Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

INFN

Results from the JLab CLAS EG4 experiment

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The EG4 experiment Group

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

E03-006 (NH_3):

Spokespeople: M. R., M. Battaglieri, A.Deur, R. de Vita

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

E06-017 (ND_3)

Spokespeople: A.Deur, G. Dodge, M. R., K. Slifer

Students: K. Adhikari✦ (ODU)

EG4 ran from Feb. to May 2006.

Main goal: inclusive analyses. Also, exclusive analysis by X. Zheng

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

✦ Graduated.

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

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

fine structure constant

target anomalous magnetic moment

target spin

target mass

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

photon spin parallel to S

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- α: fine structure constant
- κ: target anomalous magnetic moment
- S: target spin
- M: target mass
- σ_A: photoprod. cross section with photon spin anti-parallel to S
- σ_P: photon spin anti-parallel to S

Generalized GDH sum rule: valid for any Q^2. Recover the original GDH sum rule at $Q^2=0$

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

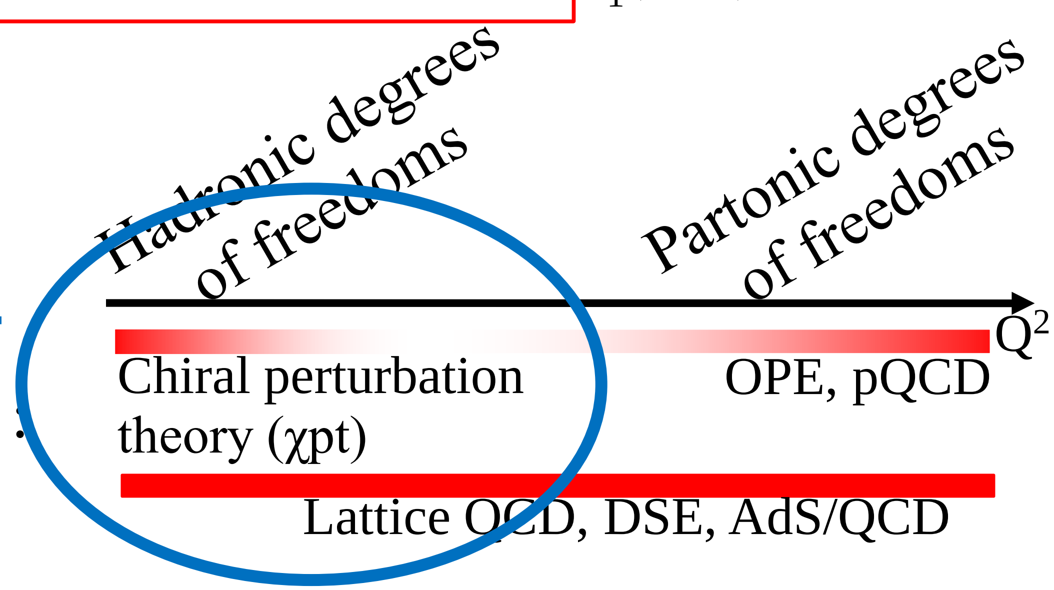
$g_1(\nu,Q^2)$: first spin structure function (mostly a longit. target pol. observable)

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

⇒Study QCD at any scale

EG4

$I_1(0,Q^2)$:



Spin Polarizabilities 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)

Spin polarizability sum rules involve higher moments:

Generalized forward spin polarizability:

$$\gamma_0 = \frac{4e^2M^2}{\pi Q^6}\int x^2\left(g_1 - \frac{4M^2}{Q^2}x^2 g_2\right)dx = \int x^2 A_1 F_1 dx$$

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

Contribution suppressed in γ_0

Longitudinal-transverse spin polarizability:

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

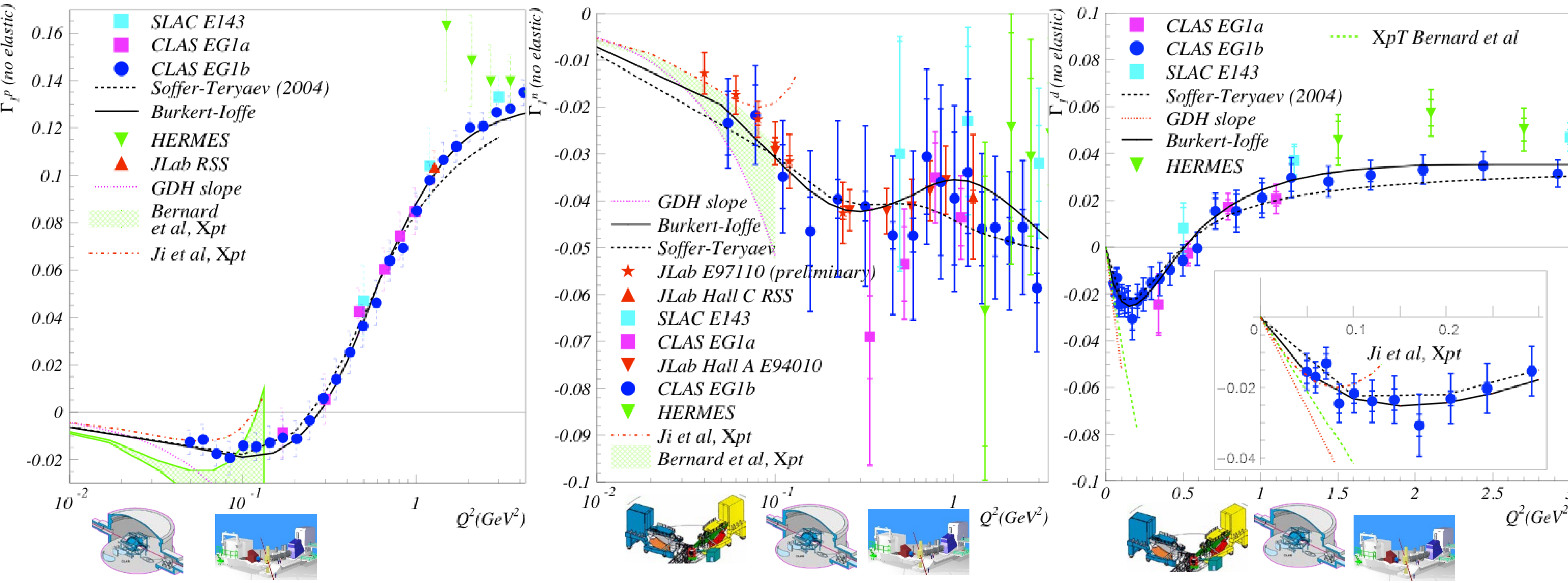
Waiting for g_2 data

Not further discussed in this presentation

Previous data: high to intermediate Q^2

Before EG4 run (2006):

Proton Neutron Deuteron



Precise mapping of intermediate Q^2 region for p, n and d.

pQCD, models and data agree.

Not so clear for χpT.

Test of χpt

A = agree
X = disagree
- = no calculation available

No significant low-x contribution
(More robust observables)

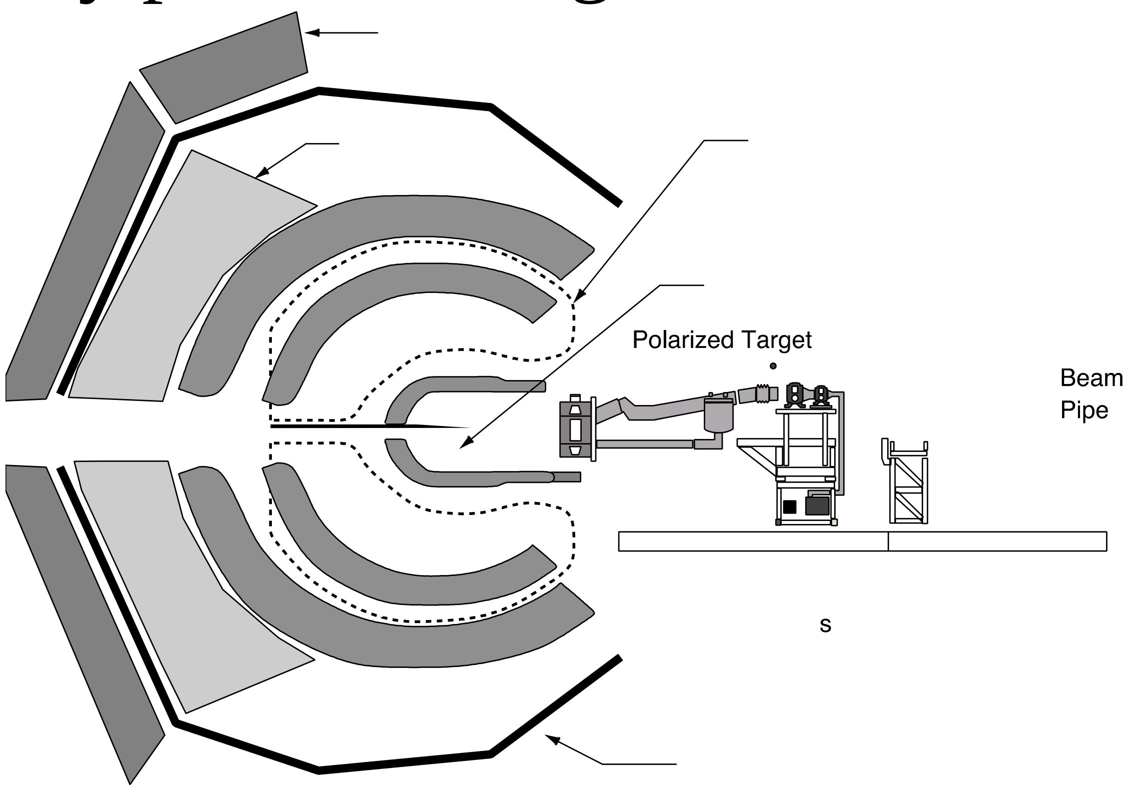
Ref.	Γ_1^p	Γ_1^n	$\boldsymbol{\Gamma_1^{p-n}}$	Γ_1^{p+n}	γ_0^p	γ_0^n	$\boldsymbol{\gamma_0^{p-n}}$	γ_0^{p+n}	$\boldsymbol{\delta_{LT}^n}$
Ji 1999	X	X	A	X	-	-	-	-	-
Bernard 2002	X	X	A	X	X	A	X	X	X
Kao 2002	-	-	-	-	X	A	X	X	X
Bernard 2012	X	X	A	X	X	A	X	X	X
Lensky 2014	X	A	A	A	A	X	X	X	$\sim$ A

No Δ_{1232} contributions
(More robust χpt calculations)

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:

