Measuring the Neutron and ^{3}He Spin Structure at Low Q^2

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Jefferson Lab

XVI International Workshop on Deep-Inelastic Scattering

and Related Subjects

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University College London

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

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

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

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

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

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

F_1, F_2, g_1, g_2: structure functions

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

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

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

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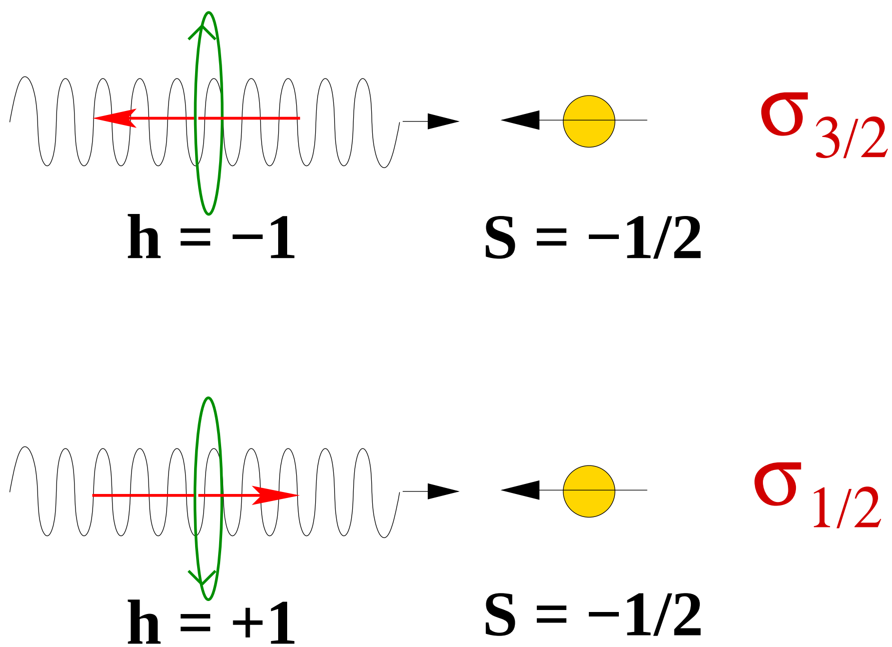
- $\sigma_{\frac{1}{2}}$ ($\sigma_{\frac{3}{2}}$) photoabsorption cross section with photon helicity parallel (anti-parallel) to the target spin.



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

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- 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.

GDH Measurements

The sum rule is valid for any target with definite spin-S.

	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

- Proton sum rule was verified to $\sim$ 10%, Mainz and Bonn:

  J. Ahrens *et al.*, PRL **87**, (2001) 022003, H. Dutz *et al.*, PRL **91**, (2003) 192001.

- Measurements for the neutron are in progress:

  H. Dutz *et al.*, PRL **94**, (2005) 162001, J. Ahrens *et al.*, PRL **97**, (2006) 202303.

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.

First moment of g_1 and g_2

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

$$\Gamma_2 = \int_0^1 g_2(x, Q^2) dx$$

- Γ_1 is closely related to generalized GDH integral as $Q^2 \to 0$.
- g_2 is suppressed at very low Q^2.

Bjorken Sum Rule ($Q^2 \to \infty$)

- g_A is the nucleon axial charge.
- The sum rule has been confirmed to 10%.

$$\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6}$$

J.D. Bjorken, Phys. Rev. **148**, 1467 (1966)

Importance of the Generalized GDH Sum Rule

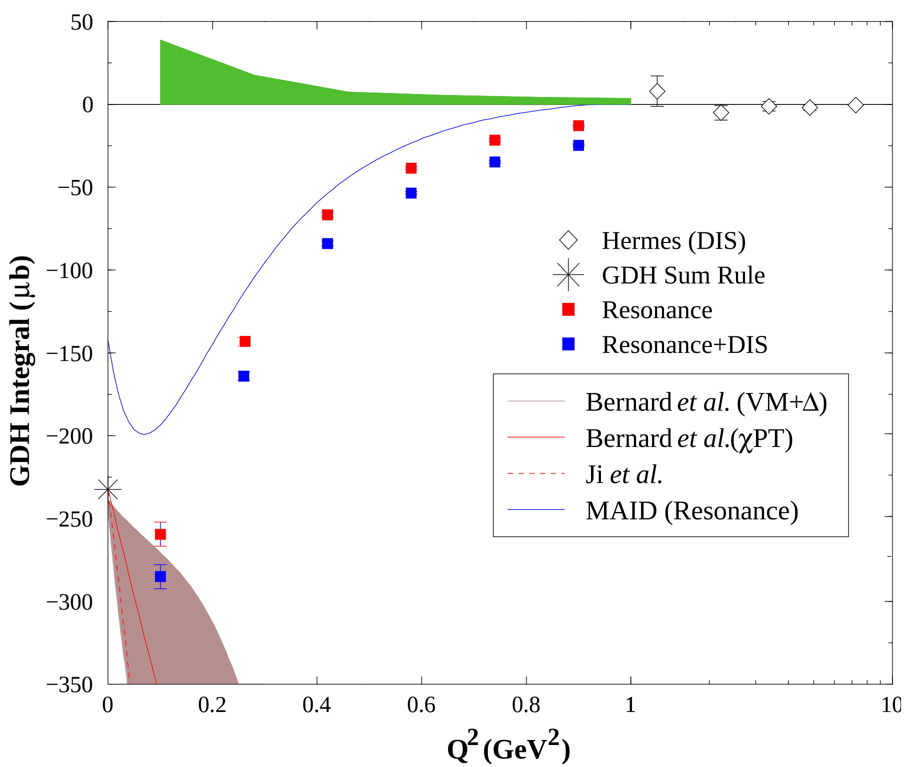
χPT   Lattice QCD   pQCD

$Q^2 = 0$ 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.

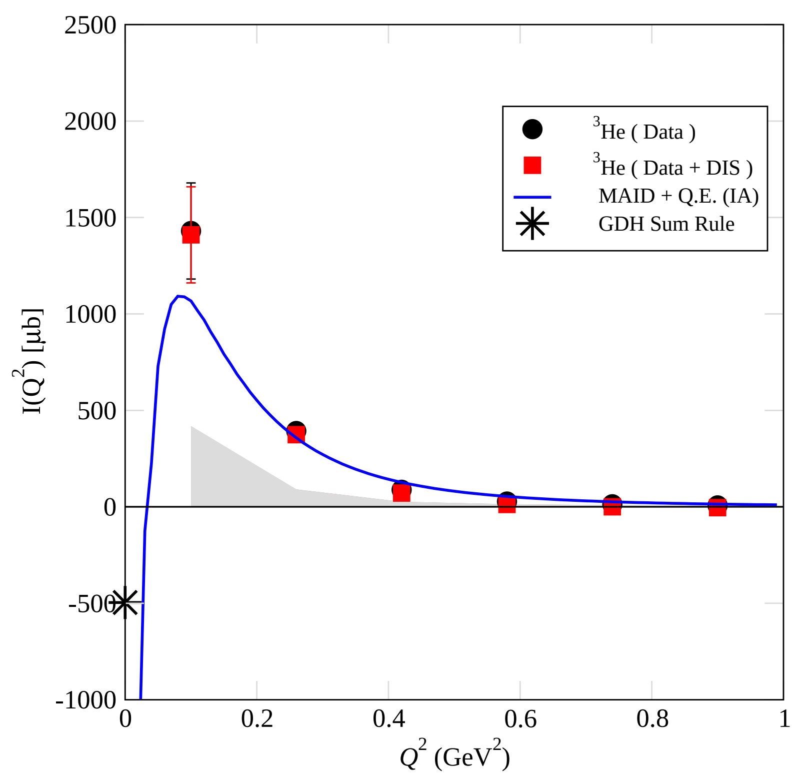
Hall A GDH Results

Neutron



M. Amarian *et al.*, PRL **89**, (2002) 242301

Helium-3



K. Slifer *et al.*, arXiv:0803.2267

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: $^3\overrightarrow{\mathrm{He}}(\vec{e},e')X$

