Nucleon spin structure in the strong QCD regime

A. Deur

Thomas Jefferson National Accelerator Facility

Why is the spin of the nucleon interesting ?

Spin is responsible for shaping world:

- fundamental components of matter: spin ½
  ⇒ matter doesn't collapse.
- spin even bosons: attractive forces. e.g. nuclear force (pion), gravitation.
  ⇒stable nuclei, burning stars, structured universe...
- spin odd bosons: repulsive between like charges, attractive between opposite charges.
  ⇒ neutral atoms.

⇒Spin is key to the marvelous diversity of the universe

Why is the spin of the nucleon interesting ?

- Human curiosity: interesting to know how $S_N = \frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark spin contribution}} + \underbrace{\Delta G + L_G}_{\text{gluon contribution}} + \underbrace{L_q}_{\text{quark orbital angular mom.}}$.

- Nucleon: most of mass of known matter in the universe. Spin: Fundamental observable.

  Fundamental understanding of matter.

  ⇒ understand its elementary bricks

- Spin degrees of freedom: additional handles to test theories.
  - Constituent quark model, Parity symmetry of physical laws, Ellis-Jaffe sum rule, …
  - Spin permits more complete study of QCD;
    - mechanism of confinement;
    - how effective degrees of freedom (hadrons) emerge from fundamental ones (quark and gluons);
    - Test effectives theories and models for nucleon/nuclear structures.

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⇒Nucleon spin composition is not trivial. Thus it reveals interesting information on the nucleon structure and the mechanisms of the strong force

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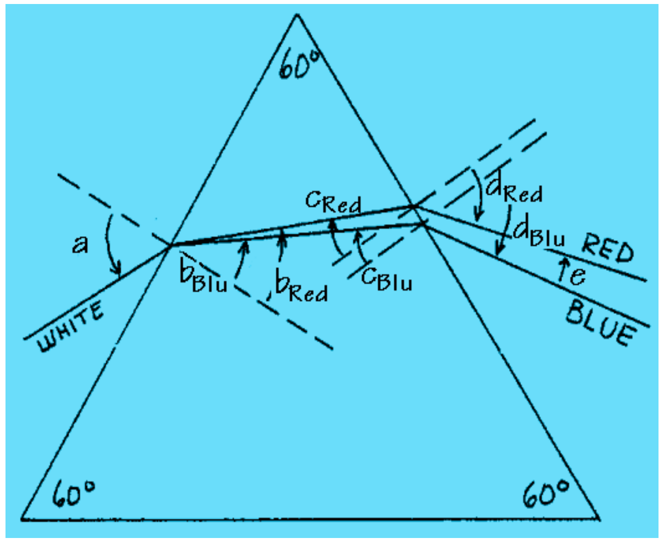
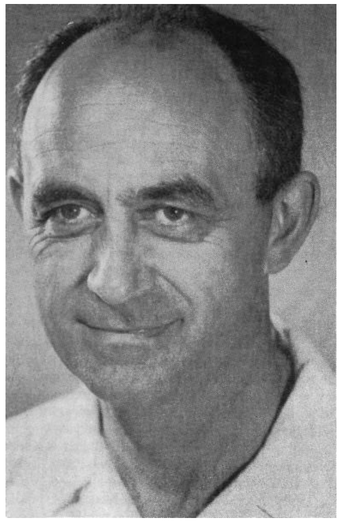
Effective descriptions of Nature

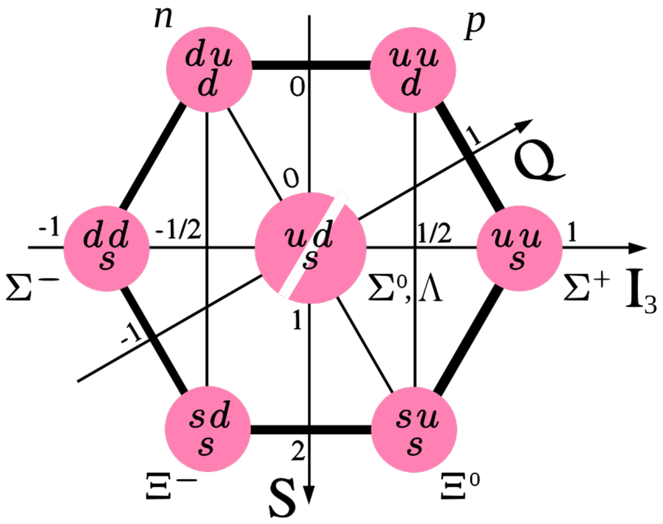
Fundamental forces: electromagnetic, weak, strong, gravitation
Fundamental particles: quarks, electrons, neutrinos…

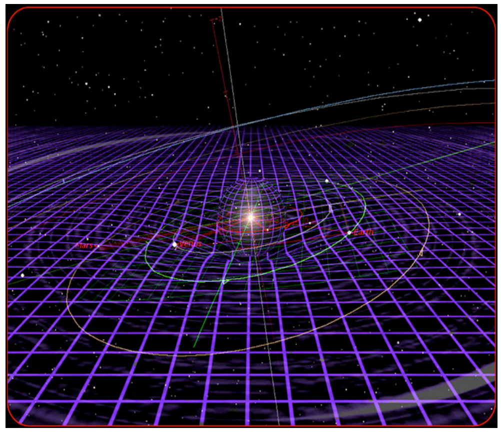
Effective descriptions of Nature

Complex systems (many interacting parts). Fundamental theories and d.o.f become too unwieldy.









Geometric optics
d.o.f: rays

Fermi theory
d.o.f: hadrons, leptons

hadronic physics
d.o.f: hadrons

General Relativity(?)

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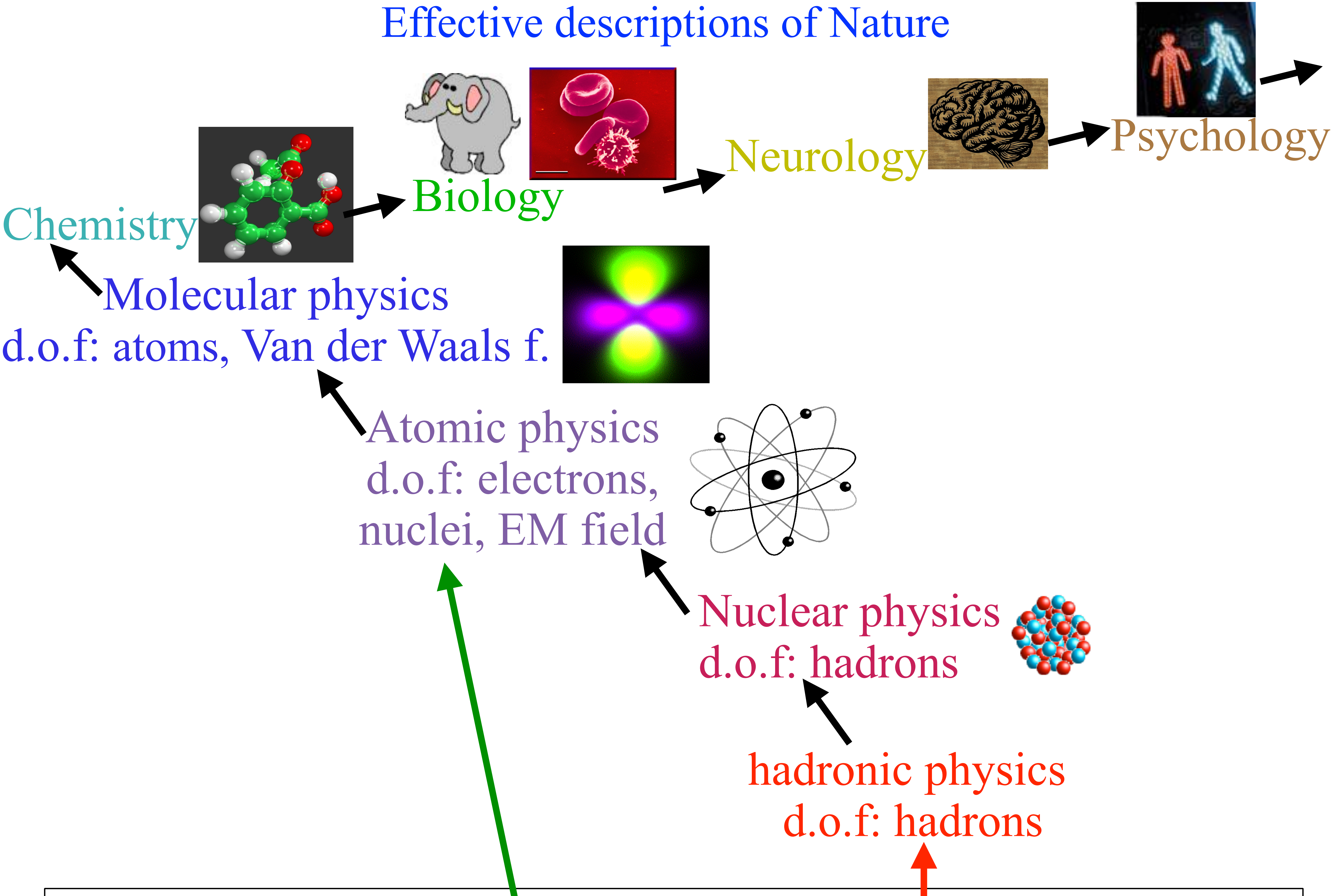
Effective descriptions of Nature



Psychology

Neurology

Biology

Chemistry

Molecular physics
d.o.f: atoms, Van der Waals f.

Atomic physics
d.o.f: electrons,
nuclei, EM field

Nuclear physics
d.o.f: hadrons

hadronic physics
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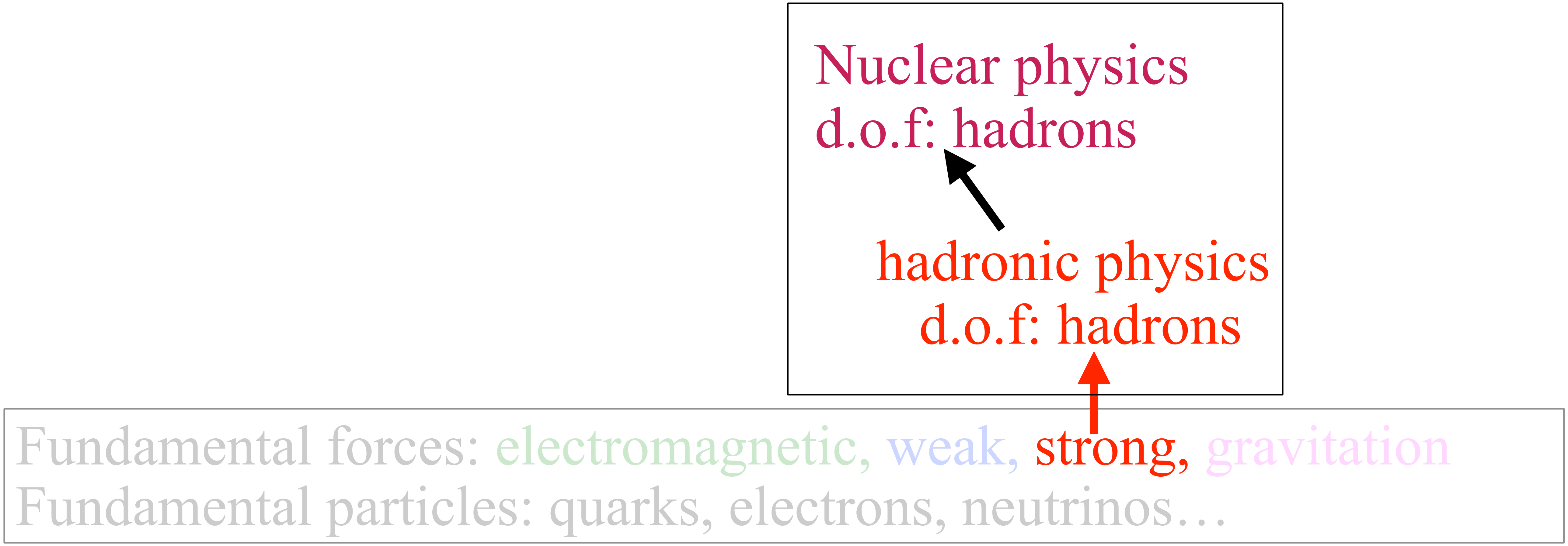

Nuclear physics
d.o.f: hadrons

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Effective descriptions of Nature

Leading effective theory: Chiral Effective Field Theory (**χEFT**). Obtained using a Lagrangian consistent with QCD's chiral symmetry (neglecting quark masses).

⇒ Crucial piece for a complete understanding of Nature.

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Emerging quantities that characterize the nucleon: charge, mass, anomalous magnetic moment, polarizabilities…

Nuclear physics
d.o.f: hadrons

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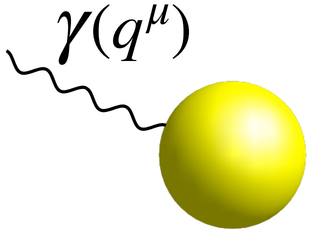
What are polarizabilities ?

Polarizabilities encode the 2nd order reaction of a body subjected to a (bona-fide, i.e. $Q^2 \equiv -q^\mu q_\mu = 0$) electromagnetic field.



