The Proton Spin Structure Function g2p Contribution to Hyperfine Splitting

Muonic Hydrogen Workshop

PSI, Switzerland

2022-10-15

Karl Slifer

University of New Hampshire

This Talk

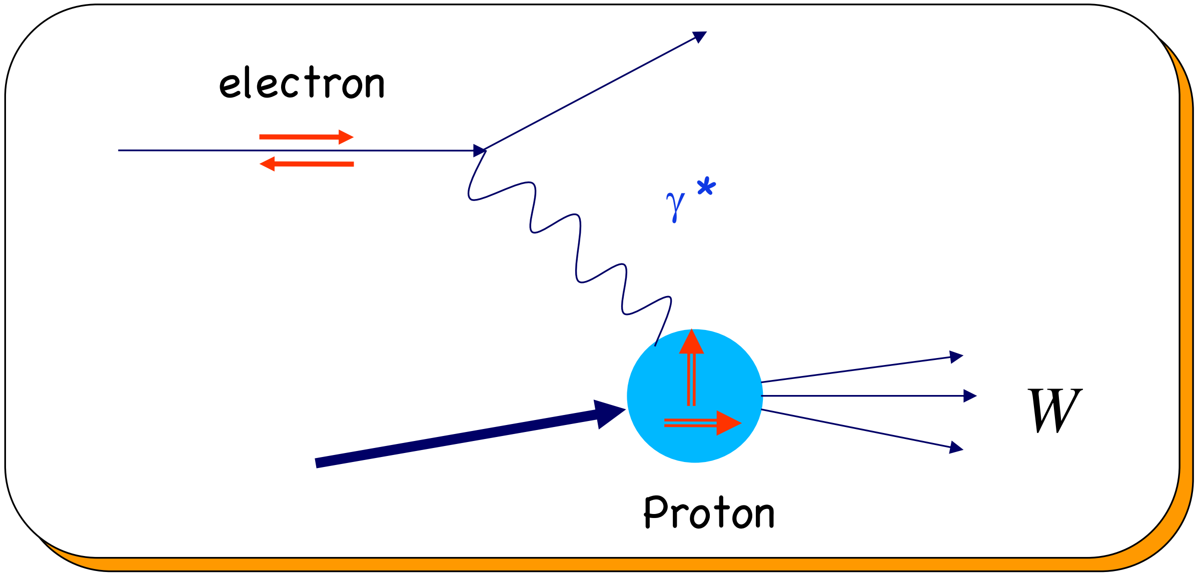
The E08-027 (g2p) experiment

- Published g_2 and g_1 results
- Hyperfine D_{pol} terms

Tensor Program at Jlab

Polarized Target at UNH

Inclusive Scattering



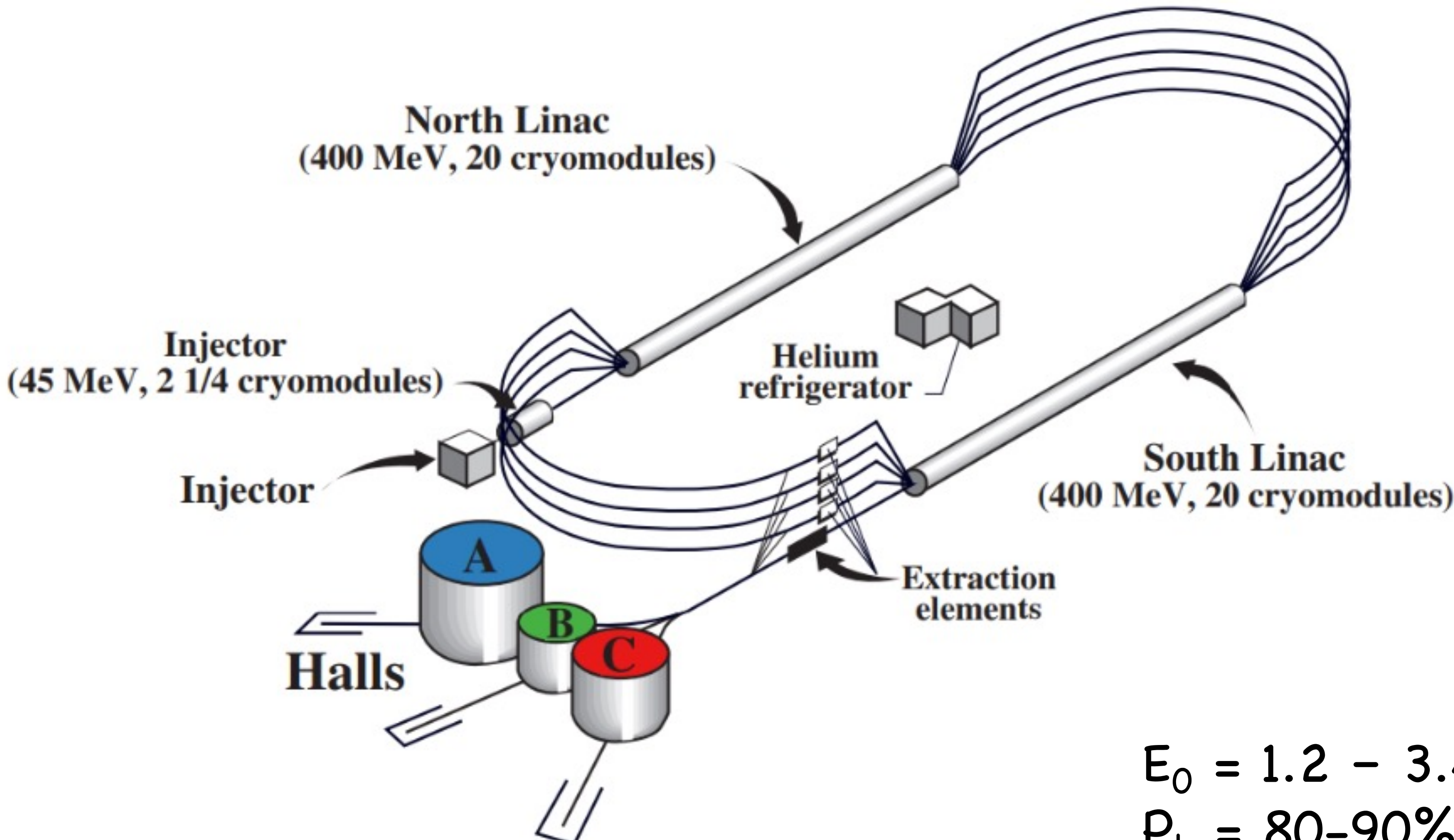
When we add spin degrees of freedom to the target and beam, 2 Additonal SF needed.

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

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

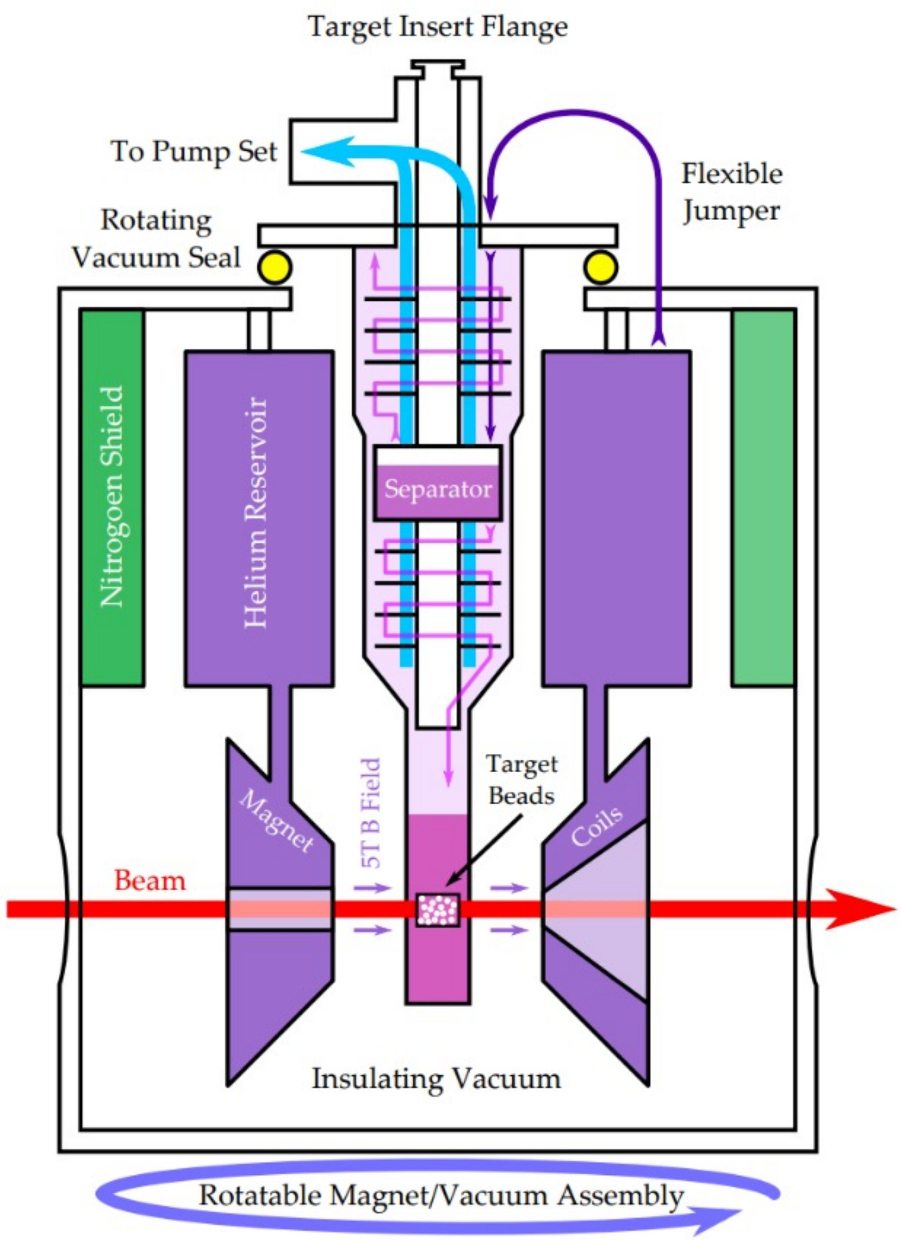
Inclusive **Polarized** Cross Section

Jefferson Lab Hall A



E_0 = 1.2 – 3.4 GeV
P_b = 80–90%
I < 100 nA

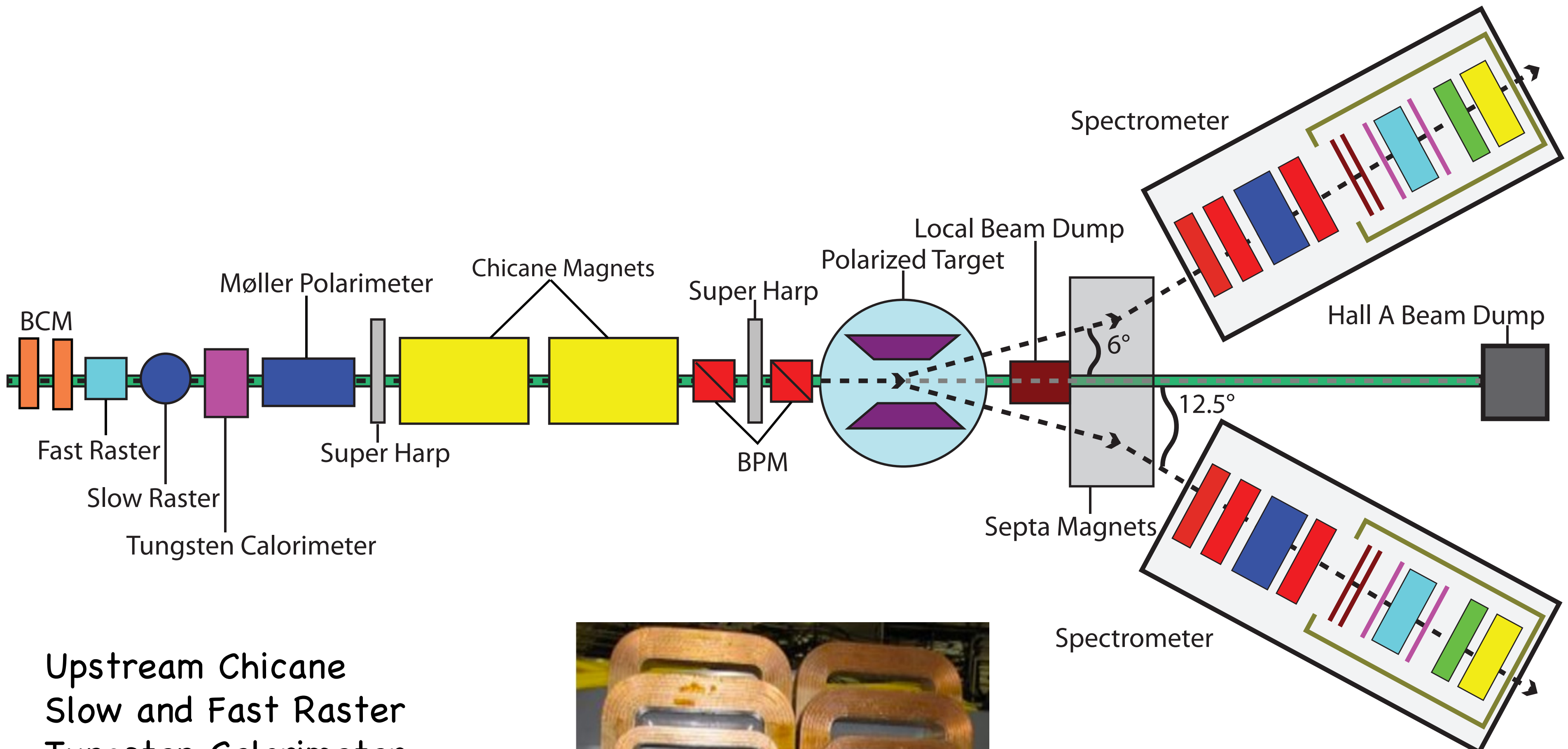
DNP Solid Polarized Target



Dynamic Nuclear Polarization

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

Hall A Beamline



Upstream Chicane
Slow and Fast Raster
Tungsten Calorimeter
RT Septa Magnet
Local Beam Dump