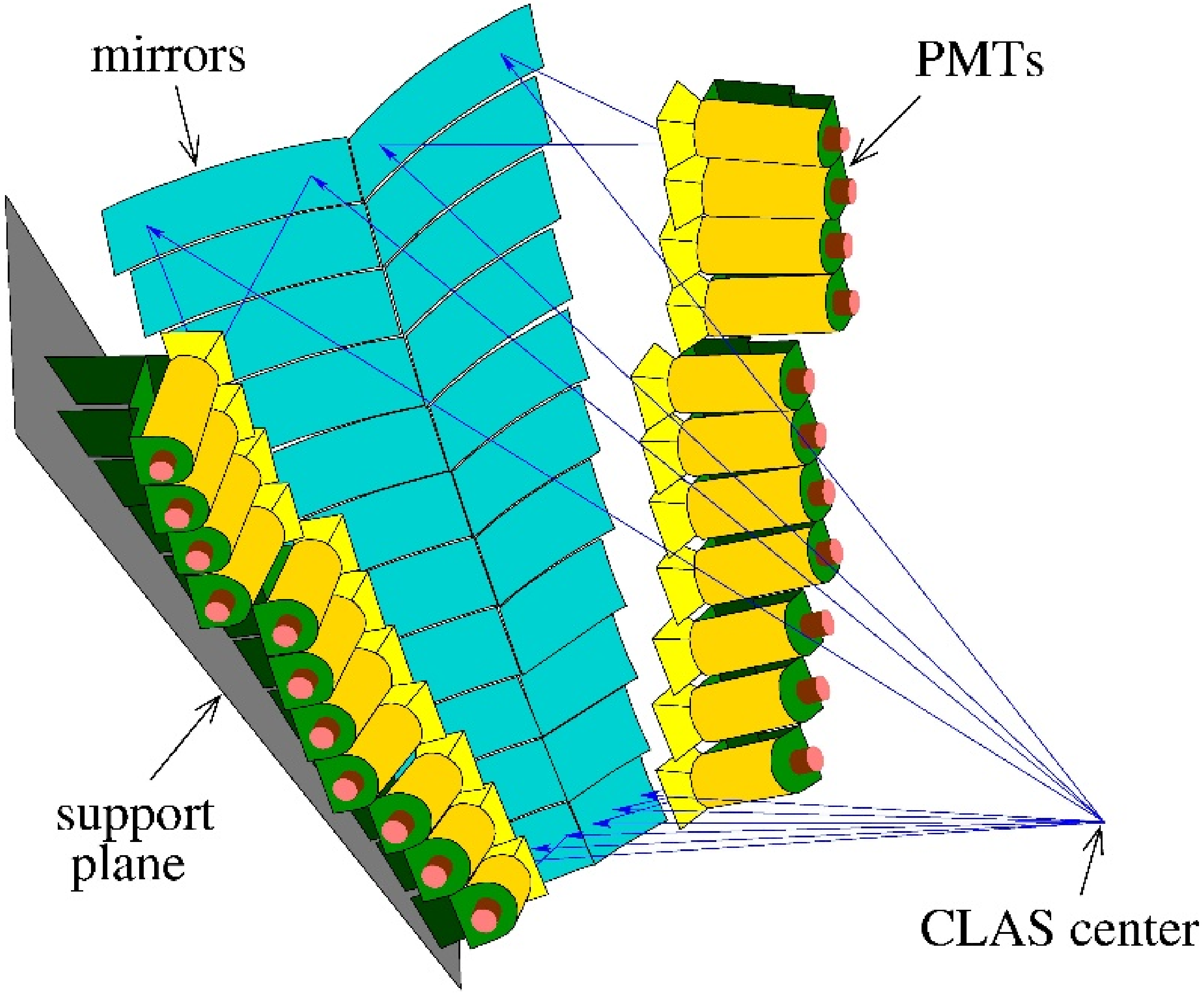


•g_1 from pol. cross-section differences (not asymmetries, as in EG1, EG1dvcs)
Advantage: dilution from unpol. target material cancels out

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

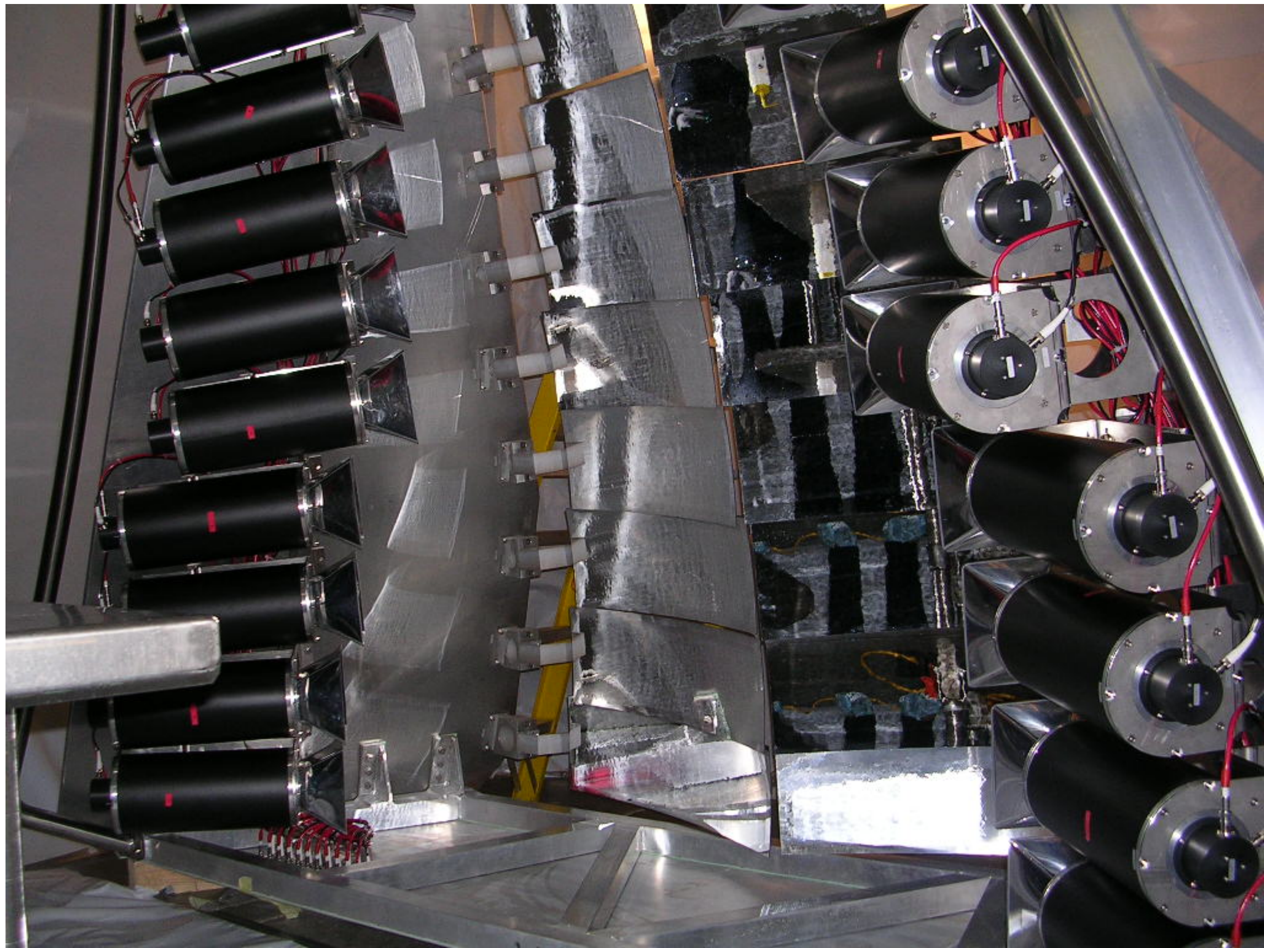
•Cross-section ⇒ controlled (i.e high) efficiency at small angles.
→New Cherenkov detector (INFN). Installed in sector 6. Cover down to 6°

EG1: Largest possible kinematic coverage -> inbending and outbending configuration, E = 1.6…5.8 GeV



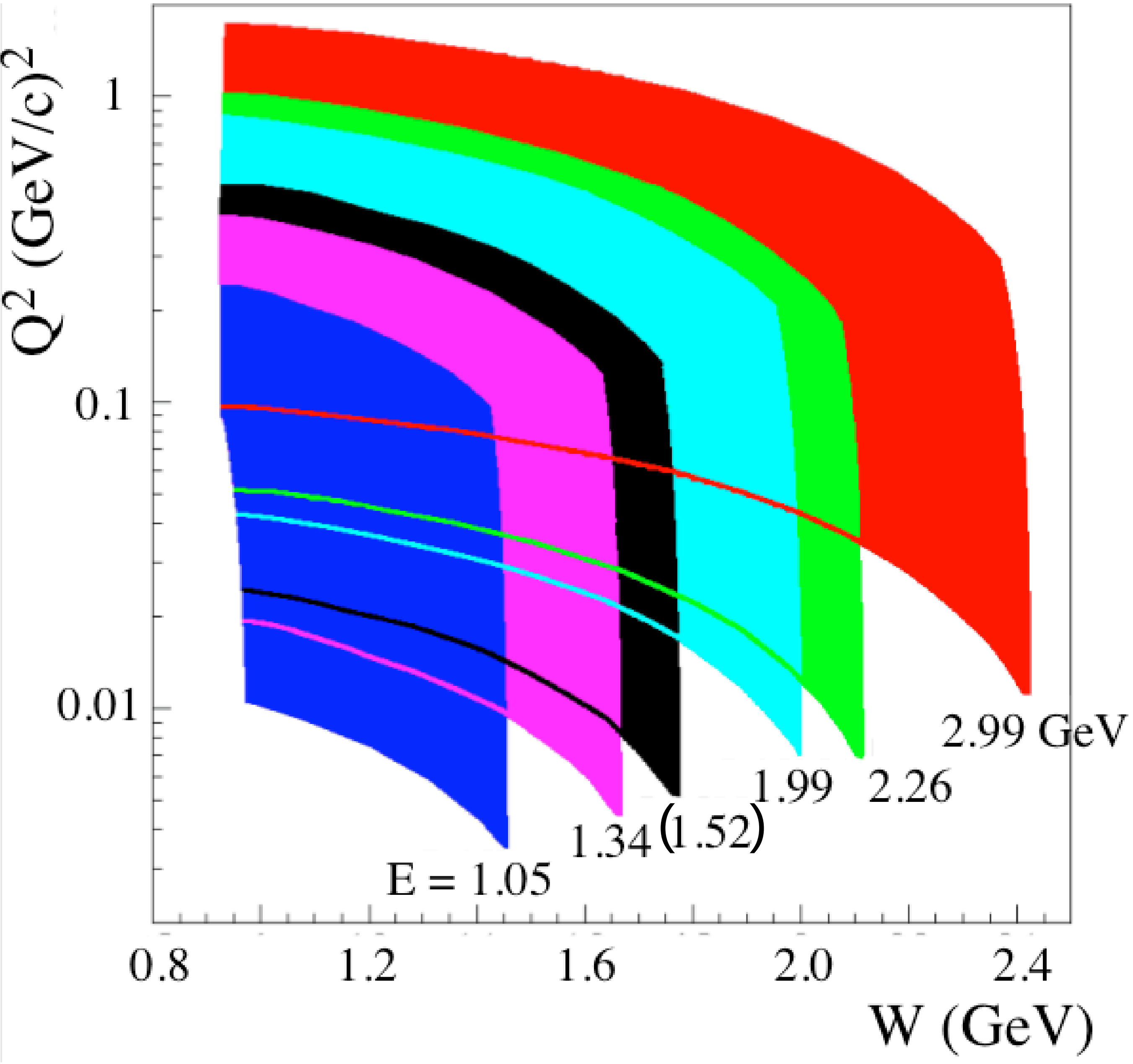
EG4: Focus on low Q^2 => lower beam energies, new Cherenkov for optimal acceptance in outbending configuration, θ_e as small as 6 degrees

