Measurements of the nucleon generalized spin polarizabilities

A. Deur

Thomas Jefferson National Accelerator Facility

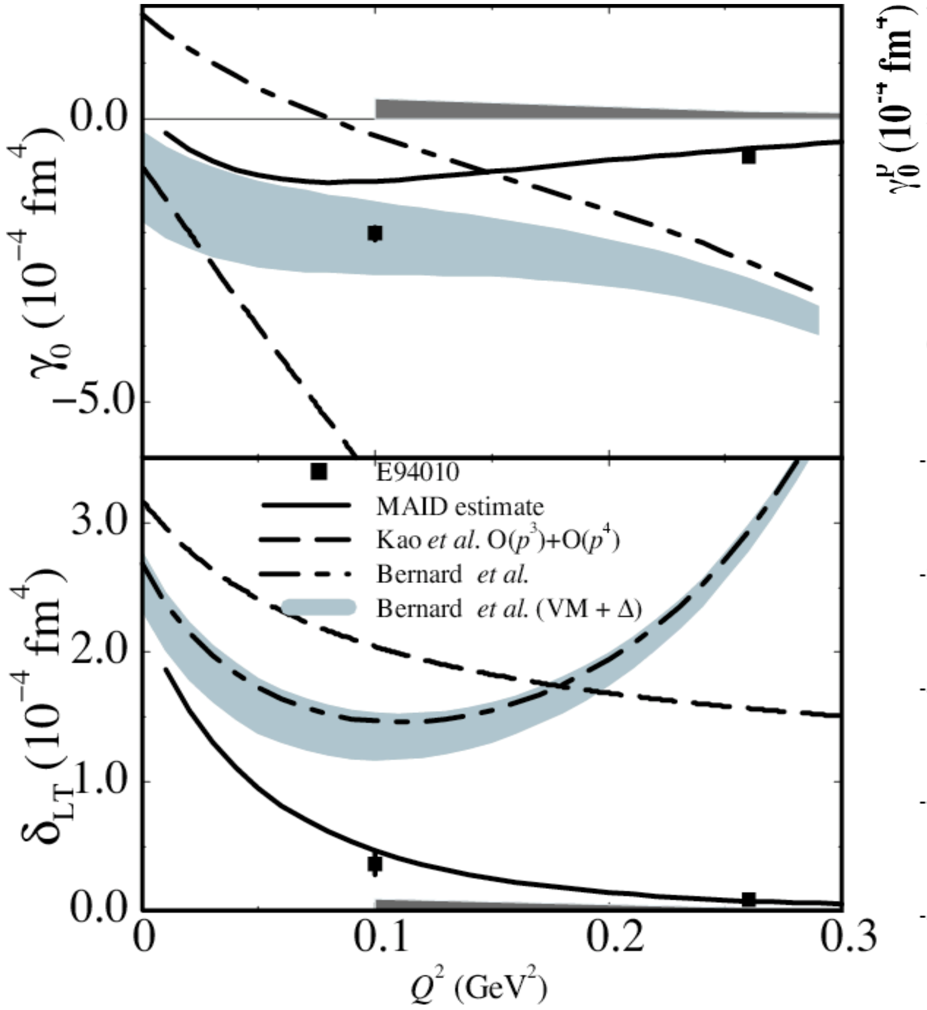
Generalized spin polarizabilities

Electromagnetic polarizabilities were discussed in the previous talks.
We will discuss here polarizabilities *generalized* to electroproduction (Q^2-dependent).

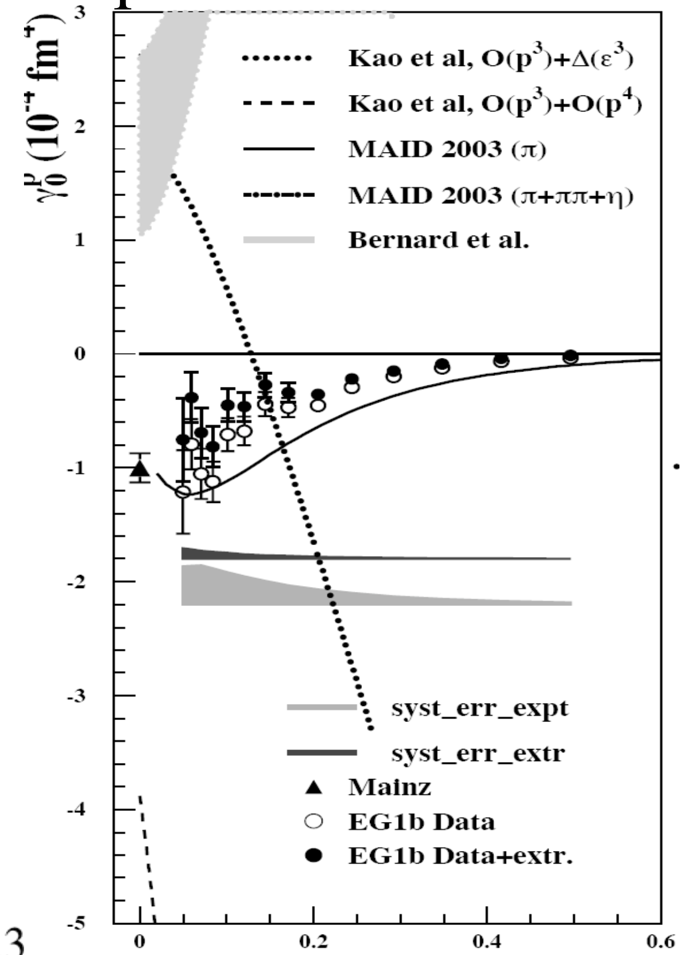
Generalized forward spin polarizability $\gamma_0(Q^2)$;
Generalized Longitudinal-transverse spin polarizability $\delta_{LT}(Q^2)$.

First measured in the 1990s at JLab: $\gamma_0(Q^2)$ on proton & neutron; $\delta_{LT}(Q^2)$ on neutron.

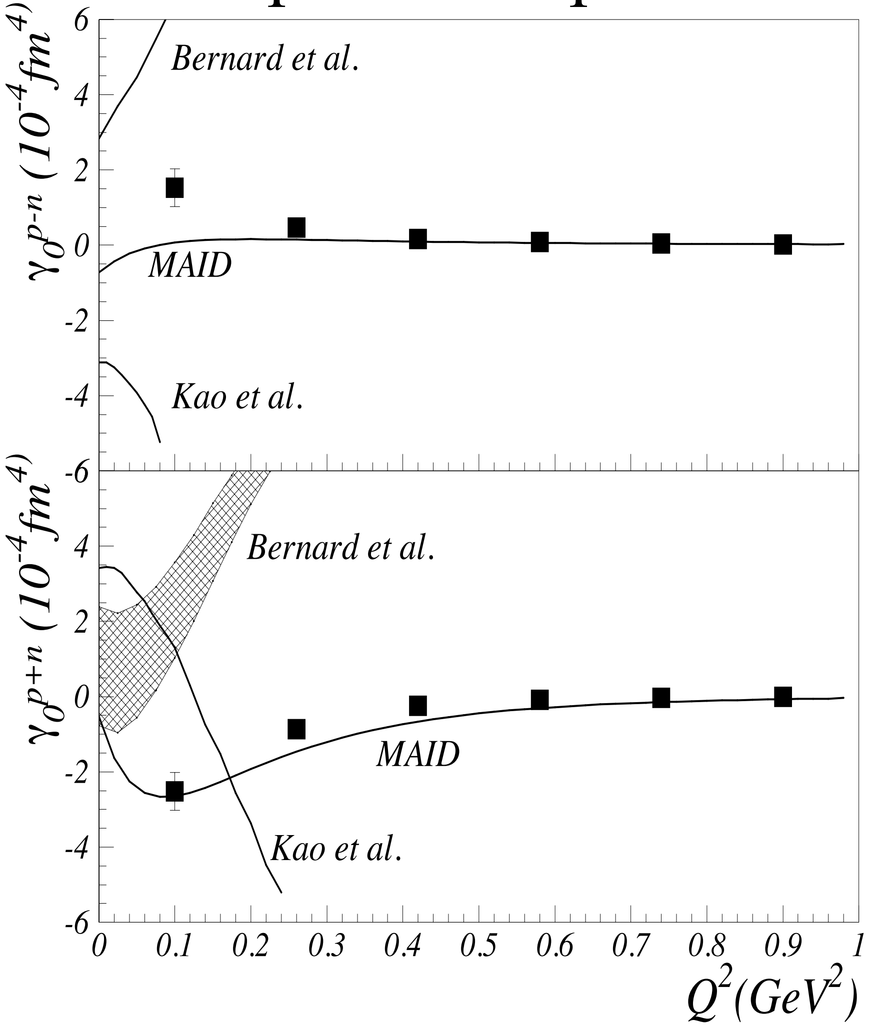
neutron JLab E94-010



proton JLab EG1b



Isospin decomposition



Theoretical predictions: Chiral effective field theory (χEFT). Phenomenology: MAID model.

First generation of measurements of generalized spin polarizabilities

Results from JLab 1990's experiments (Hall A E94010, CLAS EG1b):

A: ~agree
X: ~disagree
- : No prediction available

Ref.	Γ_1^p	Γ_1^n	$\boldsymbol{\Gamma_1^{p-n}}$	Γ_1^{p+n}	γ_0^p	γ_0^n	$\boldsymbol{\gamma_0^{p-n}}$	γ_0^{p+n}	$\boldsymbol{\delta_{LT}^p}$	$\boldsymbol{\delta_{LT}^n}$
Ji 1999	X	X	A	X	-	-	-	-	-	-
Bernard 2002	X	X	A	X	X	A	X	X		X
Kao 2002	-	-	-	-	X	X	X	X		X

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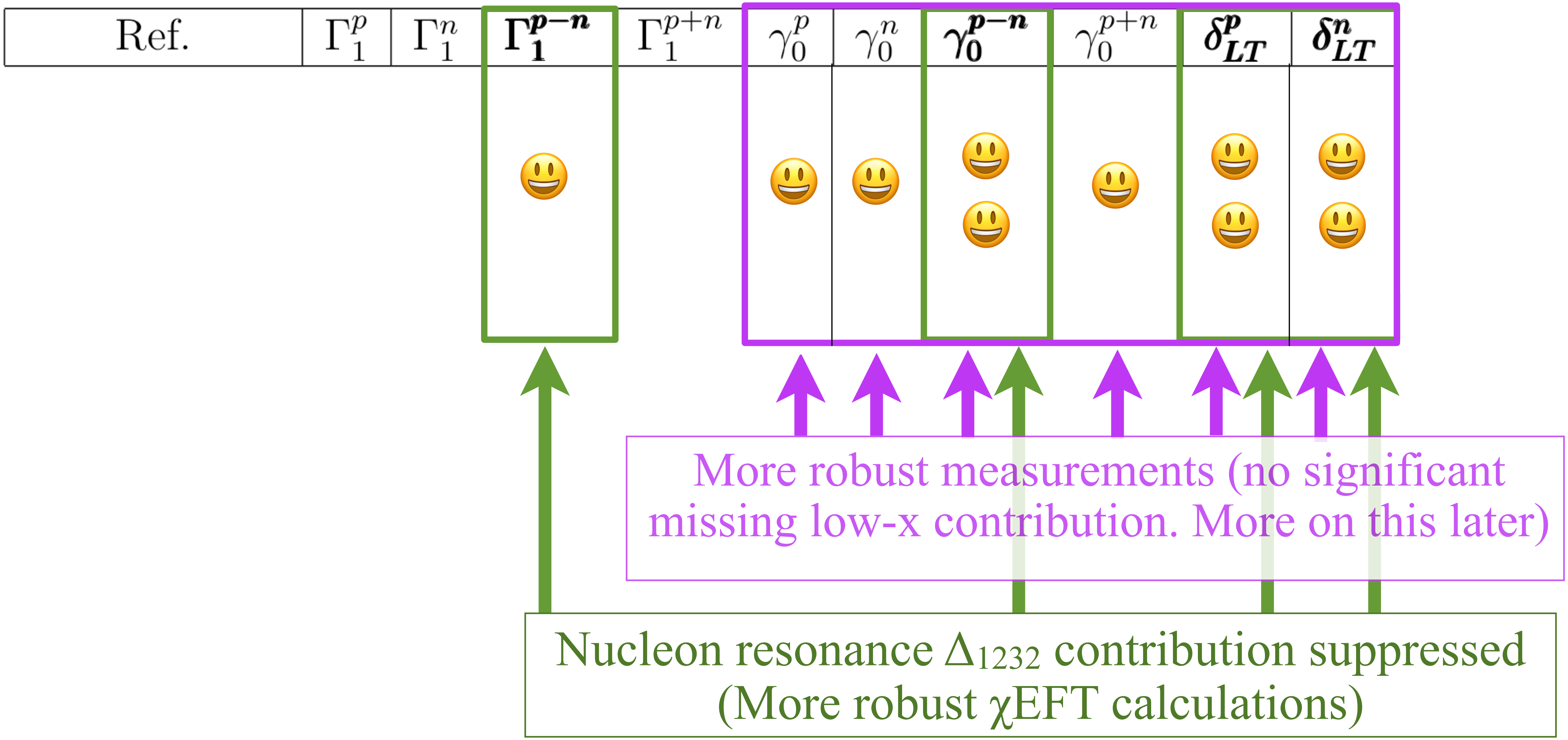
Ji 1999	X	X	A	X	-	-	-	-	-	-
Bernard 2002	X	X	A	X	X	A	X	X		X
Kao 2002	-	-	-	-	X	X	X	X		X

↑ ↑ ↑ ↑

Integral of longitudinal spin structure function: $\Gamma_1(Q^2) \equiv \int_0^1 g_1 \, dx$

1990s-2000s χEFT predictions in tension with spin observable data more often than not.