The g2p Experiment

Polarized proton target

upstream chicane

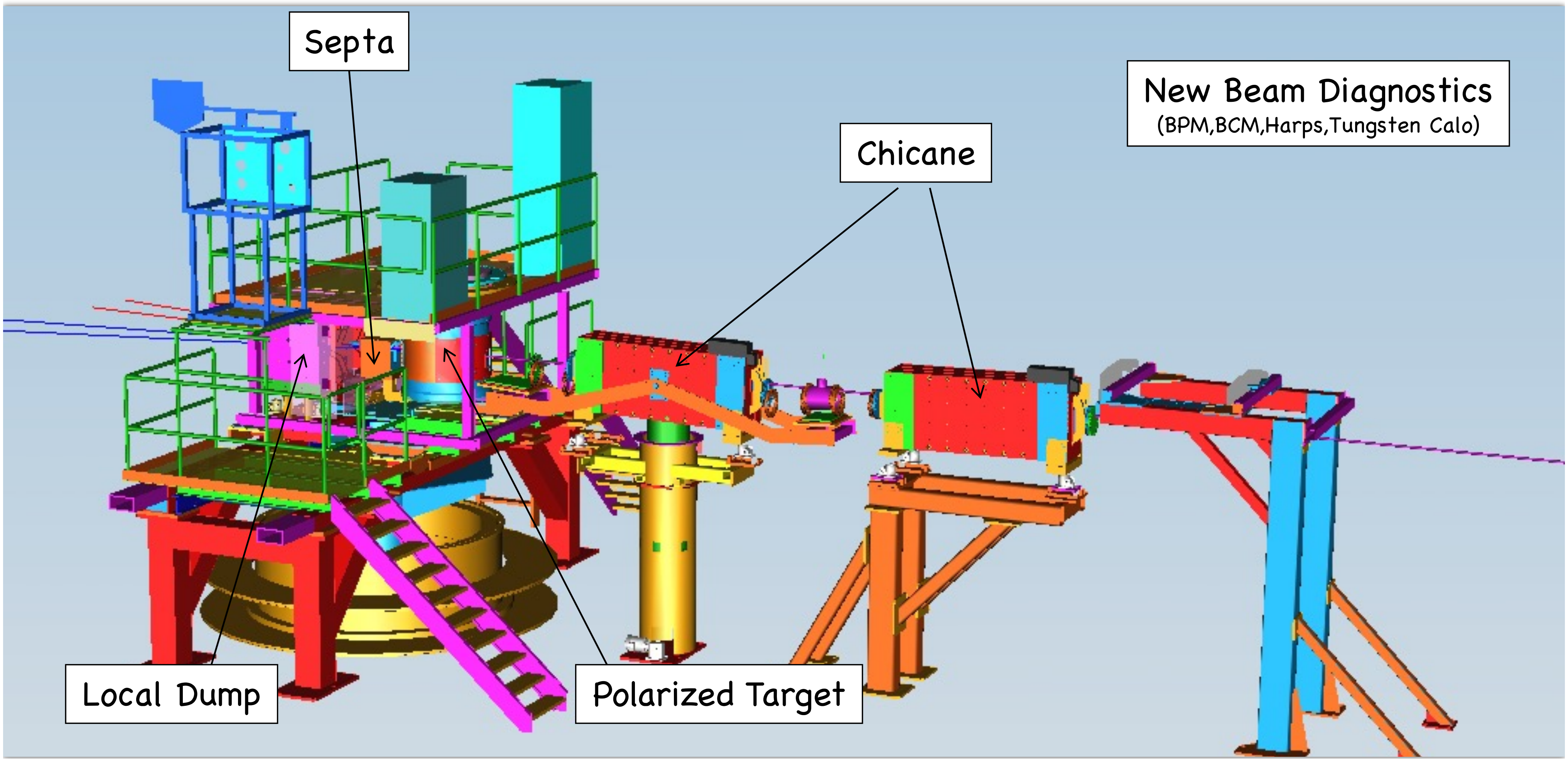
downstream local dump

Low current polarized beam

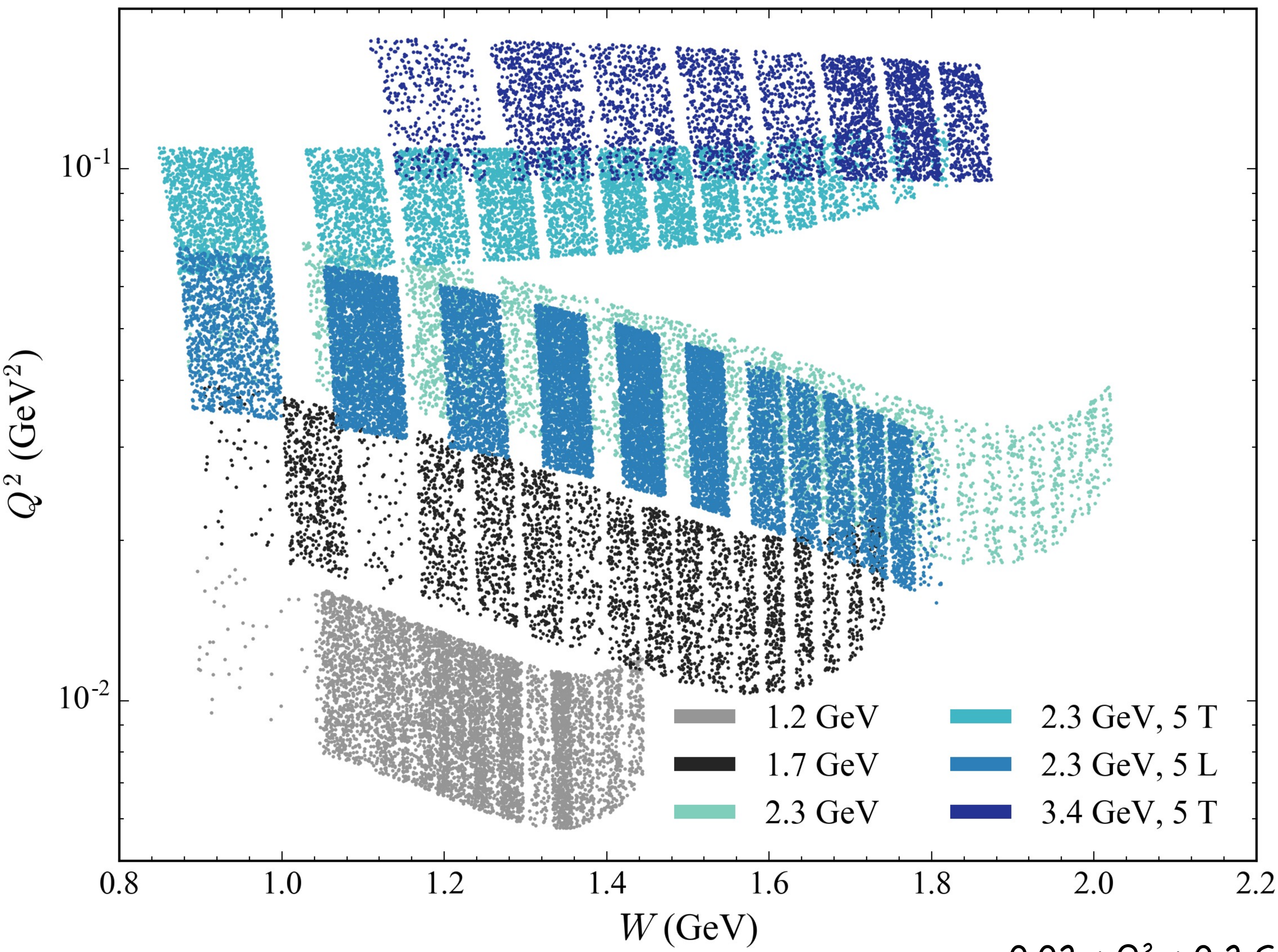
Upgrades to existing Beam Diagnostics to work at 85 nA

Lowest possible Q^2 in the resonance region

Septa Magnets to detect forward scattering



Kinematic Coverage

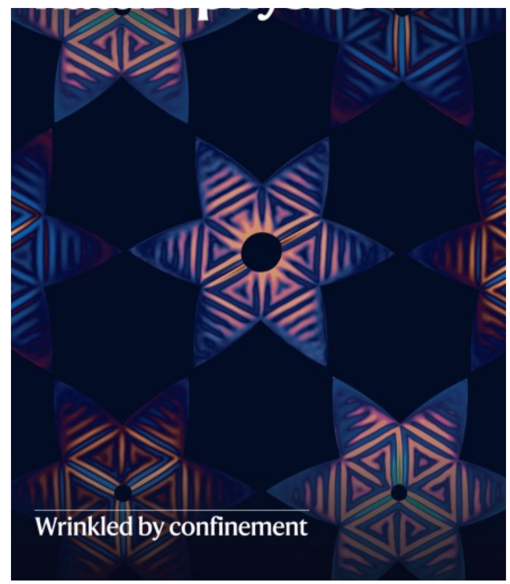


$0.02 < Q^2 < 0.2$ GeV^2

nature physics

Article

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



https://doi.org/10.1038/s41567-022-01781-y

nature physics

Article

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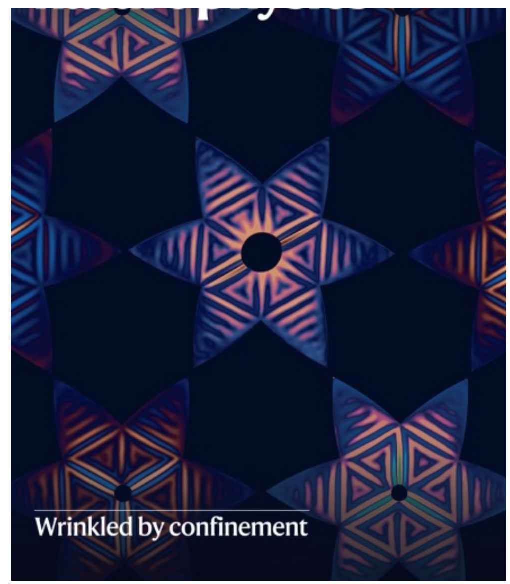

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nature physics

Article

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

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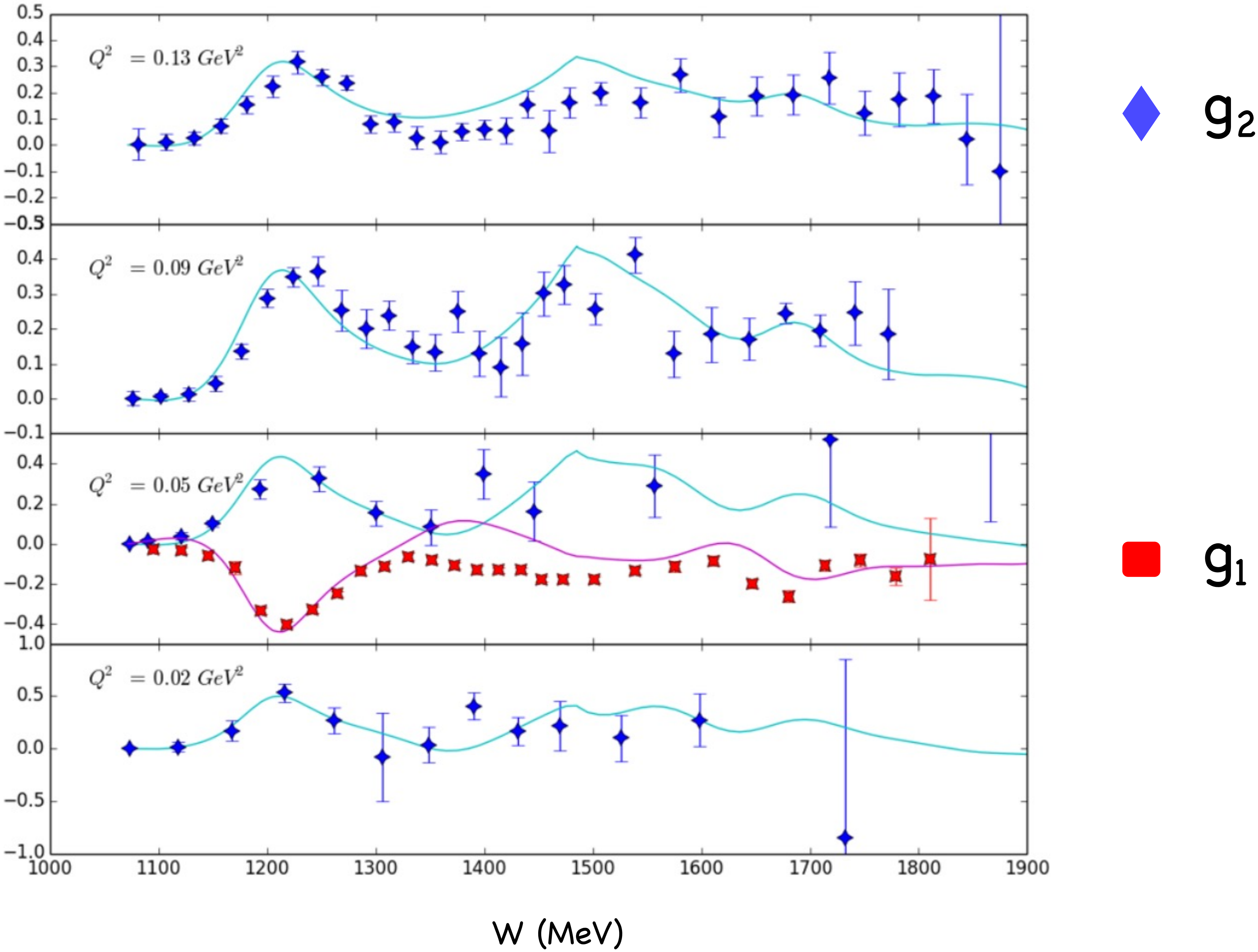
Ryan Zielinski, C. Gu, M. Cummings-Allada,T. Badman, M. Huang, J. Liu, P. Zhu

K. Allada, J. Zhang

+ Jlab Polarized Target Group

E08-027 Structure Functions



SSF Moments

Generalized GDH Sum

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

Burkhardt Cottingham

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

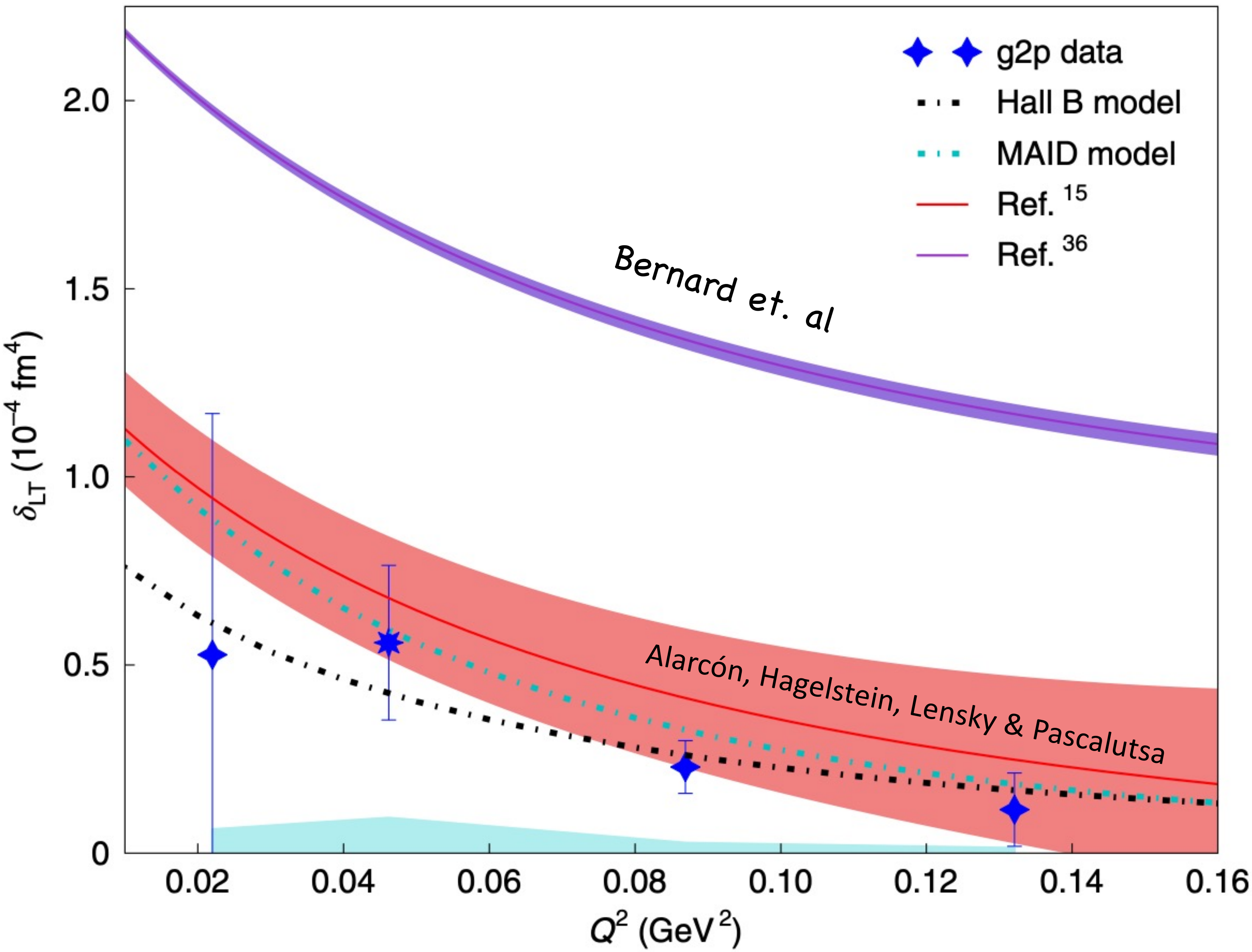
Generalized Forward Spin polarizabilities