… and EG1-DVCS: Highest statistics at large x, Q^2

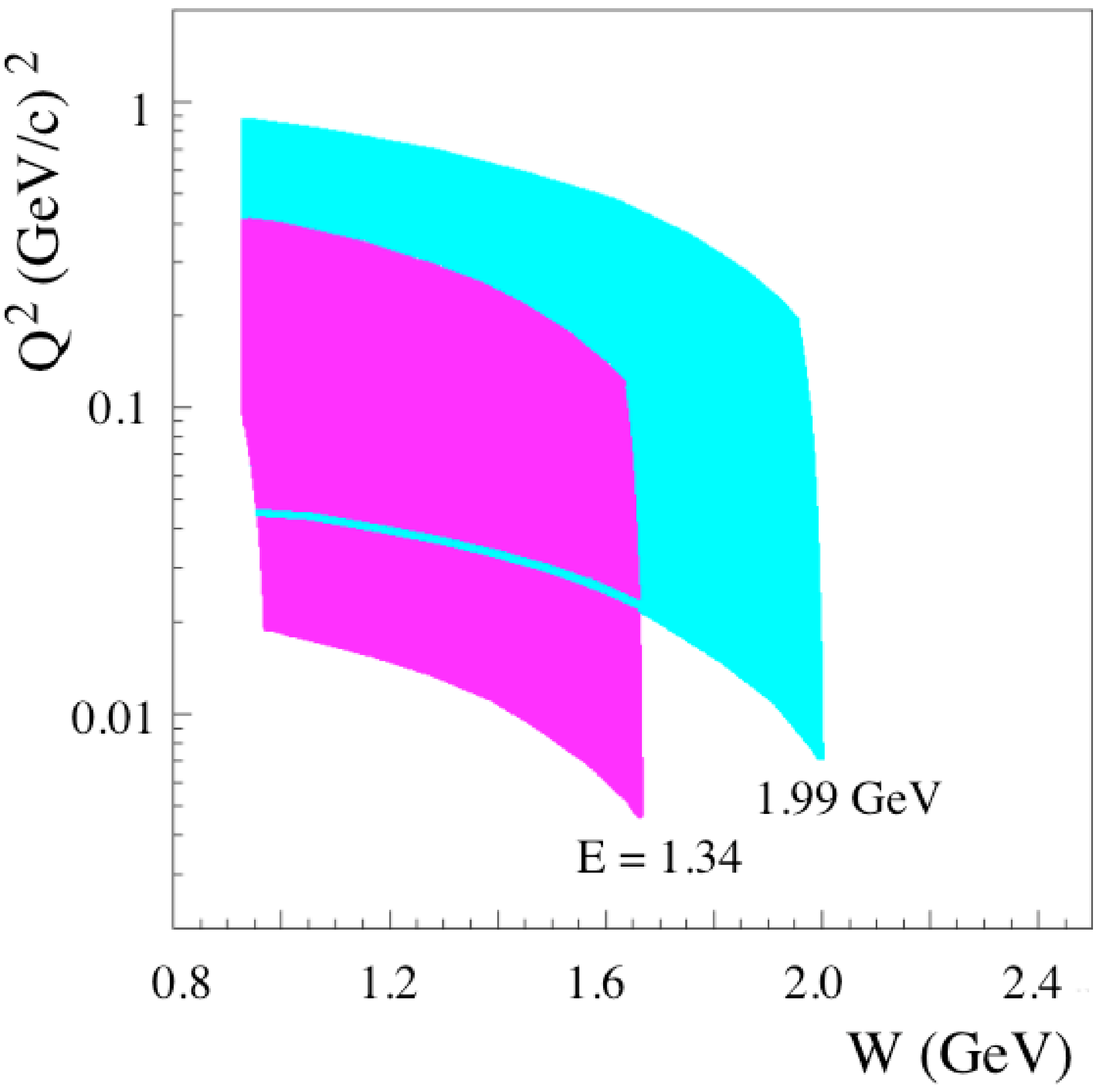


EG4 kinematic coverage

Proton



Deuteron



1.52 GeV proton only for commissioning purposes

Experimental procedure

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

$$\frac{\Delta d\sigma^{theor}}{d\Omega dE'} \equiv \frac{d\sigma^{\rightarrow\Rightarrow}}{d\Omega dE'} - \frac{d\sigma^{\leftarrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{ME\nu Q^2}\left[(E - E'cos\vartheta)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$

- Small Q^2 → small x → g_2 contribution suppressed

- Actual experimental quantity measured:

$$\Delta N^{exp}(\Delta E',\Delta\Omega) \equiv N^{\rightarrow\Rightarrow}(\Delta E',\Delta\Omega) - N^{\leftarrow\Rightarrow}(\Delta E',\Delta\Omega) = P_f \mathscr{L} P_b P_T \frac{\Delta d\sigma^{theor}}{d\Omega dE'} \Delta E' \Delta\Omega\, \epsilon_{det} \quad (*)$$

where

- P_f = packing fraction (how much target cell filling with ammonia beads)
- $\mathscr{L}$ = integrated luminosity (how many electrons on target times nominal target surface thickness) (*)
- P_b = beam polarization (85 ± 2%)
- P_b = target polarization (59 to 71 % for H, 30 to 45 % for D)
- ε_{det} = detector acceptance/efficiency

(*) there is a small correction due to the beam charge asymmetry, not shown here

Experimental procedure

First step

$$\Delta N^{exp,(quasi)elastic}(\Delta E', \Delta\Omega)$$

What CLAS actually measures

$$\equiv N^{\rightarrow\Rightarrow,(quasi)elastic}(\Delta E', \Delta\Omega) - N^{\leftarrow\Rightarrow,(quasi)elastic}(\Delta E', \Delta\Omega)$$

$$= P_f \mathscr{L} P_b P_T \frac{\Delta d\sigma^{theor,(quasi)elastic}}{d\Omega dE'} \Delta E' \Delta\Omega\, \epsilon_{det}$$

Extracted from data

Well known in terms of elastic FF or quasielastic parameterization

Monte Carlo simulation

Experimental procedure

Second step

1 $\Delta N^{exp,inelastic}(\Delta E', \Delta\Omega)$

What CLAS actually measures

$$\equiv N^{\rightarrow\Rightarrow,inelastic}(\Delta E', \Delta\Omega) - N^{\leftarrow\Rightarrow,inelastic}(\Delta E', \Delta\Omega)$$

2
$$= P_f \mathscr{L} P_b P_T \frac{\Delta d\sigma^{theor,inelastic}}{d\Omega dE'} \Delta E' \Delta\Omega \, \epsilon_{det}$$

Input from elastic

Calculated from parameterization, g_1 or A_1 F_1 varied until 1 and 2 agree at best

Monte Carlo simulation

g_1, A_1F_1

Experimental procedure

Sum rule integrals

Deuteron

$$\int_0^{x_{th}} \ldots \rightarrow \int_{0.001}^{x_{min}} Model + \int_{x_{min}}^{x(W=1.15\ GeV)} data + \int_{x(W=1.15\ GeV)}^{x(W=1.07\ GeV)} Model$$

For the lowest Q^2 bin, 0.020 GeV^2, x_{min} = 0.0073

For the largest Q^2 bin considered for integration, 0.592 GeV^2, x_{min} = 0.280

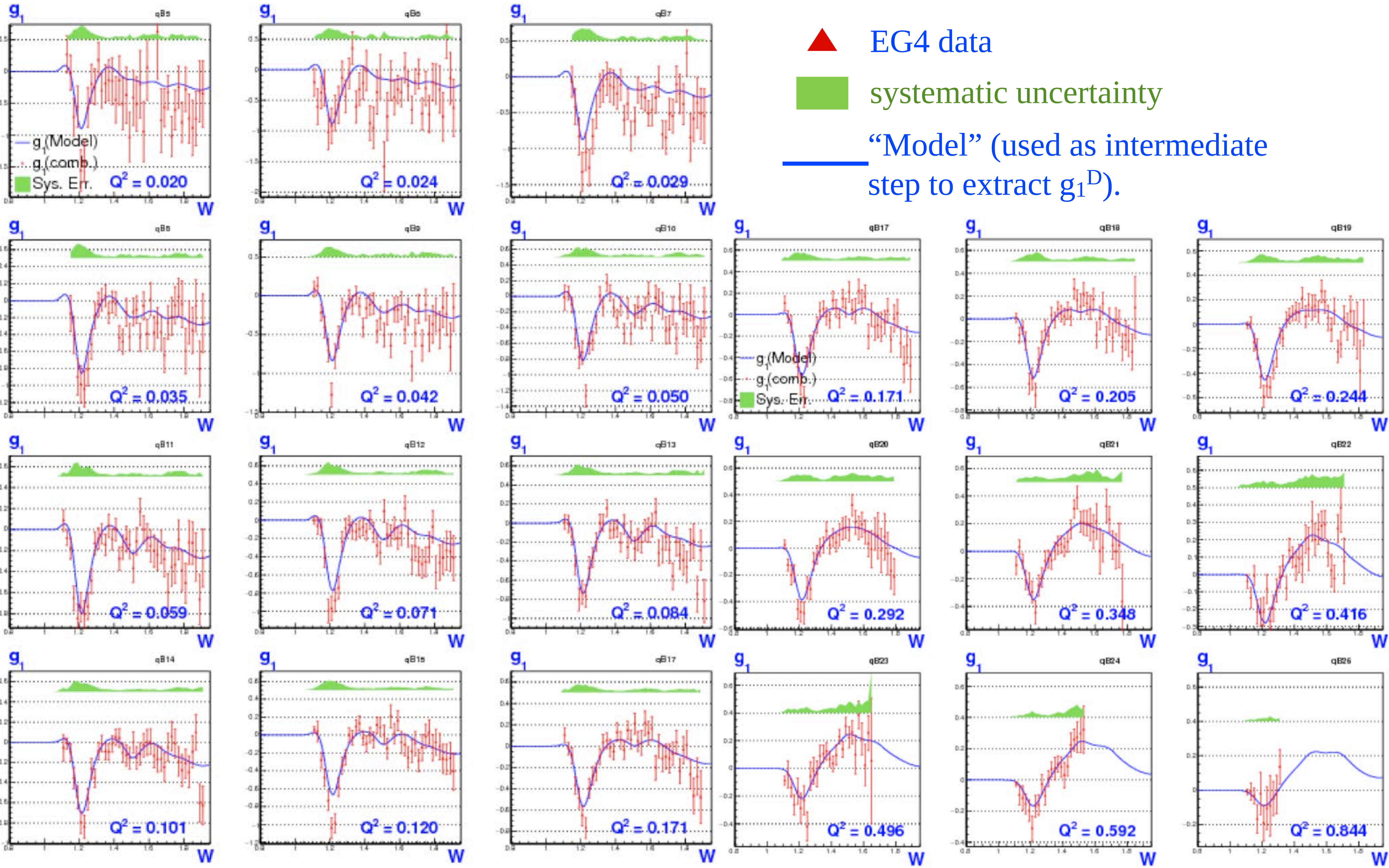
In the 3rd integral, the model is used rather than data to avoid quasielastic scattering and radiative tail contaminations

