MEASUREMENTS OF PROTON AND DEUTERON SPIN STRUCTURE AT CLAS

Keith Griffioen
College of William & Mary
Representing the CLAS Collaboration

4rd Circum-Pan-Pacific Symposium on
High Energy Spin Physics
Seattle, Washington
4–7 August 2003

- Asymmetries A_1 and structure functions g_1
- Integrals $\Gamma_1^{p,d}$
- Real photon GDH measurements
- Single spin asymmetries

The CLAS Collaboration

- ≈ 210 physicists
- 39 institutions
- Arizona State University, CEA-Saclay Service de Physique Nucléaire, University of California at Los Angeles, Carnegie Mellon University, Catholic University of America, Christopher Newport University, University of Connecticut, Duke University, Edinburgh University, Florida International University, Florida State University, The George Washington University, University of Glasgow, INFN Laboratori Nazionali di Frascatti, INFN Sezione de Genova, Institut de Physique Nucléaire ORSAY, Universität Bonn, Institute of Theoretical and Experimental Physics Moscow, James Madison University, Kungpook National University, Massachusetts Institute of Technology, University of Massachusetts, University of New Hampshire, Norfolk State University, Ohio University, Old Dominion University, University of Pittsburgh, Università Roma Tre, Rensselaer Polytechnic Institute, Rice University, University of Richmond, University of South Carolina, University of Texas at El Paso, Thomas Jefferson National Accelerator Facility, Union College, Virginia Polytechnic Institute and State University, University of Virginia, College of William and Mary, Yerevan Physics Institute

The Experiments (eg1)

- Inclusive Measurements
  - E91-023: $\vec{e}\,\vec{p} \to e'X$ (eg1a: 35%) to PRL
  - E93-009: $\vec{e}\,\vec{d} \to e'X$ (eg1a: 10%) PRC67(03)055204

- Exclusive Measurements
  - E93-036/E94-003: (eg1a: 35%)
    $\vec{e}\,\vec{p} \to e'\pi^+ n$ PRL88(02)082001
    $\vec{e}\,\vec{p} \to e'\pi^0 p$ nuclex0307004
  - Single Spin Asymmetries (SSA)
    $e\,\vec{p} \to e'\pi^+ X$ (target SSA)
    $\vec{e}\,p \to e'\pi^+ X$ (beam SSA)
    $\vec{e}\,p \to e'\pi^+ n$ (exclusive beam SSA) hepex0301005

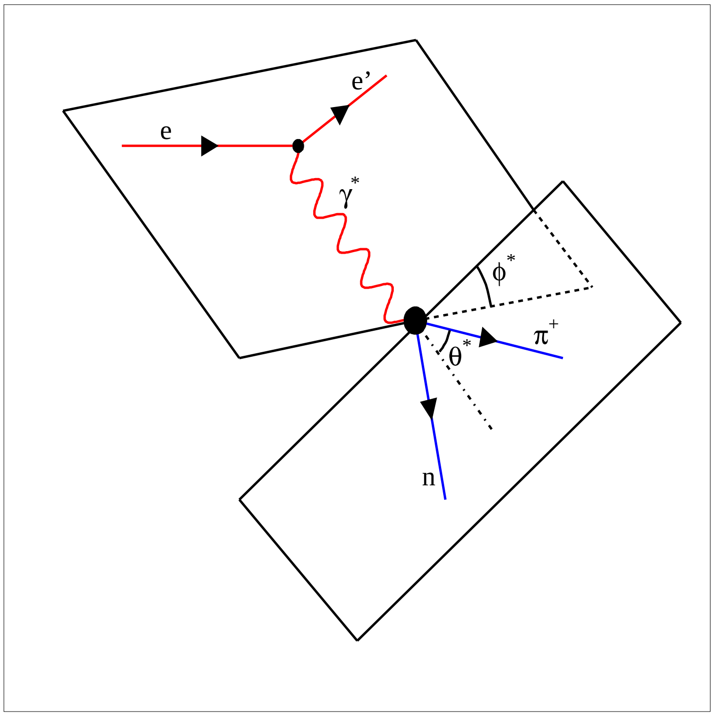
    $\vec{e}\,p \to e'p\gamma$ (DVCS) PRL87(01)182002

- Photoabsorption
  - $\sigma_{3/2} - \sigma_{1/2}$:
    $\vec{\gamma}\,\vec{p} \to X$

- First run period (eg1a): Fall 1998
  - 2.5 and 4.2 GeV beams
  - $0.1 < Q^2 < 2.7$ GeV^2, $W < 2.5$ GeV

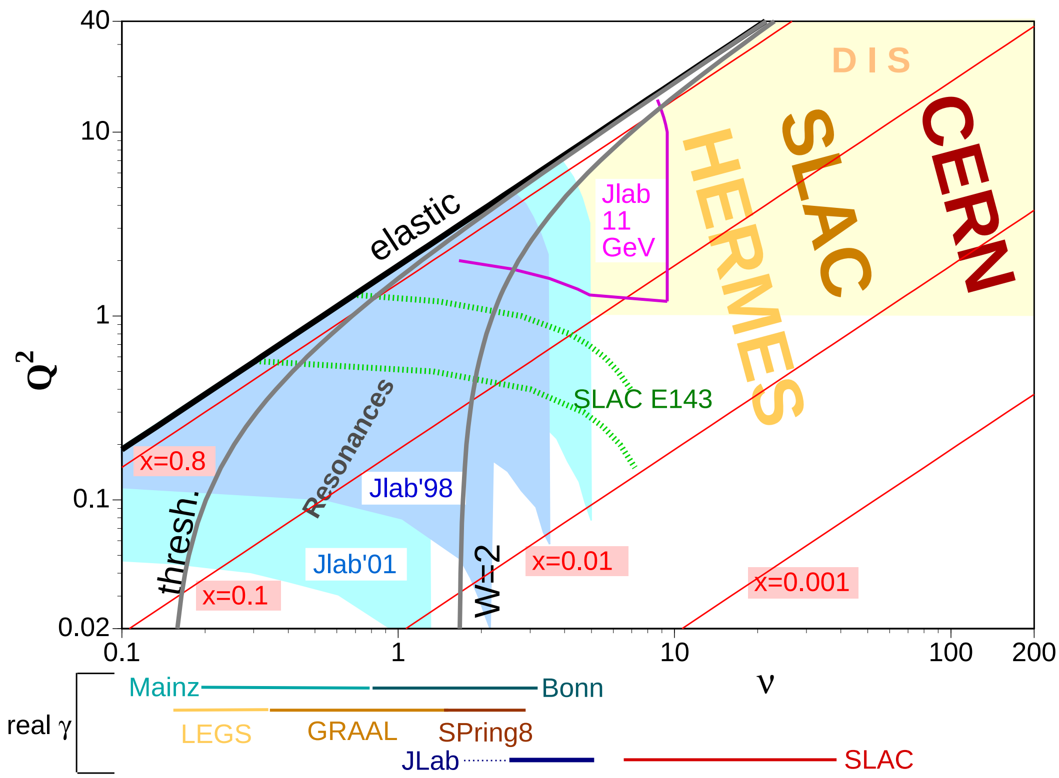
- Second run period (eg1b): Fall/Winter 2000/2001
  - 1.6, 2.5, 4.2 and 5.7 GeV beams
  - $0.05 < Q^2 < 5$ GeV^2, $W < 3$ GeV

CLAS Kinematics



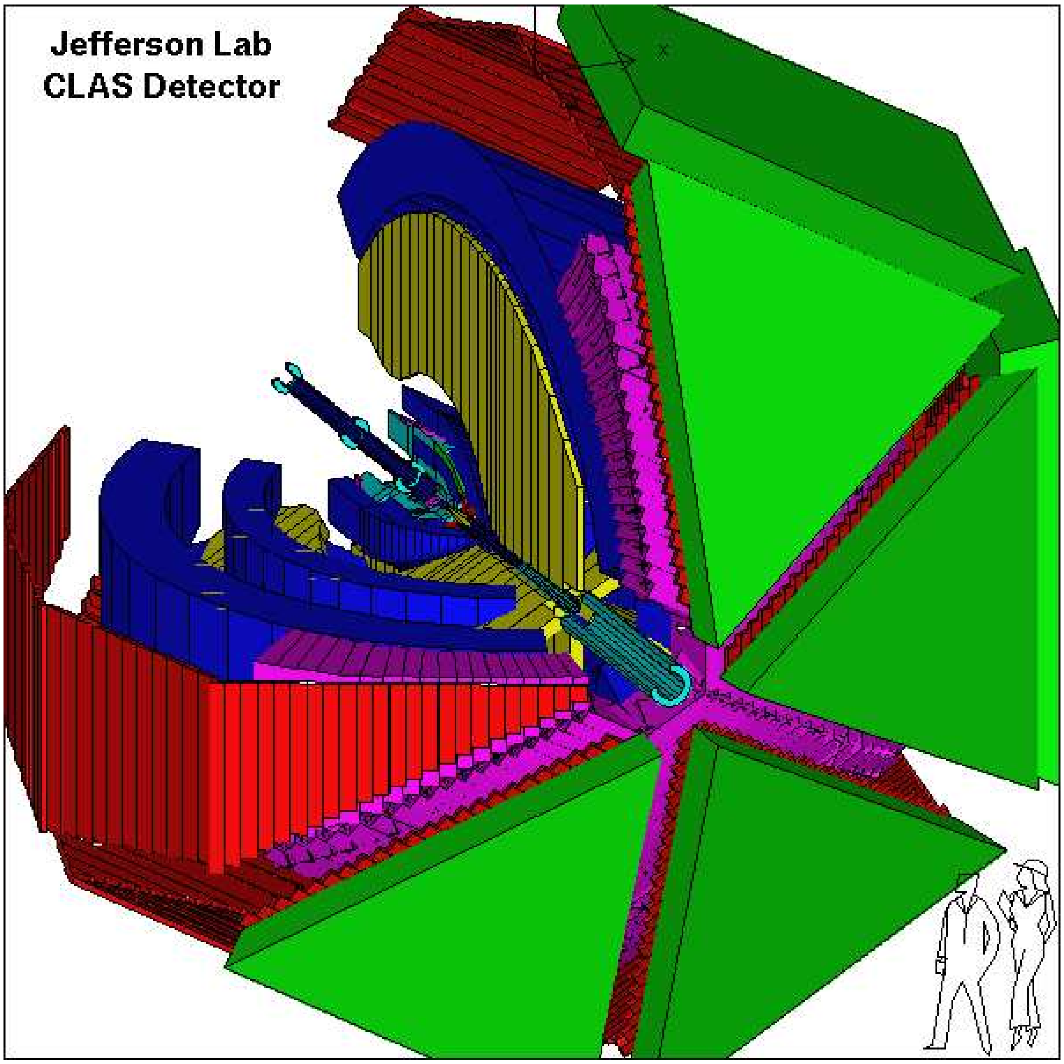
- Electron scattering angle θ
- Nucleon mass M
- Incident (E) and scattered (E') electron energies
- Energy transfer $\nu = E - E'$
- Bjorken $x = Q^2/2M\nu$; invariant mass W
- Azimuthal pion angle ϕ^*
- Polar pion angle θ^* (in lab or CM frames)

