Spin Structure at Low Q^2
with Applications to Hyperfine Splitting

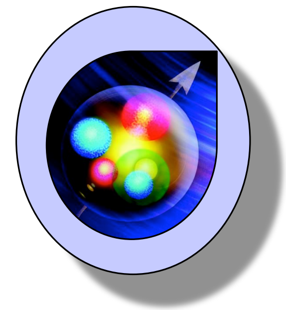
Spin 2018
23rd International
Spin Symposium

Ferrara Italy
2018-09-12

Karl Slifer
University of New Hampshire

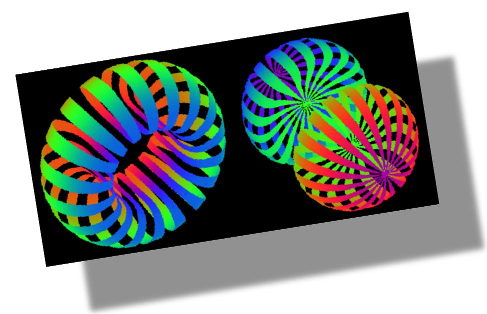
This Talk

Inclusive double polarized electron scattering



Physics Motivation

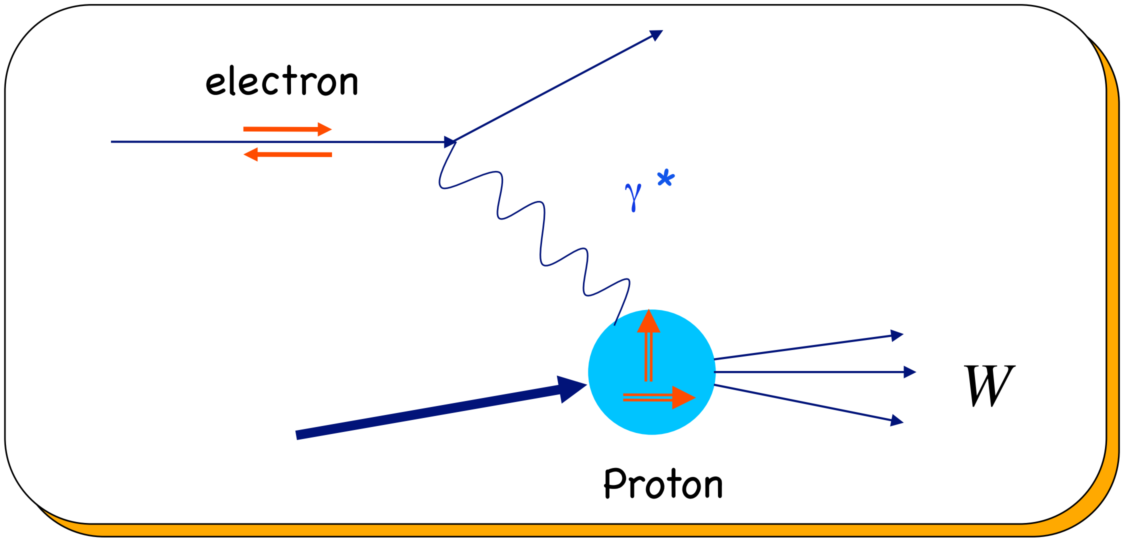
- Inclusive Scattering
- Structure Functions
- Results from the g2p & sagdh Experiments
  - Spin Polarizabilities & Moments.
  - Hyperfine Contributions



Tensor 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



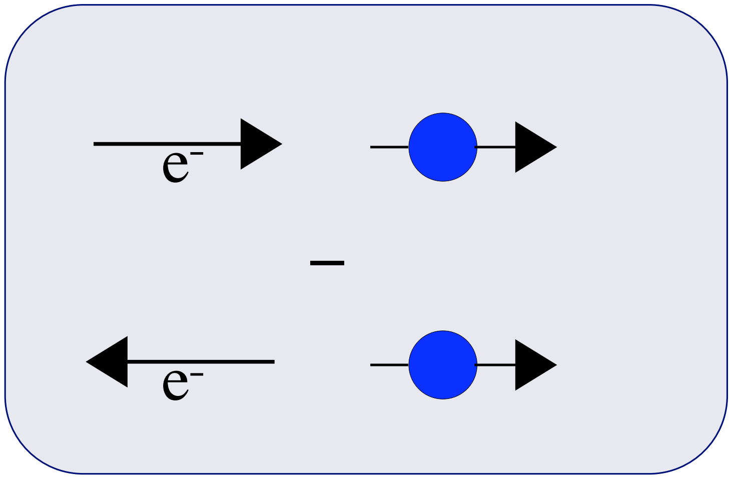
When we add spin degrees of freedom to the target and beam, 2 Additonal SF needed.

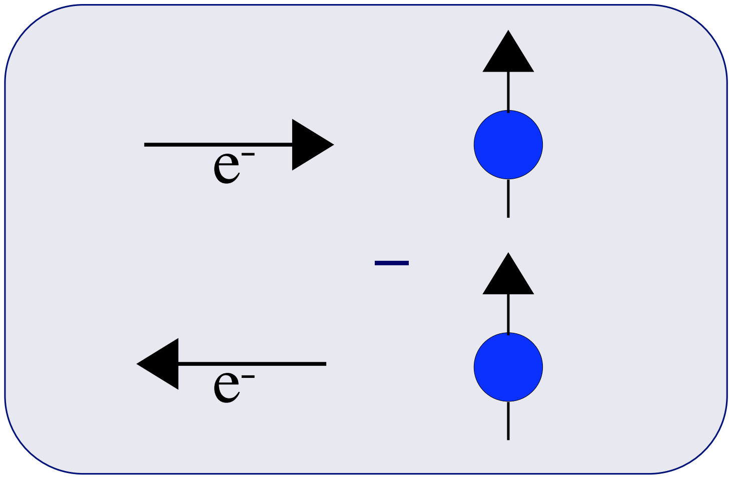
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

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

Inclusive **Polarized** Cross Section

Cross Section Differences



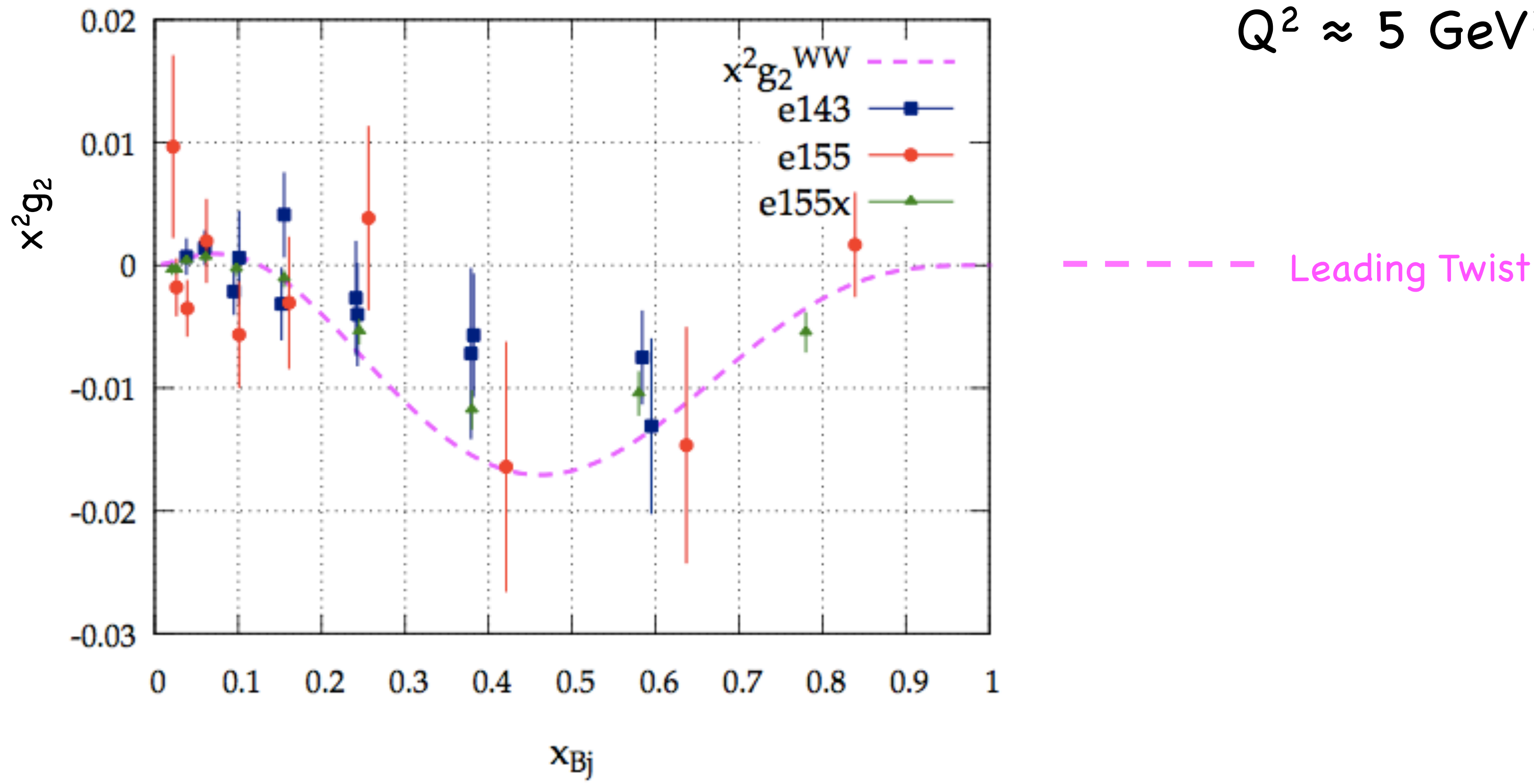


$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2}{\nu Q^2}\frac{E'}{E}\left[(E + E'\cos\theta)\,g_1 - 2Mx g_2\right]$$

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

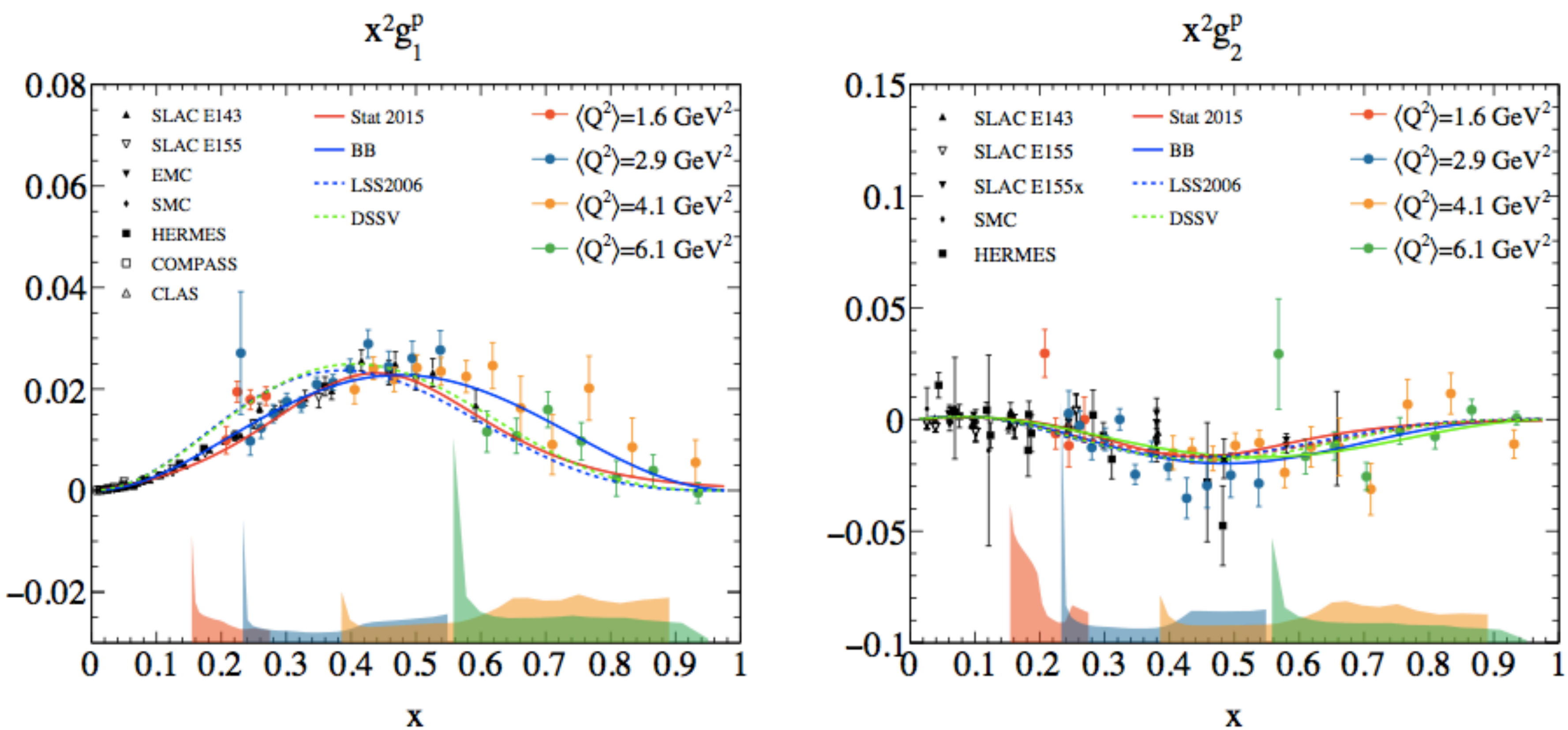
Proton g_2 data from SLAC

$Q^2 \approx 5\ GeV^2$



Precision does not allow unambiguous HT extraction

SANE Proton g_1 and g_2 ($Q^2 \approx$ 2-6 GeV^2)



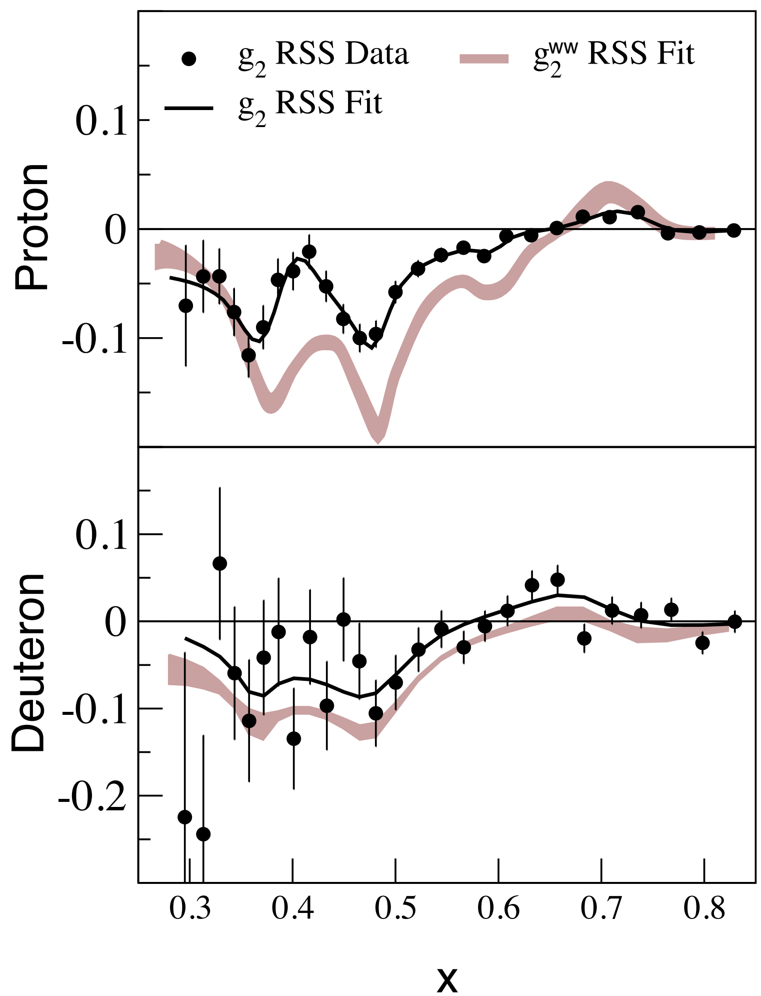
Models are showing g_2^{WW}.

W. Armstrong et al. arXiv:1805.08835

Submitted to PRL

RSS Experiment

Q^2 = 1.3 GeV^2



$$\overline{\Delta}\Gamma_2 = -0.0006 \pm 0.0021$$ (proton)

consistent with zero

=> low x HT are small in proton.

$$\overline{\Delta}\Gamma_2 = -0.0092 \pm 0.0035$$ (neutron)

non-zero by 2.6σ

=>Significant HT at low x needed to satisfy Neutron BC sum rule.

K.Slifer., O. Rondon *et al.*
PRL 105, 101601 (2010)