Testing χEFT



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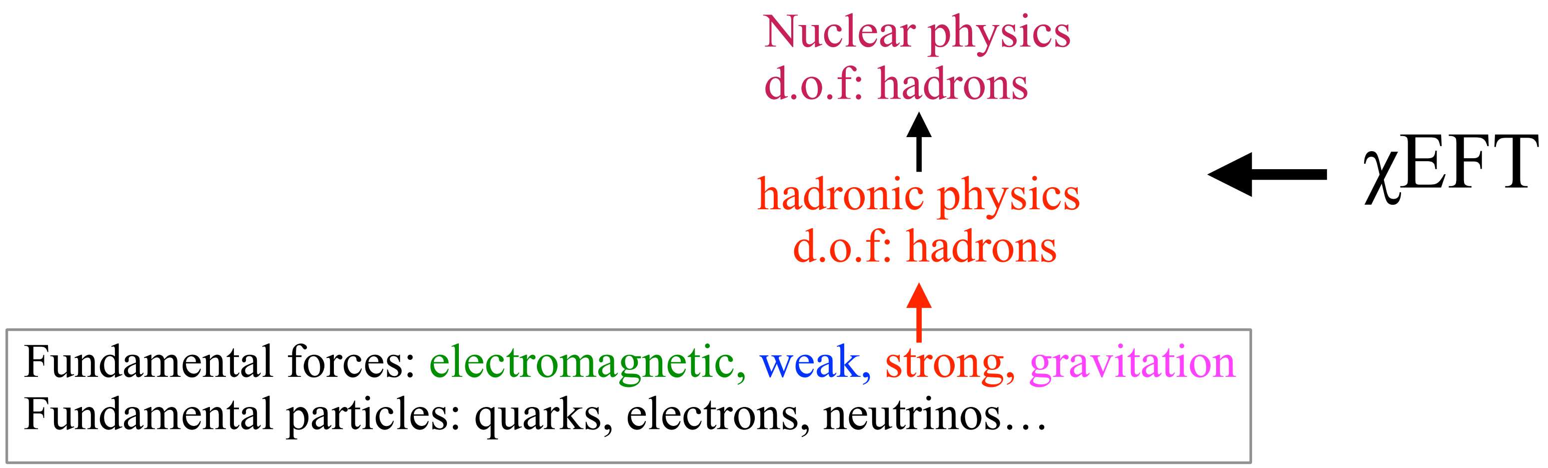
			😃		😃	😃	😃 😃	😃	😃 😃	😃 😃

More robust measurements (no significant missing low-x contribution. More on this later)

Nucleon resonance Δ_{1232} contribution suppressed (More robust χEFT calculations)

Testing χEFT

Important to test χEFT: the leading effective theory dealing with the first level of complexity emerging from the Standard Model. ⇒ Crucial piece of our global understanding of Nature.



Nuclear physics
d.o.f: hadrons

hadronic physics
d.o.f: hadrons

← χEFT

Fundamental forces: electromagnetic, weak, strong, gravitation
Fundamental particles: quarks, electrons, neutrinos…

χEFT has been very successful in describing many hadronic and nuclear phenomena. However, it has a history of not describing well nucleon spin observables.

Testing χEFT

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Kao 2002	-	-	-	-	X	X	X	X		X	-	X

1990s-2000s χEFT predictions in tension with spin observable data more often than not.

The discrepancies for δ_{LT} was particularly puzzling:

- Expected to be a robust χEFT prediction;
- Expected to be a robust measurement.

χEFT calculation problem? Or were the experiments not reaching well enough into the χEFT applicability domain, i.e., at low Q^2?

→

- Refined χEFT calculations, with improved expansion schemes & including the Δ_{1232} .
- New experimental program at JLab reaching well into the χEFT applicability domain & with improved precision.

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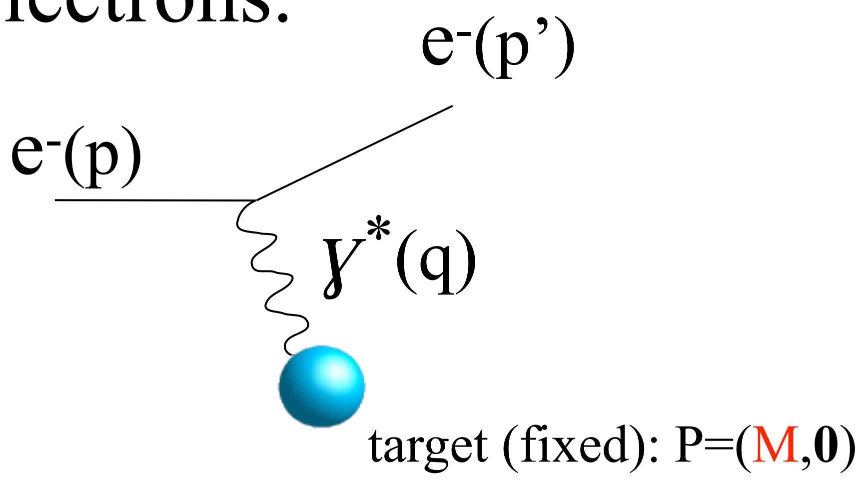
This talk: results from the new experimental program at JLab.

Our tool: Inclusive electron scattering

- Probe nucleon and nuclei using electrons.



- $p=(E,\mathbf{p})$, $p'=(E-\nu,\mathbf{p}-\mathbf{q})$, $q=(\nu,\mathbf{q})$.

- γ^*: virtual photons; $q^2 \neq 0$. Since $q^2 < 0$ here, we use $Q^2 = -q^2$.

- Inclusive experiments: only the scattered electrons are detected: target or target fragments are ignored.

- Alternately to ν, the Bjorken scaling variable $x = Q^2/2pq$ can be used.

We do not know how to measure directly generalized spin polarizabilities. To access them, we use the spin polarizability **sum rules:**

Generalized forward spin polarizability:

$$\gamma_0 = \frac{4e^2M^2}{\pi Q^6}\int_0^{1^-} x^2\left(g_1 - \frac{4M^2}{Q^2}x^2 g_2\right)dx$$

1st and 2nd nucleon spin structure functions

Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{4e^2M^2}{\pi Q^6}\int_0^{1^-} x^2(g_1+g_2)dx$$

Allow us to access experimentally $\gamma_0(Q^2)$ and $\delta_{LT}(Q^2)$.

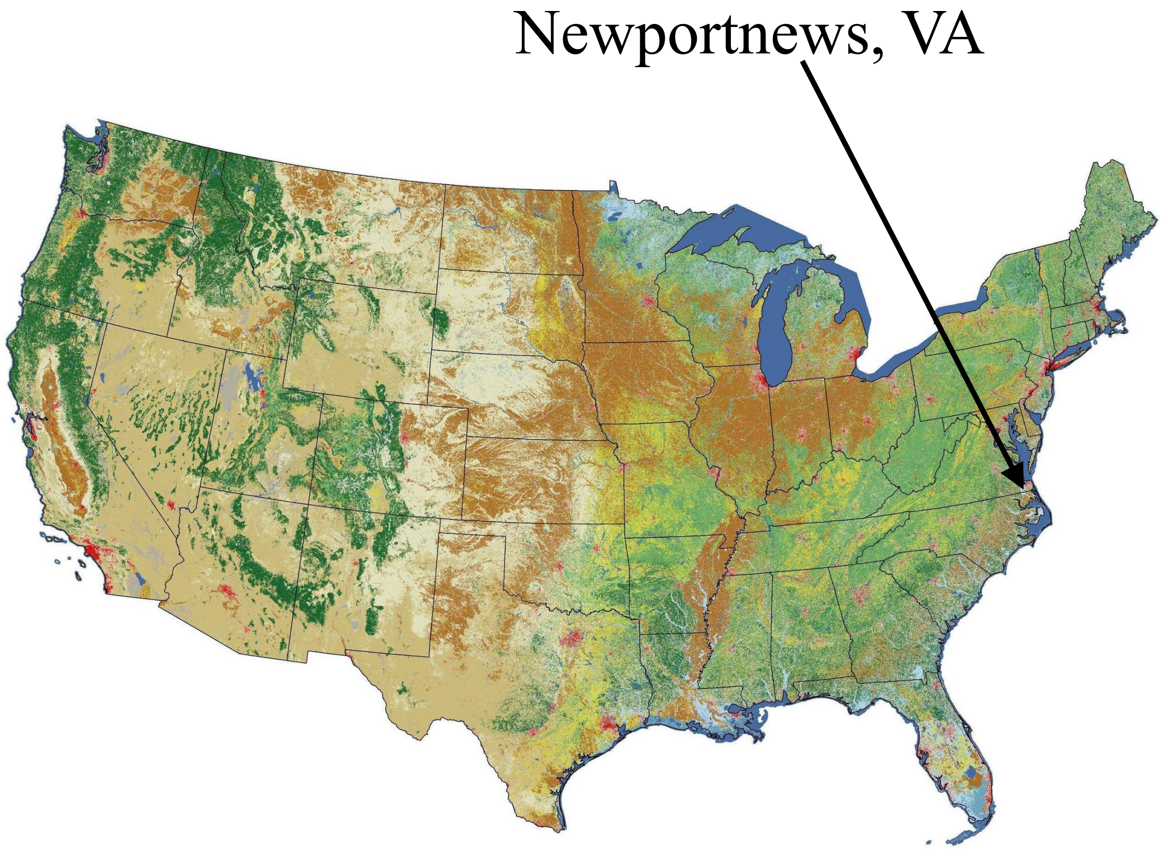
Reaching x=0 would demand infinite beam energy.

⇒ Experiments measure only partial integrals, down to x_{min}. Then, use models and Regge-guided extrapolations to estimate the missing part.
Delicate issue for first moments like Γ_1.
Not an important issue spin polarizabilities sum rules.

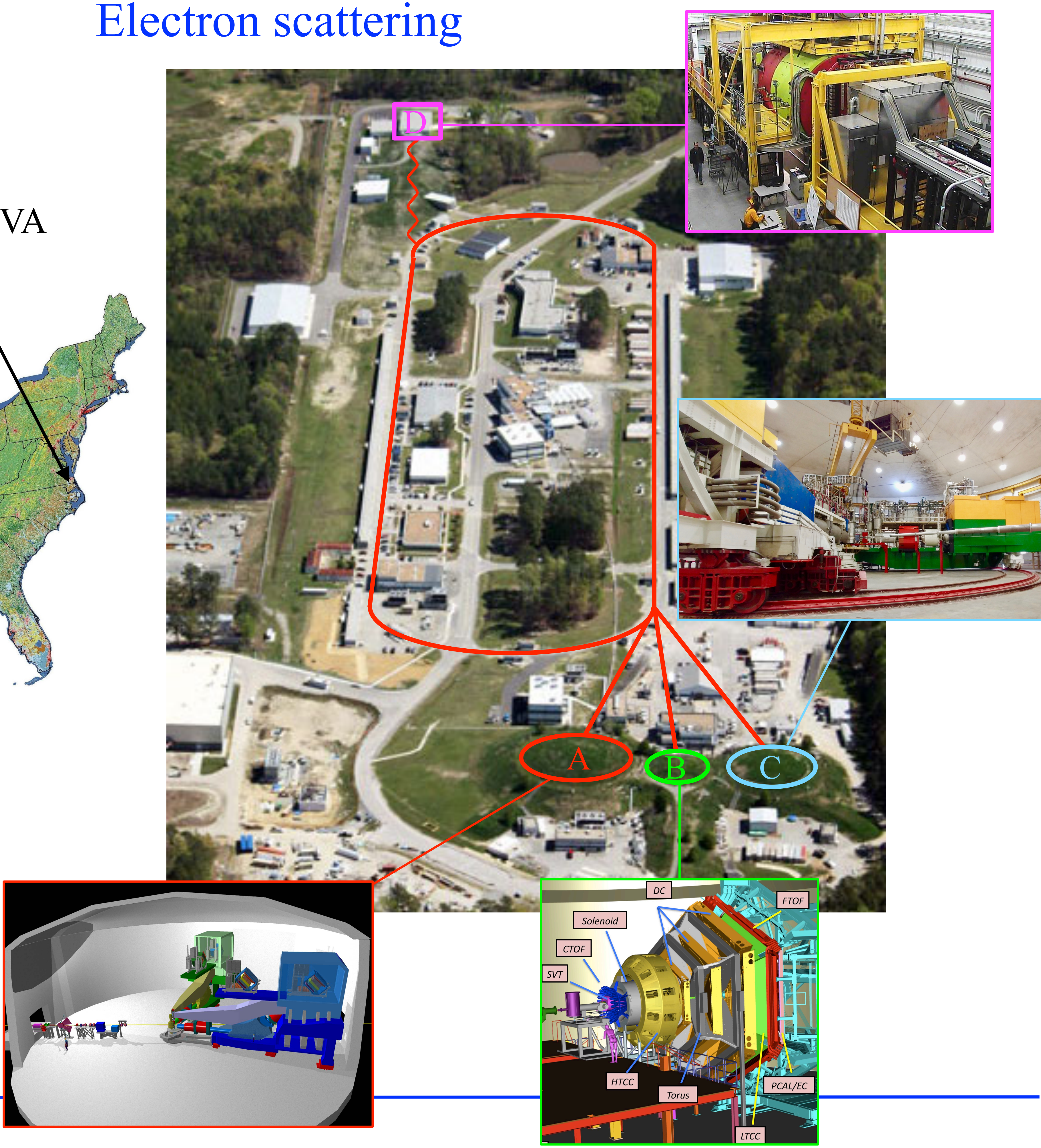
But due to x^2-weighting, γ_0 and δ_{LT} sensitive to high-x (i.e., low-ν) contribution (Karl's talk this morning).

