E97-110
The Generalized GDH Sum Rule for
Neutron and ^3He at Low Q^2

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For the Hall A and E97-110 Collaborations

January 24, 2018

Hall A Collaboration Meeting

Outline

- Generalized GDH Sum Rule
- Experiment E97-110
- Progress Report

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, anomalous magnetic moment κ, target mass M, and virtual photon energy υ
- Relates the helicity-dependent photoabsorption cross sections to static properties
- Derived from general principles

Generalized GDH sum rule

- Generalized for virtual photon via unsubtracted dispersion relation

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

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

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

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

First Moment of g_1

- First Moment of g_1

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

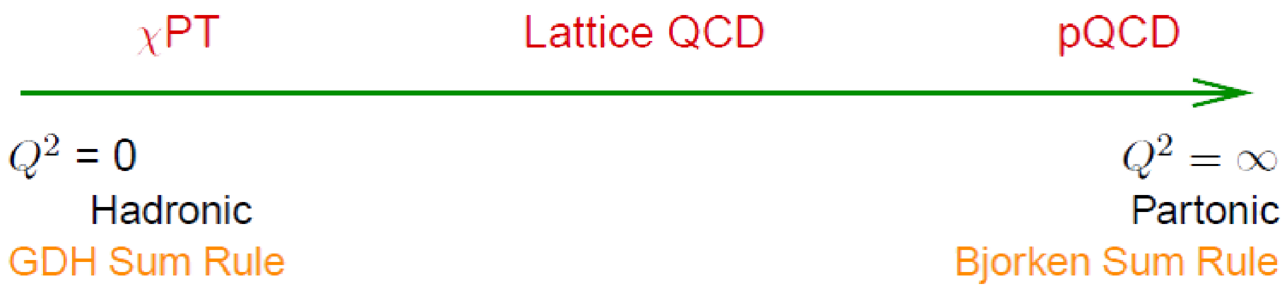
  - Connects to the total spin carried by the quarks
  - $\approx I_1\ (Q^2)$ at large Q^2

- 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 within 10%

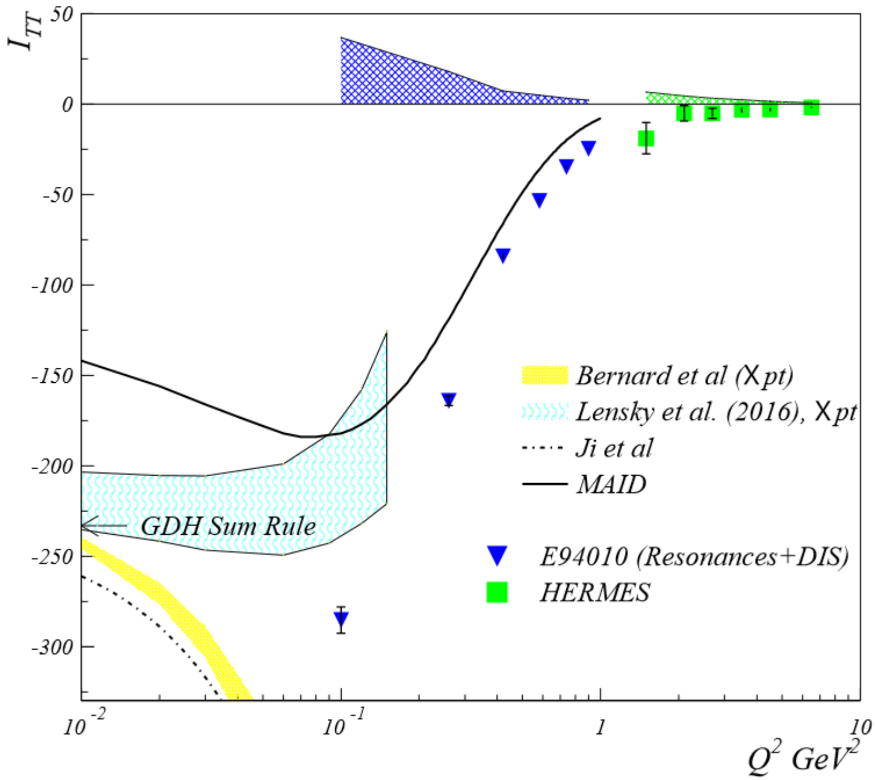
Importance of Generalized GDH Sum Rule



- Recovers the GDH sum rule for real photons ($Q^2 = 0$)
- Connects with Bjorken sum rule ($Q^2 = \infty$)
- Relates the moments of the spin dependent structure functions to virtual Compton amplitude ($Q^2 > 0$)
- Tests the theoretical calculations for the Compton amplitudes at very low Q^2
  - Baryon Chiral Perturbation Theory (HBChPT, IRBChPT, RBChPT)
  - Lattice QCD
- Studies the non-perturbative region and the transition region