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

At low photon energy ν, one can expand them in powers of ν:

QED coupling

Spin-independent ⟶ $f_1(\nu) = -\frac{\alpha}{M} + \cdots$

Nucleon anomalous magnetic moment

Spin-dependent ⟶ $f_2(\nu) = -\frac{\alpha\kappa^2}{2M^2}\nu + \cdots$

Purely elastic reaction (rigid object)

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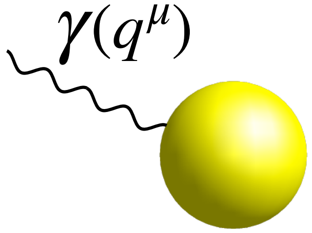

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Electric polarizability

Magnetic polarizability

Spin-independent →
$$f_1(\nu) = -\frac{\alpha}{M} + (\alpha_E + \beta_M)\nu^2 + \mathcal{O}(\nu^4)$$
← Polarizabilities

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

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Reaction with deformation (internal rearrangement)

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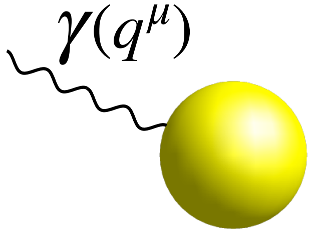

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Purely elastic reaction (rigid object)

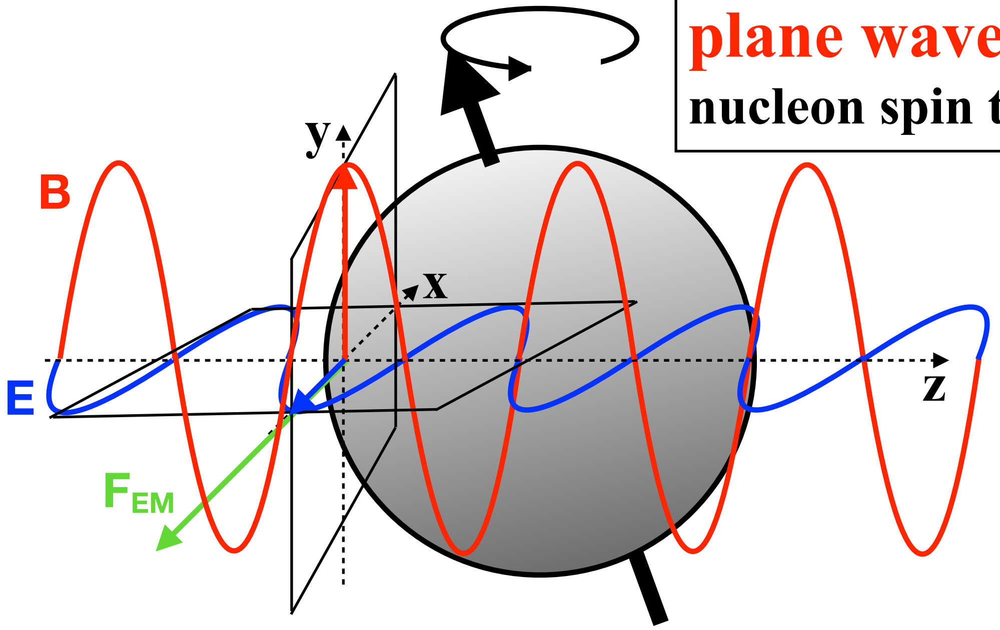
Reaction with deformation (internal rearrangement)

If $Q^2 \neq 0$, photons are virtual and have longitudinal spin components, and another spin polarizability, δ_{LT}, appears (LT stands for Longitudinal-Transverse interference term).

Spin polarizabilities: classical picture

Real photons (Q^2=0)
wavelength≳nucleon size.
Hadronic d.o.f.

Standard electromagnetic plane waves make the nucleon spin to precesses: γ_0



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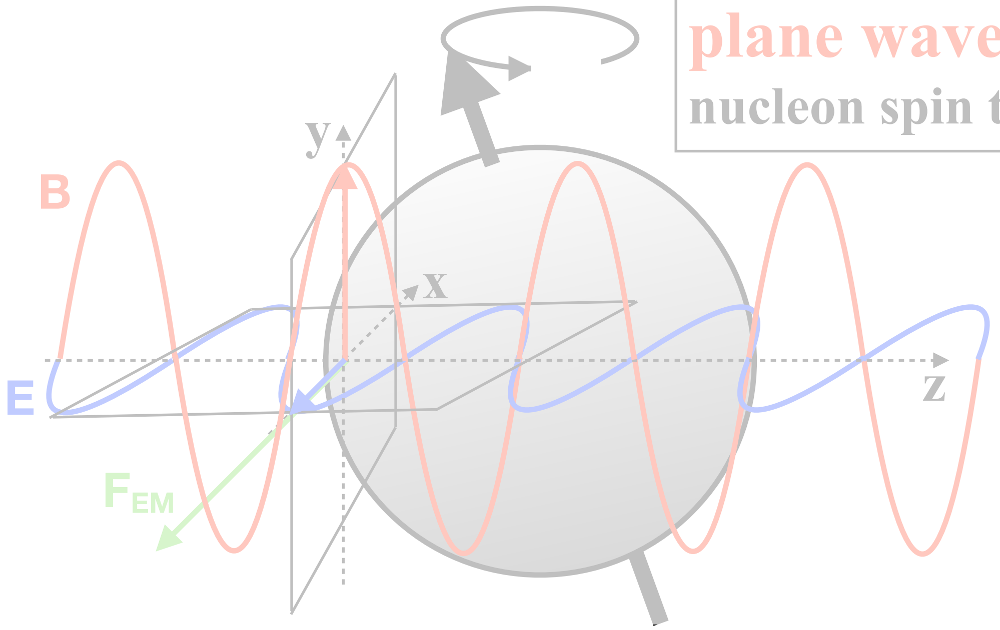
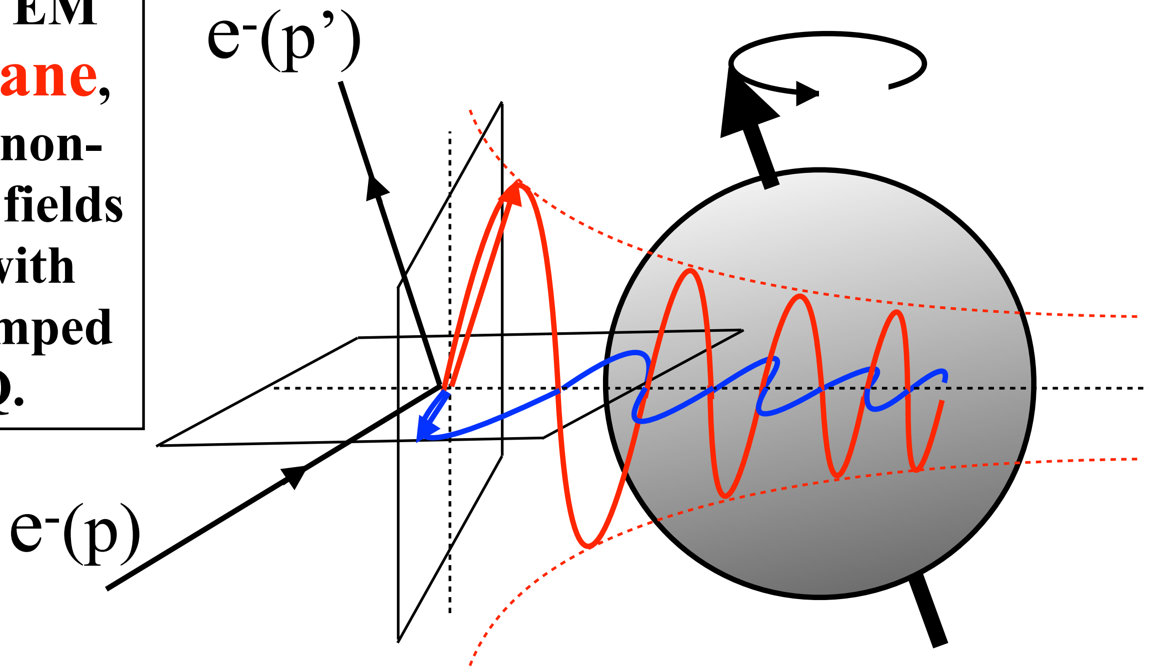


For $Q^2 \neq 0$, the EM wave is **not plane**, as pictured by non-planar **E** and **B** fields components with magnitudes damped as $1/m_\gamma \sim i/Q$.



Deformed electromagnetic waves select specific space-time windows for the measurement.
Additional **out-of-plane** degrees of freedom becomes available.

Spin polarizabilities: classical picture

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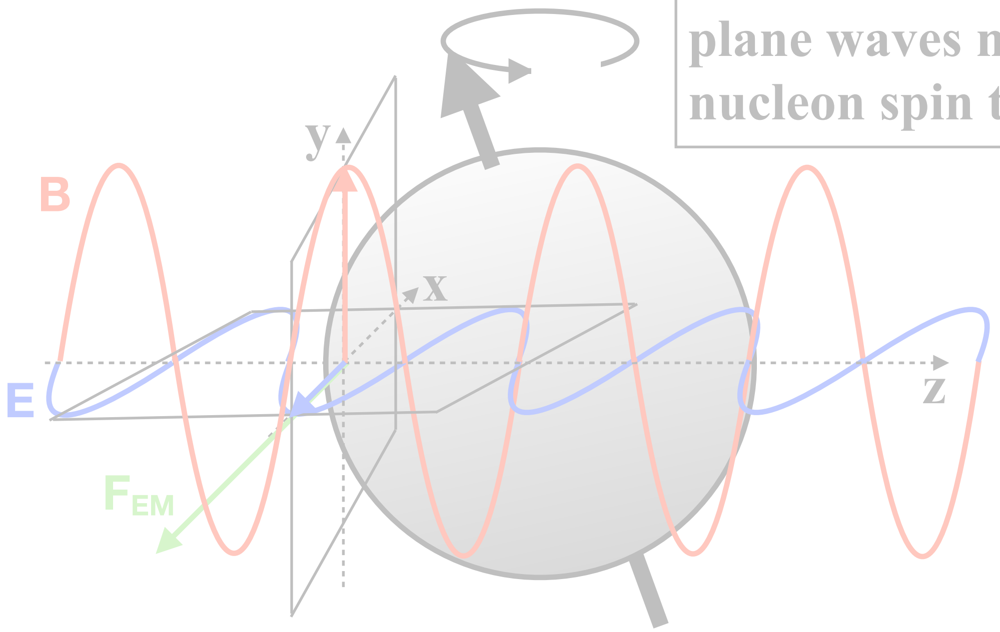

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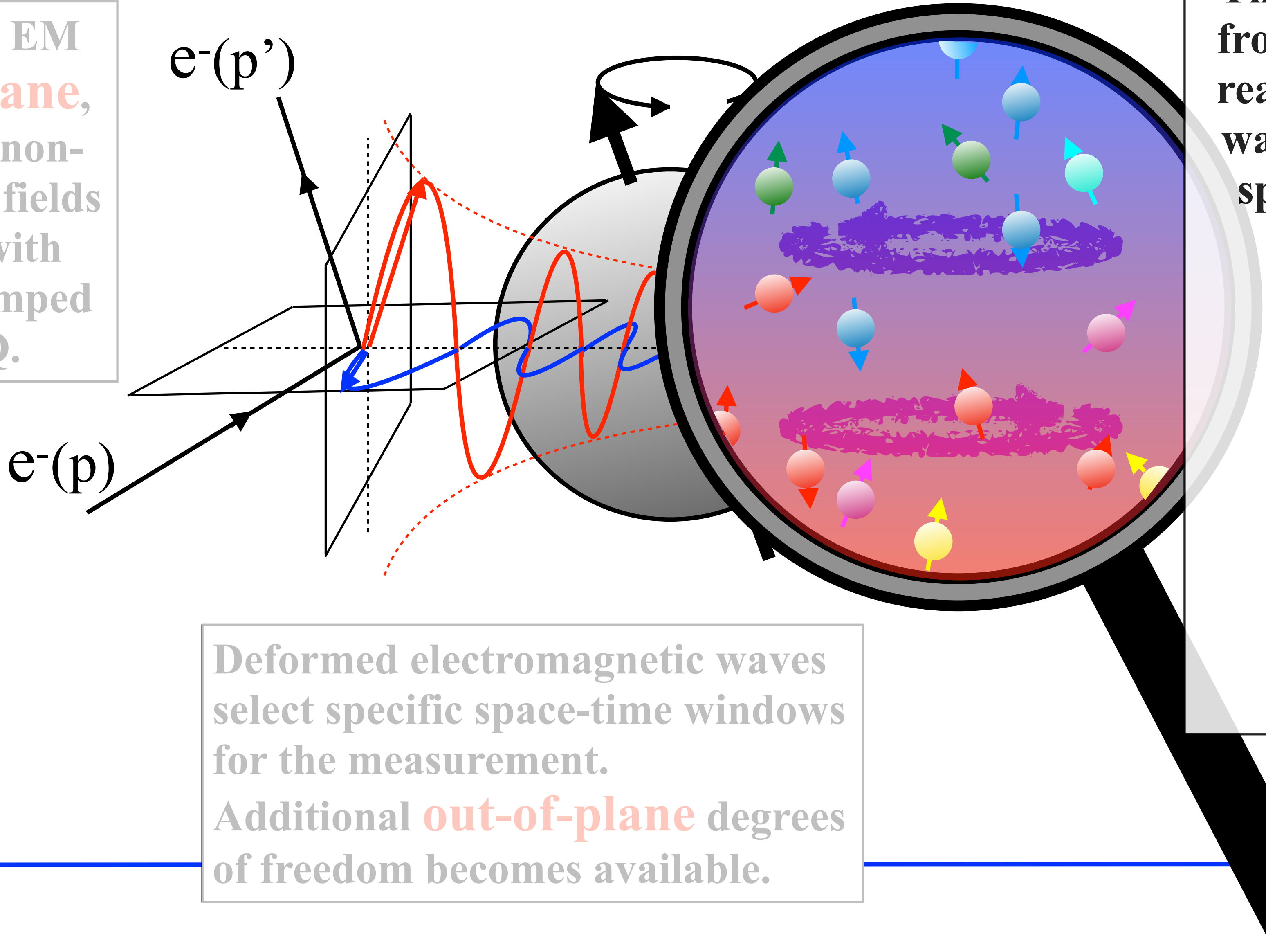

The nucleon spin ultimately arises from the quarks and gluons. Their rearrangements caused by the EM wave is manifested by the nucleon spin precession.