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

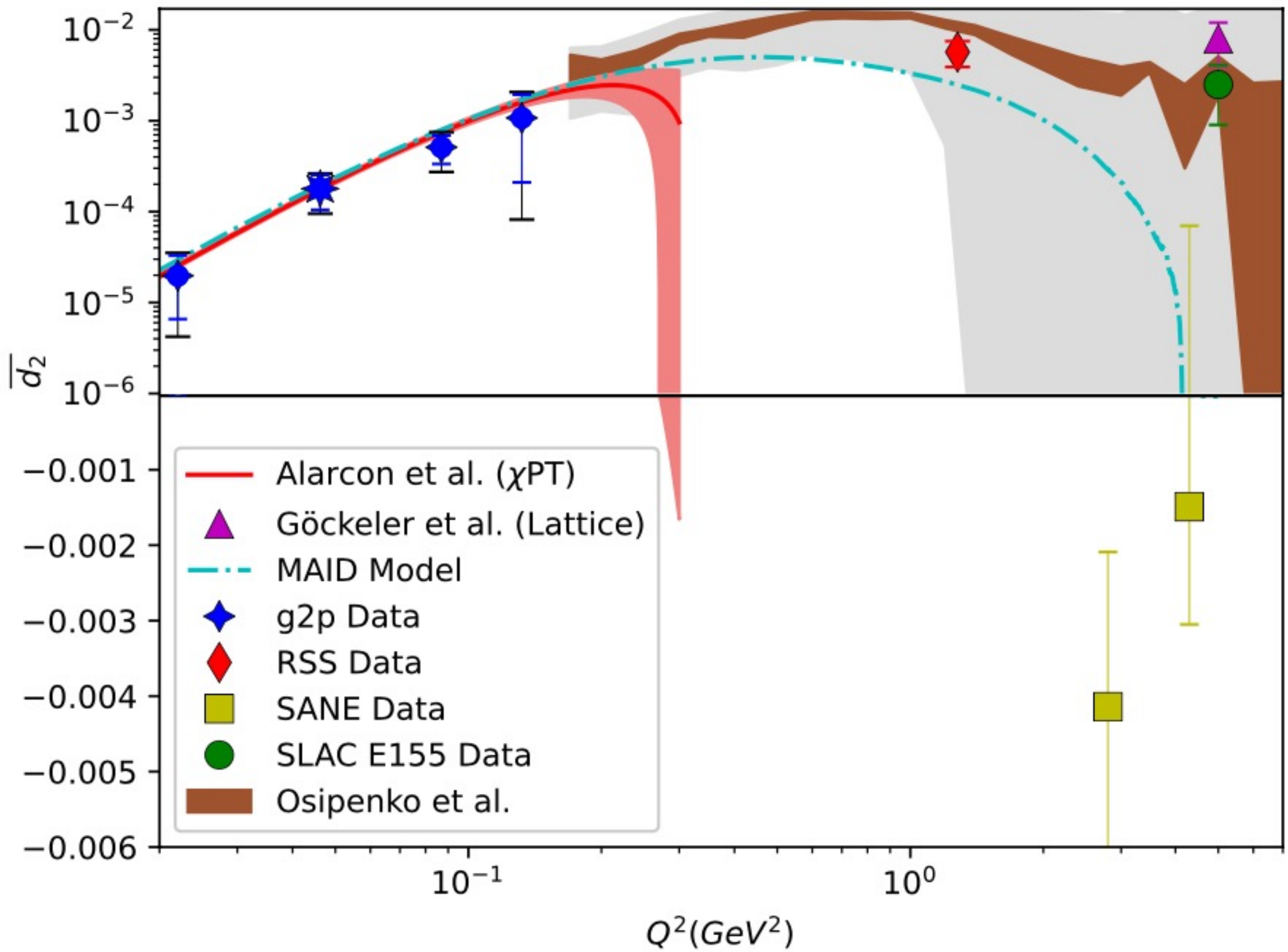
$$\delta_{LT}(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 \Big[g_1(x, Q^2) + g_2(x, Q^2) \Big]$$

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

δ_{LT} Proton (E08-027)

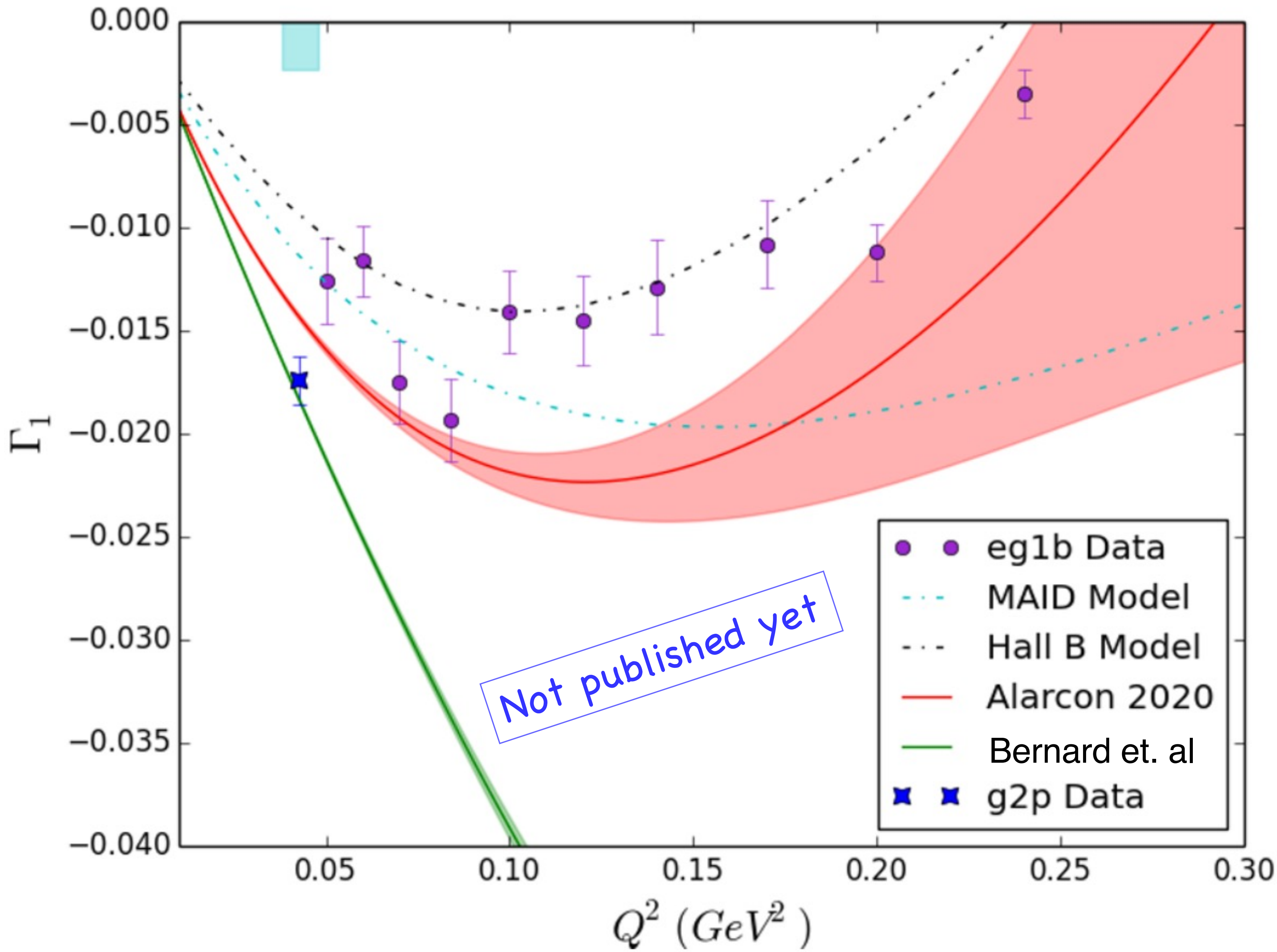


d_2 Proton

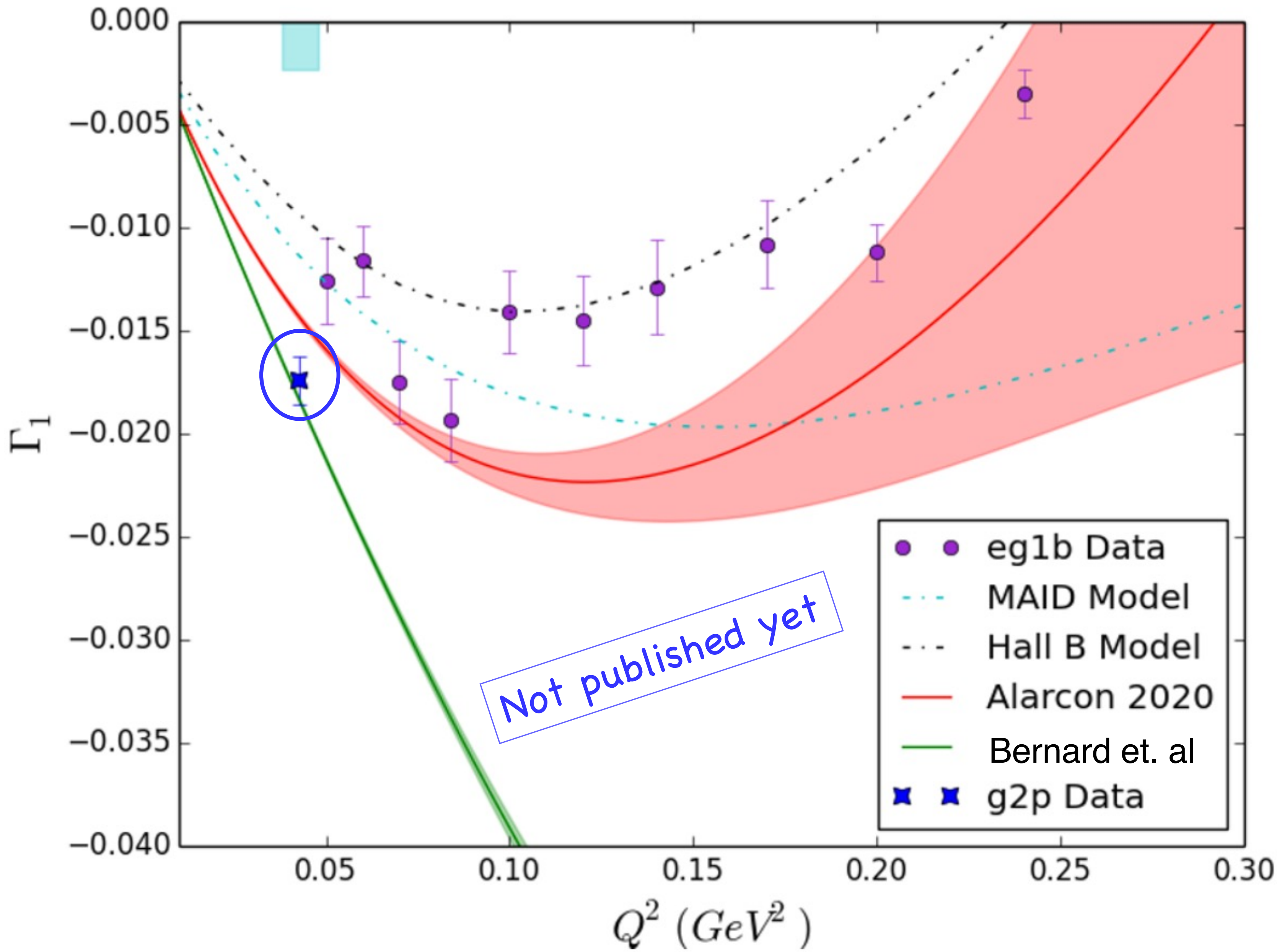


10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
−0.001
−0.002
−0.003
−0.004
−0.005
−0.006
$\overline{d_2}$
Alarcon et al. (χPT)
Göckeler et al. (Lattice)
MAID Model
g2p Data
RSS Data
SANE Data
SLAC E155 Data
Osipenko et al.
10^{-1}
10^{0}
$Q^2(GeV^2)$