Kinematic Coverage



- $Q^2 = 4EE' \sin^2 \frac{\theta}{2}$, and $\nu = E - E'$.
- Jlab experiments cover the resonance region and reach into the deep-inelastic region.
- CLAS data exist for both dark and light blue regions.
- Results presented come from light and dark blue regions.

CLAS Spectrometer



Drift Chambers

Cryostats for Superconducting Magnets

Cherenkov Counters

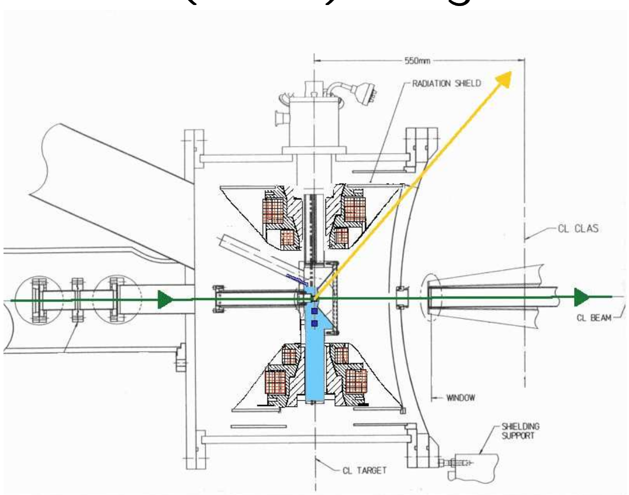
Time-of-Flight Counters

Sampling Calorimeter

CLAS Polarized Target

Dynamic Nuclear Polarization

(DNP) NH_3 and ND_3 target



B=5 Tesla

$\frac{dB}{B} \approx 10^{-4}$

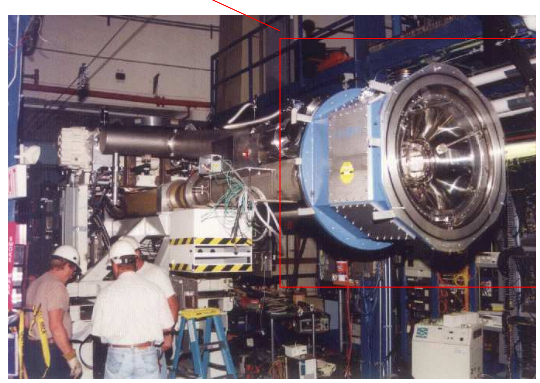
1^oK ^4He cooling bath

^{12}C and ^{15}N targets

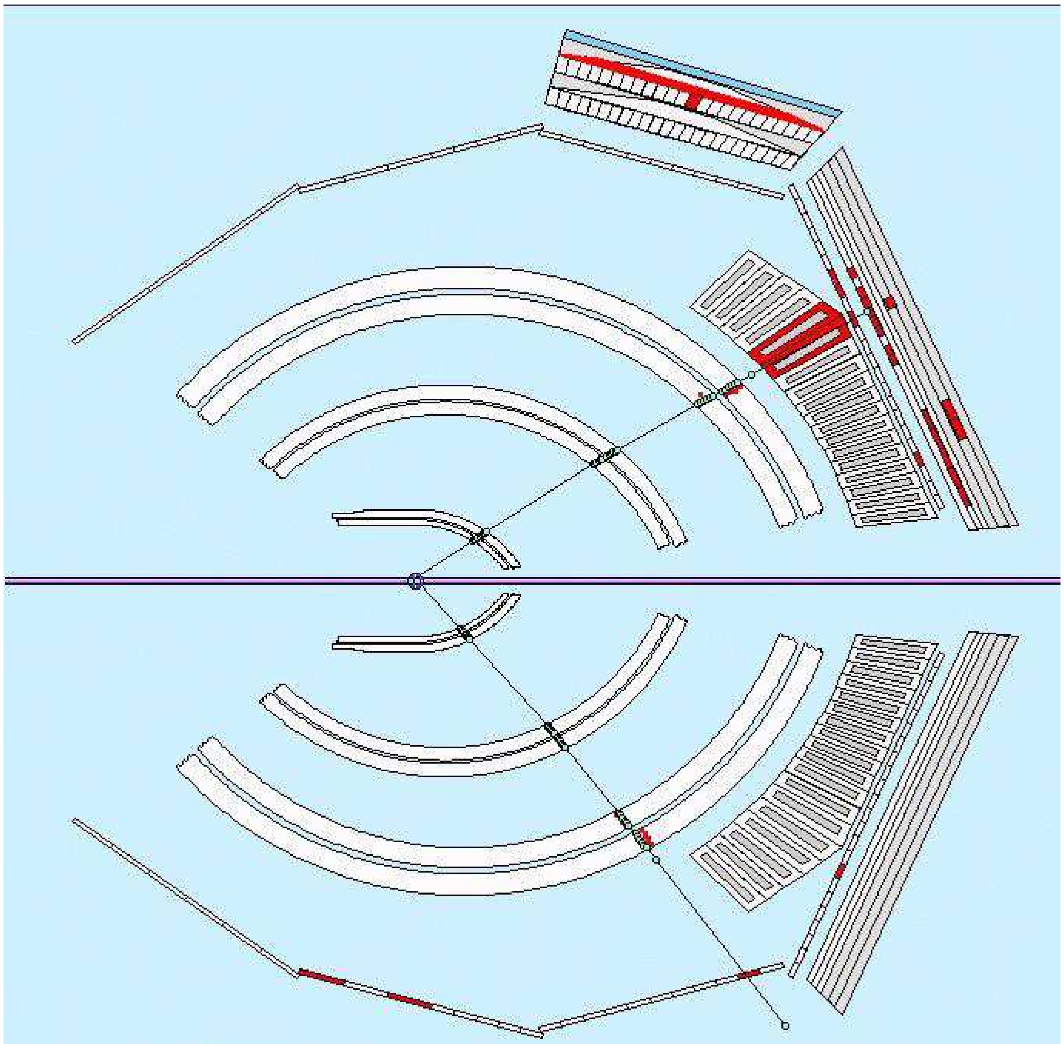
$P_{NH_3} \approx 75 \rightarrow 85\%$

$P_{ND_3} \approx 25 \rightarrow 35\%$

$\frac{\delta(P_b \cdot P_t)}{P_b \cdot P_t} \approx 3\% for NH_3$



Representative CLAS Event



- Upper track bends inward (electron)
- Lower track bends outward (π^+)

