^{3}He GDH SUM RULE at low Q^2

Chao Peng (Argonne National Laboratory)

For the E97-110 and Hall A Collaborations

HALL A/C JOINT MEETING, JULY 17, 2020

Outline

Introduction

Experiment E97-110

Experiment Results

GDH Sum Rule

Gerasimov-Drell-Hearn (GDH) Sum Rule

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

Spin S and anomalous magnetic moment κ

Relate the helicity-dependent photoabsorption cross sections to static properties

Derived from general principles

GDH Measurements

Proton, verified: Mainz, Bonn, LEGS (up to $\nu \sim 3$ GeV)

Neutron, in progress: Mainz, Bonn, LEGS, HIGS

Measurements on Deuteron and ^{3}He

	M [GeV]	Spin	κ	$I_{\mathrm{GDH}}[\mu$ b]
Proton	0.938	$\frac{1}{2}$	1.79	–204.8
Neutron	0.940	$\frac{1}{2}$	-1.91	–233.2
Deuteron	1.876	1	-0.14	–0.65
Helium-3	2.809	$\frac{1}{2}$	-8.38	–498.0

Generalized GDH sum rules

Generalized for virtual photon via unsubtracted dispersion relation

- Connect moments of spin-dependent structure functions with the Compton amplitudes

$$\mathrm{Re}\left[g_{TT}(\nu, Q^2) - g_{TT}^{pole}(\nu, Q^2)\right] = \frac{2\alpha}{M^2} I_{TT}(Q^2)\nu + \gamma_{TT}(Q^2)\nu^3 + O(\nu^5).$$

$$I_{TT}(Q^2) = \frac{M^2}{4\pi^2\alpha}\int_{\nu_{th}}^{\infty} \frac{K(\nu, Q^2)\sigma_{TT}(\nu, Q^2)}{\nu^2} d\nu$$

$$= \frac{2M^2}{Q^2}\int_0^{x_{th}} \left[g_1(x, Q^2) - \frac{4M^2}{Q^2}x^2 g_2(x, Q^2)\right] dx.$$

$$I_{LT}(Q^2) = \frac{2M^2}{Q^2}\int_0^{x_{th}} \left[g_1(x, Q^2) + g_2(x, Q^2)\right] dx,$$

Generalized GDH sum rules

Generalize it from covariant form of the spin-dependent Compton amplitudes

$$S_1(\nu, Q^2) = \frac{\nu M}{\nu^2 + Q^2}\left[g_{TT}(\nu, Q^2) + \frac{Q}{\nu} g_{LT}(\nu, Q^2)\right],$$

$$S_2(\nu, Q^2) = -\frac{M^2}{\nu^2 + Q^2}\left[g_{TT}(\nu, Q^2) - \frac{\nu}{Q} g_{LT}(\nu, Q^2)\right].$$

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

$$= \frac{M^2}{4\pi^2\alpha}\int_{\nu_{th}}^{\infty} \frac{K(\nu, Q^2)}{\nu^2 + Q^2}\left[\sigma_{TT}(\nu, Q^2) + \frac{Q}{\nu}\sigma_{LT}(\nu, Q^2)\right] d\nu.$$

Burkhardt-Cottingham (BC) sum rule

$$0 = \int_0^{\infty} \operatorname{Im} S_2(\nu, Q^2) d\nu = \int_0^1 g_2(x, Q^2)dx.$$

First Moment of g_1

First Moment of g_1

$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)dx$$

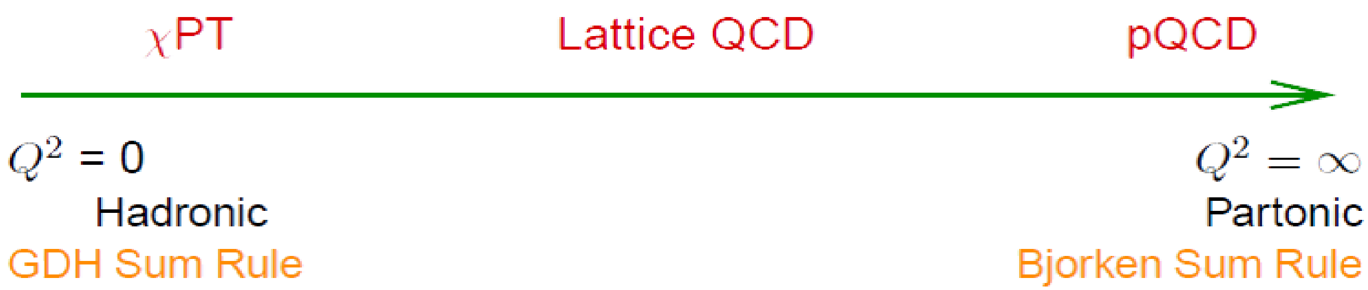
- Connects to the total spin carried by the quarks in DIS region
- $I_1(Q^2)$ + elastic contribution

Bjorken Sum Rule

$$\Gamma_1^P(Q^2) - \Gamma_1^N(Q^2) = \frac{g_A}{6} + O\big(\alpha_s(Q^2)\big) + O(\frac{1}{Q^2})$$

- g_A, nucleon axial charge
- Consistent with experimental result in 10%
- Valid in DIS region

Study the Transition



Recover the GDH sum rule for real photons ($Q^2 = 0$)

Connect with Bjorken sum rule ($Q^2 = \infty$)

Relate the moments of the spin dependent structure functions to virtual Compton AMPLITUDE ($Q^2 > 0$), and test the theoretical calculations

- Baryon Chiral Perturbation Theory (IRBChPT, RBChPT)
- Lattice QCD

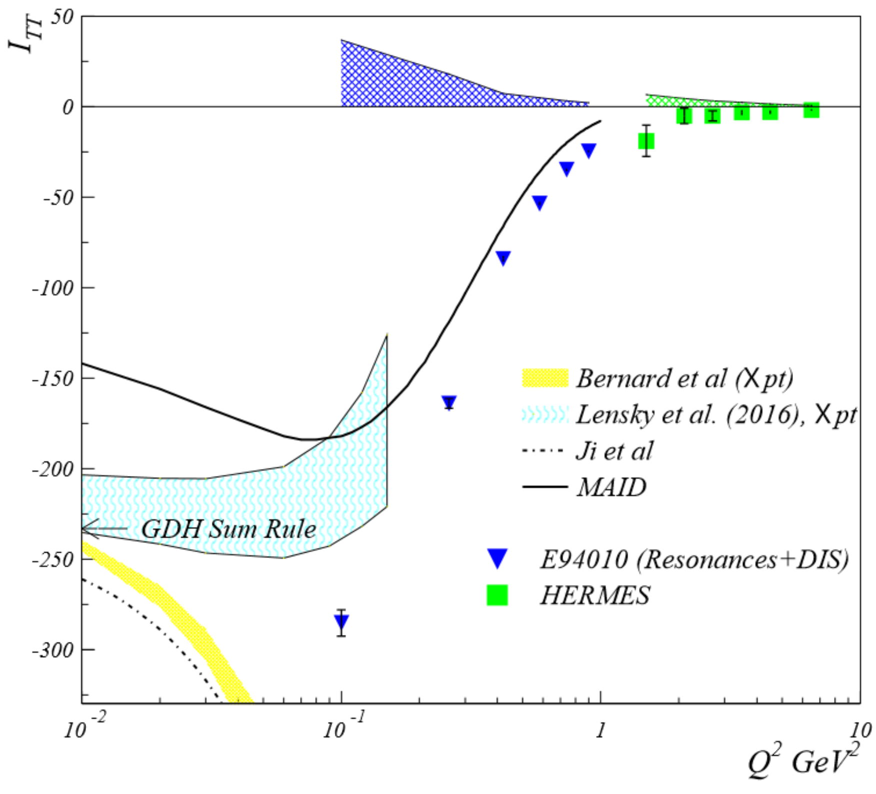
Study the transition from non-perturbative to perturbative QCD

