Soft Spin Physics at Jefferson Lab

Raffaella De Vita
Istituto Nazionale di Fisica Nucleare
Sezione di Genova

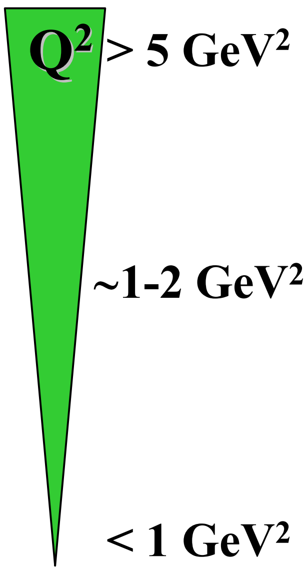
trieste_italia
october 10_16 2004

spin 2004
16th international spin physics symposium

Outline

- Physics Motivation
- Experimental Setup
- Nucleon Structure Functions at Low Q^2:
  - sum rules
  - resonance contribution and duality
  - higher twist and soft processes
- Exclusive Measurements and Resonance Contribution (π^0, π^+, η)

Spin Physics in the non perturbative domain



Measurements of spin observables at large Q^2 allowed the study of the spin dependence of parton distribution functions (CERN, SLAC, DESY)

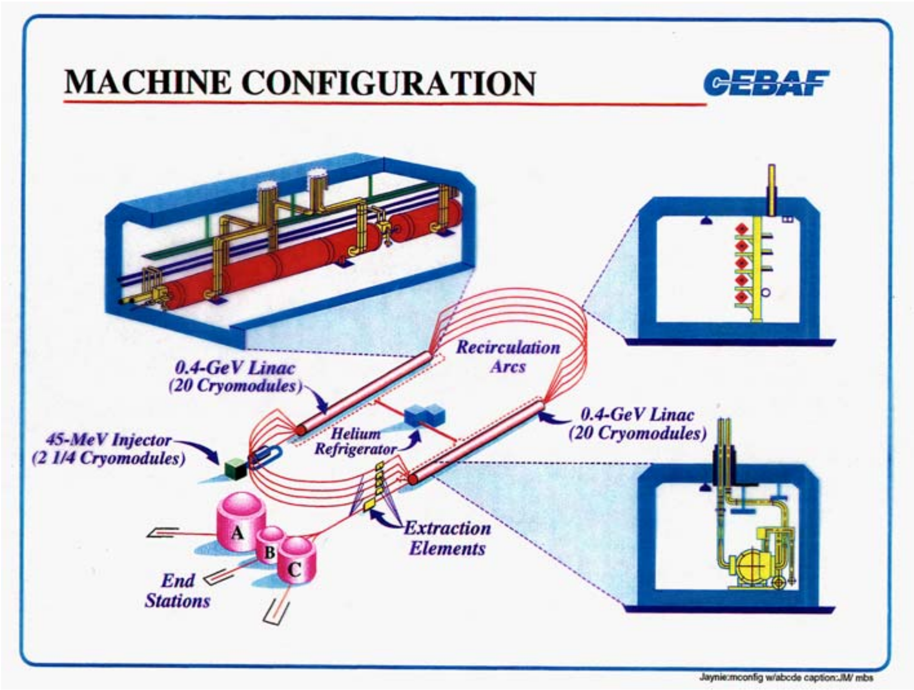
As Q^2 decreases, non perturbative effects start to play a dominant role and the connection between the nucleon properties and its elementary constituent becomes highly non trivial

At low Q^2, better description of the nucleon properties can be obtained in terms of hadronic degrees of freedom

The study of the transition region between hadronic and partonic degrees of freedom is a key issue for the understanding of the nucleon structure

A broad program to study the nucleon spin structure in the soft regime is in progress at Jefferson Lab

Jefferson Lab



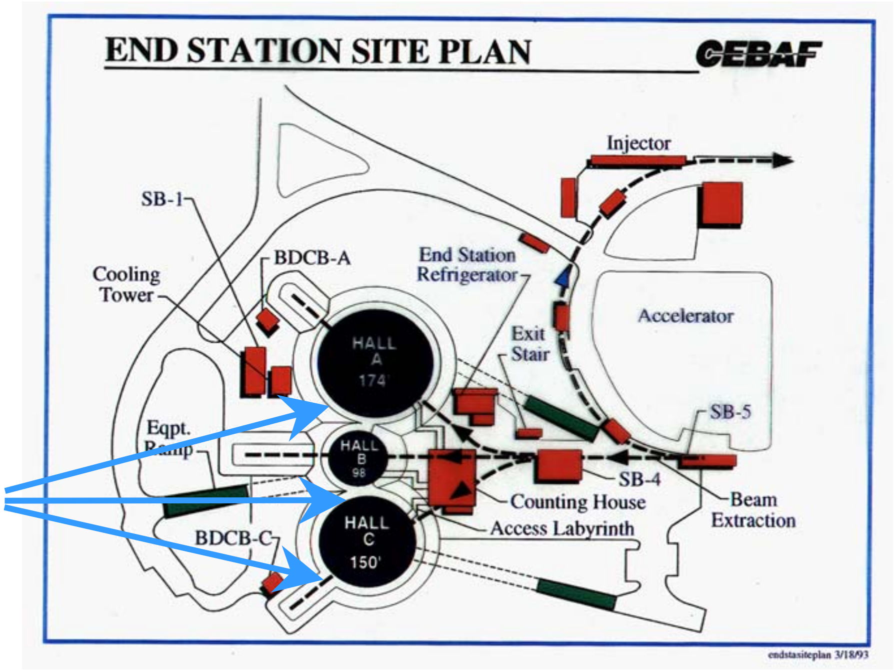
CEBAF is a superconductive electron accelerator

→ continuous beam

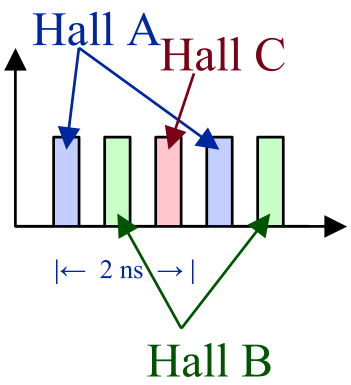
→ high longitudinal polarization

→ energy range → 0.75 –5.9 GeV

→ current range → 0.1 nA –200mA



The electron beam can be delivered simultaneously to the three halls with high polarization



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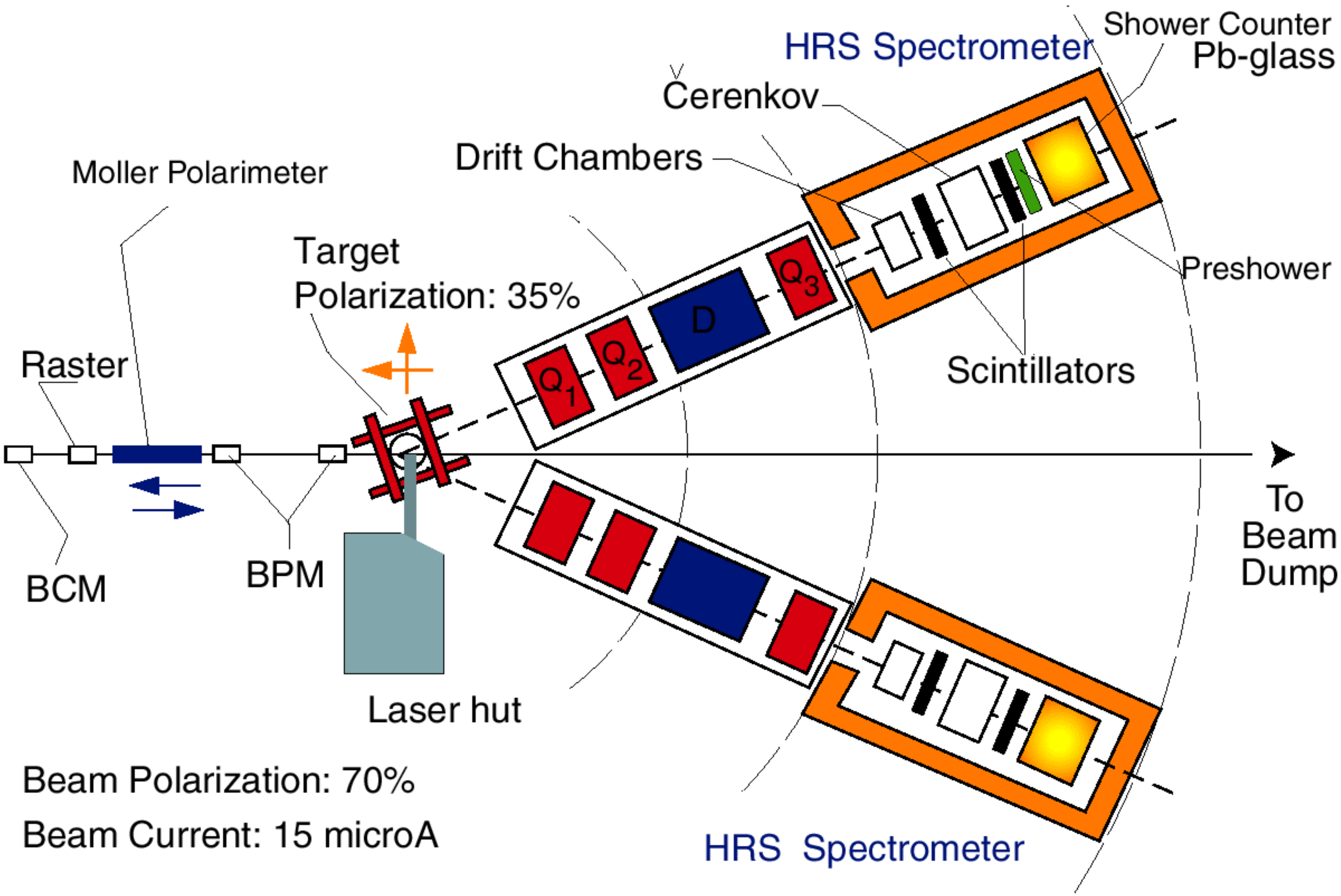
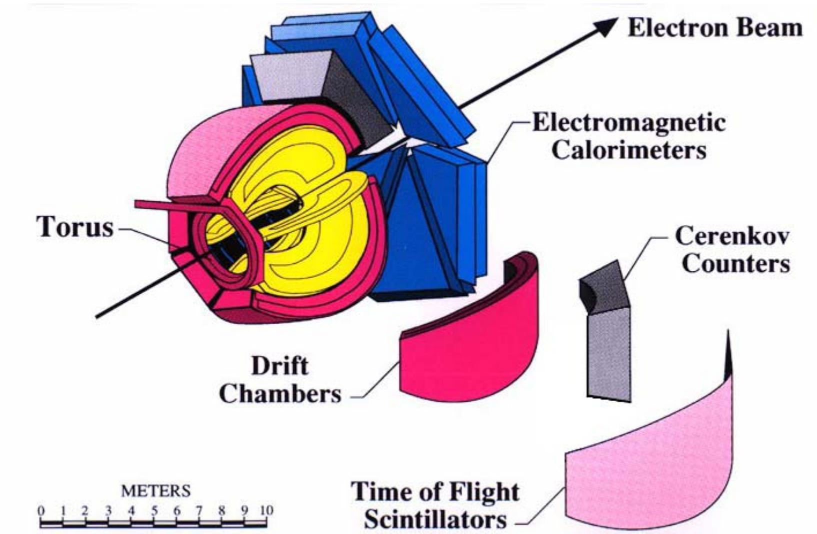
Experimental Setup: Hall A