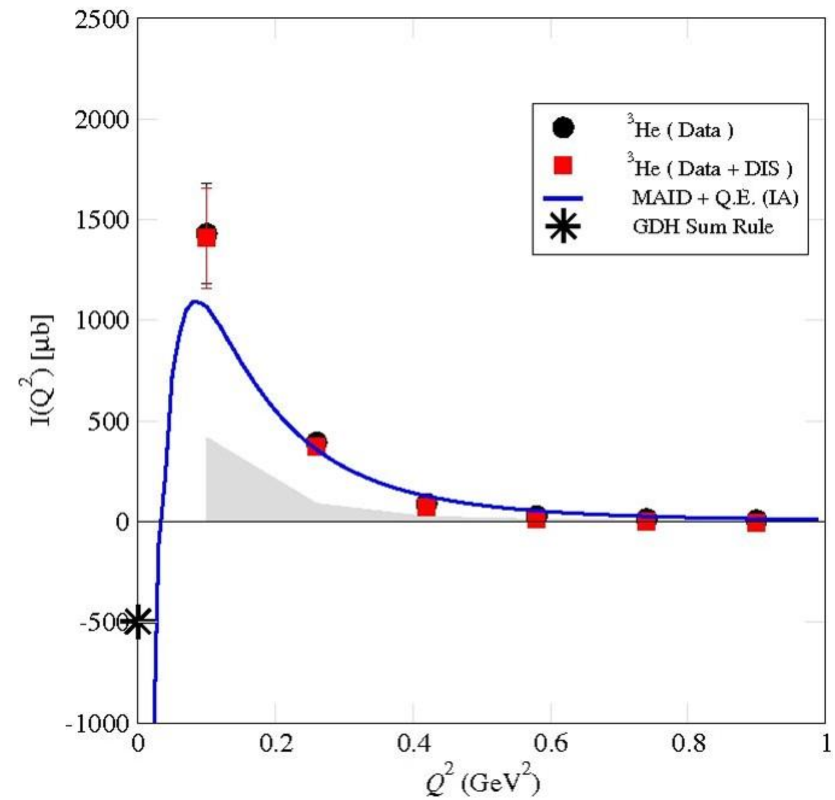
E94-010 Results

Neutron



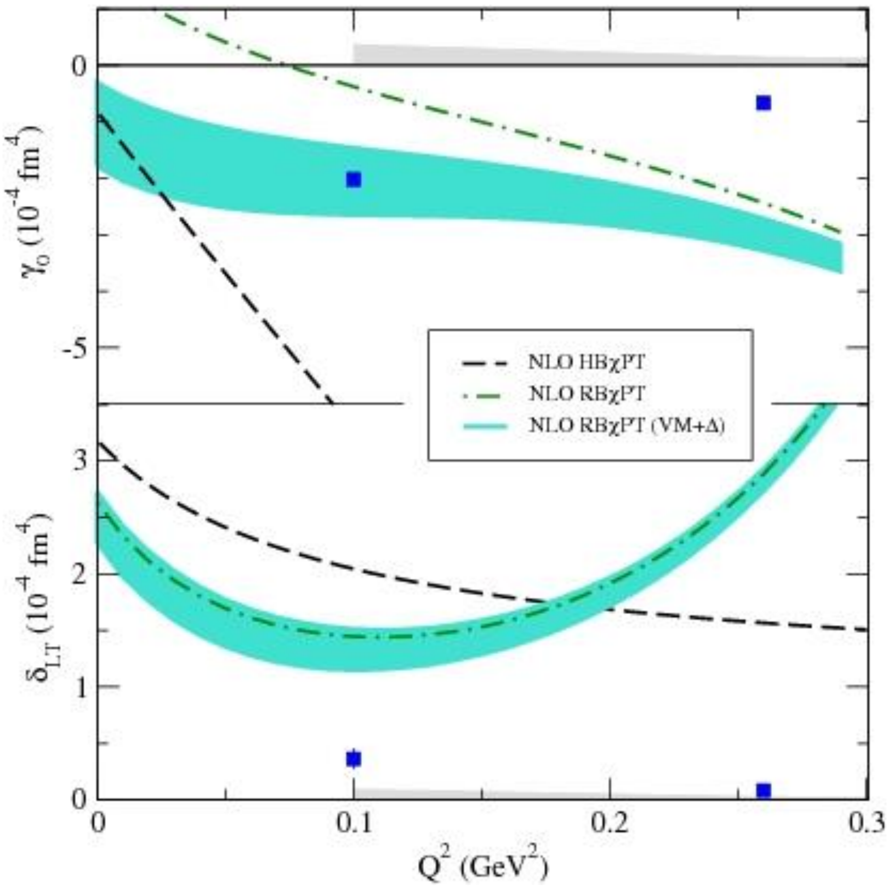
M. Amarian et al., Phys. Rev. Lett., 89:242301, Nov 2002.

Helium-3



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

E94-010 Results



$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]$$

Need further tests at low Q^2

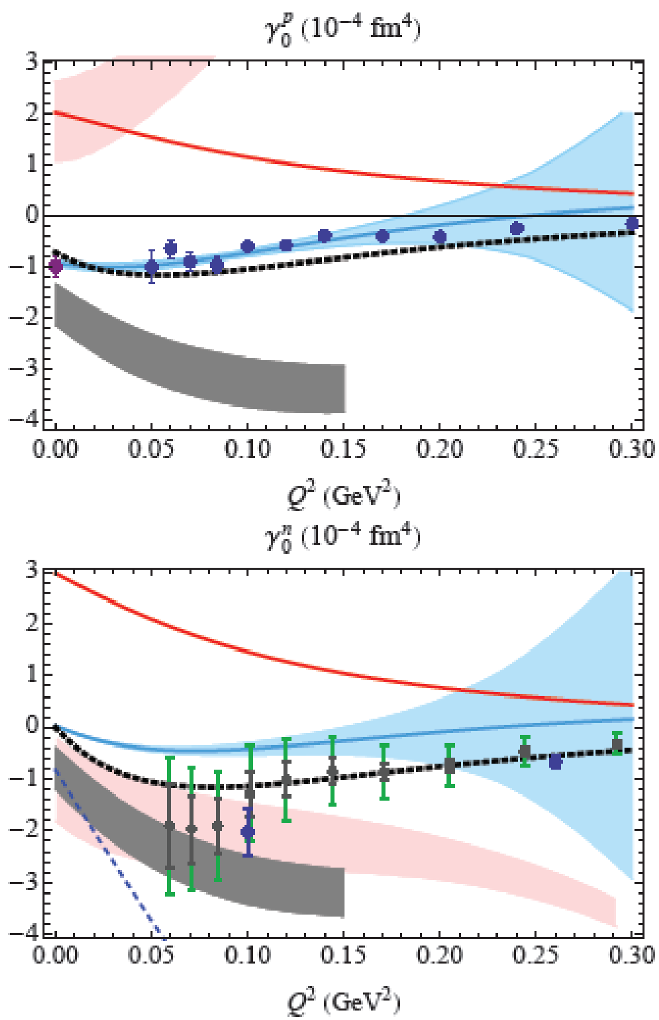
<u>Heavy Baryon χPT Calculation</u>

Kao, Spitzenberg, Vanderhaeghen
PRD 67:016001(2003)

<u>Relativistic Baryon χPT</u>

Bernard, Hemmert, Meissner
PRD 67:076008(2003)

Theoretical developments



Curves:

MAID (empir.)

