The Spin Structure of the proton at low Q^2 from CLAS EG4

A. Deur

Jefferson Lab

03/08/2019

On behalf of the EG4-proton analysis team: X. Zheng, J. Zhang, S. Kuhn, M. Ripani, M. Osipenko, H. Kang

The EG4 experiment Group

Main goal: measurement of the generalized Gerasimov-Dreall-Hearn (GDH) sum for the proton and deuteron at low Q^2.

E03-006 (NH_3):

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

Students: H. Kang (Seoul U.), K. Kovacs✦ (UVa)

E06-017 (ND_3)

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

Students: K. Adhikari✦ (ODU)

K.P. Adhikari *et al.* (CLAS Collaboration), "Measurement of the Q^2 dependence of the Deuteron Spin Structure Function g_1 and its Moments at Low Q^2 with CLAS" PRL 120, 062501 (2018)

EG4 ran from Feb. to May 2006.

Main goal: inclusive analyses. Also, exclusive analysis

X. Zheng *et al.* (CLAS Collaboration), PRC 94, 045206 (2016)

✦ Graduated.

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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)

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

QED coupling constant

target anomalous magnetic moment

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

target mass

target spin

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

photon spin parallel to S

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

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

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

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

$\Rightarrow$Study QCD at any scale

Hadronic degrees of freedoms

Partonic degrees of freedoms

Q^2

$I_1(0,Q^2)$:

Chiral perturbation theory (χpt)

OPE, pQCD

Lattice QCD, SDE, AdS/QCD

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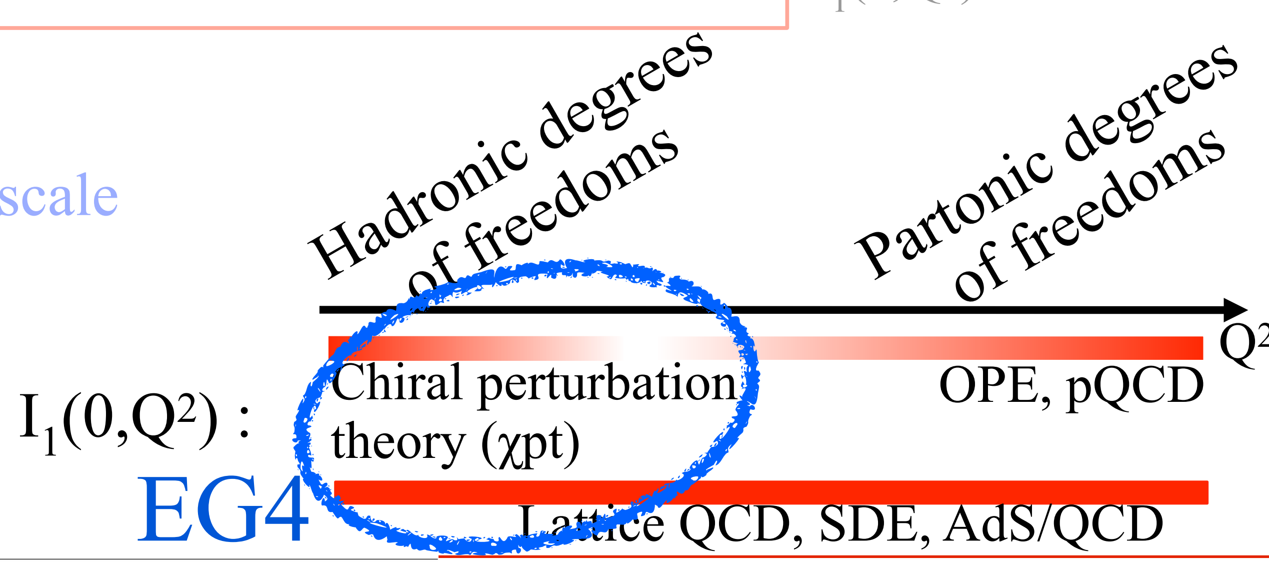

Spin polarizabilities sum rules

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- Measure the global property (e.g. spin polarizability sum rules)

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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$g_2(\nu,Q^2)$ suppressed in γ_0

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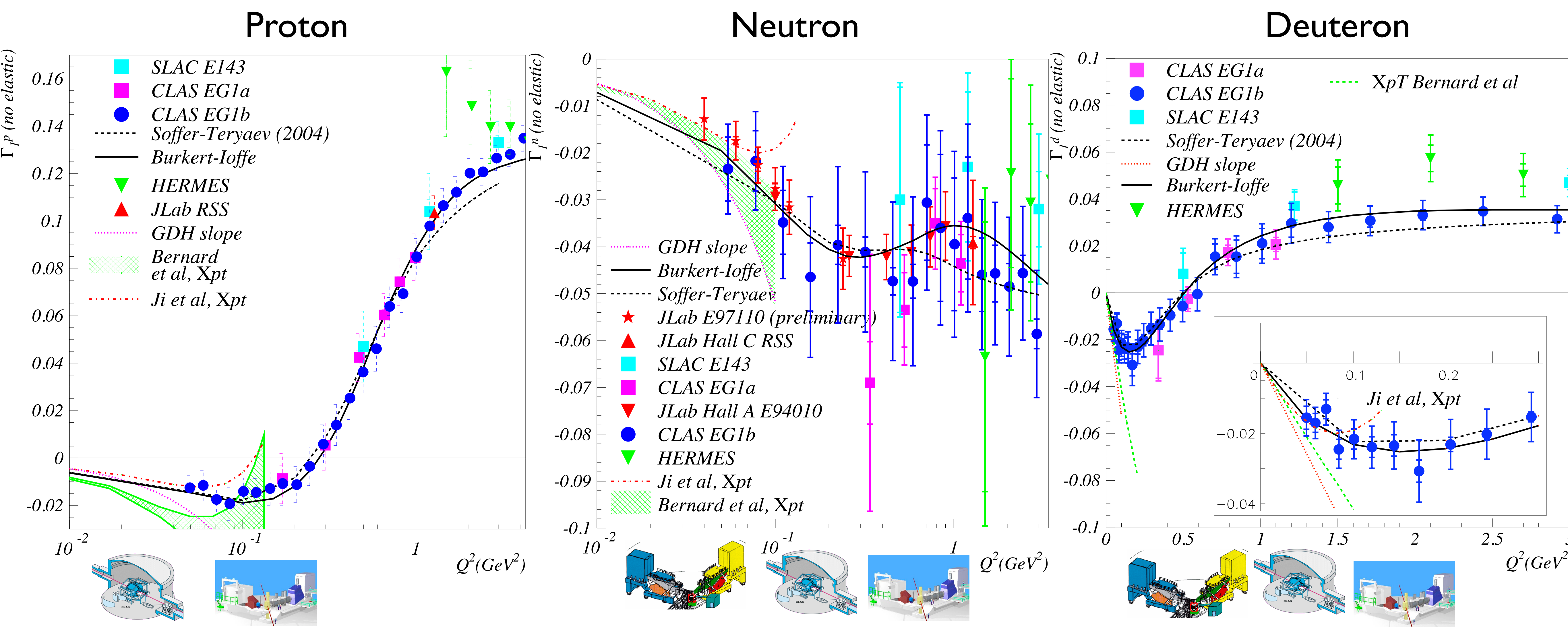
Previous JLab data: high to intermediate Q²

Before EG4 run (2006):



Precise mapping of spin structure function moments in intermediate Q² region for p, n and d.

PQCD, models and data agree.
Not so clear for χpT.

Previous data: high to intermediate Q^2

State of χpT affairs before EG4 run (2006):

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}	$\boldsymbol{\delta_{LT}^n}$	d_2^p	d_2^n
Bernard *et al.* [14]	X	X	A	X	X	A	X	X	X	-	X
Ji *et al.* [15]	X	X	A	X	-	-	-	-	-	-	-
Kao *et al.* [16]	-	-	-	-	X	A	X	X	X	-	X

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-: no calculation available

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Δ suppressed (expected)

"δ_{LT} crisis"

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Volker D. Burkert
PRD 63, 097904 (2001)
[nucl-th/0004001]

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- Mixed success of χpT;
- Surprising discrepancies (δ_{LT} crisis);
- Validity range smaller than hoped for: $Q^2 < \sim 0.1$ GeV^2 ⇒Ambiguous χpT tests.