Proton

$$\int_0^{x_{th}} \ldots \rightarrow \int_{0.001}^{x_{min}} Model + \int_{x_{min}}^{x(W=1.08\ GeV)} data$$

g_1^d from EG4 polarized cross-section difference

K. Adhikari, S. Kuhn



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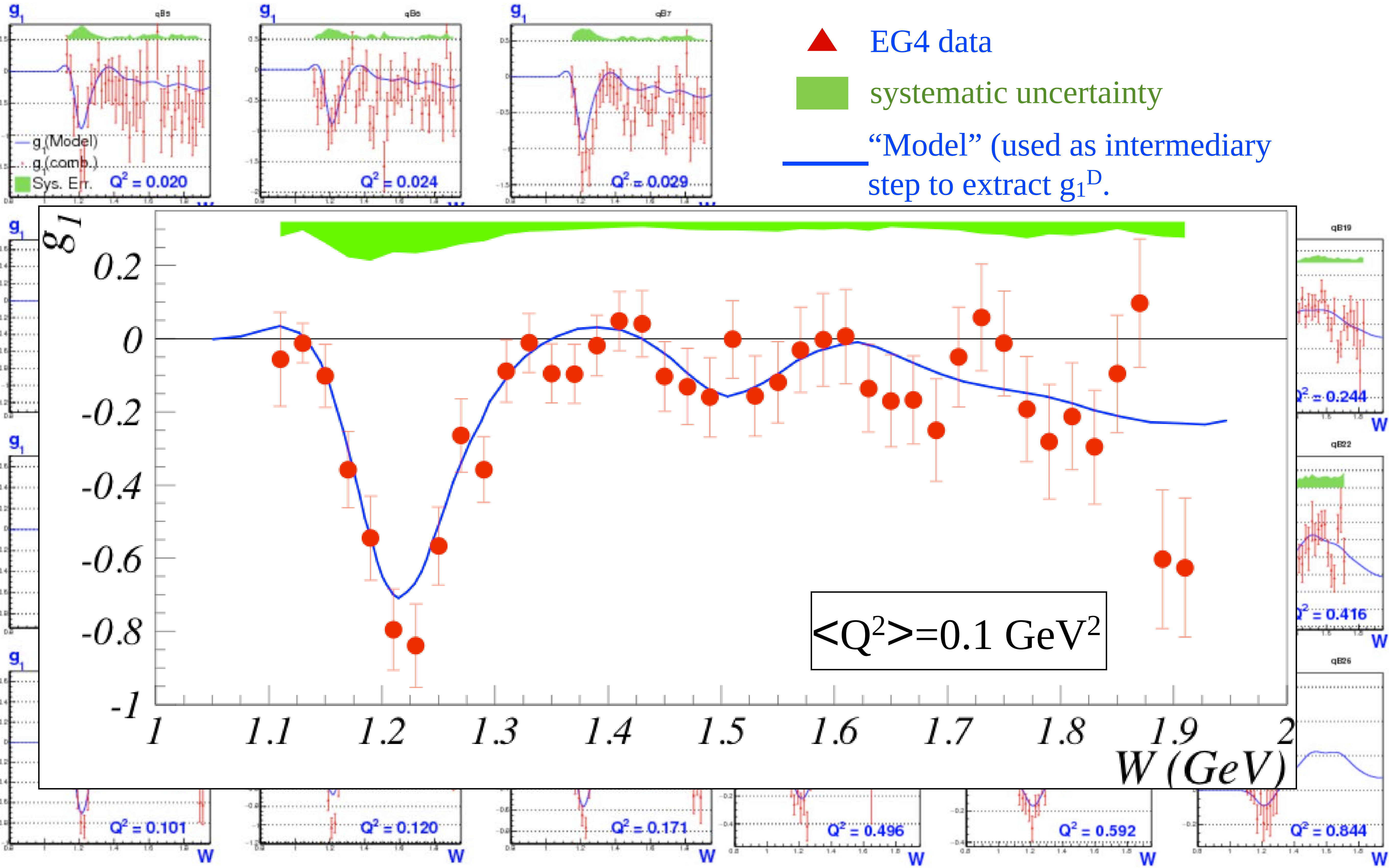
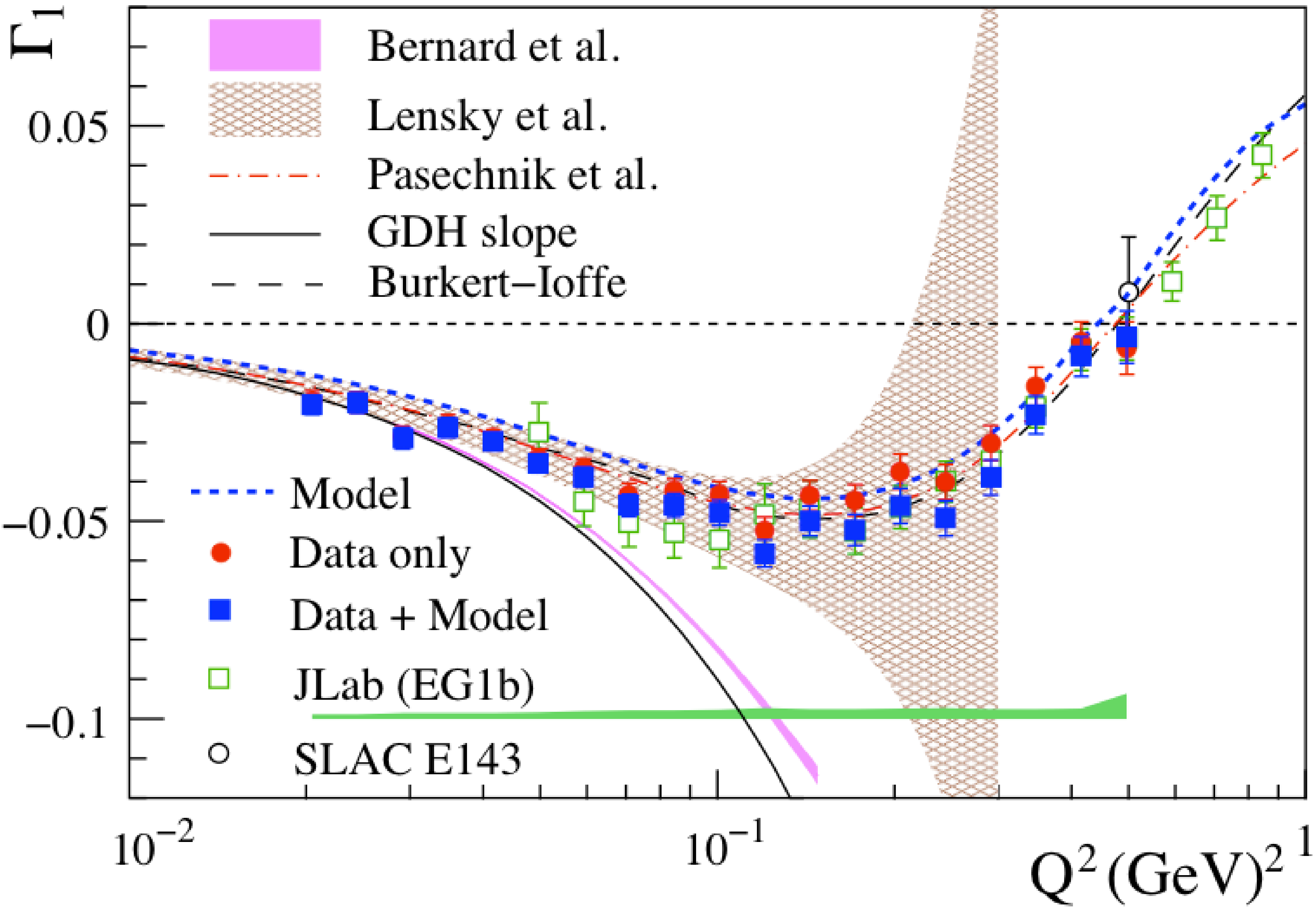


$$\Gamma_1^d = \int g_1^d(x,Q^2)dx$$

K. Adhikari, S. Kuhn

K.P. Adhikari et al. (CLAS Collaboration). PRL 120, 062501 (2018)



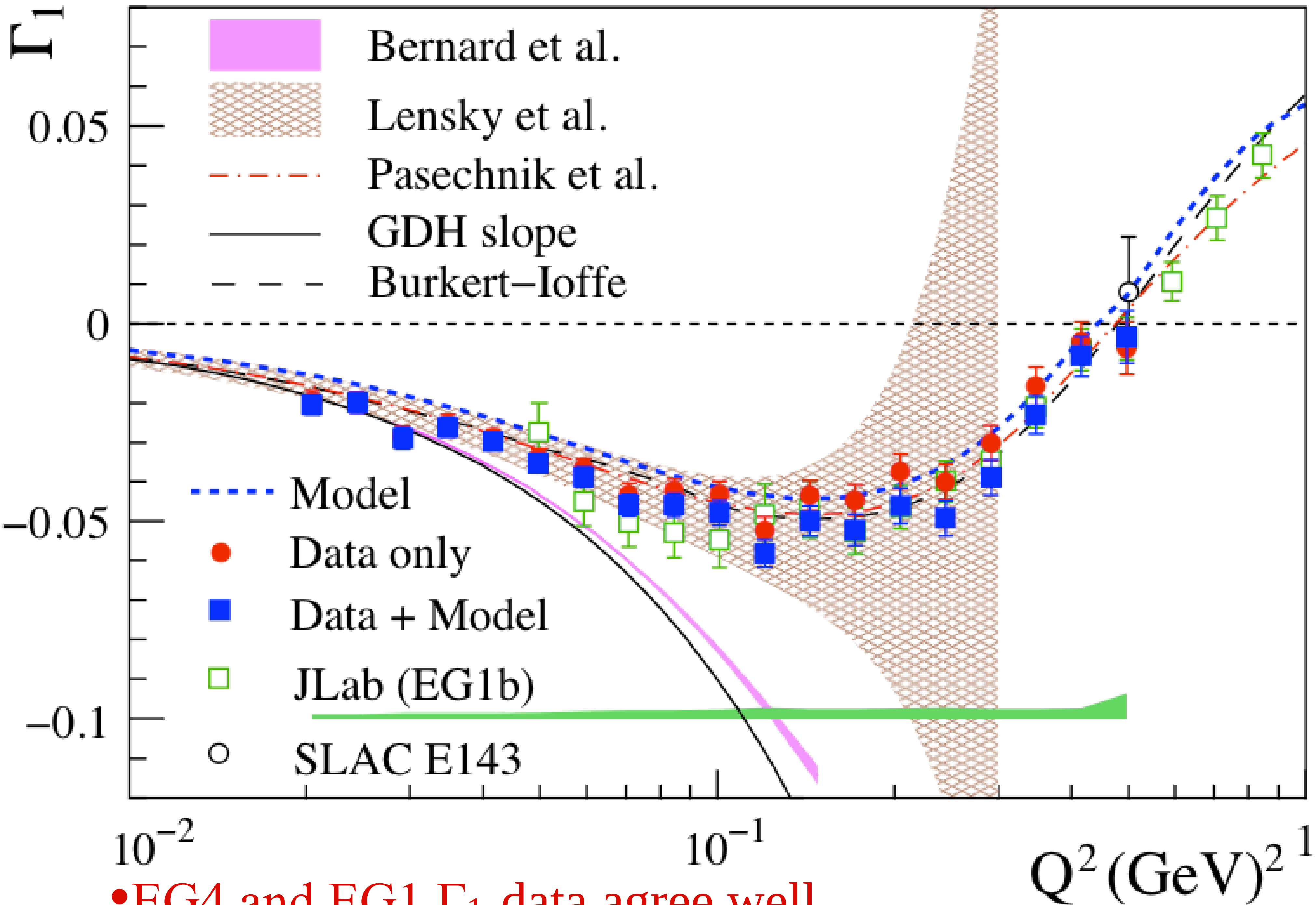
- Lowest Q^2 decreased by factor of ~2.5
- Much improved precision
- Small unmeasured low-x and large-x contributions