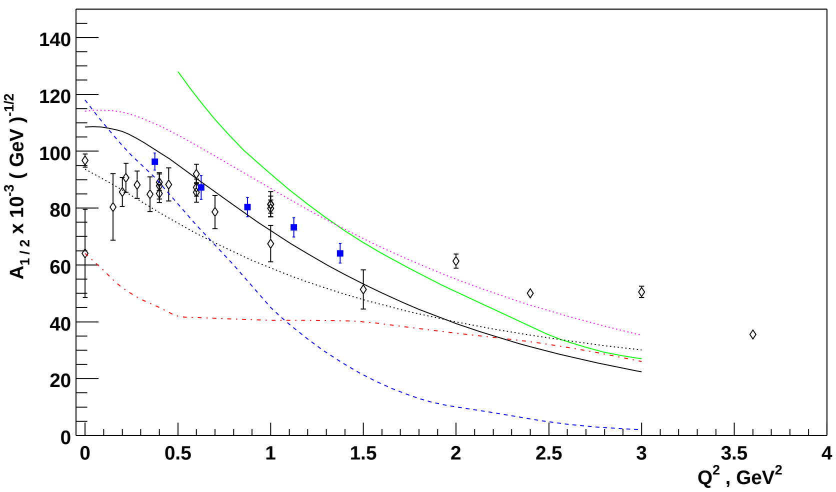
Spin Asymmetries

- Cross section:
  - $\sigma = \sigma_0 + P_b\sigma_b + P_t\sigma_t + P_bP_t\sigma_{bt}$
  - σ_0 is the unpolarized cross section
  - P_b (P_t) is the beam (target) polarization
  - σ_b (σ_t) is the beam (target) single spin cross section
  - σ_{bt} is the double spin cross section
- Asymmetry:
  - $A_{bt} = \sigma_{bt}/\sigma_0$ is the double spin asymmetry
  - $A_b = \sigma_b/\sigma_0$ is the beam single spin asymmetry
  - $A_{bt} = \frac{1}{fP_bP_t}\frac{N^{\uparrow\downarrow}+N^{\downarrow\uparrow}-N^{\uparrow\uparrow}-N^{\downarrow\downarrow}}{N^{\uparrow\downarrow}+N^{\downarrow\uparrow}+N^{\uparrow\uparrow}+N^{\downarrow\downarrow}}$
  - $A_b = \frac{1}{fP_b}\frac{N^{\uparrow\downarrow}-N^{\downarrow\uparrow}+N^{\uparrow\uparrow}-N^{\downarrow\downarrow}}{N^{\uparrow\downarrow}+N^{\downarrow\uparrow}+N^{\uparrow\uparrow}+N^{\downarrow\downarrow}}$
- Inclusive:
  - $\sigma_b, \sigma_t \approx 0$ (parity violation)
  - A_{bt} can be either $A_{||}$ or $A_{\perp} \rightarrow g_1$ and g_2
- (Semi)-Exclusive:
  - σ_b, σ_t are sensitive to polarized fragmentation functions, transversity, higher twist, etc.
  - σ_{bt} is sensitive to the isospin structure of the underlying resonances.

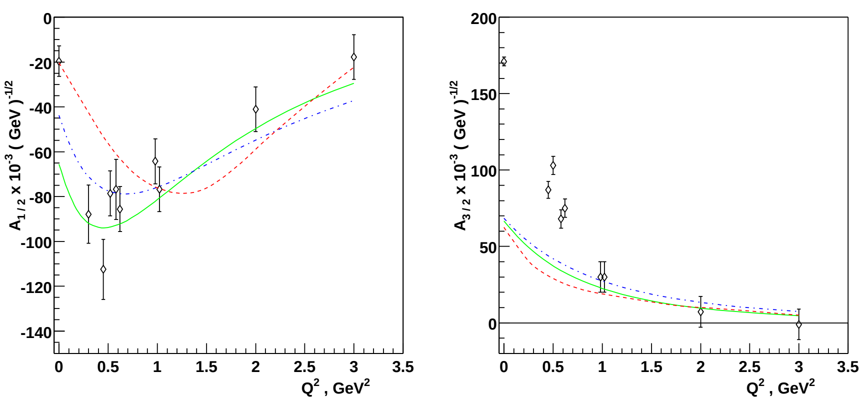
Inclusive Double Spin Asymmetries

- $\sigma_0 = \Gamma_V(\sigma_T + \epsilon\sigma_L)$
- $\sigma_{bt} \rightarrow \Delta\sigma_{||} = 2\Gamma_V D(1+\epsilon R)[\sigma_{TT} + \eta\sigma_{LT}]$
- $\sigma_{bt} \rightarrow \Delta\sigma_{\perp} = 2\Gamma_V d(1+\epsilon R)[\sigma_{LT} - \zeta\sigma_{TT}]$
  $\Gamma_V = \frac{\alpha K E'}{2\pi^2 Q^2 E(1-\epsilon)}$; $1/\epsilon = 1 + 2(1+1/\gamma^2)\tan^2\frac{\theta}{2}$; $\gamma = 2Mx/Q$; $\eta = \epsilon Q/(E - E'\epsilon)$; $\zeta = \eta(1+\epsilon)/2\epsilon$; $D = (1 - E'\epsilon/E)/(1 + \epsilon R)$; $d = D\sqrt{2\epsilon/(1+\epsilon)}$; $N = \frac{4\pi^2\alpha}{KM}$
- $\sigma_L = \sigma^L_{1/2} = NF_L/2x \propto |S_{1/2}|^2$
- $\sigma_T = (\sigma^T_{1/2} + \sigma^T_{3/2})/2 = NF_1$; $\quad R = \sigma_L/\sigma_T$
  $\sigma^T_{1/2} = N(F_1 + g_1 - \gamma^2 g_2) = 2\pi\frac{M}{W}b|A_{1/2}|^2$
  $\sigma^T_{3/2} = N(F_1 - g_1 + \gamma^2 g_2) = 2\pi\frac{M}{W}b|A_{3/2}|^2$; (b: lineshape)
- $\sigma_{LT} = \sigma^{LT}_{1/2} = N\frac{Q}{M\nu}(g_1 + g_2) \propto S^*_{1/2}A_{1/2}$; $\quad A_2 = \sigma_{LT}/\sigma_T$
- $\sigma_{TT} = (\sigma^T_{1/2} - \sigma^T_{3/2})/2 = N(g_1 - \gamma^2 g_2)$ $\quad A_1 = \sigma_{TT}/\sigma_T$
- $A_{||} = D(A_1 + \eta A_2)$; $\quad A_\perp = d(A_2 - \zeta A_1)$
- $A_1 F_1 = g_1 - \gamma^2 g_2$; $\quad A_2 F_1 = \gamma(g_1 + g_2)$
- Integrals:
  - $\Gamma_1 = \int_0^1 g_1(x, Q^2)dx$ (elastic excluded)
  - Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = \frac{1}{6}g_A C_{ns}$
  - Leading twist: $g_2^{WW} = -g_1 + \int_x^1 \frac{g_1(y,Q^2)}{y}dy$
  - GDH Sum Rule: $\Gamma_1(Q^2) = -Q^2\kappa^2/8M^2$ as $Q^2 \rightarrow 0$.

S_{11} and D_{13} Amplitudes



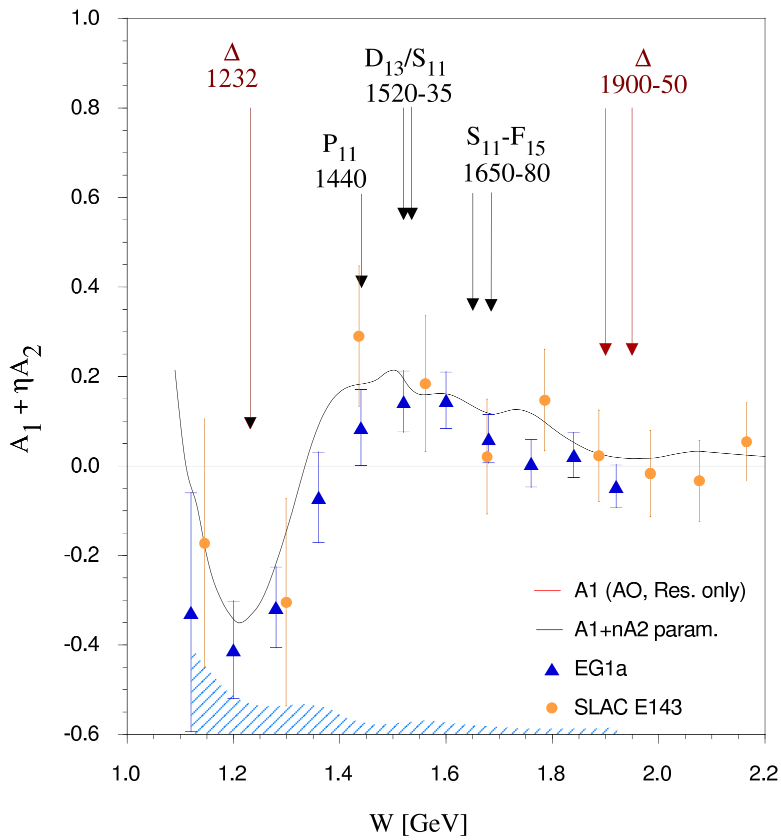
$A_{1/2}$ for the $S_{11}(1535)$ Resonance