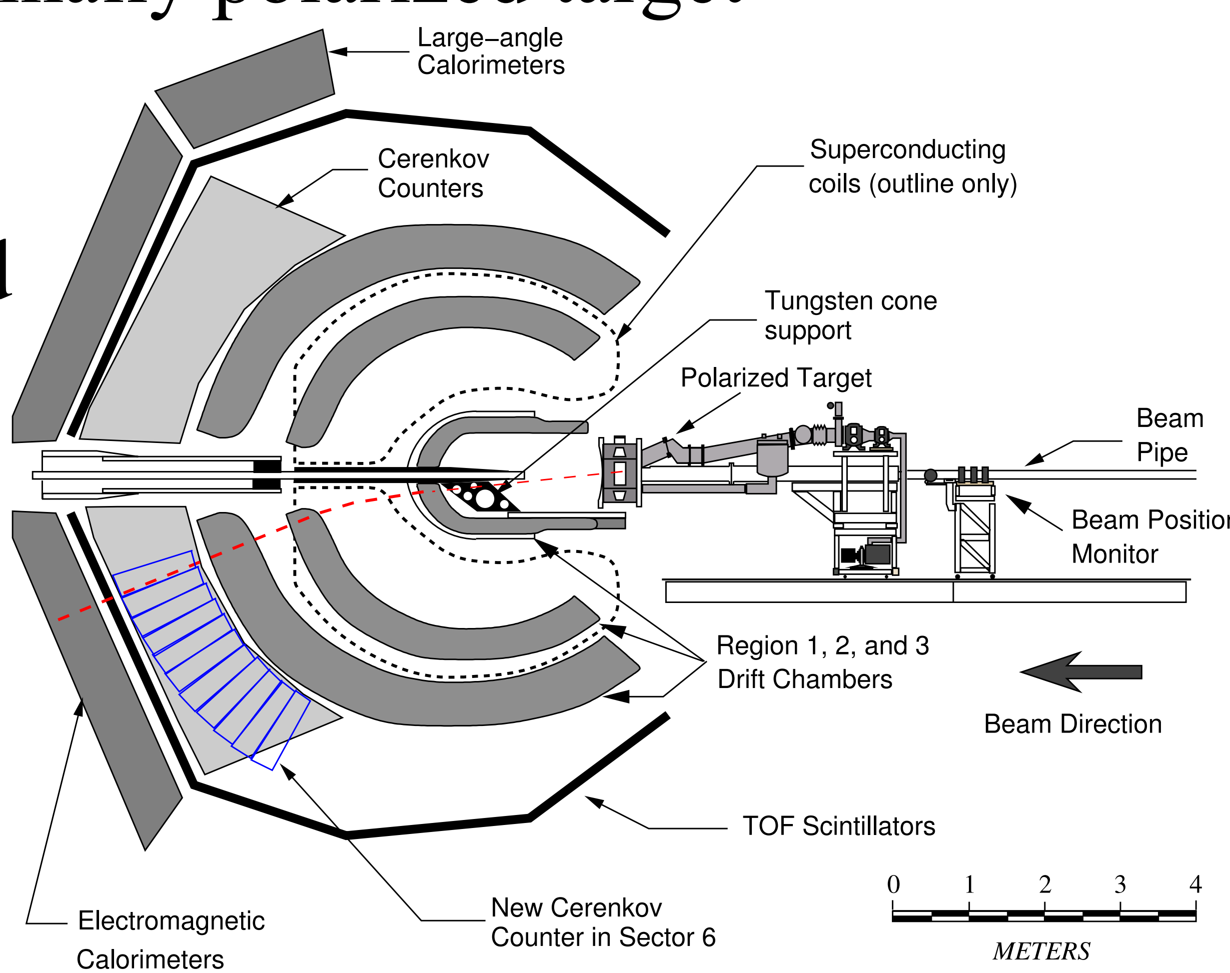
⟹ Need new data on p and n (d, ^{3}He) at very low Q^2 (i.e. for integrals over ν: low angles).

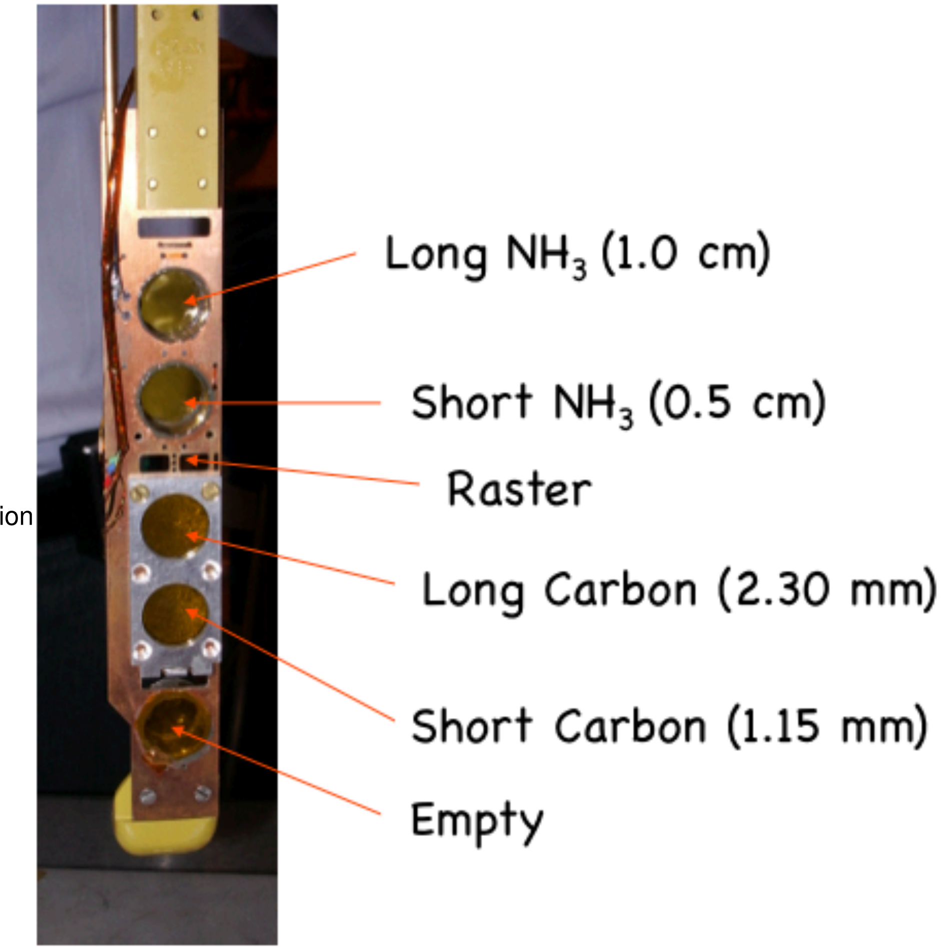
Purpose of EG4.

EG4 setup

- $Q^2>0$: electron beam (polarized). Energies: 3.0, 2.3, 2.0, 1.3 & 1.0 GeV
- $g_1^{p,n}$: ~longitudinally polarized target

DNP NH_3 and ND_3 target:





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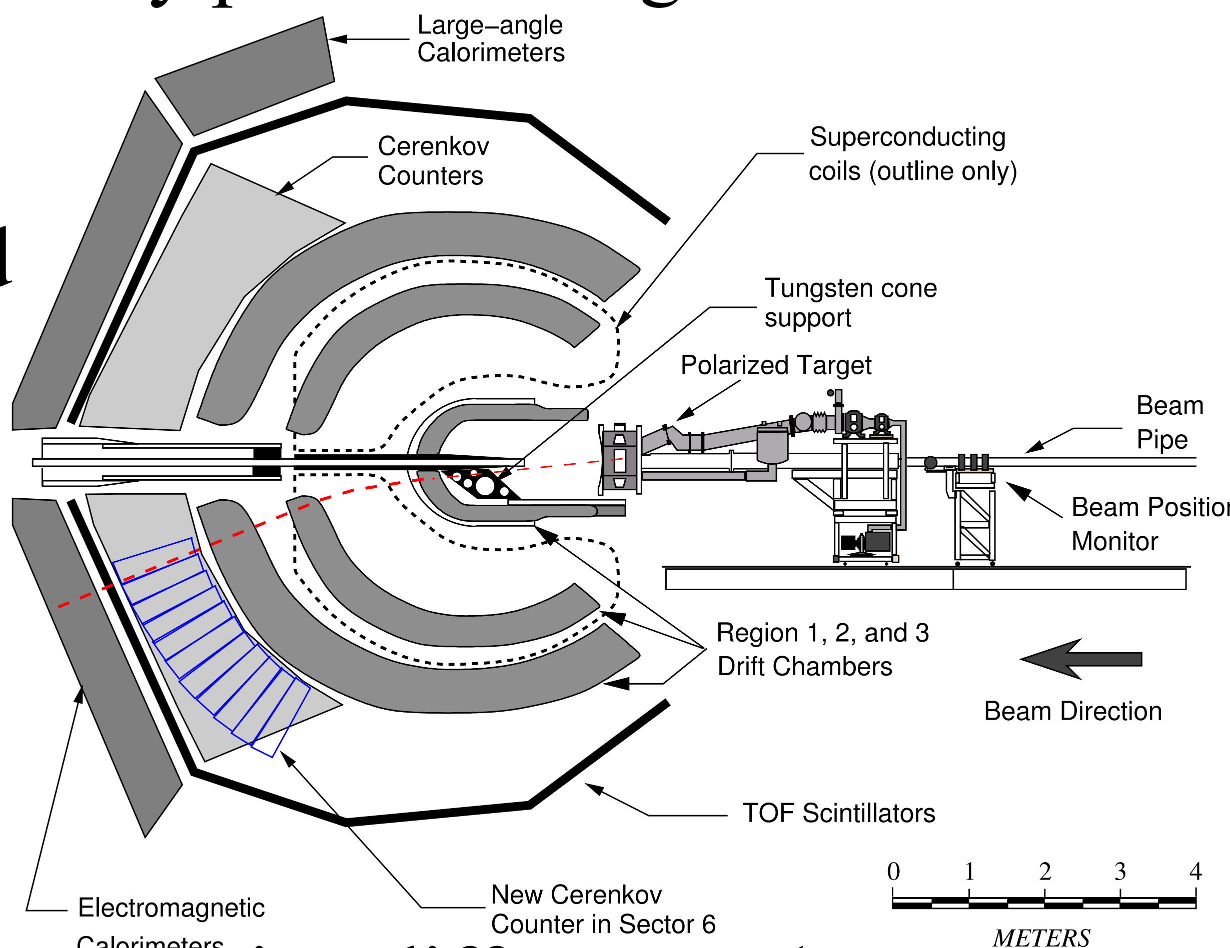
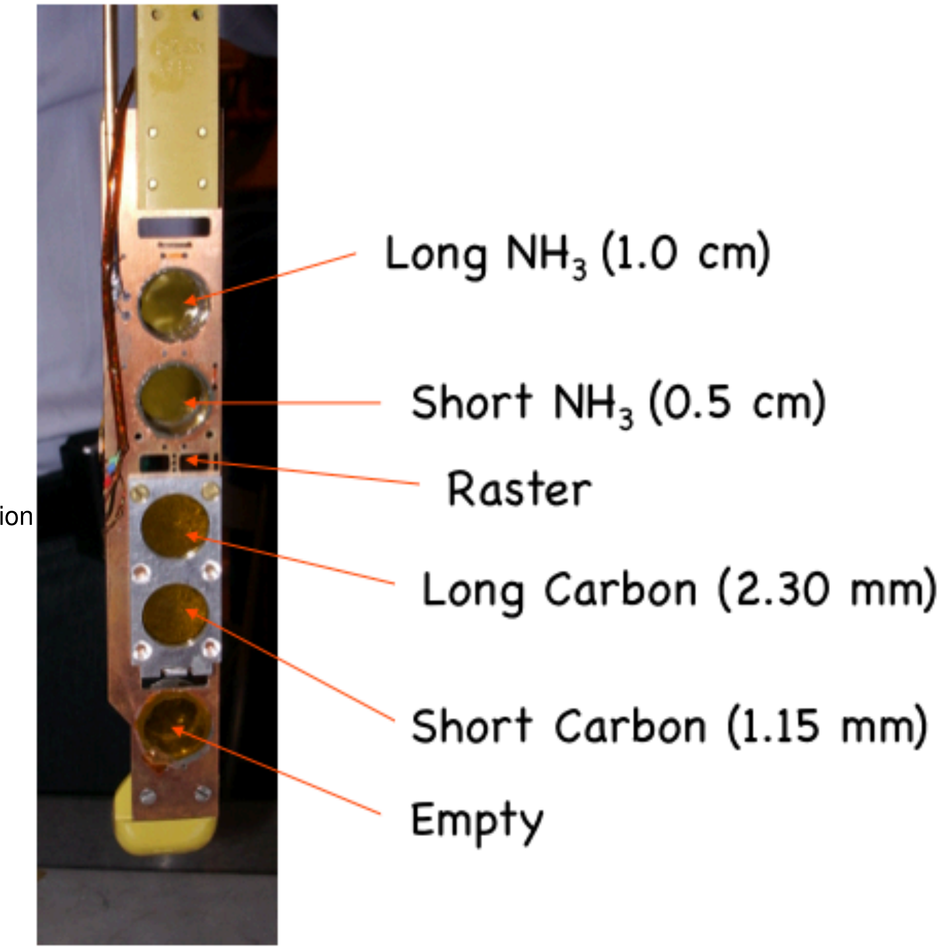
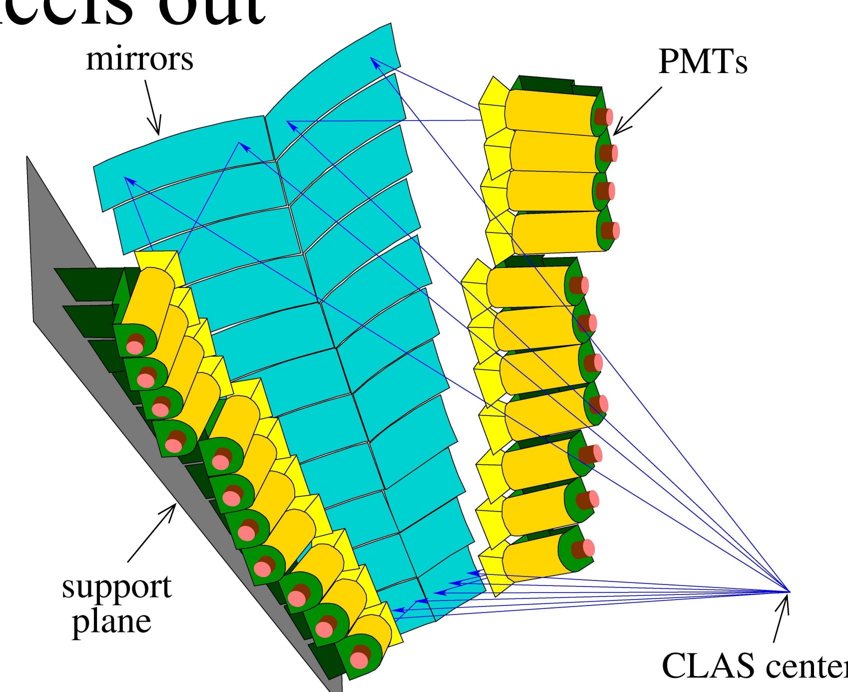




•g_1 from pol. cross-section differences (not asymmetries, as in EG1, EG1dvcs)
Advantage: dilution from unpol. target material cancels out

•Small angles: outbending torus field, new Möller shield; target at -1m

•Cross-sections ⇒ controlled (i.e high) efficiency at small angles. New Cerenkov detector (INFN). Installed in sector 6. Covered down to 6°.



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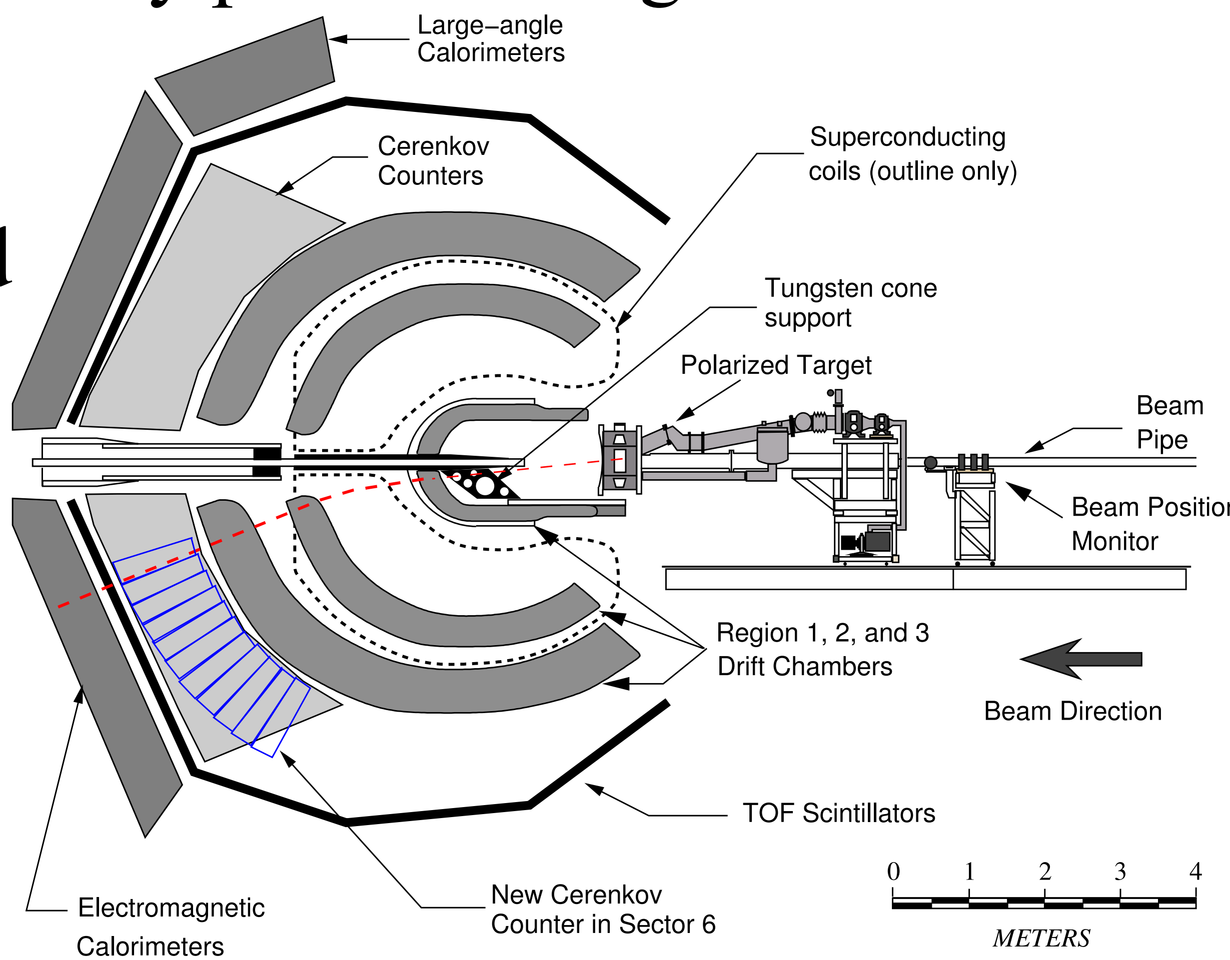
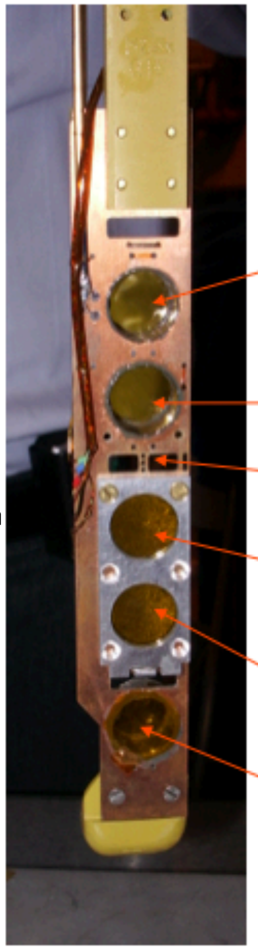


