

New Results on Proton Spin Sum Rules and Polarizabilities



Low Q Workshop
Crete, Greece
2023-05-16

Karl Slifer
University of New Hampshire

This Talk

The E08-027 (g2p) experiment

Published g_2 and polarizability results

Impact on Δ_{pol} in μP HFS

Polarized Target at UNH

Tensor Program at Jlab

Thank you to the organizers!

Special Thanks

David Ruth & Jian-ping Chen

Co-spokespersons:

A. Camsonne, D. Crabb

Graduate Students

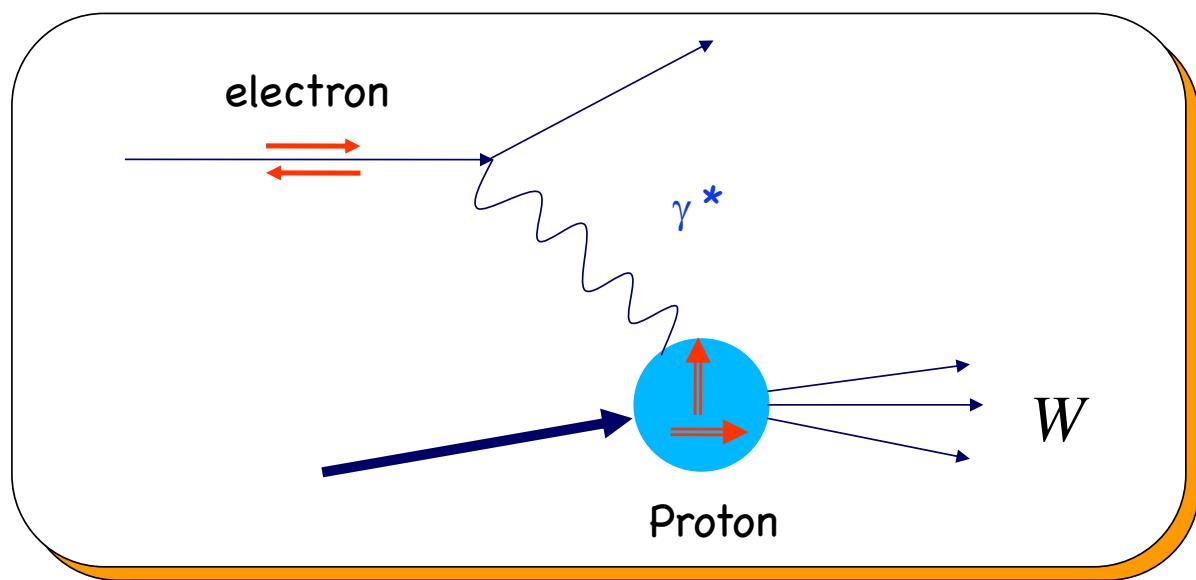
Ryan Zielinski, C. Gu, M. Cummings-Allada, T. Badman, M. Huang, J. Liu, P. Zhu

Post-Docs

K. Allada, J. Zhang

& the Jlab Polarized Target Group

Inclusive Scattering



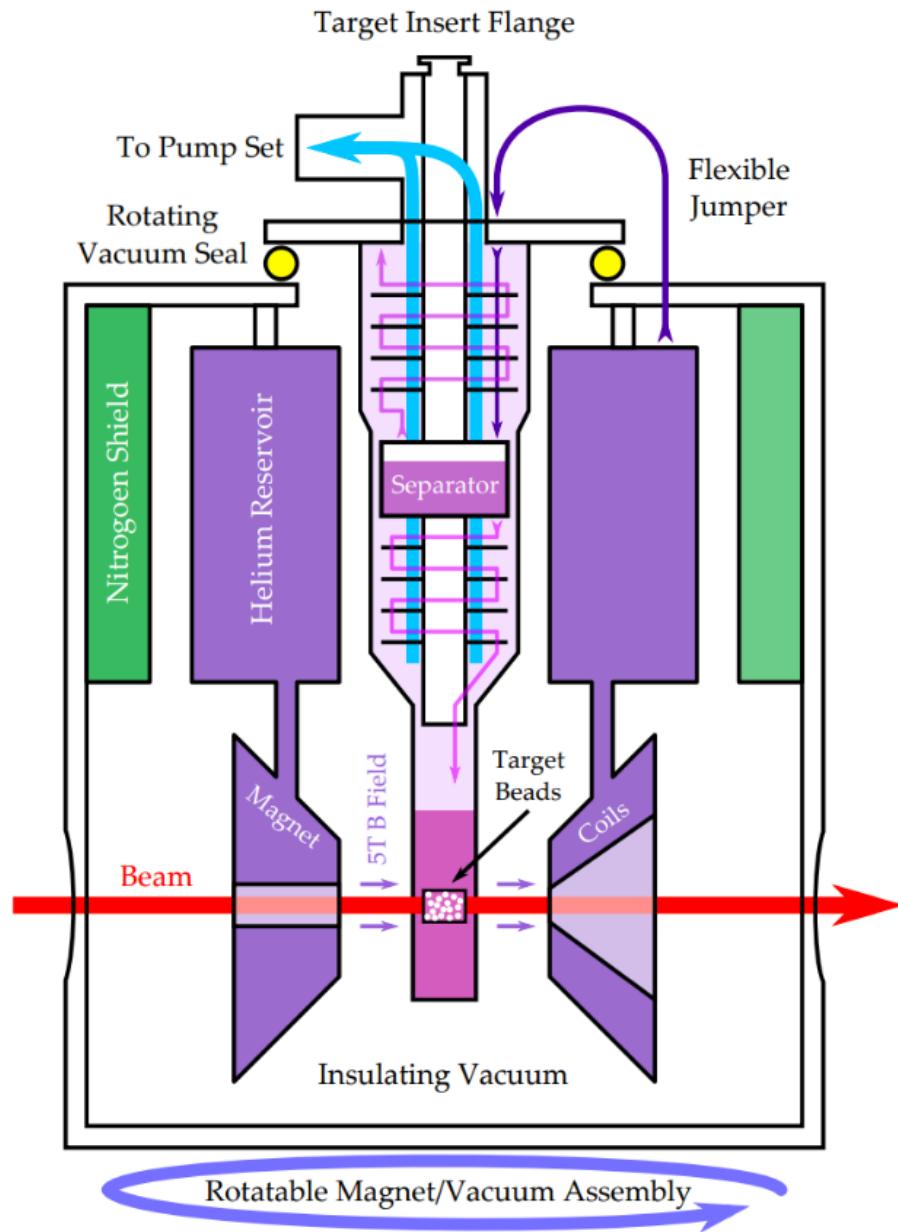
When we add spin degrees of freedom to the target and beam, 2 Additional SF needed.

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

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

Inclusive Polarized
Cross Section

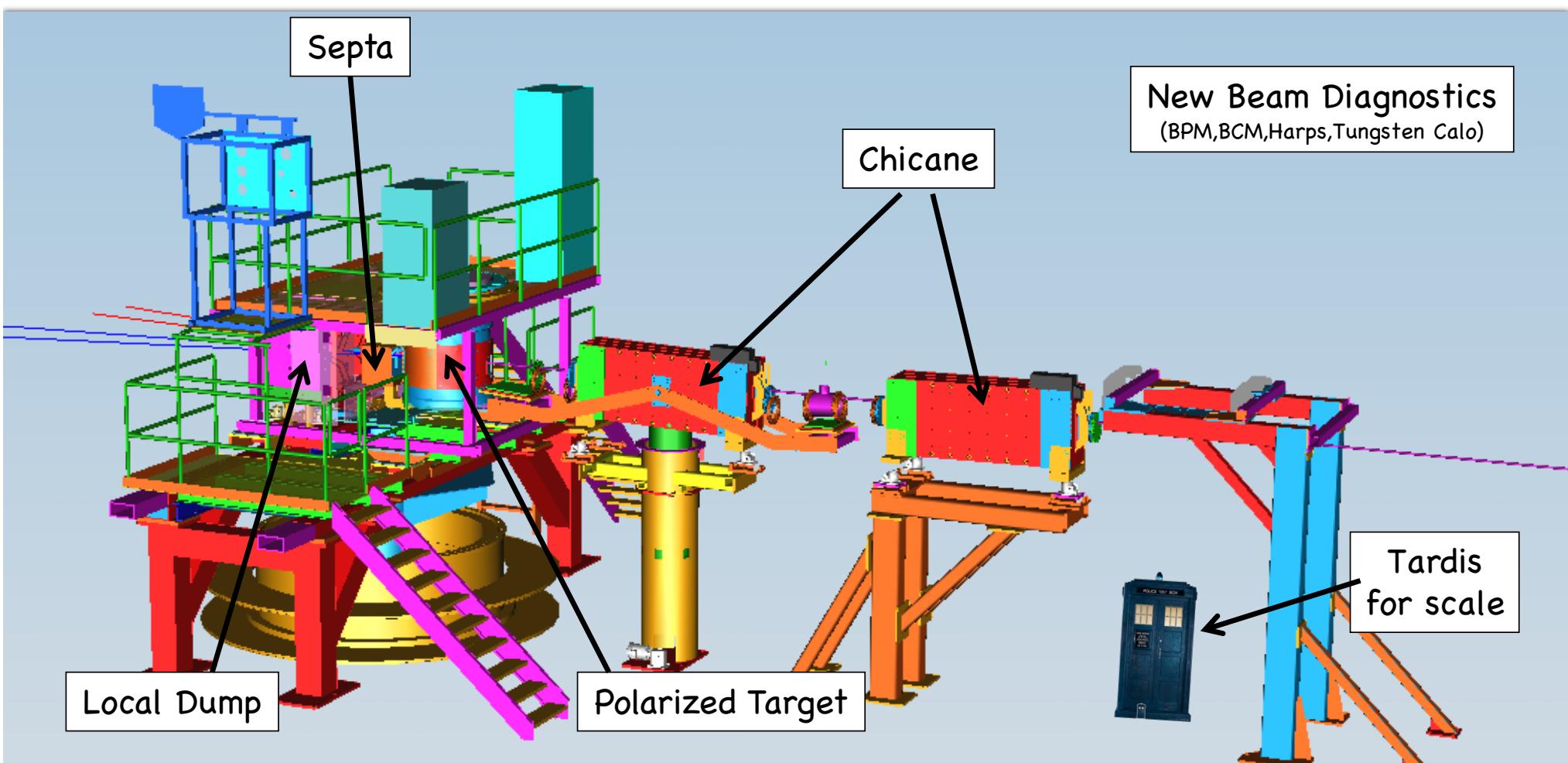
DNP Solid Polarized Target



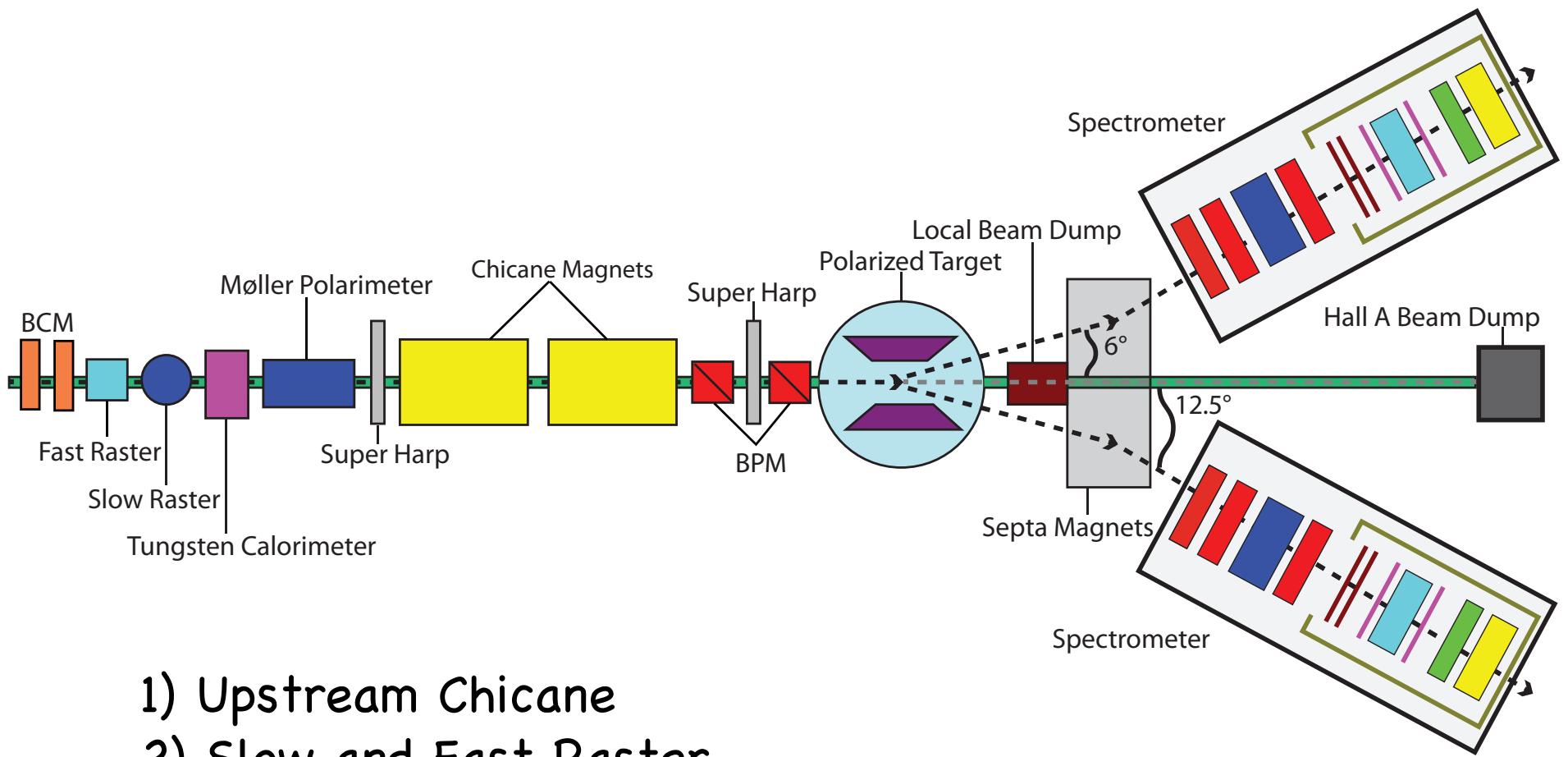
Dynamic Nuclear Polarization

5 Tesla Helmholtz Coil
1 Kelvin Helium Evap Fridge
140 GHz uwaves
 NH_3 target material
Transverse & Longitudinal

The g2p Experiment



Hall A Beamlne

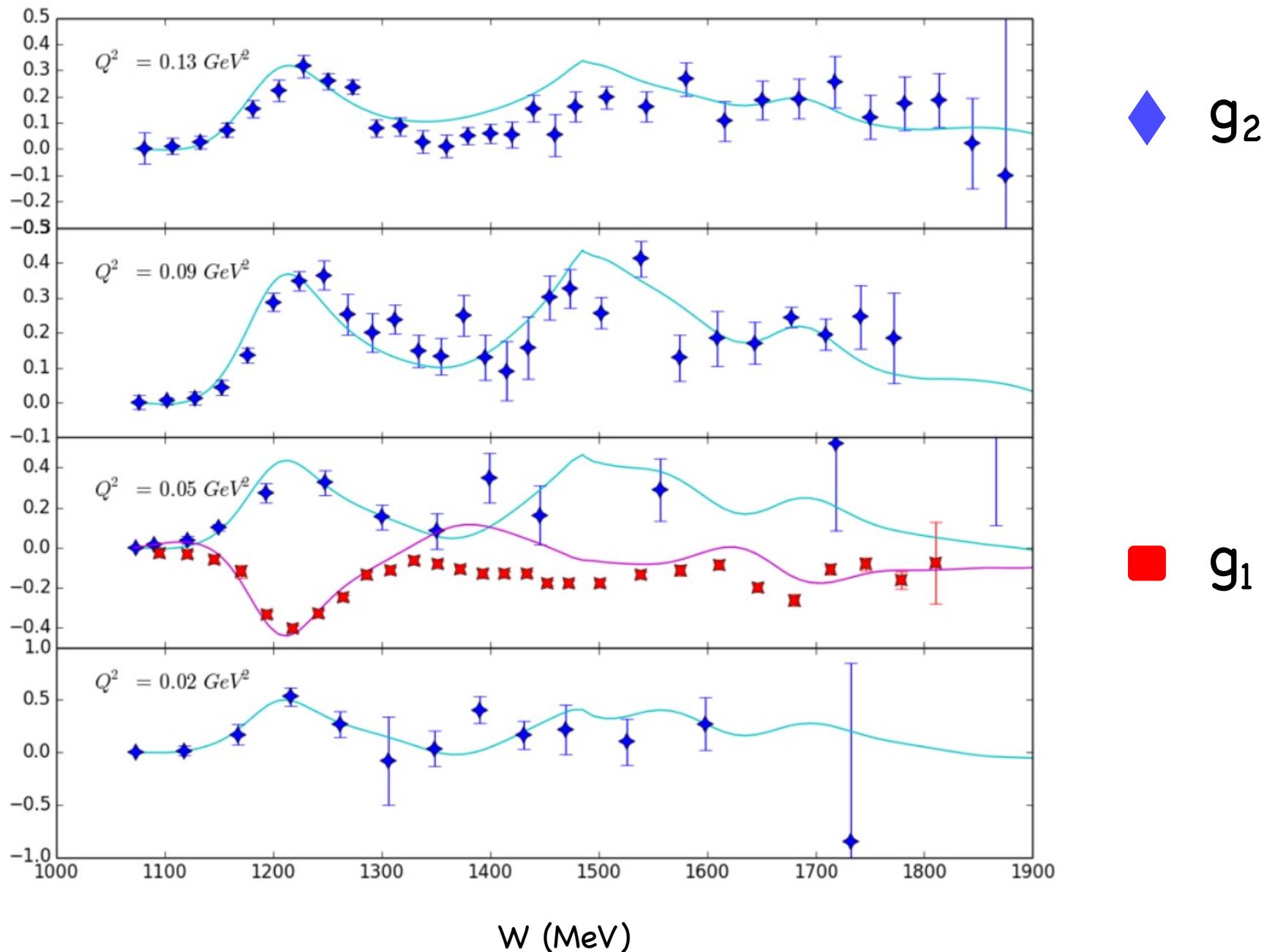


- 1) Upstream Chicane
- 2) Slow and Fast Raster
- 3) Tungsten Calorimeter
- 4) Polarized Target
- 5) RT Septa Magnet
- 6) Local Beam Dump

