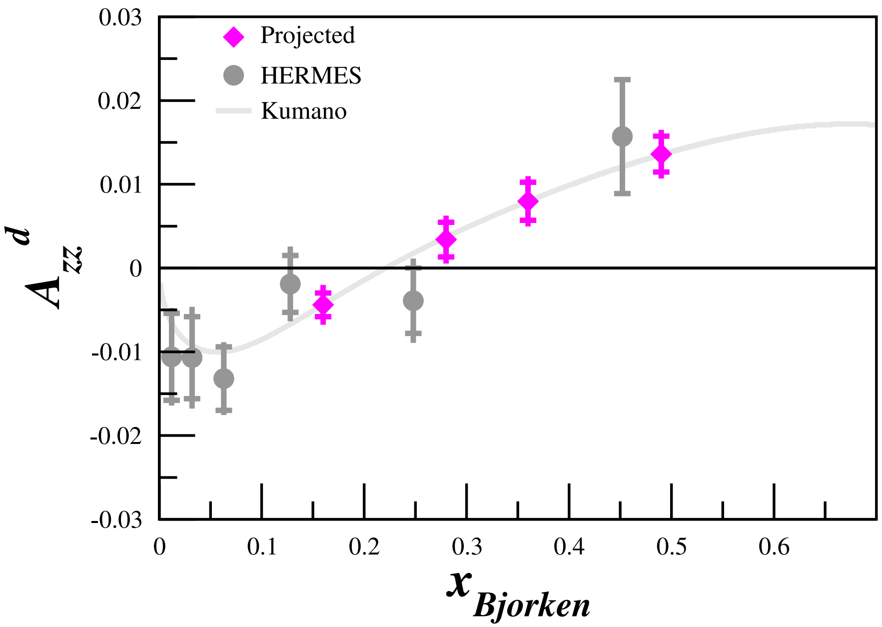


Unpolarized Beam
UVa/JLab Polarized Target

Magnetic Field Held Along Beam Line at all times

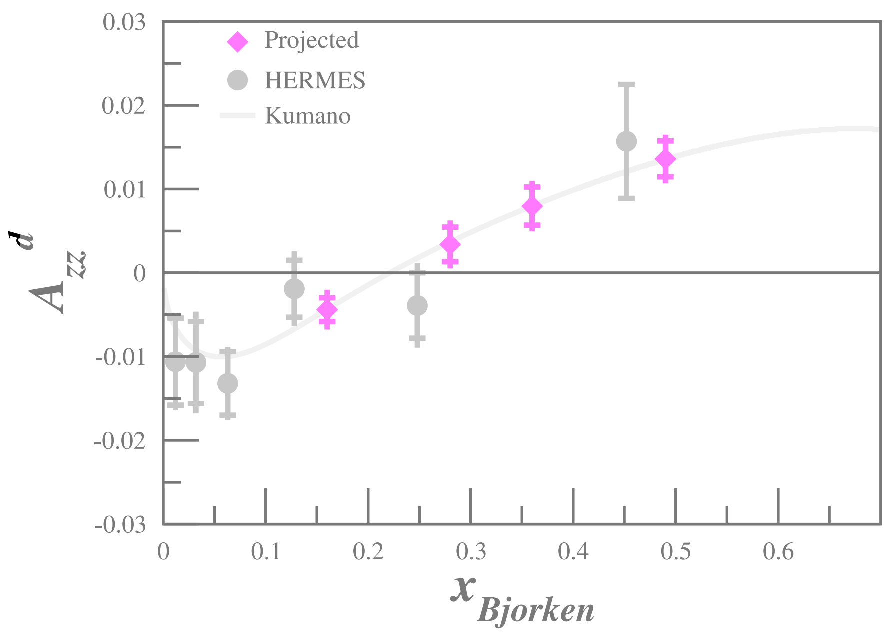
$\mathcal{L}=10^{35}$

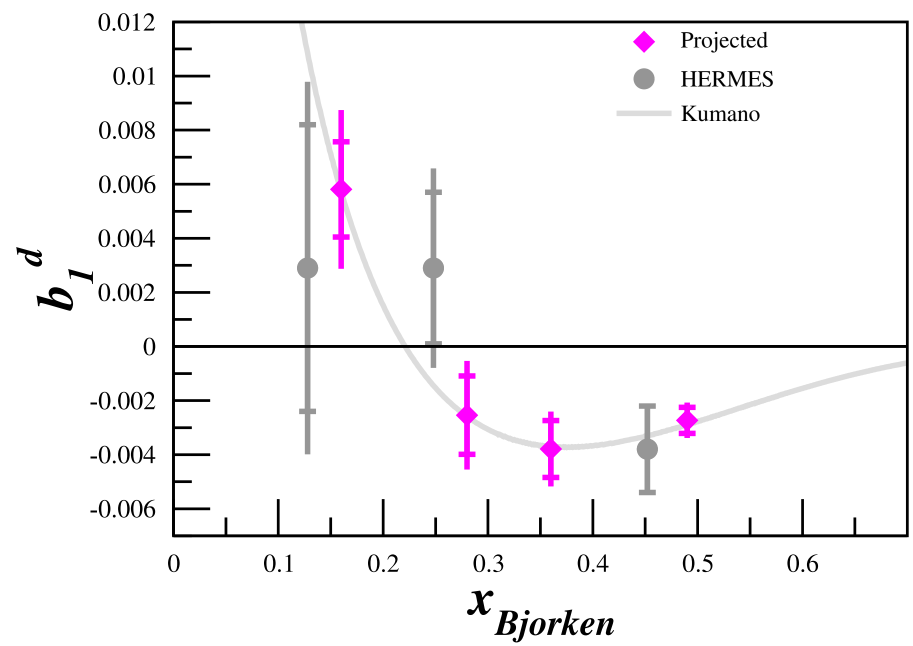
Projected Results for P_{zz} = 35%



30 Days in Jlab Hall C

Projected Results for P_{zz} = 35%

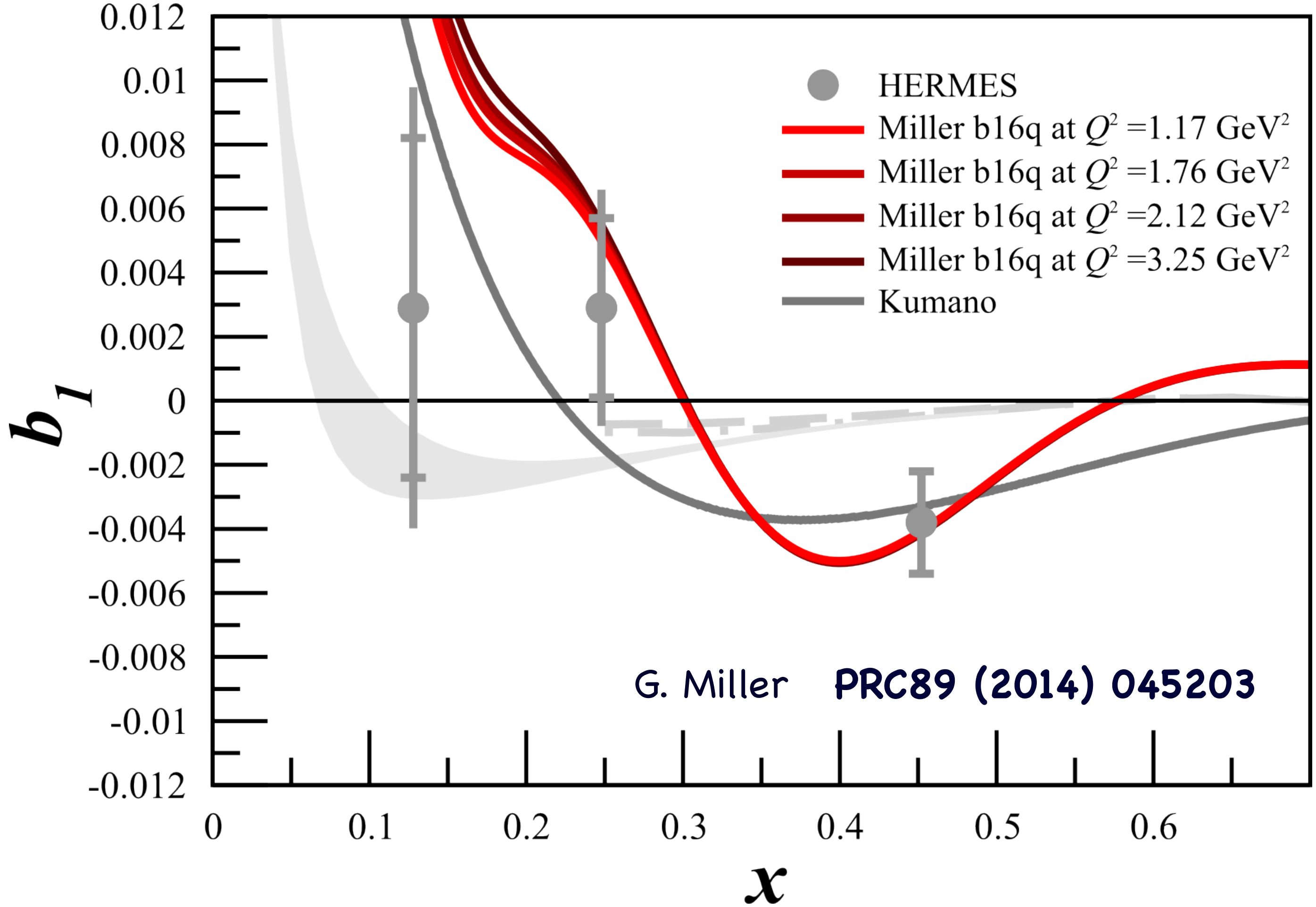




30 Days in Jlab Hall C

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.

Gluon Contribution to Tensor Structure

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

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

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!

