E97-110: Small Angle GDH Experimental Status Report

Vincent Sulkosky

Jefferson Lab

on the behalf of the Spokespersons: J.P. Chen, A. Deur and F. Garibaldi

Ph. D. Students: J. Singh and J. Yuan

Recently Graduated: V. Sulkosky

Hall A Collaboration Meeting

December 14^{th}, 2007

Gerasimov-Drell-Hearn (GDH) Sum Rule (Q^2 = 0)

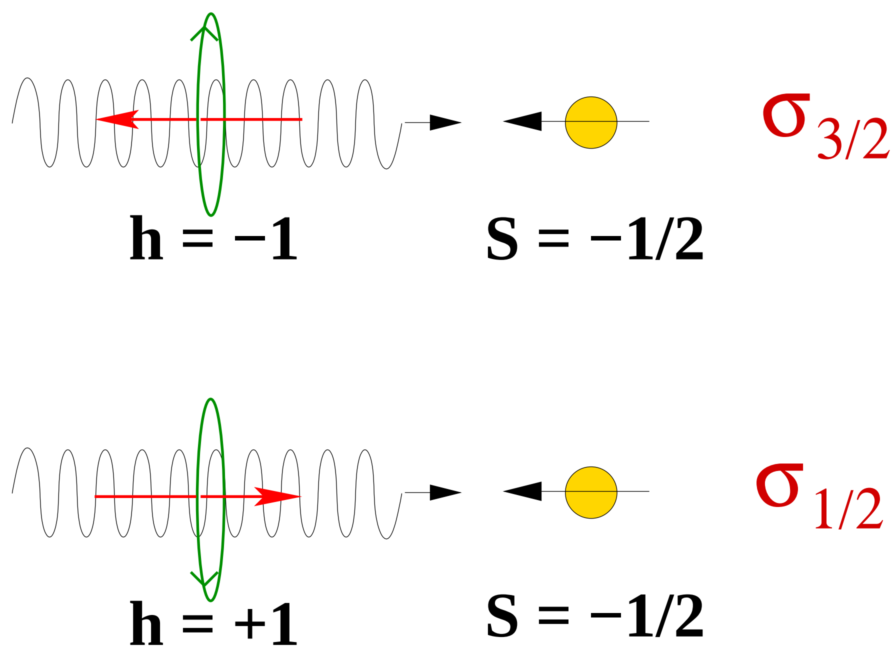
$$I_{\rm GDH} = \int_{\nu_{\rm th}}^{\infty} \frac{\sigma_{\frac{1}{2}}(\nu) - \sigma_{\frac{3}{2}}(\nu)}{\nu} d\nu = -2\pi^2\alpha(\frac{\kappa}{M})^2$$

- Circularly polarized photons incident on a longitudinally polarized spin-$\frac{1}{2}$ target.

Gerasimov-Drell-Hearn (GDH) Sum Rule ($Q^2 = 0$)

$$I_{\rm GDH} = \int_{\nu_{\rm th}}^{\infty} \frac{\sigma_{\frac{1}{2}}(\nu) - \sigma_{\frac{3}{2}}(\nu)}{\nu} d\nu = -2\pi^2\alpha\left(\frac{\kappa}{M}\right)^2$$

- $\sigma_{\frac{1}{2}}$ ($\sigma_{\frac{3}{2}}$) photoabsorption cross section with photon helicity parallel (anti-parallel) to the target spin.



Gerasimov-Drell-Hearn (GDH) Sum Rule ($Q^2 = 0$)

$$I_{\rm GDH} = \int_{\nu_{\rm th}}^{\infty} \frac{\sigma_{\frac{1}{2}}(\nu) - \sigma_{\frac{3}{2}}(\nu)}{\nu} d\nu = -2\pi^2\alpha\left(\frac{\kappa}{M}\right)^2$$

- Circularly polarized photons incident on a longitudinally polarized spin-$\frac{1}{2}$ target.
- $\sigma_{\frac{1}{2}}$ ($\sigma_{\frac{3}{2}}$) photoabsorption cross section with photon helicity parallel (anti-parallel) to the target spin.
- The sum rule is related to the target's mass M and anomalous part of the magnetic moment κ.
- The sum rule is valid for any spin-S target.

Generalized GDH Integral ($Q^2 > 0$)

$$I(Q^2) = \int_{\nu_{\rm th}}^{\infty} \left[\sigma_{\frac{1}{2}}(\nu, Q^2) - \sigma_{\frac{3}{2}}(\nu, Q^2)\right] \frac{d\nu}{\nu}$$

$$\sigma_{1/2} - \sigma_{3/2} = \frac{8\pi^2\alpha}{MK}\left[g_1(\nu, Q^2) - \left(\frac{Q^2}{\nu^2}\right) g_2(\nu, Q^2)\right]$$

- Replace photoproduction cross sections with the corresponding electroproduction cross sections.
- The integral is related to the Compton scattering amplitudes: $S_1(Q^2)$ and $S_2(Q^2)$.

$$S_1(Q^2) = \frac{8}{Q^2}\int_0^1 g_1(x, Q^2)dx = \frac{8}{Q^2}\Gamma_1(Q^2)$$

X.-D. Ji and J. Osborne, J. Phys. **G27**, 127 (2001)

At $Q^2 = 0$, the GDH sum rule is recovered.

Importance of the Generalized GDH Sum Rule

χPT — Lattice QCD — pQCD

$Q^2 = 0$ Hadronic ⟷ $Q^2 = \infty$ Partonic

- Constrained at the two ends of the Q^2 spectrum by known sum rules.
- S_1 and S_2 are calculable at any Q^2.
- Compare theoretical predictions to experimental measurements over the entire Q^2 range.
- Provides a bridge from the non-perturbative region to the perturbative region of QCD.

Experiment E97-110

Precise measurement of generalized GDH integral at low Q^2, 0.02 to 0.3 GeV^2

- Ran in spring and summer 2003
- Inclusive experiment: $^3\overrightarrow{\mathrm{He}}(\vec{e},e')X$

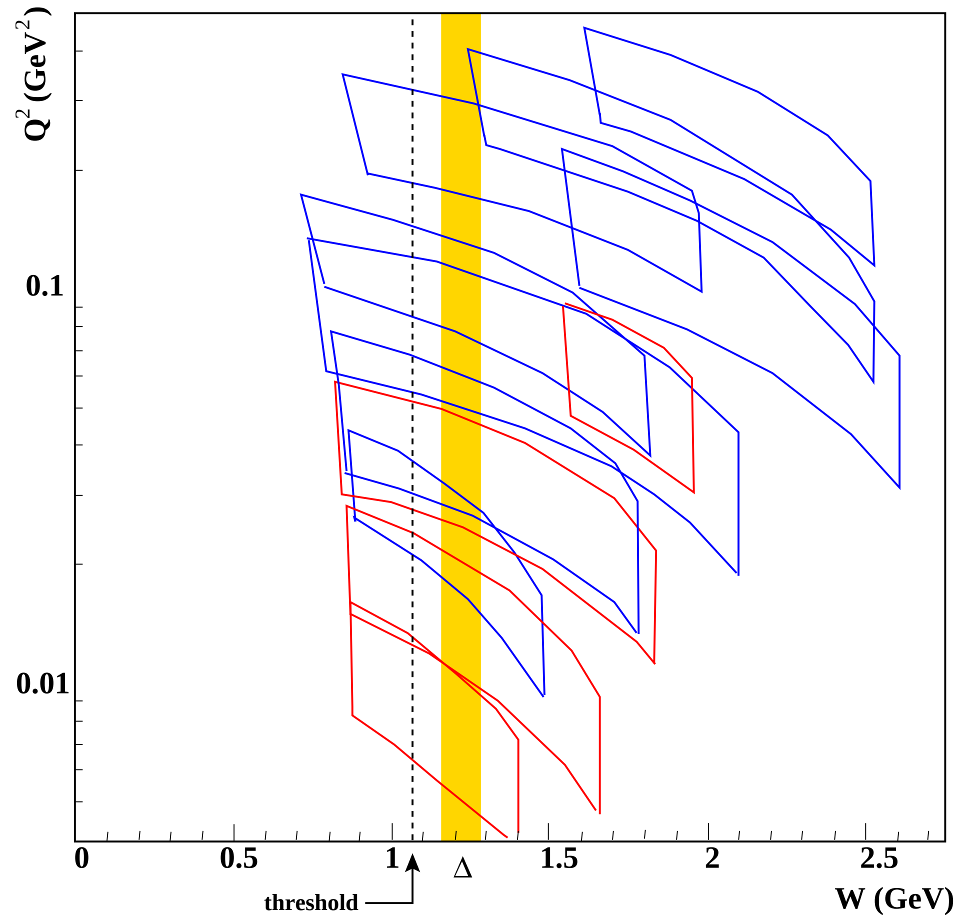
  $\Rightarrow$ Scattering angles of 6° and 9°

  $\Rightarrow$ Polarized electron beam:

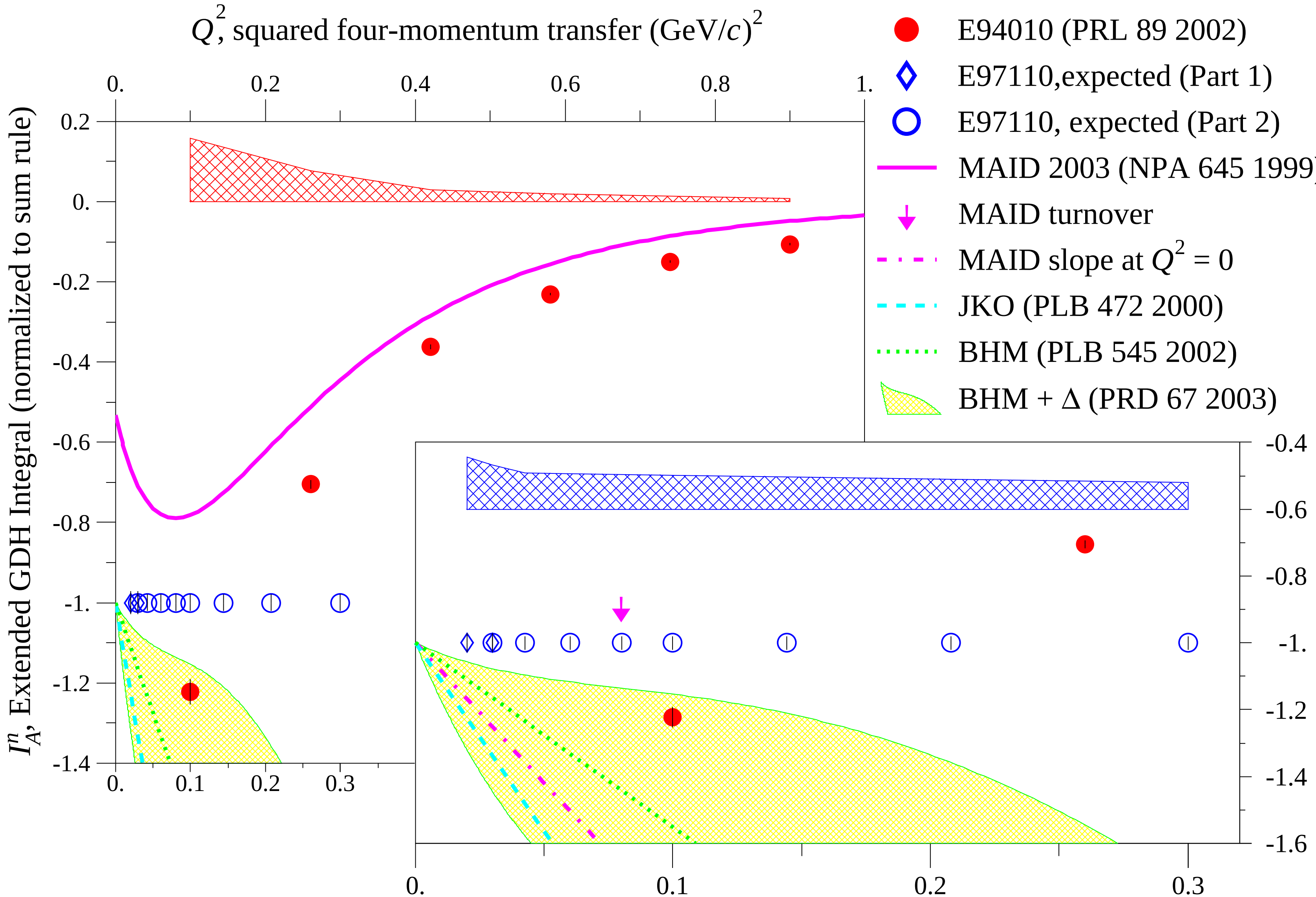
  65% $< P_{\mathrm{beam}} <$ 78%

  $\Rightarrow$ Pol. ^{3}He target (para & perp):

  $\langle P_{\mathrm{targ}} \rangle$ = 40%
- Measured polarized cross-section differences



Expected Neutron Results



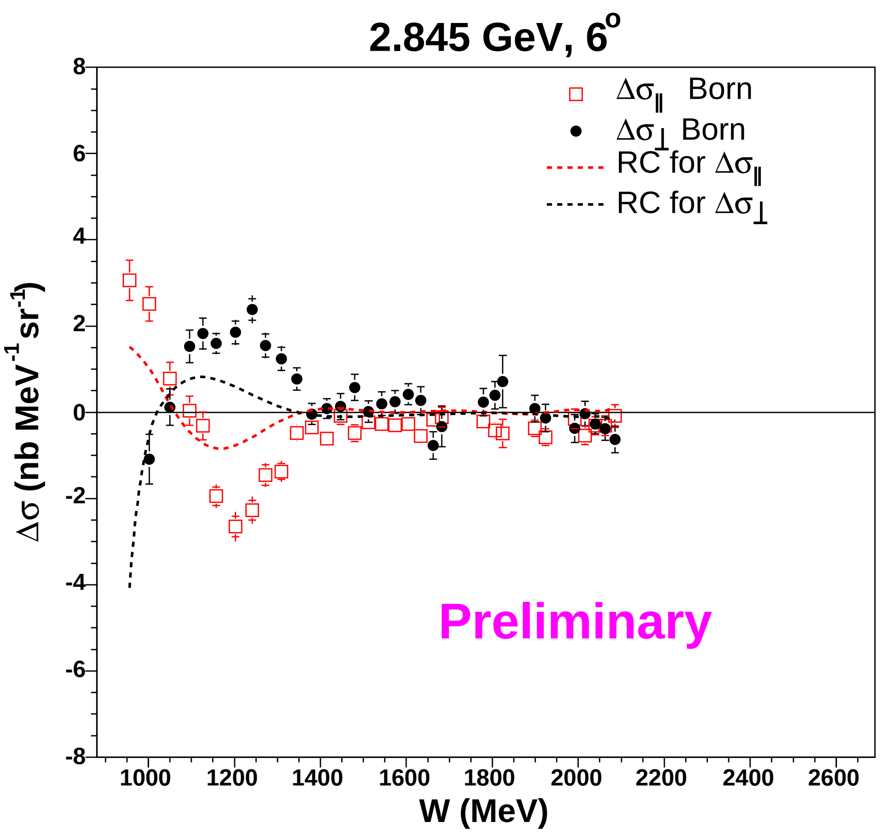
Analysis Progress

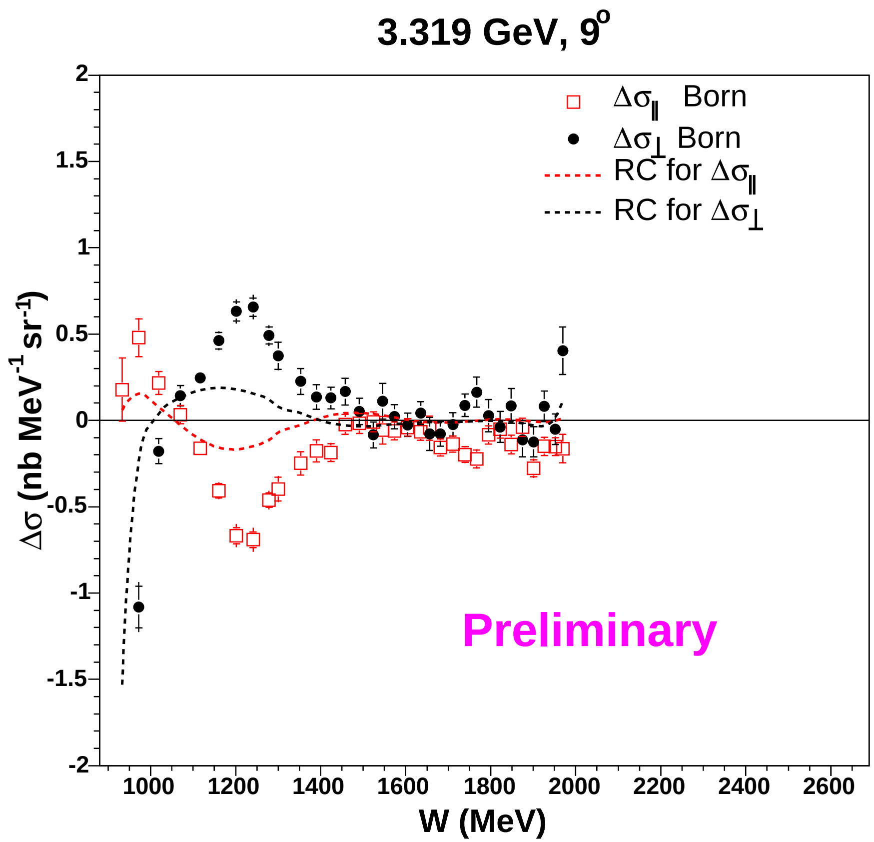
- Preliminary asymmetries and unpolarized cross sections have been generated.
- Issues that still need to be addressed:
  - Beam polarization: check bleedthrough correction with Compton where available.
  - Target polarization: track down 15% relative difference between NMR and EPR calibrations.
  - Acceptance: some issues need to be worked out, especially for 3.775 GeV 9° data.
  - Collimator background.
  - Elastic analysis as a cross check of systematics.