Proton spin structure and generalized polarizabilities in the strong quantum chromodynamics regime

D. Ruth^①, R. Zielinski¹, C. Gu², M. Allada (Cummings)³, T. Badman¹, M. Huang⁴, J. Liu², P. Zhu^⑤, K. Allada⁶, J. Zhang⁷, A. Camsonne⁷, J.-P. Chen⁷, K. Slifer^{①✉}, K. Aniol⁸, J. Annand⁹, J. Arrington^{10,11}, T. Averett^③, H. Baghdasaryan², V. Bellini¹², W. Boeglin¹³, J. Brock⁷, C. Carlin⁷, C. Chen¹⁴, E. Cisbani¹⁵, D. Crabb², A. Daniel², D. Day², R. Duve², L. El Fassi^{⑥,17}, M. Friedman^⑧, E. Fuchey¹⁹, H. Gao^④, R. Gilman¹⁶, S. Glamazdin²⁰, P. Gueye¹⁴, M. Hafez^{21,22}, Y. Han¹⁴, O. Hansen^⑦, M. Hashemi Shabestari², O. Hen^{⑩,6}, D. Higinbotham^⑦, T. Horn²³, S. Iqbal⁸, E. Jensen²⁴, H. Kang²⁵, C. D. Keith⁷, A. Kelleher⁶, D. Keller², H. Khanal¹³, I. Korover²⁶, G. Kumbartzki¹⁶, W. Li²⁷, J. Lichtenstadt²⁶, R. Lindgren², E. Long^①, S. Malace²⁸, P. Markowitz^⑬, J. Maxwell^{1,7}, D. M. Meekins^⑦, Z. E. Meziani¹⁹, C. McLean^③, R. Michaels⁷, M. Mihovilović^{29,30}, N. Muangma⁶, C. Munoz Camacho³¹, J. Musson⁷, K. Myers¹⁶, Y. Oh²⁵, M. Pannunzio Carmignotto^{②,23}, C. Perdrisat³, S. Phillips¹, E. Piasetzky²⁶, J. Pierce^{7,32}, V. Punjabi³³, Y. Qiang⁷, P. E. Reimer^⑩, Y. Roblin^⑦, G. Ron¹⁸, O. Rondon², G. Russo¹², K. Saenboonruang², B. Sawatzky^⑦, A. Shahinyan³⁴, R. Shneor²⁶, S. Širca^{29,30}, J. Sjoegren⁹, P. Solvignon-Slifer^{1,37}, N. Sparveris^⑨, V. Sulkosky⁶, F. Wesselmann^{③,35}, W. Yan⁵, H. Yang³⁶, H. Yao³, Z. Ye^②, M. Yurov^②, Y. Zhang¹⁶, Y. X. Zhao⁵ and X. Zheng^②

E08-027 Structure Functions



SSF Moments

Generalized
GDH Sum

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

Burkhardt
Cottingham

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

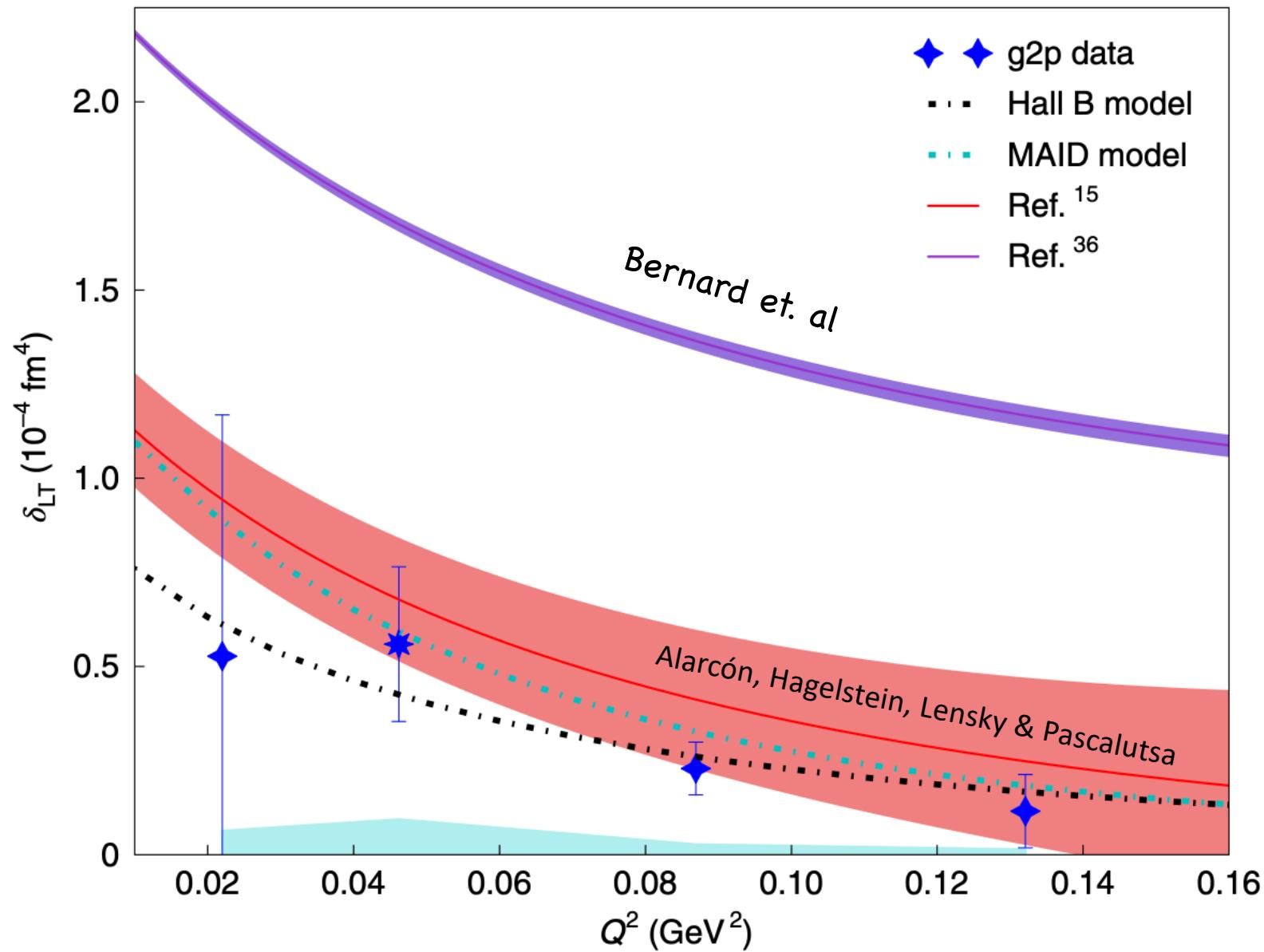
Generalized
Forward
Spin
polarizabilities

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

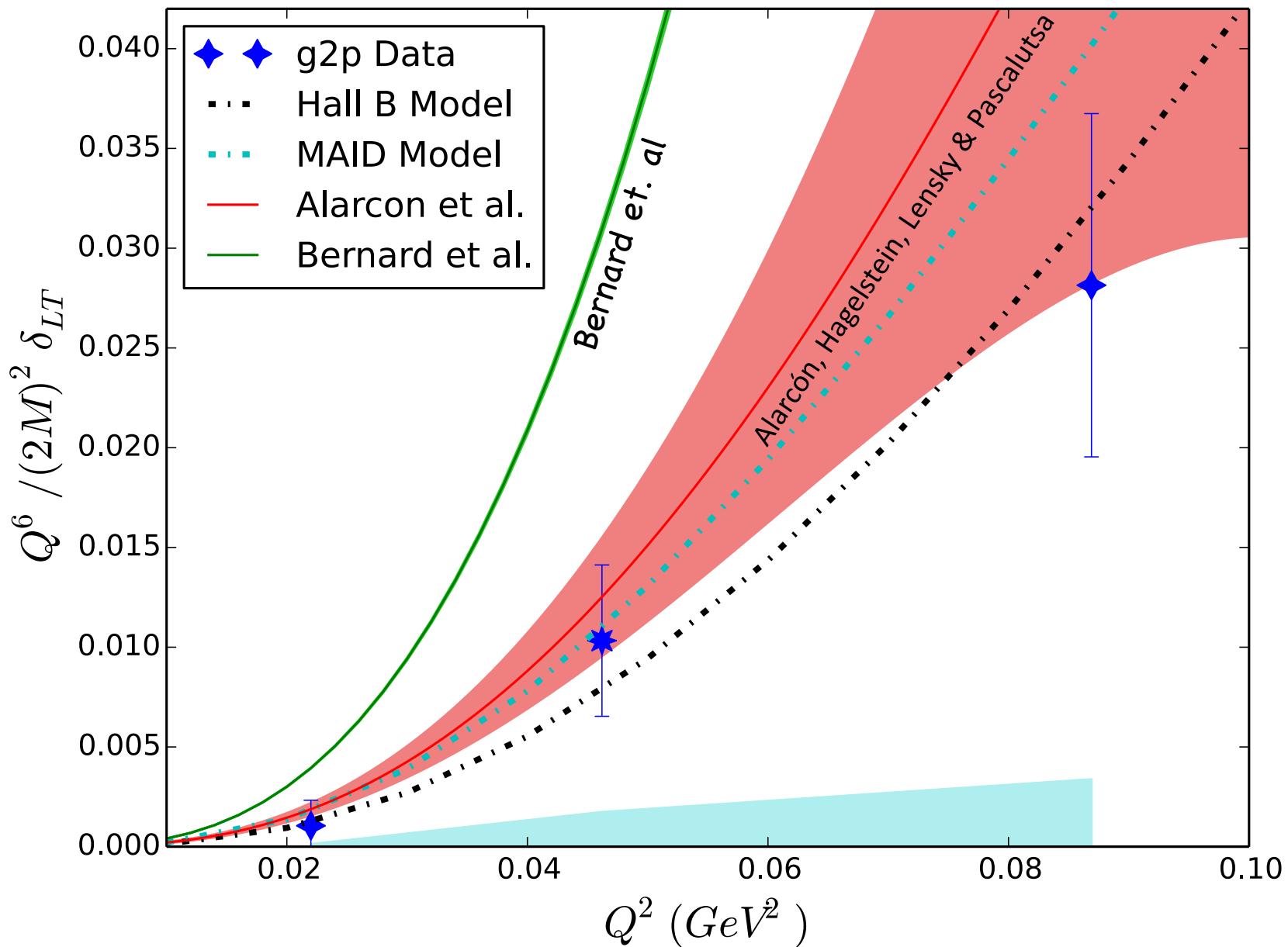
$$\delta_{LT}(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} dx x^2 \left[g_1(x, Q^2) + g_2(x, Q^2) \right]$$

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

δ_{LT} Proton (E08-027)



$Q^6 \delta_{LT}$ Proton (E08-027)

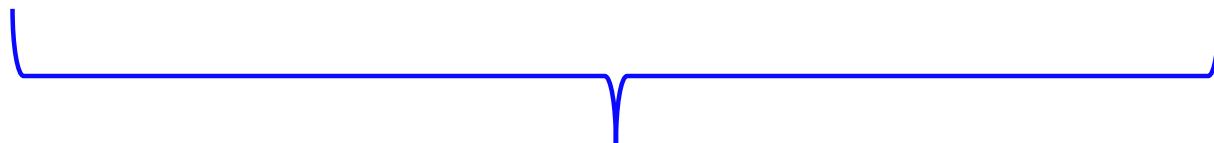


δ_{LT} Sum Rule

Lensky, Pascalutsa, Vanderhaeghen, Kao (2017)

model-independent and predictive relation among low-energy spin structure constants of the nucleon

$$\delta_{LT} = -\gamma_{E1E1} + 3M\alpha_{em} \left[P'^{(M1,M1)1}(0) - P'^{(L1,L1)1}(0) \right]$$



RCS and VCS polarizabilities

See Marc's talk from Monday

δ_{LT} relation to HFS

Hagelstein, Lensky, Pascalutsa (2023, unpublished)

Electronic Hydrogen

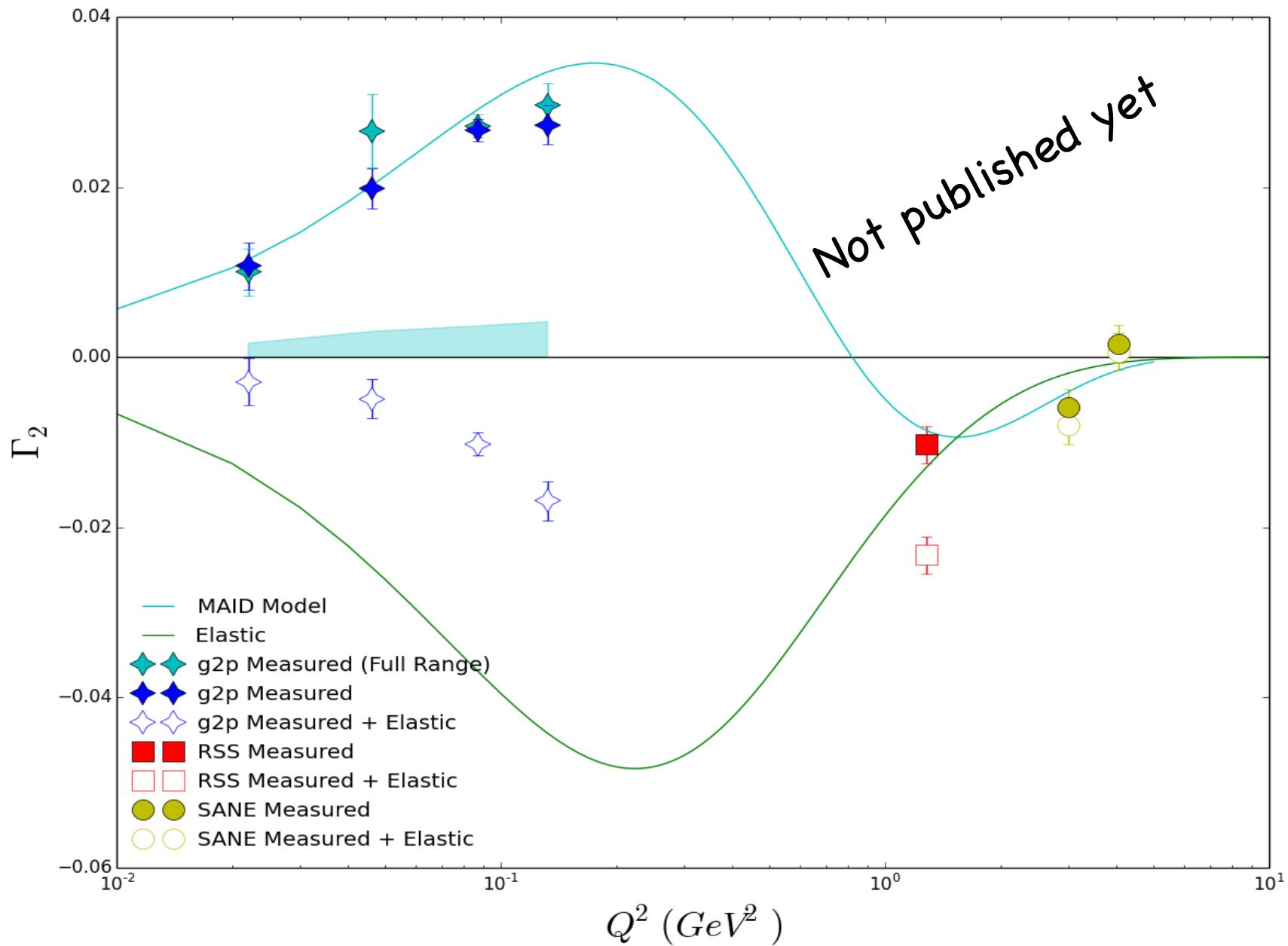
$$\delta_2[0, Q_1^2] = \frac{3M^2}{2\alpha} [\gamma_0 - \delta_{LT}] Q_1^2 + \mathcal{O}(Q_1^4).$$

Muonic Hydrogen

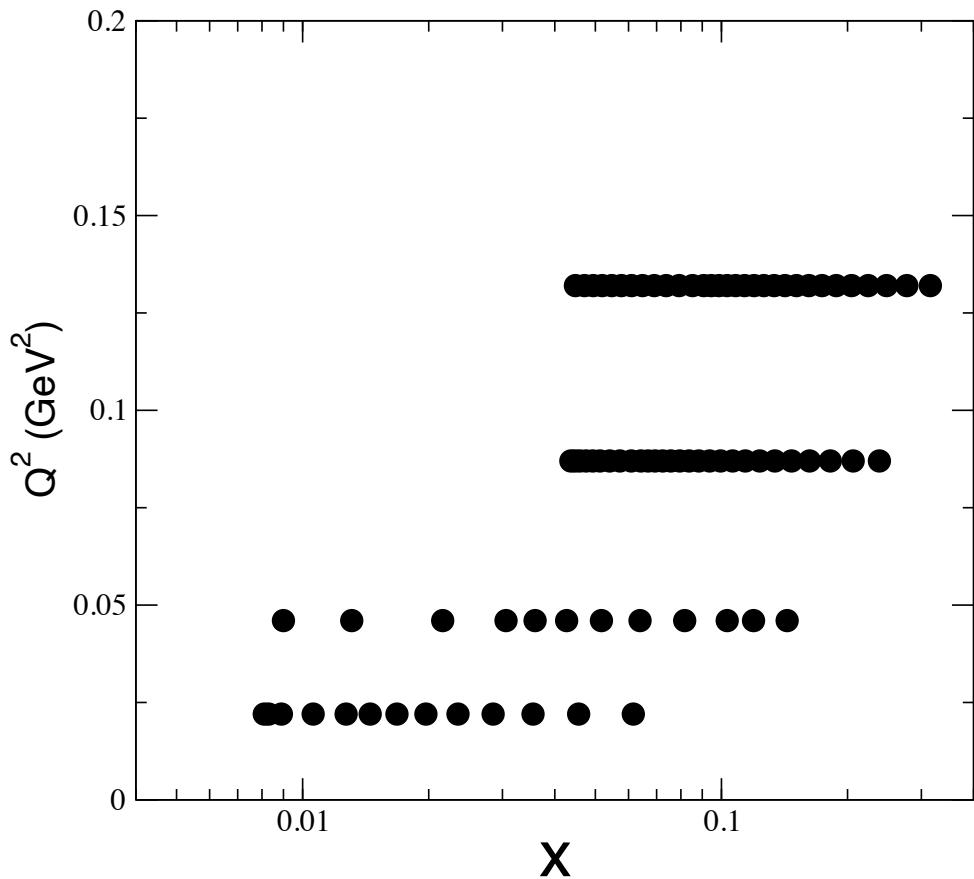
$$\delta_2[0, Q_1^2] = \frac{6M^2}{\alpha} [\gamma_0 - \delta_{LT}] \int_0^{Q_1^2} dQ^2 \beta_2(\tau_\mu) \tau_\mu.$$

Thanks to Franziska H.