Electron scattering

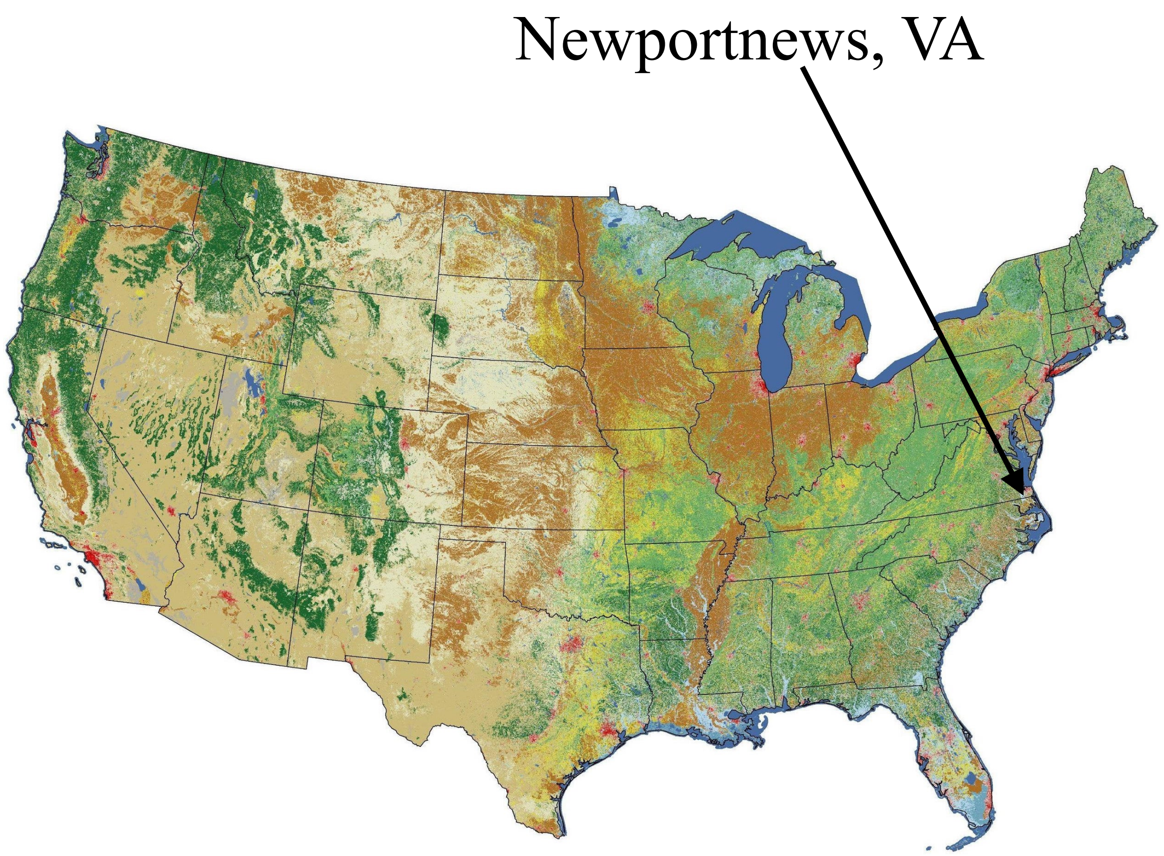
Jefferson Lab

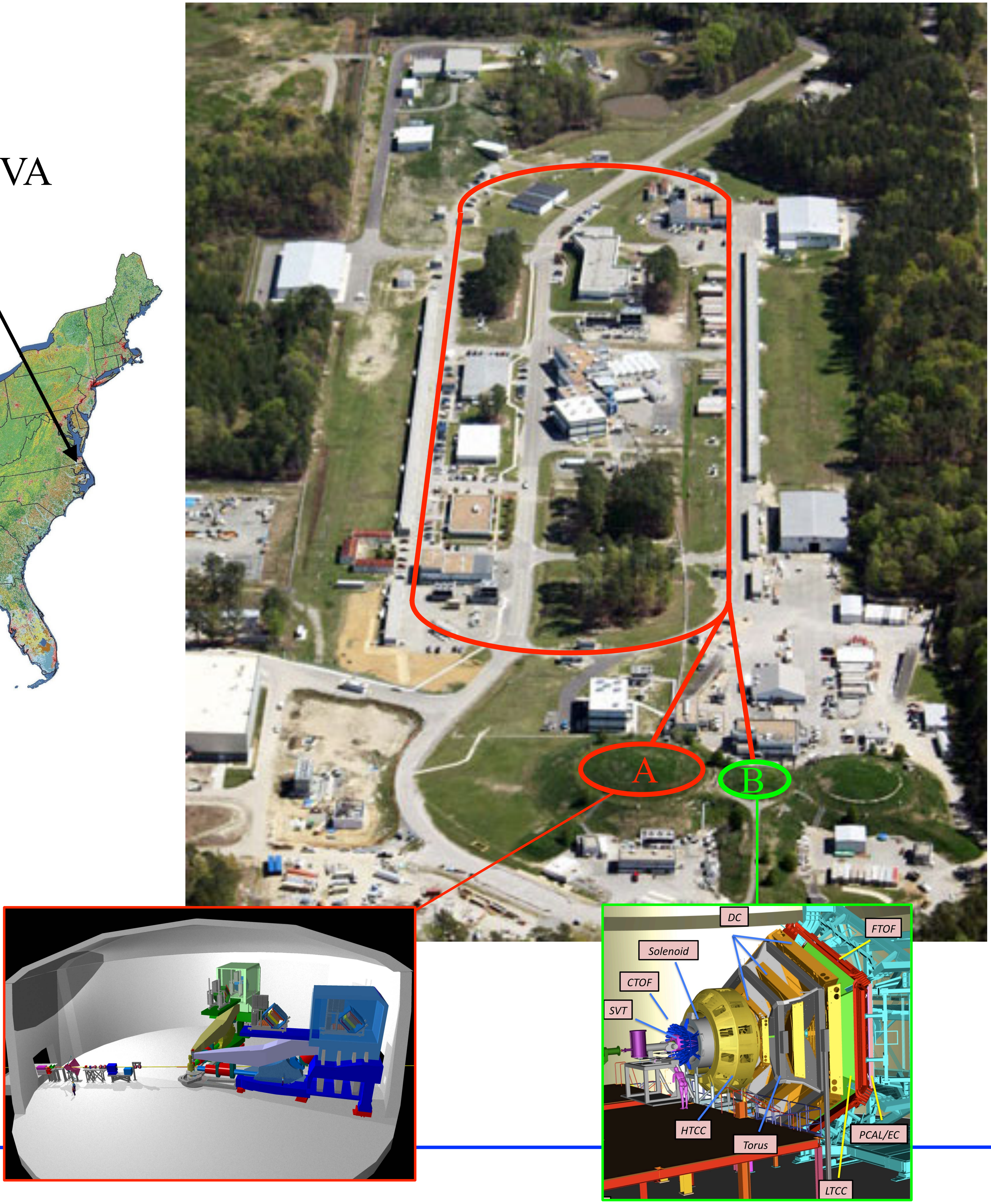


Continuous e^- beam.
up to 12 GeV.
Polarization: ~90%
Up to 200 μA.
4 experimental halls.



Electron scattering





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Estimating sum rules at low Q^2:

Low Q^2 + covering large ν range so that sum rule's integrals can be formed⇒forward angles

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Low Q^2 + covering large ν range so that sum rule's integrals can be formed⇒forward angles

E97-110 (neutron, using longitudinally and transversally polarized ^{3}He):

Spokespeople: **J.P. Chen,** A.D., F. Garibaldi
Students: C. Peng (Duke U.), J. Singh (UVa),
V. Sulkosky (W&M), J. Yuan (Rutgers U.)

E08-027 (NH_3, longitudinally and transversally polarized):

Spokespeople: A. Camsonne, J.P. Chen, D. Crabb, **K. Slifer**
Also see K. Slifer presentation earlier today

E03-006 (NH_3, longitudinally polarized):

Spokespeople: **M. Ripani**, M. Battaglieri, A.D., R. de Vita
Students: H. Kang (Seoul U.), K. Kovacs (UVa)

E06-017 (ND_3, longitudinally polarized):

Spokespeople: **A.D.**, G. Dodge, M. Ripani, K. Slifer
Students: K. Adhikari (ODU)

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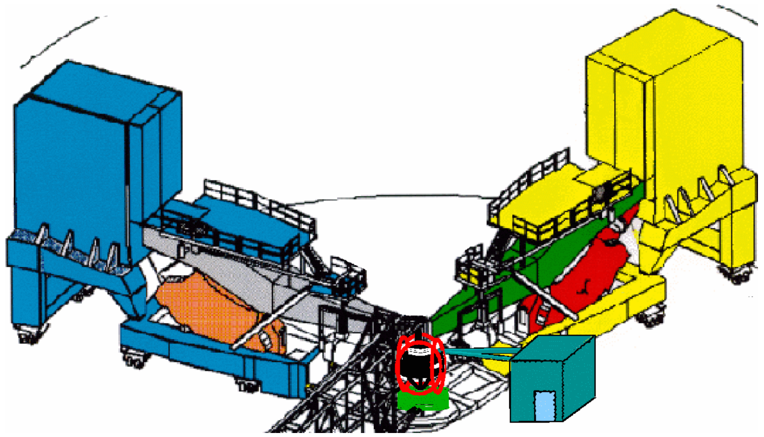
JLab Hall A:



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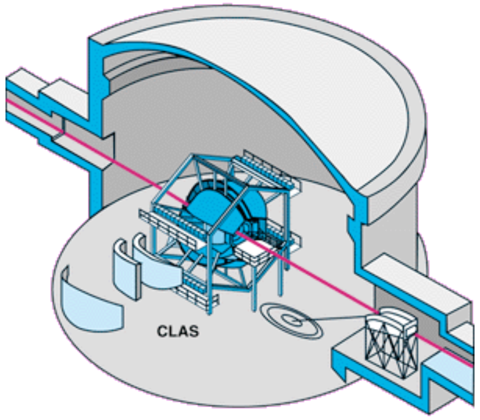
EG4 run group

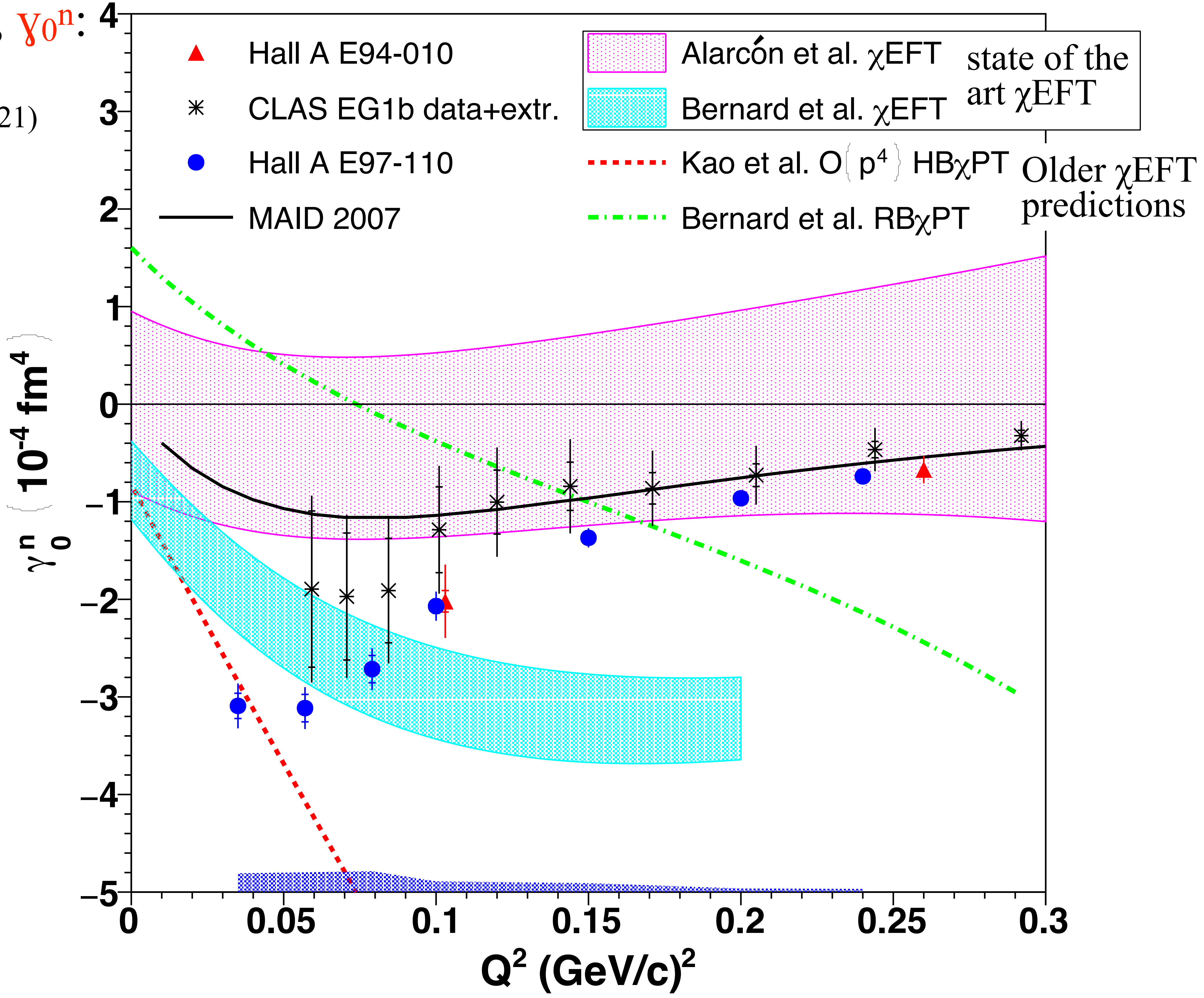
JLab Hall B:



JLab experimental results on γ_0

E97-110 neutron, γ_0^n:

V. Sulkosky et al.
Nature Physics, **17** 687 (2021)



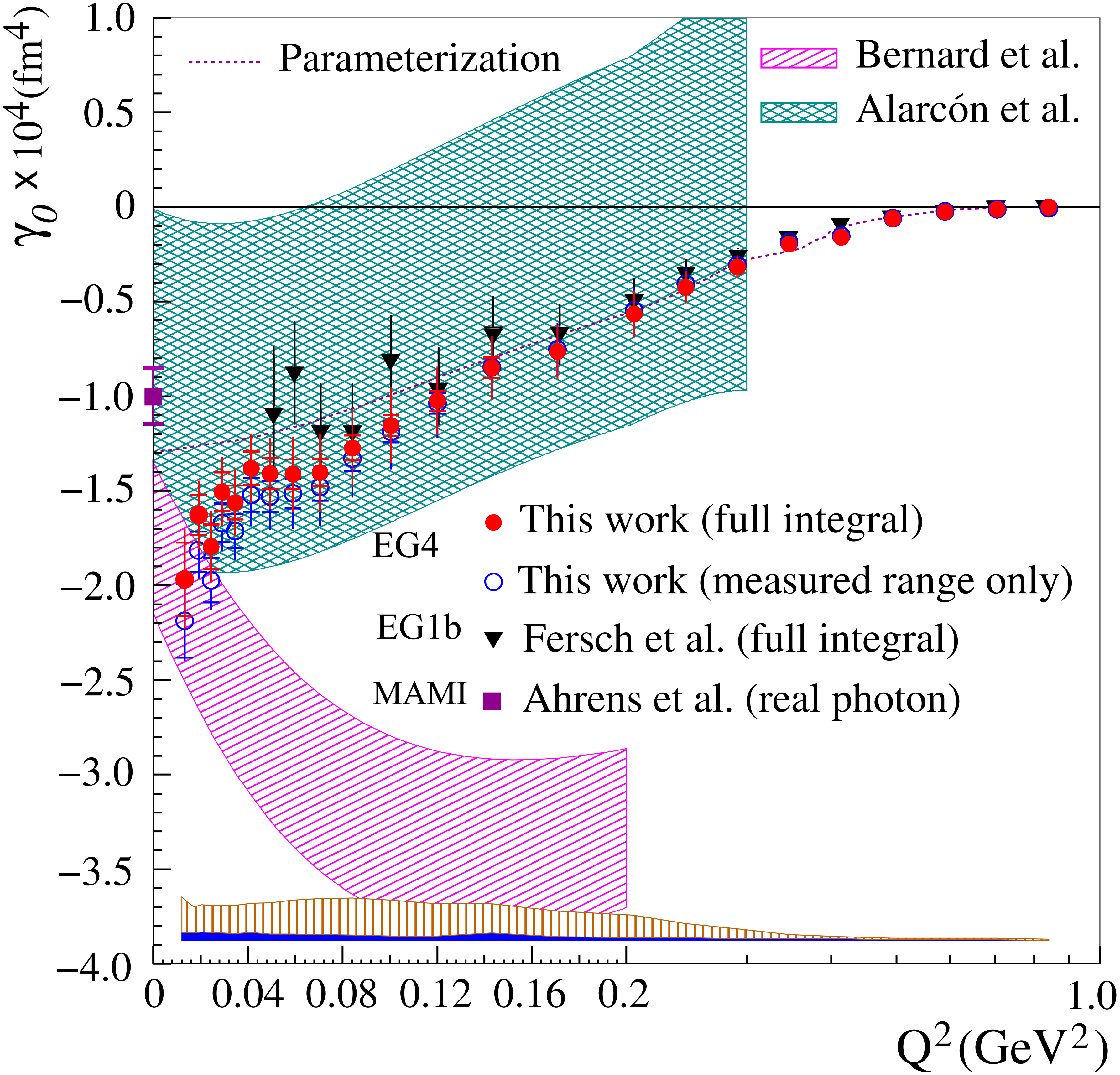
state of the art χEFT

Older χEFT predictions

JLab experimental results on γ_0

EG4 proton, γ_0^p:

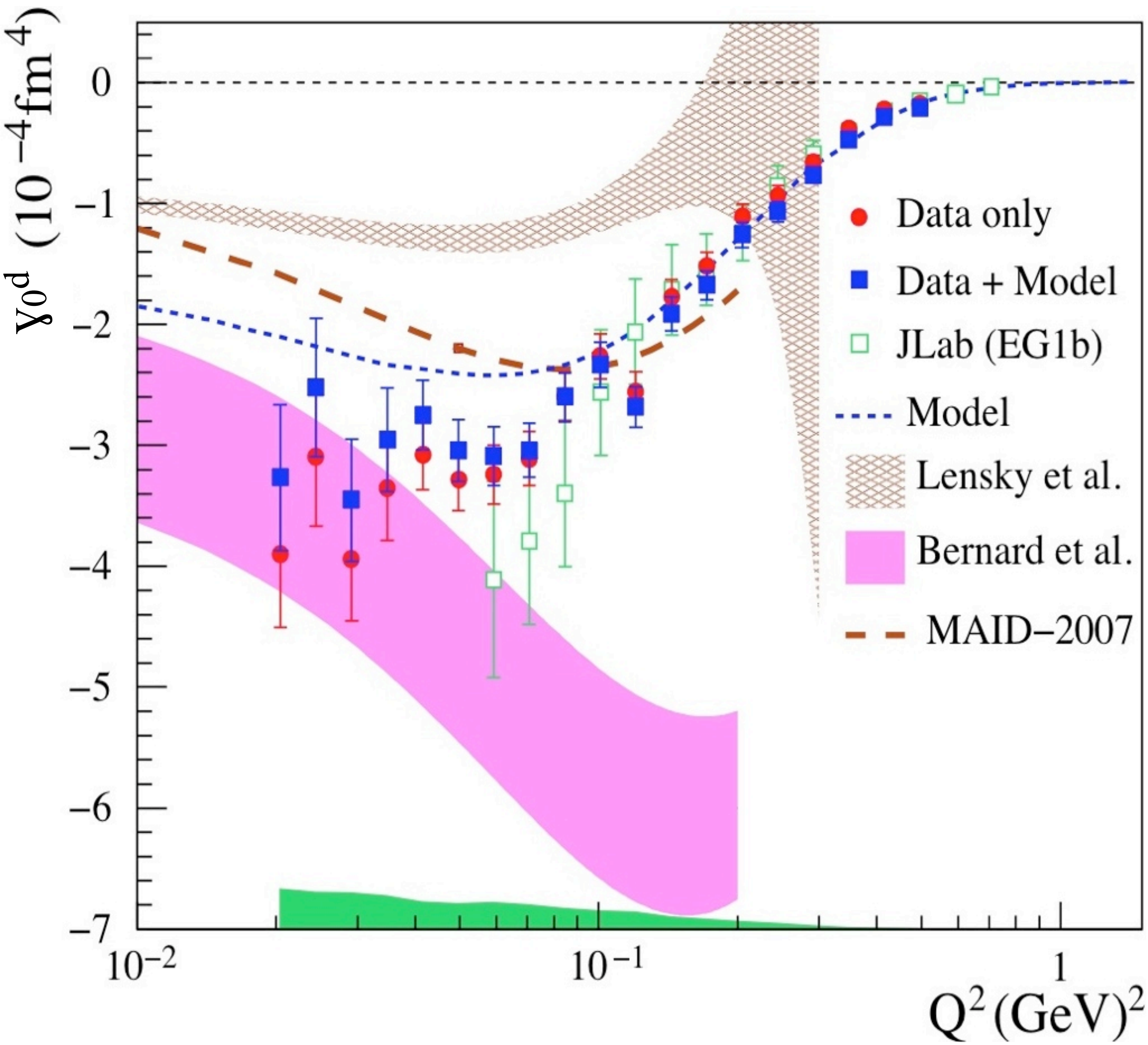
X. Zheng et al,
Nature Phys.**17** 736 (2021)



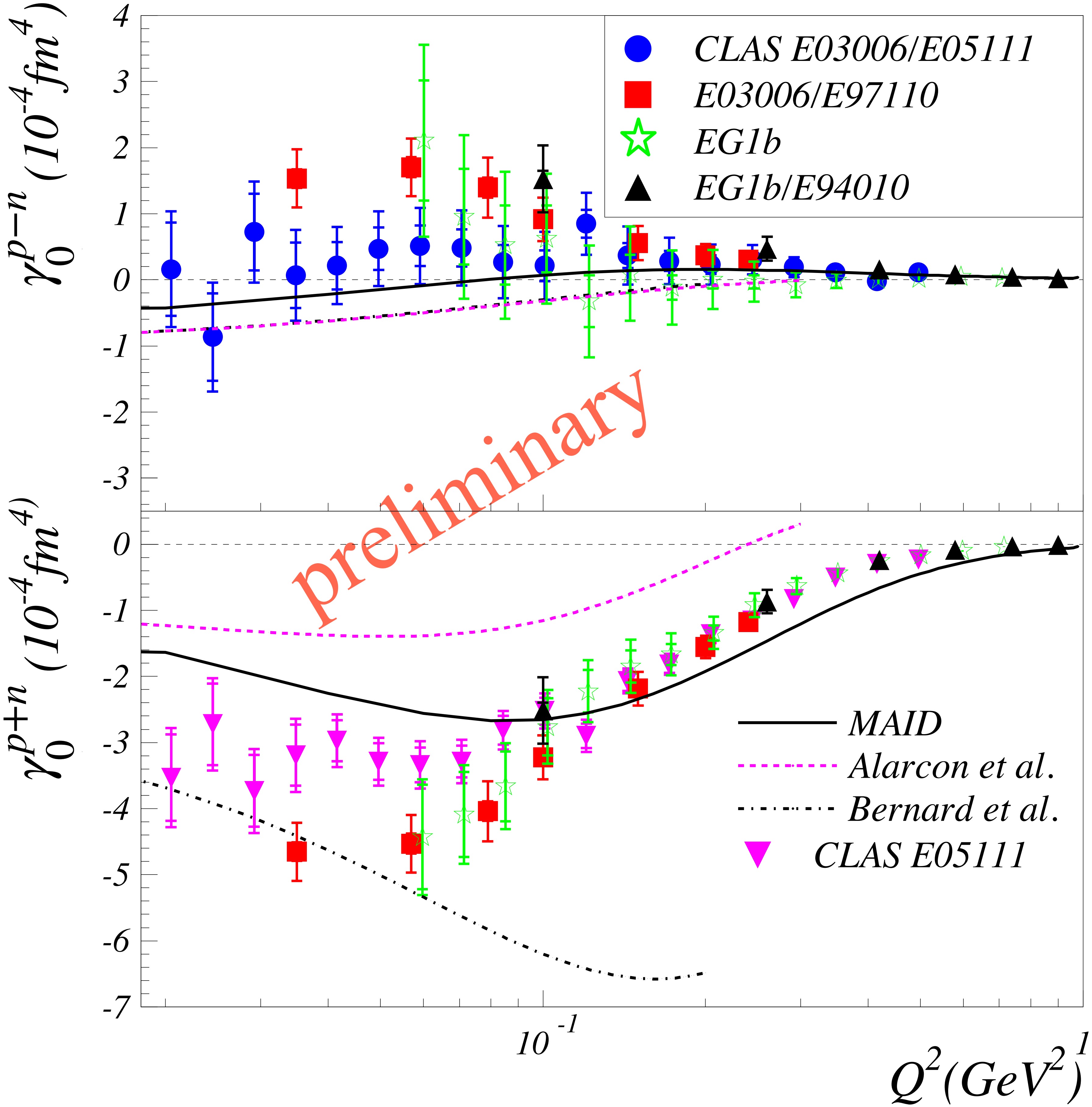
JLab experimental results on γ_0

EG4 deuteron, γ_0^d:

K. Adhikari et al.
PRL **120**, 062501 (2018)



Isospin decomposition of γ_0

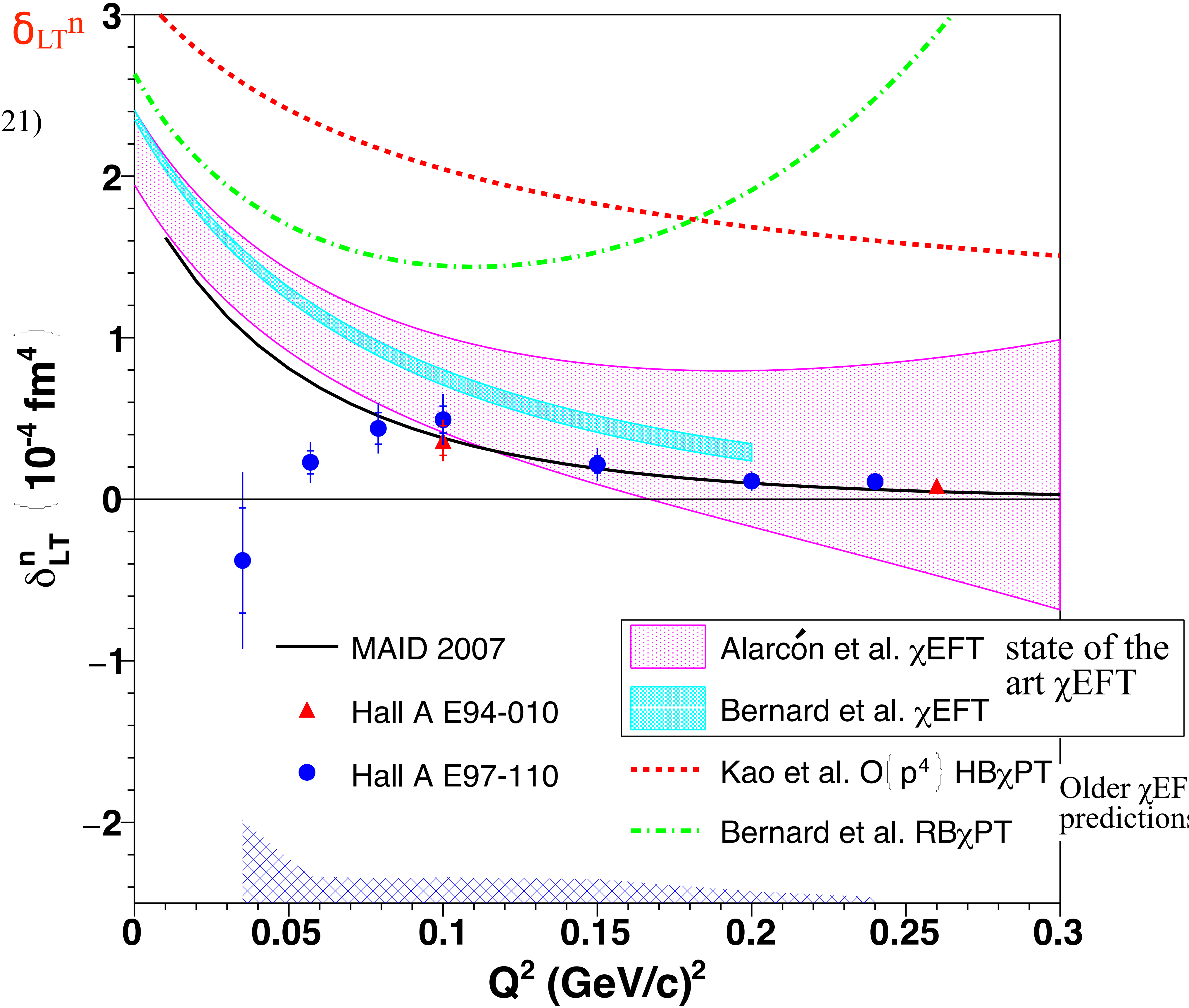


JLab experimental results on δ_{LT}

E97-110 neutron, δ_{LT}^{n}

V. Sulkosky et al.
Nature Physics, **17** 687 (2021)

Δ-resonance contribution suppressed in δ_{LT}



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Older χEFT predictions

JLab experimental results on δ_{LT}

E08-027 proton, δ_{LT}^p

D. Ruth et al. arXiv:2204.10224
To appear in Nature Physics.
See Karl Slifer talk earlier today.

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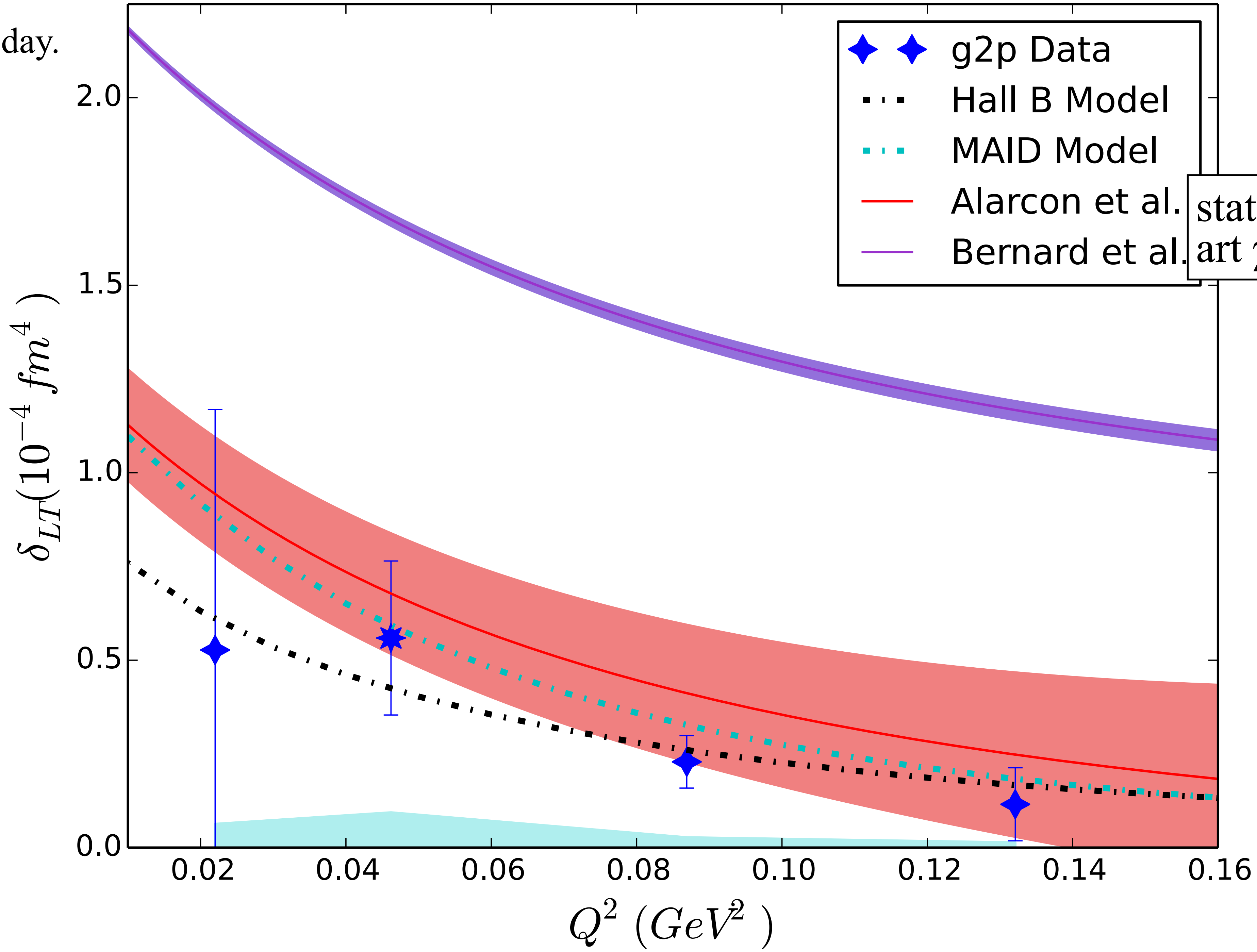