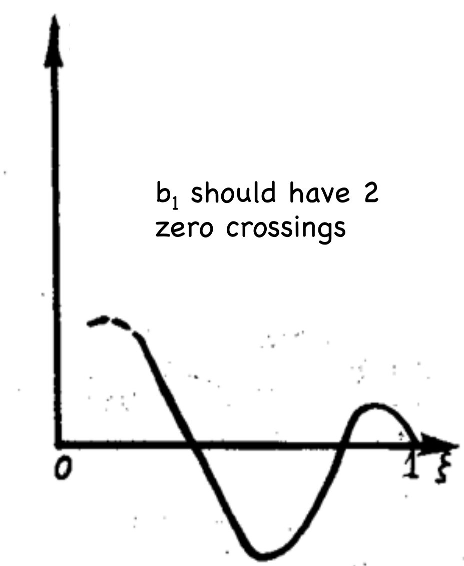


Рис. 1

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

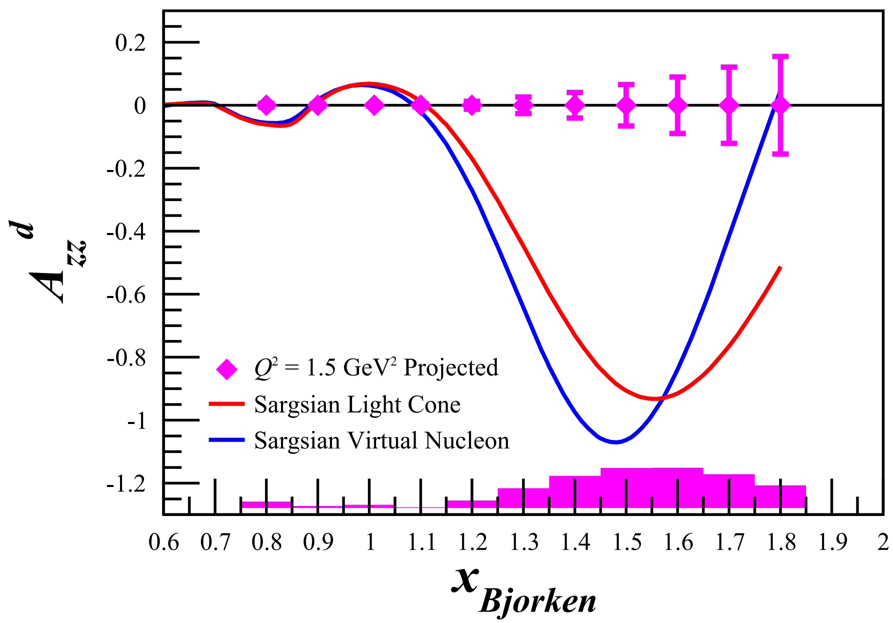
Study of b_1 allows to discriminate between deuteron components with different spins (quarks vs gluons)

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

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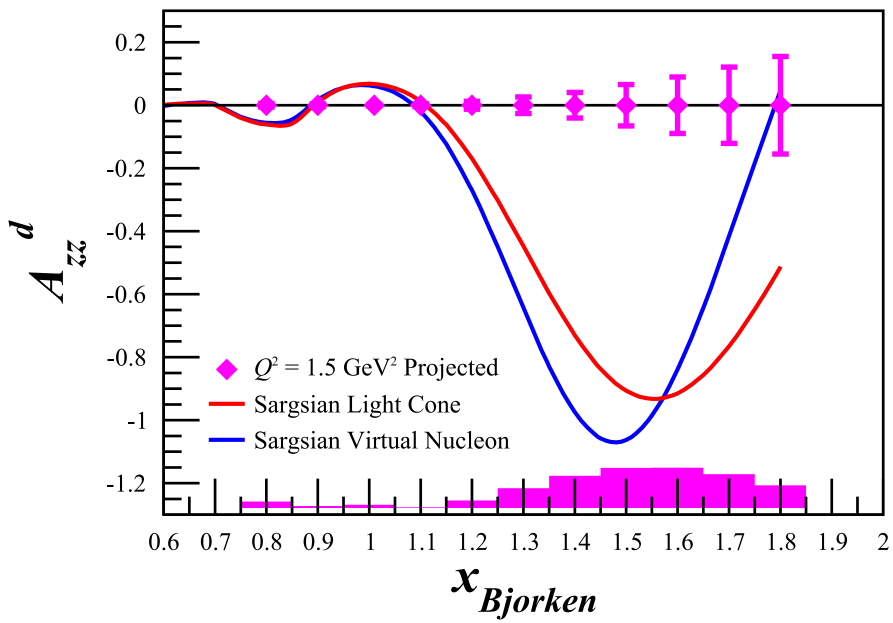

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Sensitive to the S/D-wave ratio in the deuteron wave function

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

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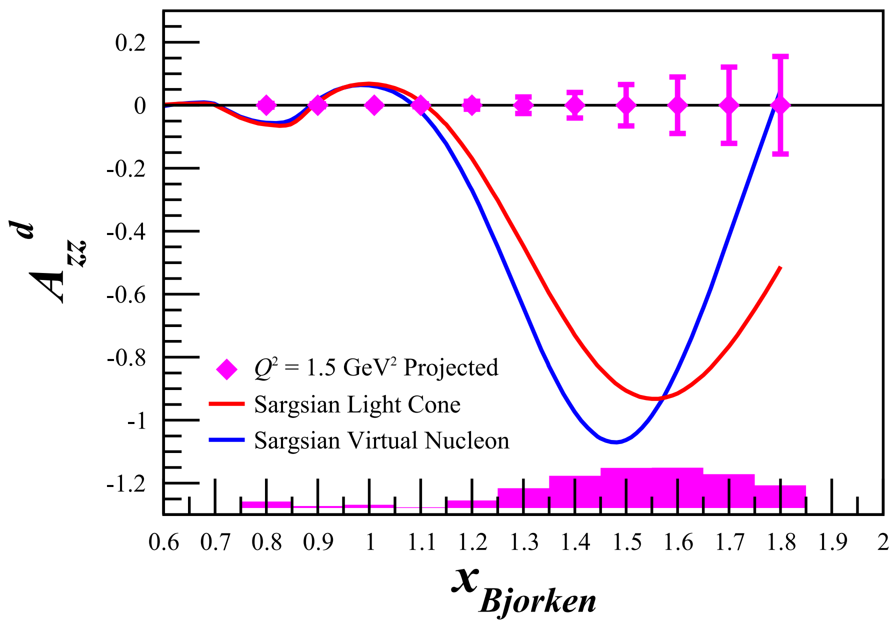

Very Large Tensor Asymmetries predicted

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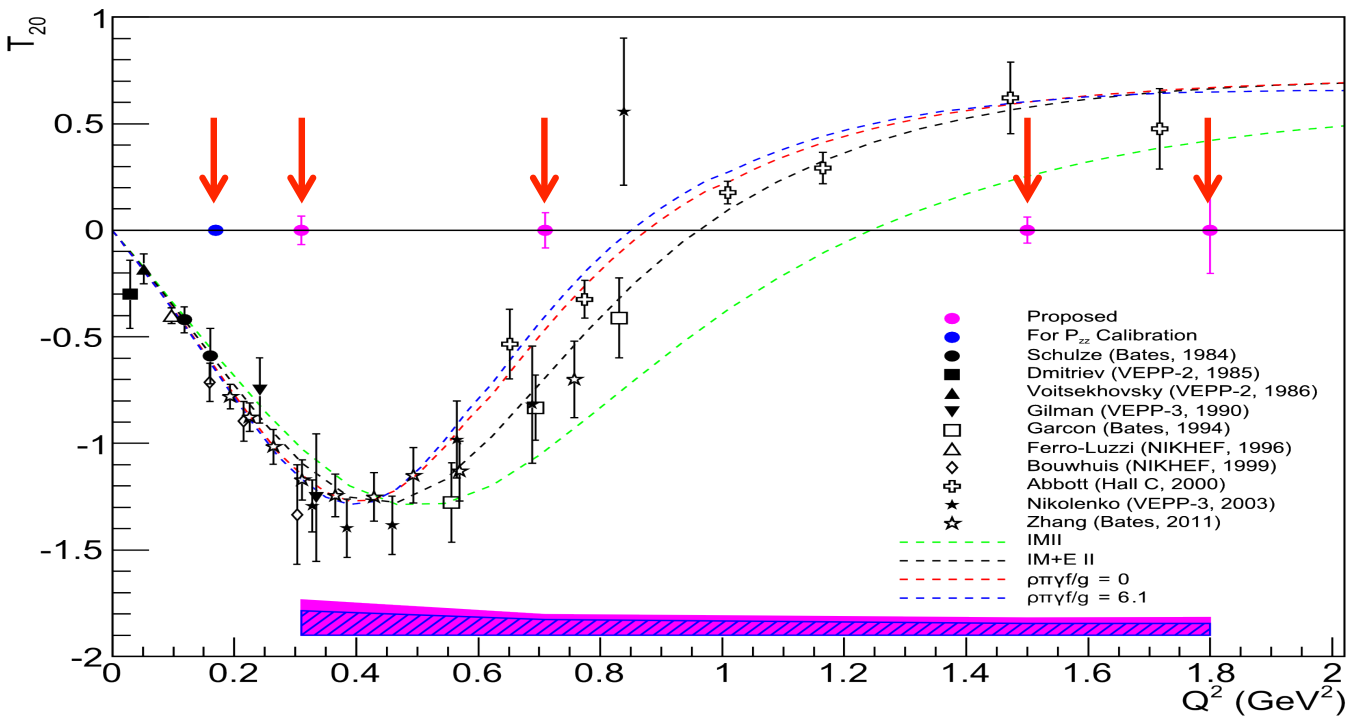
4σ discrim between hard/soft wave functions
6σ discrim between relativistic models

"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



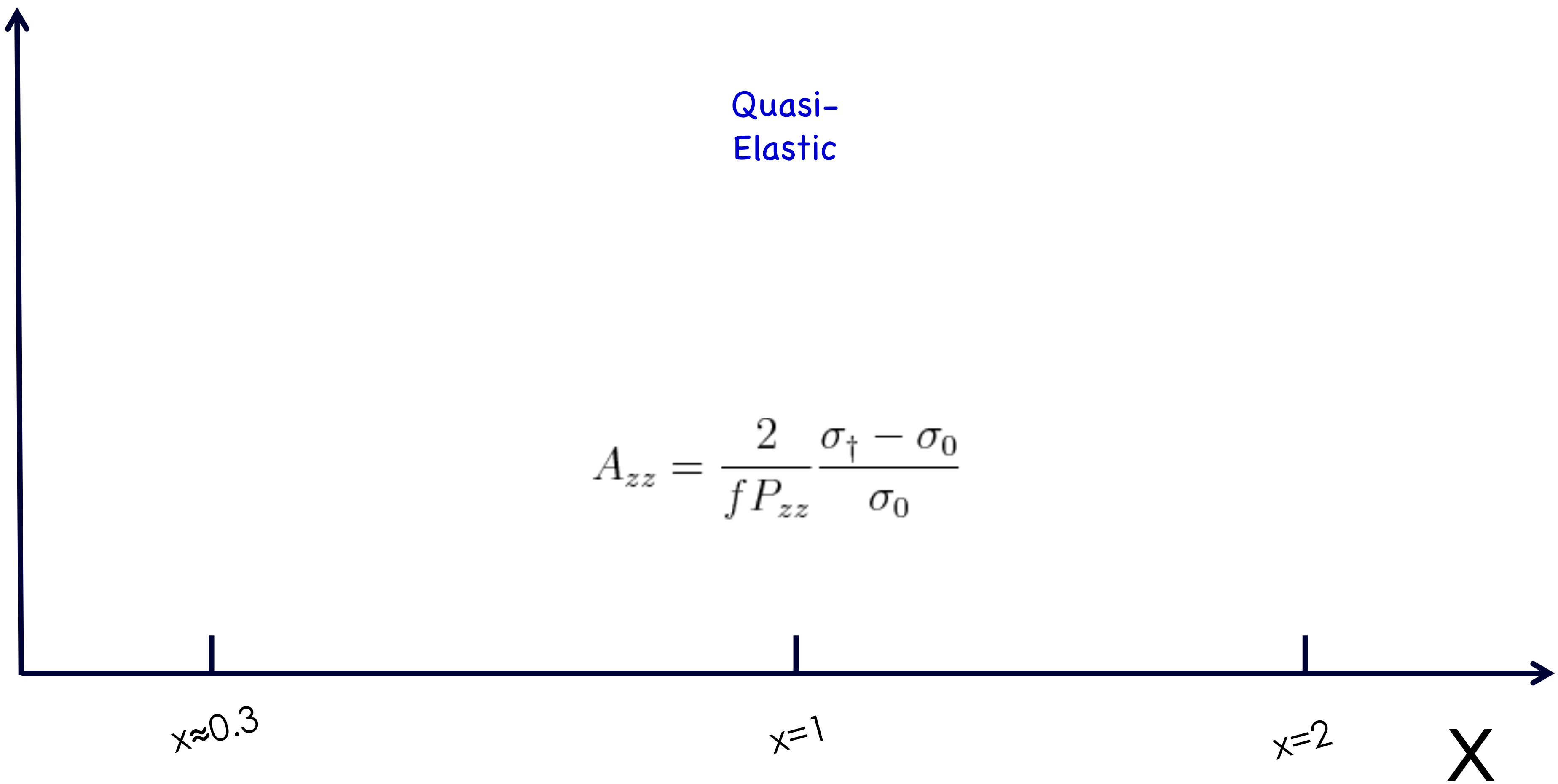
We simultaneously measure nuclear elastic