SSF Moments

Generalized GDH Sum

$$\varGamma_1(Q^2) = \int_0^{x_0} \mathrm{d}x\, g_1(x, Q^2)$$

Burkhardt Cottingham

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

Generalized Forward Spin polarizabilities

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

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

Spin Structure Experiments at Low Q^2

Jefferson Lab Hall A

g2p

NH_3 Target (proton)
$0.02 < Q^2 < 0.4$
W< 1.8 GeV
θ = 6 deg

sagdh

3He Target (neutron)
$0.02 < Q^2 < 0.4$
W< 2.5 GeV
θ = 6,9 deg

E08-027 : The Proton g2p Experiment

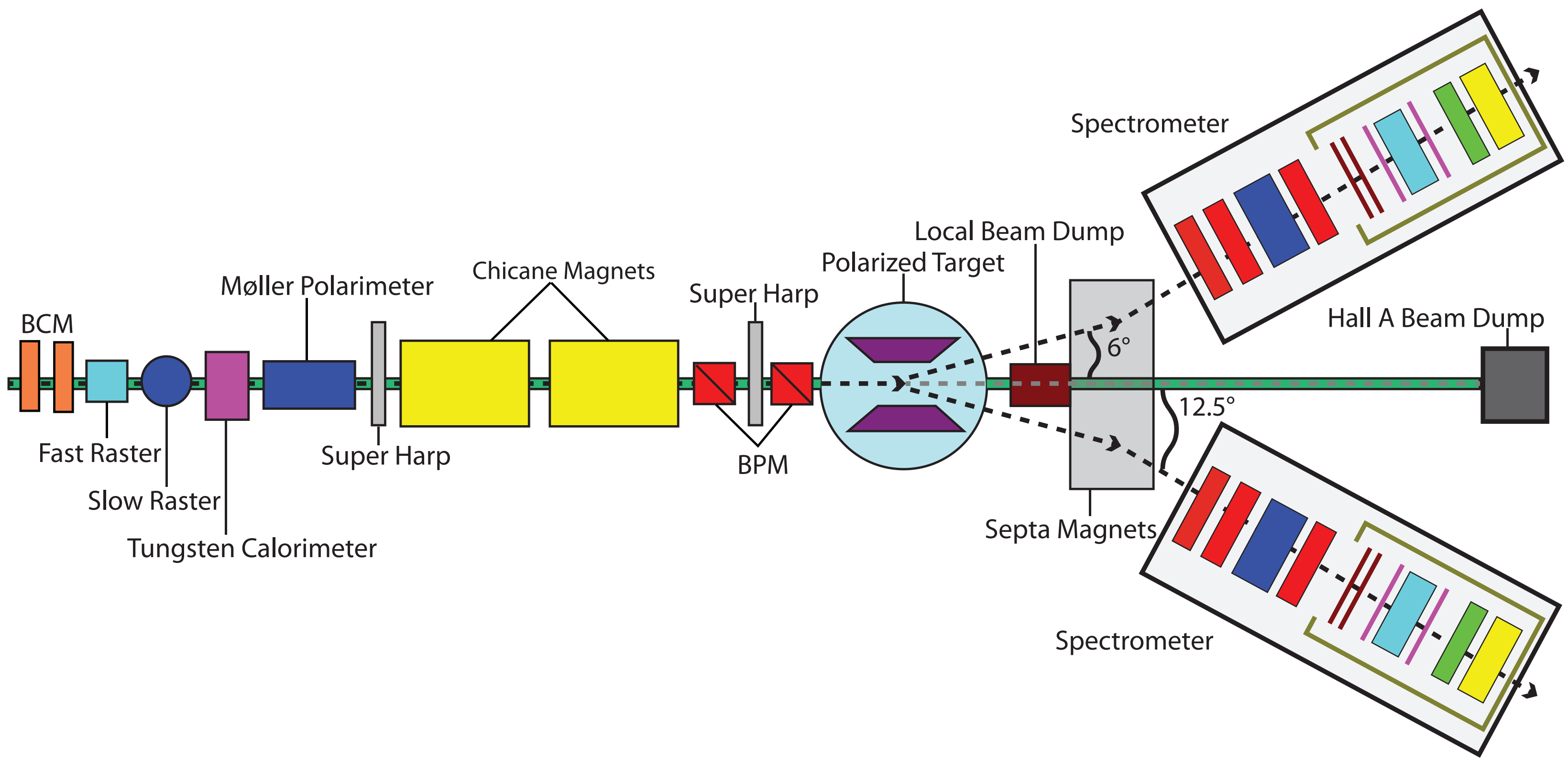
A.Camsonne, D. Crabb,

J. P. Chen, K. 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



Largest Installation in Hall A History

Polarized proton target

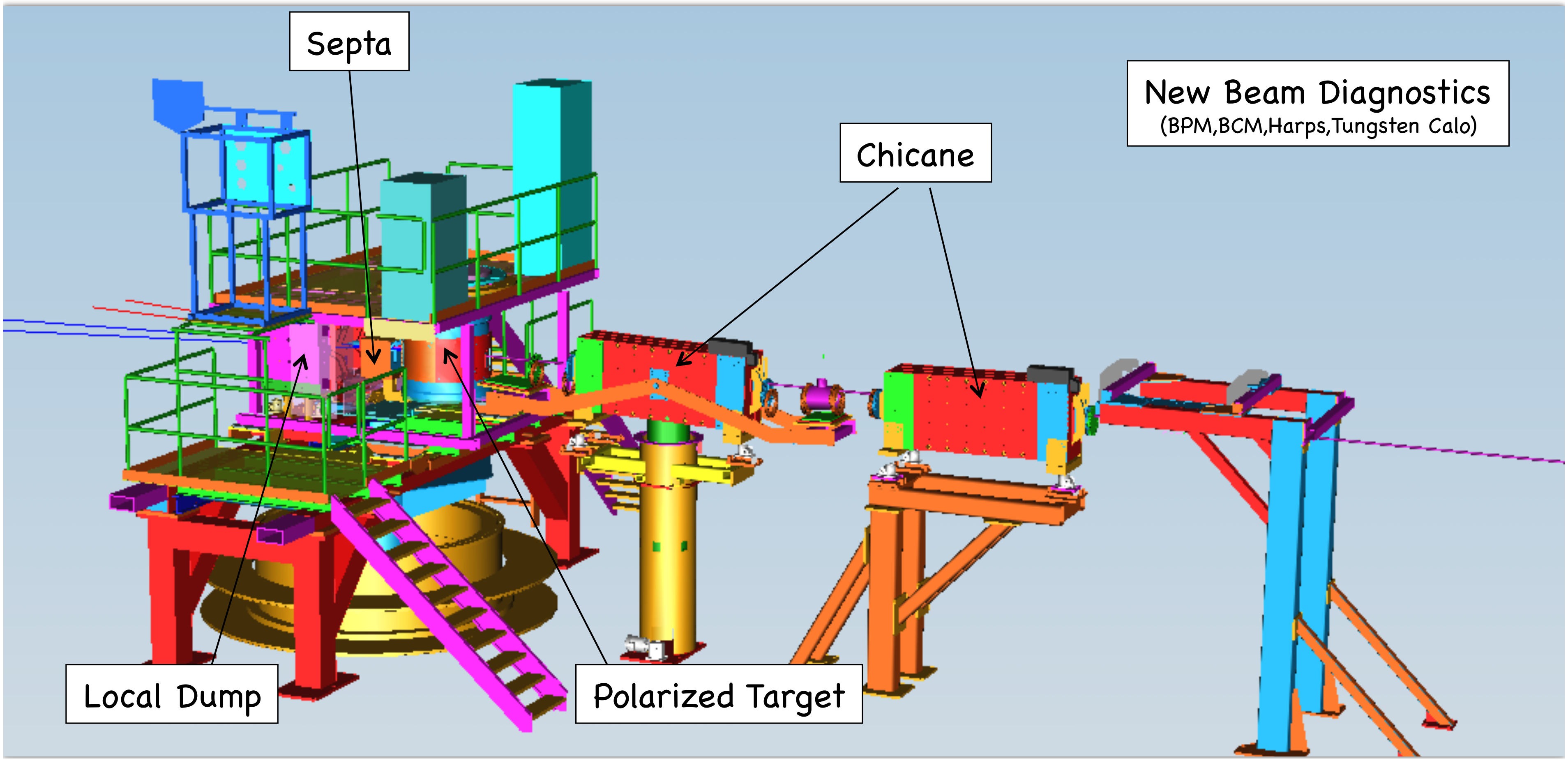
- upstream chicane
- downstream local dump

Low current polarized beam

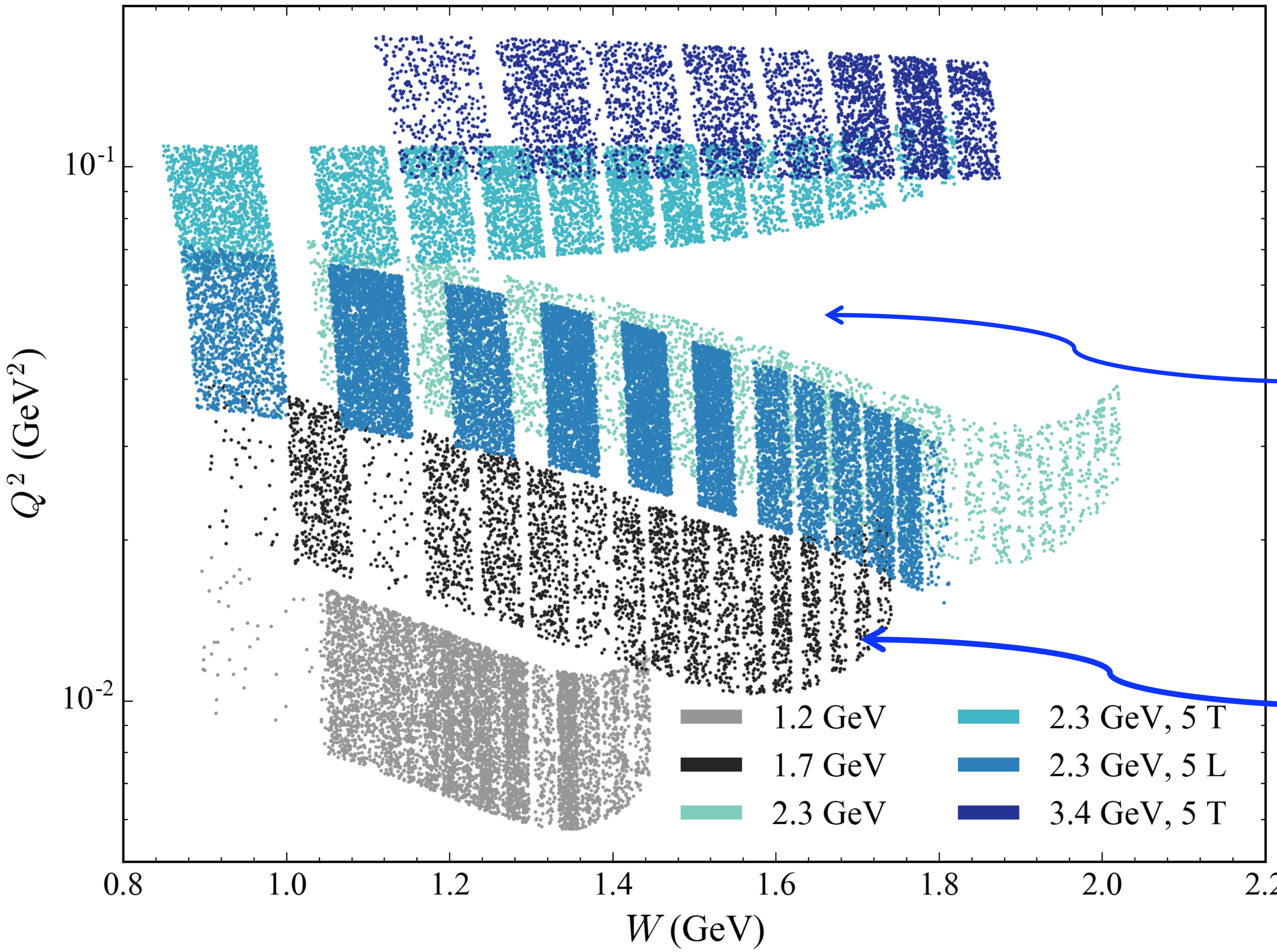
- Upgrades to existing Beam Diagnostics to work at 85 nA

Lowest possible Q^2 in the resonance region

- Septa Magnets to detect forward scattering



E08-027 : Proton g_2 Structure Function



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

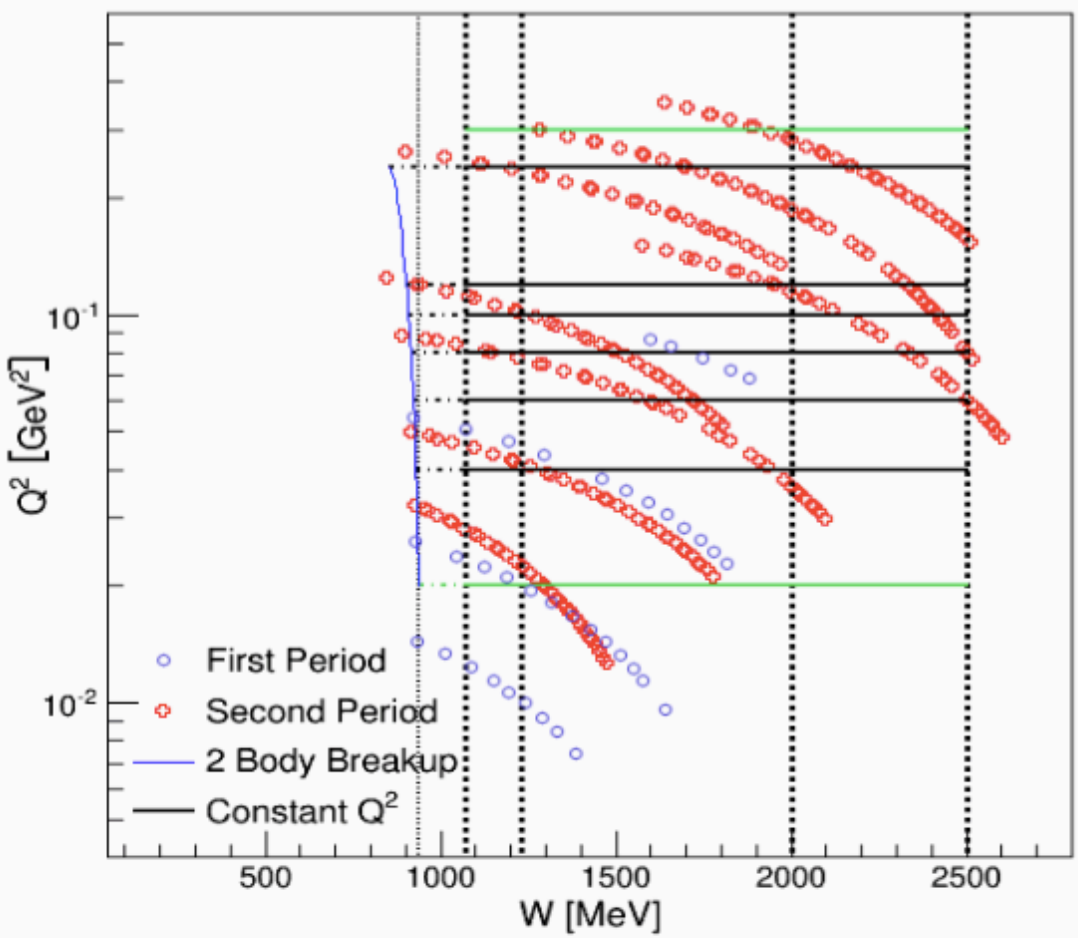
2.5T: Low Q^2 data
preliminary
finalizing
Packing Fraction

courtesy R. Zielinski

sagdh experiment

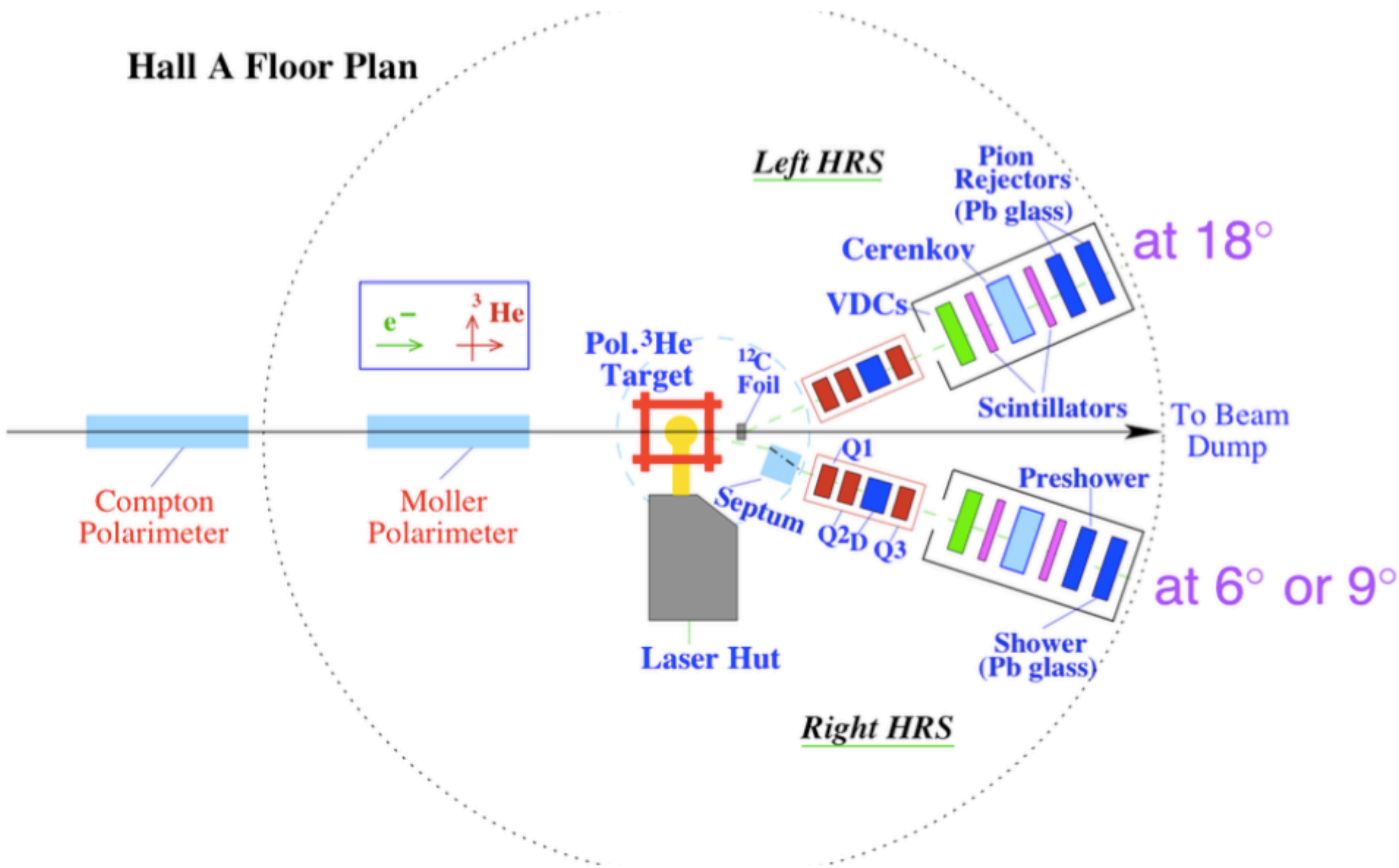
Spokesmen: J.-P. Chen, A. Deur, F. Garibaldi

PhD Students: V. Solkosky, J. Singh, J. Yuan, C. Peng, N. Ton

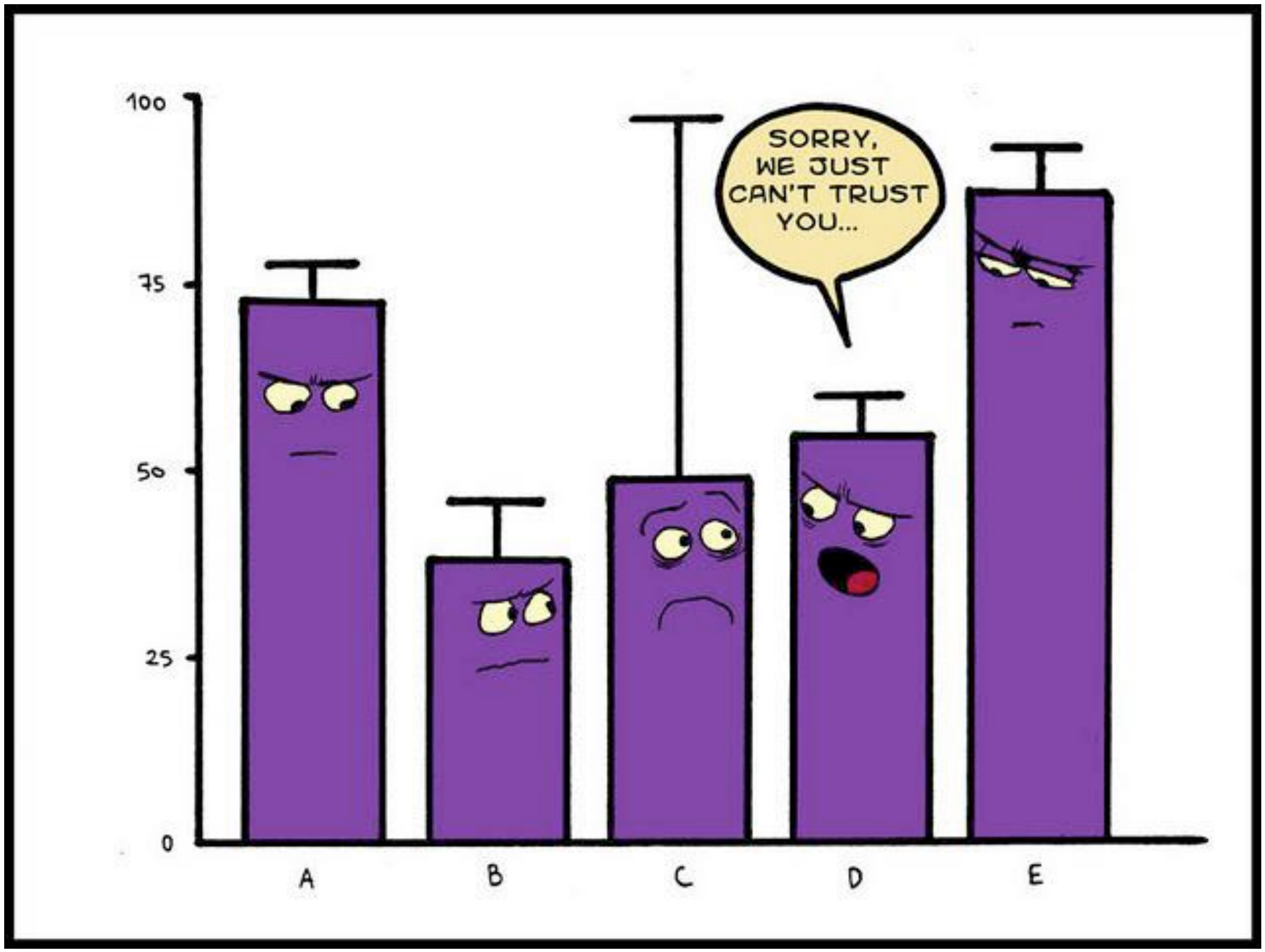


Target Cell	Angle	Beam Energy (MeV)
Penelope	6.10°	2134.2
Priapus	6.10°	2134.9
Priapus	6.10°	2844.8
Priapus	6.10°	4208.8
Priapus	9.03°	1147.3
Priapus	9.03°	2233.9
Priapus	9.03°	3318.8
Priapus	9.03°	3775.4
Priapus	9.03°	4404.2