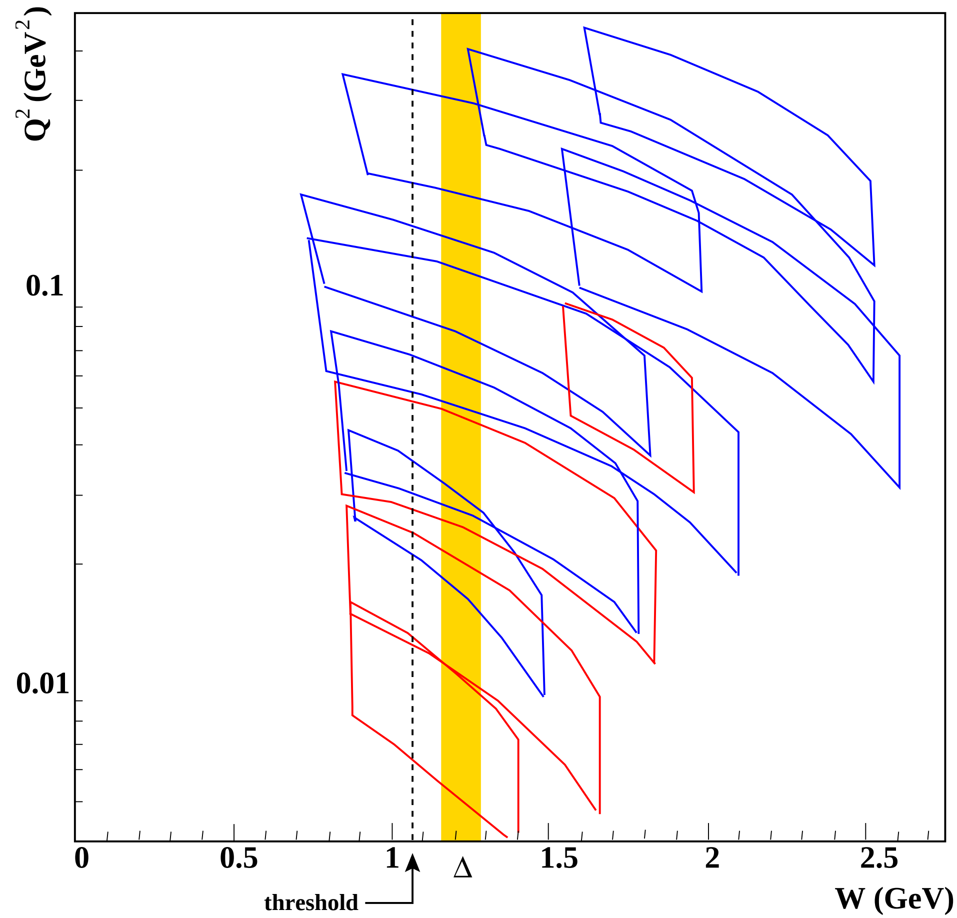
  $\Rightarrow$ Scattering angles of 6° and 9°

  $\Rightarrow$ Polarized electron beam:

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

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

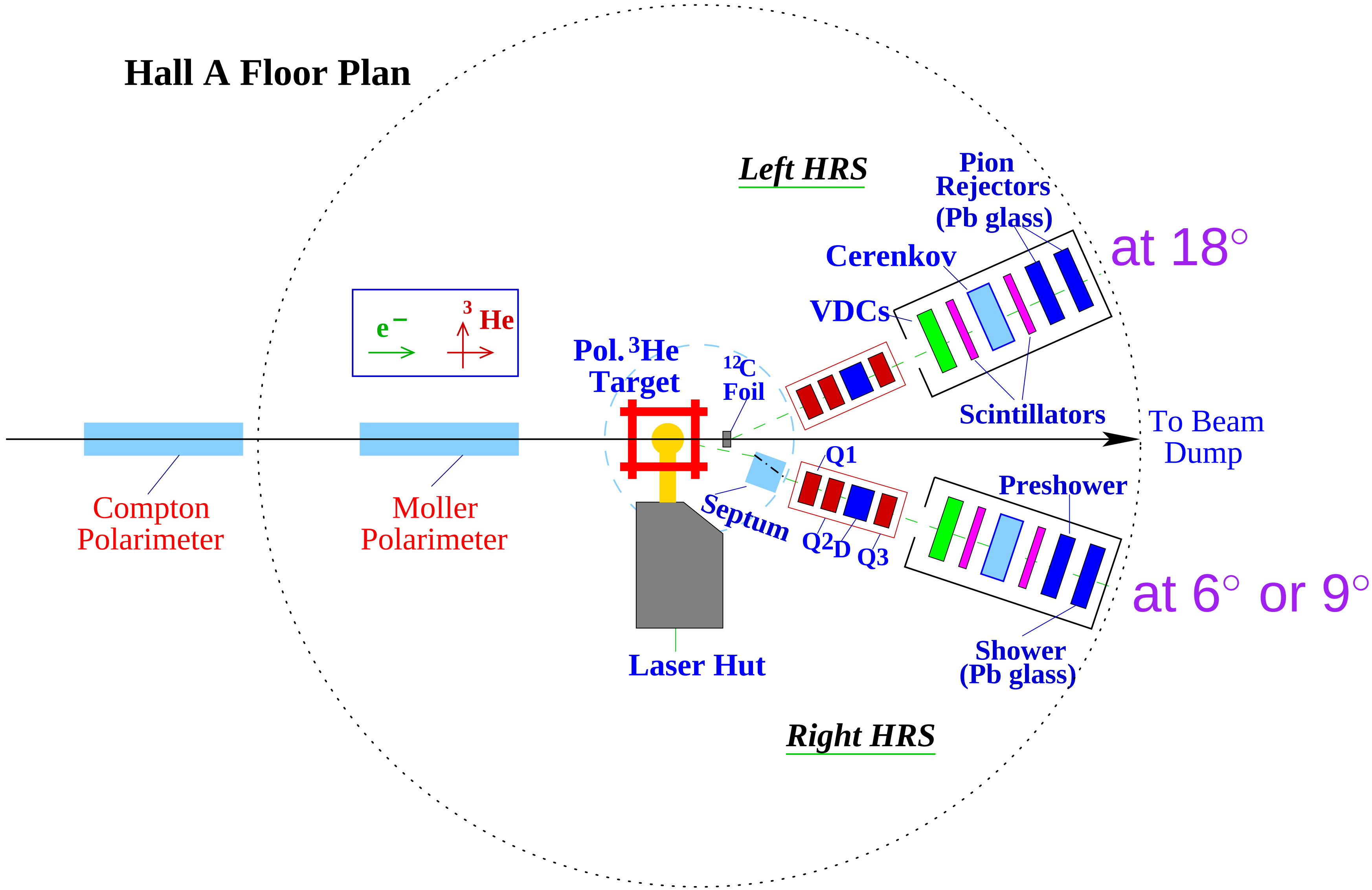
  $\langle P_{\mathrm{targ}} \rangle = 40\%$
- Measured polarized cross-section differences



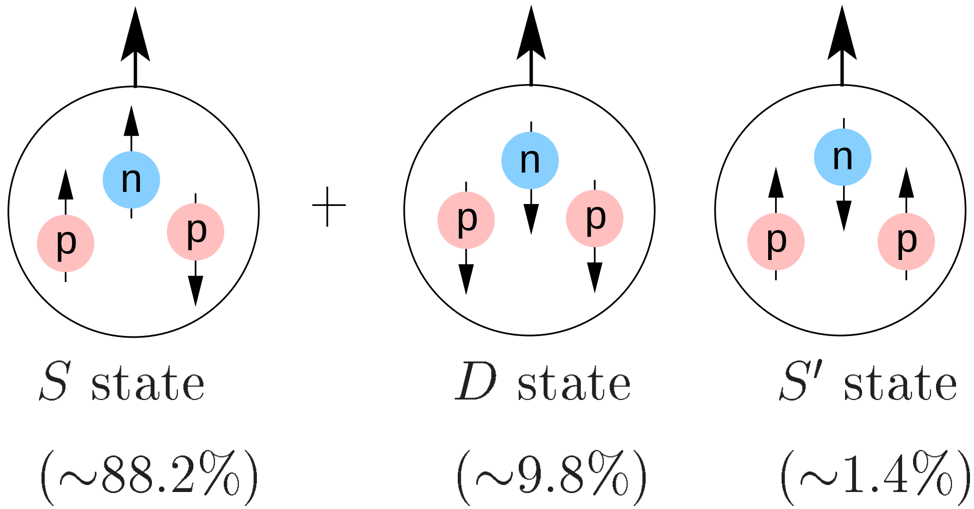
Spokespersons: J.P. Chen, A. Deur, and F. Garibaldi

