Nucleon spin structure at low Q: Hyperfine view

Outlook

A. Deur
Thomas Jefferson National Accelerator Facility

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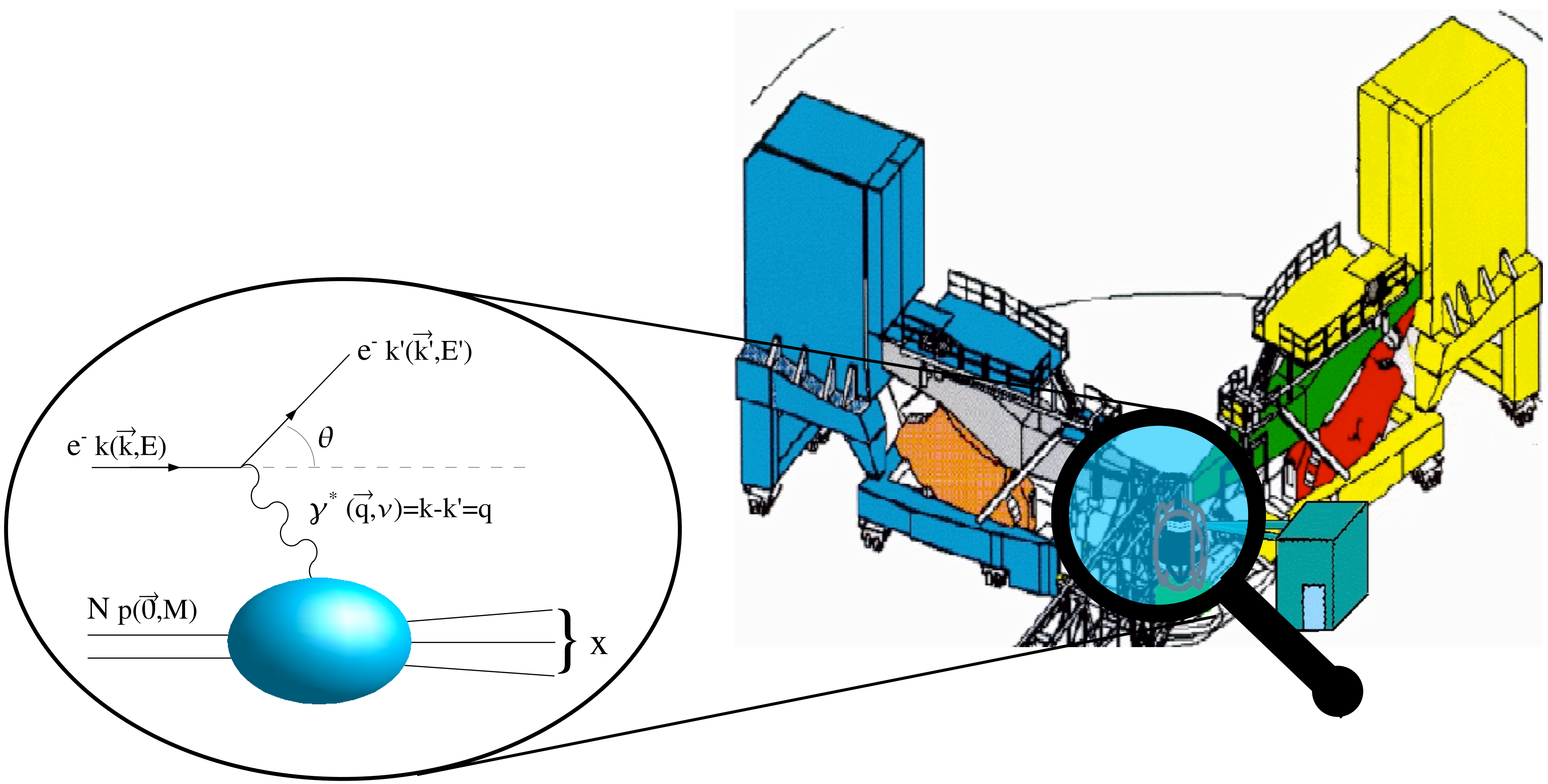

Goals of the workshop

- Review the latest experimental and theoretical developments on:
  - Low Q nucleon spin structure functions, spin polarizabilities and sum rules
  - Nucleon form factors and polarizabilities
  - The light atoms' hyperfine structure at the intersection between nuclear and atomic physics: High precision atomic measurements ⇒ 2-photon exchange, G_m and above observables needed for hadronic corrections.

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- Interpretation of the new data/comparison

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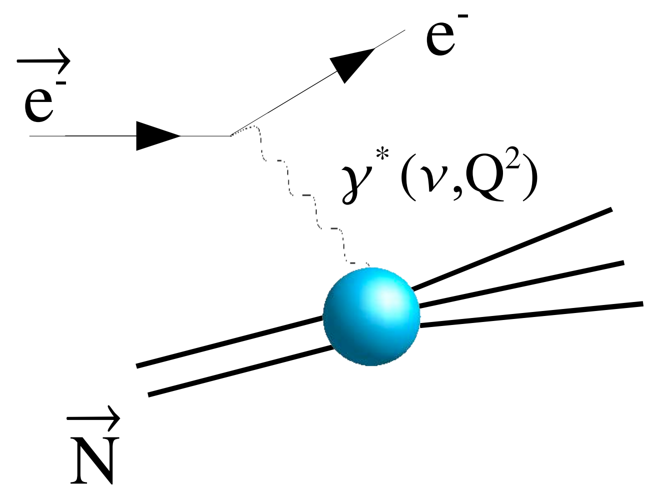
- Interpretation of the new data/comparison
- What new experiments are needed?
- What theoretical advances are need?

Inclusive polarized lepton scattering



Structure functions:

$$\text{cross section}=[\text{cross section}_{\text{pointlike object}}]\times[\alpha F_1(x,Q^2)+\beta F_2(x,Q^2)+(\gamma g_1(x,Q^2)+\delta g_2(x,Q^2))]$$

⇧ ⇧ unpolarized ⇧ ⇧ polarized

In Deep Inelastic scattering, interpreted in terms of parton distributions and polarizations.

$$x=\frac{Q^2}{2M\nu}$$ ~momentum of the struck quark normalized to nucleon mom. (0<x<1)

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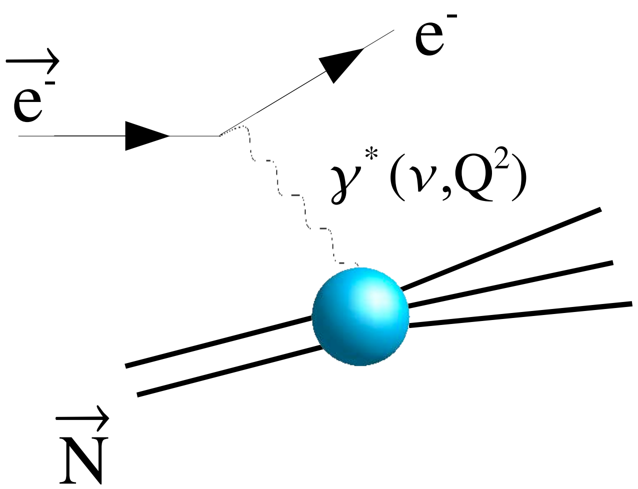

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Lower Q^2 response of the (excited) nucleon to virtual photon spin (T & L):

$$\sigma_T \equiv \frac{\sigma_{T,1/2}+\sigma_{T,3/2}}{2} = \frac{8\pi^2\alpha}{M\kappa_{\gamma^*}}F_1, \qquad \sigma_L \equiv \sigma_{L,1/2} = \frac{4\pi^2\alpha}{M\kappa_{\gamma^*}}\left[-F_1(Q^2,\nu)+\frac{M}{\nu}(1+\frac{1}{\gamma^2})F_2(Q^2,\nu)\right]$$

$$\sigma_{TT} \equiv \frac{\sigma_{T,1/2}-\sigma_{T,3/2}}{2} \equiv -\sigma'_{TT} = \frac{4\pi^2\alpha}{M\kappa_{\gamma^*}}(g_1-\gamma^2 g_2), \qquad \sigma'_{LT} \equiv \sigma'_{LT,3/2} = \frac{4\pi^2\alpha}{\kappa_{\gamma^*}}\frac{\gamma}{\nu}\left[g_1(Q^2,\nu)+g_2(Q^2,\nu)\right]$$

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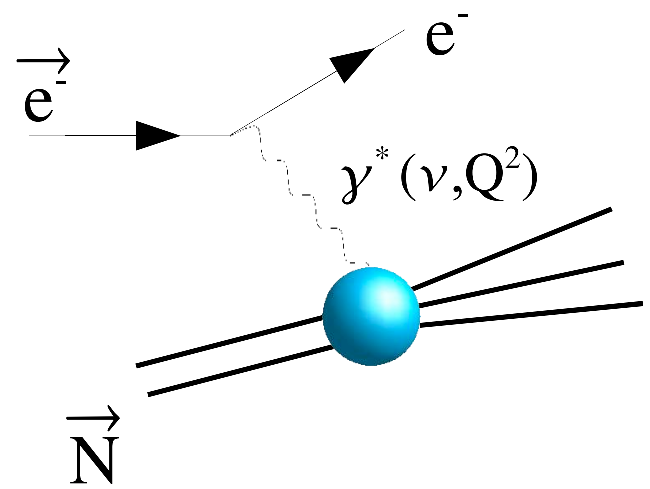

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x=1: Elastic scattering

e.g. ^{3}He

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\frac{E'}{E}\left(\frac{G_E^2+\tau_r G_M^2}{1+\tau_r}+2\tau_r G_M^2\tan^2(\theta/2)\right)$$

Inclusive polarized lepton scattering

$$\Gamma_1 = \int g_1 \, dx, \quad \Gamma_2 = \int g_2 \, dx$$

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GDH sum rule: $$\int_{\nu_{thr}}^{\infty} (\sigma^{1/2} - \sigma^{3/2}) \frac{d\nu}{\nu} = \frac{-2\alpha\pi^2\kappa^2}{M^2}$$

Photo-absorption cross sections

Photon energy

anomalous magnetic moment

Measured/being measured at $Q^2=0$ at MAINZ/ELSA, LEGS and HIGS (see M. Ahmed and P. Martel's talks). But max. $\nu \sim 3$ GeV may not be enough to test sum rule's convergence ν

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Photo-absorption cross sections

Originally derived for photo-absorption (Q^2=0)

Later generalized to Q^2>0: $$\frac{16\alpha\pi^2}{Q^2}\int_0^{1^-} g_1\, dx = 2\alpha\pi^2 S_1 \xrightarrow[Q^2 \to 0]{} \frac{-2\alpha\pi^2\kappa^2}{M^2}$$

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Generalized forward spin polarizability:

$$\gamma_0 = \frac{4e^2M^2}{\pi Q^6}\int x^2\left(g_1 - \frac{4M^2}{Q^2}\ x^2 g_2\right)dx$$

Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{4e^2M^2}{\pi Q^6}\int x^2(g_1+g_2)dx$$

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BC sum rule: $\Gamma_2 = \int_0^1 g_2 \, dx = 0$

New sum rules

sum rule for I_1

$$(S_1 - S_1^{\text{pole}})(\nu = 0, Q^2) = \frac{e^2}{2\pi M} I_1(Q^2) \quad \text{with} \quad I_1(Q^2) = \frac{2M^2}{Q^2} \int_0^{x_0} dx\, g_1(x, Q^2)$$

$$I_1'(0) = \frac{\kappa^2}{12}\langle r_2^2 \rangle + \frac{2\pi M^2}{e^2}\gamma_{E1M2} - \frac{3M^3}{2}\left[P'^{(M1,M1)1}(0) + P'^{(L1,L1)1}(0)\right]$$

Sum rules relating RCS, VCS, VVCS
Can be tested by experiment !

Both for $Q^2=0$ and $Q^2>0$.

See M. Vanderhaeghen's talk

$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1E2} - \gamma_{M1M1}$

Components measurable (MAMI, HIGS).

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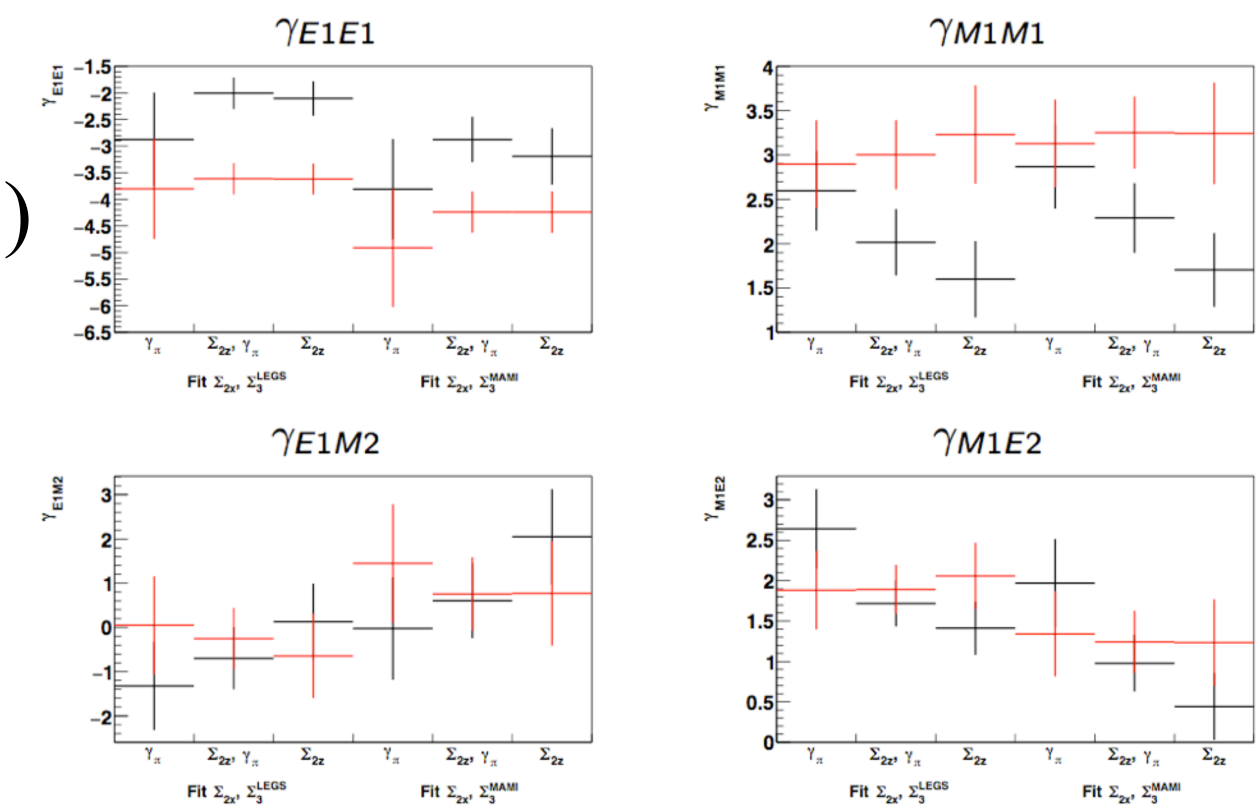
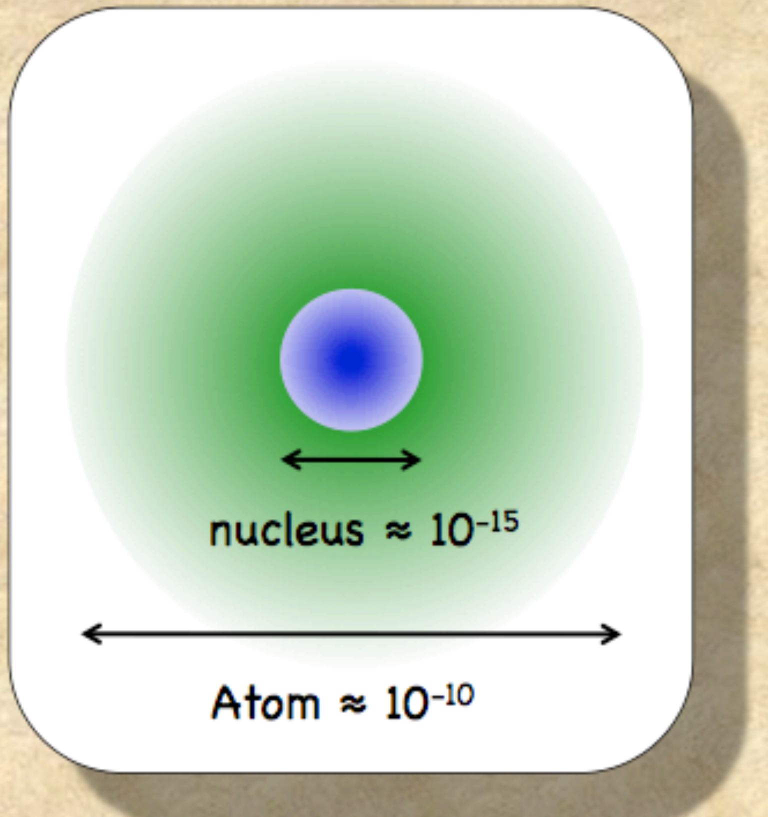


See P. Martel's talk
(see also cool active target development)

Connection with atomic physics



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

Hydrogen HF Splitting

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

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

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

Stolen from K. Slifer's talk

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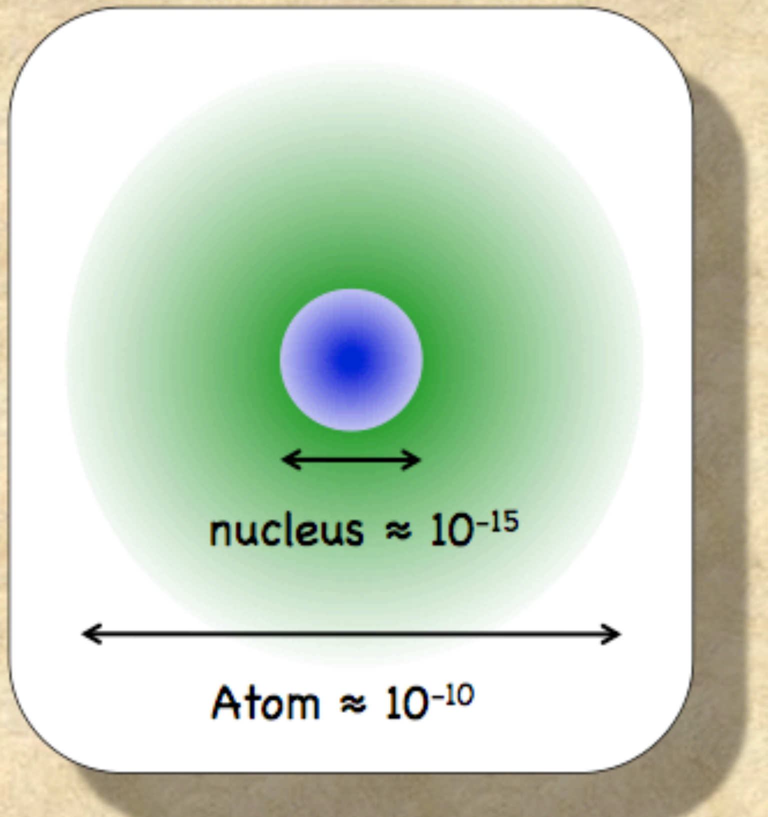

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$$\Delta_S = \Delta_Z + \Delta_{POL}$$

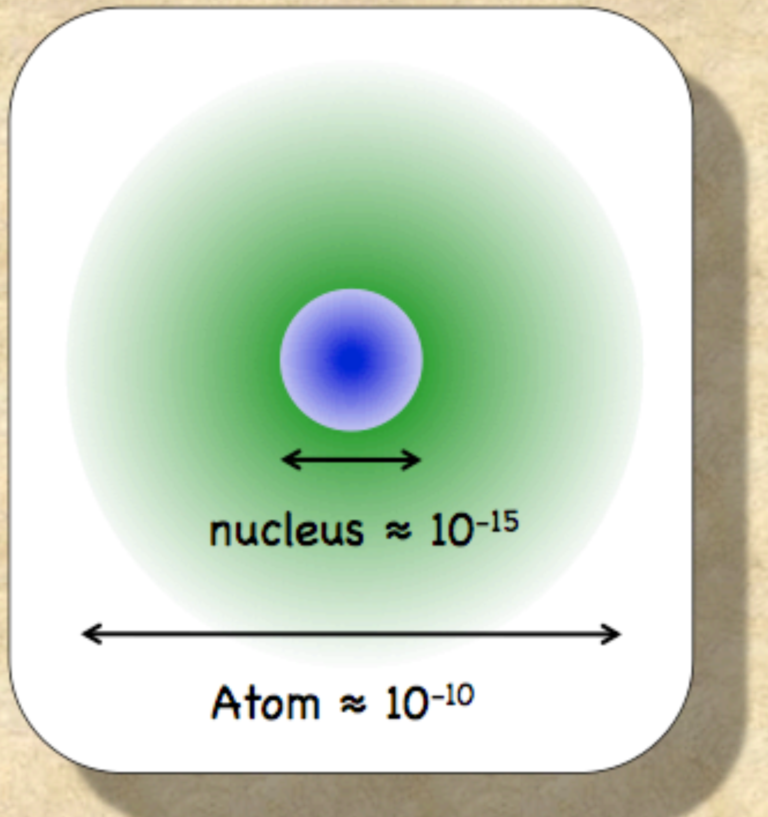
Elastic Scattering

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

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

Δ_Z=-41.0±0.5ppm

Connection with atomic physics



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

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

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

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

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

Latest developments on low Q spin structure functions and spin polarizabilities.

Following the "δ_{LT} puzzle" discovered early 2000s, a low Q experimental program was run at JLab to provide a test of χEFT. 4 experiments with focus on:

•GDH's I_{TT} (σ_{TT}, or g_1 and g_2) on neutron and ^{3}He: J.P. Chen's talk

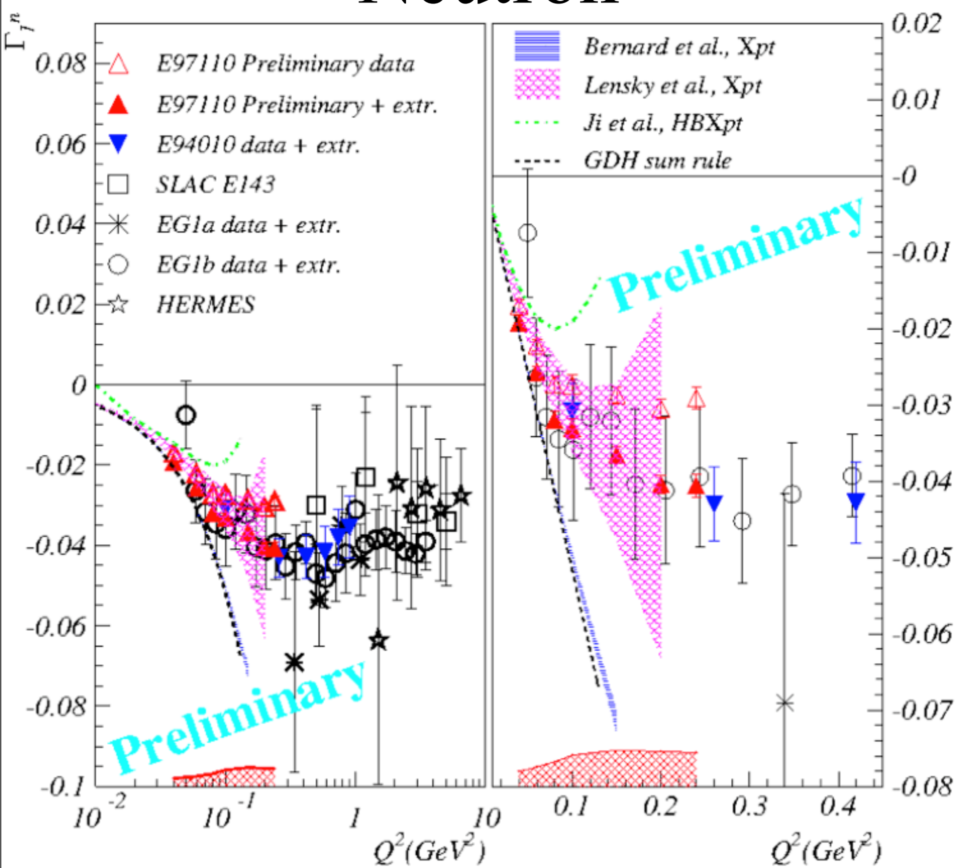
•GDH's Γ_1 (g_1) on proton: M. Ripani's talk

•GDH's Γ_1 (g_1) on neutron (D): M. Ripani's talk

•δ_{LT} (g_2) on proton: K. Slifer's talk

First moments: GDH sum(s)