Experimental progress

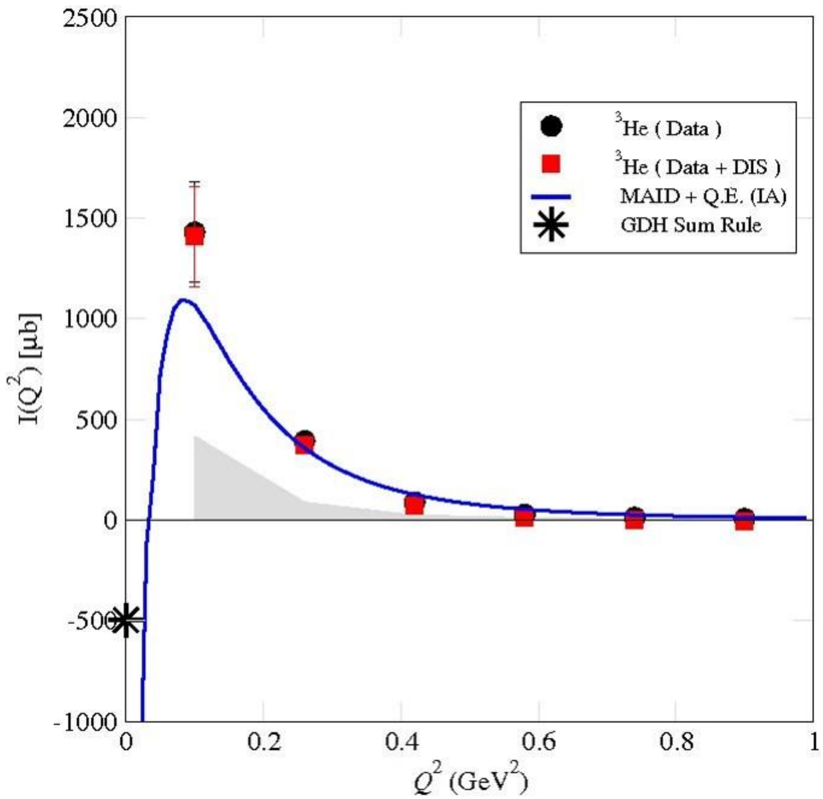
Observable	H target	D target	^{3}He target
g_1, g_2, Γ_1 & Γ_2 at high Q^2	SLAC JLAB SANE	SLAC	SLAC JLAB E97-117 JLAB E01-012 JLAB E06-014
g_1 & Γ_1 at high Q^2	SMC HERMES JLAB EG1	SMC HERMES JLAB EG1	HERMES
Γ_1 & Γ_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
Γ_1 at low Q^2	SLAC HERMES JLAB EG1	SLAC HERMES JLAB EG1	HERMES
$\Gamma_1, Q^2 << 1$ GeV^2	JLab EG4	JLab EG4	JLab E97-110
$\Gamma_2, Q^2 << 1$ GeV^2	JLab E08-027		JLab E97-110

