Experimental studies of the neutron generalized spin polarizabilities and spin sum rules at low Q^2

A. Deur

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+

^{3}He spin sum rules at low Q^2

(For C. Peng)

JLab Hall A experiment E97-110

V. Sulkosky et al.
Nature Physics, **17** 687 (2021);
Phys.Lett.B 805 135428 (2020)

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

Students: C. Peng (Duke U.), V. Laine (Clermont-Fd U.) J. Singh (UVa), V. Sulkosky (W&M),
N. Ton (U.Va), J. Yuan (Rutgers U.).

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Motivations for E97-110 are the same as for EG4 (talk on Tuesday):

* Provide very low Q^2 nucleon spin data to test χEFT,
* Test original GDH sum rule with inclusive data.
* Observable of interest the same as EG4: spin sum rules, generalized spin polarizabilities.

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*Observable of interest the same as EG4: spin sum rules, generalized spin polarizabilities.

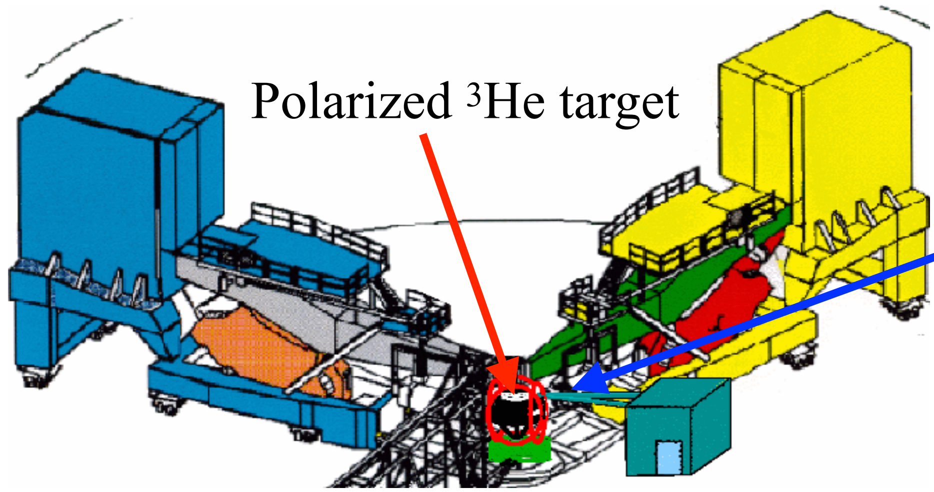
E97-110 aimed at precision measurement of neutron spin structure (polarized ^{3}He target).
E97-110 in Hall A: high resolution, small solid angle detectors. (EG4: Hall B, lower resolution, large solid angle).

^{3}He target has transverse polarization capability:
*No need to model $g_2(x, Q^2)$ for $\Gamma_1(Q^2)$, $I_{TT}(Q^2)$ and $\gamma_0(Q^2)$,
*$g_2(x, Q^2)$ data and associated sum rules,
*$\delta^n_{LT}(Q^2)$ data.

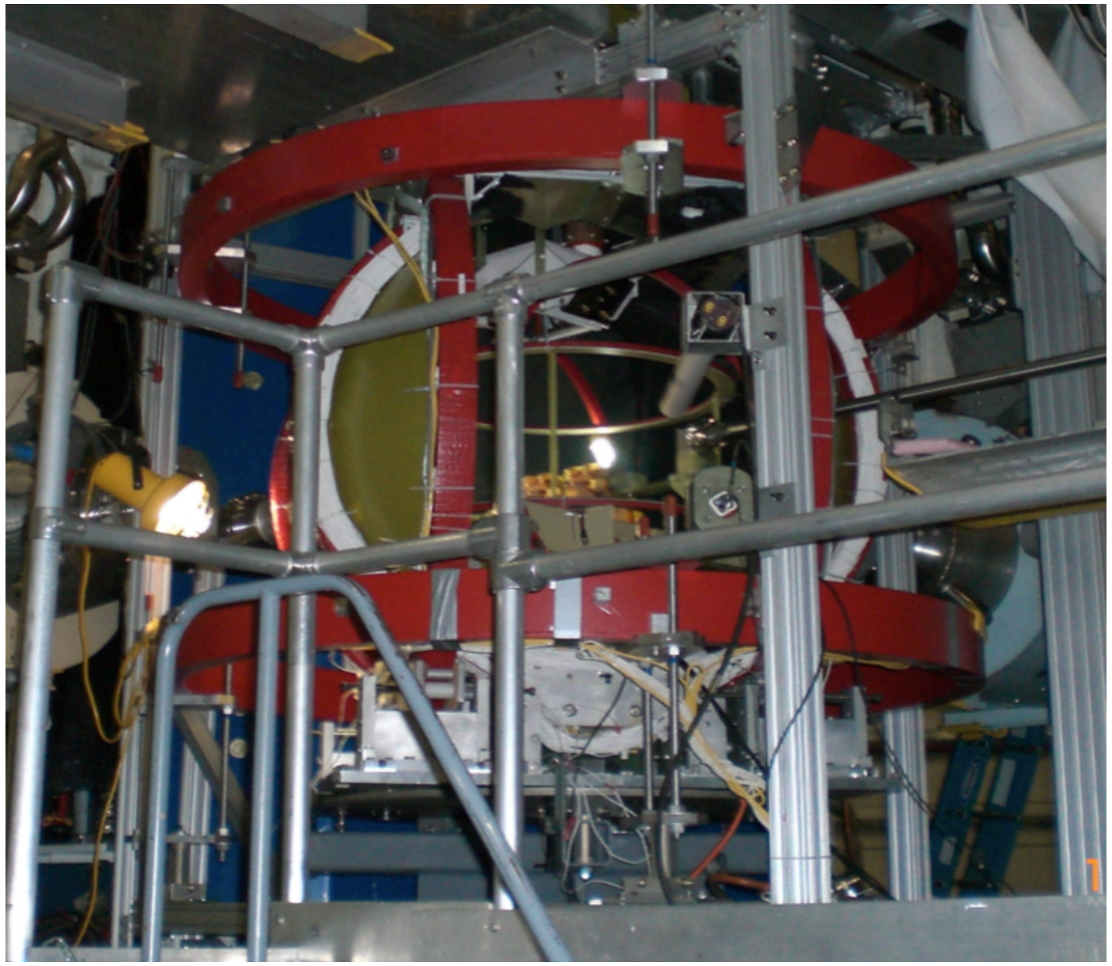
JLab Hall A experiment E97-110

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

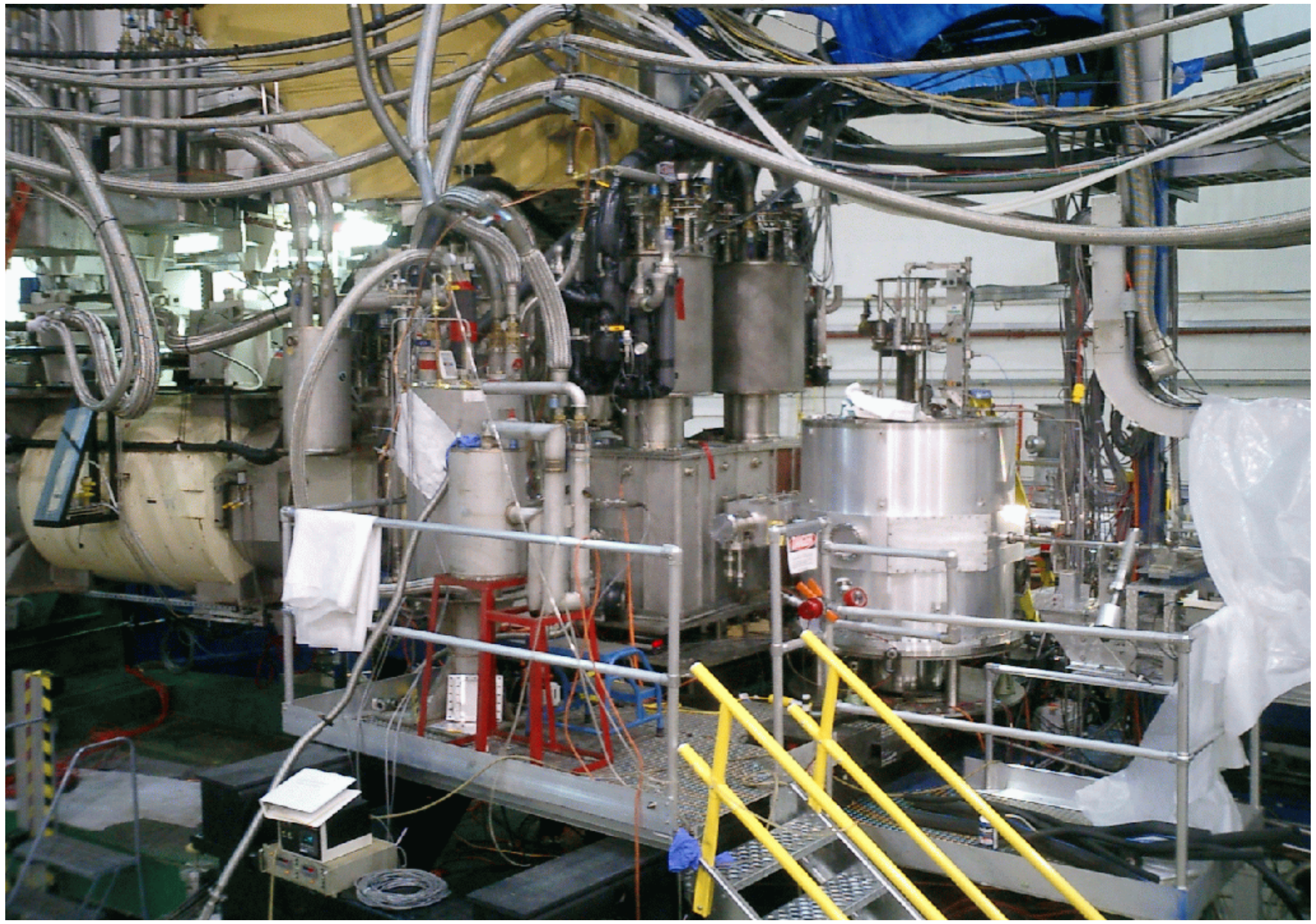
JLab Hall A:



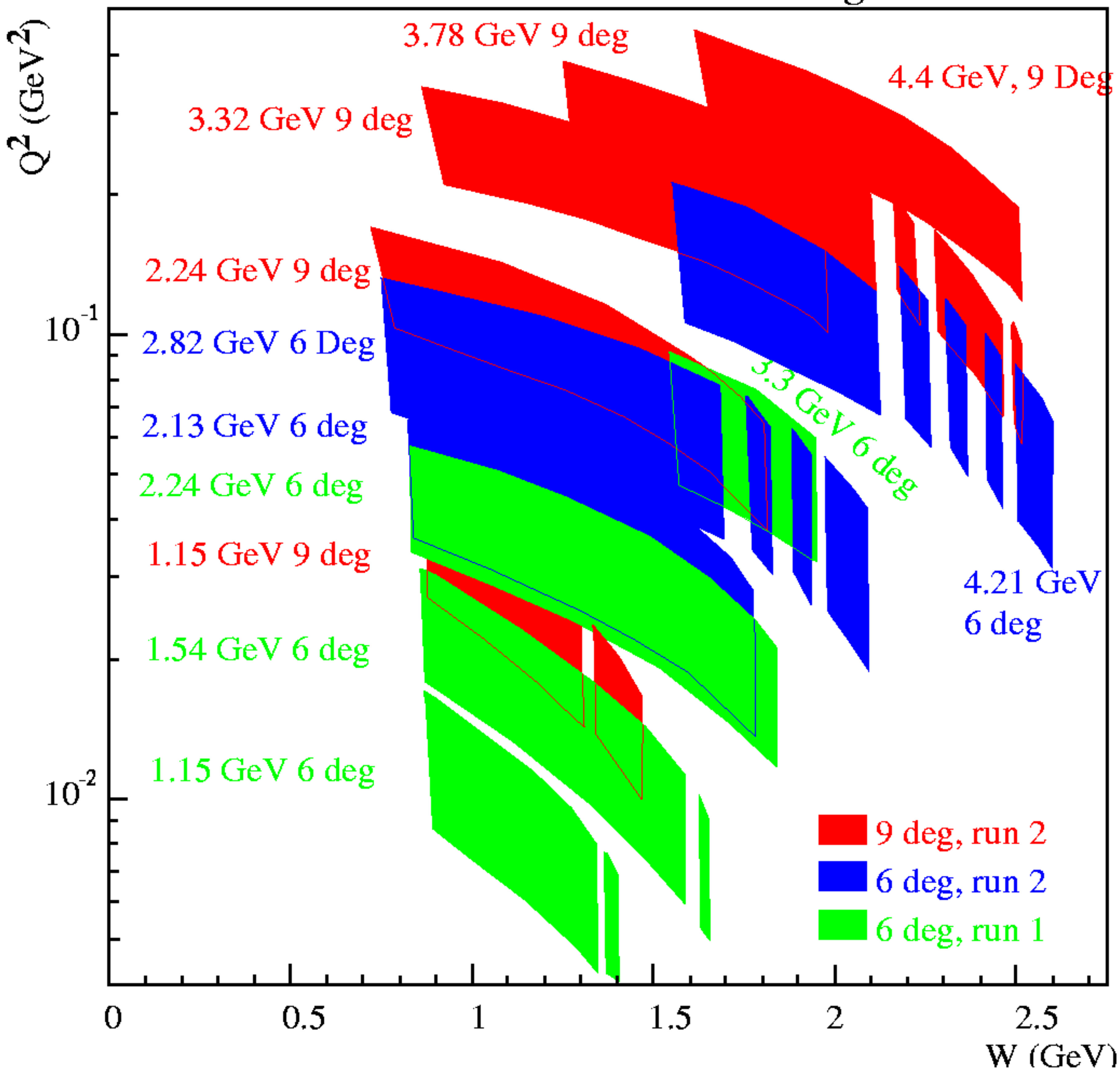
JLab Polarized ³He target

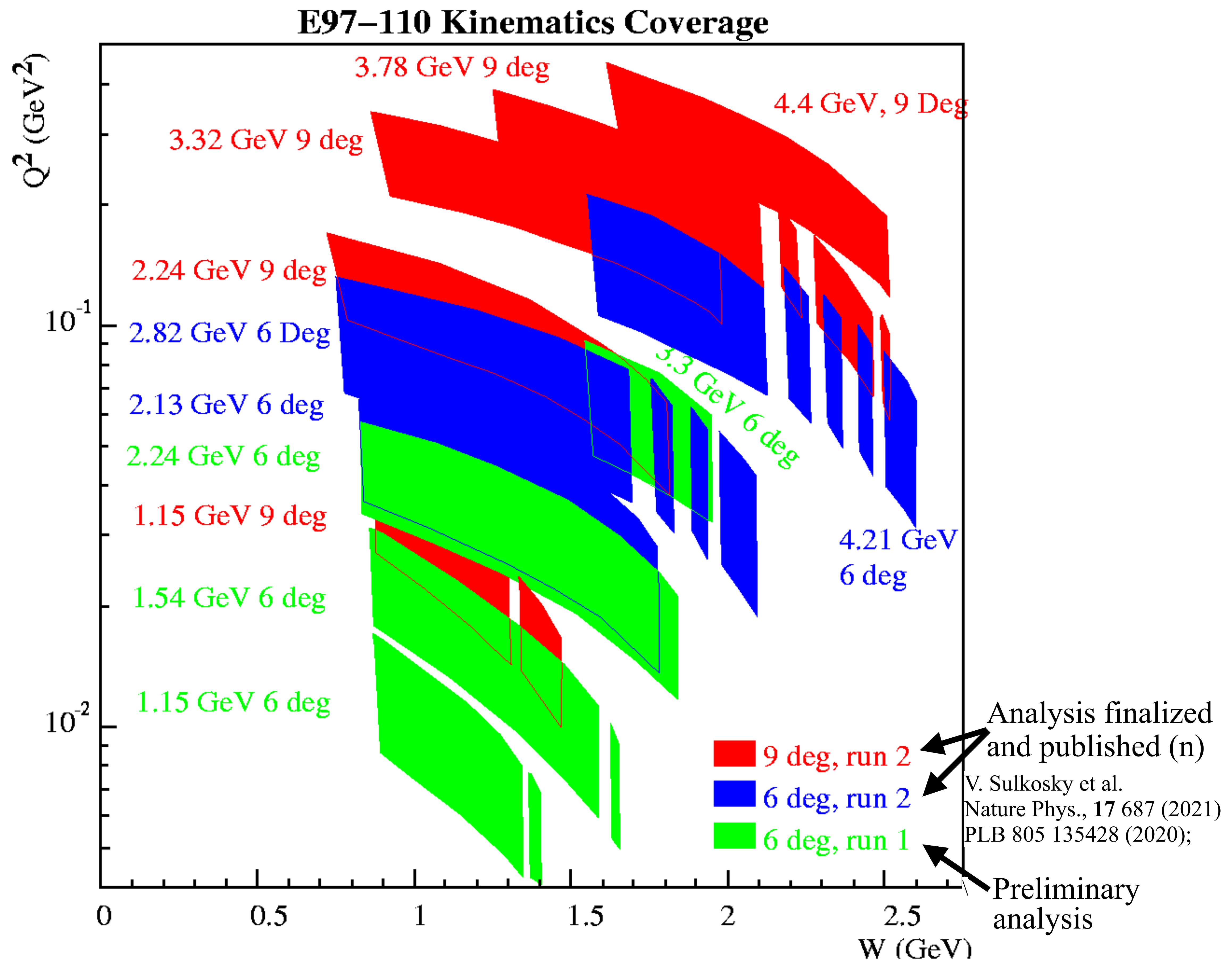


New magnet



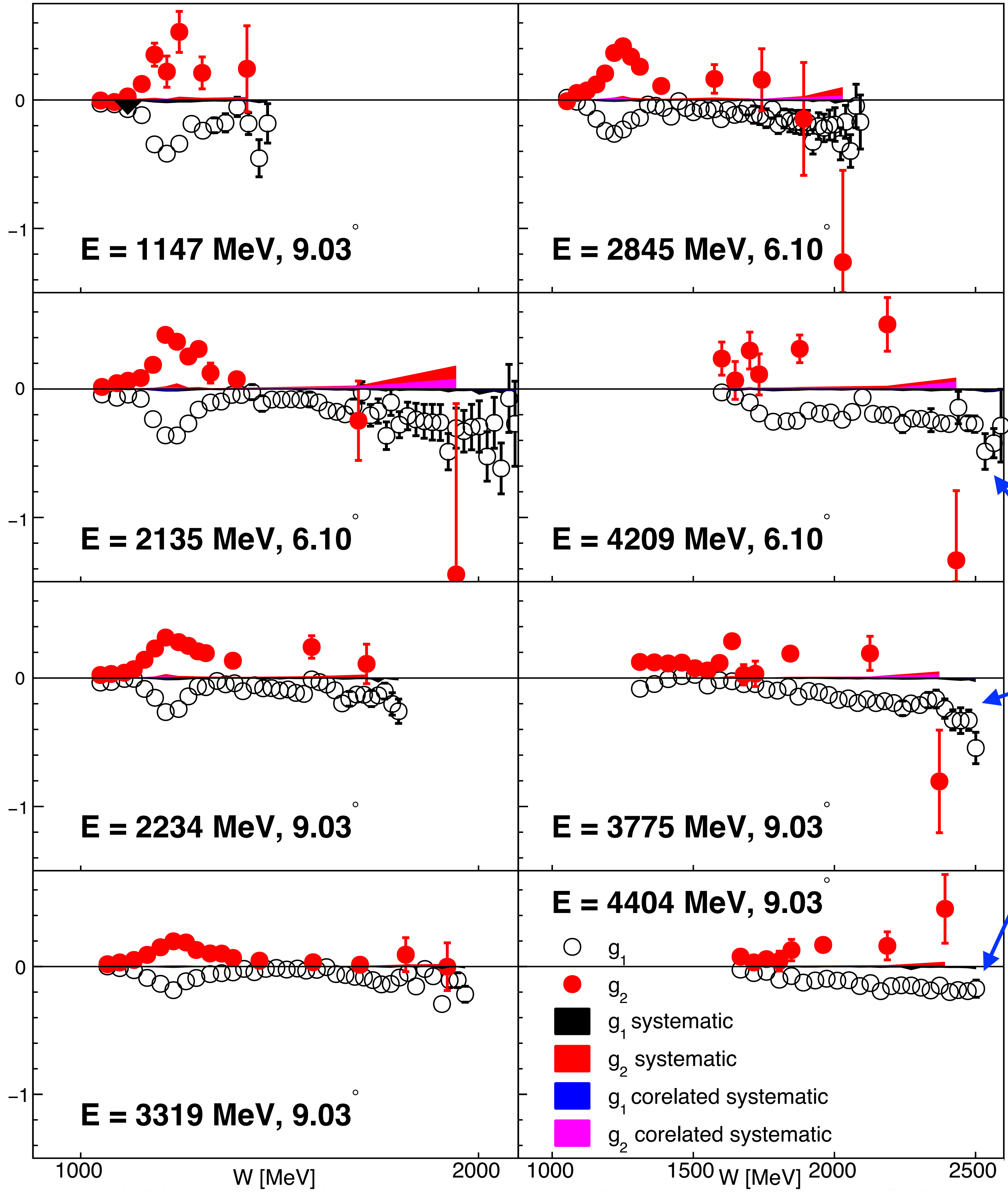
E97–110 Kinematics Coverage




E97–110 Kinematics Coverage
3.78 GeV 9 deg
4.4 GeV, 9 Deg
3.32 GeV 9 deg
2.24 GeV 9 deg
2.82 GeV 6 Deg
3.3 GeV 6 deg
2.13 GeV 6 deg
2.24 GeV 6 deg
1.15 GeV 9 deg
4.21 GeV
6 deg
1.54 GeV 6 deg
1.15 GeV 6 deg
9 deg, run 2
6 deg, run 2
6 deg, run 1
Q² (GeV²)
10⁻¹
10⁻²
0
0.5
1
1.5
2
2.5
W (GeV)
Analysis finalized
and published (n)
V. Sulkosky et al.
Nature Phys., **17** 687 (2021)
PLB 805 135428 (2020);
Preliminary
analysis

Spin structure function $g_1^{^3He}(W,Q^2)$ and $g_2^{^3He}(W,Q^2)$ data from E97-110

We do not know how to reliably extract neutron information from ³He for non-integrated quantities (e.g., spin structure functions, polarized cross-section difference…)



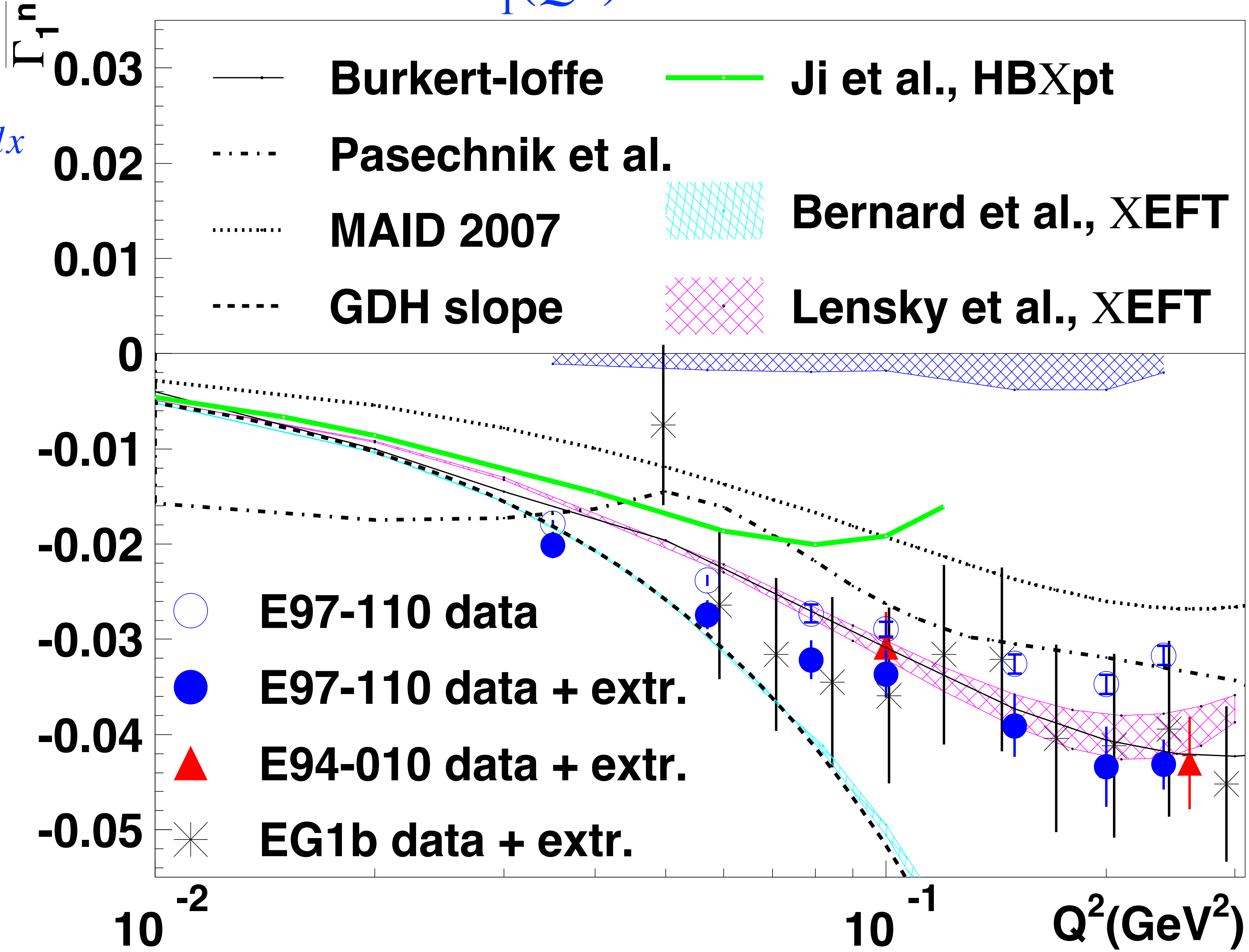
We observe the expected $g_1 \simeq -g_2$ symmetry near the Δ_{1232}.

Δ: ~M₁ transition $\Rightarrow \sigma_{LT} \propto g_1 + g_2 \simeq 0$

Large W coverage to test sum rule convergency

First moments: $\Gamma_1^n(Q^2)$ measurement from E97-110

$$\Gamma_1^n = \int_0^{1^-} g_1^p(x, Q^2)dx$$

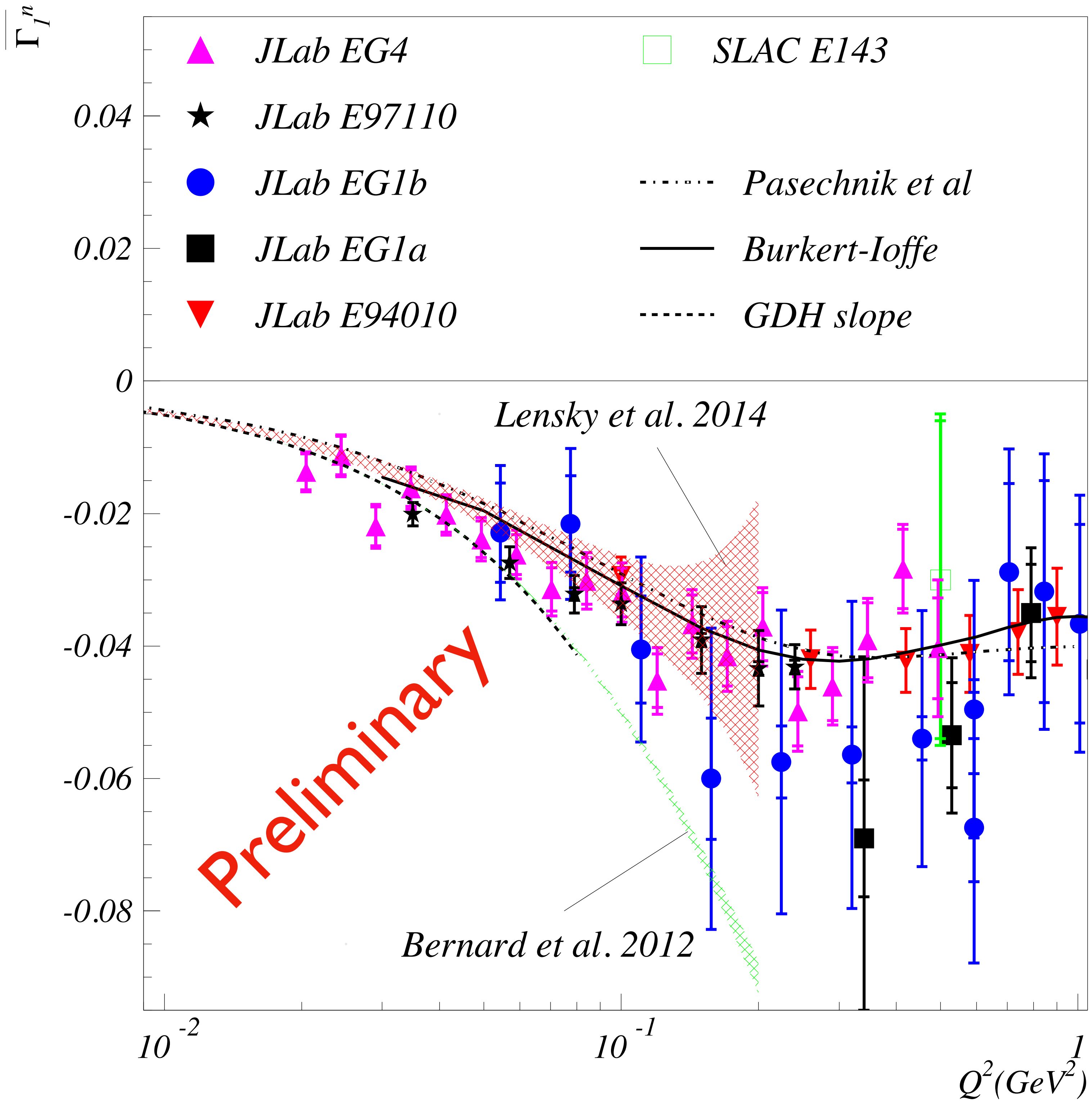


- E97-110 agree with older data at larger Q^2 (EG1b, E94-010).
- E97-110 and χEFT agree up to Q^2 ~0.06 GeV^2 (Bernard et al) or Q^2 >0.08 GeV^2 (Lensky et al.)
- Some phenomenological models (Burkert-Ioffe) agree well with data, other (MAID, Pasechnik et al) not as much.

First moments: $\Gamma_1^n(Q^2)$ measurements from E97-110 and EG4

$$\Gamma_1^n = \int_0^{1^-} g_1^p(x, Q^2)dx$$

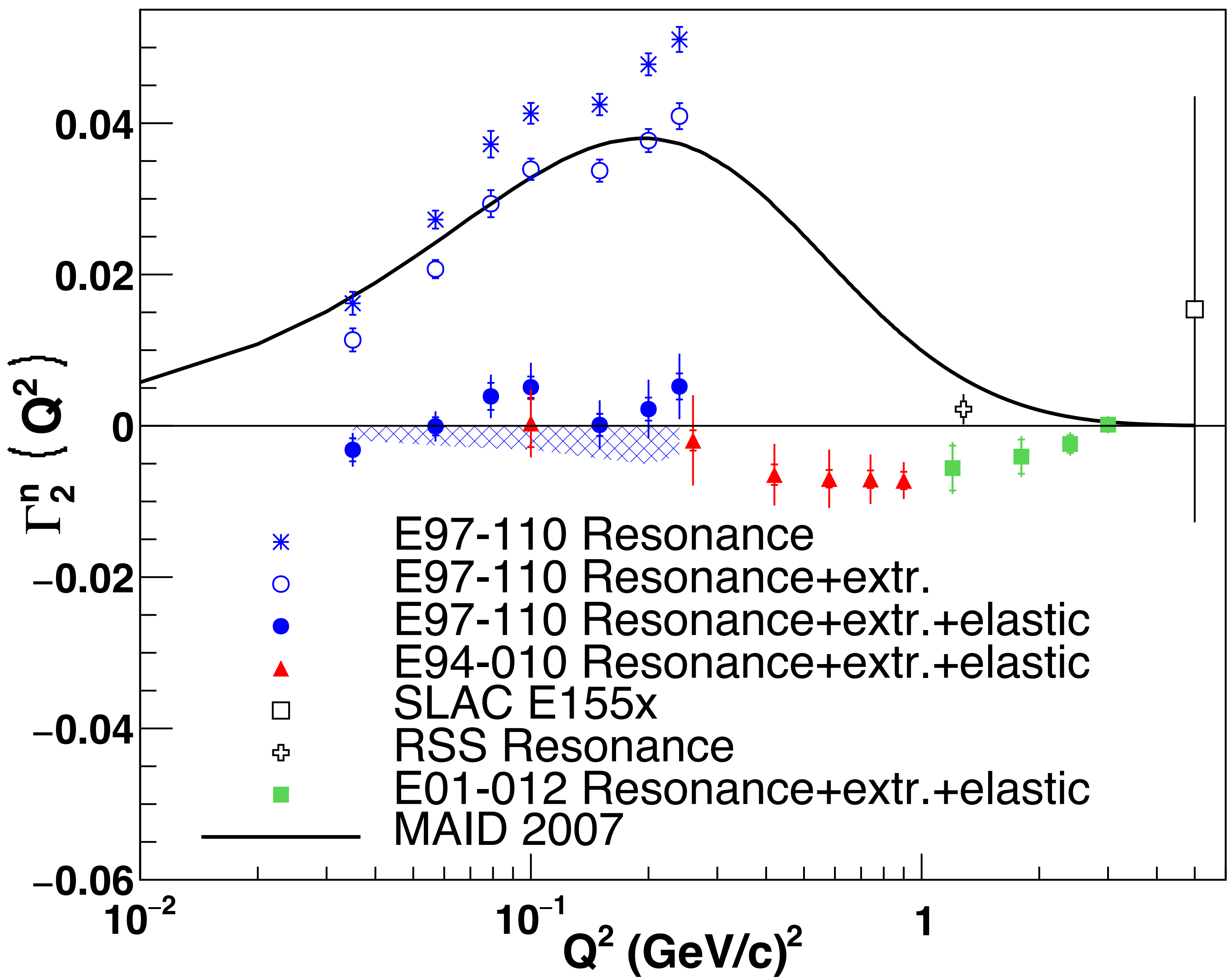
$$\Gamma_1^n = 2\Gamma_1^d/\left(1 - 1.5\omega_d\right) - \Gamma_1^p$$



E97-110 and EG4 agree well.