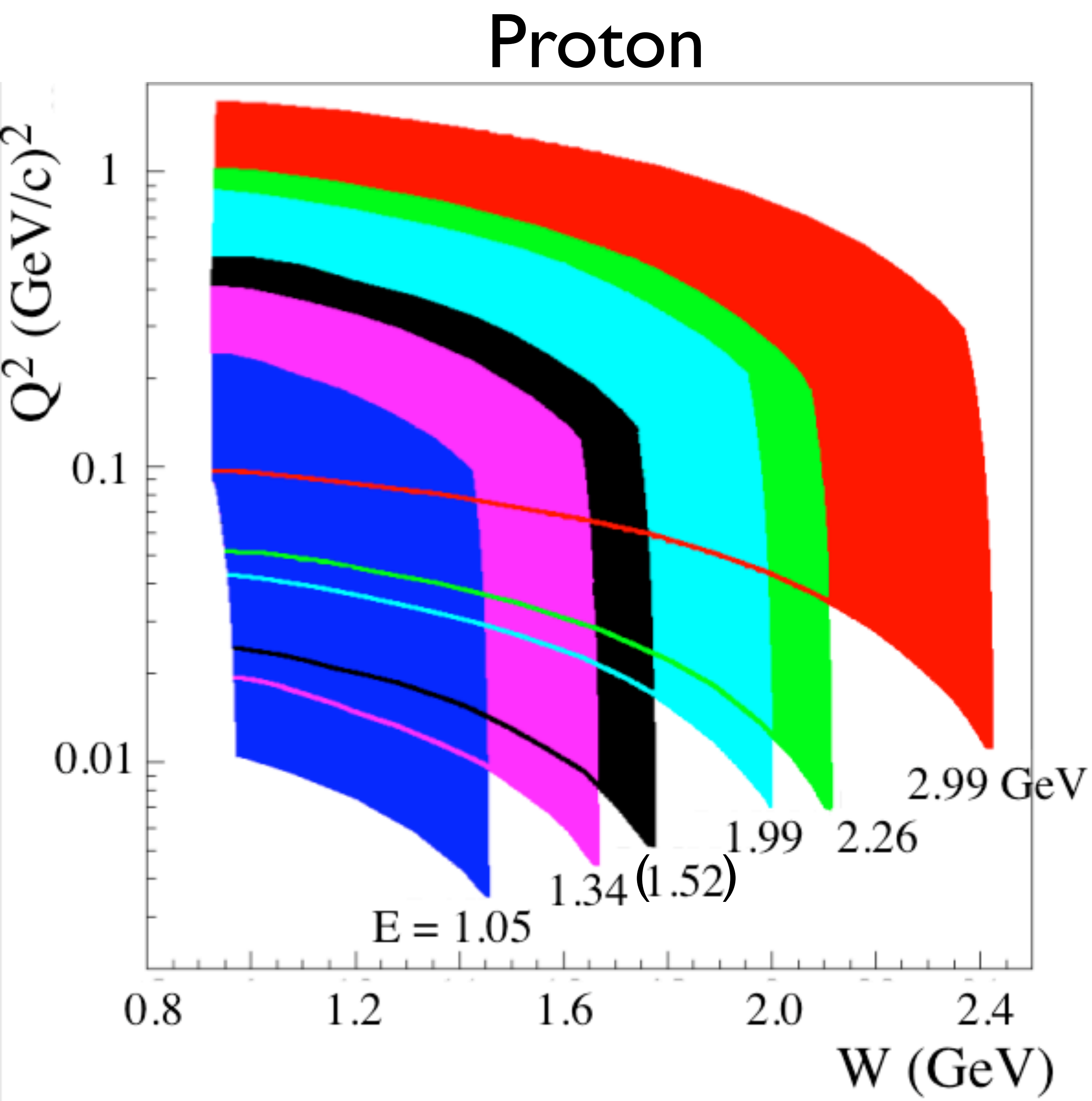


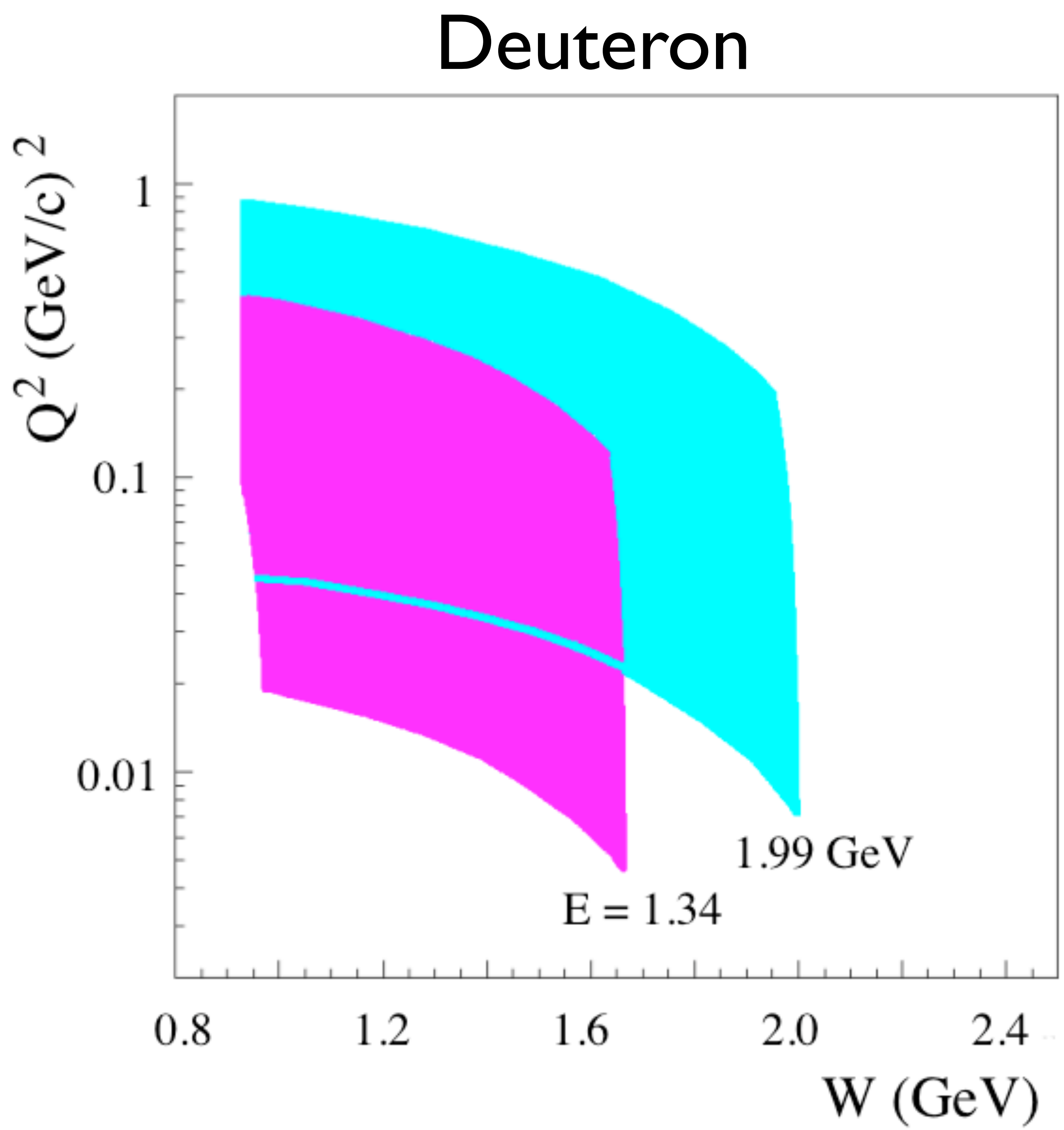
Two different target lengths to verify external radiative corrections (big elastic tails at low Q+high ν).

So far, only long target data have been analyzed.

(Deuteron data: only on long target.)