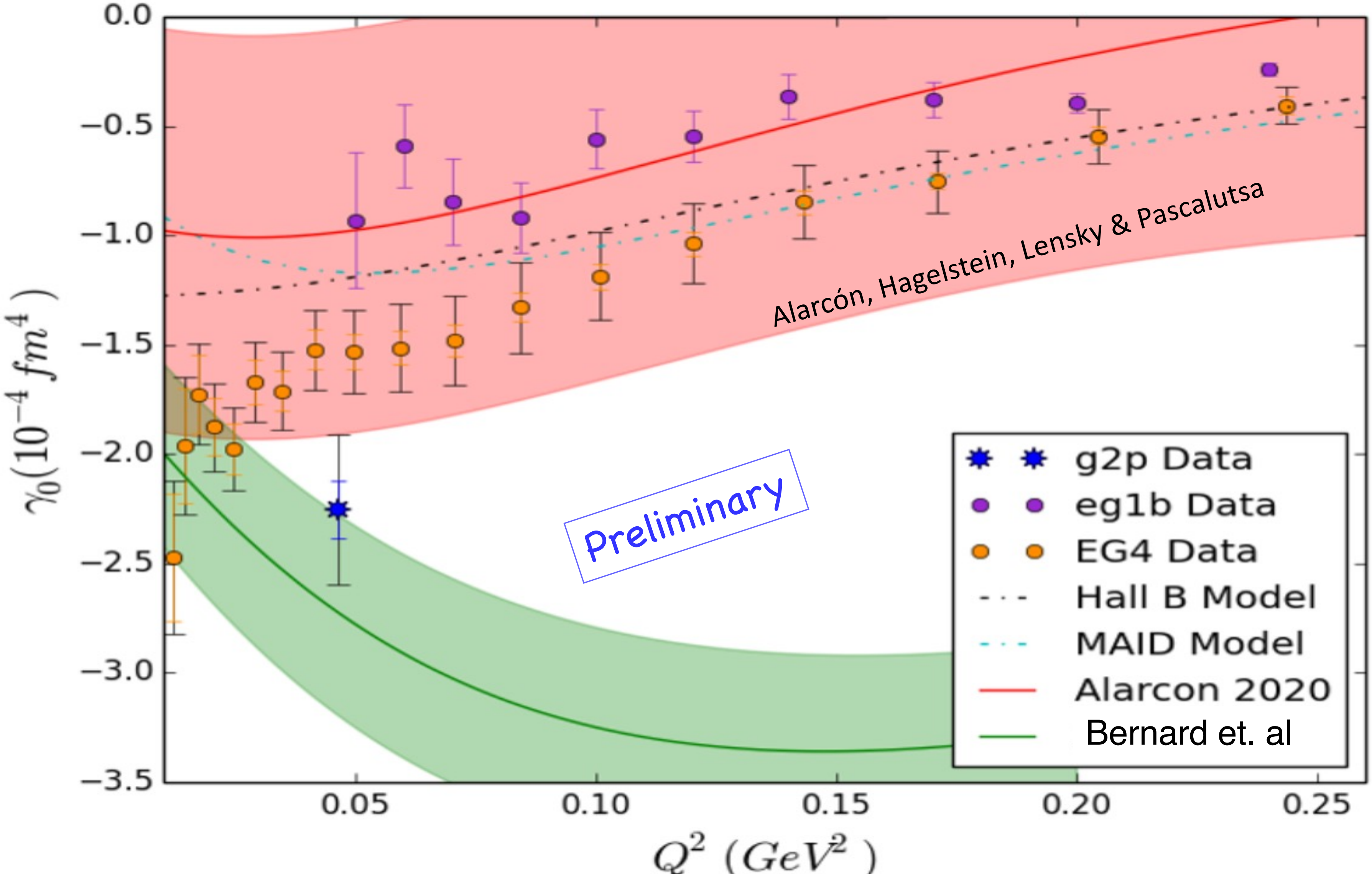
g_1 1^{st} Moment



1st Moment Γ_1



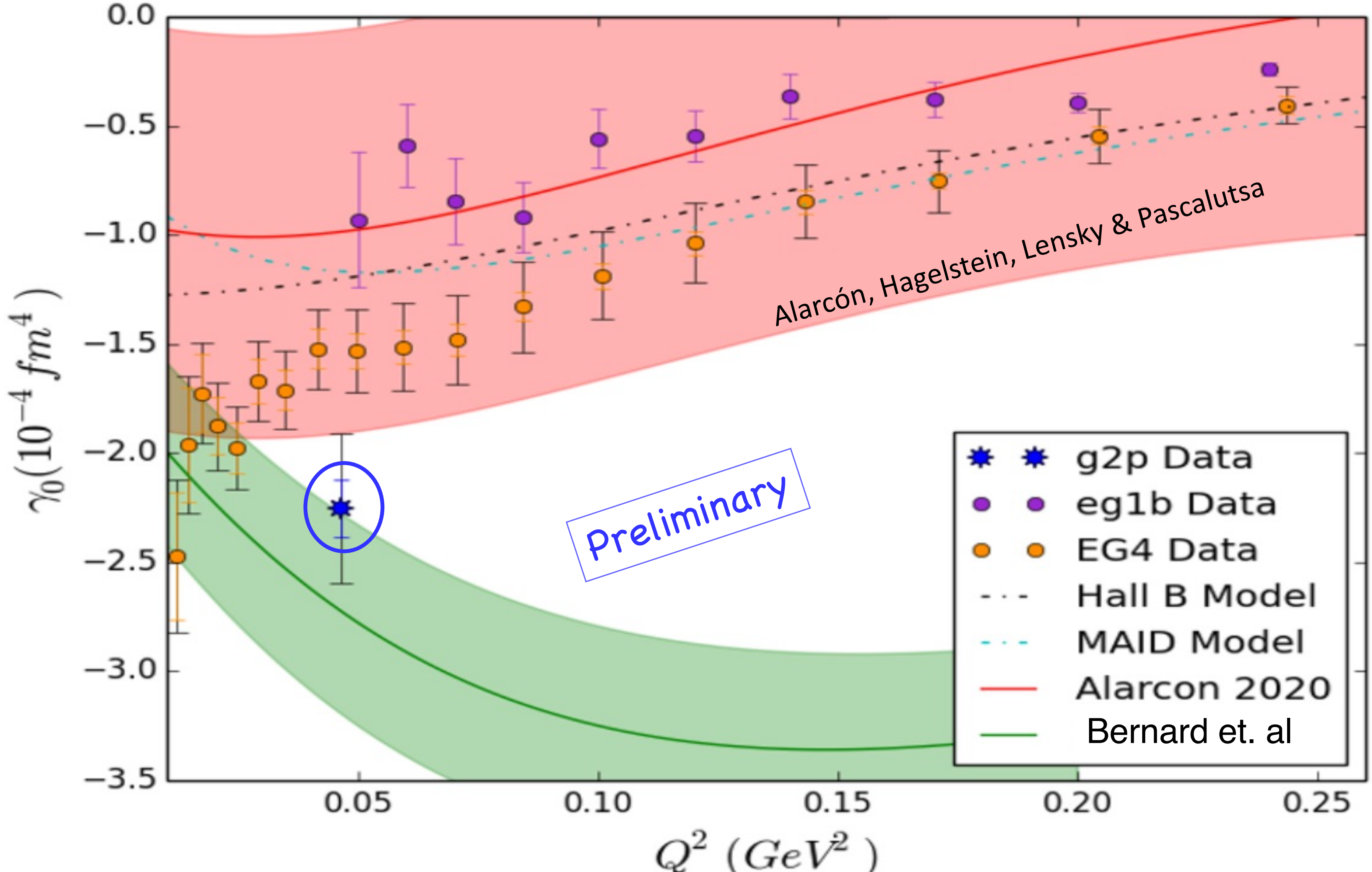
Proton γ_0



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

Some disagreeement
Between Hall A & B

Proton γ_0



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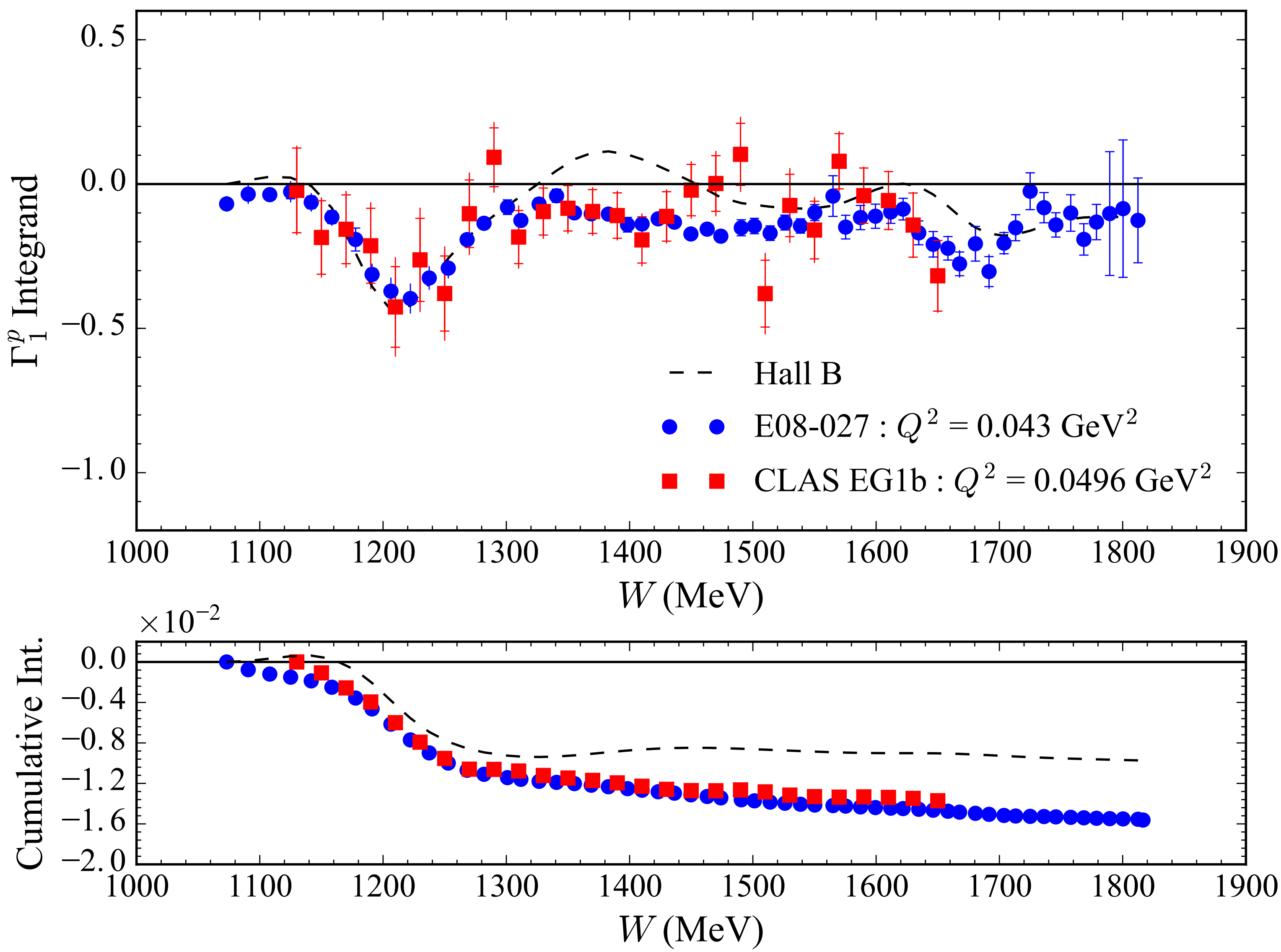
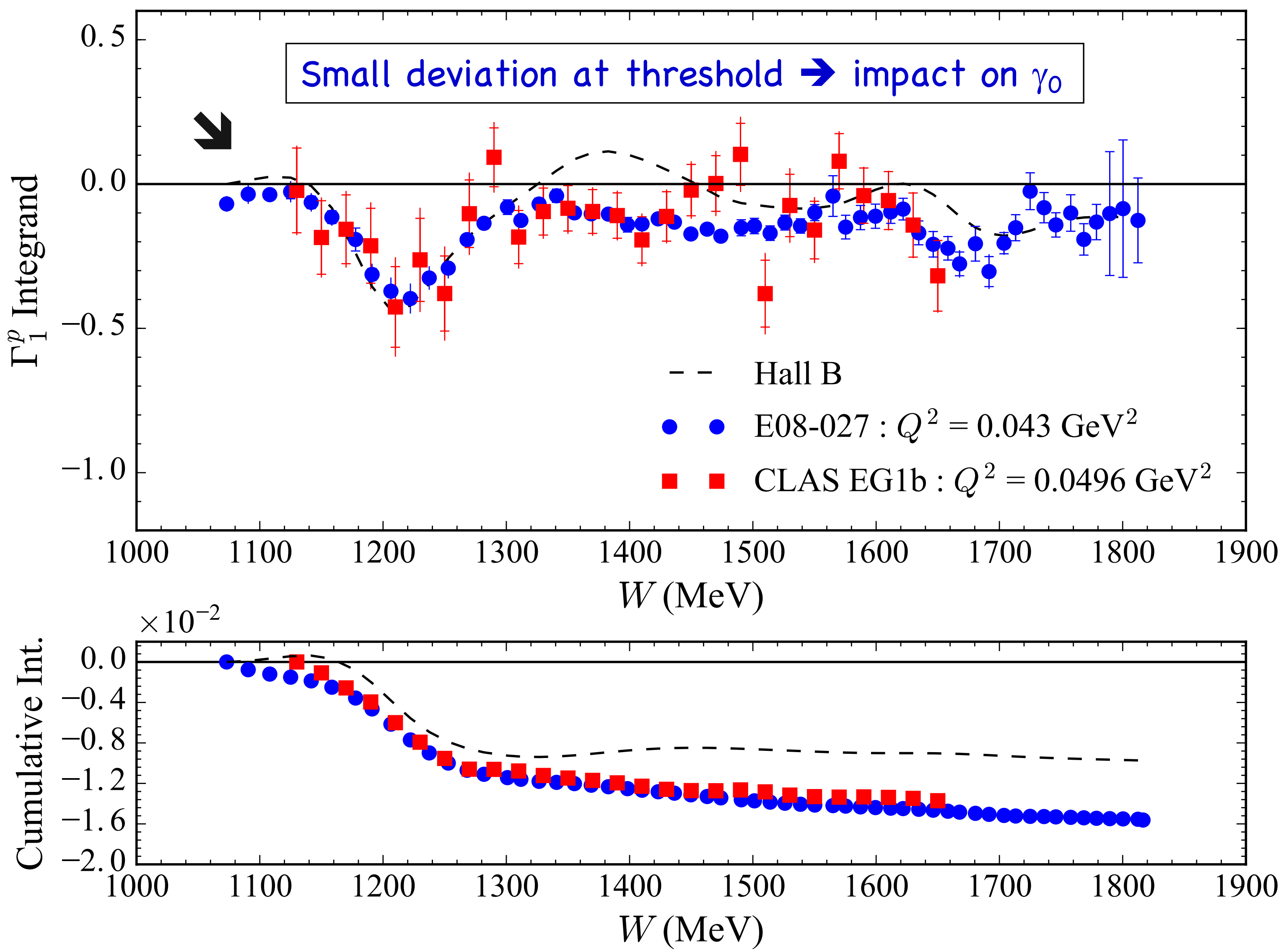
Some disagreeement
Between Hall A & B

Proton g1 (E08-027 vs. CLAS)



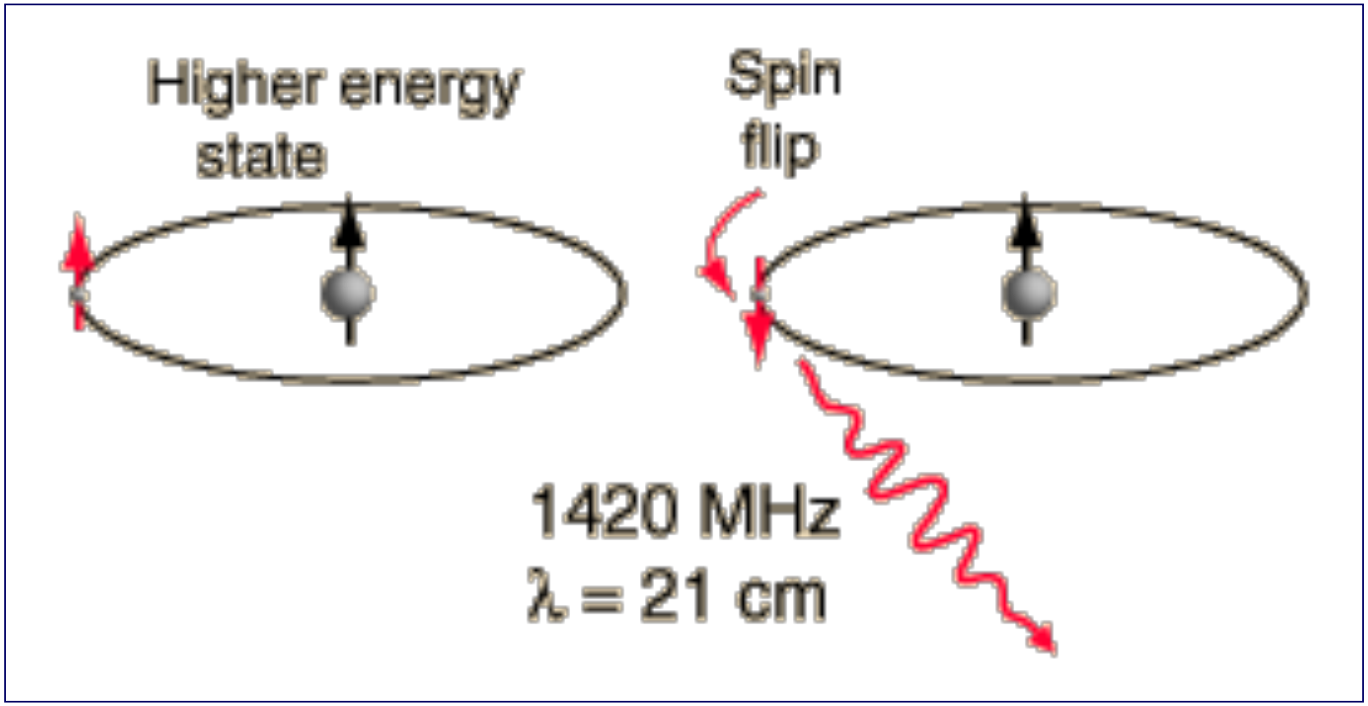
courtesy R. Zielinski, UNH

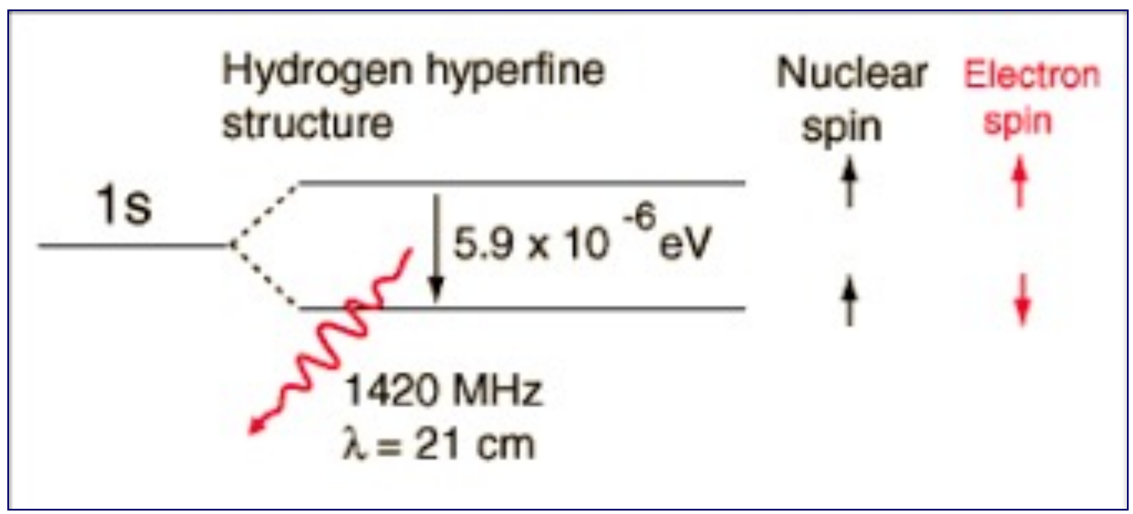
Proton g1 (E08-027 vs. CLAS)