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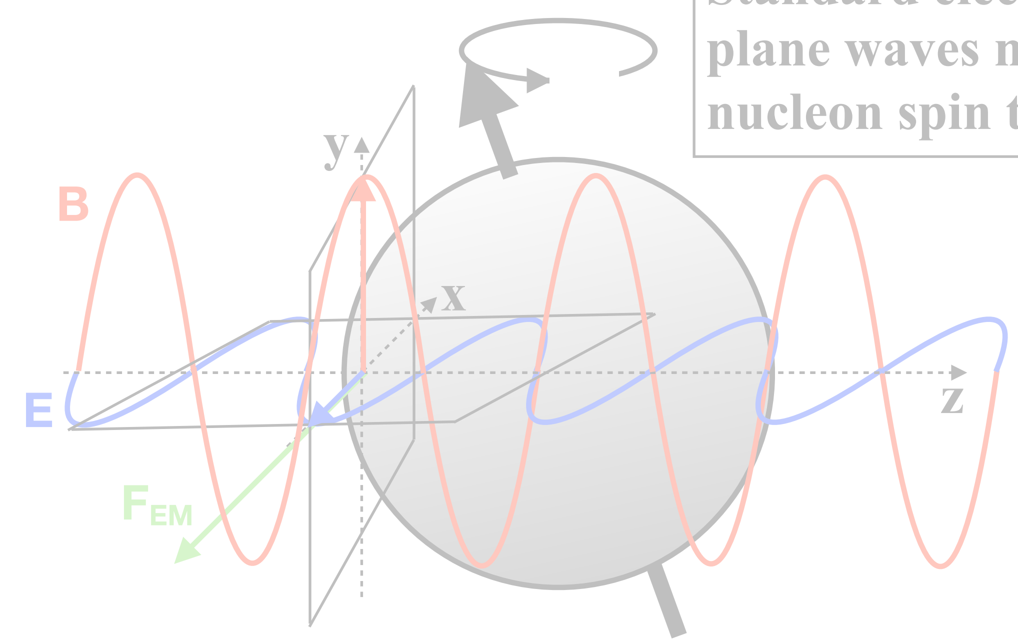

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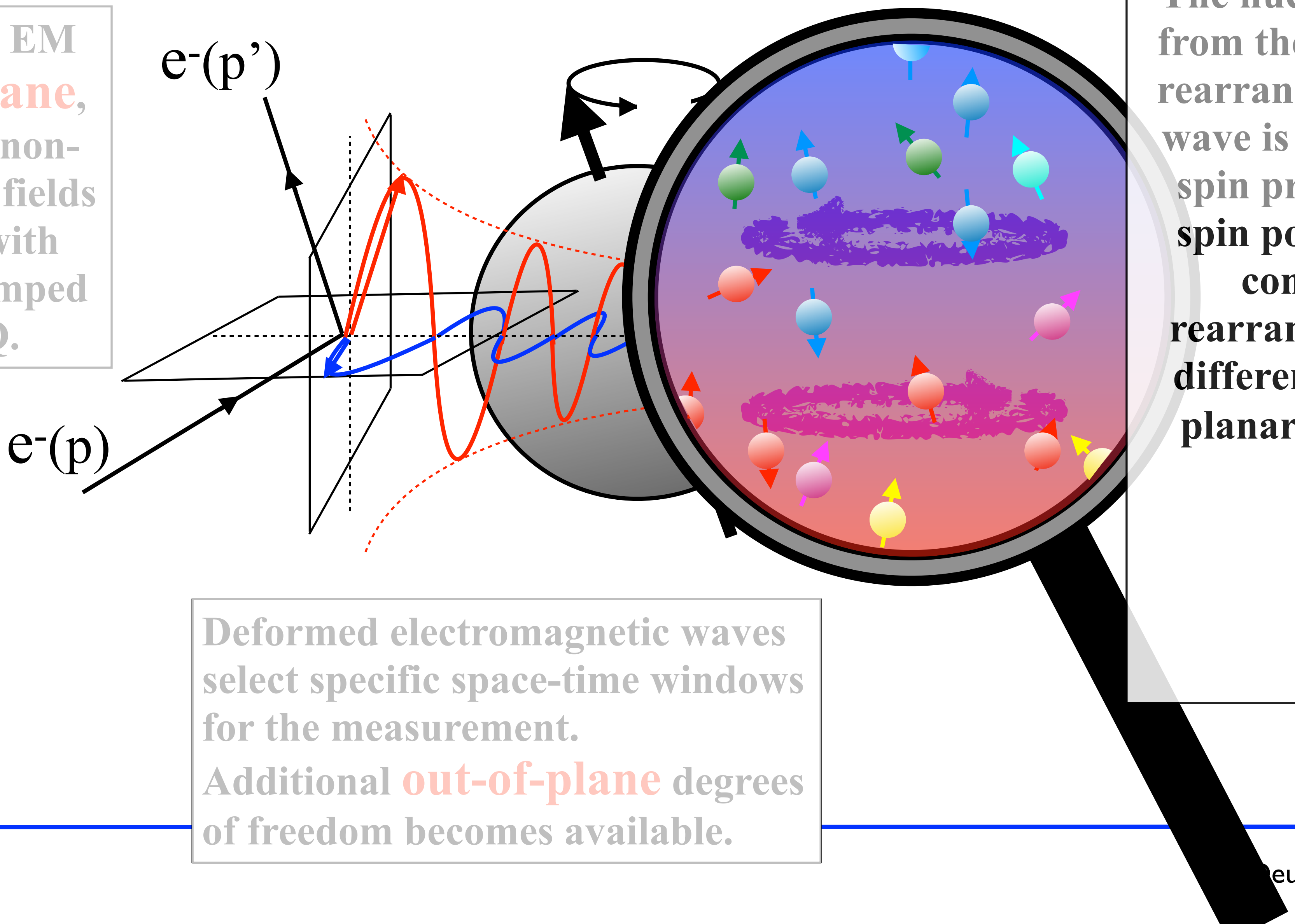

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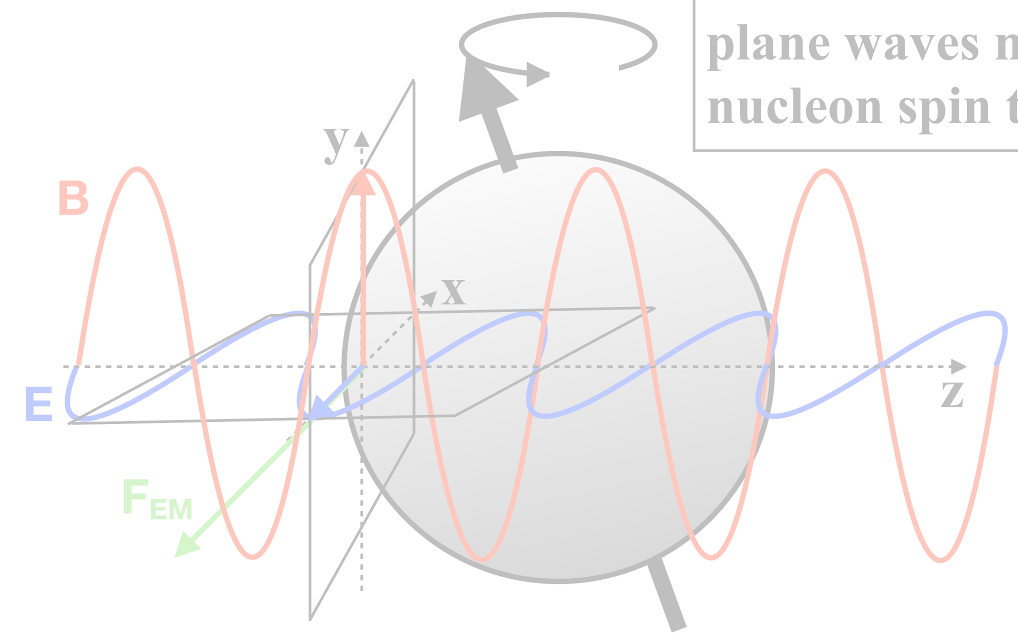

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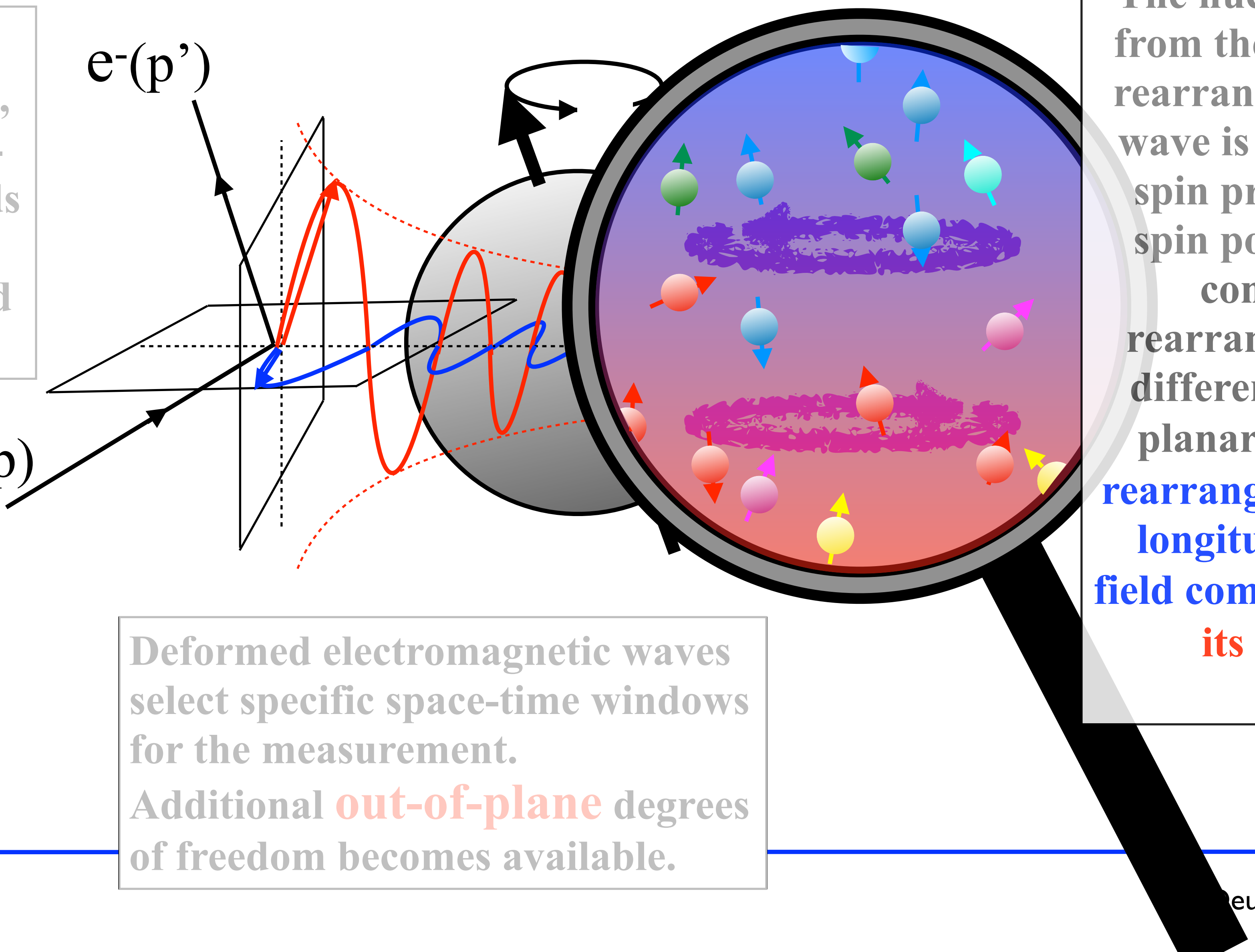


The nucleon spin ultimately arises from the quarks and gluons. Their rearrangements caused by the EM wave is manifested by the nucleon spin precession. The generalized spin polarizabilities describe the consequences of the local rearrangements coming from the different components of the non-planar EM field: δ_{LT} reveals the rearranging effect of the interfering longitudinal and transverse EM field components, and γ_0 the effect of its interfering transverse components.

Deformed electromagnetic waves select specific space-time windows for the measurement.
Additional out-of-plane degrees of freedom becomes available.

We do not know how to experimentally measure γ_0 and δ_{LT} directly, so *sum rules* are used to measure them.

Sum rule: relation (rule) between a static property of the target and an integral (sum) over a dynamical quantity

Spin polarizabilities sum rules:

Generalized forward spin polarizability:

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

Longitudinal-Transverse polarizability:

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

1st spin structure function

Bjorken-x

2nd spin structure function

JLab studies of the spin structure of the neutron and proton at low Q^2

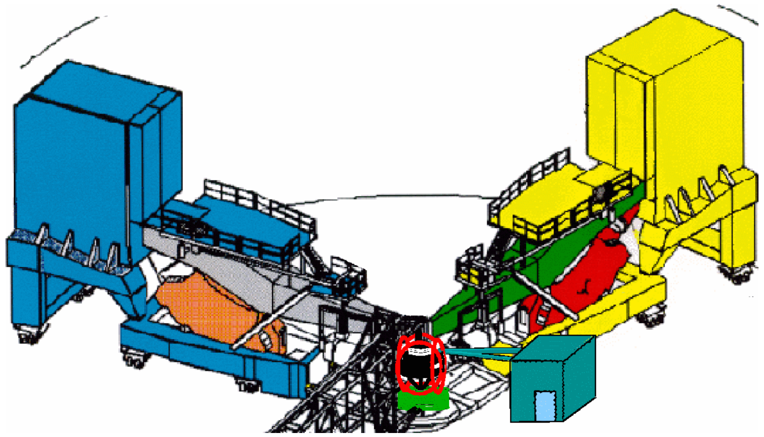
E97-110 (neutron, using longitudinally and transversally polarized ^{3}He):

Spokespeople: **J.P. Chen,** A.D., F. Garibaldi

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

Spokespeople: A. Camsonne, J.P. Chen, D. Crabb, **K. Slifer**

JLab Hall A:



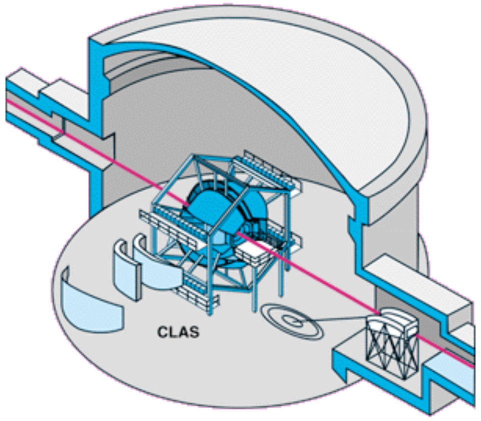
E03-006 (NH_3, longitudinally polarized):