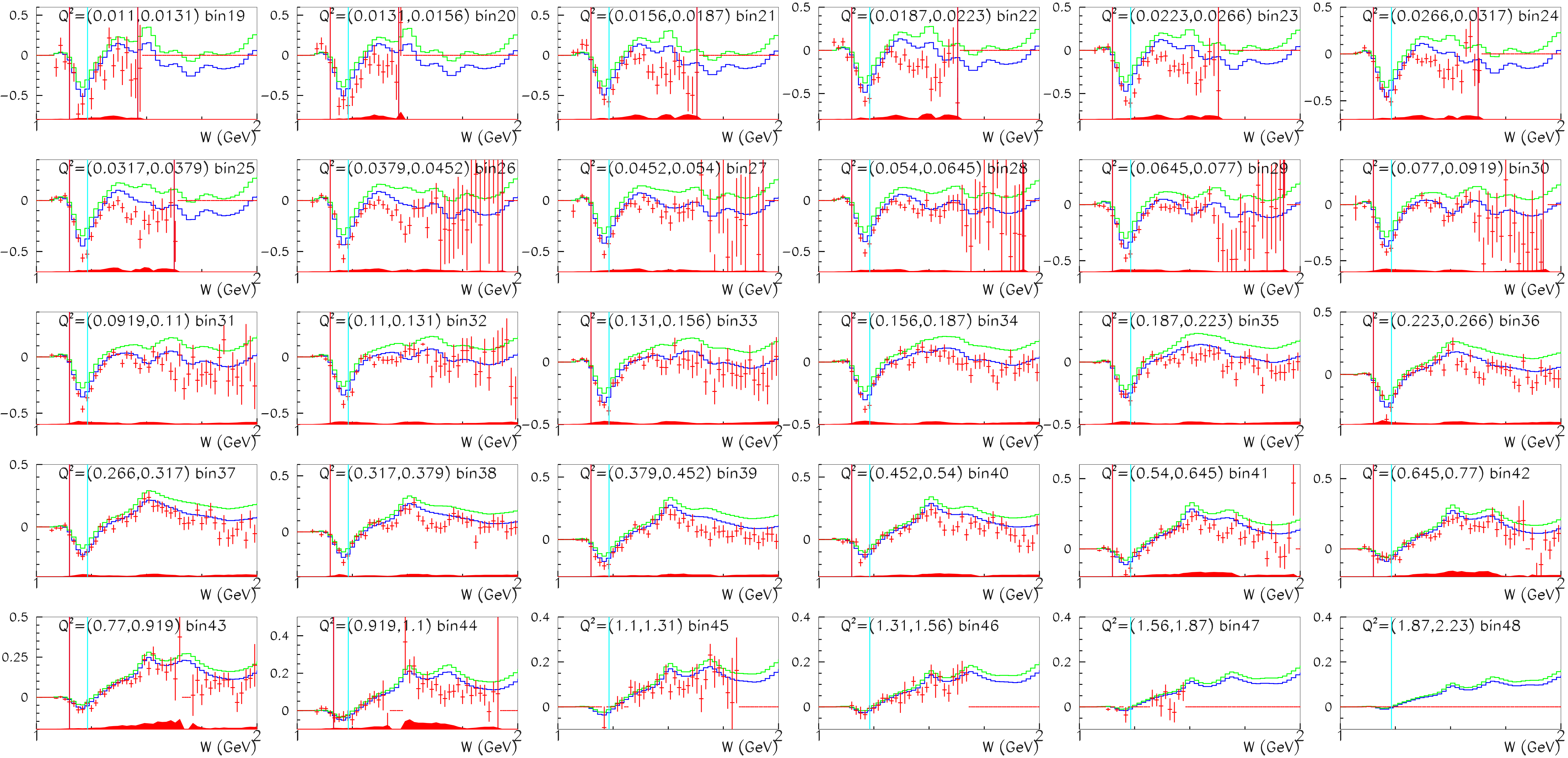
EG4 kinematic coverage





g_1^p from EG4 polarized cross-section difference

X. Zheng, J. Zhang, S. Kuhn, M. Ripani, M. Osipenko, A. D.,…



EG4 data

"Model" (Fit to EG1b (+ other published data)+extrap. Used as intermediary step to extract g_1^p.)

Example of "Model" variation: assess uncertainties on extraction method, radiative corrections, ….

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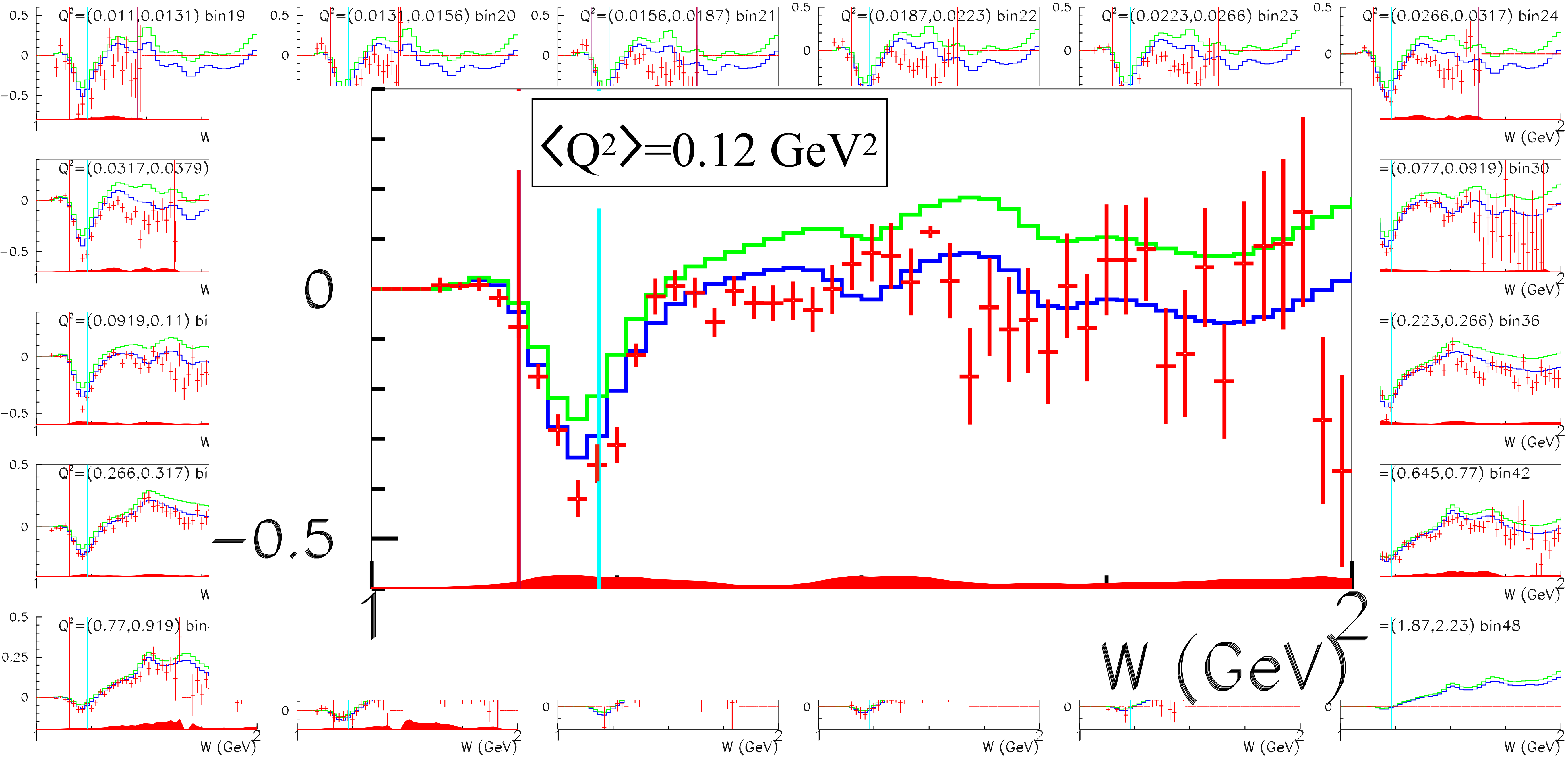