Students: J. Singh, V. Sulkosky, and J. Yuan

Experimental Setup



^{3}He as an Effective Polarized Neutron Target



P_n = 86% and P_p = -2.8%

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

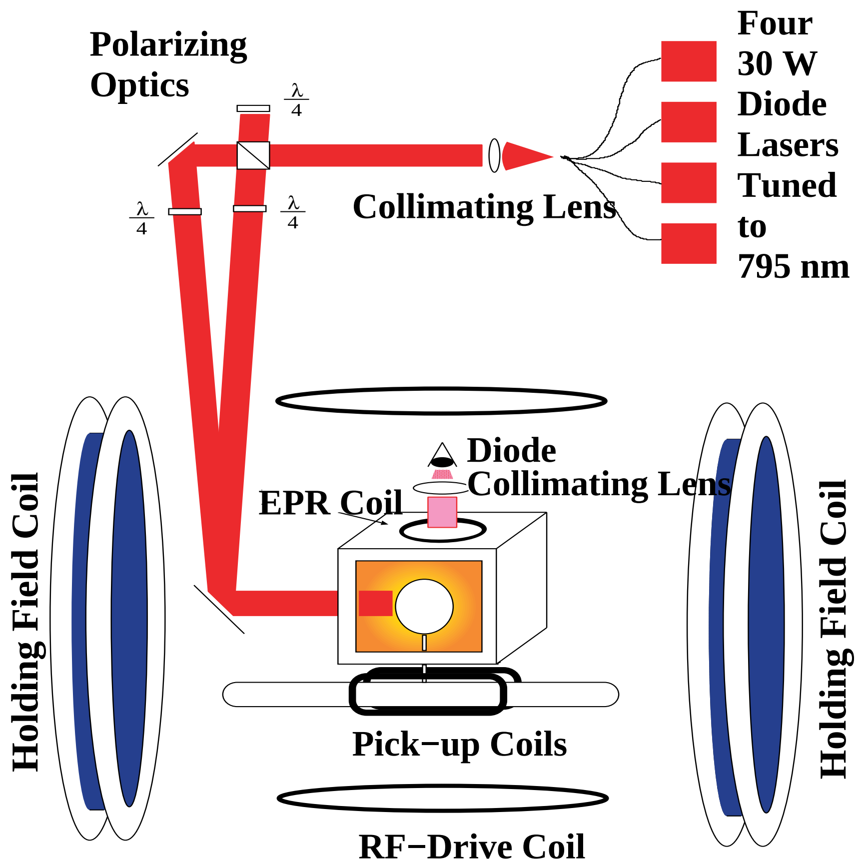
Extraction of Neutron Results

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

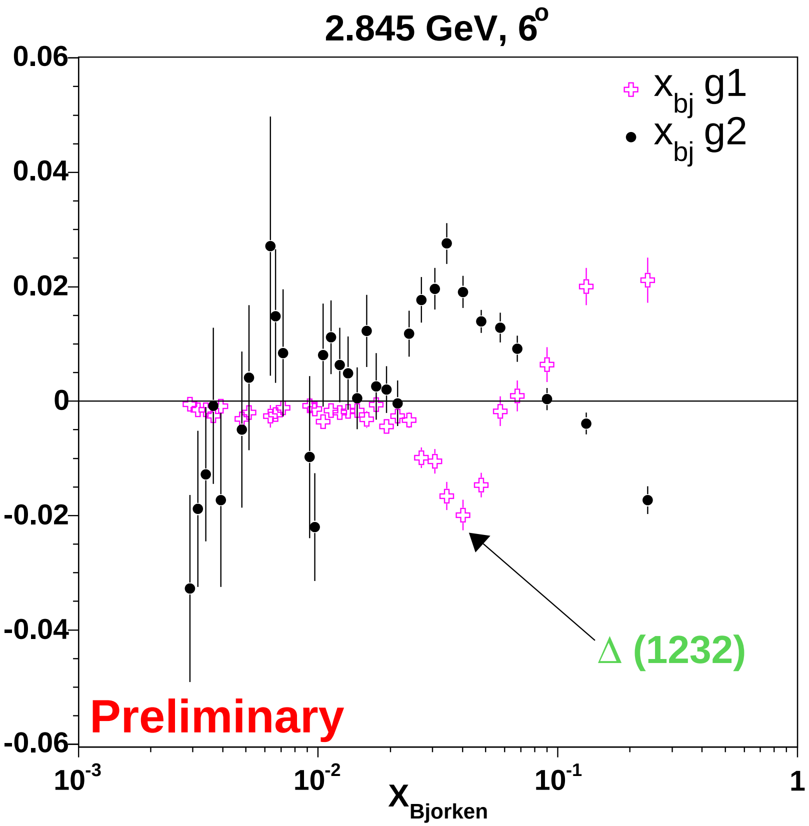
C. Ciofi degli Atti & S. Scopetta, PLB **404**, (1997) 223

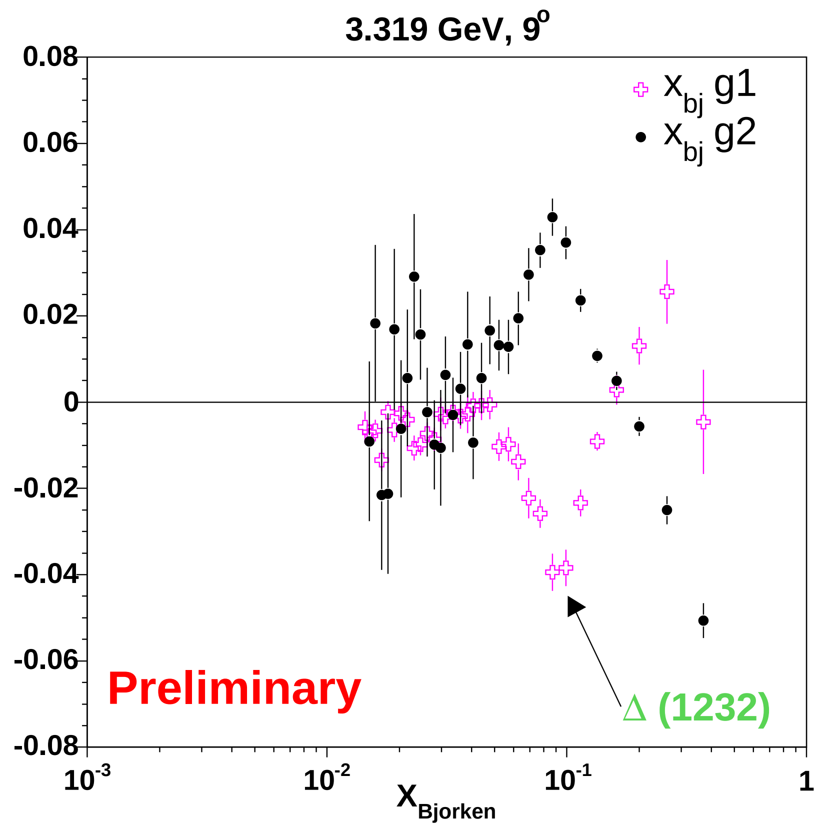
Polarized ^{3}He System

- Both longitudinal and transverse configurations.
- Two independent polarimetries: NMR and EPR.