Neutron



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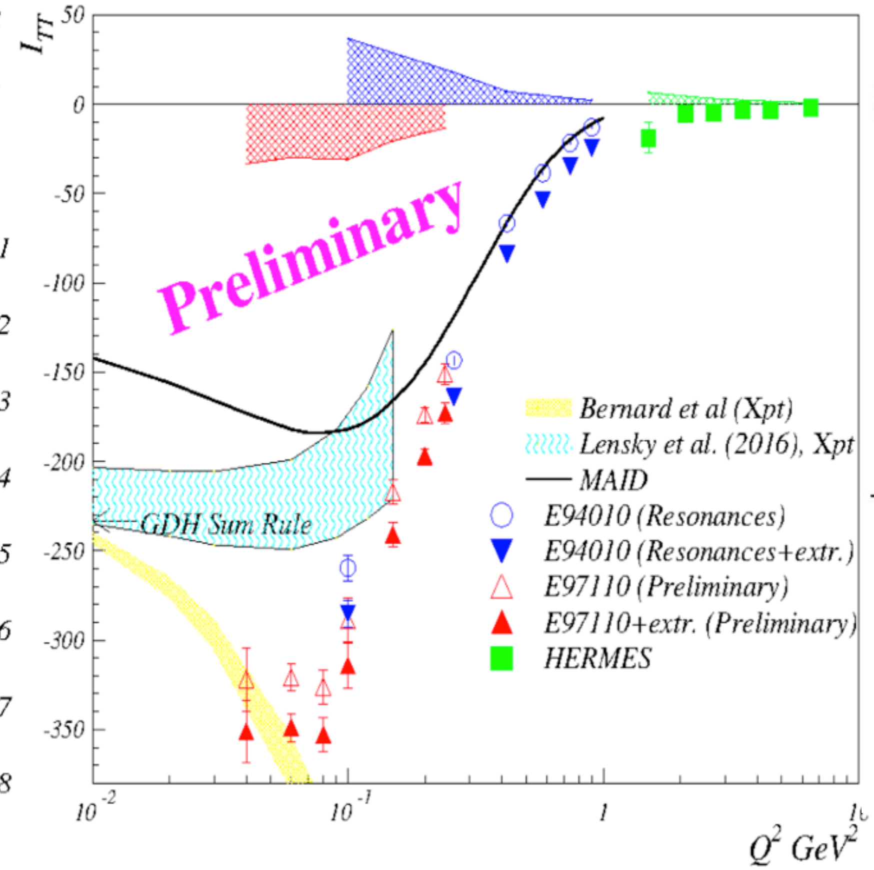
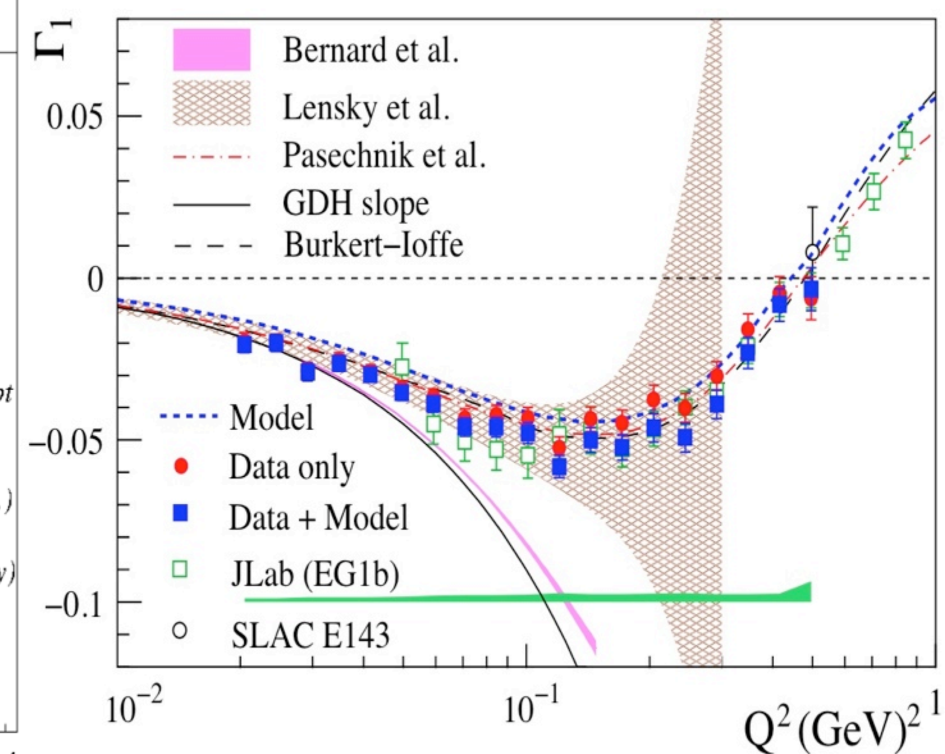


~proton+neutron (D)



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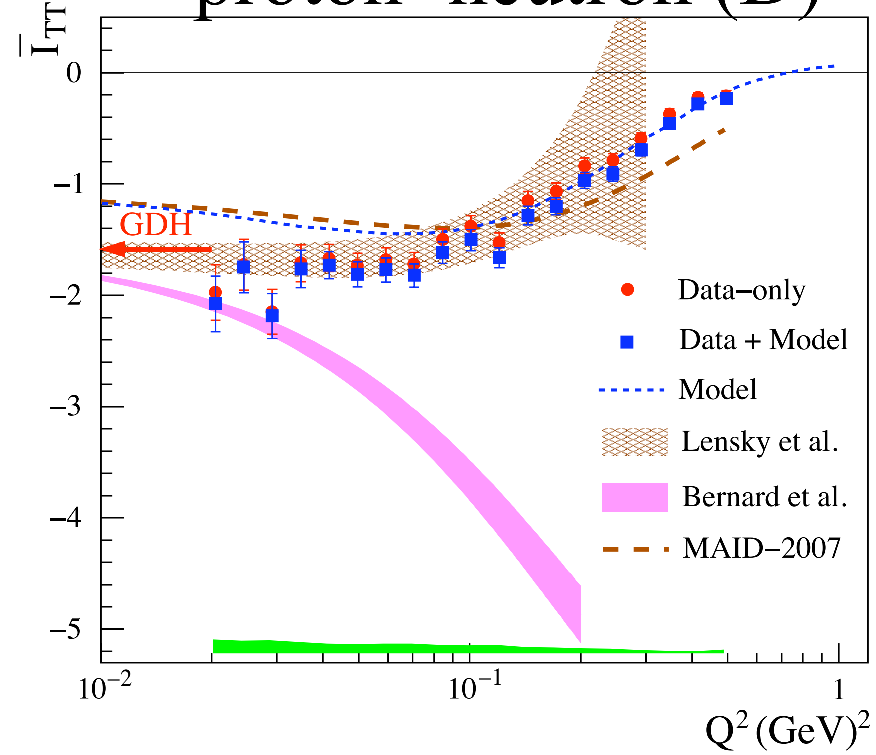

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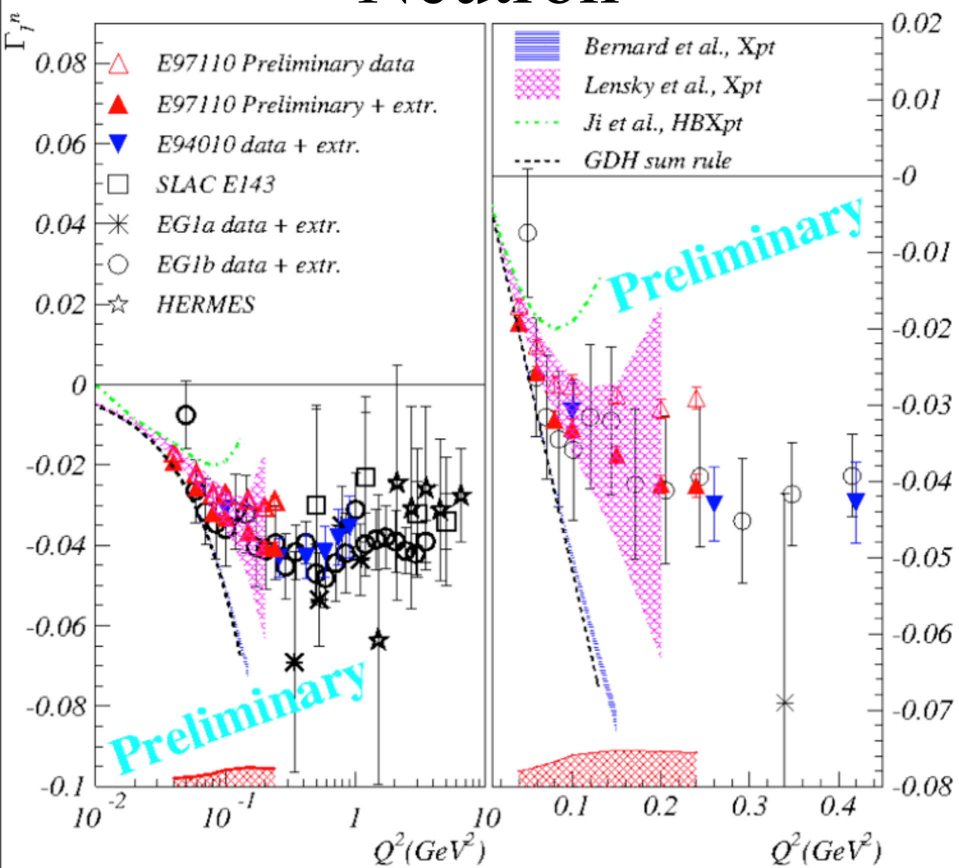

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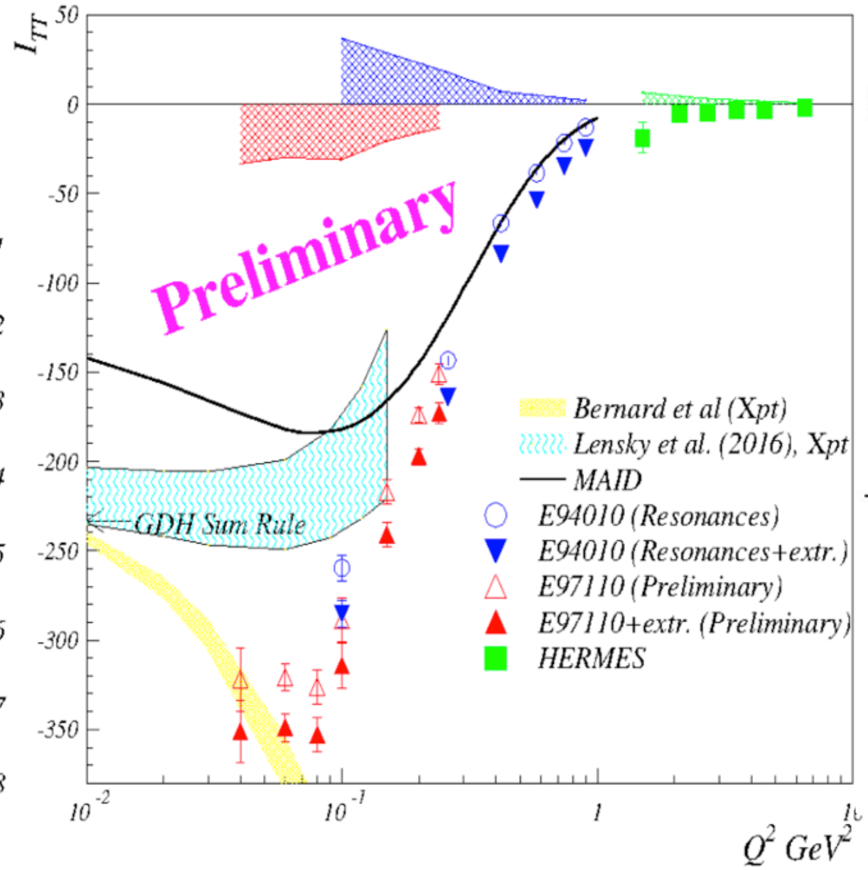

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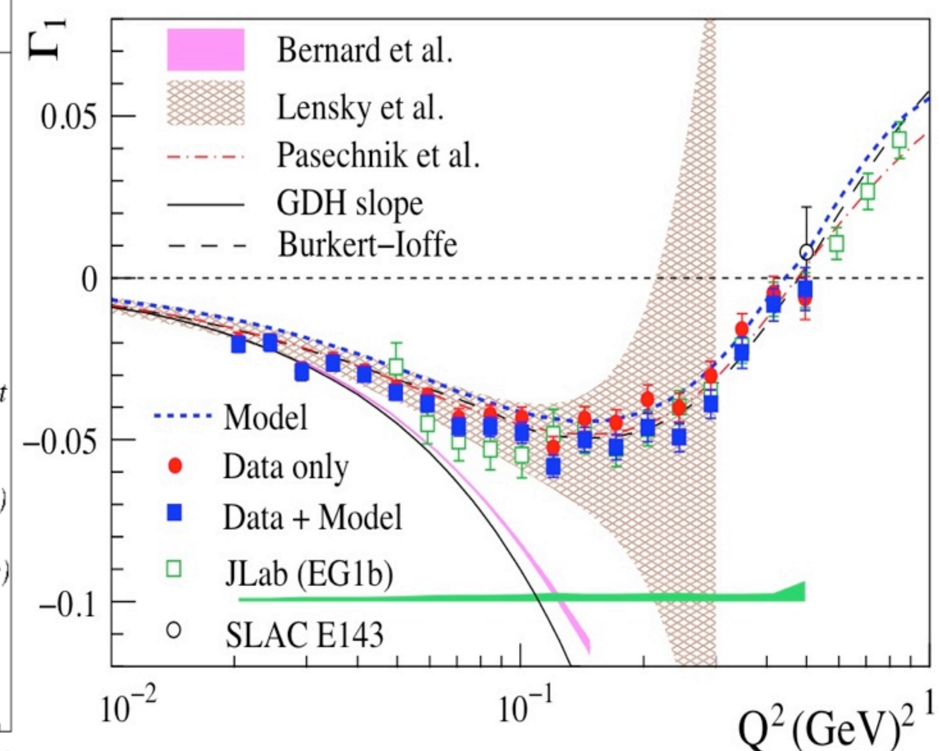

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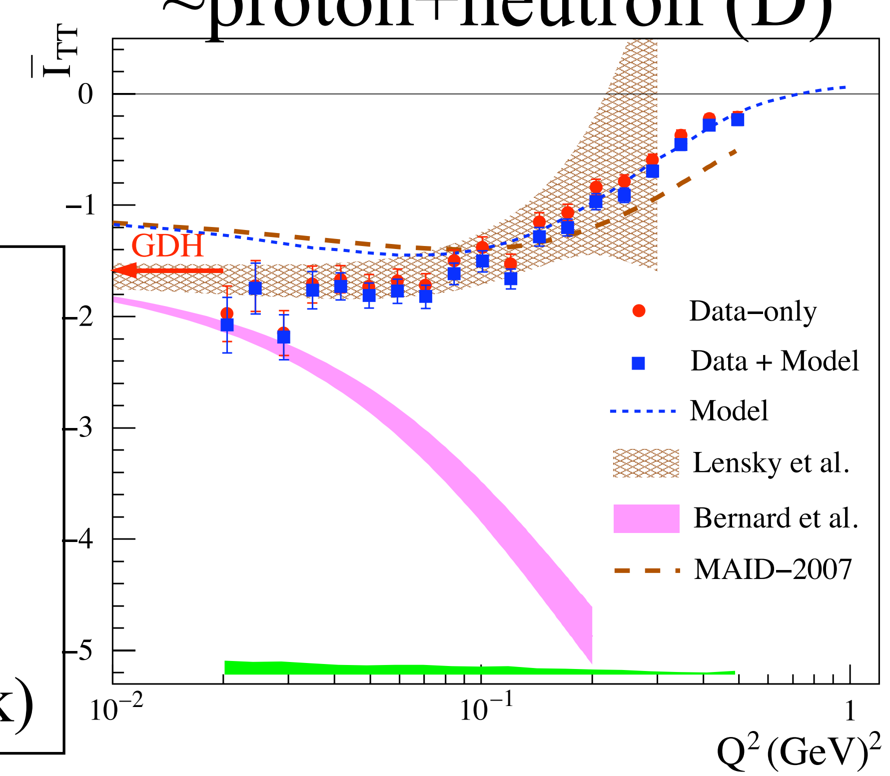

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$\Rightarrow$ Lensky et al. χEFT successful with Γ_1 but problem with Γ_2?

Bernard et al. χEFT reliable only at the lowest Q^2.

What differs between Lensky et al. and Bernard et al. χEFT calculations? (no big diff. identified, see V. Pascaltusa's talk)

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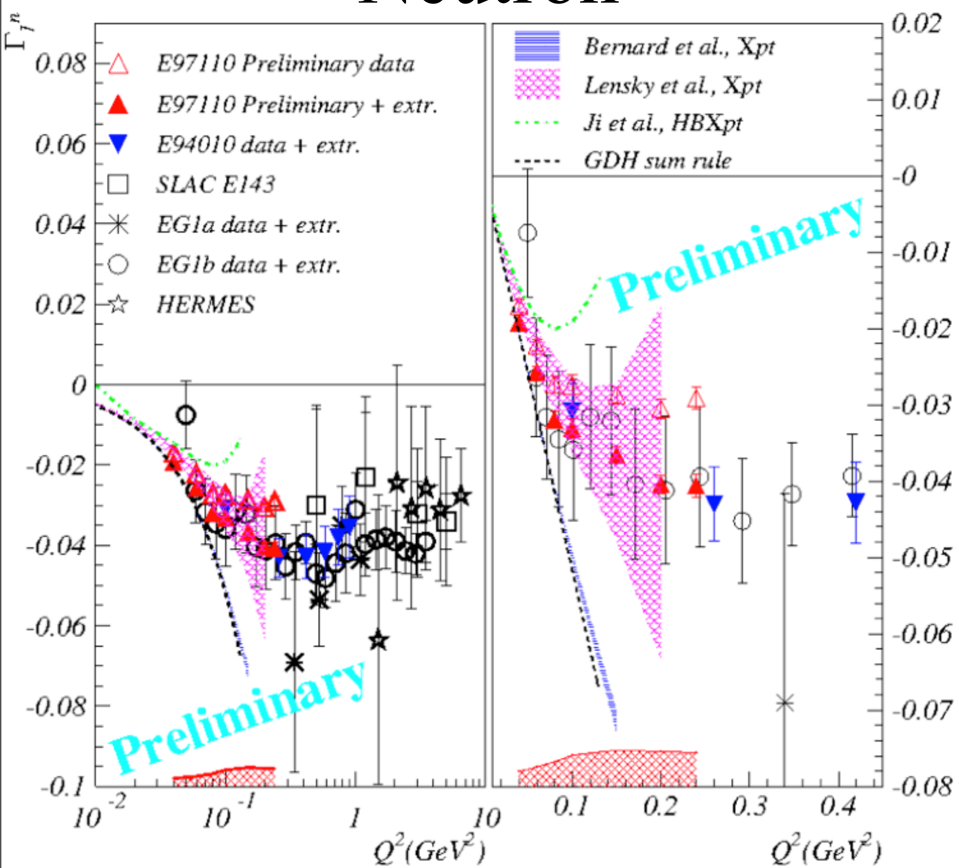

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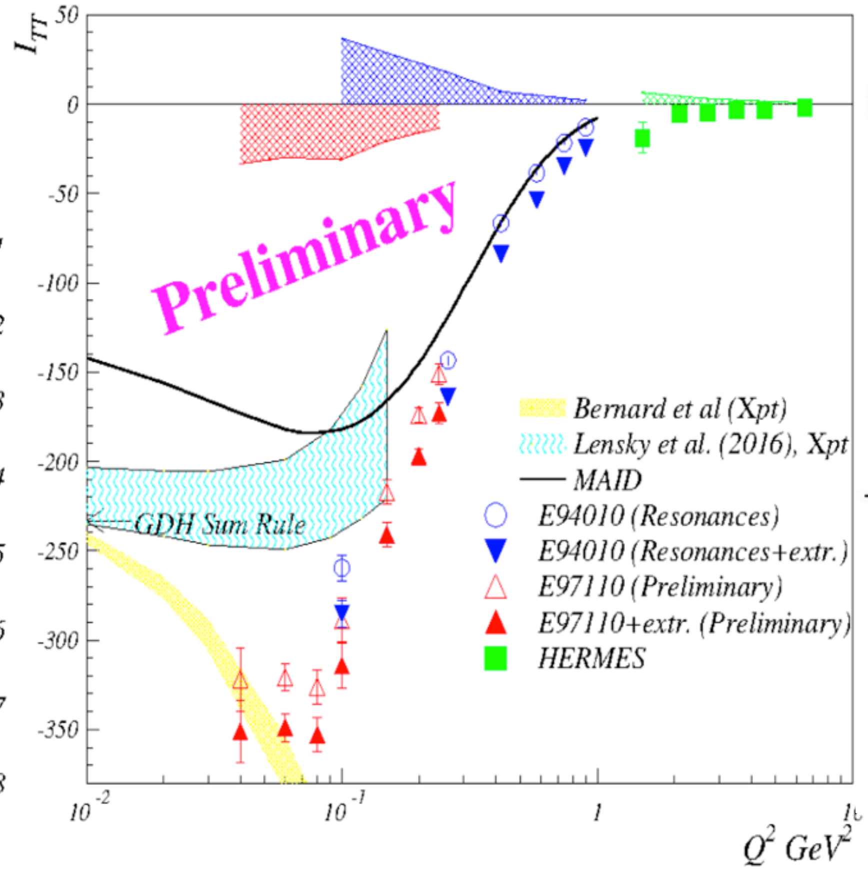

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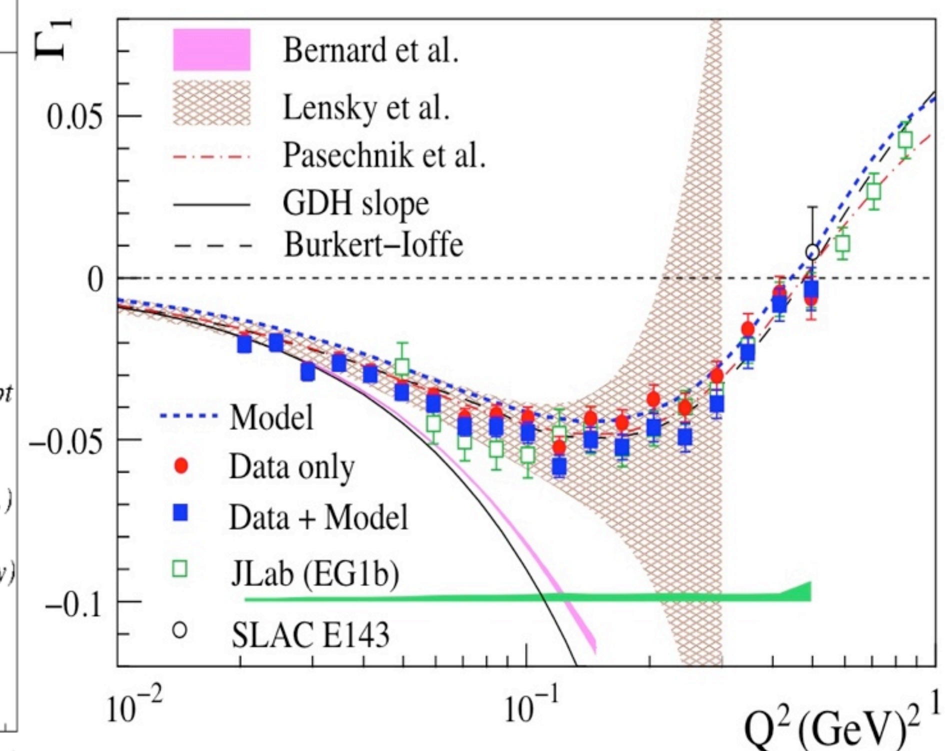

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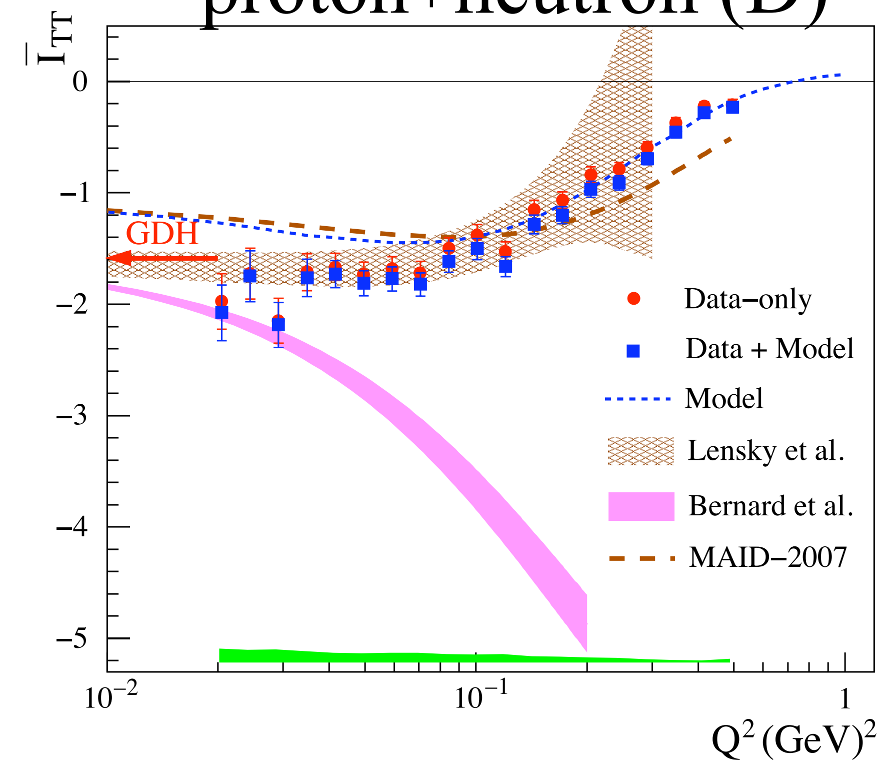

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Need global parameterization of low Q data.