+ EG4 data

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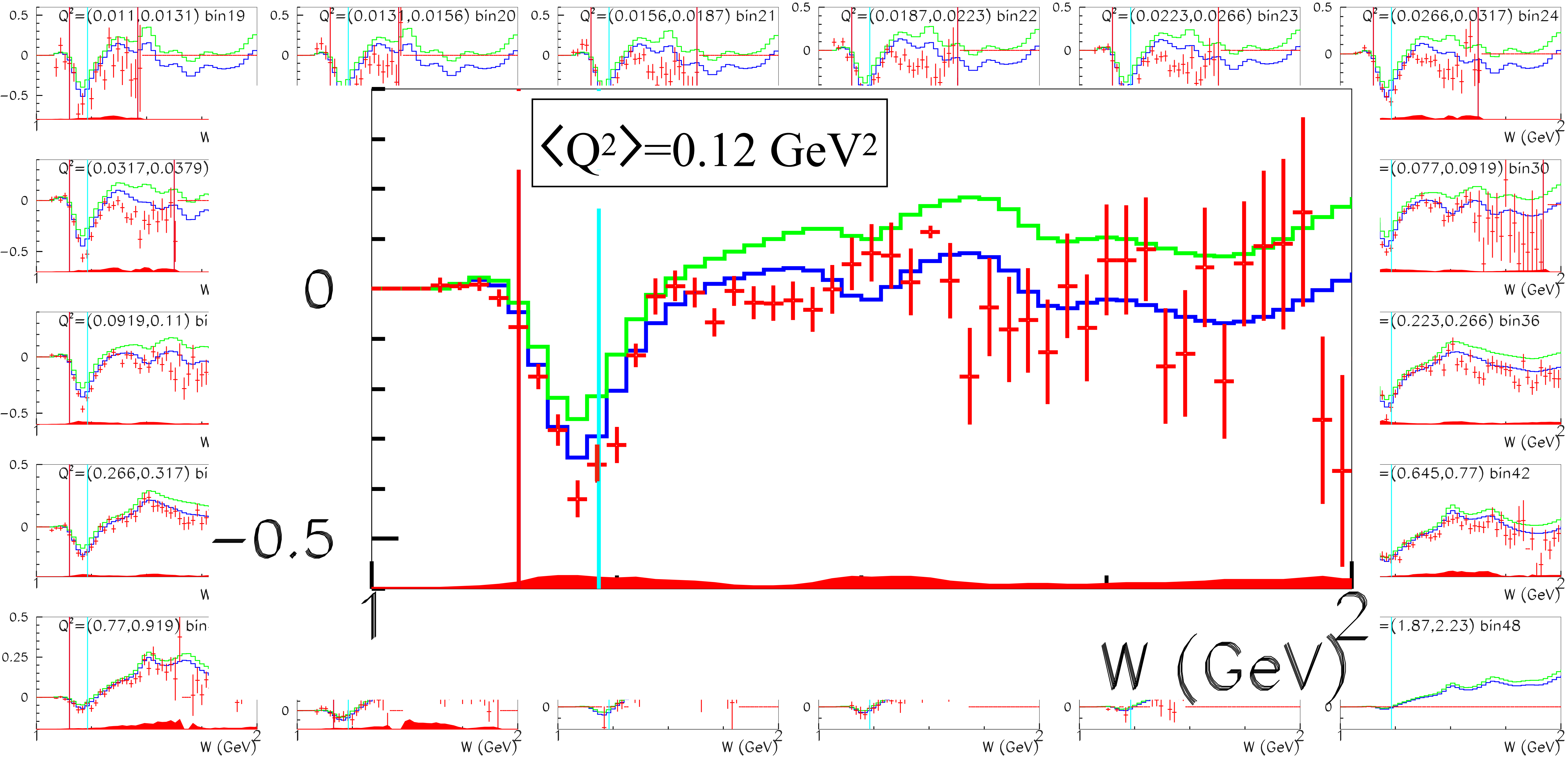

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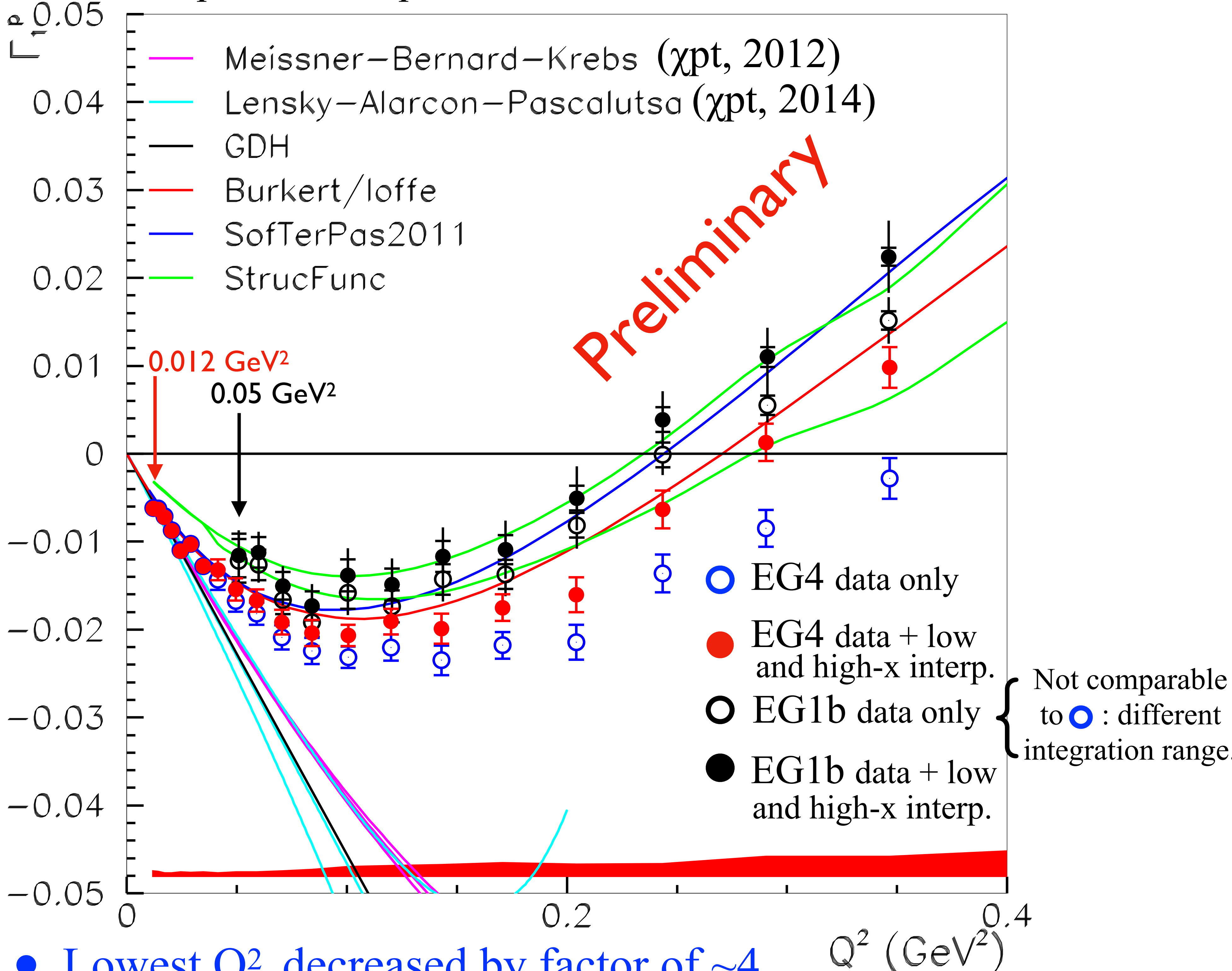
Example of "Model" variation: assess uncertainties **g_1^p not model-dependent** ections, ….

$\Gamma_1^p = \int g_1^p(x,Q^2)dx$

X. Zheng, J. Zhang, S. Kuhn, M. Ripani, M. Osipenko, A. D.,…

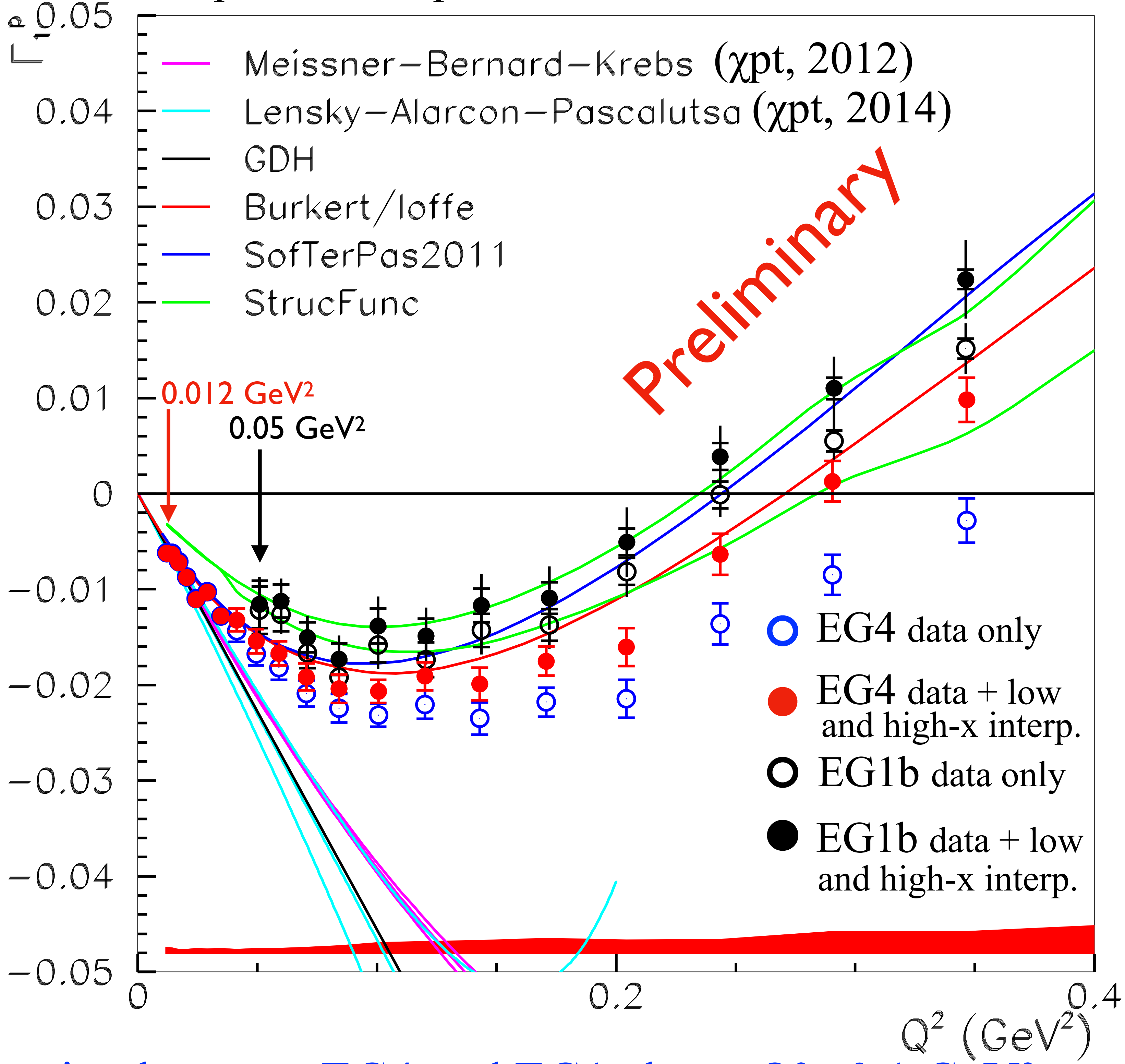


- Lowest Q^2 decreased by factor of ~4
- Much improved precision
- Small unmeasured low-x contribution