Systematic Uncertainties

Source	Systematic Uncertainty		
Angle	6°	9°	3.775 GeV, 9°
Target density		2.0%	
Acceptance/Effects	5.0%	5.0%	15.0%
VDC efficiency	3.0%	2.5%	2.5%
Charge		1.0%	
PID Detector and Cut effs.		$<$ 1.0%	
$\delta\sigma_{\mathrm{raw}}$	6.4%	6.2%	15.5%
Nitrogen dilution		0.2–0.5%	
$\delta\sigma_{\mathrm{exp}}$	6.5%	6.3%	15.5%
Beam Polarization		3.5%	
Target Polarization		7.5%	
Radiative Corrections		5–10% in Δ region	
Total on $\Delta\sigma$	11.6–14.5%	11.5–14.4%	18.3–20.2%

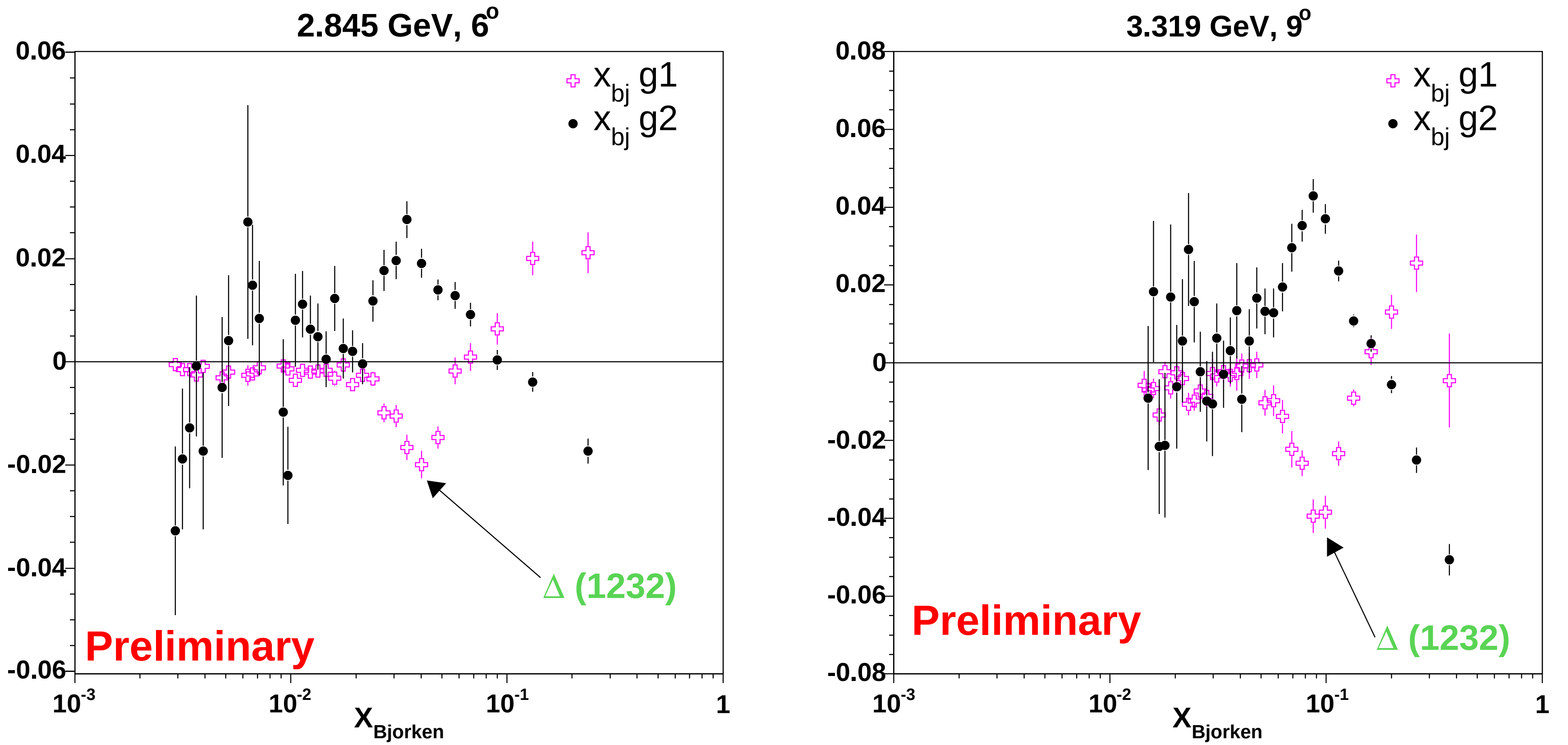
Cross Section Differences



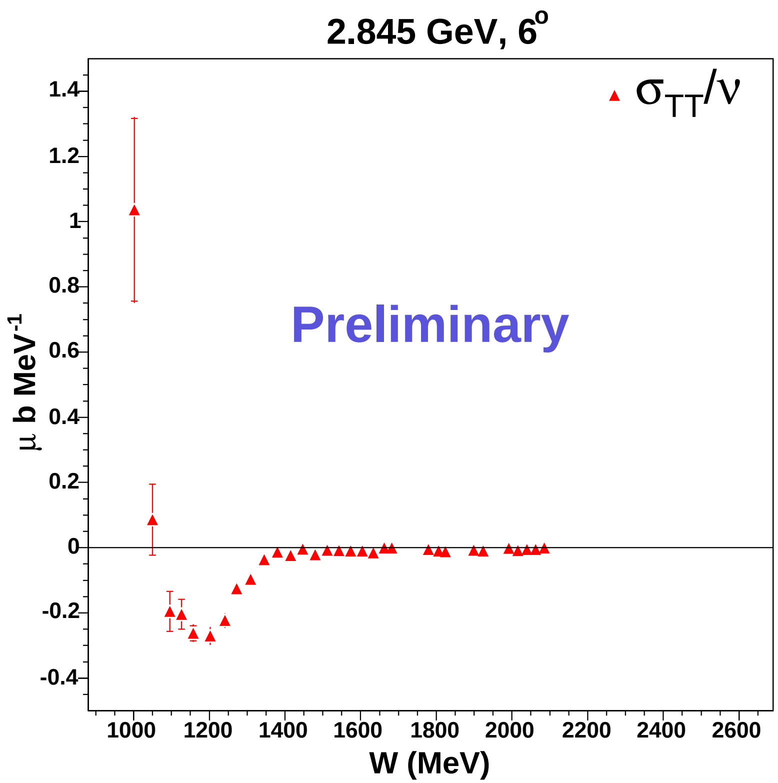


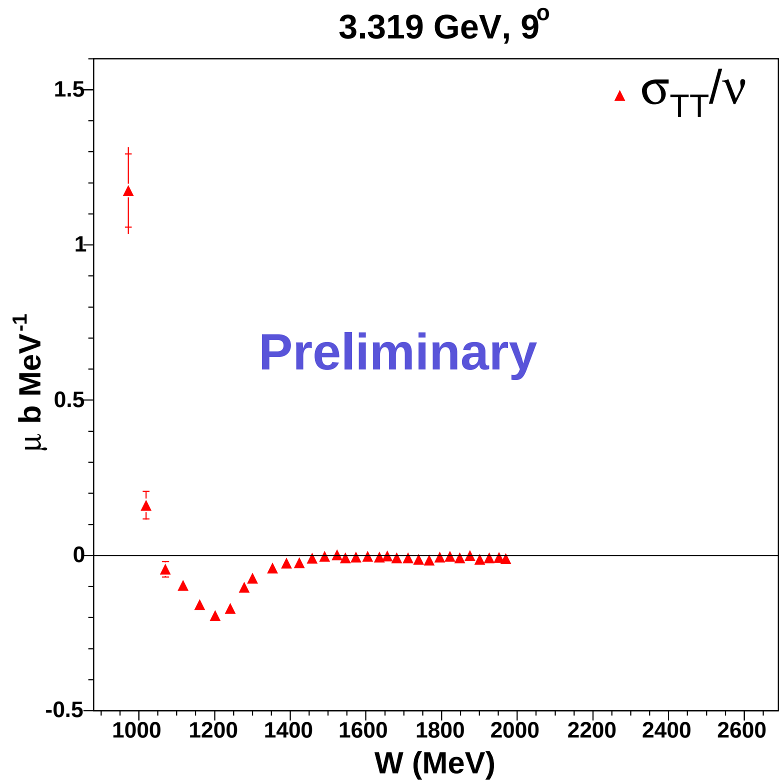
Radiative corrections: formalism of L. Mo and Y. Tsai (unpolarized) and POLRAD (polarized), work done by J. Singh.