LO-HBChPT

NLO-HBChPT

NLO- IRBChPT
[Bernard et al (2006)]

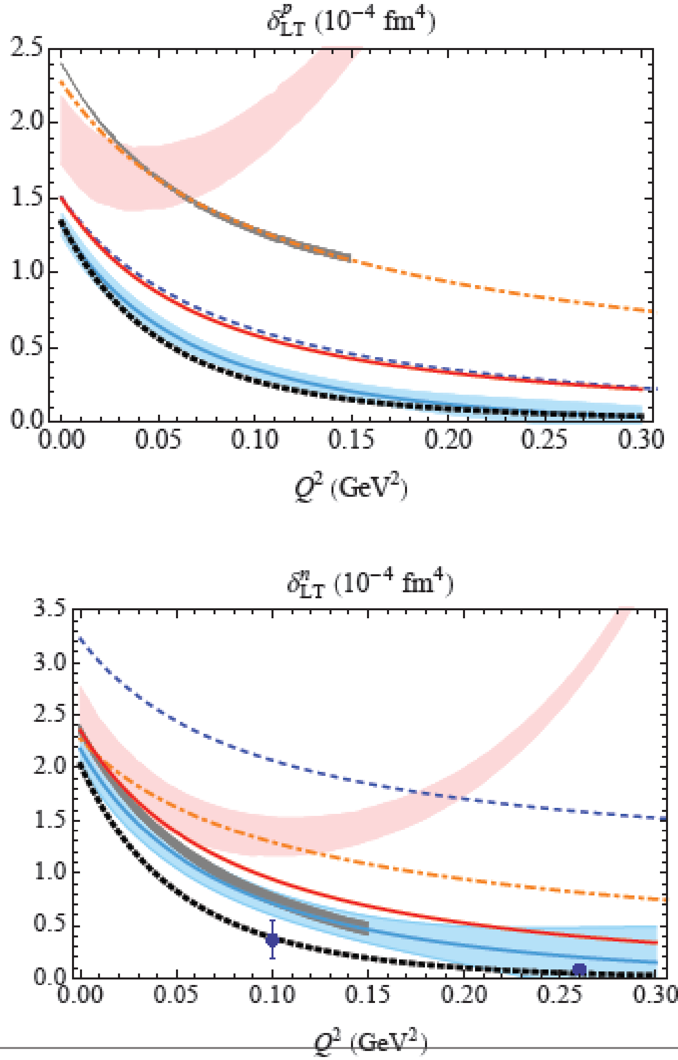
LO-BChPT

NLO-BChPT
[Lensky, Alarcon & V.P, PRC (2014)]

NLO-BChPT
[Bernard et al (2013)]
see talk by H. Krebs

Data points:
K. Slifer, J.-P. Chen, S. Kuhn, et al
[Jefferson Lab spin program]

Theoretical developments



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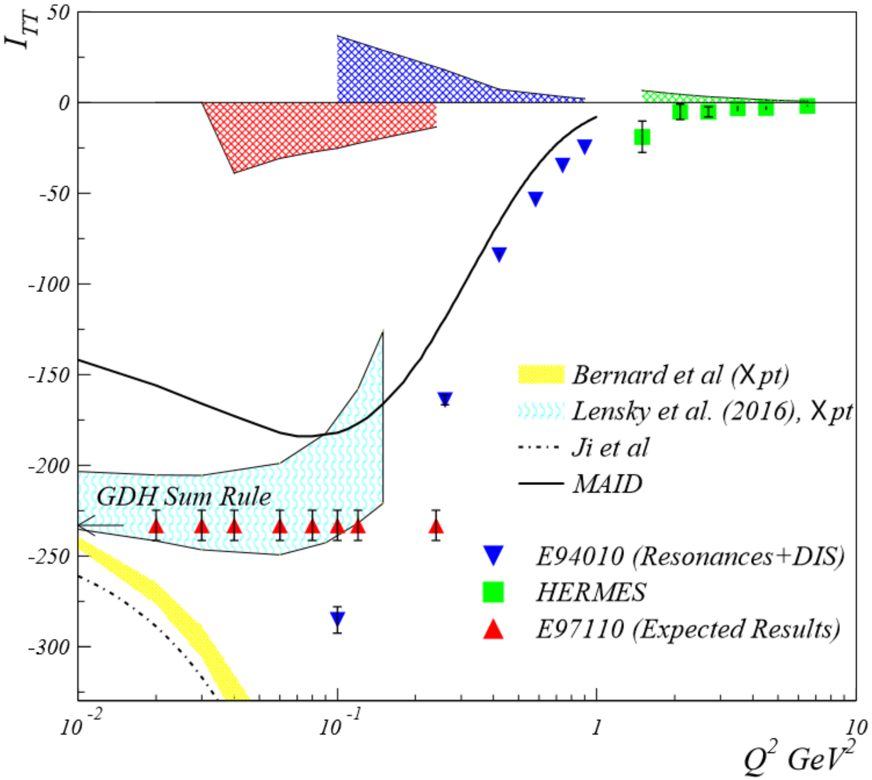
[Jefferson Lab spin program]