^3He Spin Structure Functions

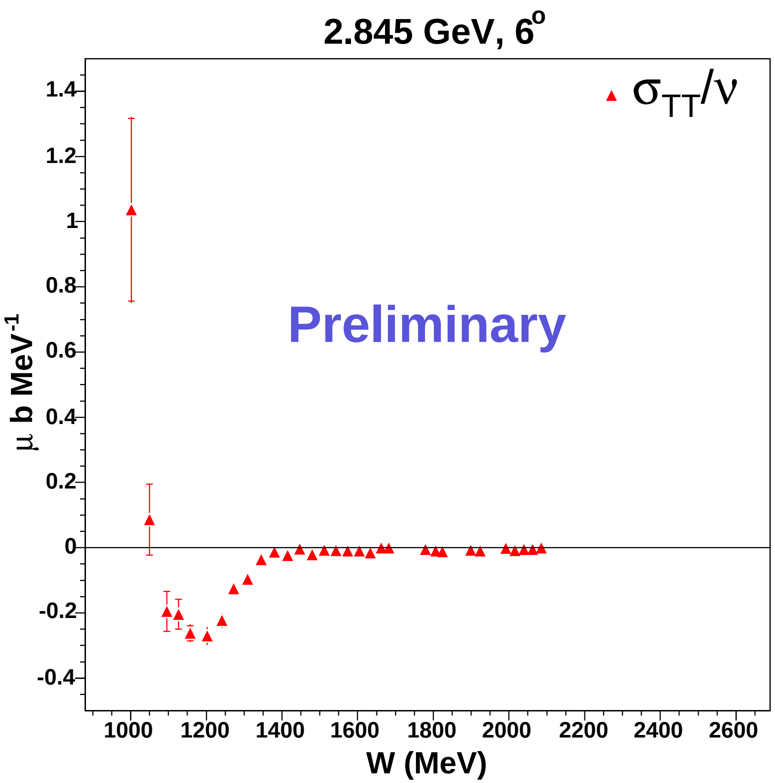


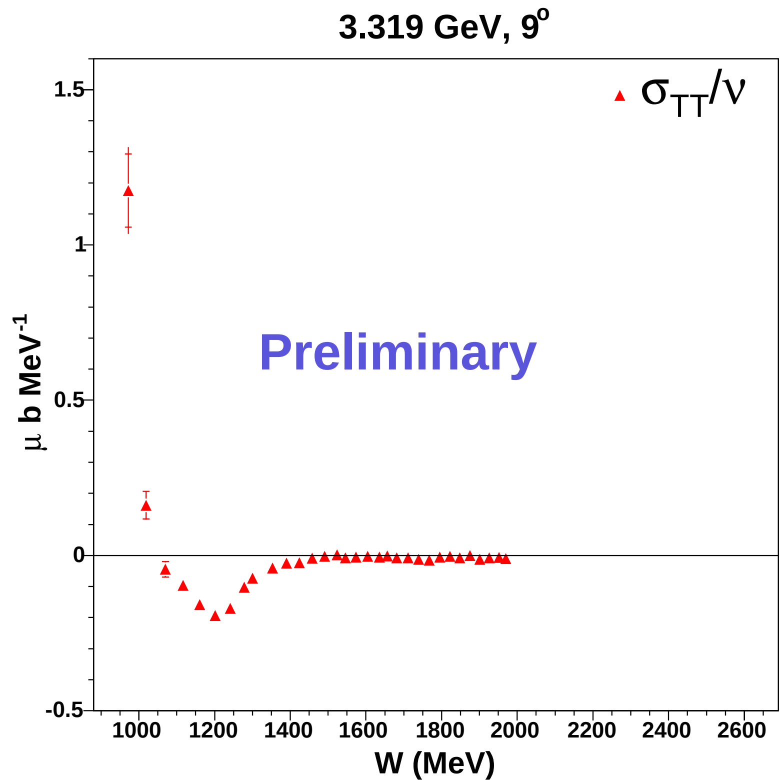


$Q^2(\Delta)$ = 0.077 GeV^2

$Q^2(\Delta)$ = 0.23 GeV^2

The GDH Integrand: σ_{TT}

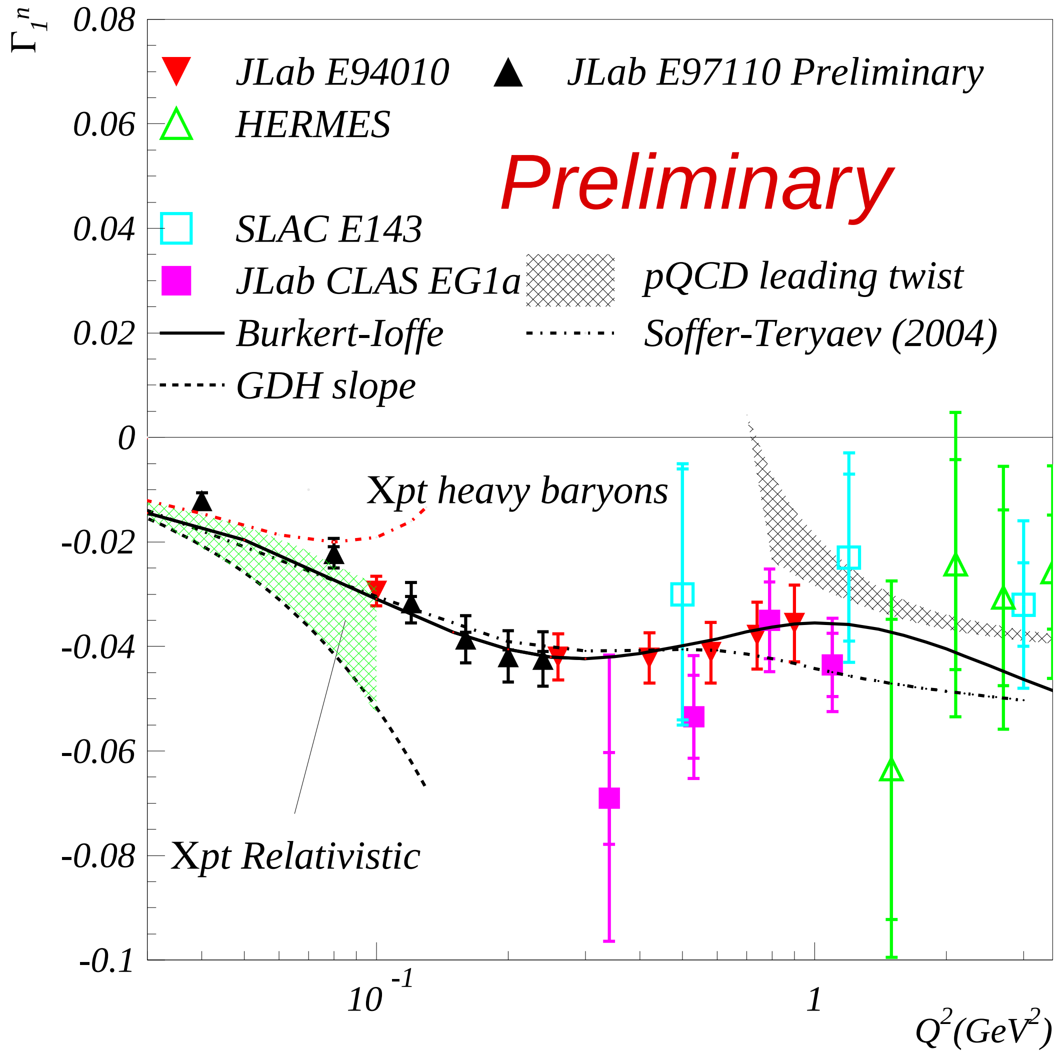




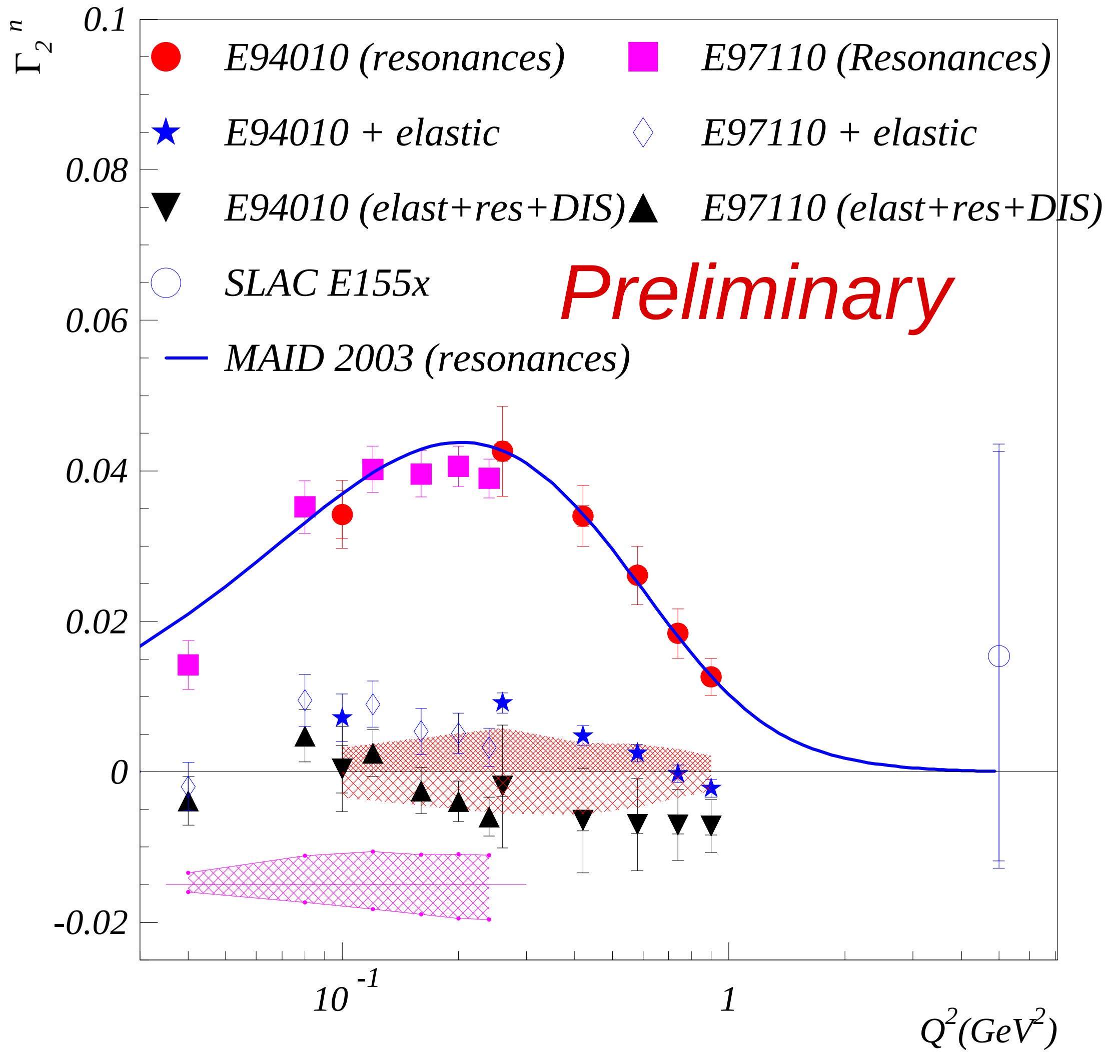
$$I(Q^2) = \int_{\nu_{\mathrm{th}}}^{\infty} \frac{2\sigma_{\mathrm{TT}}}{\nu} d\nu; \quad 2\sigma_{\mathrm{TT}} = \sigma_{1/2}(\nu, Q^2) - \sigma_{3/2}(\nu, Q^2)$$