First moments: Burkhardt–Cottingham sum rule

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



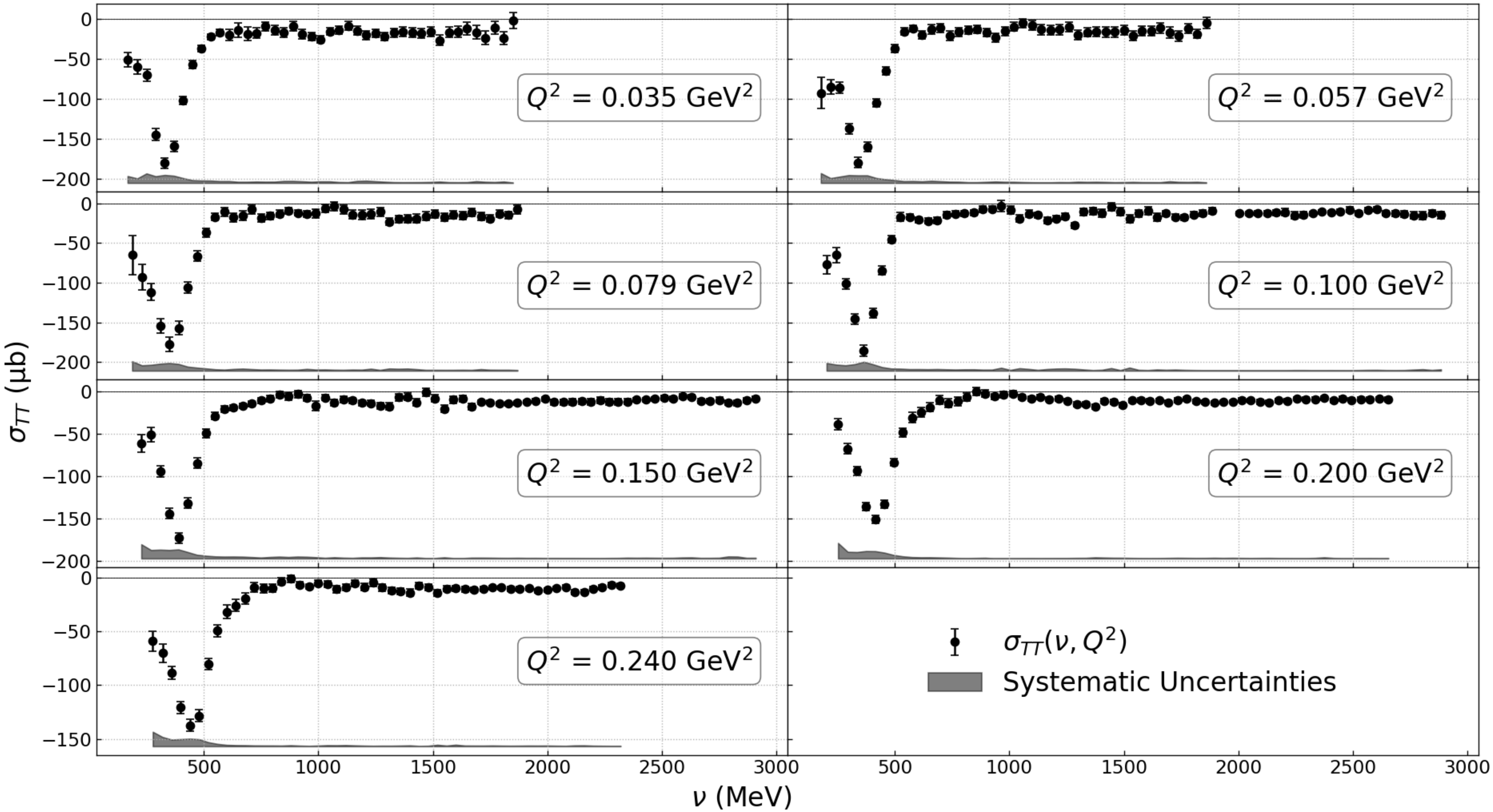
E97-110 verifies the B-C sum rule at low Q^2. Older experiments at higher Q^2 also verify it.

Polarized cross-section $\sigma_{TT}^{^3He}(\nu, Q^2)$ data from E97-110

We do not know how to reliably extract neutron information from ³He for non-integrated quantities (e.g., spin structure functions, polarized cross-section difference…)

$$\sigma_{TT} = \frac{\sigma_A - \sigma_p}{2} = \frac{4\pi^2\alpha}{MK}(g_1 - \gamma^2 g_2)$$

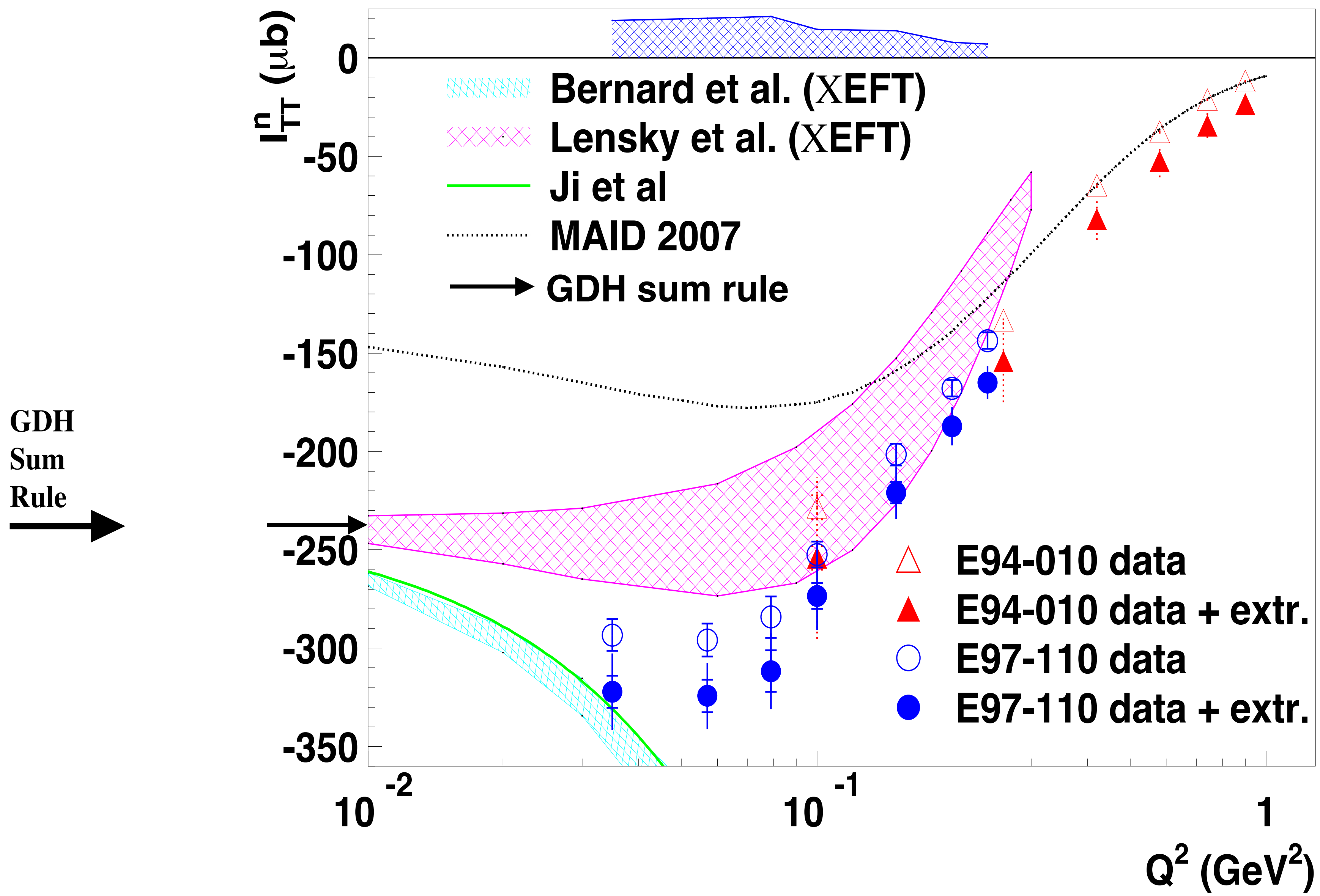
K: virtual photon flux



First moments: GDH sum ($I^n_{TT}(Q^2)$) measurement from E97-110

$$I_{TT}(Q^2) \equiv \frac{M^2}{8\pi^2\alpha}\int_{\nu_{thr}}^{\infty}\frac{K}{\nu}\frac{\sigma_A-\sigma_P}{\nu}d\nu$$

GDH
Sum
Rule

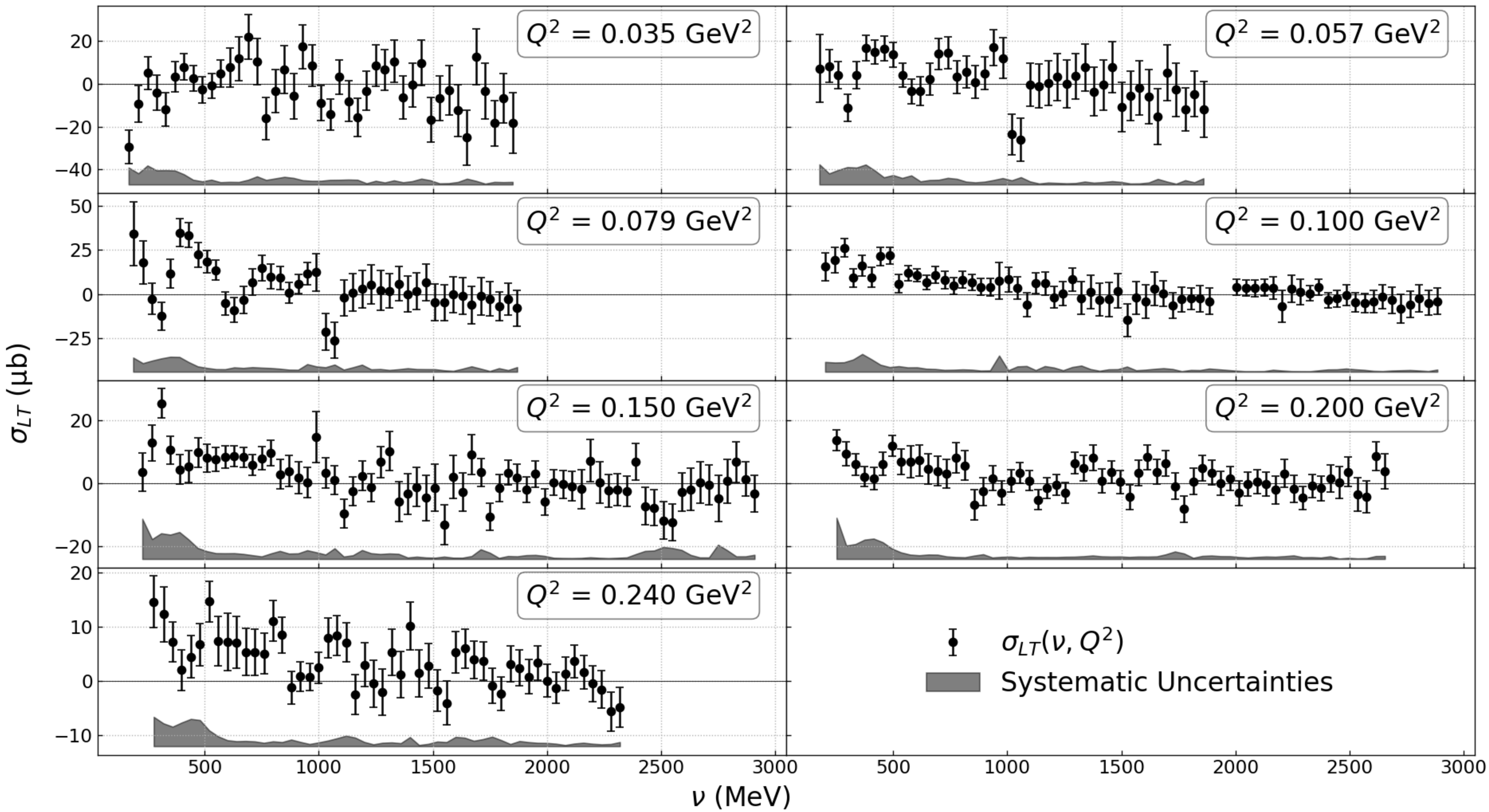


- E97-110 agree with older data at larger Q^2.
- E97-110 and χEFT:
  - agree for lowest data point (Q^2 ~0.04 GeV^2) for Bernard *et al.*
  - disagree with Lensky *et al*. except at the higher Q^2.
- Maid disagree with the data.

Polarized cross-section $\sigma_{LT}^{^3He}(\nu, Q^2)$ data from E97-110

We do not know how to reliably extract neutron information from ^{3}He for non-integrated quantities (e.g., spin structure functions, polarized cross-section difference…)

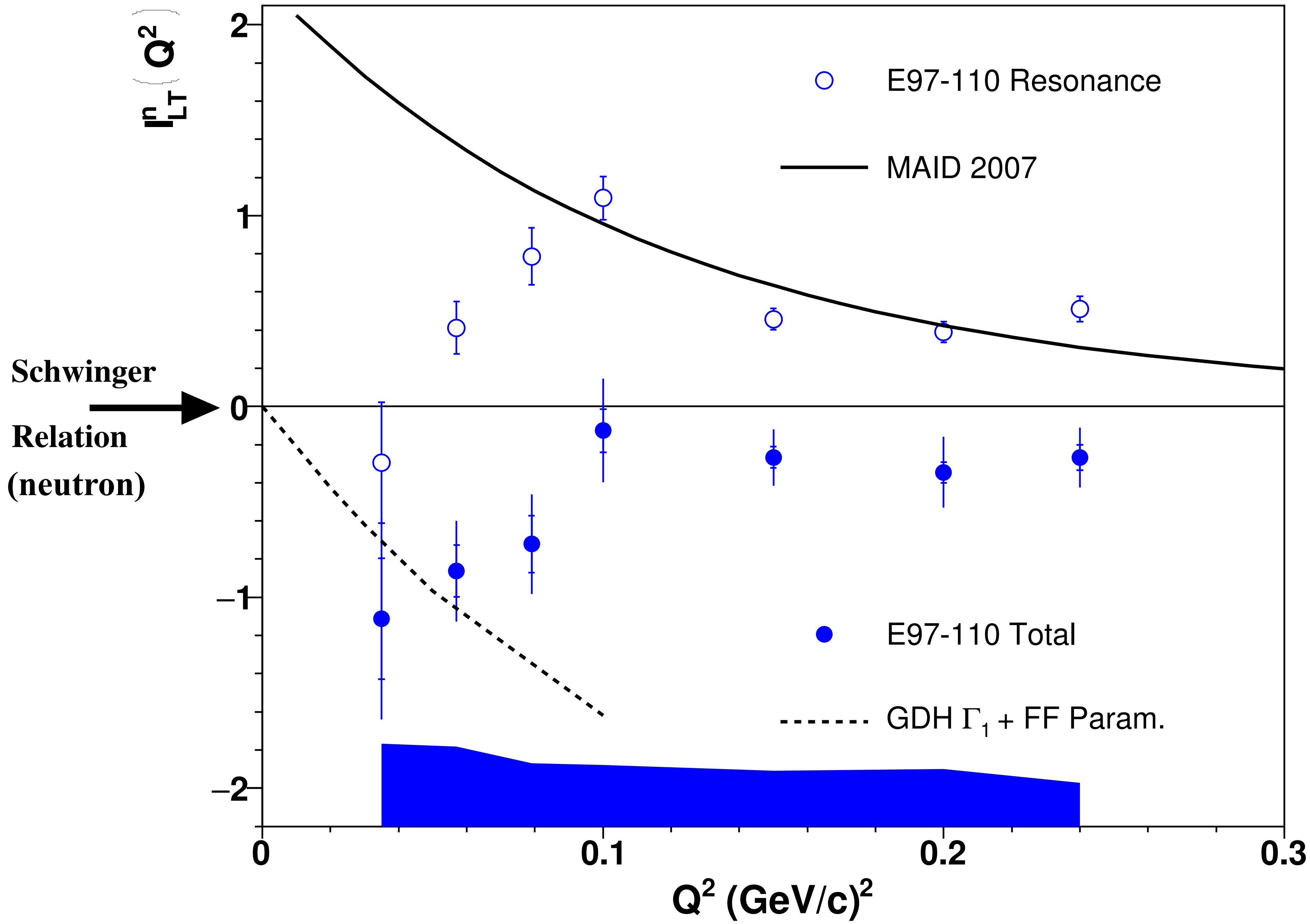
$$\sigma_{LT} = \frac{4\pi^2\alpha}{MK}\gamma(g_1 + g_2)$$



First moments: Schwinger sum rule

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

anomalous magnetic moment×charge

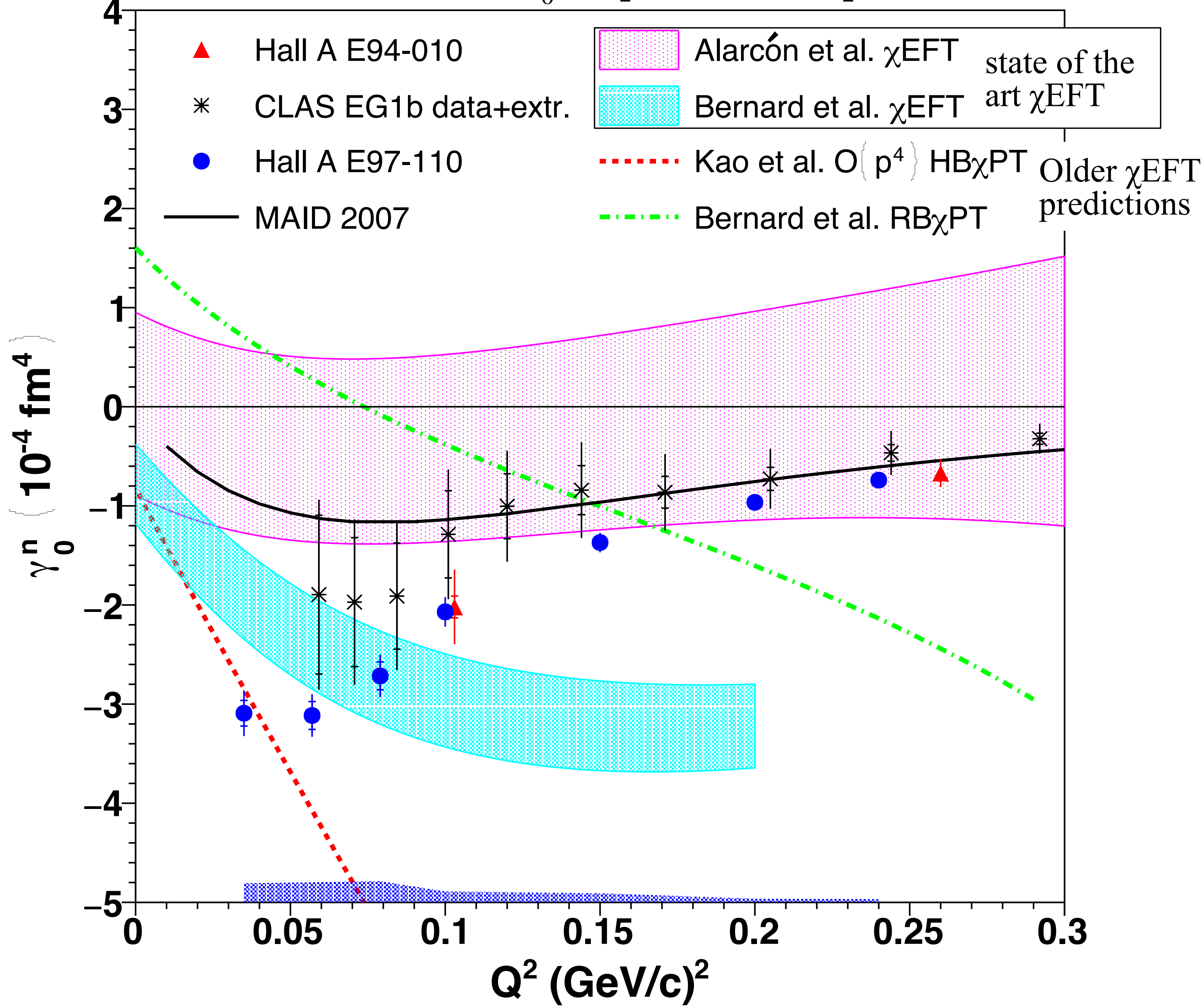


E97-110 (+GDH+BC sum rule+known neutron elastic form-factor) agrees with Schwinger sum rule.