E97-110 at Jefferson Lab



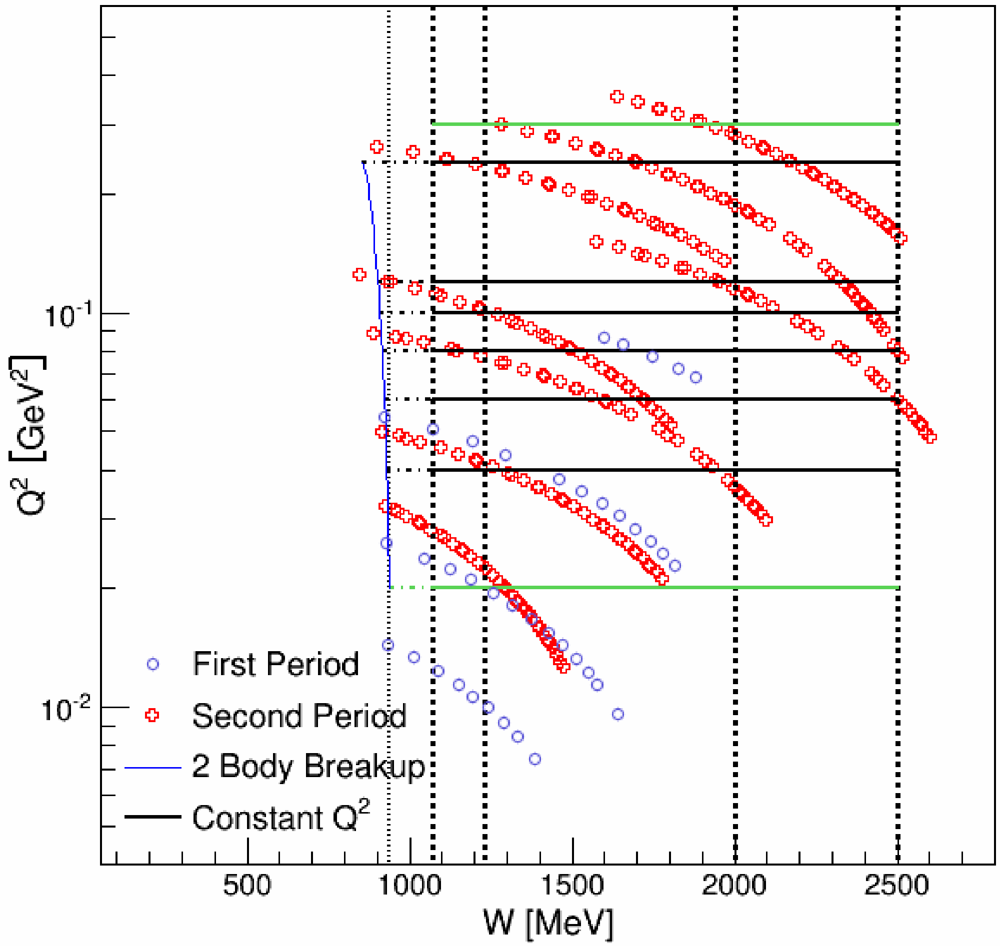
- Inclusive measurement, $^3\vec{\mathrm{He}}(\vec{e},e')X$
  - Scattering angles: 6° and 9°
  - Polarized electron beam, P_{beam} = 75%
  - Polarized ^{3}He target, P_{target} = 40%
  - Septum magnet for detection of forward scattering angles
- Measured the differences of polarized cross sections
  - Parallel (anti-parallel)
  - Perpendicular

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

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

Kinematic Coverage

- **First Period** – lowest Q^2
- **Second Period** – higher Q^2



Progress Update (V. Sulkosky)

- **Current Students:**
  - Chao Peng (Duke): analysis on the ^{3}He moments
  - Nguyen Ton (UVA): first period analysis
- **Finalized** acceptance (V. Sulkosky)
- **Finalized** radiative corrections
  - Preliminary work done by J. Singh
  - Work continued by M. Meziane (Duke) and C. Peng
- **Finalized** estimation of QE contribution to neutron results (V. Sulkosky)
- Constant Q^2 interpolation and extraction of neutron moments **in progress**

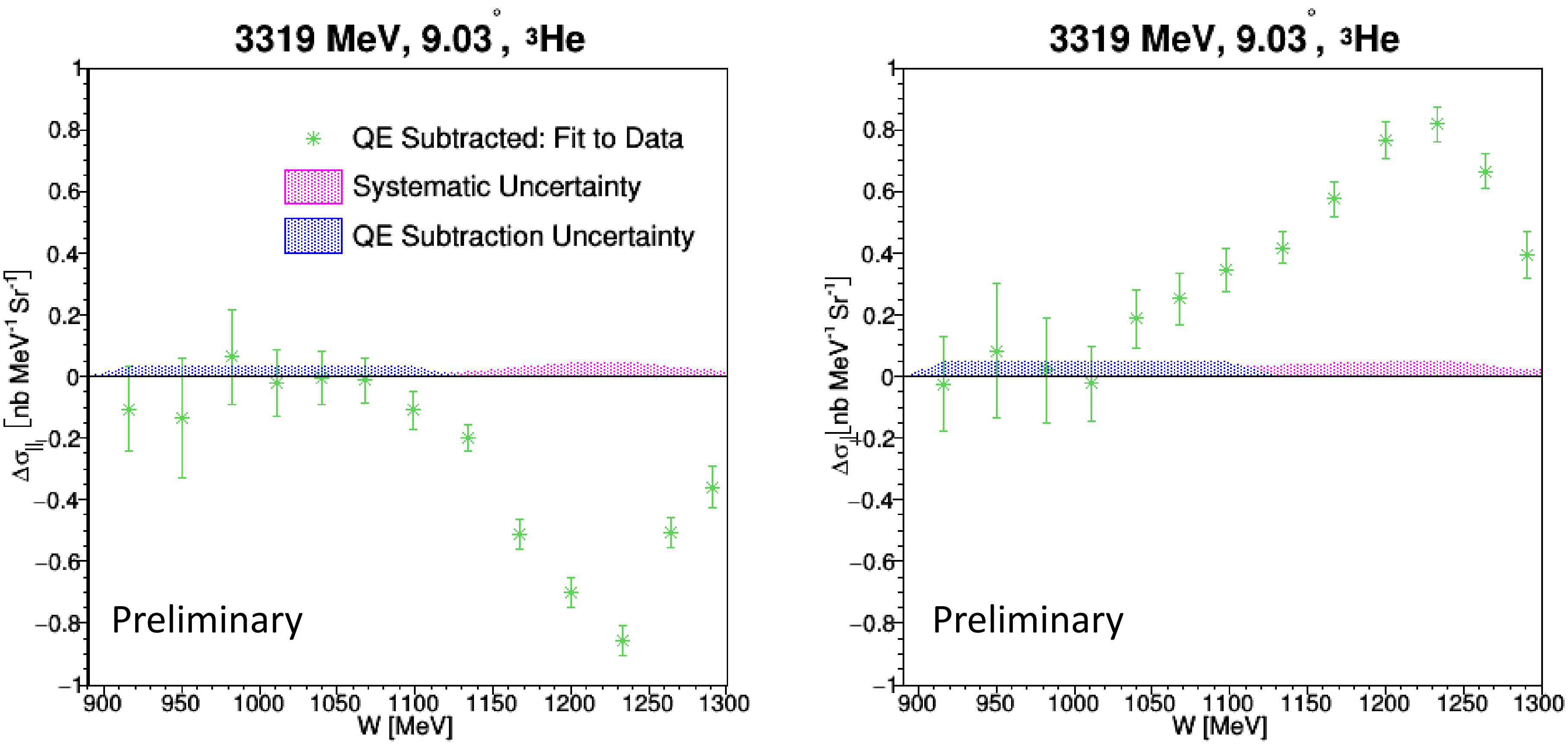
First Period Analysis (N. Ton)