$A_{1/2}$ and $A_{3/2}$ for the $D_{13}(1520)$ Resonance

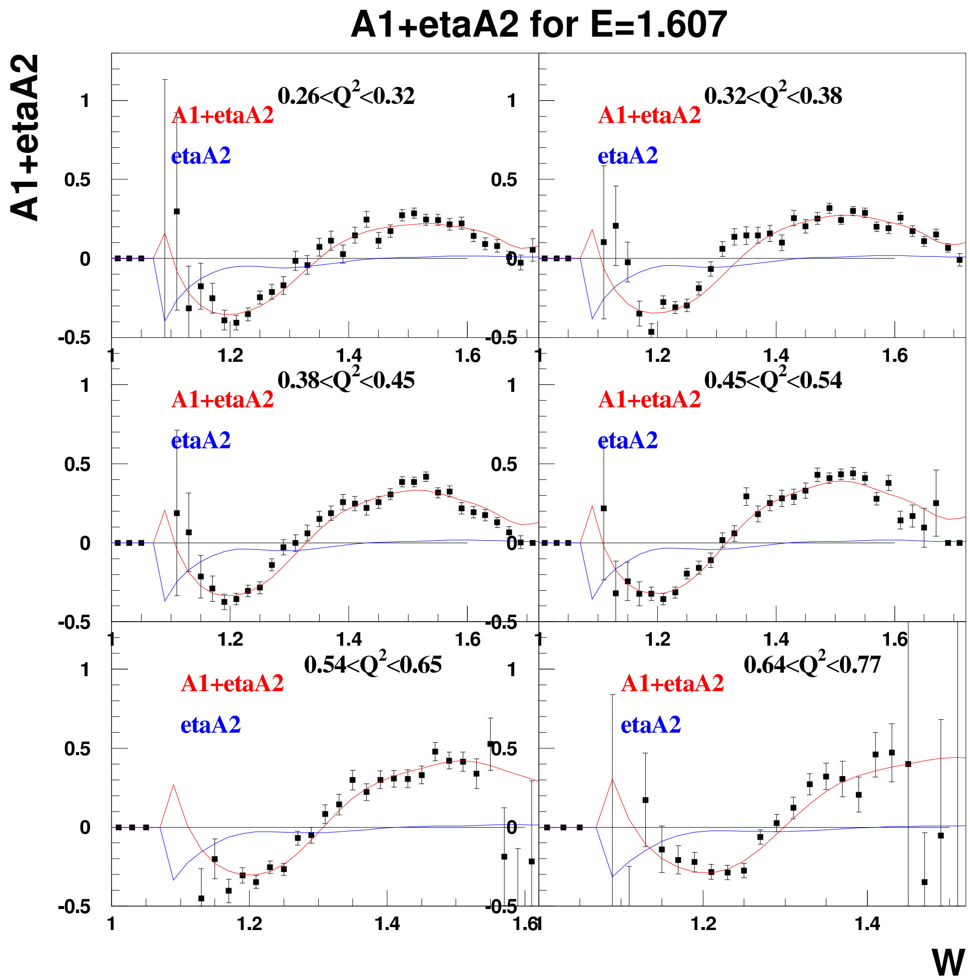
$$A_1 = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2}$$

CLAS (eg1a) $A_1 + \eta A_2$ for d



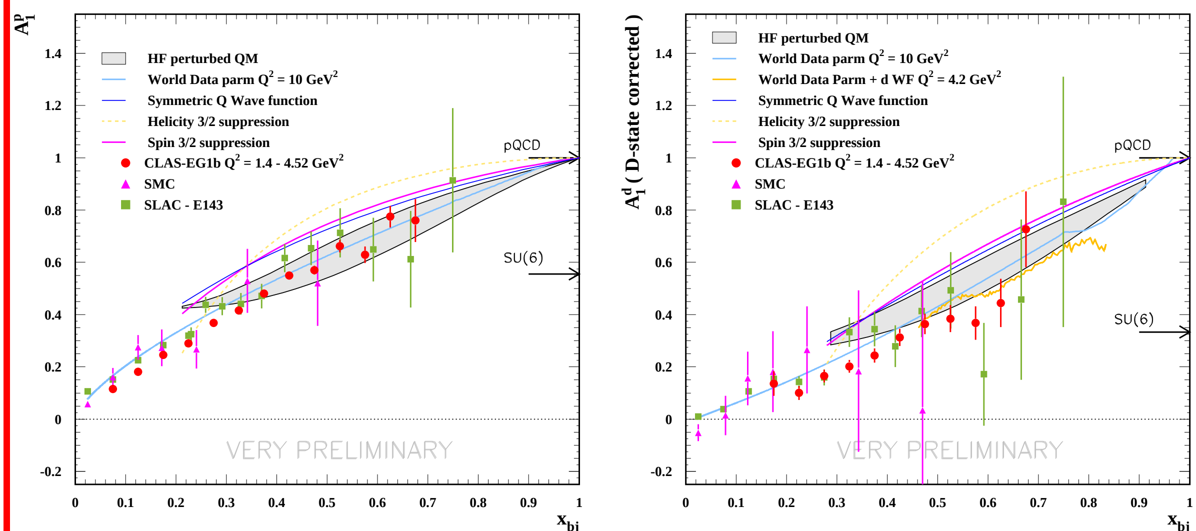
- CLAS can only measure $\parallel$ spin configurations.
- Therefore, $A_1 = \sigma_{TT}/\sigma_T$ cannot be separated from $A_2 = \sigma_{LT}/\sigma_T$.
- η is generally small, so A_1 dominates.

CLAS (eg1b) $A_1 + \eta A_2$ vs. x for p



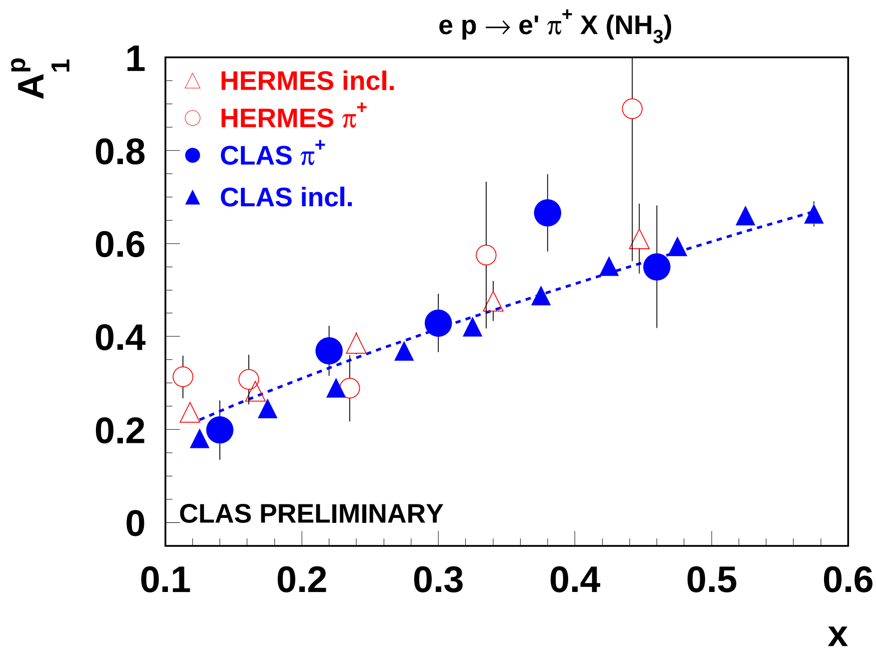
- Red curve: MODELS (eg1 parametrization of world data).
- Blue curve: estimate of ηA_2 from MODELS.
- Plotted versus W, the data show resonance structure at fixed positions.

A_1^p and A_1^d vs. x (eg1b)



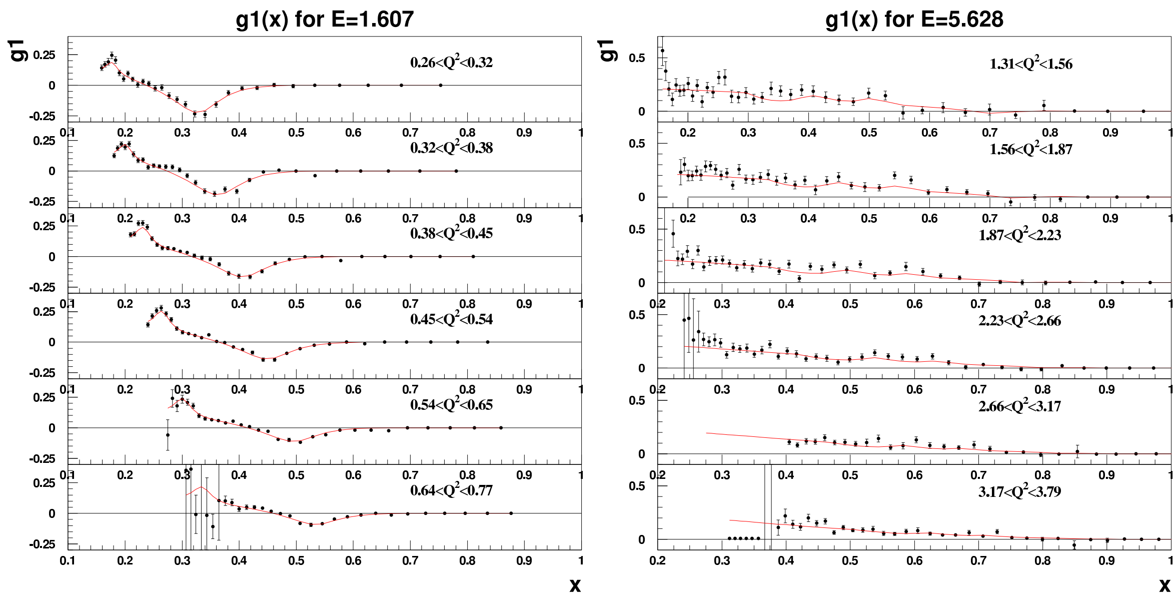
- A_1 varies little with Q^2 in DIS region; therefore, $1.4 < Q^2 < 4.5$ on graph.
- CLAS results complement Hall A results for A_1^n at $x = 0.33, 0.47$ and 0.60
- Shaded region: Isgur, PRD59(99)034013, Hyperfine-Perturbed Quark Model.
- Other theoretical curves: Close and Melnitchouk, hepph0302013.