⇒Clean test of χpt

$\Gamma_1^p = \int g_1^p(x,Q^2)dx$

X. Zheng, J. Zhang, S. Kuhn, M. Ripani, M. Osipenko, A. D.,…

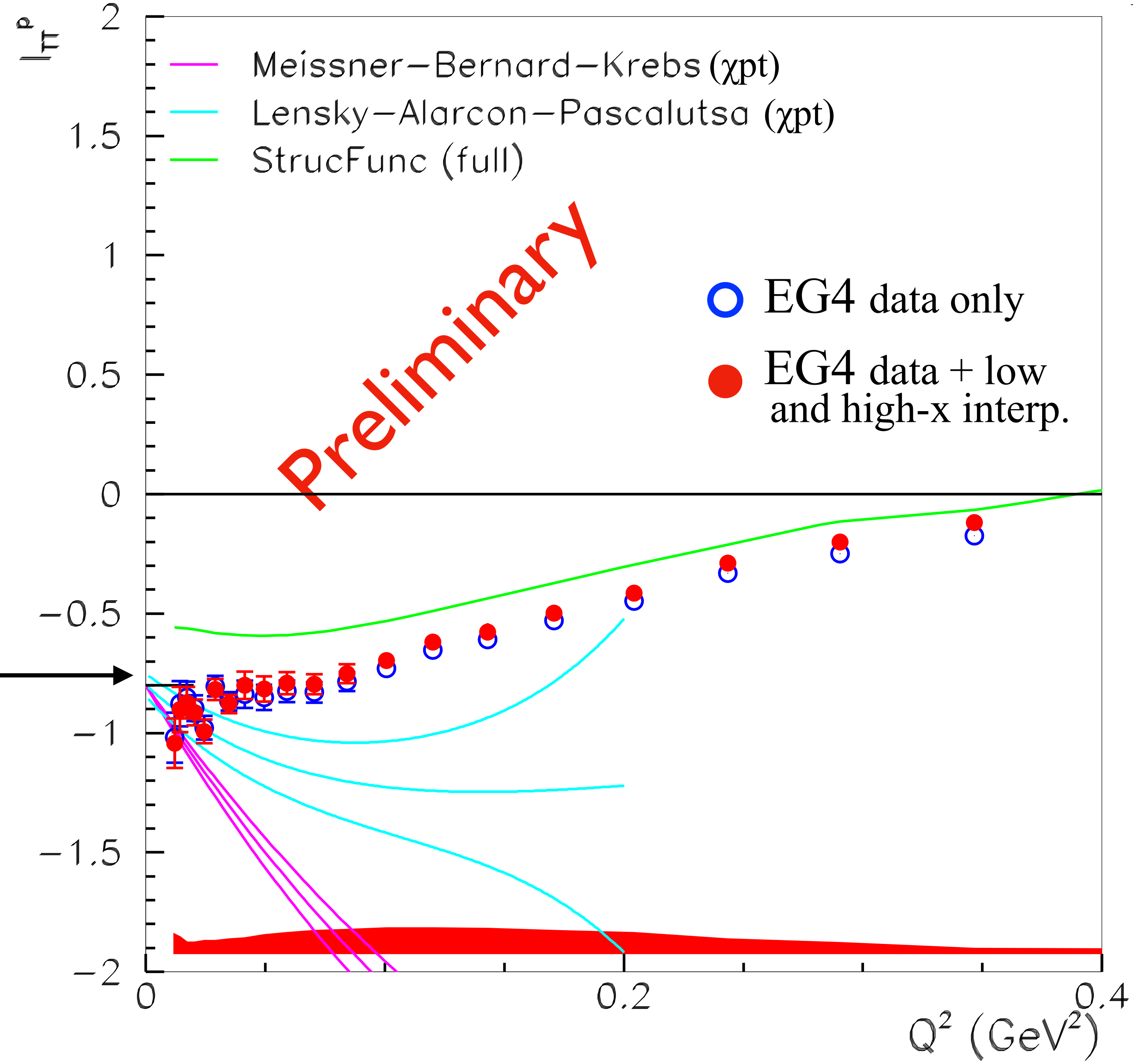


- Tension between EG4 and EG1 above $Q^2 \sim 0.1$ GeV^2.
- EG4 data and χPT results agree up to $Q^2 \sim 0.04$ GeV^2.
- Phenomenological models (Pasechnik et al, Burkert-Ioffe) agree well.

Another generalization of GDH sum: $I_{TT} = \int_{\nu_{thr}}^{\infty} \frac{K_f}{\nu} \frac{\sigma_A(\nu,Q^2)-\sigma_P(\nu,,Q^2)}{\nu} d\nu$

No suppressing Q^2 factor.
Contains g_2 (not measured by EG4)

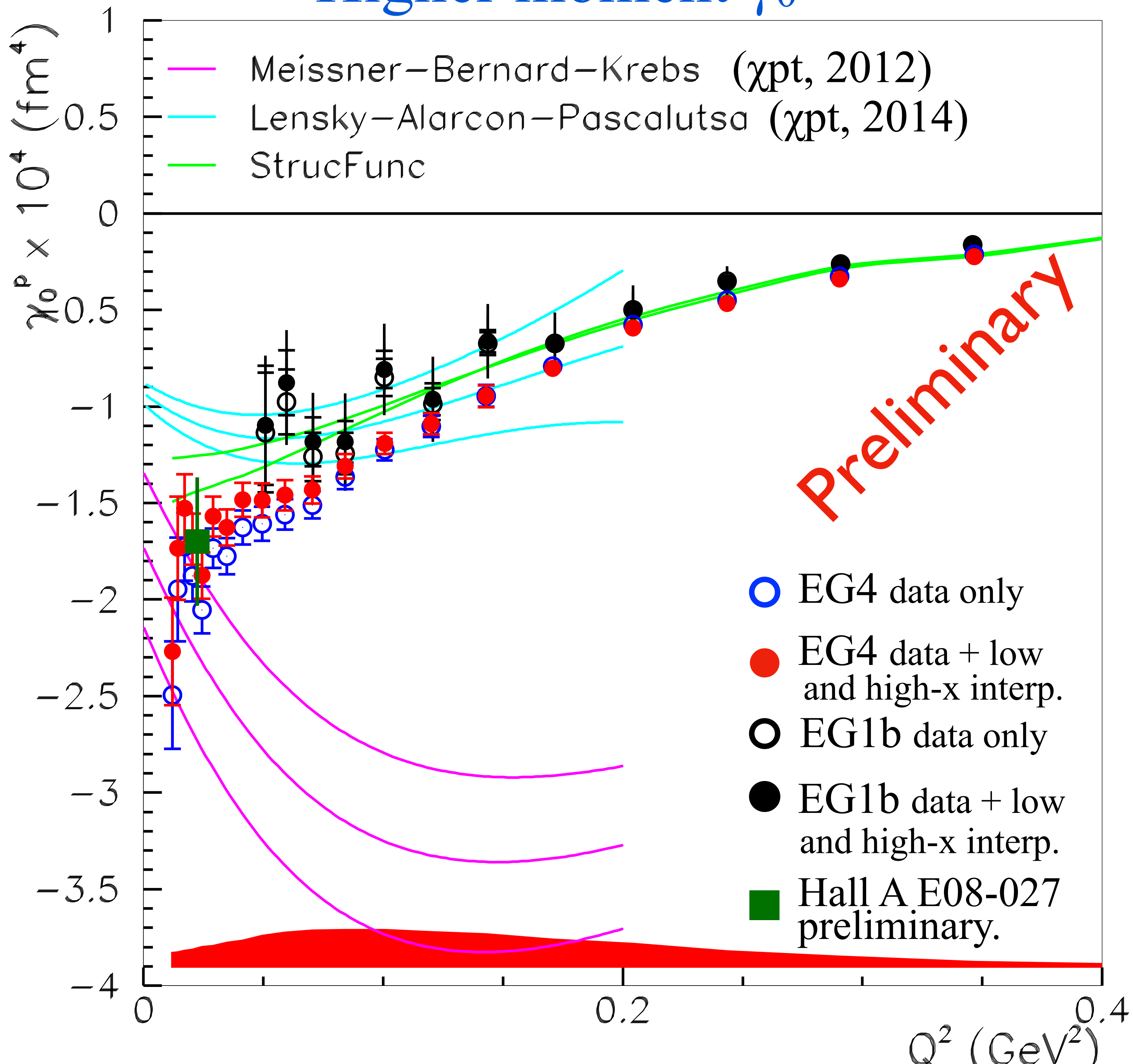
K_f : virtual photon flux



Original GDH sum rule: $-0.526\ GeV^{-2}$

- χPT results of Lensky et al. agree with data up to $Q^2 \sim 0.035\ GeV^2$.
- Bernard et al. χPT calculation agrees with data up to $Q^2 \sim 0.02\ GeV^2$.
- Data compatible with GDH sum rule.