- Finished optic study
- Analyzed ^{3}He elastic cross sections
- Study of the saturation effect in the septum magnet for 2.2 GeV

1.1 GeV	σ_{sim} [nb]	σ_{data} [nb]	Rel. Diff. [%]
Dp = -2%	187954	191766	-1
Dp = 0%	187138	189587	-2
Dp = 2%	180331	173123	+4

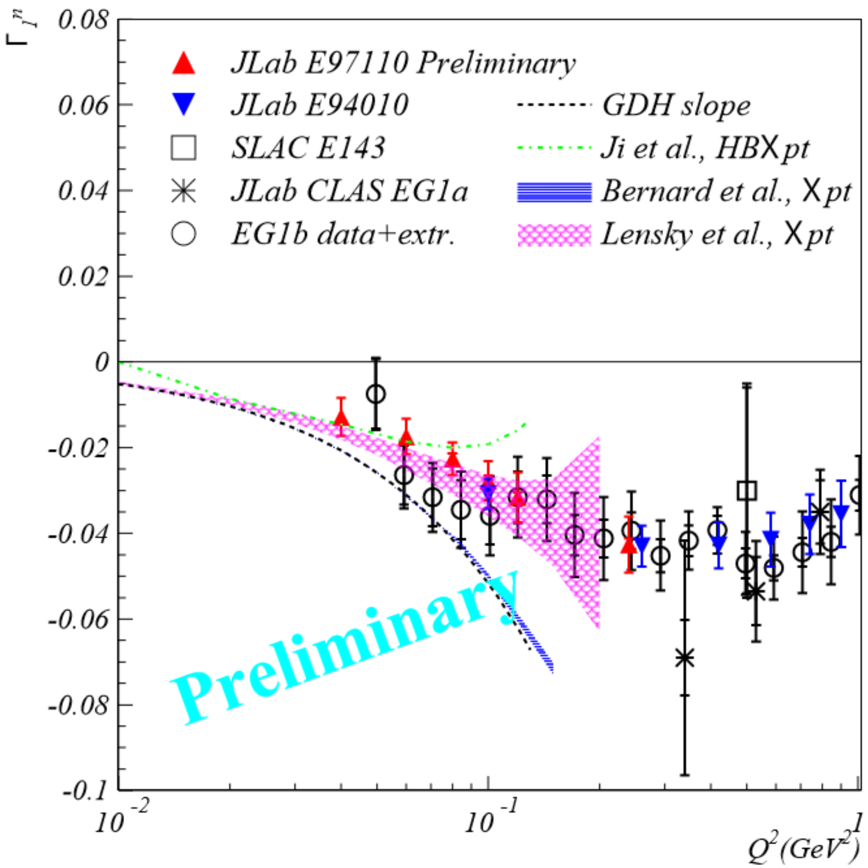
Ebeam (all dp =0%)	σ_{sim} (nb)	σ_{data} (nb)	Rel. Diff. [%]
1.5 GeV	78774	72836	8
2.2 GeV	12412	8819	29