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

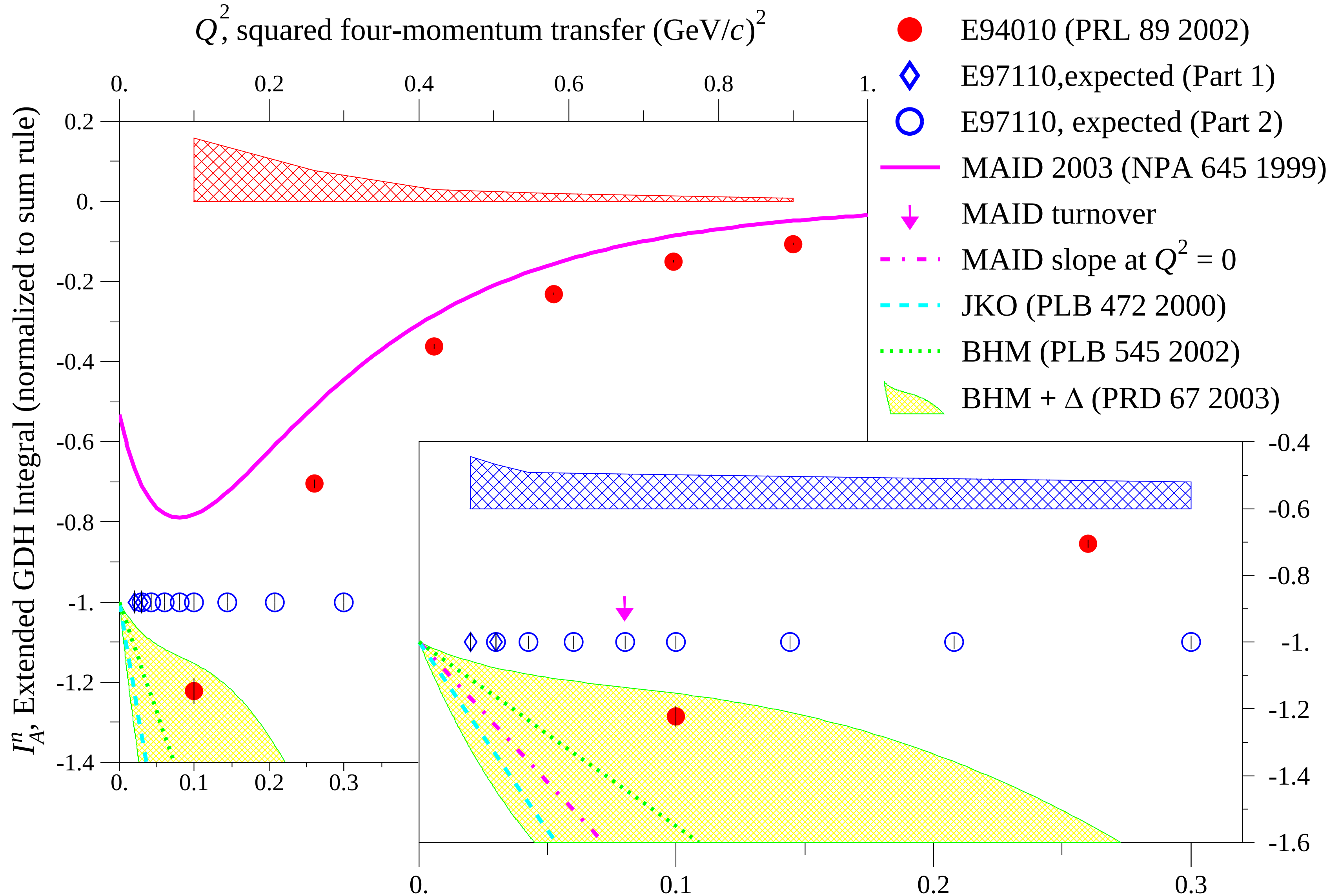
Γ_1^n: First Moment of g_1



Γ_2^n: BC Sum Rule



Expected Neutron Results



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Summary and Conclusion

Generalized GDH:

- 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 neutron moments are available.
- Work on systematics are in progress.
- Expect final neutron results in a few months.
- These data allow us to check χPT at very low Q^2.

The E97-110 Collaboration

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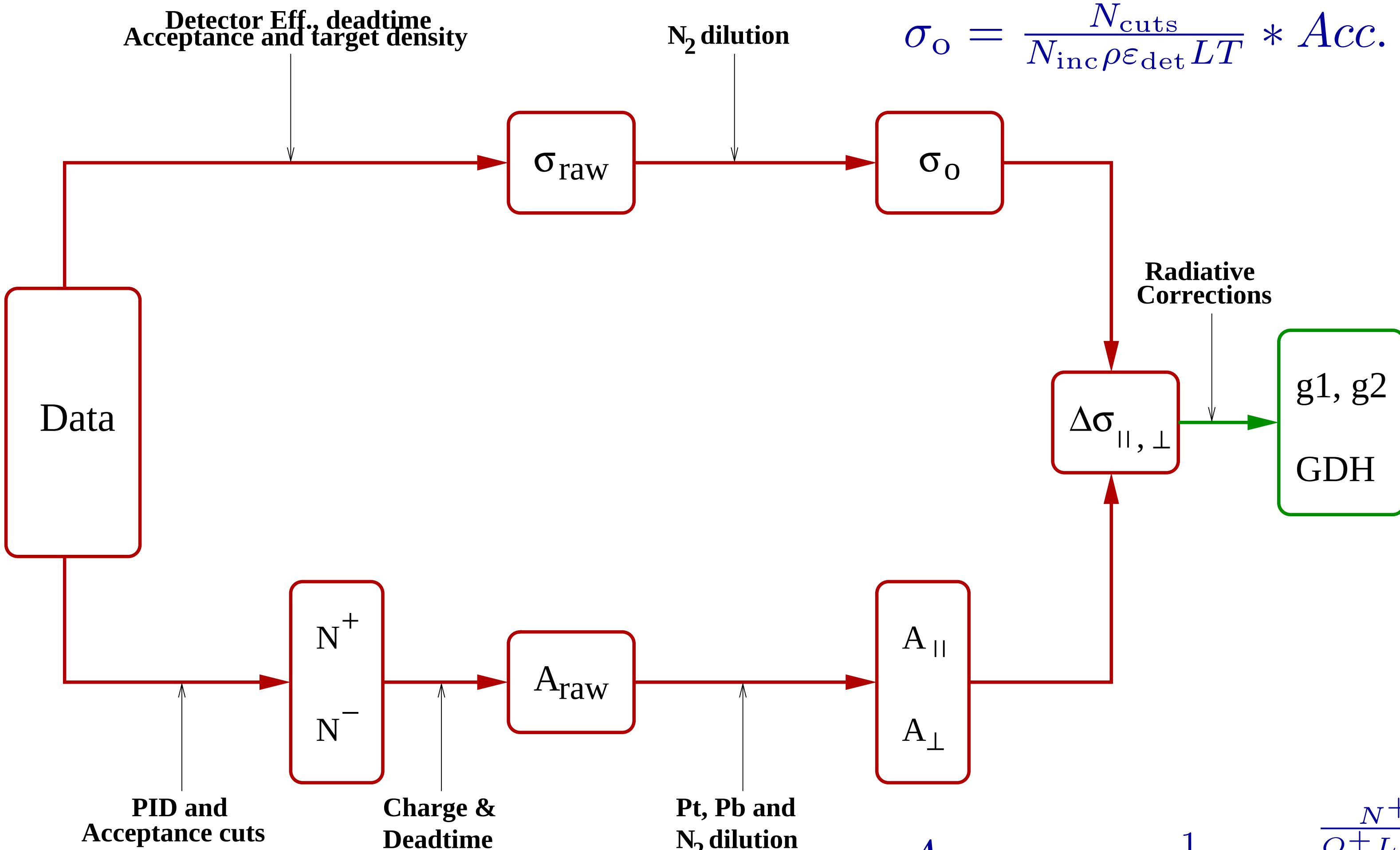
and the Jefferson Lab Hall A Collaboration

Extra Slides

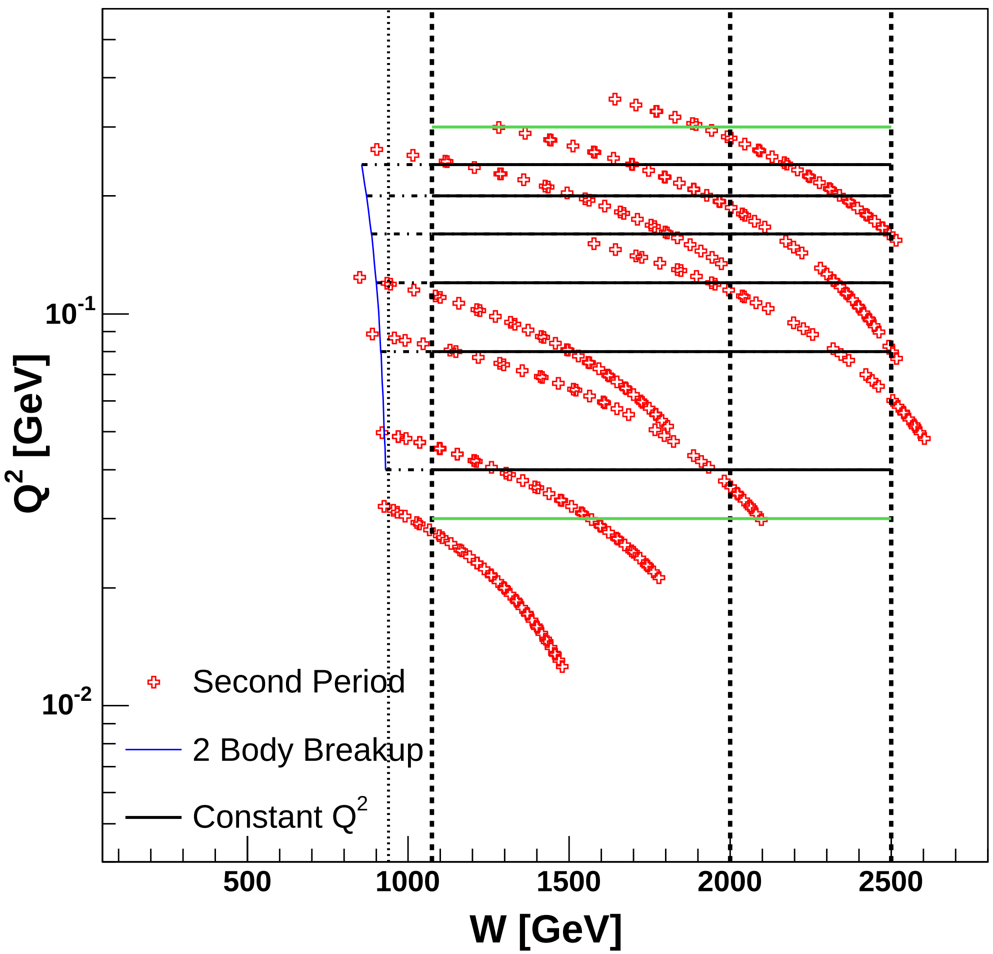
Analysis Procedure

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



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

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%).