A_1^p versus x from Semi-Inclusive Data



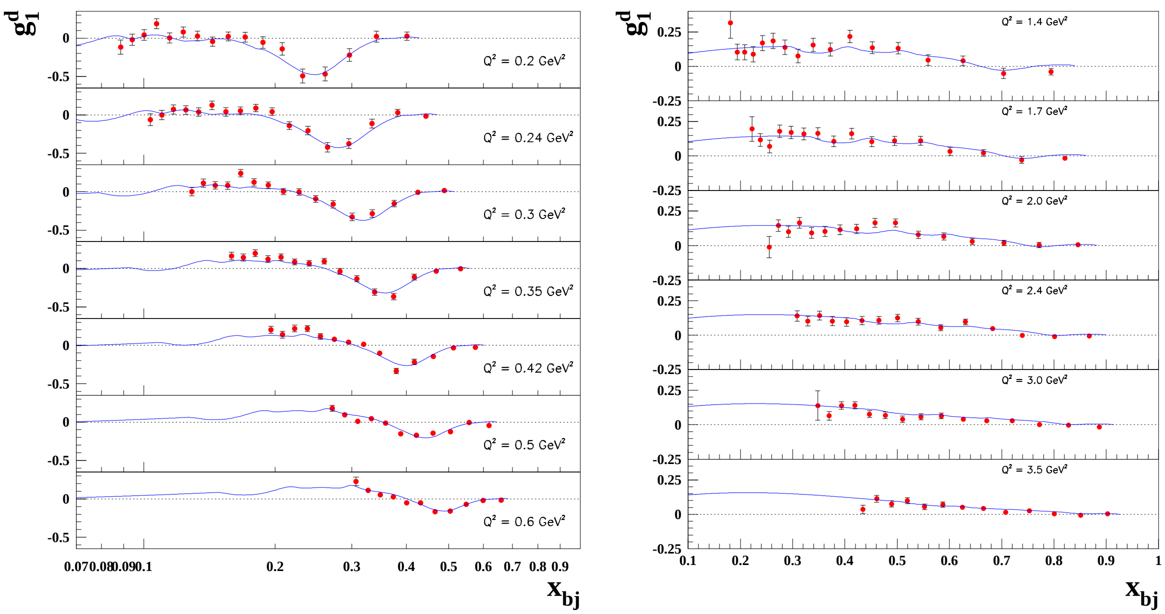
- Target limits π acceptance to $\theta < 50^\circ$ and $75^\circ < \theta < 105^\circ$.
- $\vec{e}\vec{p} \to e'\pi^+X$
- $W^2 > 4$, $Q^2 > 1$, $y < 0.85$ (reduce rad.cor.), $0.5 < z < 0.8$ (suppress target fragmentation events).
- $A_1 \approx g_1/F_1 = \frac{\sum_i \Delta q_i(x,Q^2) \int_{z_{\min}}^{z_{\max}} dz D_i^h(z,Q^2)}{\sum_i q_i(x,Q^2) \int_{z_{\min}}^{z_{\max}} dz D_i^h(z,Q^2)}$
- Results are in reasonable agreement with inclusive extractions of A_1.

CLAS (eg1b) g_1^p vs. x



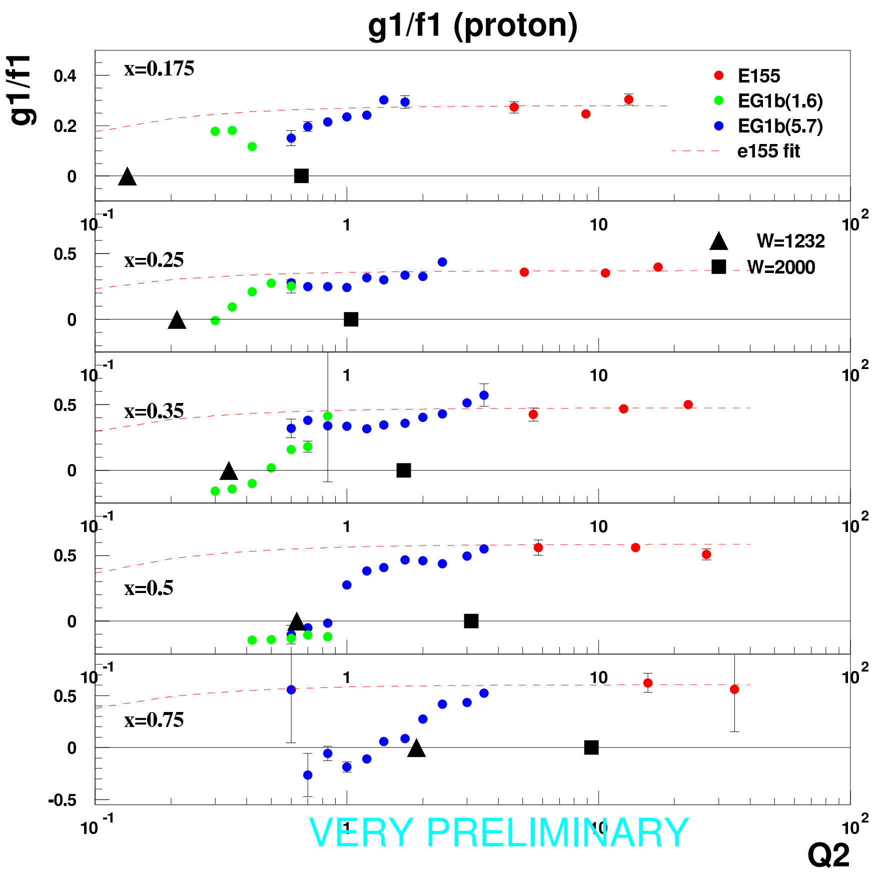
- Representative CLAS data.
- The Δ drives the 1.6 GeV data negative.
- For the 5.6 GeV data, g_1 is positive.
- The eg1b data cover a wider kinematic range with significantly better statistics than the eg1a data now being published.

CLAS (eg1b) g_1^d vs. x



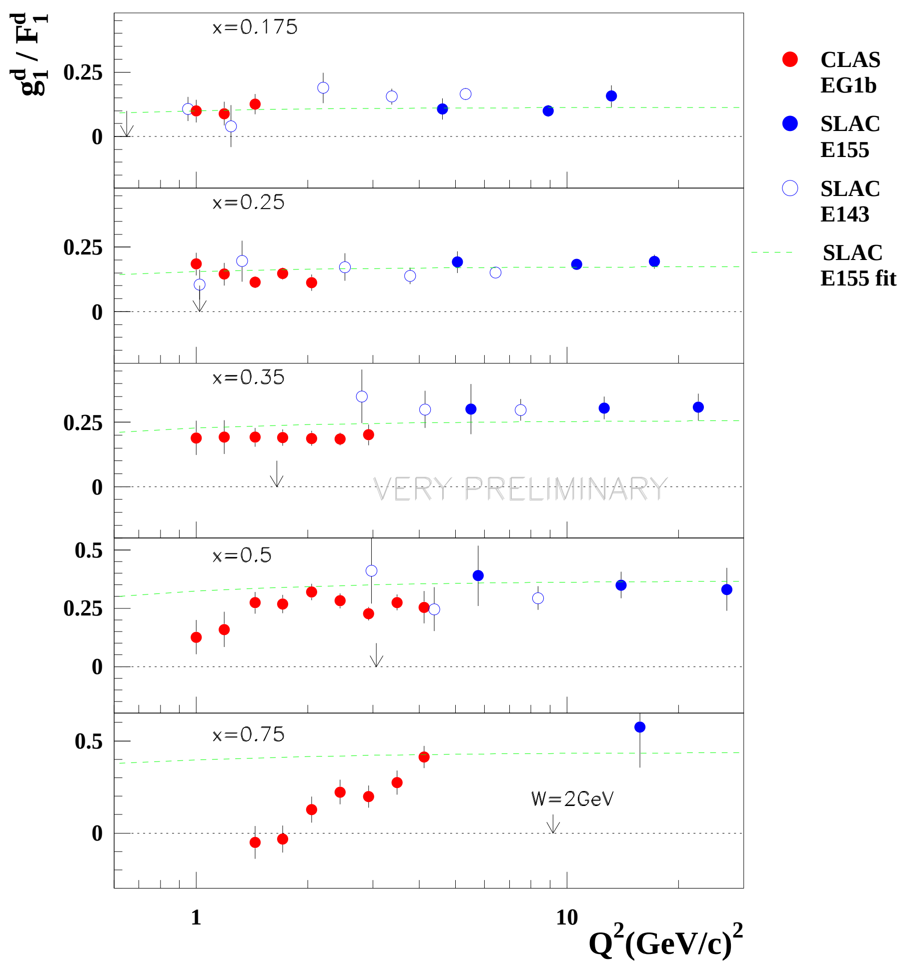
- CLAS took data with both NH_3 and ND_3 targets.
- The deuteron data show the same negative g_1 for the Δ, which disappears at higher Q^2.
- Curve is eg1 MODELS: DIS fits to data; resonance calculations using AO with helicity amplitudes modified to fit data; smooth interpolation between the two regions.