Higher moments: Generalized forward spin polarizability γ_0^n from E97-110

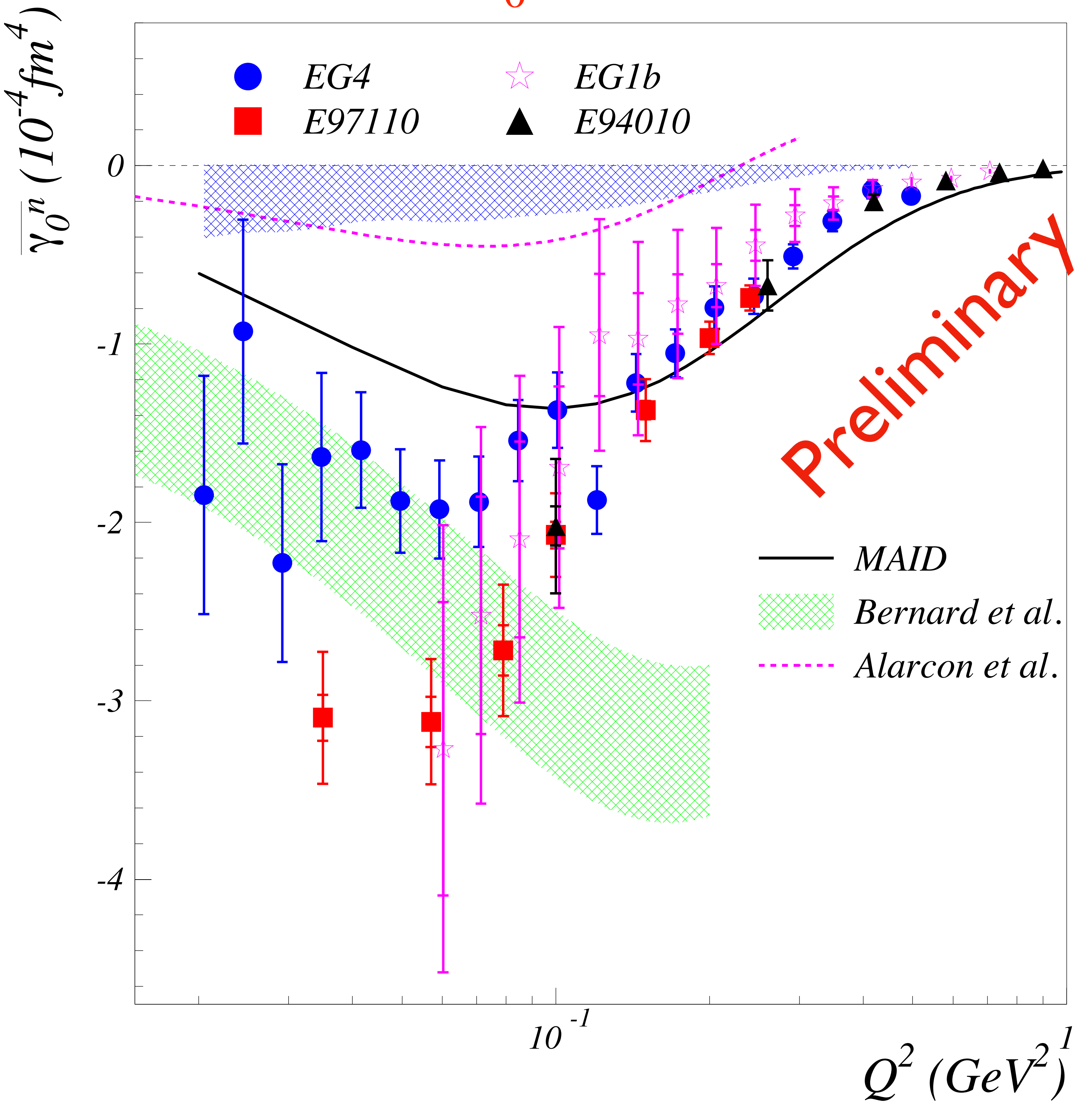
$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{1^-} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]dx$$

E97-110, γ_0^n:



- E97-110 agree with older data at larger Q^2 (EG1b, E94-010). Maid disagrees with the data.
- χEFT result of Alarcón et al disagrees with data.
- Bernard et al. χPT calculation agrees for lowest Q^2 points.

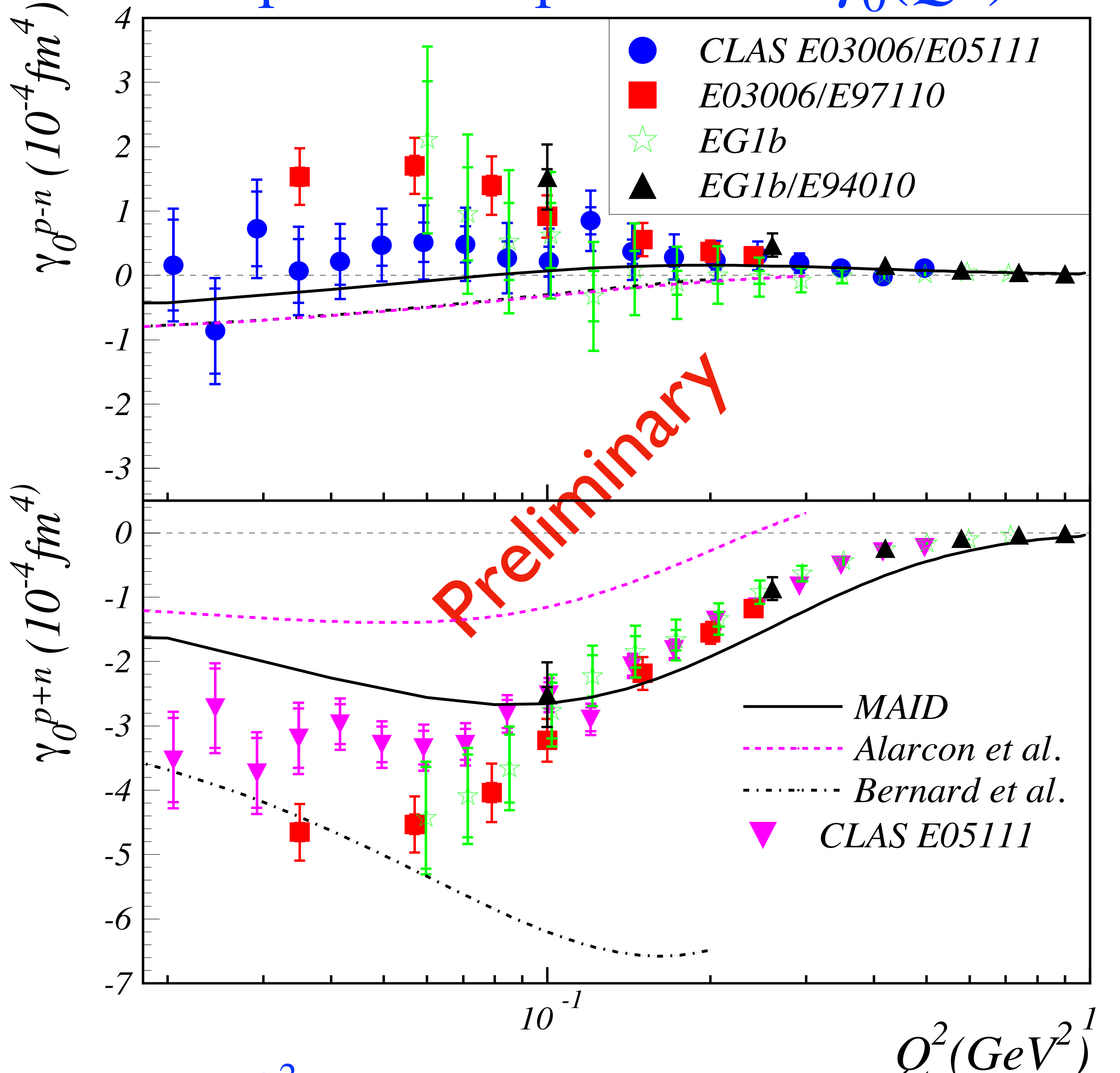
Higher moments: γ_0^n from E97-110 and EG4



Some tension between EG4 and E97-110

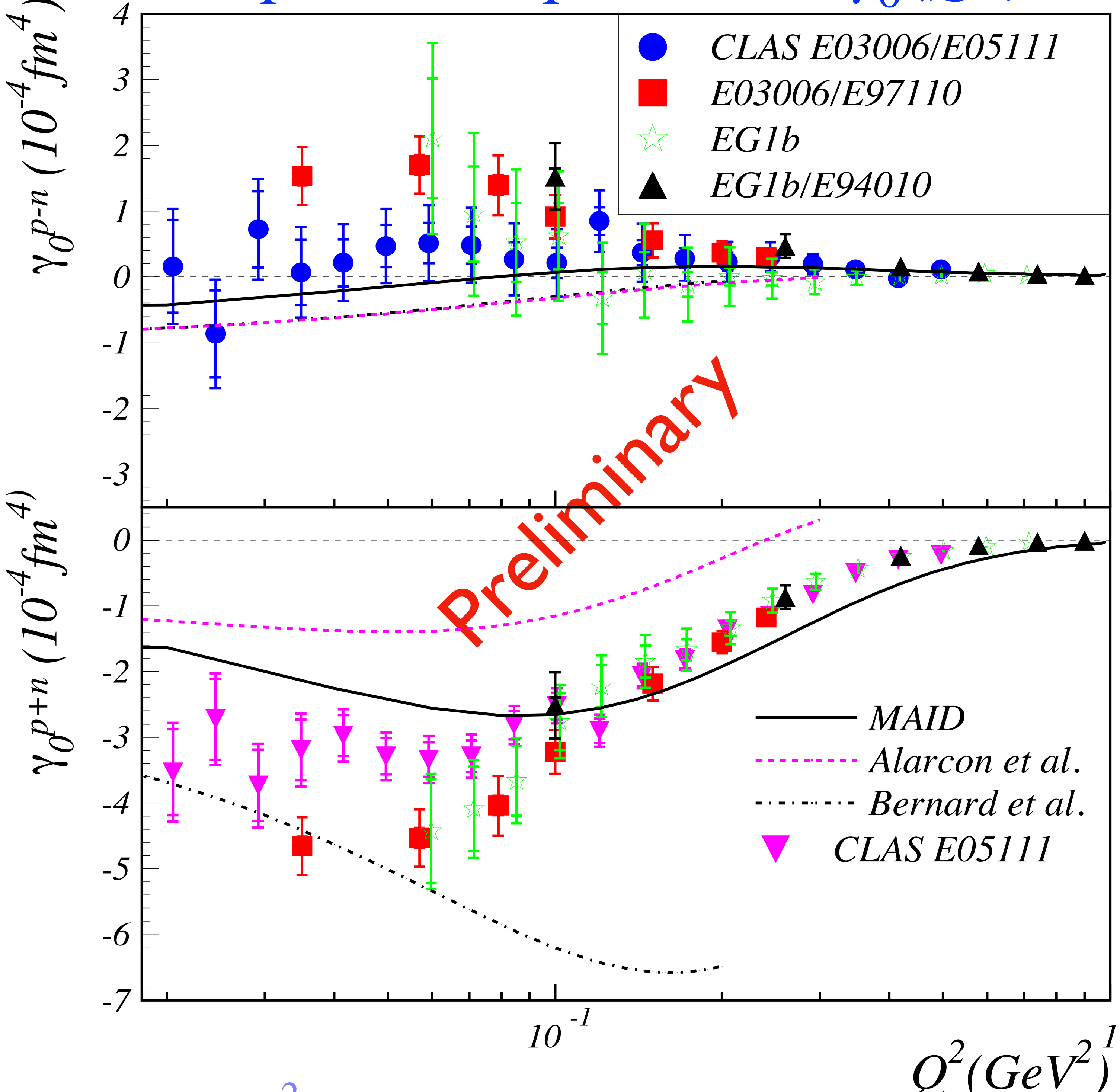
(we will discuss it when showing $\gamma_0^{p\pm n}$ isospin separation)

Isospin decomposition of $\gamma_0(Q^2)$



- Agreement with older (larger Q^2) experiment, EG1b, E94010.
- Tension between EG4 (p from H and D, n from D) and EG4/E97110 (p from H and n from ³He).
- χEFT result of Alarcón et al disagrees with data.
- Bernard et al. χEFT calculation agrees for γ_0^{p+n} and for γ_0^{p-n} for lowest Q^2 points.
- Both new and old data (from 5 different experiments) indicate that γ_0^{p-n} is positive.

Isospin decomposition of $\gamma_0(Q^2)$



- Agreement with older (larger Q^2) experiment, EG1b, E94010.
- Tension between EG4 (p from H and D, n from D) and EG4/E97110 (p from H and n from ³He).

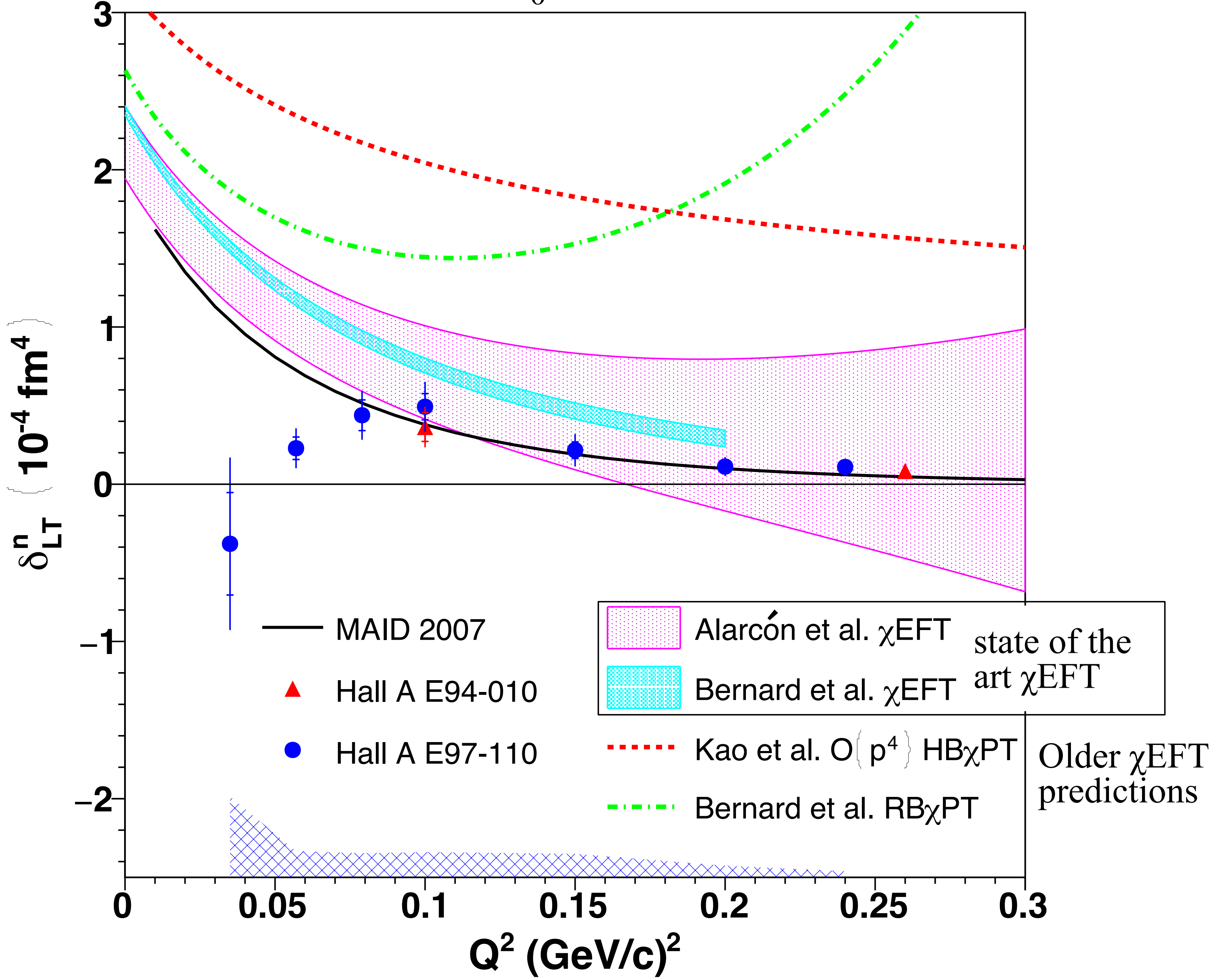
Tension may come from adding systematic uncertainties from E03006, E05111 or E97110 quadratically. If we combine linearly the total systematic uncertainties of each experiments, there is not tension.

- Both new and old data (from 5 different experiments) indicate that γ_0^{p-n} is positive.

