The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR.1751 - 16

Fifth International Conference on
PERSPECTIVES IN HADRONIC PHYSICS
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

22 - 26 May 2006

Nucleon Spin Physics with CLAS at Jlab

Marco RIPANI
Istituto Nazionale di Fisica Nucleare
Sezione di Genova
Dipartimento di Fisica
Via Dodecaneso 33
16146 Genova
ITALY

Nucleon spin physics with CLAS at Jlab

Marco Ripani

INFN Genova, Italy

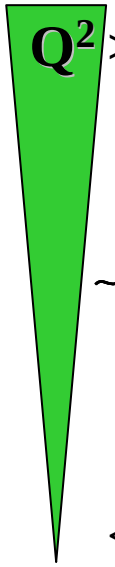
For the EG1 group and CLAS collaboration

Fifth International Conference on PERSPECTIVES IN HADRONIC PHYSICS
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies
22 - 26 May 2006, ICTP Trieste, Italy

Outline

- Physics Motivation
- Experimental Setup
- Nucleon Structure Functions:
  - Spin structure function and their x and Q^2 dependence
  - Large-x behavior
  - Sum rules, Moments and Higher Twists
  - New low Q^2 experiment

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)

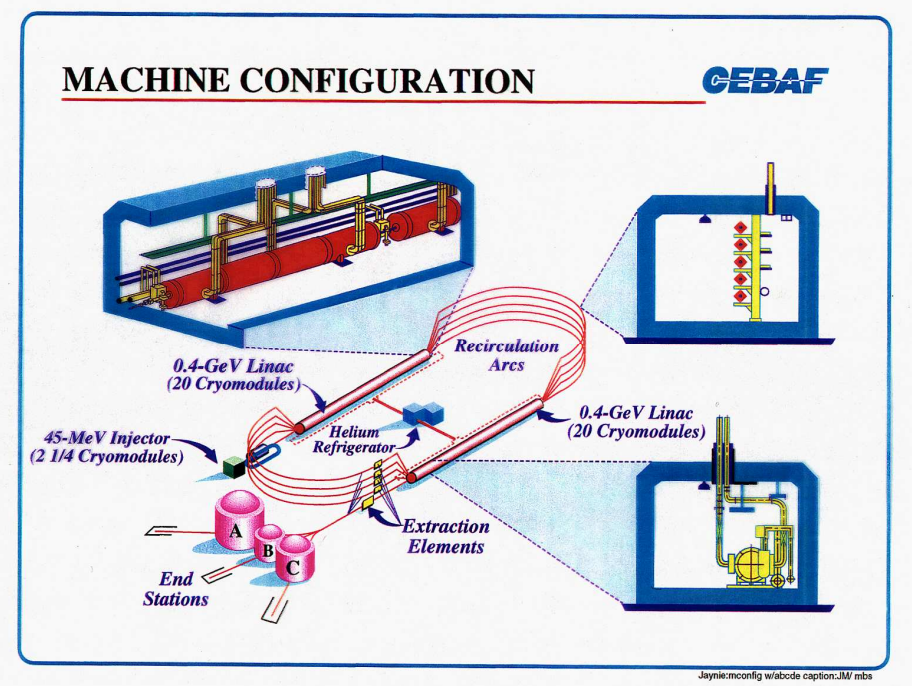
As Q^2 decreases, non-perturbative effects start to play a dominant role and the connection between the observed nucleon properties and its elementary constituent becomes highly non trivial

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 in Hall B at Jefferson Lab with the goal of mapping this kinematic region