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

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

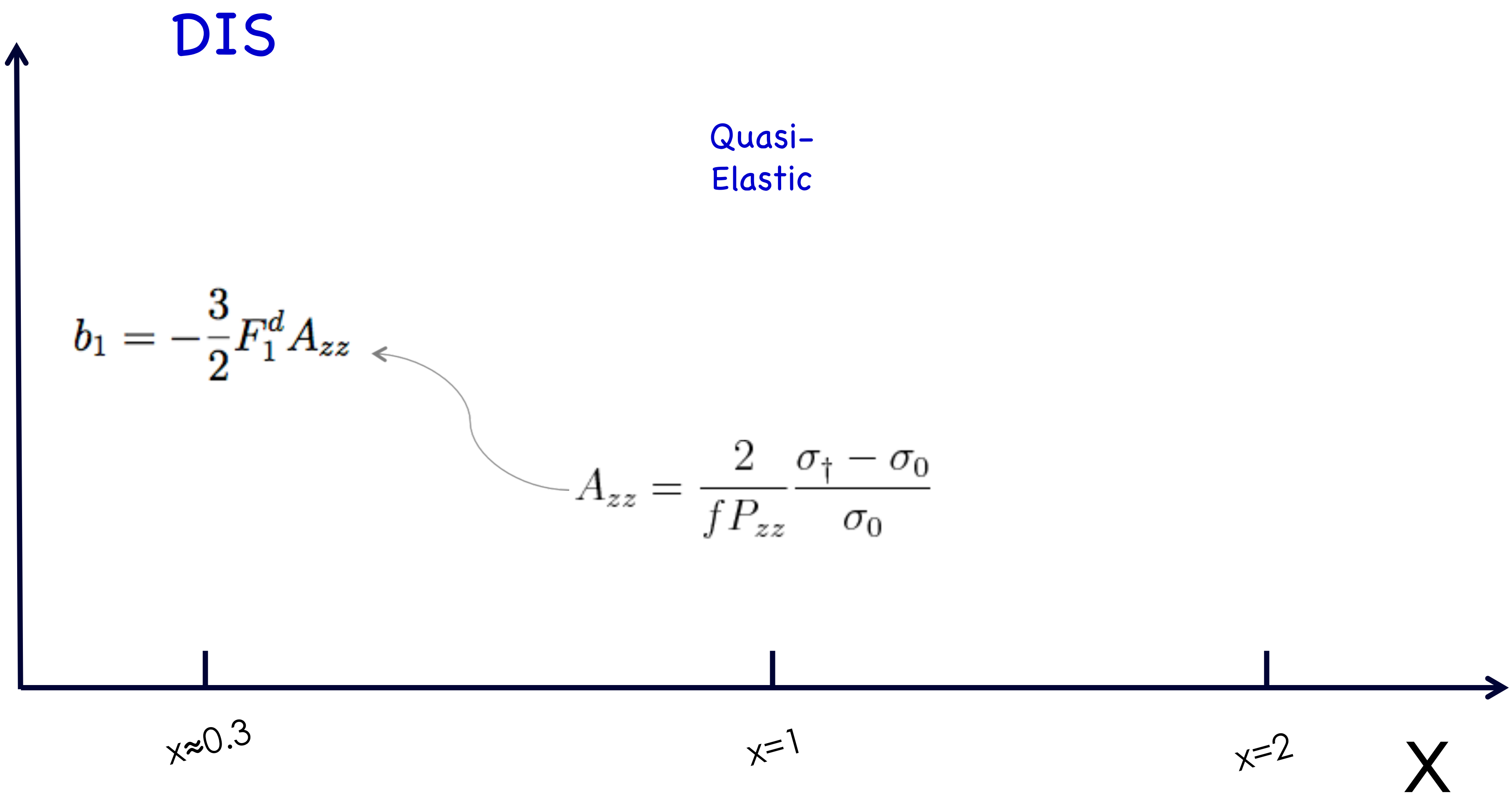
-> will use to cross-check Pzz

Tensor Spin Observables



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

Tensor Spin Observables



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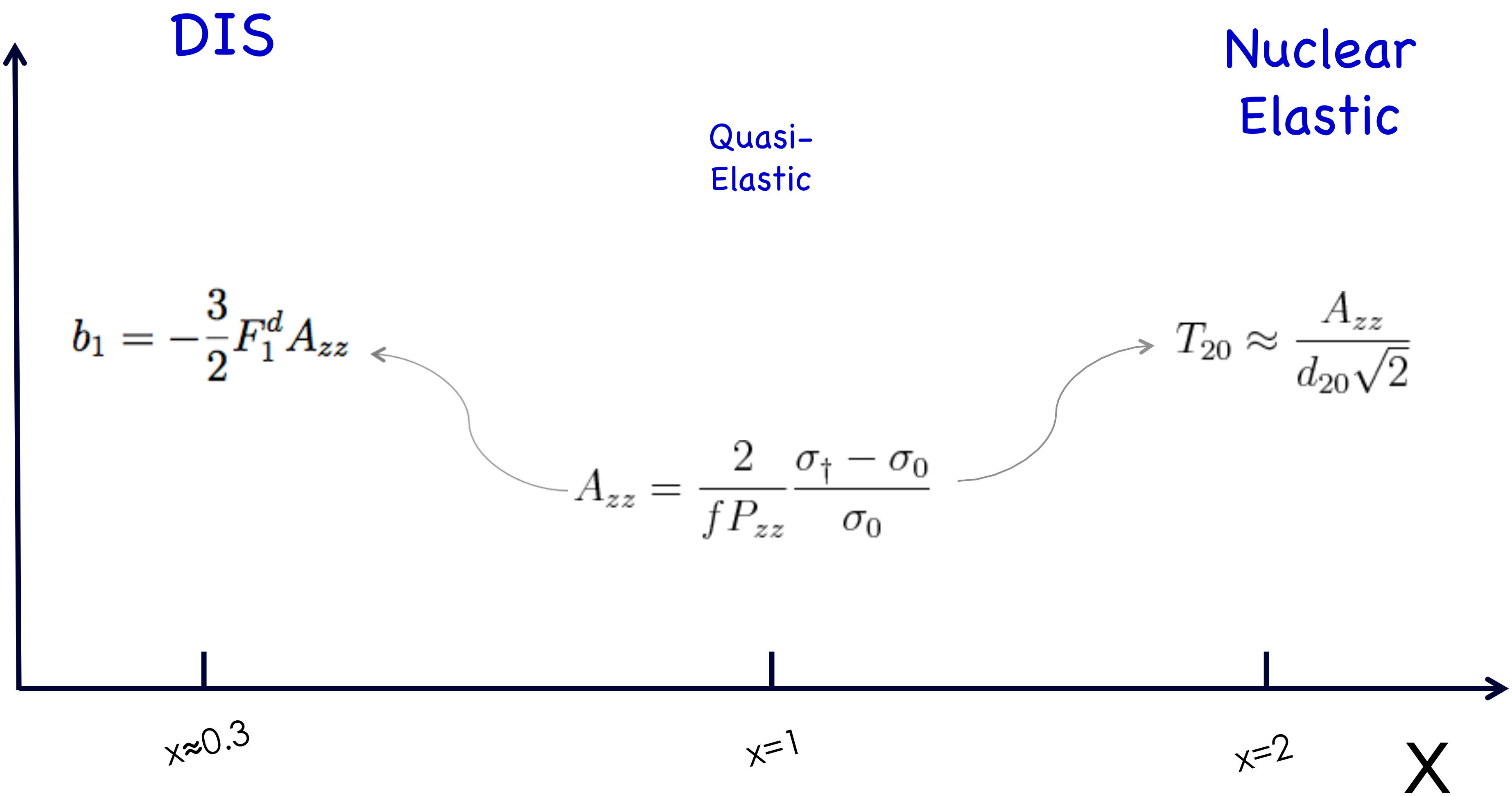
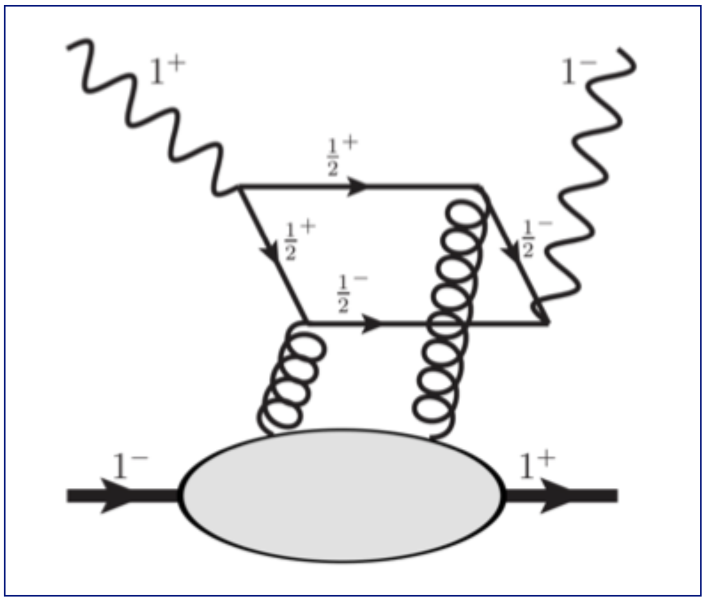
Tensor Spin Observables