⇒Clean test of χpt

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

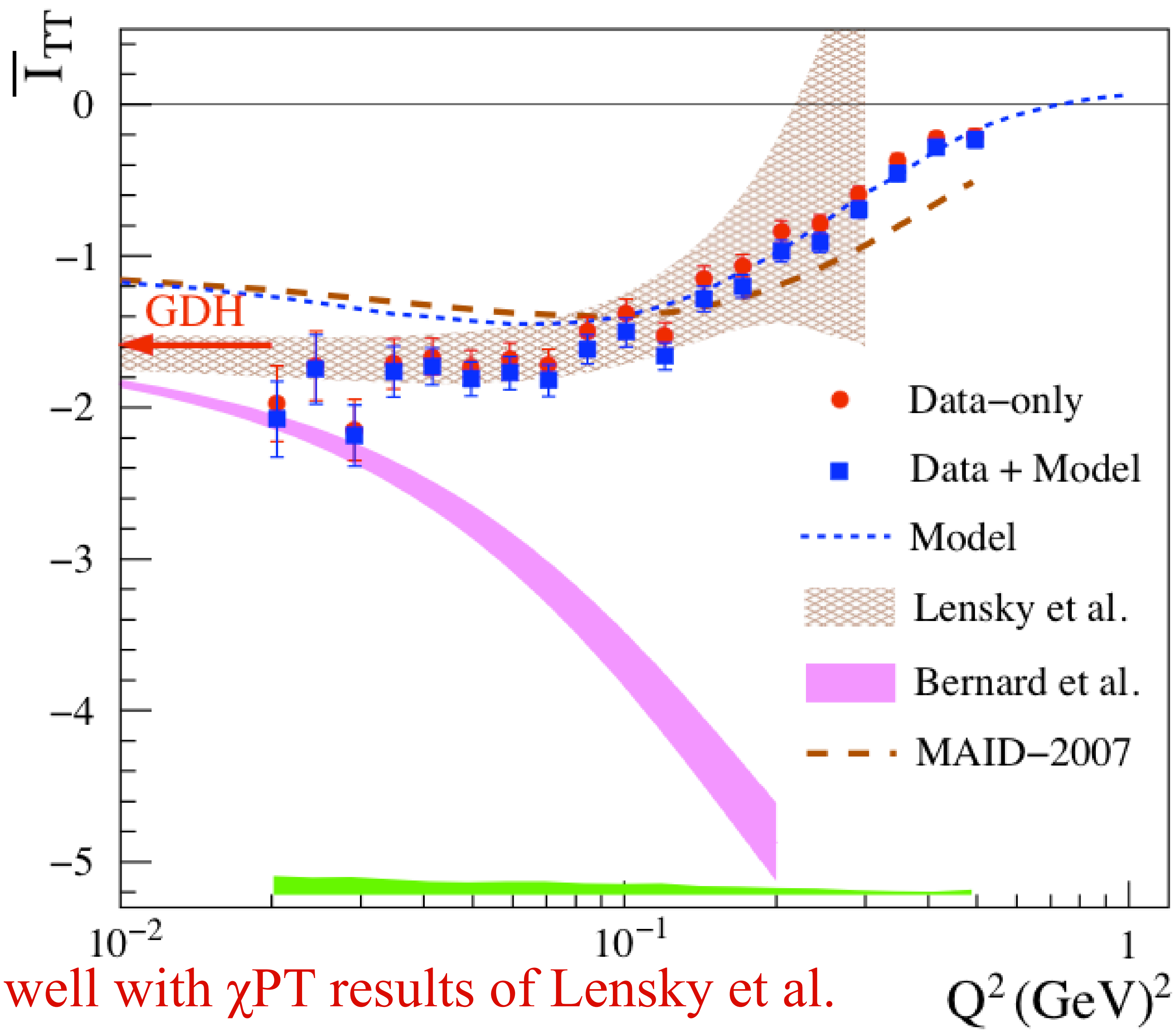
K. Adhikari, S. Kuhn

K.P. Adhikari et al. (CLAS Collaboration). PRL 120, 062501 (2018)



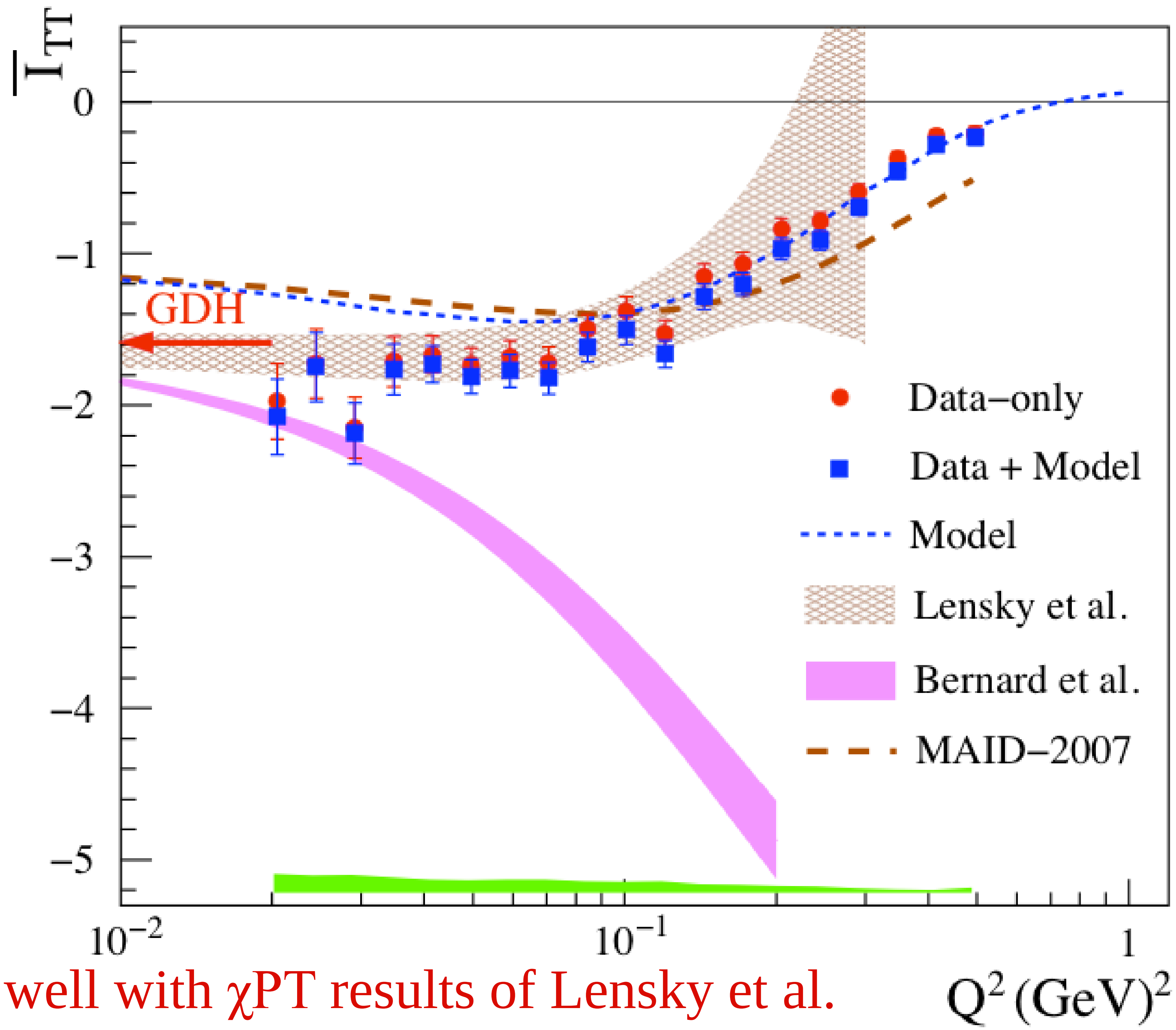
- EG4 and EG1 Γ_1 data agree well.
- EG4 data agree well with χPT results of Lensky et al.
- Bernard et al. χPT calculation agrees only for the lowest Q^2 points.
- Phenomenological models (Pasechnik et al, Burkert-Ioffe) agree well.

Generalized GDH sum $\bar{I}_{TT} = \int \frac{\sigma_A(\nu)-\sigma_P(\nu)}{\nu} d\nu$



- Data agree well with χPT results of Lensky et al.
- Bernard et al. χPT calculation does not agree as well.
- Maid model disagrees at low Q^2=0.

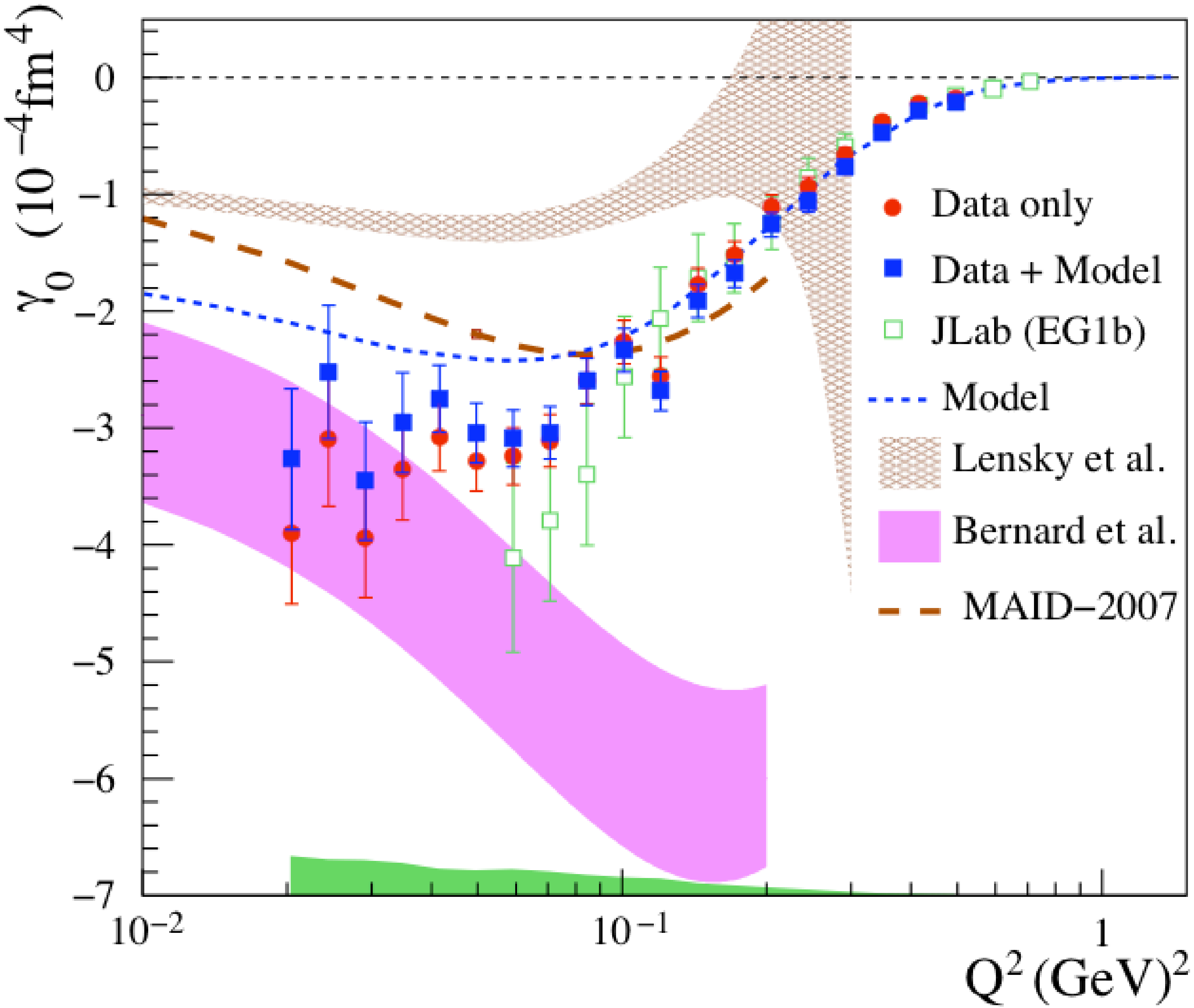
Generalized GDH sum $\bar{I}_{TT} = \int \frac{\sigma_A(\nu)-\sigma_P(\nu)}{\nu} d\nu$