^{3}He Spin Structure Functions



The GDH Integrand: σ_{TT}

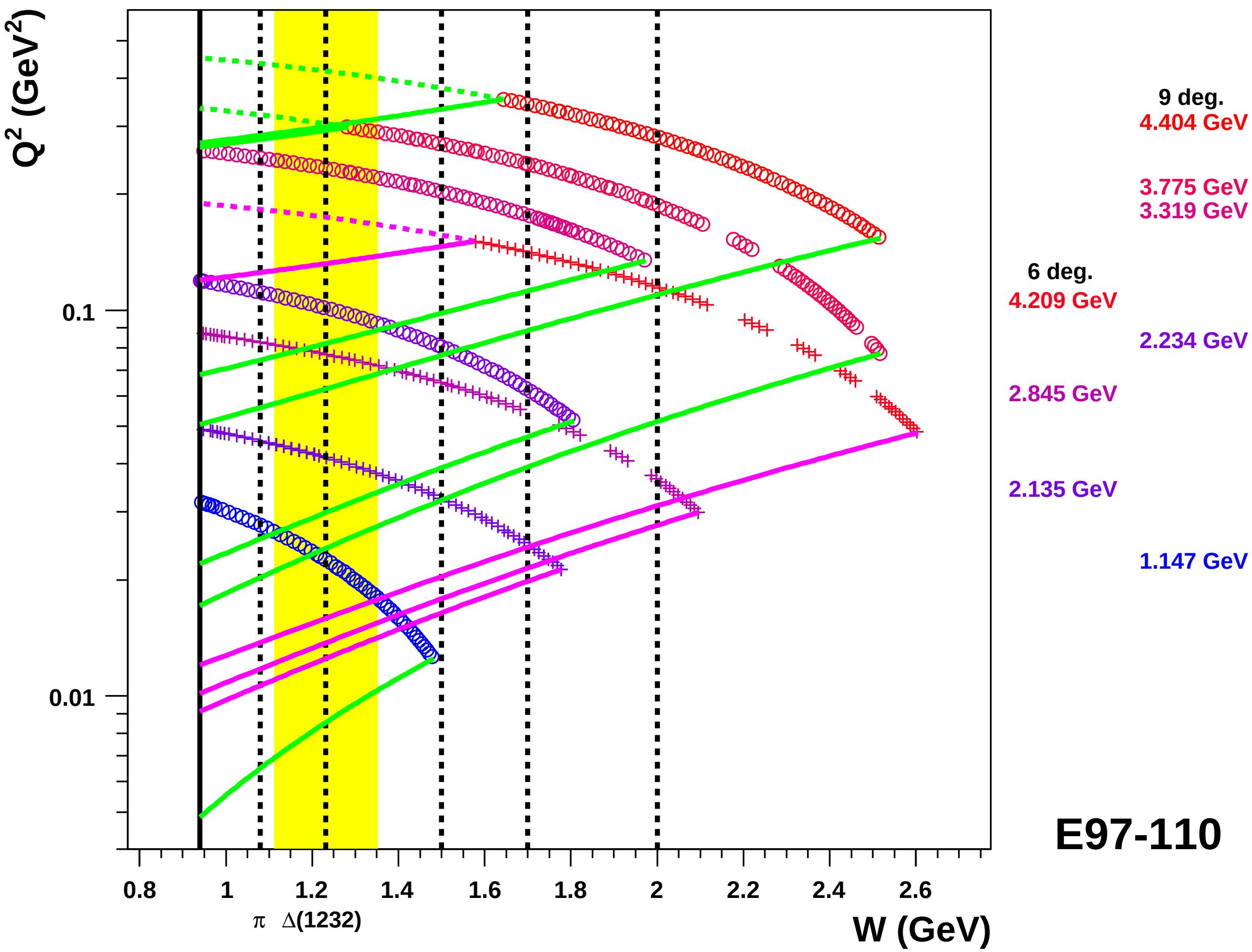




$$I(Q^2) = \int_{\nu_{\mathrm{th}}}^{\infty} \frac{2\sigma_{\mathrm{TT}}}{\nu} d\nu; \quad 2\sigma_{\mathrm{TT}} = \sigma_{1/2}(\nu, Q^2) - \sigma_{3/2}(\nu, Q^2)$$

$$\sigma_{\mathrm{TT}} = \frac{4\pi^2\alpha}{MK}\left[g_1(\nu, Q^2) - \left(\frac{Q^2}{\nu^2}\right) g_2(\nu, Q^2)\right]$$

Kinematic Coverage and Interpolation



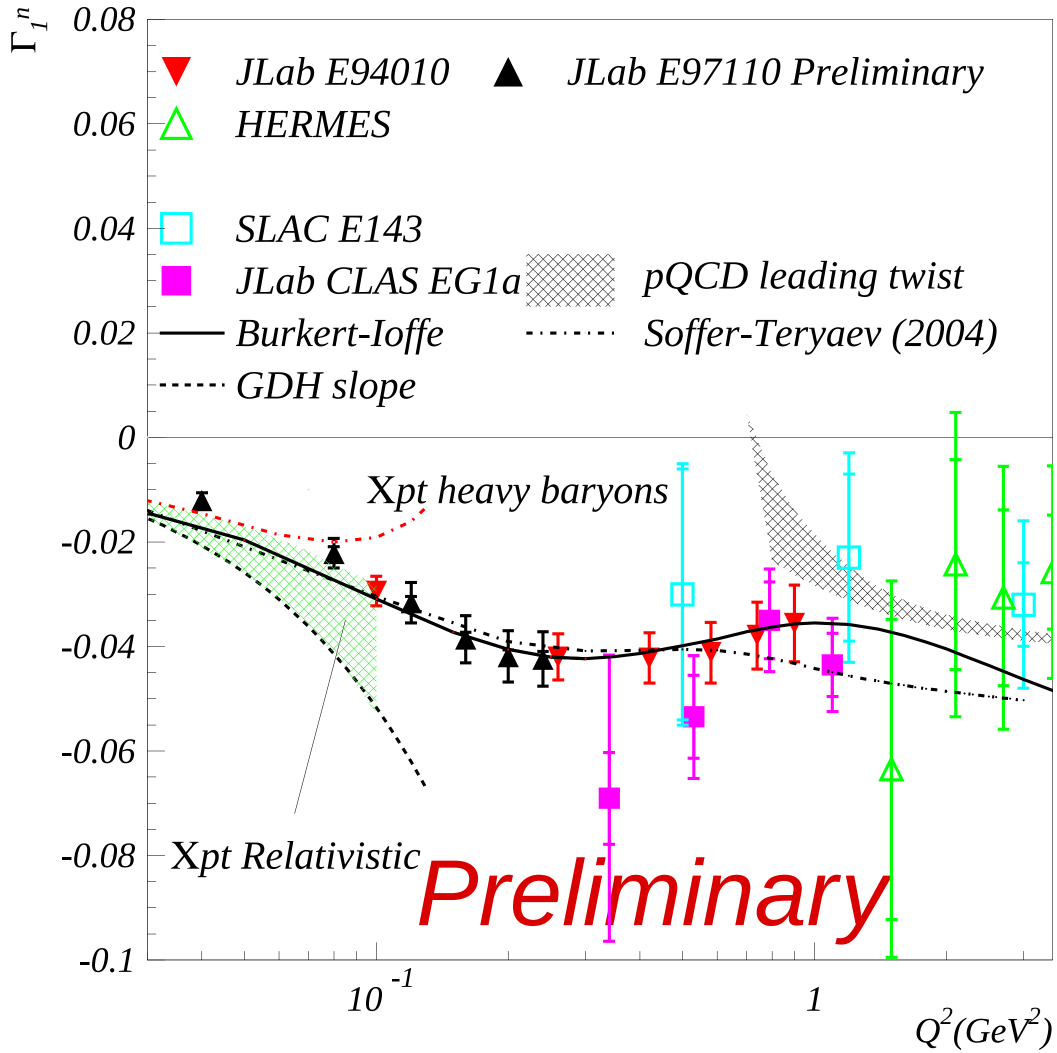
Six evenly spaced points 0.04–0.24 GeV^2 with steps of 0.04 GeV^2.

Constant Q^2 Interpolation and Integral Extraction

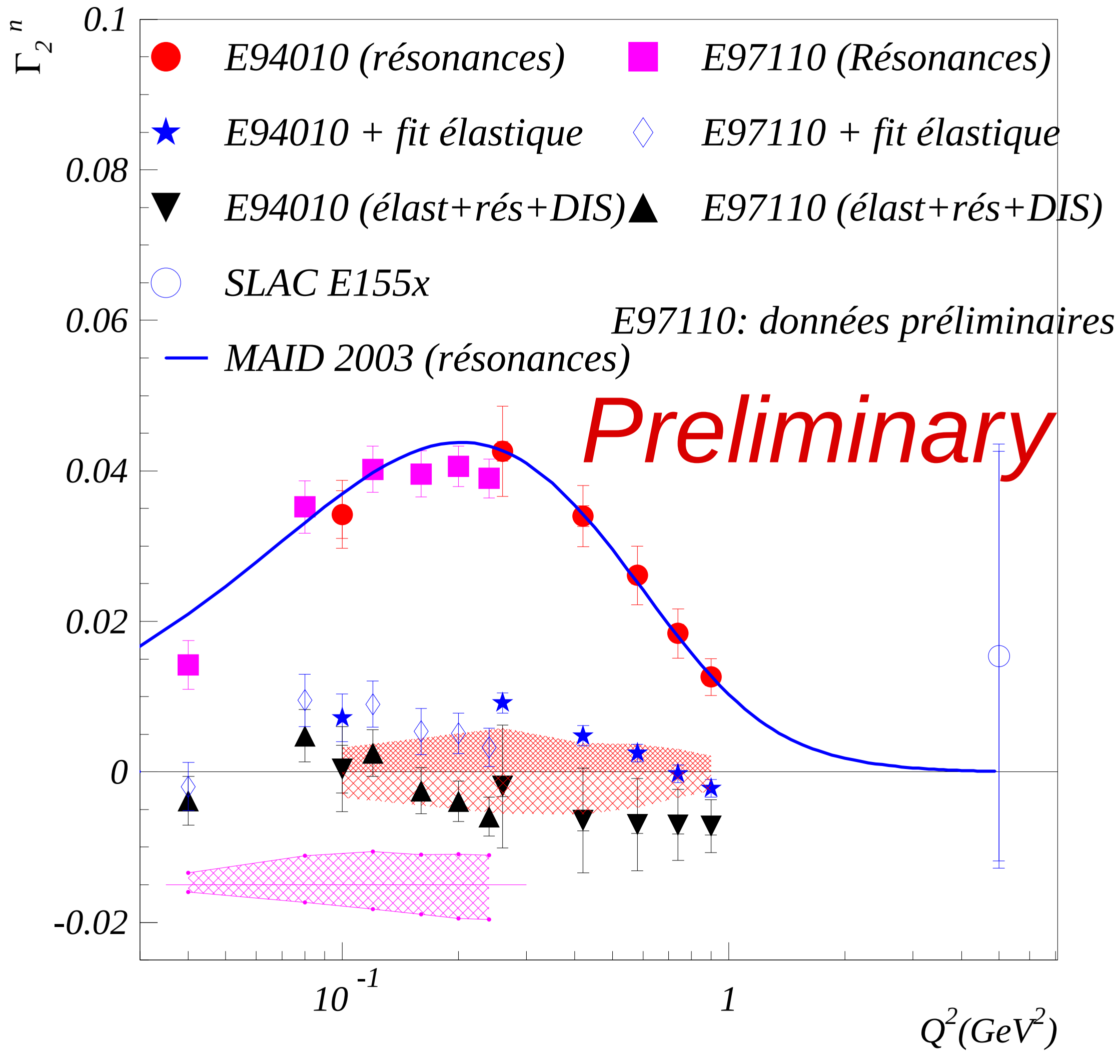
Procedure:

- First interpolate to constant W for each energy.
- Second interpolation with respect to Q^2.
- Integrals formed from W = 1073 GeV to 2000 GeV.
- We could use our own data above W = 2000 GeV.
- DIS contribution included up to W = $\sqrt{1000}$ using Thomas and Bianchi parameterization.
- Neutron extraction performed using calculation from Scopetta and Ciofi degli Atti paper for $Q^2 >= 0.1$ GeV^2.
- $Q^2 < 0.1$ GeV^2 use effective polarization technique (difference $\sim$ 5–10%).