CLAS g_1/F_1 Proton

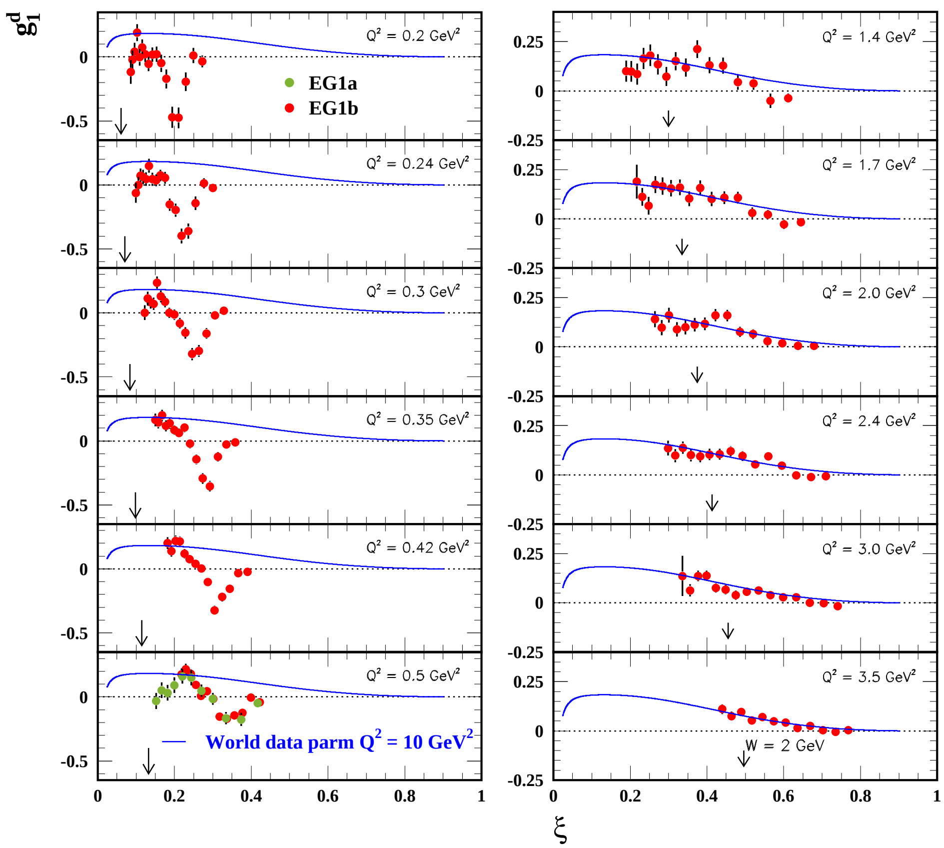


- For DIS, g_1 scales almost like F_1, and g_1/F_1 is nearly flat. [$A_1 \approx g_1/F_1$ at large Q^2.]
- The resonance structure causes g_1 to evolve very differently from F_1 at low Q^2.
- g_1/F_1 goes negative at the Δ resonance.

CLAS g_1/F_1 Deuteron

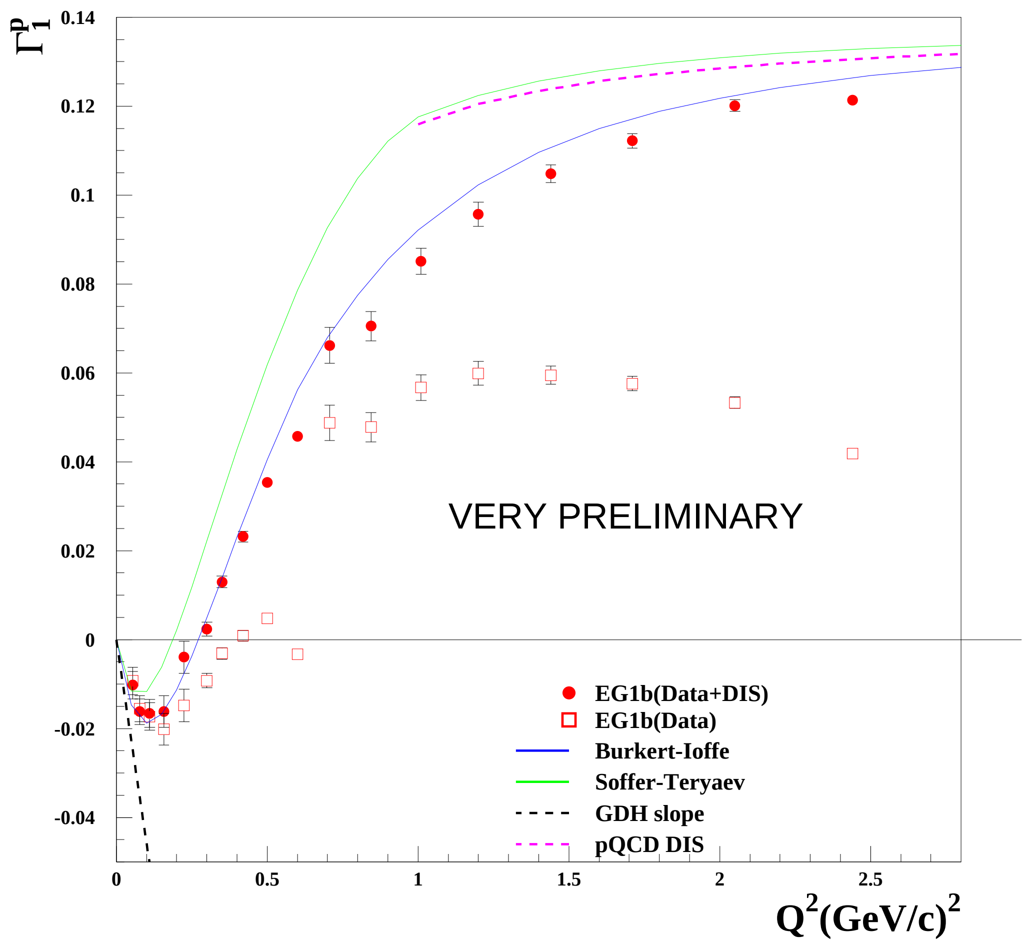


g_1^d versus ξ



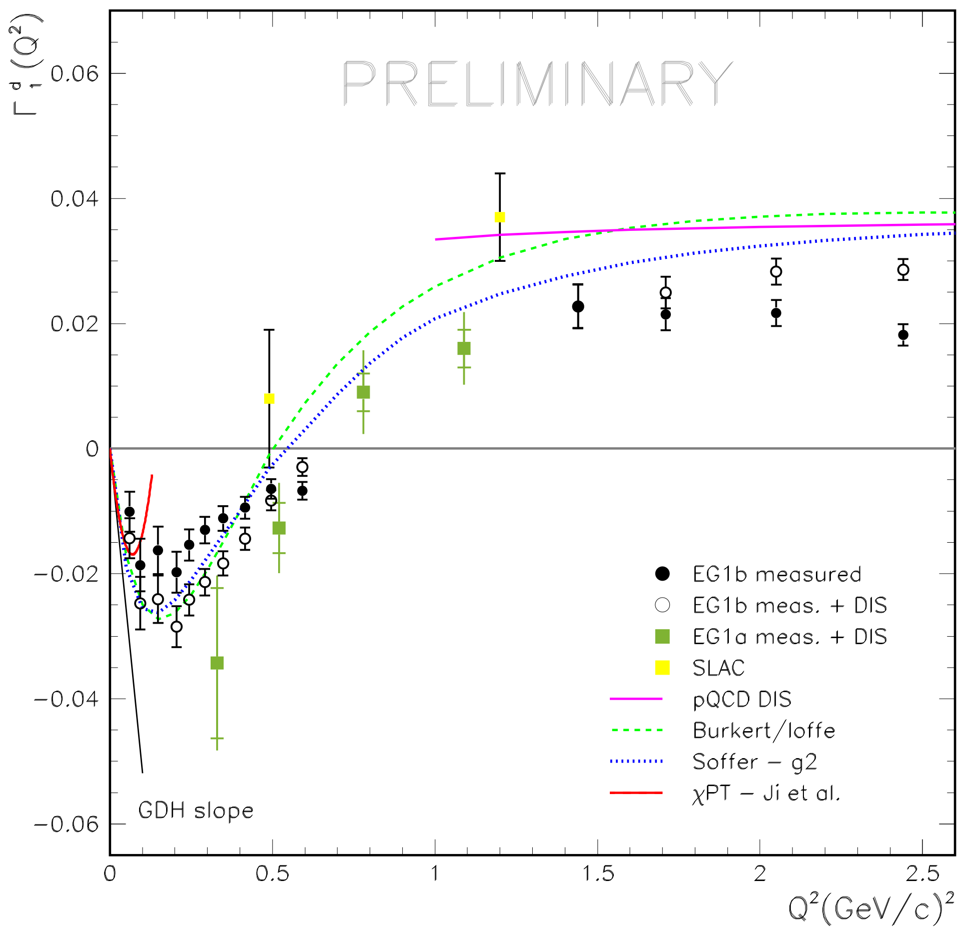
- Nachtmann variable $\xi = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$ (target mass correction)
- The Δ resonance causes g_1 to deviate strongly from the DIS systematics.
- (see talk by Oscar Rondon for details)

Γ_1^p vs. Q^2 (eg1b)