- Data agree well with χPT results of Lensky et al.
- Bernard et al. χPT calculation does not agree as well.
- Maid model disagrees at low Q^2=0.
- Extrapolation to Q^2=0 tests original GDH sum rule:

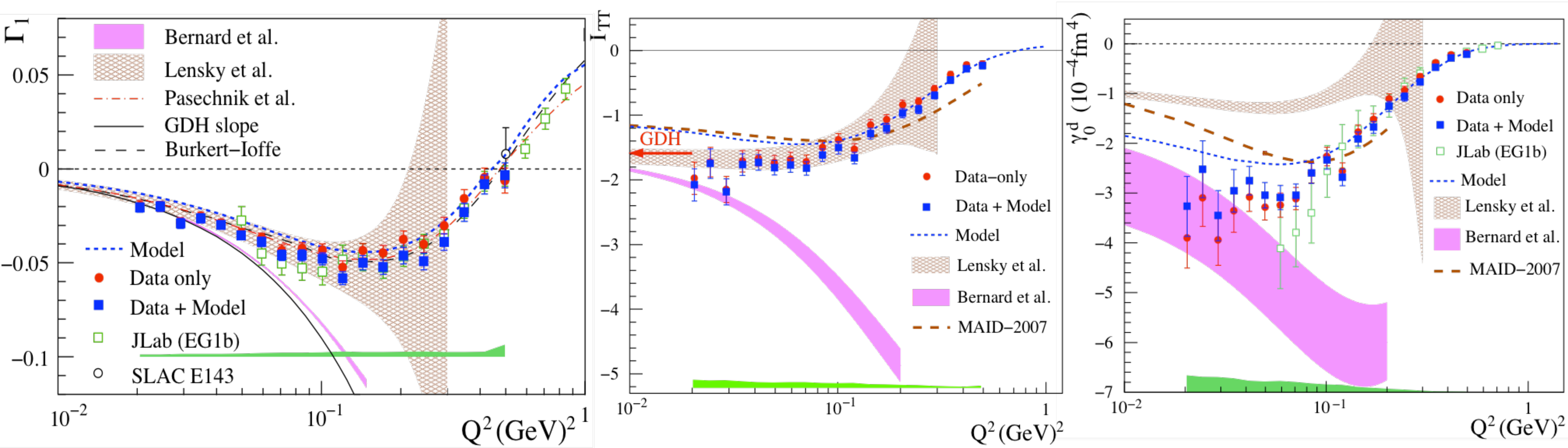
$\bar{I}_{TT}^{d} = -1.724 \pm 0.027(\text{stat}) \pm 0.050(\text{syst})$
Sum rule expectation: -1.574 ± 0.026
$I_{TT}^{n} = -0.955 \pm 0.040(\text{stat}) \pm 0.113(\text{syst})$
Sum rule expectation: -0.803

Higher moment γ_0



- Incoherent sum of p and n → χPT results of Lensky et al. disagree with data.
- Bernard et al. χPT calculation agree for lowest Q^2 points only.
- Maid model disagrees at low Q^2.

Conclusion from deuteron data

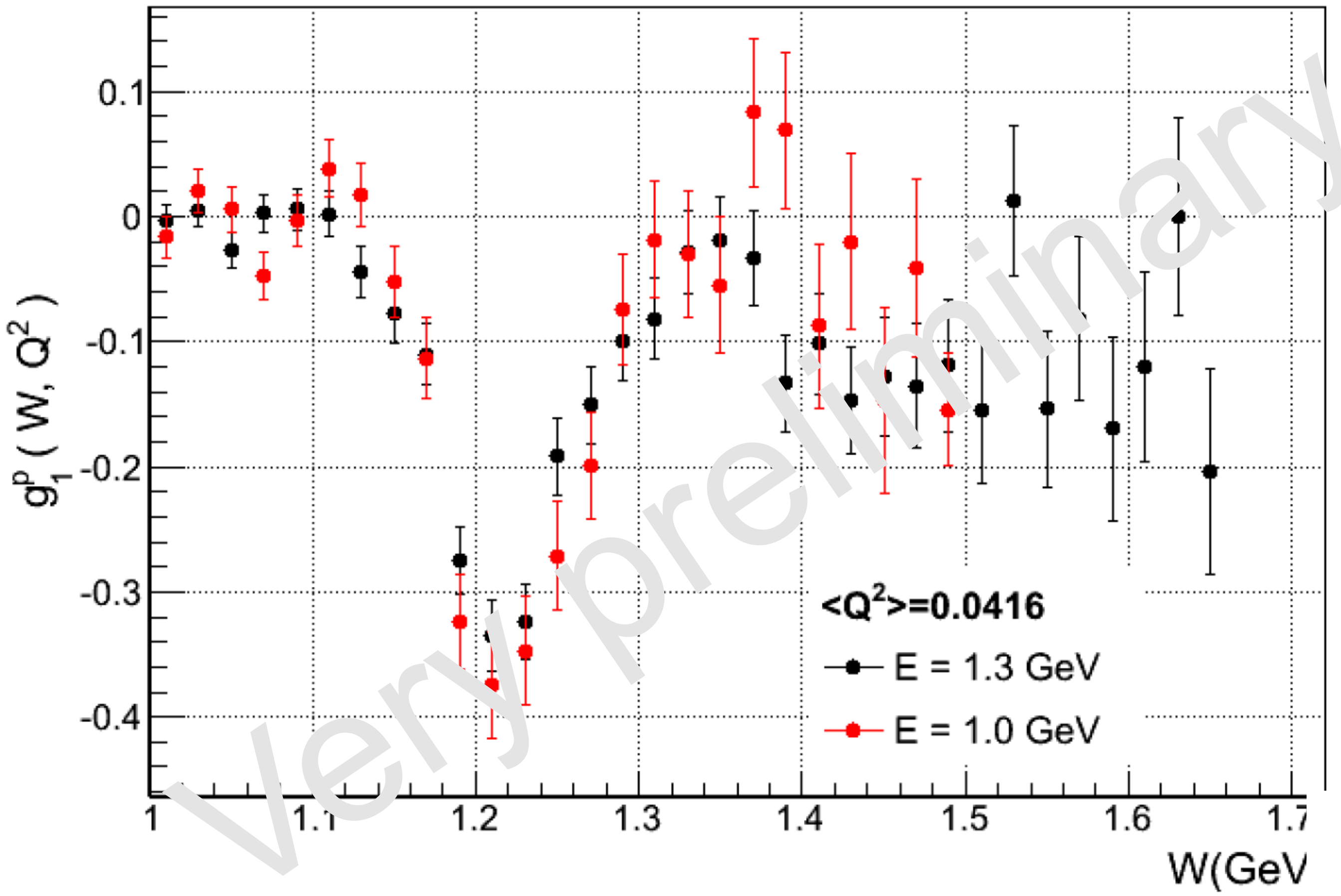


No χPT single method describes well both Γ_1, $\overline{I}_{TT}$, and γ_0, except at the lowest Q^2.

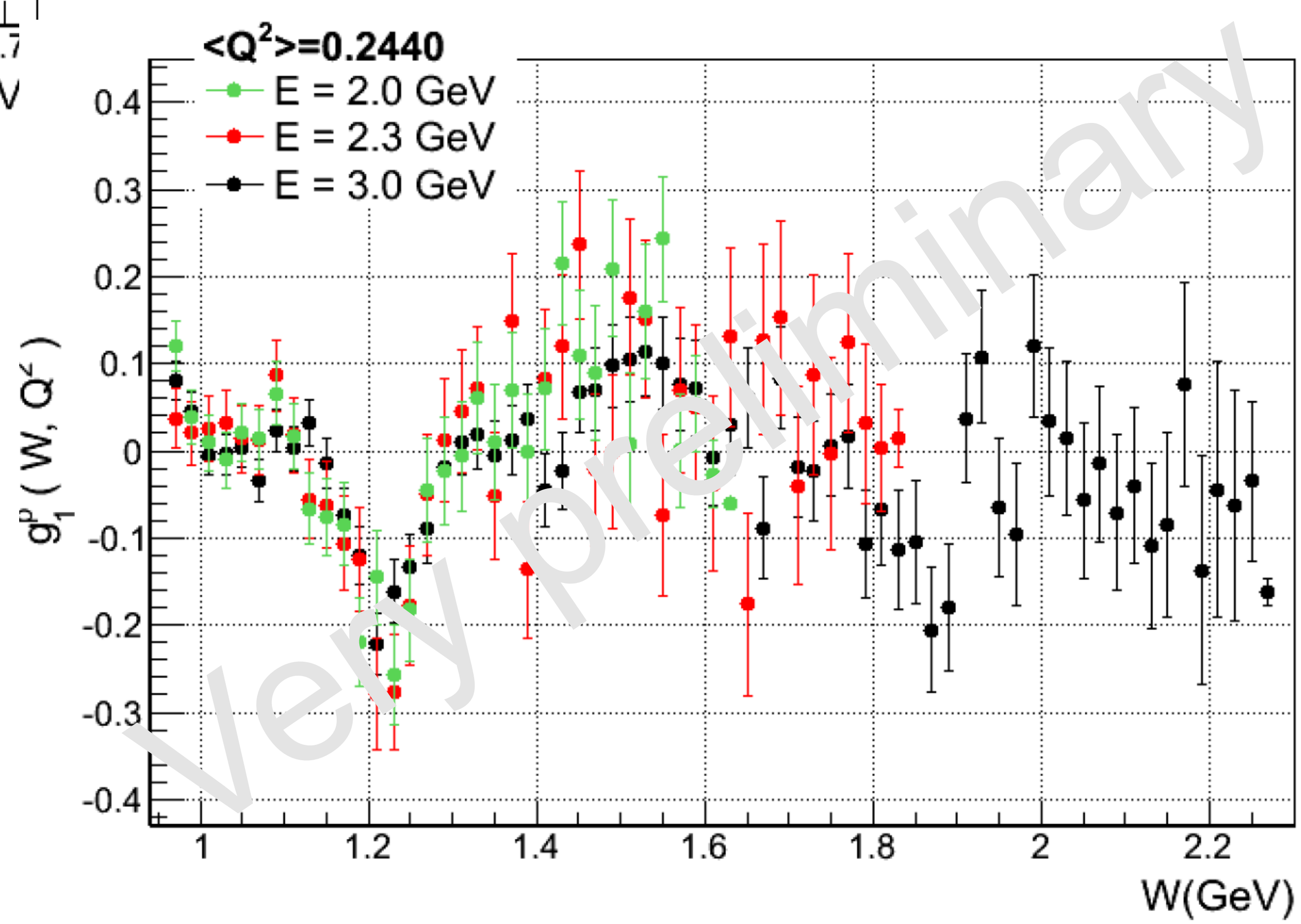
A satisfactory theoretical description of spin observables at low Q^2 remains challenging.

g_1^p from EG4 polarized cross-section difference

H. Kang



Initial approach was to correct expl data with combination of factors derived from elastic analysis, then invert equations to get g_1