state of the art χEFT

Testing χEFT

A: agree over range $0<Q^2\lesssim 0.1$

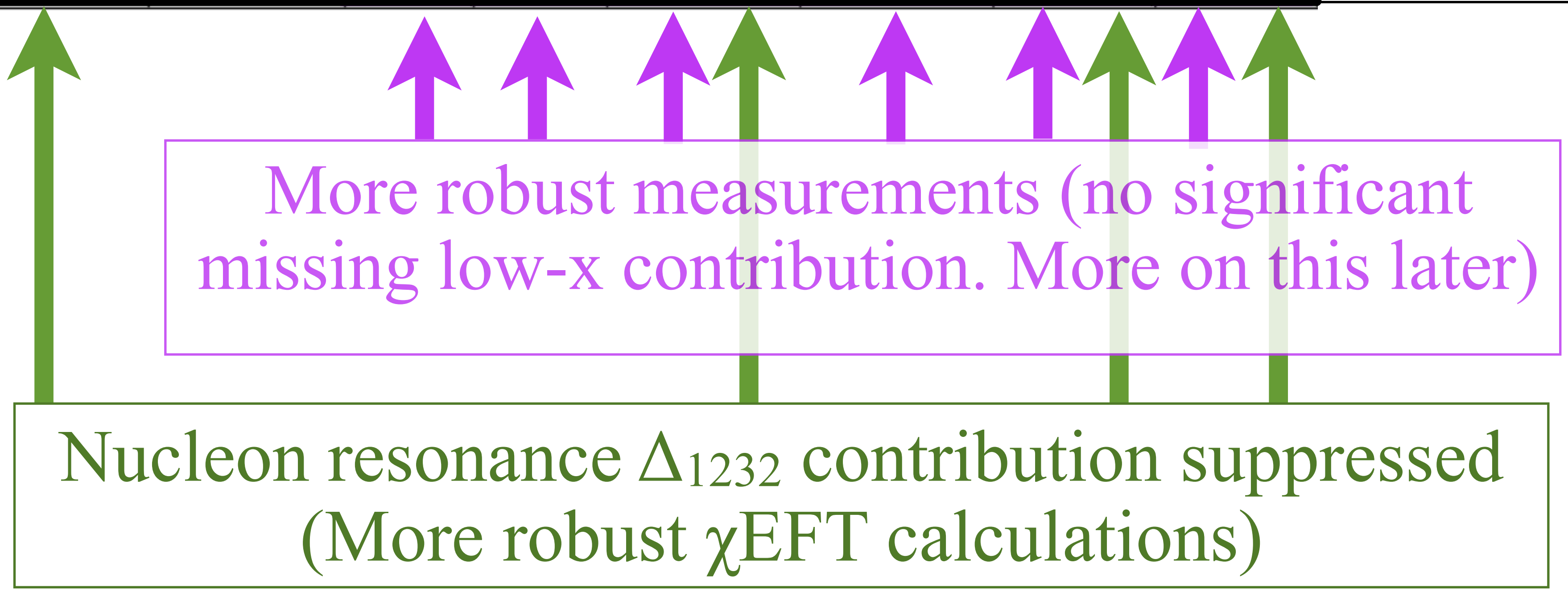
X: disagree over range $0<Q^2\lesssim 0.1$

- : No prediction available

*: Preliminary data

Ref.	Γ_1^p	Γ_1^n	Γ_1^{p-n}	Γ_1^{p+n}	γ_0^p	γ_0^n	γ_0^{p-n}	γ_0^{p+n}	δ_{LT}^p	δ_{LT}^n
Ji 1999	X	X	A	X	-	-	-	-	-	-
Bernard 2002	X	X	A	X	X	A	X	X		X
Kao 2002	-	-	-	-	X	X	X	X		X
Bernard 2012	X	X	~A	X	X	A	X*	X*	X	X
Alarcon 2020	A	A	~A	A	~A	X	X*	X*	A	X

state of the art χEFT



More robust measurements (no significant missing low-x contribution. More on this later)

Nucleon resonance Δ_{1232} contribution suppressed (More robust χEFT calculations)

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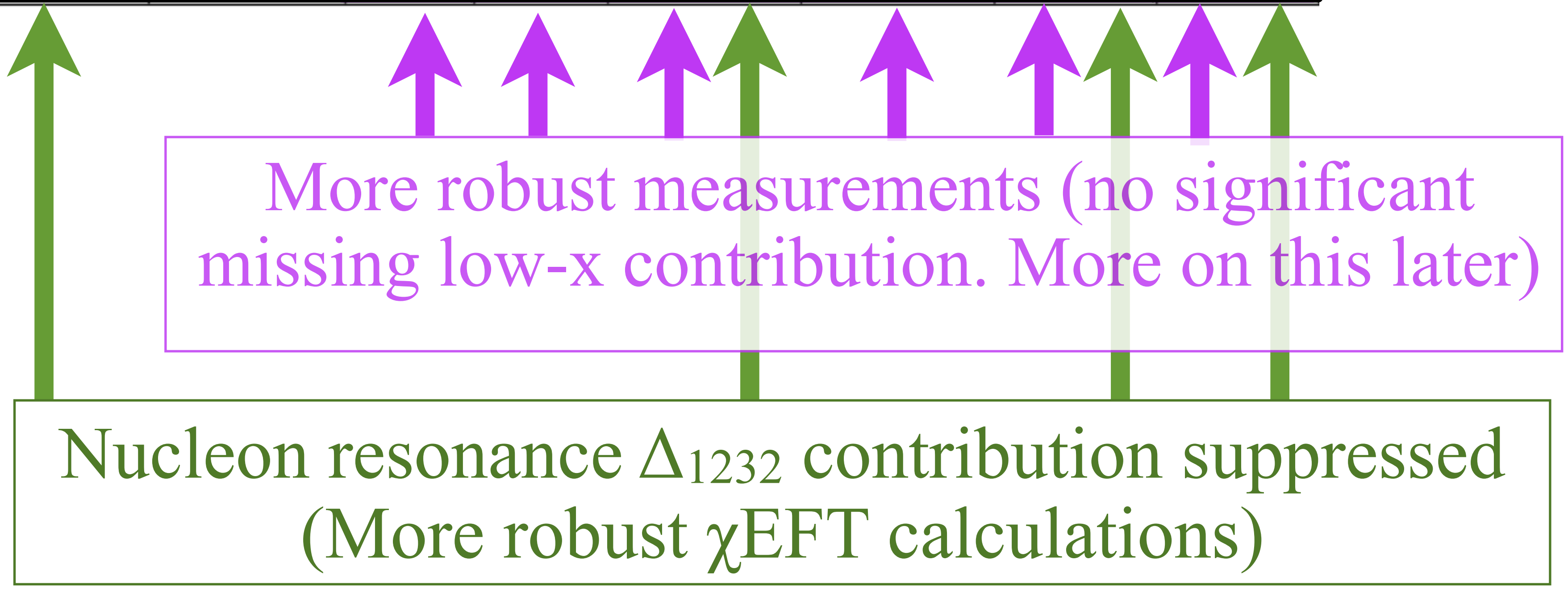
state of the art χEFT



More robust measurements (no significant missing low-x contribution. More on this later)

Nucleon resonance Δ_{1232} contribution suppressed (More robust χEFT calculations)

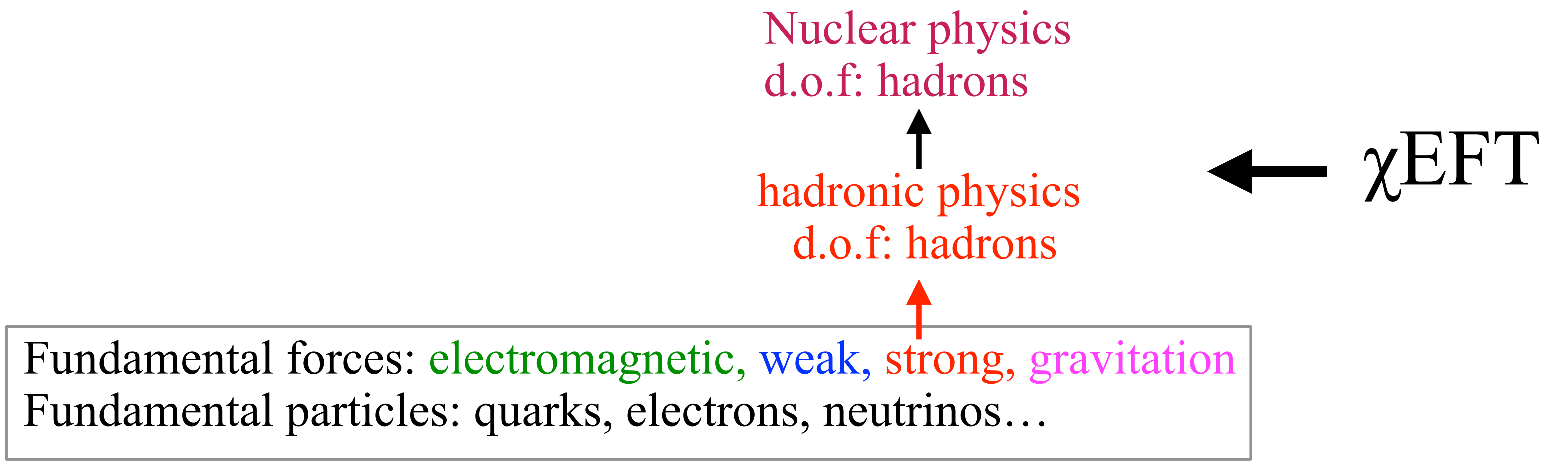
Well-controlled χEFT calculation of spin observables at large distance remains challenging.

Conclusion

χEFT, although successful in many instances is challenged by results from dedicated polarized experiments at low Q^2.

To be sure, low Q^2 sum rule measurements are challenging (low-x extrapolation, high-x contamination). But the experiments were run independently with very different detectors and methods: consistent experiment message.
Also, some χEFT predictions disagree with each other.

This is a problem in our endeavor for a complete description of Nature at all levels: χEFT is the leading approach to manage the first level of complexity arising above the Standard Model, in the strong force sector. Just as if atomic physics could not provide the theoretical foundations of chemistry.



Fundamental forces: electromagnetic, weak, strong, gravitation
Fundamental particles: quarks, electrons, neutrinos…

Thank You!

Back-up slides

Spin polarizabilities

Polarizabilities encode the 2nd order reaction of a body subjected to an electromagnetic field.

The full reaction is described by two Compton scattering amplitudes, f_1 (spin-independent) and f_2 (spin-dependent).

At low (real) photon energy *ν*, one can expand them in powers of *ν*:

Electric polarizability

Magnetic polarizability

$$f_1(\nu) = -\frac{\alpha}{M} + \left(\alpha_E + \beta_M\right)\nu^2 + \mathcal{O}(\nu^4)$$

Forward spin polarizability

$$f_2(\nu) = -\frac{\alpha\kappa^2}{2M^2}\nu + \gamma_0\nu^3 + \mathcal{O}(\nu^5)$$

Purely elastic reaction (rigid object)

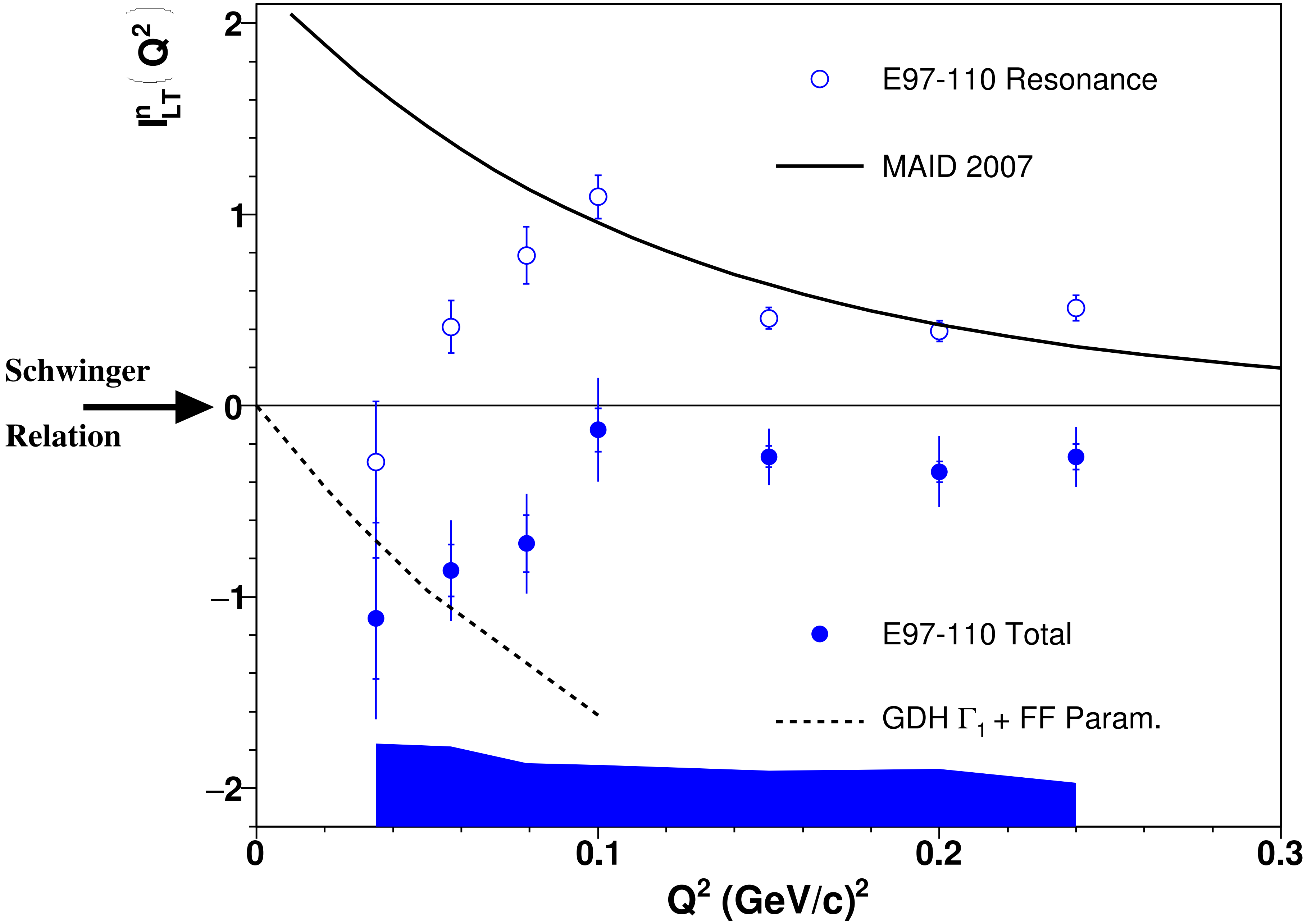
Reaction with deformation (internal rearrangement)

If $Q^2 \neq 0$, the virtual photon has a longitudinal spin component, and δ_{LT} appears (LT stands for Longitudinal-Transverse interference term). For $Q^2 \neq 0$, we talk of *generalized* polarizabilities.