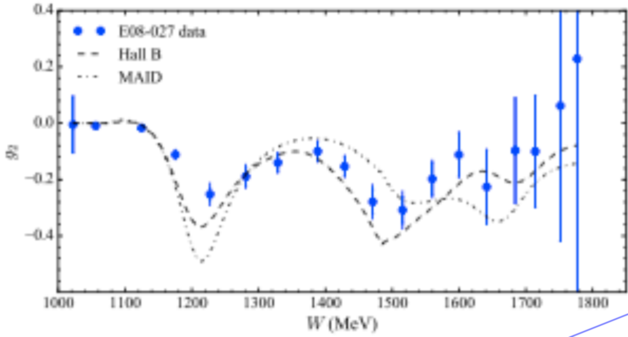
sagdh Floor Plan



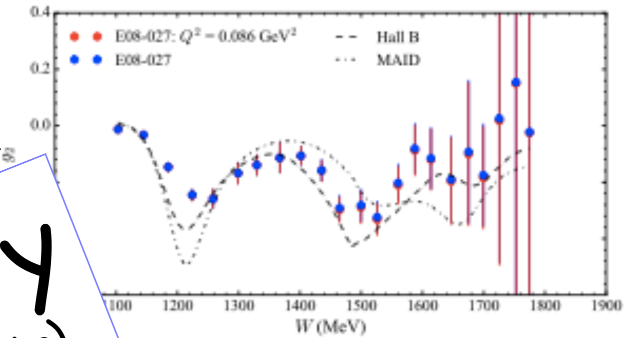
data



E08-027 Structure Functions (5T data)



(a) E_0 = 2254 MeV 5T Transverse

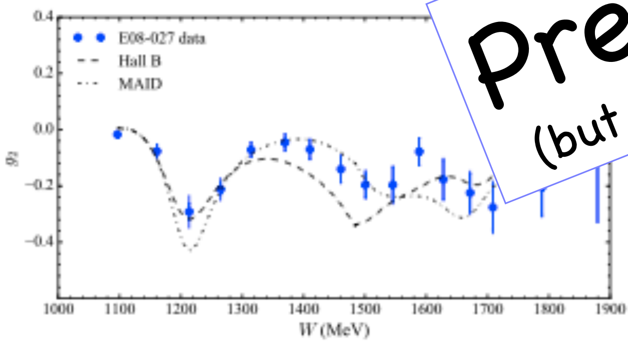


(a) E_0 = 2254 MeV 5T Transverse

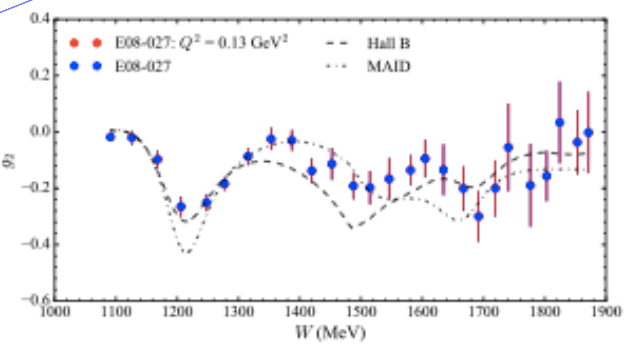
Q^2= 0.08 GeV^2

Preliminary

(but analysis complete)

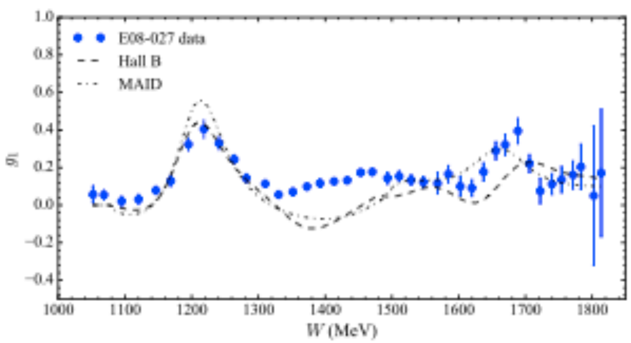


(b) E_0 = 3350 MeV 5T Transverse

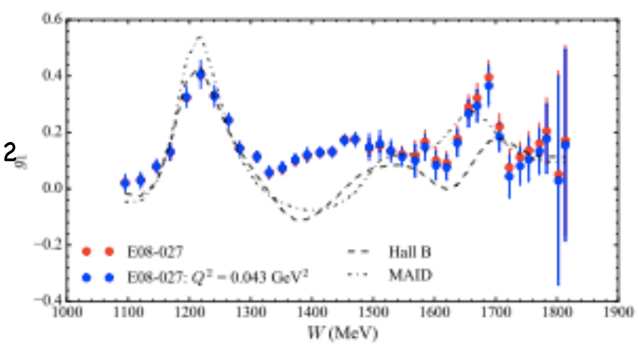


(b) E_0 = 3350 MeV 5T Transverse

Q^2= 0.13 GeV^2



(c) E_0 = 2254 MeV 5T Longitudinal



(c) E_0 = 2254 M

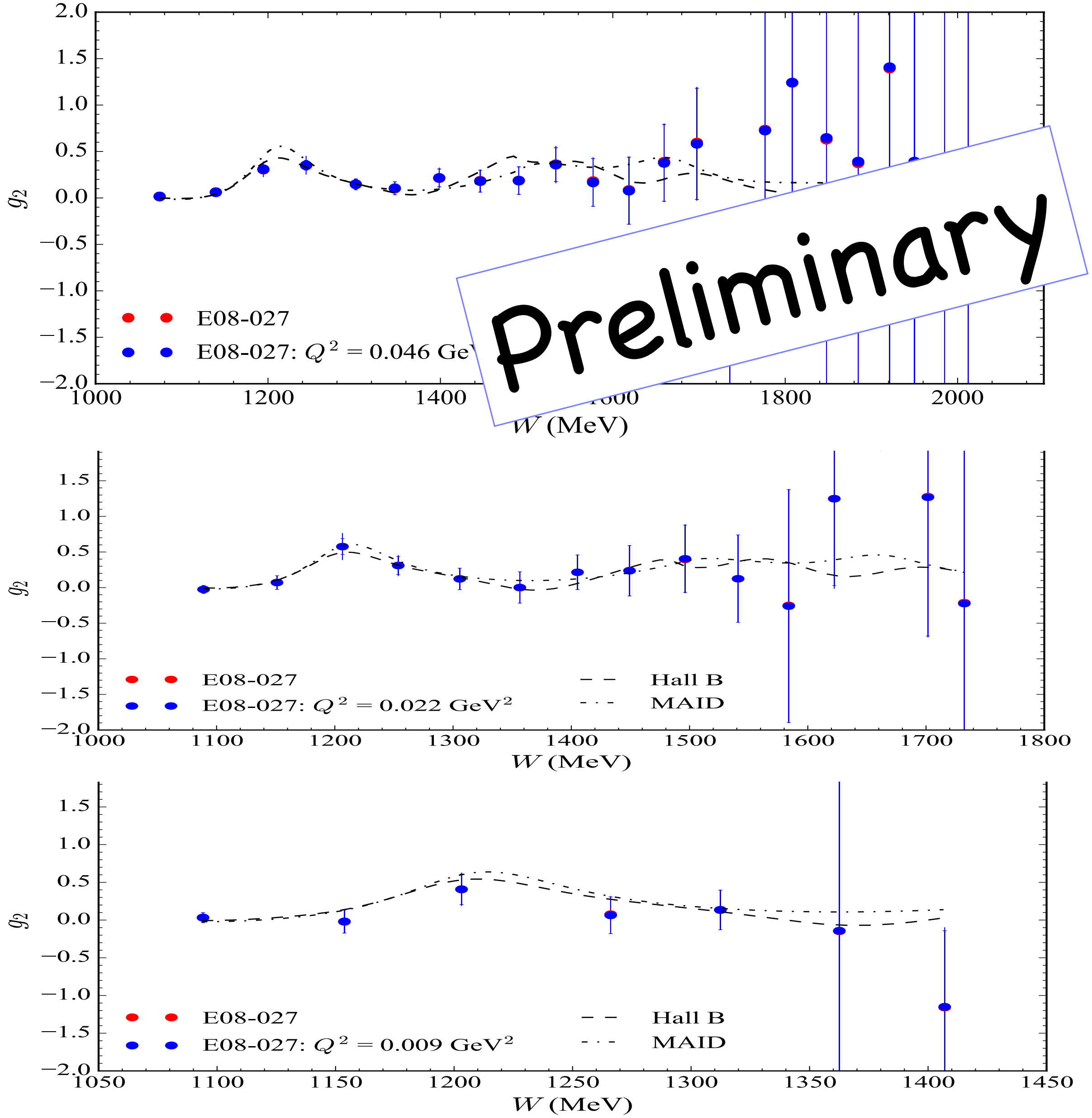
Q^2= 0.04 GeV^2

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

Figure 8-24: E08-027 spin structure functi

courtesy R. Zielinski, UNH

g2p 2.5T data



Q^2= 0.05 GeV^2

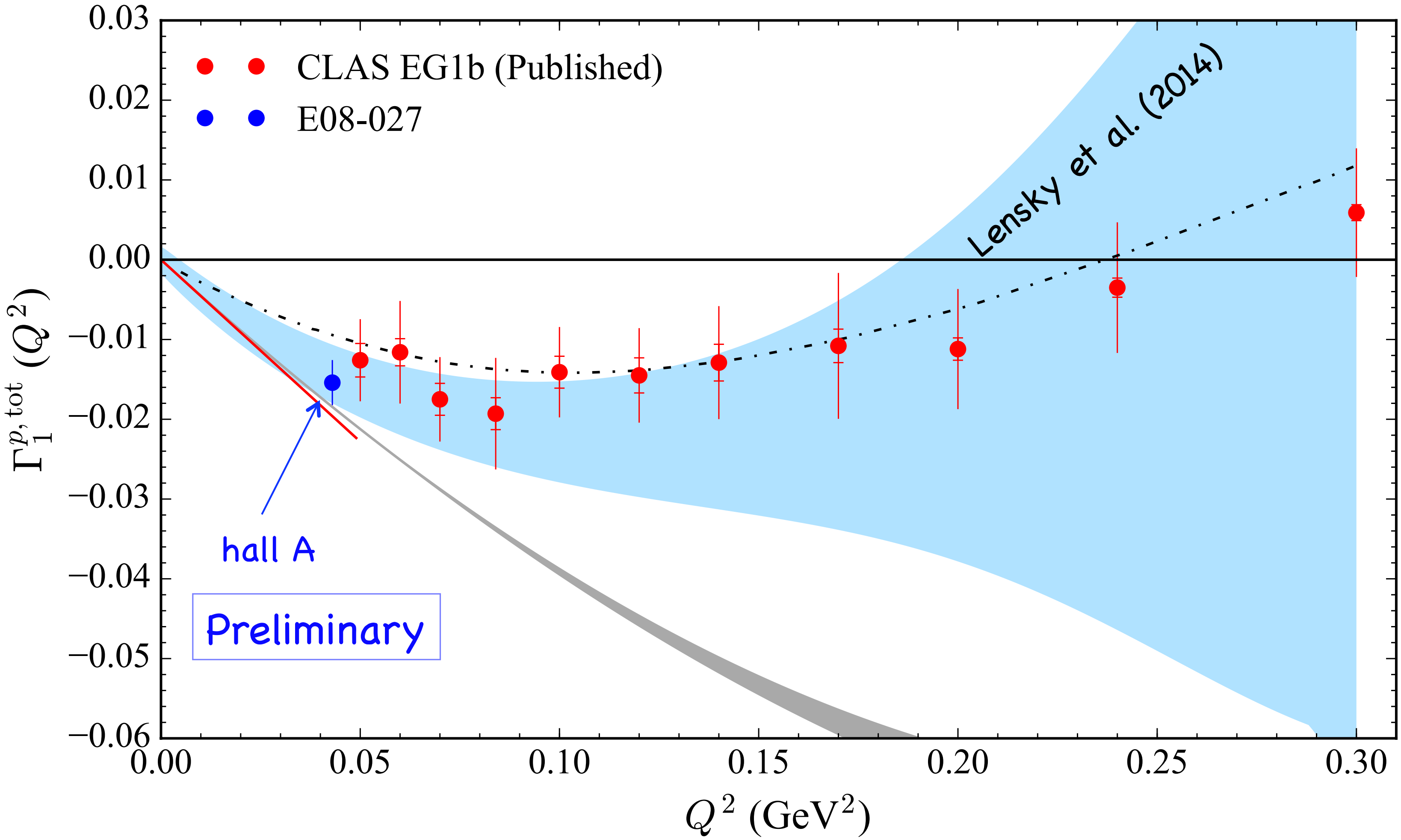
Q^2= 0.02 GeV^2

Q^2= 0.01 GeV^2

Finalizing df/pf

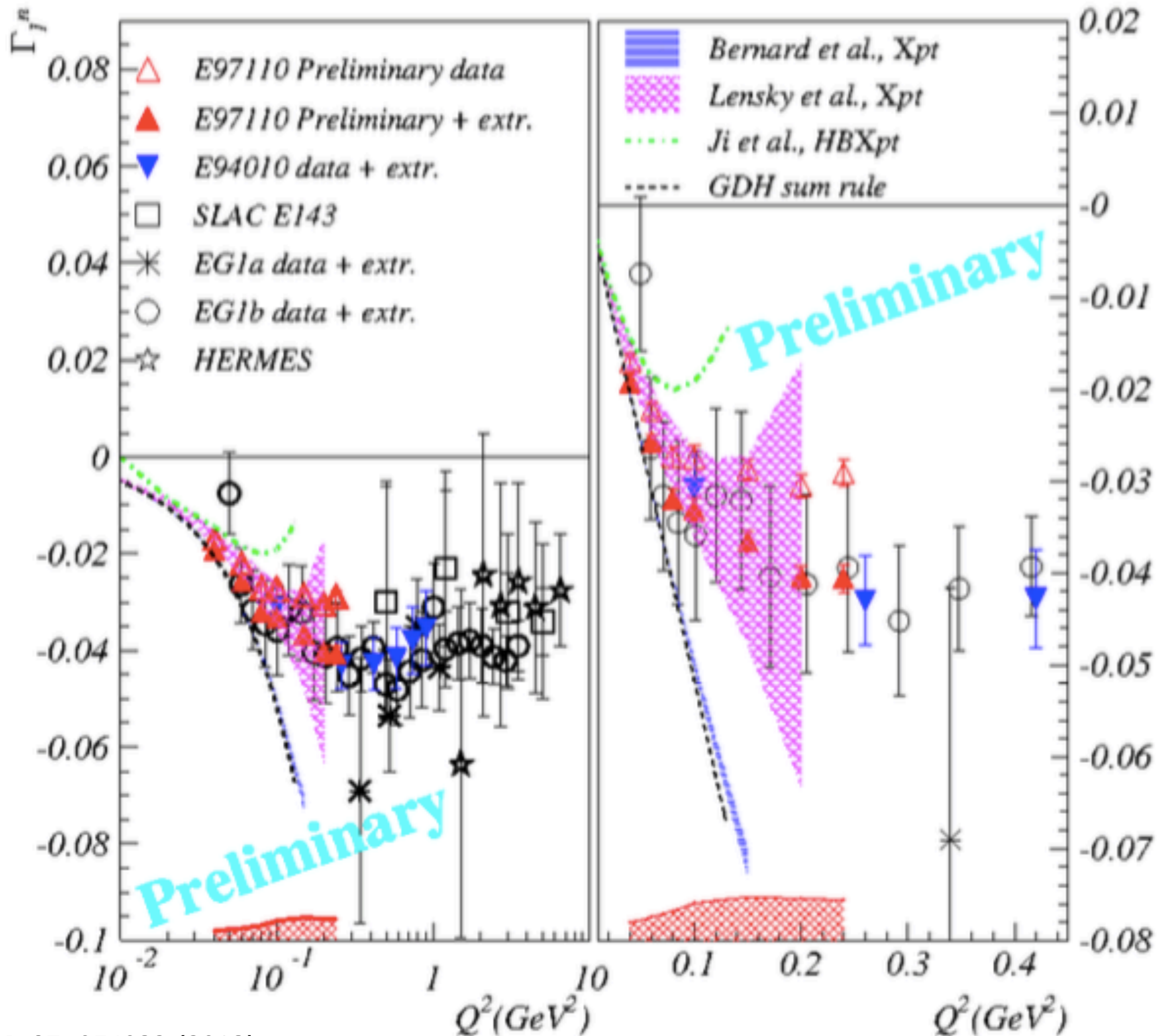
courtesy R. Zielinski, UNH

E08-027 Proton 1st Moment



courtesy R. Zielinski, UNH

Neutron Γ_1 (saGHD)



BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202

BC Sum Rule

$$\int_0^1 g_2(x, Q^2)dx = 0$$

H.Burkhardt and W.N. Cottingham
Annals Phys. **56** (1970) 453.

Assumptions:

the virtual Compton scattering amplitude S_2 falls to zero faster than $1/x$

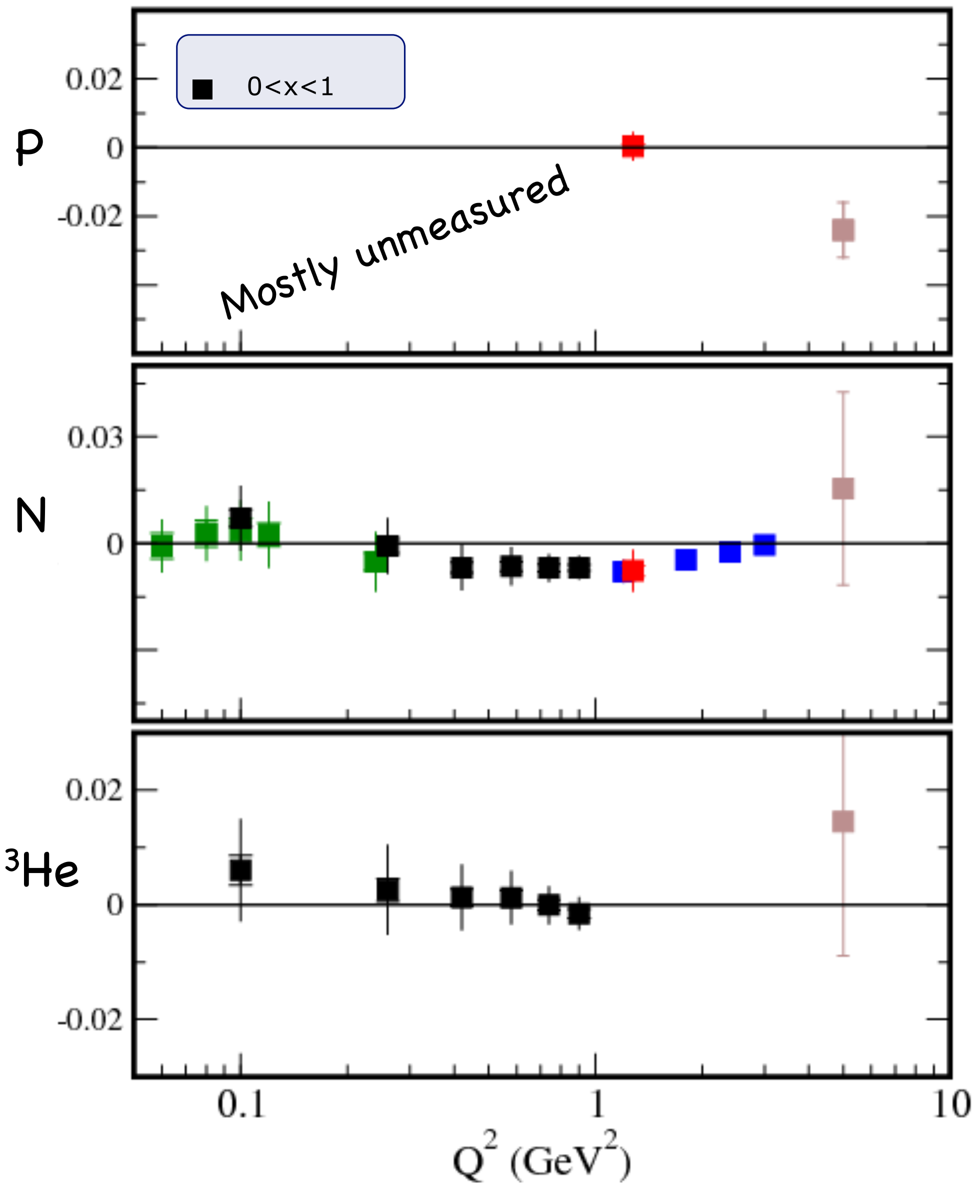
g_2 does not behave as $\delta(x)$ at $x=0$.