- Sebastian Kuhn Model.
- MAID

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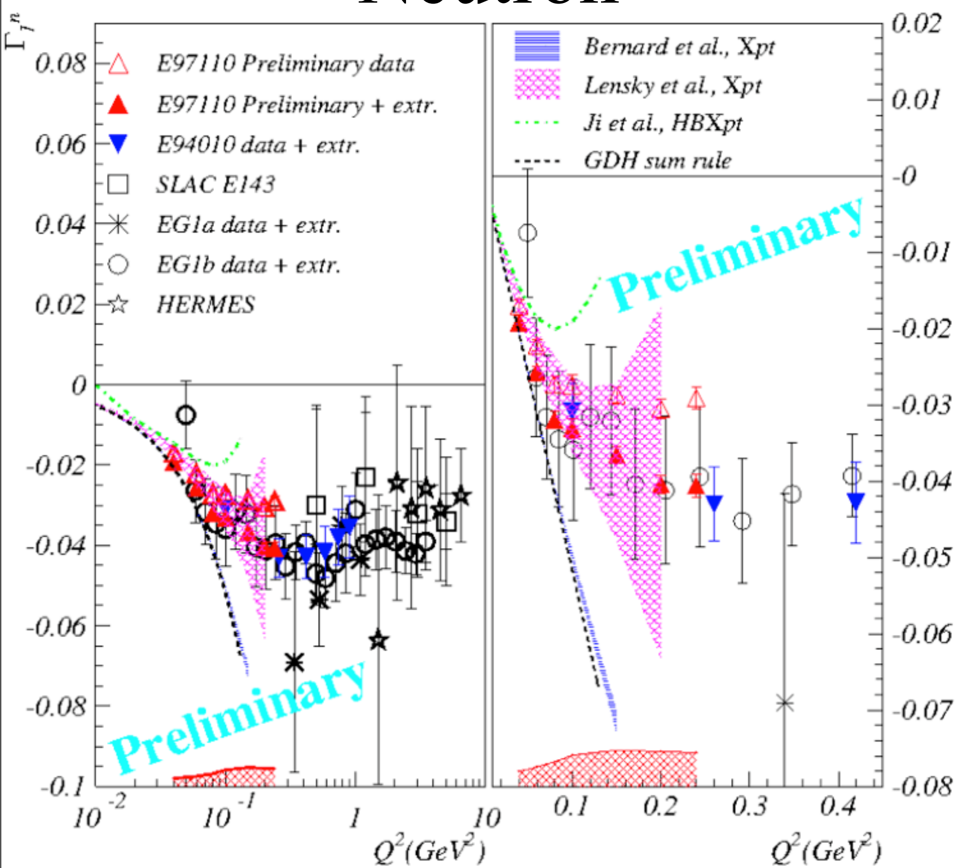

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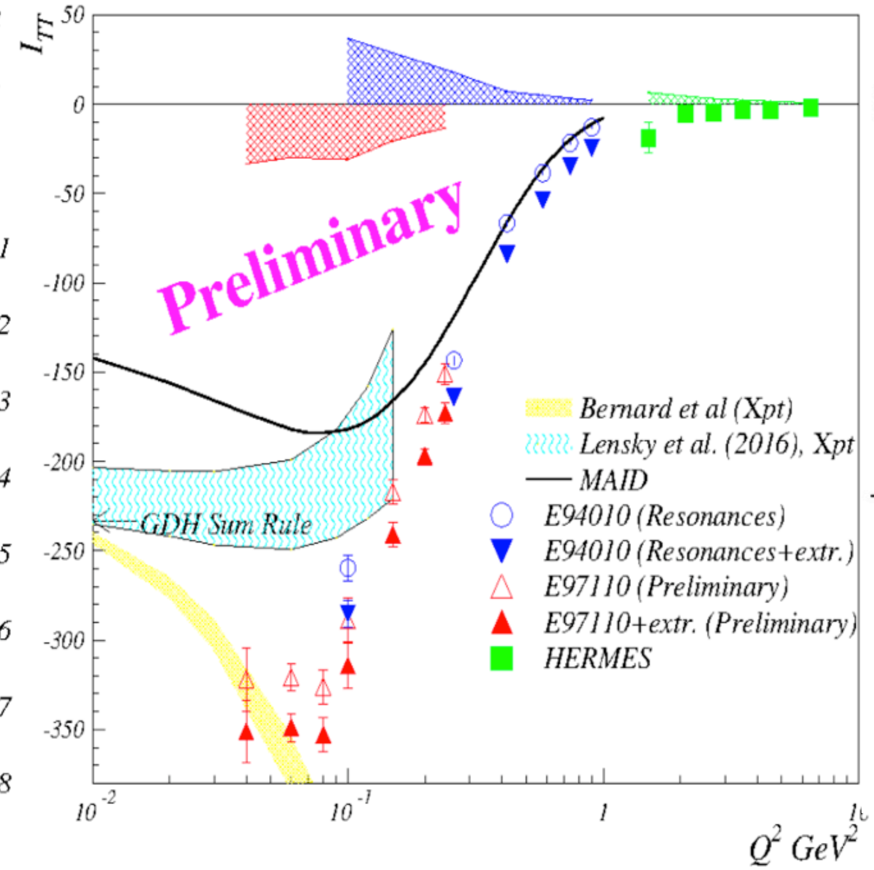

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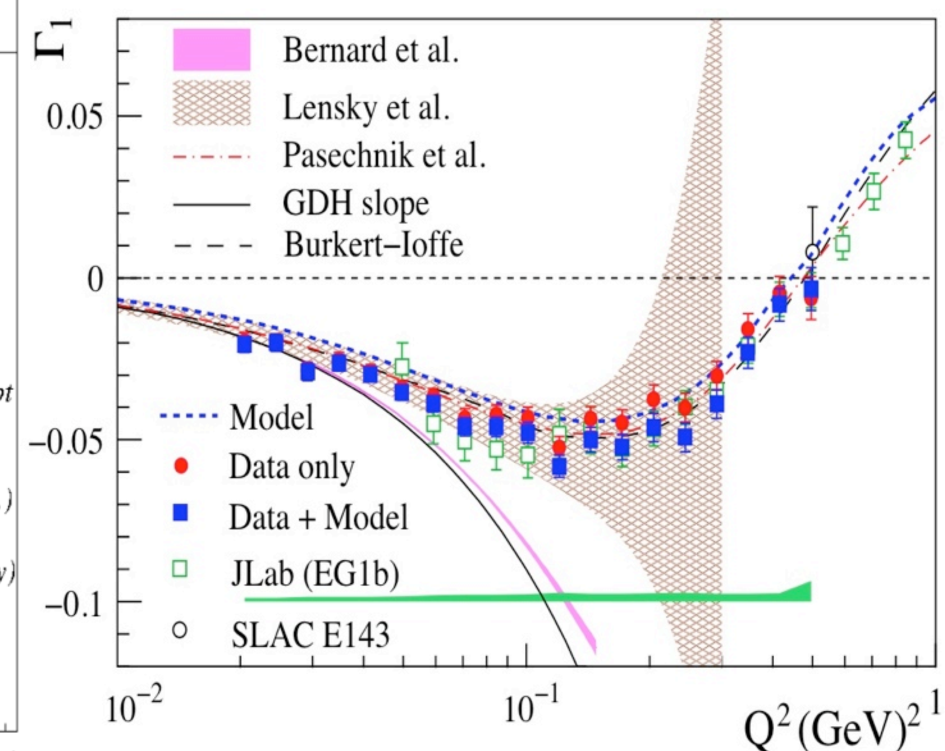

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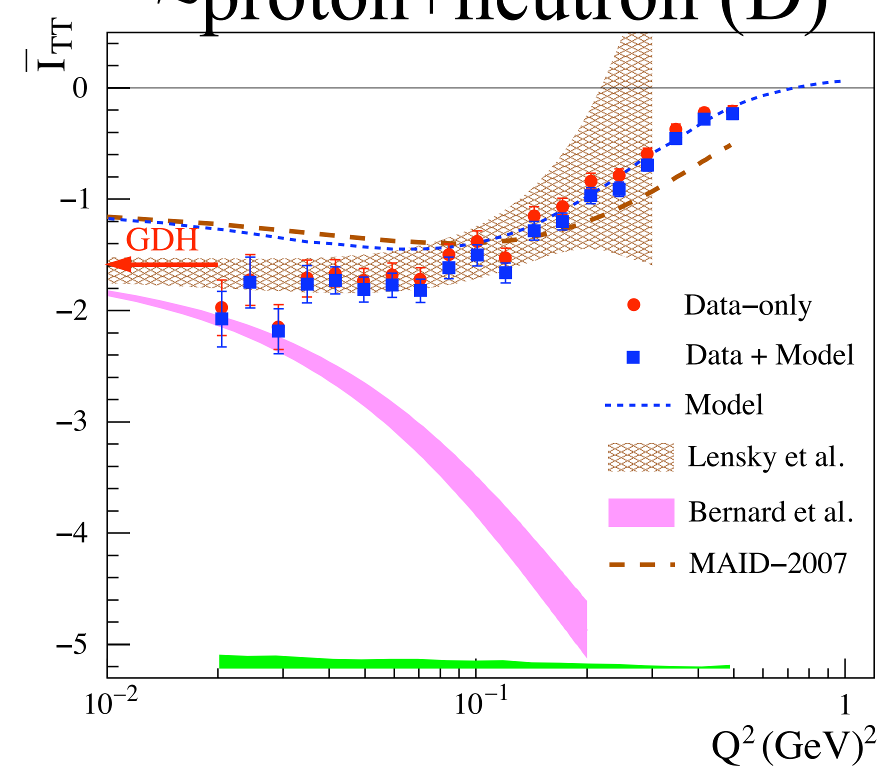

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No Lattice result on moments available yet at low and intermediate Q^2. Challenge: need to compute 4-point functions.

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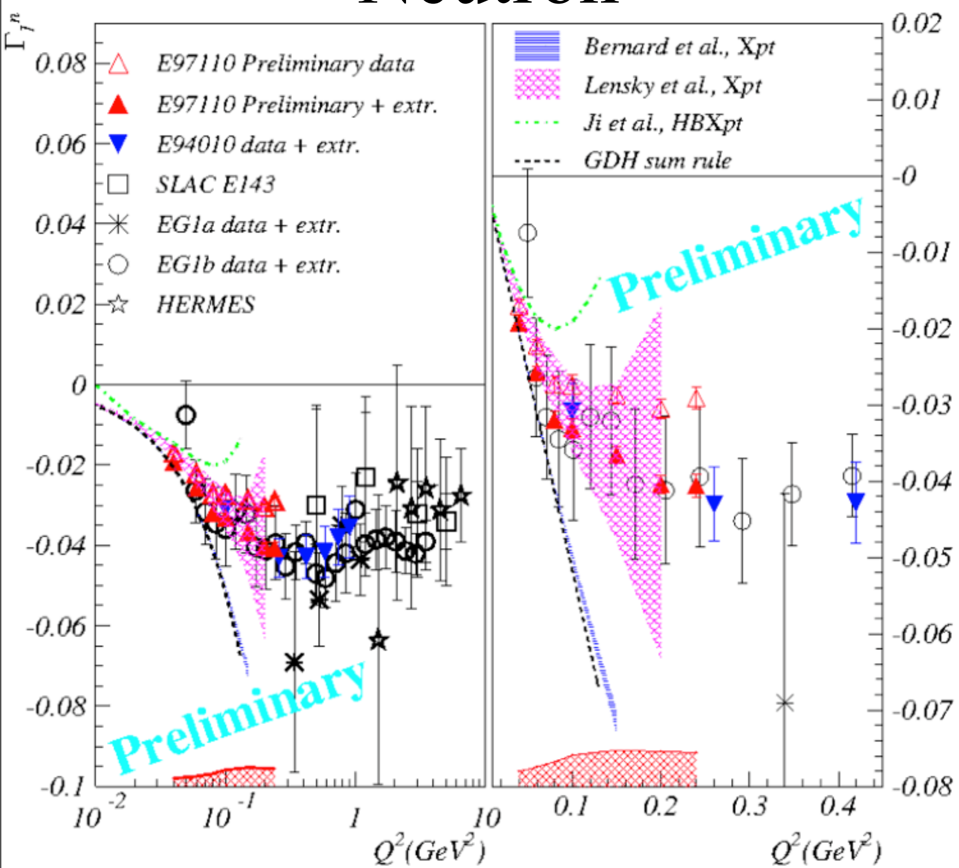

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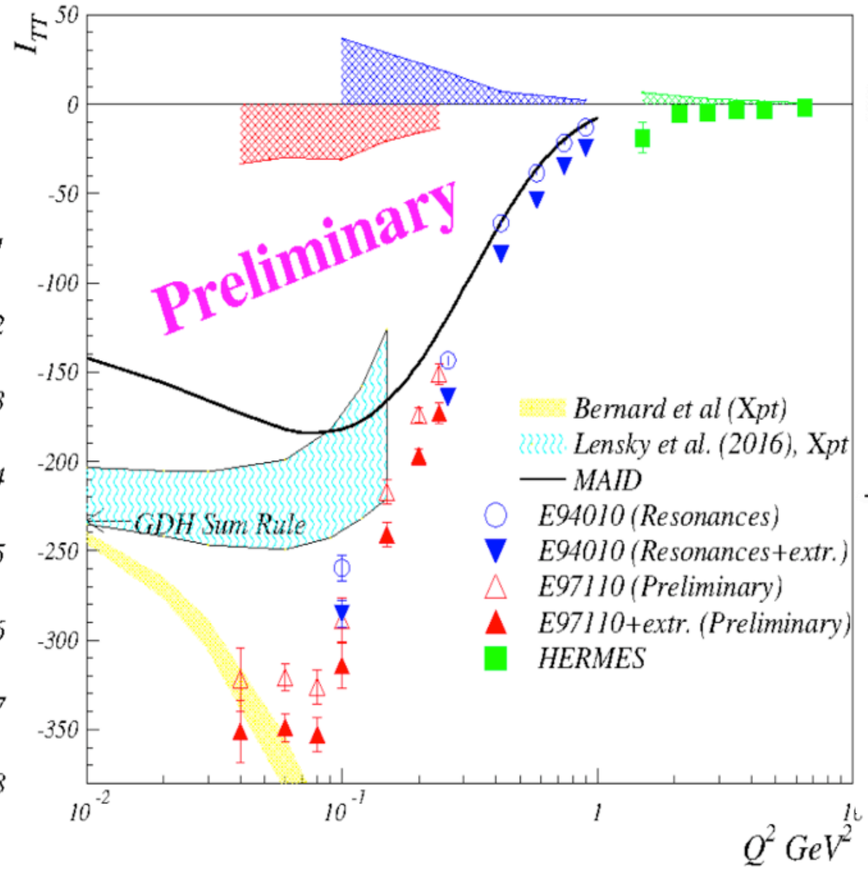

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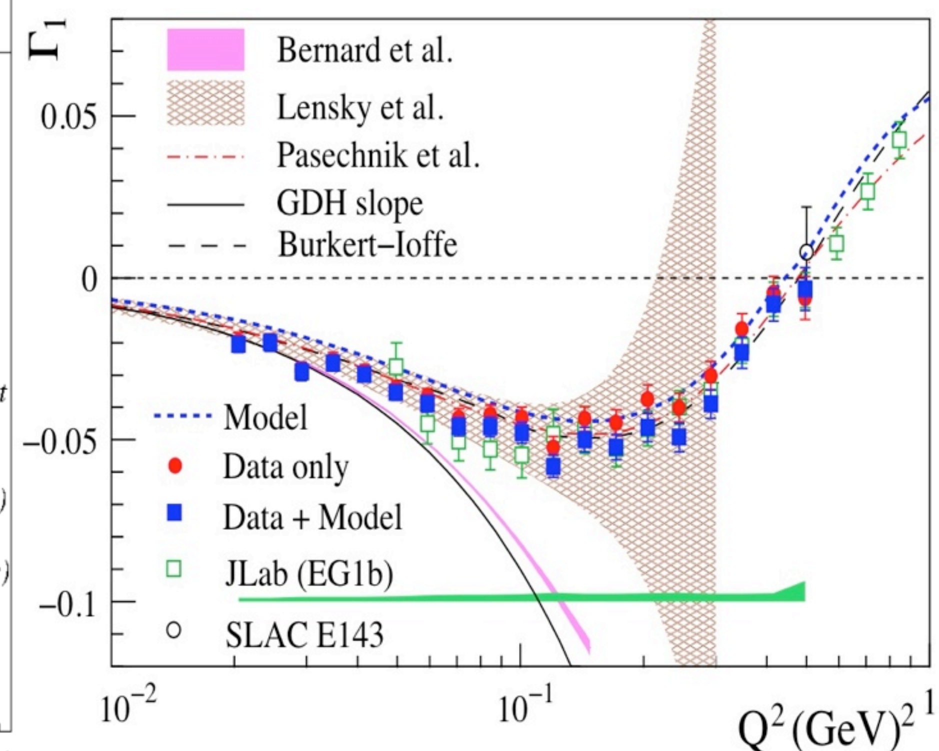

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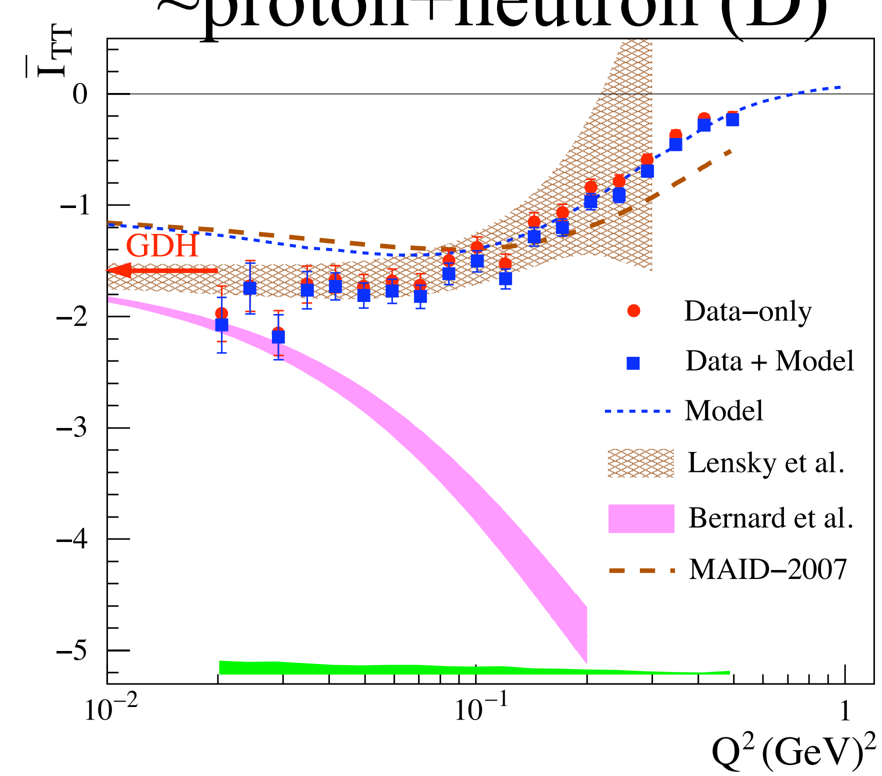

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Full spin decomposition (spin sum rule) at large Q^2.

C. Alexandrou's talks

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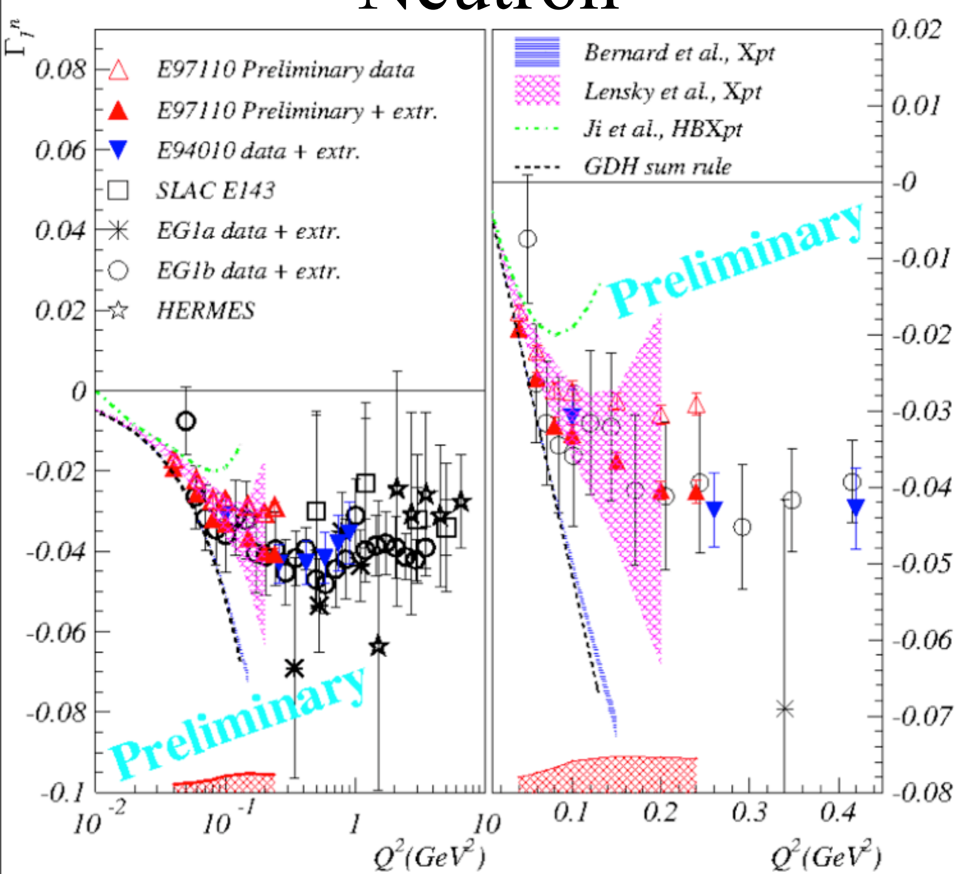

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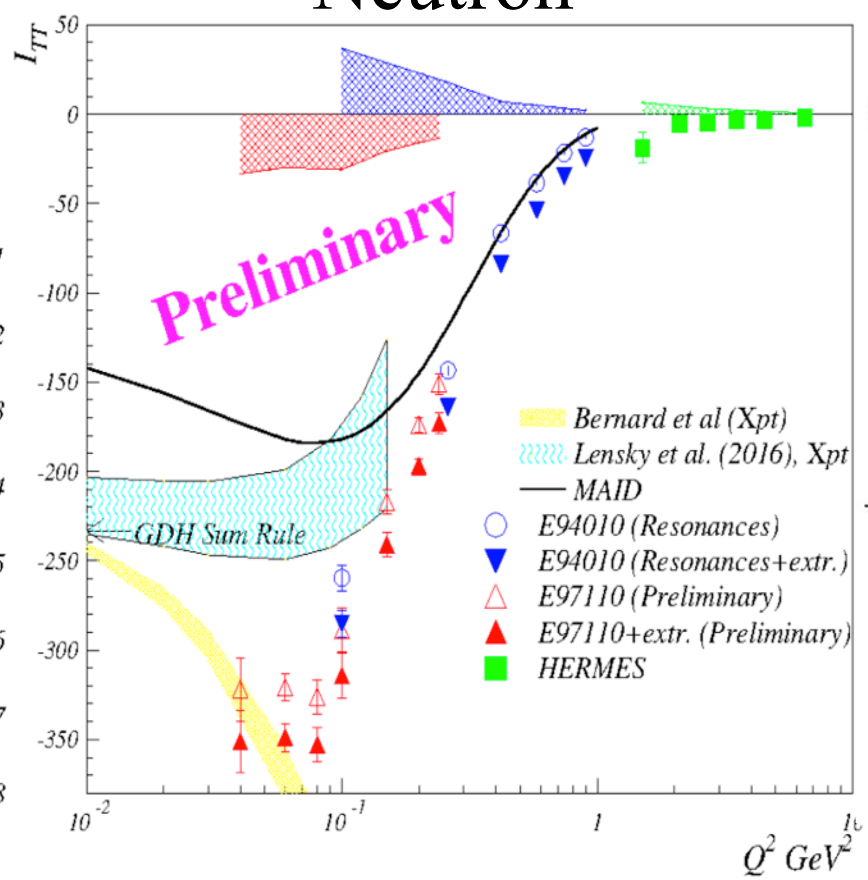

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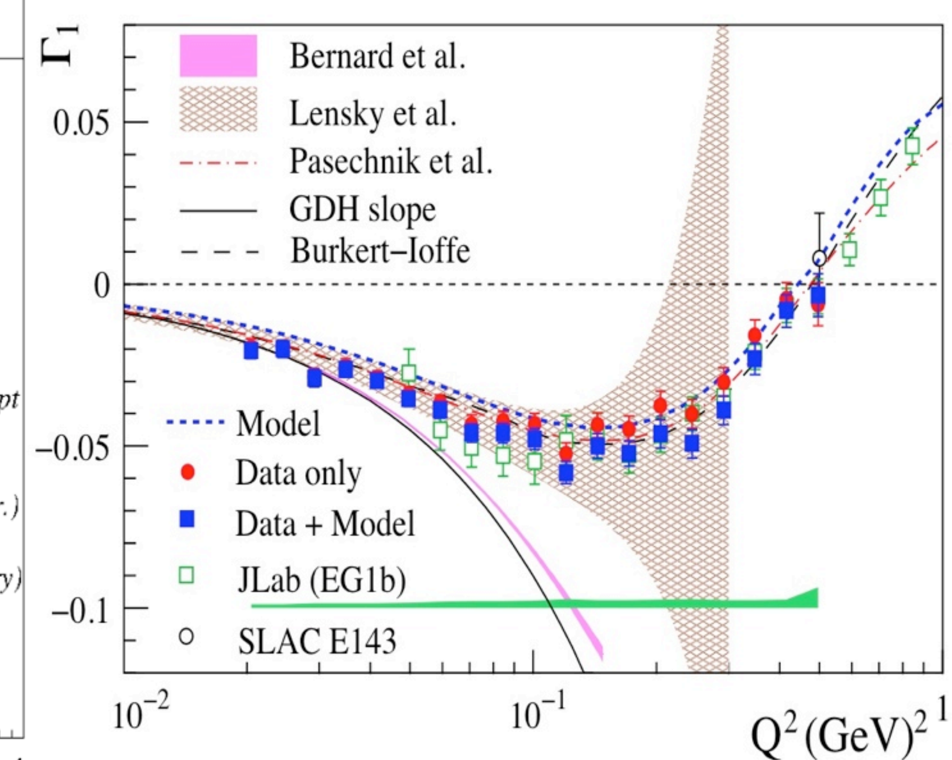

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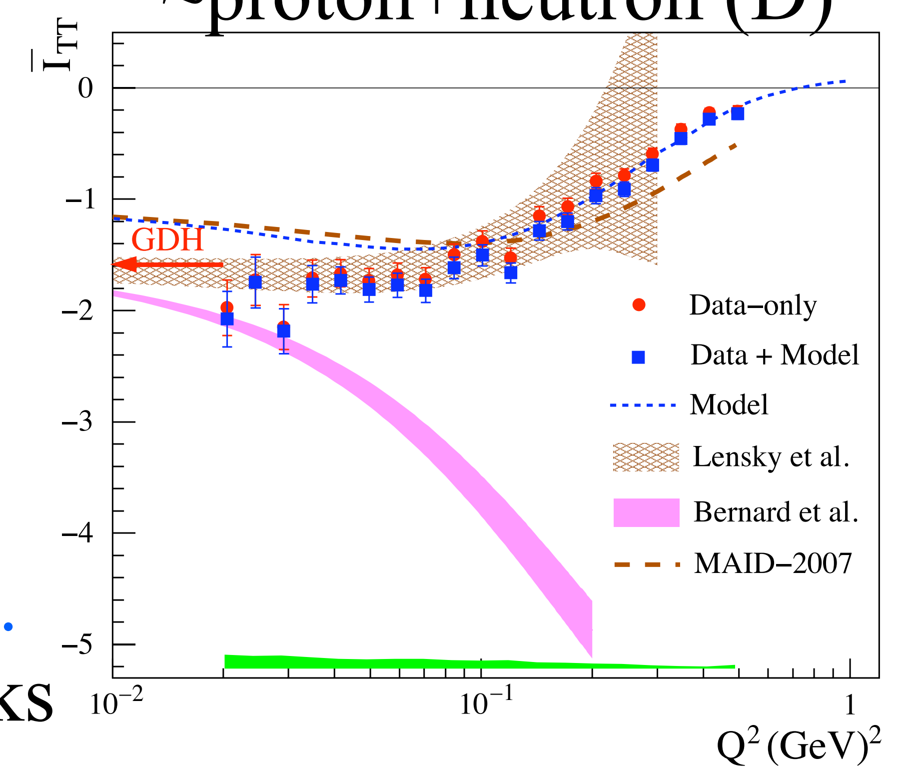

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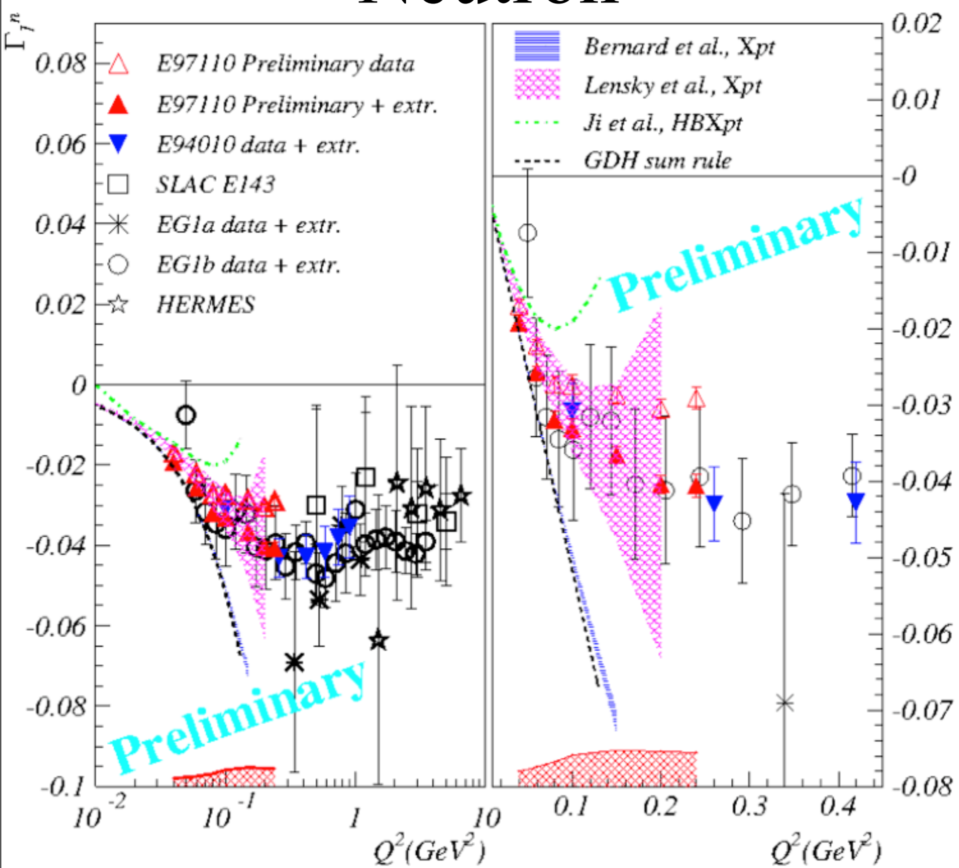
Axial charges of the nucleon now successfully obtained.