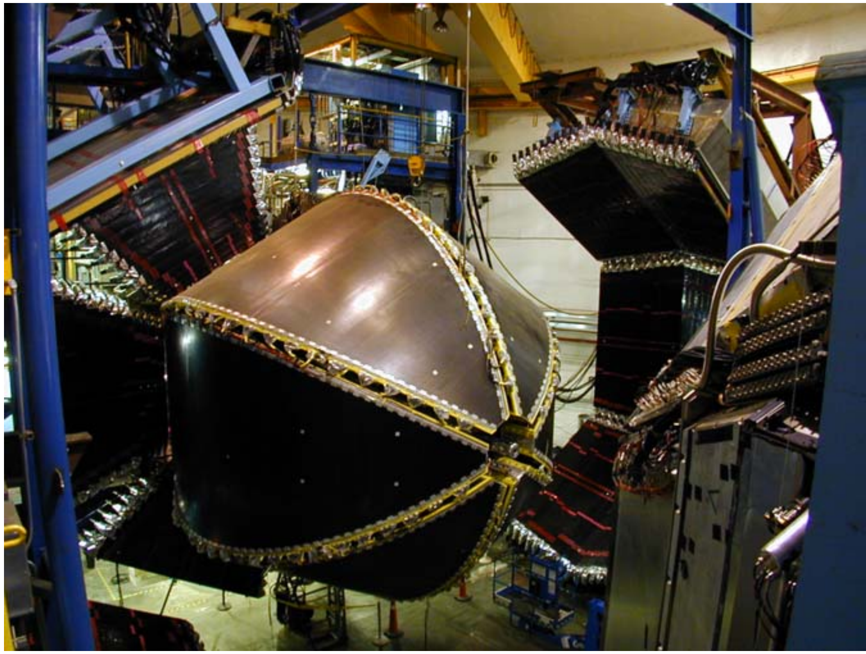
Beam Polarization: 70%

Beam Current: 15 microA

Experimental Setup: Hall B

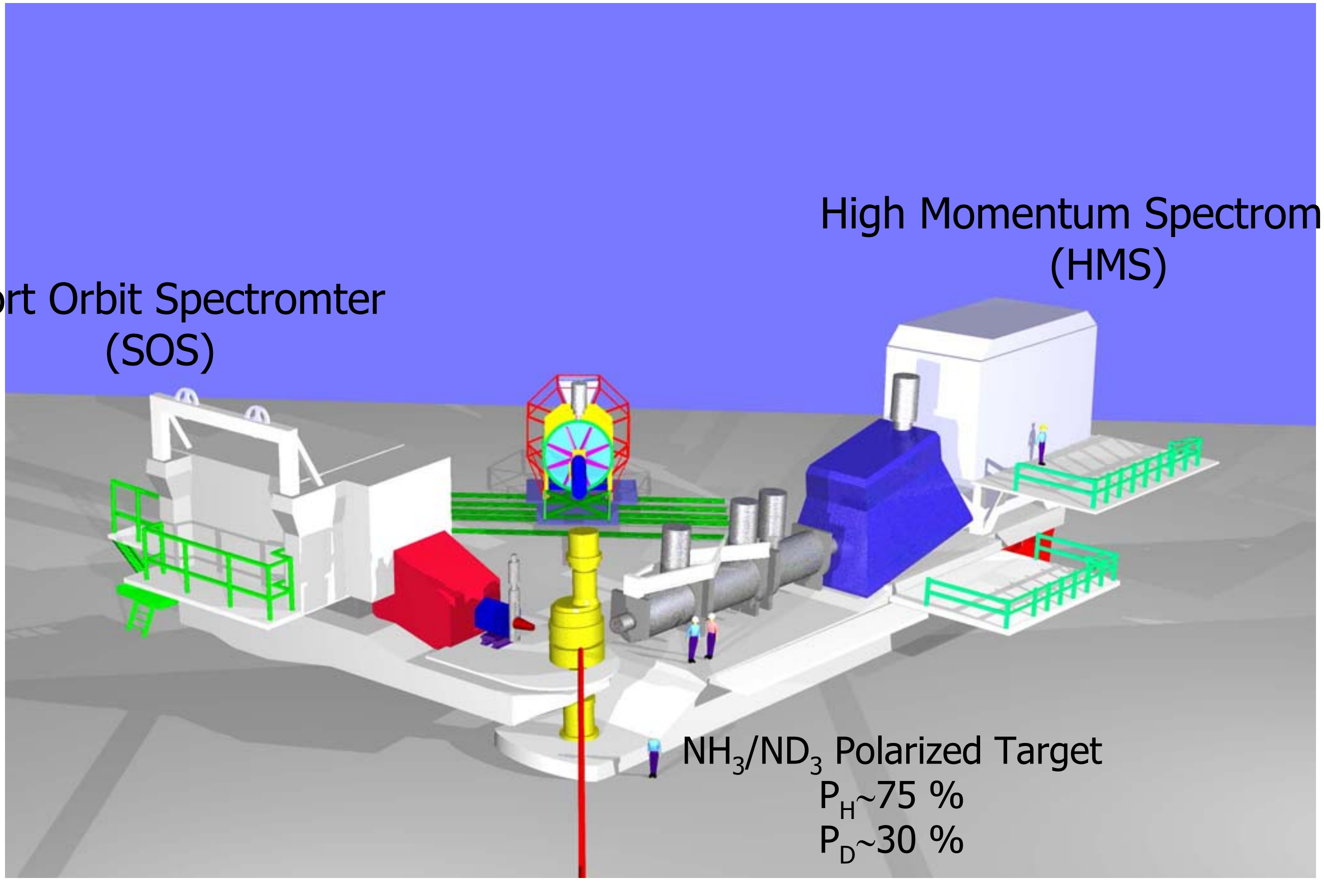


CEBAF
Large
Acceptance
Spectrometer



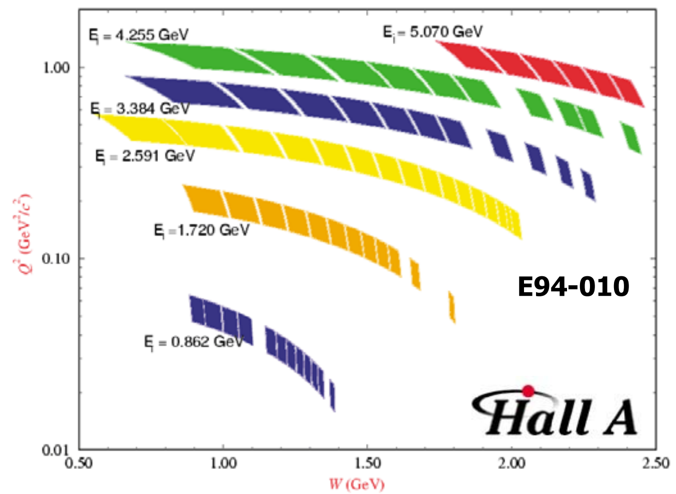
- large kinematical coverage
- simultaneous measurement of exclusive and inclusive reactions
- central field-free region well suited for the insertion of the polarized target

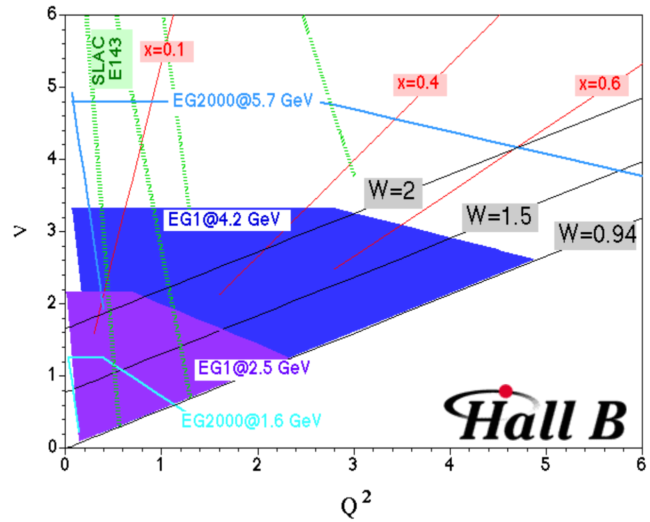
Experimental Setup: Hall C



Experimental Program

- measurement of the nucleon spin structure functions in the resonance region
- test of the generalized Gerasimov-Drell-Hearn Sum Rule on the proton and neutron
- measurement of nucleon spin polarizabilities at low Q^2
- test of duality of spin structure function
- extraction of the moments of the proton and neutron structure functions and study of higher twist contribution
- study of the nucleon resonance structure from polarization observables in exclusive meson production





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Sum Rules and Integrals of Spin Structure Functions

GDH Sum Rule

$$I_{GDH} = \frac{M^2}{8\alpha\pi^2} \int_{thr}^{\infty} (\sigma_{1/2} - \sigma_{3/2}) \frac{d\nu}{\nu} = -\frac{1}{4}\kappa^2$$

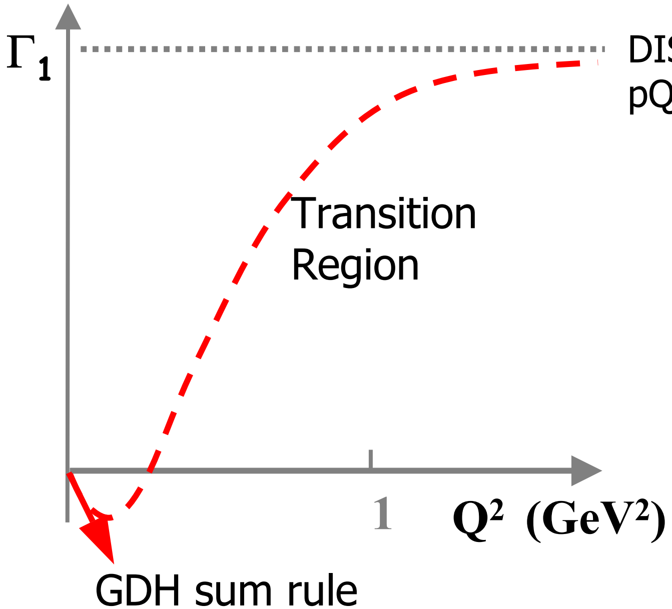
- relates the difference of the photo-absorption cross section for helicity 1/2 and 3/2 to the nucleon magnetic moment, i.e. a connection between dynamic and static properties

- based on very general principles, as gauge invariance, dispersion relation, low energy theorem

- at finite Q^2 can be related to the integral of the spin structure function g_1

$$\Gamma_1 = \int g_1(x, Q^2)dx \xrightarrow[Q^2 \to 0]{} \frac{Q^2}{2M^2} I_{GDH}$$

- strong variation of nucleon spin properties as a function of Q^2



Generalized GDH Integral

A generalization of the GDH sum rule has been suggested by Ji and Osborne by relating the virtual-photon forward Compton amplitude to the to the nucleon structure function Γ_1

X.Ji et al., Phys.Lett.B472 (2000) 1

$$I_{GDH}(Q^2) = \frac{8}{Q^2}\int_{x_0}^{\infty} dx\, g_1(x,Q^2)$$

$Q^2 < 0.1\ GeV^2$ → GDH sum rule and Chiral Perturbation Theory

$$-\frac{\kappa^2}{M^2} + cQ^2 + O(Q^4)$$

$0.1 < Q^2 < 0.5\ GeV^2$ → Lattice?

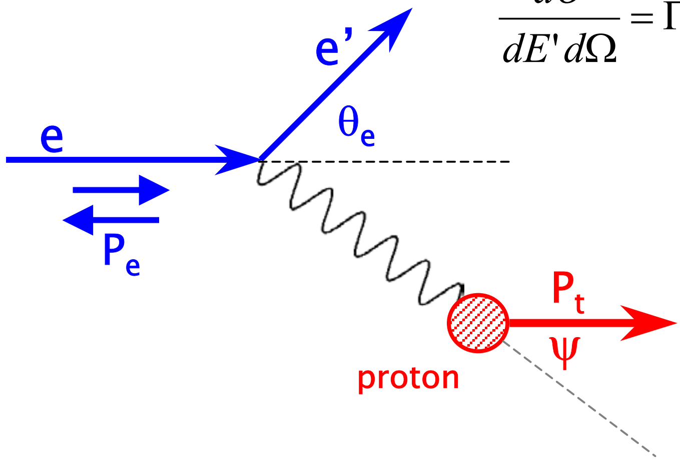
$Q^2 > 0.5\ GeV^2$ → Bjorken Sum rule and Operator Product Expansion

$$\sim \sum_{\tau=2,4,\ldots} \frac{\mu_\tau(Q^2)}{Q^{t-2}}$$

the left side is a calculable quantity

the right side is a measurable quantity

Asymmetries and Spin Structure Functions



$$\frac{d\sigma}{dE'd\Omega} = \Gamma_v \left[\sigma_T + \varepsilon\sigma_L + P_e P_t \left(\sqrt{1-\varepsilon^2}\mathbf{A_1}\sigma_T \cos\psi + \sqrt{2\varepsilon(1-\varepsilon)}\mathbf{A_2}\sigma_T \sin\psi \right) \right]$$

$$\mathbf{A_1} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \qquad \mathbf{A_2} = \frac{\sigma_{LT'}}{\sigma_T}$$

the structure functions $\mathbf{A_1}$ and $\mathbf{A_2}$ can be extracted by varying the direction of the nucleon polarization