Spokespeople: **M. Ripani**, M. Battaglieri, A.D., R. de Vita

E06-017 (ND_3, longitudinally polarized):

Spokespeople: **A.D.**, G. Dodge, M. Ripani, K. Slifer

EG4 run group
JLab Hall B:



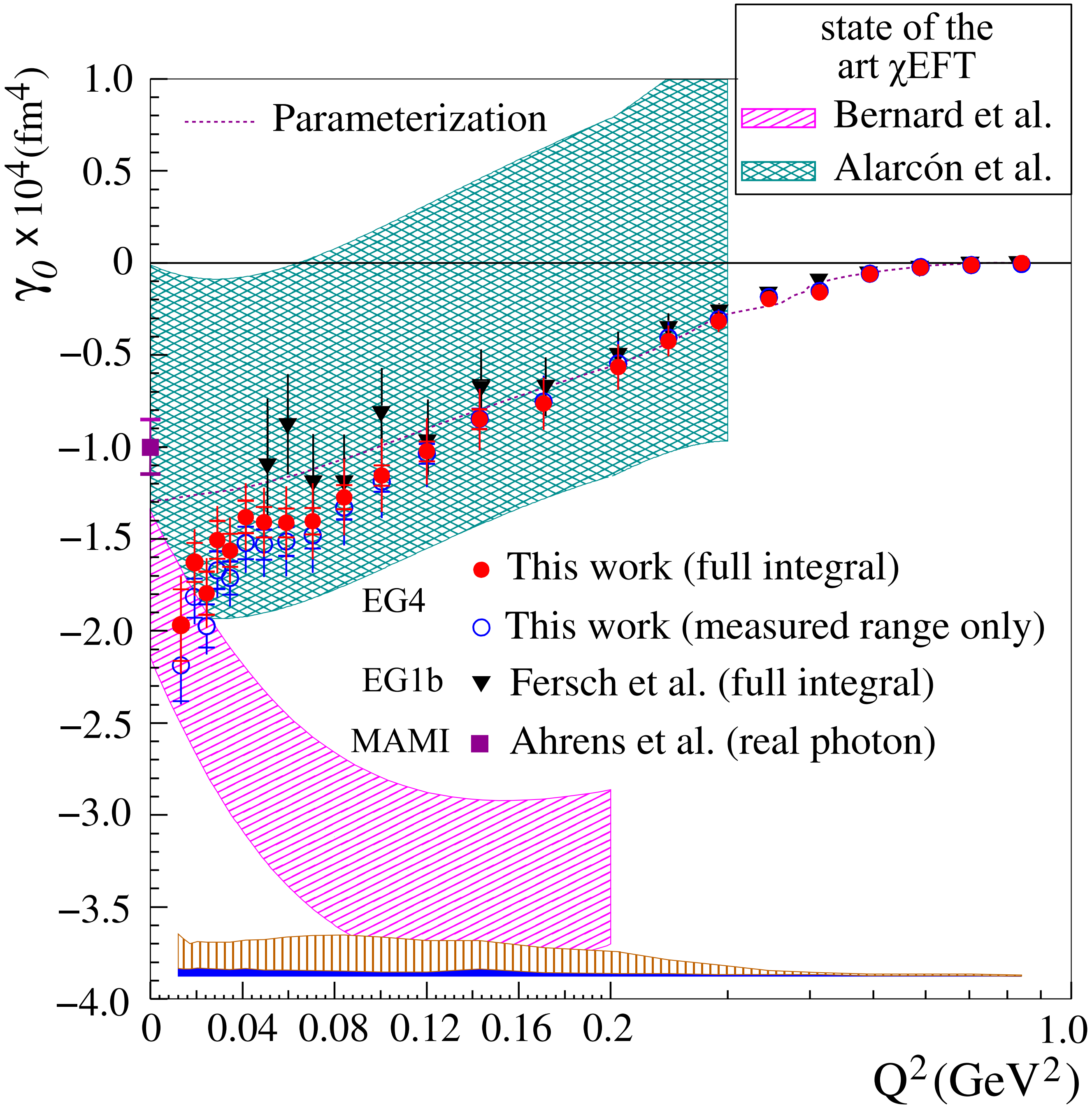
First nucleon spin structure JLab data reaching well into the χEFT applicability domain.

JLab low Q^2 experimental results $\gamma_0(Q^2)$ and $\delta_{LT}(Q^2)$

EG4 proton,

$\gamma_0^p(Q^2)$: X. Zheng et al,
Nature Phys.**17** 736 (2021)

Archival: AD *et al.* PRC (2025)



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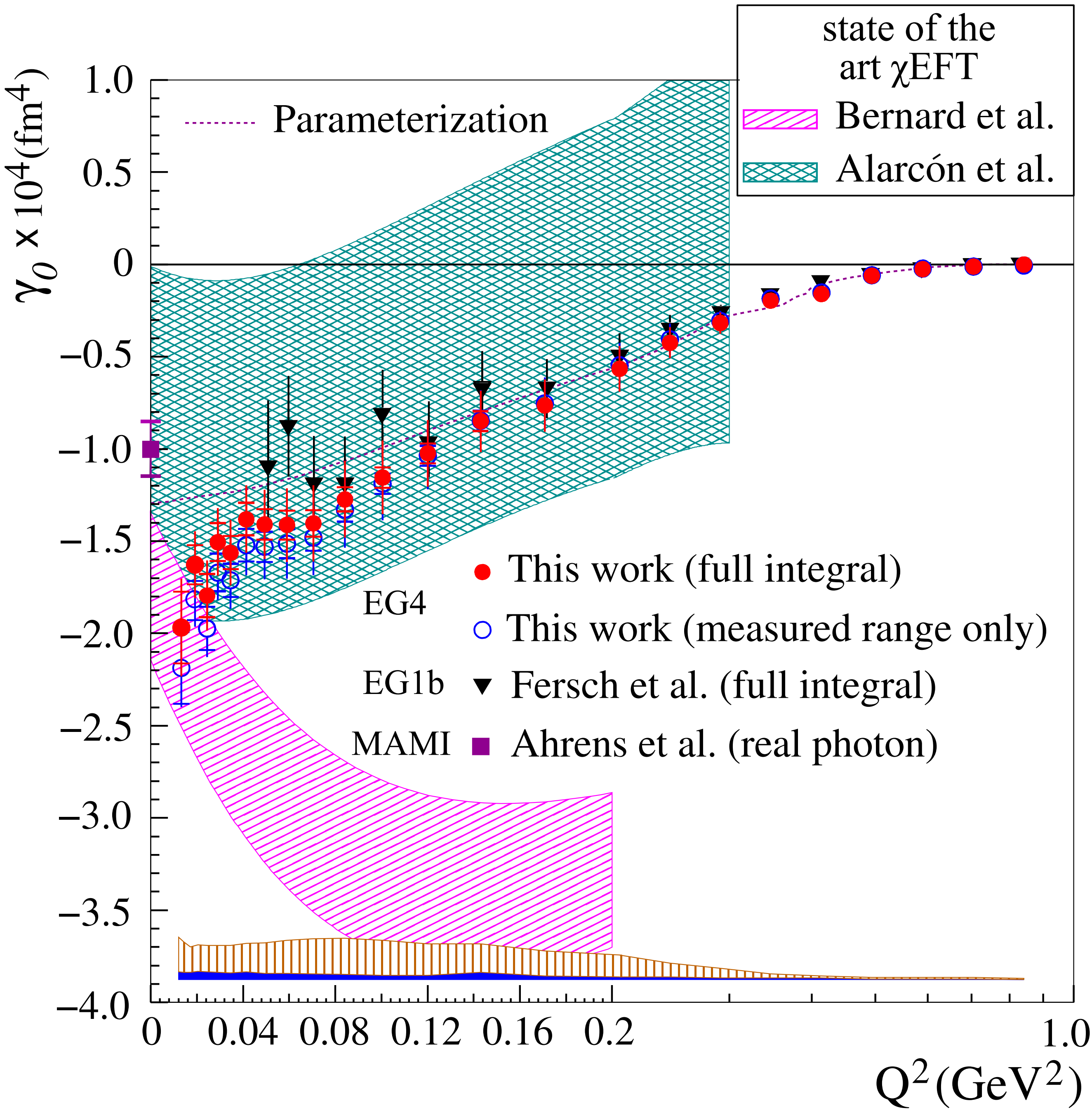
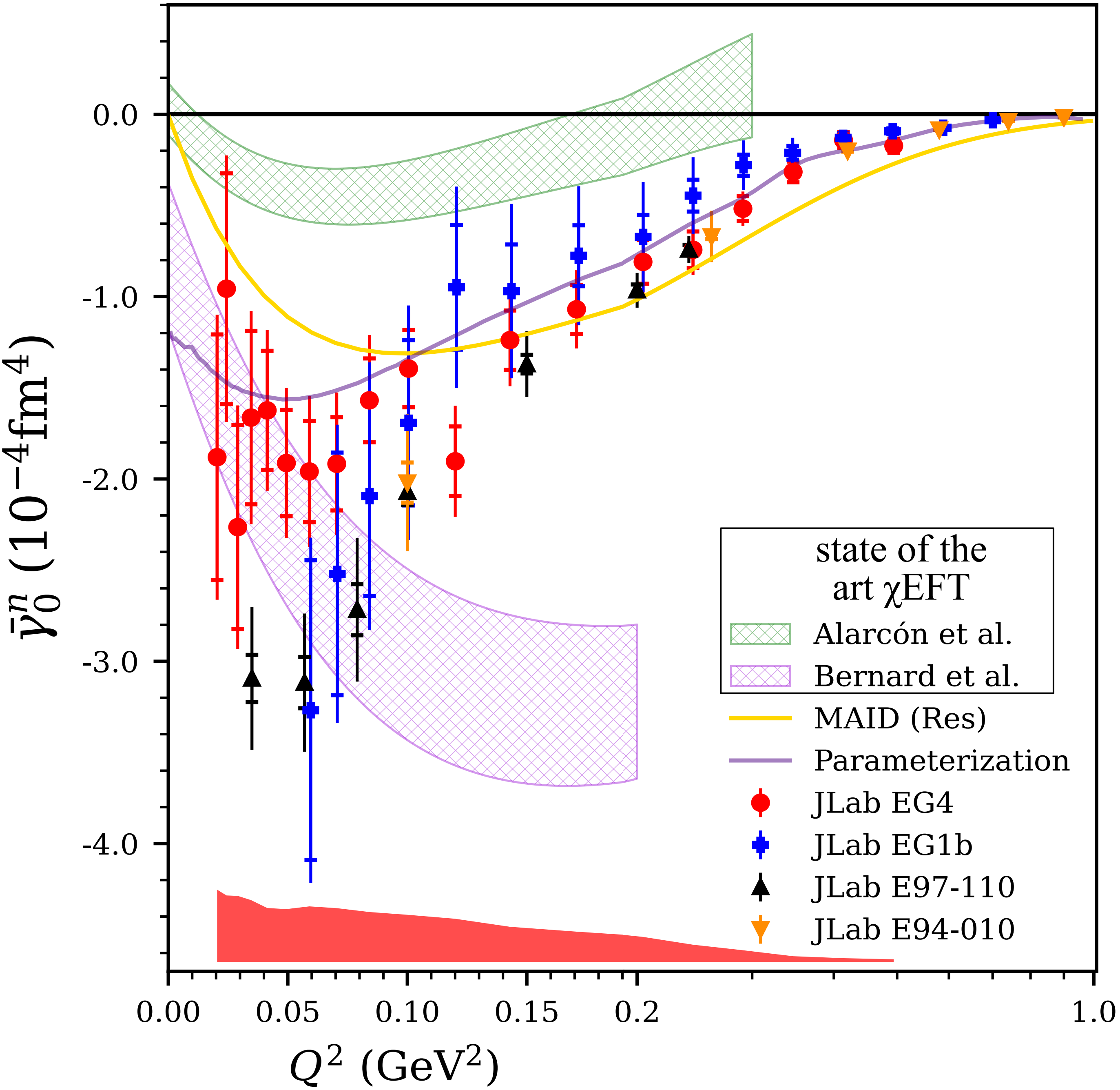


E97-110 neutron,

$\gamma_0^n(Q^2)$: V. Sulkosky et al.
Nature Physics, **17** 687 (2021)

EG4 deuteron and proton,

AD *et al.* PRC (2025)