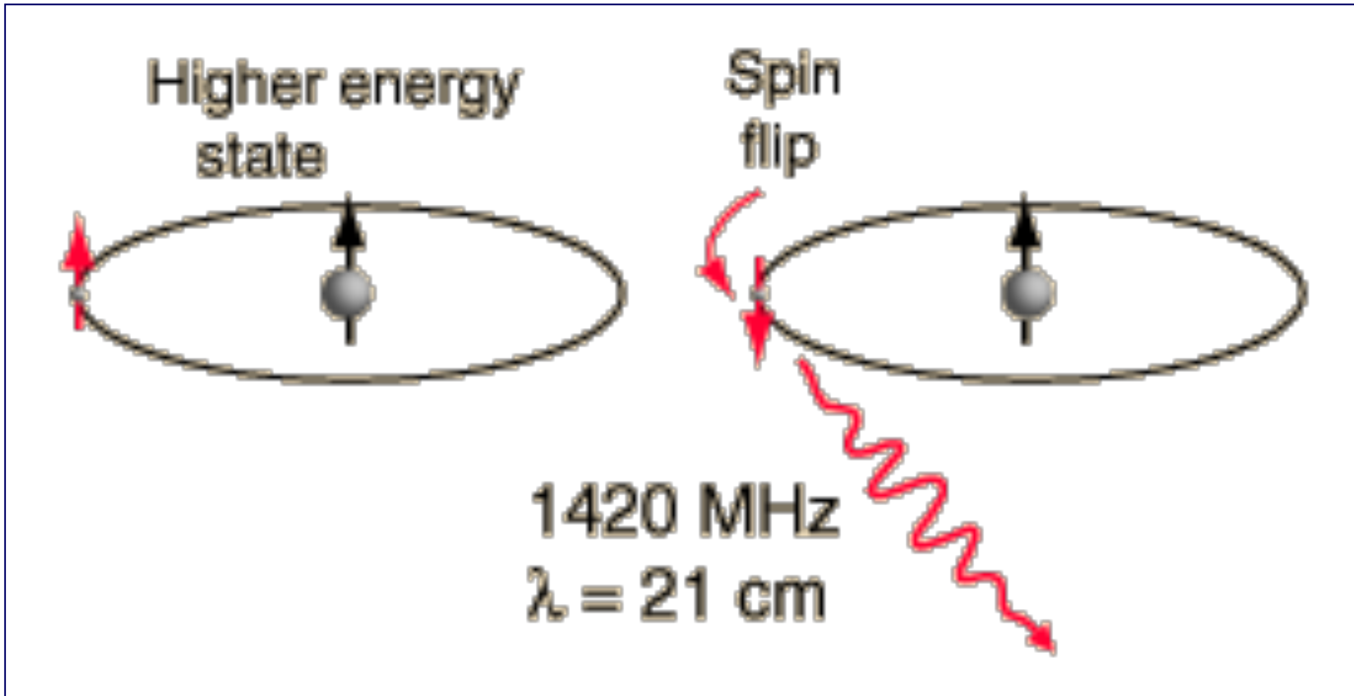
courtesy R. Zielinski, UNH

Hydrogen Hyperfine Splitting



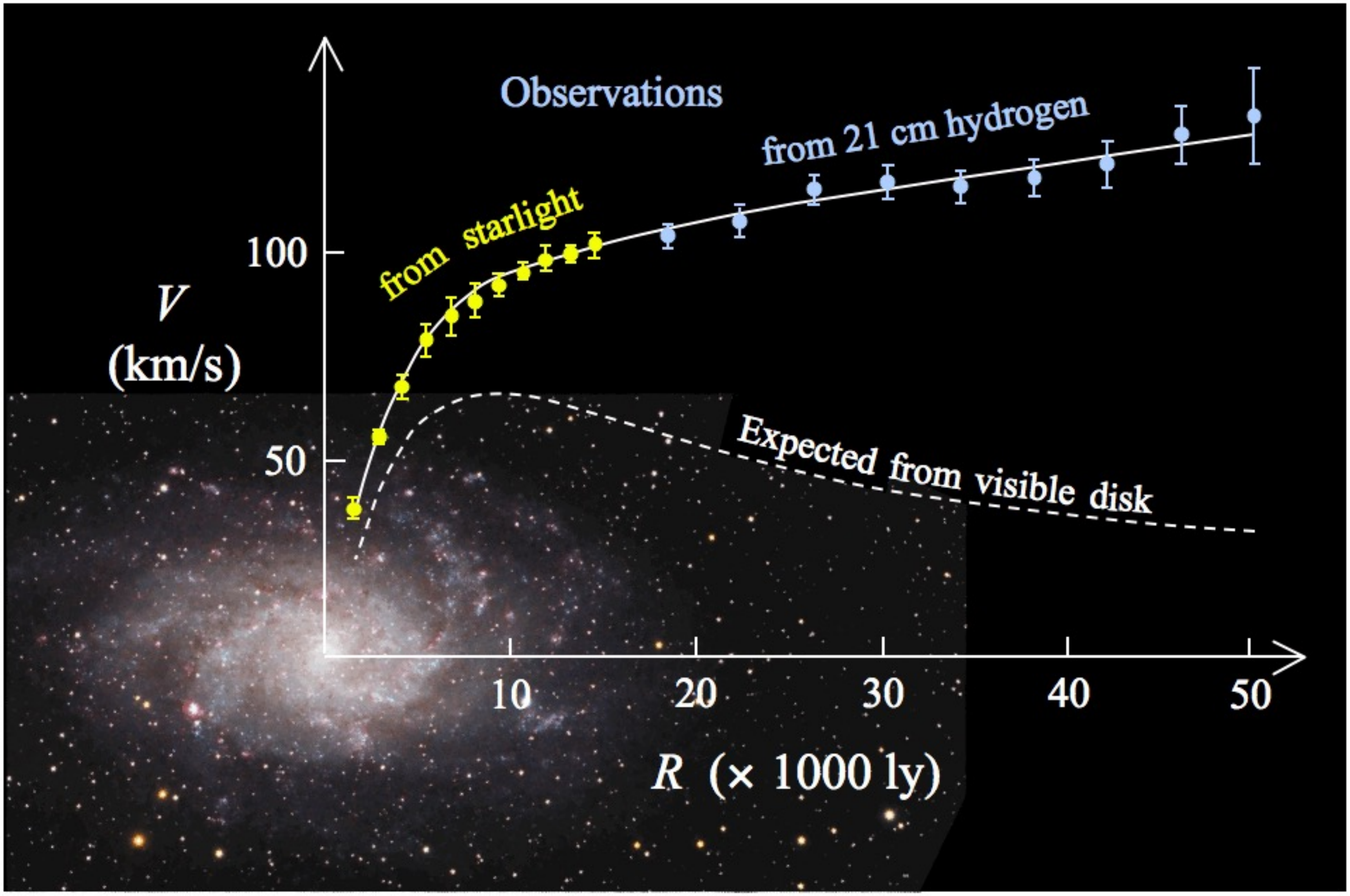


Hydrogen Hyperfine Splitting



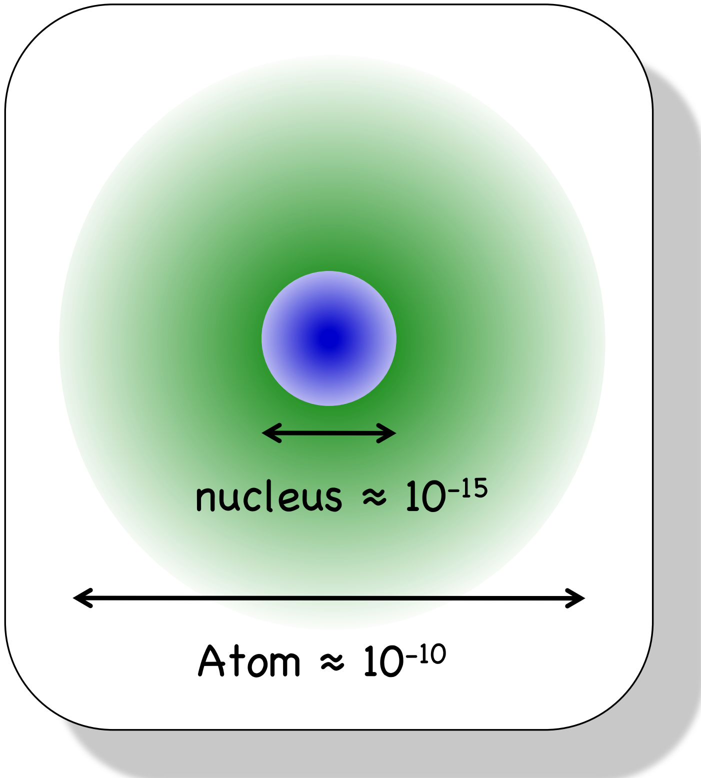
Discovery of 21 cm line → birth of radio astronomy

Hydrogen Hyperfine Splitting



First evidence for existence of dark matter

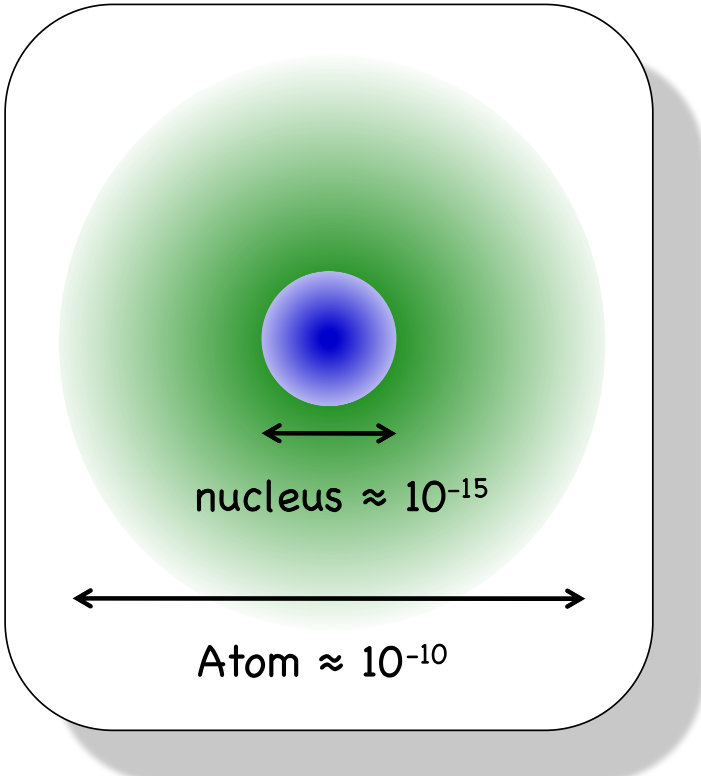
Hydrogen Hyperfine Splitting



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

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

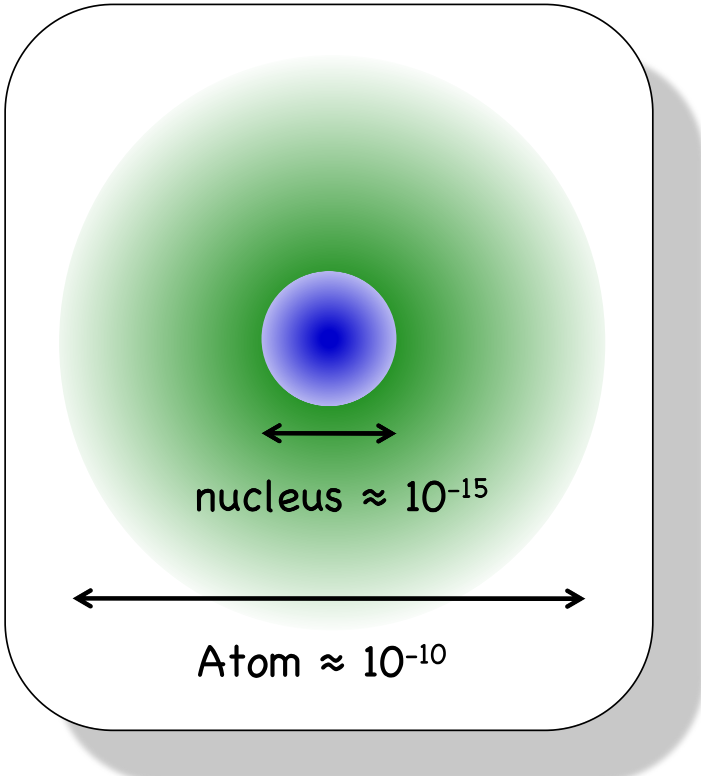
Hydrogen Hyperfine Splitting



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

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

Hydrogen Hyperfine Splitting



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

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

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

Hydrogen Hyperfine Splitting

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

Hydrogen Hyperfine Splitting

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

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

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

Hydrogen Hyperfine Splitting

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

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

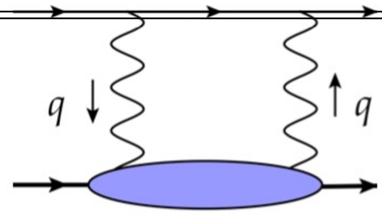
$$B_1(Q^2) = \int_0^{x_{pp}} \beta_1(\tau) g_1(x, Q^2) dx$$

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

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

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

Chiral Perturbation Theory and Dispersive approaches

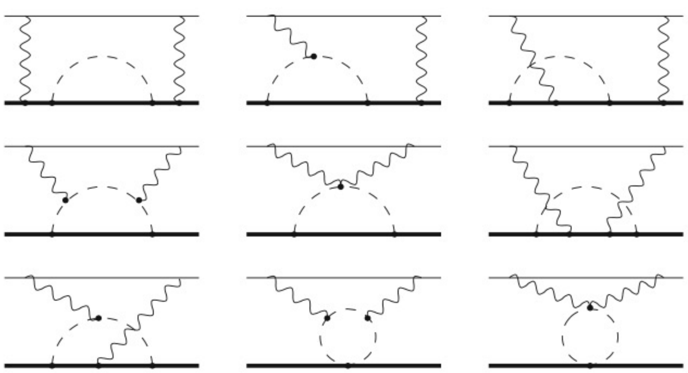


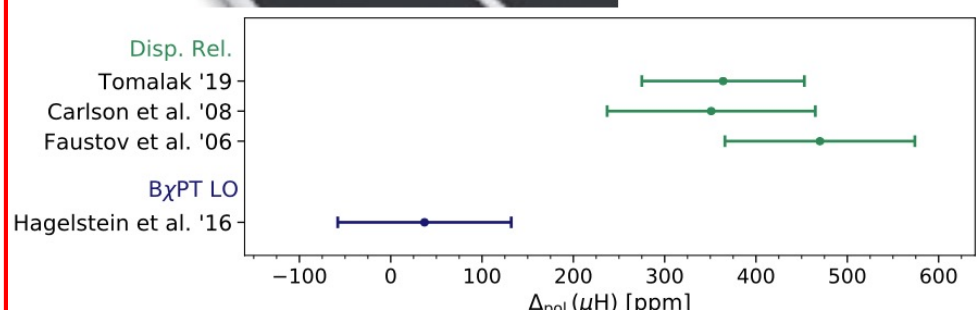
Dispersion relation+ data: $g_1(x,Q^2)$, $g_2(x,Q^2)$, F_1, G_E...