K. Ottnad and C. Alexandrou's talks

First moments: GDH sum(s)

Neutron



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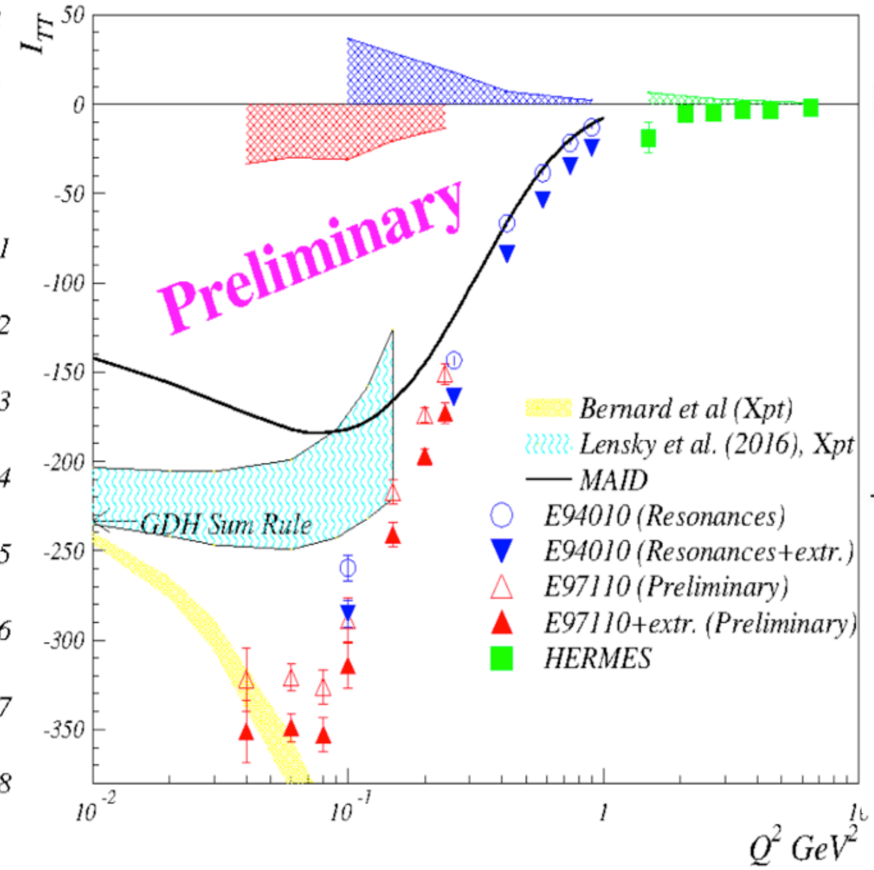

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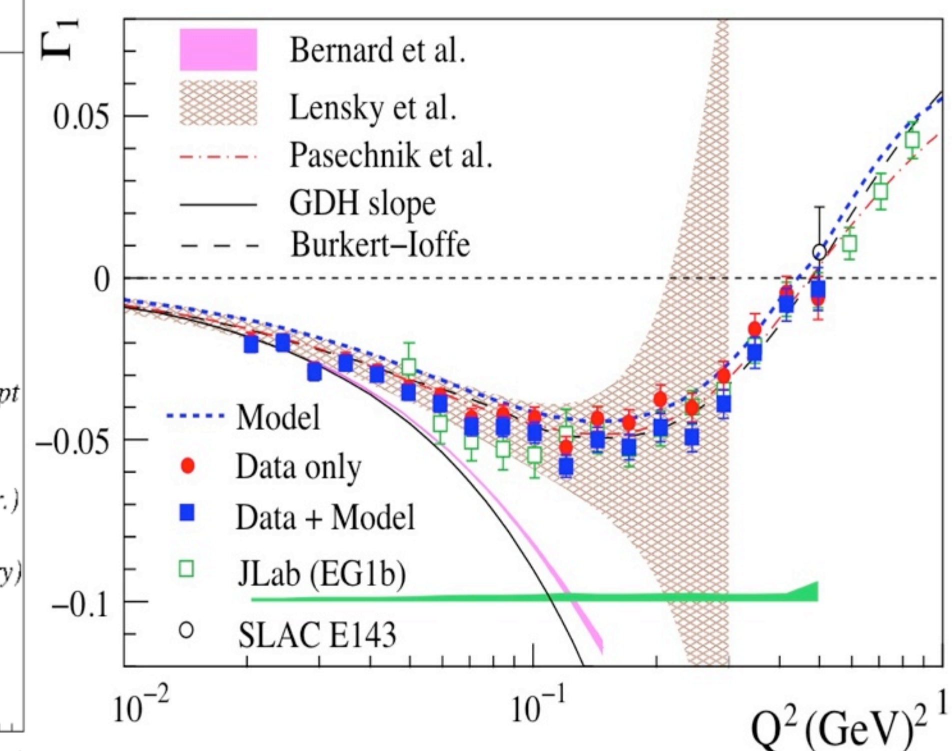

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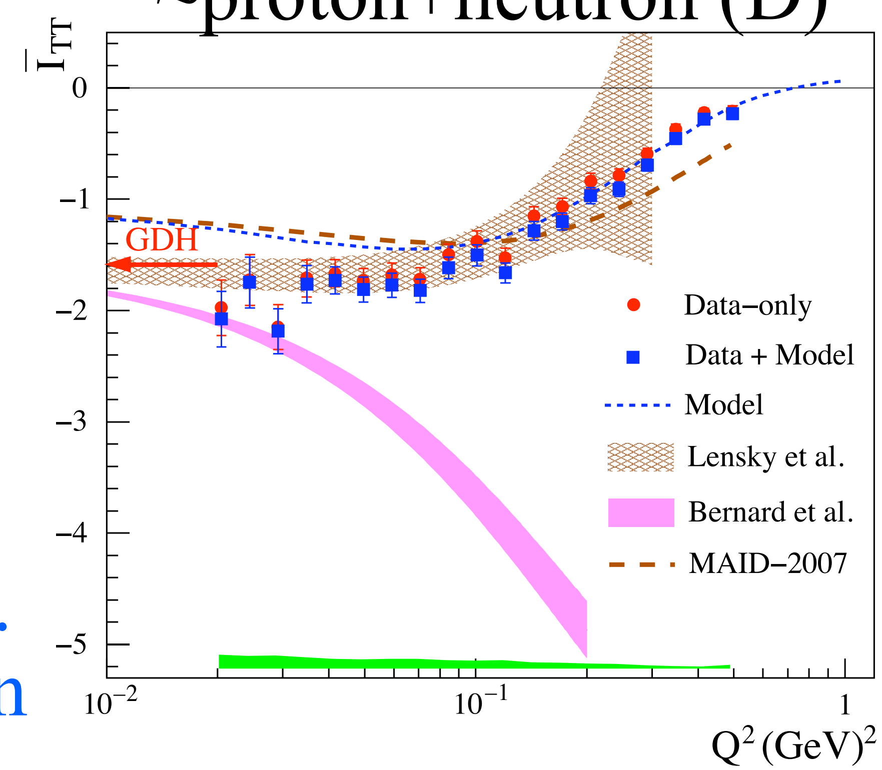

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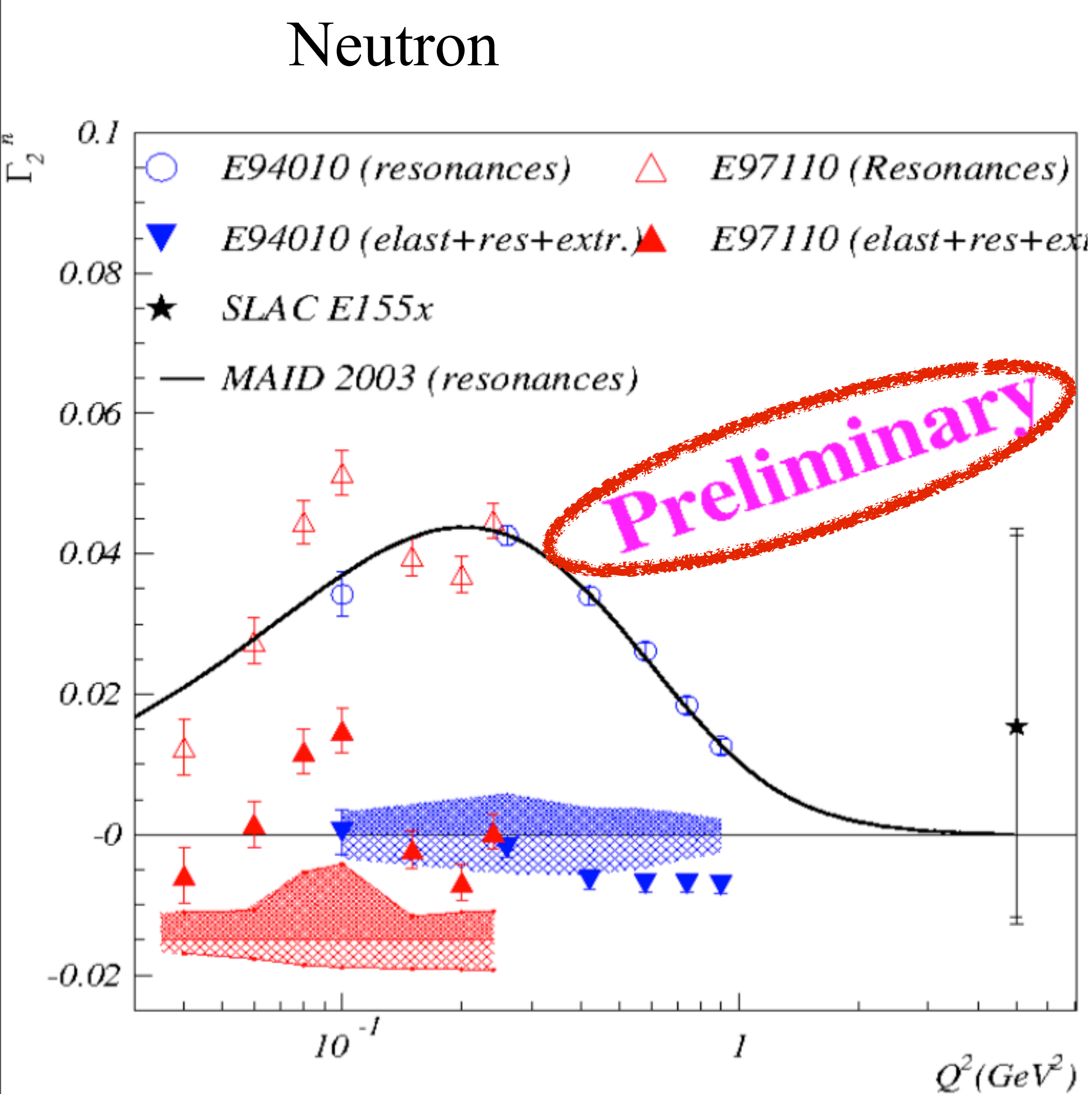
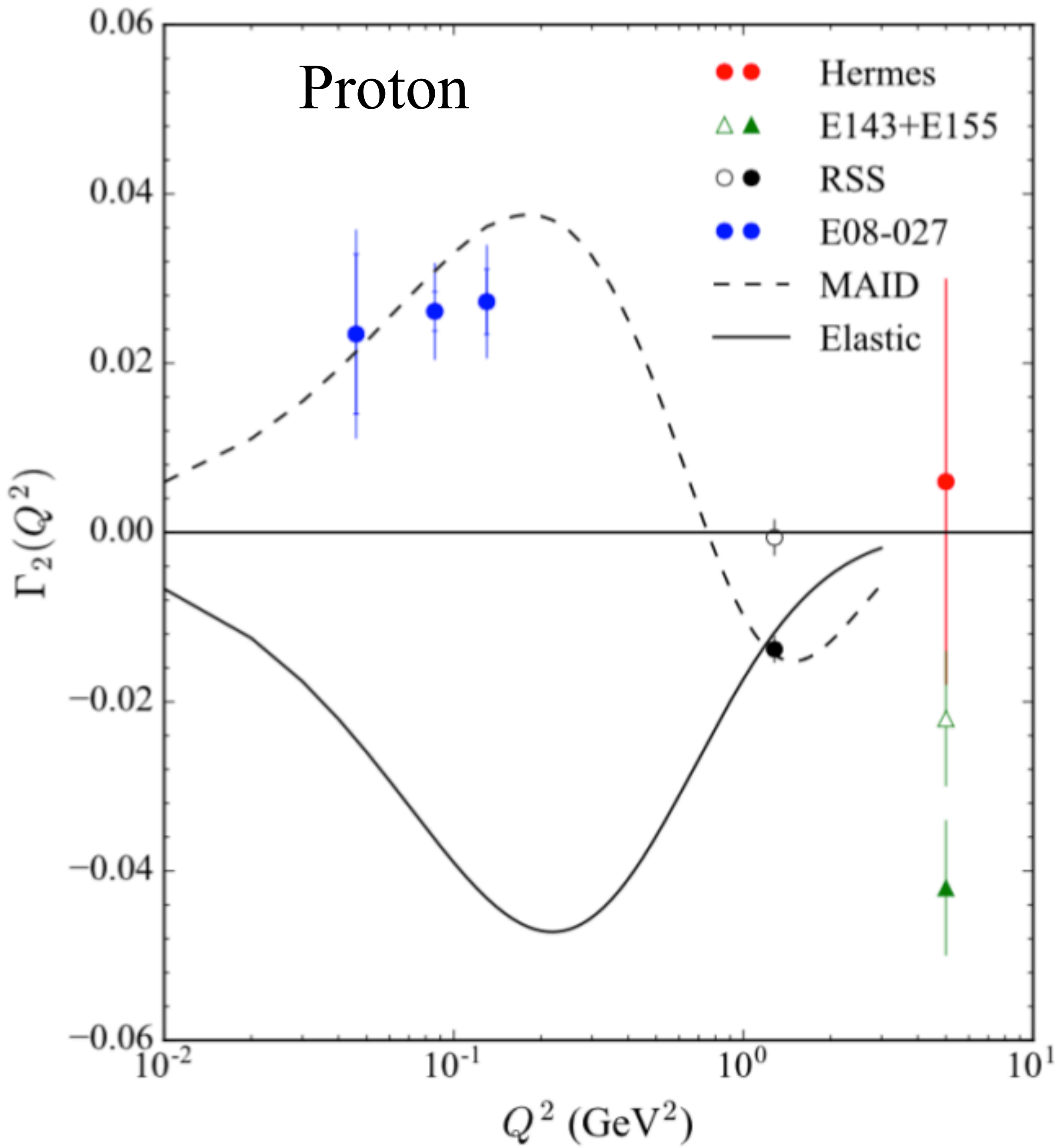
Struct. Funct. x-dep: Quasi-PDF: critical development in Lattice QCD. Not applicable at these Q^2.

H-W Lin and C. Alexandrou's talks

BC sum rule: $\Gamma_2 = \int_0^1 g_2\, dx = 0$

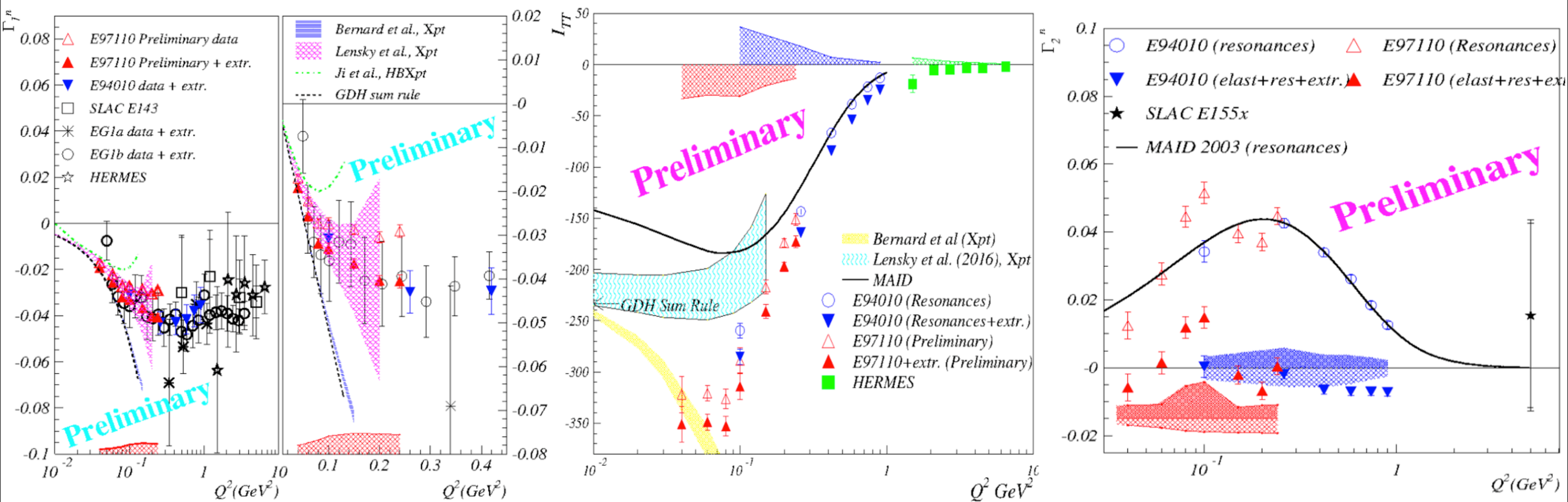




BC sum rule seems valid at low Q^2.

Bump for neutron seems to be due to systematics in interpolation

Latest developments on low Q spin structure functions and spin polarizabilities.



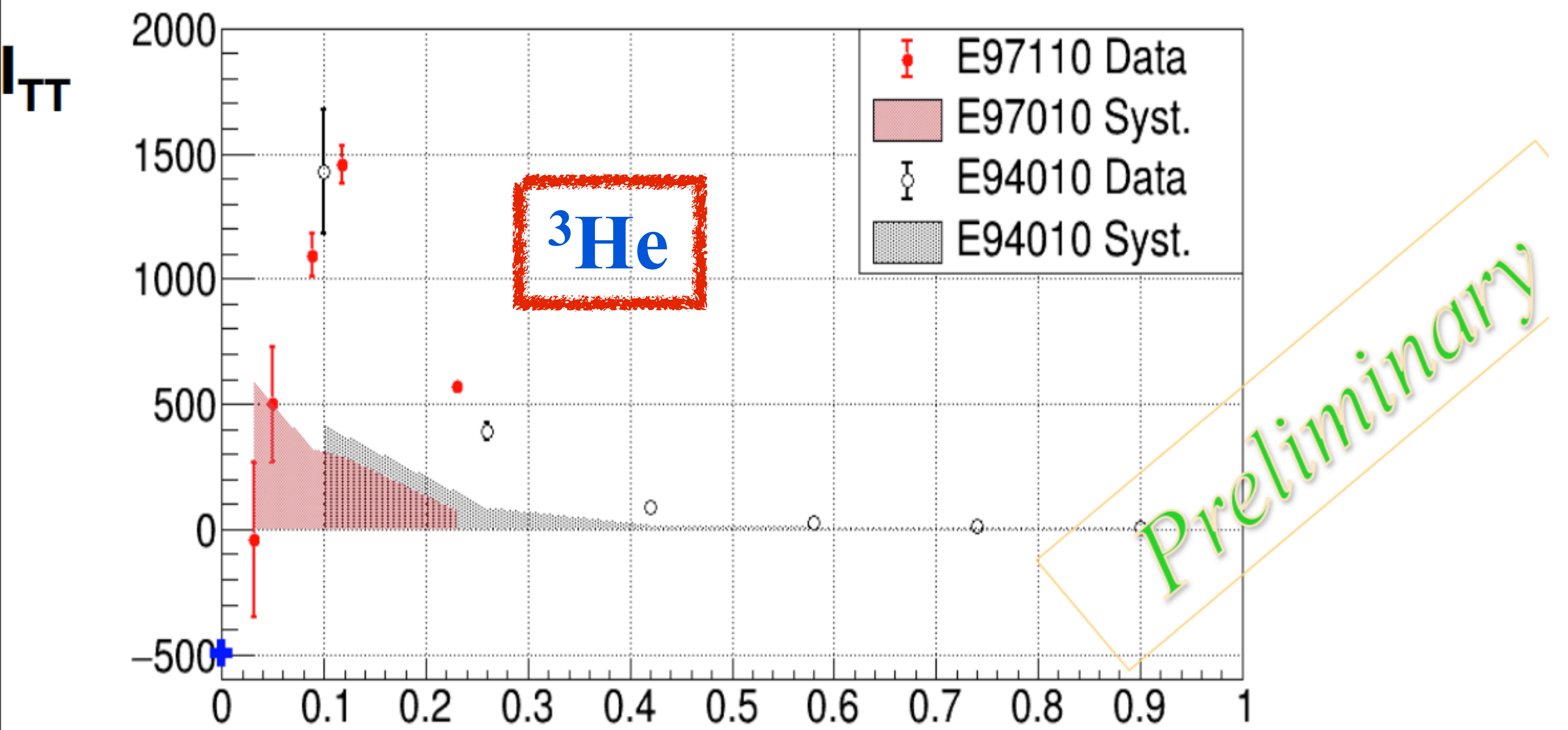
Reliability of extraction of neutron information from ^{3}He at very low Q.