Discussion of possible causes of violations

R.L. Jaffe Comm. Nucl. Part. Phys. 19, 239 (1990)

"If it holds for one Q^2 it holds for all"

BC Sum Rule

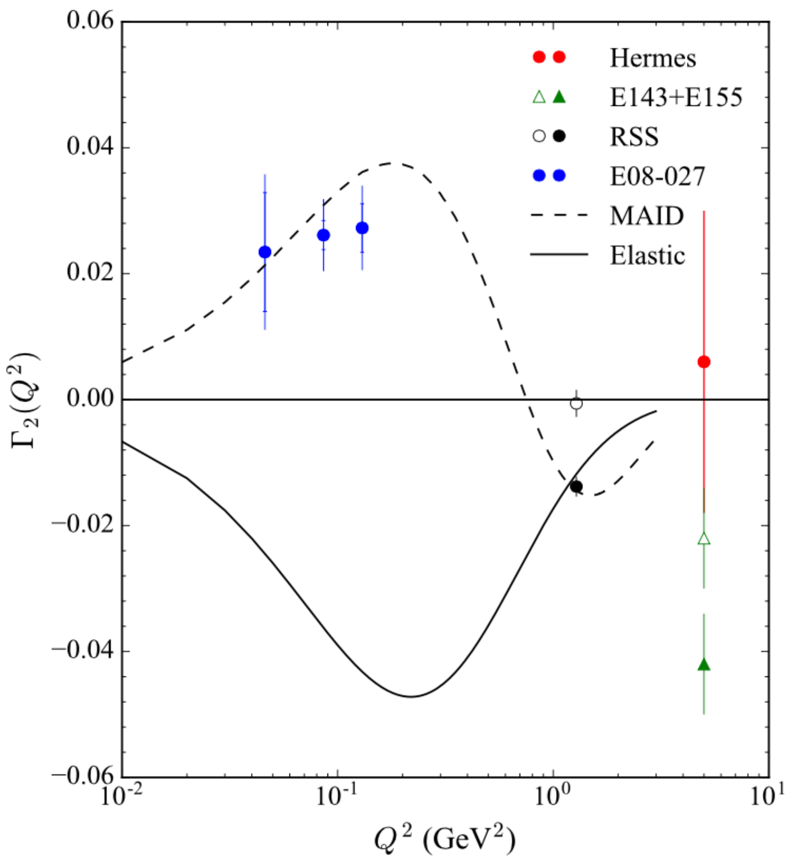


BC satisfied w/in errors for JLab Proton
2.8σ violation seen in SLAC data

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

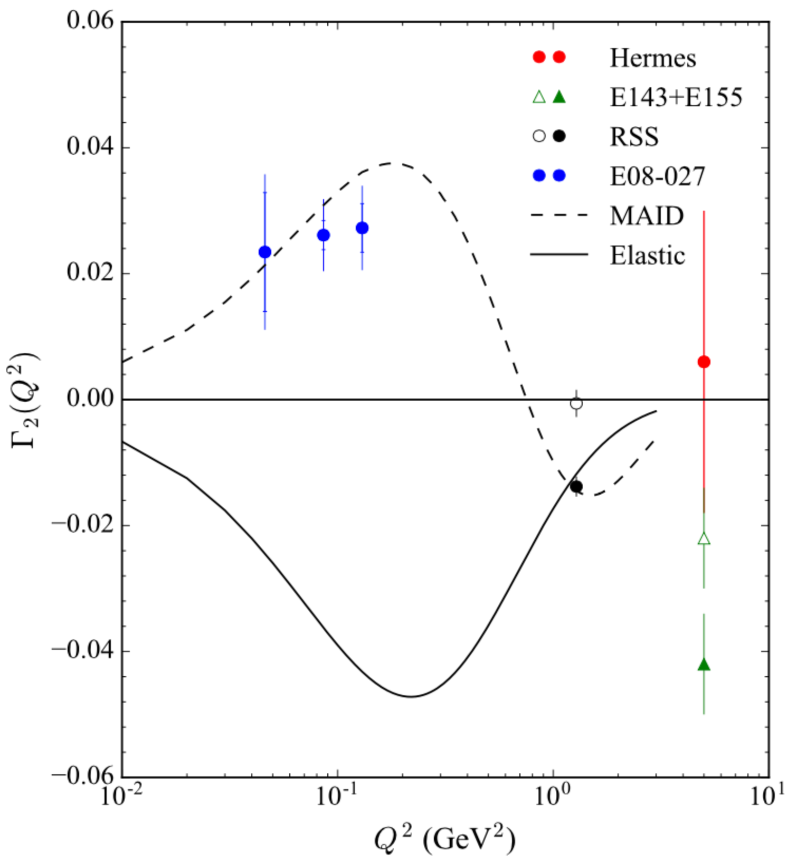
← Nuclear Sum Rule

E08-027 Proton BC Integral



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

E08-027 Proton BC Integral



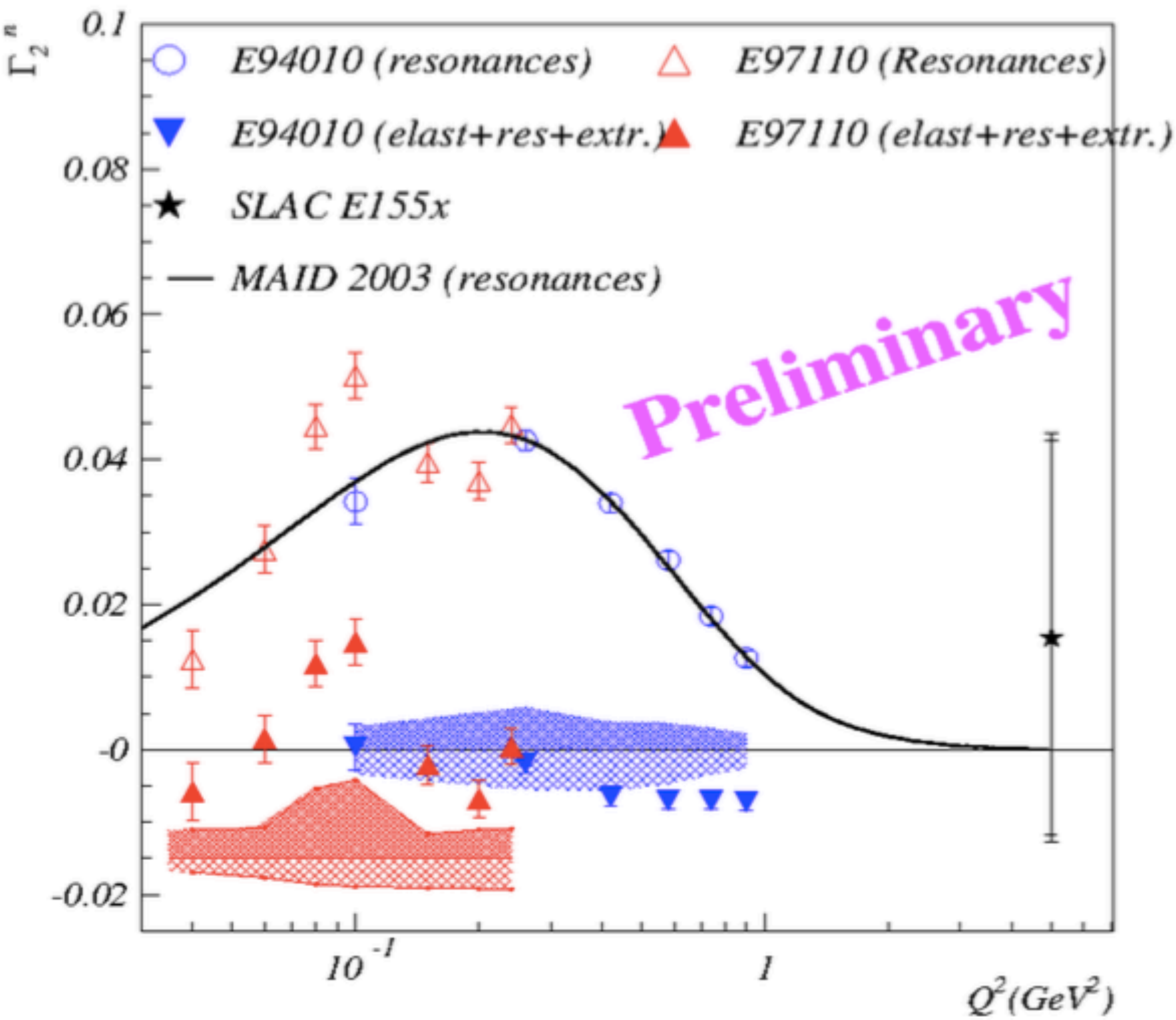
Source	x Integral ($0 < x < x_{\text{meas}}$)	% contribution relative to measured region
CLAS	-0.003	12%
AAC PPDF	0.013	52%
GRSV PPDF	0.012	48%
Required	0.015	60%

TABLE V. Typical low x contributions to the first moment of g_2 at the E08-027 kinematics.

Unmeasured low x contribution has large uncertainty at low Q^2.

=>Difficult to make strong statement on BC with current low x estimates

Neutron Γ_2 (saGHD)



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 : Treats the Baryon as a heavy static particle
Kao, Vanderhaeghen, et al

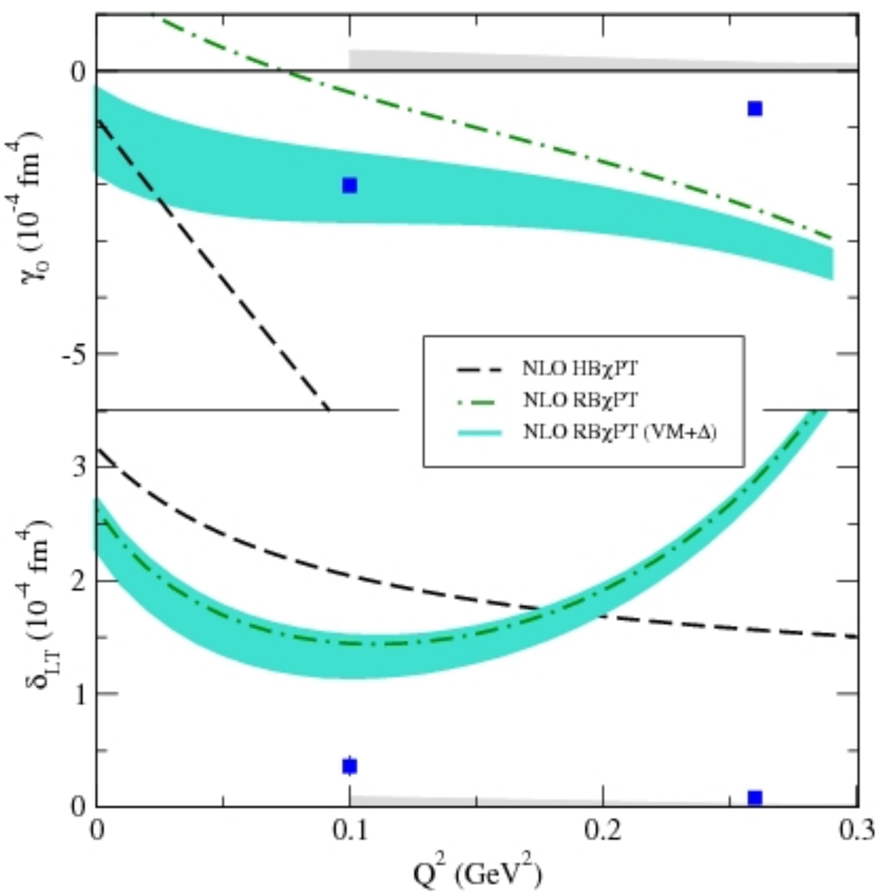
Relativistic Baryon : large momentum effects are absorbed in the low energy consts
Δ(1232) included explicitly. Other Resonances are included systematically through additional low energy constants

1: Meissner, Bernard, Krebs, Epelbaum
2: Lensky, Alarcon, Pascalutsa

δ_{LT} Puzzle

Neutron

PRL 93: 152301 (2004)



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

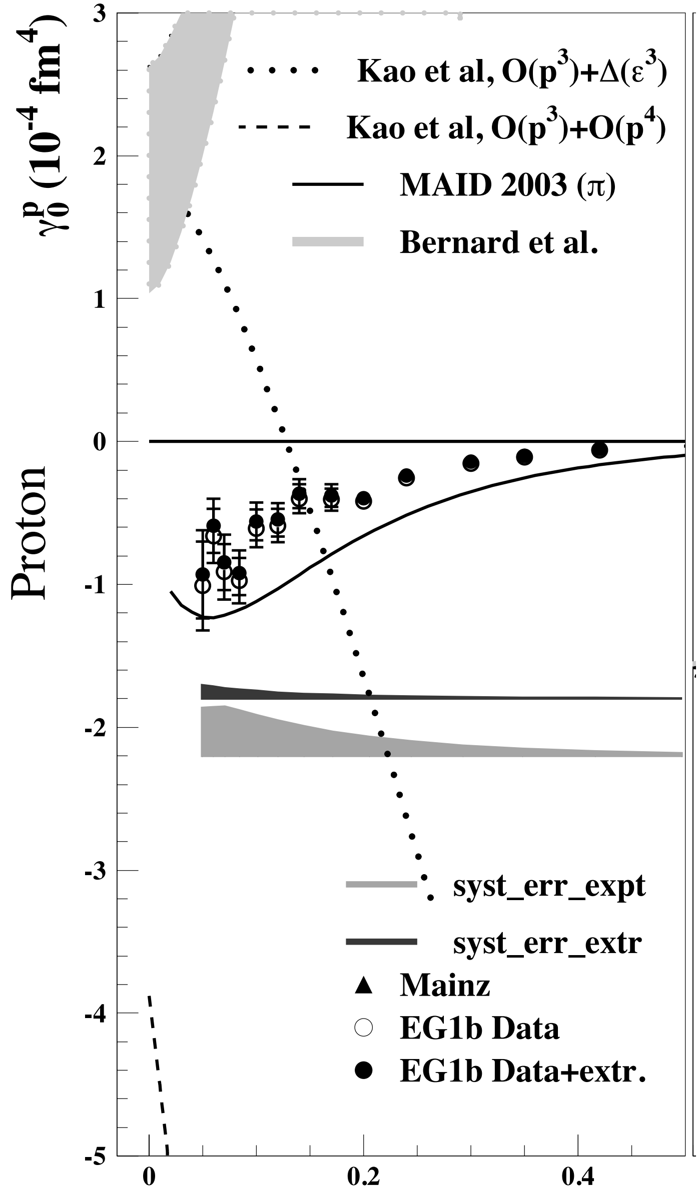
$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]$$

Dramatic Discrepency
with χPT

Heavy Baryon *Ch*PT Calculation
Kao, Spitzenberg, Vanderhaeghen
PRD 67:016001(2003)

Infrared Relativistic Baryon *Ch*PT
Bernard, Hemmert, Meissner
PRD 67:076008(2003)

Proton γ_0



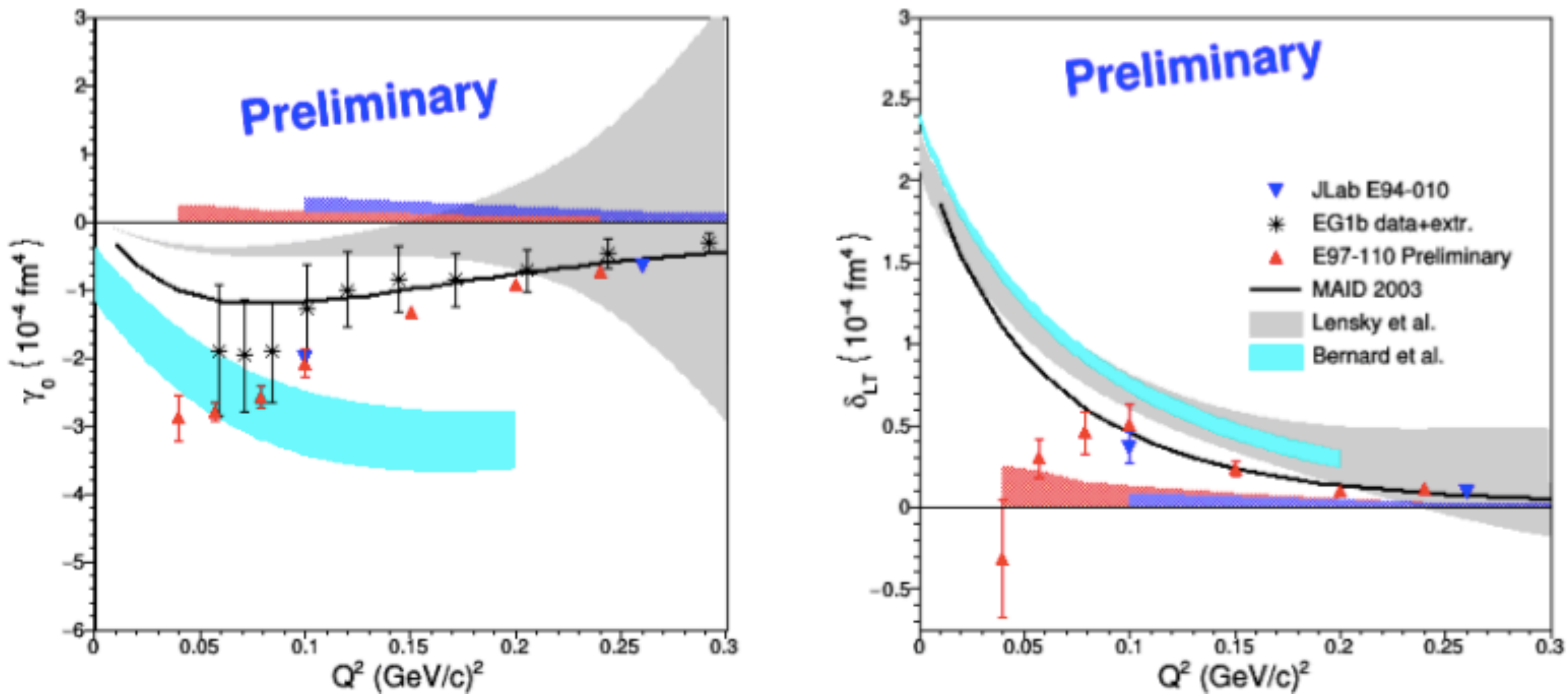
$$\gamma_0 = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right]$$

Older Calcs also failed for proton γ_0

PLB 672 12, 2009

published data goes down to about 0.06 GeV^2

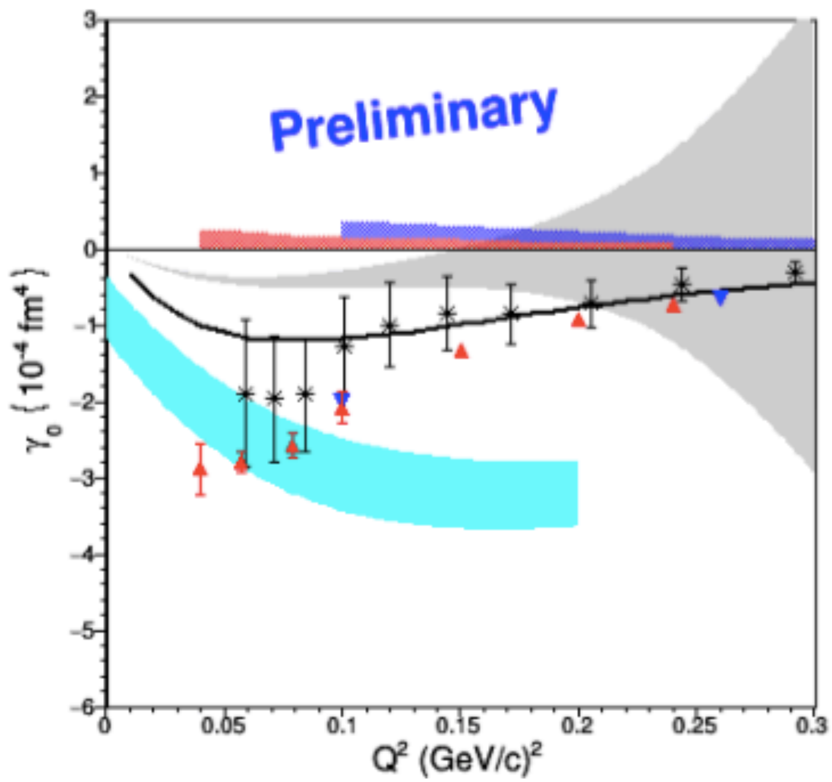
Neutron γ_0 and δ_{LT} (saGHD)