JLab low Q^2 experimental results $\gamma_0(Q^2)$ and $\delta_{LT}(Q^2)$

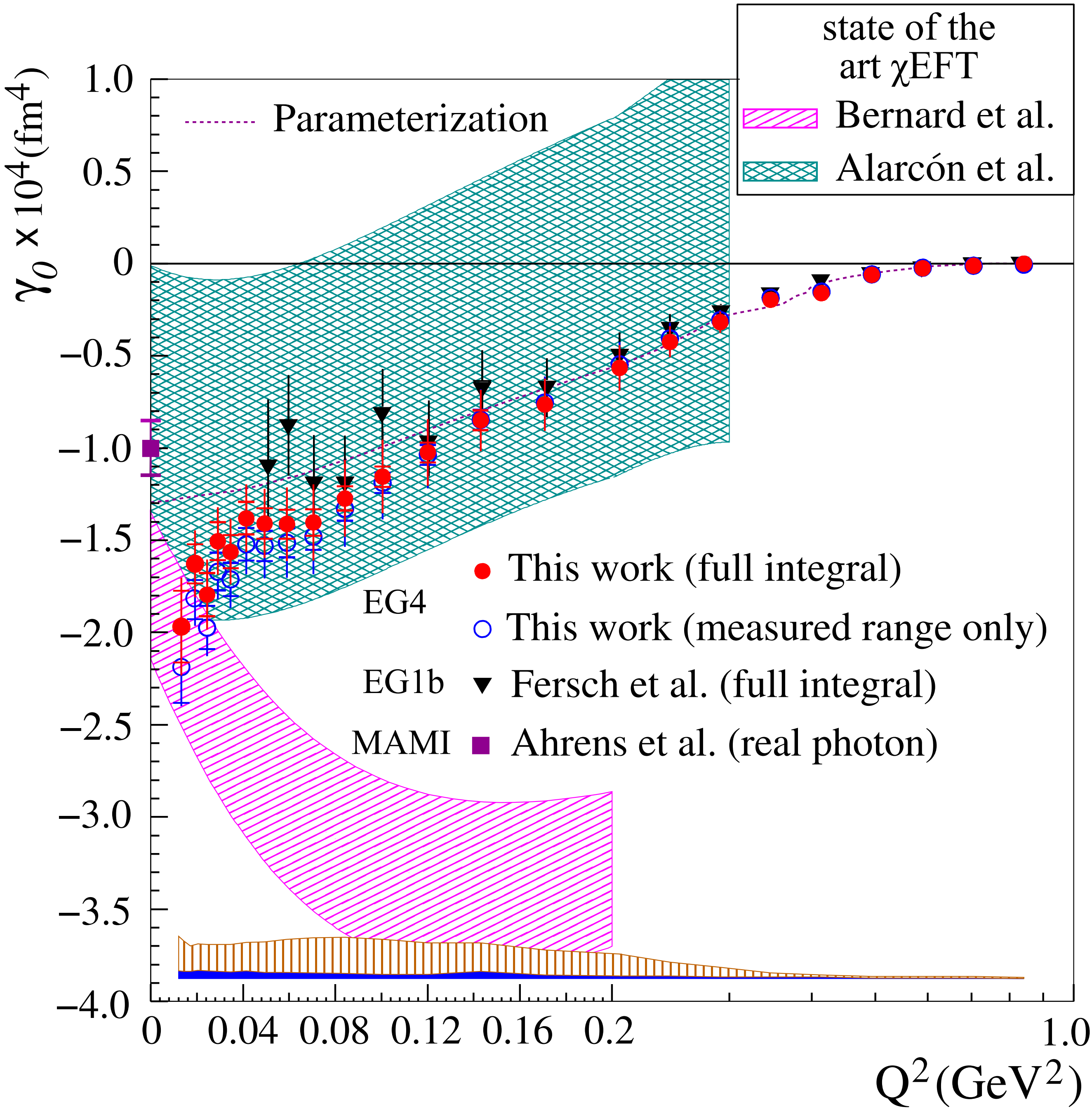
Interpretation from effective theory (hadronic d.o.f)

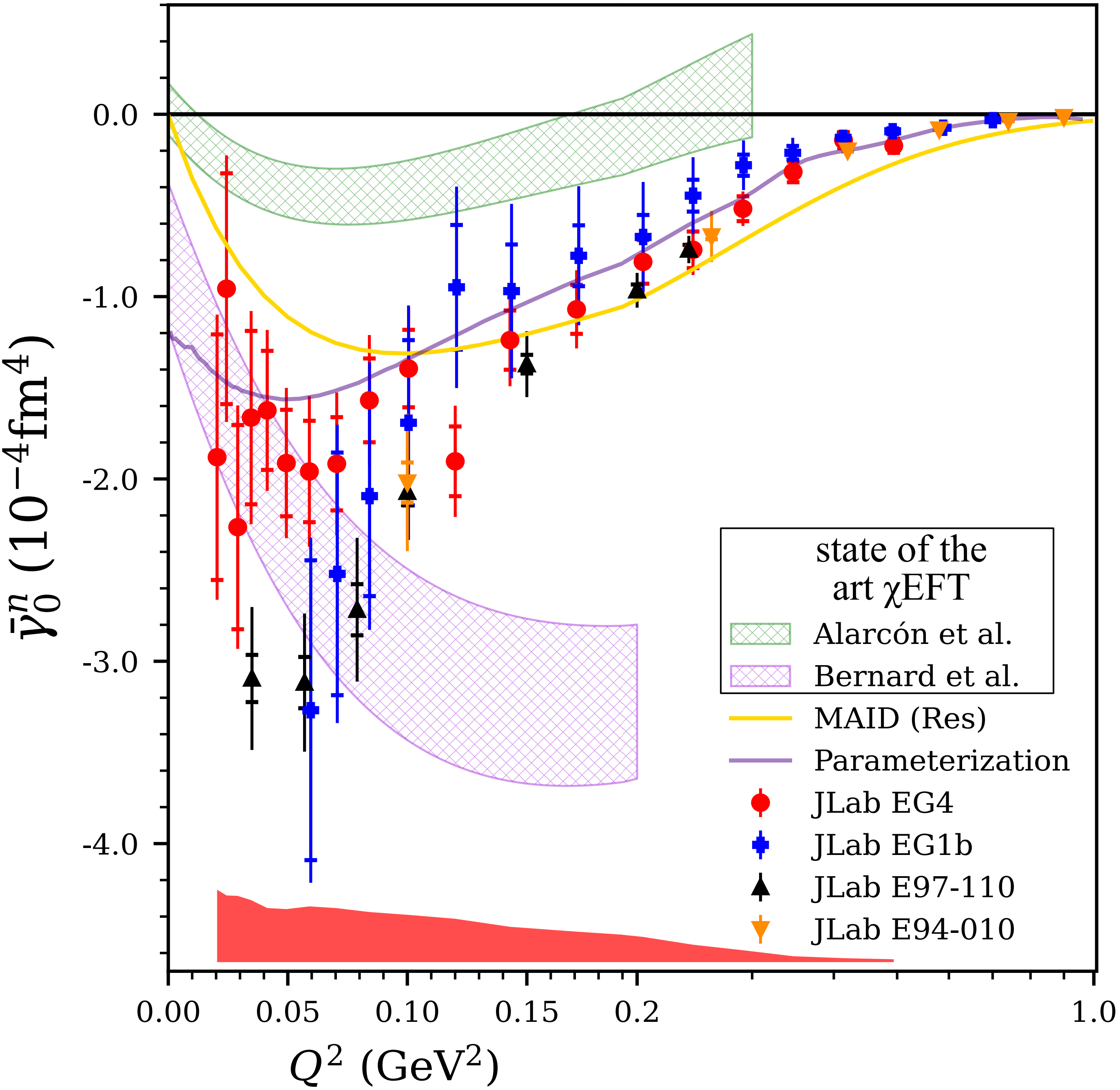
γ_0: ~ difference between contributions from *Δ* resonance (negative) and the nucleon's pion cloud (positive).

$Q^2 = 0$: *Δ* dominates.

Growing Q^2: spacetime resolution becomes finer ⇒ (extended) pion cloud contributes even less.

Larger Q^2, γ_0 vanishes since it is a global property of the nucleon.





JLab low Q^2 experimental results $\gamma_0(Q^2)$ and $\delta_{LT}(Q^2)$

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

- *Δ* resonance (negative) contribution suppressed: Expect to be a robust χEFT prediction (*Δ* d.o.f difficult to include in χEFT calculations);
- Higher moment: Expect to be a robust moment measurement (essentially no unmeasured low-x issue).

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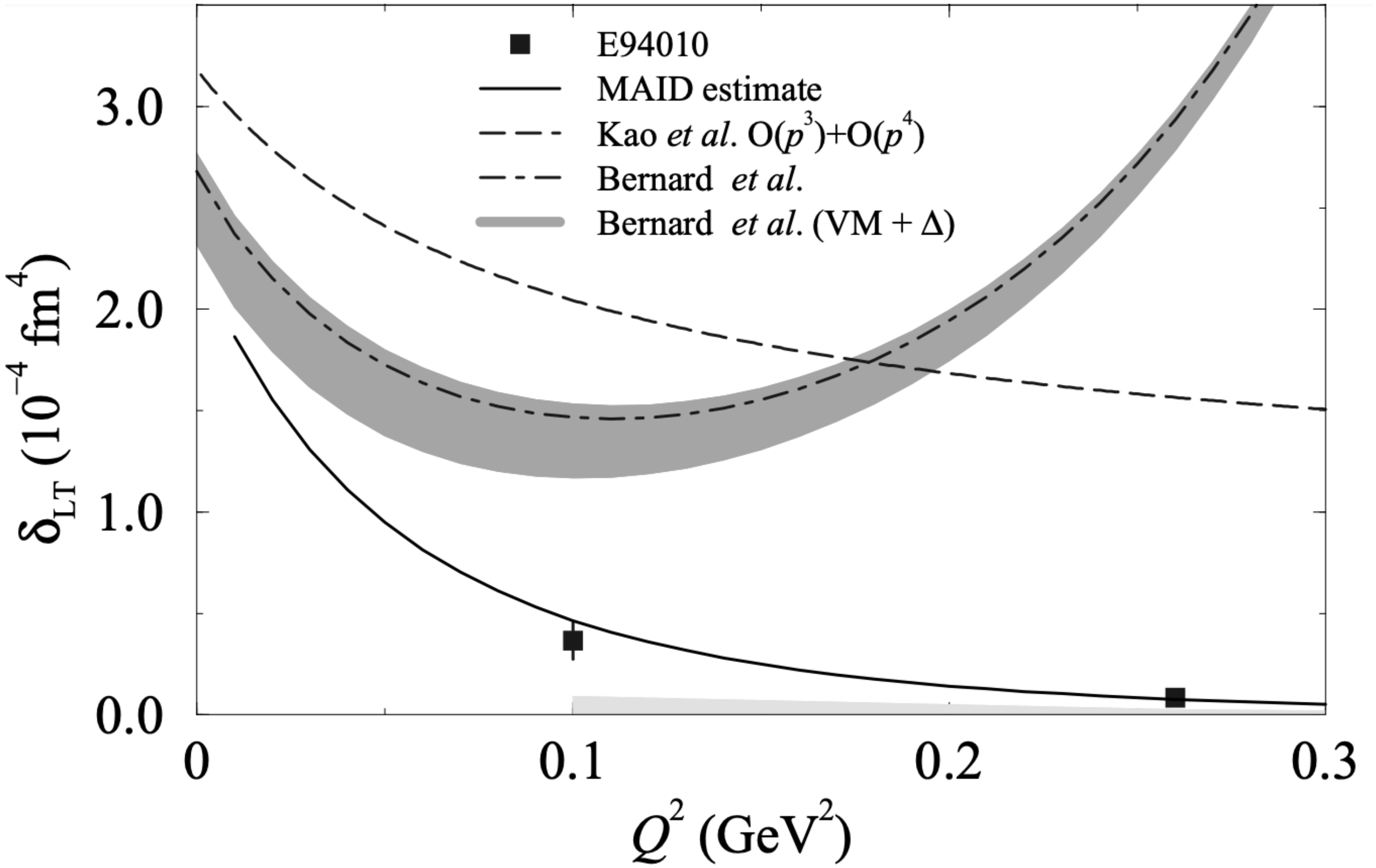
⇒ The disagreement between $\delta^n_{LT}(Q^2)$ data from an earlier experiment (E94-010) and χEFT was particularly surprising: "δ_{LT} puzzle".



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$\delta^n_{LT}(Q^2)$:

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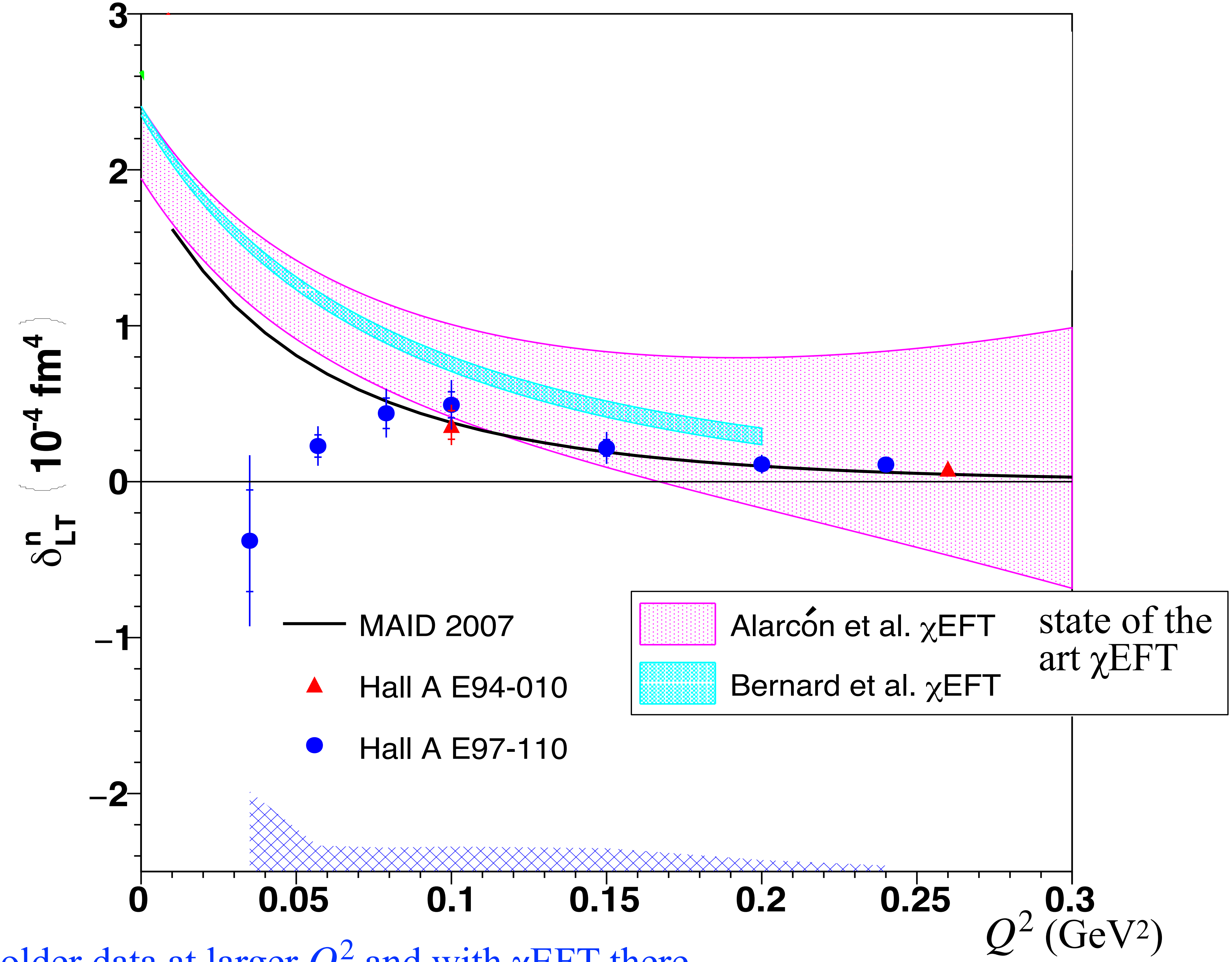
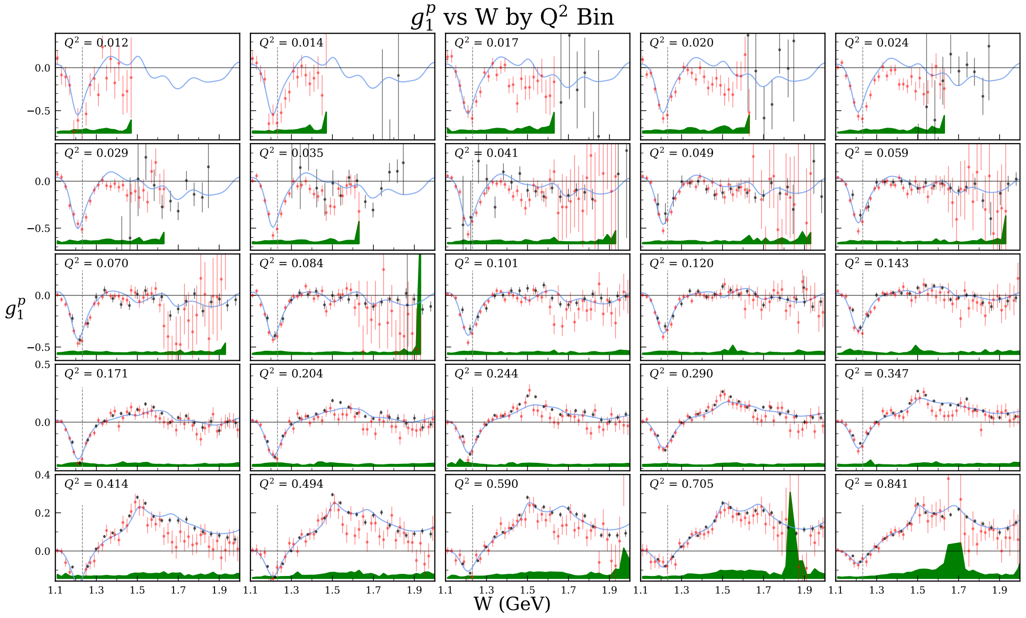