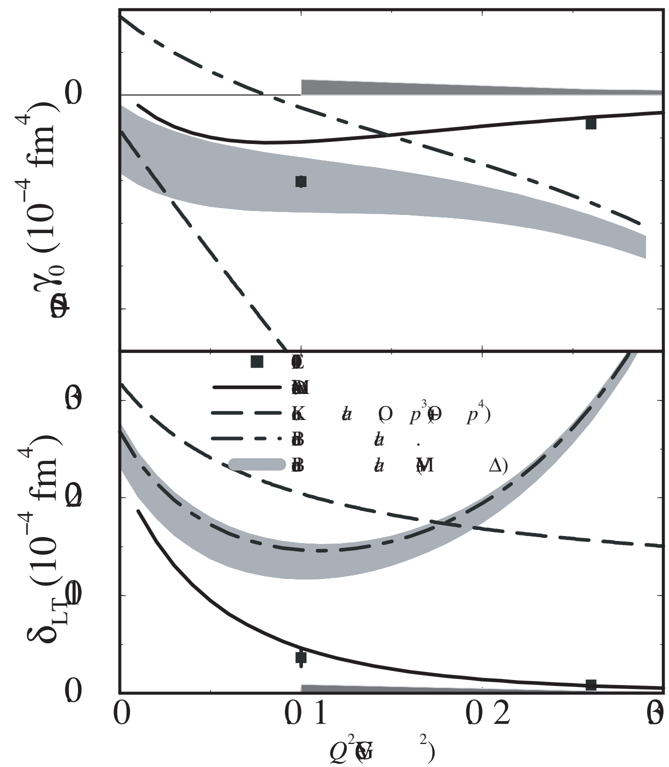
Systematic Uncertainties

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%

Spin Polarizabilities

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

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



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

Inclusive Electron Scattering

Energy transfer:

$$\nu = E - E^{'}$$

4-momentum transfer squared:

$$\vec{q} = \vec{k} - \vec{k'}$$

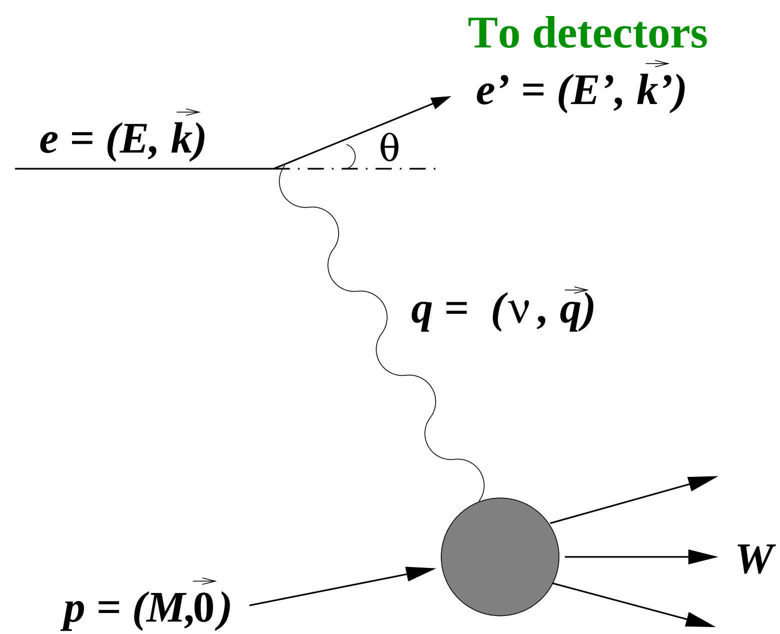
$$Q^2 = -q^2 = 4EE^{'} \sin^2 \frac{\theta}{2}$$

Invariant Mass:

$$W^2 = M^2 + 2M\nu - Q^2$$

Bjorken variable:

$$x = \frac{Q^2}{2M\nu}$$



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.

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

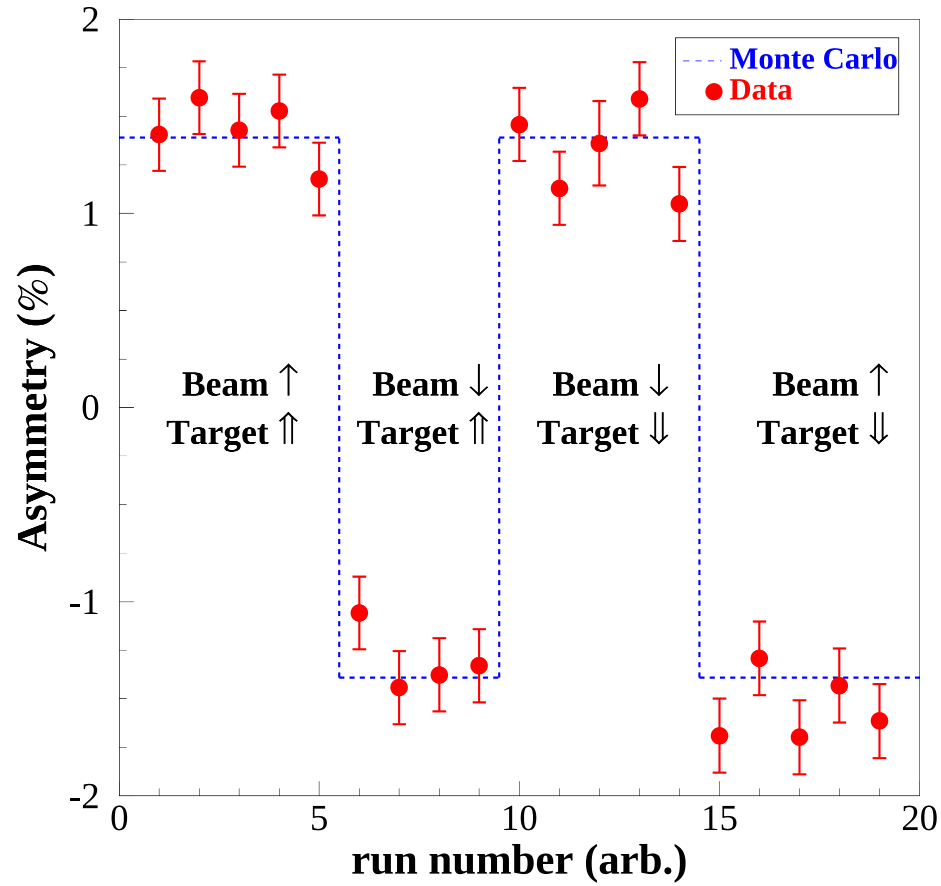
GDH Derivation

Based on fundamental physical arguments

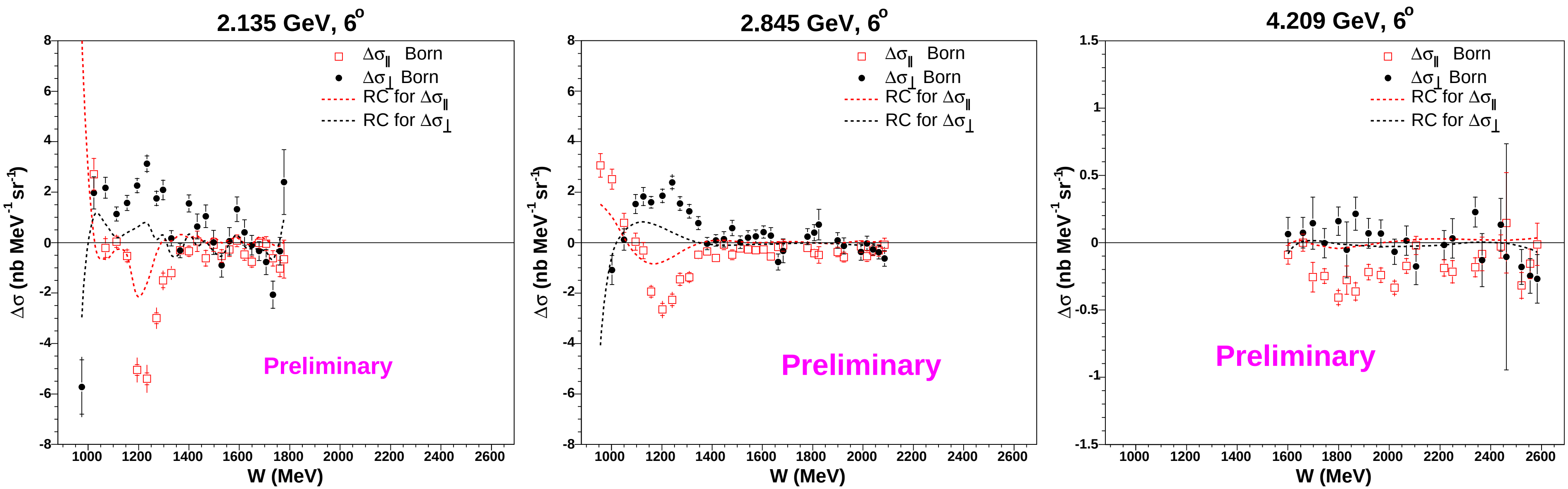
- Lorentz and gauge invariance: low energy theorem, Phys. Rev. **96**, 1428 (1954).
- Unitarity of the S-matrix: optical theorem.
- Causality: dispersion relations for forward compton scattering.