Carlson, Vanderhaegher, Martynenko, Tomalak, Pascalutsa, Hagelstein,

Chiral EFT

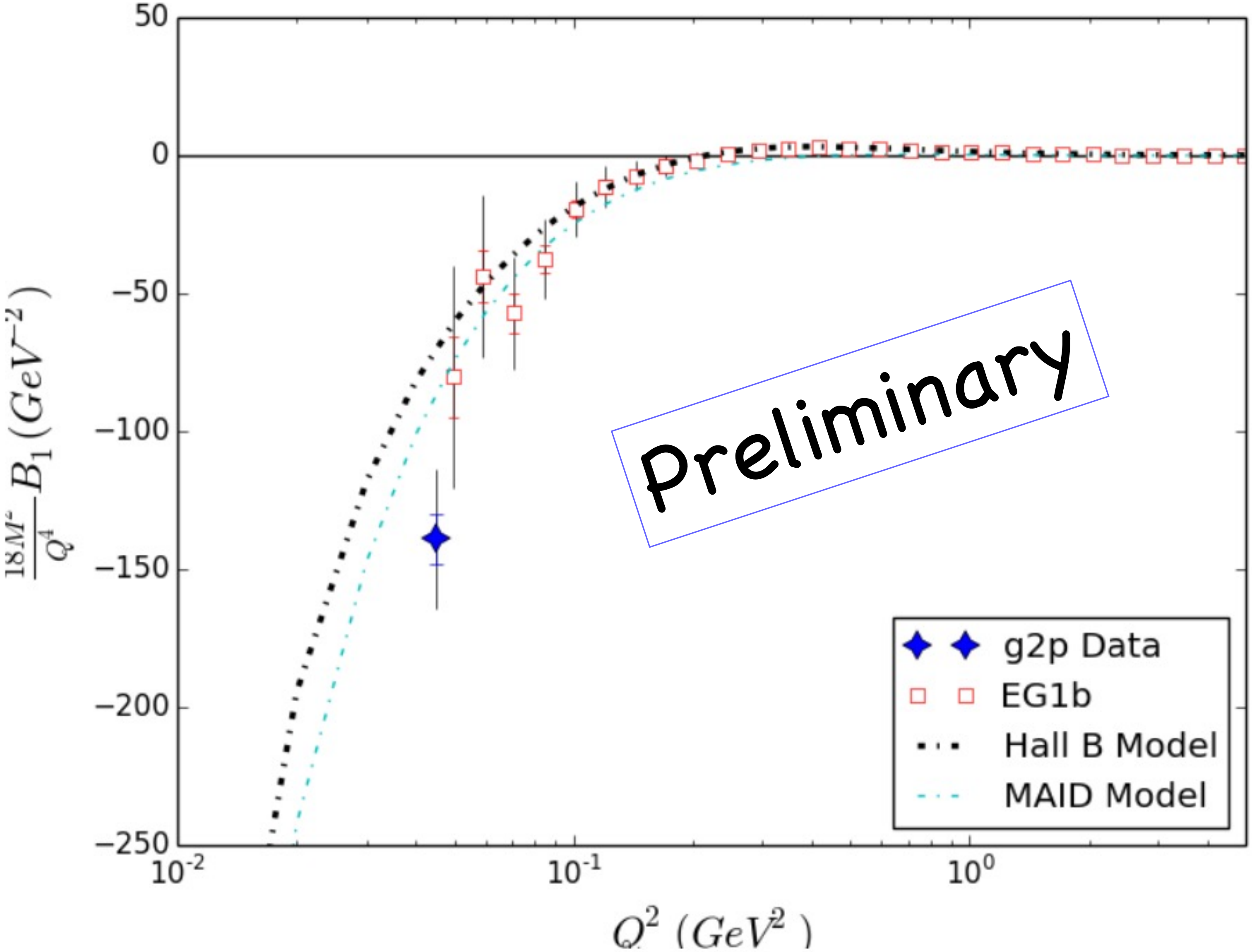
Pascalutsa, Hagelstein
Pineda, Peset





From A. Antognini's talk

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

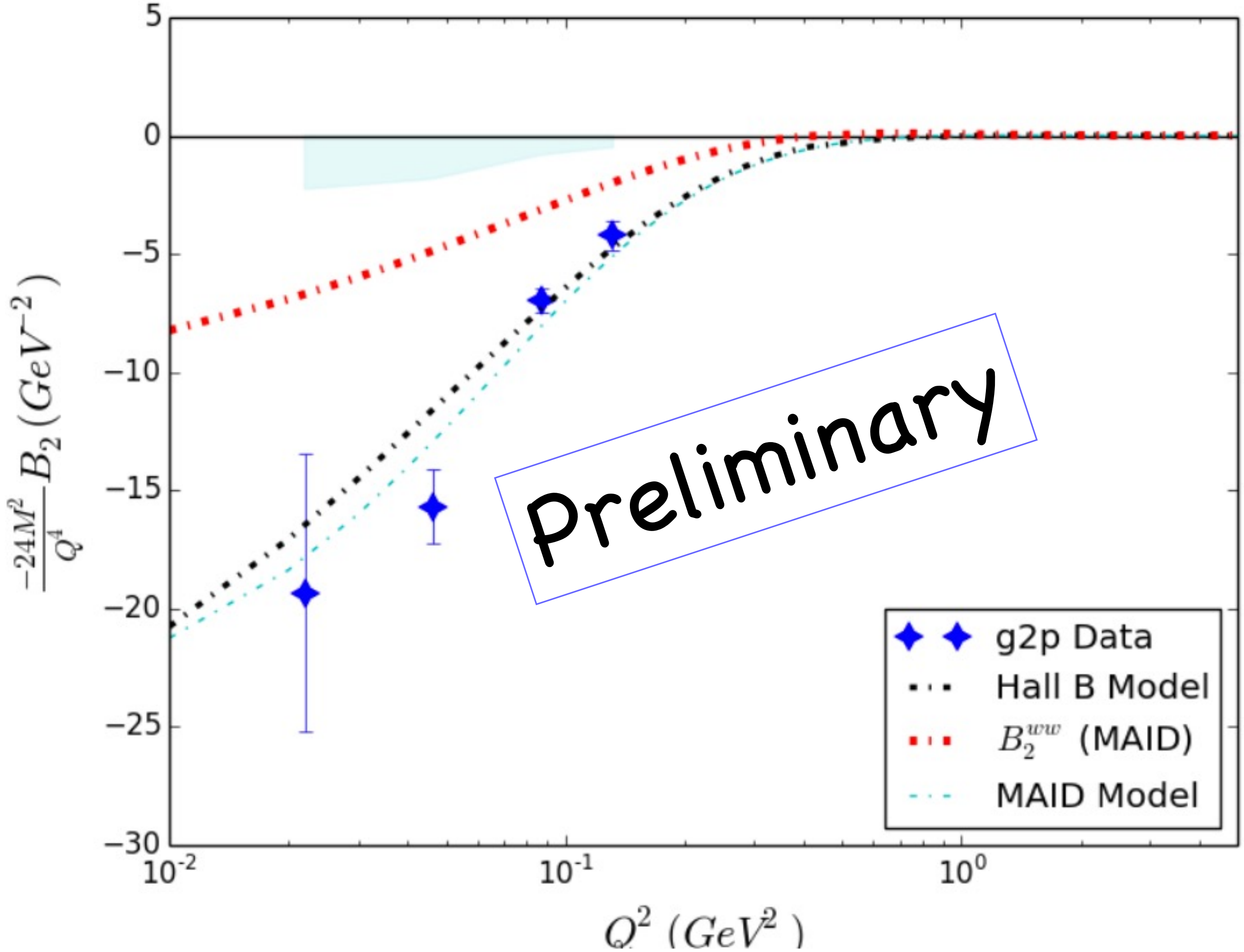
Preliminary

Compares favorably with published results

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

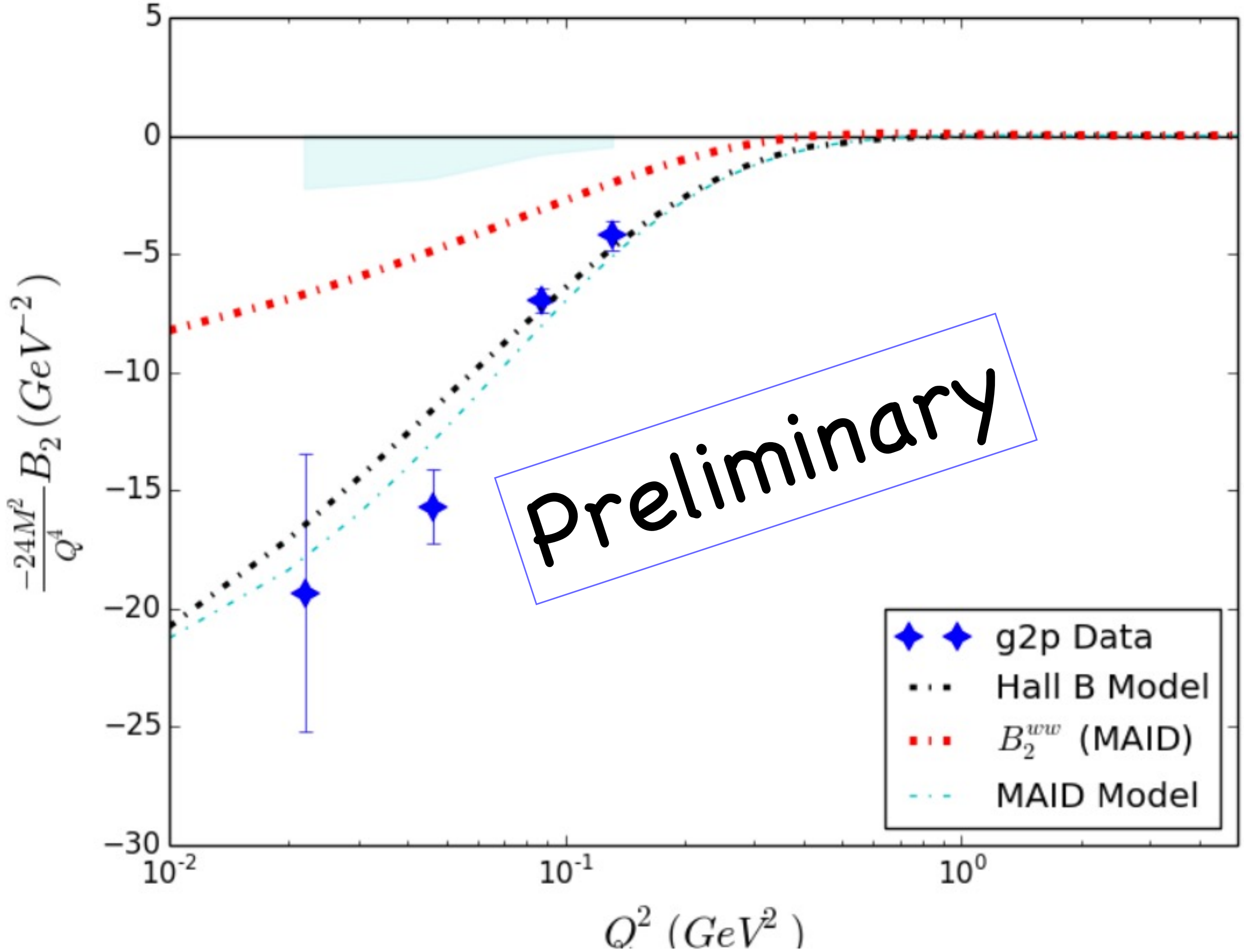
Phys.Rev.A.78.022517

g_2 contribution to Δ_{pol}



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

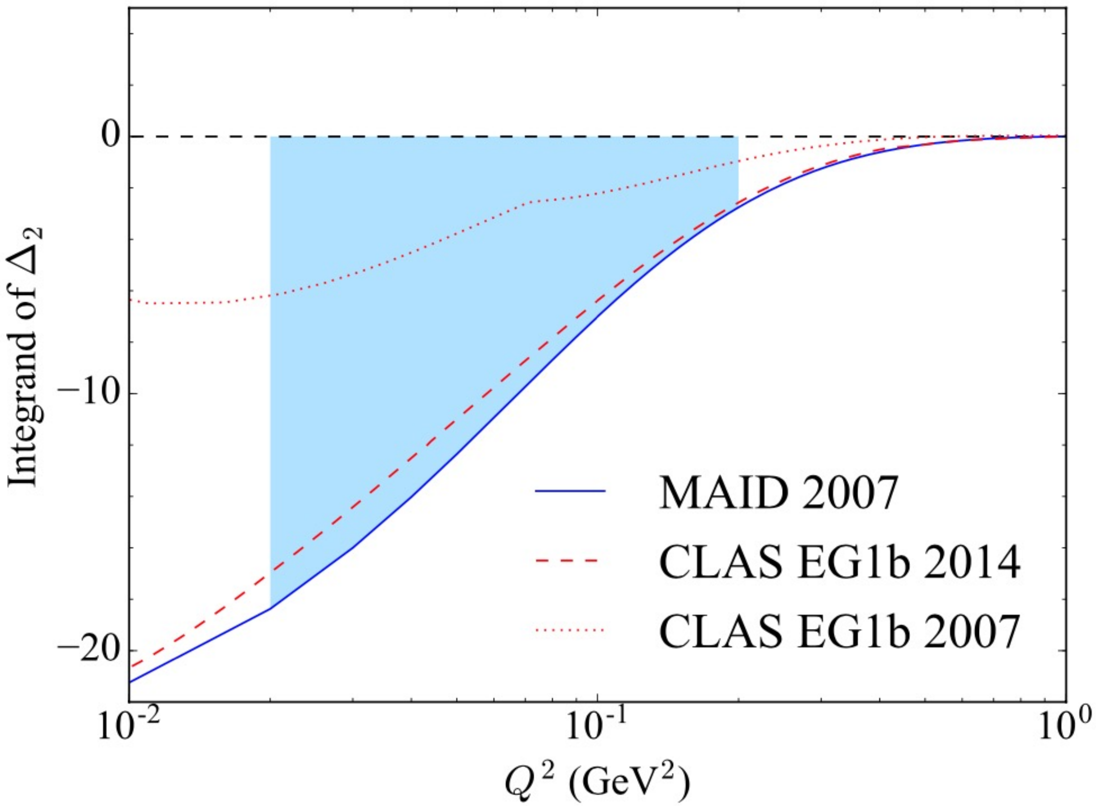
g_2 contribution to Δ_{pol}



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

Significant difference from g2ww

Δ_2 Model Dependence



Term	Q^2 (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.78.022517

Significant difference from 2007 CLAS model

g2p Experiment Summary