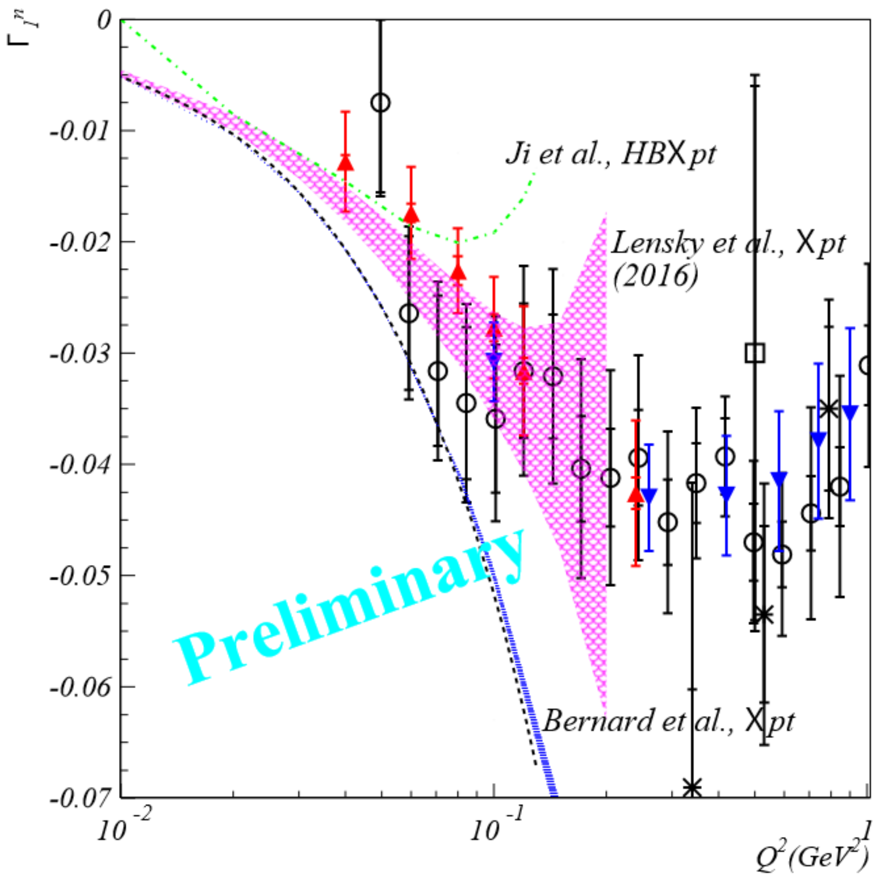
Quasi-elastic subtraction (V. Sulkosky)



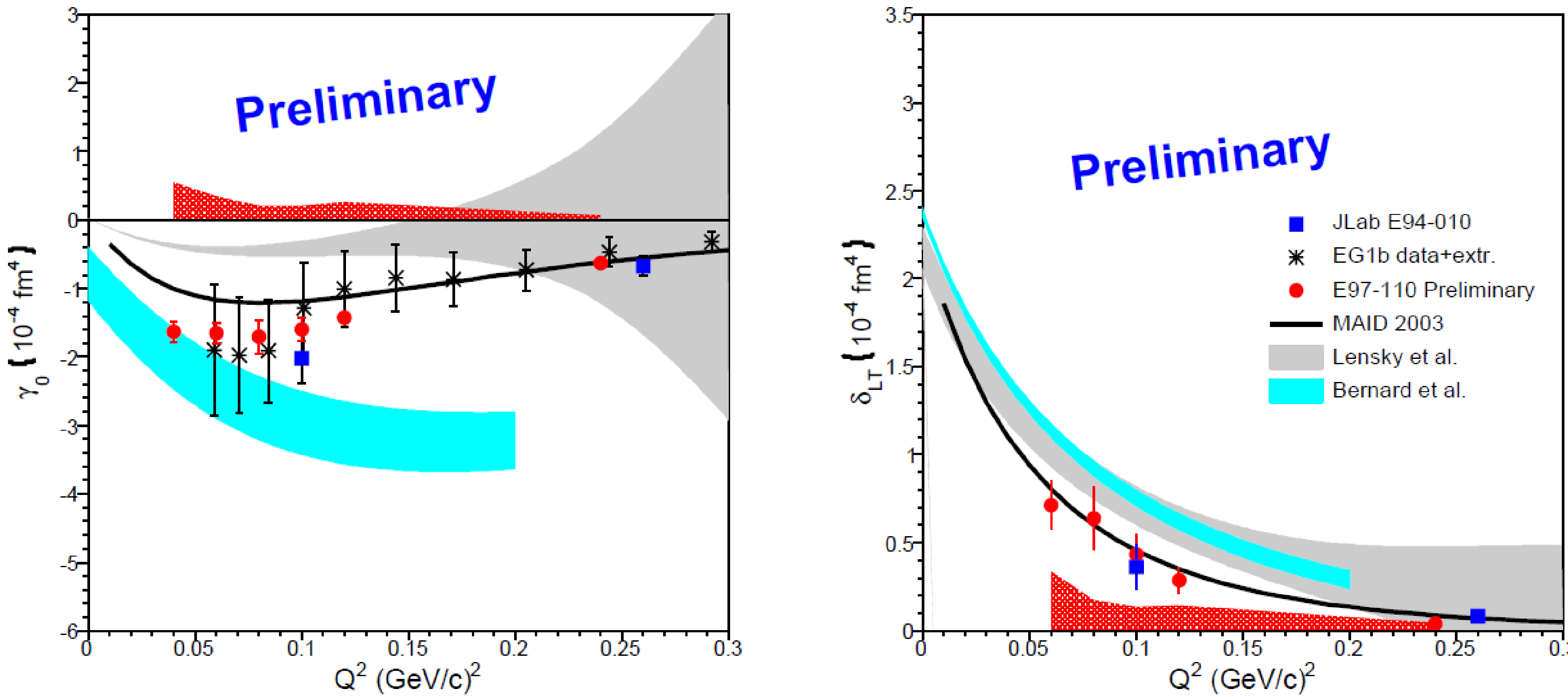
Preliminary Neutron Result (V. Sulkosky)

- First moment of g_1





Neutron Spin Polarizabilities (V. Sulkosky)