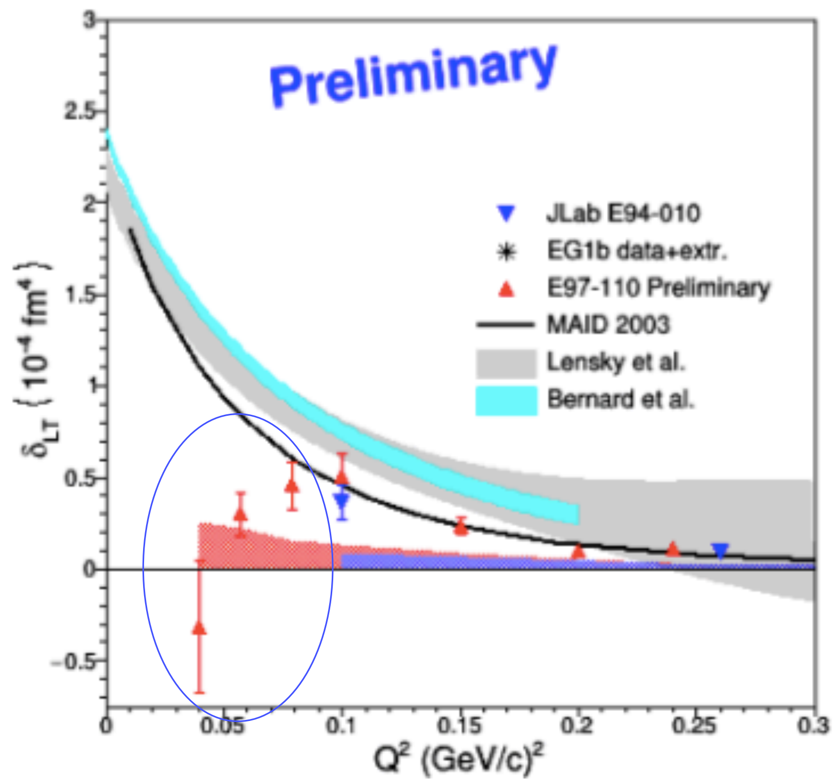


BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202

Neutron γ_0 and δ_{LT} (saGHD)



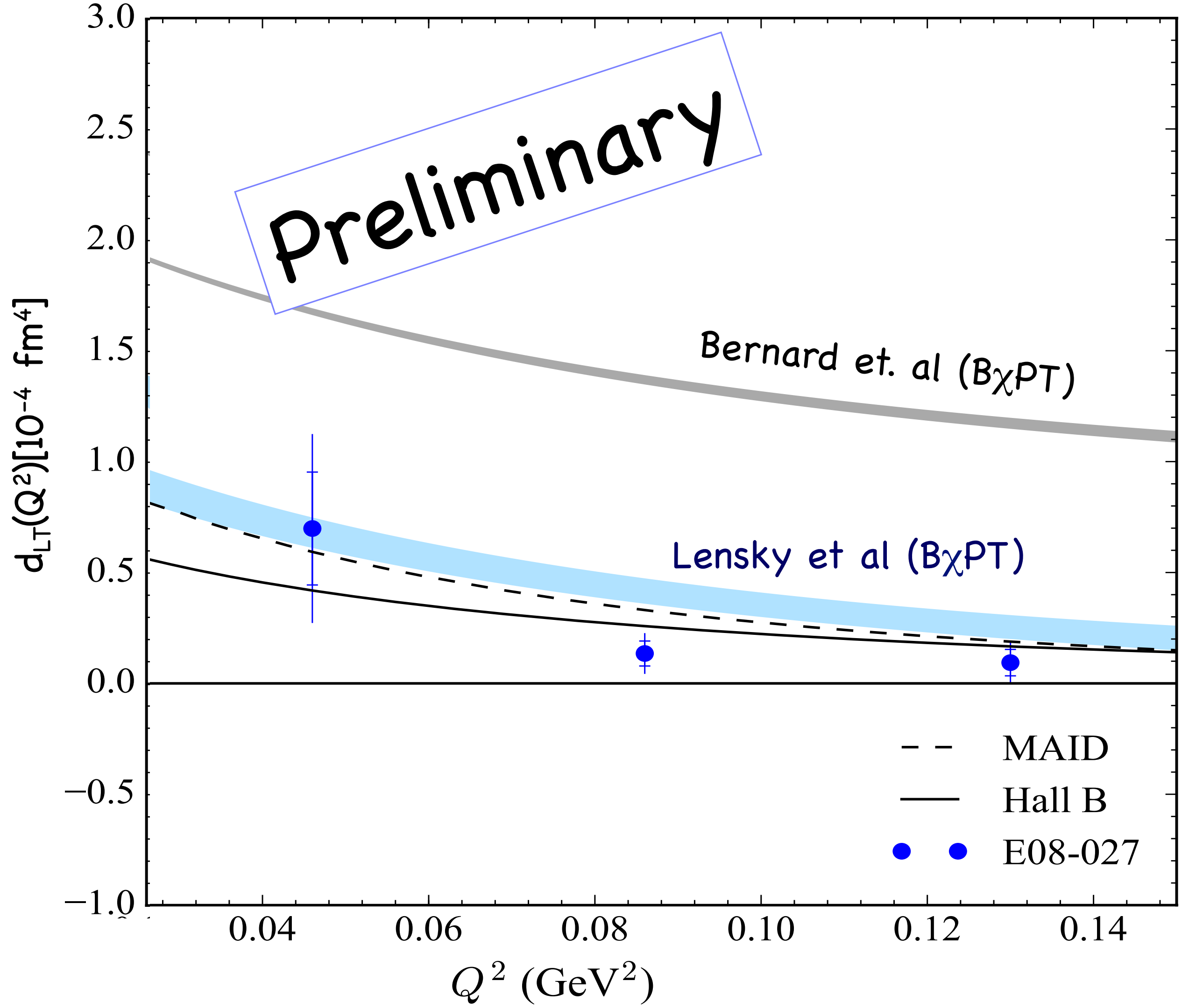


BERNARD et al. PRD 87, 054032 (2013)

Lensky et al. PRC 90(2014) 055202

Big disagreement with data

δ_{LT} Proton (E08-027)



χPT Comparison Summary

Γ_1 Pretty good agreement with χPT calculations

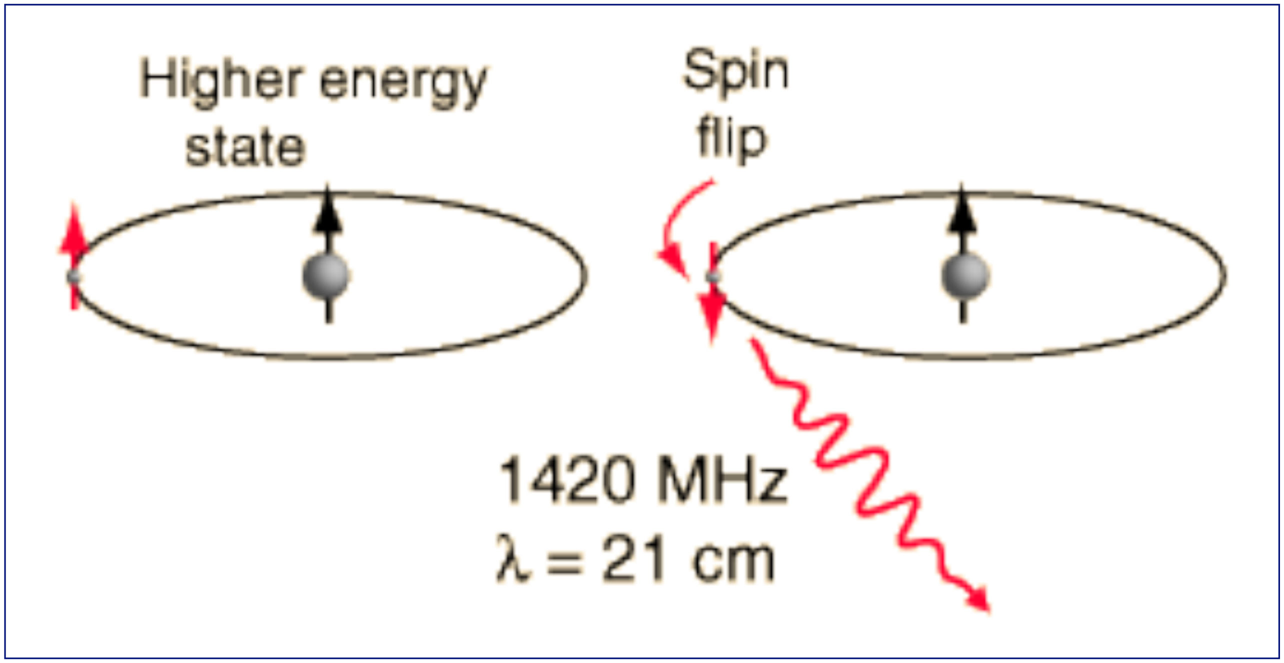
δ_{LT} Big disagreement for neutron for all calcs
Proton data favors BχPT (Lensky et al)

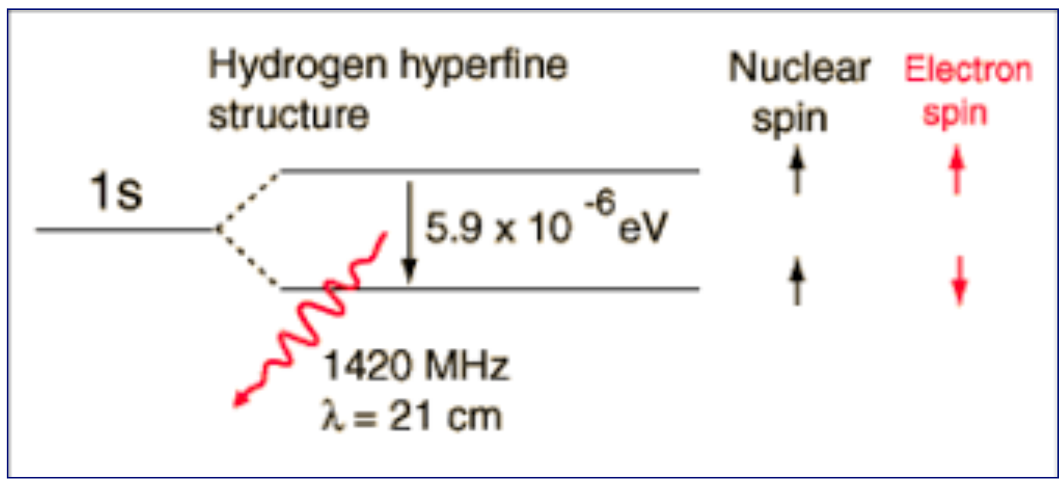
γ_0 Good agreement for proton for BχPT (Lensky et al)
Decent agreement for neutron for BχPT (Bernard et al)

Some tension remains between data and χPT
Some tension remains between χPT calculations

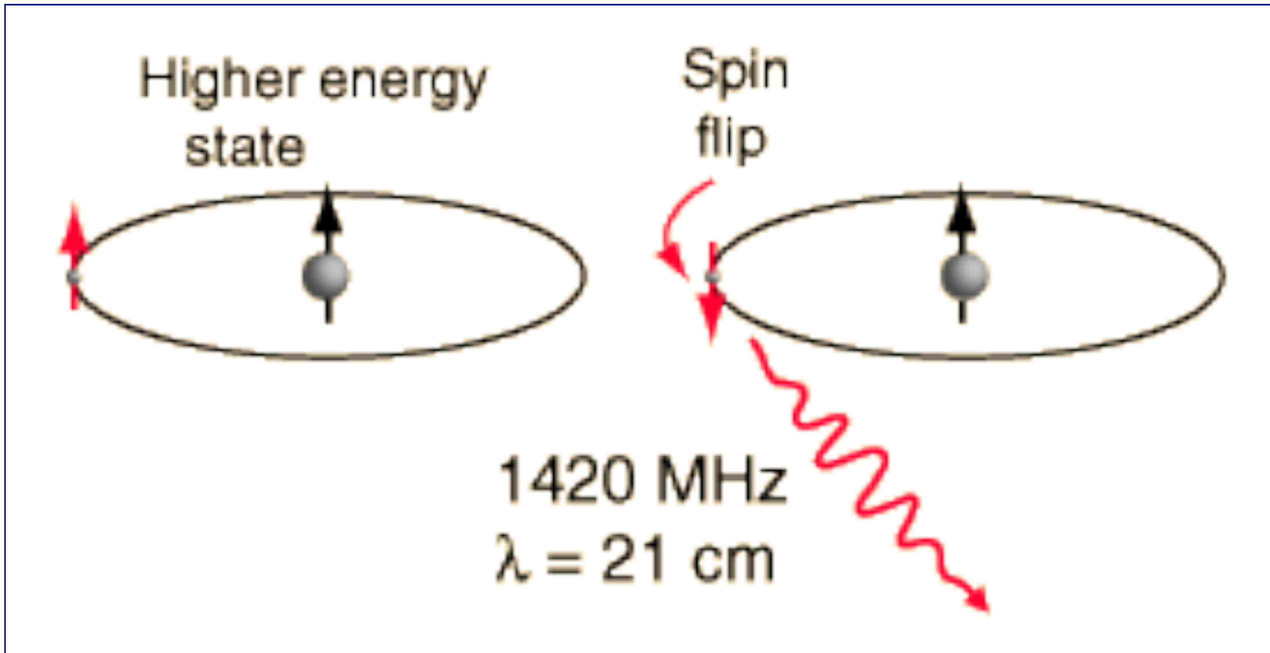
Hyperfine Splitting

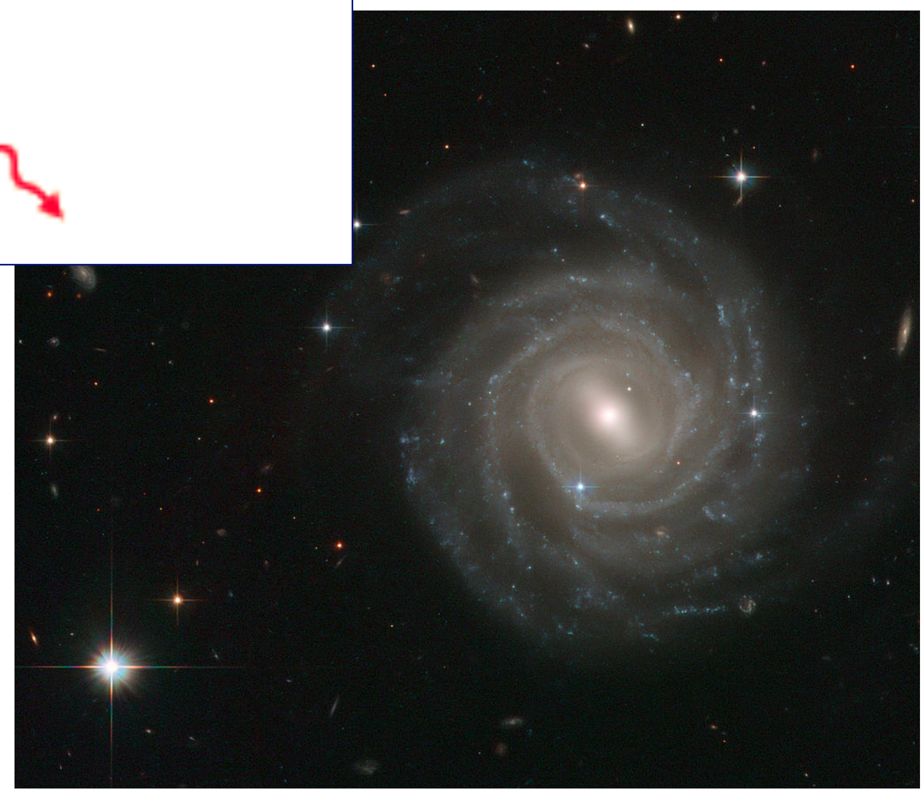
Hydrogen Hyperfine Splitting





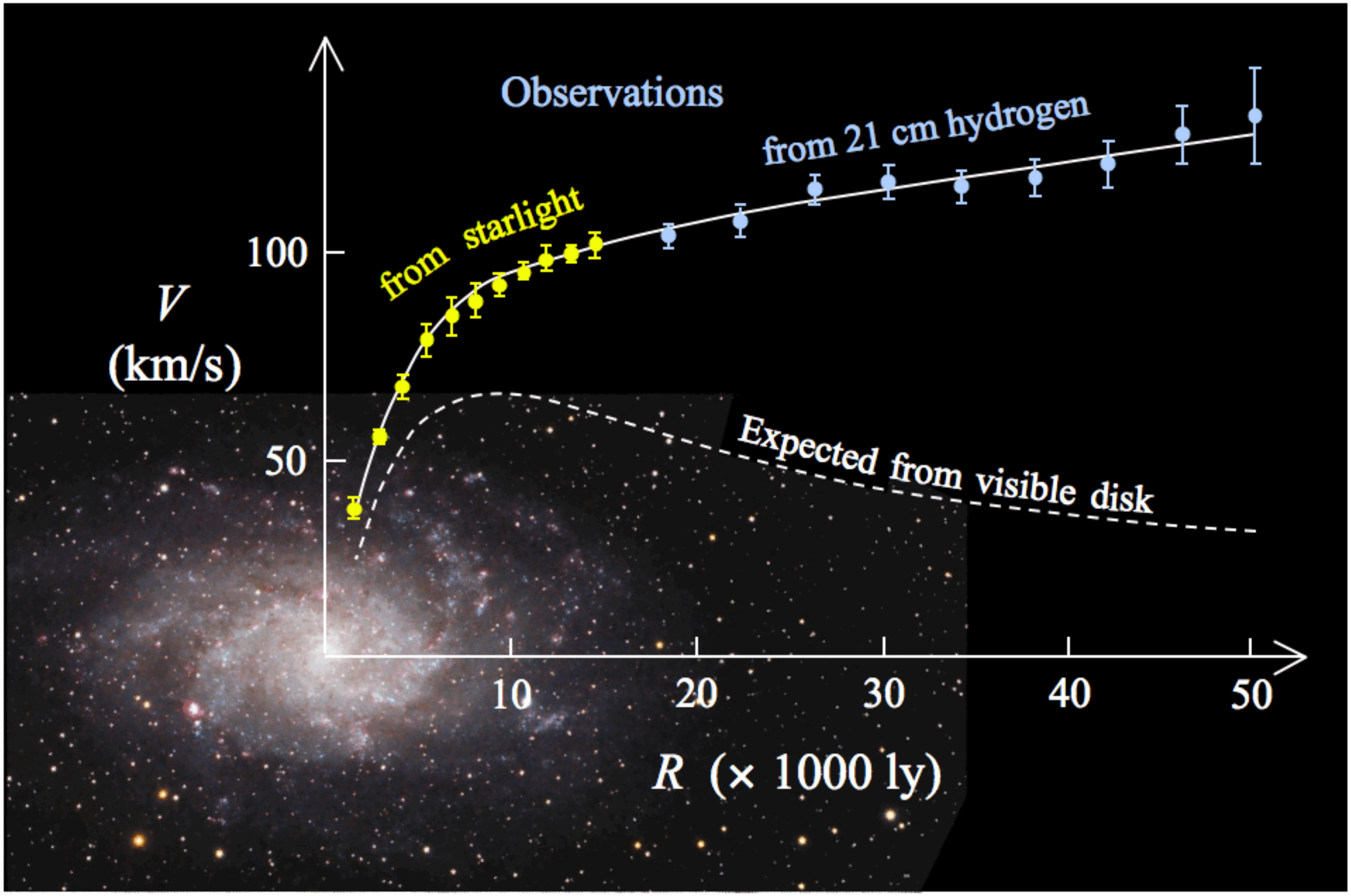
Hydrogen Hyperfine Splitting





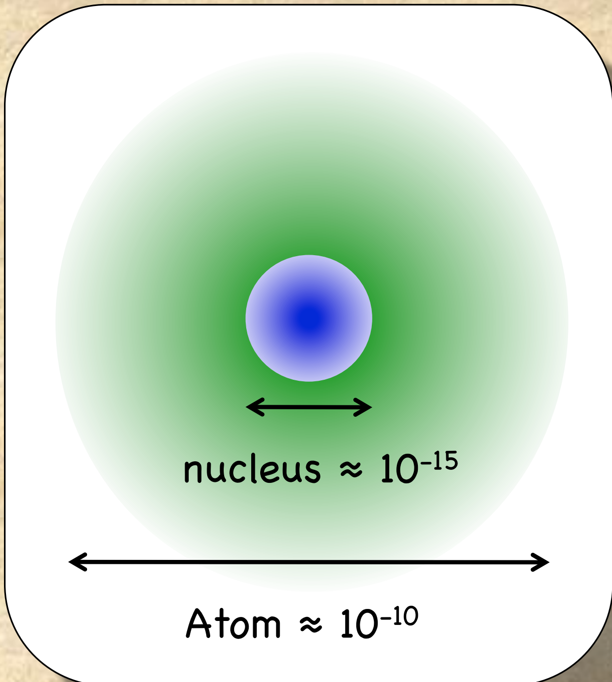
Discovery of 21 cm line → birth of radio astronomy

Hydrogen Hyperfine Splitting



First evidence for existence of dark matter

Applications to Bound State Q.E.D.