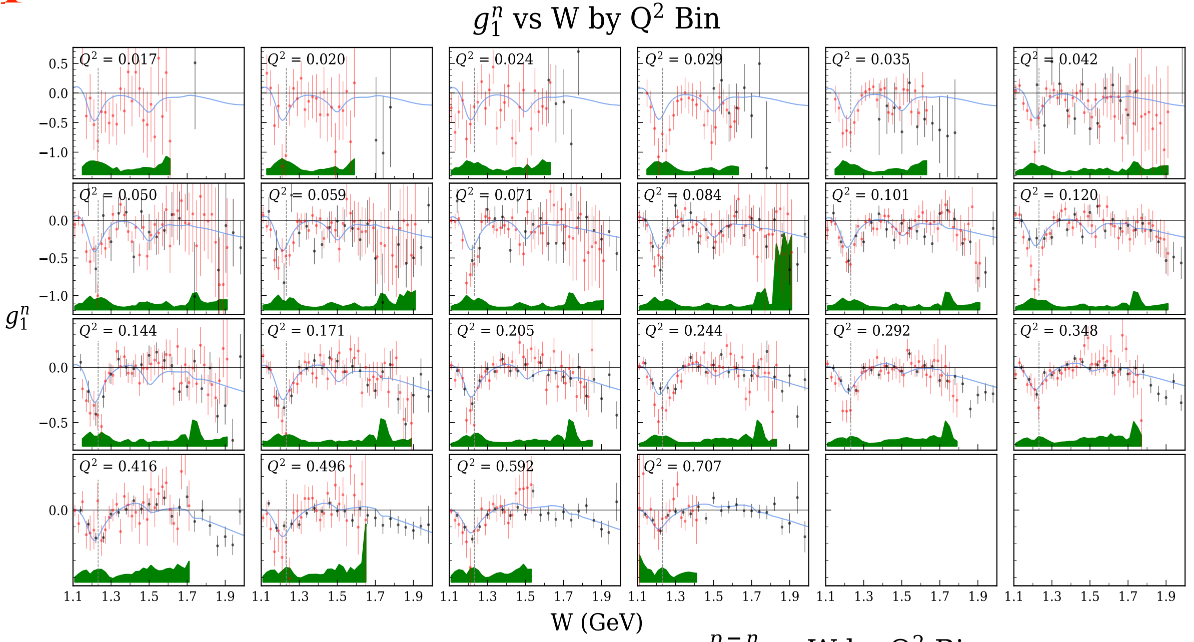
state of the art χEFT

- Good agreement with older data at larger Q^2 and with χEFT there.
- Disagreement with χEFT at lower Q^2, although first moment $\int[g_1 + g_2]dx$ agrees with Schwinger sum rule, see back-up slides.
- ⇒“$\delta^n_{LT}(Q^2)$ puzzle” still remains.

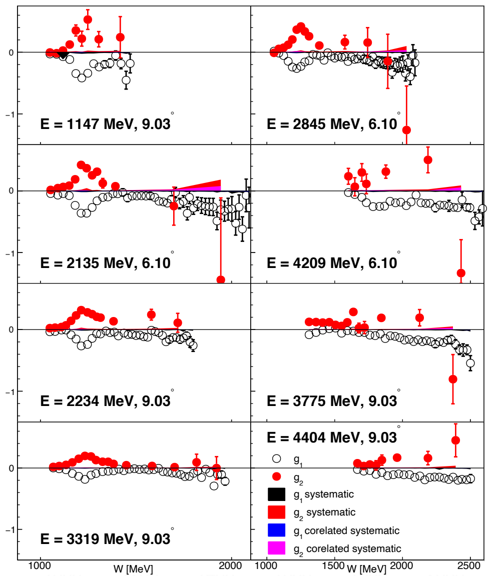
Lots more data on spin structure functions and their moments