BC Sum Rule



BC Sum Rule



Minimum X	Q^2
8×10^{-3}	0.022
9×10^{-3}	0.046
4×10^{-2}	0.087
4×10^{-2}	0.123

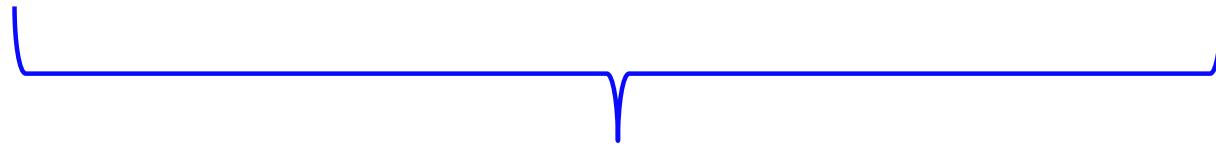
Low- x contribution to the integral suppressed at low Q^2

I₂ Sum Rule

Lensky, Pascalutsa, Vanderhaeghen, Kao (2017)

model-independent and predictive relation among low-energy spin structure constants of the nucleon

$$I_2^{(3)\prime}(0) = \frac{M^2}{2} \left\{ -\frac{1}{\alpha_{\text{em}}} [\gamma_0 + \gamma_{E1E1}] + 3M \left[P'^{(M1,M1)1}(0) - P'^{(L1,L1)1}(0) \right] \right\}$$

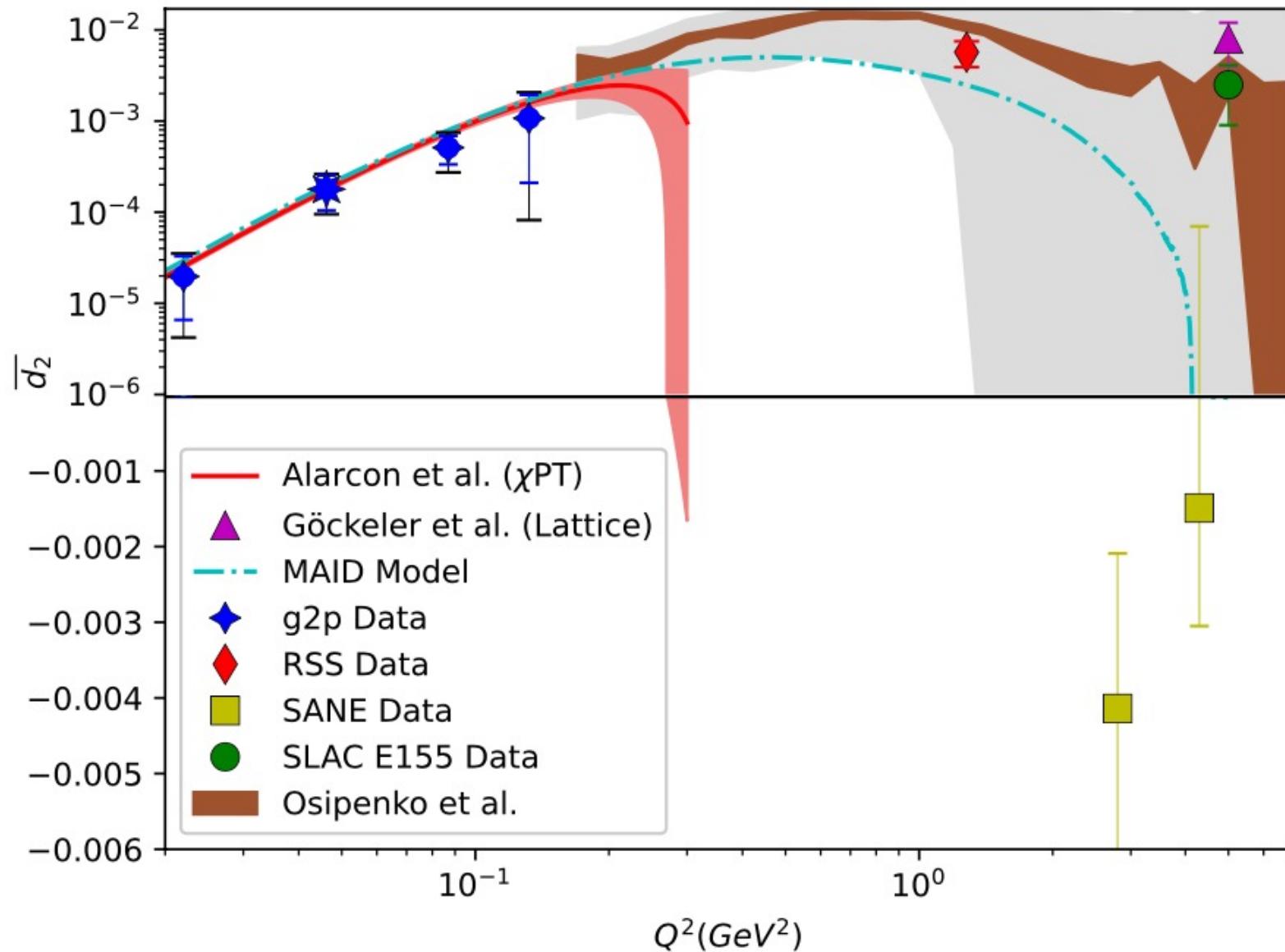


RCS and VCS polarizabilities

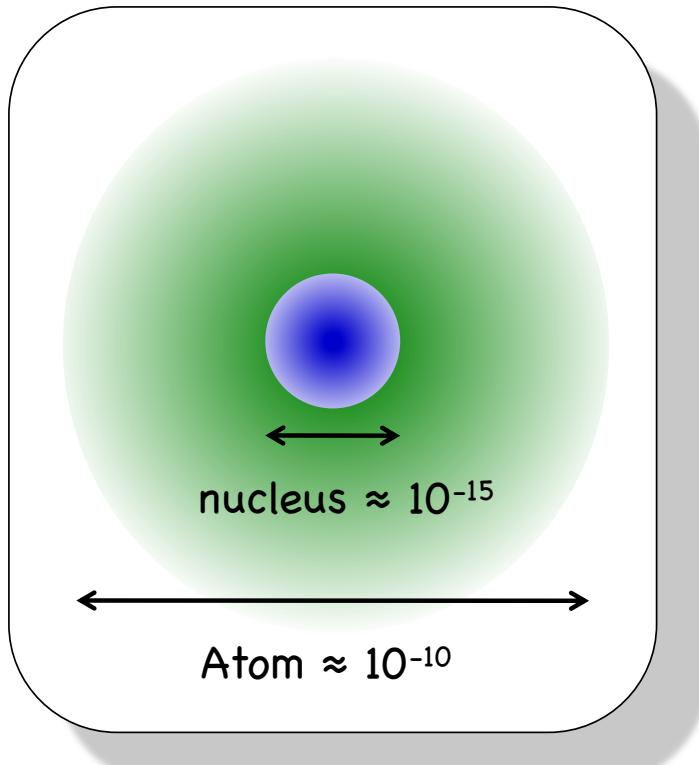
$$\begin{aligned} I_2^{(3)}(Q^2) &\equiv \frac{8M^4}{Q^4} \int_0^{x_0} dx x^2 g_2(x, Q^2), \\ &= I_1(Q^2) - I_{TT}(Q^2), \end{aligned}$$

See Marc's talk from Monday

d_2 Proton



Finite size corrections



eP HFS

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

$$\delta = (\Delta_{QED+weak} + \Delta_{hVP} + \Delta_Z + \Delta_R + \Delta_{pol})$$

$$\Delta_{pol} = \frac{\alpha m}{2\pi(1 + \kappa)M} [\Delta_1 + \Delta_2]$$

Hyperfine Splitting

$$\Delta_1 = \frac{9}{4} \int_0^\infty \frac{dQ^2}{Q^2} \left[\left(\frac{G_M(Q^2) + G_E^2(Q^2)}{1 + \tau} \right)^2 + \frac{8M_p^2}{Q^2} B_1(Q^2) \right] \quad \Delta_2 = -24m_p^2 \int_0^\infty \frac{dQ^2}{Q^4} B_2(Q^2).$$

$$B_1(Q^2) = \int_0^{x_{pp}} \beta_1(\tau) g_1(x, Q^2) dx$$

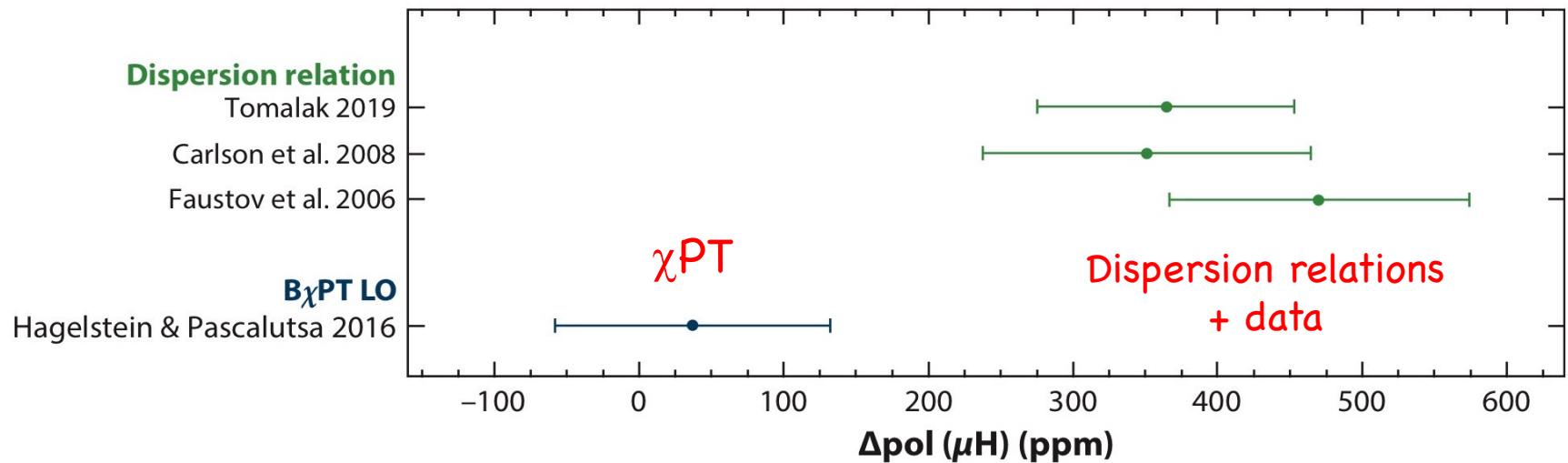
$$B_2(Q^2) = \int_0^{x_{\text{th}}} dx \beta_2(\tau) g_2(x, Q^2),$$

$$\beta_1(Q^2) = \frac{4}{9} \left(-3\tau + 2\tau^2 + 2(2 - \tau)\sqrt{\tau(\tau + 1)} \right)$$

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

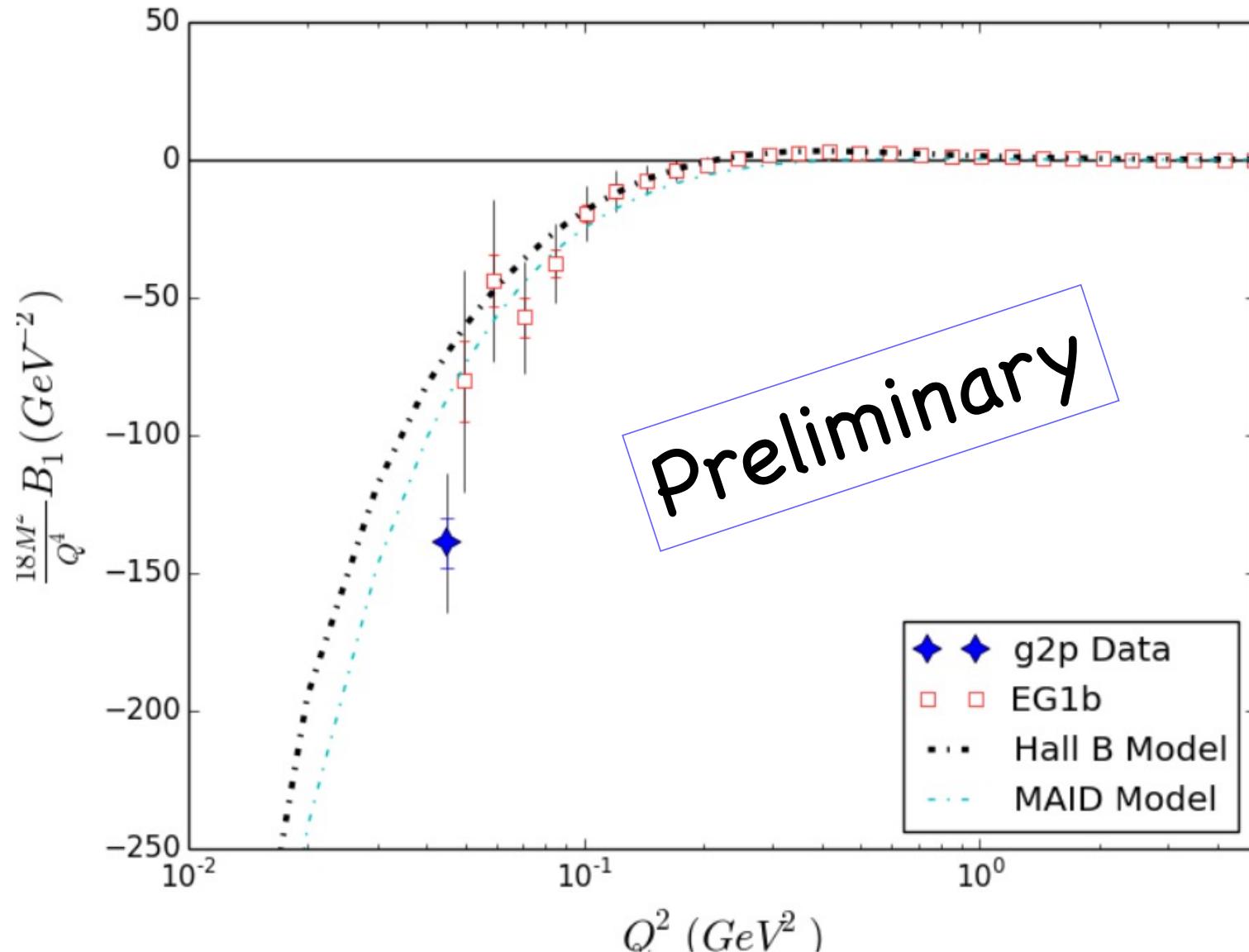
Carlson et al. PRA 78 022517 (2008)

Δ_{pol} Muonic Hydrogen



Antognini, Hagelstein, Pascalutsa (2022)

g_1 contribution to Δ_{pol}



courtesy David Ruth, UNH

Preliminary Evaluation of Δ_1

Term	Q^2 (GeV 2)	Contribution	Result	Stat	Sys
Δ_1	(0,0.043)	F_2 and g_1	1.28	0.20	0.83
	(0.043,5.0)	F_2	7.65	—	0.45
	(0.043,5.0)	g_1	-0.77	0.22	2.46
	(5.0, ∞)	F_2	0.00	—	—
	(5.0, ∞)	g_1	0.45	—	0.45
Total Δ_1			8.63	0.30	4.19