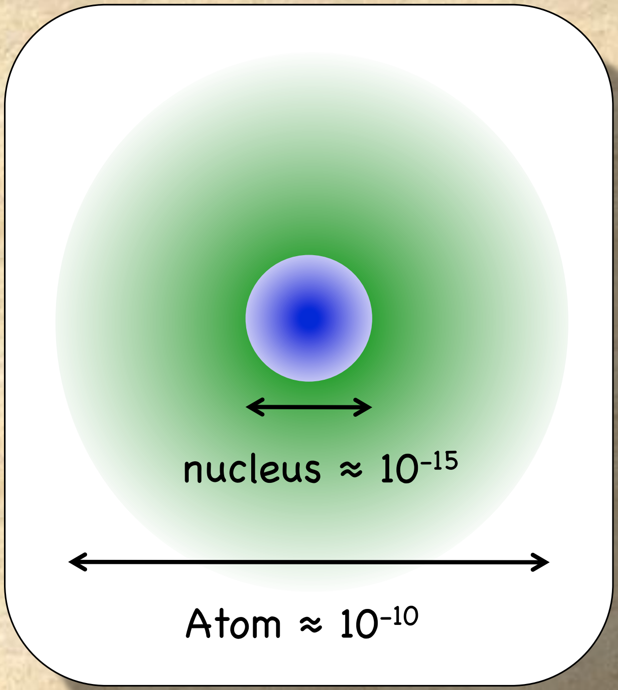


The finite size of the nucleus plays a small but significant role in atomic energy levels.

Hydrogen HF Splitting

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

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

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

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

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

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

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 g_1 & F_1

pretty well determined from 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

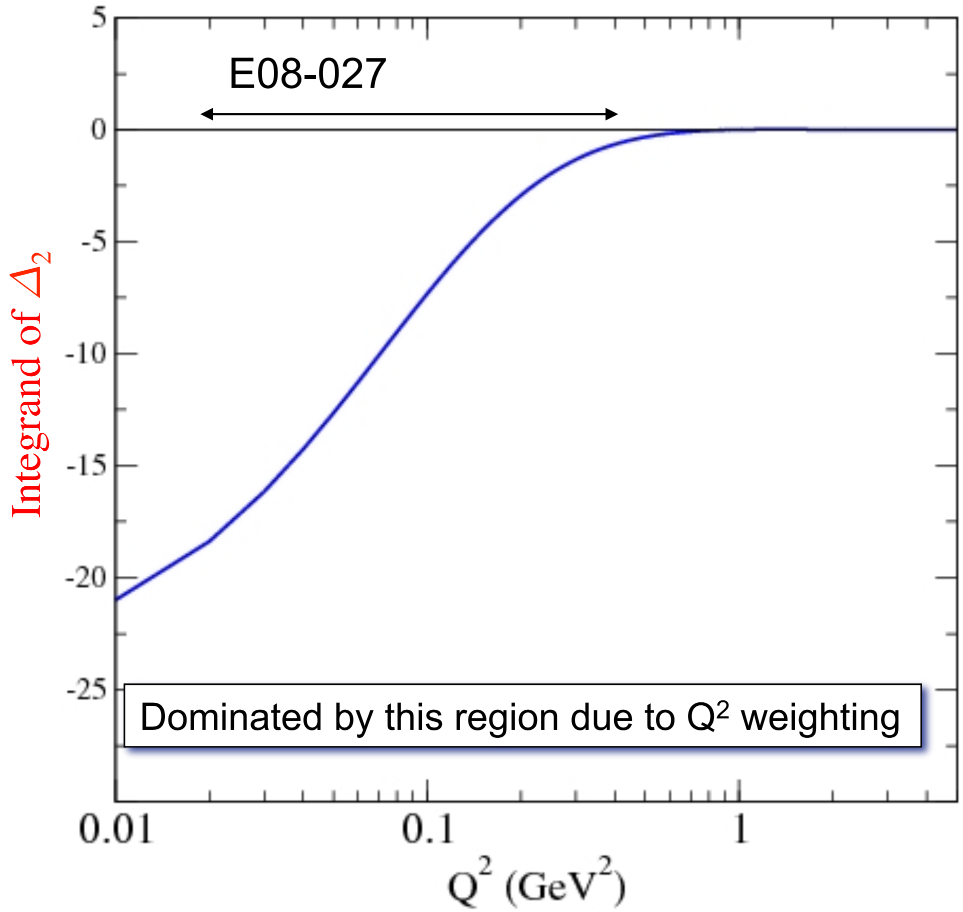
$$\Delta_{POL} = 0.2265 \quad (\Delta_1 + \Delta_2) \text{ppm}$$

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

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

weighted heavily to low Q^2

Hydrogen Hyperfine Structure

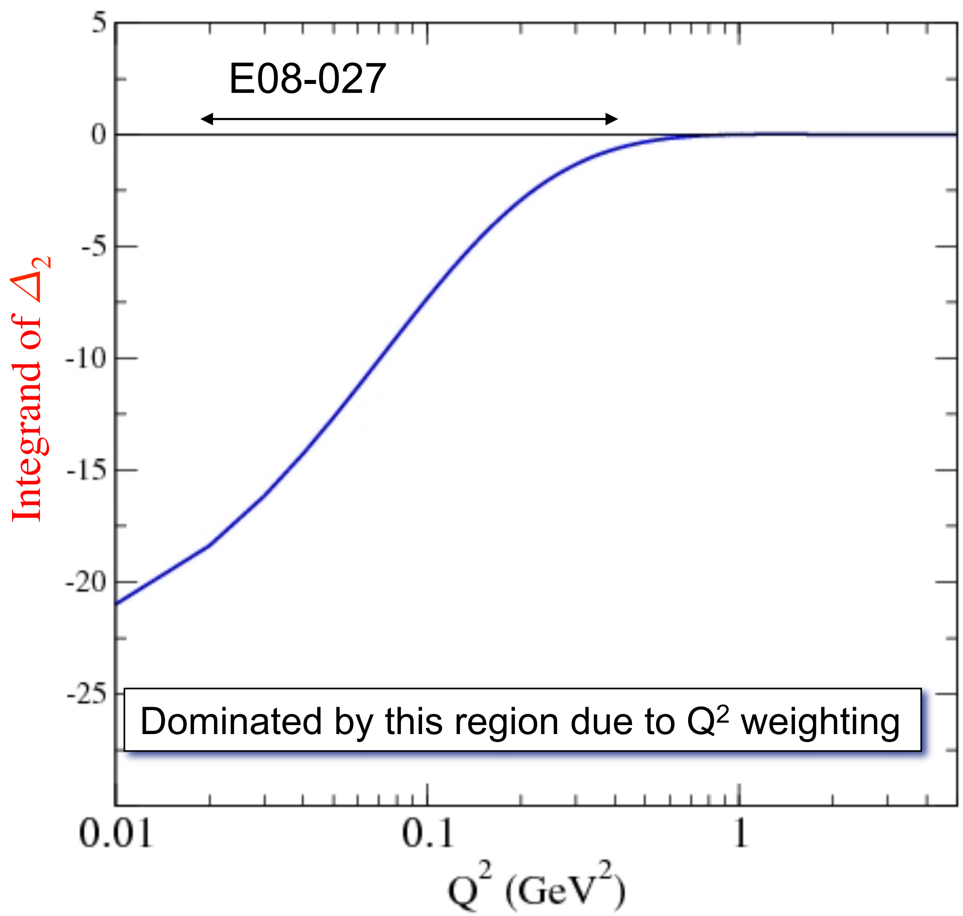


$$\Delta_2 = -24 m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2)$$

$$= -0.57 \pm 0.57$$

assuming CLAS model with 100% error

Hydrogen Hyperfine Structure



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

$$= -0.57 \pm 0.57$$

assuming CLAS model with 100% error

But, g_2^p unknown in this region:

$$\Delta_2 = -1.98 \quad \text{MAID Model}$$

$$\Delta_2 = -1.86 \quad \text{Simula Model}$$

So 100% error probably too optimistic

E08-027 will provide first real constraint on Δ_2

g_2 contribution to the Hyperfine Splitting

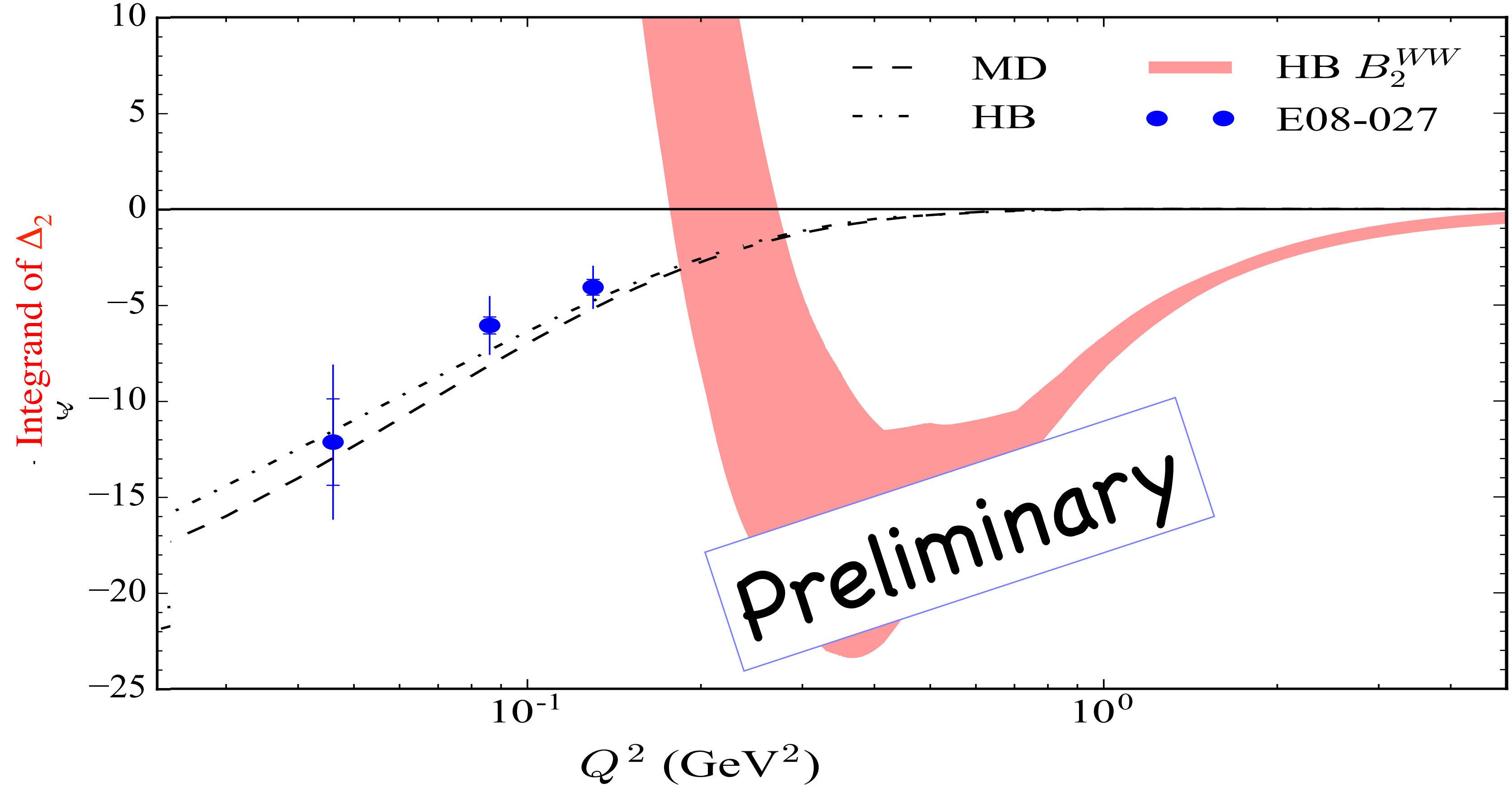
$$\Delta_2 = -24m_p^2 \int_0^\infty \frac{\mathrm{d}Q^2}{Q^4} B_2(Q^2)$$

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

$$\beta_2(\tau) = 1 + 2\tau - 2\sqrt{\tau(\tau+1)}$$

- Dev. from leading twist expected
- Agreement within uncertainty to two models

g_2 contribution to Hyperfine Structure



good agreement with the MAID and *most recent* Hall B models

200% difference from Hall B 2007 model used in PRA78, 02251

Tensor Spin Observables

E12-13-011: "The b_1 experiment"

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

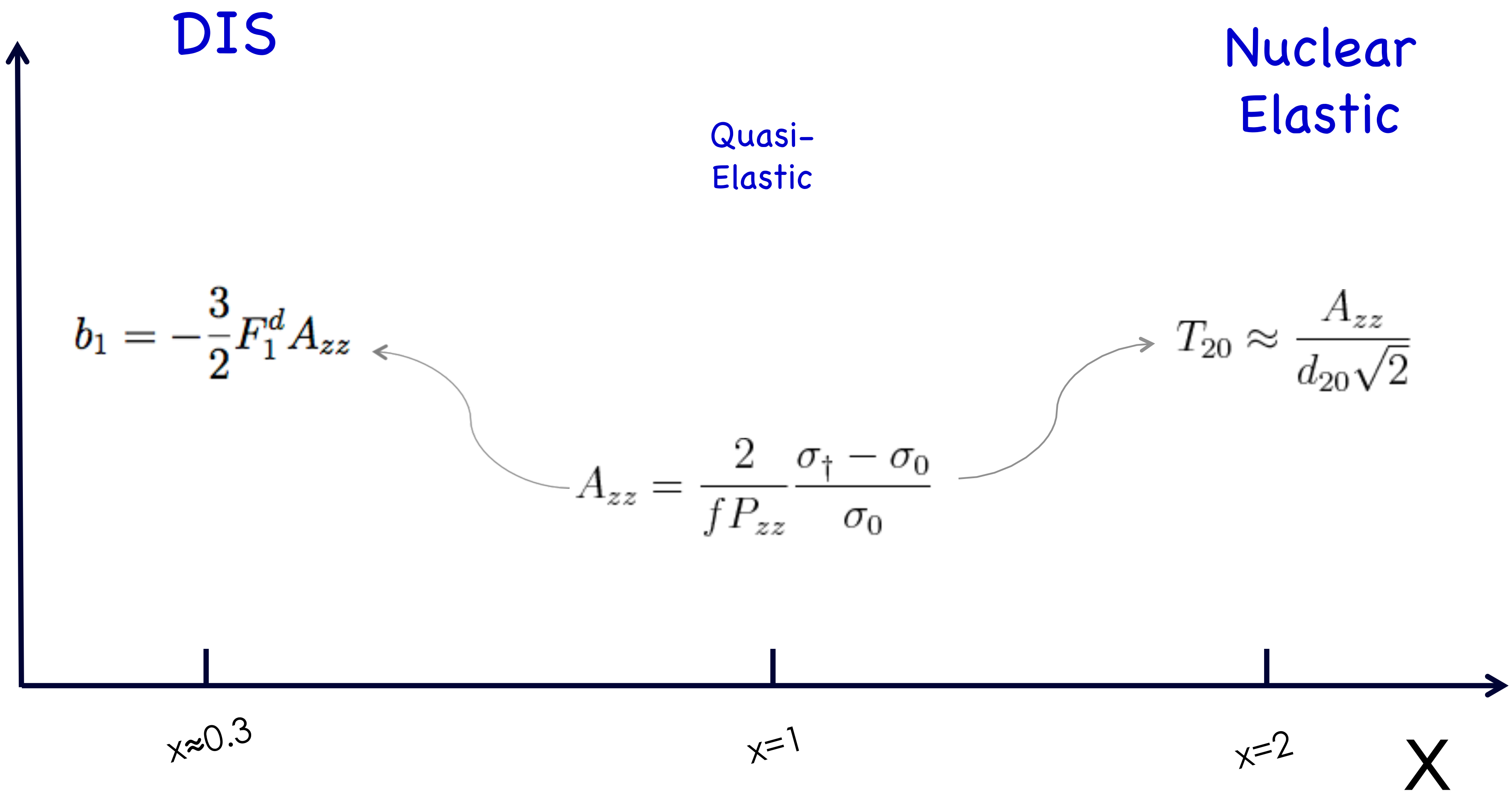
Contact : K. Slifer, UNH

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

Tensor Spin Observables

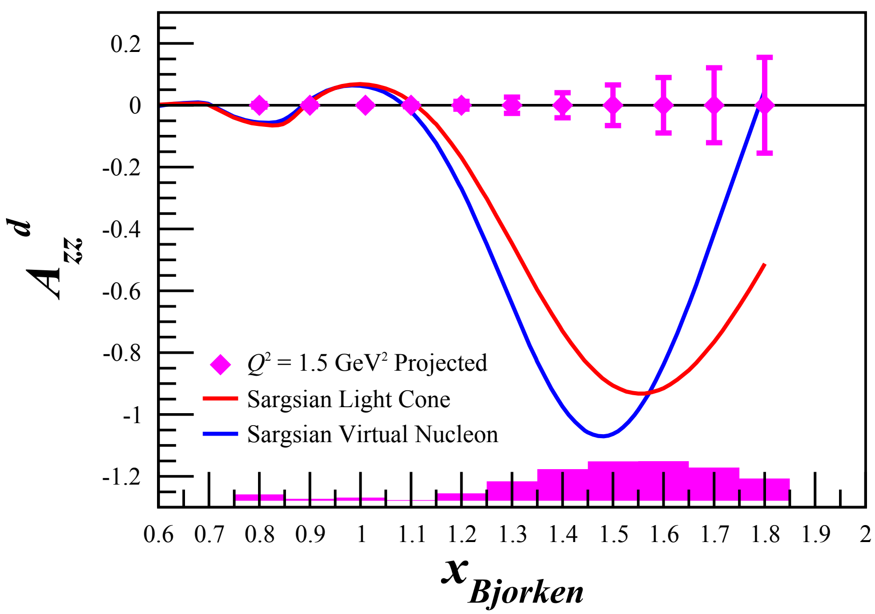


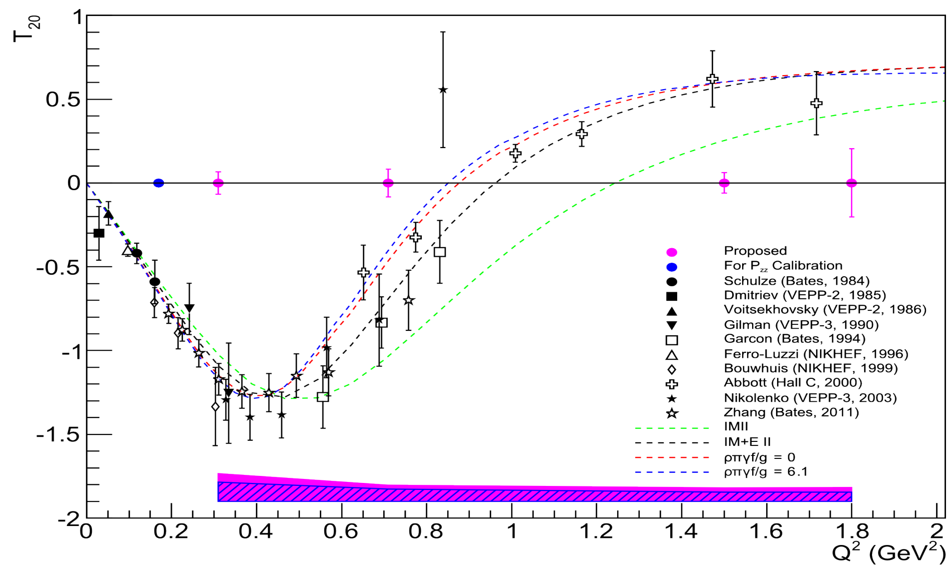
Jefferson Lab E12-15-005

See Ellie Long's Talk

Long (Contact), Slifer, Solvignon, Day, Higinbothan, Keller

Projected Results for P_{zz} = 35%, 30 Days





- Measure tensor A_{zz} in the x>1 Region, and T_{20}
- Very large Tensor Asymmetries predicted
- Sensitive to the S/D-wave ratio
- 4σ discrim between hard/soft wave functions
- 6σ discrim between relativistic models
- A$^-$ rating, Conditional on target performance

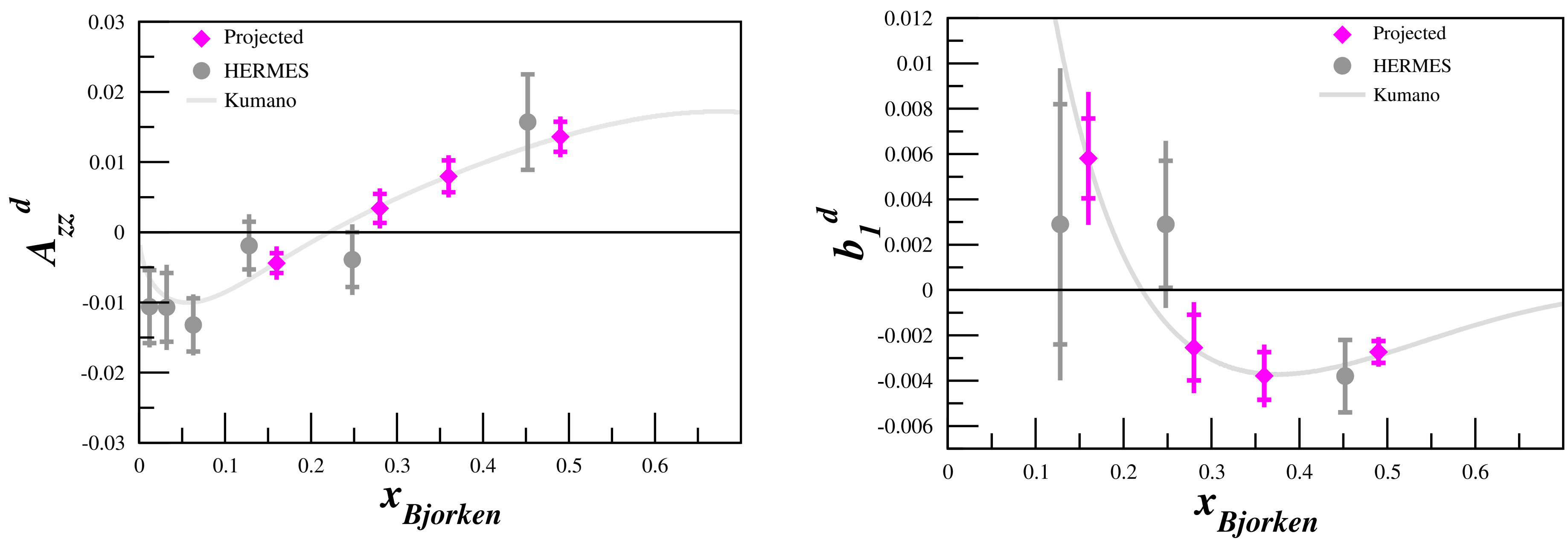
"further explores the nature of short-range pn correlations, the discovery of which was one of the most important results of the 6 GeV nuclear program."