LOI-12-16-006



James Maxwell (contact)

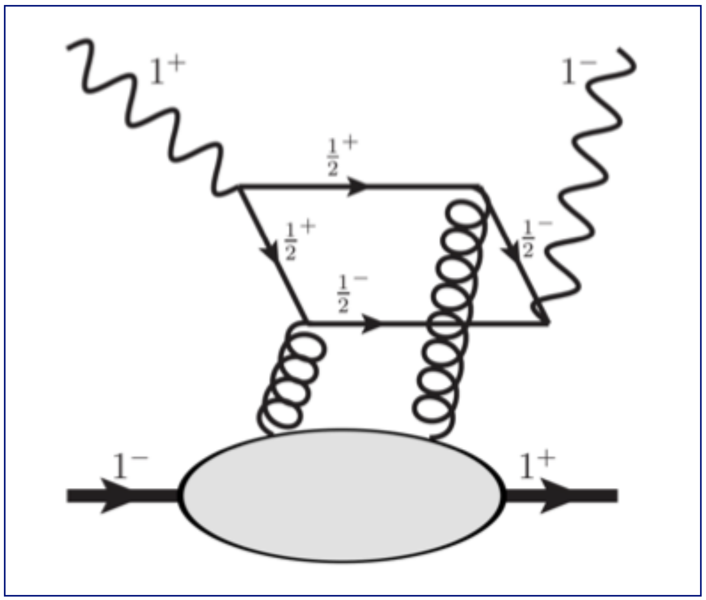
"Nuclear Gluonometry"

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

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

LOI-12-16-006



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

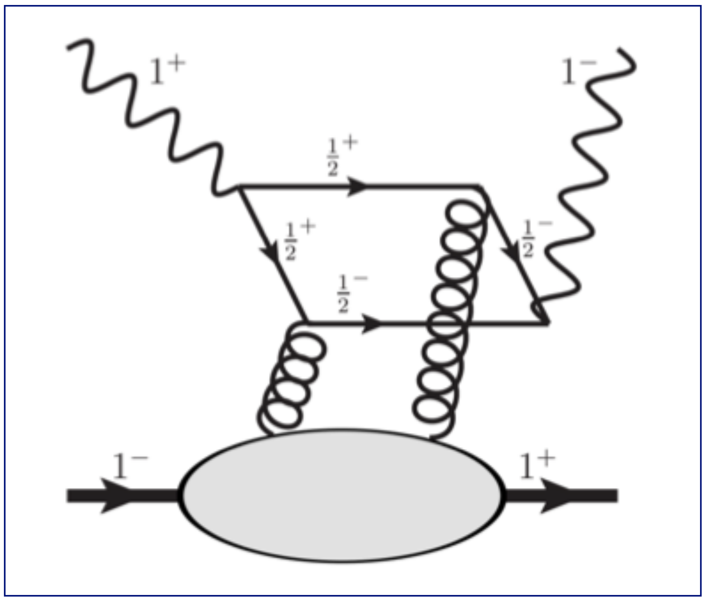
Encouraged for full submission by PAC44

LOI-12-16-006

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

James Maxwell (contact)

"Nuclear Gluonometry"



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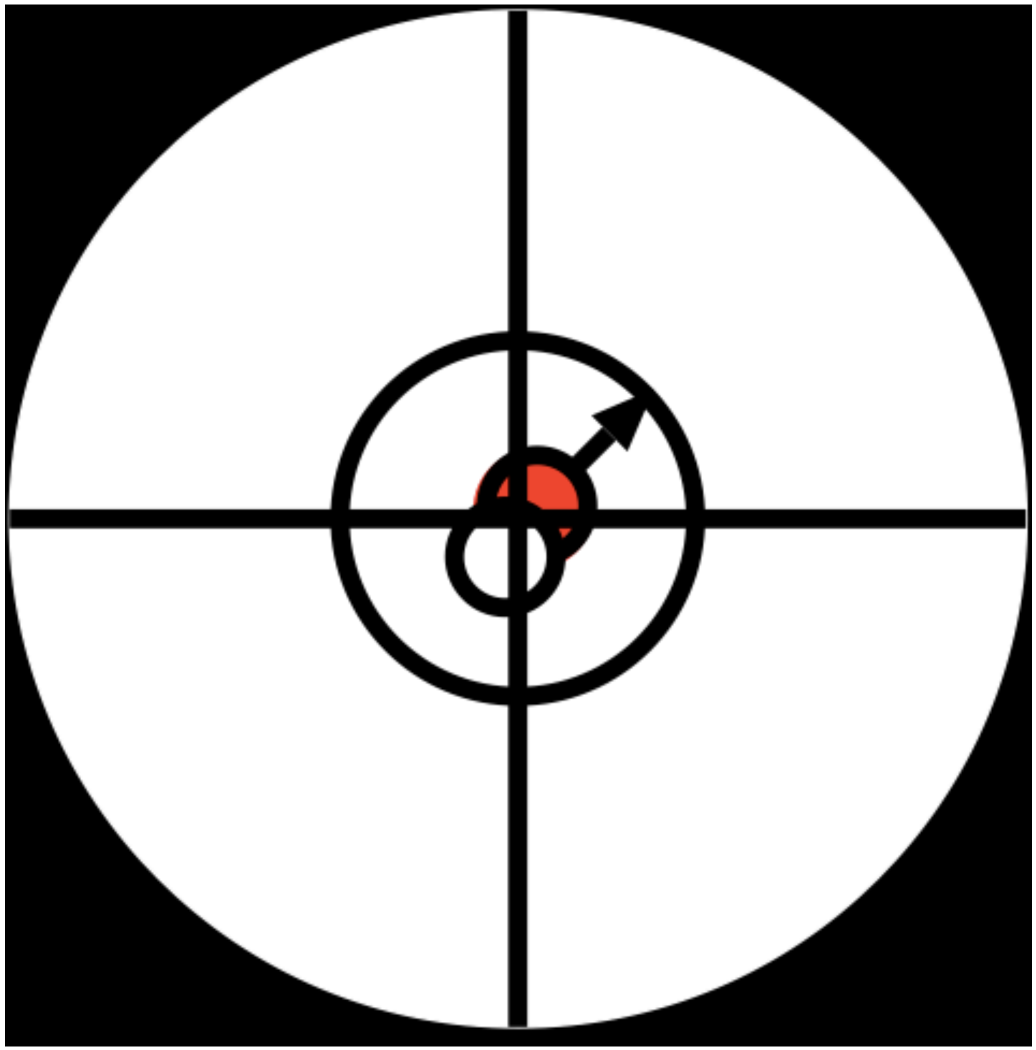
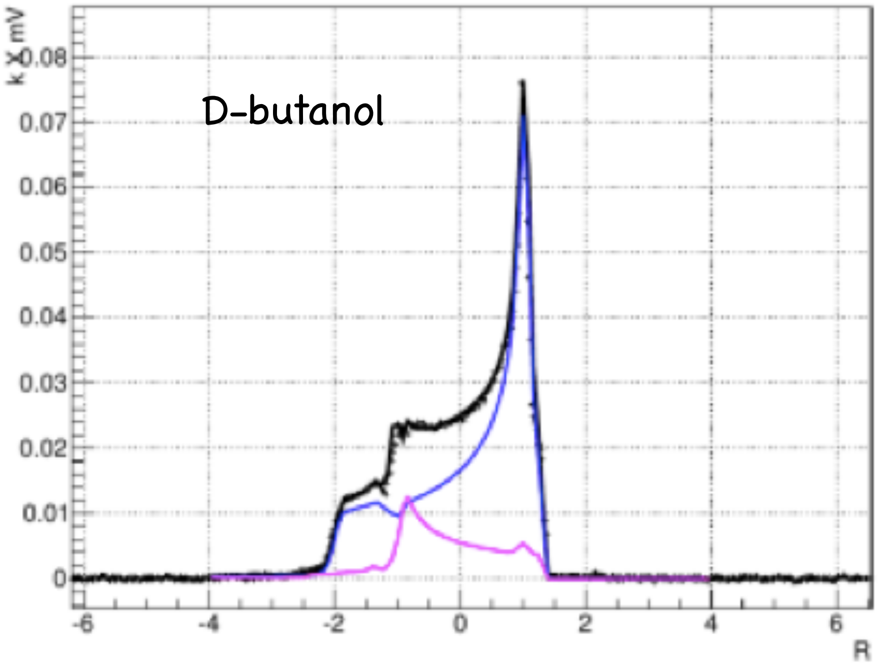
Technical Developments