Jefferson Lab



CEBAF is a superconductive electron accelerator

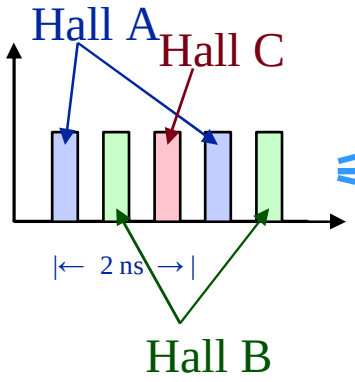
→ continuous beam

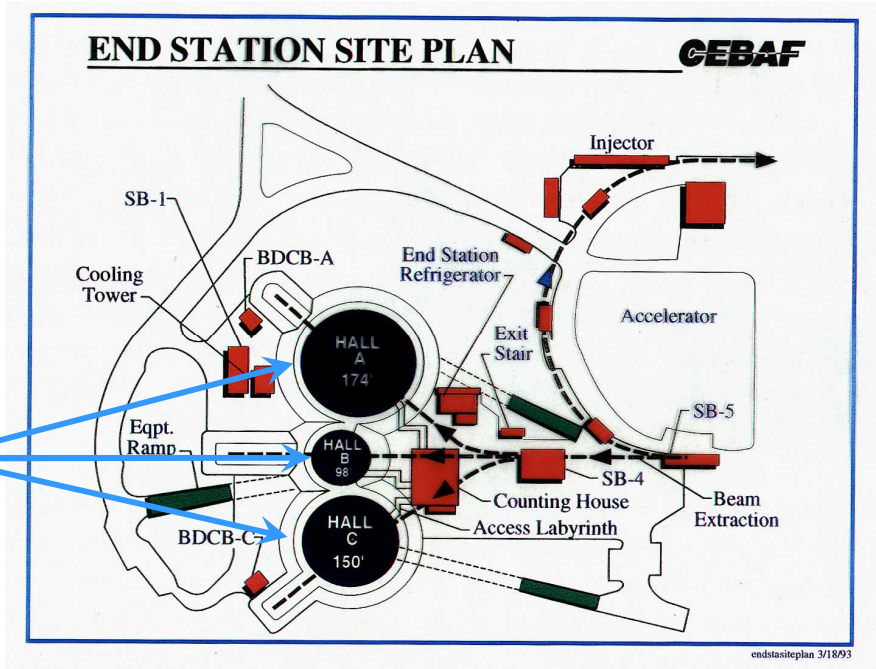
→ high longitudinal polarization

→ energy range → 0.75 –5.9 GeV

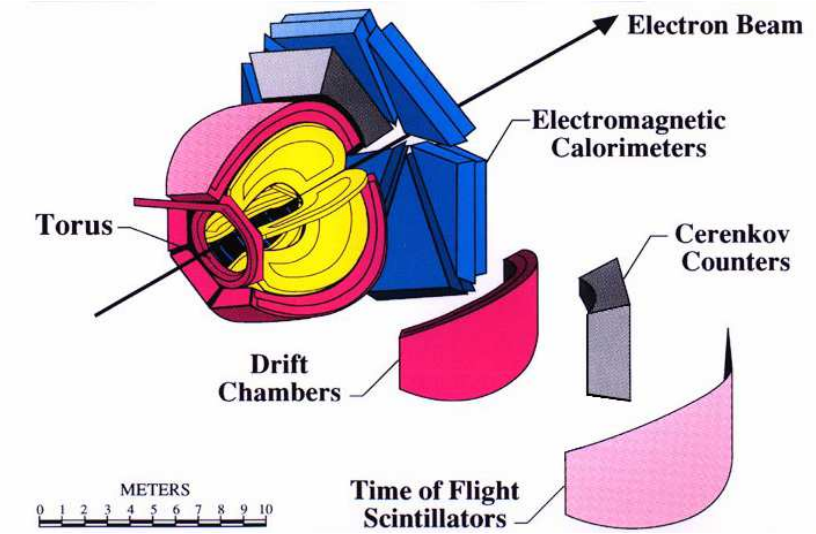
→ current range → 0.1 nA –200μA

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

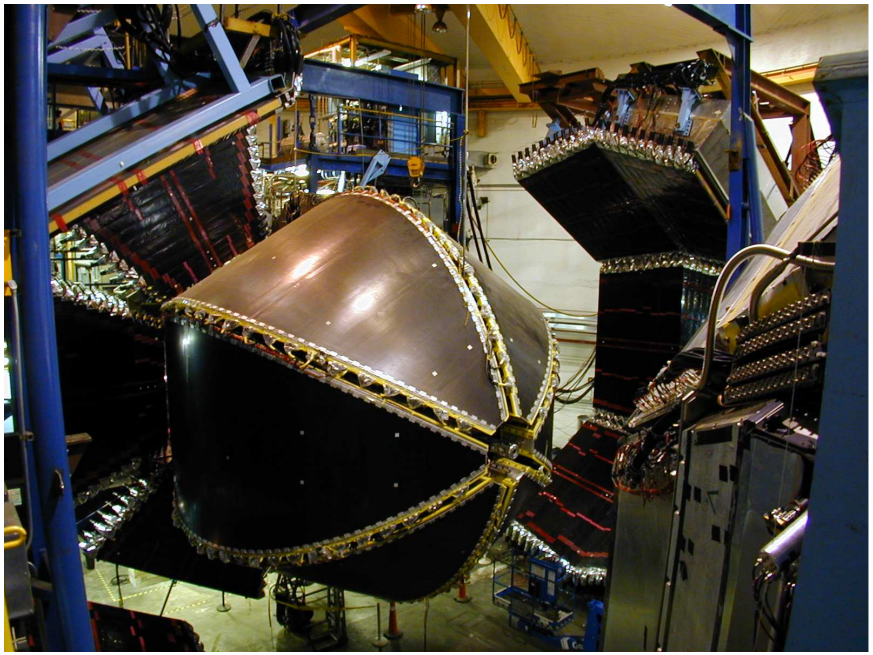




Experimental Setup



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 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 deuteron