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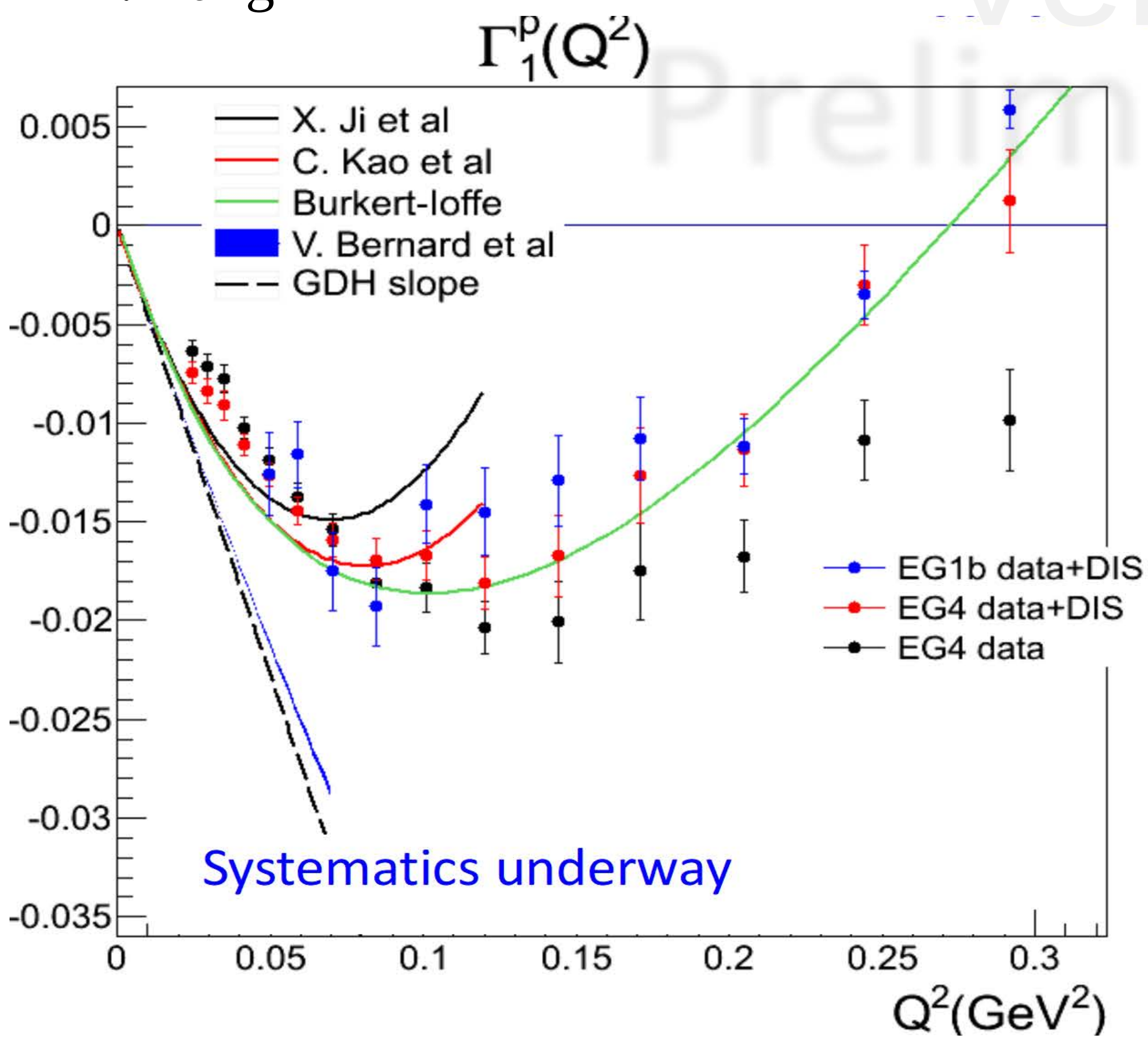
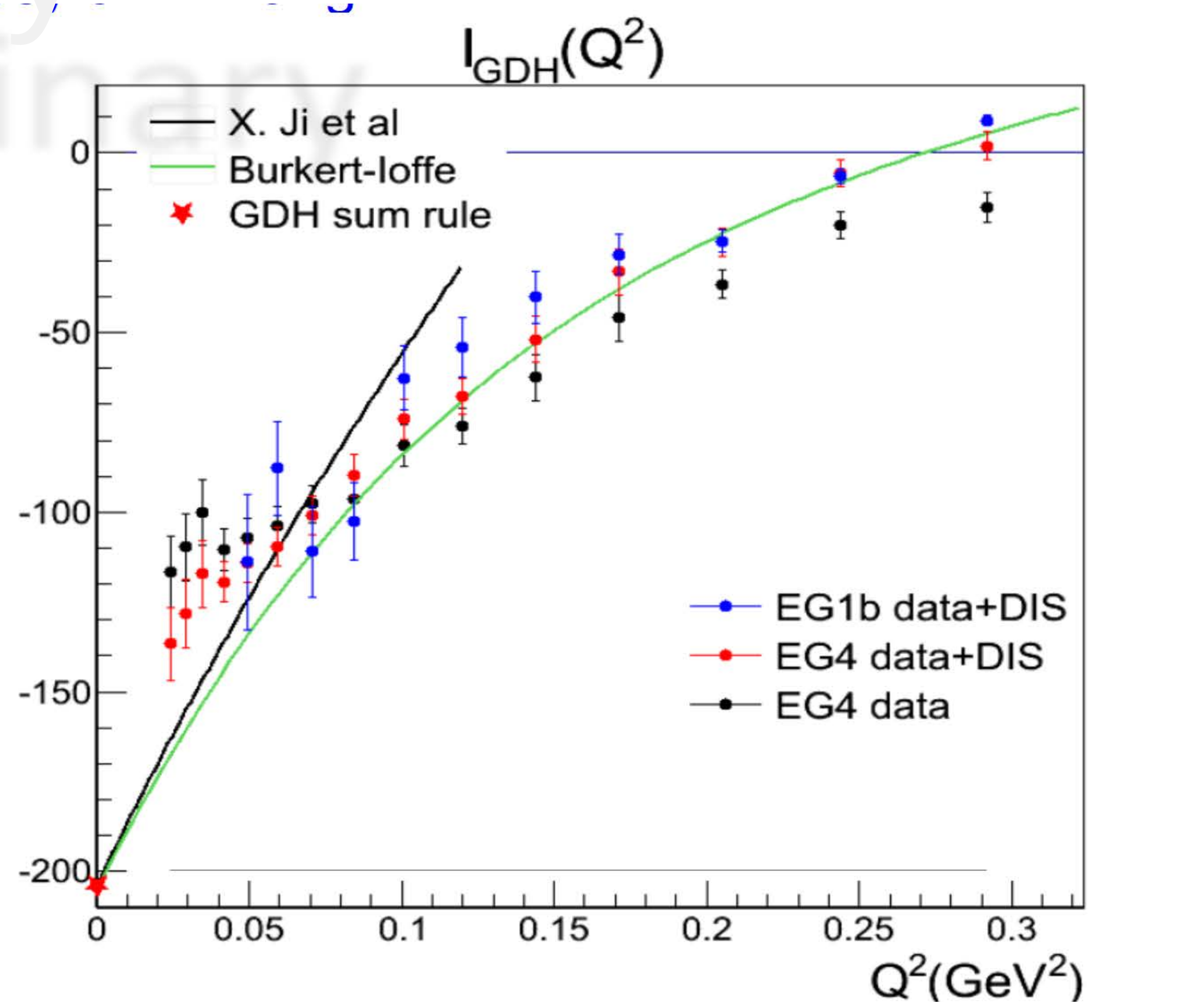
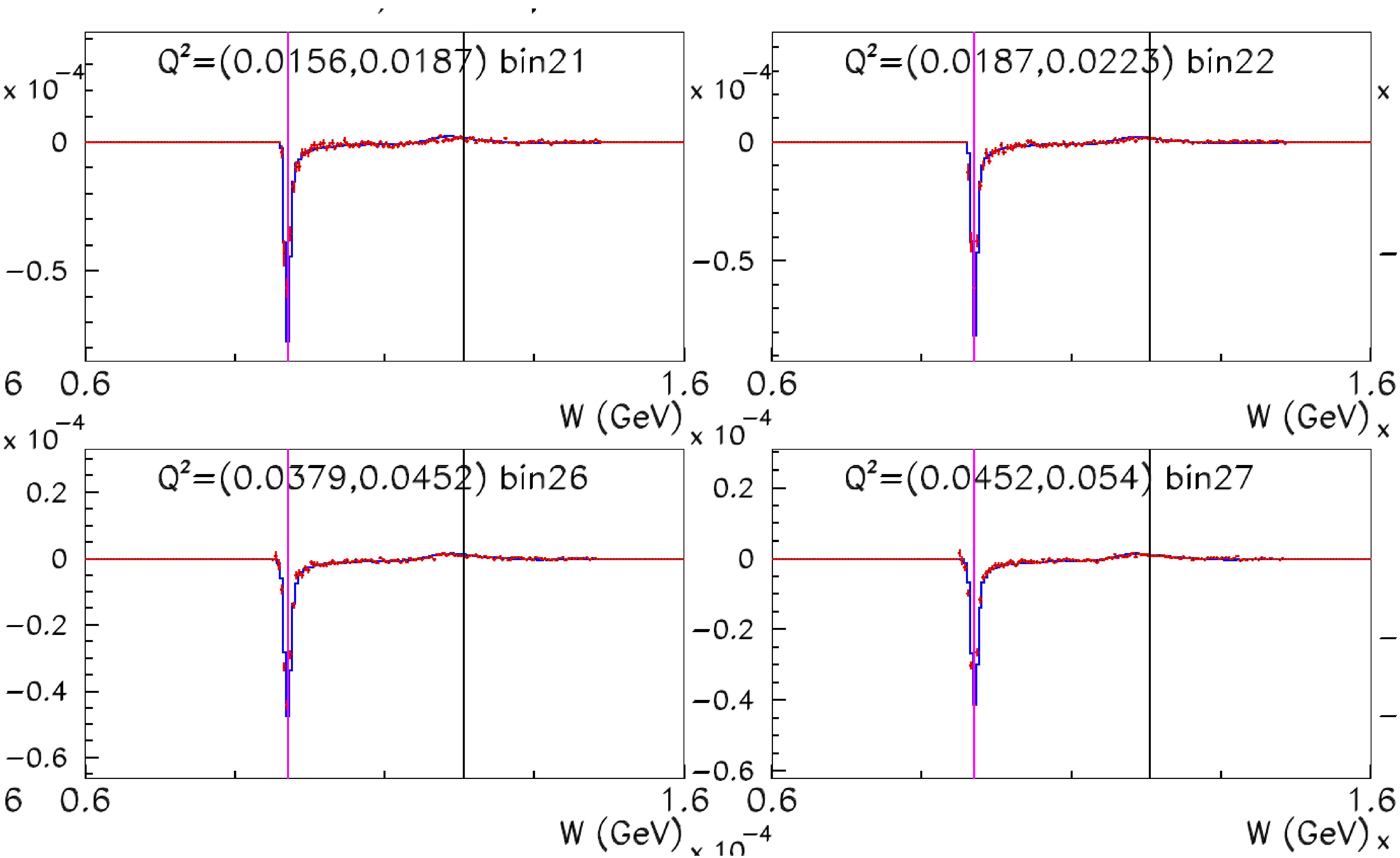
Very Preliminary