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

New Publication on tensor polarized target lineshape

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

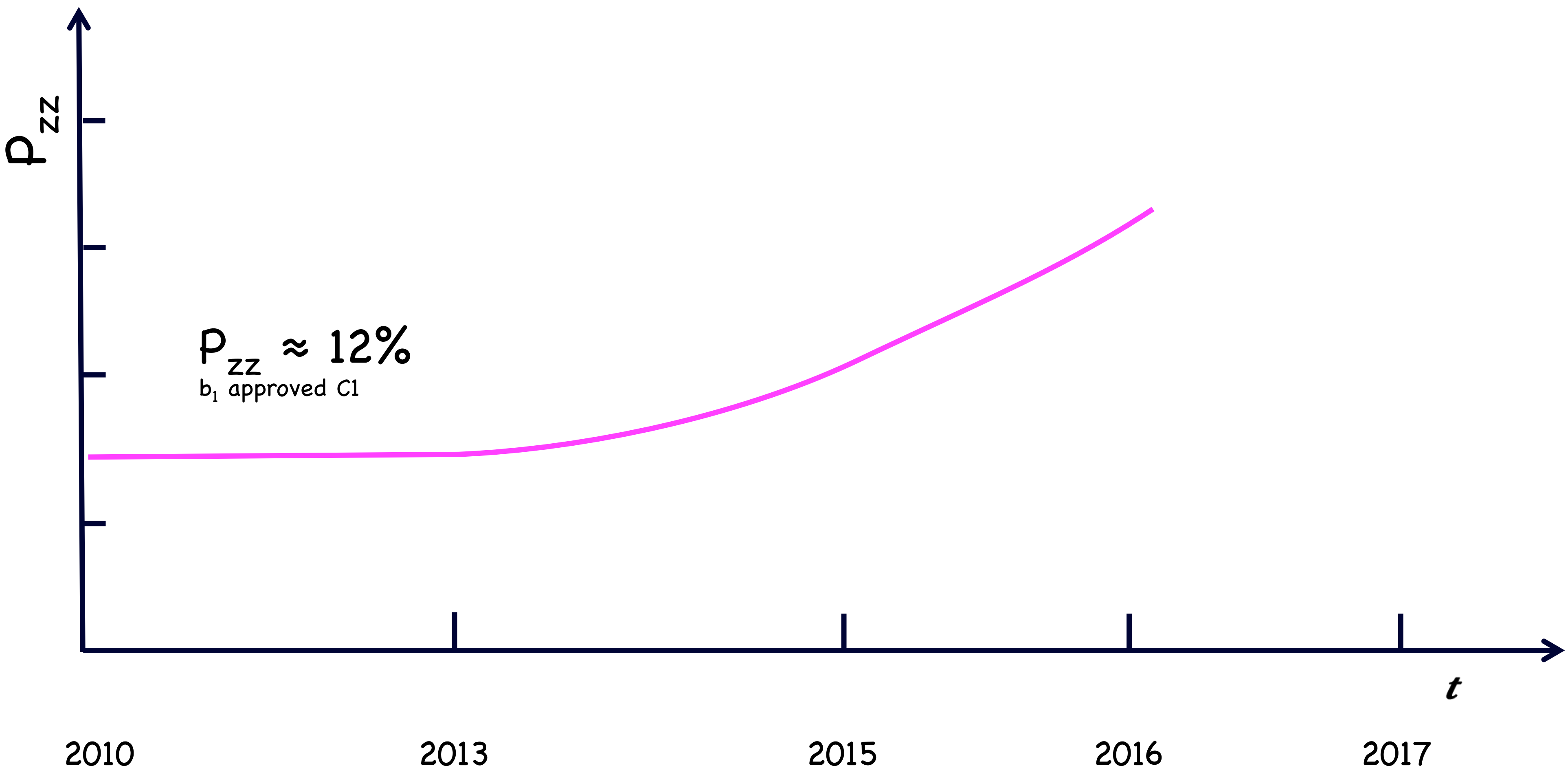
D. Keller[a]

University of Virginia, Charlottesville, VA 22901, USA

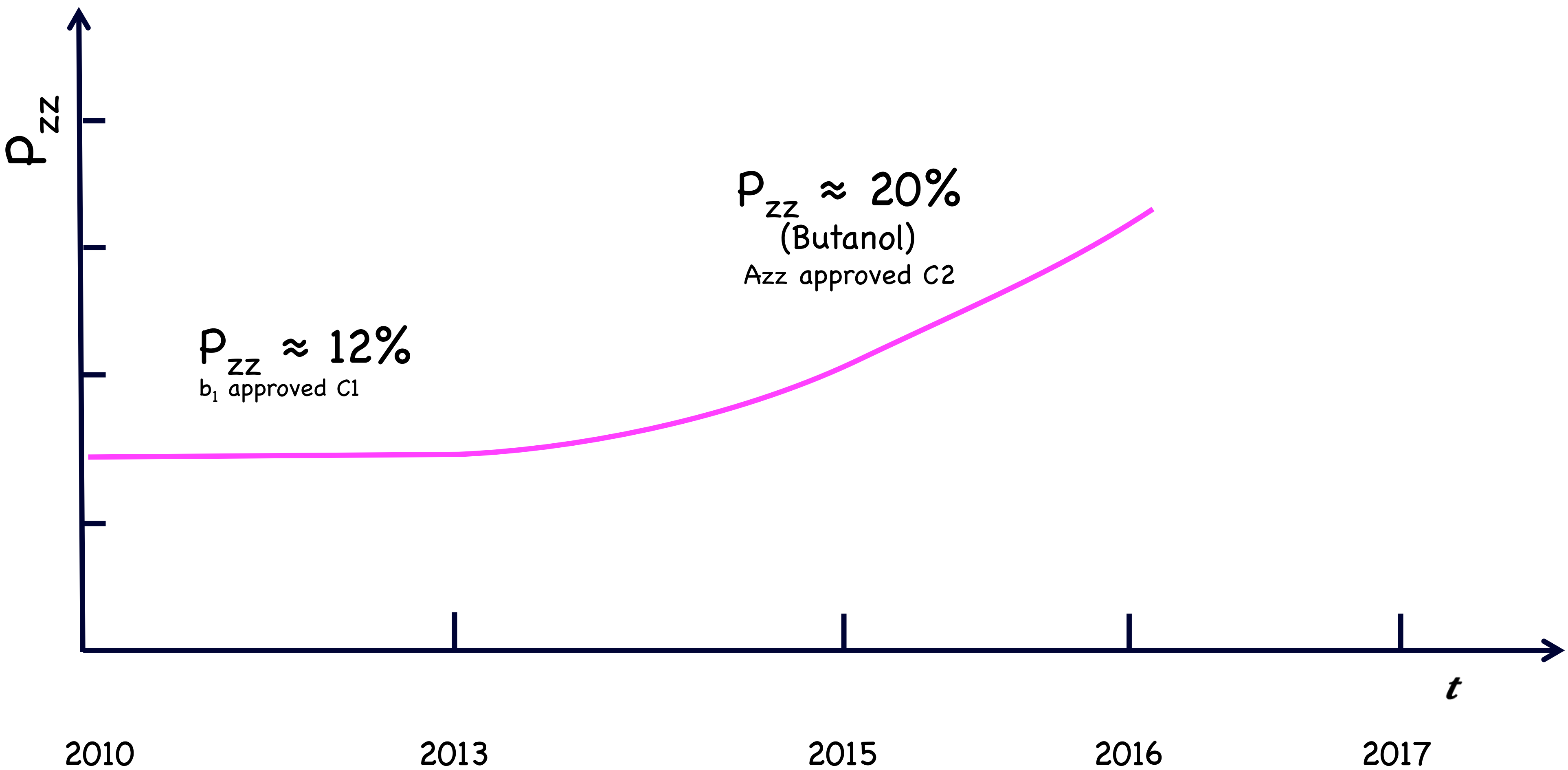
Received: 1 May 2017 / Revised: 16 June 2017
Published online: 26 July 2017 – © Società Italiana di Fisica
Communicated by M. Anselmino

Abstract. A model of dyn… …frequency (RF) irradiation produced perpendicular to th… …pin-1 system required for tensor-polarized fixed-target exp… …RF produced close to the Larmor frequency of the nucleus and … …onance linewidth to be much smaller than the nuclear magnetic resonance … equations are solved numerically to study a semi-saturated steady-state resulting from … 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.