1) Published in Nature Physics October 13, 2022

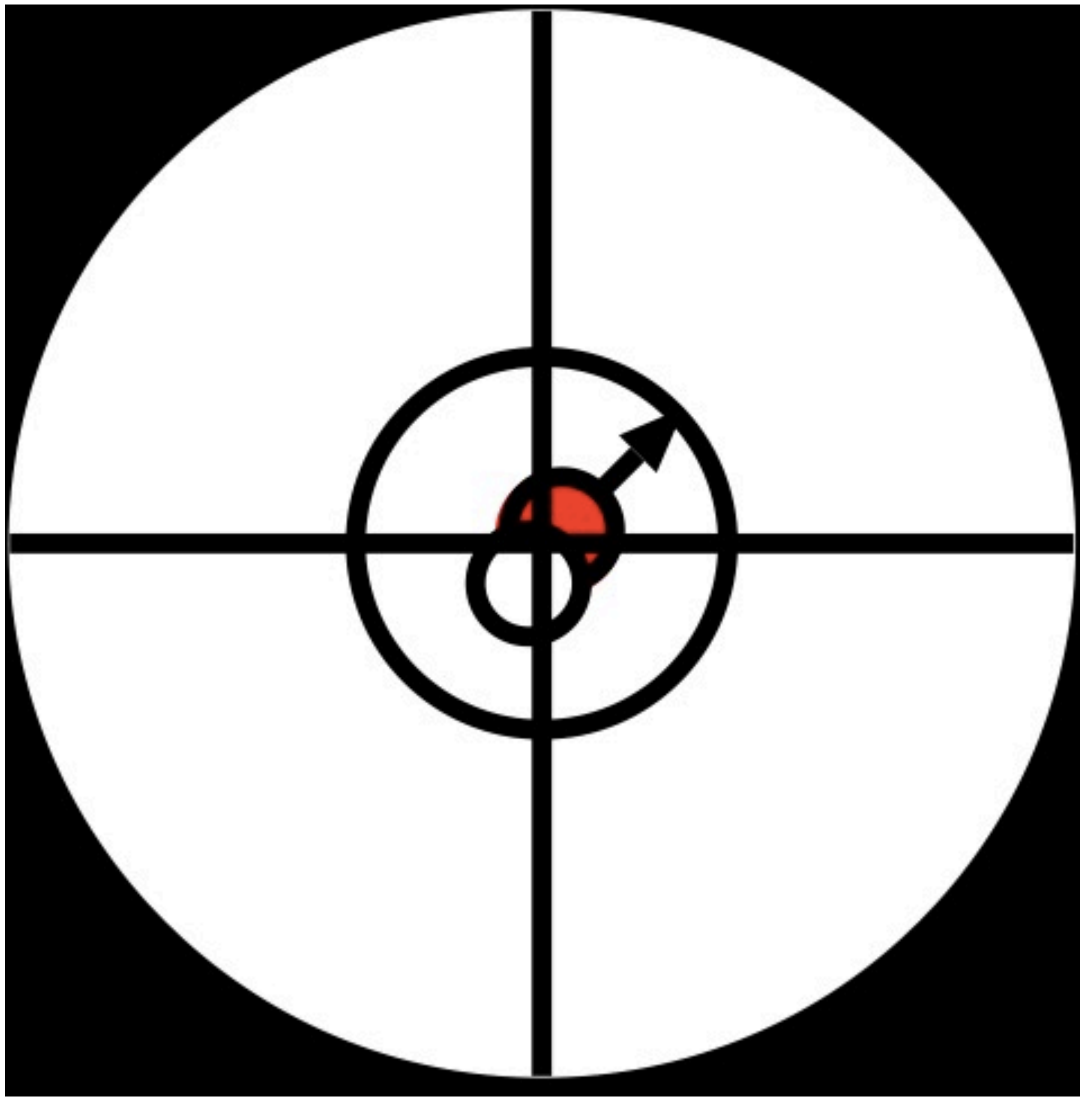
2) Longitudinal Data agrees with Hall B (except at threshold).

3) δ_{LT} favors Alarcon et al χPT calculation

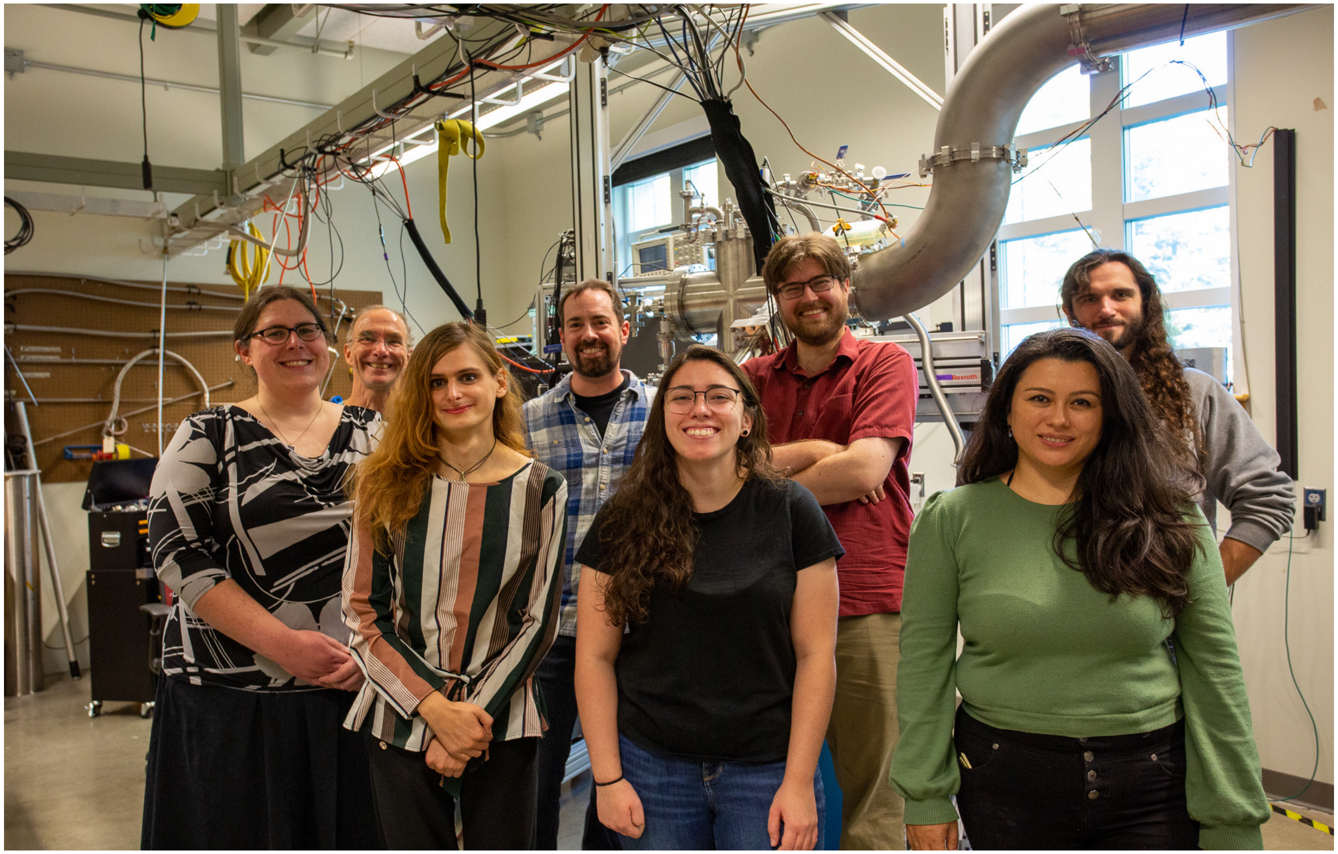
4) Hyperfine splitting contributions from g_1 is consistent with previous values within large error bars

5) g_2 contribtion is very different from previous model based predictions.

Technical Developments



UNH Polarized Target Lab



3 faculty
-Slifer, Long, Santiesteban

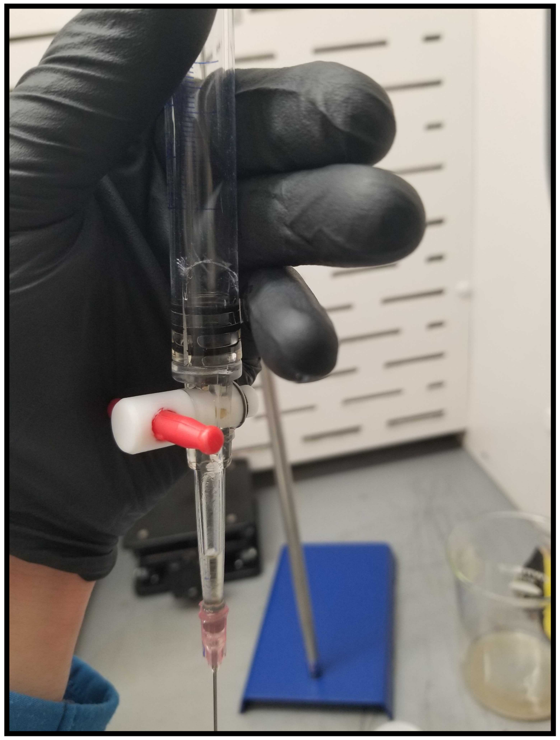
1 post-doc
3 grad students:
--David R : significant time
--Nathalie S. : partial time
--Michael S. : full time

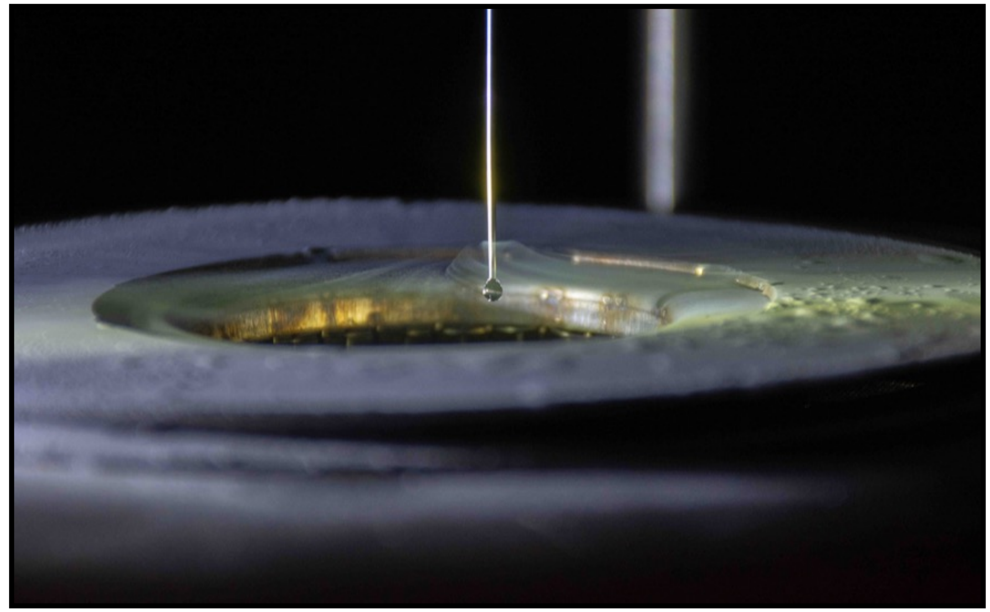
lots of undergrads

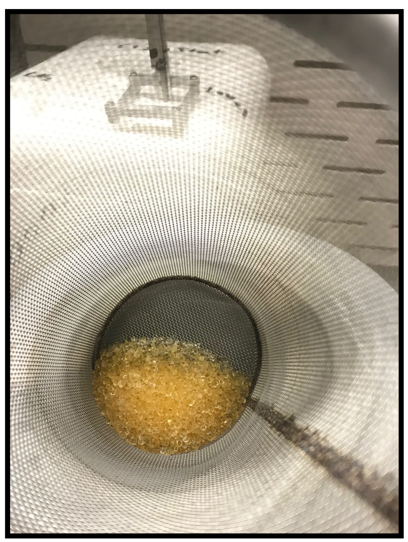
Projects

- Polarized Target Material Production & Labview controls
- Tensor Polarization R&D