E94-010 Results

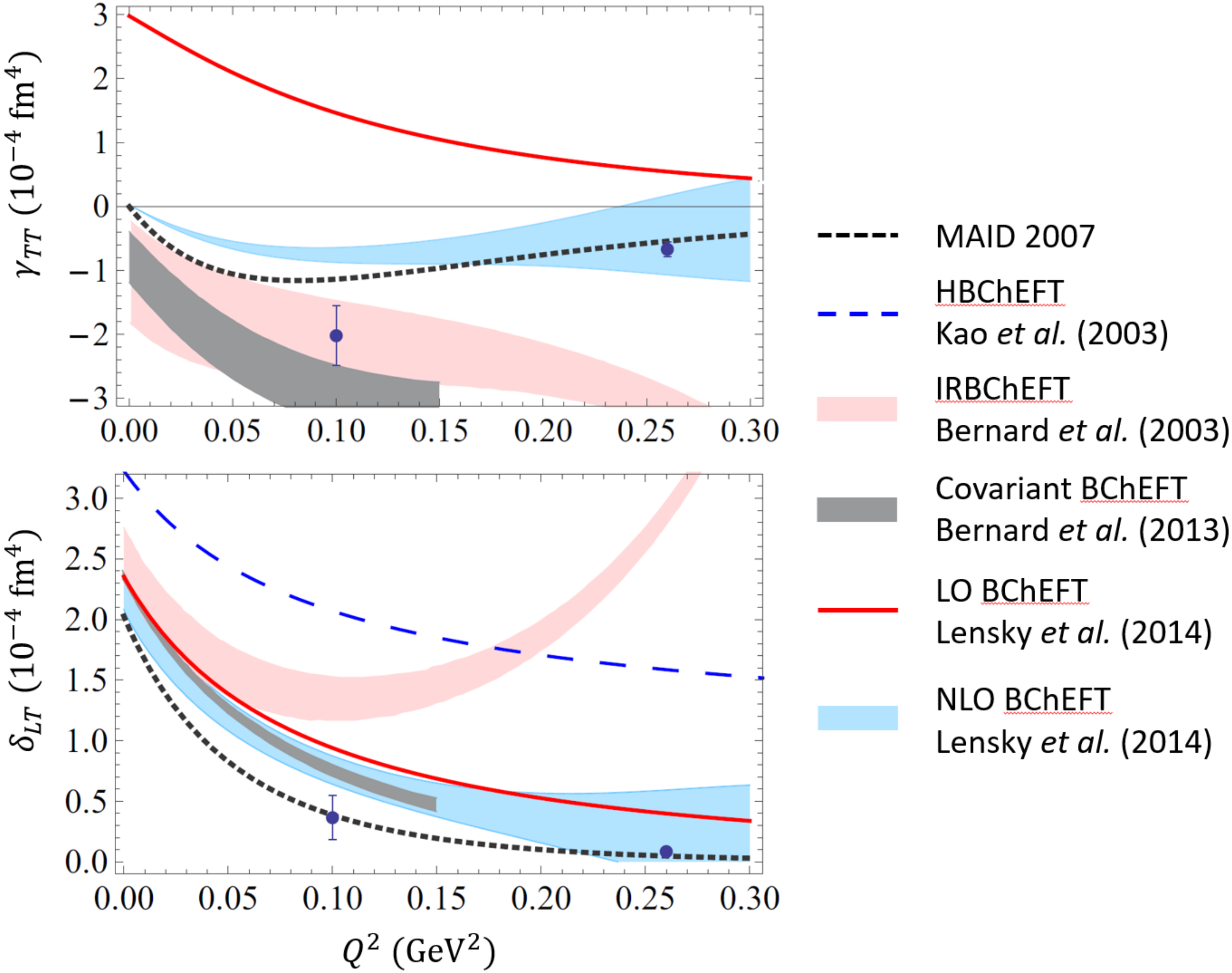
Neutron | **Helium-3**



M. Amarian et al., Phys. Rev. Lett., 89:242301, 2002.



K. Slifer et al., Phys. Rev. Lett., 101:022303, 2008.



3
2
1
0
−1
−2
−3
γ_{TT} (10^{-4} fm^4)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
3.0
2.5
2.0
1.5
1.0
0.5
0.0
δ_{LT} (10^{-4} fm^4)
Q^2 (GeV^2)
MAID 2007
HBChEFT
Kao *et al.* (2003)
IRBChEFT
Bernard *et al.* (2003)
Covariant BChEFT
Bernard *et al.* (2013)
LO BChEFT
Lensky *et al.* (2014)
NLO BChEFT
Lensky *et al.* (2014)

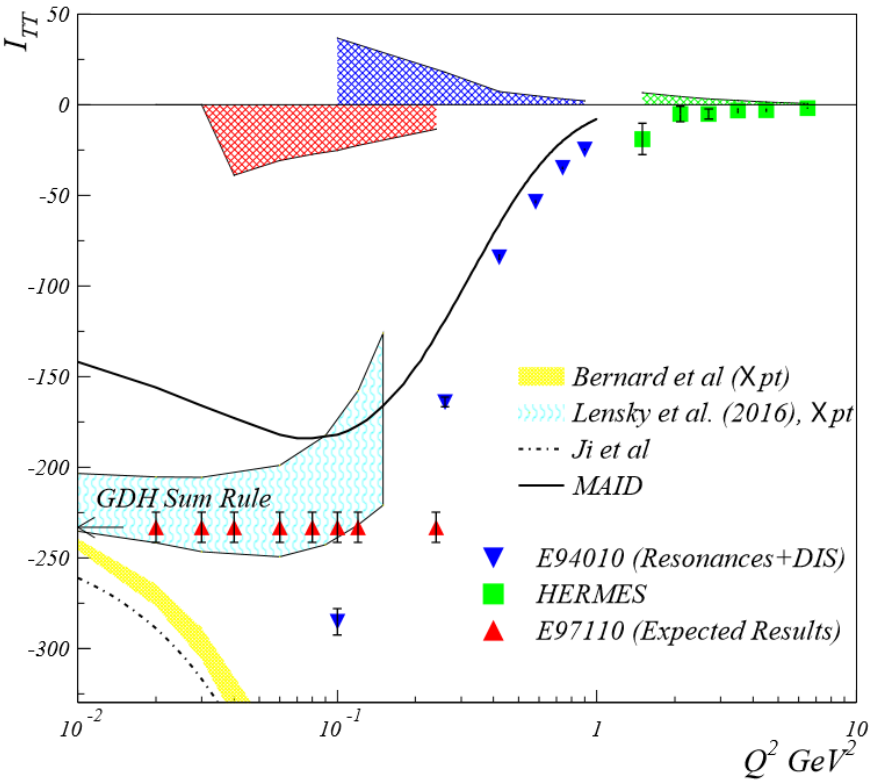
Outline

Introduction

Experiment E97-110

Experiment Results

E97-110 at Jefferson Lab



Inclusive measurement, $^3\vec{\mathrm{He}}(\vec{e},e')X$

- Scattering angles: 6^o and 9^o
- Polarized electron beam, P_{beam} = 75%
- Polarized ^{3}He target, P_{target} = 40%

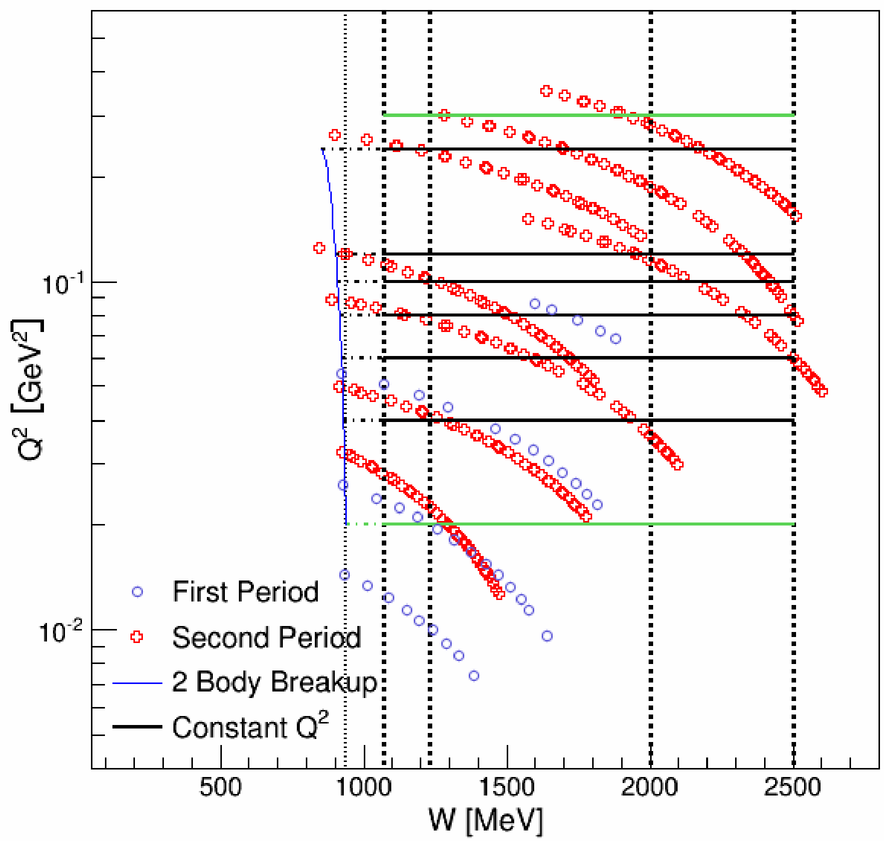
Measured the differences of polarized cross sections

- Parallel (anti-parallel)
- Perpendicular

Spokespersons: J.-P. Chen, A. Deur, F. Garibaldi

Graduate students: J. Singh, V. Sulkosky, J. Yuan, C. Peng, N. Ton

E97-110 at Jefferson Lab



Target Cell	Angle	Beam Energy (MeV)
Penelope	6.10°	2134.2
Priapus	6.10°	2134.9
Priapus	6.10°	2844.8
Priapus	6.10°	4208.8
Priapus	9.03°	1147.3
Priapus	9.03°	2233.9
Priapus	9.03°	3318.8
Priapus	9.03°	3775.4
Priapus	9.03°	4404.2