Γ_1^n: First Moment of g_1



Γ_2^n: First Moment of g_2



What Needs to be Done

- Check and refine constant Q^2 interpolation and integral extraction (V. Sulkosky).
- Second pass radiative corrections (J. Singh).
- Model and subtract QE contribution (V. Sulkosky).
- Collimator background (T. Holmstrom).
- Finalize target polarization (J. Singh).
- Elastic analysis (J. Singh, V. Sulkosky).
- Finalize acceptance for cross sections (V. Sulkosky).

Summary and Conclusion

- The GDH integral is an important tool that can be used to study nucleon spin structure over the full Q^2 range.
- E97-110 provides precision data for the generalized GDH integral at low Q^2, 0.02 to 0.3 GeV^2
- Preliminary results of the ^{3}He structure functions and the GDH integrand are available.
- Extractions of the GDH integral and moments of the spin structure functions are in progress.
- These data allow us to check χPT at very low Q^2.
- Final results available in about 6 months, then publications.

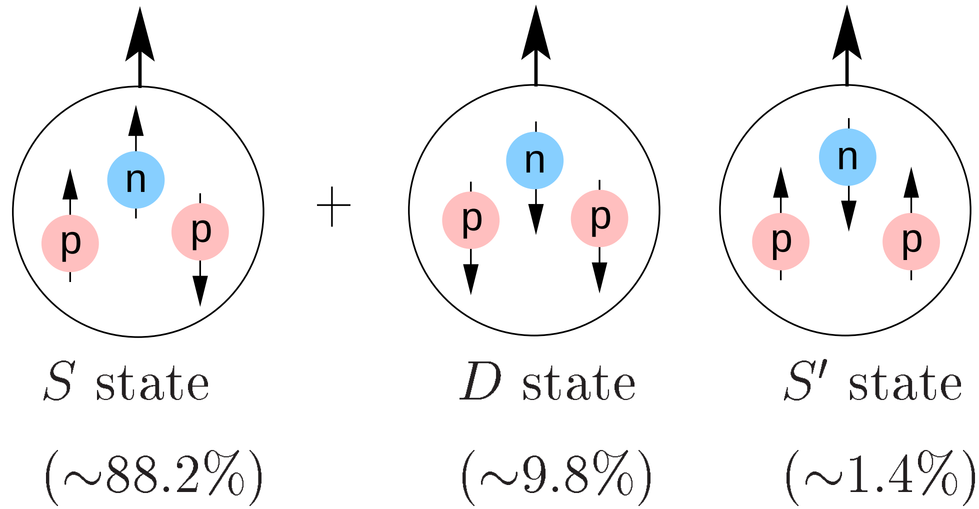
The E97-110 Collaboration

S. Abrahamyan, K. Aniol, D. Armstrong, T. Averett, S. Bailey,
P. Bertin, W. Boeglin, F. Butaru, A. Camsonne, G.D. Cates,
G. Chang, **J.P. Chen**, Seonho Choi, E. Chudakov, L. Coman,
J. Cornejo, B. Craver, F. Cusanno, R. De Leo, C.W. de Jager,
A. Deur, K.E. Ellen, R. Feuerbach, M. Finn, S. Frullani,
K. Fuoti, H. Gao, **F. Garibaldi**, O. Gayou, R. Gilman,
A. Glamazdin, C. Glashausser, J. Gomez, O. Hansen, D. Hayes,
B. Hersman, D. W. Higinbotham, T. Holmstrom, T.B. Humensky,
C. Hyde-Wright, H. Ibrahim, M. Iodice, X. Jiang, L. Kaufman,
A. Kelleher, W. Kim, A. Kolarkar, N. Kolb, W. Korsch,
K. Kramer, G. Kumbartzki, L. Lagamba, G. Laveissiere,
J. LeRose, D. Lhuillier, R. Lindgren, N. Liyanage, B. Ma,
D. Margaziotis, P. Markowitz, K. McCormick, Z.E. Meziani,
R. Michaels, B. Moffit, P. Monaghan, S. Nanda, J. Niedziela,
M. Niskin, K. Paschke, M. Potokar, A. Puckett, V. Punjabi,
Y. Qiang, R. Ransome, B. Reitz, R. Roche, A. Saha, A. Shabetai,
J. Singh, S. Sirca, K. Slifer, R. Snyder, P. Solvignon, R. Stringer,
R. Subedi, **V. Sulkosky**, W.A. Tobias, P. Ulmer, G. Urciuoli,
A. Vacheret, E. Voutier, K. Wang, L. Wan, B. Wojtsekhowski,
S. Woo, H. Yao, **J. Yuan**, X. Zheng, L. Zhu

and the Jefferson Lab Hall A Collaboration

Extra Slides

^{3}*He as an Effective Polarized Neutron Target*



$P_{\rm n}$ = 86% and $P_{\rm p}$ = -2.8%

J.L. Friar *et al.*, PRC **42**, (1990) 2310

Extraction of Neutron Results

$$\Gamma_1^{\rm n}(Q^2) = \frac{1}{P_{\rm n}}\left[\Gamma_1^{^3{\rm He}}(Q^2) - 2P_{\rm p}\Gamma_1^{\rm p}(Q^2)\right]$$

C. Ciofi degli Atti & S. Scopetta, PLB **404**, (1997) 223

Inclusive Cross Sections

- Unpolarized cross sections

$$\frac{d^2\sigma}{dE'd\Omega} = \sigma_{\mathrm{Mott}} \left[\frac{1}{\nu} F_2(x,Q^2) + \frac{2}{M} F_1(x,Q^2) \tan^2\frac{\theta}{2}\right]$$

- Polarized cross sections

$$\Delta\sigma_{\parallel} = \frac{d^2\sigma^{\downarrow\Uparrow}}{dE'd\Omega} - \frac{d^2\sigma^{\uparrow\Uparrow}}{dE'd\Omega} = K\left[(E + E'\cos\theta)\, g_1(x,Q^2) - \left(\frac{Q^2}{\nu}\right) g_2(x,Q^2)\right]$$

$$\Delta\sigma_{\perp} = \frac{d^2\sigma^{\downarrow\Rightarrow}}{dE'd\Omega} - \frac{d^2\sigma^{\uparrow\Rightarrow}}{dE'd\Omega} = K E'\sin\theta\left[g_1(x,Q^2) + \frac{2E}{\nu} g_2(x,Q^2)\right]$$

$$K = \frac{4\alpha^2}{M\nu Q^2}\frac{E'}{E}$$

$\downarrow$, $\uparrow$ are for electron spin

$\Uparrow$, $\Rightarrow$ are for target spin direction

F_1, F_2, g_1, g_2: structure functions

Spin-$\frac{1}{2}$ Targets

$$I_{\rm GDH} = \int_{\nu_{\rm th}}^{\infty} \frac{\sigma_{\frac{1}{2}}(\nu) - \sigma_{\frac{3}{2}}(\nu)}{\nu} d\nu = -2\pi^2\alpha\left(\frac{\kappa}{M}\right)^2$$

The sum rule is valid for any target.

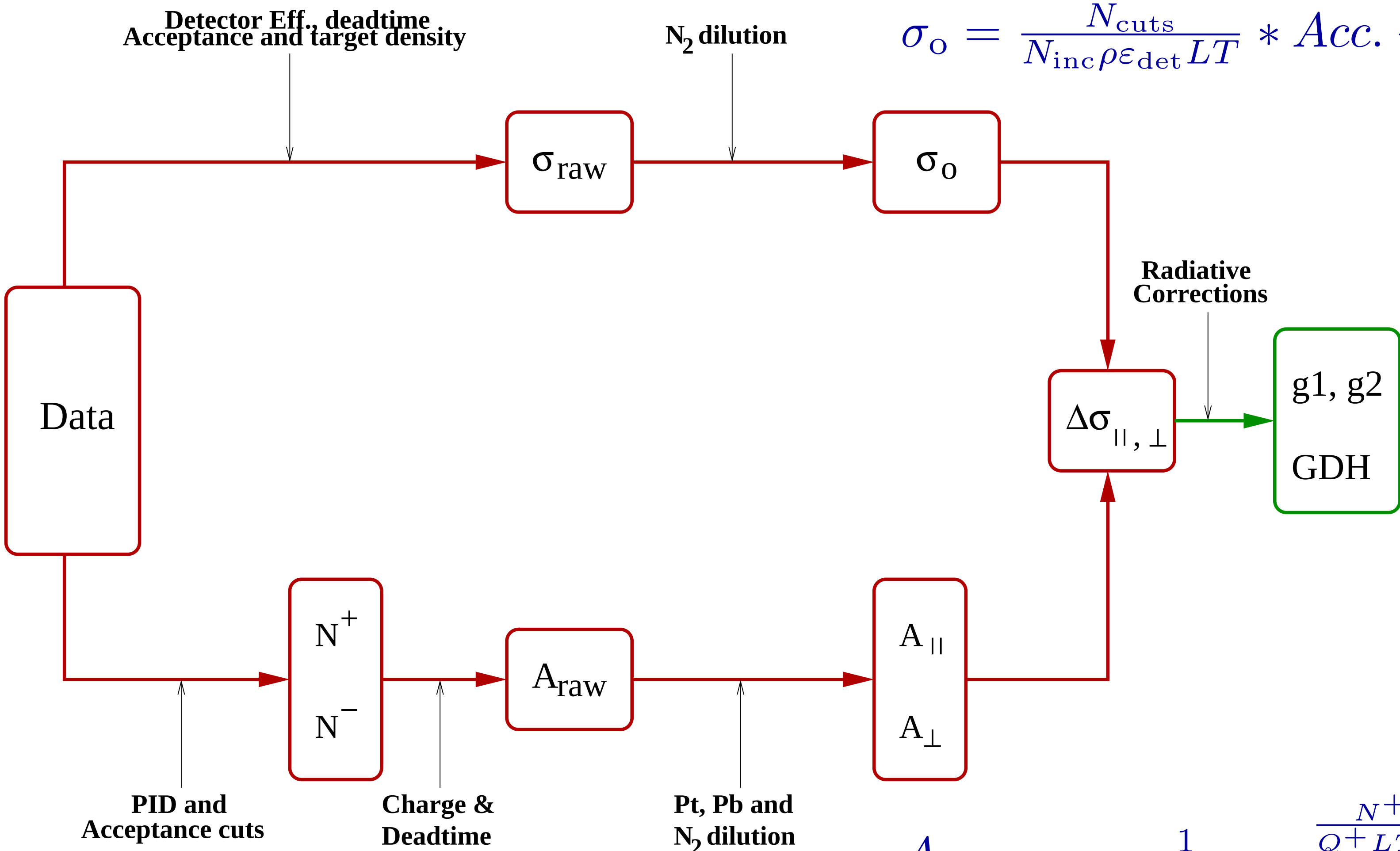
	M [GeV]	Spin	κ	$I_{\rm GDH}$ [μ b]
Proton	0.938	$\frac{1}{2}$	1.79	–204.8
Neutron	0.940	$\frac{1}{2}$	-1.91	–233.2
Deuteron	1.876	1	-0.14	–0.65
Helium-3	2.809	$\frac{1}{2}$	-8.38	–498.0