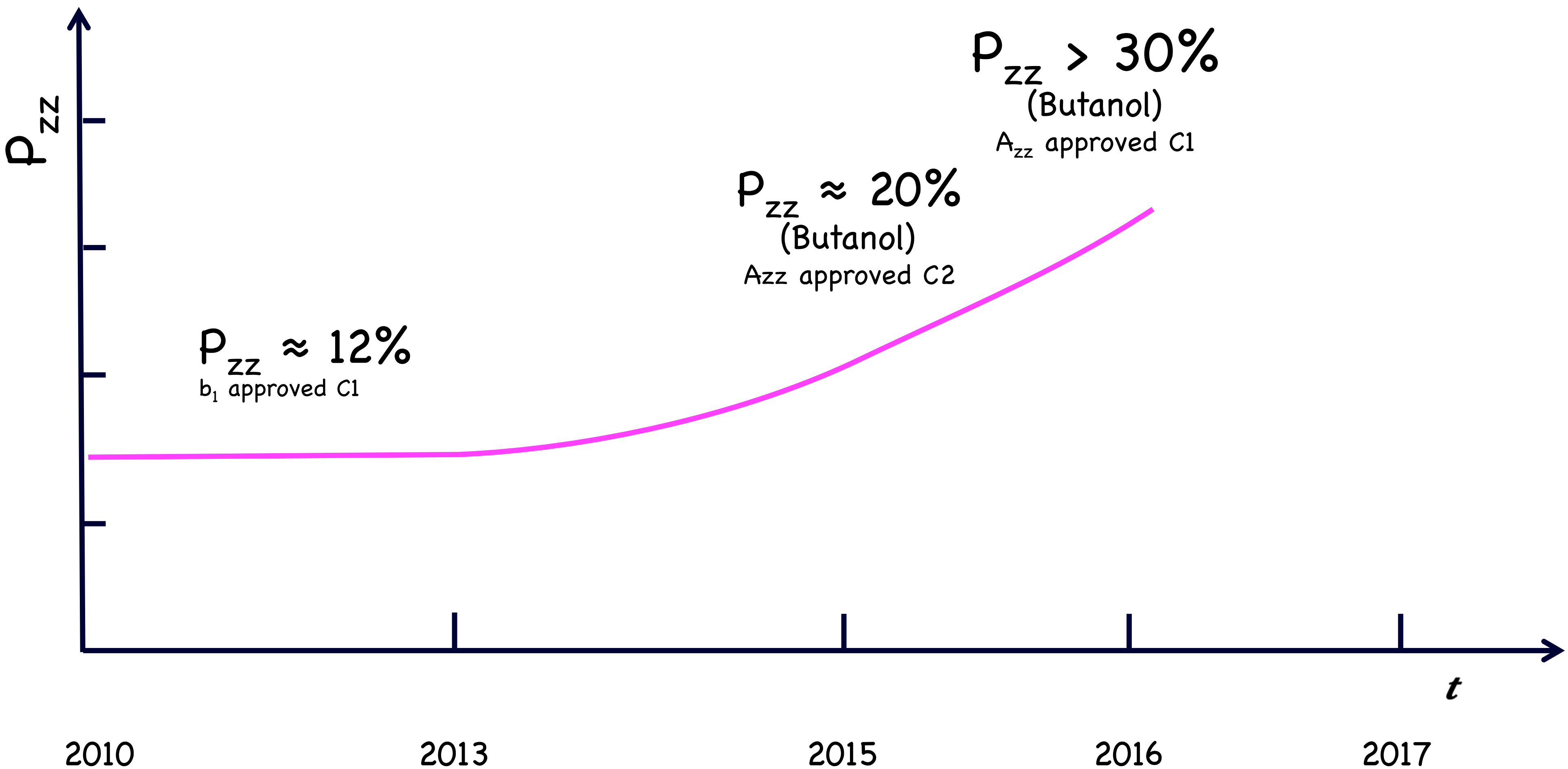
Tensor Polarization progress



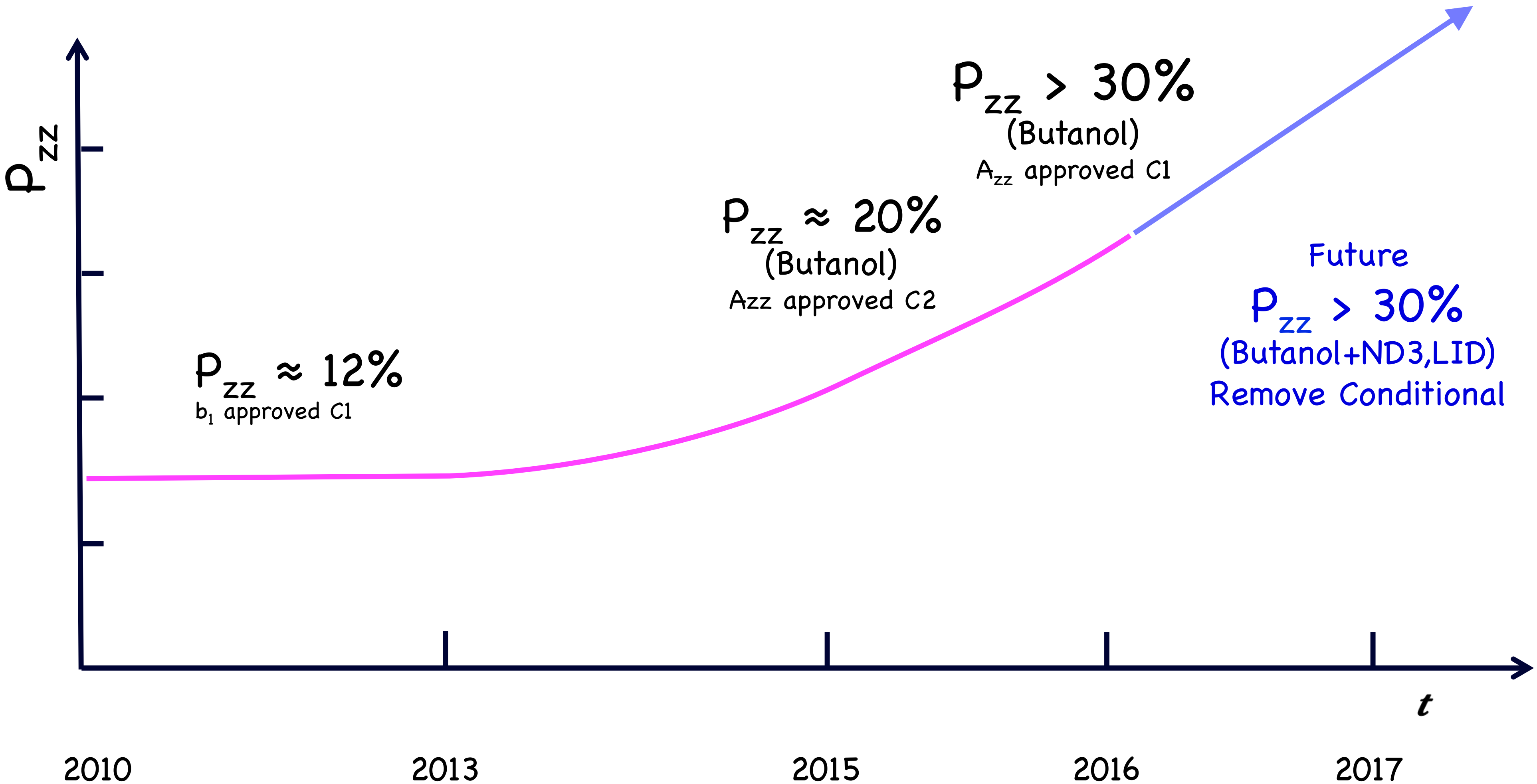
Tensor Polarization progress



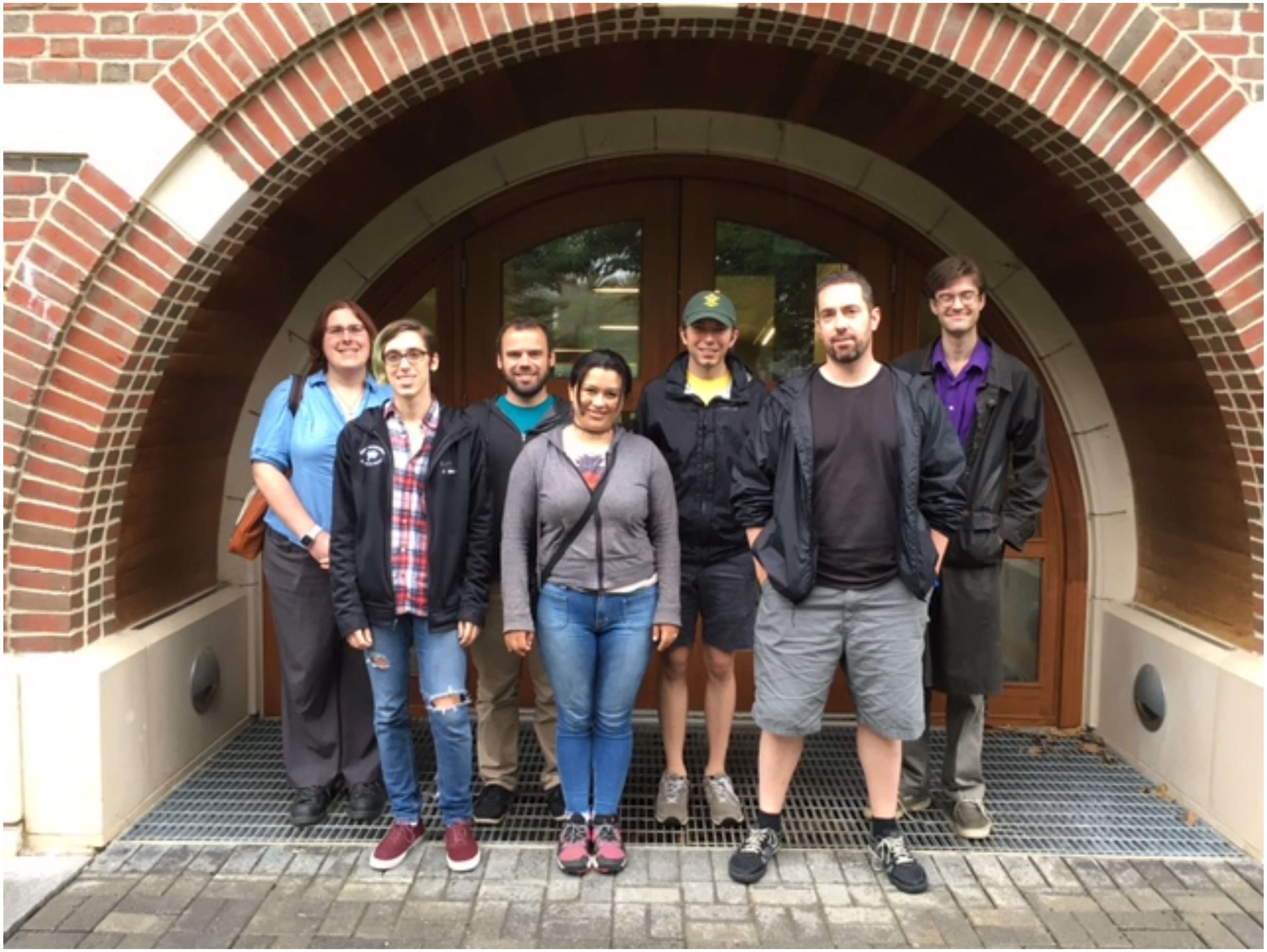
Tensor Polarization progress



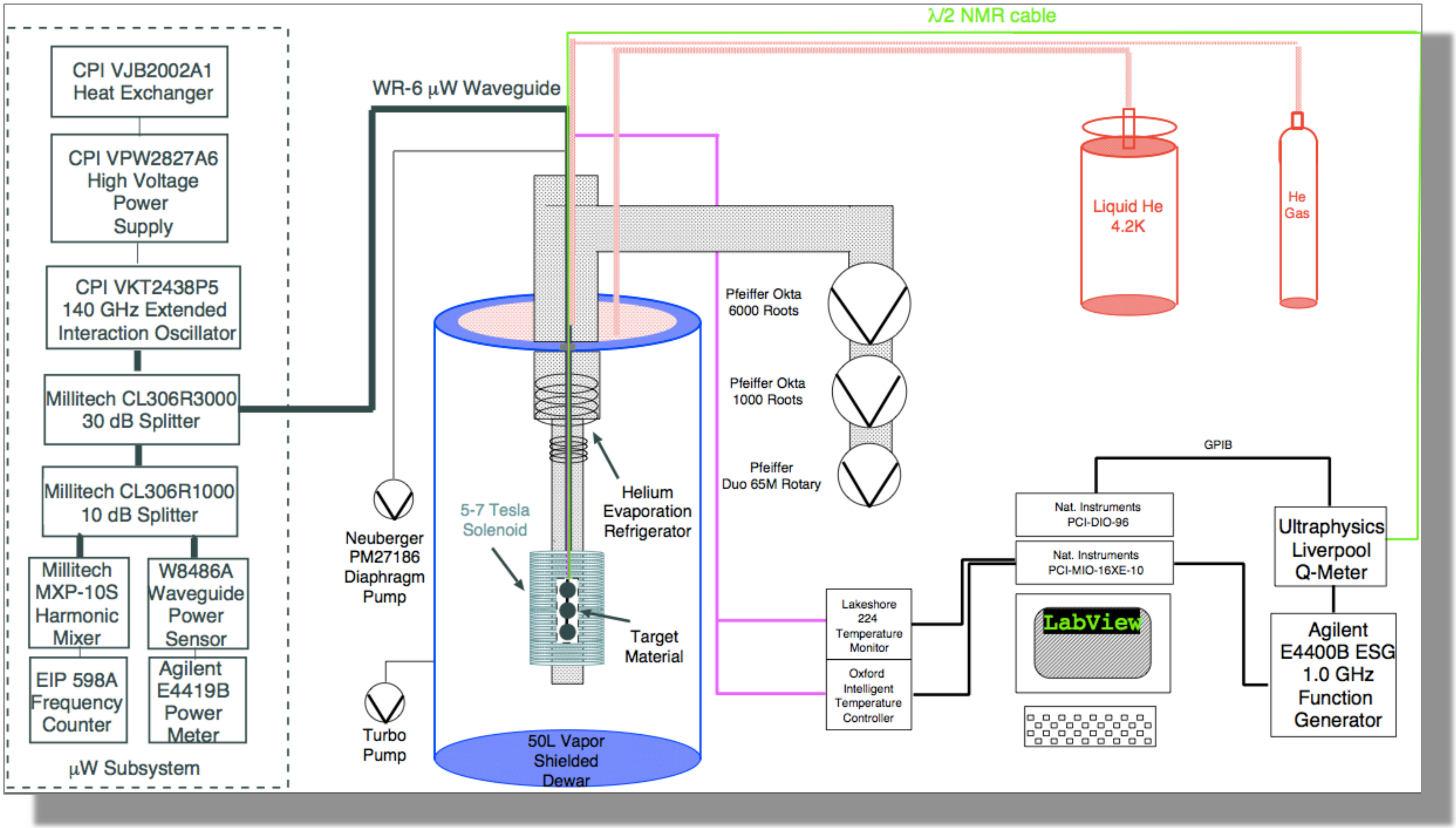
Tensor Polarization progress



UNH Polarized Target Lab



UNH Polarized Target Lab



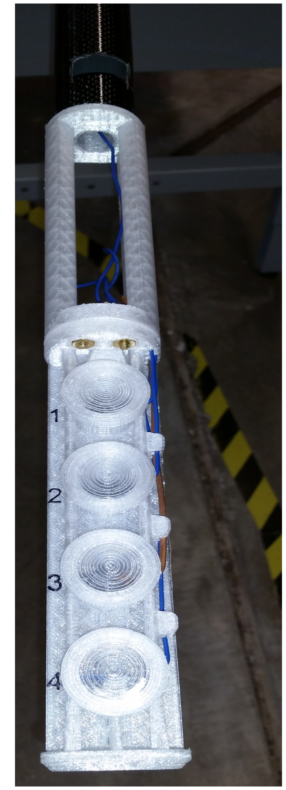
Microwave subsystem focus for the fall/spring