Schwinger sum rule

$$I_{LT}(Q^2) = \frac{8M^2}{Q^2}\int_0^{1^-}(g_1+g_2)dx \xrightarrow[Q^2\to 0]{} \kappa e_t$$

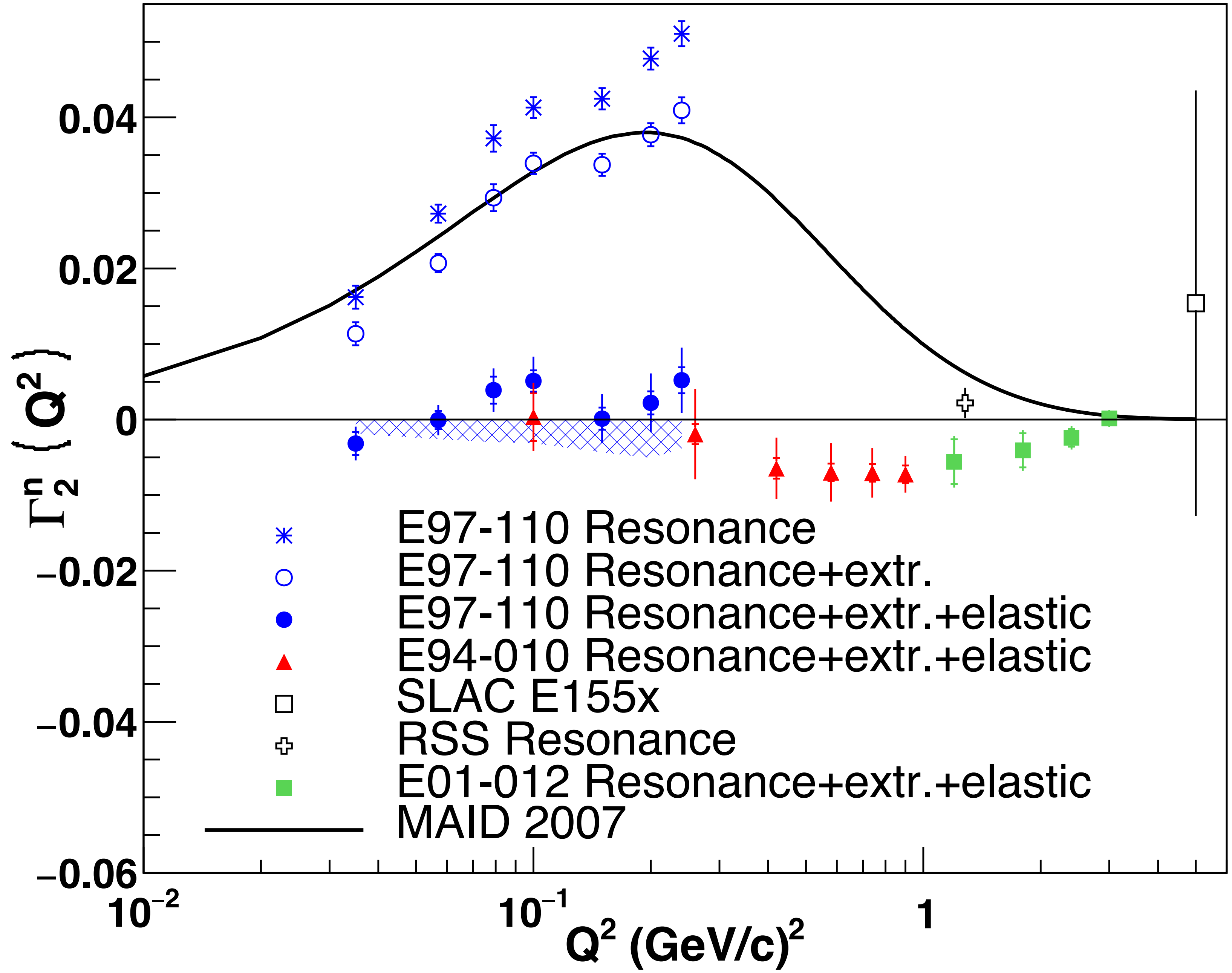
Neutron



Burkhardt–Cottingham sum rule

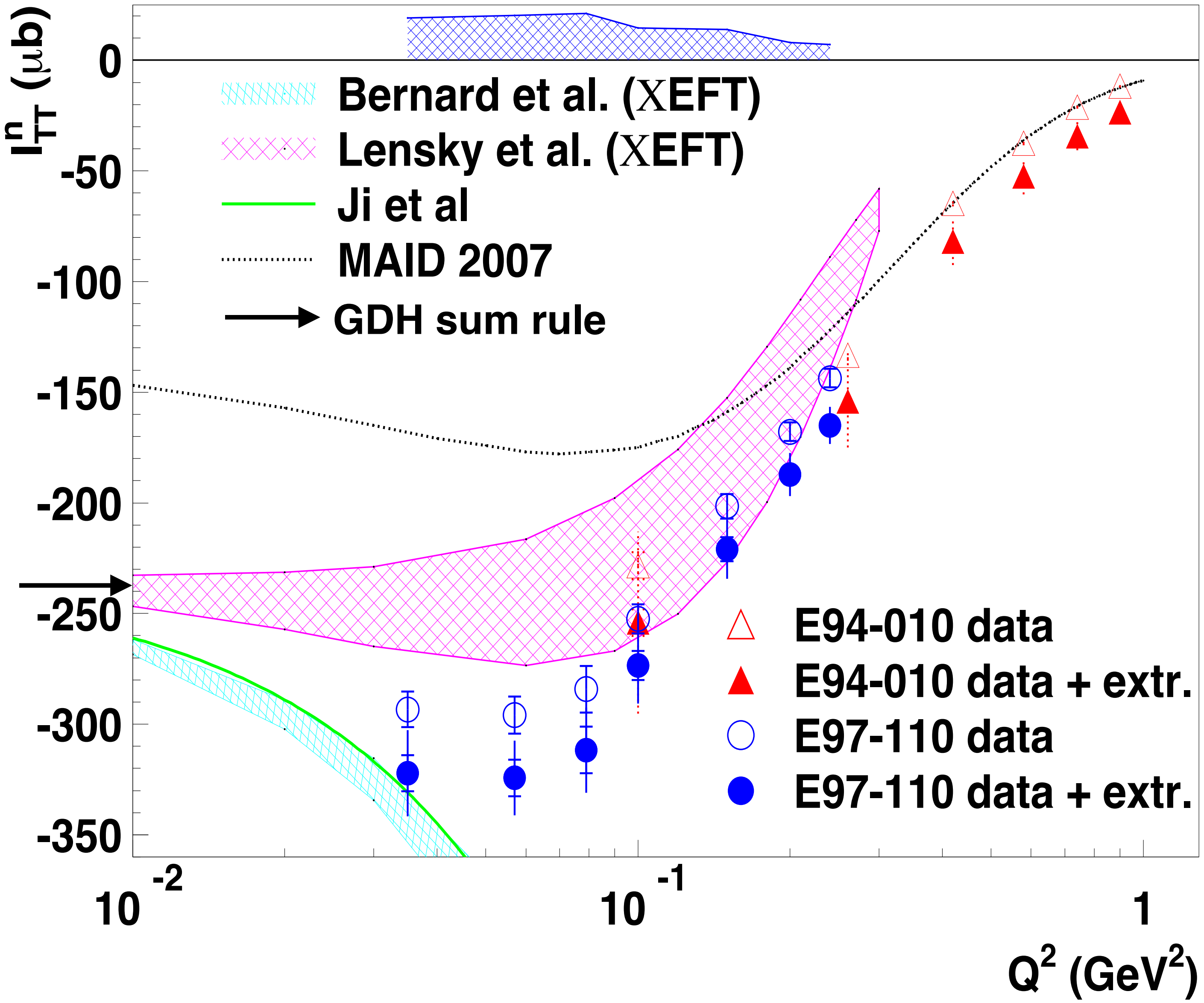
$$\Gamma_2(Q^2) \equiv \int_0^1 g_2 \, dx = 0$$