Higher moments: LT spin polarizability δ_{LT} from E97-110

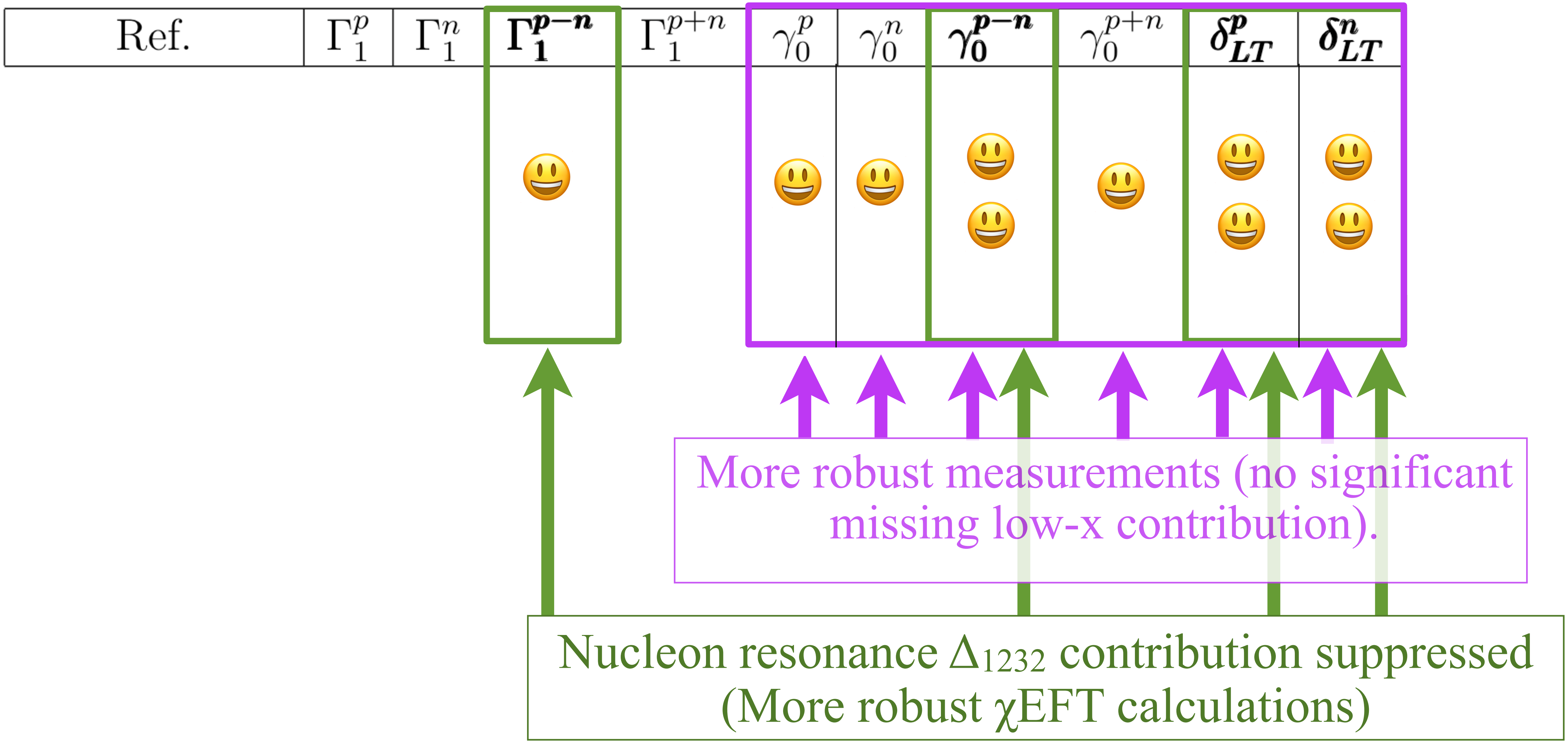
$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{1^-} x^2\left[g_1+g_2\right]dx$$

E97-110 neutron, δ^n_{LT}



- Good agreement with older data at larger Q^2 and with χEFT & MAID there.
- Disagreement at lower Q^2, although first moment $\int_0^{1^-} x^2[g_1+g_2]dx$ satisfies Schwinger SR.
- "$\delta^n_{LT}(Q^2)$ puzzle" still remains.

Testing χEFT



Testing χEFT

State of χEFT affairs before E97-110/EG4 run:

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

Testing χEFT

A: agree over range $0<Q^2\leq 0.1$ GeV^2
X: disagree over range $0<Q^2\leq 0.1$ GeV^2
- : No prediction available
*: Preliminary data

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
Alarcón 2020	A	A	~A	A	~A	X	X*	X*	A	X

state of the art χEFT (Bernard 2012, Alarcón 2020)

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

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

A: agree over range $0<Q^2\leq 0.1$
X: disagree over range $0<Q^2\leq 0.1$
- : No prediction available
*: Preliminary data

Testing χEFT

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
Alarcón 2020	A	A	~A	A	~A	X	X*	X*	A	X

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.

Conclusion

E97-110 provides high precision neutron spin structure data at very low Q^2, in the domain where χEFT is expected to be valid.

General good agreement with other experiments. Some possible tension with EG4 for the low Q^2 points.

Mixed of agreement/disagreement with χEFT, depending on observable, Q^2 range and calculations. "$\delta_{LT}^{n}(Q^2)$ puzzle", remains and γ_0^{p-n} disagree with χEFT expectation.

Experimental studies of the neutron generalized spin polarizabilities and spin sum rules at low Q^2

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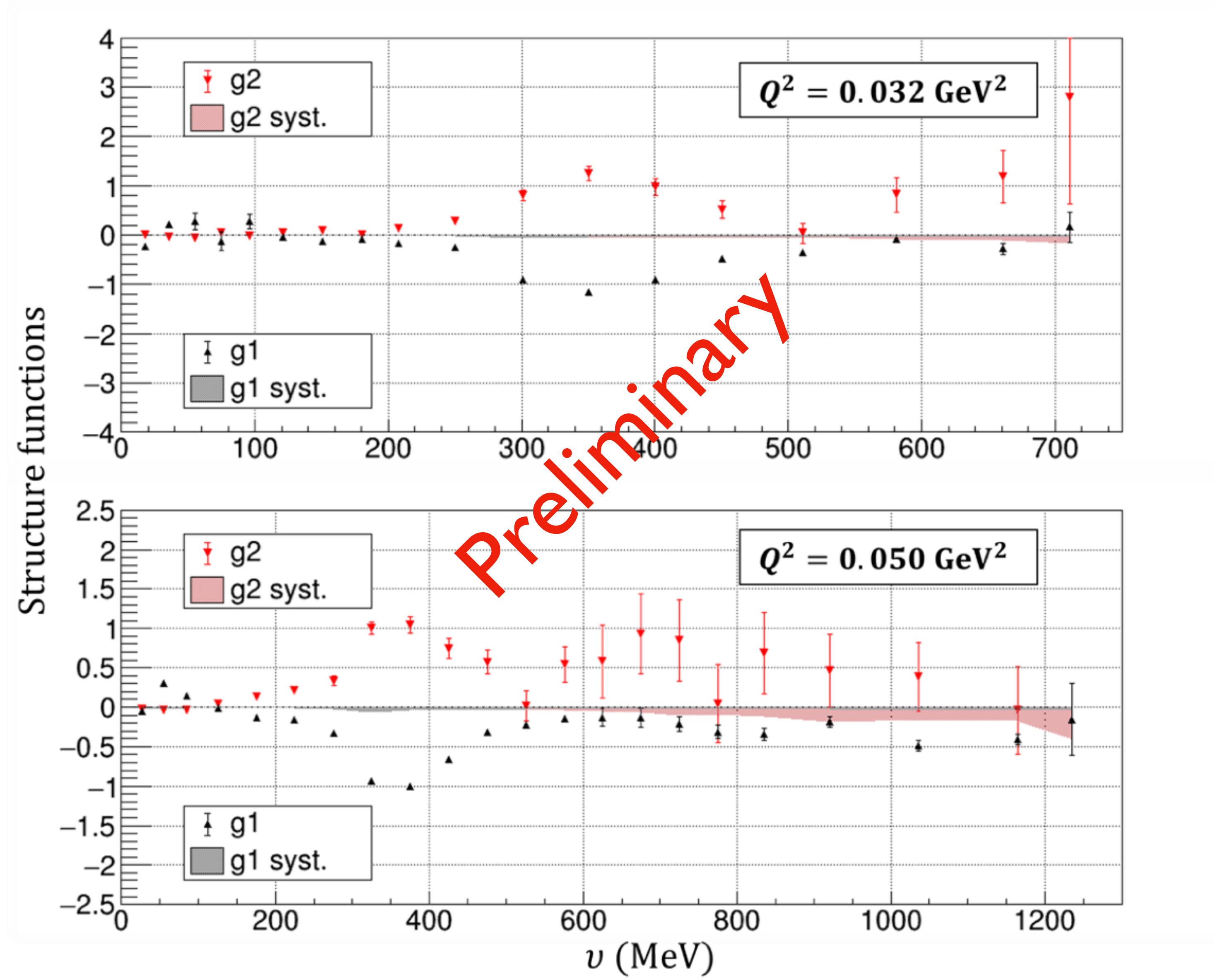
^{3}He spin sum rules at low Q^2

(For C. Peng)

^{3}He Spin-dependent Structure Functions

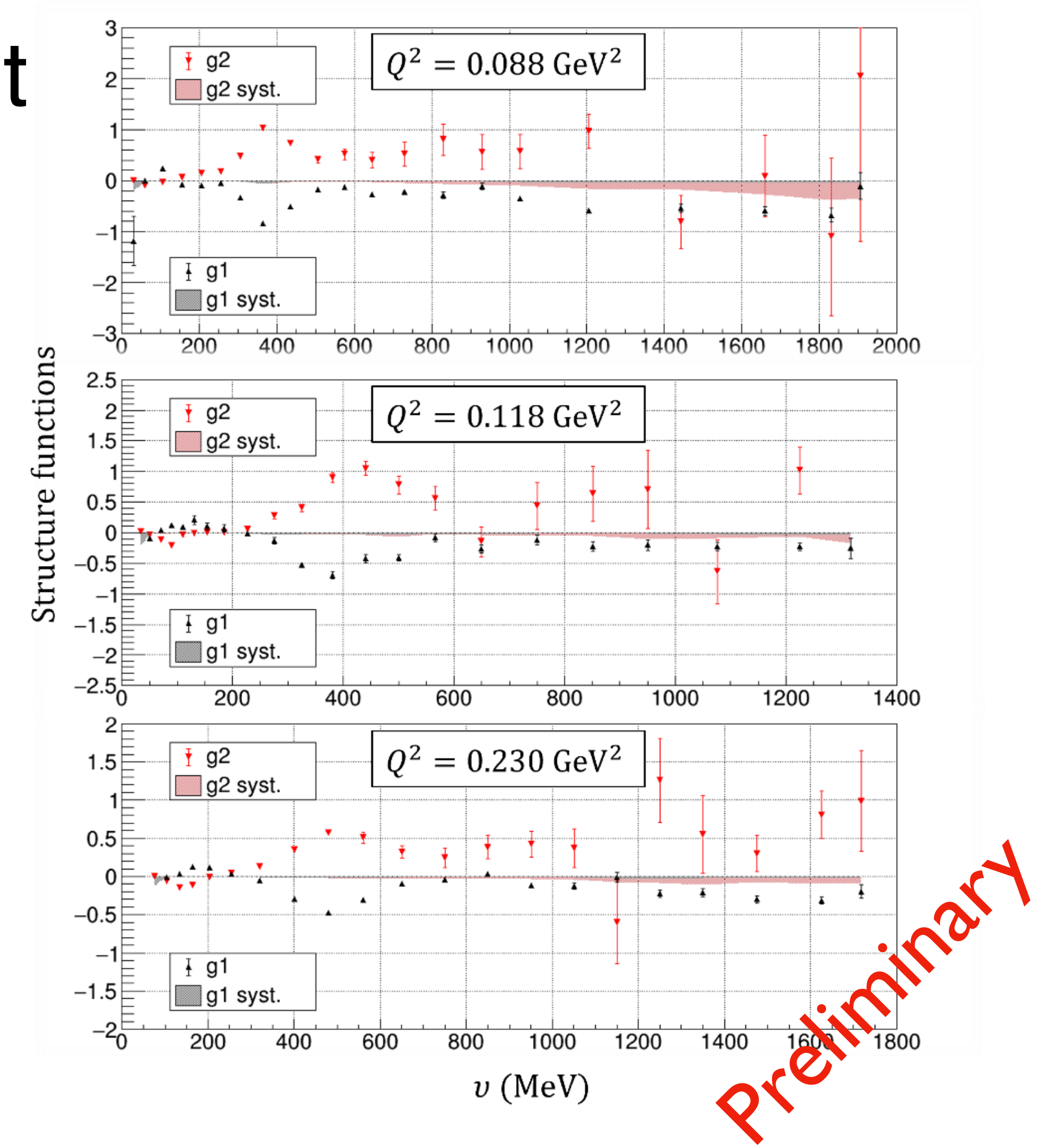
- Two lowest Q^2 point
  - Interpolated from
    - 1.1 GeV @ 9°
    - 2.1 GeV @ 6°
    - 2.8 GeV @ 6°

- $g_1 + g_2 \approx 0$ for $\Delta(1232)$



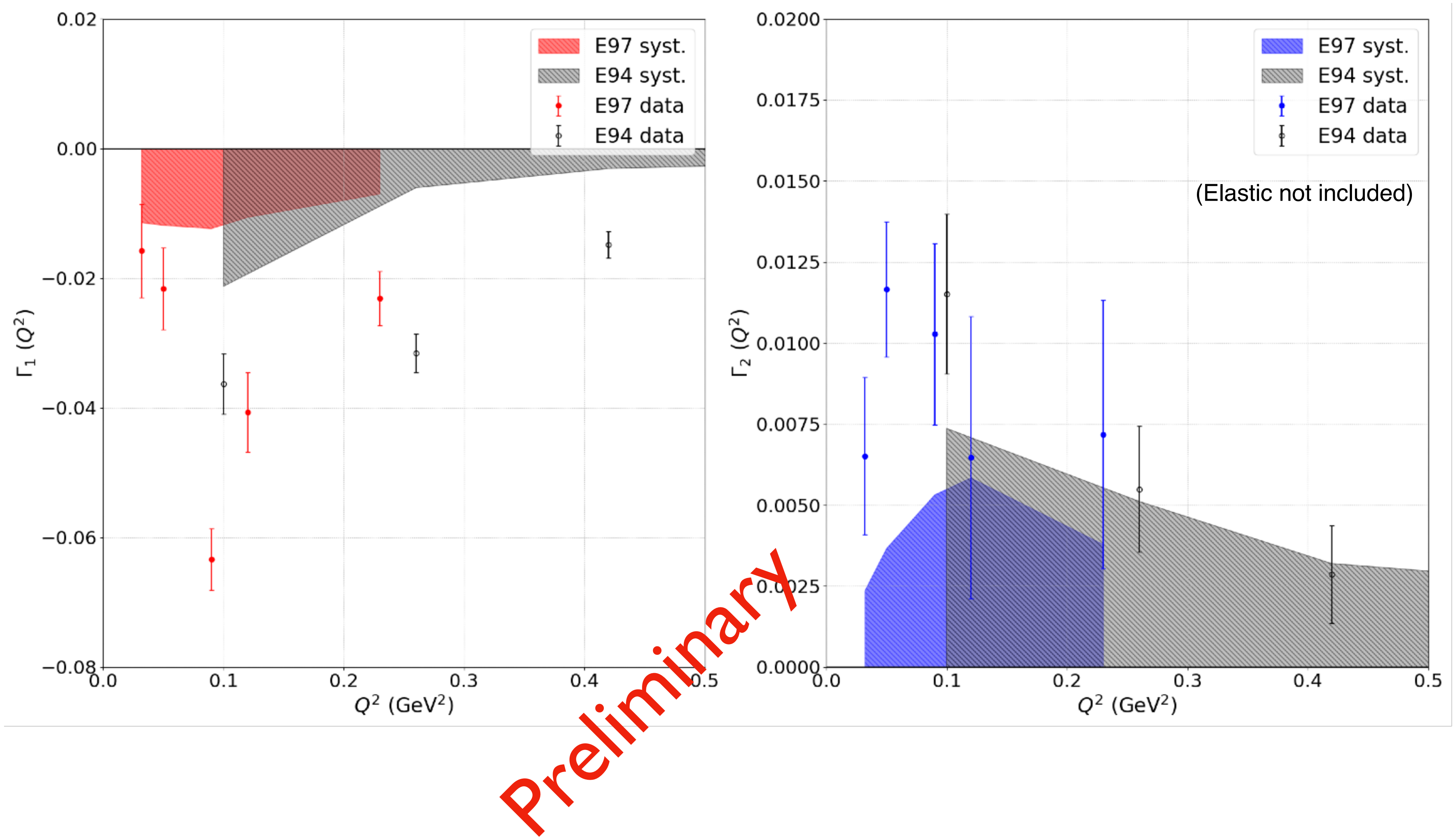
^{3}He Spin-dependent Structure Functions

- Three higher Q^2 point
  - Interpolated from
    - 2.8 GeV @ 6°
    - 2.2 GeV @ 9°
    - 3.3 GeV @ 9°
  - Additional constraints from
    - 4.2 GeV @ 6°
    - 3.8 GeV @ 9°
    - 4.4 GeV @ 9°