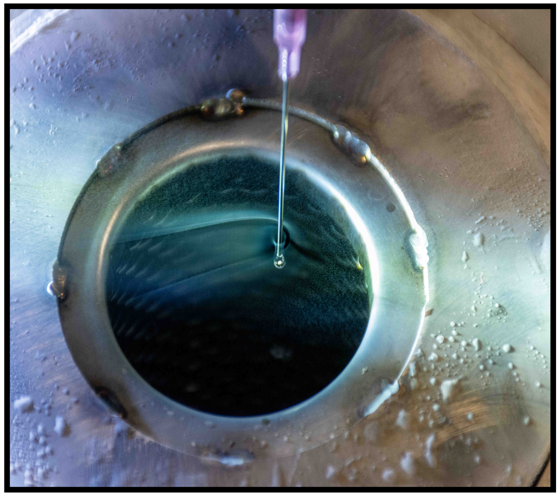
Target Material Production at UNH







Target Material Production at UNH

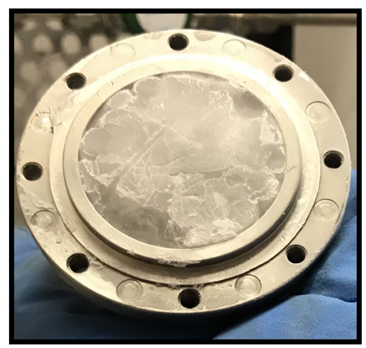


Butanol and other alcohols solidification

grade 5.5 NH_3 & ND_3

Chemical Doping

Rapid vs SlowCooling of NH_3



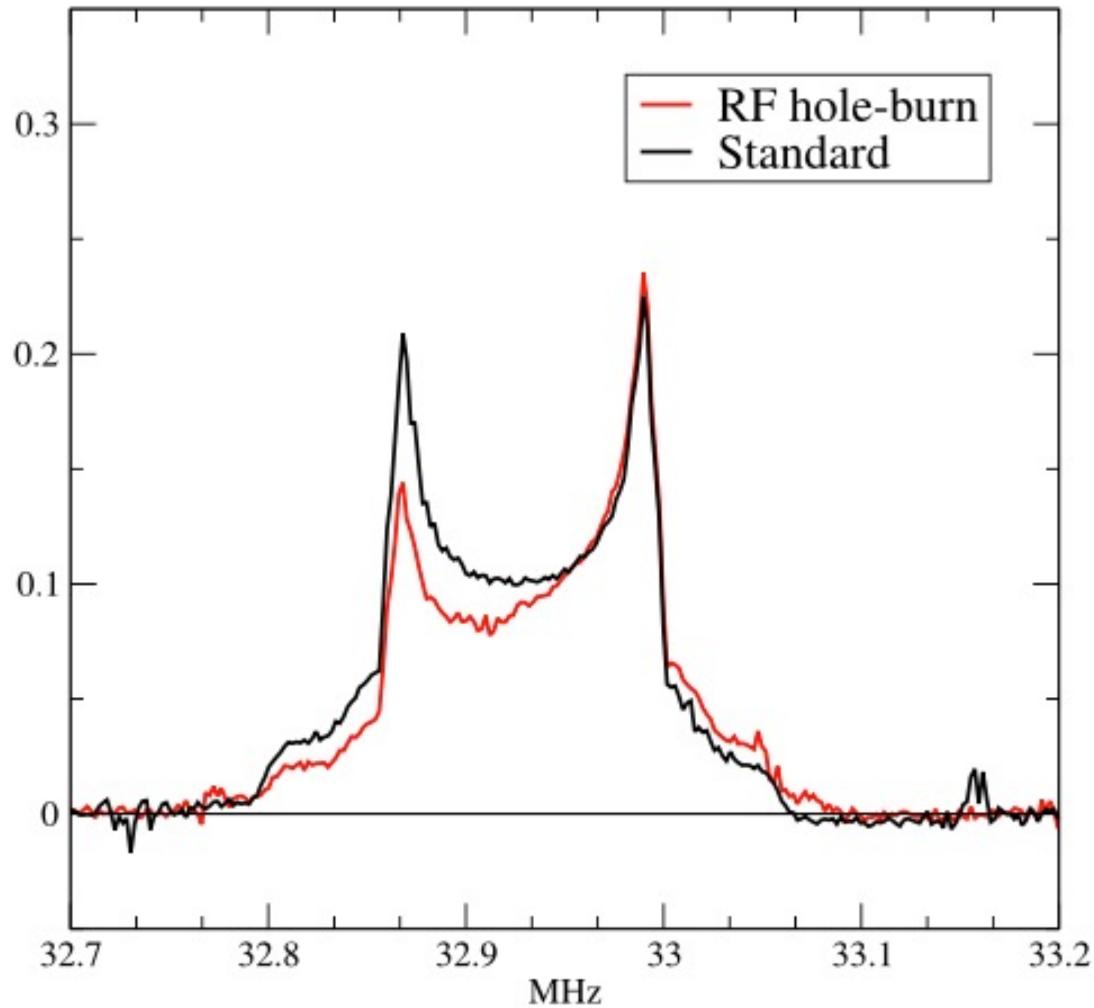
Target Material Production at UNH

-Dedicated **fume hood** for Handling Ammonia and other caustic/toxic materials

-**Vacuum GloveBox** allows for over/under-pressuring

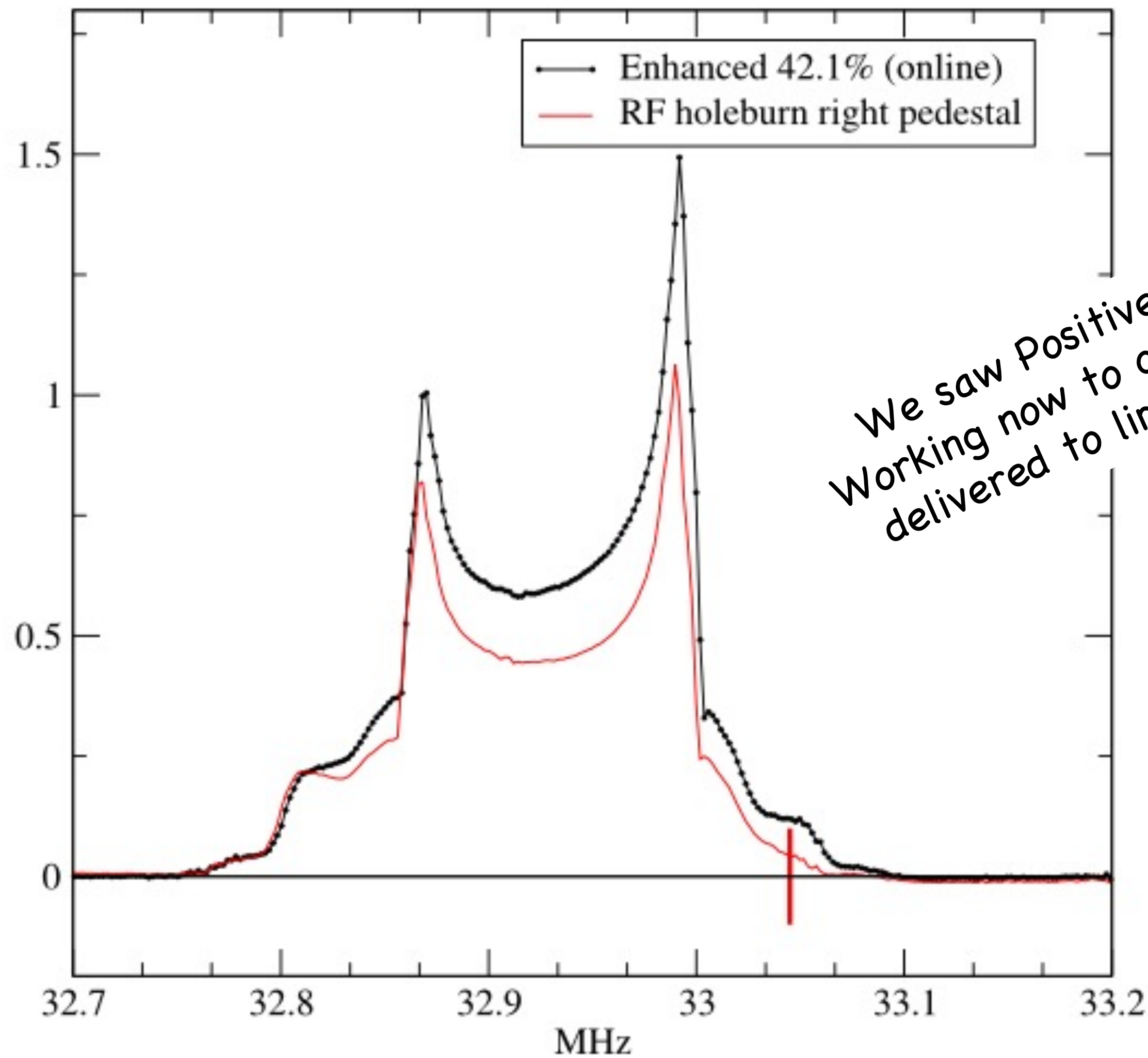
-Primarily chemical doping of ammonia and alcohols for now.
But potential to do much more.

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



We saw Positive First Results!!
Working now to optimize rf power
delivered to limit depolarization

Tensor Enhancement to $P_{zz} \cong 16(\pm 5)\%$

after rf-hole burning the left peak and right shoulder.

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

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

Conditional Status Removed
August 1, 2022
Now both experiments Fully Approved!

C12-13-011: The

30 Days i
A- Ph

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

44 Days in Jlab Hall C
A- Physics Rating

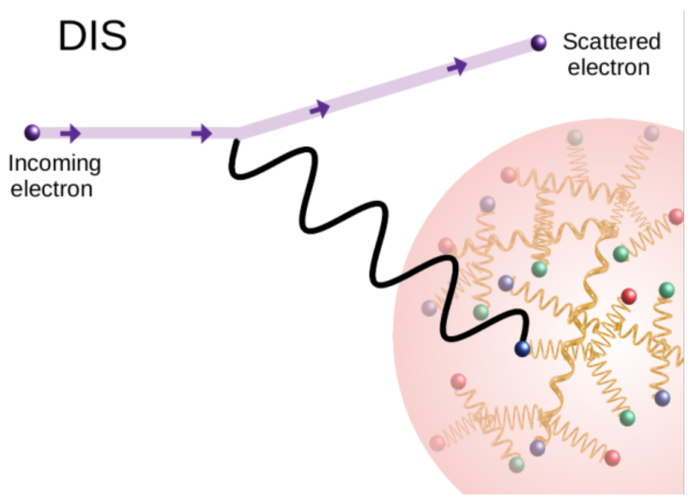
RunGroup Spokespersons

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

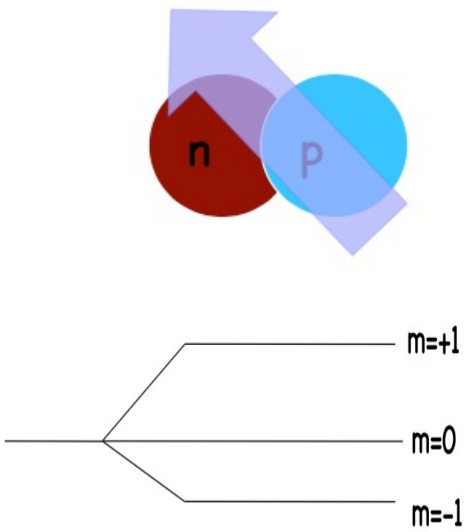
b_1 structure function

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

DIS (probing quarks)



but depends on the Deuteron spin state



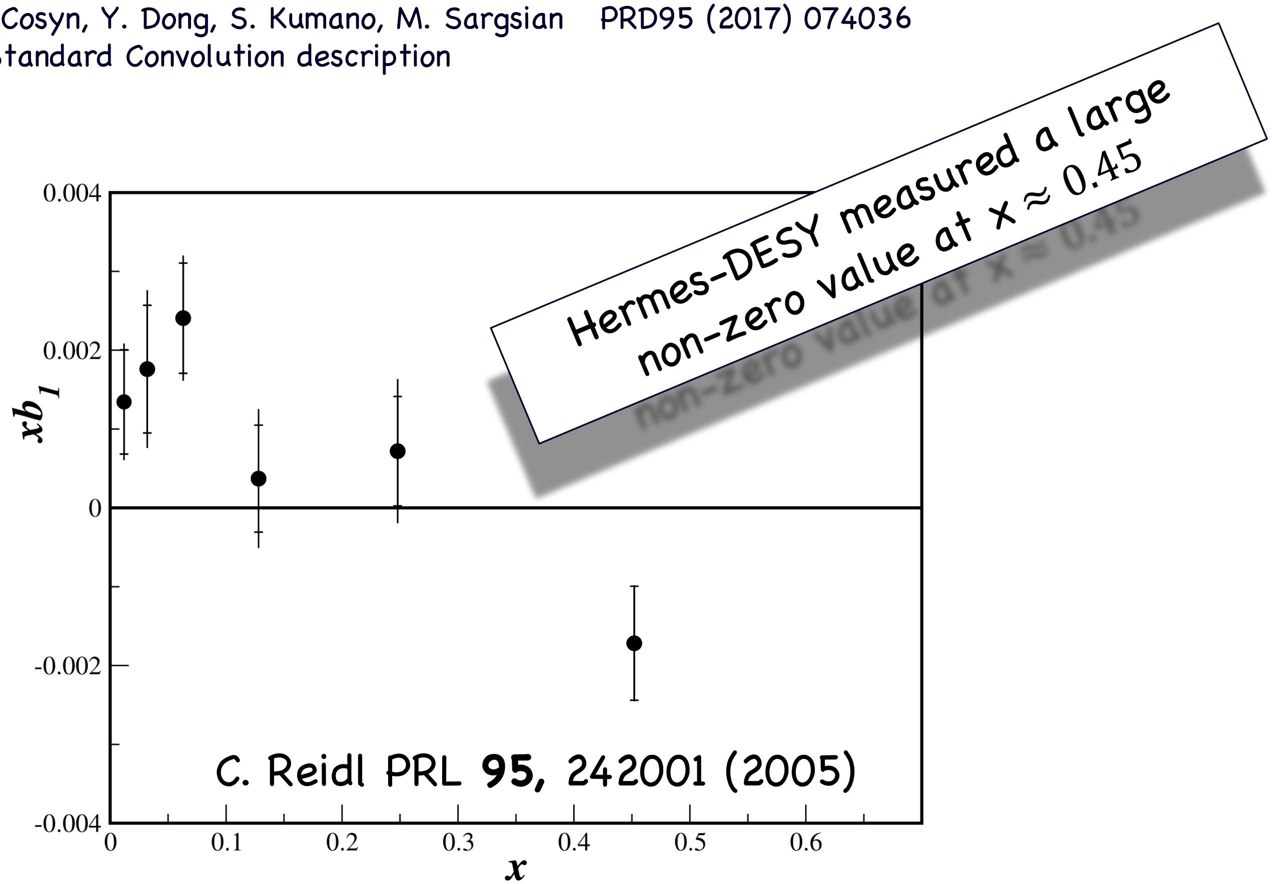
Data from HERMES

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

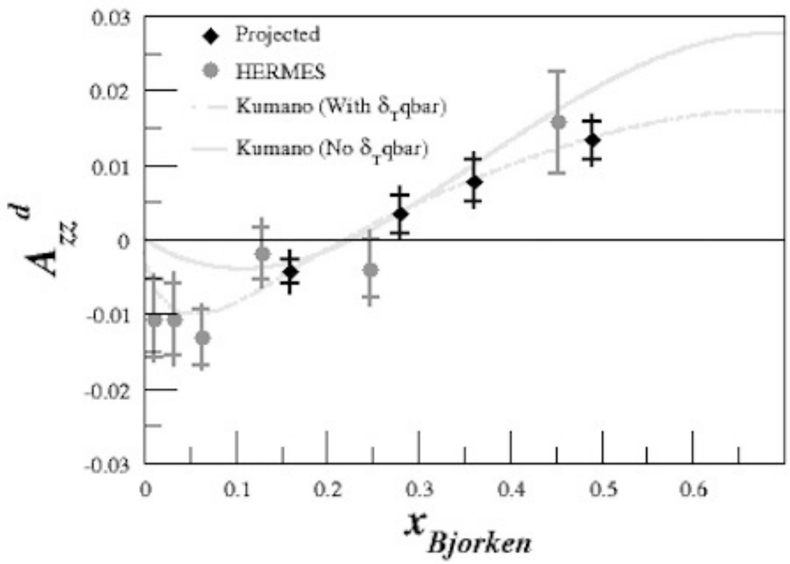
Khan & Hoodbhoy, PRC 44 ,1219 (1991) : $b_1 \approx O(10^{-4})$
Relativistic convolution model with binding

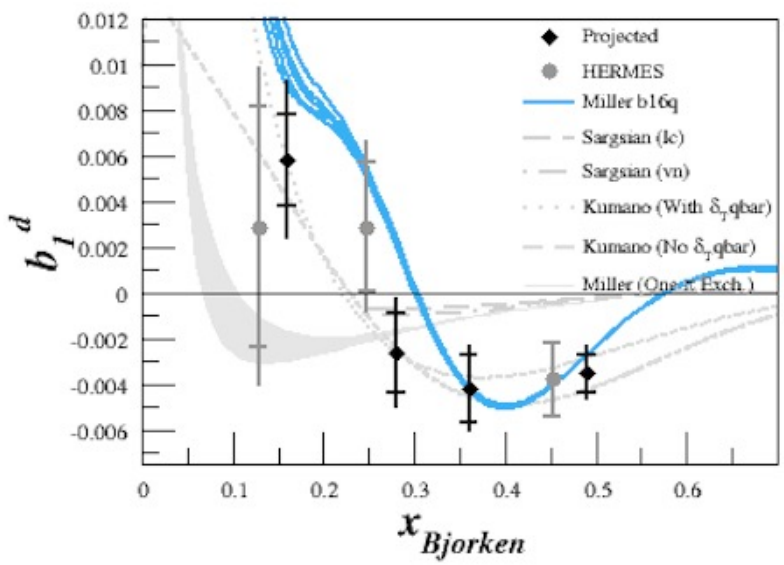
Umnikov, PLB 391, 177 (1997) : $b_1 \approx O(10^{-3})$
Relativistic convolution with Bethe-Salpeter formalism

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



Projected Results for Q = 30%

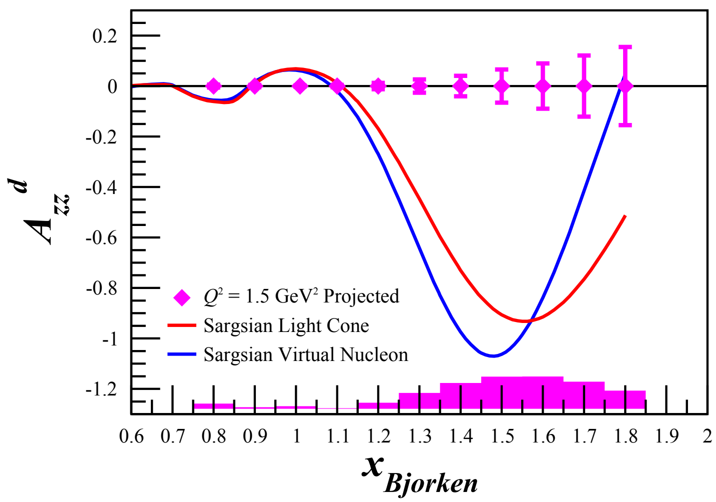




verification of zero crossing
essential for satisfaction of CK Sum

E12-15-005

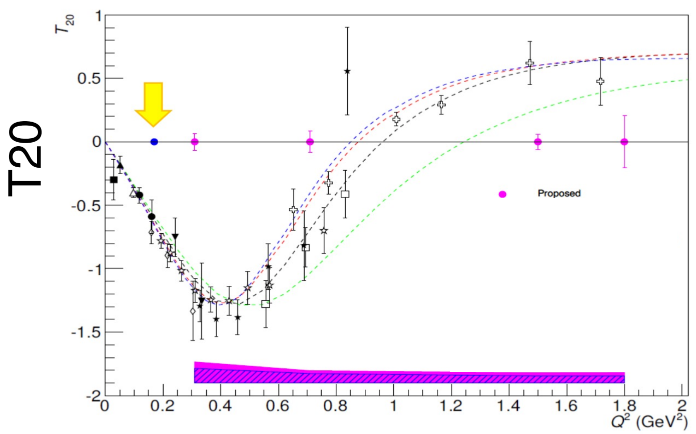
A_{zz} in the x>1 Region



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

Questions?