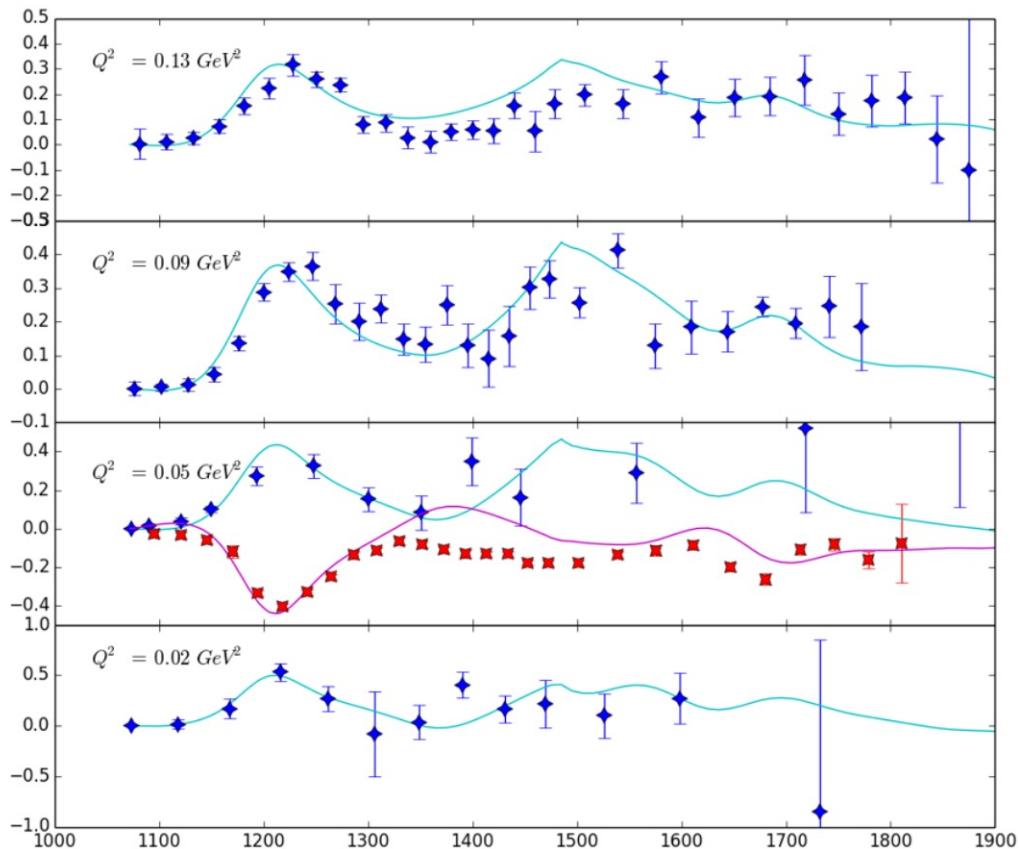
Preliminary

Compares favorably with published results

$$\Delta_1 = 8.85 \pm 0.30 \text{ (stat)} \pm 3.57 \text{ (sys)}$$

Phys. Rev. A. 78.022517

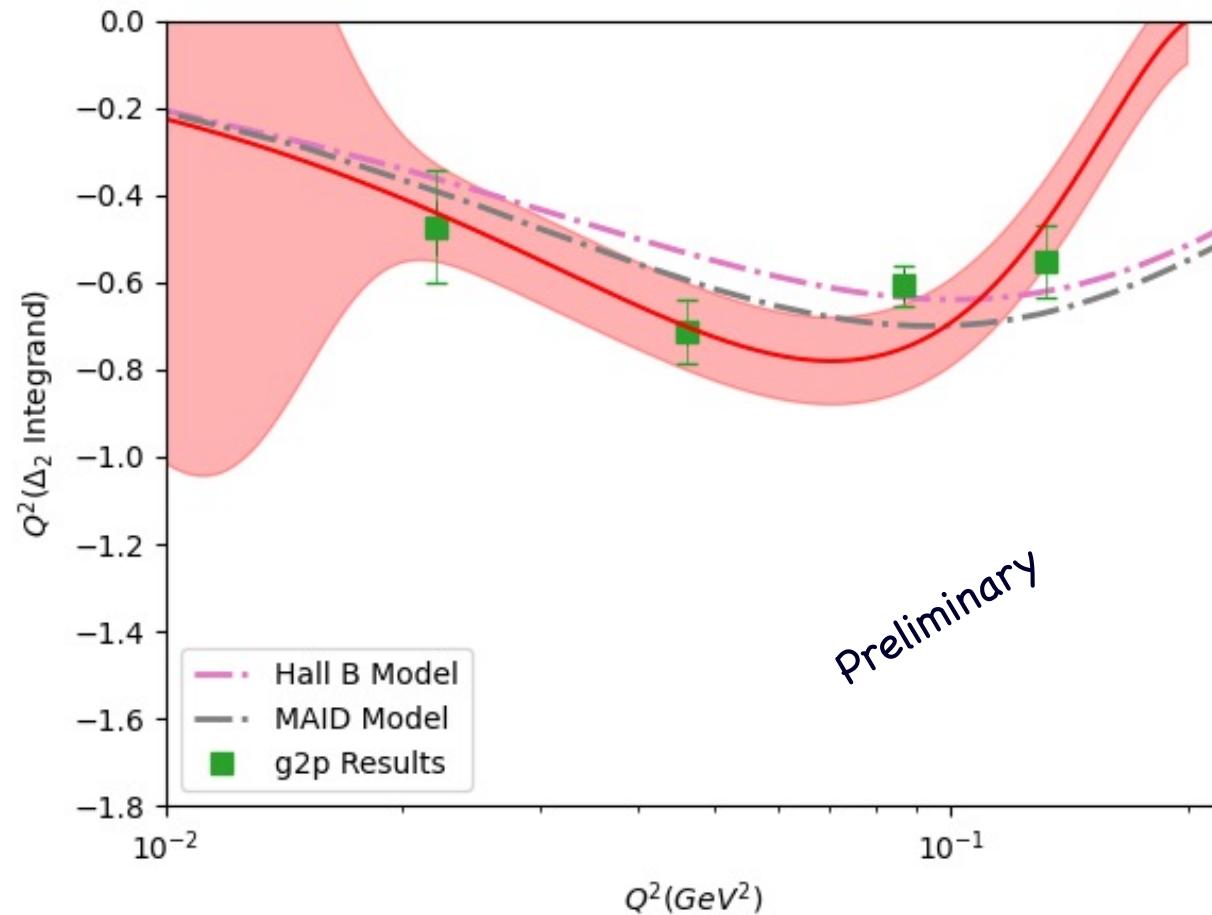
g_2 contribution to Δ_{pol} electronic Hydrogen



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

$g_2 > 0 \rightarrow \Delta_2 \text{ negative}$

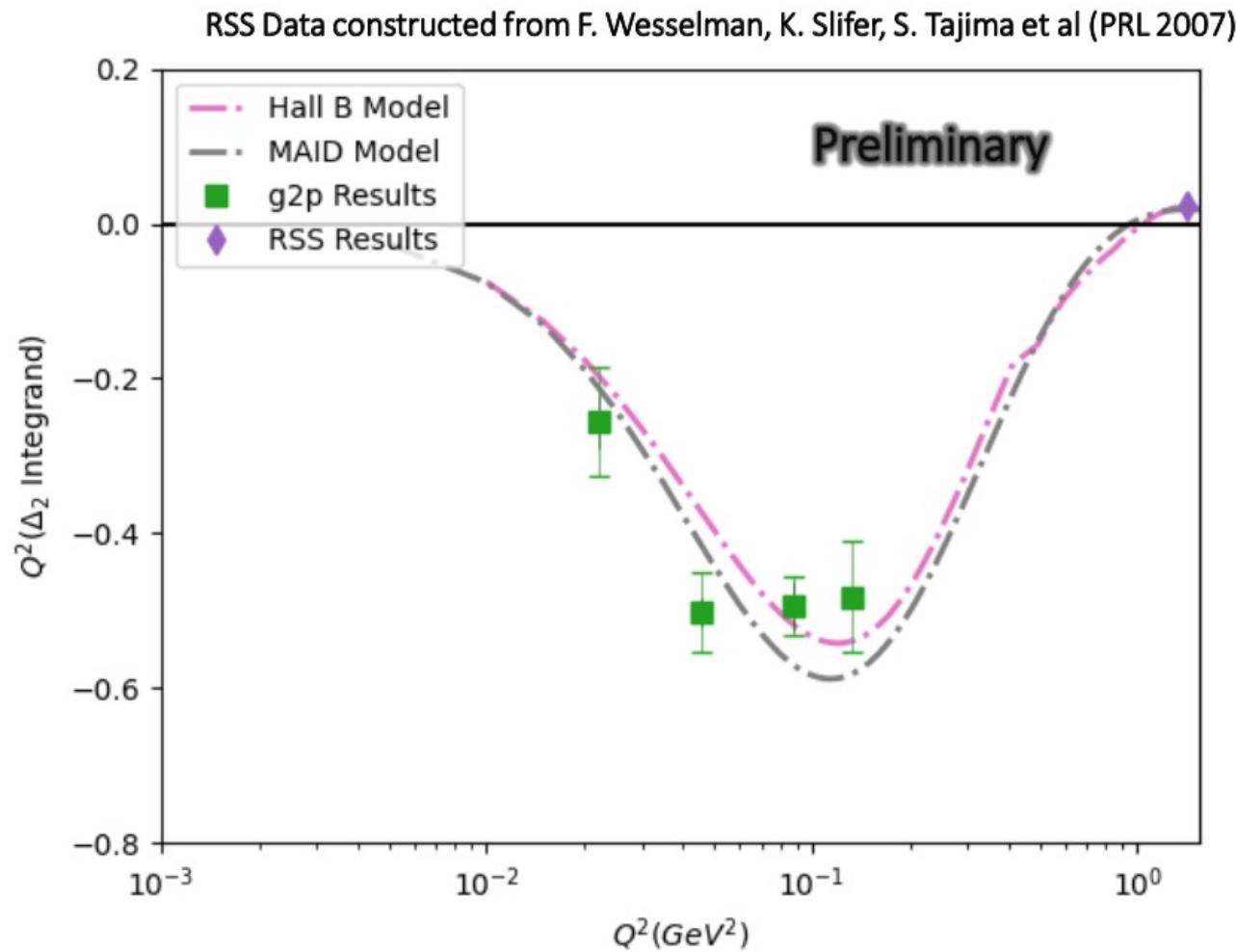
g_2 contribution to Δ_{pol} electronic Hydrogen



See D. Ruth's talk

Significant difference from g2ww

g_2 contribution to Δ_{pol} Muonic Hydrogen



See D. Ruth's talk

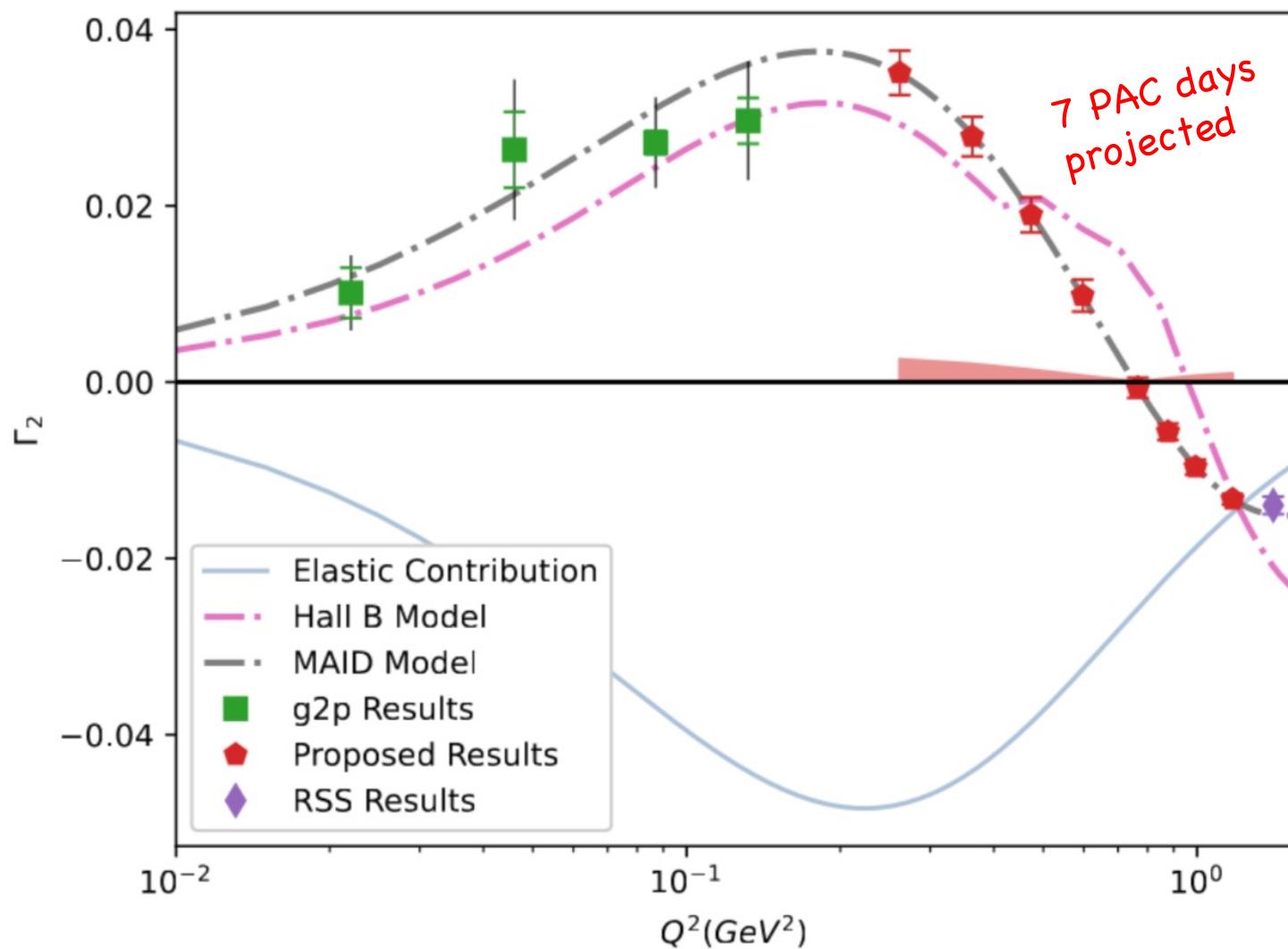
g_2 contribution to Δ_{pol} Muonic Hydrogen

Further Details in David's Talk

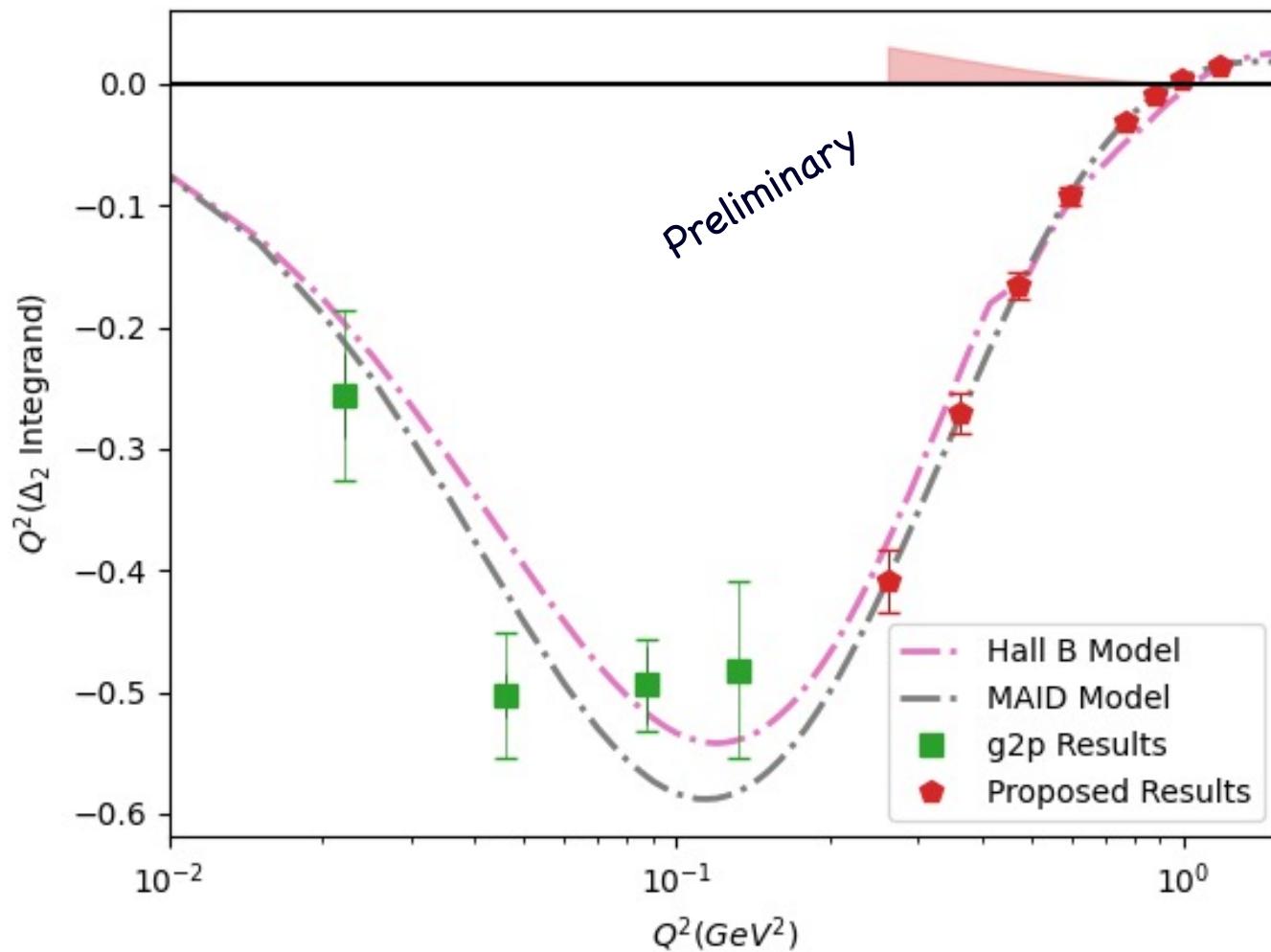
g_2 proposal at intermediate Q^2

Hall C HMS& SHMS
Transversely Polarized target
2.2 GeV and 4.4 GeV
 $0.4 < Q^2 < 1.2 \text{ GeV}^2$
85 nA polarized beam