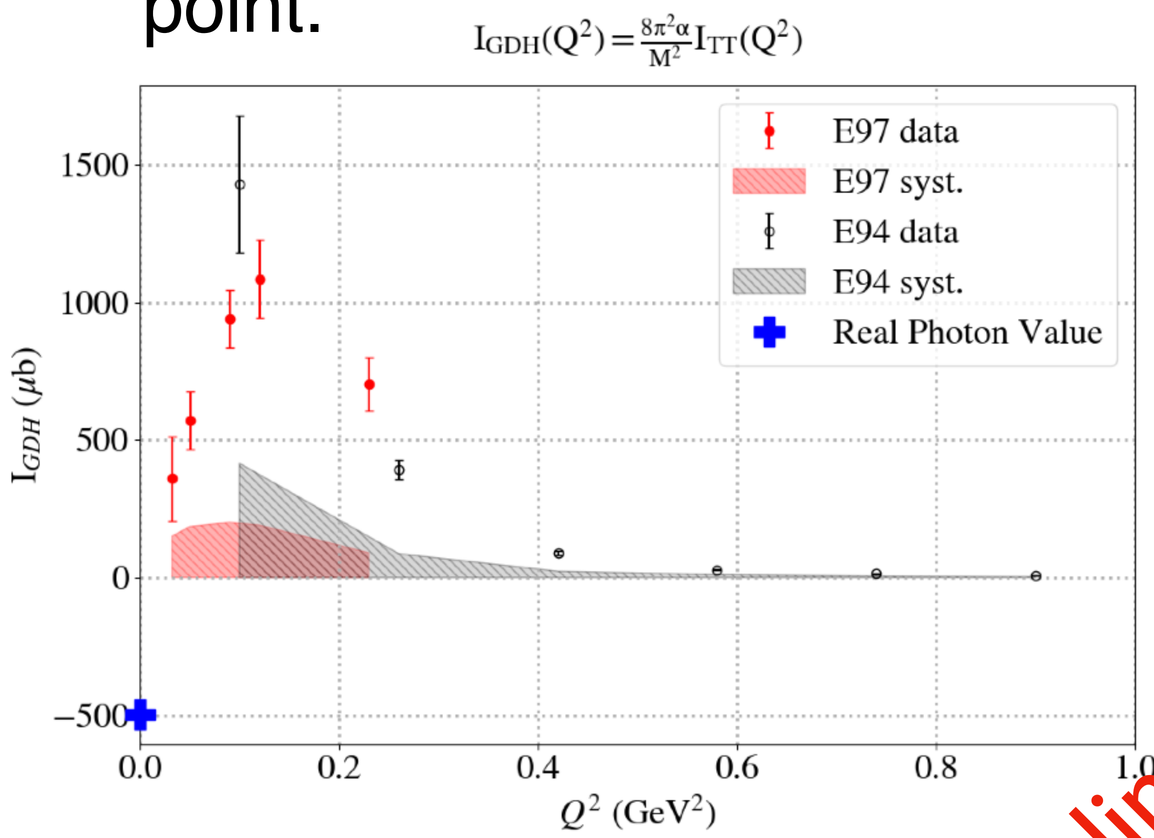
^{3}He First Moments Γ_1, Γ_2

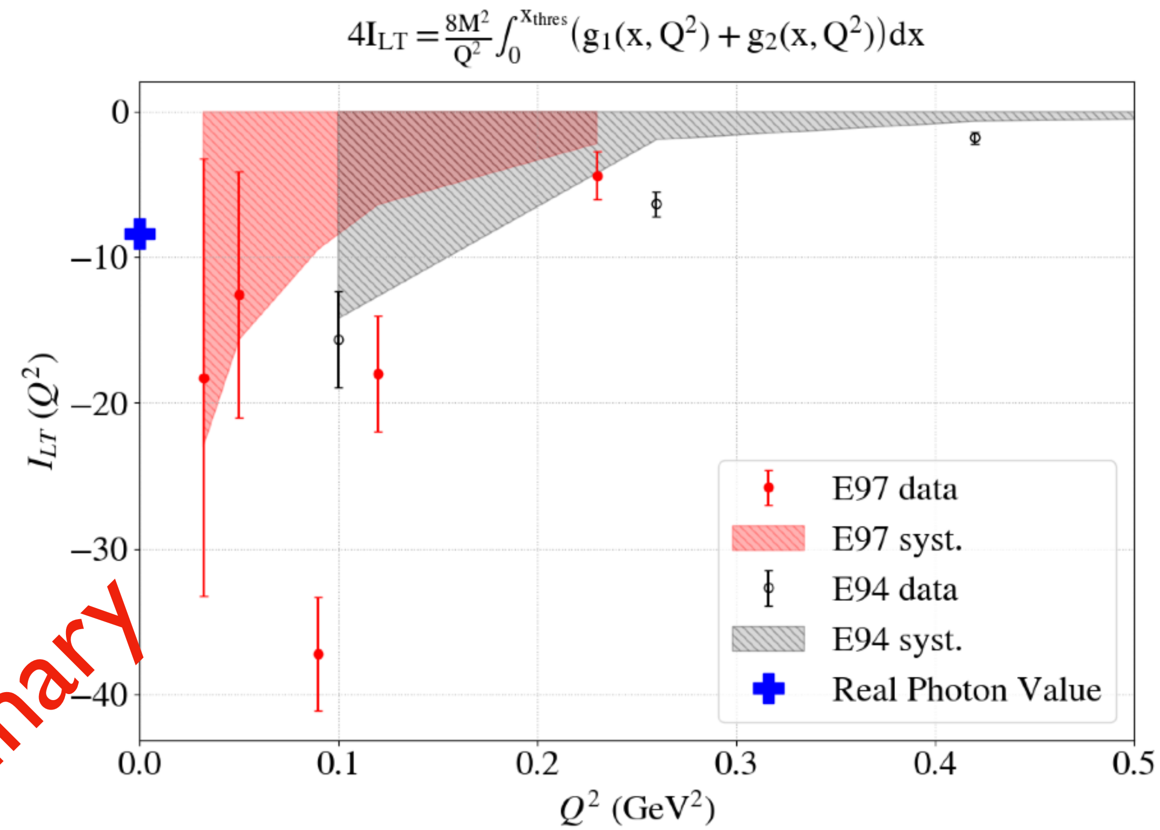
Consistent with E94 results at overlapping Q^2, a turning point observed at < 0.1 GeV^2



^{3}He Results - Sum Rules I_{TT}, I_{LT}

A turning point observed at < 0.1 GeV², data curve is approaching the real point.

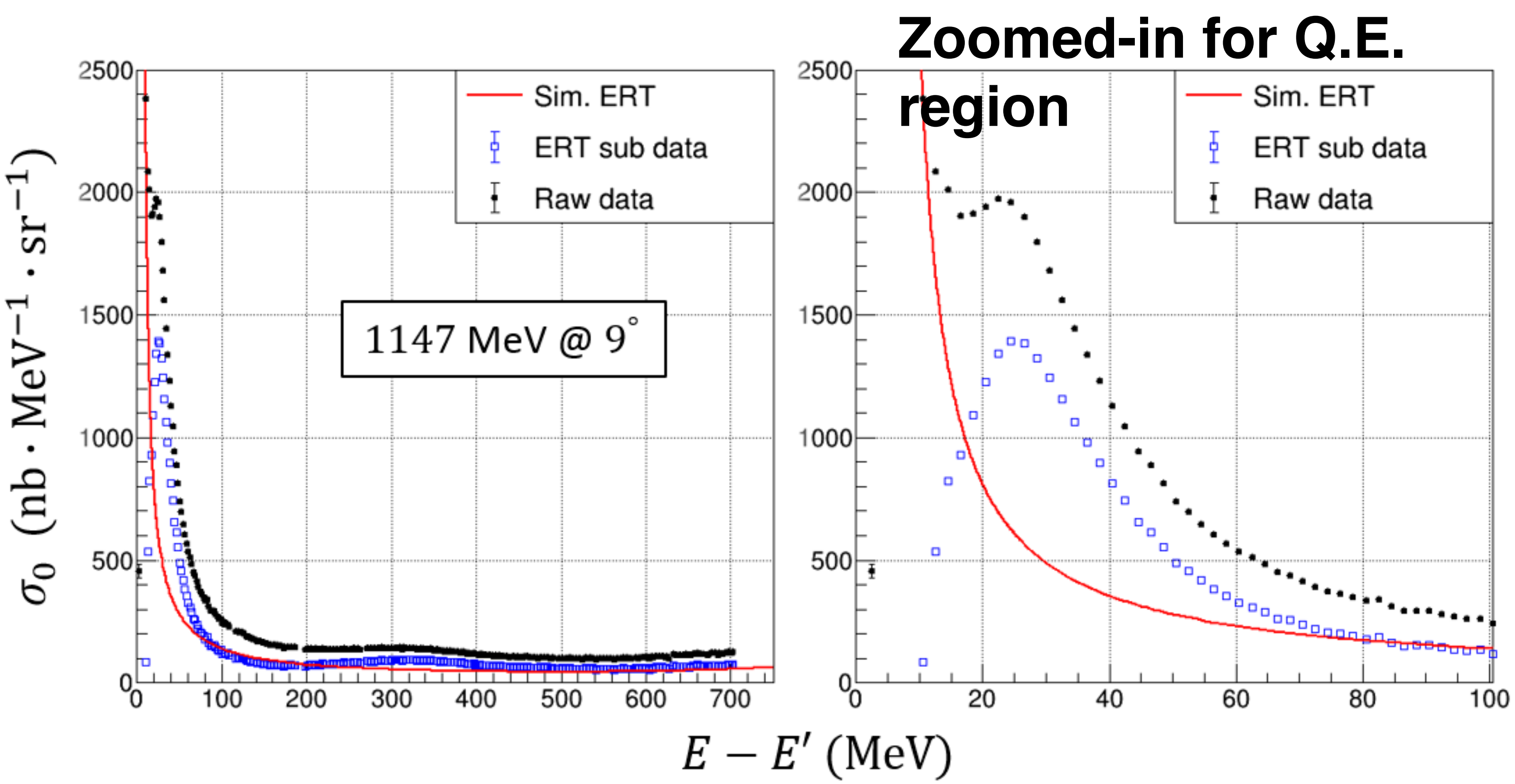




Backup Slides

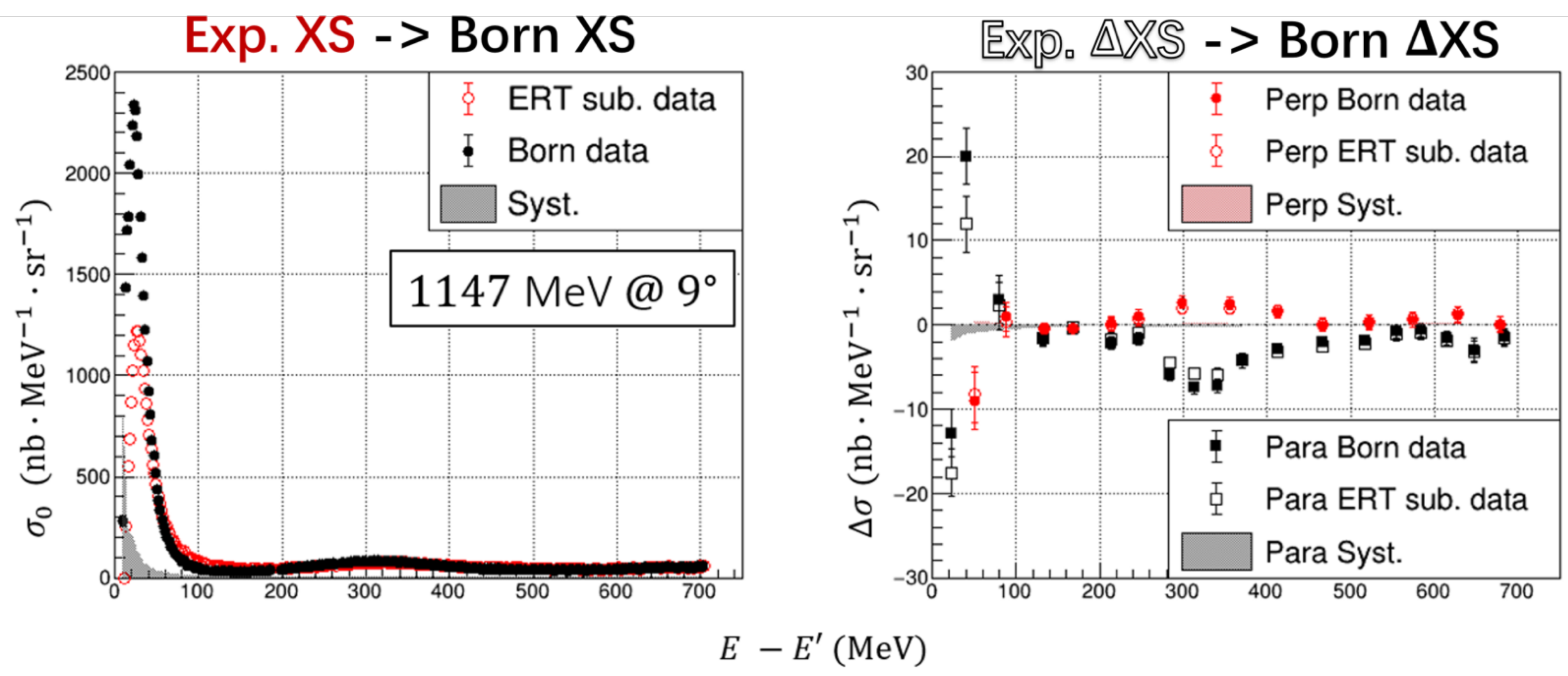
Radiative Corrections – ERT Subtraction

- Elastic radiative tail subtraction
  - The dominant systematic term at low $(\nu,\ Q^2)$



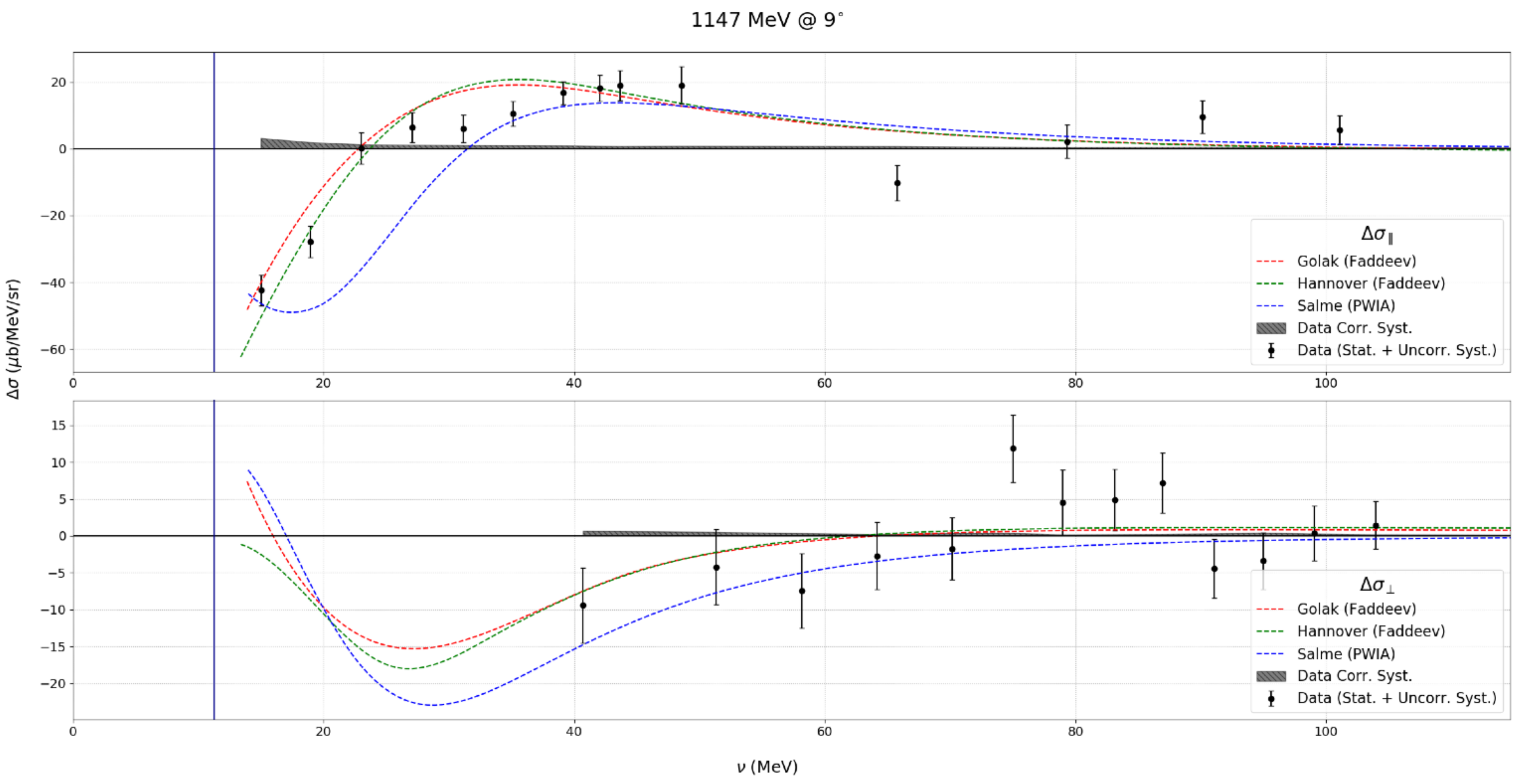
Radiative Corrections – Inelastic Spectrum

- Radiative correction for inelastic spectrum
  - Iterative process using the experimental data as a pseudo XS model