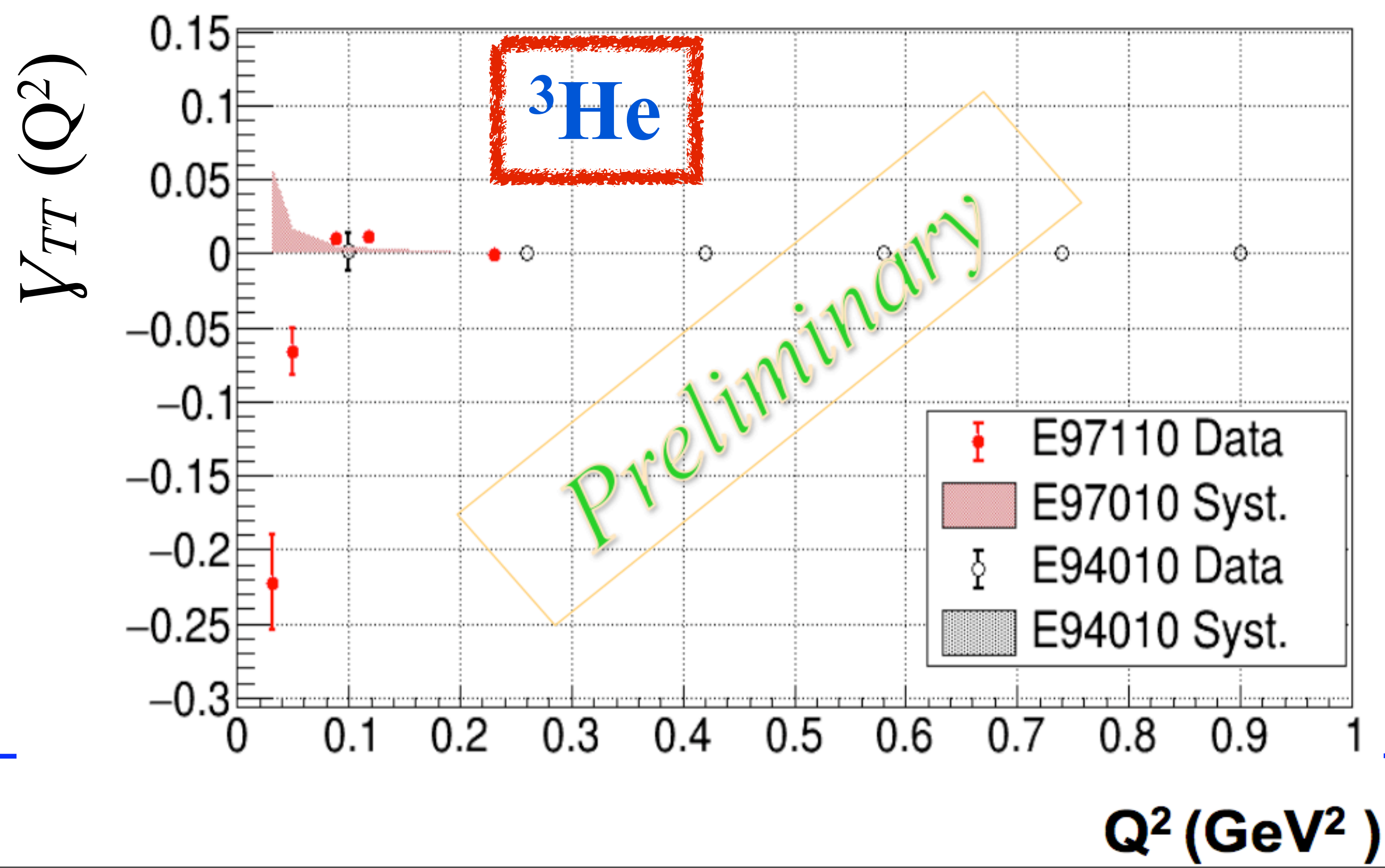
E. Pace's talk and discussion. Now using Light-Front form approach.

E. Pace to revisit 20 year old preliminary estimate on extraction uncertainty.

Do the data verify the Schwinger sum rule?

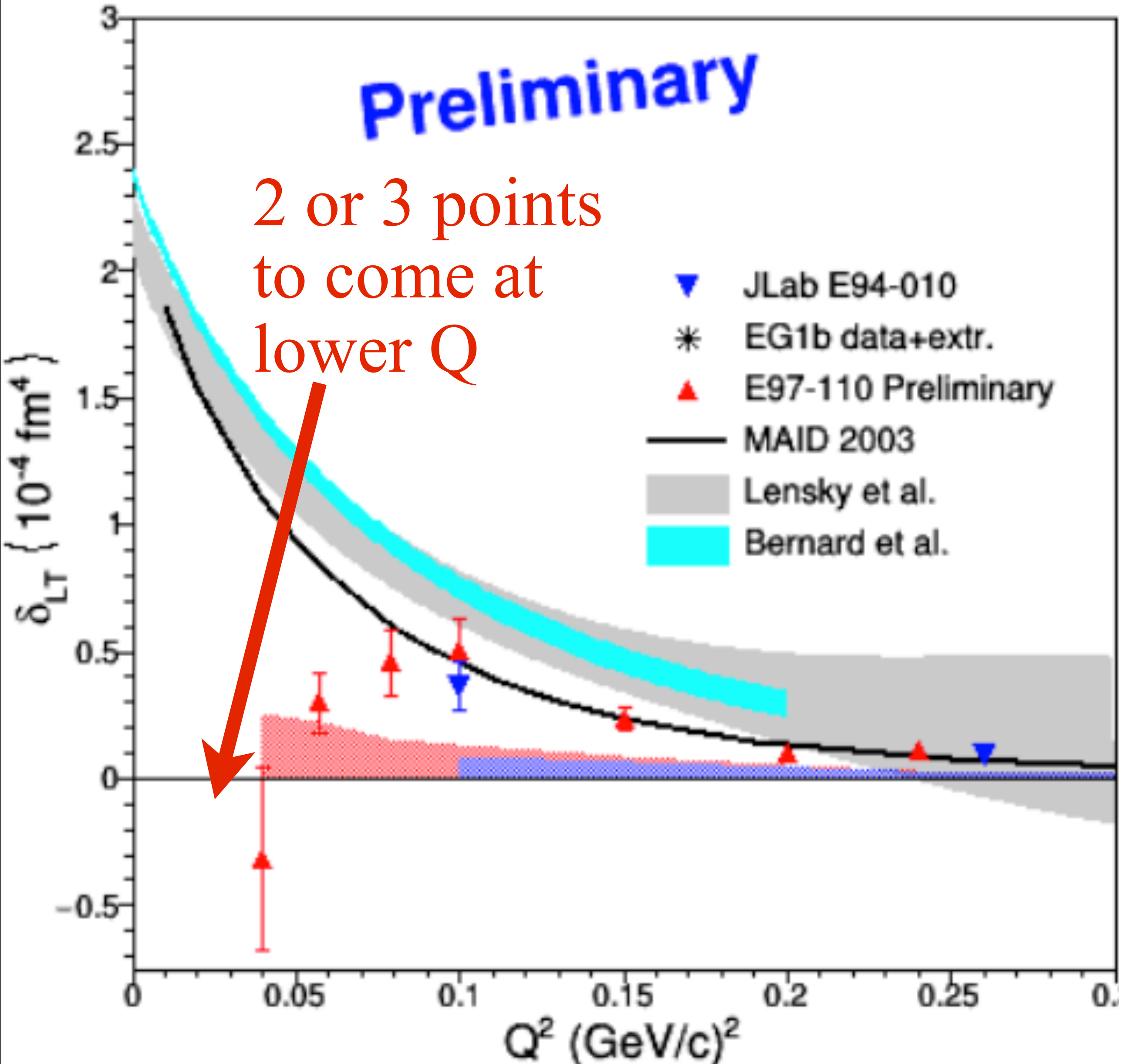
GDH sum and spin polarizability on ^{3}He.



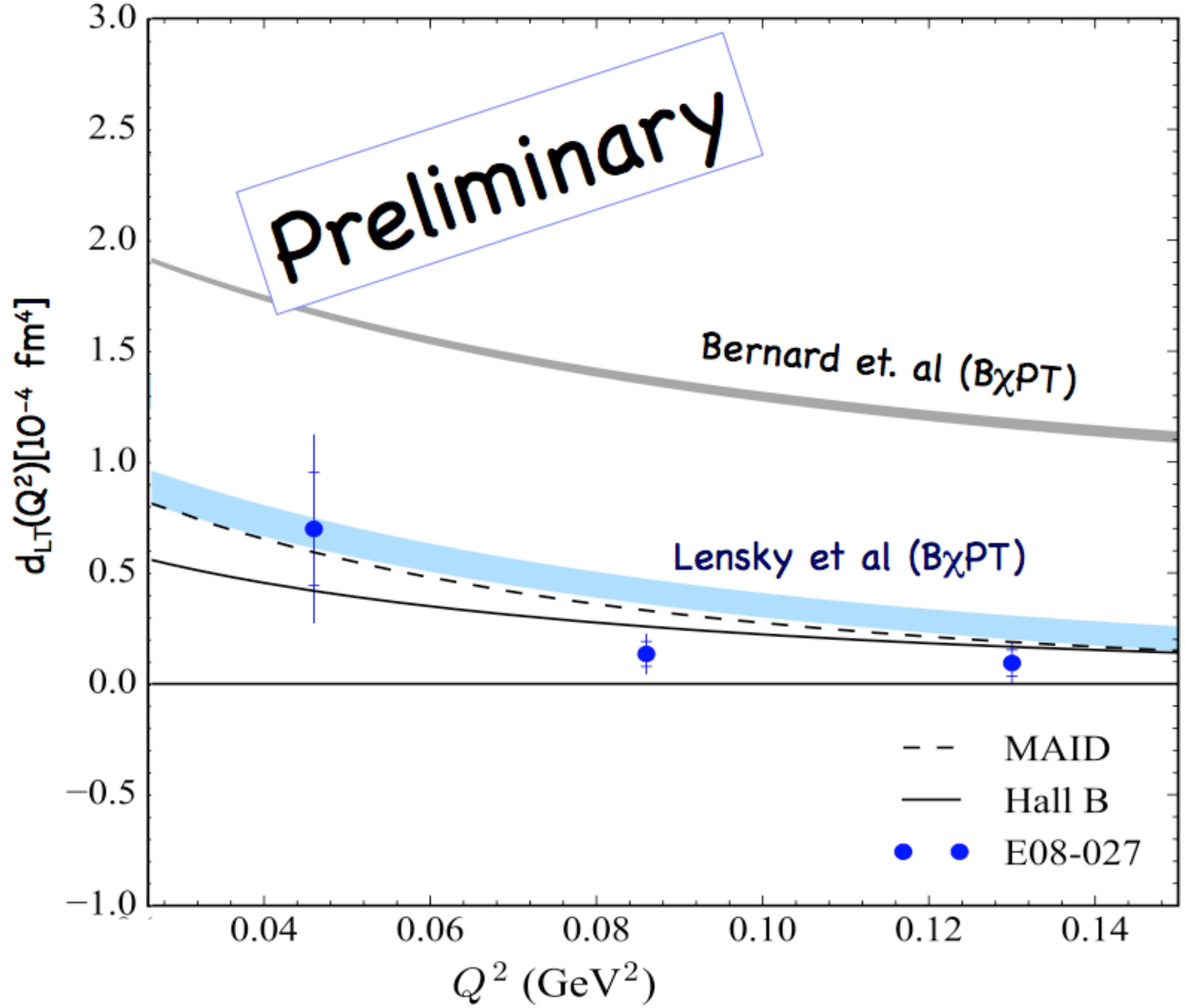


$\delta_{LT}(Q^2)$ puzzle

Neutron



Proton



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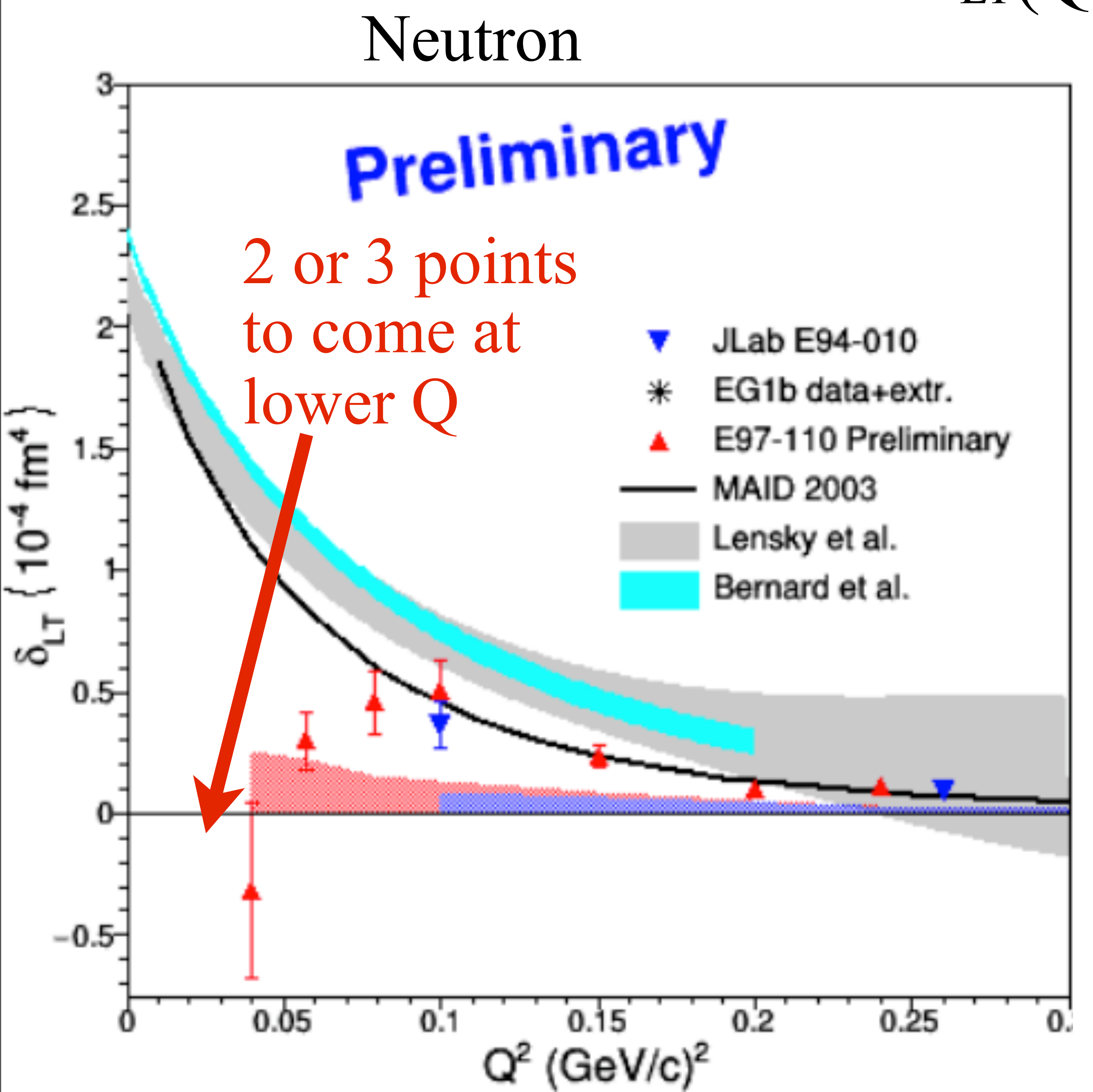
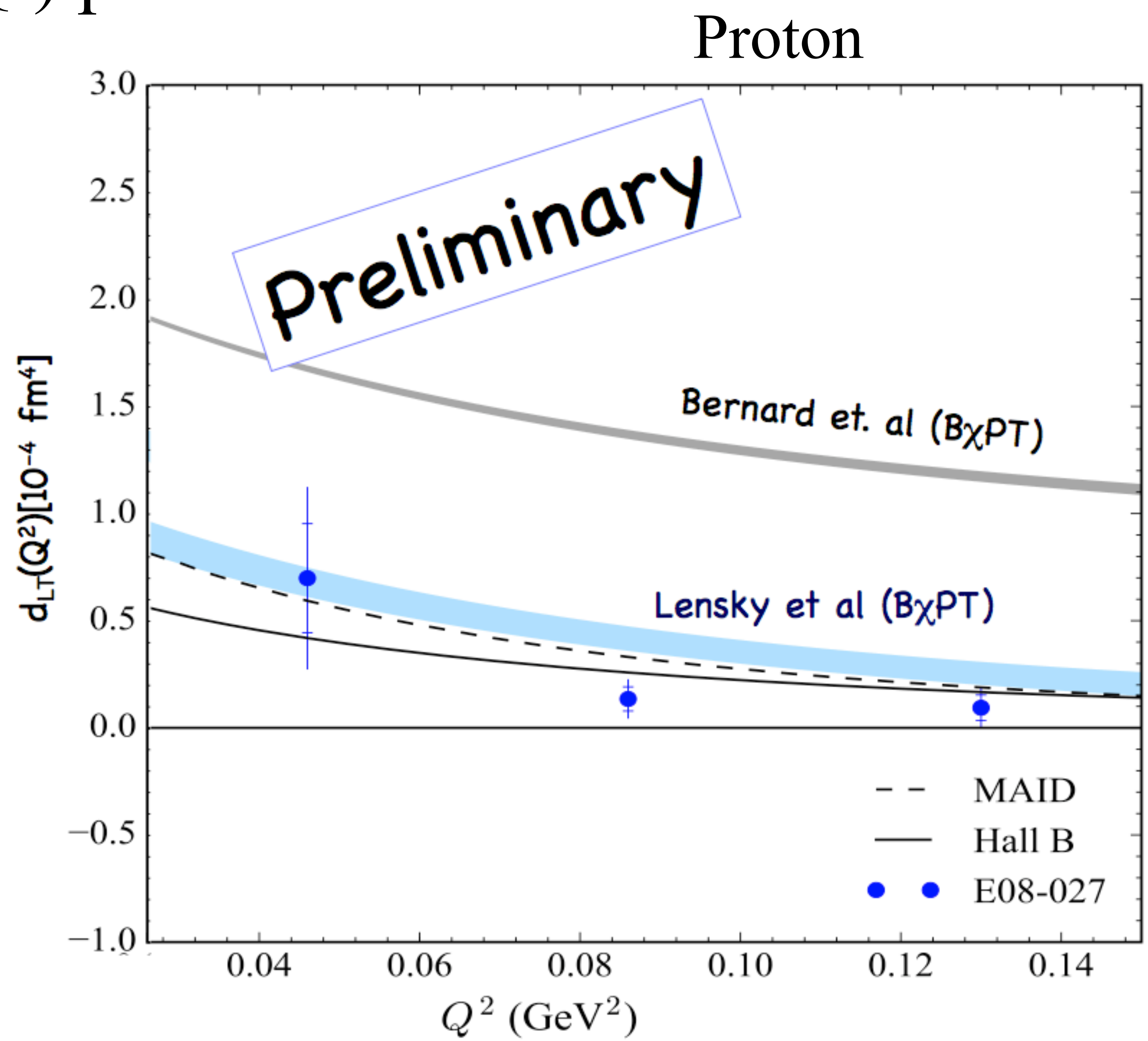


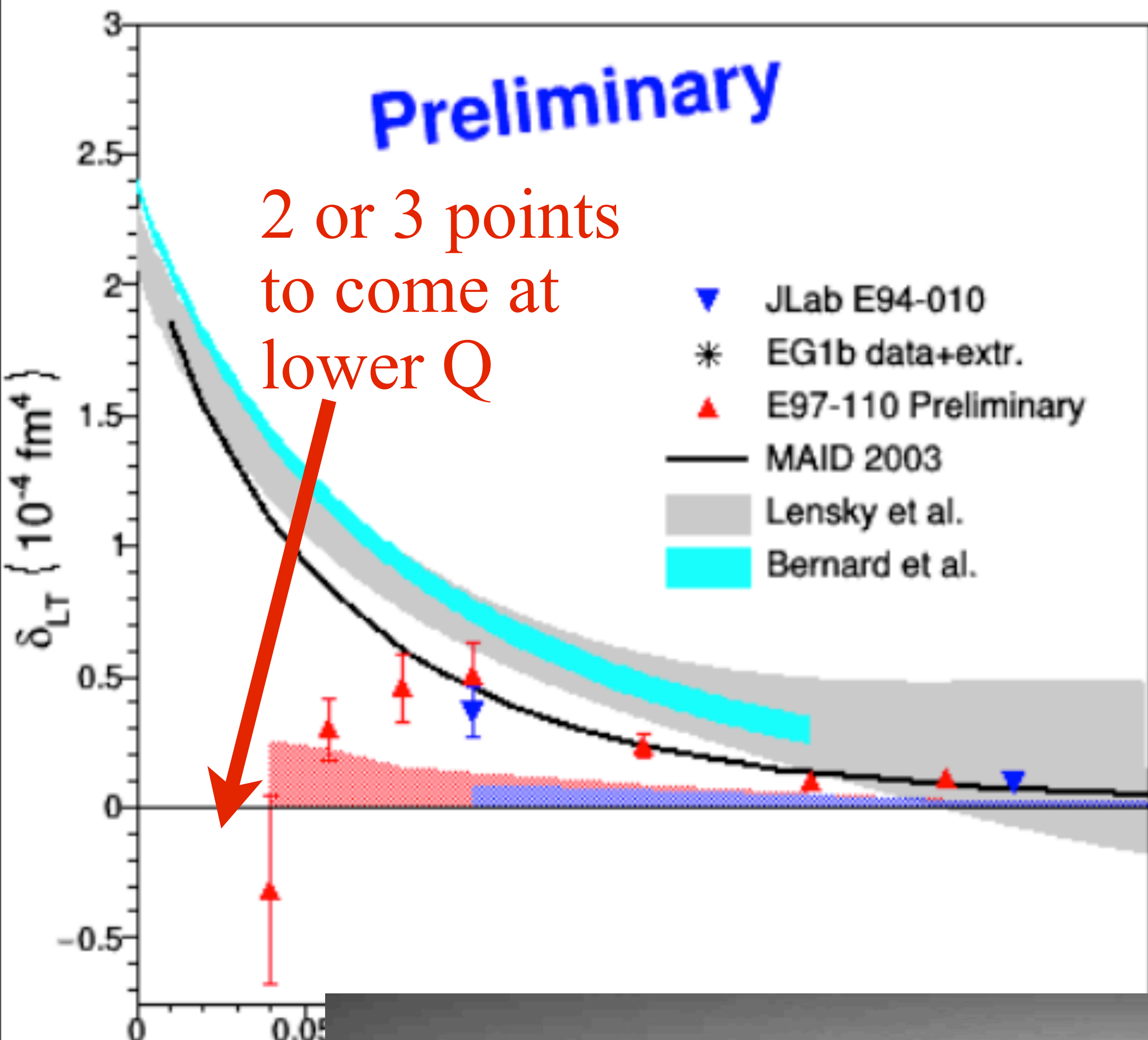


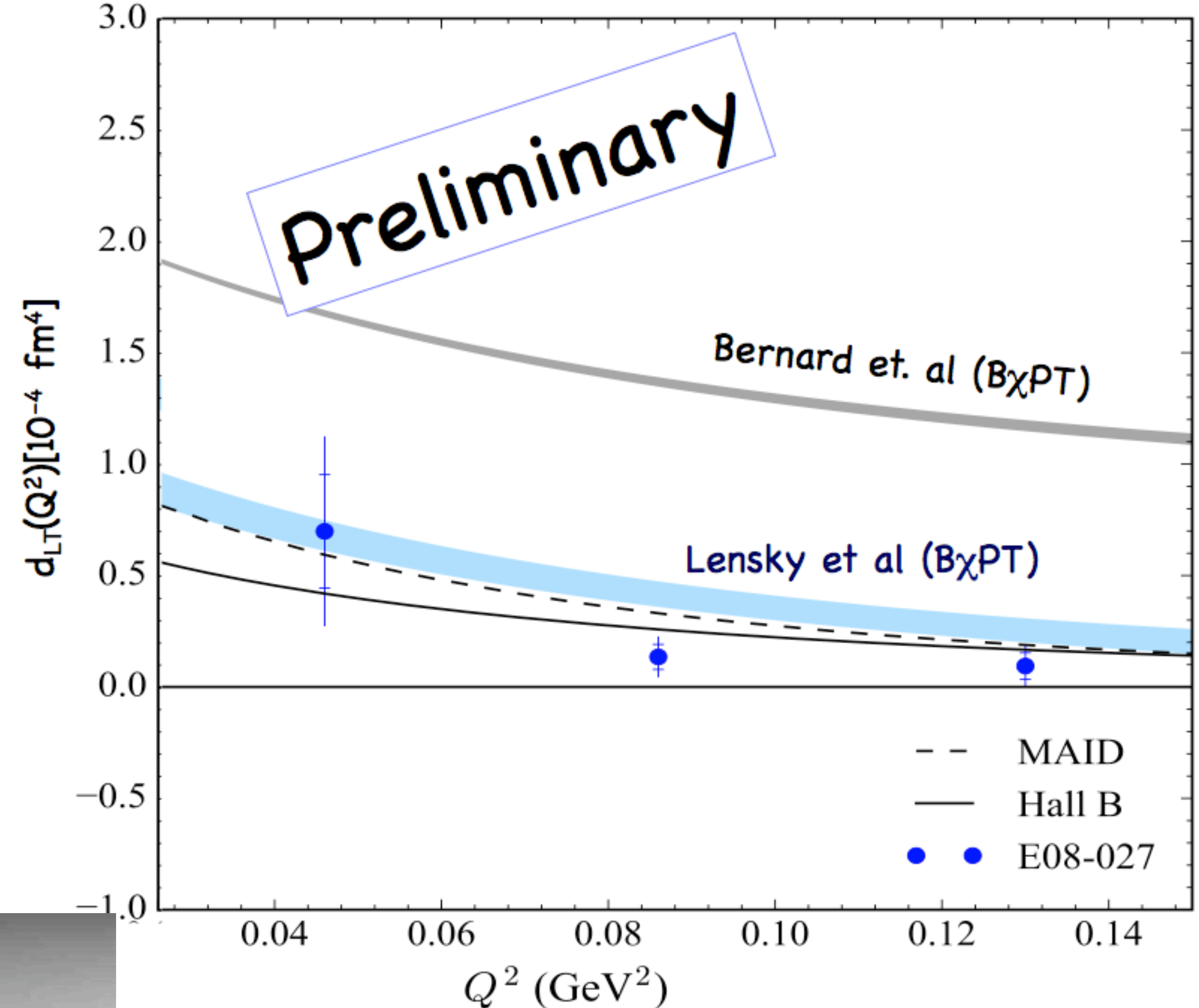
Argument that Δ does not contribute not exactly true (See V. Pascalutsa's talk).

If preliminary analyses confirmed, new δ_{LT} puzzle? Consistency with 1-pion production?

Lensky et al. χEFT calculations and constraints on Lamb shift: V. Lensky's talk.