1 μb = 10^{-34} m^2

- Proton sum rule was verified to $\sim$ 10%, Mainz and Bonn.
- Measurements for the neutron are in progress.

Analysis Procedure

$$\sigma_o = \frac{N_{\rm cuts}}{N_{\rm inc}\rho\varepsilon_{\rm det} LT} * Acc. - \frac{2\rho_{\rm N_2}}{\rho + \rho_{\rm N_2}}\sigma_{\rm N_2}$$



$$A_{\parallel,\perp} = \frac{1}{f_{\rm N_2} P_{\rm tg} P_{\rm beam}} \frac{\frac{N^+}{Q^+ LT^+} - \frac{N^-}{Q^- LT^-}}{\frac{N^+}{Q^+ LT^+} + \frac{N^-}{Q^- LT^-}}$$

Chiral Symmetry

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4g^2} G^{\alpha}_{\mu\nu} G^{\mu\nu}_{\alpha} + \bar{q} i \gamma^{\mu} D_{\mu} q - \bar{q} \mathcal{M} q$$
$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}_0 + \mathcal{L}_{sb}$$

- Consider the limit where the light quark masses vanish.
- For massless fermions, chirality (handedness) is identical to a particle's helicity.
- Extra symmetry to the Lagrangian and obtain left and right handed quark fields.

$$q_{L,R} = \frac{1}{2}(1 \mp \gamma_5) q \,,$$

GDH Derivation

Based on fundamental physical arguments

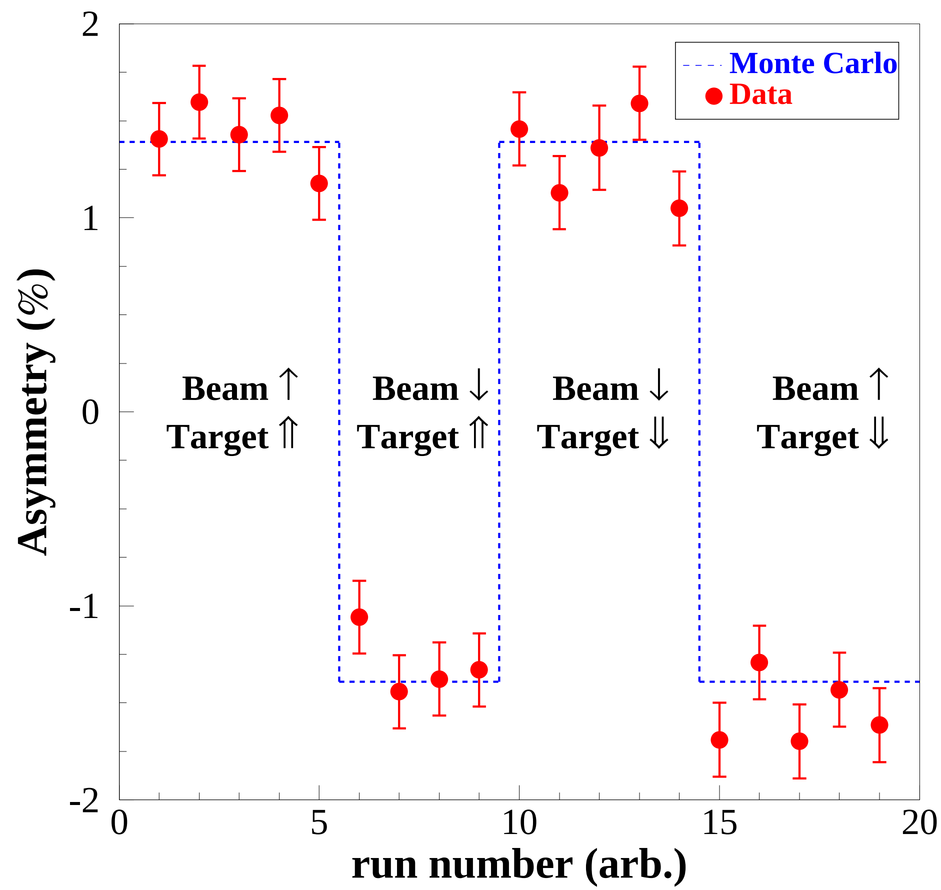
- Lorentz and gauge invariance: low energy theorem, Phys. Rev. **96**, 1428 (1954).
- Unitarity of the S-matrix: optical theorem.
- Causality: dispersion relations for forward compton scattering.

^{3}He Elastic Asymmetry

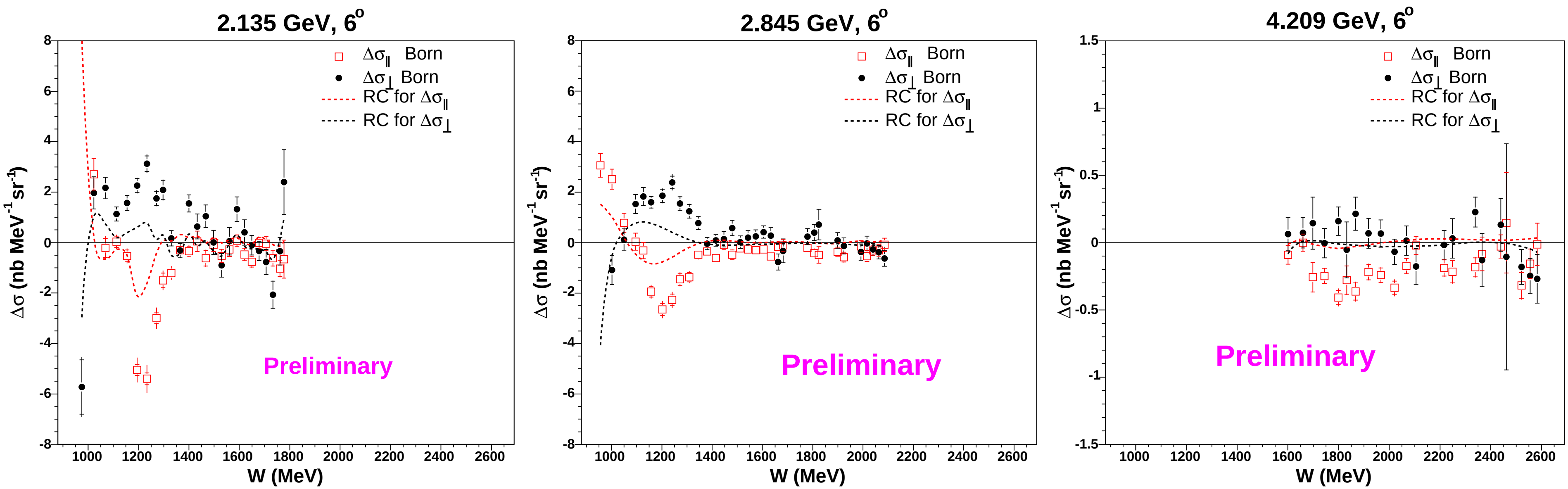
- Monte Carlo prediction: 1.390%
- Preliminary data analysis:

  (1.403 $\pm$ 0.044)% (stat. only)