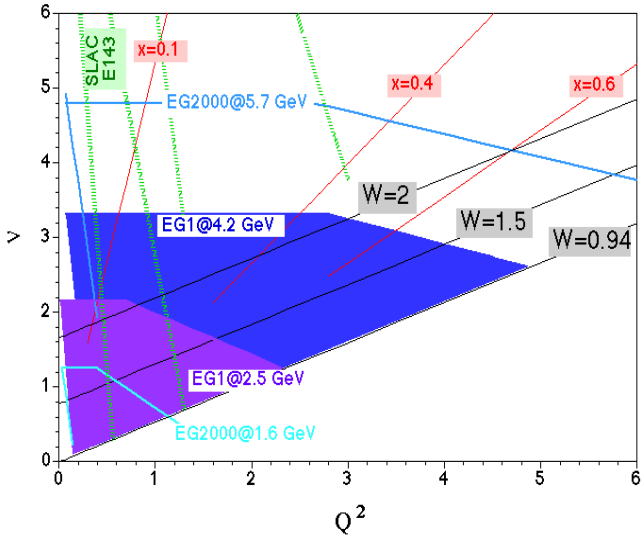
- test of duality of spin structure function
  (see talk by P. Bosted)

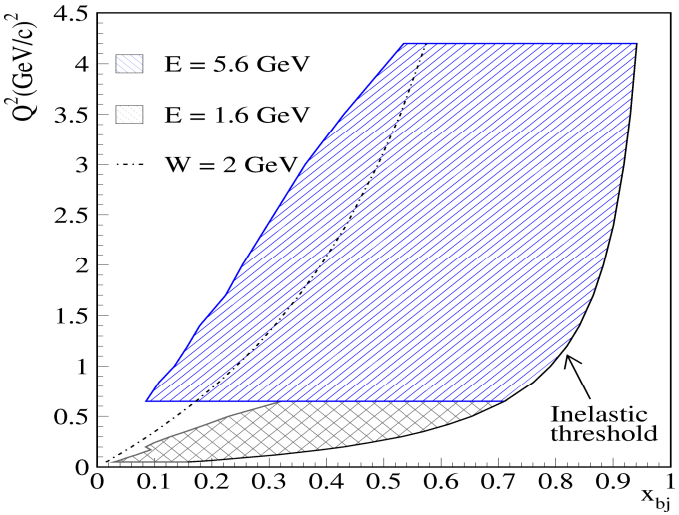
- extraction of the moments of the proton and neutron structure functions and study of higher twist contribution

- study of the nucleon resonance structure from polarization observables in exclusive meson production

- measurement of spin asymmetries in semiinclusive processes

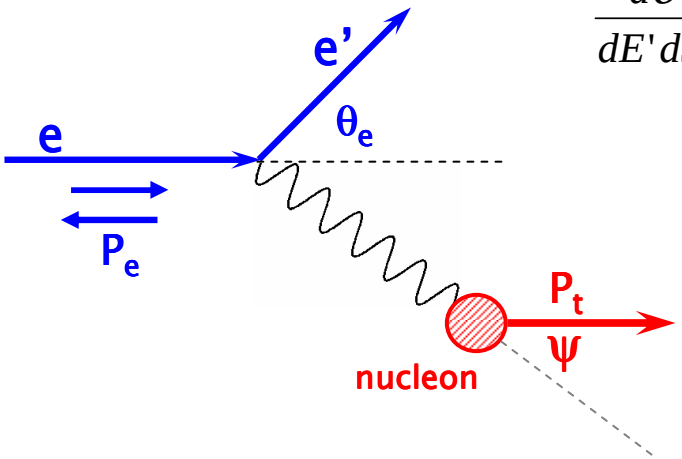
- deeply virtual compton scattering on polarized target