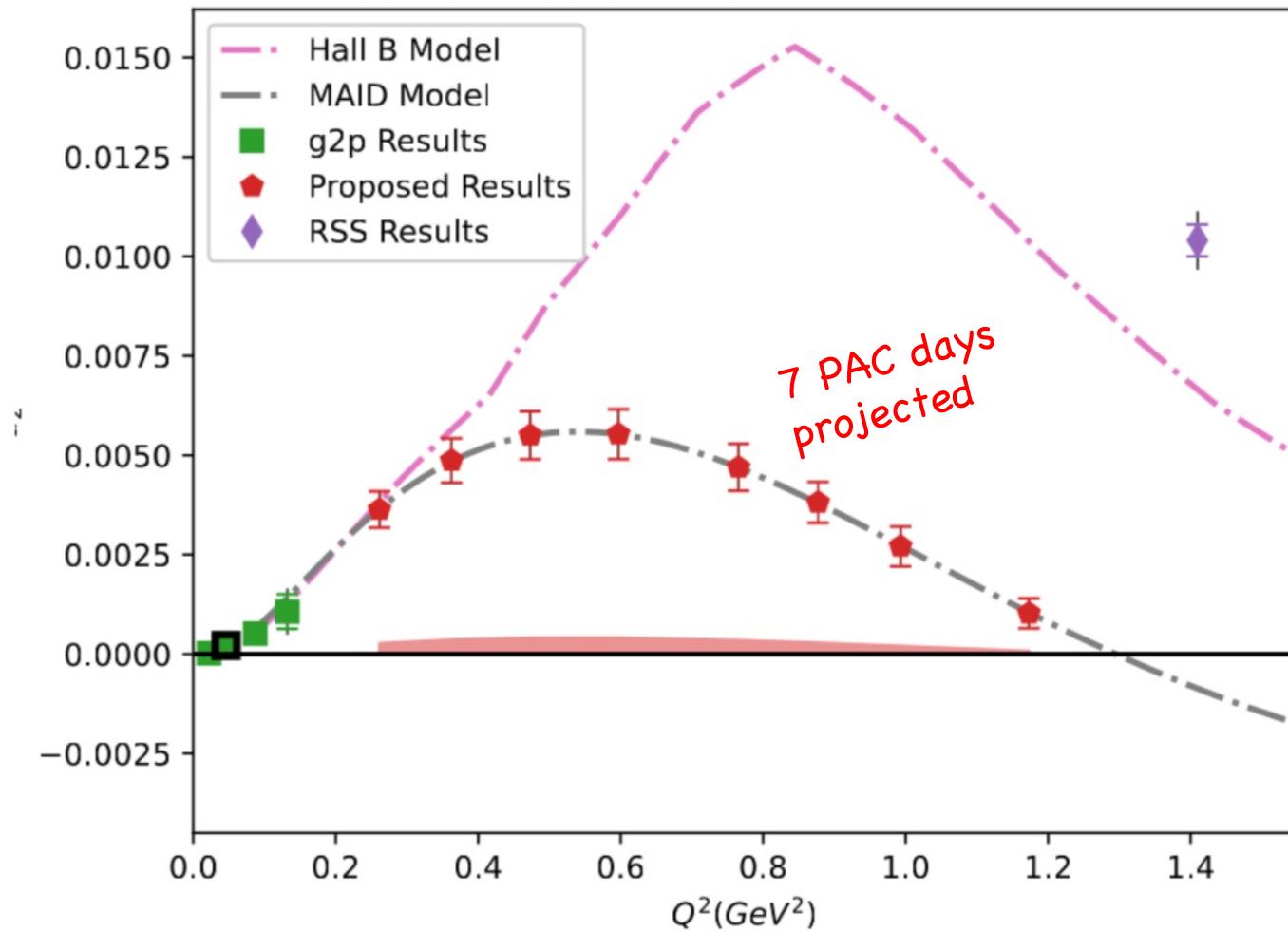
BC Sum Rule Projected



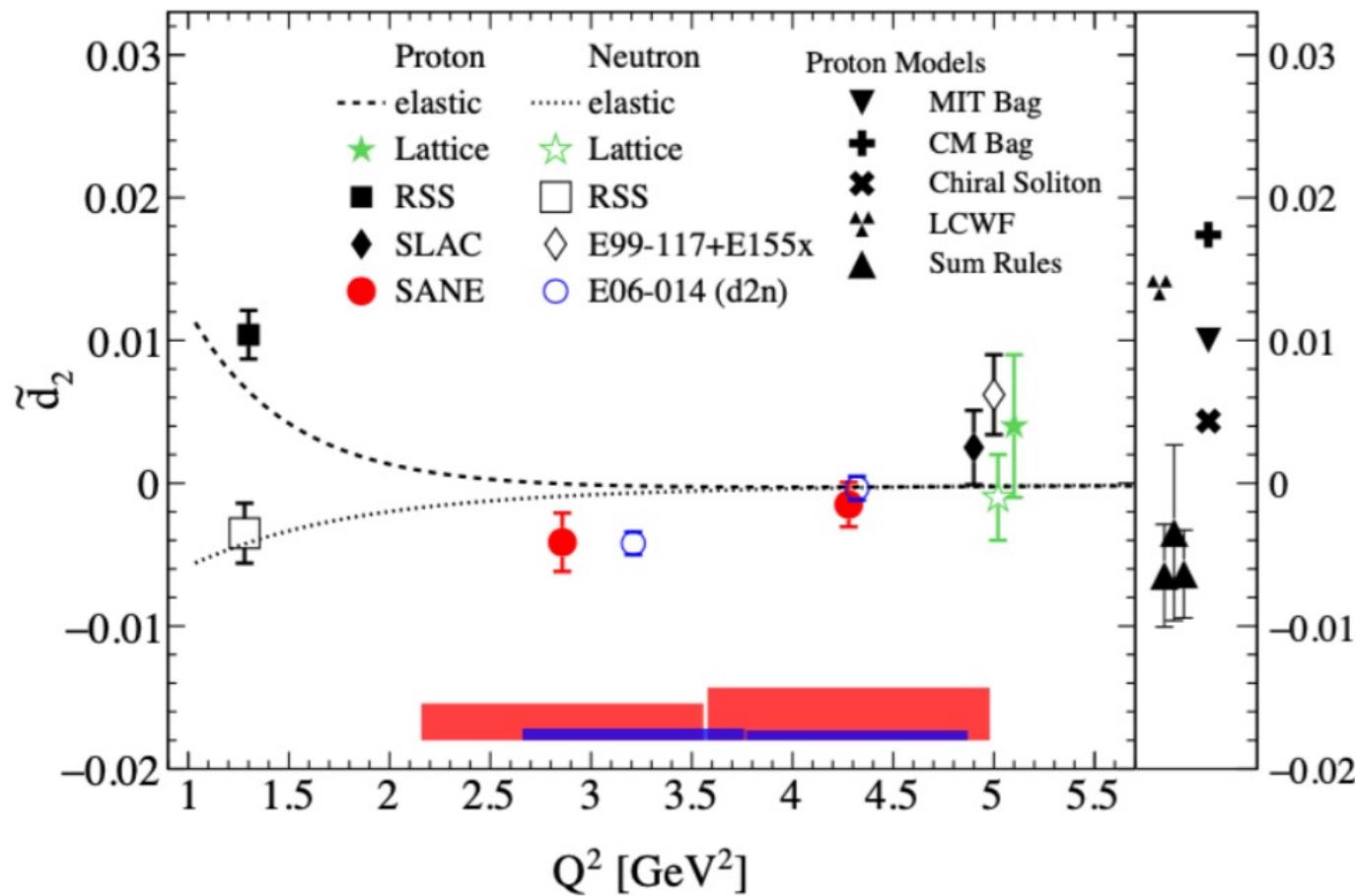
Δ_2 Muonic Hydrogen Projected



d_2 Projected



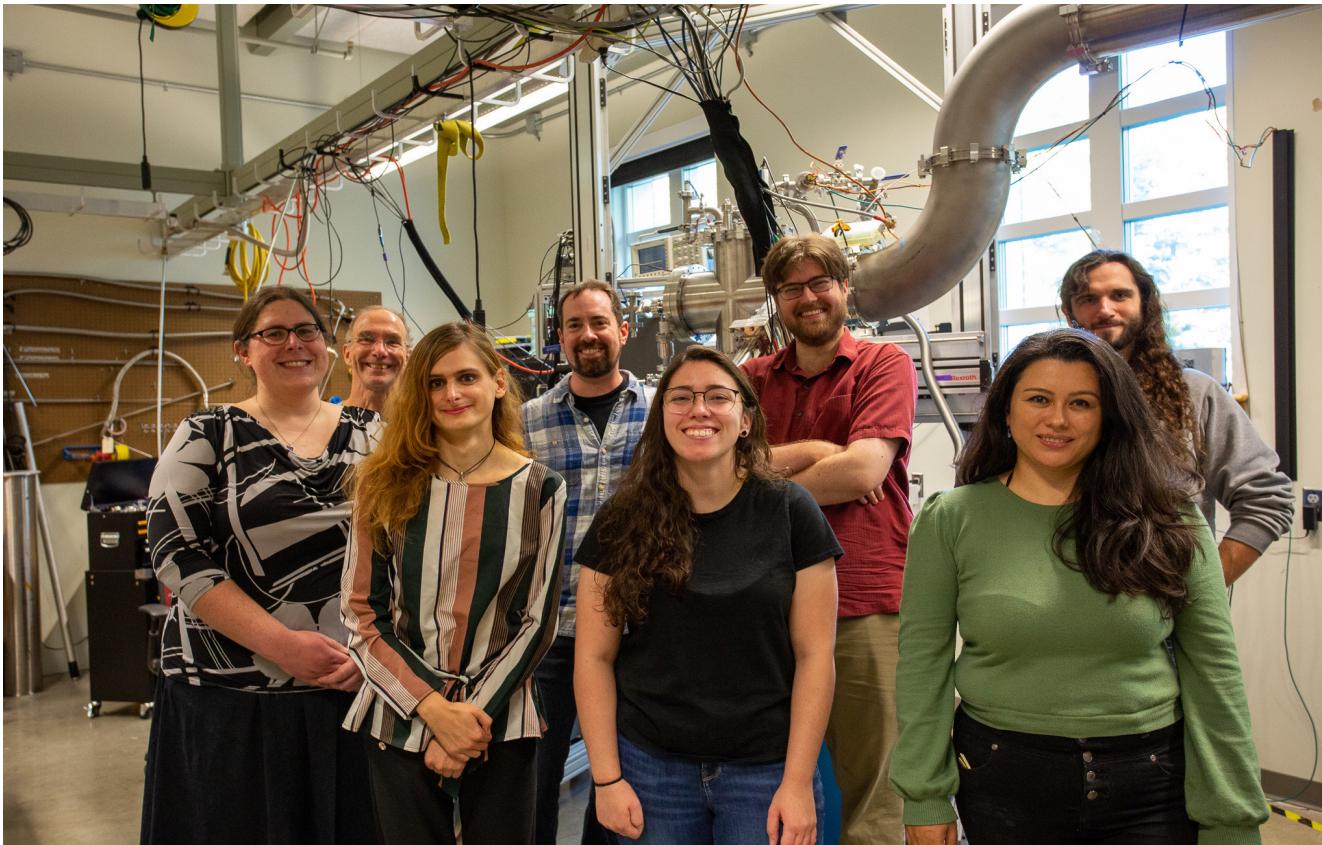
SANE Experiment



SANE experiment found interesting d_2 results
at odds with other data and most QCD predictions

Armstrong et al (2019)

UNH Polarized Target Lab



3 faculty

-Slifer, Long, Santiesteban

2 post-docs

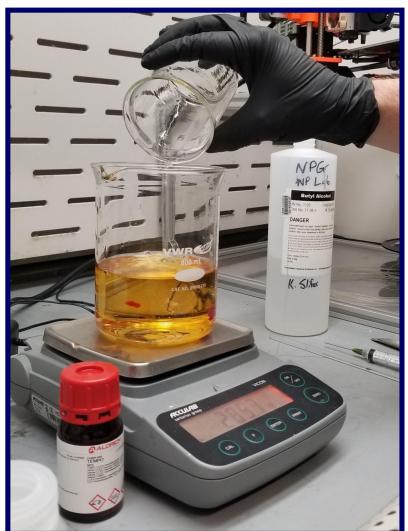
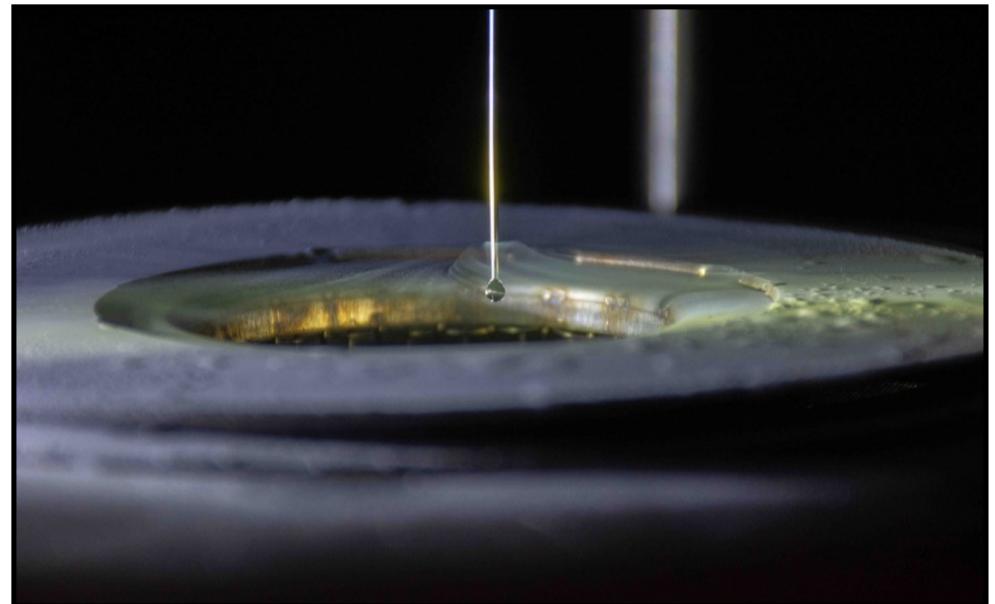
3 grad students:

lots of undergrads

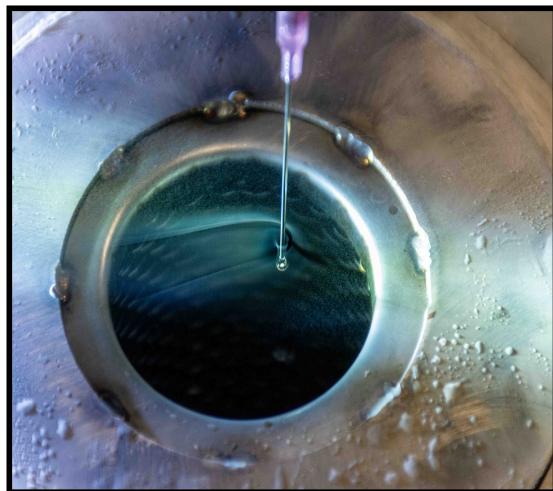
Projects

- Polarized Target Material Production & Labview controls
- Tensor Polarization for the b1/Azz experiment

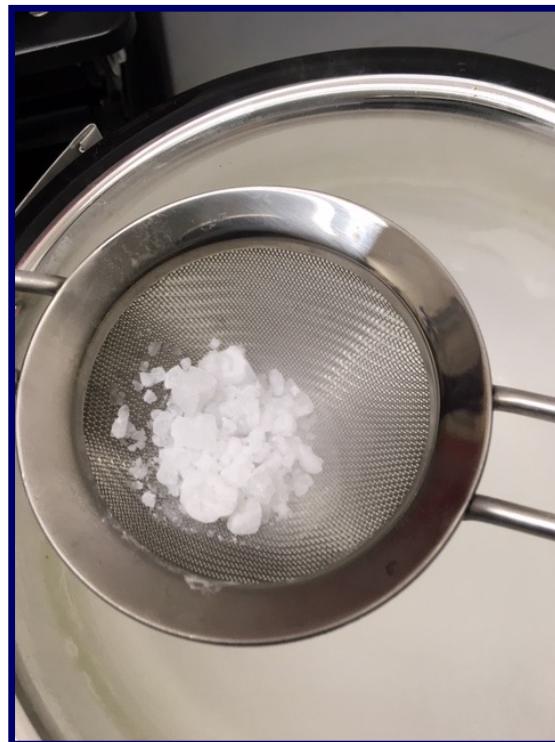
Target Material Production at UNH



Target Material Production at UNH



Butanol and other alcohols solidification



grade 5.5 NH_3 & ND_3



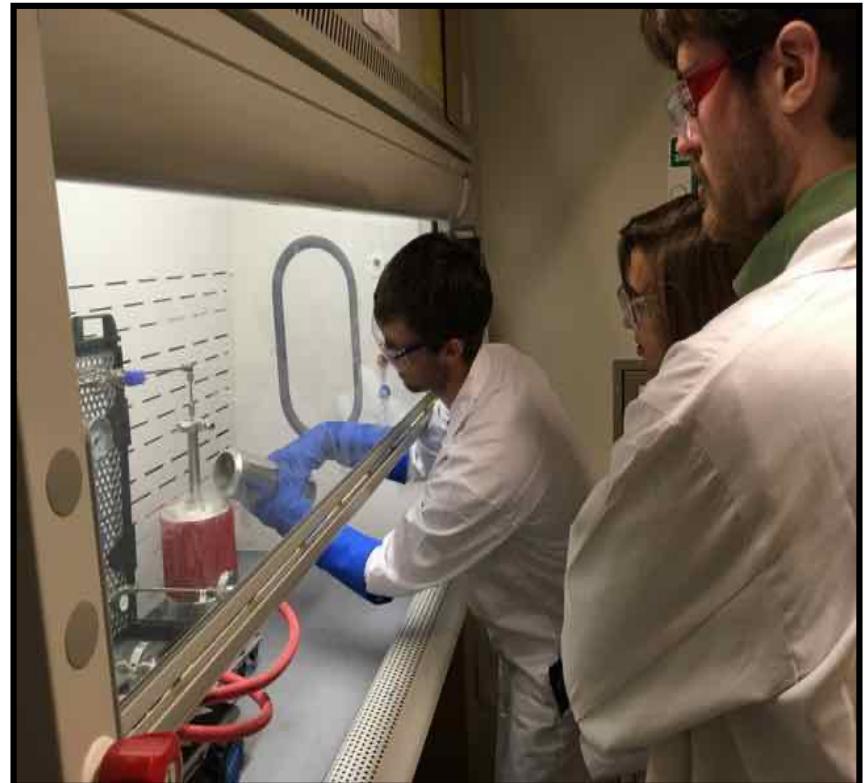
Chemical Doping



Rapid vs Slow Cooling of NH_3



Target Material Production at UNH



- Dedicated fume hood for Handling Ammonia and other caustic/toxic materials
- Vacuum GloveBox** allows for over/under-pressuring
- Primarily chemical doping of ammonia and alcohols for now.
But potential to do much more.