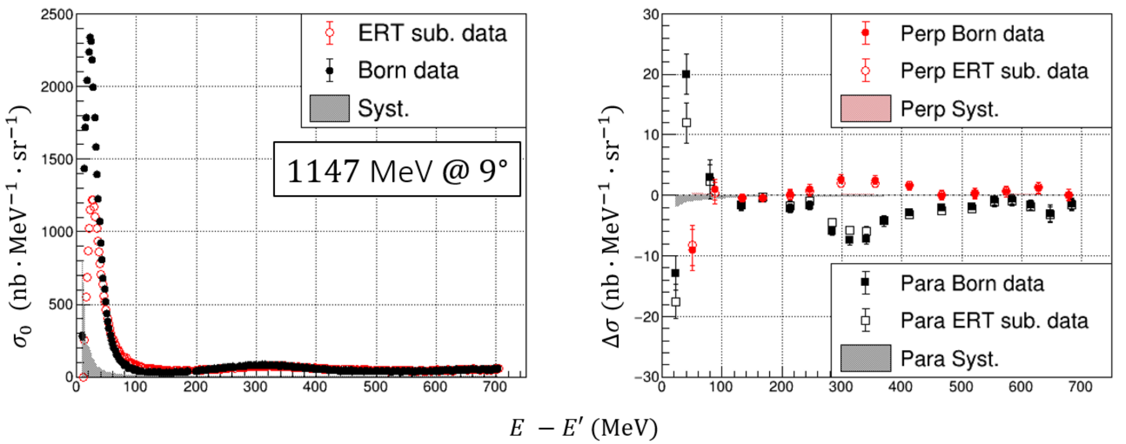
Second Period Systematics (V. Sulkosky)

Source	σ_{syst} **[%]**
Target density	1.6
VDC Multi-tracks	< 1
Charge	1
Detector Efficiencies GC,Sh,Scint	1.5 -2
Yield Stability ν-dependent	< 1.5
Acceptance	$3 - 4$
Beam polarization	3.5
Target Polarization	$3 - 5$

Inelastic Radiative Correction

Iterative correction

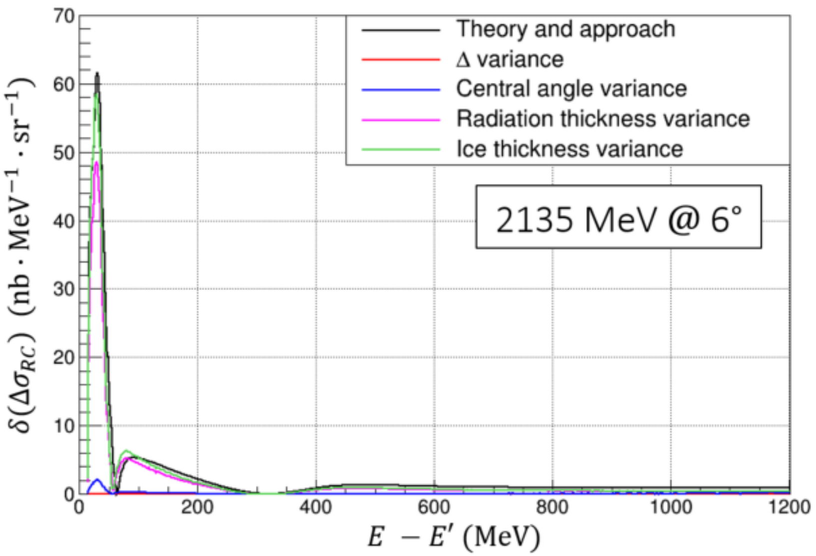
- Build pseudo-model with experimental data
- Interpolation and extrapolation (or filled by other models) for unmeasured points
- Calculate radiative effects with this pseudo-model
- Unfold Born cross sections, and then update the pseudo-model
- Repeat until results are converged



Inelastic Radiative Correction

Systematic uncertainties

- Internal effects by comparing different approaches < 3%
- Extrapolation or model dependency for the unmeasured region
  - Cross-check with each other < 3%
- Free parameter Δ for singular integral of $I(E, E', l)$
  - $\Delta = 1 \pm 0.5$ MeV tested, negligible
- Material thickness uncertainty
- Particle trajectory uncertainty
  - Varied the central angle by $\pm 0.1^{\circ}$