$\delta_{LT}(Q^2)$ puzzle

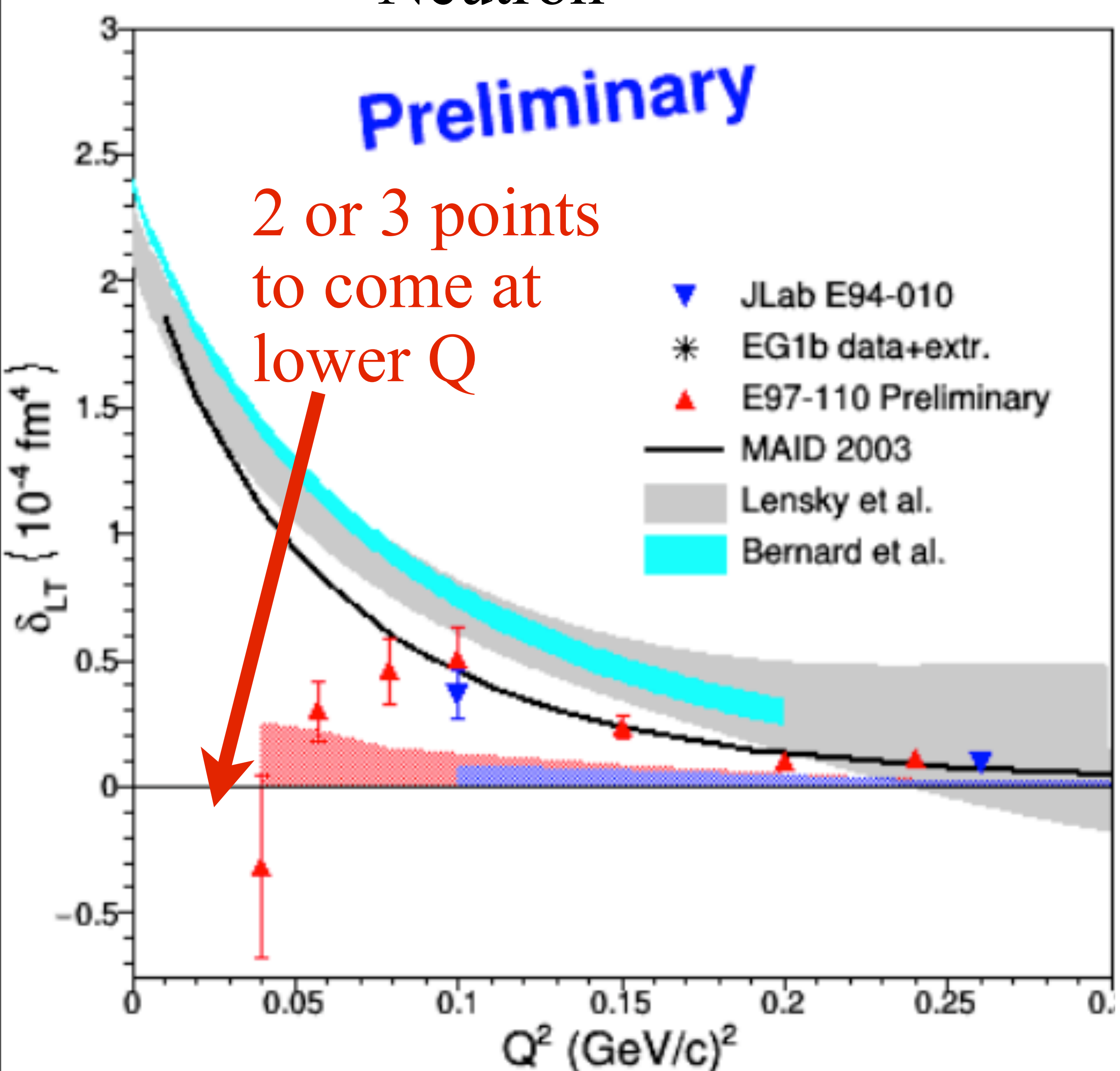




Now, χEFT calculations work at at large Q^2 only !

$\delta_{LT}(Q^2)$ puzzle

Neutron



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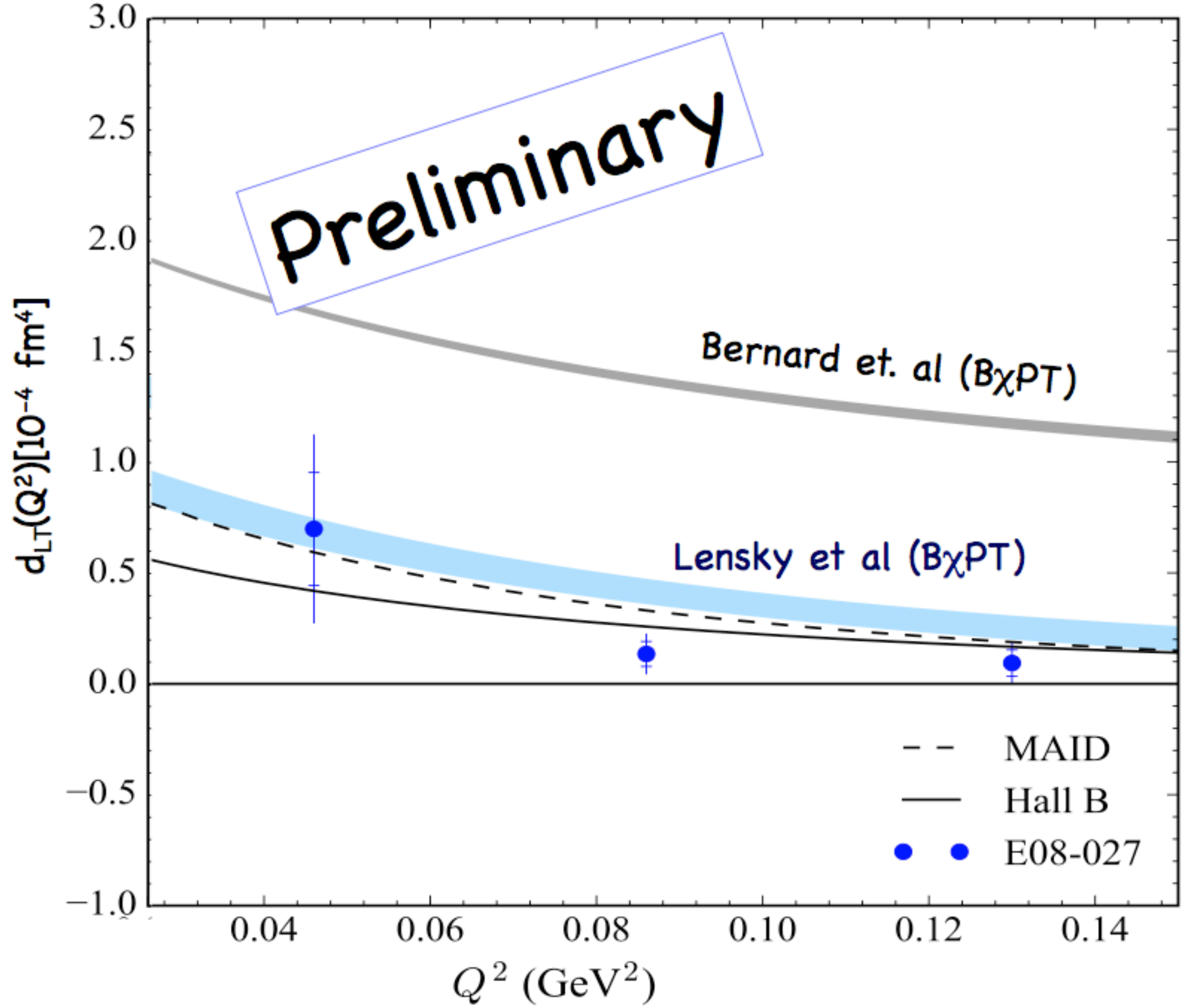
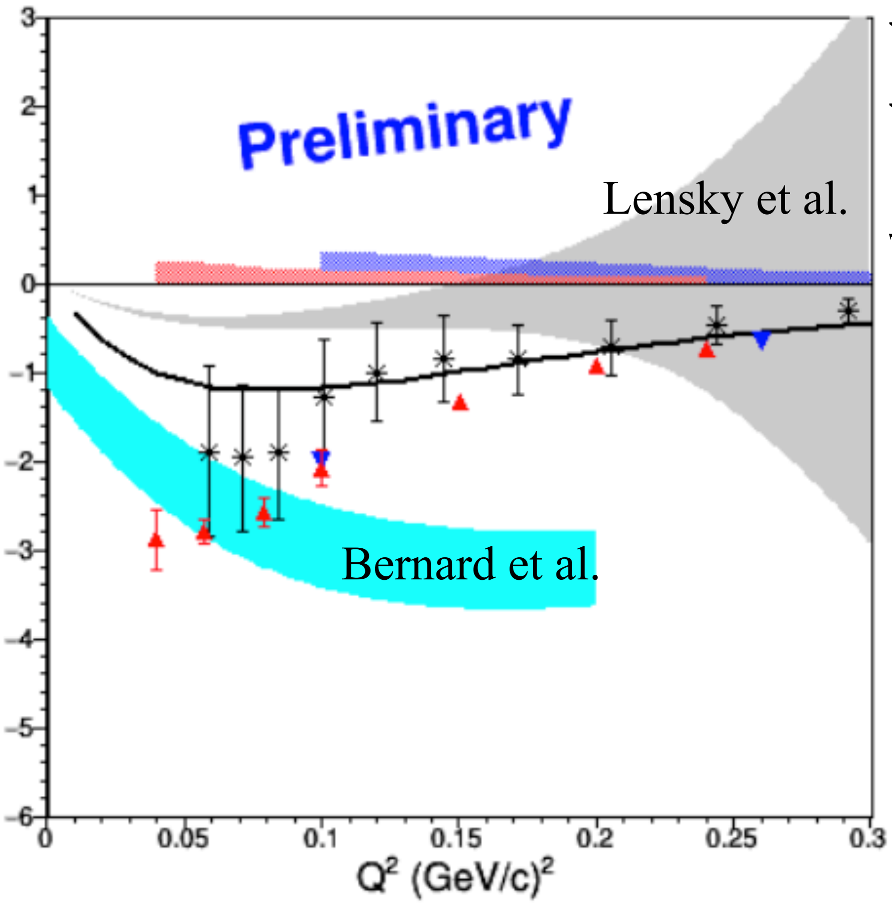


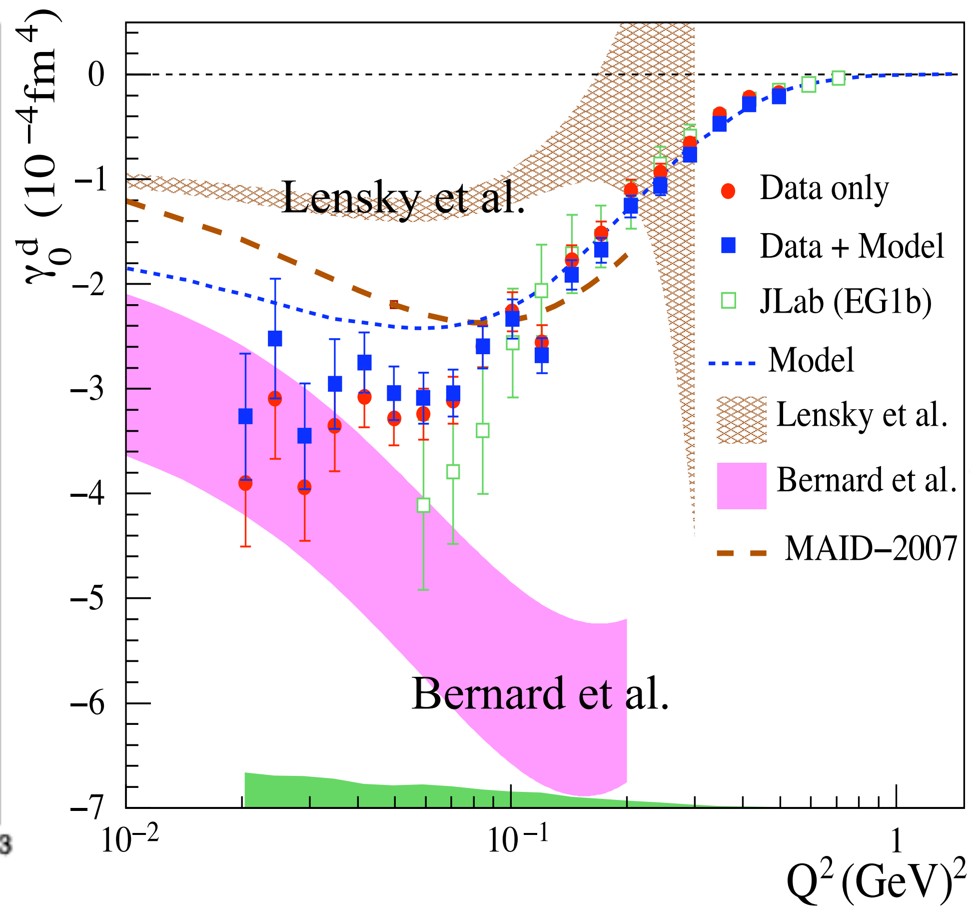
Showing running integrals is useful, see K. Slifer's talk. TBD for neutron and ^{3}He.

Generalized forward spin polarizability γ_0 on nucleons

γ_0 Neutron



~proton+neutron



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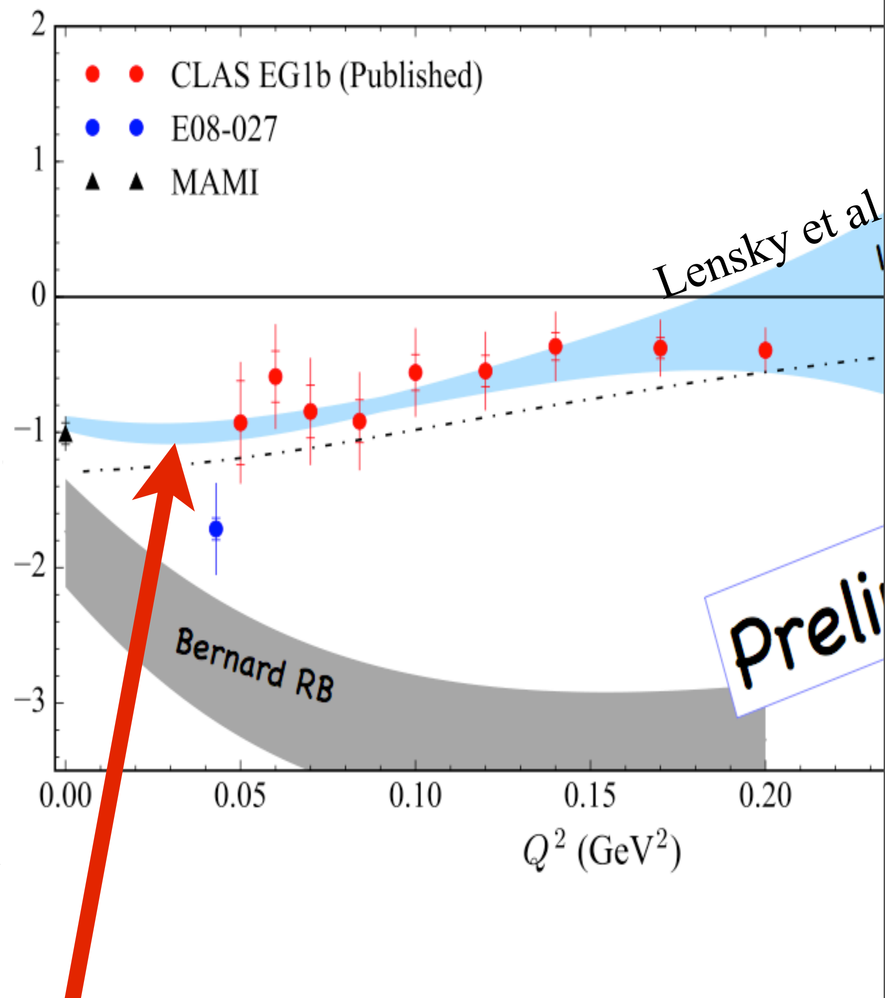

EG4 data
to come

Lensky et al. χEFT calculations and constraints on Lamb shift: V. Lensky's talk.

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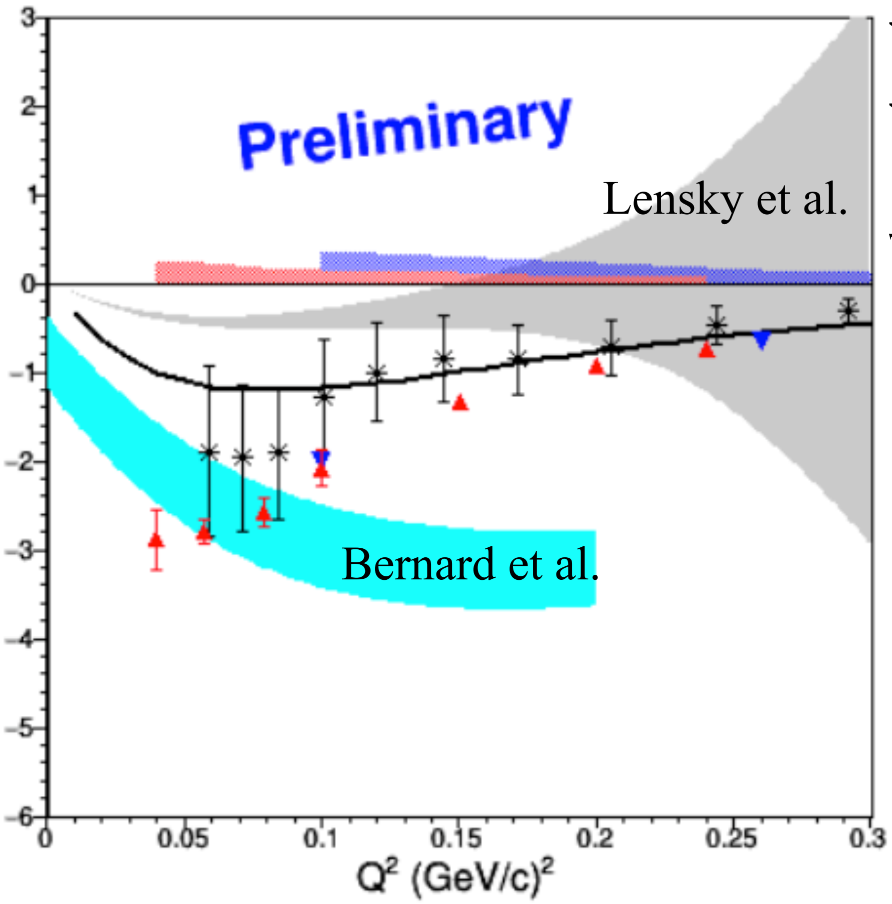

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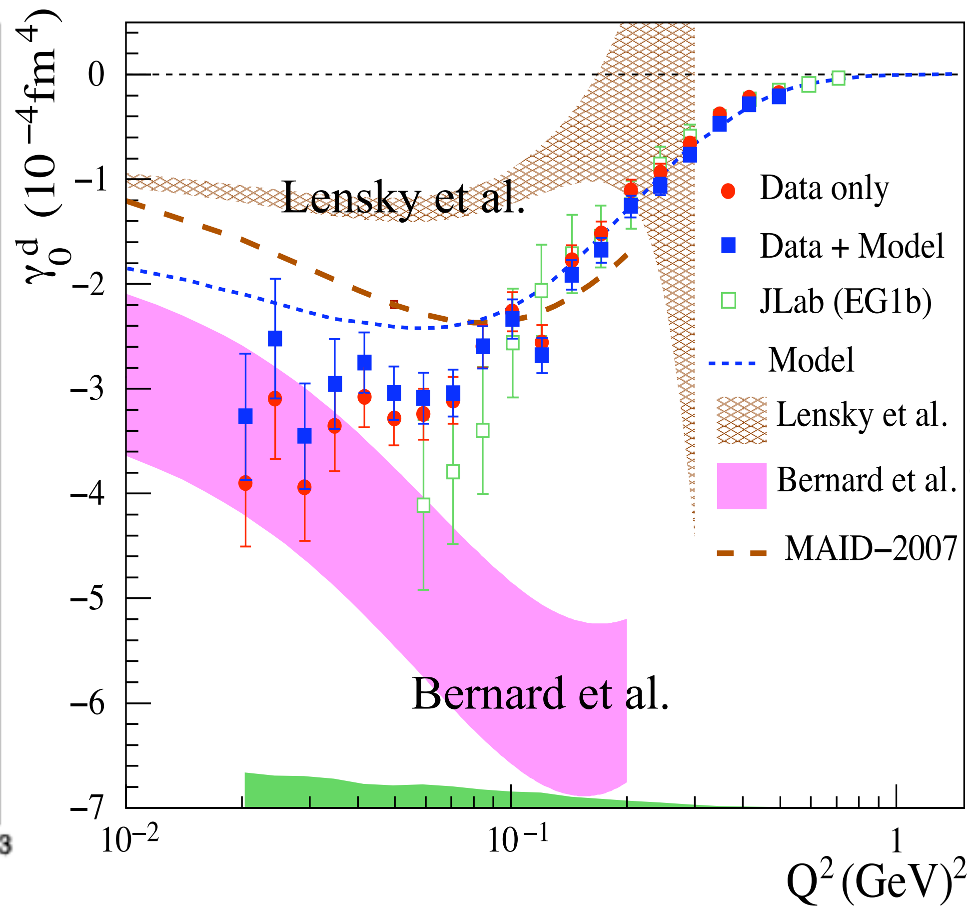

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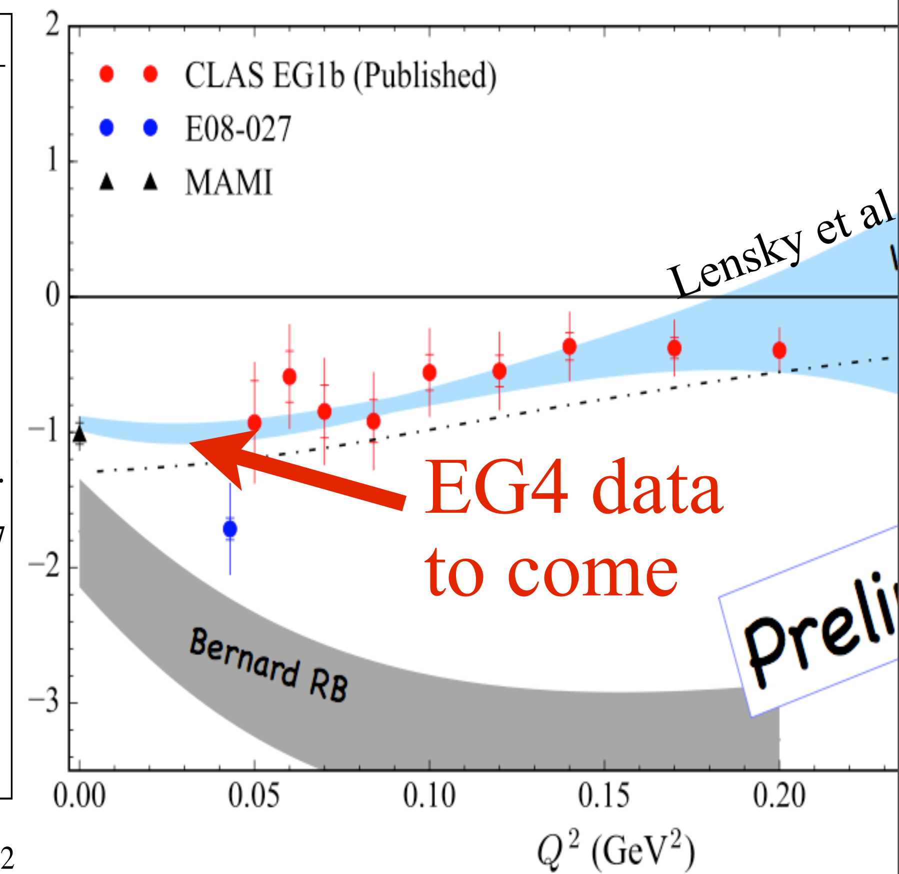

Lensky et al. χEFT describes proton at larger Q^2 and Q^2=0. Situation unclear in between. Disagreement for neutron and neutron+proton.

Bernard et al. χEFT describes γ_0 neutron and neutron+proton.

⇒ Need detailed comparison between exp. data sets.
Need EG4 proton data to clarify situation.

Latest developments on polarizabilities.

Photon point (Q=0). Second order reaction to photon probe (nucleon deformation)
Can be generalized to Q>0.

Calculated in χEFT (V. Lensky's talk)

New method for data analysis developed (See talk by S. Sconfietti)

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Several nice cartoons of what polarizabilities are.

Personal* request: cartoon for **generalized** polarizabilities.

*So that Jian-Ping doesn't have to explain me every 2 months what they mean.

Latest developments on polarizabilities.

New MAMI experiments in A1 and A2 (ran already).

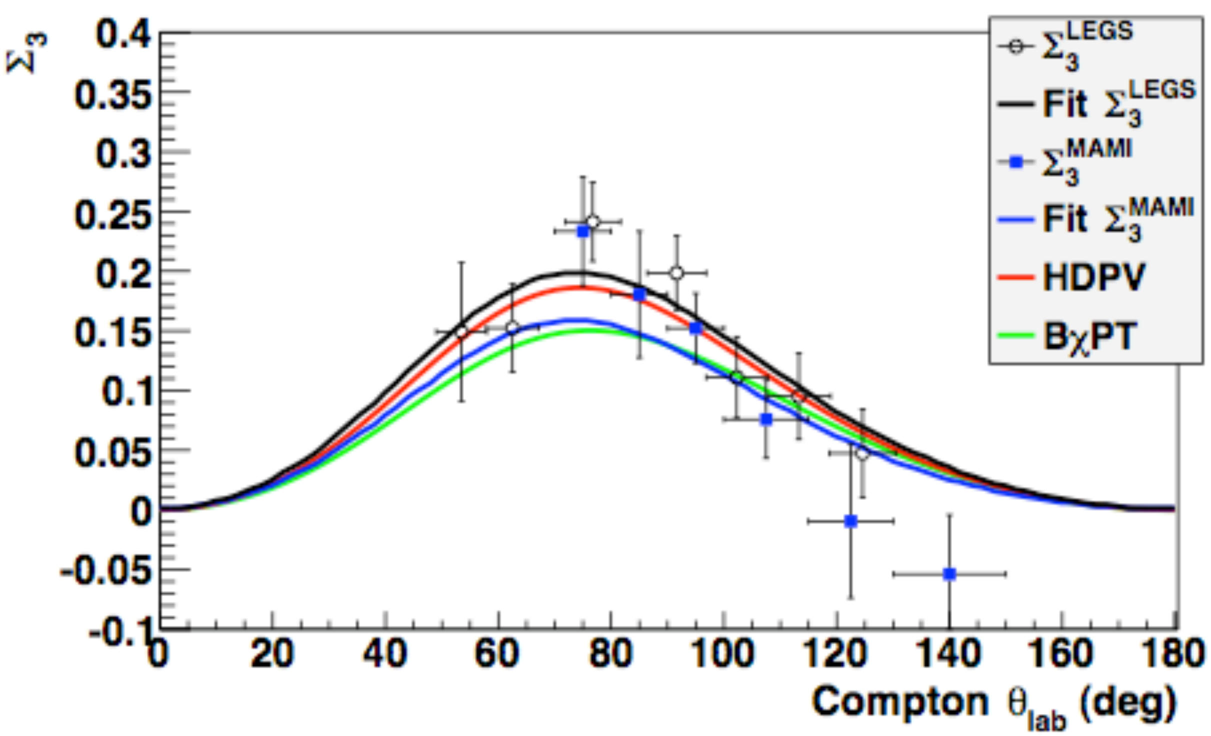
Latest developments on polarizabilities.