$$A^{\parallel} = D(A_1 + \eta A_2)$$
$$A^{\perp} = d(A_1 + \zeta A_2)$$

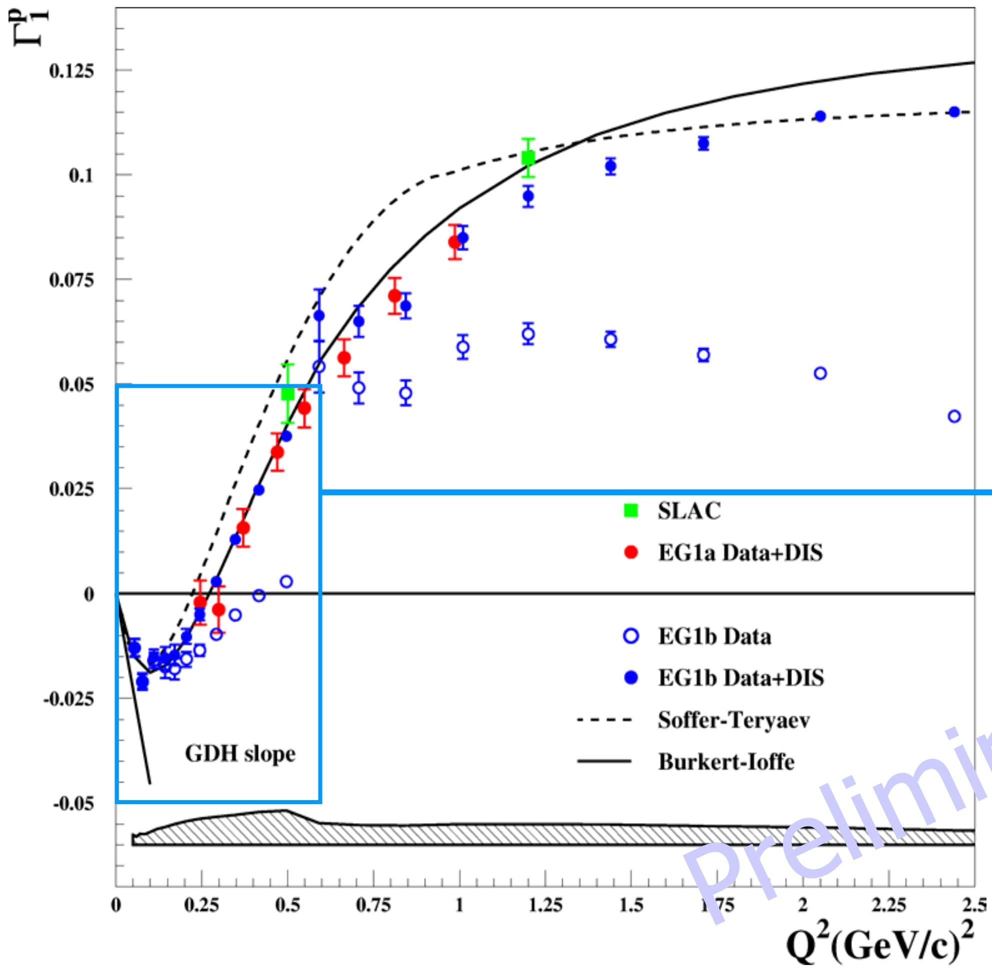
where D, η, d, ξ are function of Q^2, W, E_0, R

the structure functions $\mathbf{g_1}$ and $\mathbf{g_2}$ are linear combination of $\mathbf{A_1}$ and $\mathbf{A_2}$

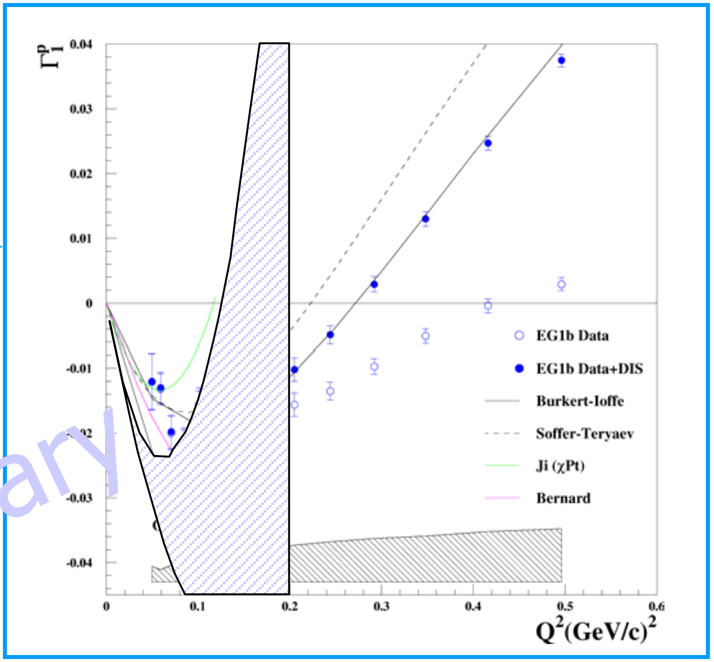
$$\mathbf{g_1(x,Q^2)} = \frac{Q^2}{Q^2 + 4M^2x^2}\left(A_1 + \frac{2Mx}{\sqrt{Q^2}} A_2 \right) F_1(x,Q^2)$$

$$\mathbf{g_2(x,Q^2)} = \frac{Q^2}{Q^2 + 4M^2x^2}\left(\frac{\sqrt{Q^2}}{2Mx} A_2 - A_1 \right) F_1(x,Q^2)$$

Integral of g_1 on the Proton



- consistent with previous SLAC data
- shows strong Q^2 dependence
- change in slope occurs at 0.15 GeV^2



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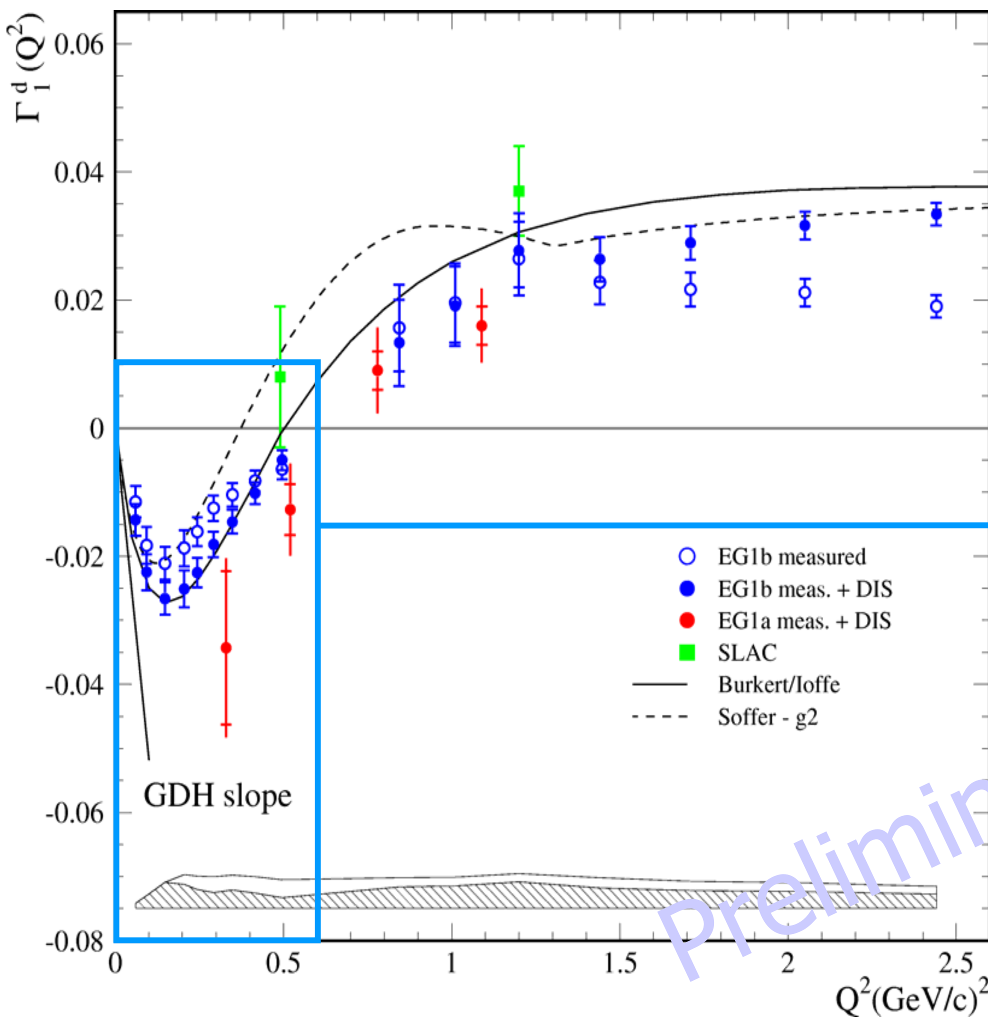
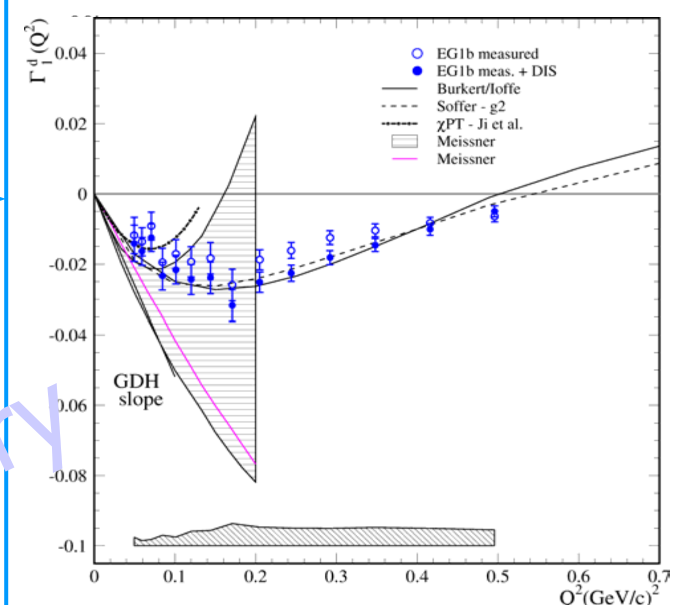
Integral of g_1 on the Deuteron



- consistent with previous SLAC data
- slower transition than for the proton
- change in slope occurs at 0.2 GeV^2



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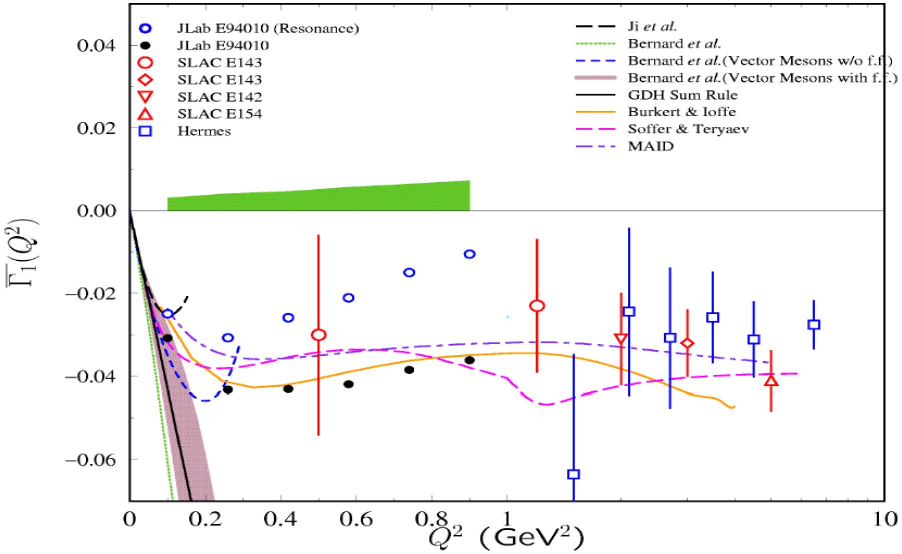
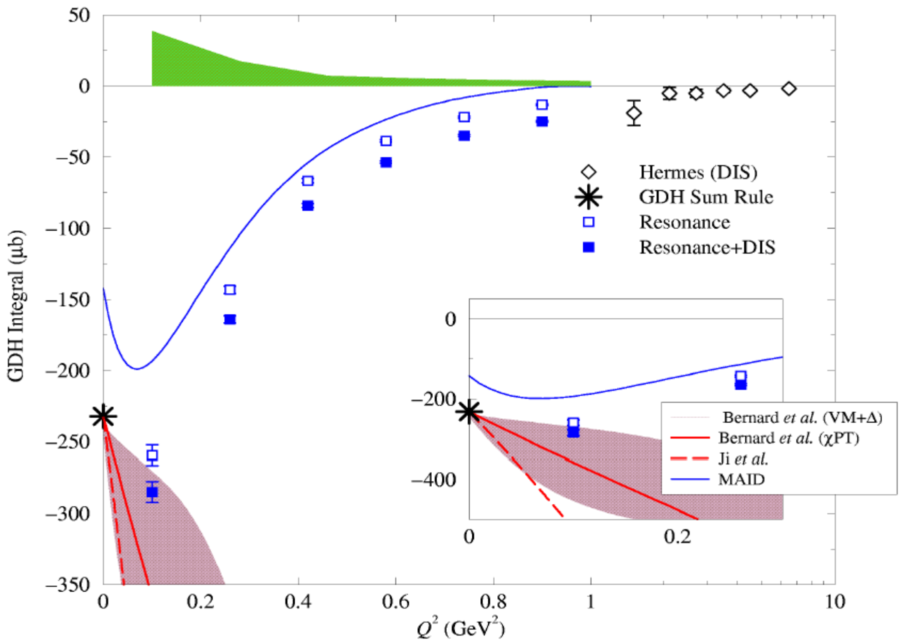
g_1 and GDH Integral on the Neutron