Spin Structure Functions and their x and Q^2 dependence

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

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

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 $\mathbf{A_2}$

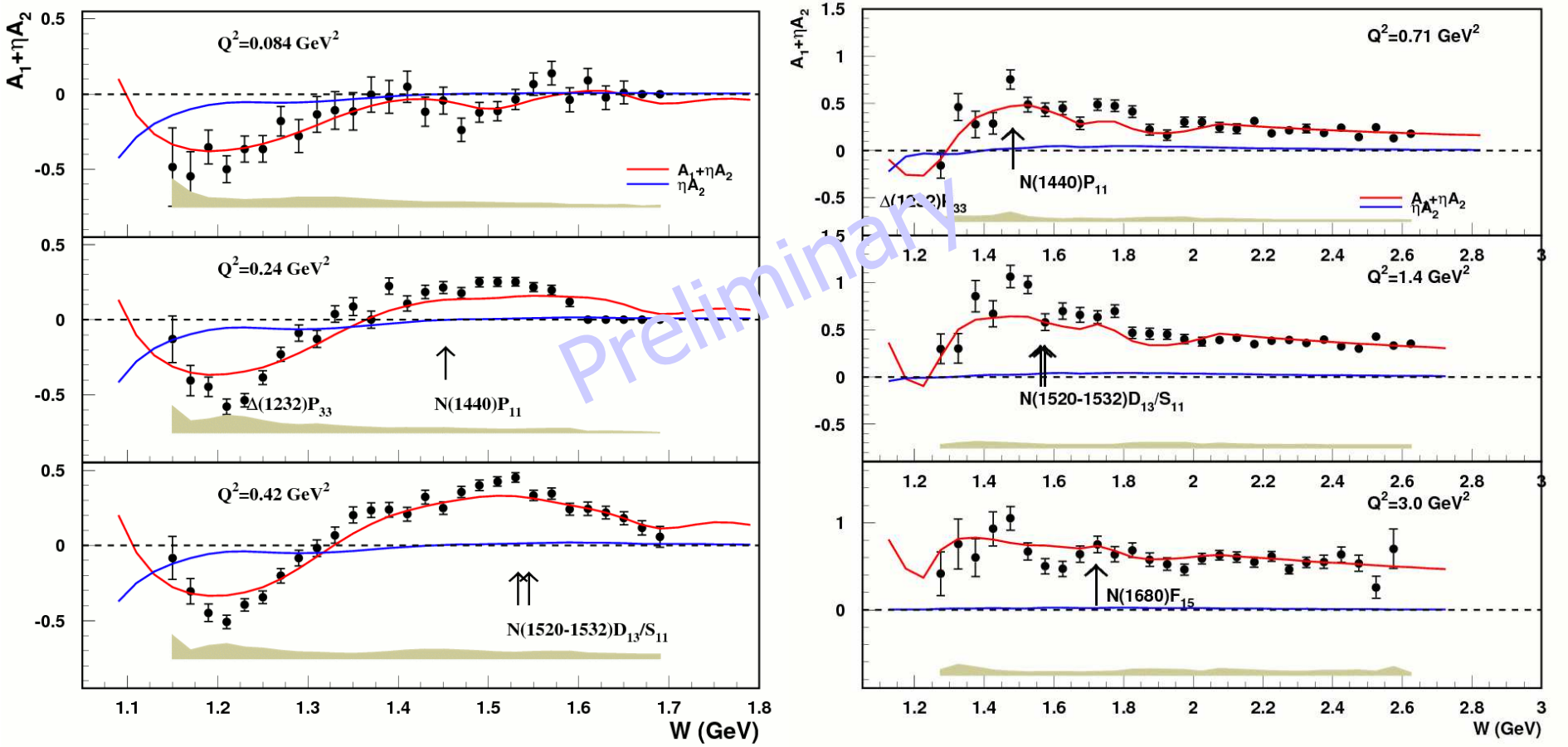
$$\mathbf{g_1(x,Q^2)} = \frac{Q^2}{Q^2+4M^2x^2}\left(A_1 + \frac{2Mx}{\sqrt{Q^2}}A_2\right)F_1\left(x,Q^2\right)$$