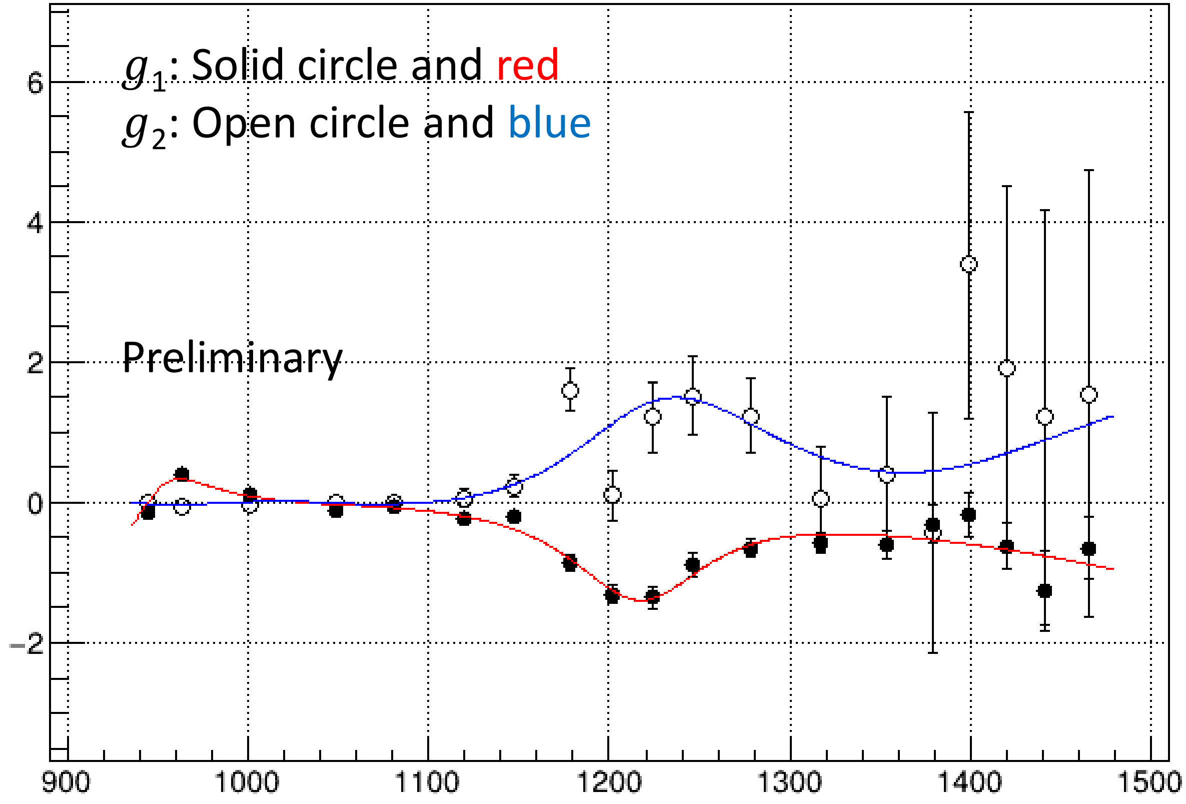
Second Period ^{3}He Analysis

- Finished
  - Elastic tail subtraction
  - Radiative correction
  - Interpolation on constant Q^2
  - Associated systematics

- Ongoing
  - Generalized GDH integral
  - Parameterization for the unmeasured high energy contribution