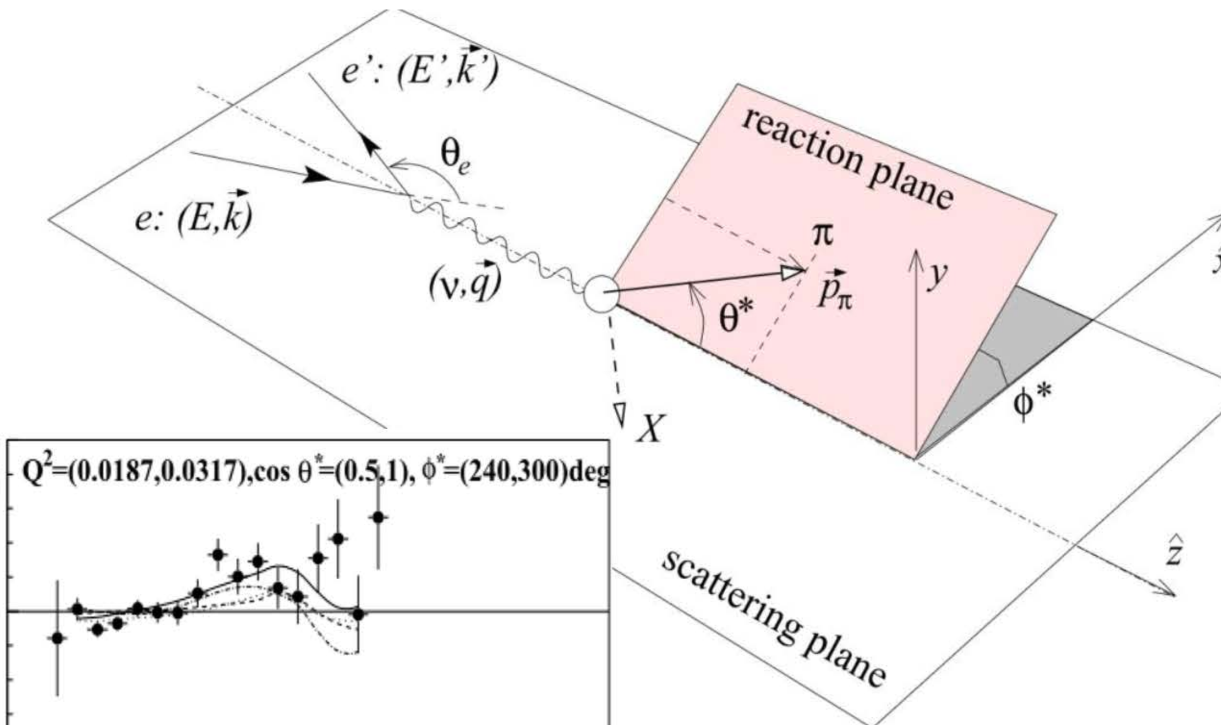
Currently revisiting analysis with same technique as deuteron
(X. Zheng with essential support from L. El Fassi and J. Zhang)

Comparison between data and simulations in new approach

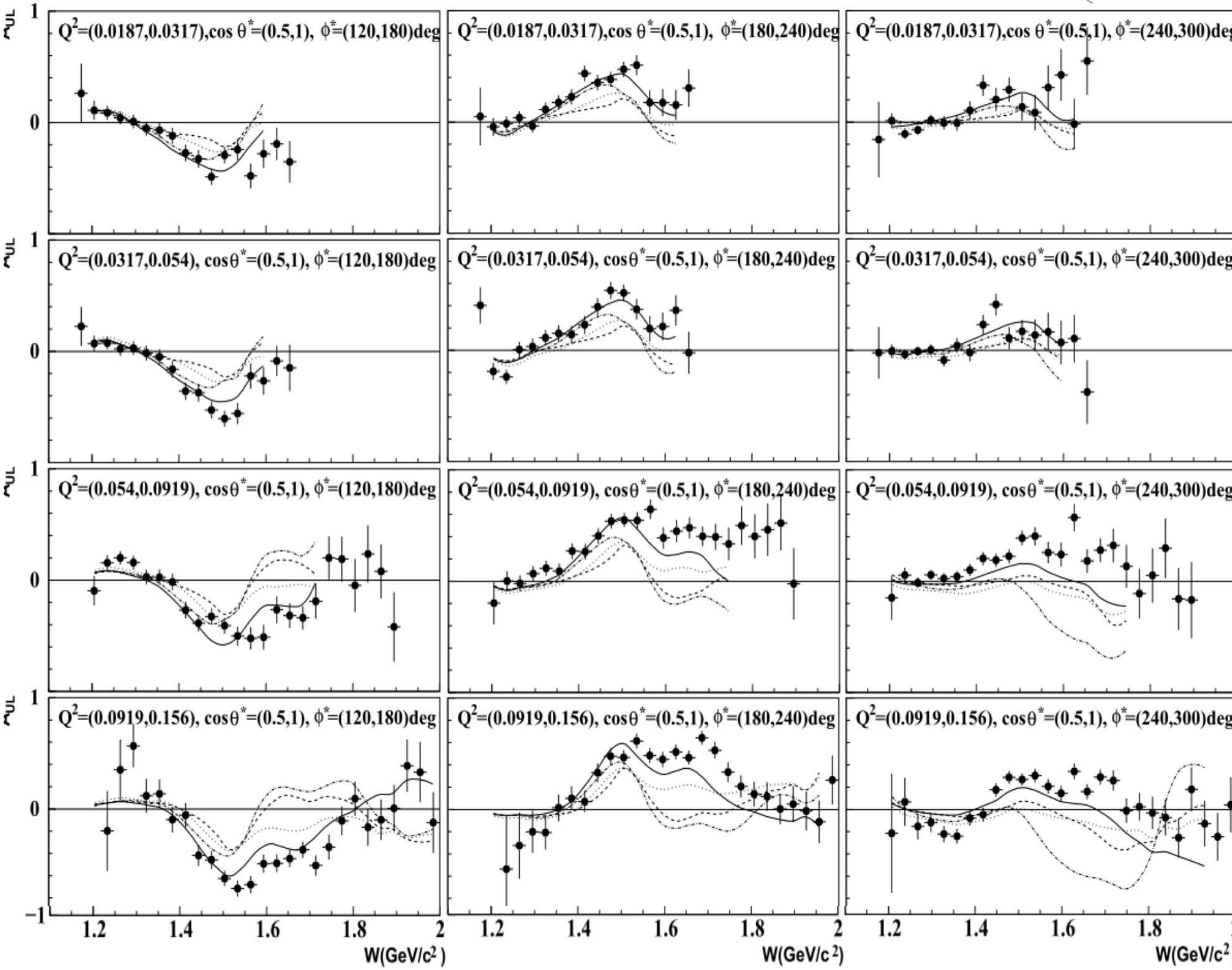


Data
Simulations

EG4: Spin Asymmetry A_{UL} Results on $p(e,e'\pi^+)n$



Plots courtesy of Xiaochao Zheng

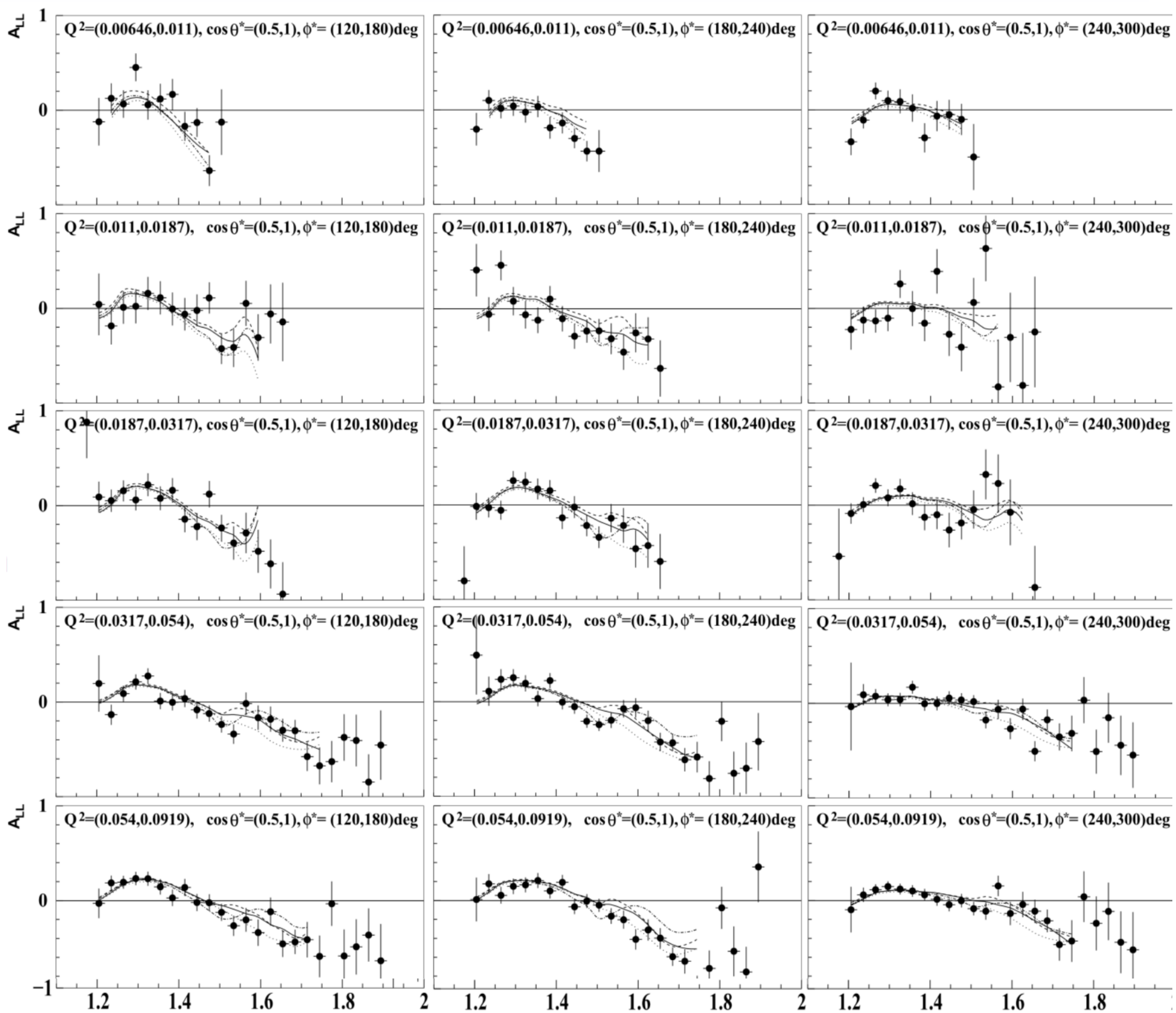


The target spin asymmetries A_{UL} for the π^+n channel

EG4: Spin Asymmetry A_{LL} Results on $p(e,e'\pi^+)n$

Plots courtesy of
Xiaochao Zheng

Results on the double-spin symmetries A_{LL} for π^+n channel in different Q^2 bins



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

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.
- Exclusive data for 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 recently published K.P. Adhikari et al. (CLAS Collaboration), PRL 120, 062501 (2018)
- Data on Γ_1, $\overline{I_{TT}}$, and γ_0 for the deuteron shows that χPT has mixed success, depending on the χPT method and observable.
- Original GDH sum rule (Q^2=0) checked on d and n.
- First result of larger JLab program to measure benchmark spin observables for χPT

$\Rightarrow$More low Q^2 data to come:

  - g_1, Γ_1, I_{TT}, and γ_0 for the proton (CLAS EG4).
  - g_1, g_2, Γ_1, Γ_2, I_{TT}, γ_0 and δ_{LT} for the neutron and ^{3}He (Hall A E97110).
  - g_2, g_1, Γ_2, Γ_1, I_{TT}, δ_{LT} and γ_0 for the proton (Hall A E08027).