Neutron

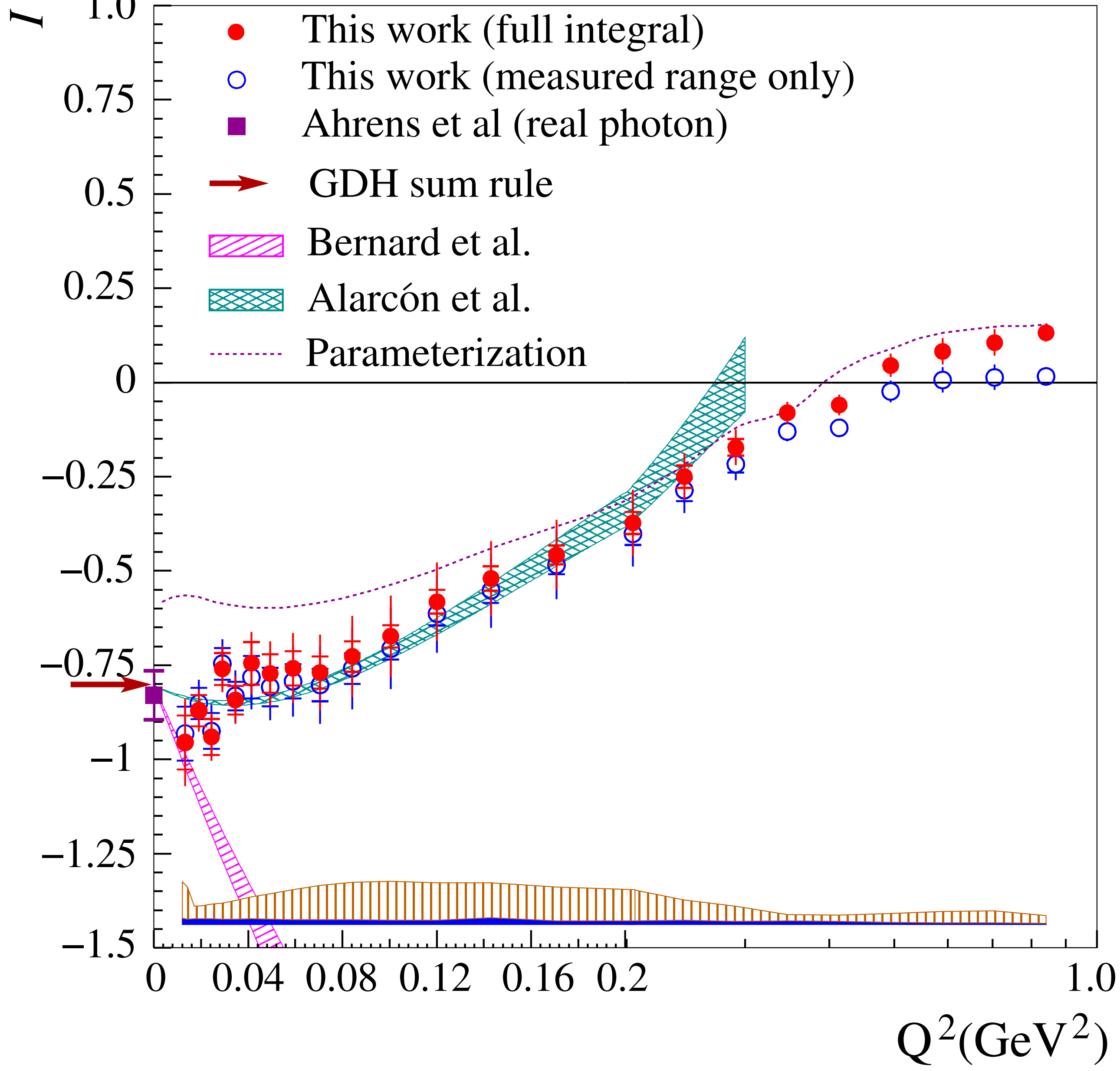


GDH sum measurements

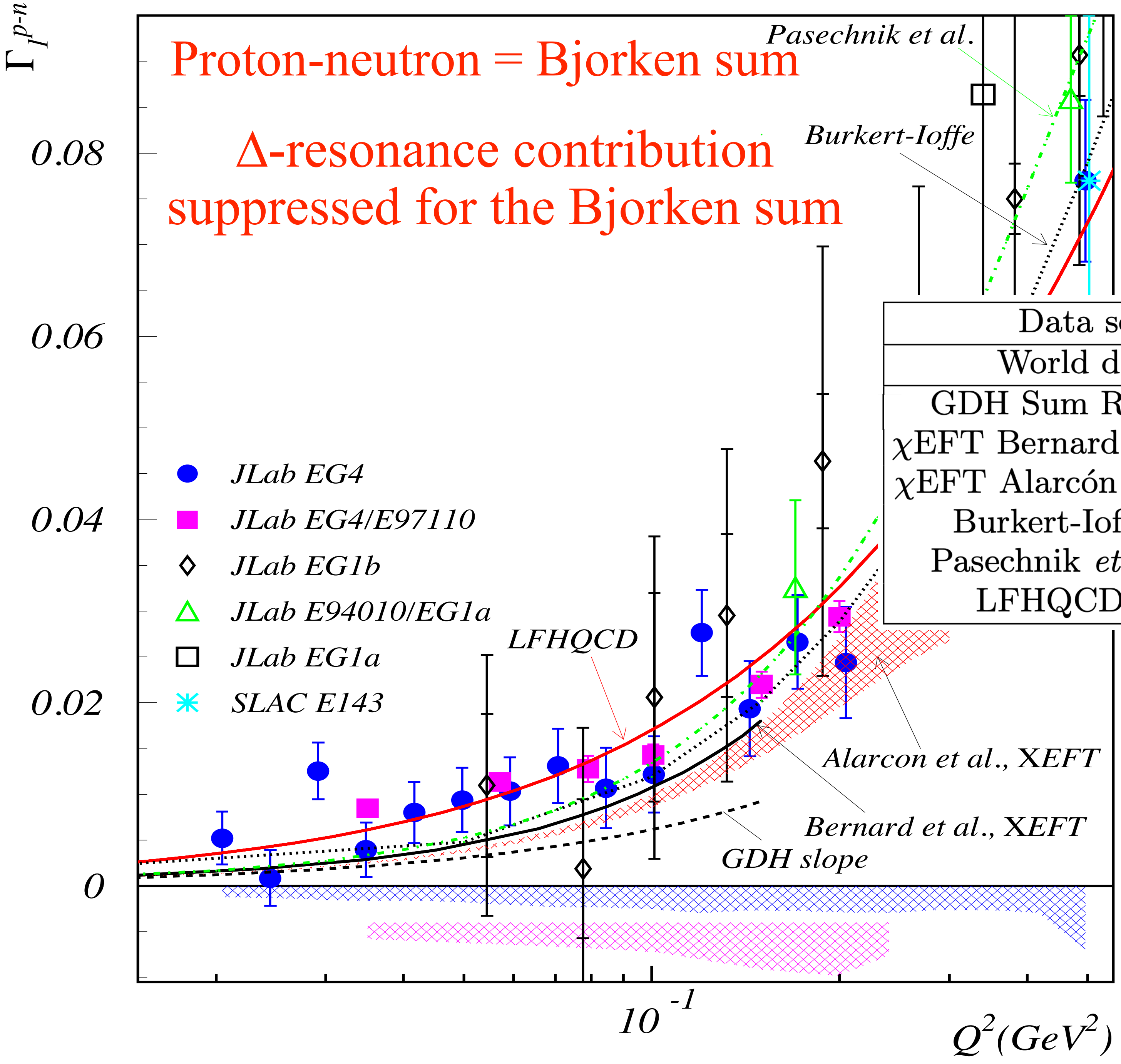
Neutron



Proton



Γ_1 measurements from E97-110 and EG4



Proton-neutron = Bjorken sum

Δ-resonance contribution suppressed for the Bjorken sum

χEFT prediction

Fit $\Gamma_1 = bQ^2+cQ^4$:

Data set	$(b \pm uncor \pm cor)$ [GeV^{-2}]	$c \pm uncor \pm cor$ [GeV^{-4}]
World data	$0.182 \pm 0.016 \pm 0.034$	$-0.117 \pm 0.091 \pm 0.095$
GDH Sum Rule	0.0618	-
χEFT Bernard *et al.*	0.07	0.3
χEFT Alarcón *et al.*	0.066(4)	0.25(12)
Burkert-Ioffe	0.09	0.3
Pasechnik *et al.*	0.09	0.4
LFHQCD	0.177	-0.067

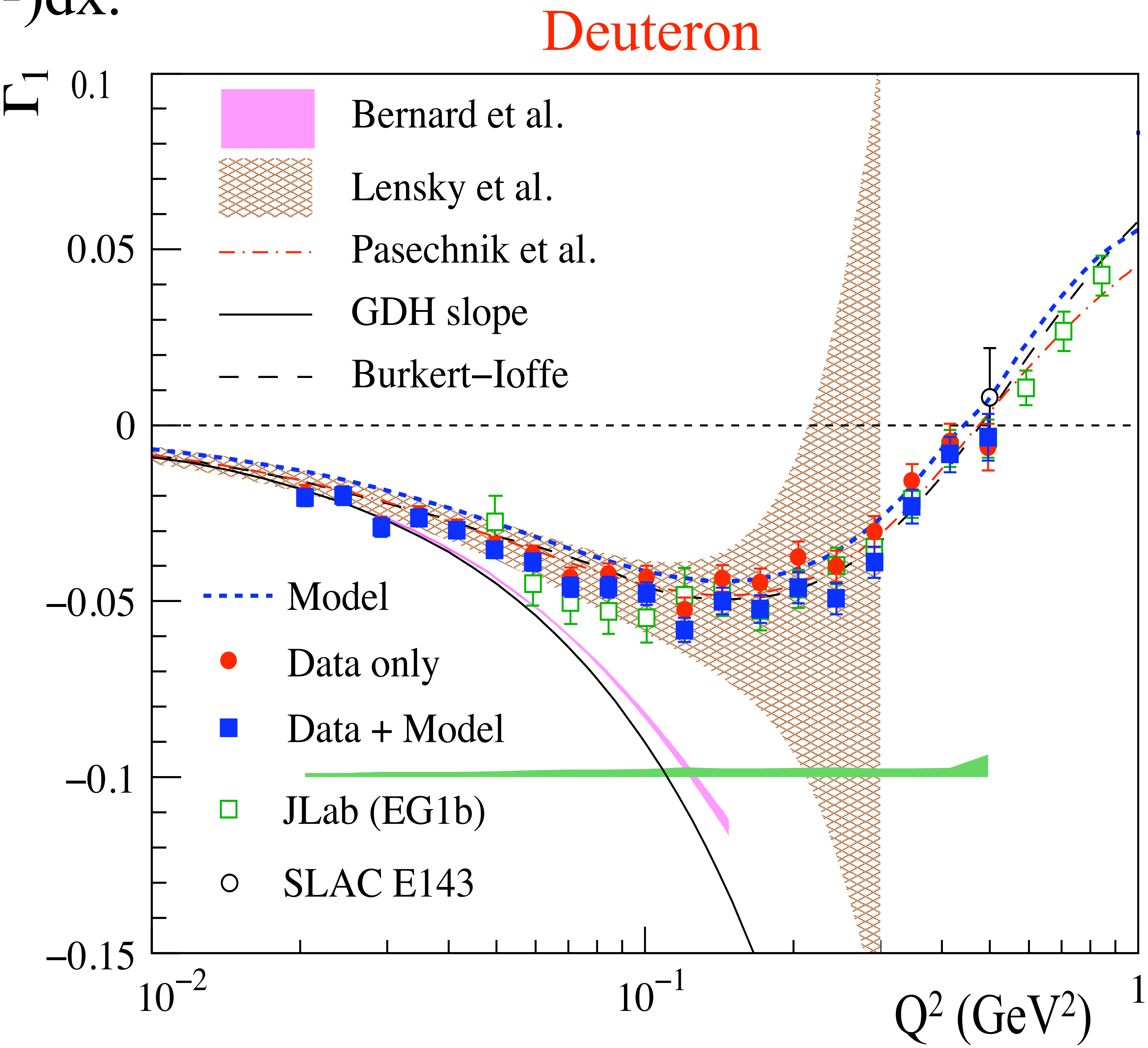
χEFT prediction

Fits $\Gamma_1 = a + bQ^2+cQ^4+dQ^6$:

Data set	$(a \pm uncor \pm cor)$	$(b \pm uncor \pm cor)$ [GeV^{-2}]	$c \pm uncor \pm cor$ [GeV^{-4}]	$d \pm uncor \pm cor$ [GeV^{-6}]	$\chi^2/n.d.f.$
EG4, no low-x	NA	$0.093 \pm 0.032 \pm 0.000$	$-0.137 \pm 0.191 \pm 0.000$	NA	1.24
EG4/E97110, no low-x	NA	$0.112 \pm 0.022 \pm 0.028$	$-0.123 \pm 0.118 \pm 0.078$	NA	1.00
EG4	NA	$0.170 \pm 0.032 \pm 0.000$	$-0.046 \pm 0.191 \pm 0.000$	NA	1.04
EG4/E97110	NA	$0.185 \pm 0.023 \pm 0.027$	$-0.144 \pm 0.123 \pm 0.075$	NA	1.00
World data	NA	$\mathbf{0.182 \pm 0.016 \pm 0.034}$	$\mathbf{-0.117 \pm 0.091 \pm 0.095}$	NA	**1.00**
World data	NA	$b^{GDH} \equiv 0.0618$	$1.41 \pm 0.17 \pm 0.39$	$-4.30 \pm 0.80 \pm 1.48$	1.97
World data	$(4.3 \pm 1.8 \pm 0.1) \times 10^{-3}$	$0.092 \pm 0.042 \pm 0.031$	$0.213 \pm 0.167 \pm 0.086$	NA	0.82

Γ_1 measurements from E97-110 and EG4

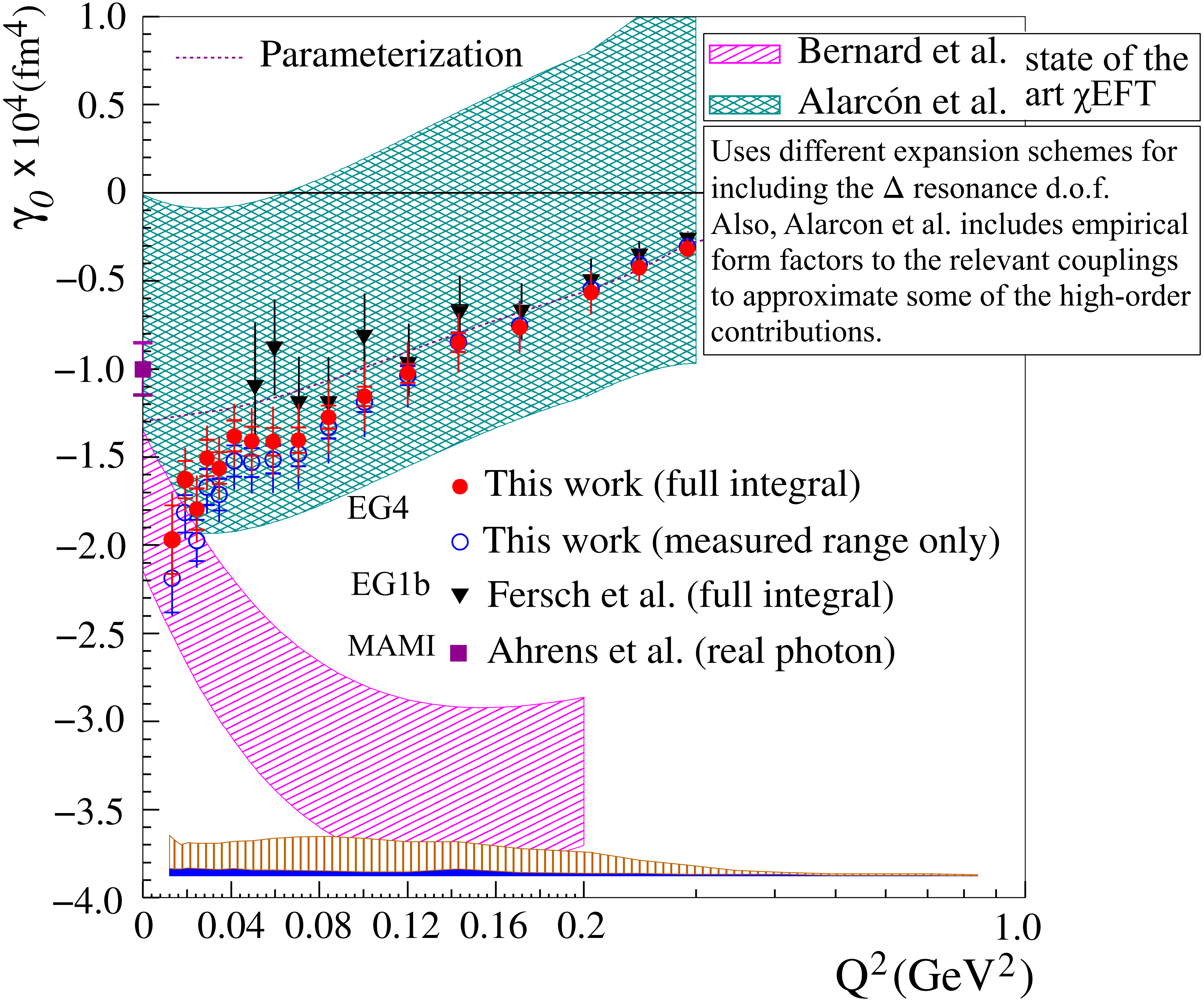
$\Gamma_1 \equiv \int g_1(x,Q^2)dx.$



JLab experimental results on γ_0

EG4 proton, γ_0^p:

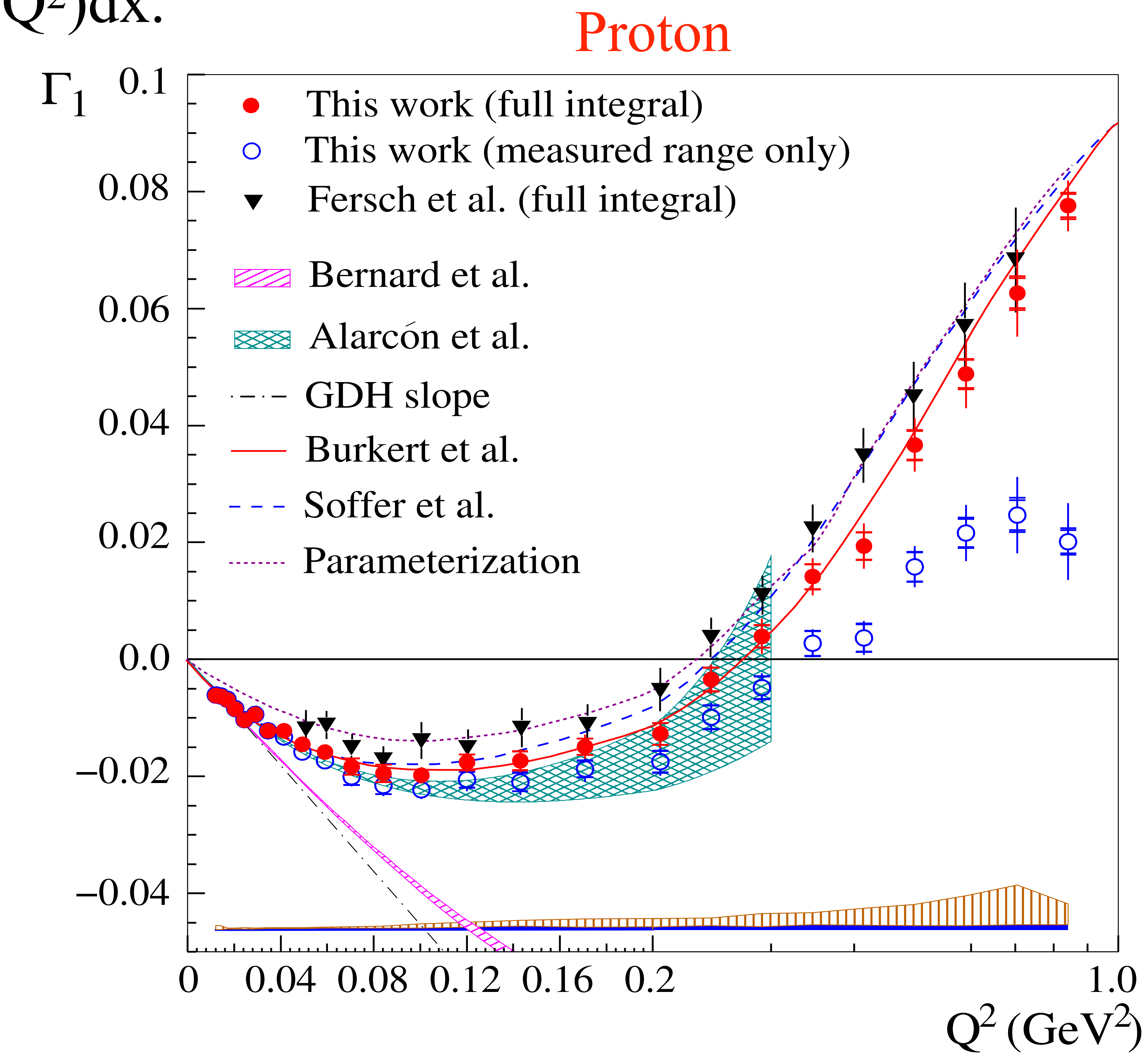
X. Zheng et al,
Nature Phys.**17** 736 (2021)



Uses different expansion schemes for including the Δ resonance d.o.f. Also, Alarcon et al. includes empirical form factors to the relevant couplings to approximate some of the high-order contributions.