^{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



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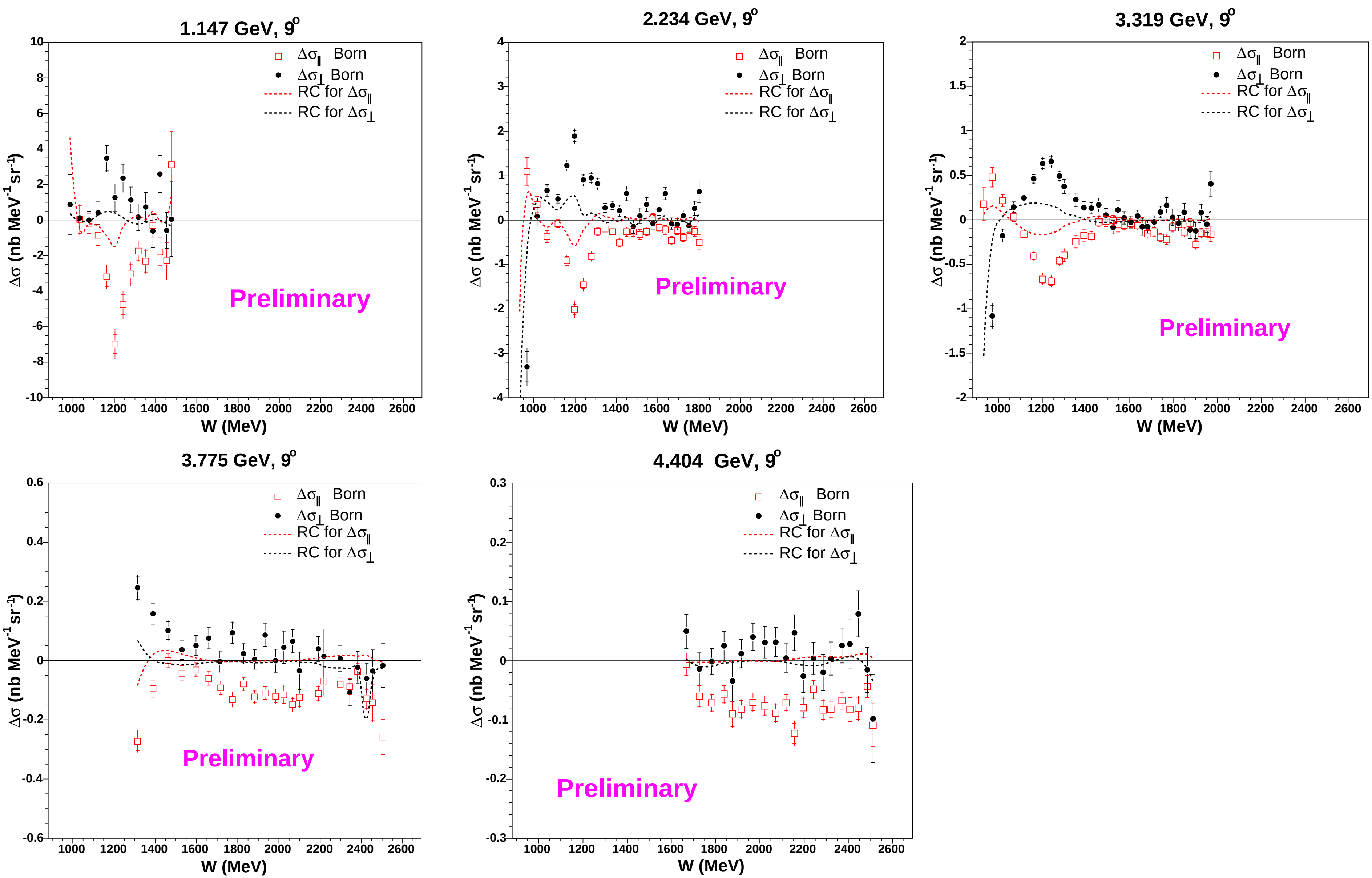
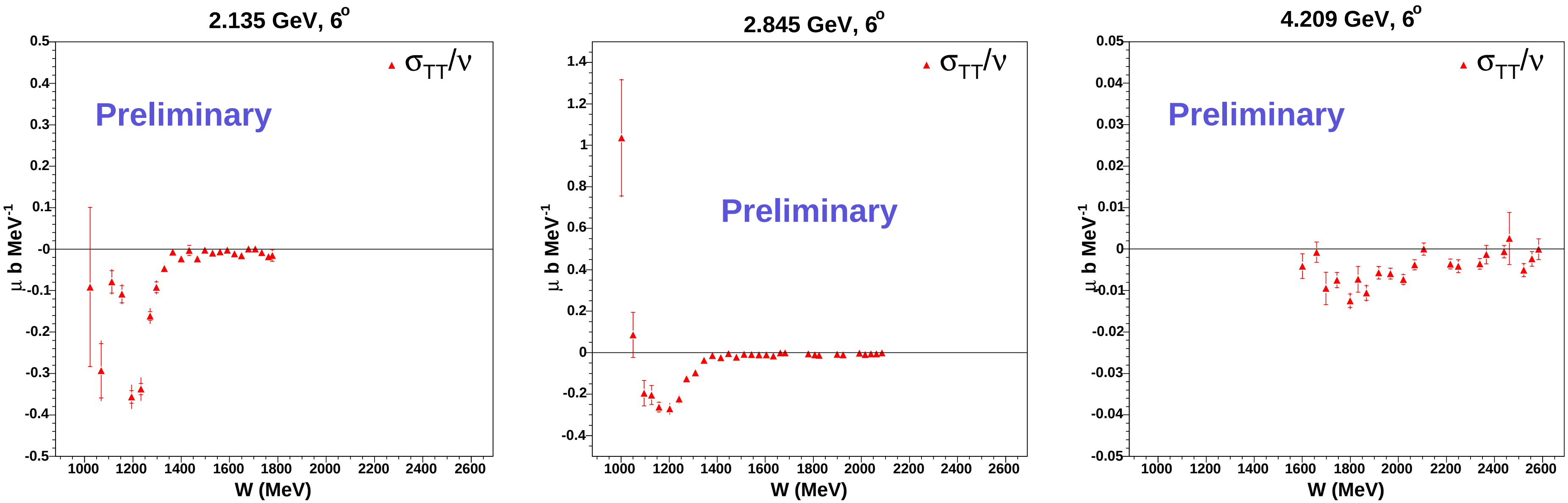