- complementary to Hall B beacsue of different target and analysis procedure
- consistent with previous SLAC data
- integral is negative and shows smoot Q^2 dependence

- strong variation of GDH integral from 0.1 to 1. GeV^2
- integral starts to approach Sum Rule at Q2=0.1 GeV^2
- first point consistnet with χPT prediction

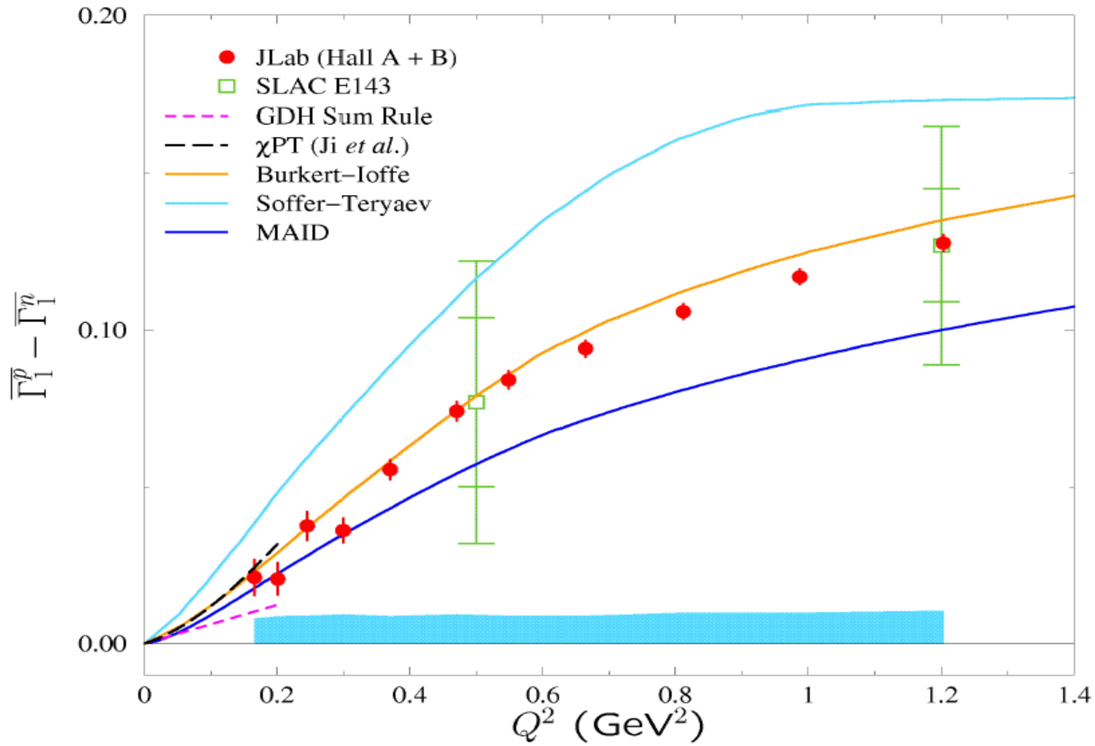


Bjorken Sum Rule

$$\Gamma_1^p - \Gamma_1^p = \int \left(g_1^p - g_1^n \right) dx \xrightarrow[Q^2 \to \infty]{} \frac{g_a}{6}$$

→ see talk by A. Deur

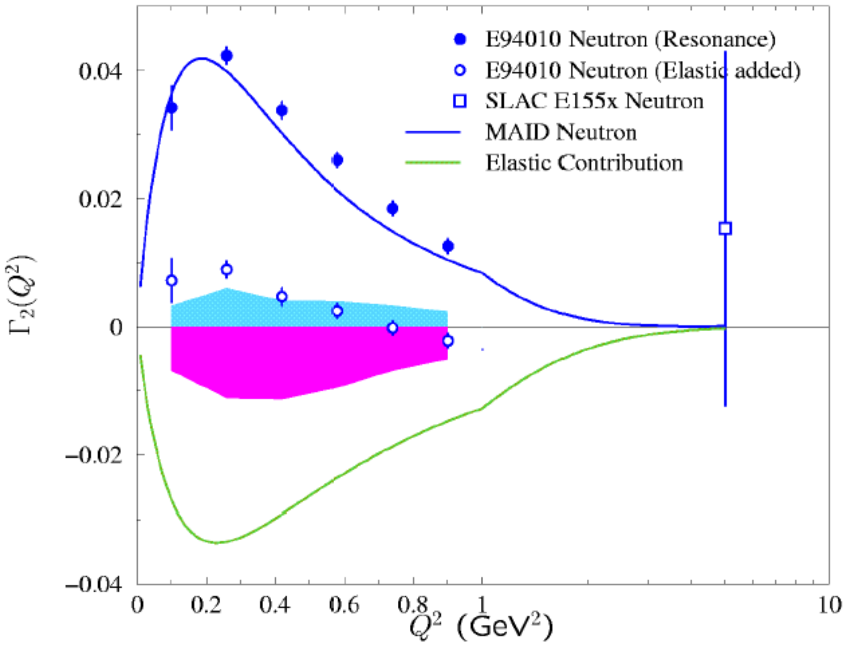
- combined analysis of Hall A and Hall B measurements
- consistent with previous SLAC data
- Δ and other isospin 3/2 contribution cancel out
- better agreement with χPT than for separated proton and neutron integrals



Integral of g_2 on the Neutron

(Burkardt-Cottingham Sum Rule)

$$\Gamma_2(Q^2) \equiv \int_0^1 g_2(x, Q^2)\, dx = 0$$



- From superconvergence of corresponding Compton Amplitude
- Valid for every Q^2
- No confirmation from Operator Product Expansion
- At $Q^2 = 5$ GeV^2, possible satisfaction from SLAC E155x

Spin Polarizabilities

Virtual Compton Scattering

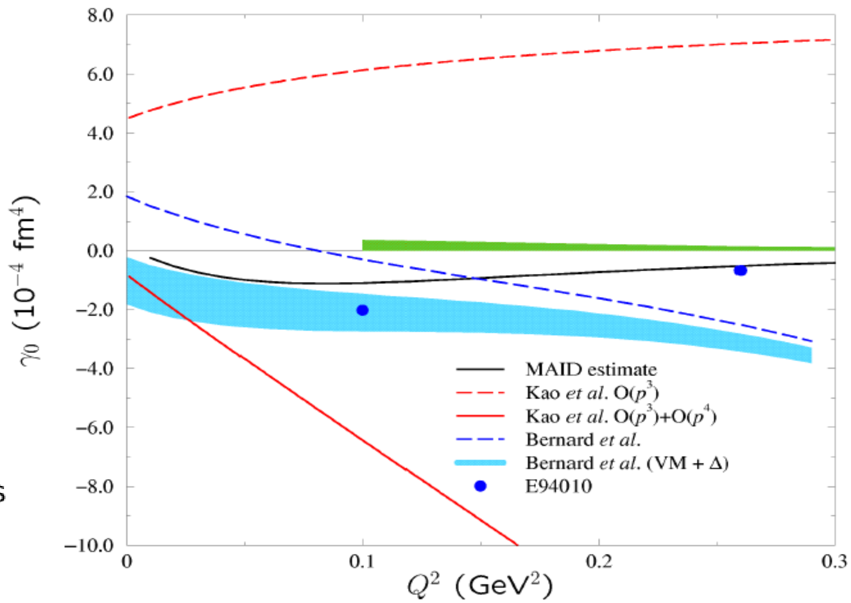
$$
\begin{aligned}
T(\nu, Q^2) &= \varepsilon'^* \cdot \varepsilon f_T(\nu, Q^2) + f_L(\nu, Q^2) \\
&\quad + i\sigma \cdot (\varepsilon'^* \times \varepsilon) g_{TT}(\nu, Q^2) \\
&\quad - i\sigma \cdot [(\varepsilon'^* - \varepsilon) \times \hat{q}] g_{LT}(\nu, Q^2)
\end{aligned}
$$

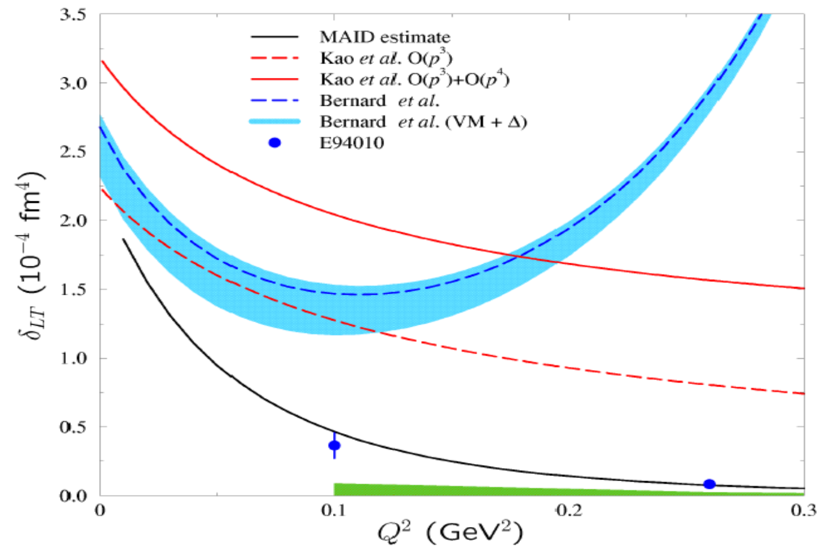
f_T	$\to \alpha + \beta$	electric and magnetic polarizabilities
g_{TT}	$\to \gamma_0$	forward spin polarizability
f_L	$\to \alpha_L$	longitudinal polarizability
g_{LT}	$\to \delta_{LT}$	longitudinal-transverse polarizability

$$
\gamma_0(Q^2) = \frac{16 M^2 \alpha_{\rm em}}{Q^6} \int_0^{x_0} x^2 \left\{ g_1(x, Q^2) - \frac{Q^2}{\nu^2} g_2(x, Q^2) \right\} dx
$$

$$
\delta_{LT}(Q^2) = \frac{16 M^2 \alpha_{\rm em}}{Q^6} \int_0^{x_0} x^2 \left\{ g_1(x, Q^2) + g_2(x, Q^2) \right\} dx
$$