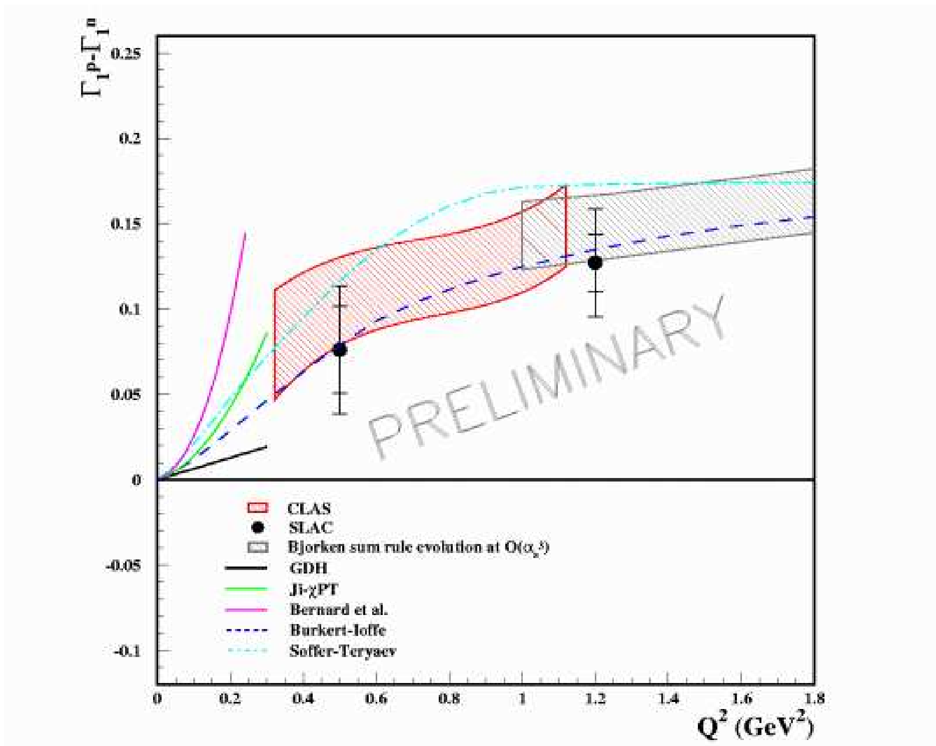
- (see talk by Gail Dodge for details)
- $\Gamma_1 = \int_0^1 g_1(x, Q^2)dx$
- Errors are statistical using only the measured data

Γ_1^d vs. Q^2 (eg1b)



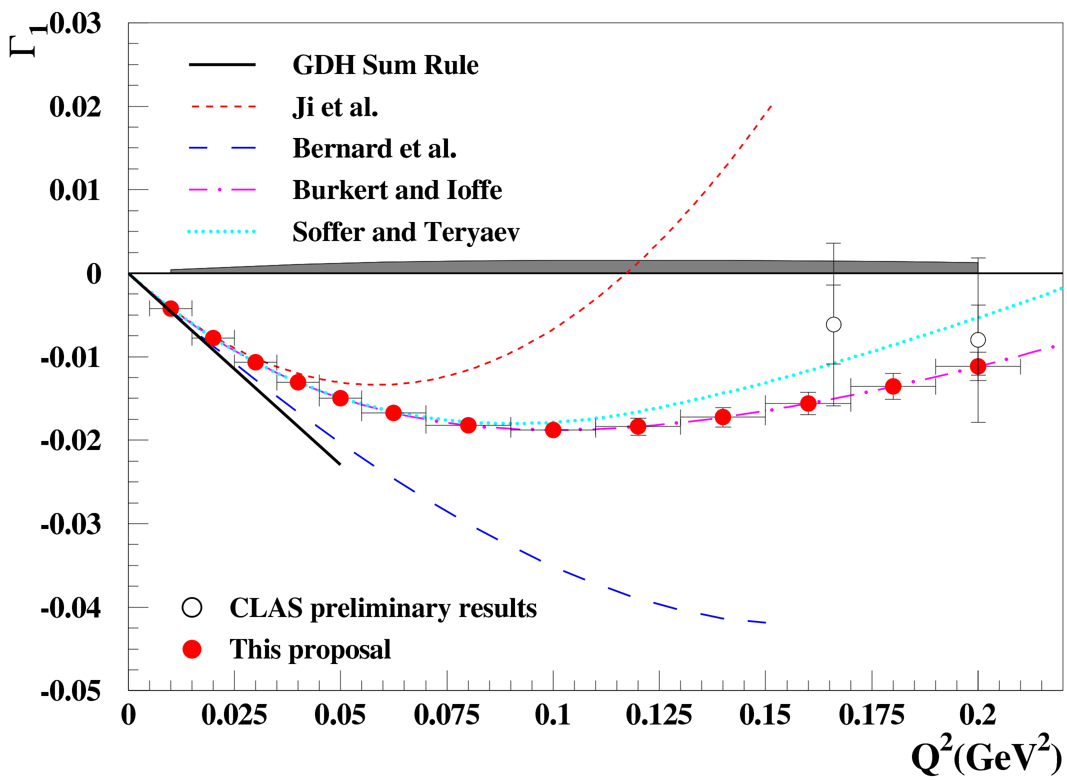
- First precise deuteron results for Γ_1^d at $Q^2 < \frac{1}{2}$.

$\Gamma_1^p - \Gamma_1^n$ (eg1a)



- Bjorken Sum Rule: $\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_A C_{\mathrm{ns}}$
- C_{ns} evolves with Q^2.
- At low Q^2 where resonances dominate, the pQCD extrapolation fails.
- More data to come as the analysis progresses.

Future GDH Measurements with CLAS

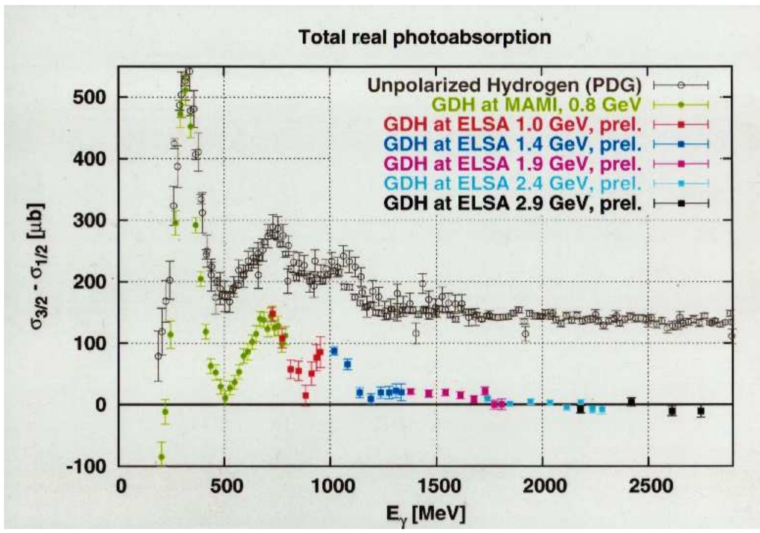


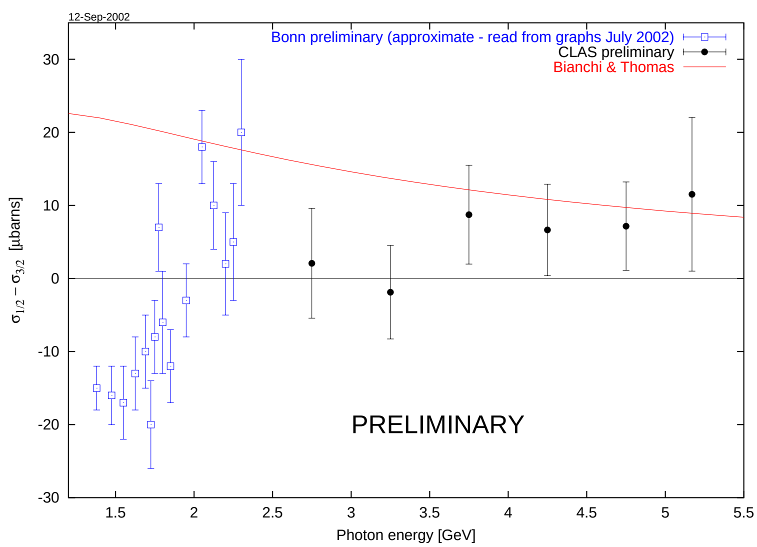
- E03-006: Battaglieri, DeVita and Ripani.
- Requires a new small-angle Cherenkov counter.

Real Photon Measurements

- $I_{\rm GDH} = \int_{\nu_{\rm th}}^{\infty}(\sigma_{1/2} - \sigma_{3/2})\frac{d\nu}{\nu} = -\frac{2\pi^2\alpha\kappa^2}{M^2}$
  - $I_{\rm GDH}(Q^2) = 16\pi^2\alpha\Gamma_1(Q^2)/Q^2$
- 3-day real photon GDH test run during eg1b (Jan. 2001)
- Polarized electrons of E=5.63 GeV; tagged photons of E_γ =2.5–5.3 GeV; 220 M triggers with on polarized $^{15}NH_3$.
- Measured roughly half of $\sigma_{\rm tot}$; correct asymmetries with known $\sigma_{\rm tot}$.
- Much more CLAS data expected in the future using a frozen spin target for E_γ = 3–6 GeV.
- SLAC E159 plans to measure from 5-45 GeV, where there may be a significant negative cross section difference.