The GDH Integrand: σ_{TT}



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

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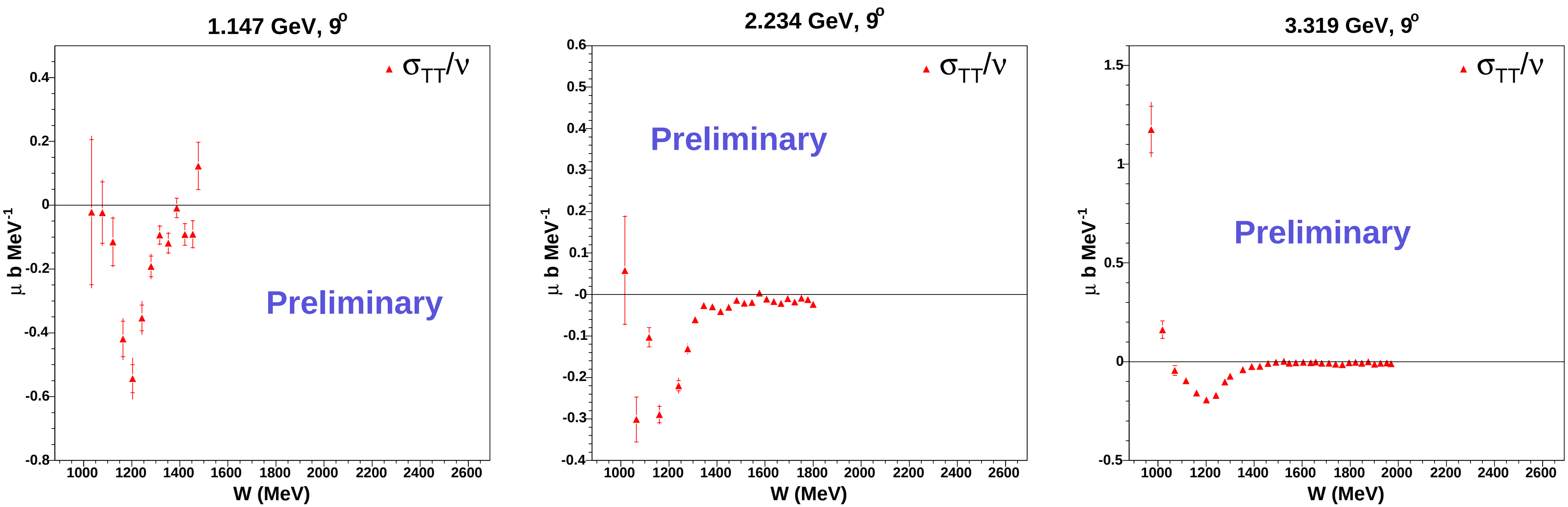
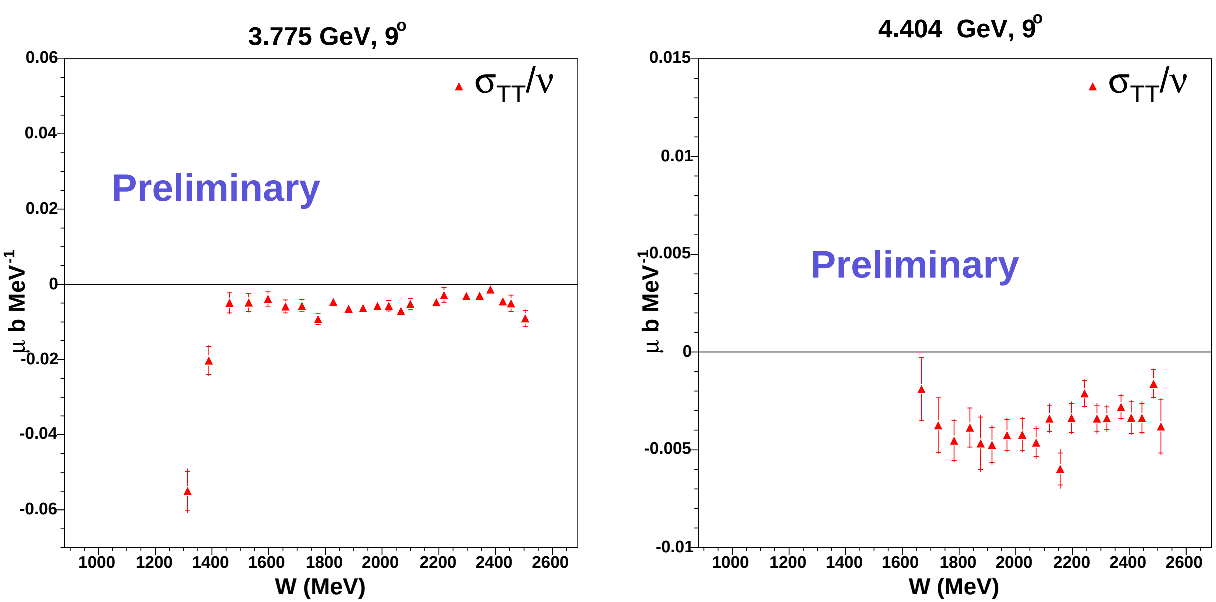
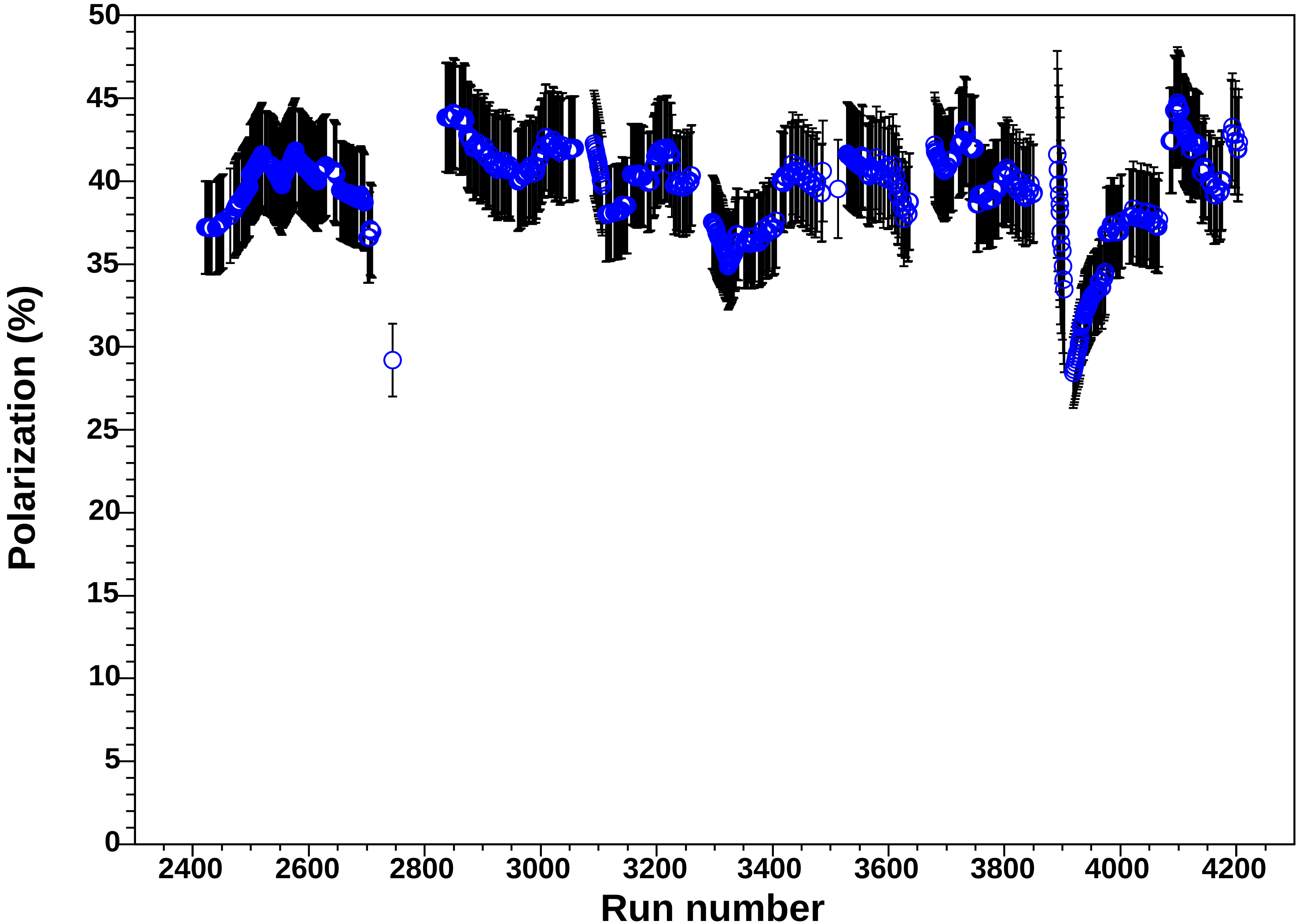


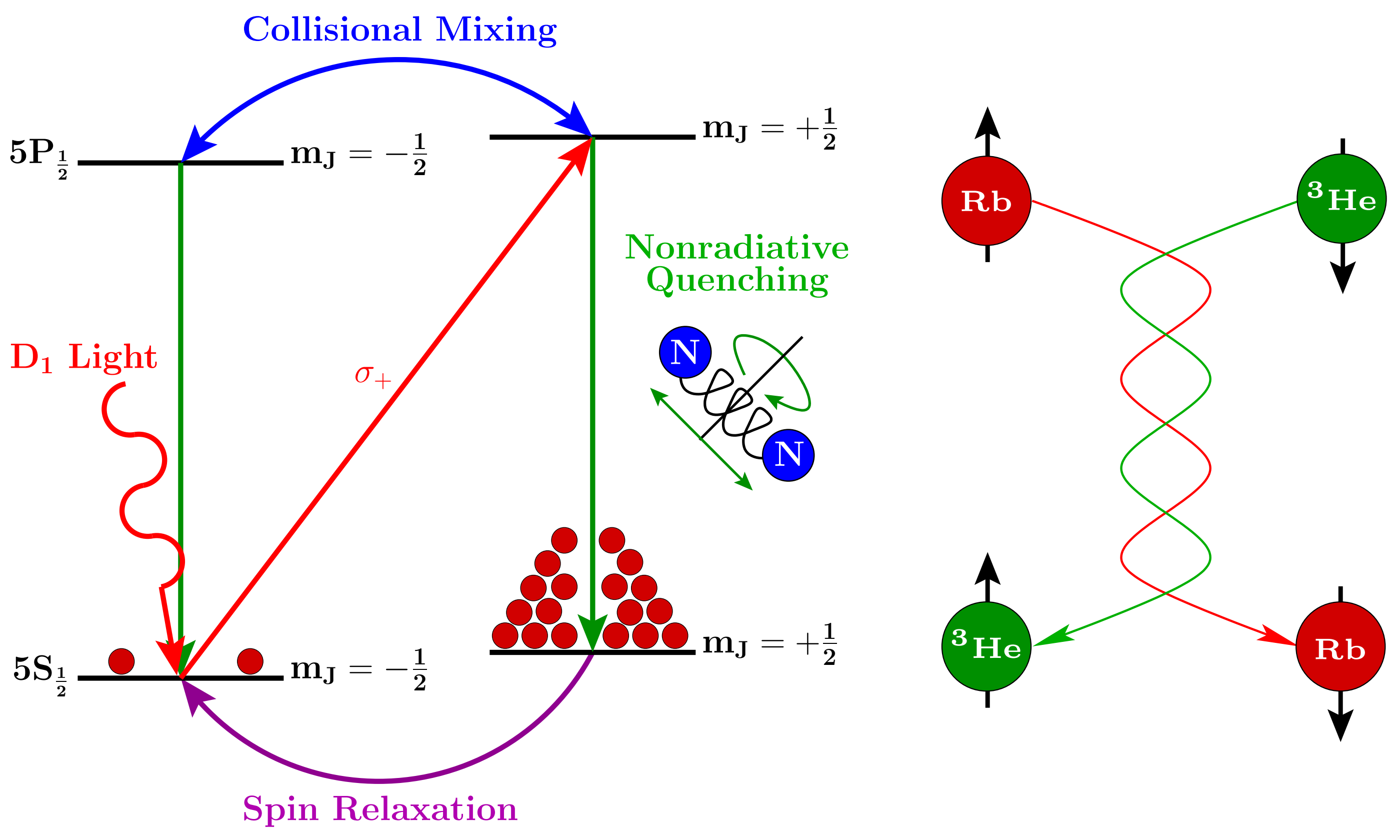


$$I(Q^2) = \int_{\nu_{\mathrm{th}}}^{\infty} \frac{2\sigma_{\mathrm{TT}}}{\nu} d\nu$$

Preliminary Target Polarization



Spin Exchange Optical Pumping



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