$$
\delta_{LT}(Q^2) \to \frac{1}{3} \gamma_0(Q^2), \quad Q^2 \to \infty
$$

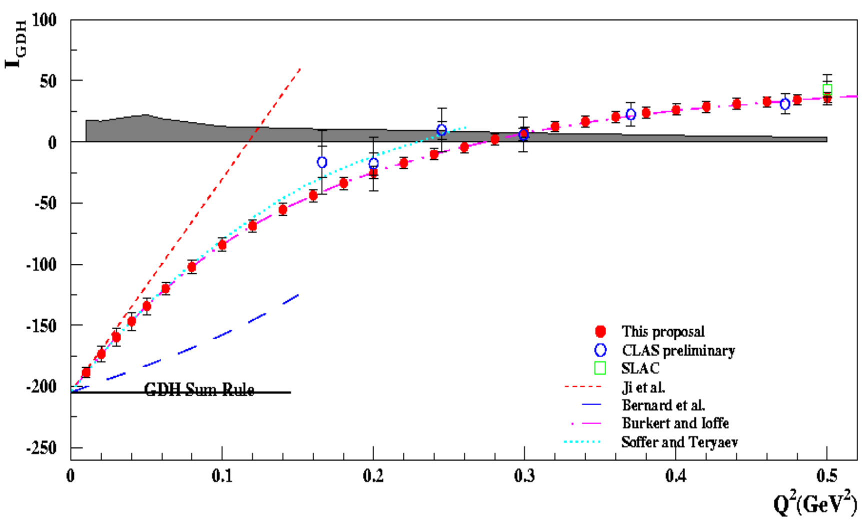


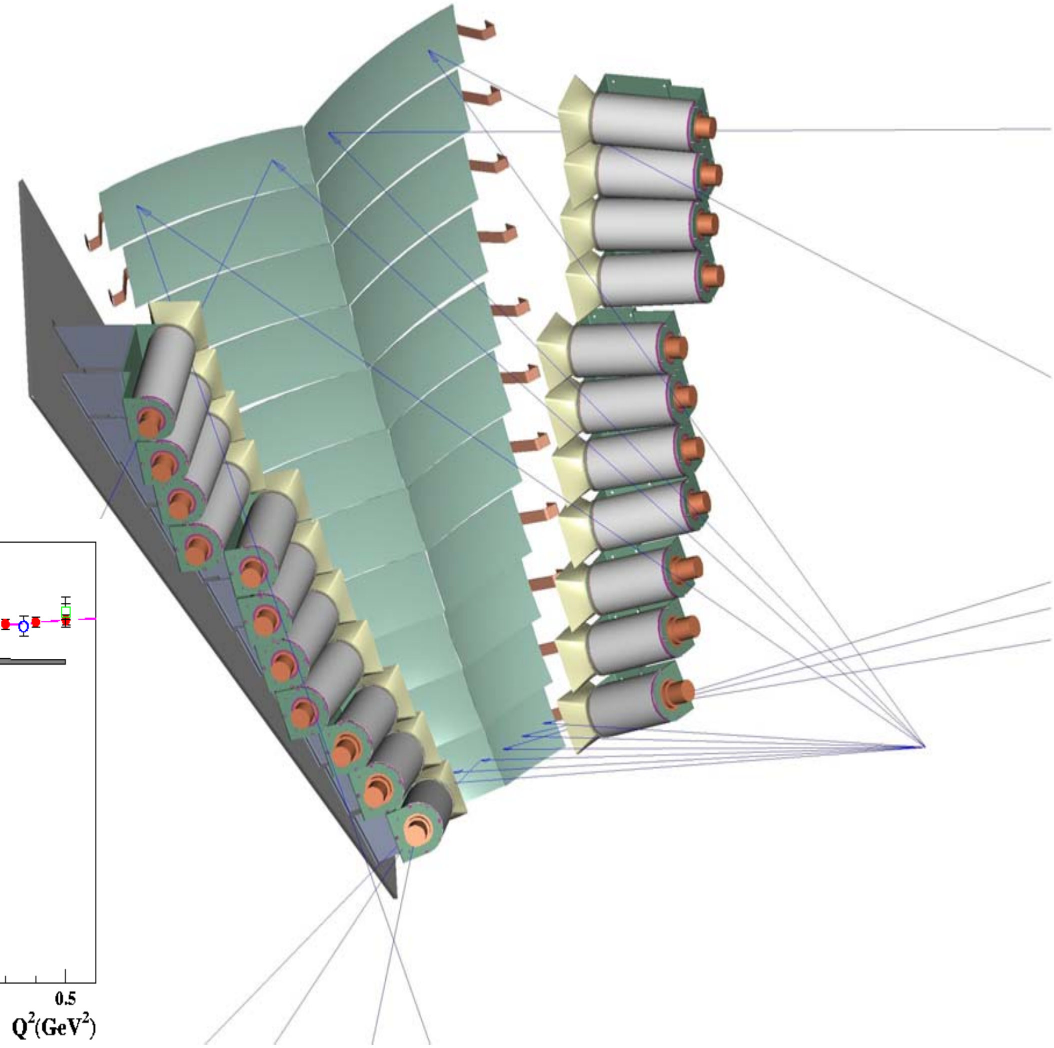


Hall B

Proton Structure Function at Very Low Q^2

- Extension of previous experiments
- Test of χPT at $Q^2 \rightarrow 0$
- New Cerenkov Counter to detect scattered elecrons at 5 deg. (INFN-Genova)





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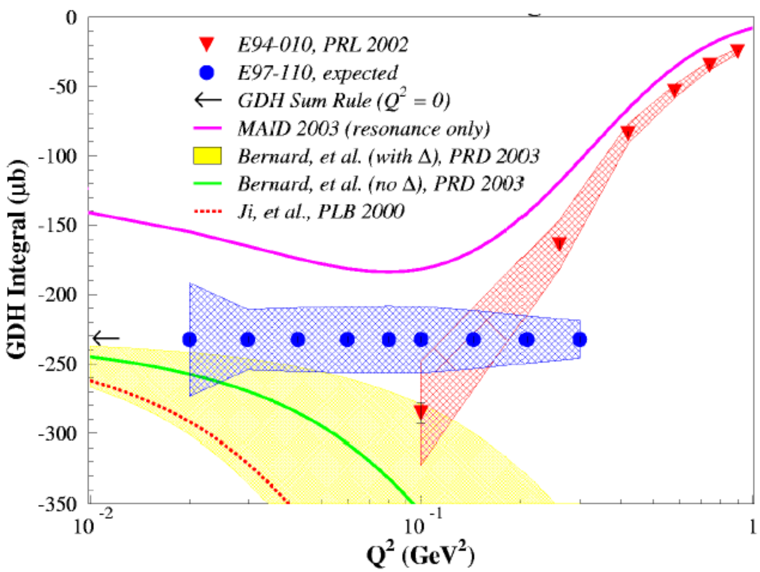
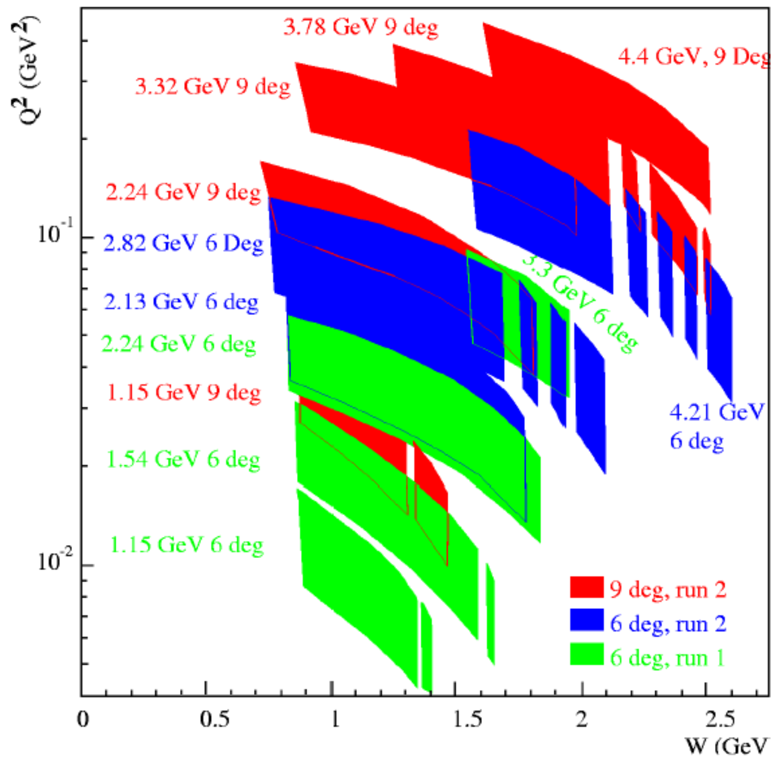
Neutron Structure Function at Very Low Q^2

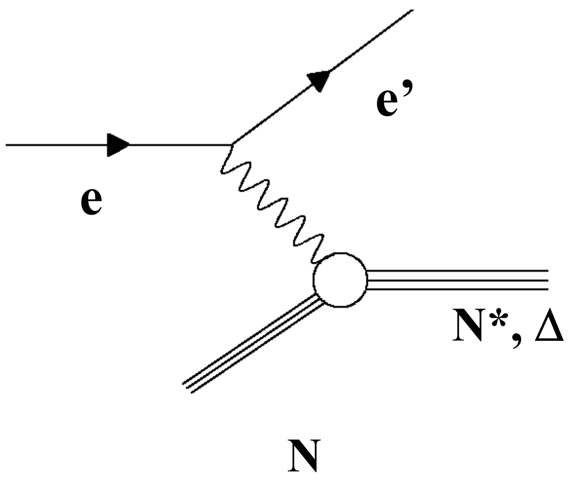
- Extension of previous experiments
- Test of χPT at $Q^2 \rightarrow 0$
- Data taking completed in 2003, analysis in progress

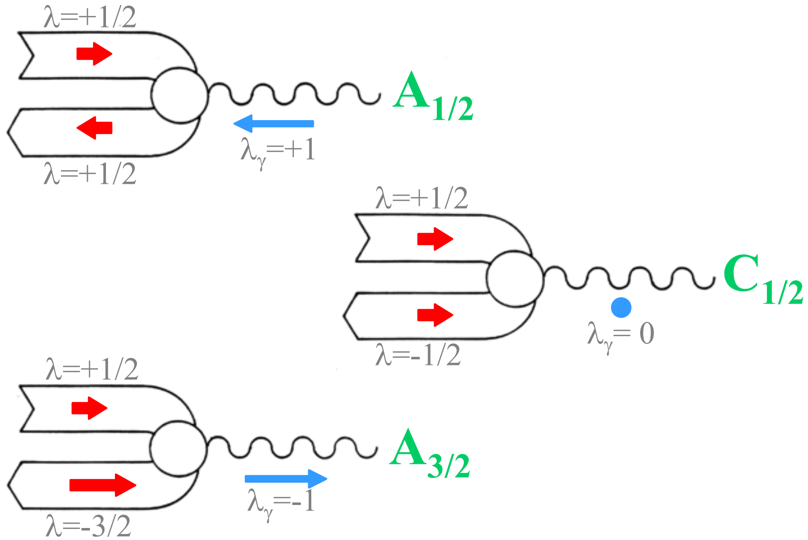




Resonance Contribution to Spin Structure Functions and Duality

Helicity Structure of Baryons Resonances





- the helicity amplitudes provide information on the structure of the excited states

$$\sigma_T = \sigma_{1/2} + \sigma_{3/2} = |A_{1/2}|^2 + |A_{3/2}|^2$$

- their Q^2 dependence is determined by the spatial structure of the excited state

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \rightarrow |A_{1/2}|^2 - |A_{3/2}|^2$$

- polarization measurements are necessary to extract the helicity amplitudes

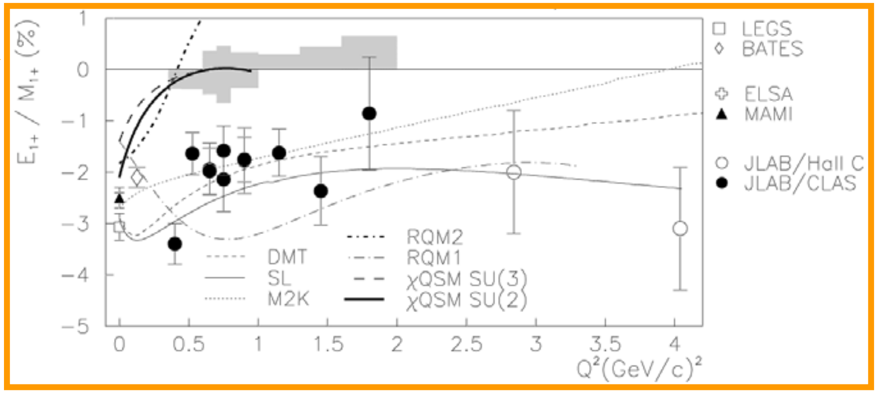
$$A_2 = \frac{\sigma_{LT'}}{\sigma_T} \rightarrow C^*_{1/2} A_{1/2}$$

Helicity Structure of Baryons Resonances

$P_{33}(1232)$

the helicity asymmetry can be written in the assumption of M_{1+} dominance as

$$A_1 \approx -\frac{1}{2} + 3\frac{\mathrm{Re}\left(E_{1+}^{*}M_{1+}\right)}{\left|M_{1+}\right|^2}$$