C12-13-011: The b_1 experiment

30 Days in Jlab Hall C
A- Physics Rating

C12-15-005: A_{zz} for $x > 1$

44 Days in Jlab Hall C
A- Physics Rating

RunGroup Spokespersons

Chen, Day, Higinbothan, Kalantarians, Keller
Long, Rondon, Slifer, Solvignon



Jefferson Lab

WZ

C12-13-011: The

30 Days :
A- Physics Rating

Conditional Status Removed
August 1, 2022

Now both experiments Fully Approved!

C12-15-005: A_{zz} for $x > 1$

44 Days in Jlab Hall C
A- Physics Rating

RunGroup Spokespersons

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Long, Rondon, Slifer, Solvignon



C12-13-011: The b_1 experiment

30 Days in Jlab Hall
A- Physics Rating

C12-15-005: A_{zz} for $x > 1$

44 Days in Jlab Hall C
A- Physics Rating

Jeopardy Review this summer

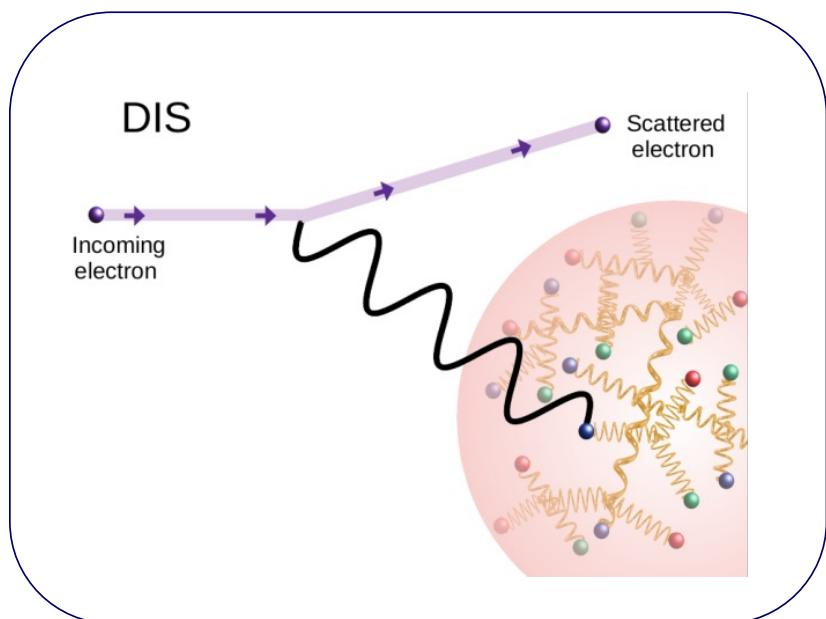
RunGroup Spokespersons

Chen, Day, Higinbothan, Kalantarians, Keller
Long, Rondon, Slifer, Solvignon

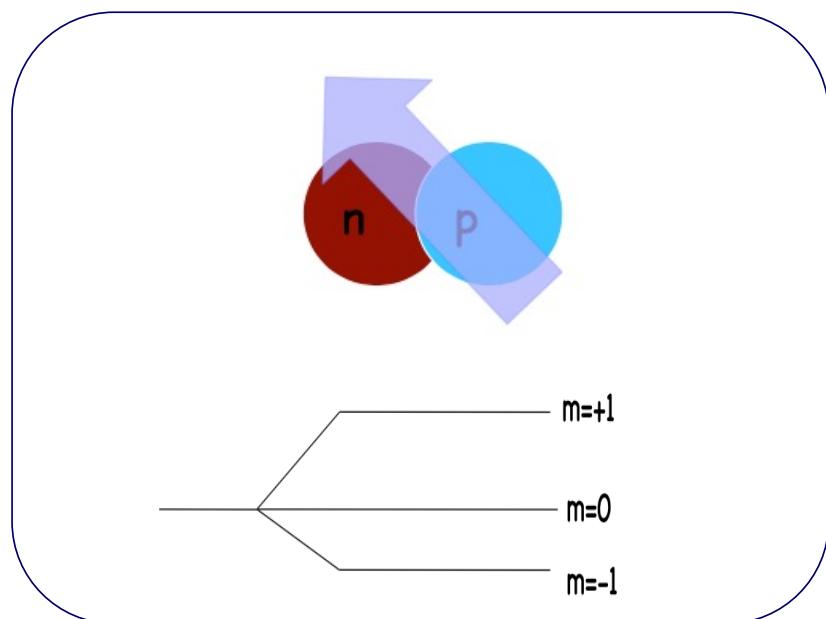
b_1 structure function

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

DIS (probing quarks)



but depends on the Deuteron spin state



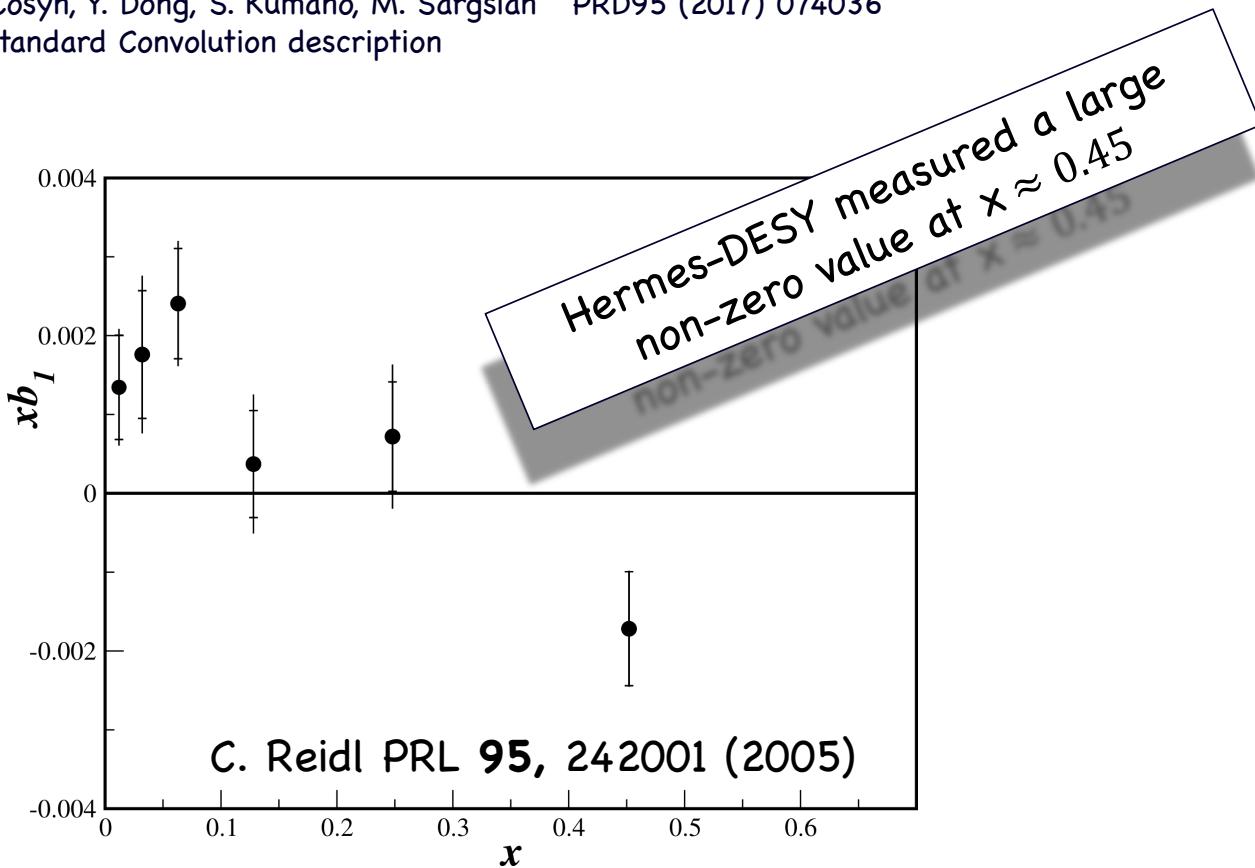
Data from HERMES

Conventional Nuclear Physics predicts b_1 to be vanishingly small at large x

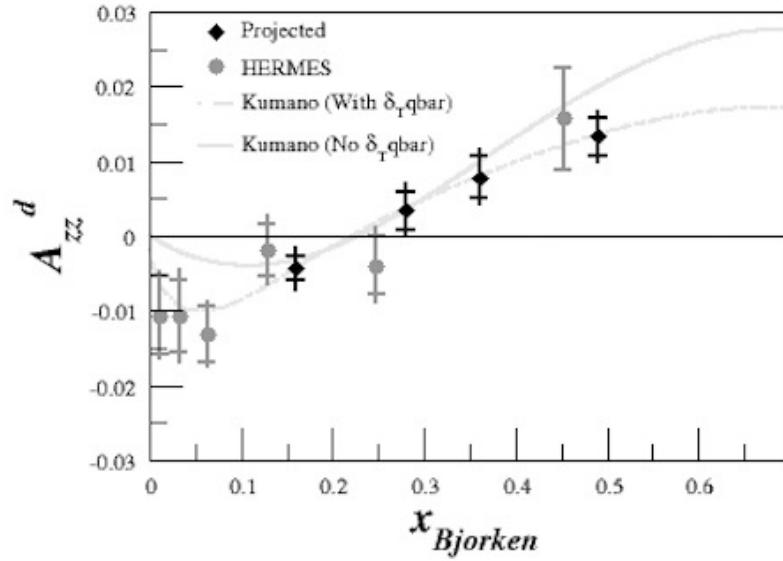
Khan & Hoodbhoy, PRC 44 ,1219 (1991) : $b_1 \approx O(10^{-4})$
Relativistic convolution model with binding

Umnikov, PLB 391, 177 (1997) : $b_1 \approx O(10^{-3})$
Relativistic convolution with Bethe-Salpeter formalism

W. Cosyn, Y. Dong, S. Kumano, M. Sargsian PRD95 (2017) 074036
Standard Convolution description

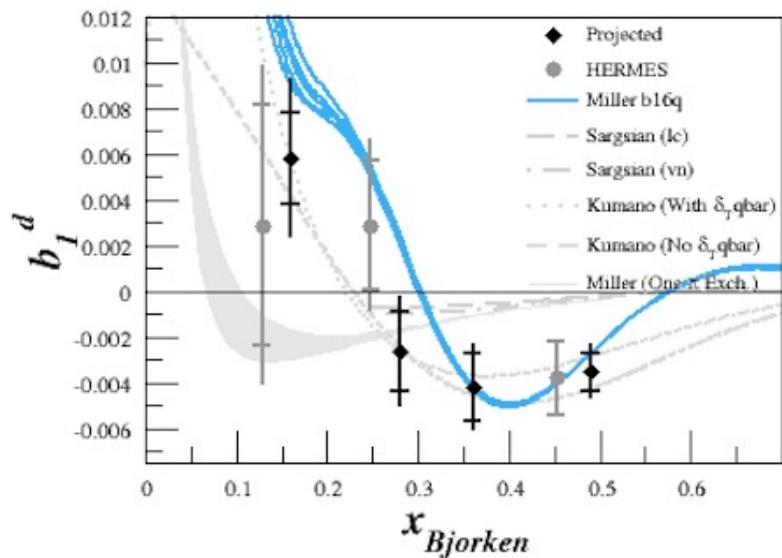


Projected Results for Q = 30%

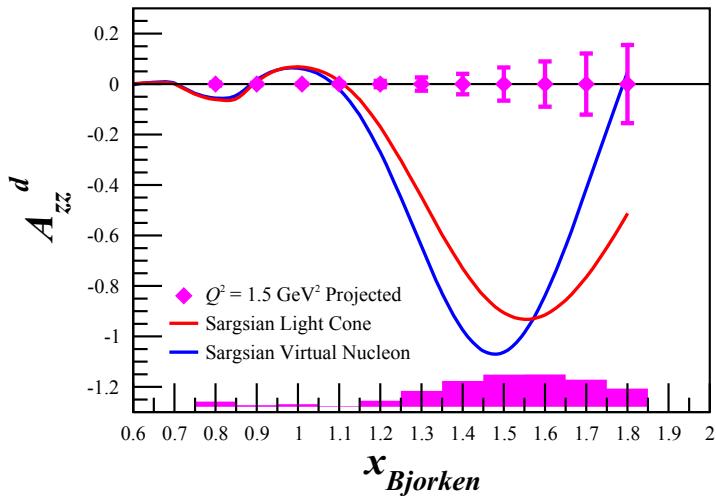


Unique probe of exotic contributions
To the Deuteron wavefunction

Hidden Color/6q configurations



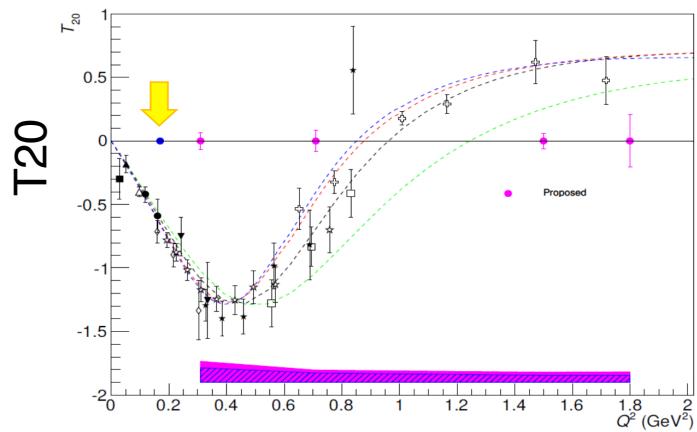
A_{zz} in the x>1 Region



Very Large Tensor Asymmetries predicted

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

4 σ discrim between hard/soft wave functions
6 σ 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.”

Summary

δ_{LT} favors Alarcon et al χ PT calculation

Hyperfine splitting contributions from g_1 is consistent with previous values within large error bars

g_2 HFS contribution is very different from previous model based predictions.

Proposal to measure g2p for $0.4 < Q^2 < 1.2$

UNH Target Lab

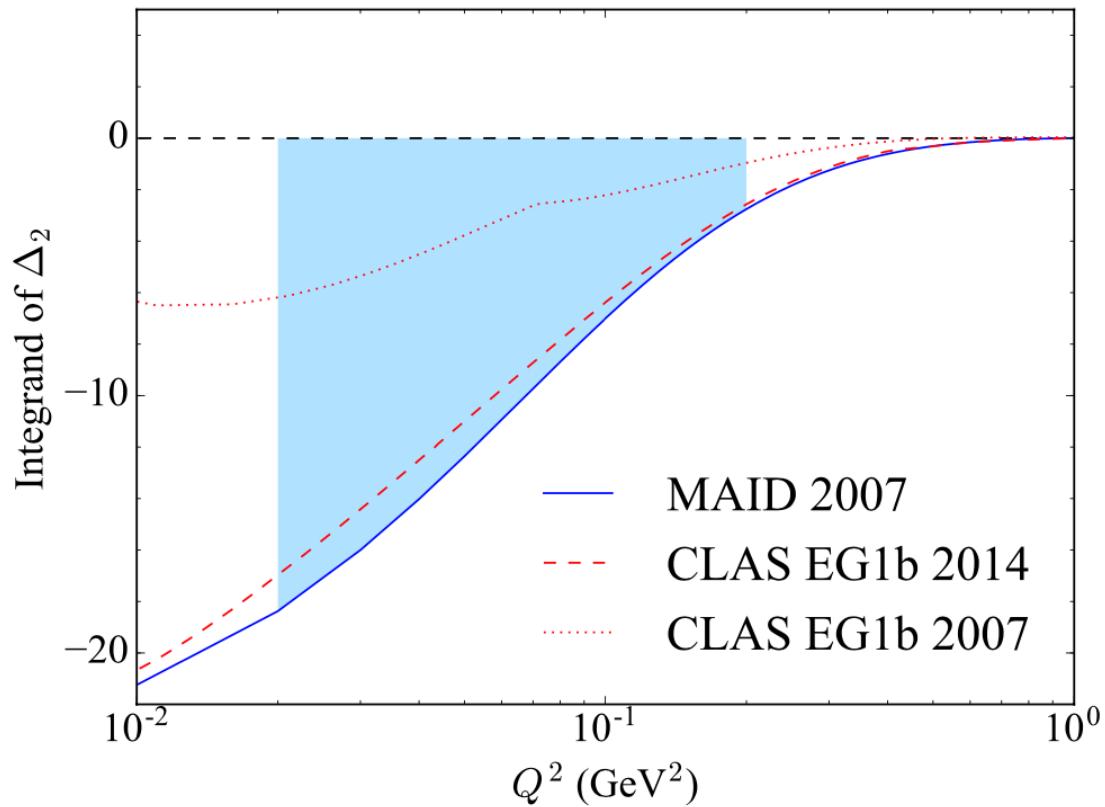
Tensor program at Jlab > 2026

See David Ruth's talk for full discussion of μP HF results

Questions?