PAC44 Theory Report

Jefferson Lab E12-14-011

Slifer (contact), Solvignon, Long, Chen, Rondon, Kalantarians

Projected Results for P_{zz} = 35%, 30 Days



- Measure leading twist tensor structure function b1 with a solid ND_3 target in Jlab Hall C
- b_1 allows to discriminate between deuteron components with different spins (quarks/gluons)
- Provides a unique probe of 6 quark hidden color effects
- Verification of the zero crossing essential for satisfaction of Close-Kumano Sum
- A^- physics rating, Conditional on target performance

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!

b_1 should have 2 zero crossings

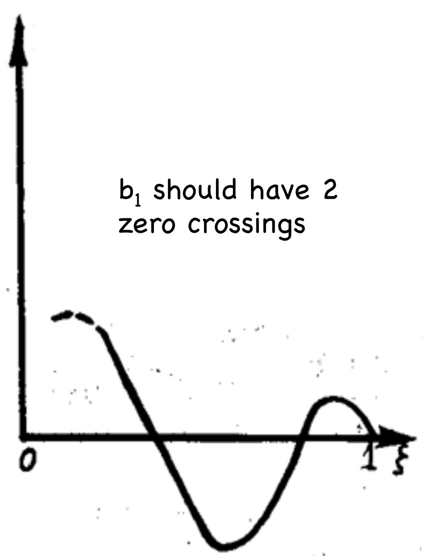


Рис.1

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

Gluon Contribution to Tensor Structure

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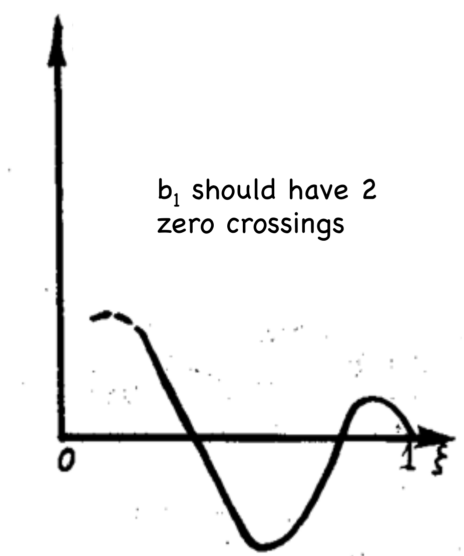


Рис.1

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

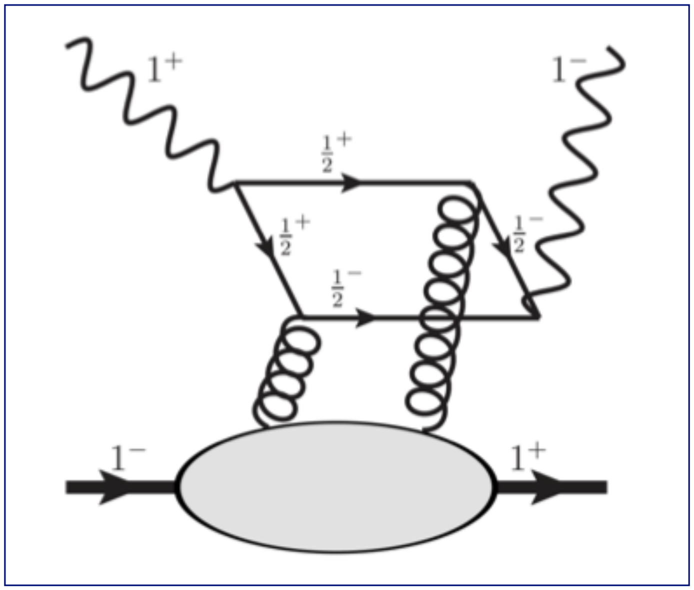
Study of b_1 allows to discriminate between deuteron components with different spins (quarks vs gluons)

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

LOI-12-16-006

James Maxwell (contact), R. Milner, ...

"Nuclear Gluonometry"



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

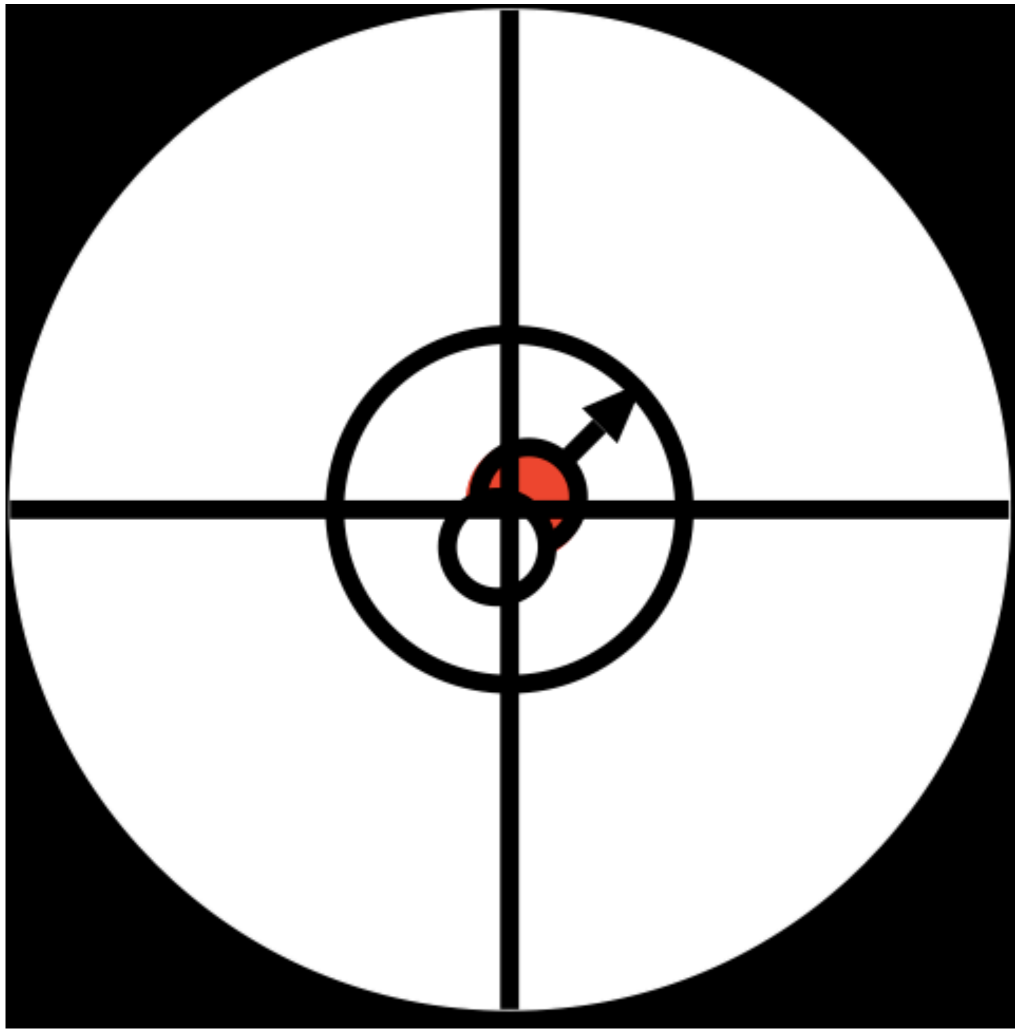
Look for novel gluonic components in nuclei that are not present in nucleons

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

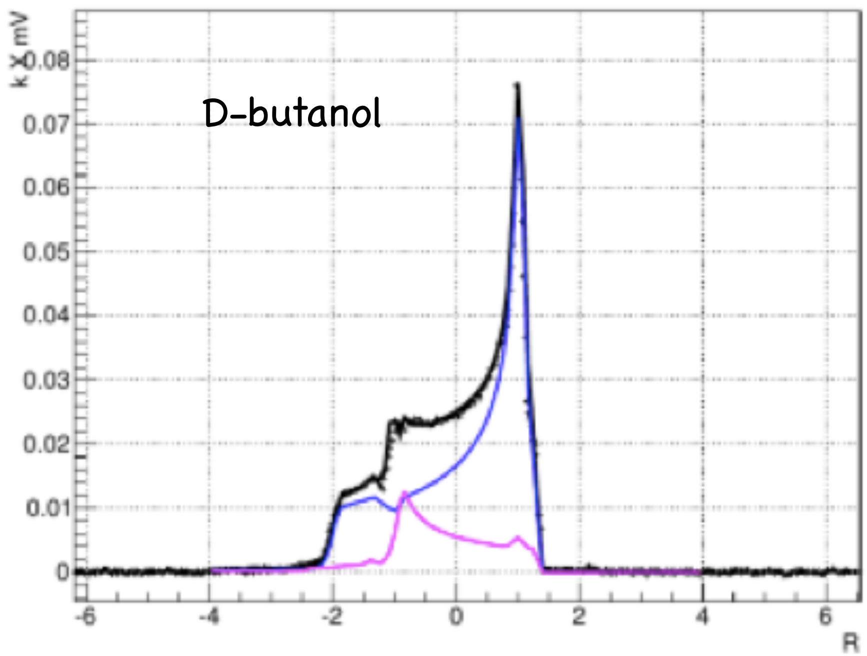
Deep inelastic scattering experiment:
- Unpolarized electrons
- Polarized $^{14}NH_3$ Target
- Target spin aligned transverse to beam

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.,**53** no.7, 155 (2017)
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)

T_{20} measurement at Higs to verify NMR analysis

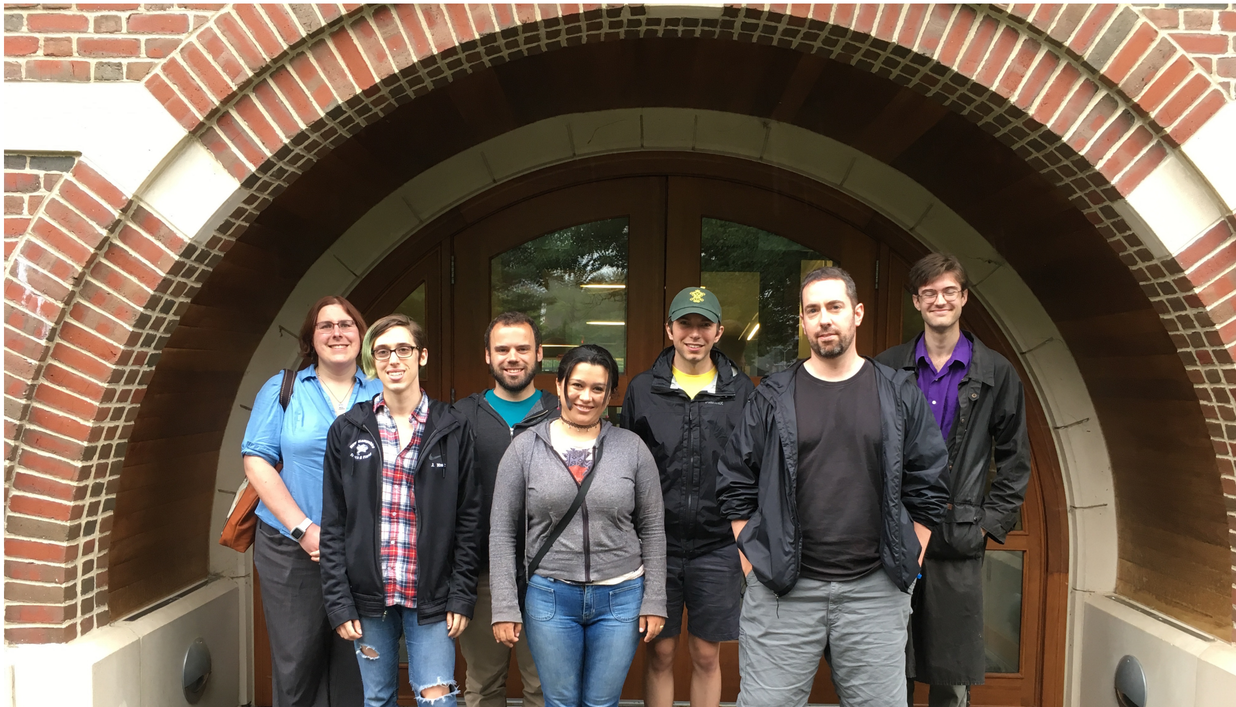
Dustin Keller
Hall A/C collab

Achieved so far

- Before recent research (1984): ~20%
- Recent studies SSS (2014-2015): ~30%
- AFP with SSS (2016): ~34%
- Rotation SSS so far: ~38% (neg Q possible)

Still more to come, we can probably do much better than this by improving B/T should expect Q>>40%

UNH Polarized Target Group



2 faculty
-K.Slifer & Ellie Long

1 post-doc to hire

3 grad students:
--David R : significant time
--Nathalie S. : partial time
--Michael S. : full time

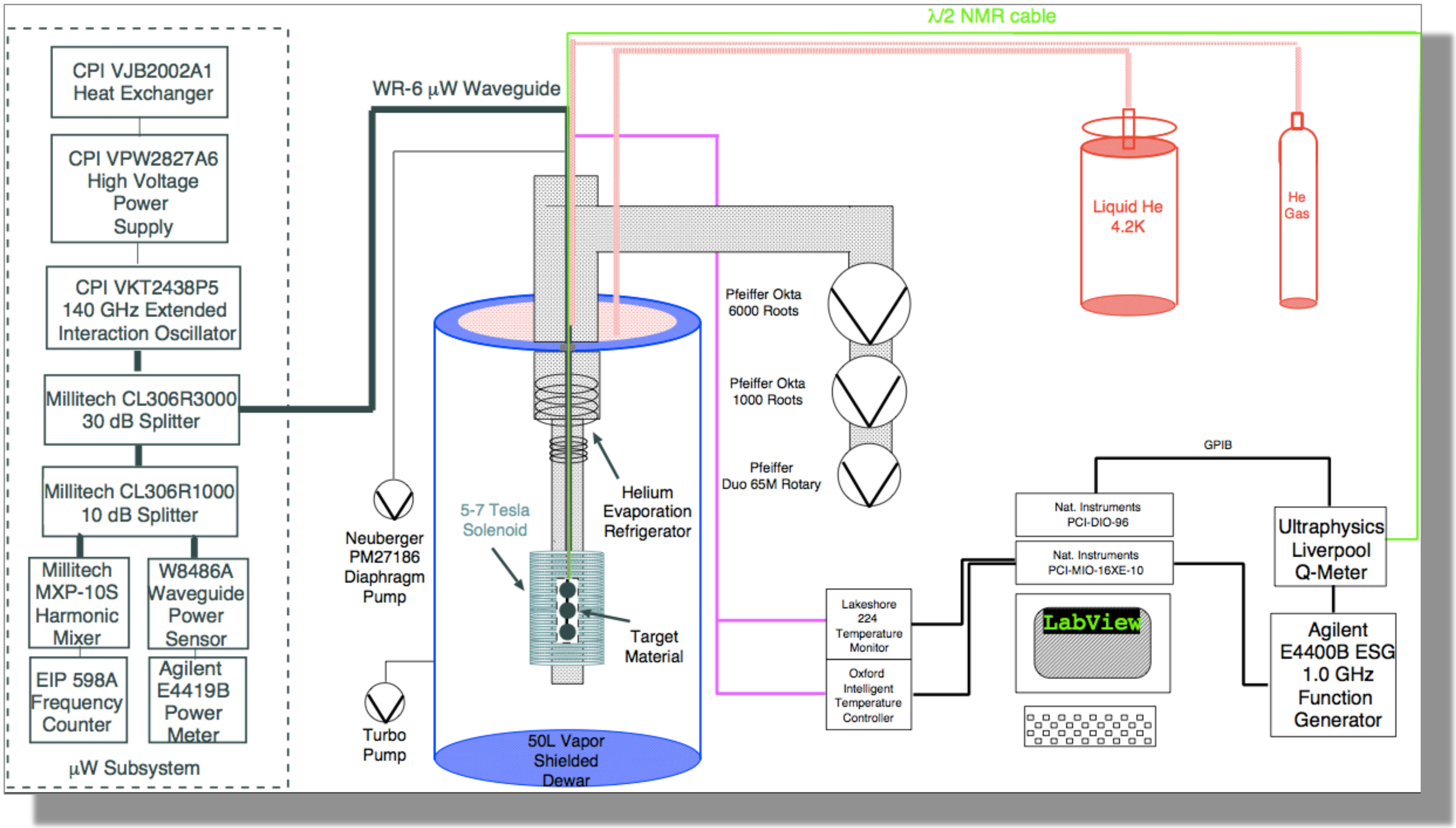
lots of undergrads

<u>Projects</u>

- Polarized Target Material Production & Labview controls for E1039

- Tensor Polarization R&D

UNH Polarized Target Lab



UNH He Evaporation Refrigerator

(assemb "upside down")

UNH Machinist

Phil DeMaine

All Machining at UNH

- ✓ Heat Exchanger
- ✓ Separator Pot
- ✓ Radiation Baffles
- ✓ Needle valves
- ✓ Vacuum Shells