New MAMI experiments in A1 and A2 (ran already). Polarizabilities: Σ_{2x} results and $\Sigma_{2x,2z,3}$ preliminary results (P. Martel's talk). Ex: Σ_3

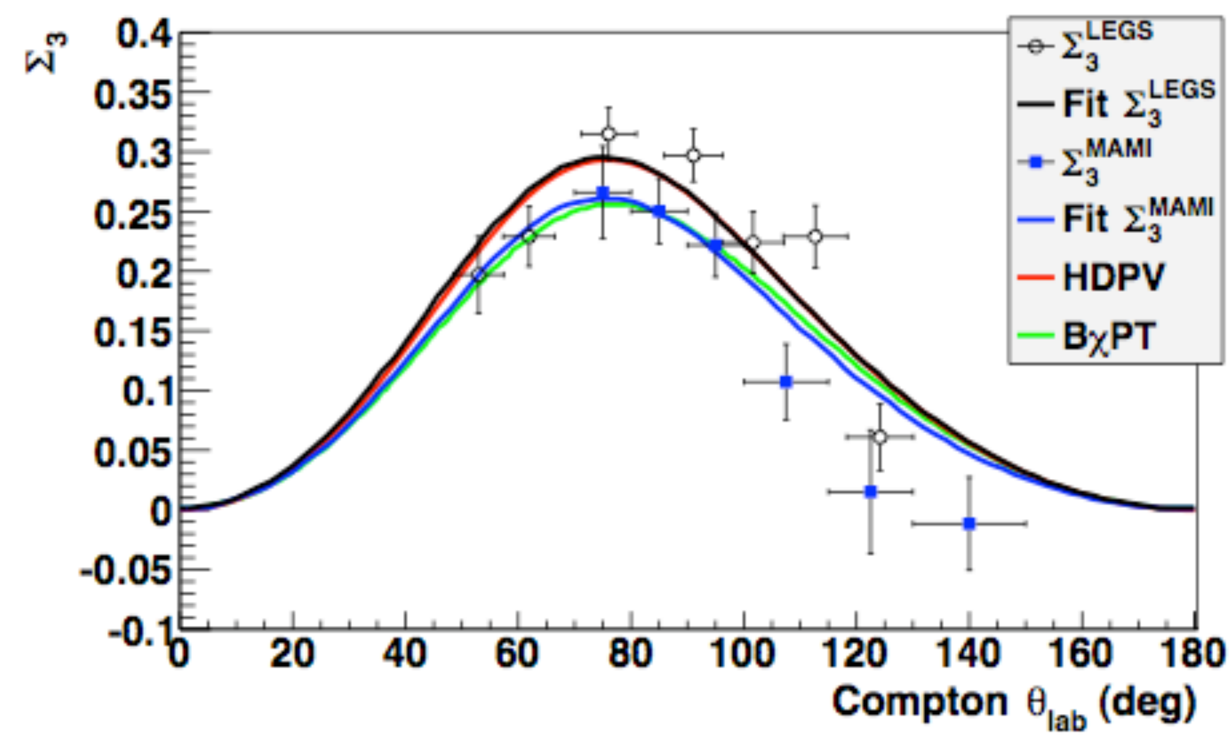
- Linearly polarized photons, unpolarized protons.

$$\Sigma_3 = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$

E_γ=267-287 MeV



E_γ=287-307 MeV



V. Lensky and V. Pascalutsa are developing model-indep. PWA approach to obtain these data.

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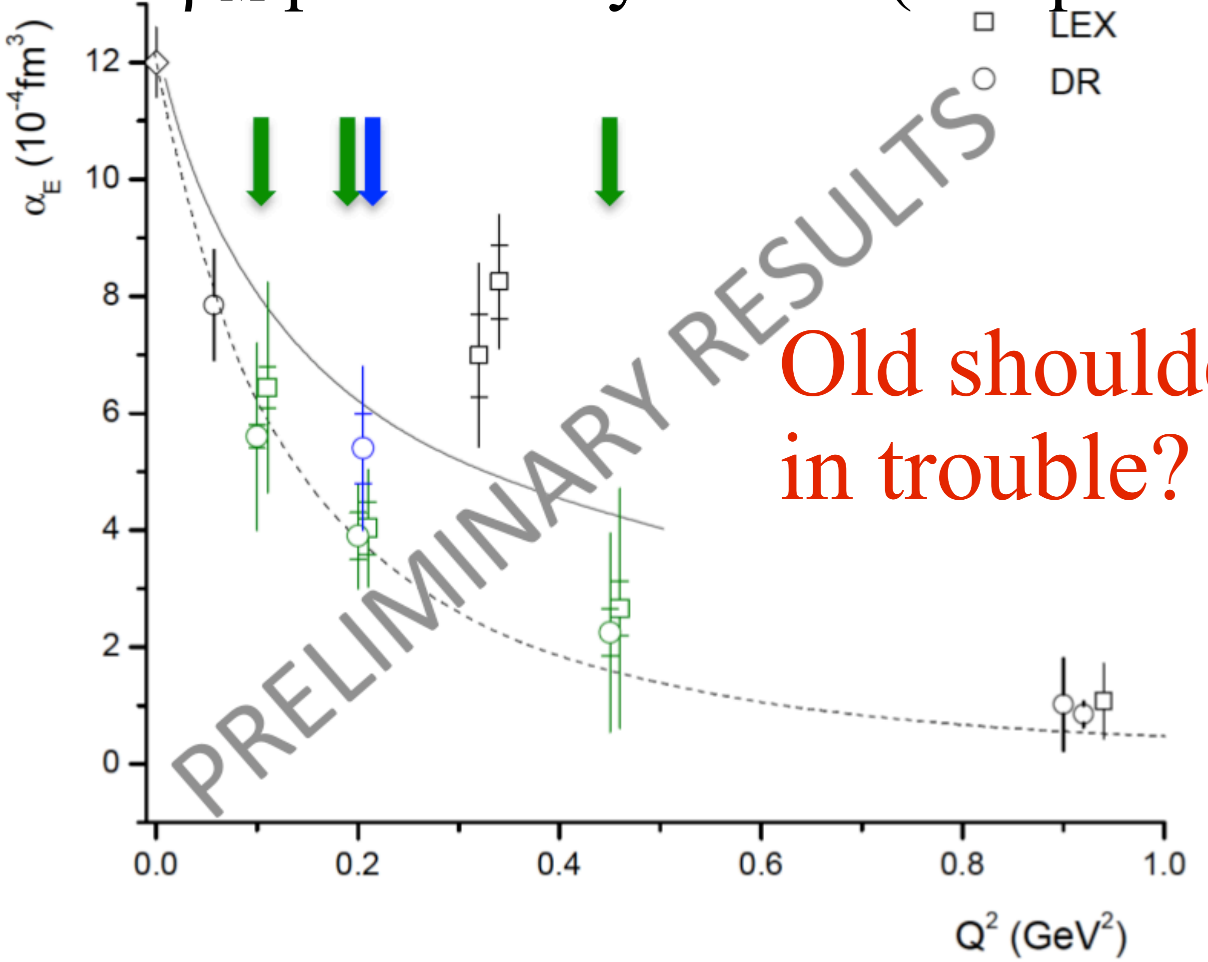

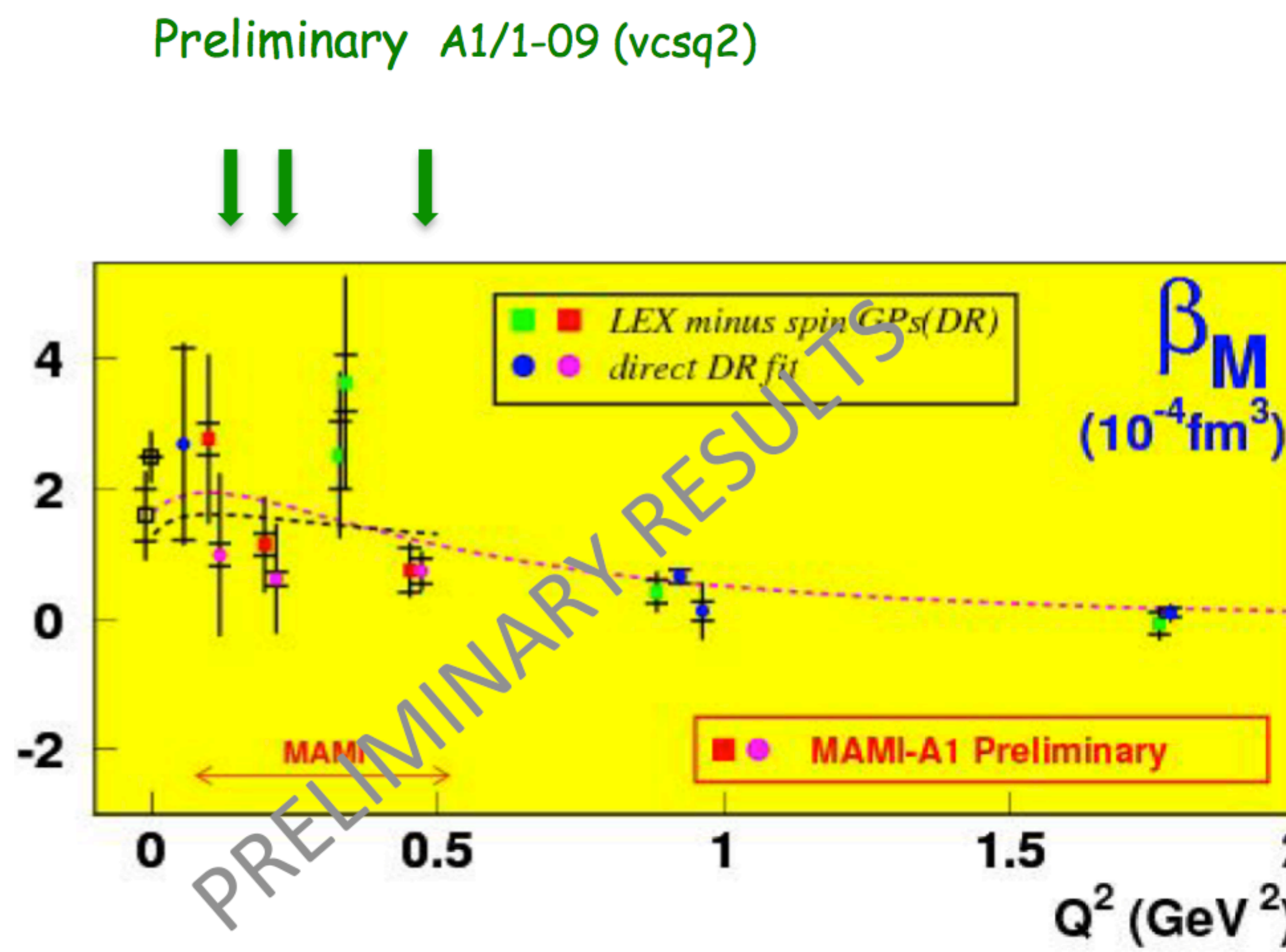

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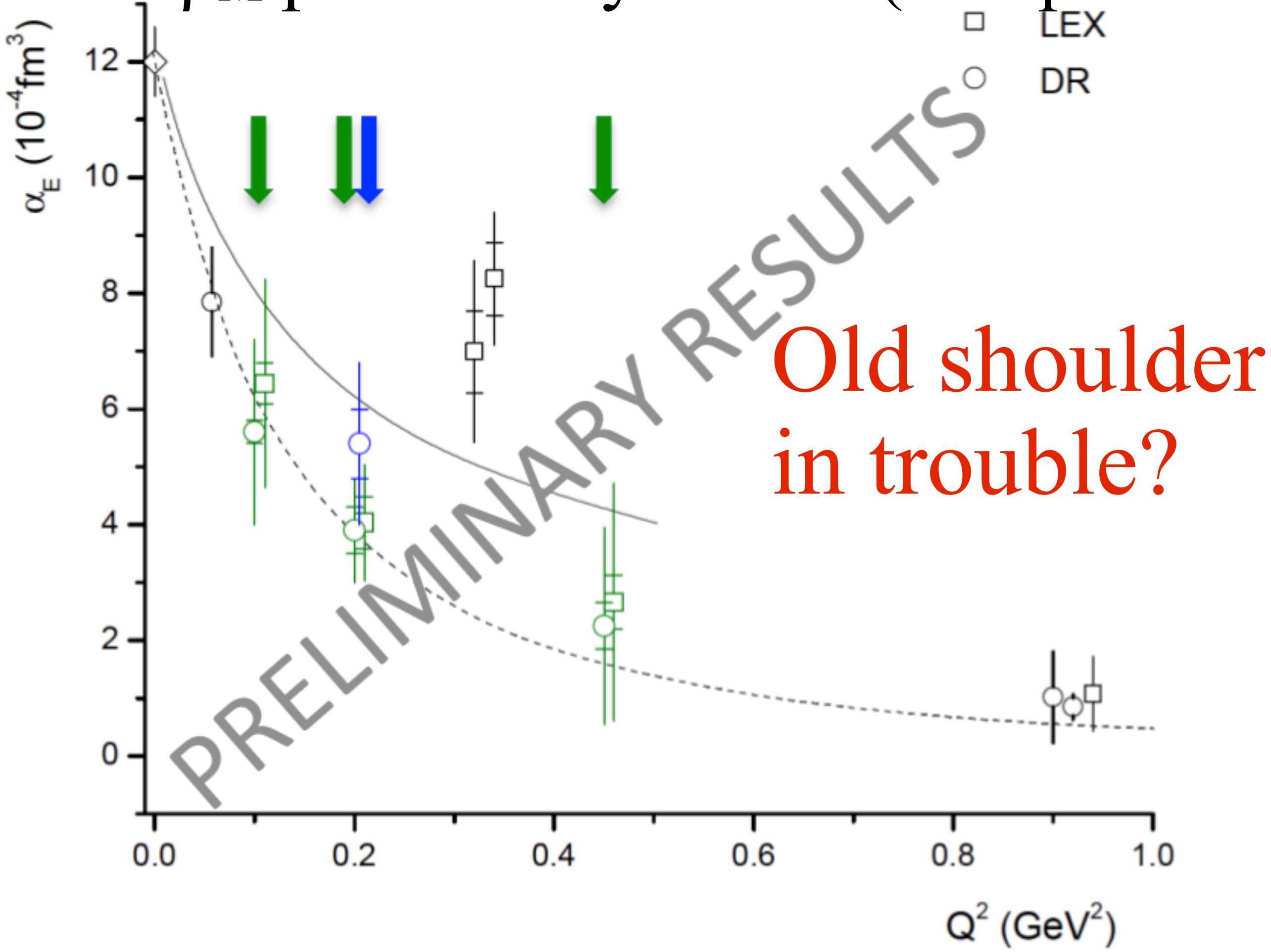

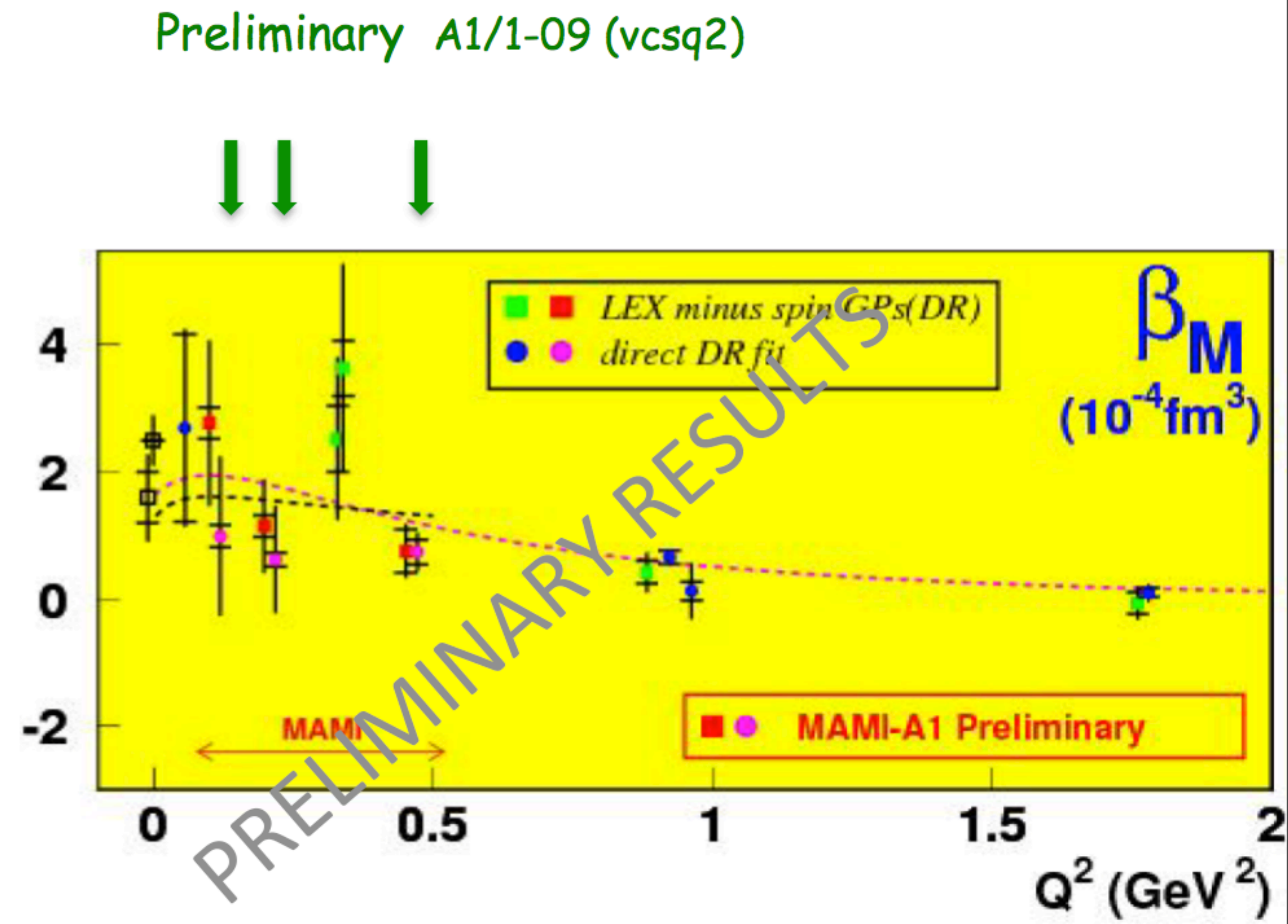

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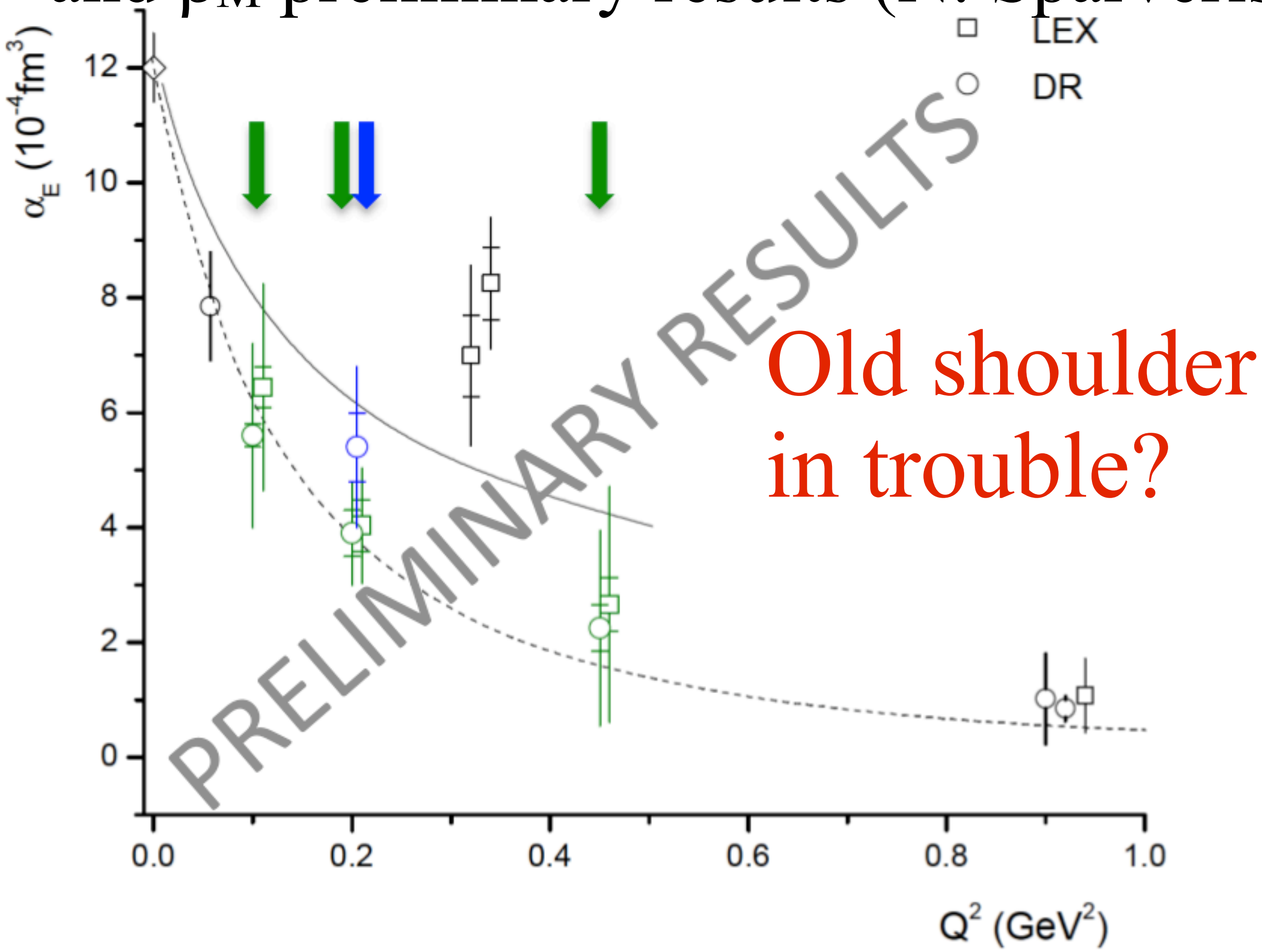

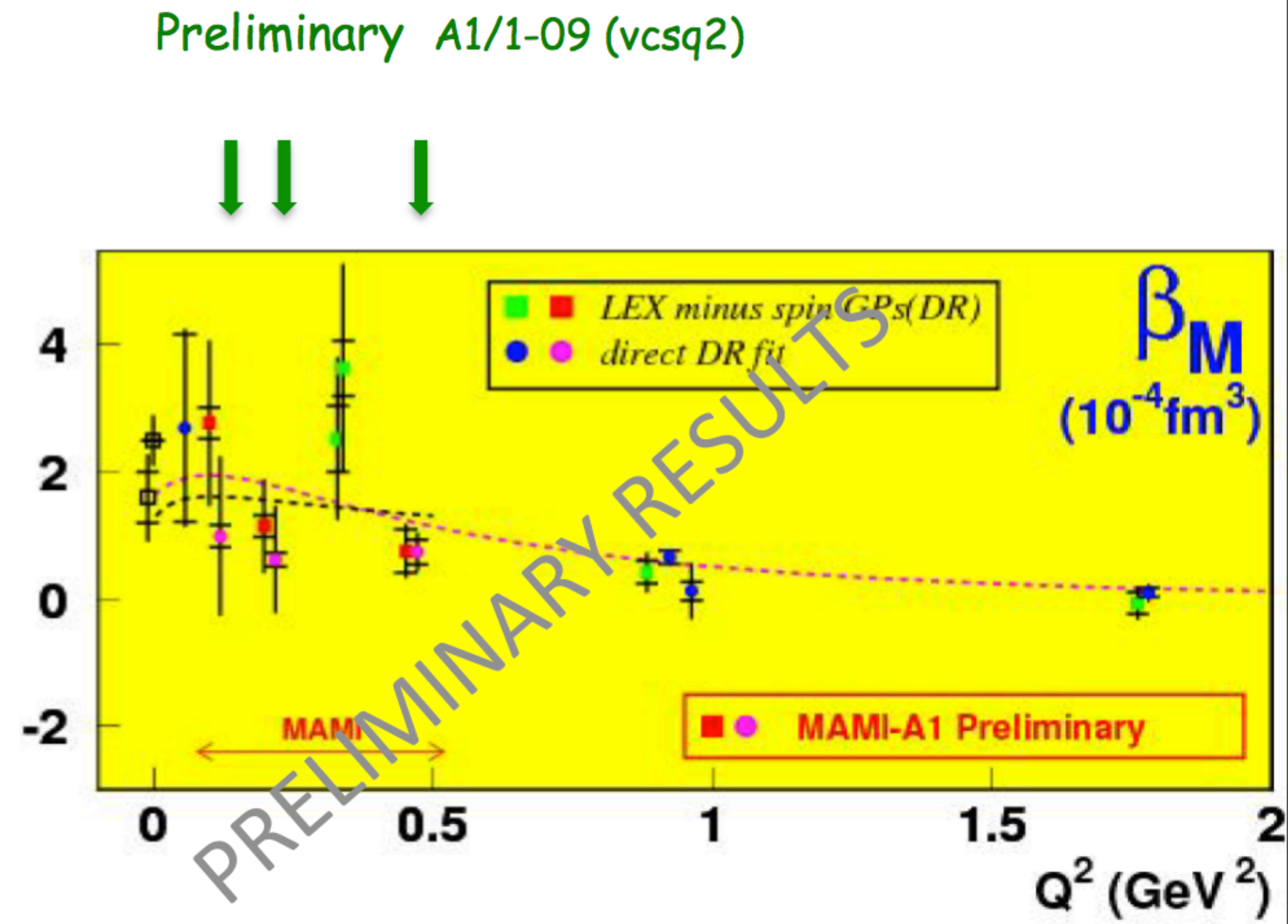

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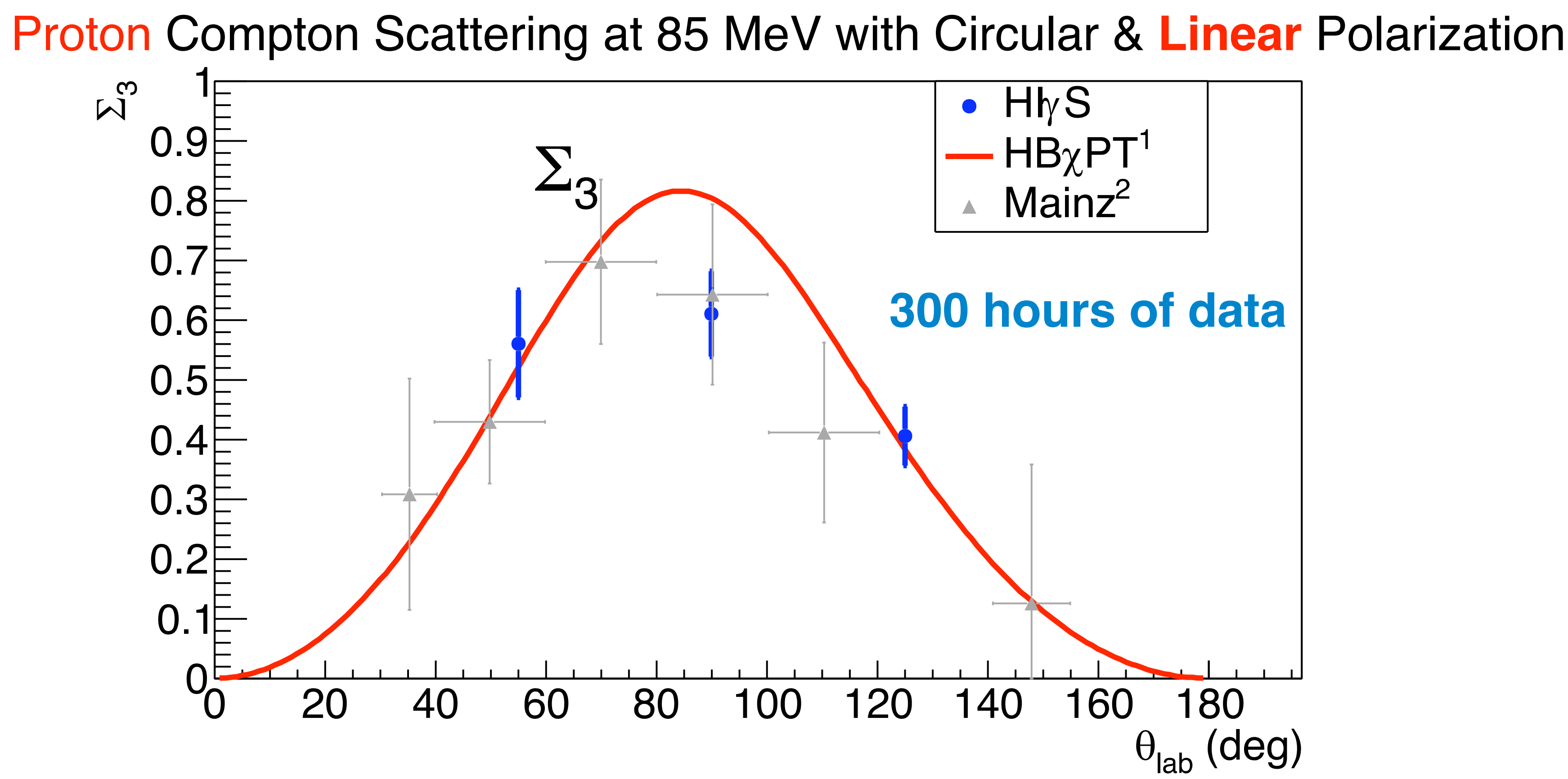
"Old" MAMI data re-analyzed using same analysis method as more recent data.