Structure functions at constant beam energy

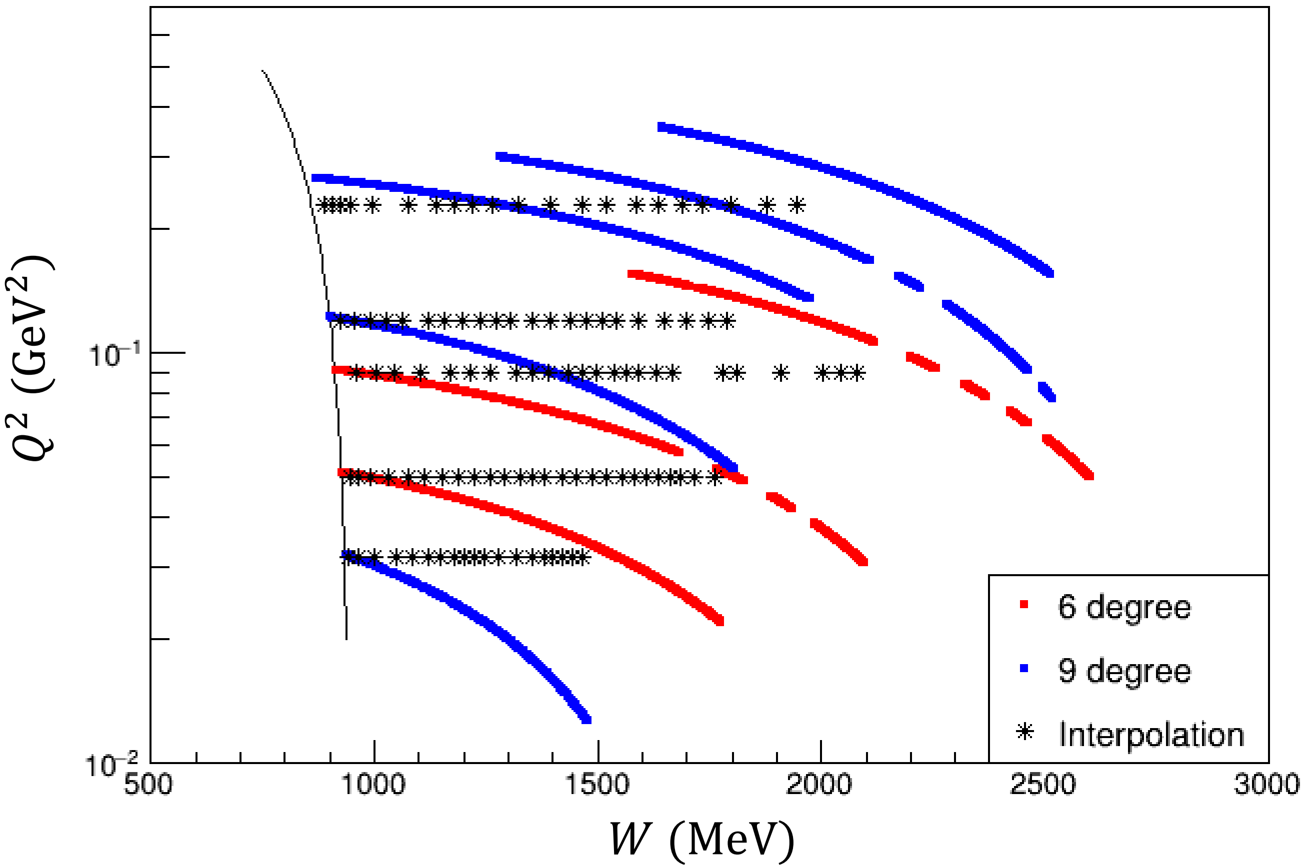
E = 1147 MeV



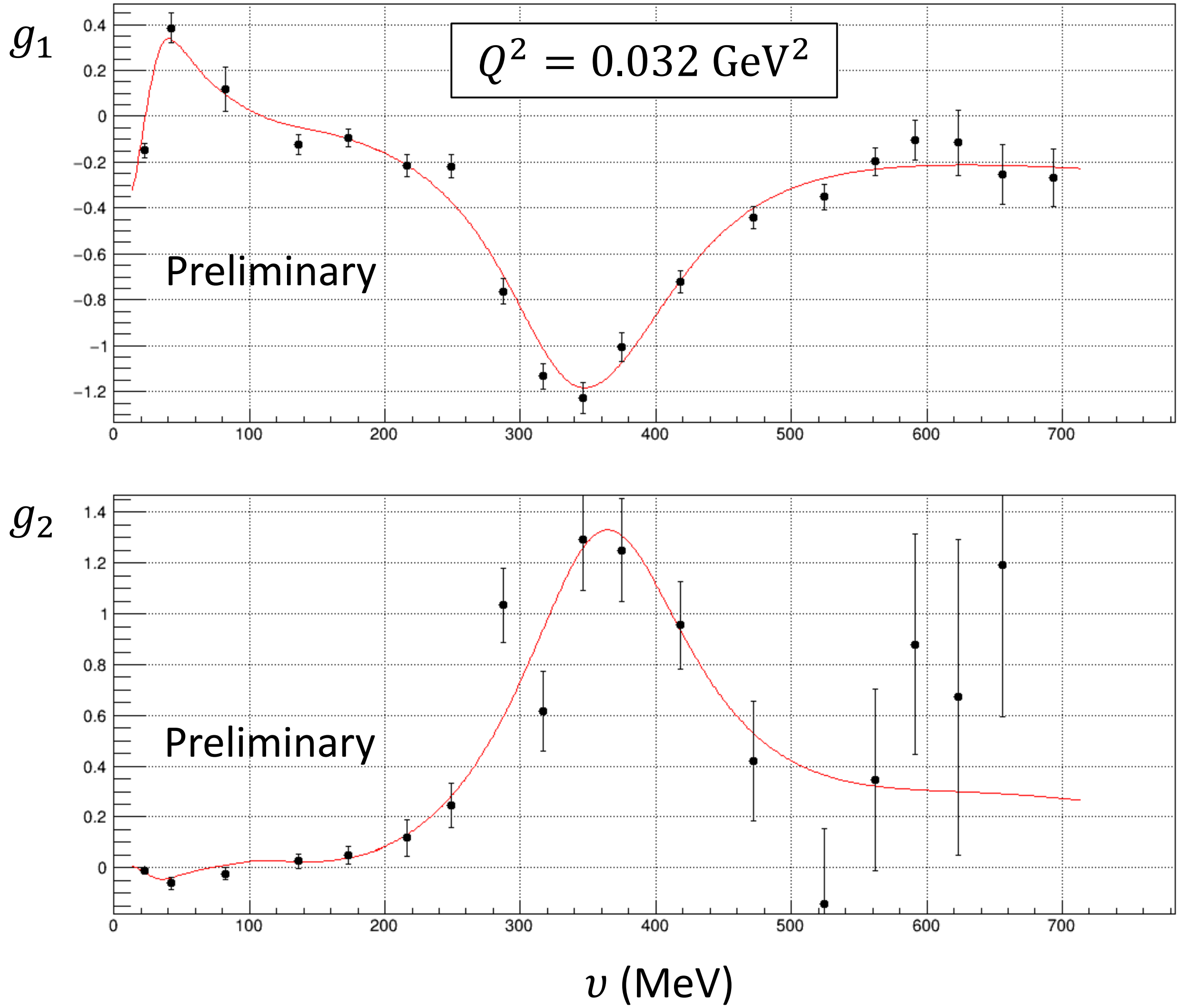
W (MeV)

Interpolation to constant Q^2

$Q^2 = 0.032 \sim 0.23\ \mathrm{GeV}^2$ (Second Period)



Structure functions at constant Q^2



Summary

- First period analysis
  - Progress on the optic study
  - Cross section analysis is ongoing
  - Publication forseen in 2018-2019

- Second period analysis
  - Neutron result, finalizing systematics
  - ^{3}He result, obtained spin structure functions, getting generalized GDH sum rule and g_1, g_2 moments
  - Neutron data soon to be published (several weeks)
  - ^{3}He data to be published in Spring of 2018

Thank you

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Second Period Systematics (V. Sulkosky)

Source	$\boldsymbol{\sigma_{syst}}$ **[%]** **Preliminary**	$\boldsymbol{\sigma_{syst}}$ **[%]** **Final**
Target density	2	1.6
VDC Multi-tracks	2.5 – 3	< 1
Charge	1	1
Detector Efficiencies GC,Sh,Scint	1	1.4 –1.9
Yield Stability ν-dependent	-----	$0 - 1.25$
Acceptance	5–15	$2 - 3$
Beam polarization	3.5	3.5
Target Polarization	7.5	$3 - 5.2$

Second Period Systematics (V. Sulkosky)

Other systematics:

1. Radiative corrections, including elastic tail subtraction.
2. Quasi-elastic tail removal for neutron moments.
3. Interpolation and extrapolation to constant Q^2.
4. Neutron extraction from ^{3}He: 5% to 10%.

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

GDH Measurements

- Proton, verified: Mainz, Bonn, LEGS
- Neutron, in progress: Mainz, Bonn, LEGS, HIGS
- Measurements on Deuteron and ^{3}He

	M [GeV]	Spin	κ	I_{GDH} [μ 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