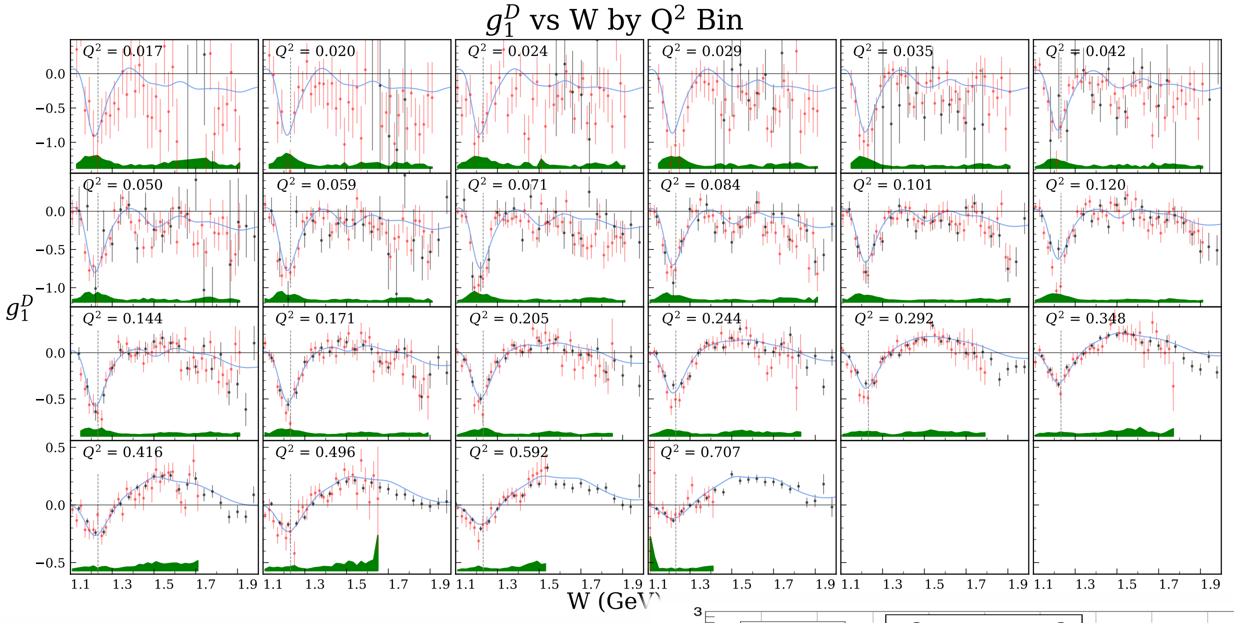


g_1^p vs W by Q^2 Bin

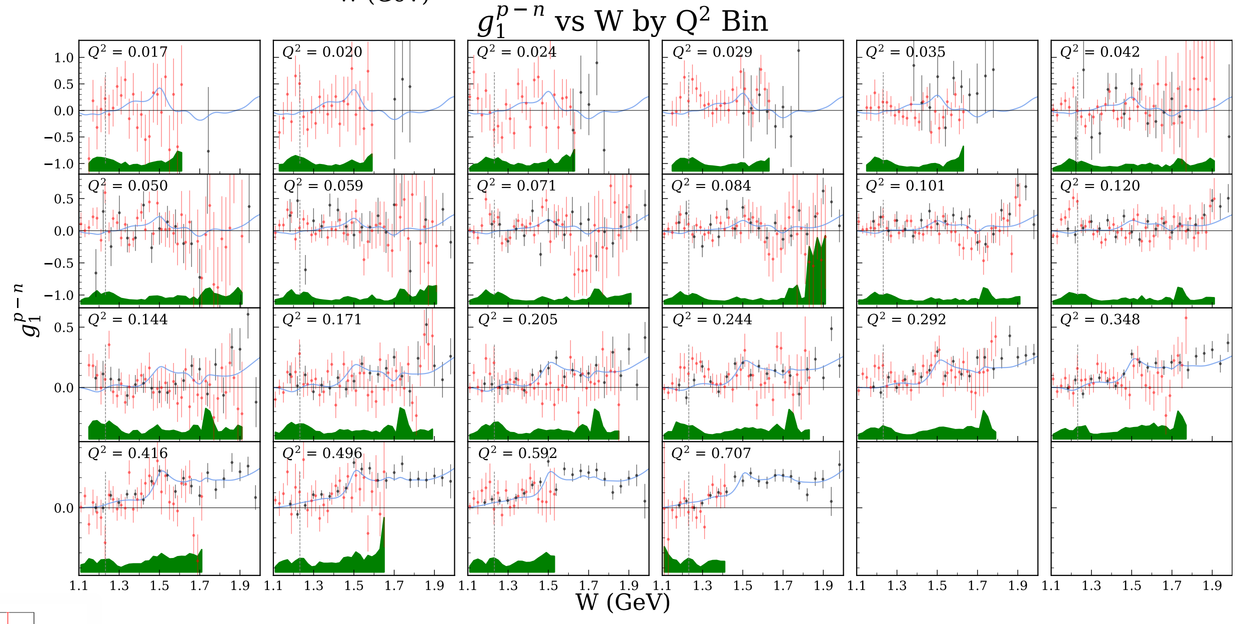


g_1^n vs W by Q^2 Bin

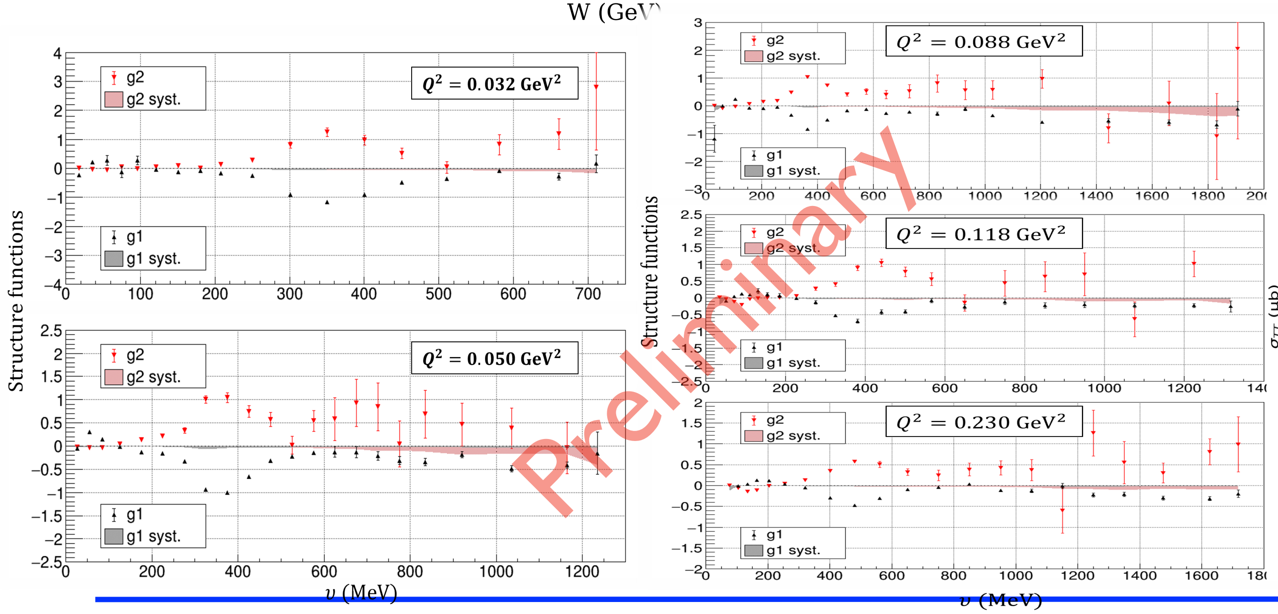


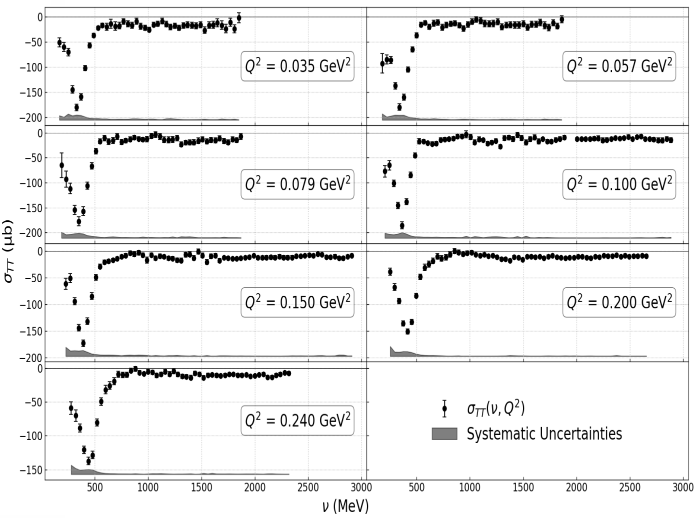


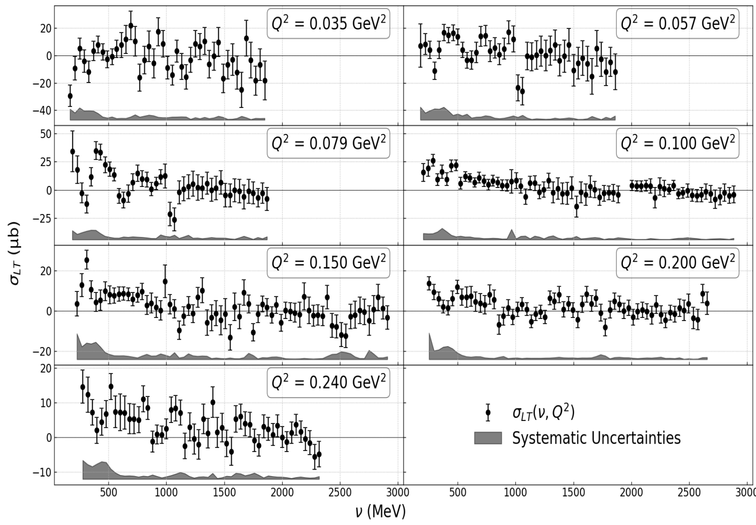
g_1^D vs W by Q^2 Bin



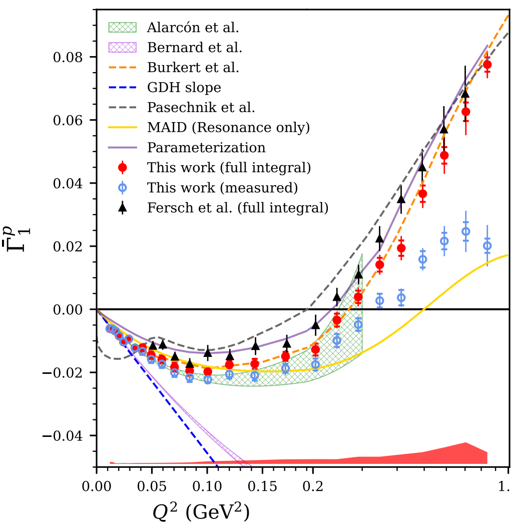
g_1^{p-n} vs W by Q^2 Bin

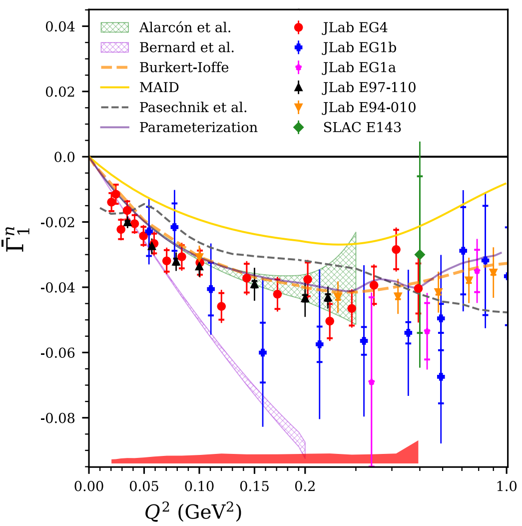


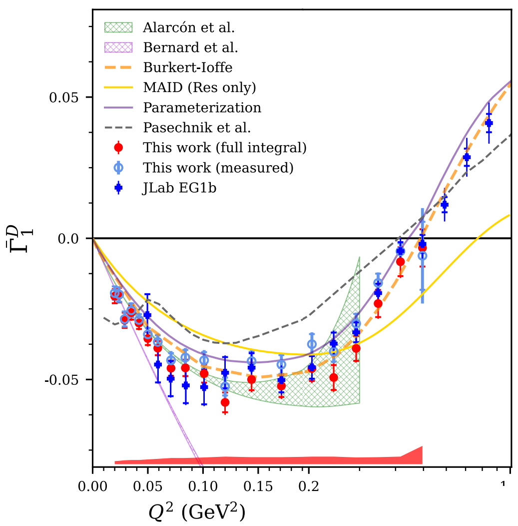


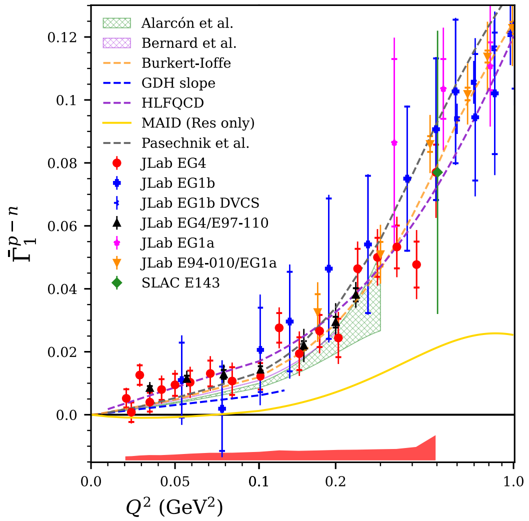


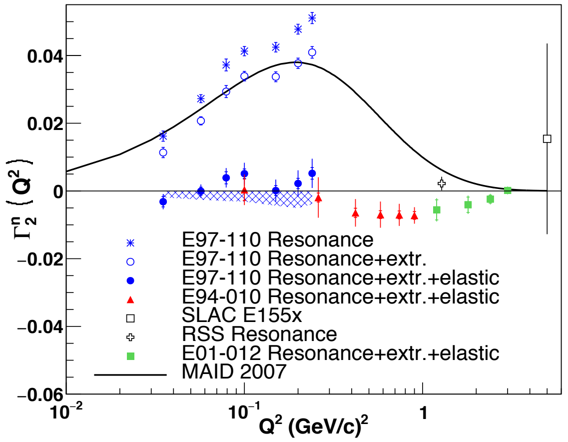
Lots more data on spin structure functions and their moments

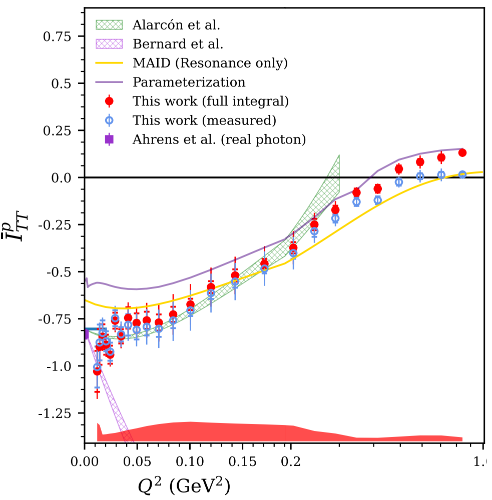


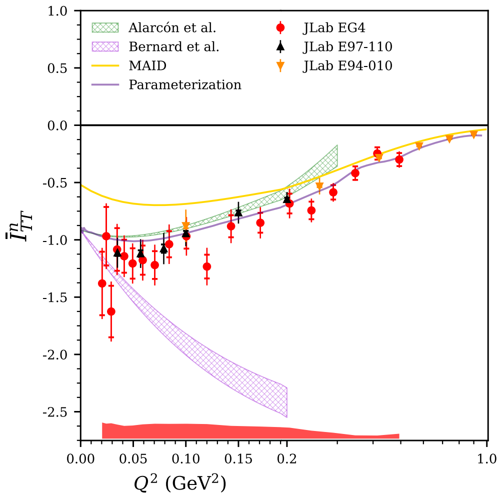


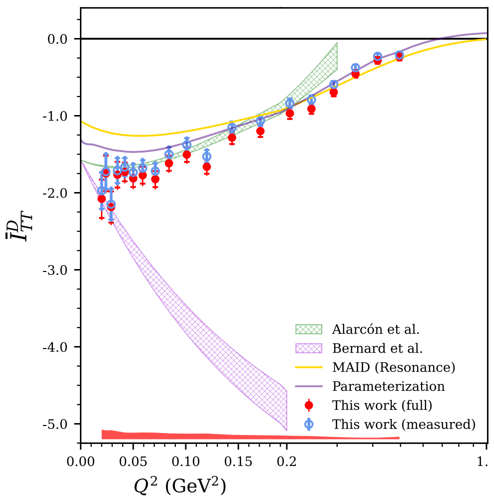


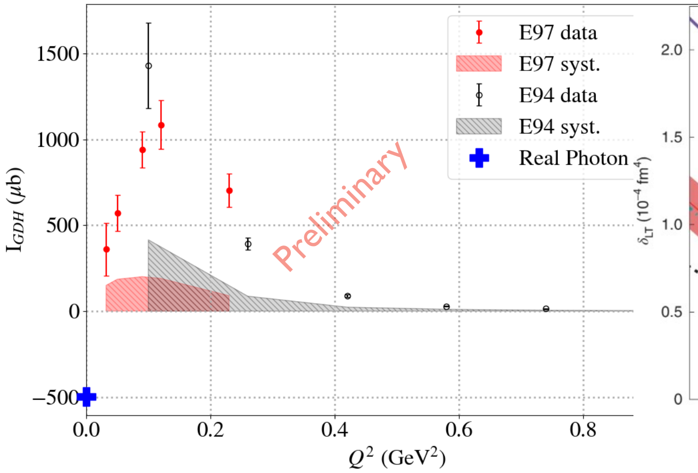


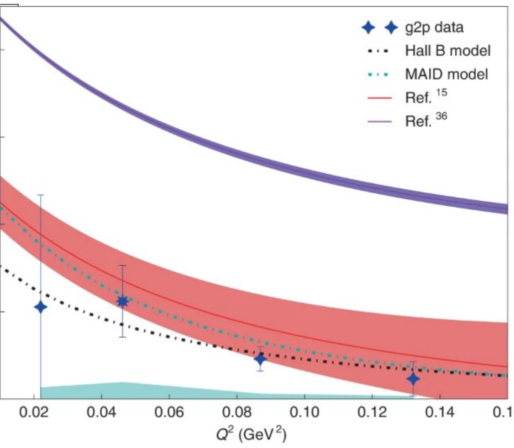


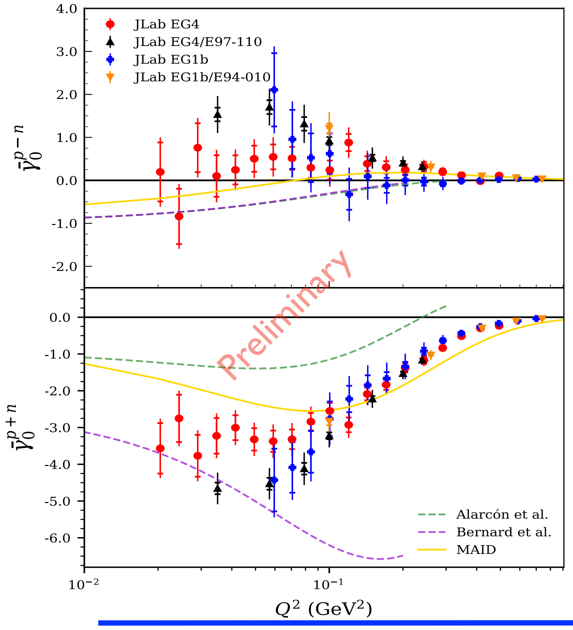




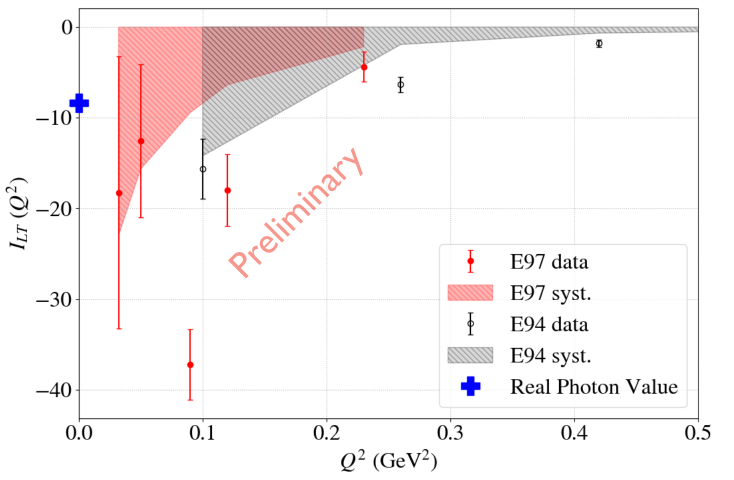


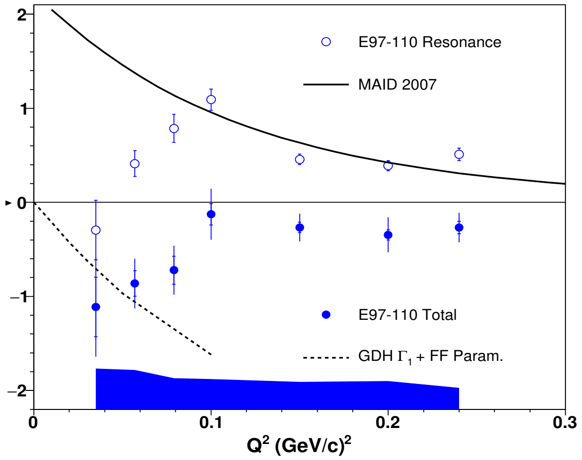


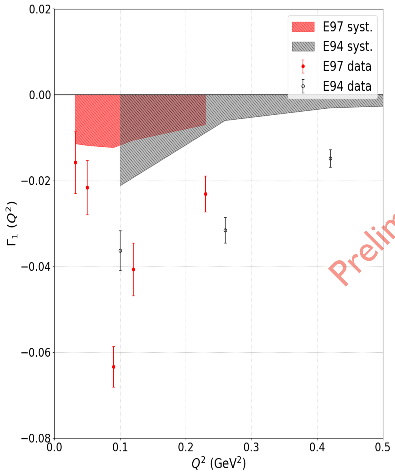


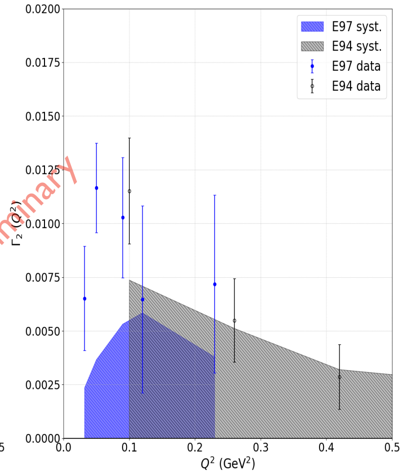


$$4I_{LT} = \frac{8M^2}{Q^2}\int_0^{x_{thres}}(g_1(x,Q^2)+g_2(x,Q^2))dx$$









Extensive test of χEFT with spin degrees of freedoms

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

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

- : No prediction available

No significant low-x contribution
(More robust measurements)