Latest developments on polarizabilities.

RCS experiments at HIGS (M. Ahmed's talk). Proton and light nuclei.



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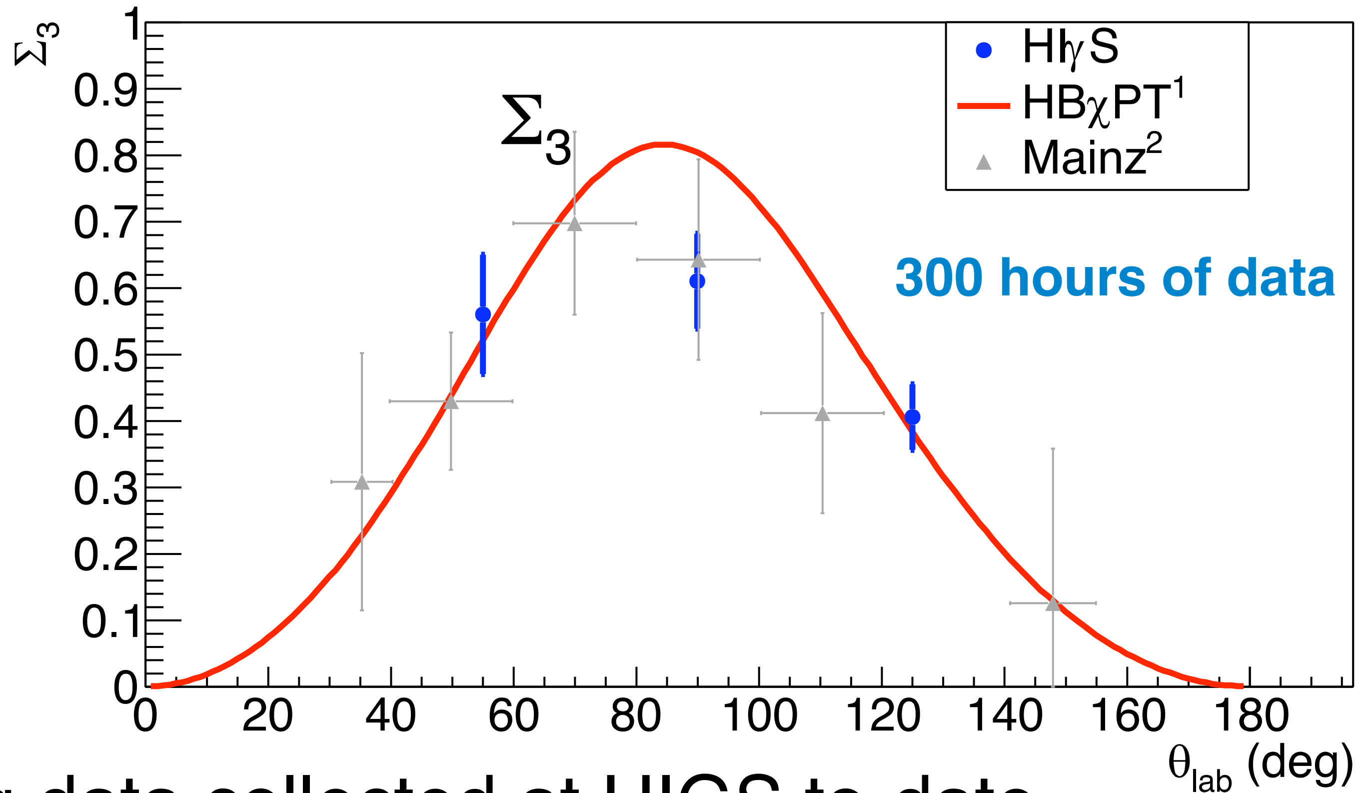
Proton Compton Scattering at 85 MeV with Circular & **Linear** Polarization



Compton Scattering data collected at HIGS to-date

Target	Z	A	E_γ[MeV]	40°	55°	75°	90°	110°	125°	145°	159°
Hydrogen	1	1	84		X		X		X		
Deuterium	1	2	65	X	X	X	X	X	X	X	X
			85	X	X	X	X	X	X	X	X
Helium-4	2	4	61	X	X	X		X	X	X	X
			84		X		X		X		
Lithium-6	3	6	60	X	X	X	X	X	X	X	X
			86	X	X	X	X	X		X	X
Oxygen-16	8	16	60	X	X	X	X	X	X	X	X
			86	X	X	X	X	X		X	X

Plans for next 3 years:
^{3}He/D Compton Scattering

Will double world data on D polarizabilities.

Latest developments on nucleon form factors.

Hot topic: Proton radius crisis, Zemach radius, TPE...

A. Gasparian's talk. Proton radius from PRAD in a few weeks.

Not subject of this workshop but:
Proton radius puzzle remains mysterious, with apparently contradictory measurements

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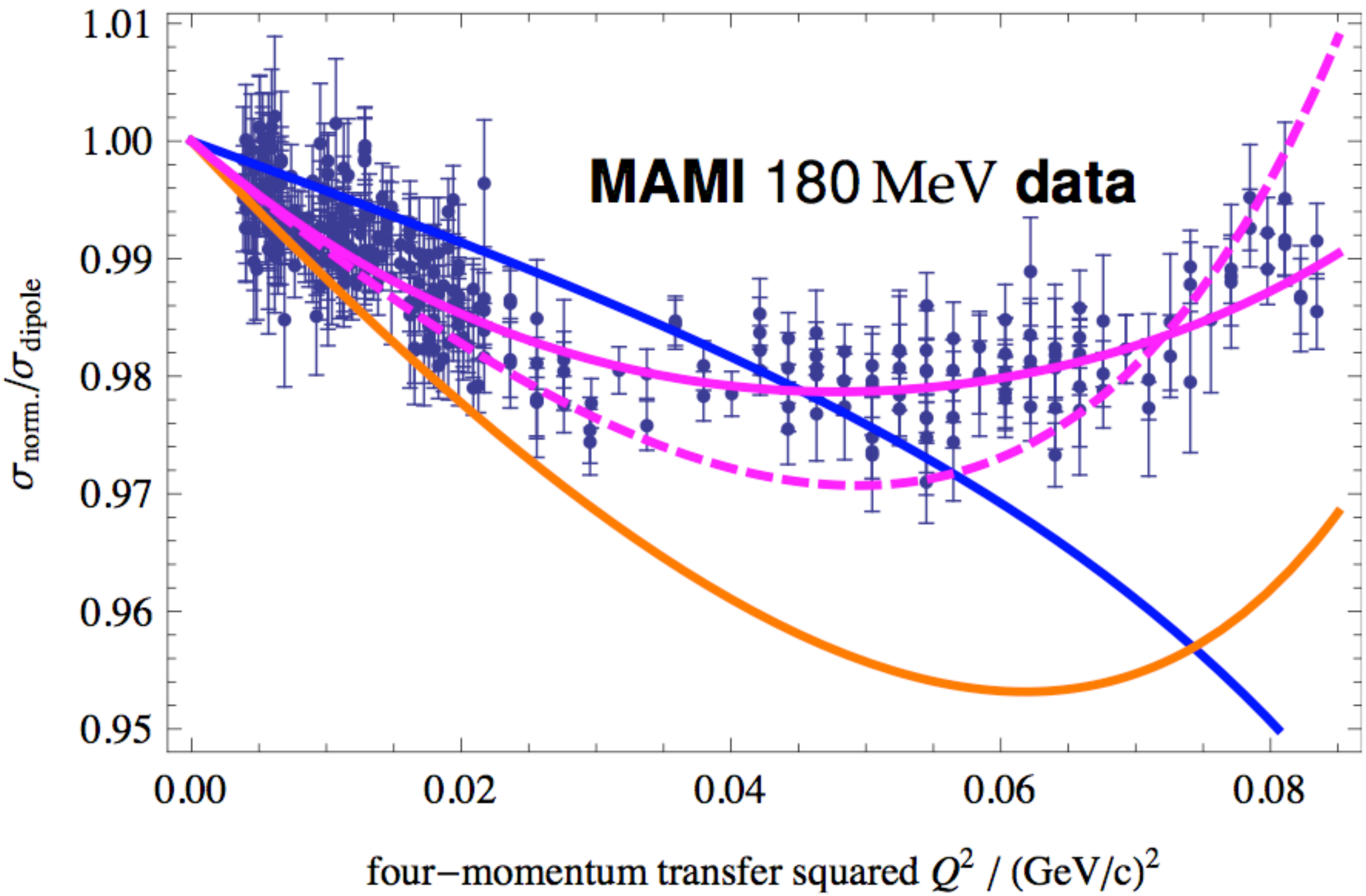

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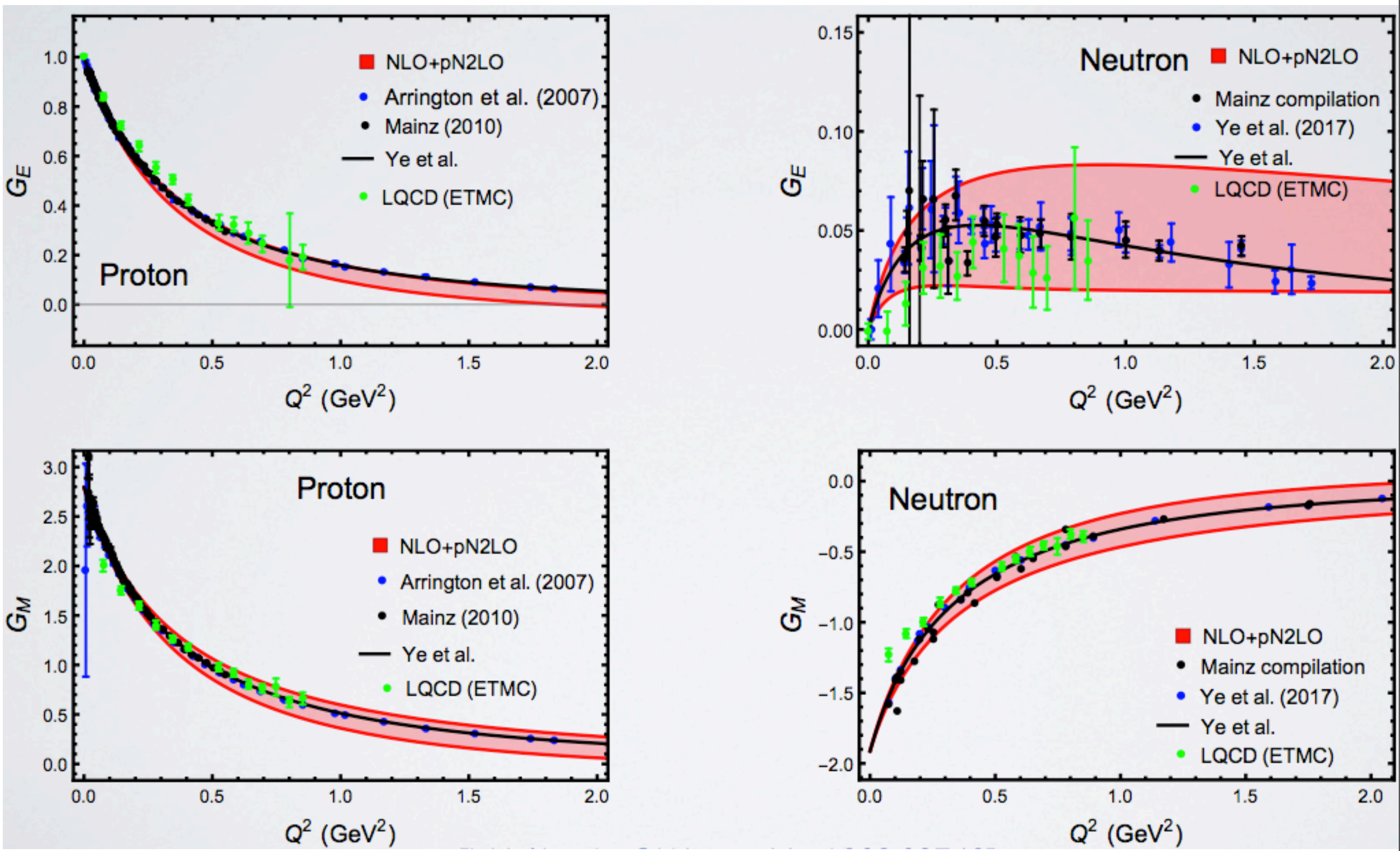
New approach to compute FF: Dispersively improved χEFT. See M. Alarcon's talk
Very recent predictions on proton and neutron FF ($Q^2 > 2$ GeV^2 w/ χEFT):
Proton radius ~0.85 fm
(Same as eyeballed from PRAD results presented by A. Gasparian)



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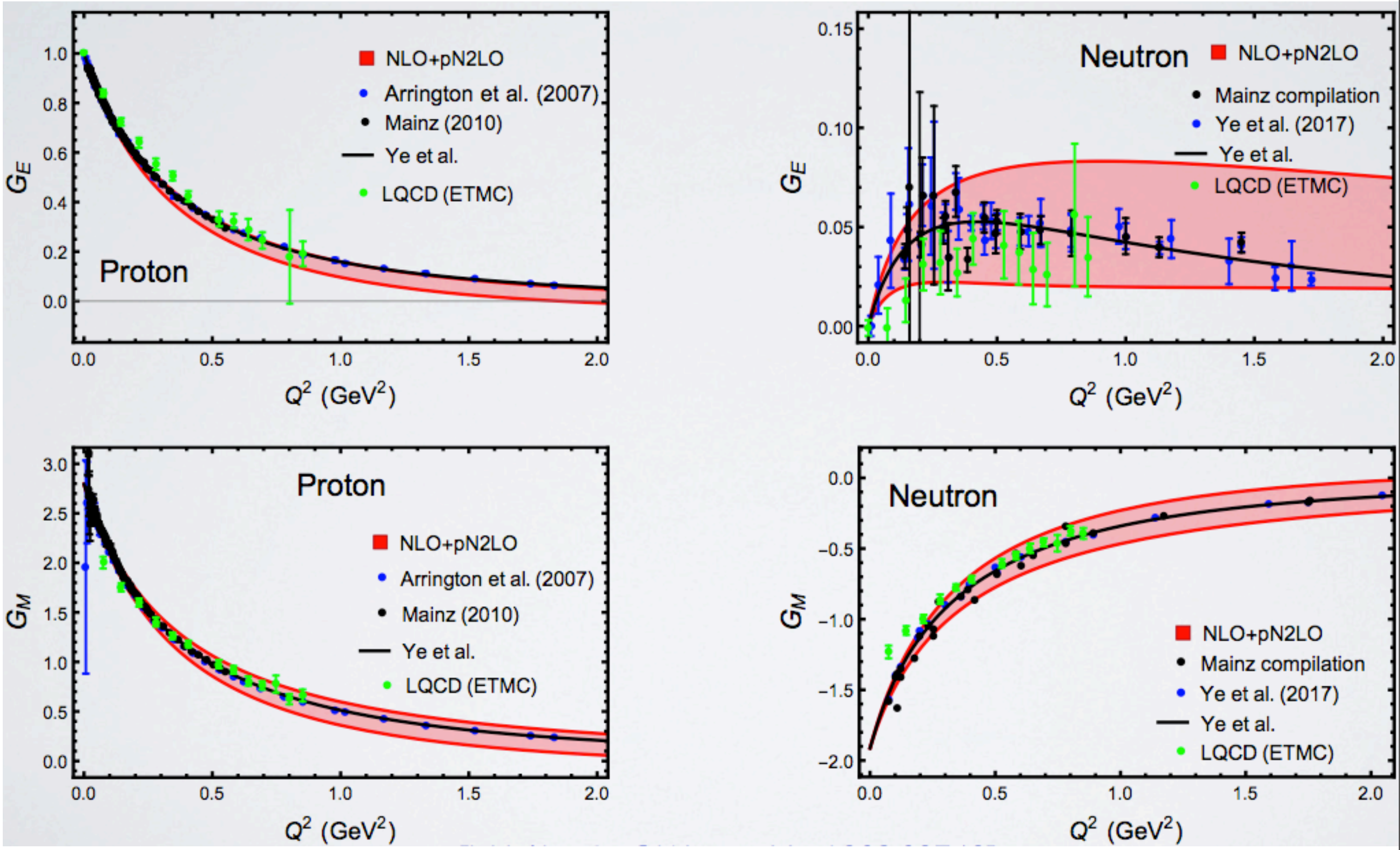
Jealous ☹



Intersection of atomic and nuclear physics: proton radius and HFS

C. Carlson's overview

Potential for physics beyond the standard model (e.g. lepton universality violation).

3 new experiments to run to measure HFS of μ-hydrogen at ppm level:

C. Carlson's review current precision on ingredients of HFS

- Riken-CAP (S. Kanda's talk): Asymmetry measurement in μ decay. 2ppm goal (Zemach radius at 0.03%).
- CREMA at PSI (A. Antognini's talk): Counting exp. Zemach radius at better than 0.02%.
- FAMU at Riken-Ral (A. Vacchi's talk). 10 ppm goal (Zemach radius at 0.15%)

Very different technics. Different systematics.

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Very different technics. Different systematics.

TPE dominant uncertainty on HFS calculations. Two calculations approaches:

- χEFT (F. Haegelstein and A. Pineda's talks)
- Dispertion relations+struct. func. data

some tensions (A. Antognini's talk)

g_2 data scarce. More g_1 data also welcome. $1/Q^{4,2}$ weighted, respc.

•δ_{LT} (g_2) on proton: K. Slifer's talk

g_2 contribution to the Hyperfine Splitting

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

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

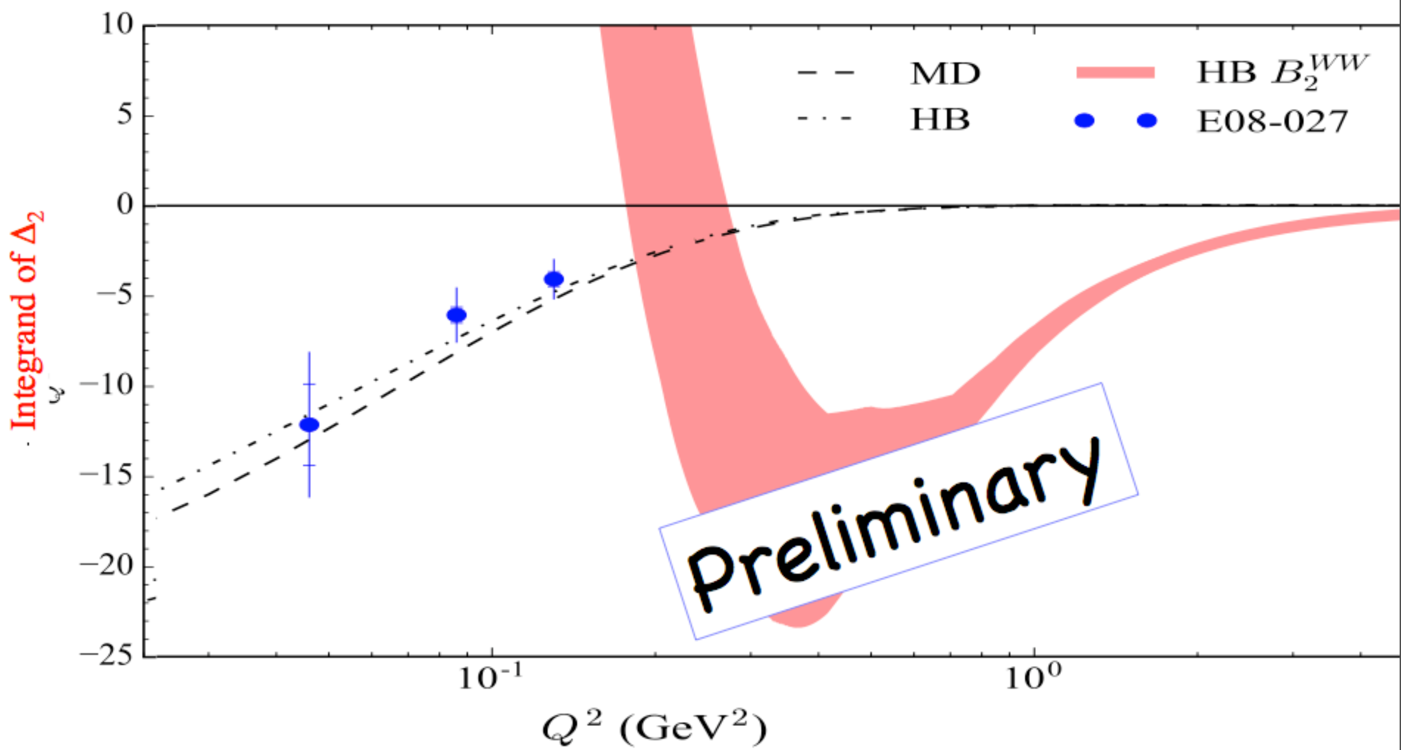
$$\beta_2(\tau) = 1 + 2\tau - 2\sqrt{\tau(\tau+1)}$$

- How do new models compare with previous publications?

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



Conclusions: wish list to find the line

QED

- check QED contributions in H to improve the TPE(H)
- higher-order QED corrections in μp
- Summary of all contributions would be very helpful (at 1 ppm level).

Is the meson exchange already included in the TPE computed with dispersion relations?

Zemach radius

- improve determination of Zemach radius, mainly through magnetic FF
- Study correlations R_z vs R_p

Polarisability contribution

- re-evaluate the pol contribution given the new g_1 and g_2 data
- improve chPT prediction also in view of interpretation of HFS measurement
- subtraction term really absent?

Stolen from A. Antognini's talk

A TPE contribution with an accuracy of 25 ppm of HFS is needed to find the line

Open issues for theory and experiments.

- χEFT consistencies (Mainz/Bonn, proton/neutron). Direct comparison with SSF at low Q^2 and ν.

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  - Full parameterization of g_1 and g_2. Build on Sebastian Kuhn's Model, MAID, with additional constraints (1-pion production).
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  - ^{3}He next-to ideal neutron target, but no neutron information on g_1 and g_2 from it (outside of pQCD).
  - Extraction of $\Gamma_{1,2}$ from ^{3}He at very low Q^2.

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- Behavior of g_1 (and g_2) at large ν (convergence of GDH SR). Q^2=0 in HD. Q^2>0 in Hall A (SoliD, 3He) and B (CLAS12: p,D)

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- Low-Q atomic/nuclear collaboration to provides state-of-art on observables and description consistency of theories. ("Low-Q data group"). 1-page summaries, white paper, new workshop (when?).