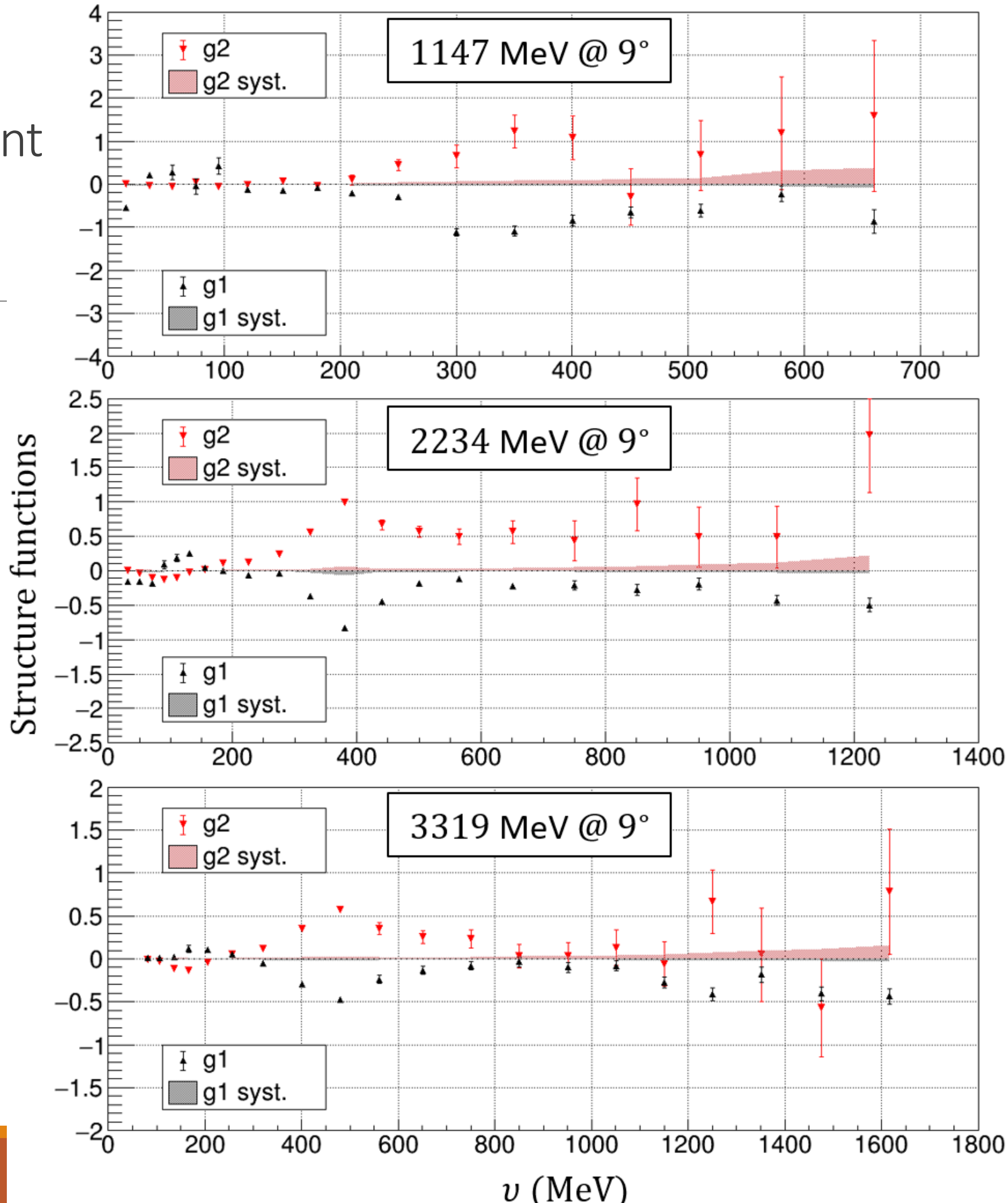
Outline

Introduction

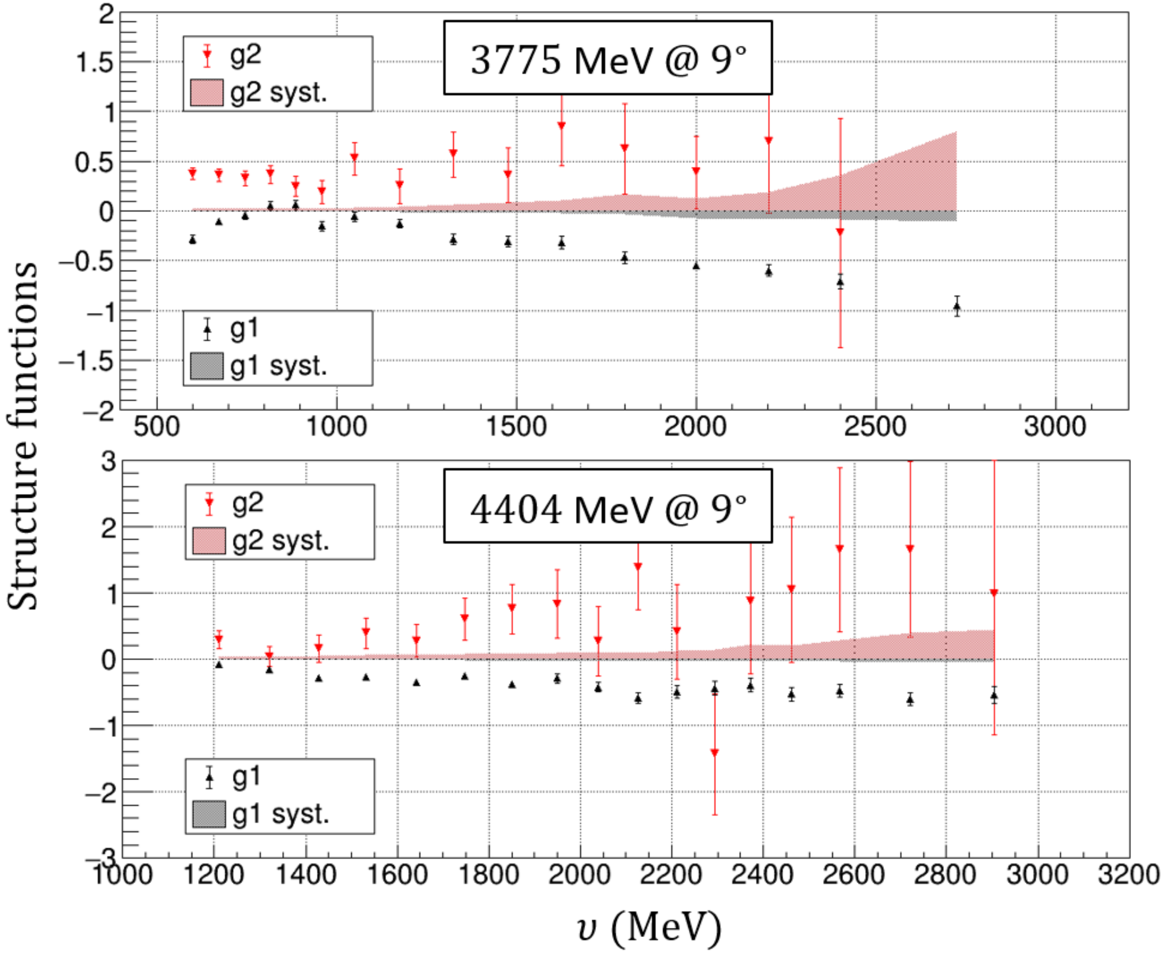
Experiment E97-110

Experiment Results

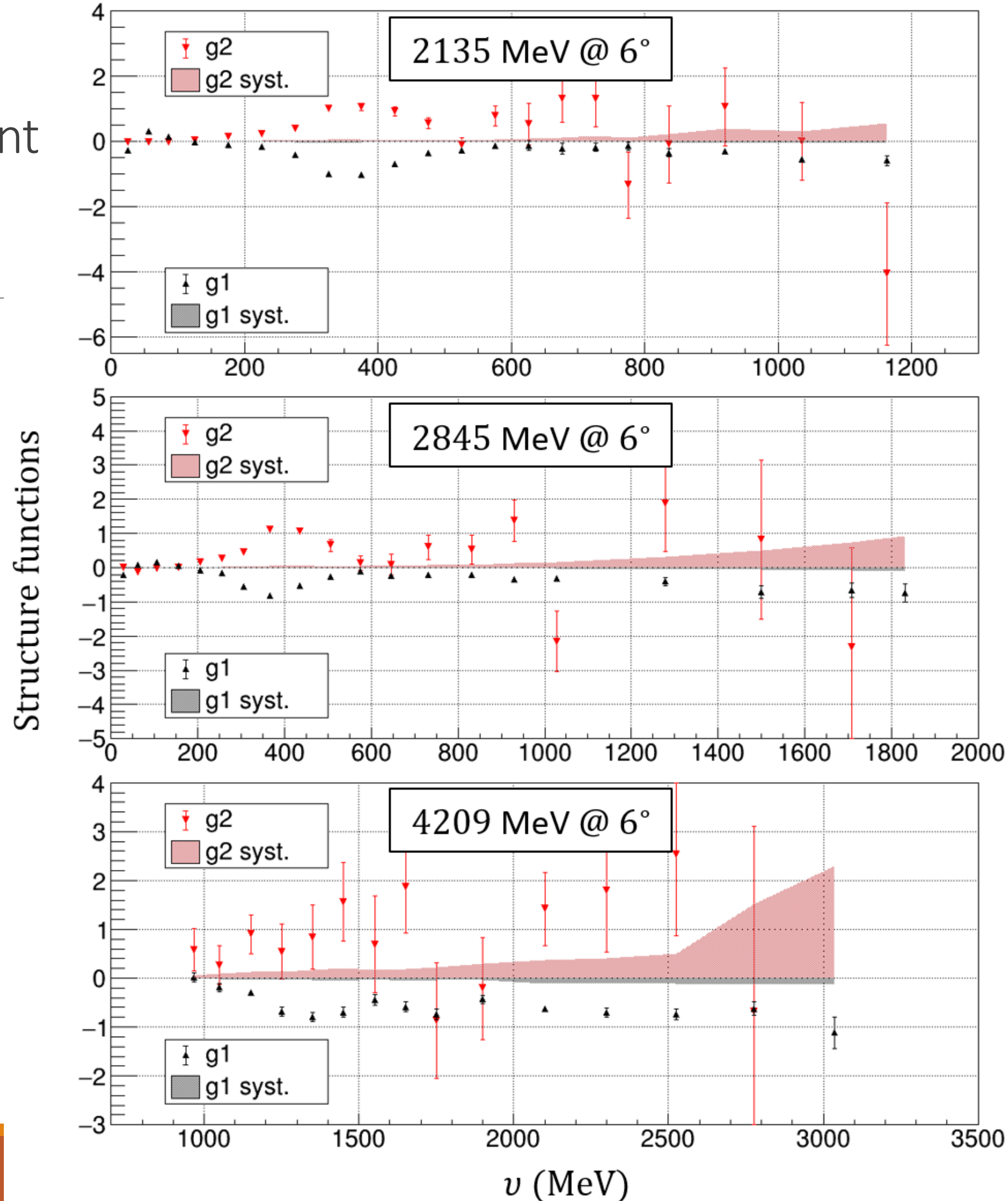
Spin-dependent Structure functions



Spin-dependent Structure functions

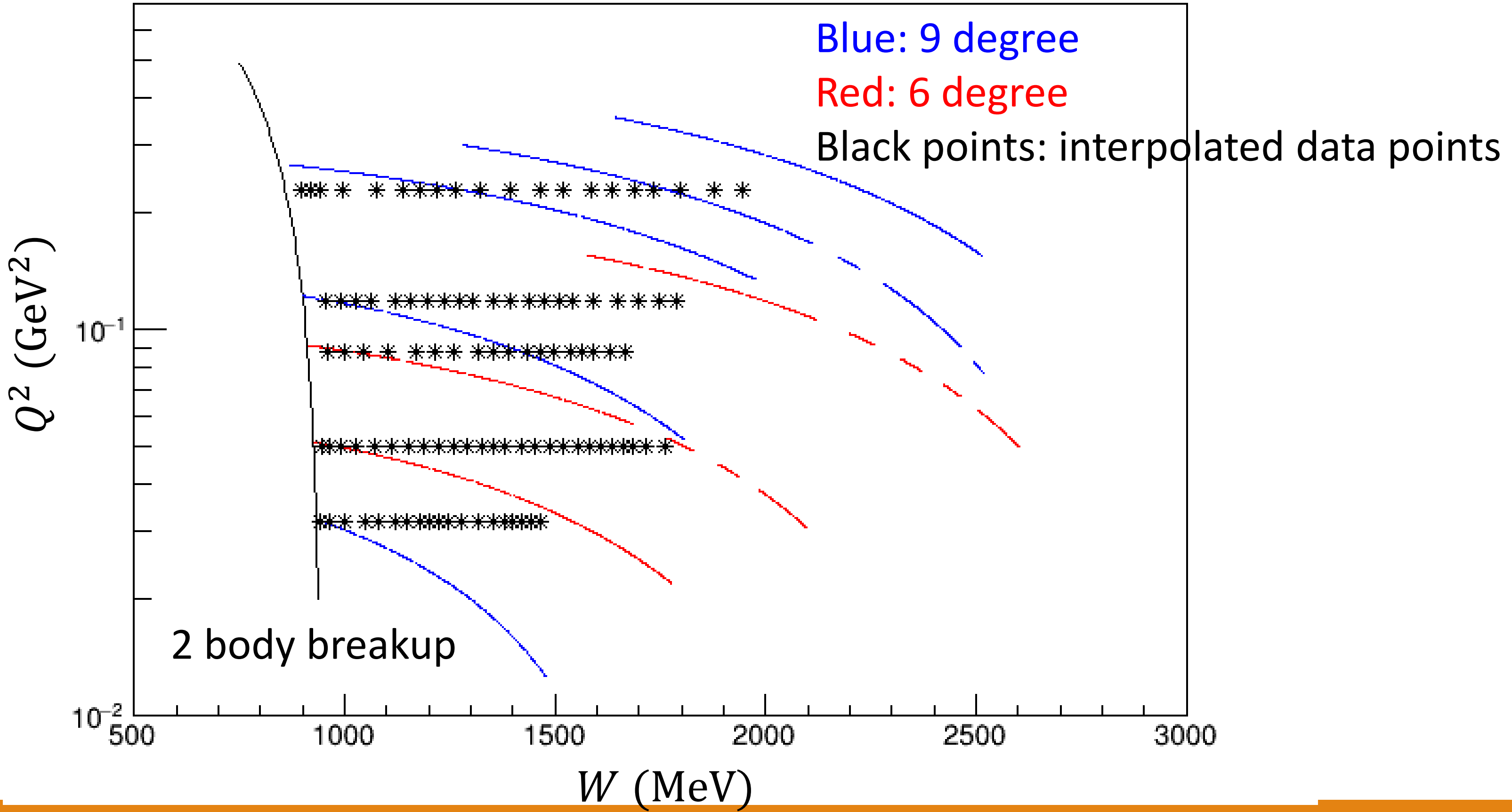


Spin-dependent Structure functions