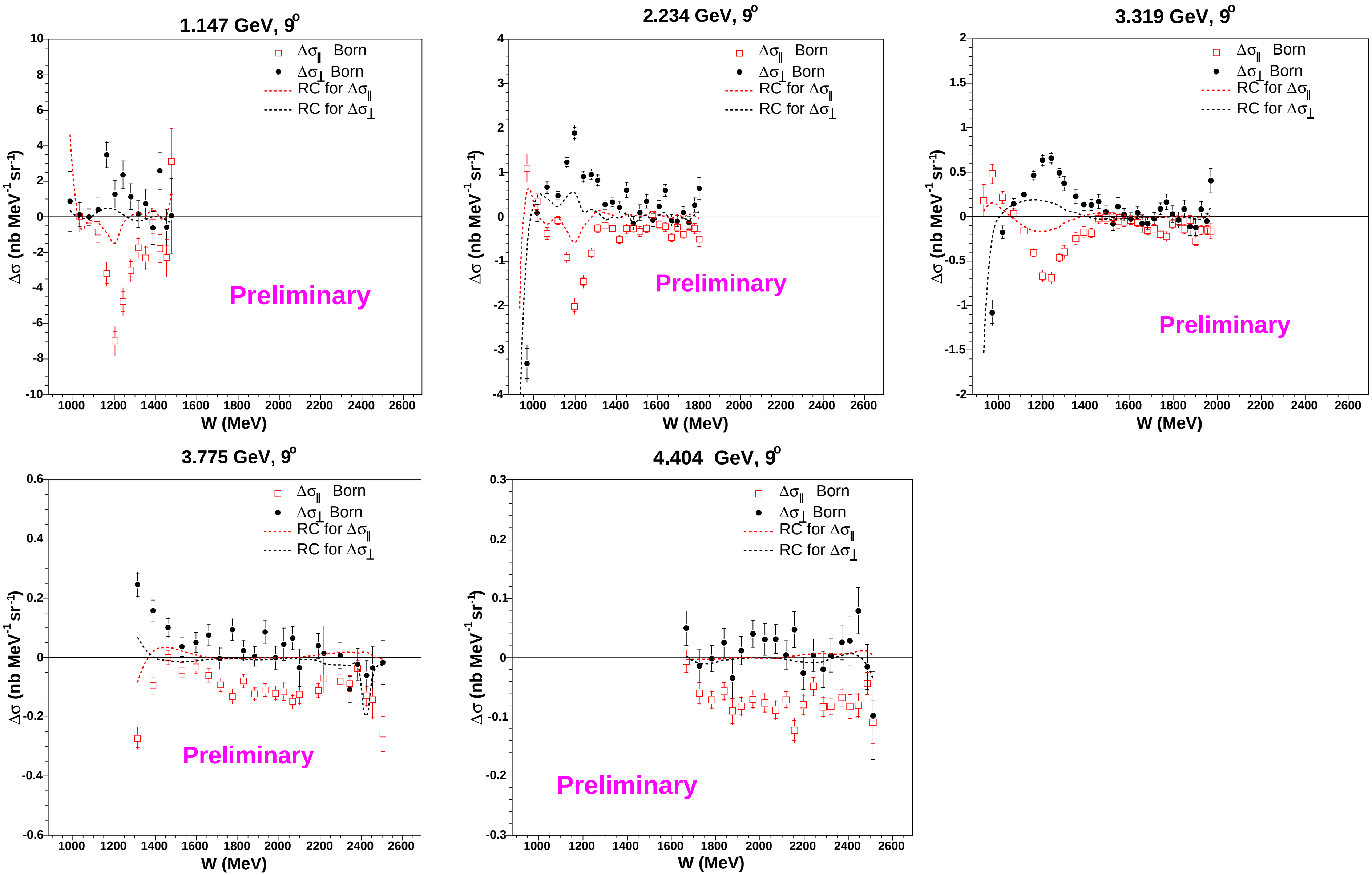
  $\chi^2/\mathrm{N_{dof}}$ = 1.08.
- Four target and beam configurations
- For seven out of the twelve beam energies, elastic data were acquired.



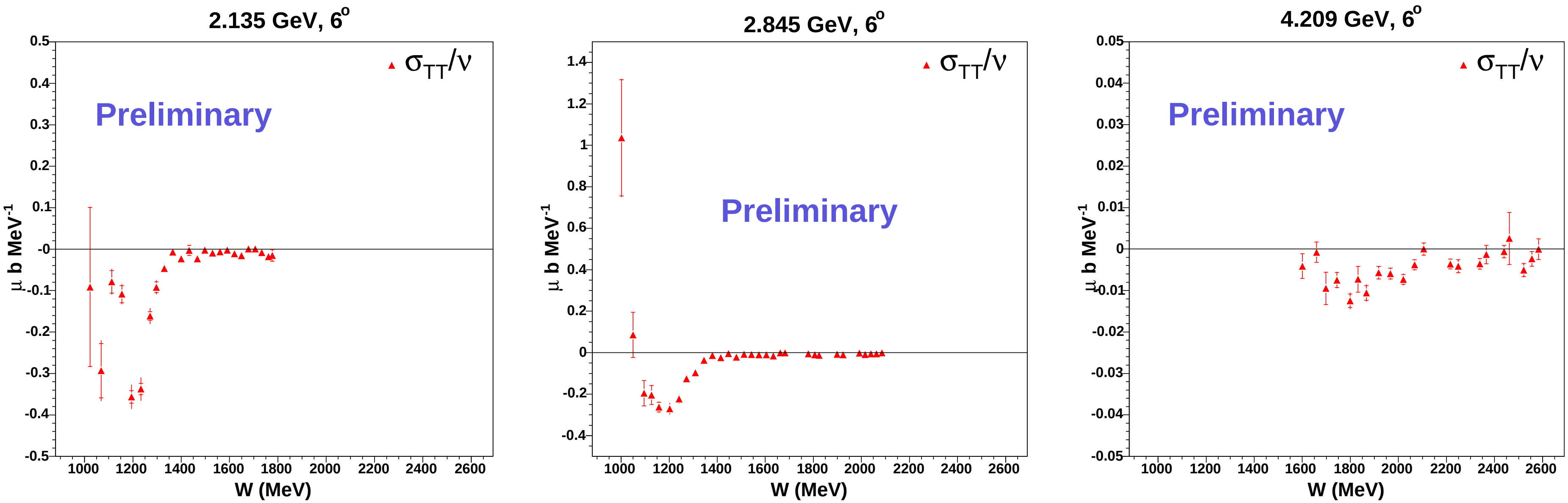
Cross Section Differences



Cross Section Differences



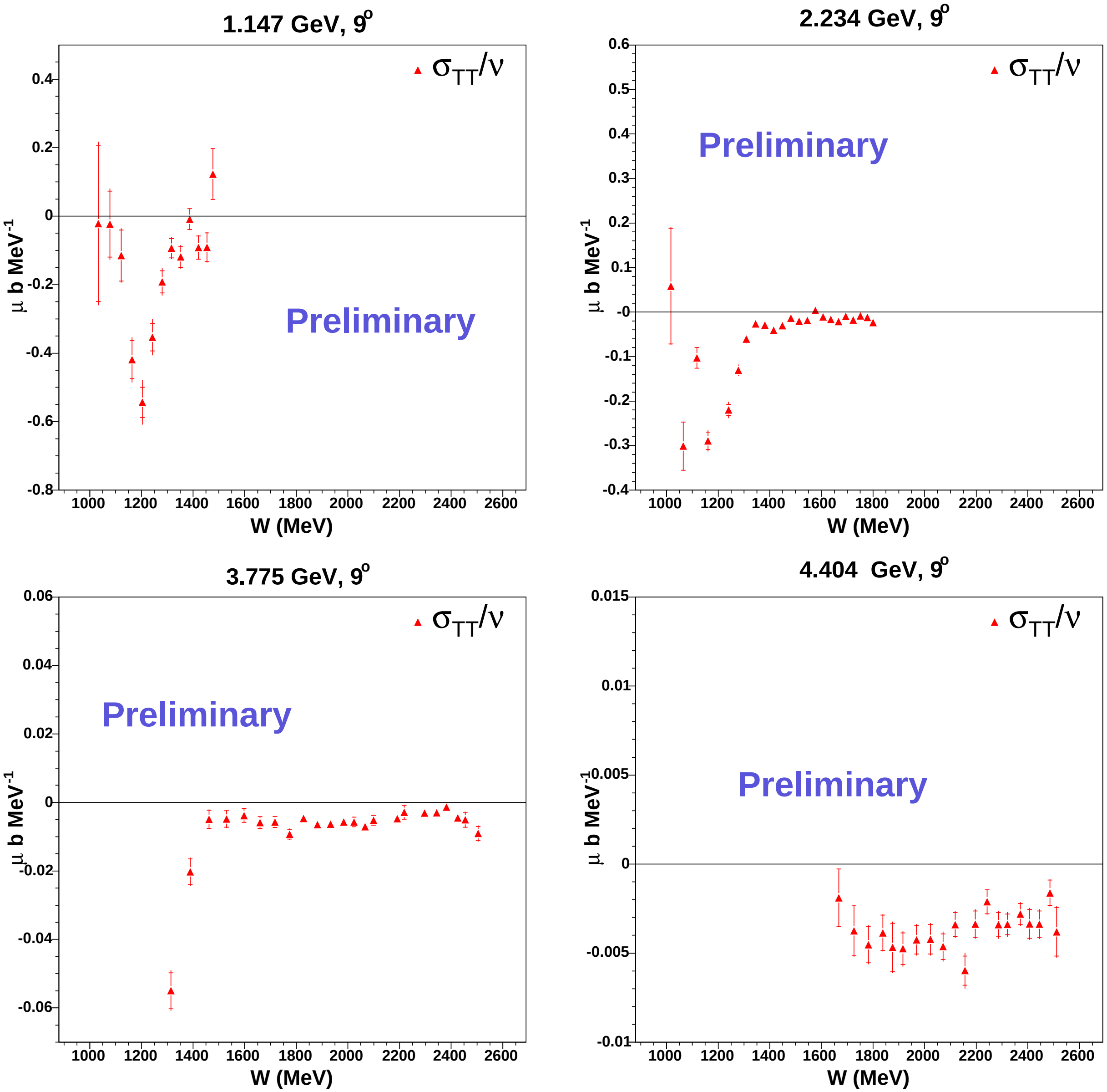
The GDH Integrand: σ_{TT}



$$2\sigma_{\mathrm{TT}} = \sigma_{1/2}(\nu, Q^2) - \sigma_{3/2}(\nu, Q^2)$$

$$\sigma_{\mathrm{TT}} = \frac{4\pi^2\alpha}{MK}\left[g_1(\nu, Q^2) - \left(\frac{Q^2}{\nu^2}\right) g_2(\nu, Q^2)\right]$$