Backups

Δ_2 Model Dependence

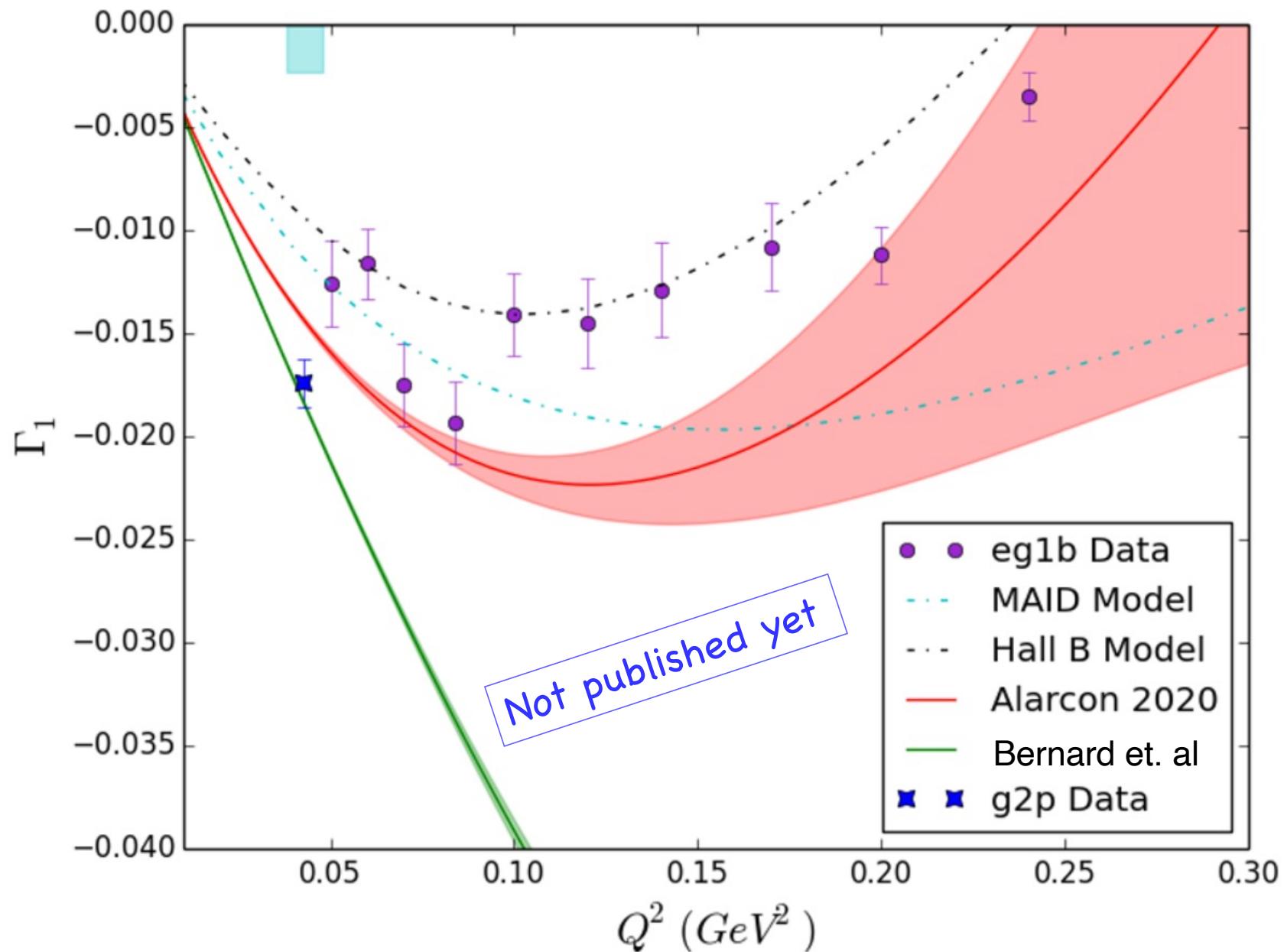


Term	$Q^2 (\text{GeV}^2)$	MAID	Hall B	HB 2007
Δ_2	(0,0.05)	-0.87	-0.80	-0.23
	(0.05,20)	-1.26	-1.16	-0.33
	(20, ∞)	0.00	0.00	0.00
Total Δ_2		-2.13	-1.96	-0.56