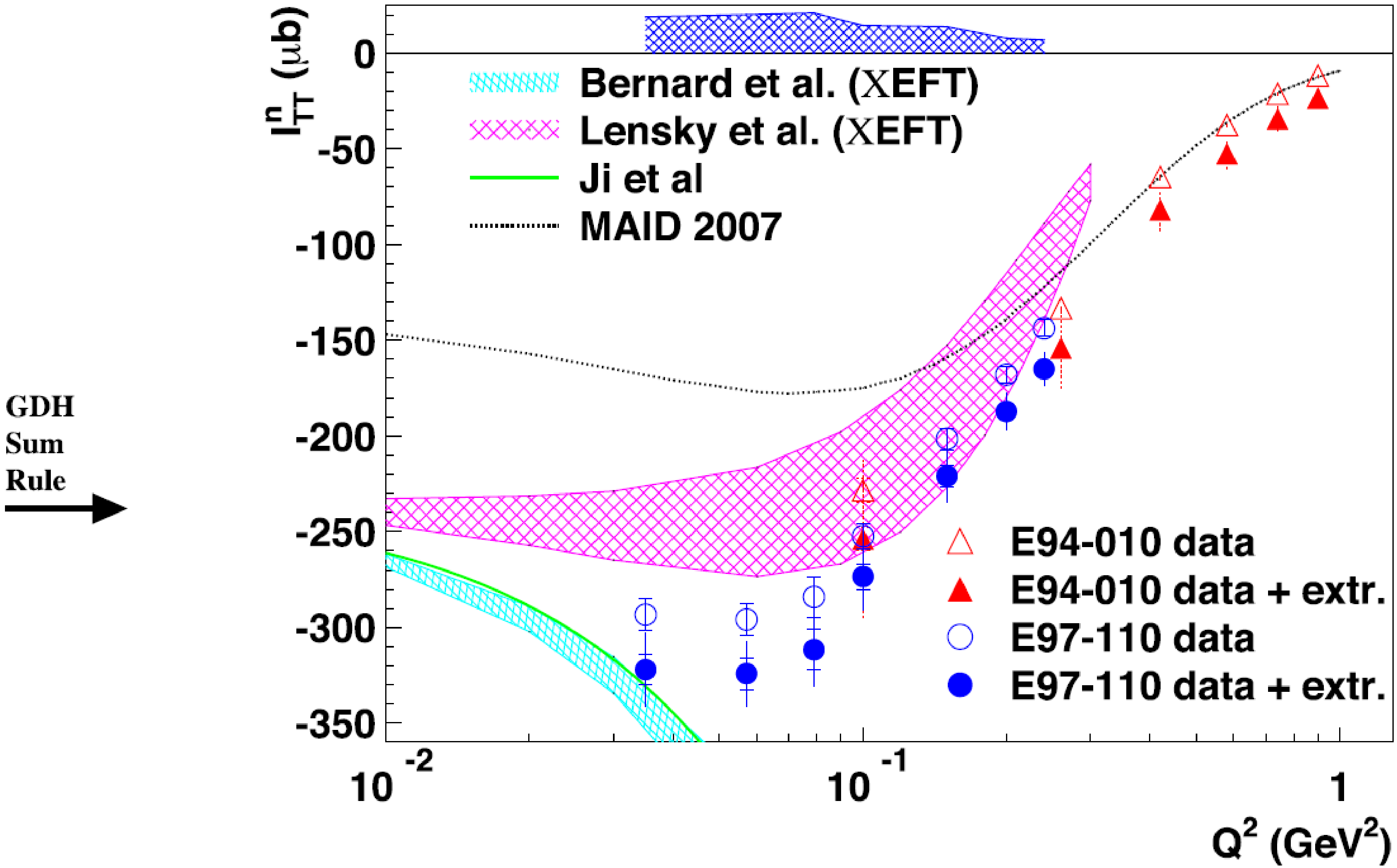


Interpolation to constant Q^2

$Q^2 = 0.032 \sim 0.23\ \mathrm{GeV}^2$

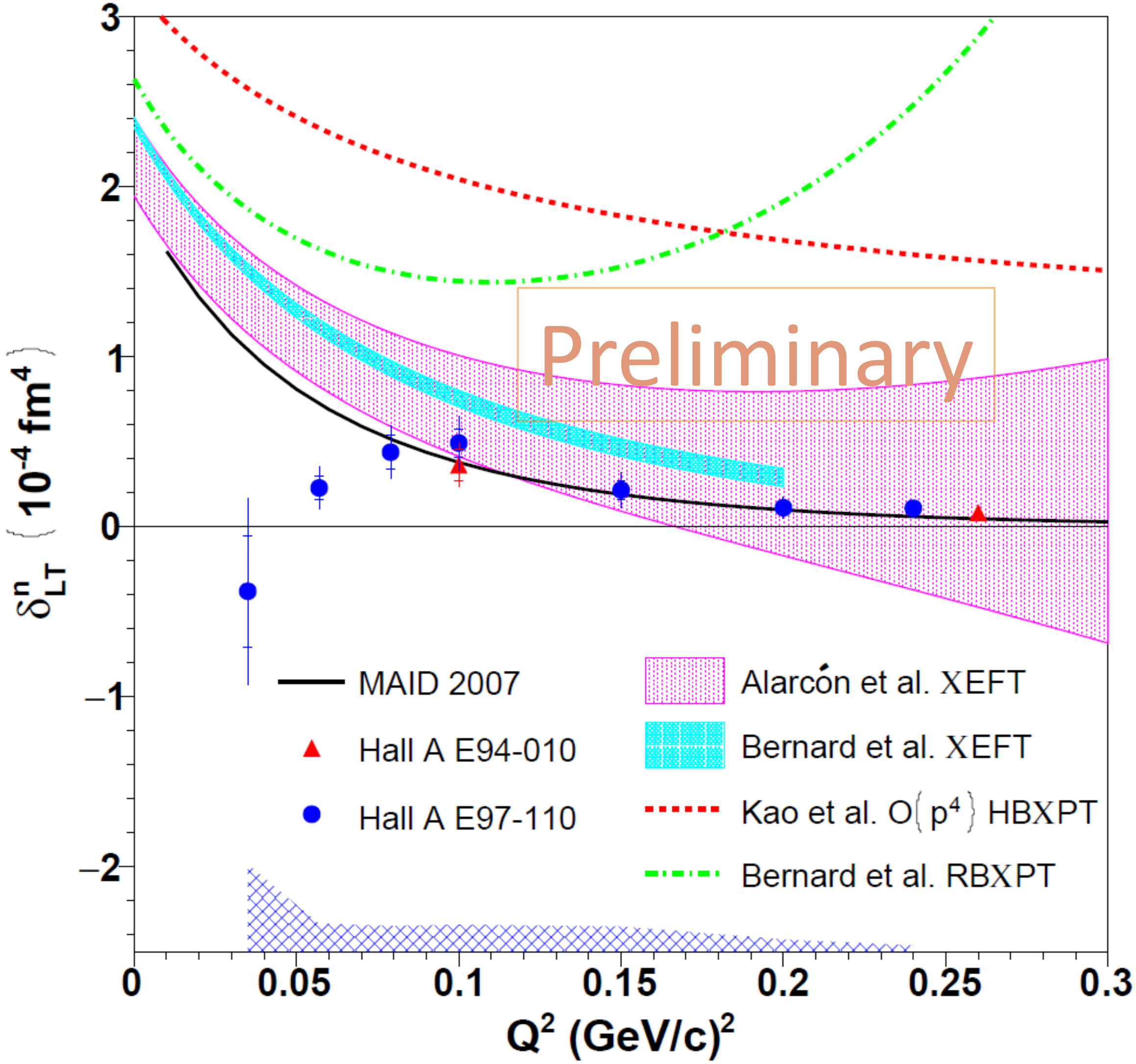


Neutron Results



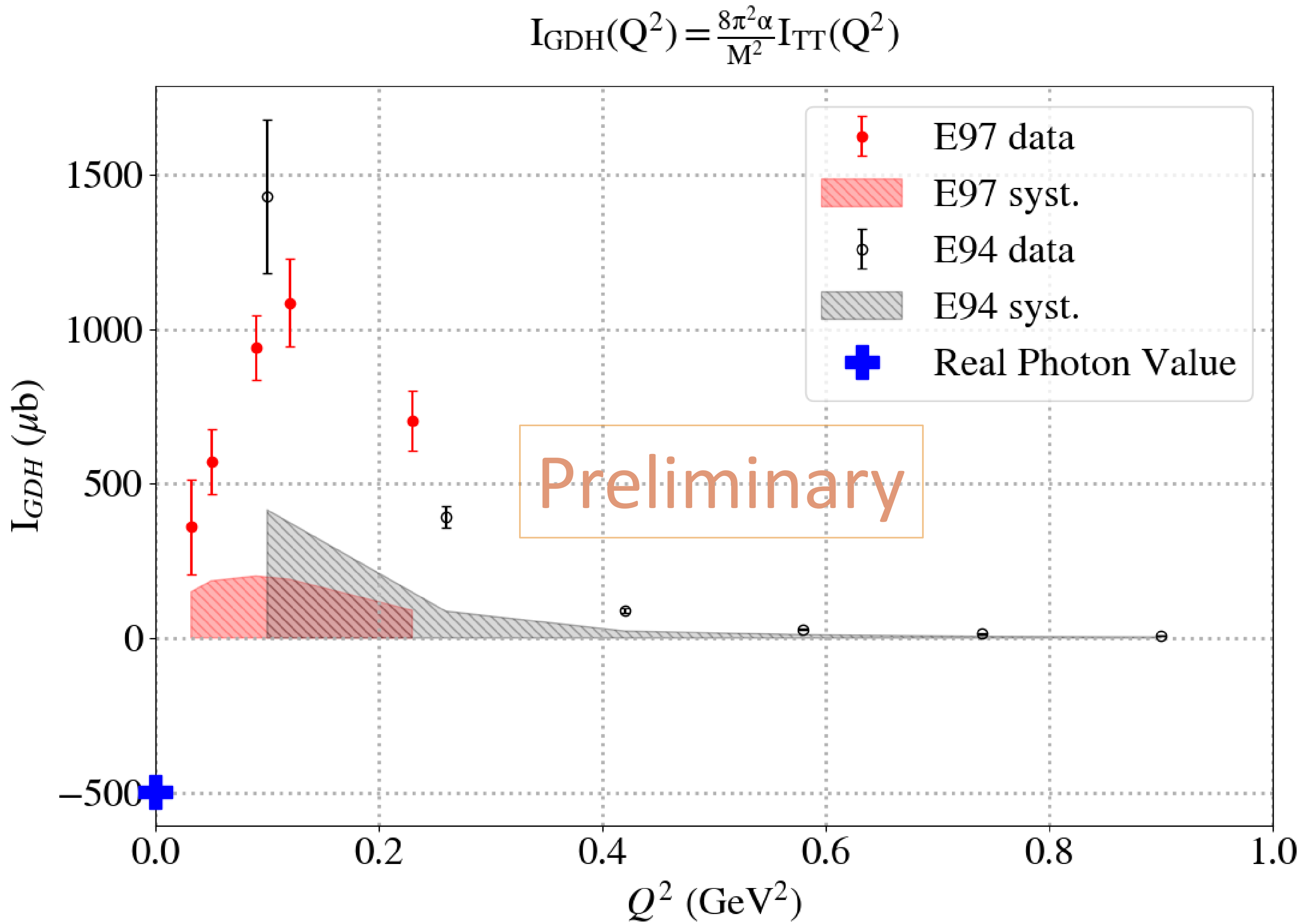
V. Sulkosky *et al.*, Phys. Lett. B 805 (2020) 135428

Neutron Results



δ_{LT} remains puzzling