The GDH Integrand: σ_{TT}

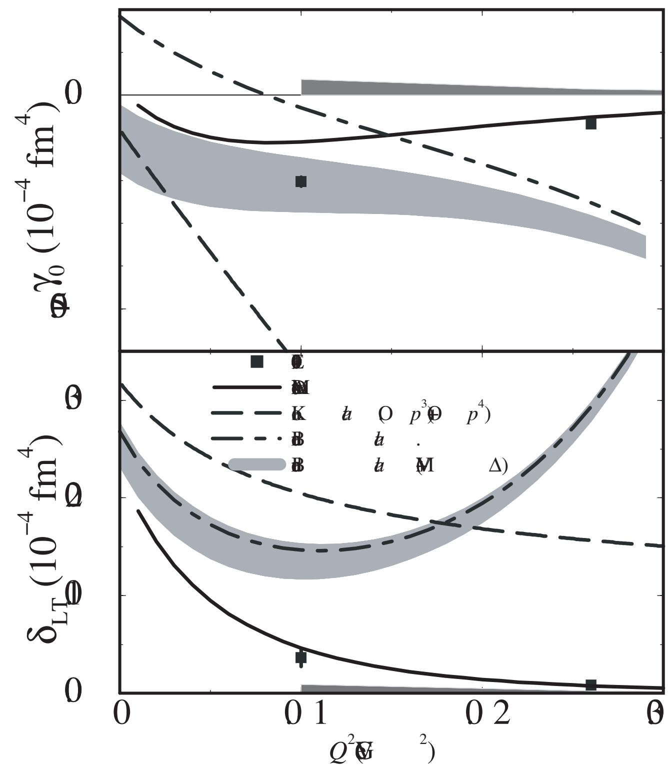


$$I(Q^2) = \int_{\nu_{\mathrm{th}}}^{\infty} \frac{2\sigma_{\mathrm{TT}}}{\nu} d\nu$$

Spin Polarizabilities

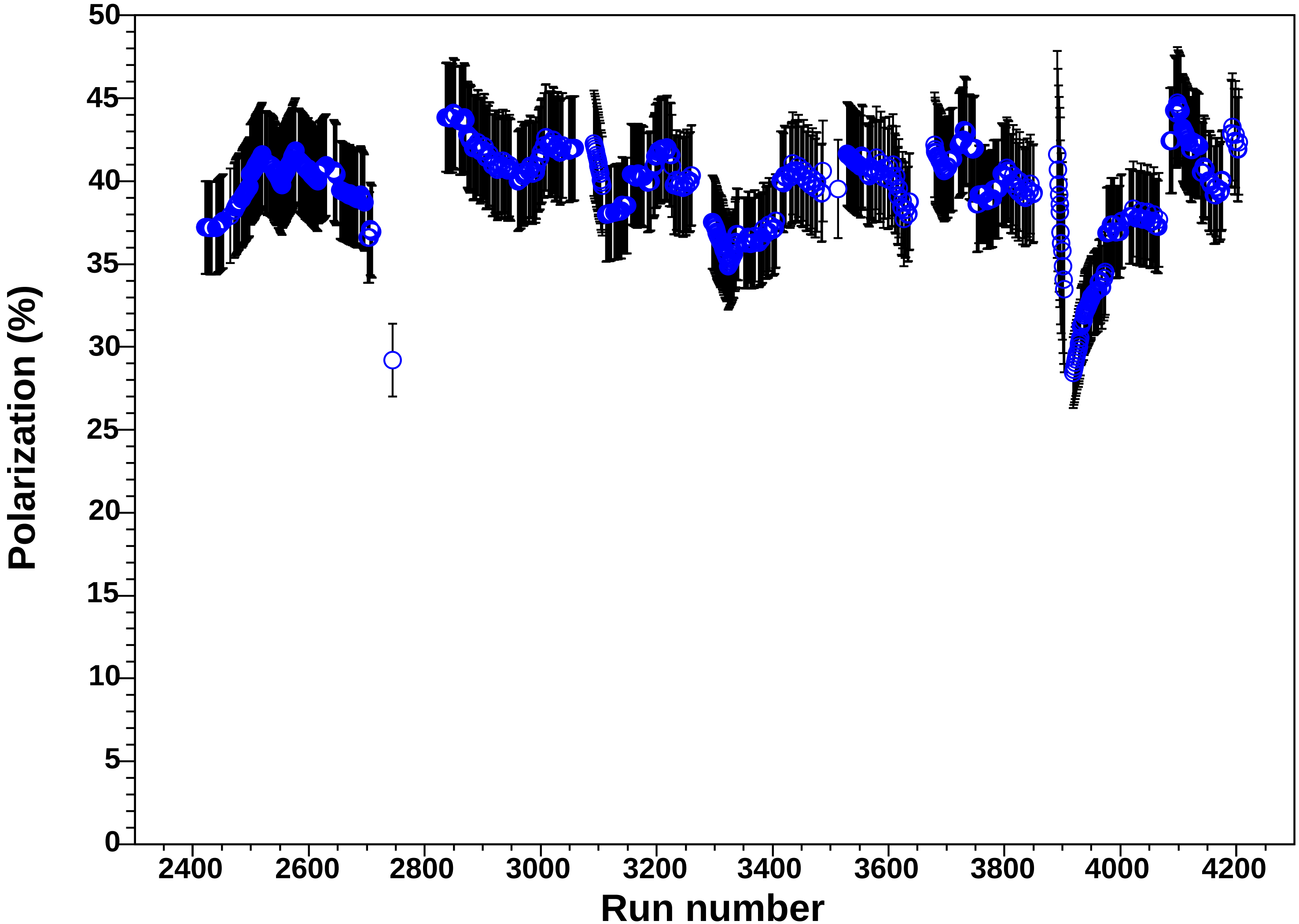
$$\gamma_0 = \frac{4e^2M^2}{\pi Q^6}\int_0^{x_0} x^2\left(g_1 - \frac{4M^2}{Q^2}x^2 g_2\right)dx$$

$$\delta_{\mathrm{LT}} = \frac{4e^2M^2}{\pi Q^6}\int_0^{x_0} x^2\,(g_1 + g_2)\,dx$$



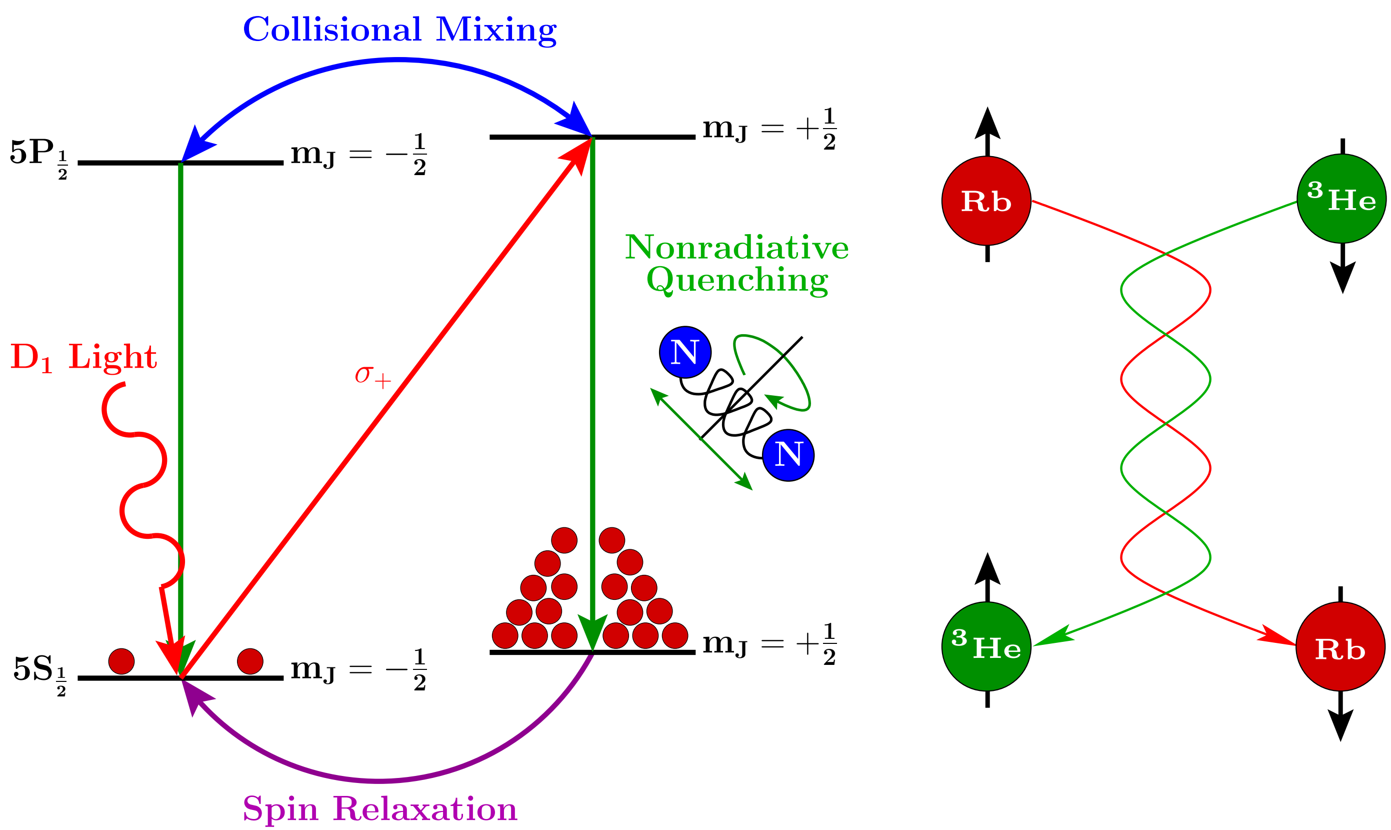
M. Amarian *et al.* , PRL **93**, 152301 (2004)

Preliminary Target Polarization



Jefferson Lab

Spin Exchange Optical Pumping



^{3}He nucleus is polarized via spin-exchange with optically pumped Rb atoms.