We've run at 1K/7Tesla

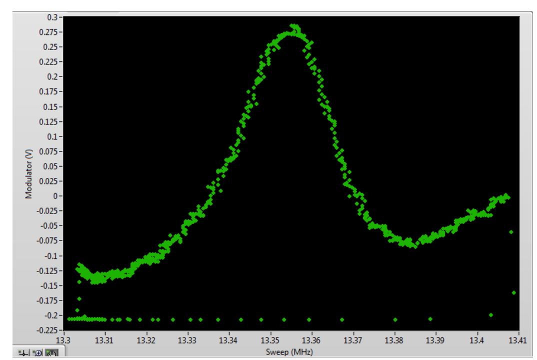
Constructing New 1 K Fridge almost complete

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

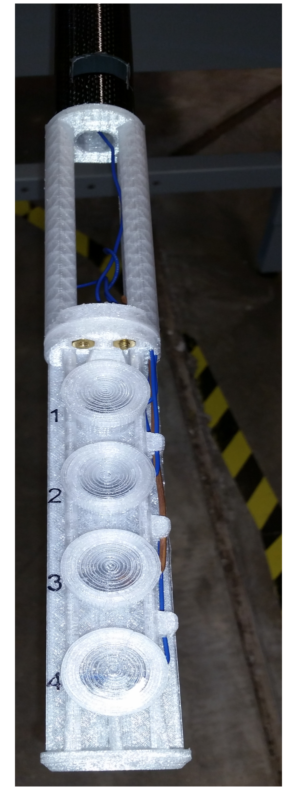
UNH Polarized Target Lab



Reached 1K/7T
Have Working NMR system
Developing high vacuum expertise
Completing Construction of new 1K fridge
Constructing the microwave subsystem this fall



UNH Polarized Target Lab



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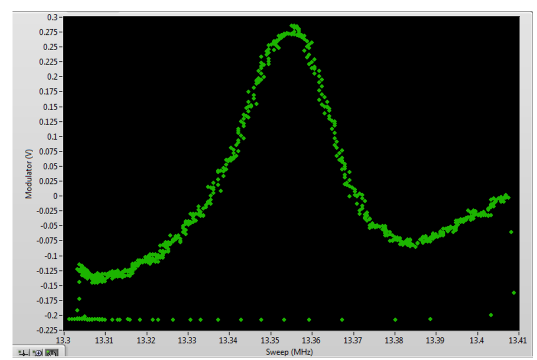


New Faculty hire (Elena Long)
University made a significant investment in infrastructure
We should be fully operational by end of year

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. Eg4, sagdh and g2p 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 to be fully operational by end of year.

Moments

Spin polarizabilities

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

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

color polarizability

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

Generalized GDH

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

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

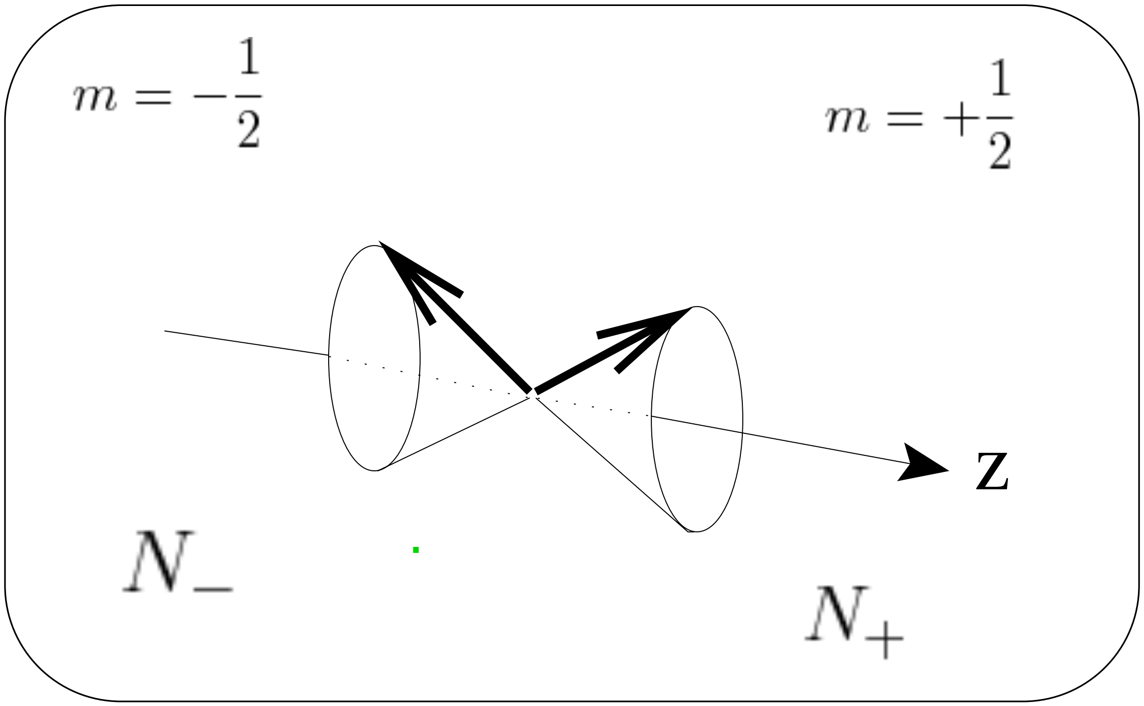
Burkhardt Cottingham

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

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

Spin-1/2

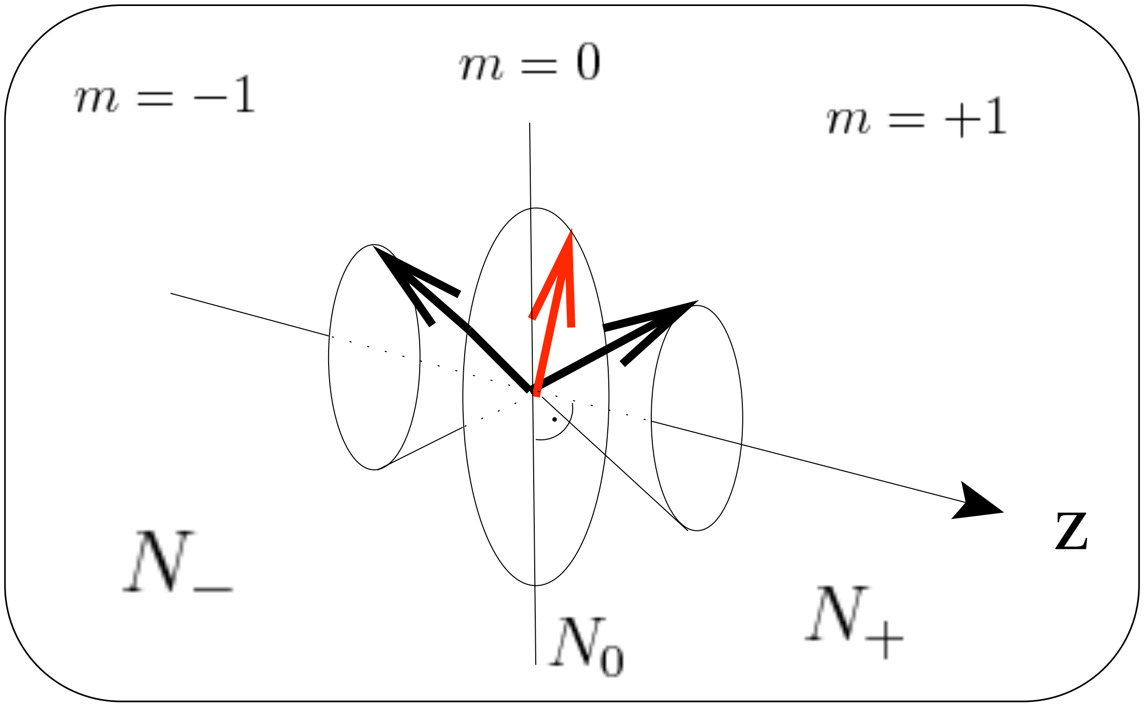
Spin-1/2 system in B-field leads to 2 sublevels due to Zeeman interaction