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

$A_1+\eta A_2$ for proton

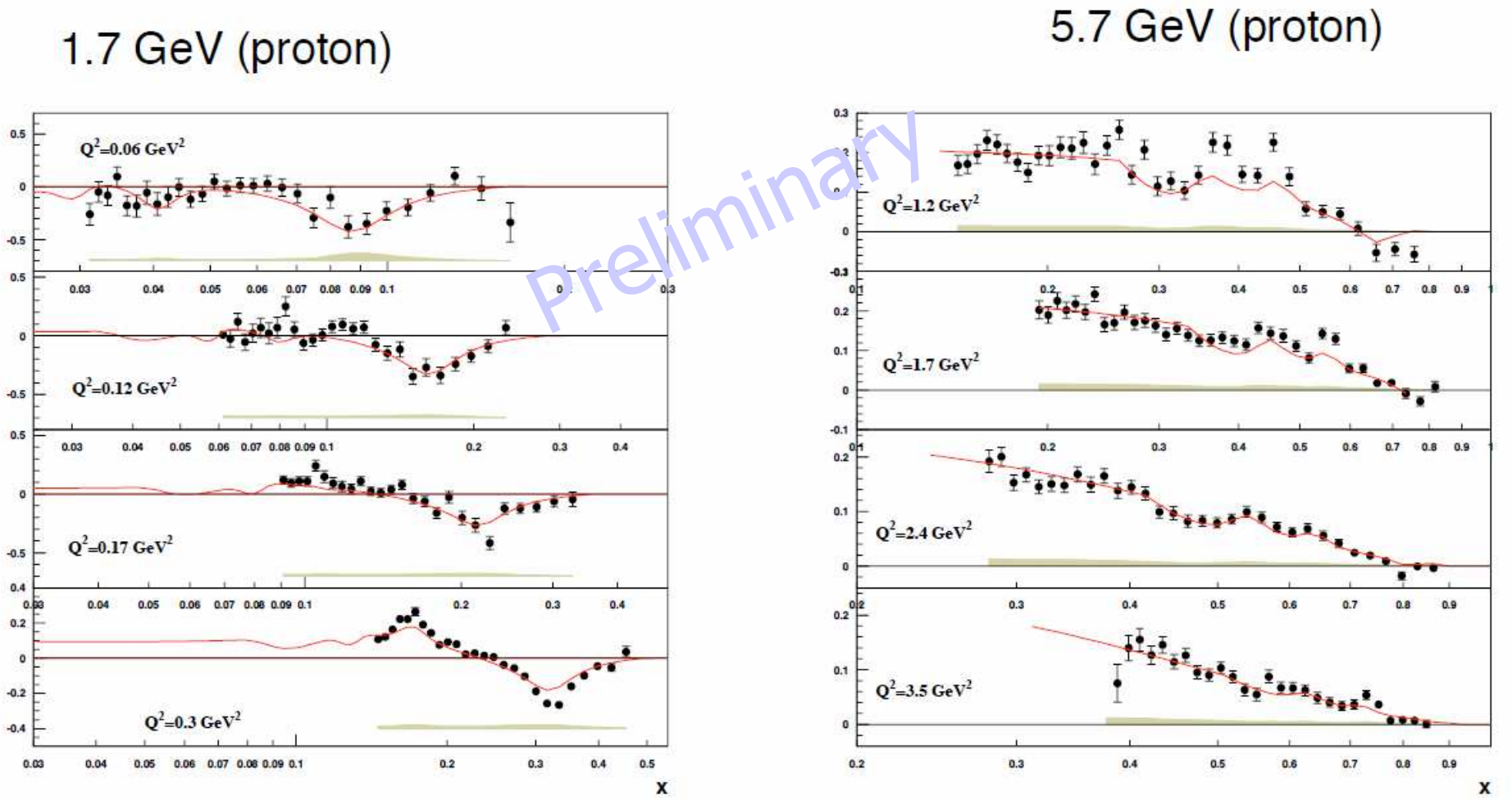
1.7 GeV (proton)

5.7 GeV (proton)



Red solid line = Parametrization of previous world data, including CLAS data
(S. Kuhn et al. following original work from L. Stuart at SLAC,
further updated to include "AO" and "MAID2000" codes for resonance region)
Blue solid line = Estimated contribution from the unmeasured
asymmetry A_2 to the asymmetry $A_1+\eta A_2$