Faddeev Calculation Comparison

- Good agreement at lowest Q^2



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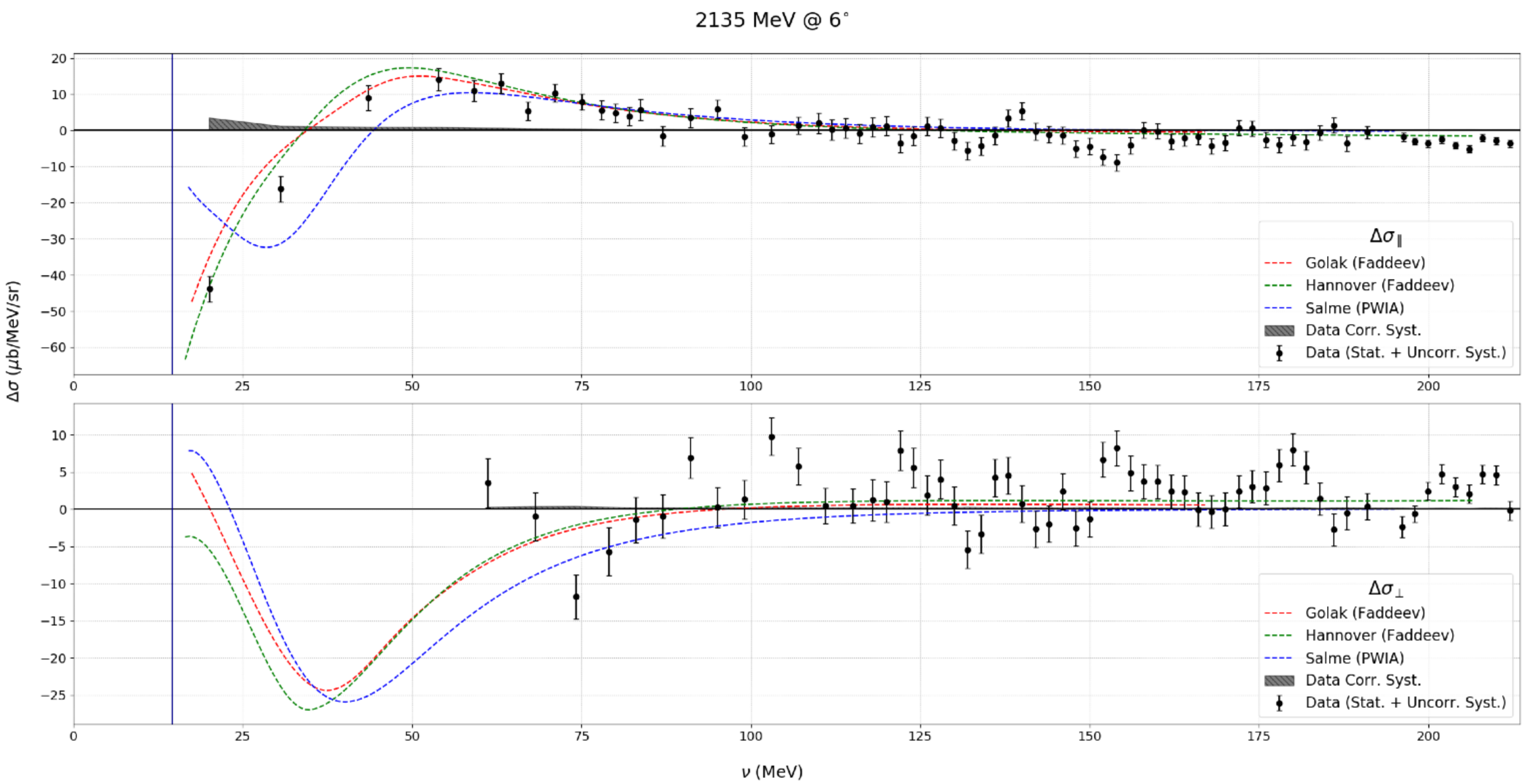
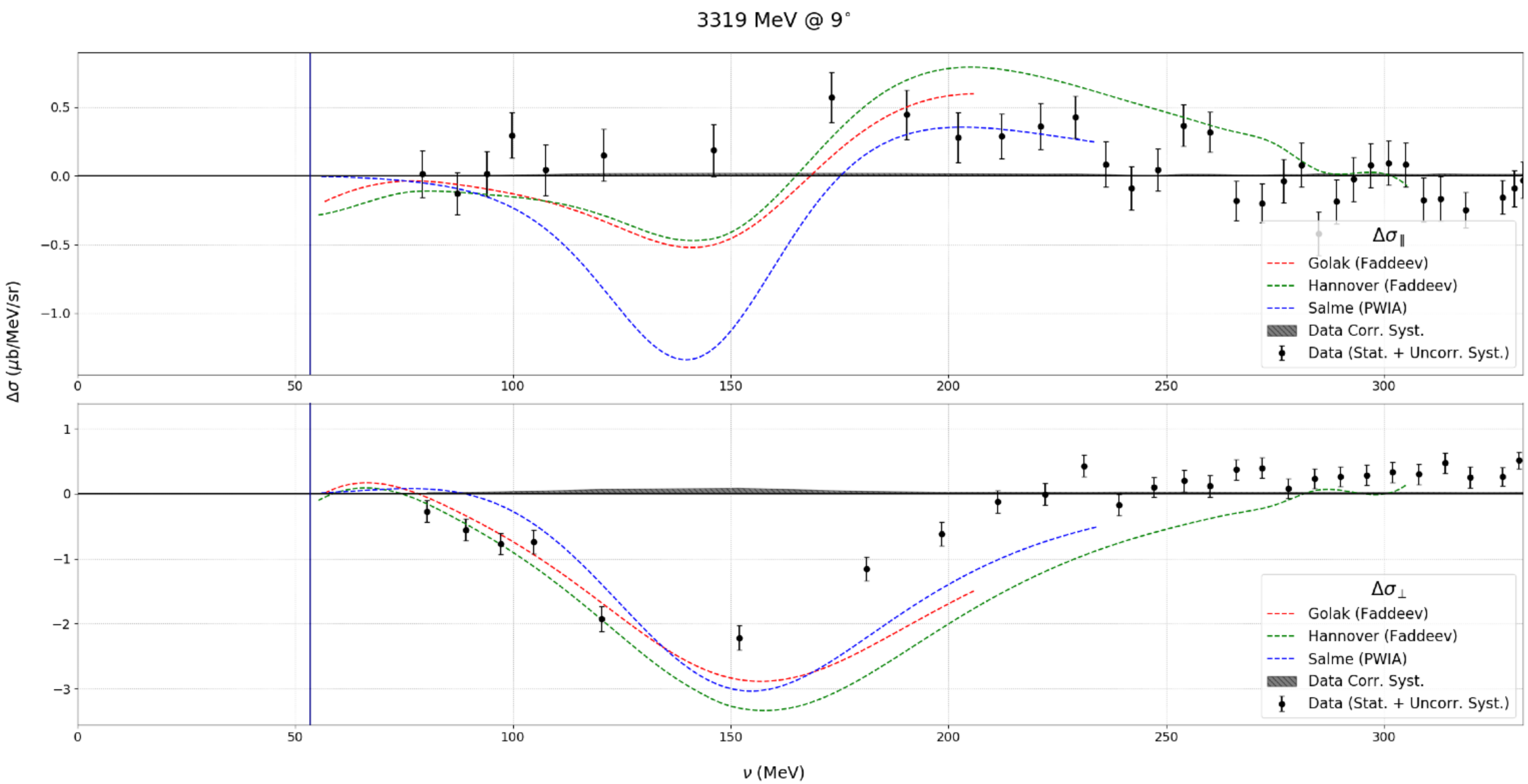


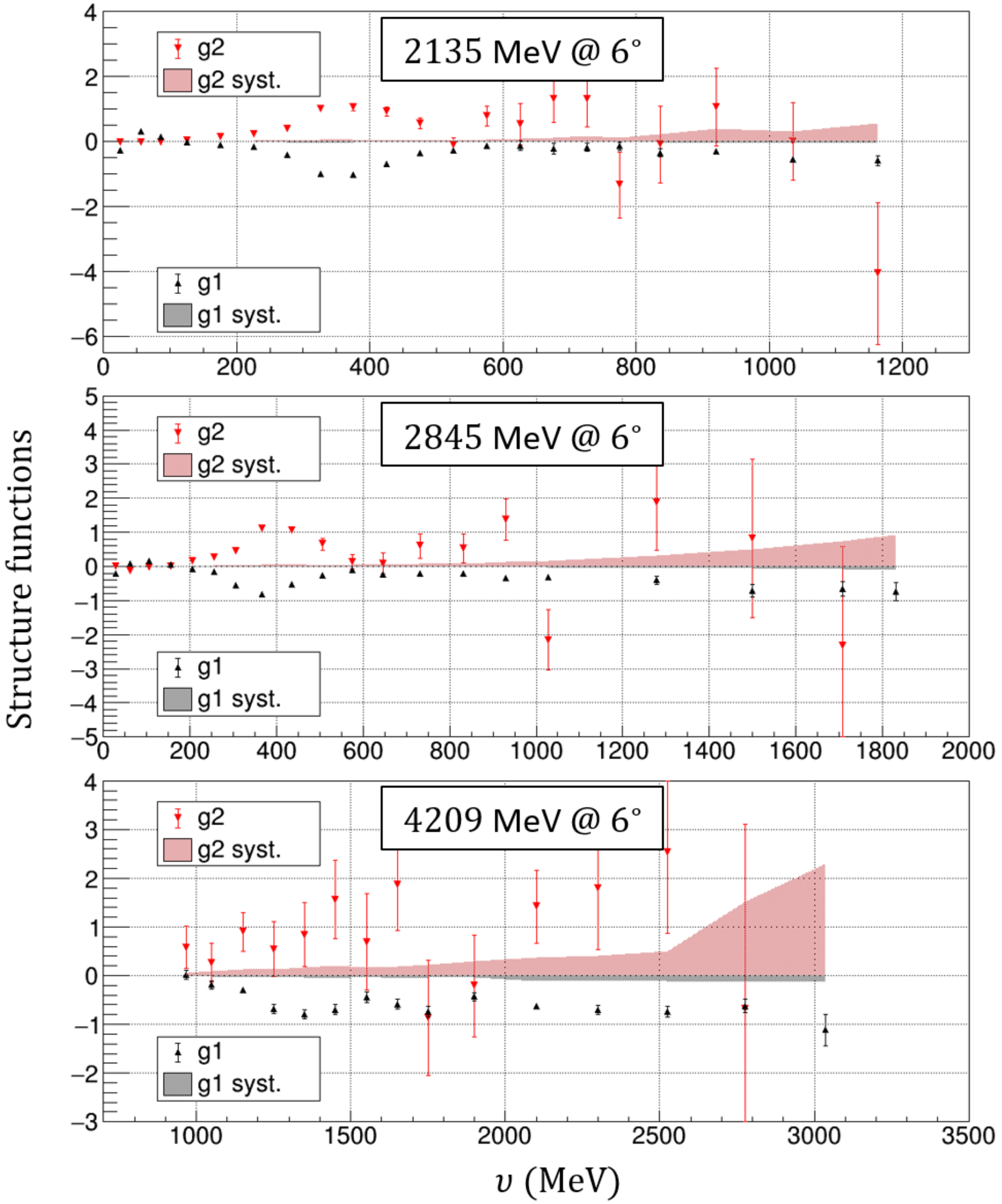
Faddeev Calculation Comparison

- Both Faddeev and PWIA are not working well at intermediate Q^2

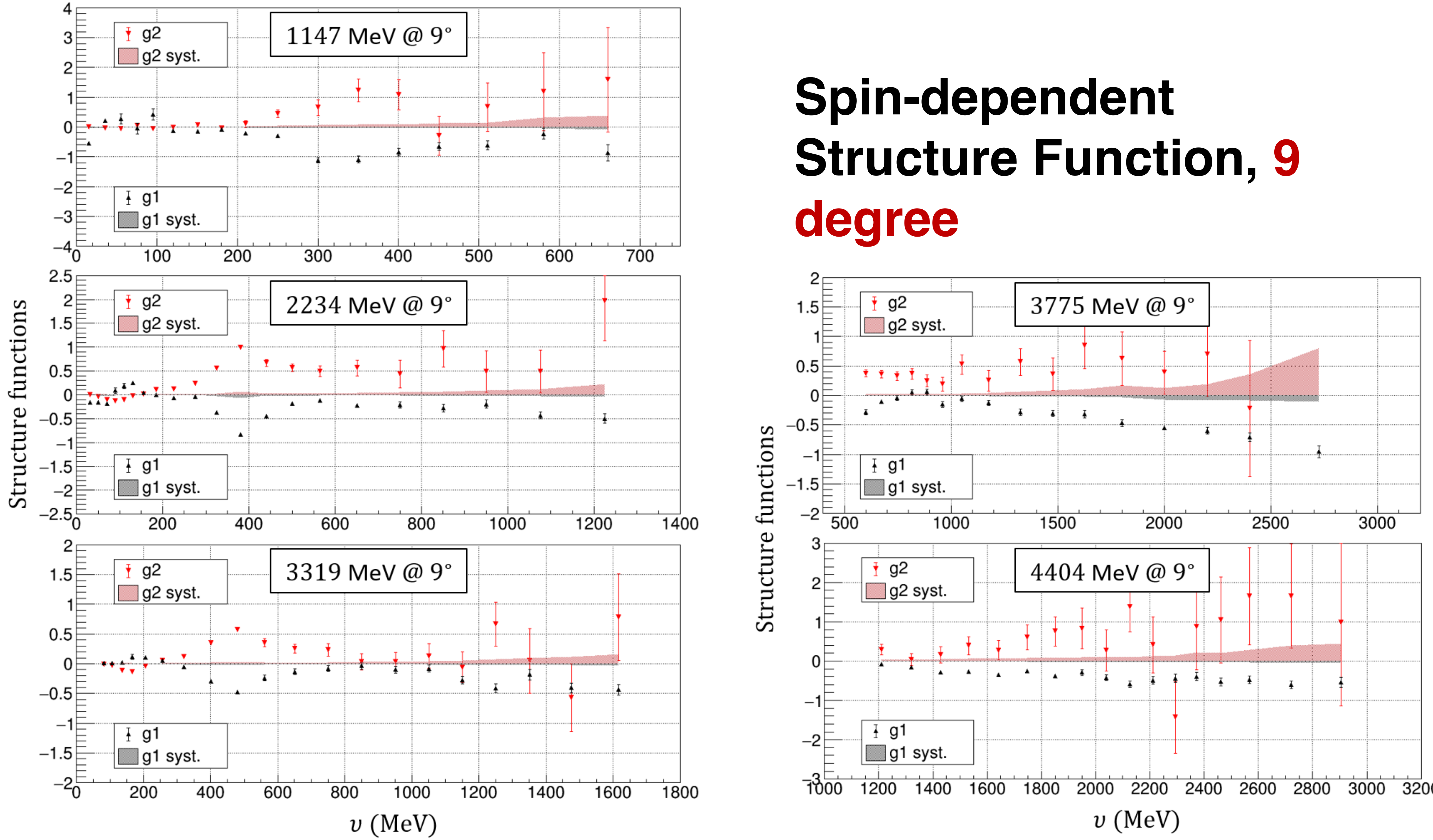


Spin-dependent Structure Function, 6 degree

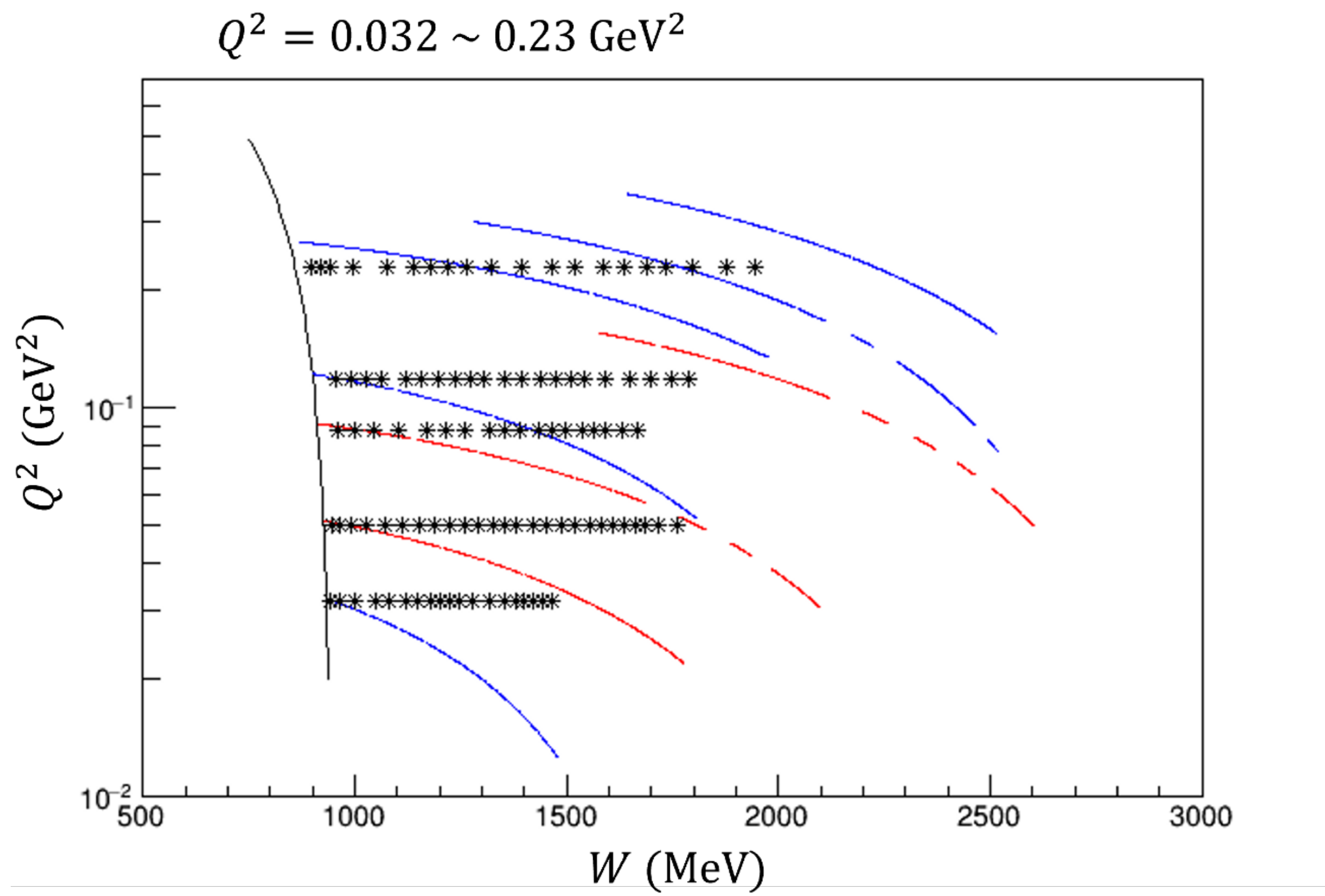
- $g_1 + g_2 \approx 0$ for Delta resonance



Spin-dependent Structure Function, 9 degree



Interpolation to Constant Q2 (He3 results)



Back-up slides

The GDH and Generalized GDH Sum Rules

Sum rule: relation between an integral of a dynamical quantity (cross section, structure function,...) and a global property of the target (mass, spin,...).