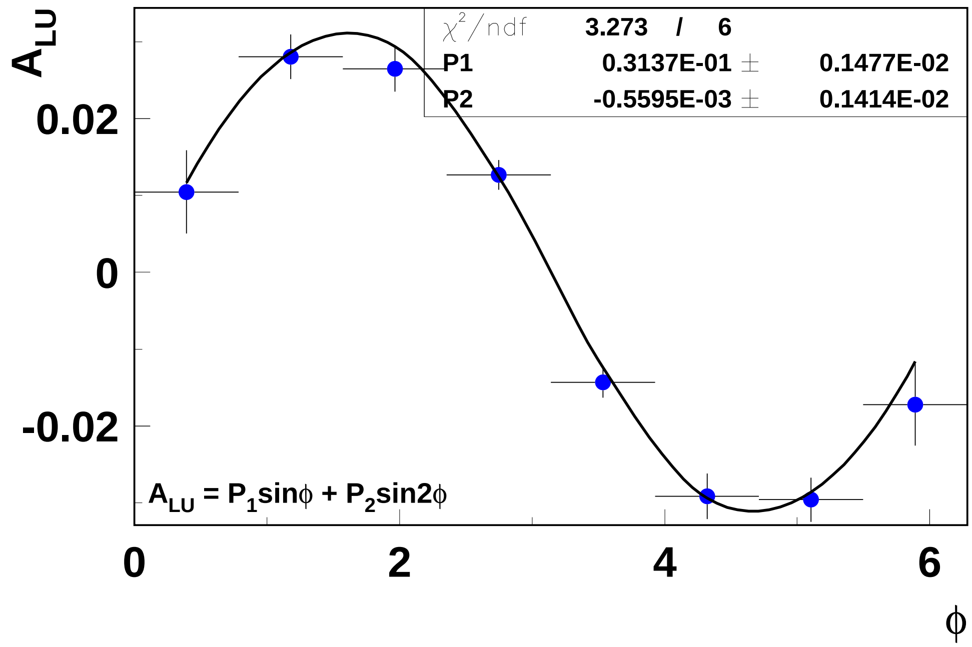
Real Photon Measurements





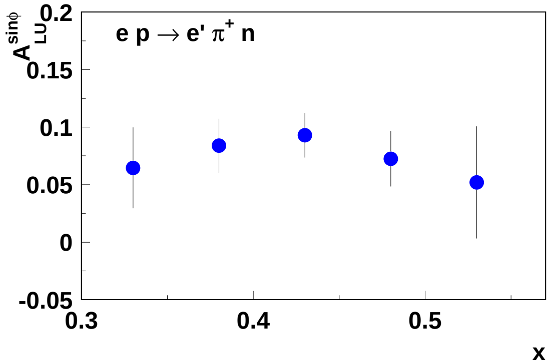
- Lower graph is negative of upper graph.
- $\sigma_{1/2} - \sigma_{3/2}$ changes sign around 2 GeV.

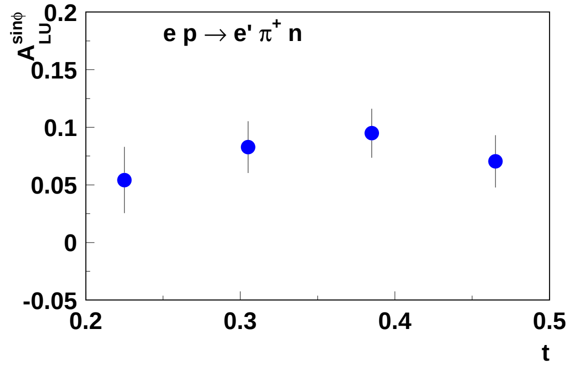
Beam SSA



- Single spin asymmetries can be determined for each hadron azimuthal angle ϕ
- The figure shows a fit to $A_{LU}(\phi) = a_1 \sin\phi + a_2 \sin 2\phi$
- The sine-moments provide new insight into nucleon structure
- $Q^2 > 1$ GeV^2, $0.5 < z < 0.8$, $W^2 > 4$ GeV^2, $y < 0.85$, and $M_X > 1.1$ GeV.
- (see talk by Harut Avakian for details)

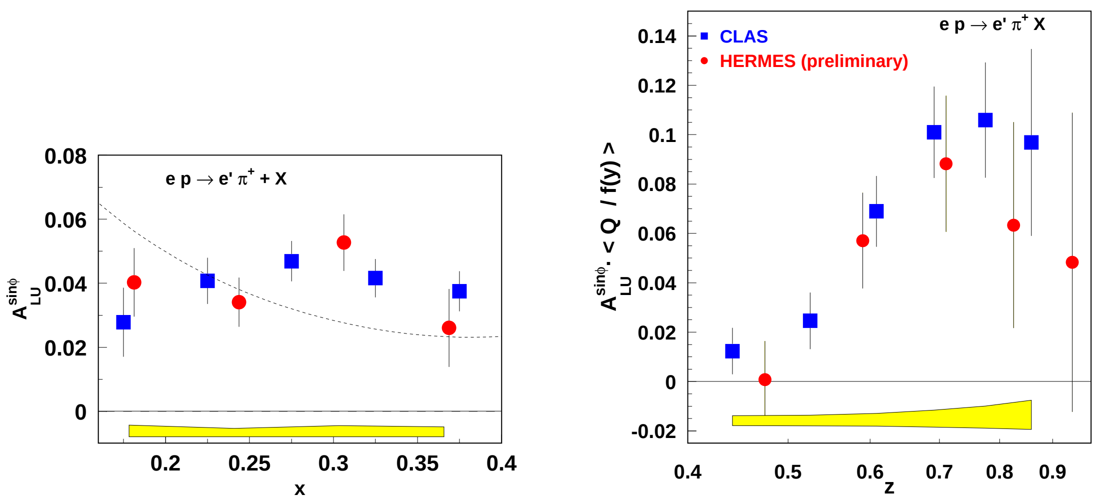
Exclusive Beam SSA





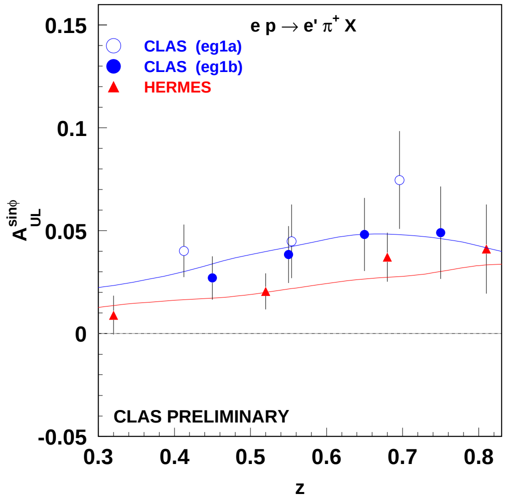
- Beam SSA's for exclusive channels may provide access to Generalized Parton Distributions (GPD's).
- $-t < 0.5$ GeV^2, $W^2 > 5$ GeV^2, $Q^2 > 2.5$ GeV^2 and $< Q^2 >= 3$ GeV^2.
- CLAS data shown as a function of x (left) and $-t$ (right).

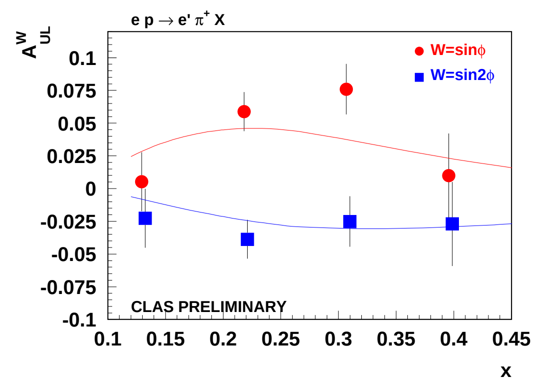
Semi-Inclusive Beam SSA



- $\sigma_{LU}^{\sin\phi} \propto e(x) H_1^{\perp}(z)$ (Collins' Mechanism)
- $e(x)$ is the twist-3 unpolarized distribution function
- $H_1^{\perp}(z)$ is the Collins fragmentation function
- Curve: Afanasev and Carlson (Sivers Mechanism)
- $A_{LU}^{\sin\phi} \sim H_1^{u,\pi^+}(z)/D_1^{u,\pi^+}(z)$ for sum over x.

Semi-Inclusive Target SSA





- $\sigma_{UT}^{\sin\phi} \propto S_T \sum_q e_q^2 f_{1T}^{\perp q}(x) D_1^q(z)$
- $\sigma_{UT}^{\sin\phi} \propto S_T \sum_q e_q^2 h_1^q(x) H_1^{\perp q}(z)$
- $\sigma_{UL}^{\sin\phi} \propto S_L \frac{M}{Q} \sum_q e_q^2 x h_L^q(x) H_1^{\perp q}(z)$
- $\sigma_{UL}^{\sin 2\phi} \propto S_L \sum_q e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z)$
- $A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp(1)u}(x)/f_1^u(x)$ when summed over z

Conclusions

- CLAS has taken extensive data with longitudinally polarized electrons and longitudinally polarized p and d targets.
- Precision structure functions g_1^p and g_1^d cover a wide kinematic range for $0.1 < Q^2 < 2.5$ GeV^2.
- $\Gamma_1^{p(n)}$ deviates from DIS systematics below $Q^2 = 2.5$ GeV^2, becomes negative at $Q^2 \approx 0.3(0.6)$ GeV^2, and turns upward below $Q^2 \approx 0.1$ GeV^2.
- Real photon absorption measurements confirm that $\sigma_{3/2} - \sigma_{1/2}$ is negative above 2 GeV.
- Single spin asymmetries show remarkable similarity to HERMES data at higher energies, which allows access to polarized fragmentation functions and new structure functions.
- eg1b still has a significant data sample at 2.5 and 4.2 GeV beam energies which is presently being analyzed.