$P_{11}(1440)$ - $S_{11}(1535)$

$$A_1 = 1$$

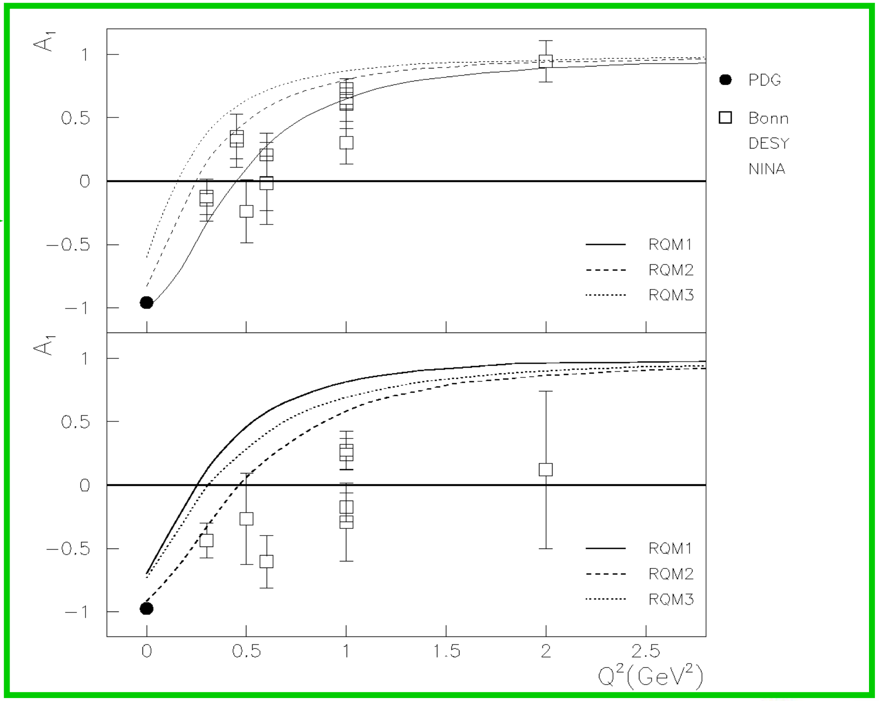
$D_{13}(1520)$ - $F_{15}(1680)$

the helicity asymmetry is predicted by the NRQM to be

$$A_1 = \frac{-1 + \left[\left(\vec{q}^2/\alpha^2 - 1\right)/3\right]^2}{1 + \left[\left(\vec{q}^2/\alpha^2 - 1\right)/3\right]^2}$$

$$\xrightarrow{Q^2 \to 0} -1$$

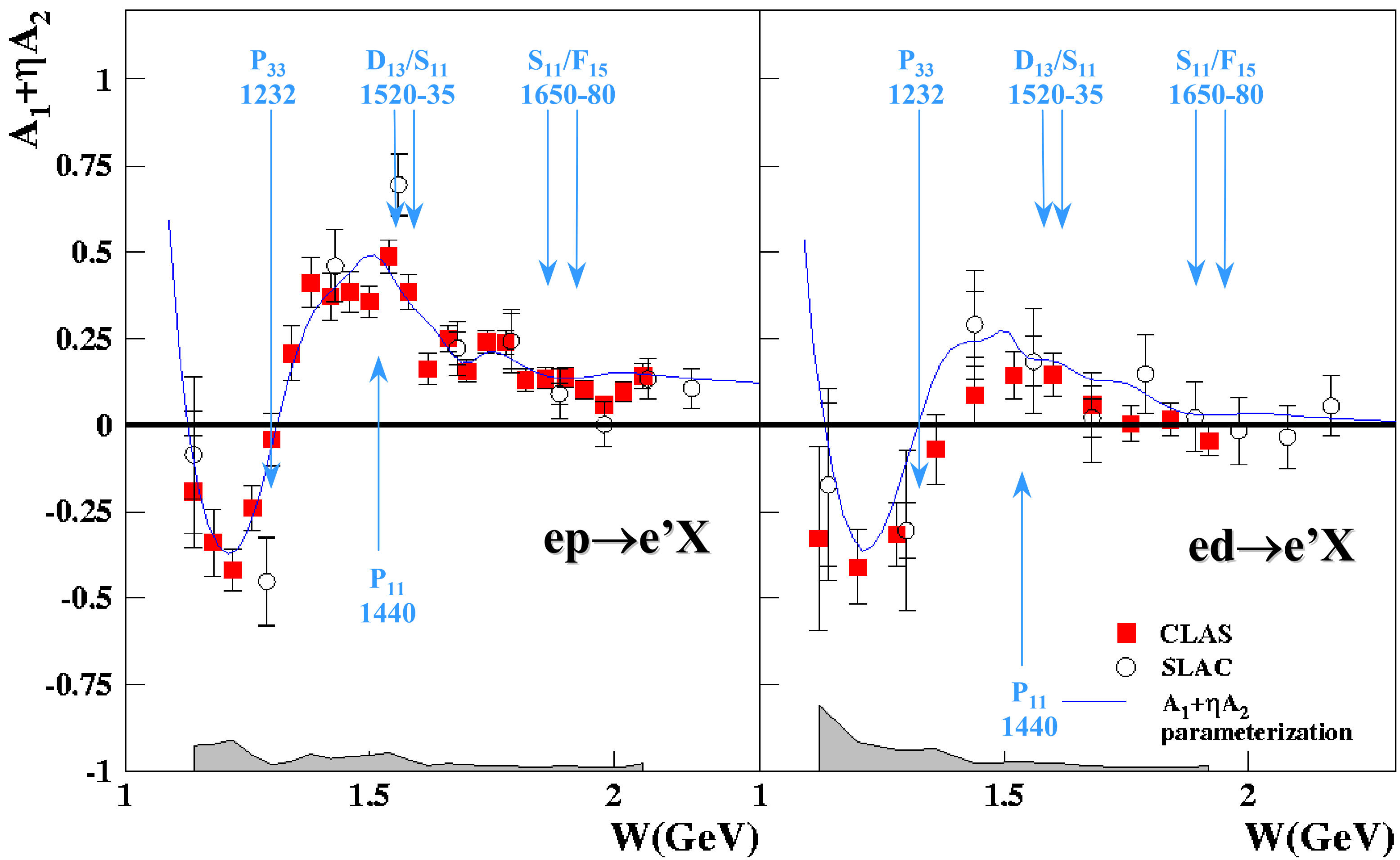
$$\xrightarrow{Q^2 \to \infty} +1$$



$A_1+\eta A_2$ for proton and deuteron

Hall B

$0.4 < Q^2 < 0.6\ GeV^2$



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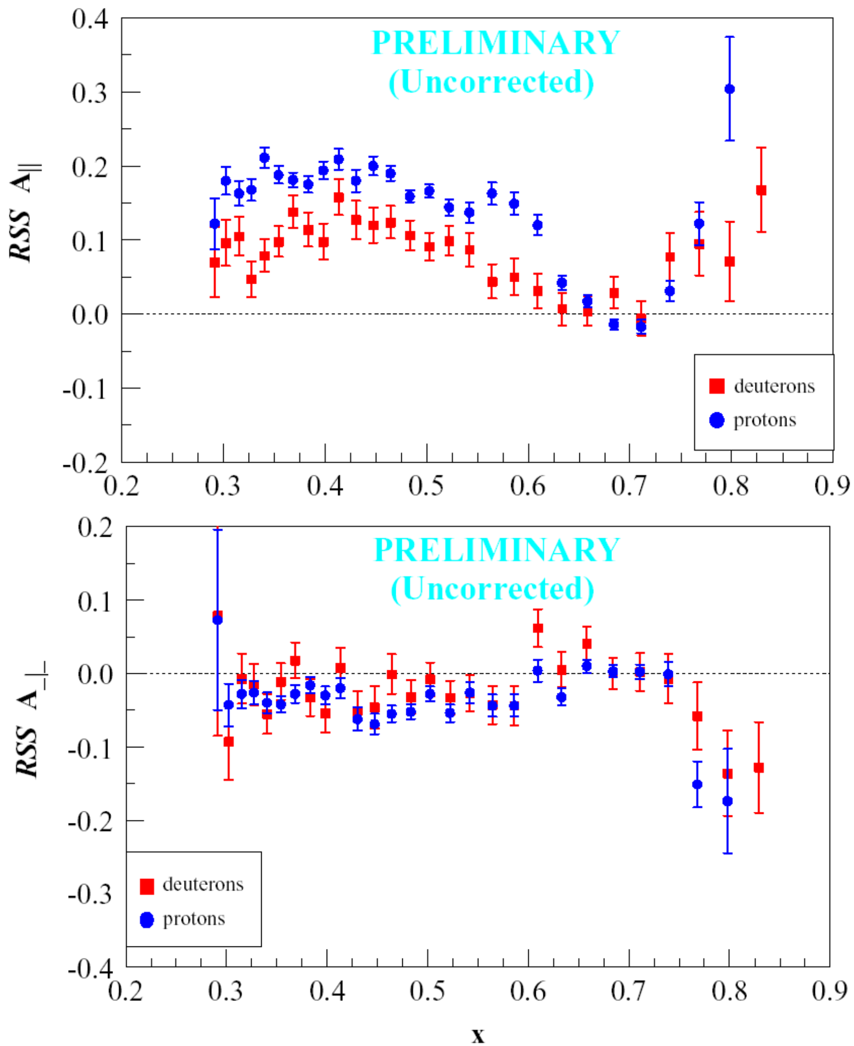
$A_{||}$ and $A_{\perp}$ for proton and deuteron

Hall C

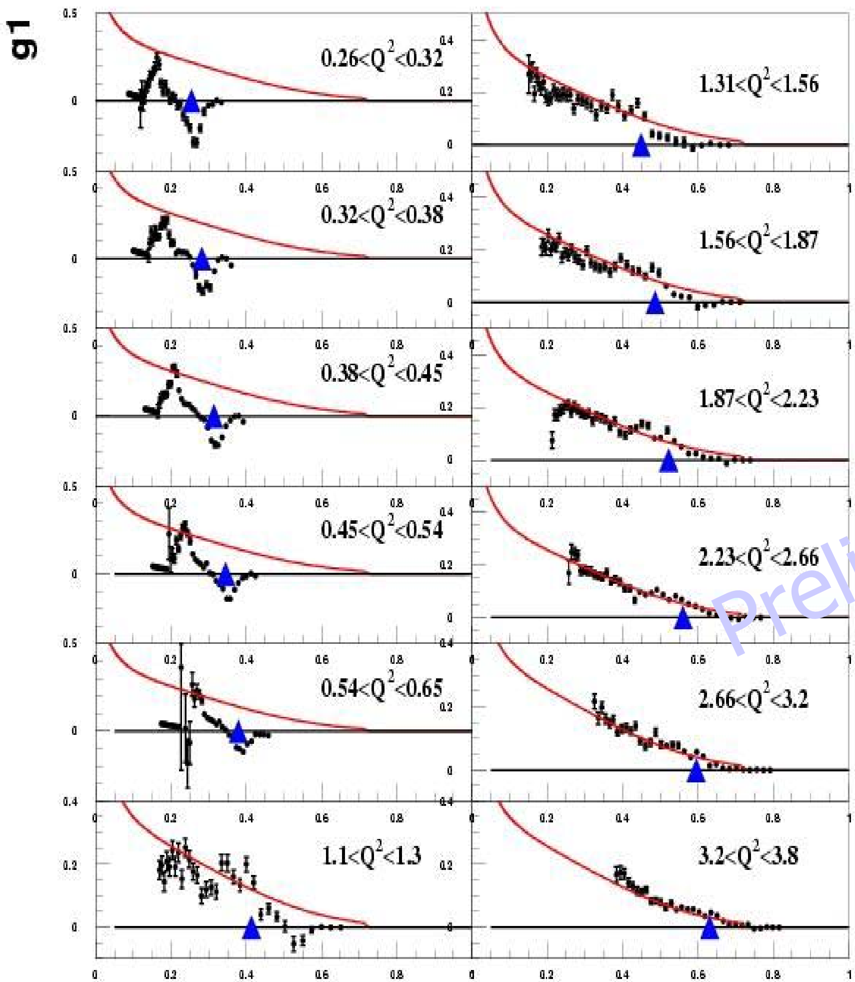
E01-006
Precision of the Nucleon Spin Struture Functions in the Resonance Region