Can be used to:

- Test theory (e.g. QCD) and hypotheses with which they are derived. Ex: GDH, Ellis-Jaffe, Bjorken sum rules.
- Measure the global property (e.g. spin polarizability sum rules)

GDH sum rule: derived for real photons ($Q^2 = 0$):

$$\int_{\nu_{thr}}^{\infty} \frac{\sigma_A(\nu)-\sigma_P(\nu)}{\nu}\, d\nu = \frac{-4\pi^2 S\alpha\kappa^2}{M^2}$$

QED coupling constant

target anomalous magnetic moment

target spin

target mass

photoprod. cross section with photon spin anti-parallel to S

photon spin parallel to S

The GDH and Generalized GDH Sum Rules

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$$\int_{\nu_{thr}}^{\infty} \frac{\sigma_A(\nu)-\sigma_P(\nu)}{\nu} d\nu = \frac{-4\pi^2 S\alpha\kappa^2}{M^2}$$

QED coupling constant (α)

target anomalous magnetic moment (κ)

target spin (S)

target mass (M)

photoprod. cross section with photon spin anti-parallel to S (σ_A)

photon spin parallel to S (σ_P)

Generalized GDH sum rule: valid for any Q^2. Recover the original GDH sum rule as $Q^2 \to 0$

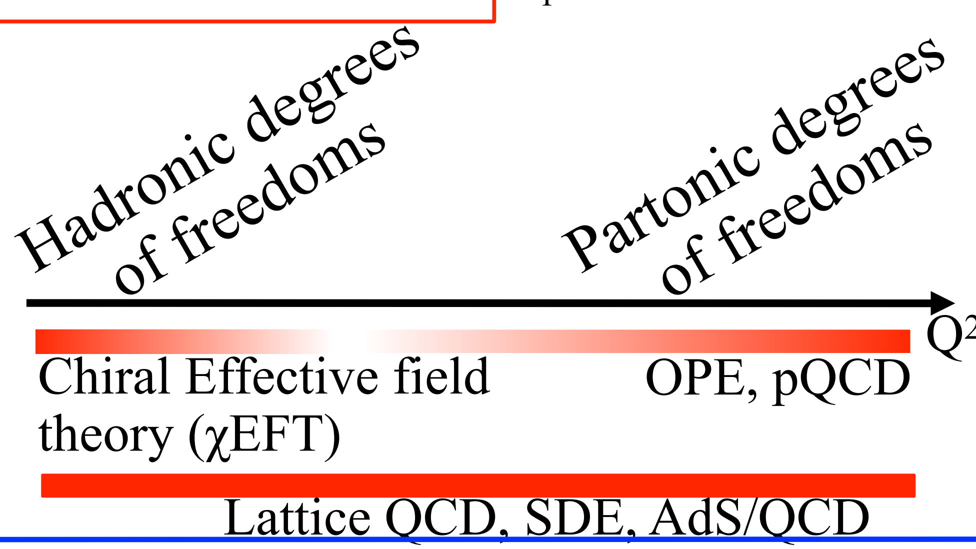
$$\Gamma_1(Q^2) = \int_0^{x_{th}} g_1(x,Q^2)dx = \frac{Q^2}{2M^2} I_1(0,Q^2)$$

$g_1(\nu,Q^2)$: first spin structure function (mostly a longit. target pol. observable)

$I_1(\nu,Q^2)$: first covariant polarized VVCS amplitude

⇒Study QCD at any scale

$I_1(0,Q^2)$:



The GDH and Generalized GDH Sum Rules

Sum rule: relation between an integral of a dynamical quantity (cross section, structure function,...) and a global property of the target (mass, spin,...).

Can be used to:

- Test theory (e.g. QCD) and hypotheses with which they are derived. Ex: GDH, Ellis-Jaffe, Bjorken sum rules.
- Measure the global property (e.g. spin polarizability sum rules)

GDH sum rule: derived for real photons ($Q^2=0$):

$$\int_{\nu_{thr}}^{\infty} \frac{\sigma_A(\nu)-\sigma_P(\nu)}{\nu} d\nu = \frac{-4\pi^2 S\alpha\kappa^2}{M^2}$$

QED coupling constant

target anomalous magnetic moment

target spin

target mass

photoprod. cross section with photon spin anti-parallel to S

photon spin parallel to S

Generalized GDH sum rule: valid for any Q^2. Recover the original GDH sum rule as $Q^2 \to 0$

$$\Gamma_1(Q^2) = \int_0^{x_{th}} g_1(x,Q^2)dx = \frac{Q^2}{2M^2} I_1(0,Q^2)$$

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E97-110

Spin polarizabilities sum rules

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Spin polarizability sum rules involve higher moments:

Generalized forward spin polarizability:

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

$g_2(\nu,Q^2)$: second spin structure function (mostly a perp. target pol. observable)

Longitudinal-Transverse polarizability:

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

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Longitudinal-Transverse polarizability:

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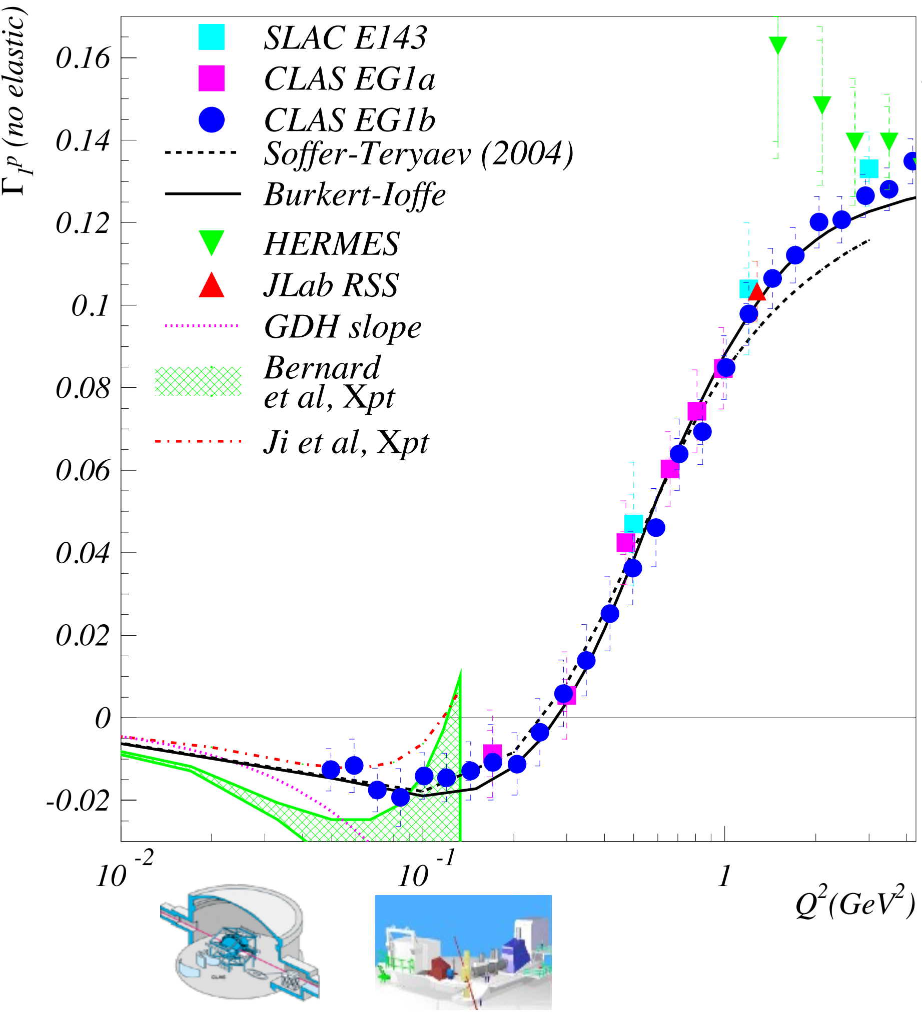
We do not know how to measure directly generalized spin polarizabilities. The spin polarizability sum rules are used to access them.

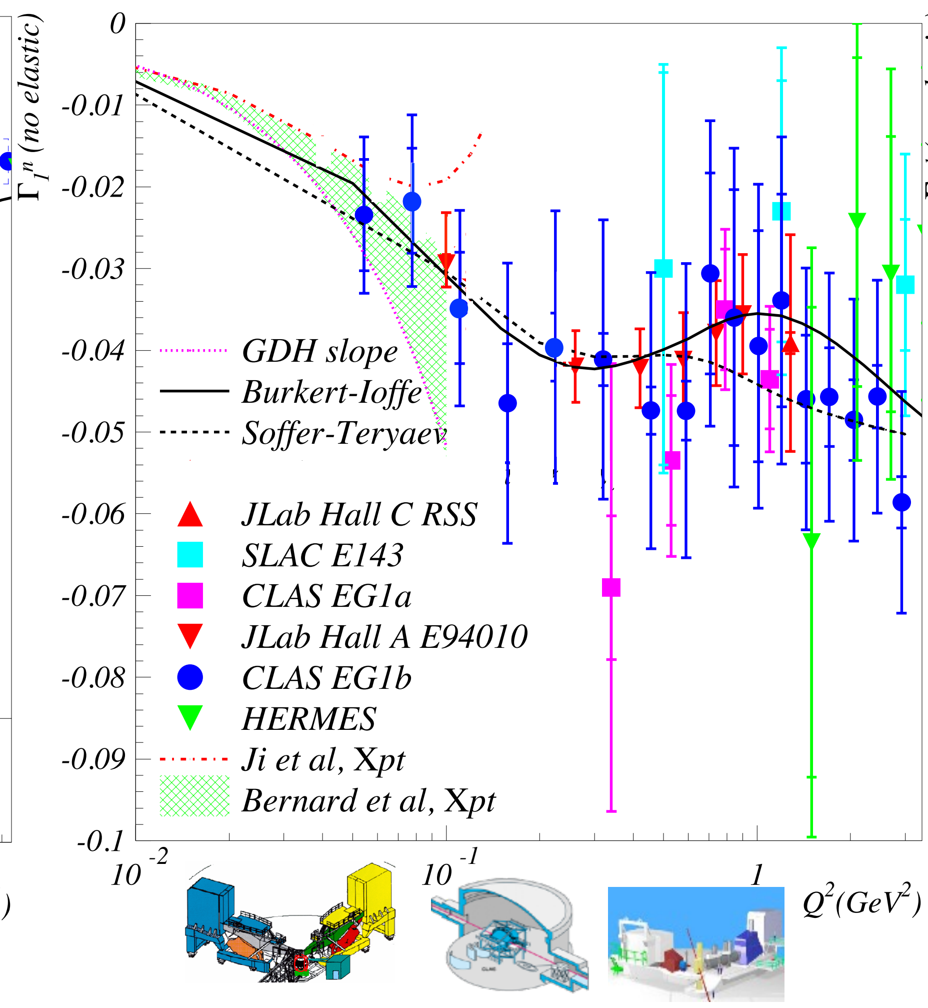
Previous JLab data: high to intermediate Q^2

$\Gamma_1(Q^2)$ Before EG4 run:

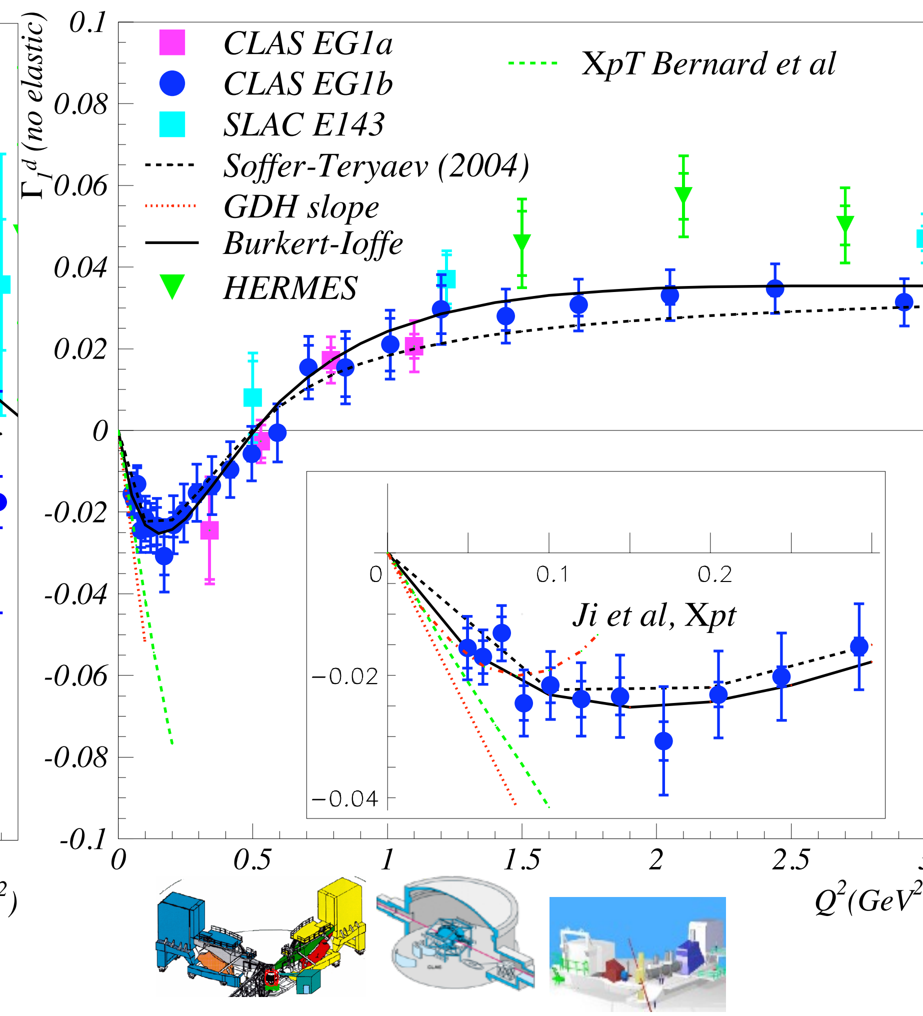
Proton



Neutron



Deuteron

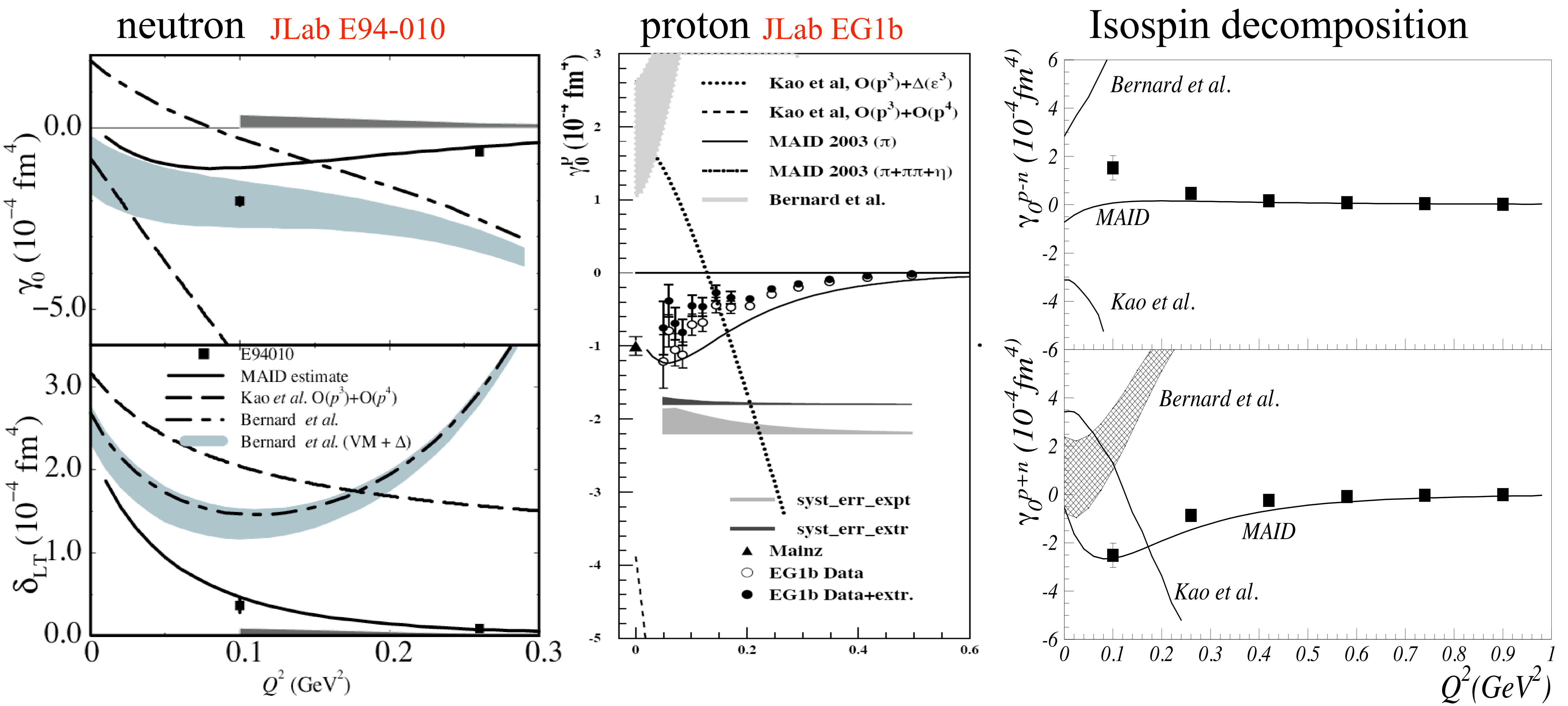


Precise mapping of spin structure function moments in intermediate Q^2 region for p, n and d.

PQCD, models and data agree.
Not so clear for the χEFT predictions available at that time.

Previous JLab data: high to intermediate Q^2

$\gamma_0(Q^2)$ Before EG4 run:



No agreement with the χEFT predictions available at that time.

Previous data: high to intermediate Q^2

State of χEFT affairs before EG4 run:

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

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

Testing χEFT

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}	$\boldsymbol{\delta_{LT}^p}$	$\boldsymbol{\delta_{LT}^n}$
			😃		😃	😃	😃	😃	😃	😃
							😃		😃	😃

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

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

Testing χEFT

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

State of χEFT affairs before EG4 run:

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

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

The discrepancies for δ_{LT}^n 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., reaching low enough 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.