Higher moment γ_0^p

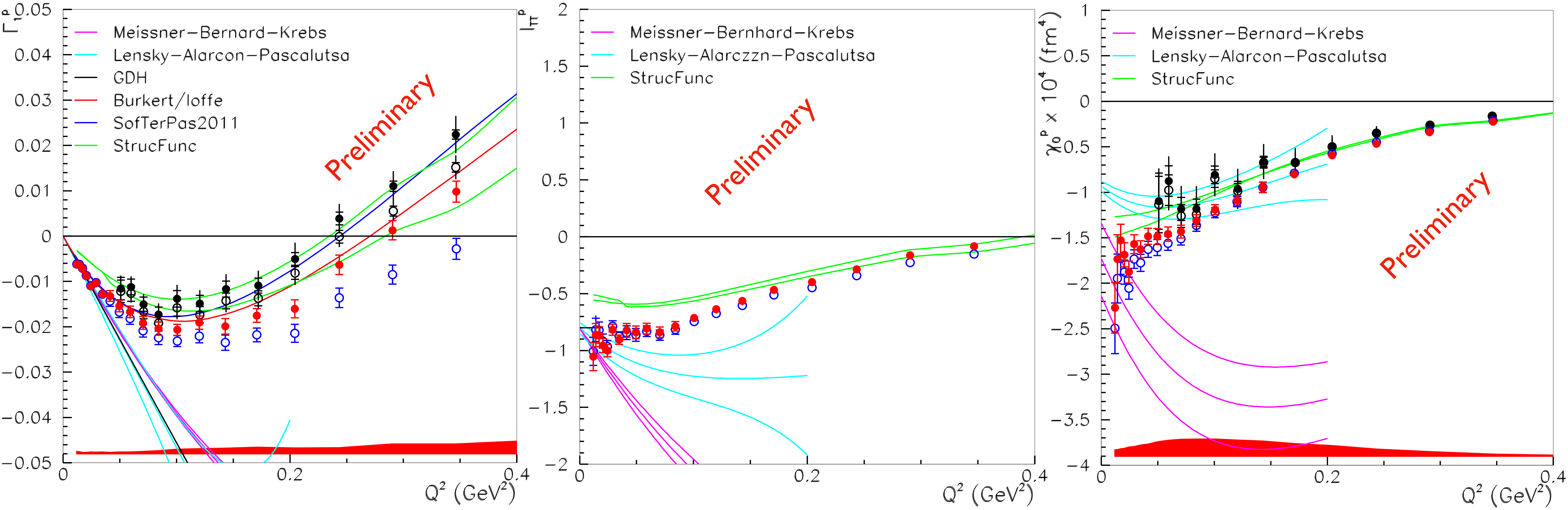


- Tension with EG1b, but EG4 and Hall A preliminary data agree.
- χPT results of Lensky et al. disagree with data.
- Bernard et al. χPT calculation agrees for lowest Q^2 points only.

What left to do for EG4:

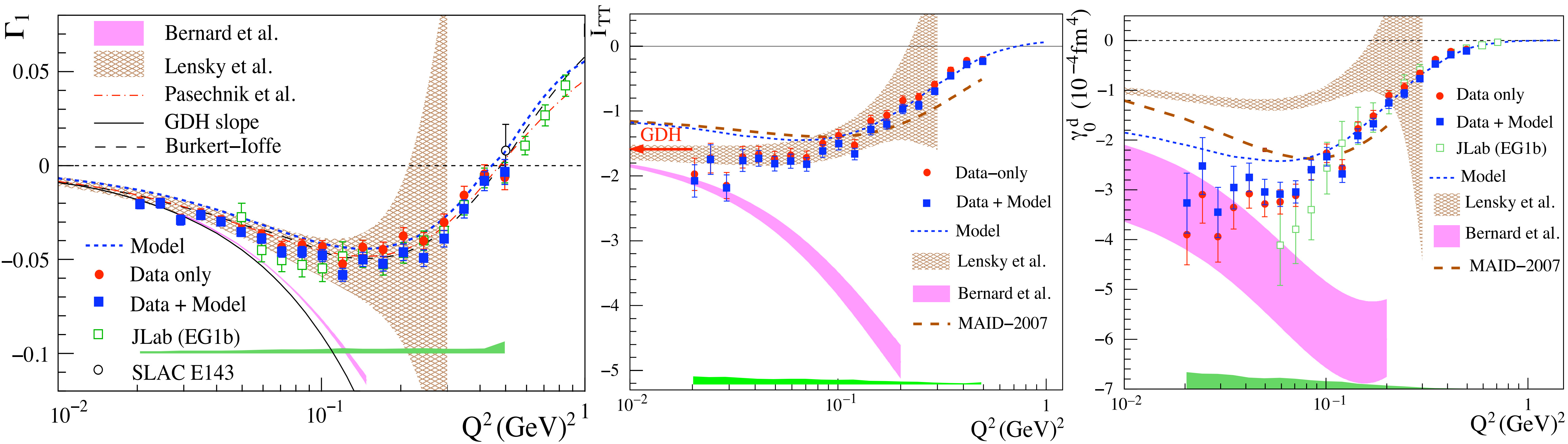
- Finalize systematic analysis (soon);
- Include short target data into analysis (soon);
- Finalize analysis note, and write paper.

Conclusion



General agreement with χPT, but its Q^2-range of validity is limited (up to Q^2 ~0.04 GeV^2)

Compare with deuteron case



General agreement with χPT, but its Q^2-range of validity is limited (up to Q^2 ~0.04 GeV^2)
For the EG4 results from deuteron: Lensky et al. agrees (typically up to Q^2 ~0.1 GeV^2)

A satisfactory theoretical description of spin observables at low Q^2 remains challenging

Previous data: high to intermediate Q^2

State of χpT affairs before EG4 run (2006):

~no unmeasured low-x

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}	$\boldsymbol{\delta_{LT}^n}$	d_2^p	d_2^n
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- Mixed success of χpT;
- Surprising discrepancies (δ_{LT} crisis);
- Validity range smaller than hoped for: $Q^2 < \sim 0.1$ GeV^2 ⇒Ambiguous χpT tests.

⇒ Need new data on p and n (d, ^{3}He) at very low Q^2 (i.e. for integrals over ν: low angles).

Purpose of EG4.

Up to date state of χpT affairs (2019)

Agreement between data and χpT up to $Q^2 = 0.1$ GeV^2:

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Ji et al. 1999	X	X	A	X	-	-	-	-	-	-
Bernard et al. 2002	X	X	A	X	X	A	X	X	X	X
Kao et al. 2002	-	-	-	-	X	A	X	X	X	X
Bernard et al. 2012	X	X	A	X	X	A	X	X	X	-
Lensky et al. 2014	X	A	A	A	X	X	X	X	X	A

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Table would have more **A** if we lower the Q^2 range for comparison.

Summary and perspectives

•EG4: Low Q^2 measurement using polarized e^- on polarized p and d, over a large x-range in order to study spin sum rules.

•New detector necessary to reach these kinematics.

•Main goal: unambiguous test of χPT.

•Doubly polarized inclusive cross-section analysis.

Summary and perspectives

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- New detector necessary to reach these kinematics.
- Main goal: unambiguous test of χPT.
- Doubly polarized inclusive cross-section analysis.
- Exclusive data on π^+ and π^- spin-dep. electroprod. on p published in 2016 (asym. analysis).
  X. Zheng *et al.* (CLAS Collaboration), PRC 94, 045206 (2016)
- Inclusive analysis on d published in 2018.
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- EG4: part of JLab program to measure benchmark spin observables for χPT $\Rightarrow$ More low Q^2 data to come:
  - g_1, g_2, Γ_1, Γ_2, I_{TT}, γ_0 and δ_{LT} for the neutron and ^{3}He (Hall A E97110). Coming soon.
  - g_2, g_1, Γ_2, Γ_1, I_{TT}, δ_{LT} and γ_0 for the proton (Hall A E08027). Coming soon.

Extra slides

Differences between EG1b and EG4

- Radiative corrections.

  Large radiative tails for EG4 kinematics $\Rightarrow$ revisited standard RCSLACPOL code and improved its handling of elastic tails (external elastic radiative tail seems to have been missing).

- Different detector for main trigger and electron ID (new INFN Cherenkov counter for EG4).

  Much higher efficiency for outbending electrons, but still some systematic uncertainty for point-to-point electron detection efficiency and acceptance.

- Absolute cross-sections differences used to extract g_1^p, not relative asymmetries.

  Absolute normalization needed. But no target dilution (usually, a large correction). No F_1^p input needed.

- Different kinematics (beam energy, angles) to obtain x and Q^2 common to EG4 and EG1b.

  Implies in particular different g_2^p inputs.

Some of these differences may be the origin of the tension between the EG4 and EG1b results.

The issue is still being investigated.

Agreement with Hall A preliminary result is reassuring (but non-binding).

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 ($Q^2=0$):

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

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 $Q^2 \to 0$

x_{th} Q^2

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

χpt: low energy effective theory of QCD obtained using a Lagrangian consistent with QCD's chiral symmetry (neglecting quark masses).
Captures the main essence of QCD at low Q^2, without the complicated details.
Systematic perturbative expansion valid for e.g. $Q \ll m_\pi$.