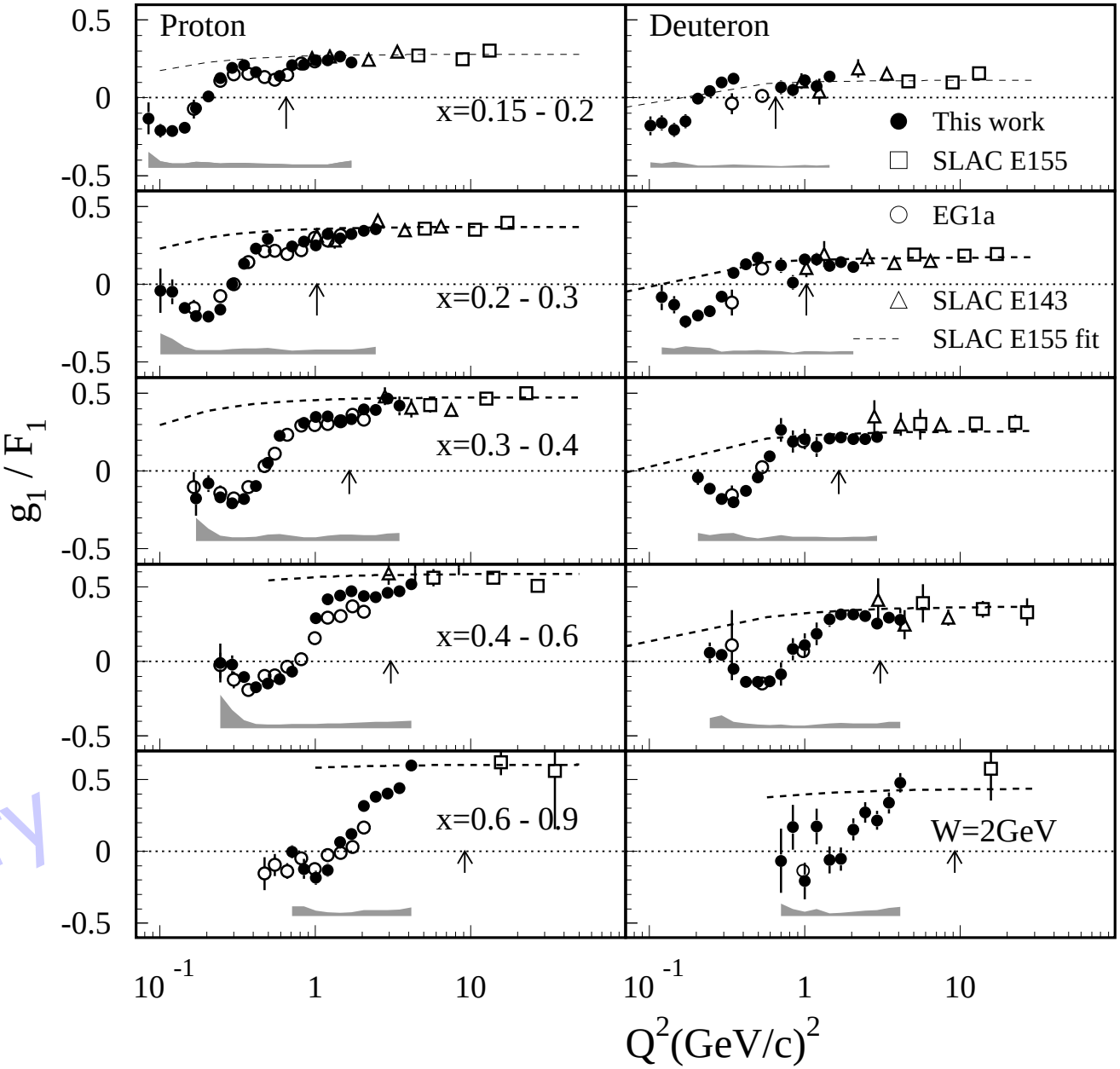
g_1 for the proton



Red solid line =
Parameterization of previous world data, including CLAS data

Q^2 dependence of g_1/F_1

- Q^2 dependence of g_1 at fixed x is very similar to F_1 in the DIS region
- Our data show a decrease in g_1/F_1 even in the DIS region
- Resonance region ➔ different Q^2 dependence ➔ goes negative at Δ



Large x behavior

Large-x behavior of the A_1 asymmetry

- SU(6) ➔ $A_1^p = \frac{5}{9},\ A_1^n = 0$

- Hyperfine perturbed QM **Isgur, PRD 59, 034013 (2003)**
  - ✓ makes S=1 pairs more energetic than S=0 pairs
  - ✓ At large x struck quark carries the spin of the nucleon

- Duality **Close and Melnitchouk, PRC 68, 035210 (2003)**
  - ✓ Suppress transitions to specific resonances (56^+ and 70^-)

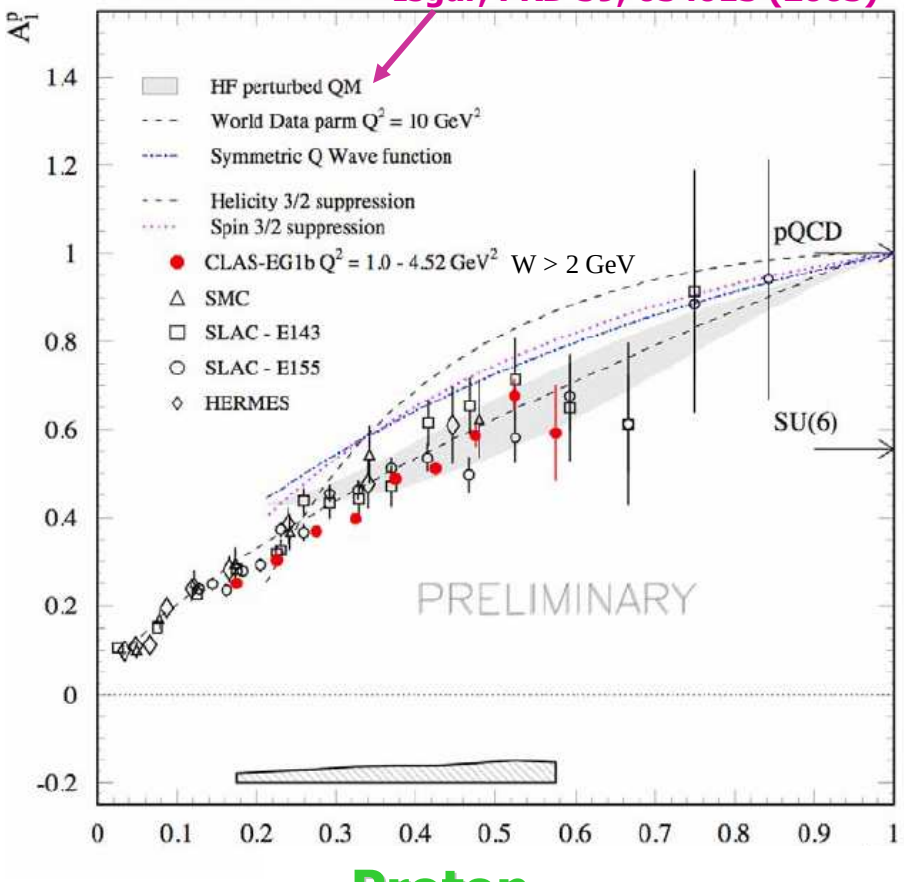
- In DIS, $A_1 \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)} \rightarrow \frac{\sum e_i^2 \Delta q_i(x)}{\sum e_i^2 q_i(x)}$ and in PQCD
  - ✓ Minimal gluon exchanges
  - ✓ Spectator pair: quarks have opposite helicities
  - ✓ A1 →1