			❤️		💜	💜	❤️💜	💜	❤️💜	❤️💜
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
Bernard 2012	X	X	~A	X	X	A	X	X	X	X
Alarcon 2020	A	A	~A	A	~A	X	X	X	A	X

} 1^{st} generation experiments and χEFT predictions

} 2^{nd} generation (this talk)

Nucleon resonance Δ_{1232} contribution is suppressed (more robust χpt calculations)

Extensive test of χEFT with spin degrees of freedoms

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

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

- : 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
Bernard 2012	X	X	~A	X	X	A	X	X	X	X
Alarcon 2020	A	A	~A	A	~A	X	X	X	A	X

Improvement compared to the state of affaires of early 2000s.

Yet, mixed agreement, depending on the observable, despite χEFT refinements (new expansion scheme, including the Δ_{1232} d.o.f,…) and despite data now being well into the expected validity domain of χEFT.

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

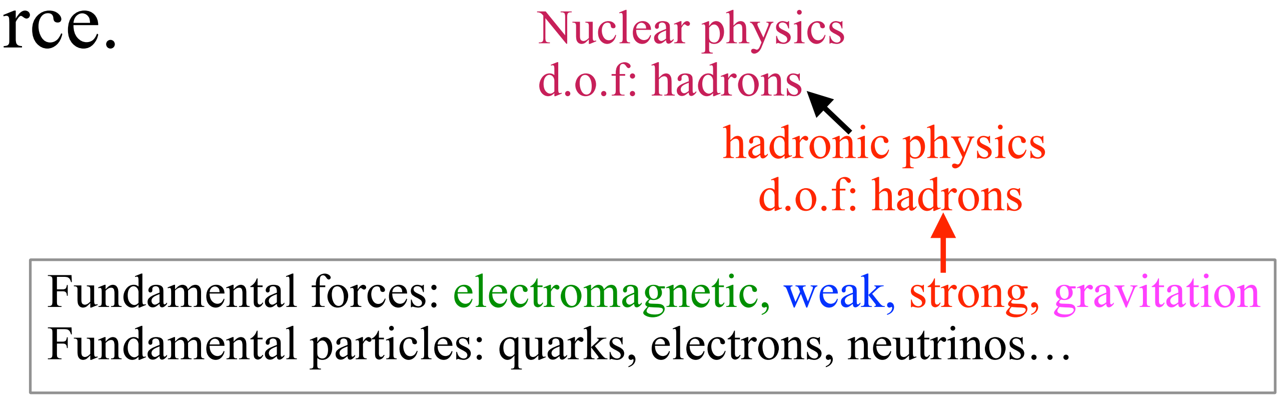
Conclusion

χEFT, although successful in many instances, is challenged by results from dedicated (low Q^2, χEFT domain) spin experiments.

To be sure, low Q^2 sum rule measurements are challenging (forward angles, low-x extrapolation, high-x contamination). But the experiments were run independently with very different detectors and methods. ⇒ We seem to be verifying James Bjorken's statement:

> "Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self protection."

This is a problem: χEFT is the leading approach to manage the first level of complexity of the strong force.



Nuclear physics
d.o.f: hadrons

hadronic physics
d.o.f: hadrons

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

Back-up slides

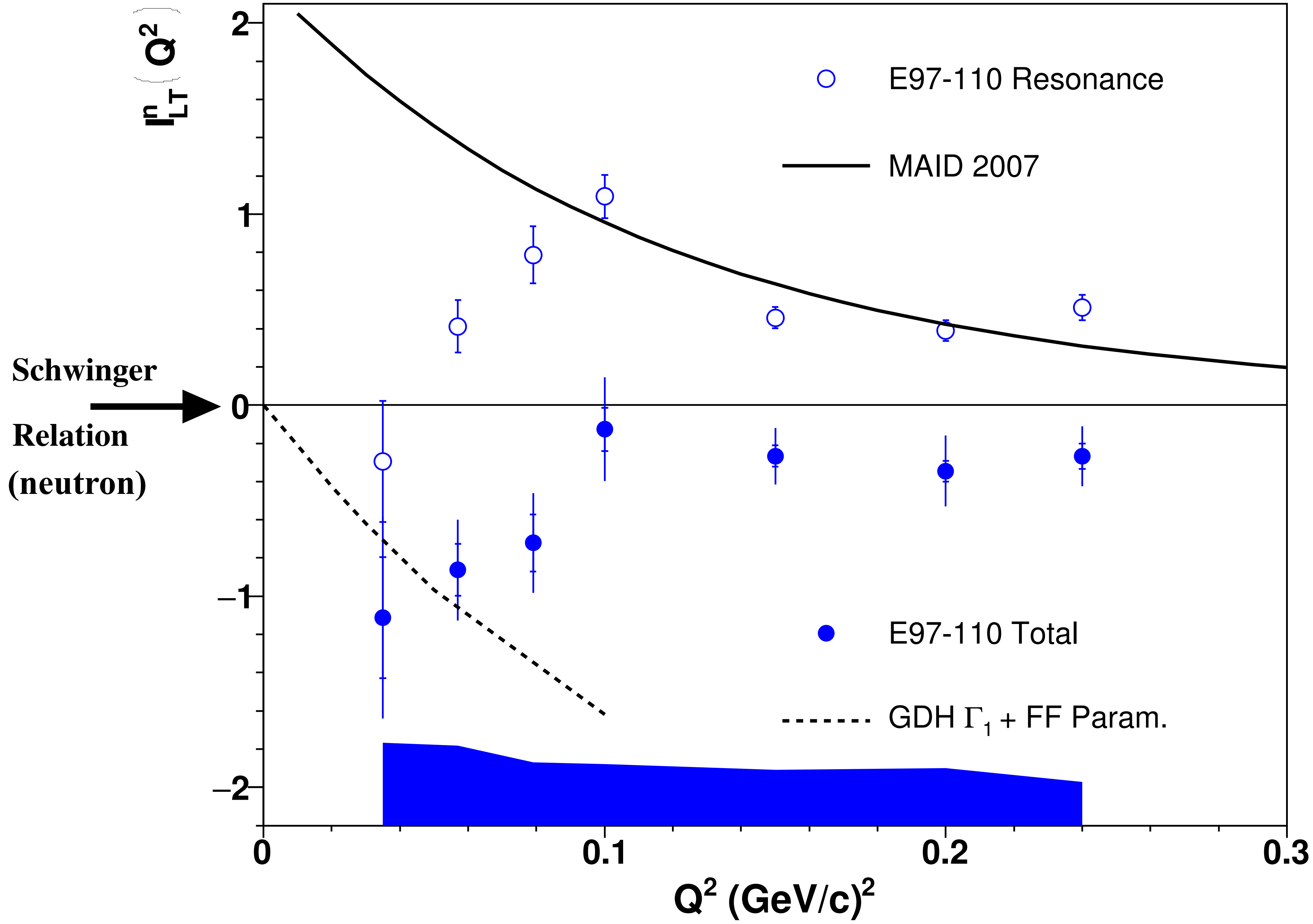
First moments: Schwinger sum rule on neutron from E97-110

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

anomalous magnetic moment×charge

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

Schwinger Relation (neutron)

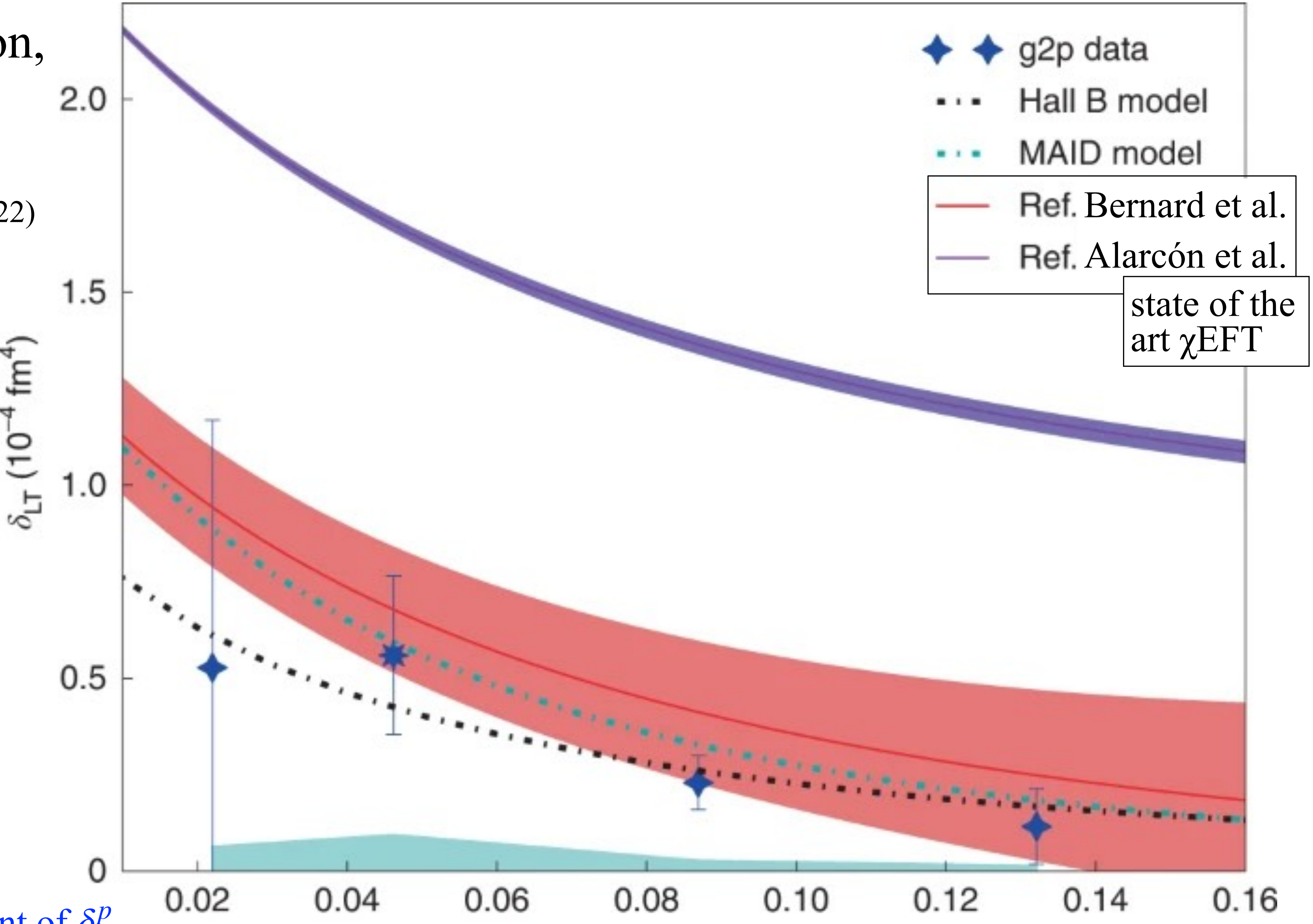


E97-110 (+GDH+BC sum rule+known neutron elastic form-factor) agrees with Schwinger sum rule.

JLab low Q^2 experimental results $\gamma_0(Q^2)$ and $\delta_{LT}(Q^2)$

E08-027 proton,
$\delta^p_{LT}(Q^2)$:

D. Ruth, et al,
Nat. Phys.**18** 1441 (2022)



state of the
art χEFT

- First measurement of δ^p_{LT}
- Agree with χEFT state-of the χEFT (Alarcón et al) for relative Q^2-behavior (not absolute value).
- "$\delta_{LT}(Q^2)$ puzzle" solved?

χEFT series

Domain of applicability: $Q^2=0$ to somewhere between $m_\pi^2 \approx 0.02$ GeV^2 and $\Lambda_\chi^2 \approx 1$ GeV^2 (the chiral symmetry breaking scale).
Depends on the order at which the series is expanded.

Main χPT expansion (π-N loops): small parameter m_π/Λ_χ.

Including Δ effects (Δ-N loops): additional expansion parameter(s). Two schemes:

- $\delta_{N\Delta} \equiv M_\Delta - M_N$ considered to be of same order as m_π (Bernard et al)
- $\delta_{N\Delta}$ considered as intermediate scale > m_π (Alarcon et al.)

⇒ various Δ contributions may arise at different order in the two schemes.

At high enough order, the scheme difference should be negligible.

Bigger difference between two state of the art calculations:
Alarcón et al. includes empirical form factors to the relevant couplings to approximate some of the high-order contributions. Accounts for the suppression of γ_0 and δ_{LT} at large Q^2.
Bernard et al. is a purer calculation, with no such empirical addition, but does not account well for large Q^2 suppression.