Γ_1 measurements from E97-110 and EG4

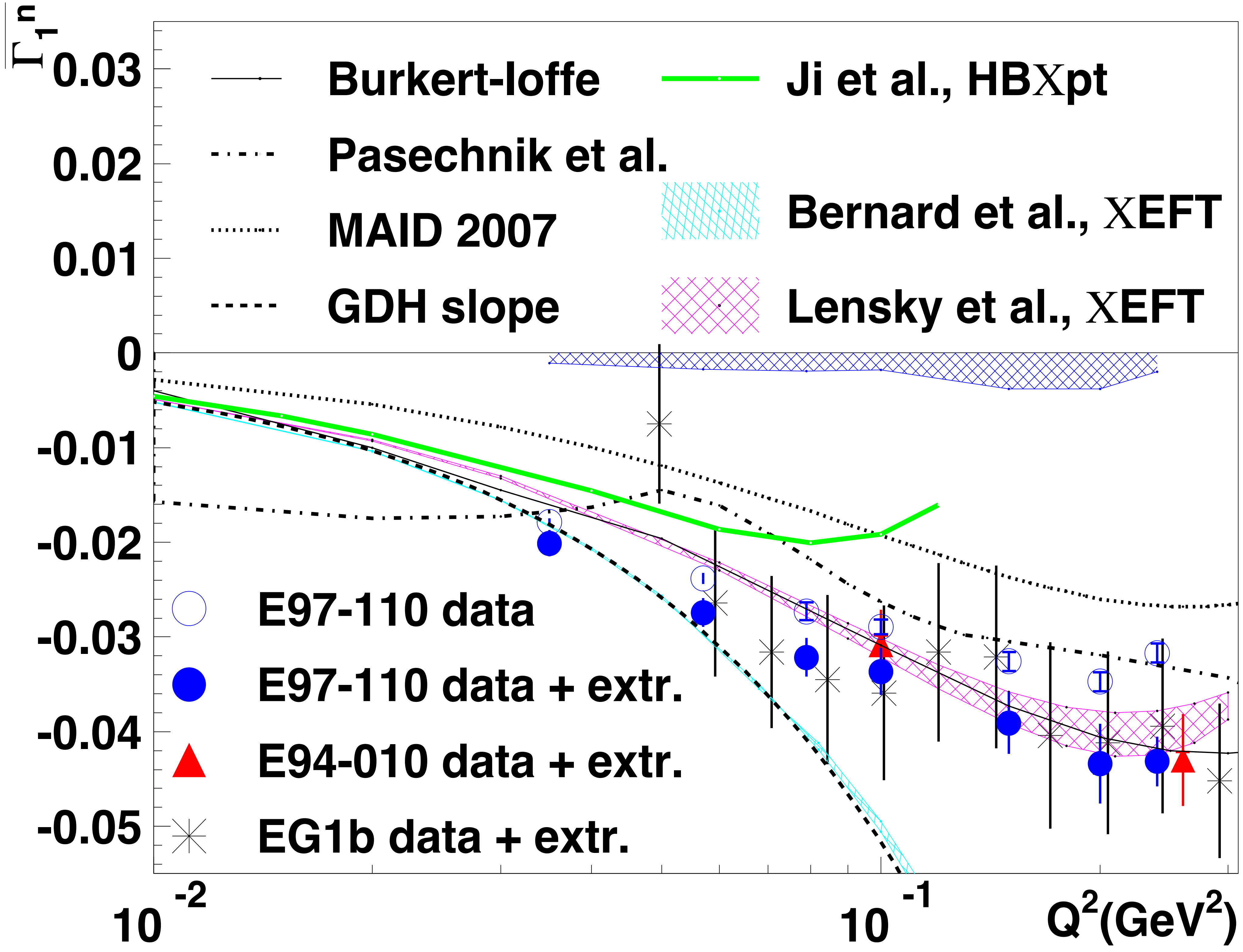
$\Gamma_1 \equiv \int g_1(x,Q^2)dx.$



Γ_1 measurements from E97-110 and EG4

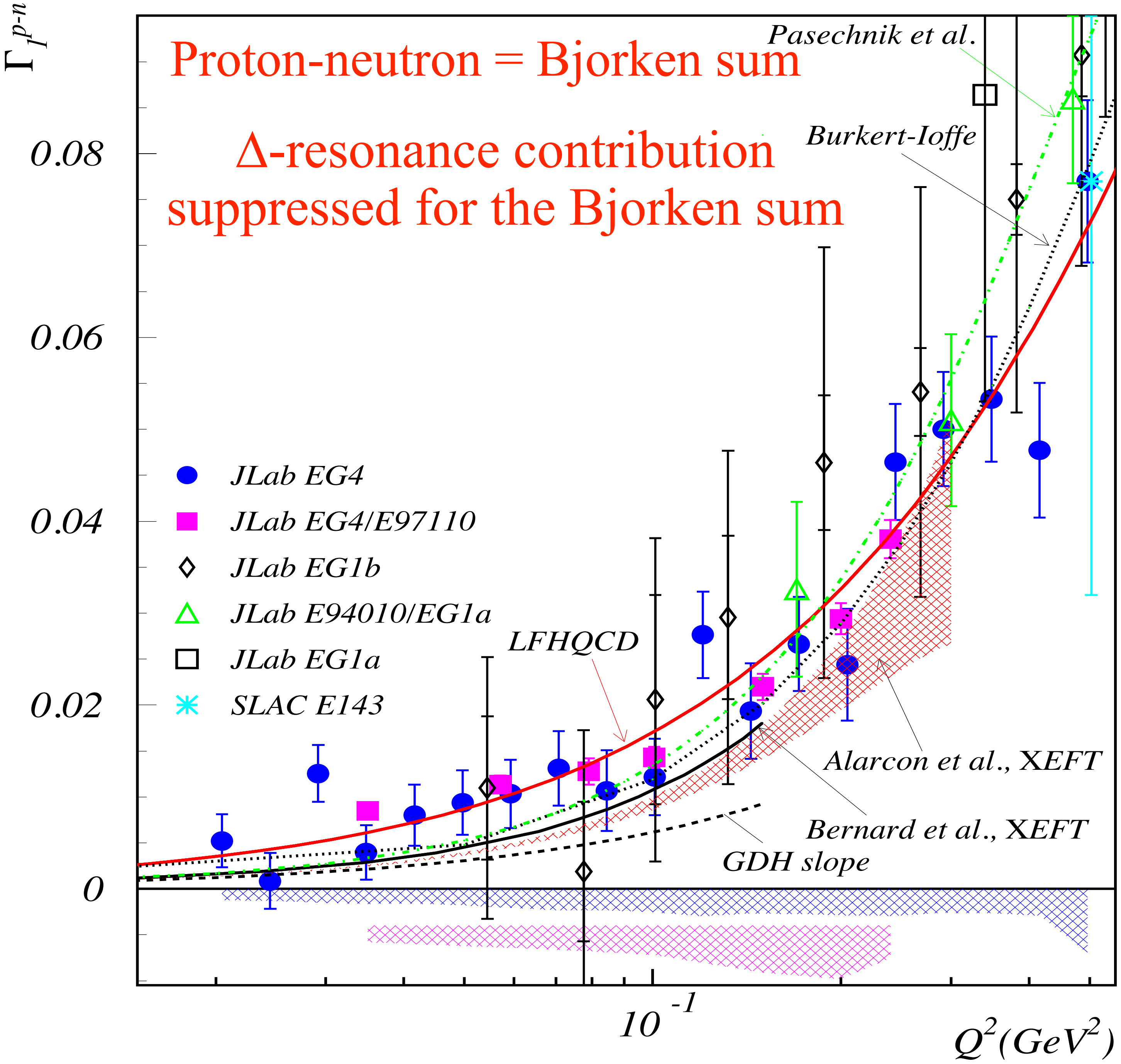
$\Gamma_1 \equiv \int g_1(x,Q^2)dx.$

Neutron



Γ_1 measurements from E97-110 and EG4

$\Gamma_1 \equiv \int g_1(x,Q^2)dx.$

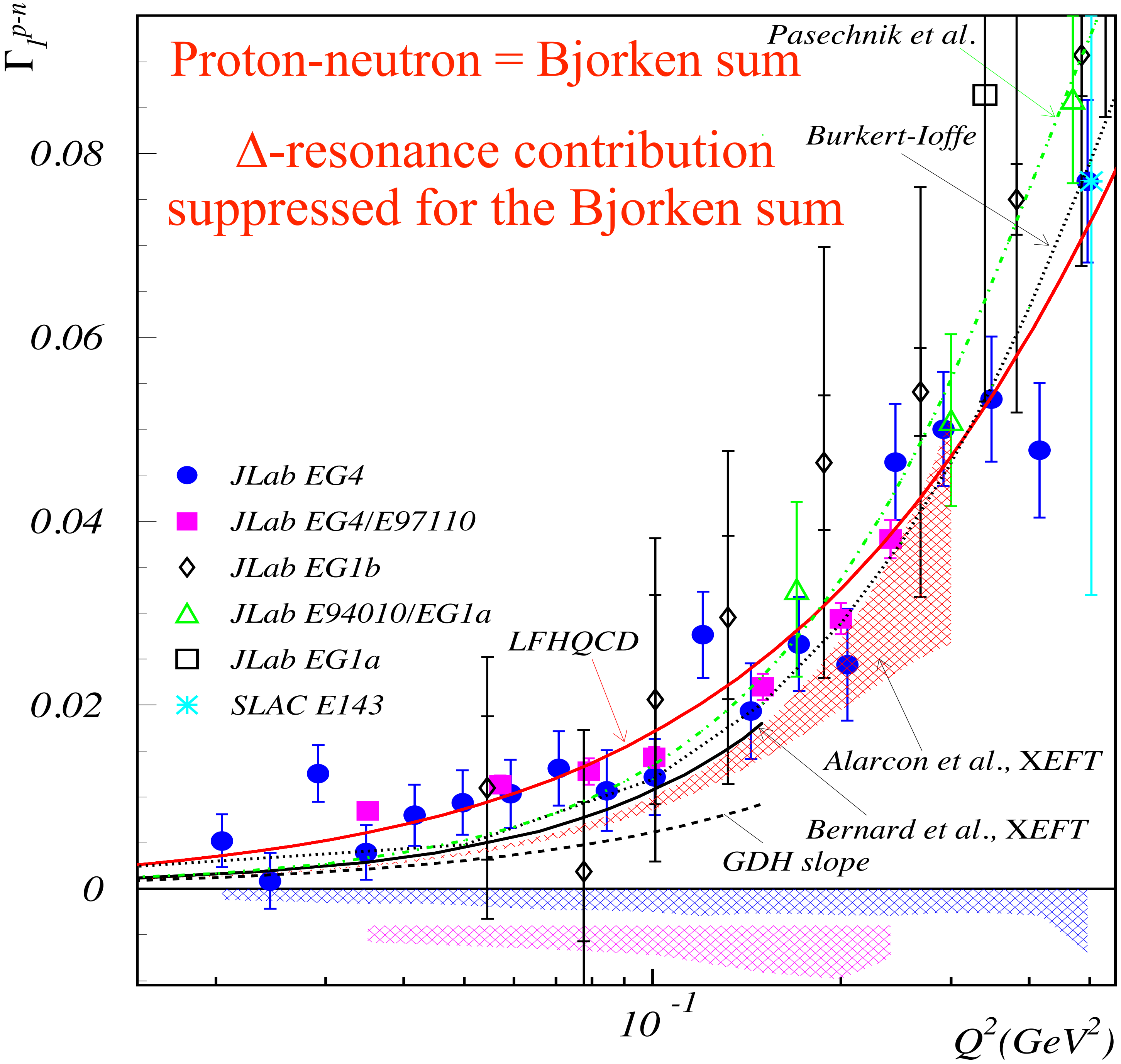


Proton-neutron = Bjorken sum

Δ-resonance contribution suppressed for the Bjorken sum

Γ_1 measurements from E97-110 and EG4

$\Gamma_1 \equiv \int g_1(x,Q^2)dx.$



Fit $\Gamma_1 = bQ^2+cQ^4$:

χEFT prediction

Data set	$(b \pm uncor \pm cor)$ [GeV^{-2}]	$c \pm uncor \pm cor$ [GeV^{-4}]
World data	$0.182 \pm 0.016 \pm 0.034$	$-0.117 \pm 0.091 \pm 0.095$
GDH Sum Rule	0.0618	-
χEFT Bernard *et al.*	0.07	0.3
χEFT Alarcón *et al.*	0.066(4)	0.25(12)
Burkert-Ioffe	0.09	0.3
Pasechnik *et al.*	0.09	0.4
LFHQCD	0.177	-0.067