Farrar and Jackson, PRL 35, 1416 (1975)

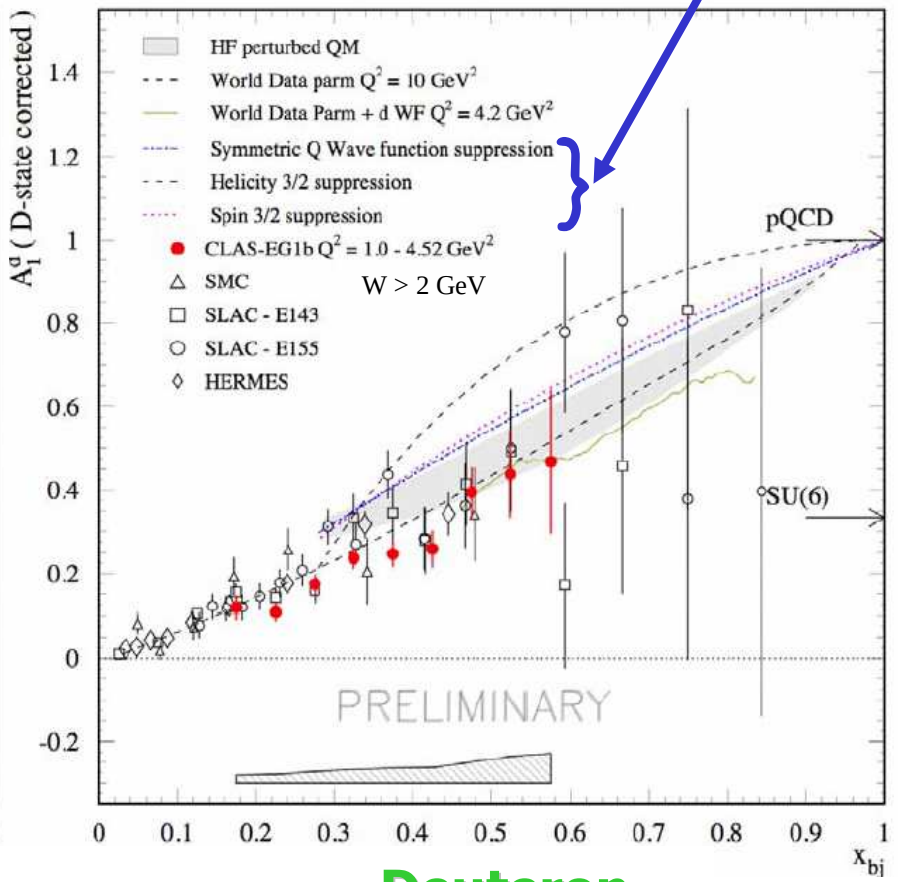
Large-x behavior of A_1

Isgur, PRD 59, 034013 (2003)

Close and Melnitchouk, PRC 68, 035210 (2003)



Proton



Deuteron

- P and d results fall below parameterization of world data at 10 GeV^2 → include in DGLAP fits
- To be used to extract $\Delta q/q$ in this momentum transfer region (see talk by M. Garçon)
- P and d results are in better agreement with the HFP quark model