Welding done off-site at Lesker

UNH He Evaporation Refrigerator

Complete Fridge

Vacuum shell assembly

All Machining at UNH

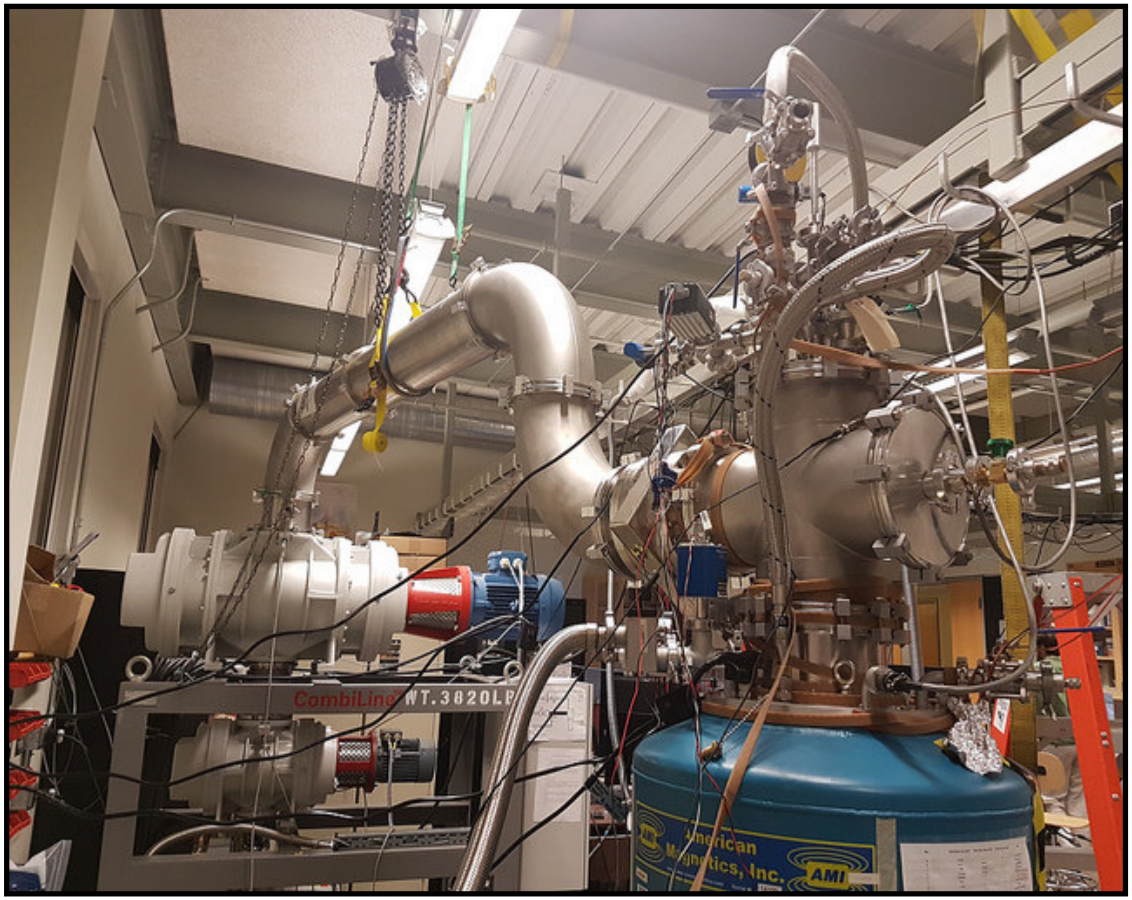
- ✓ Heat Exchanger
- ✓ Separator Pot
- ✓ Radiation Baffles
- ✓ Needle valves
- ✓ Vacuum Shells

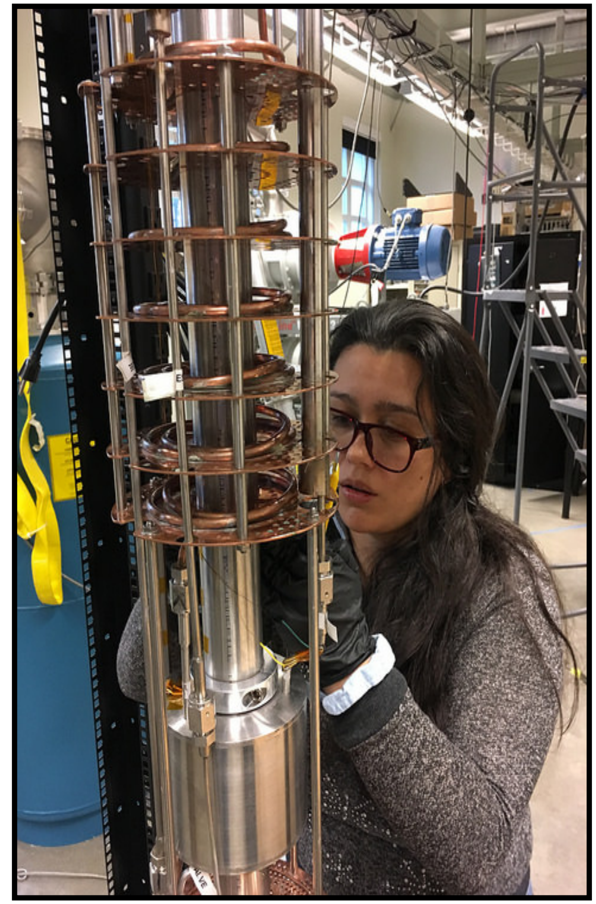
Welding done off-site at Lesker

LHe Cooldown in Feb and Apr

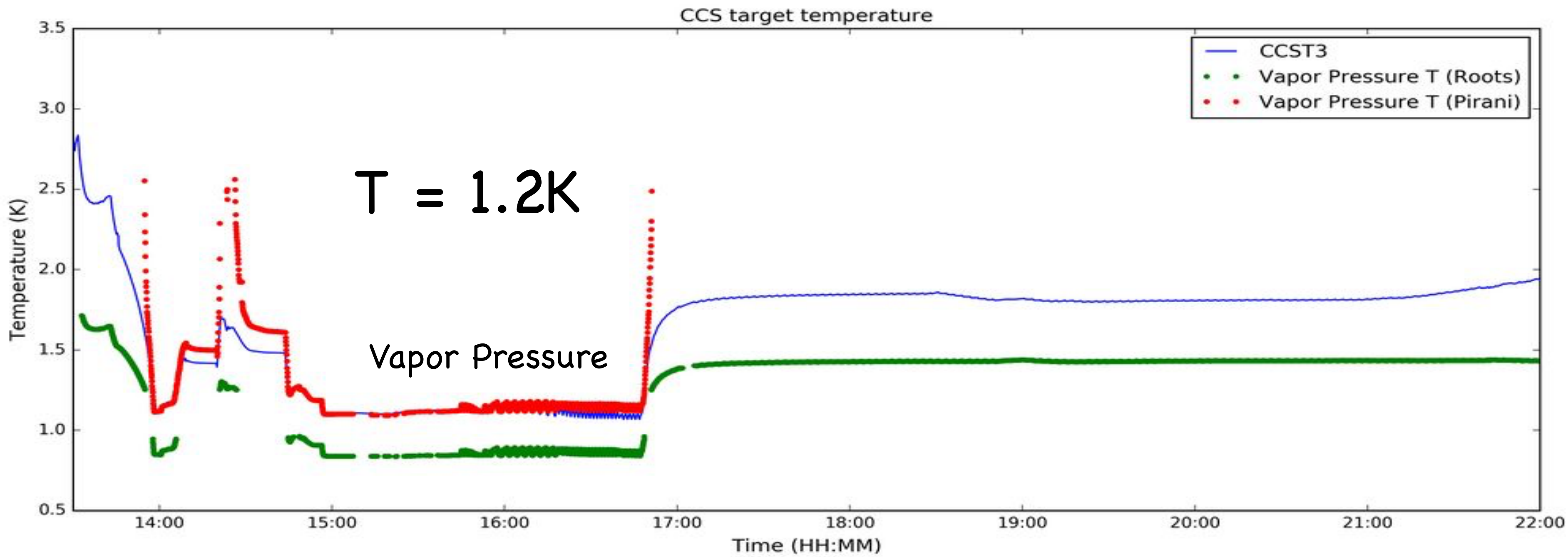
Achieved 1 K in new fridge

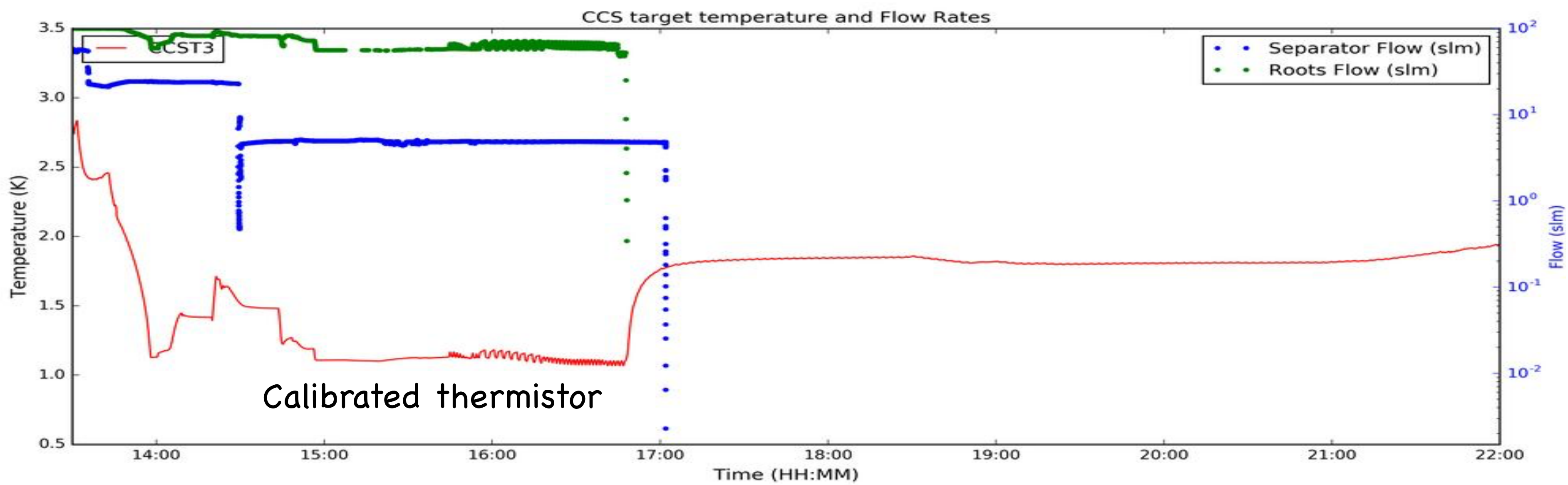
UNH Polarized Target Lab



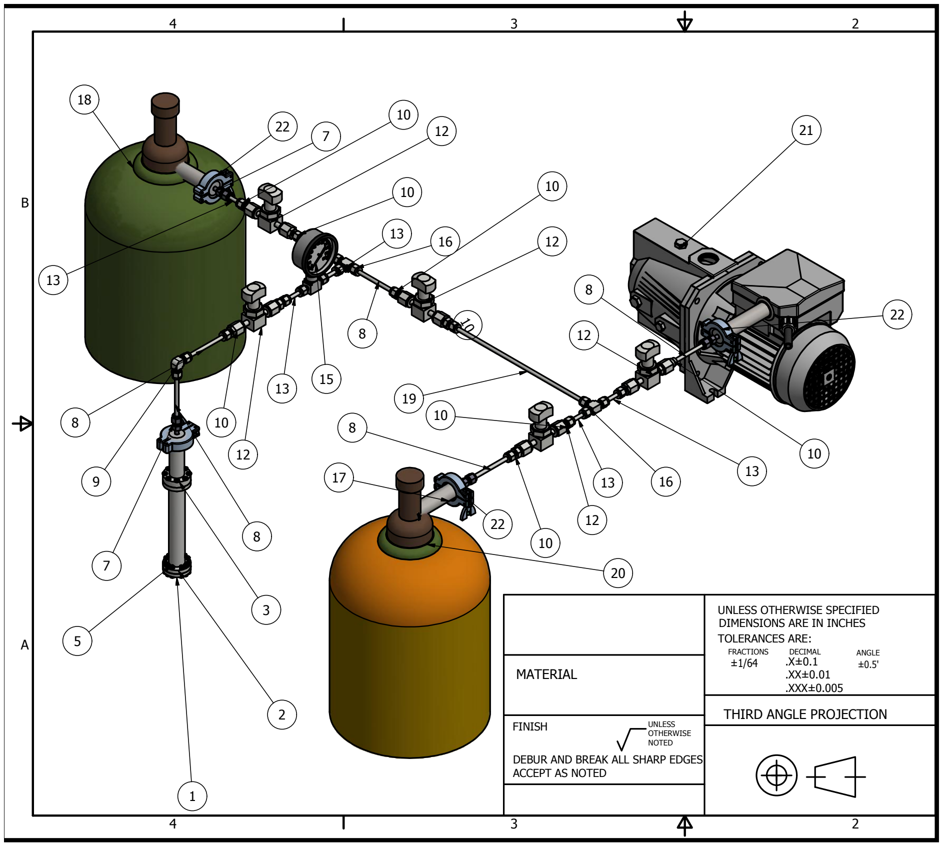


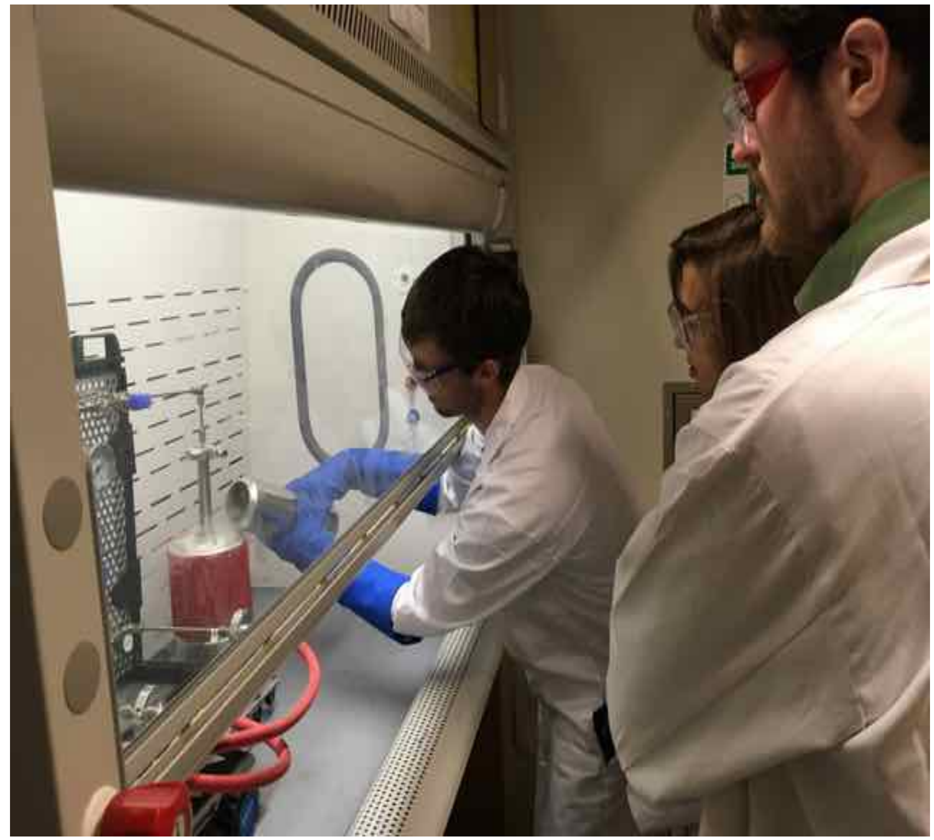
Reached 1K/7T
Have Working NMR system
Developed high vacuum expertise
Just Completed Commissioning of a new fridge
Still assembling the microwave subsystem


CCS target temperature
CCST3
Vapor Pressure T (Roots)
Vapor Pressure T (Pirani)
T = 1.2K
Vapor Pressure
Temperature (K)
Time (HH:MM)


CCS target temperature and Flow Rates
CCST3
Separator Flow (slm)
Roots Flow (slm)
Calibrated thermistor
Temperature (K)
Flow (slm)
Time (HH:MM)

Target Material Production at UNH





Status

-Gas line completed

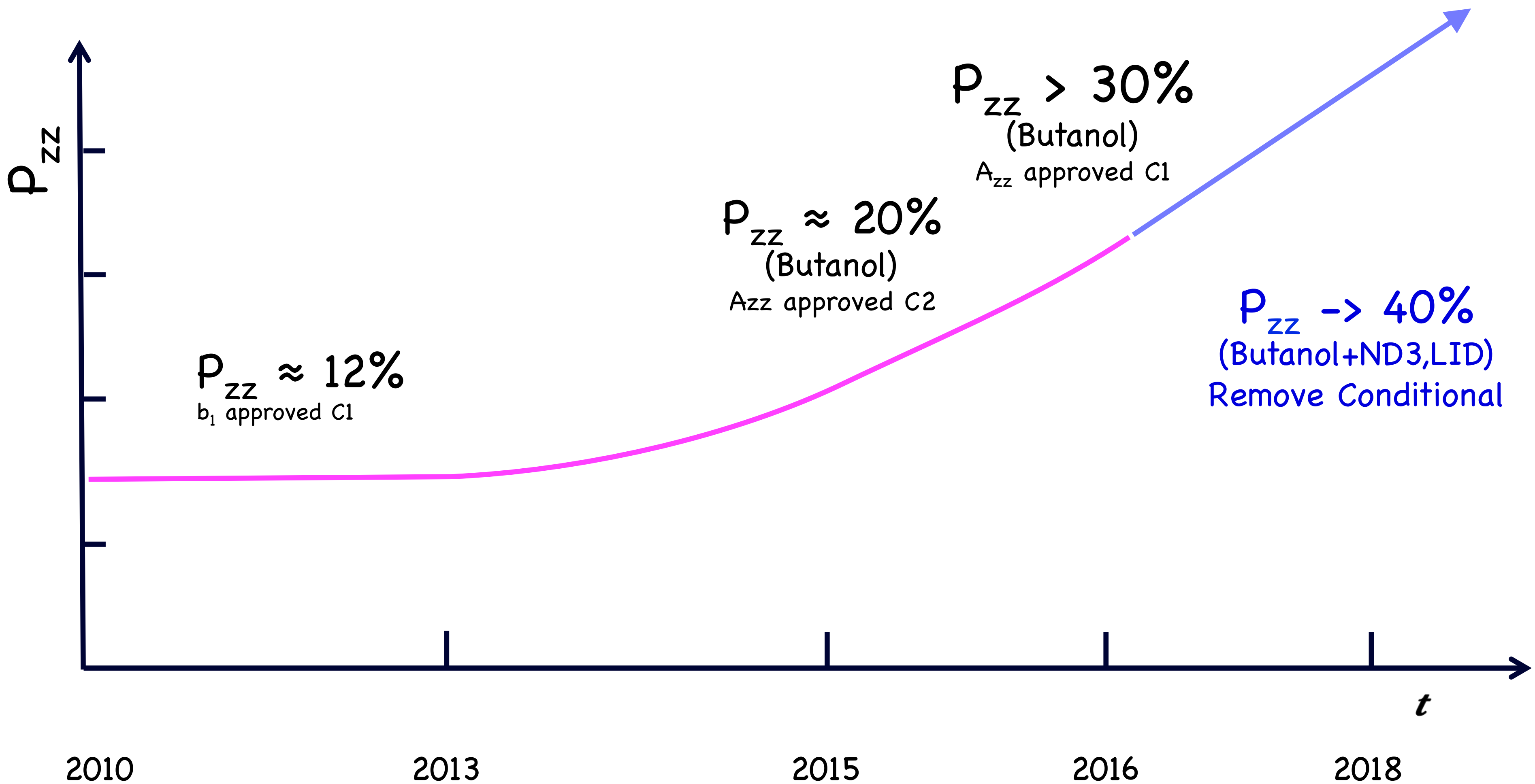
-System completely contained in fume hood

-We produced about 200 grams of NH_3 so far for E1039

Target Material Production at UNH

-We produced about 200 grams of NH_3 so far for E1039
-Aiming for 1 kg by end of year.

Tensor Polarization progress



Summary

g2p

Hyperfine splitting contributions from g2 very different from previous model pred

Large Q2 data finalized. Low Q2 data we are still working on PF systematics.

δ_{LT} favors Lensky et al (BχPT)

sagdh

neutron δ_{LT} results can not be understood by any existing calculation

Analysis finalized. Publication soon to follow.

Tensor Program/Target

E12-13-001: b_1 of the Deuteron (systematics suppressed by $1/P_{zz}$)

E12-14-002: A_{zz} for x>1 (HUGE asymmetries expected)

LOI12-14-001: Tensor Structure Function Δ

High tensor polarizations demonstrated with SSS and rotation: P_{zz} -> 40%
Dramatic improvement in statistic and systematic uncertainties.

No reason this represents a limit. Much higher polarizations may be possible.

UNH target lab soon fully functional.