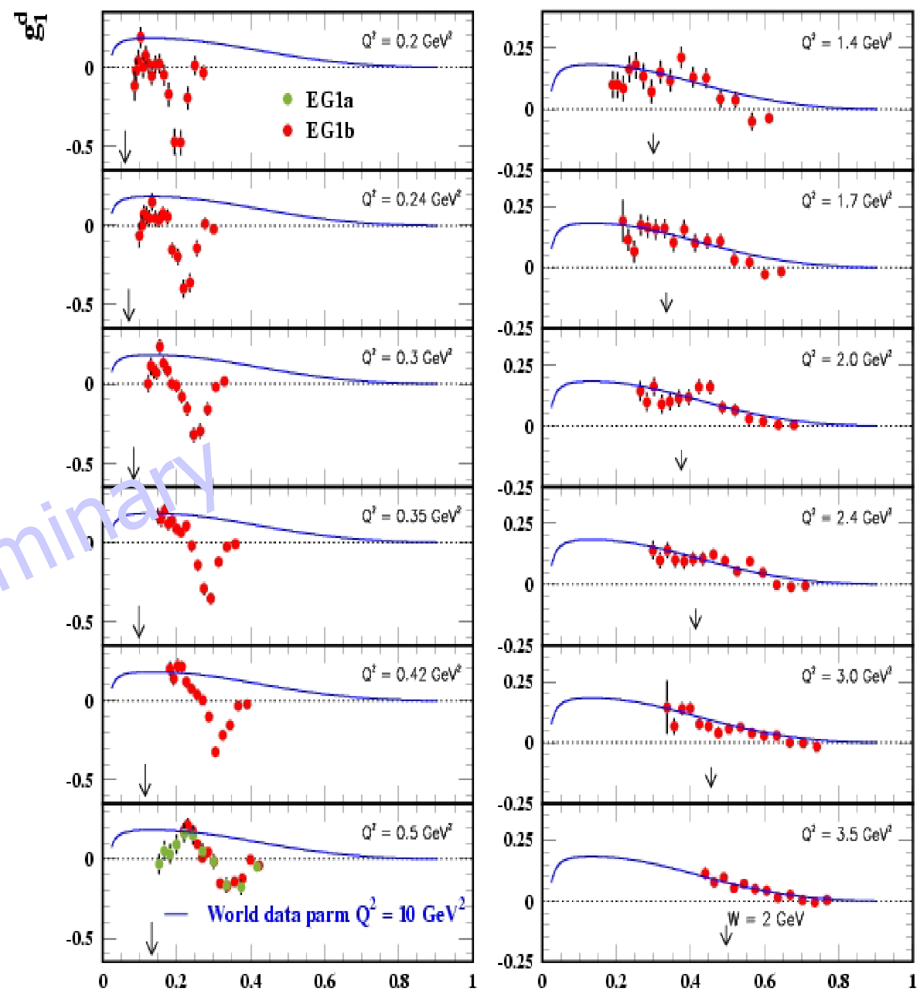
$\theta_e = 13.5°$
$Q^2 \approx 1.3\ GeV^2$
$0.8 < W < 2.0\ GeV$

Analysis in progress



Duality in Spin Structure Functions





Proton ξ **Deuteron** ξ

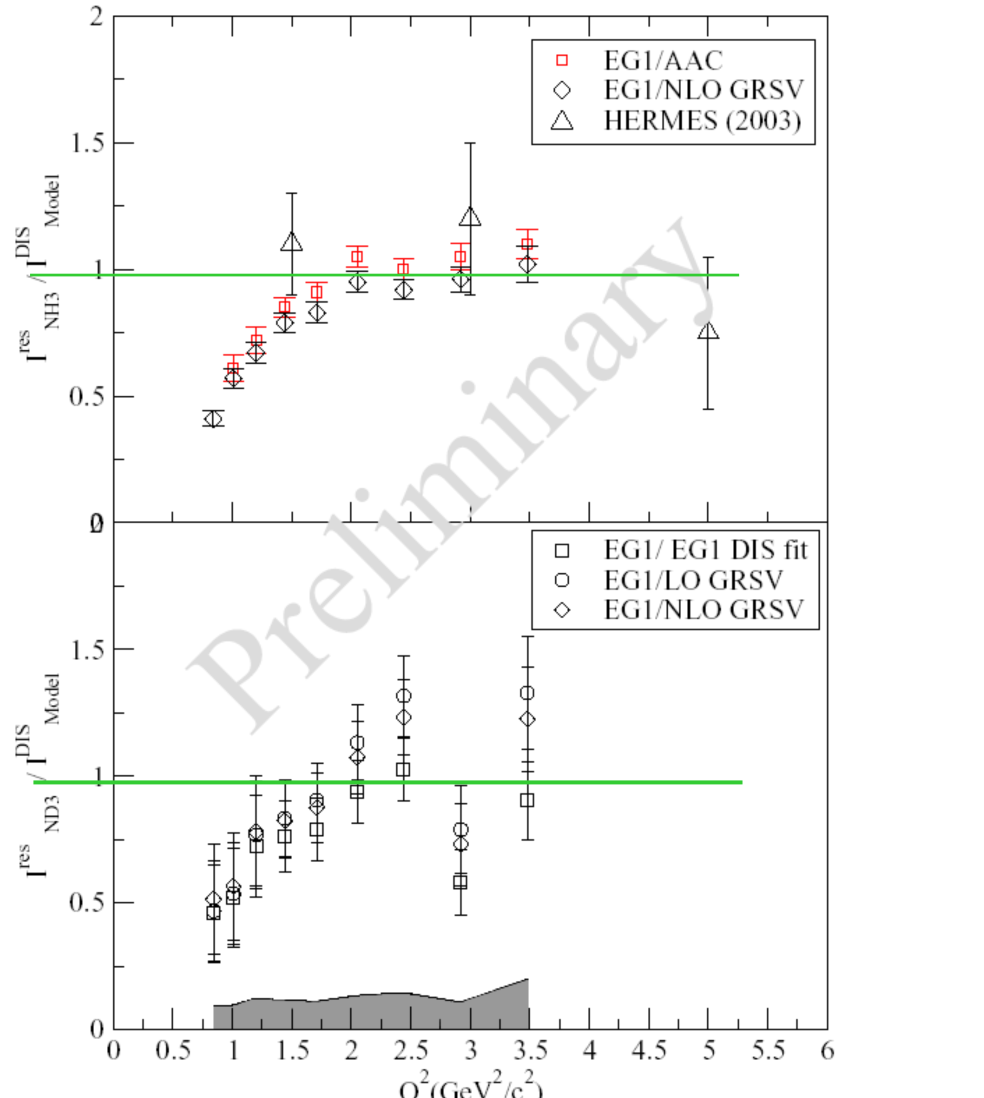
Duality (Cont.)

Duality can be tested in quantitative way constructing the ratio of

$$I^{RES} = \int_{x_{min}}^{x_{max}} g_1^{RES}(x,Q^2)dx$$

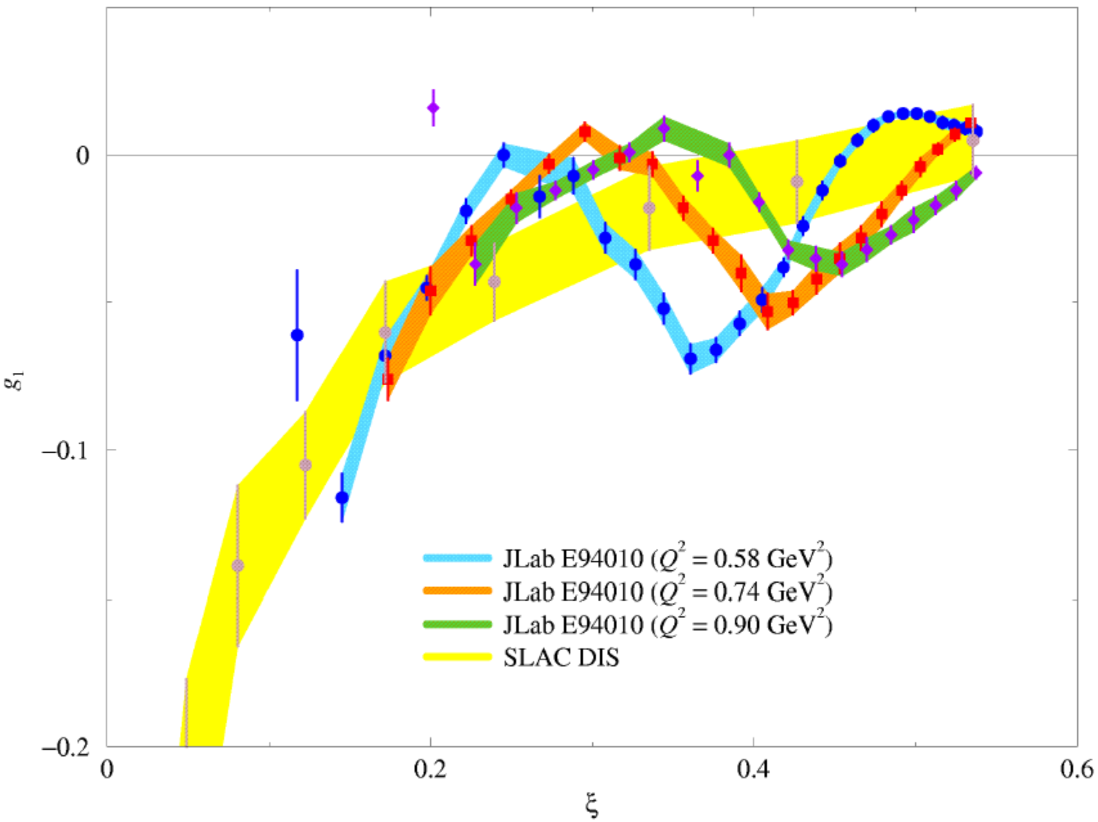
$$I^{DIS} = \int_{x_{min}}^{x_{max}} g_1^{DIS}(x,Q^2)dx$$

- Good agreements with previous HERMES results
- Ratio consistent with unity for $Q^2 > 2\ GeV^2$
- Significant deviation below



Duality (Cont.)

measured structure function seems follow quantitavely the Q^2-evolved DIS measurements



- new experiment on ^{3}HE target (E01-012) completed in 2003 is presently under analysis

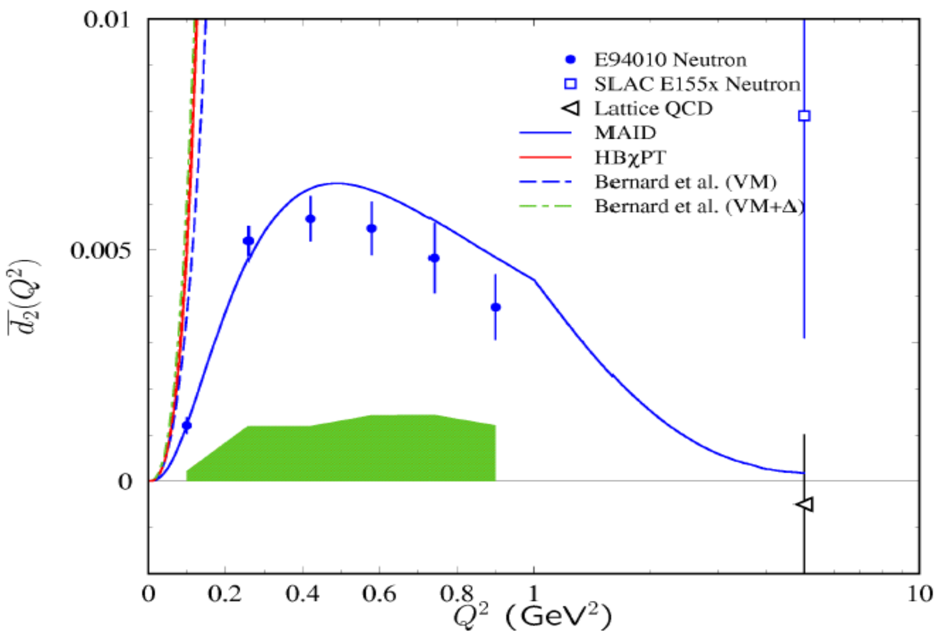
- complementary measurement on proton and deuetron planned in Hall C (E03-109)