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

$-1 < P_z < +1$

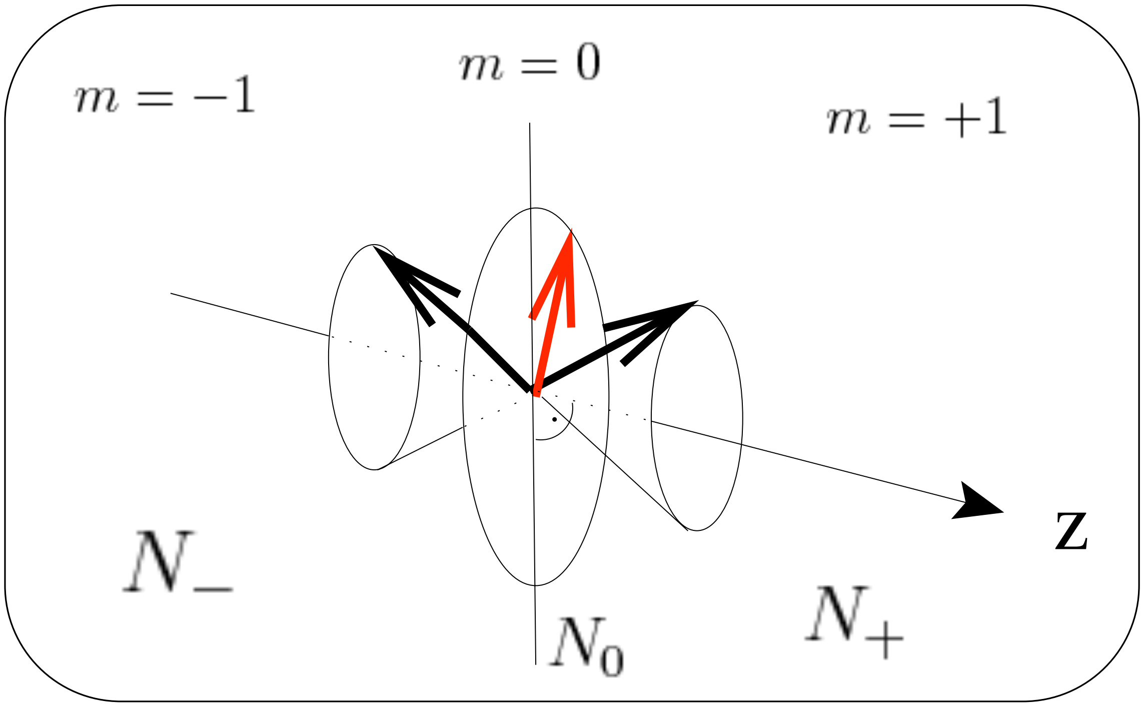
Spin-1



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

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

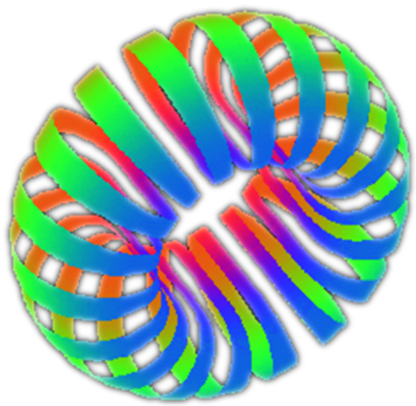
Spin-1



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

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

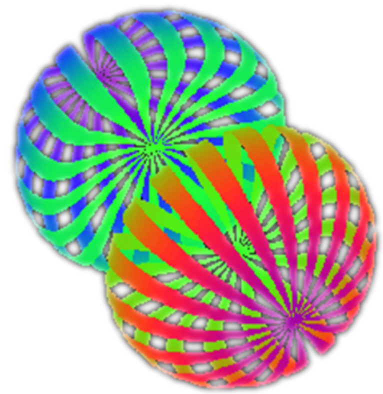
Spin-1



$P_{zz} = -2$

Pure Tensor Polarization

All spins in the m=0 level



$P_{zz} = +1$

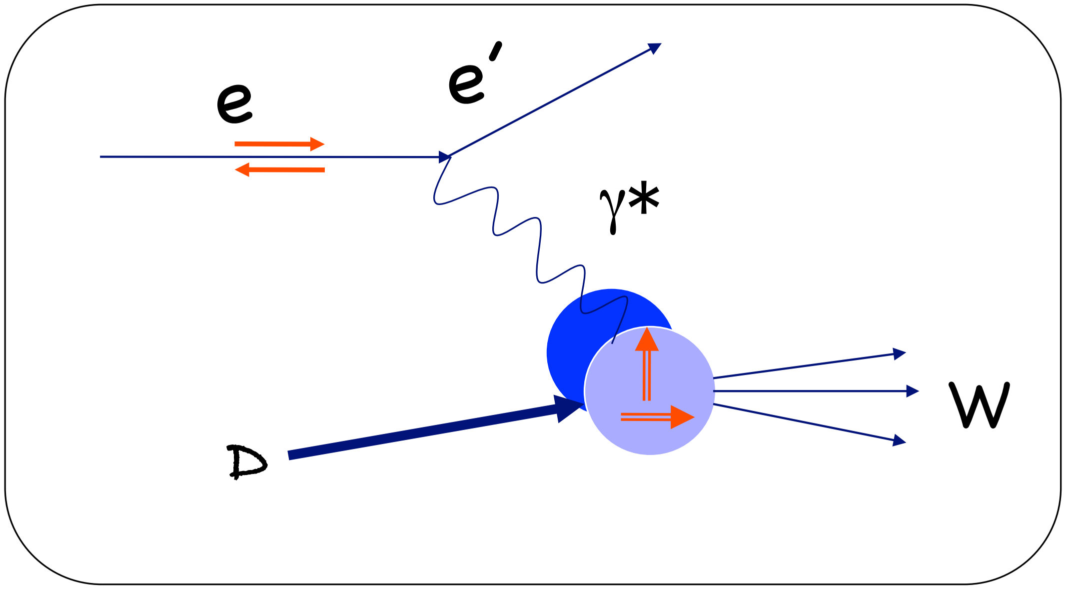
Pure Vector Polarization

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)

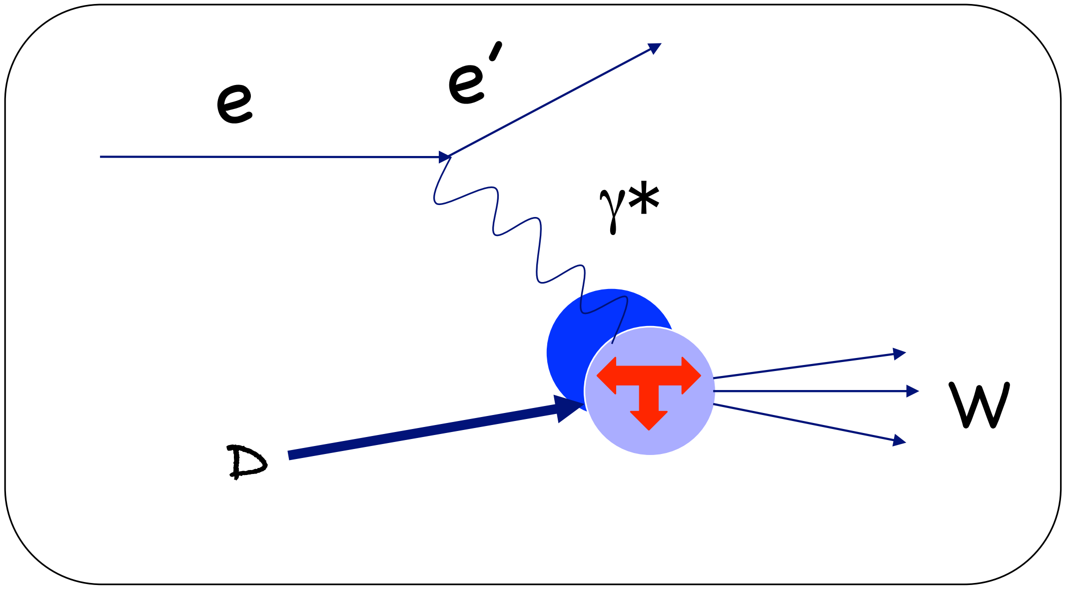
$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu}$$

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



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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

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	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^{1/2} - q_\downarrow^{-1/2}]$	$\frac{1}{2}\sum_q e_q^2[q_\uparrow^1 - q_\downarrow]$
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

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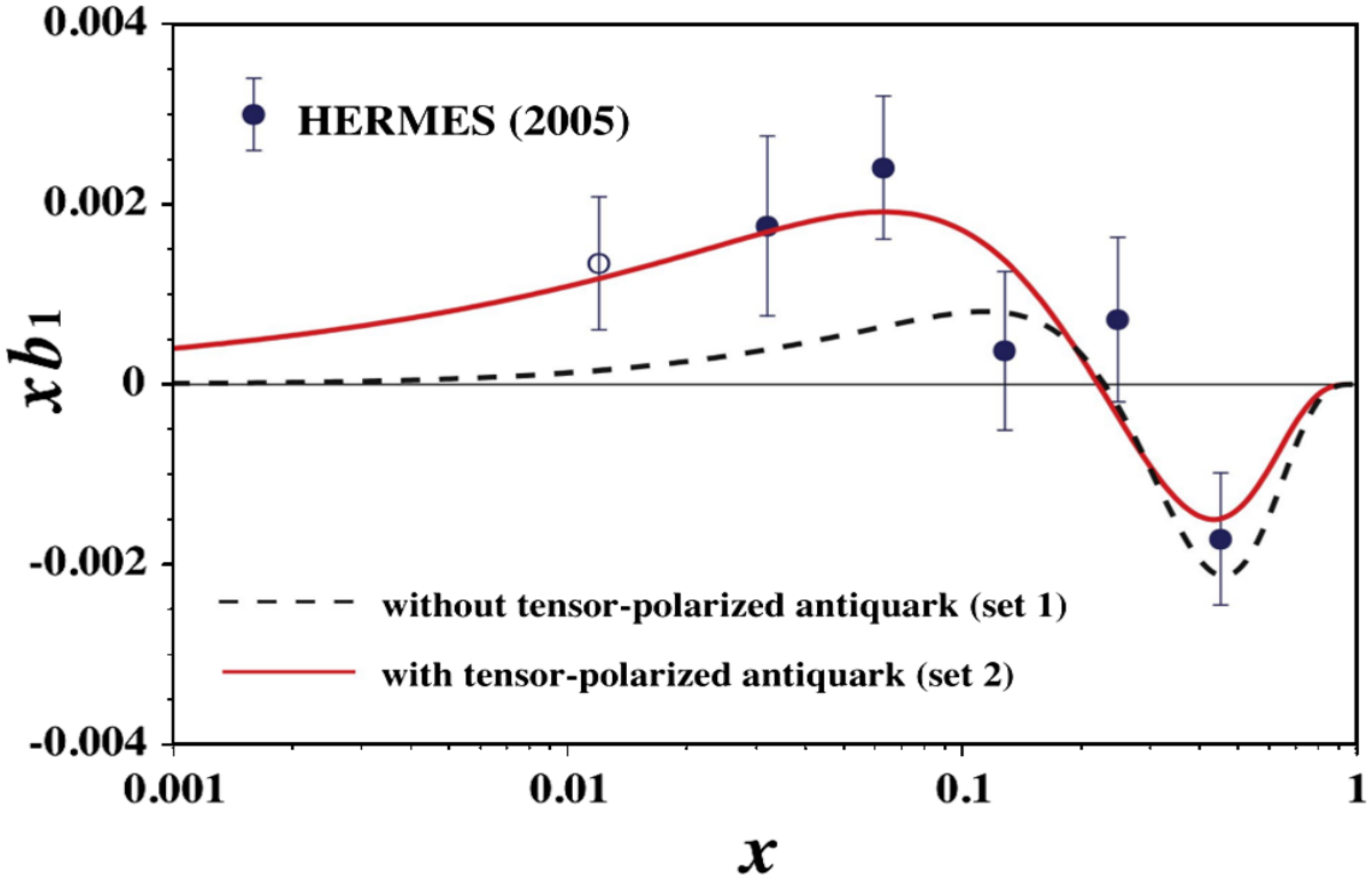
$$q^0(x) = q^0_\uparrow(x) + q^0_\downarrow(x)$$

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

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

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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