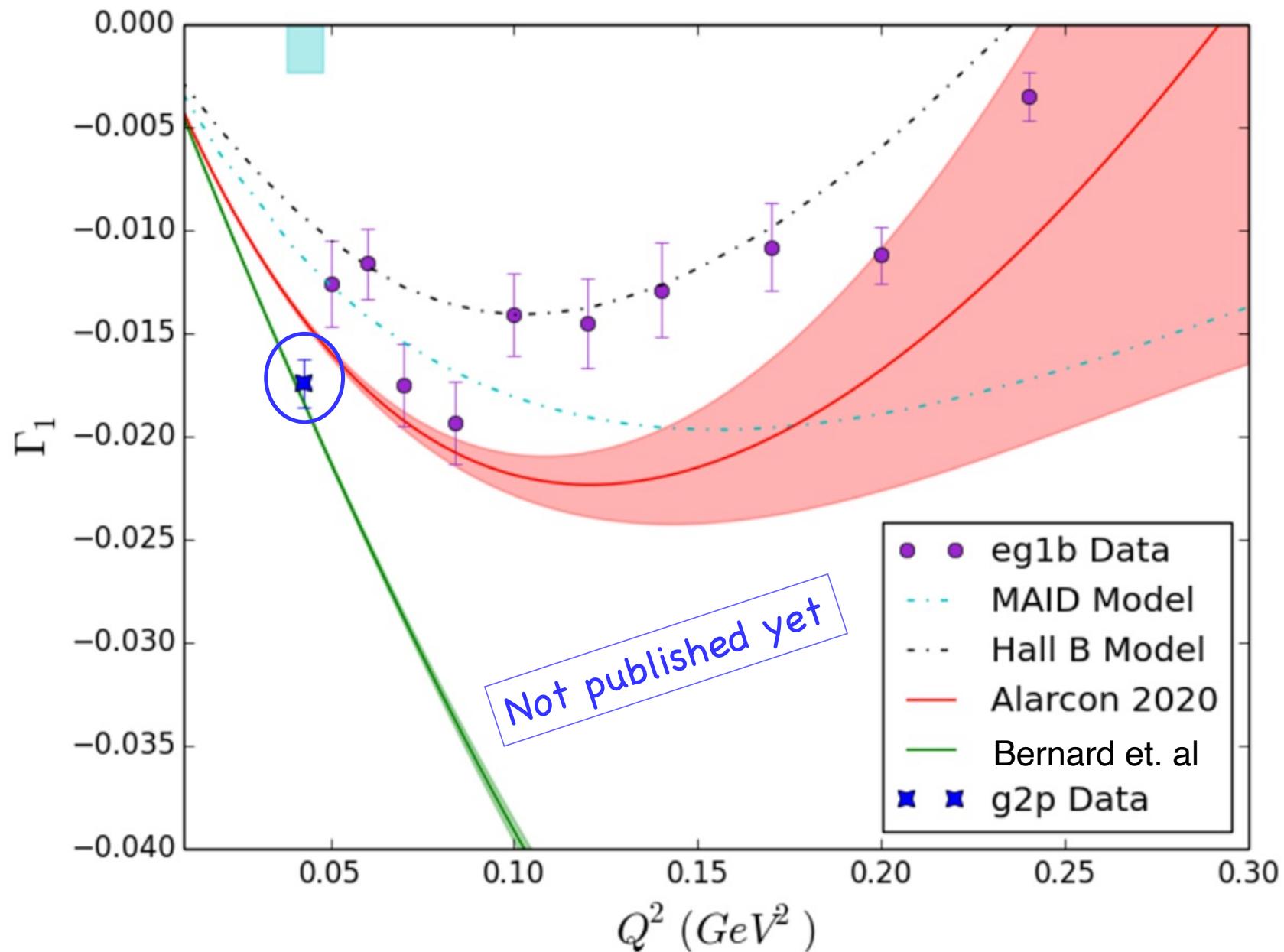
Phys.Rev.A.78.022511

Significant difference from 2007 CLAS model

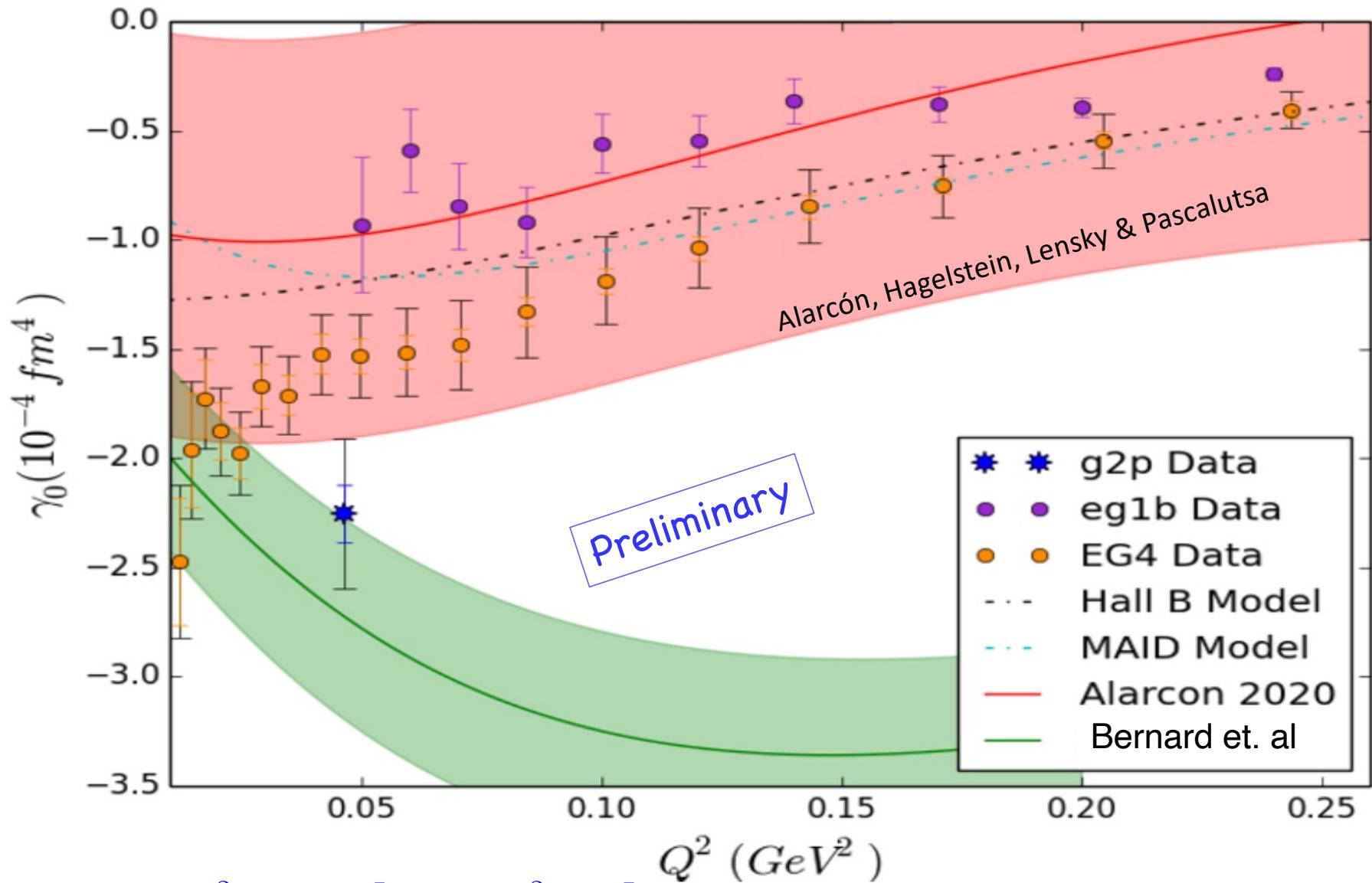
1st Moment Γ_1



1st Moment Γ_1



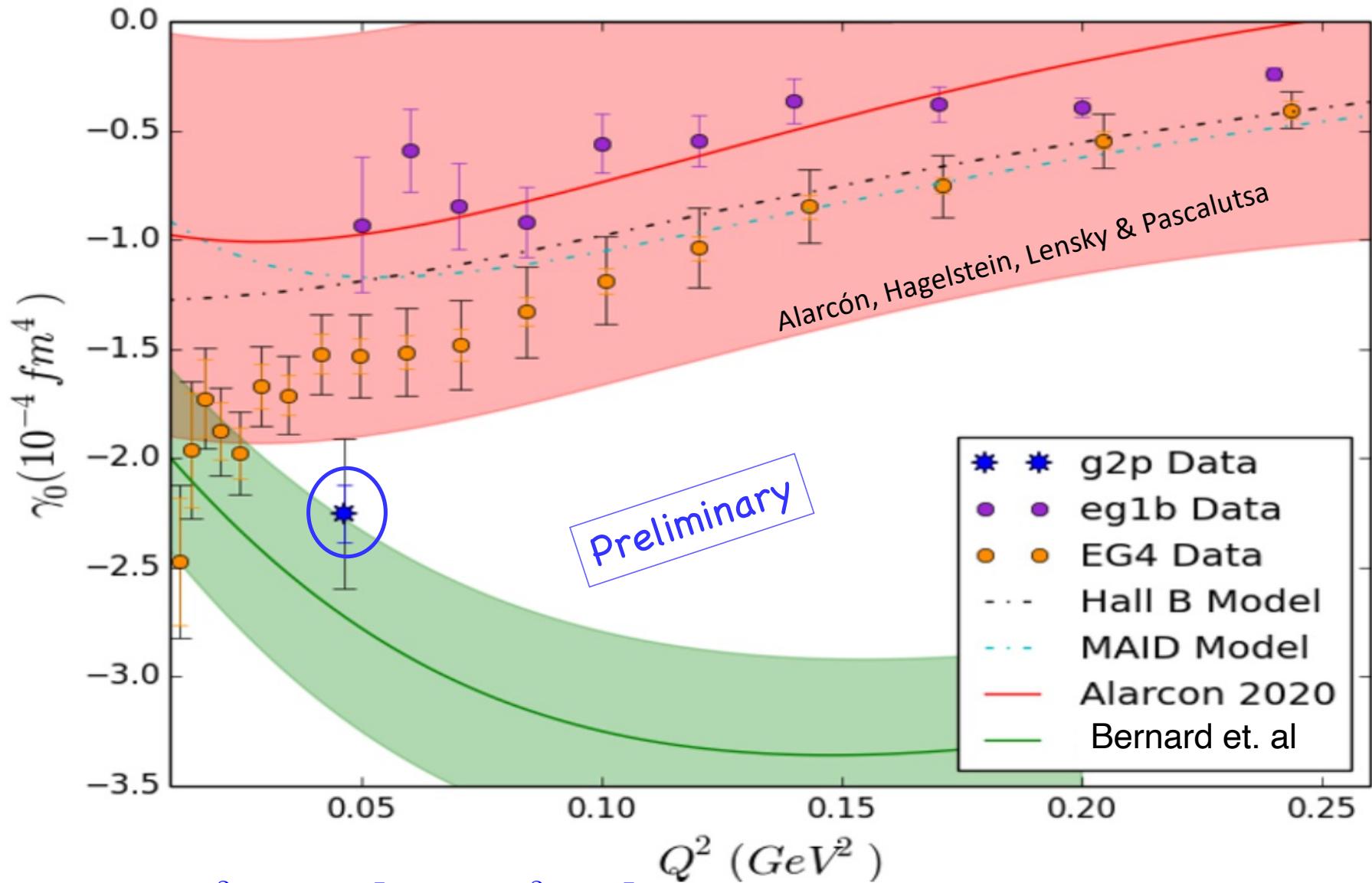
Proton γ_0



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

Some disagreement
Between Hall A & B

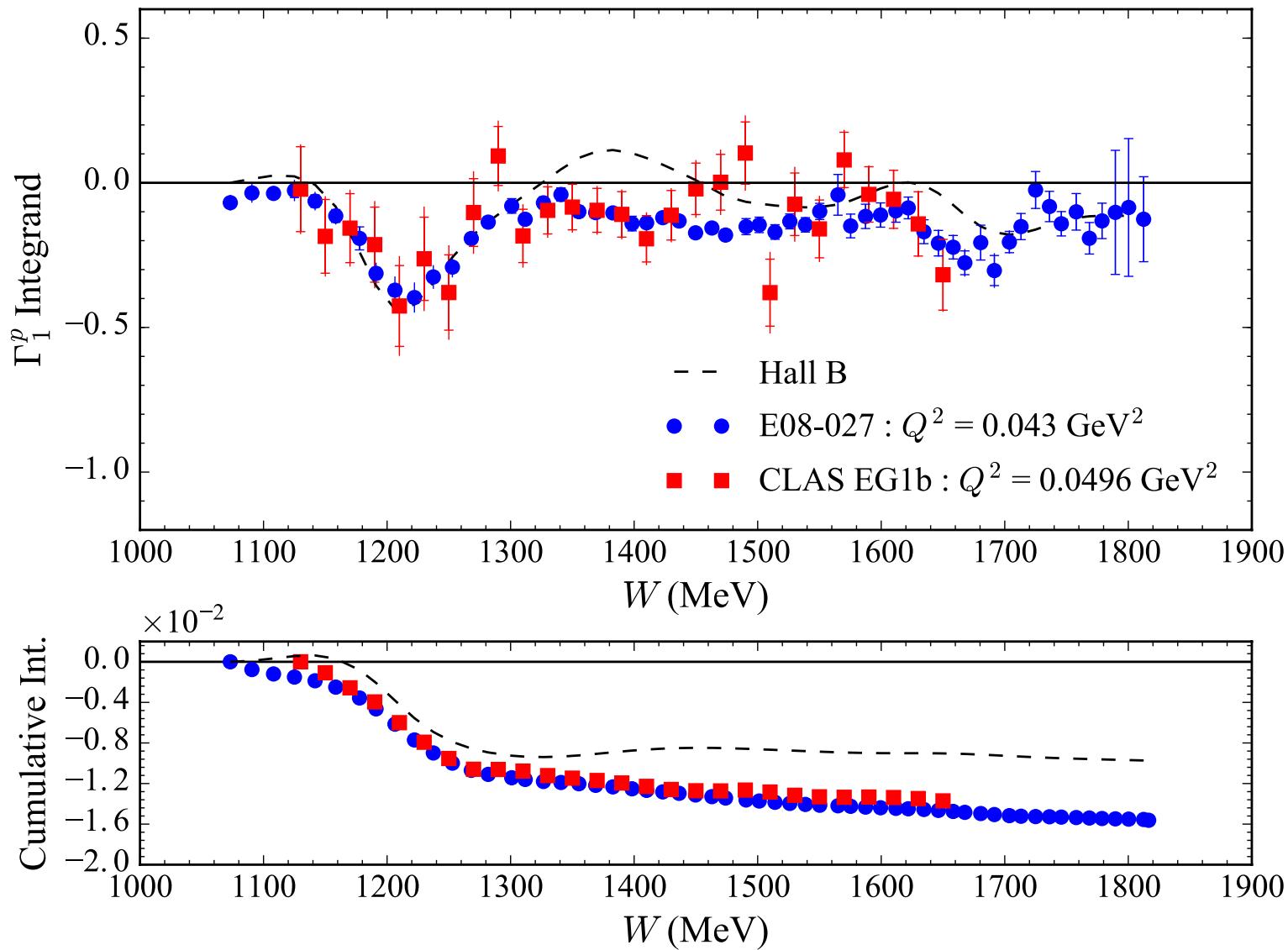
Proton γ_0



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

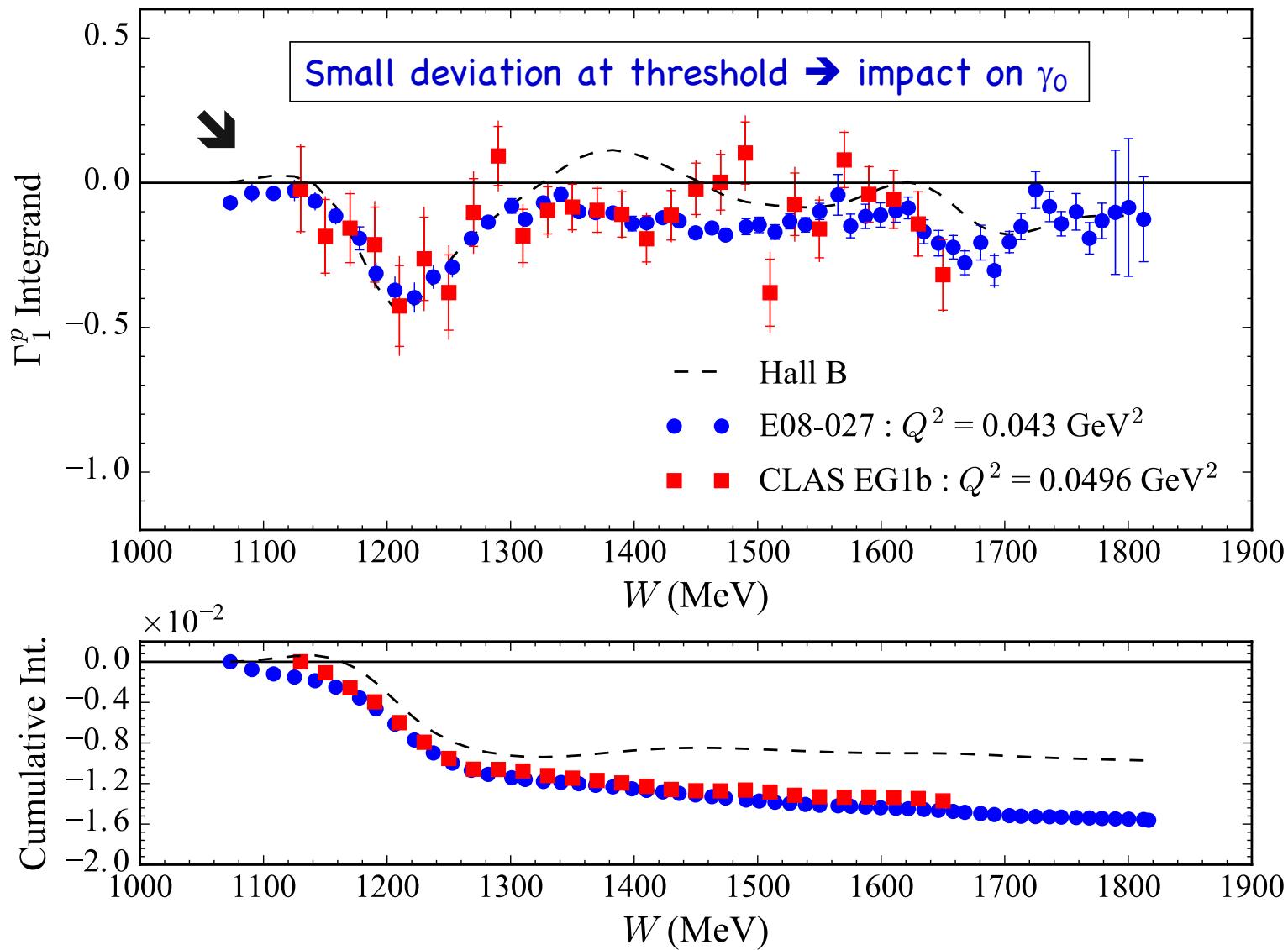
Some disagreement
Between Hall A & B

Proton g1 (E08-027 vs. CLAS)



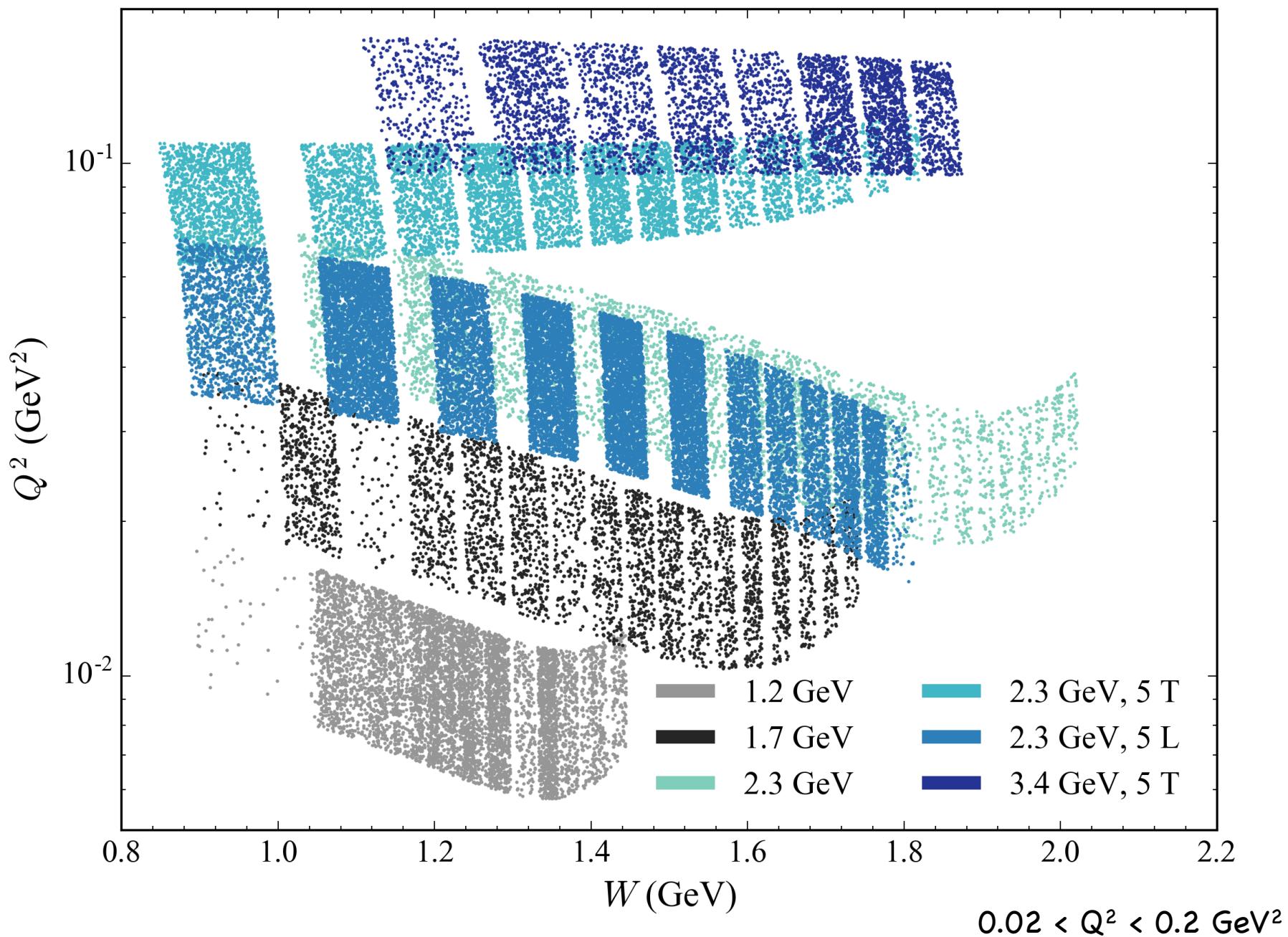
courtesy R. Zielinski, UNH

Proton g1 (E08-027 vs. CLAS)

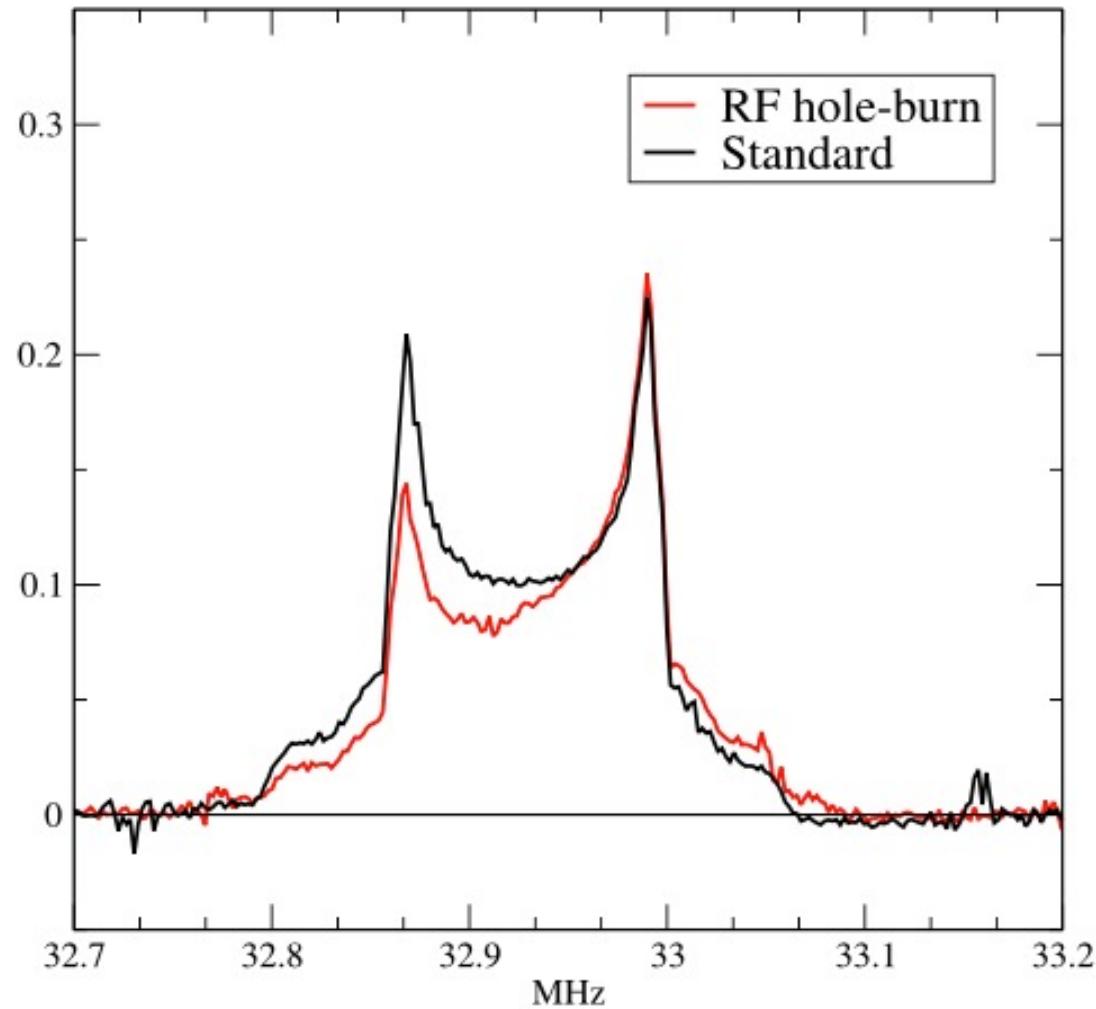


courtesy R. Zielinski, UNH

Kinematic Coverage

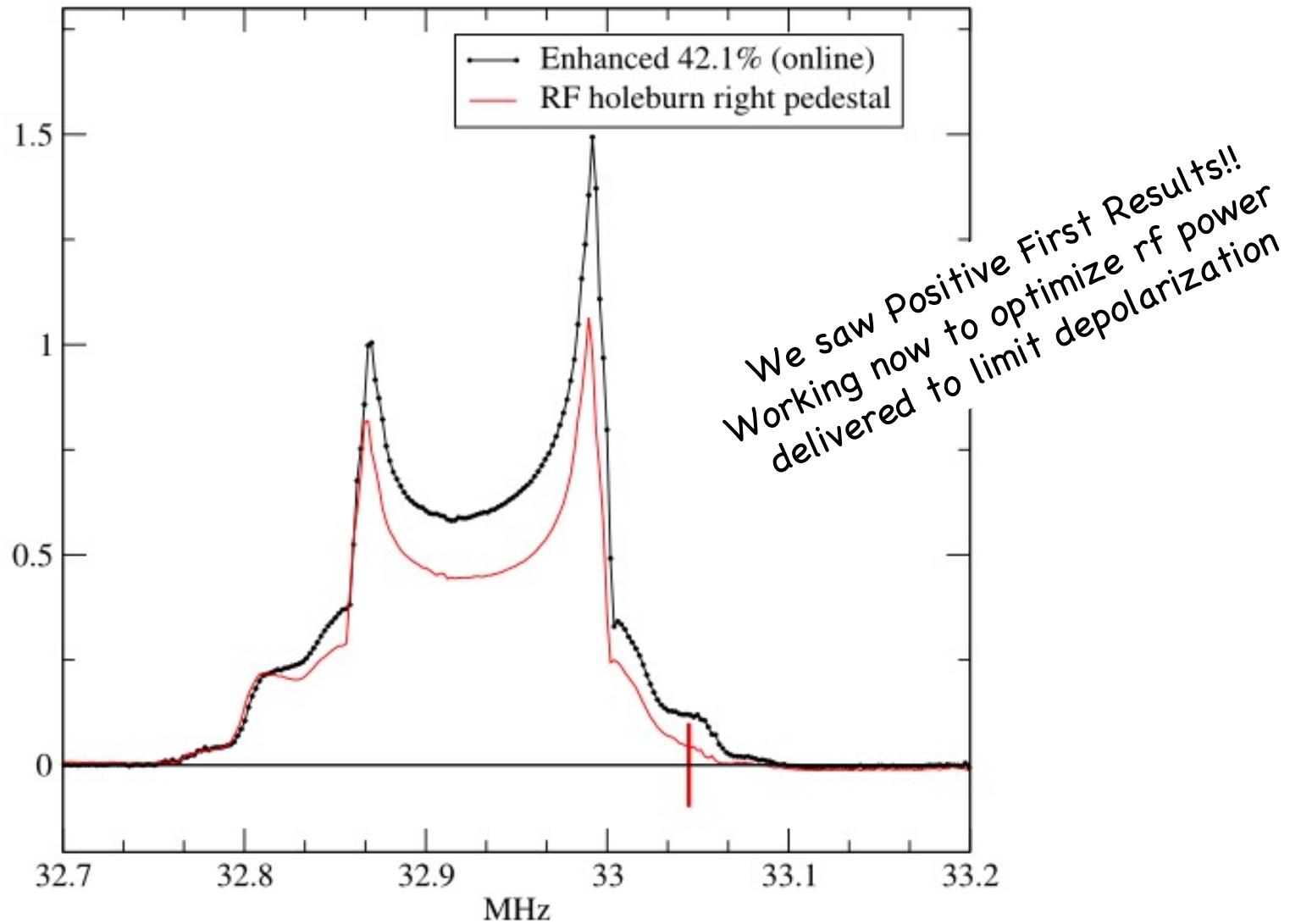


Deuteron Tensor Enhancement



Tensor Enhancement by factor of 5.7 after rf-hole burning the left peak
1,2-Propanediol-d8, chemically doped with OX063, with 5T/1K

Deuteron Tensor Enhancement



Tensor Enhancement to $P_{zz} \approx 16(\pm 5)\%$
after rf-hole burning the left peak and right shoulder.

1,2-Propanediol-d8, chemically doped with OX063, with 5T/1K