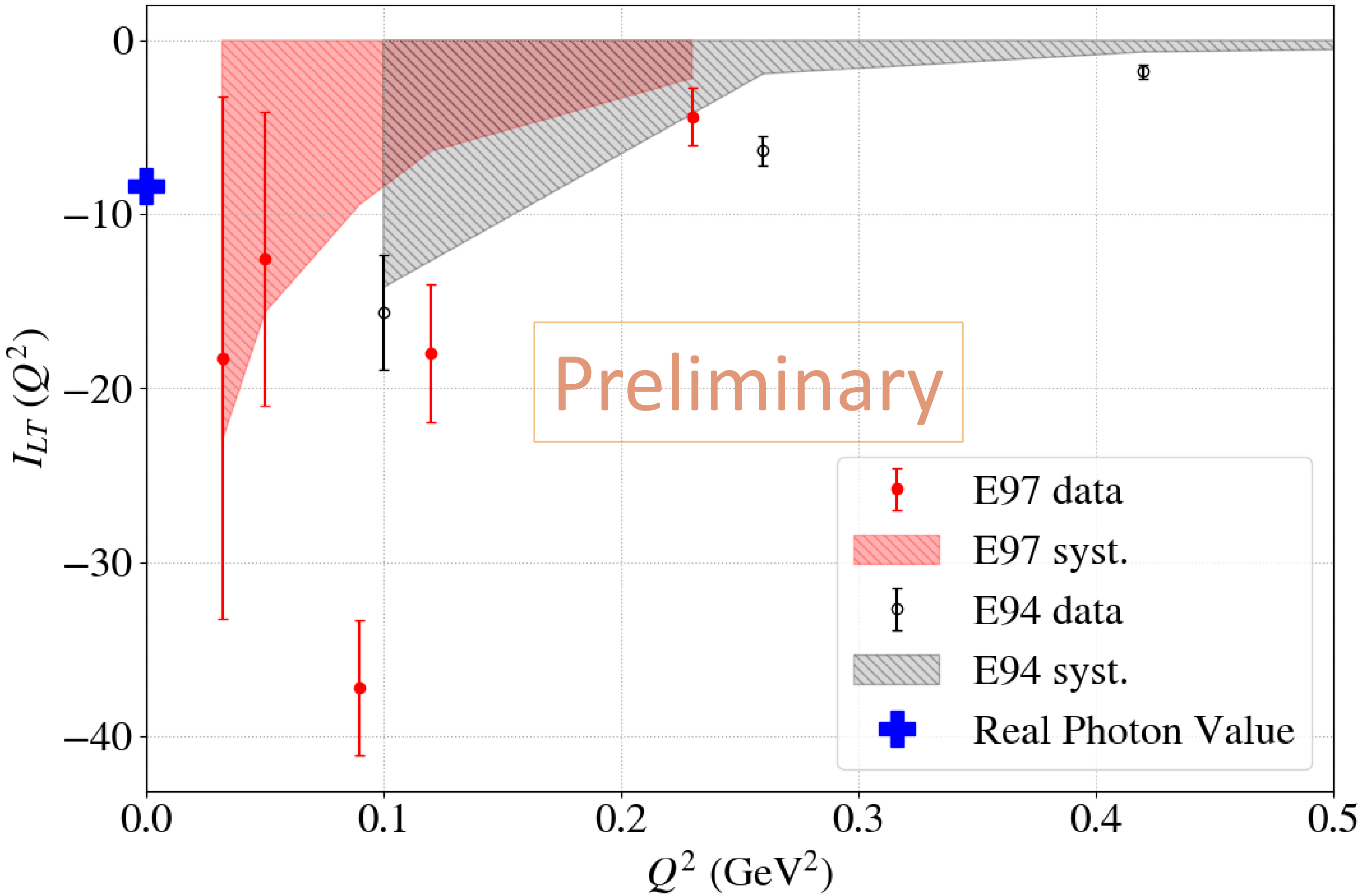
^{3}He Results



$I_{GDH}(Q^2) = \frac{8\pi^2\alpha}{M^2} I_{TT}(Q^2)$
E97 data
E97 syst.
E94 data
E94 syst.
Real Photon Value
Preliminary
1500
1000
500
0
−500
0.0
0.2
0.4
0.6
0.8
1.0
I_{GDH} (μb)
Q^2 (GeV^2)

^{3}He Results

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



Summary

Neutron results are published

- One publication for Γ_1, Γ_2, I_{TT}
- δ_{LT} paper drafted

Prepare for publication of ^{3}He results

- Lower Q^2 data shows a trend to recover the real photon point.

This work is supported in part by the U.S. Department of Energy, under Contract No. DE-AC02-06CH11357, and DE-FG02-03ER41231