Higher Twists Effects in g_2

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + g_2^{H.T.}(x,Q^2)$$

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{g_1(y,Q^2)}{y}\,dy$$

$$d_2(Q^2) = 3\int_0^1 x^2\left[g_2(x,Q^2) - g_2^{WW}(x,Q^2)\right]dx$$



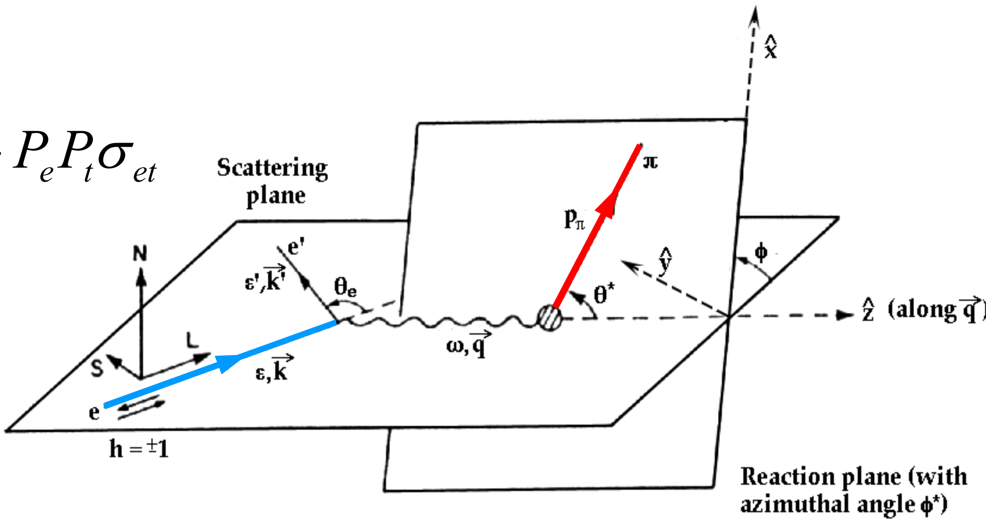
- provide direct information on higher twist contributions in spin structure functions
- precise evaluation of d_2 using world data for g_1
- measured values are systematically greater than zero

Spin Observables in Exclusive Reactions

Asymmetries and Resonance Amplitudes

Electroproduction Cross Section

$$\sigma\left(W, Q^2, \theta^*, \varphi^*\right) = \sigma_0 + P_e\sigma_e + P_t\sigma_t + P_eP_t\sigma_{et}$$



σ_0 : unpolarized cross section

$\sigma_e, \sigma_t, \sigma_{et}$: polarization cross sections

P_e, P_t : beam and target poalrization

$$A_{et} = \frac{\sigma_{et}}{\sigma_0}$$

→ related to the inclusive asymmetries A_1 and A_2

$$A_e = \frac{\sigma_e}{\sigma_0}$$

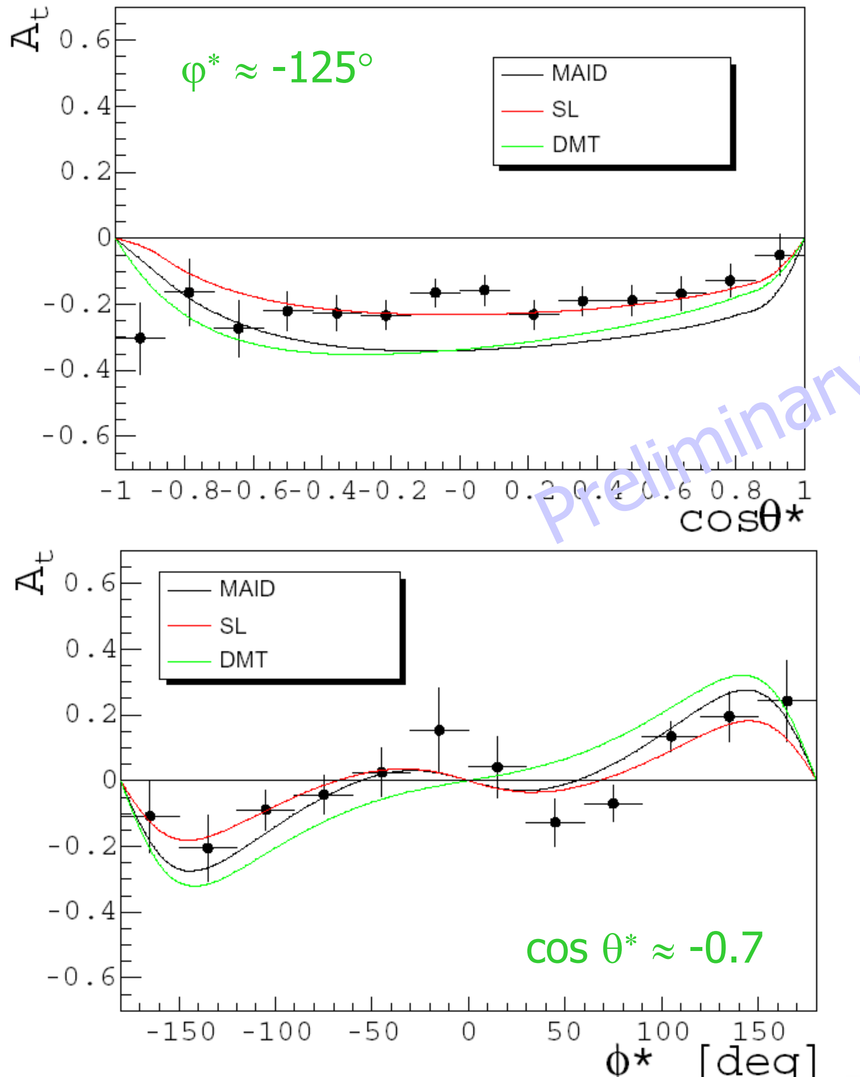
$$A_t = \frac{\sigma_t}{\sigma_0}$$

contain complementary information to what accessible in inclusive measurements, powerfull tool to investigate resonance structure

The $\Delta(1232)$ in π^0 production

$Q^2 \approx 0.4$ GeV^2
1.2 < W < 1.25 GeV

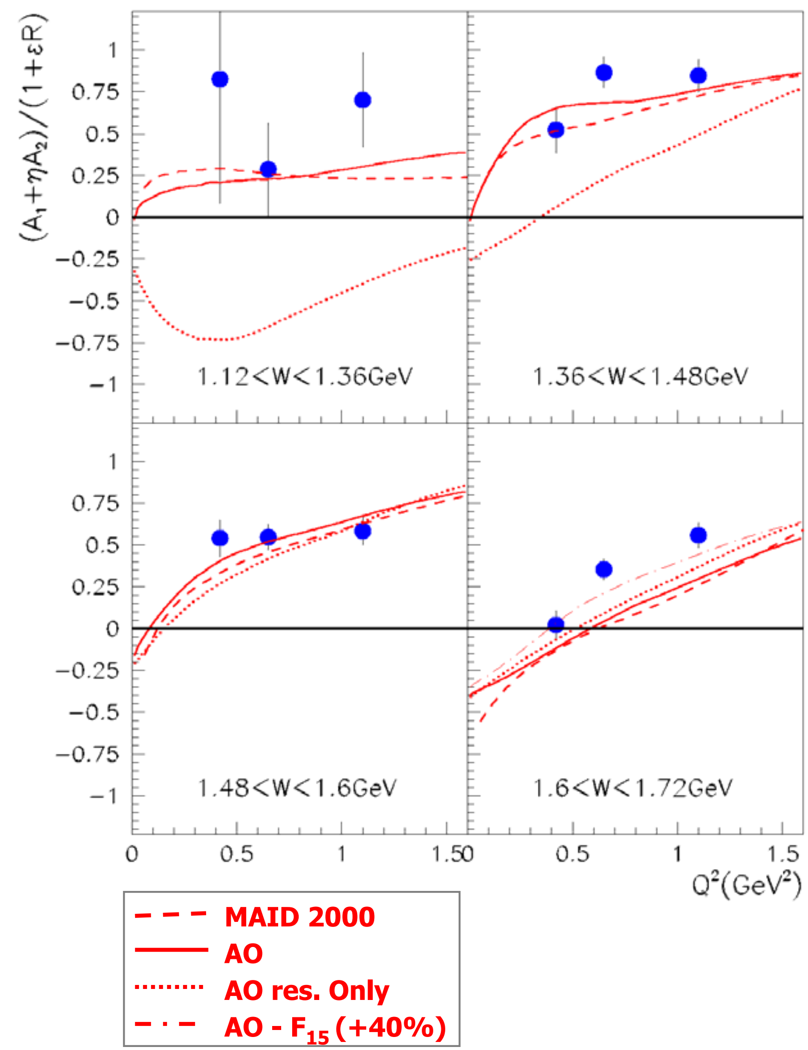
- At low Q^2 Δ production is dominated by the magnetic multiple M_1 (spin flip)
- At large Q^2 pQCD predicts $E_2/M_1 \rightarrow 1$
- Study of this transition requires extraction of small multipoles contribution $\rightarrow$ model dependence
- Measured target asymmetry shows sensitivity to resonance and background contribution and provide constrain to mnodel calculations



Resonance Contribution in $ep \rightarrow e'\pi^+ n$

E_0 = 2.5 GeV
$Q^2 \approx$ 0.5 GeV^2

- First measurement of double spin asymmetry
- Strong coupling of π^+ channel with second and third resonance region states
- Dominance of resonance contribution for W > 1.3 GeV
- Positive values of the measured asymmetry indicate dominance of $A_{1/2}$ amplitude
- Comparison with model predictions shows sensitivity single resonance contribution



Hall B

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η electroproduction

- η production channel is dominated by the decay of the $S_{11}(1535)$ resonance

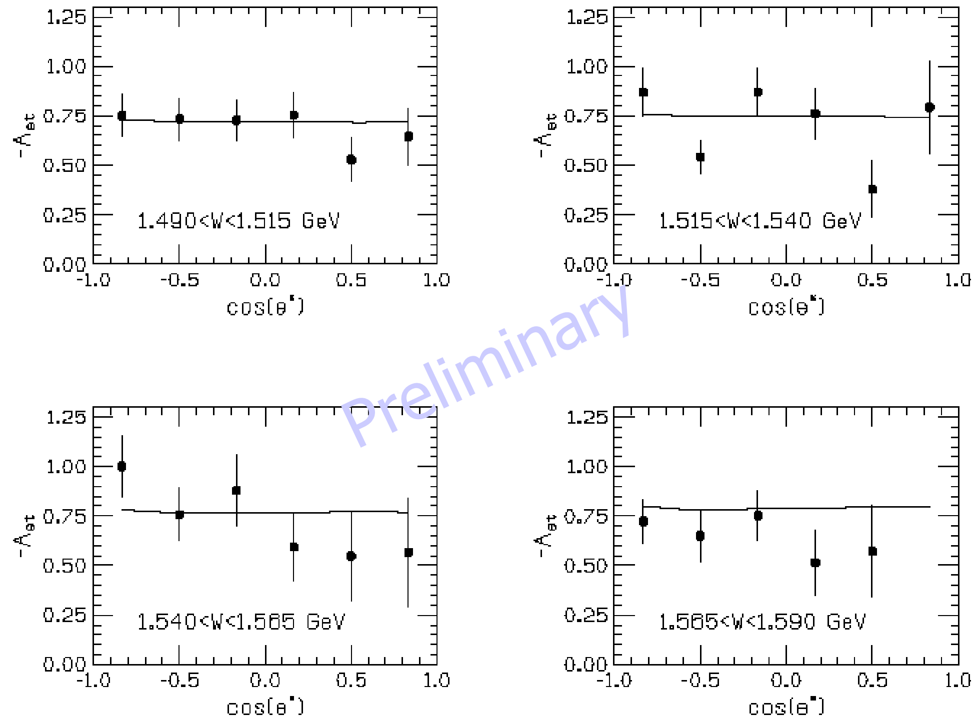
- in the the assumption of S_{11}dominance the double spin asymmetry is expected to be constant

$$A_{et} = D = \left(1 - \varepsilon \frac{E'}{E}\right)$$

- measured asymmetries are consistent with the hypothesis of S_{11} dominance

- good agreement with the prediction of eta-Maid model

E_0 = 1.6 GeV



→ see P. Bosted talk

Summary

◆ A broad physics program to study the nucleon spin structure in the non perturbative regime is in progress at Jefferson Lab

◆ These measurements aim at understanding the transition between hadronic and partonic degrees of freedom investigating phenomena such as resonance excitation, duality in spin structure functions, higher twists,...

- ◇ Inclusive measurements have shown that spin structure functions undergo to a dramatic change as Q^2 varies between 0.1 and 2 GeV^2.
- ◇ Significant contribution from higher twist have been found in the same Q^2 range.
- ◇ Measurement of spin polarizabilities indicates inconsistencies with χPT prediction.
- ◇ Duality in spin structure functions is found to hold for $Q^2 > 2$ GeV^2
- ◇ Measurement of spin observables in exclusive channels shows strong sensitivity to resonance parameters and allow to put stringent constraints on effective models

◆ New measurements to extend and complete the existing program are planned in the near future