Sum Rules, Moments and Higher Twists

GDH Sum Rule

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

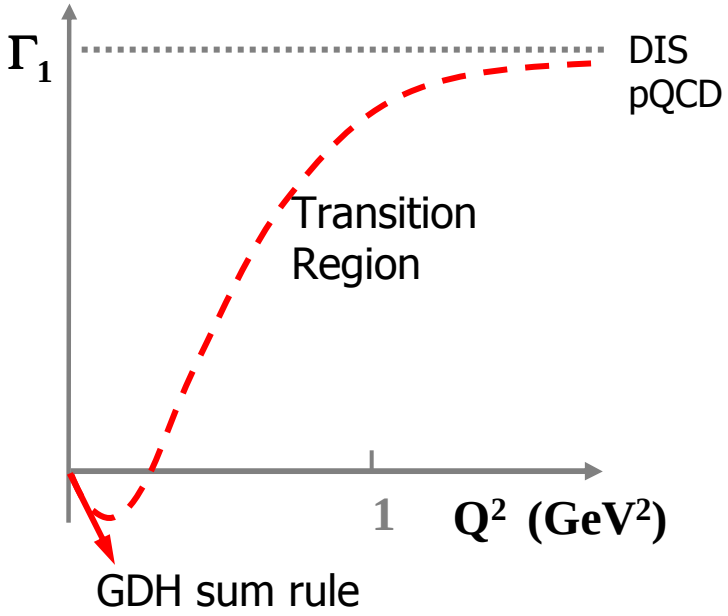
- relates the difference of the photo-absorption cross section for helicity 1/2 and 3/2 to the nucleon magnetic moment, i.e. a connection between dynamic and static properties. Recent measurements at Bonn and Mainz, ongoing efforts at other labs

- 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

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

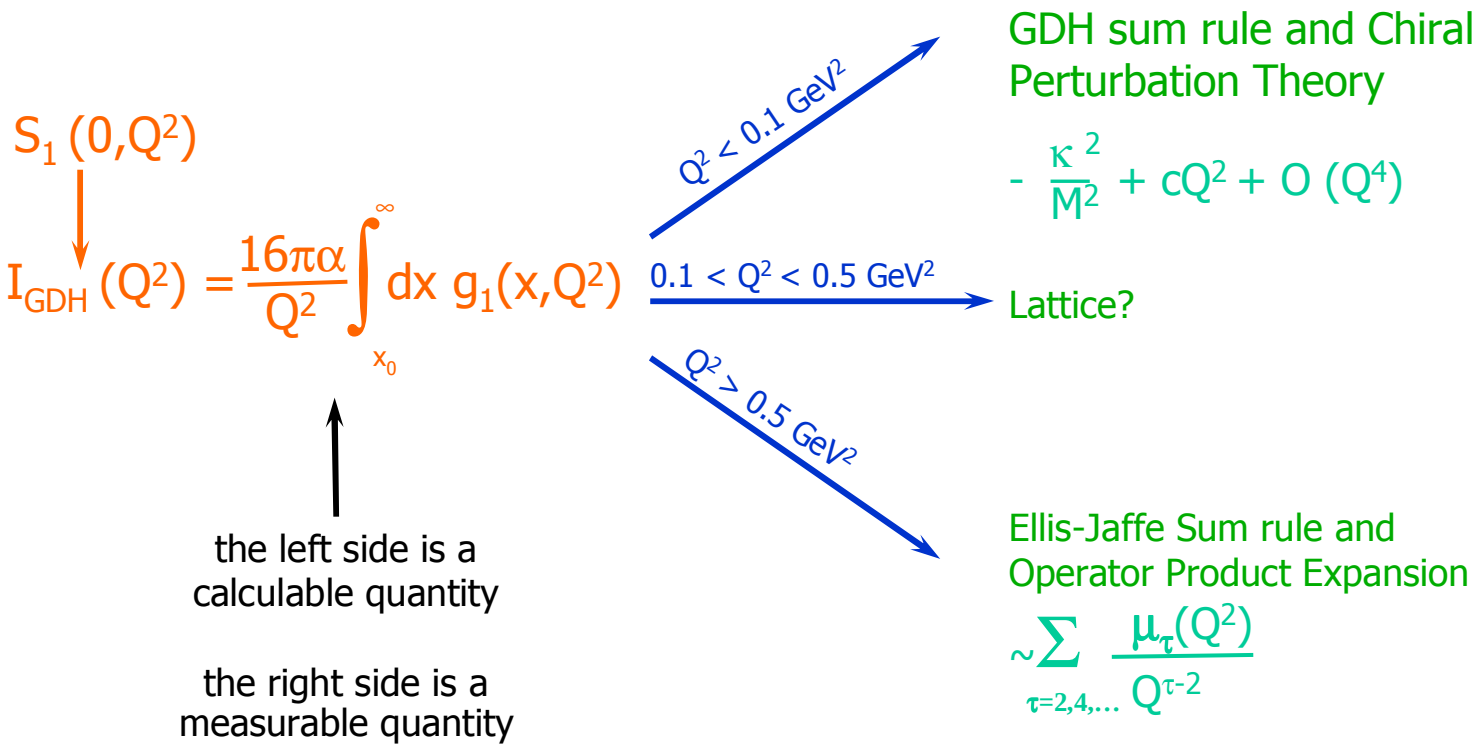
- strong variation of nucleon spin properties as a function of Q^2



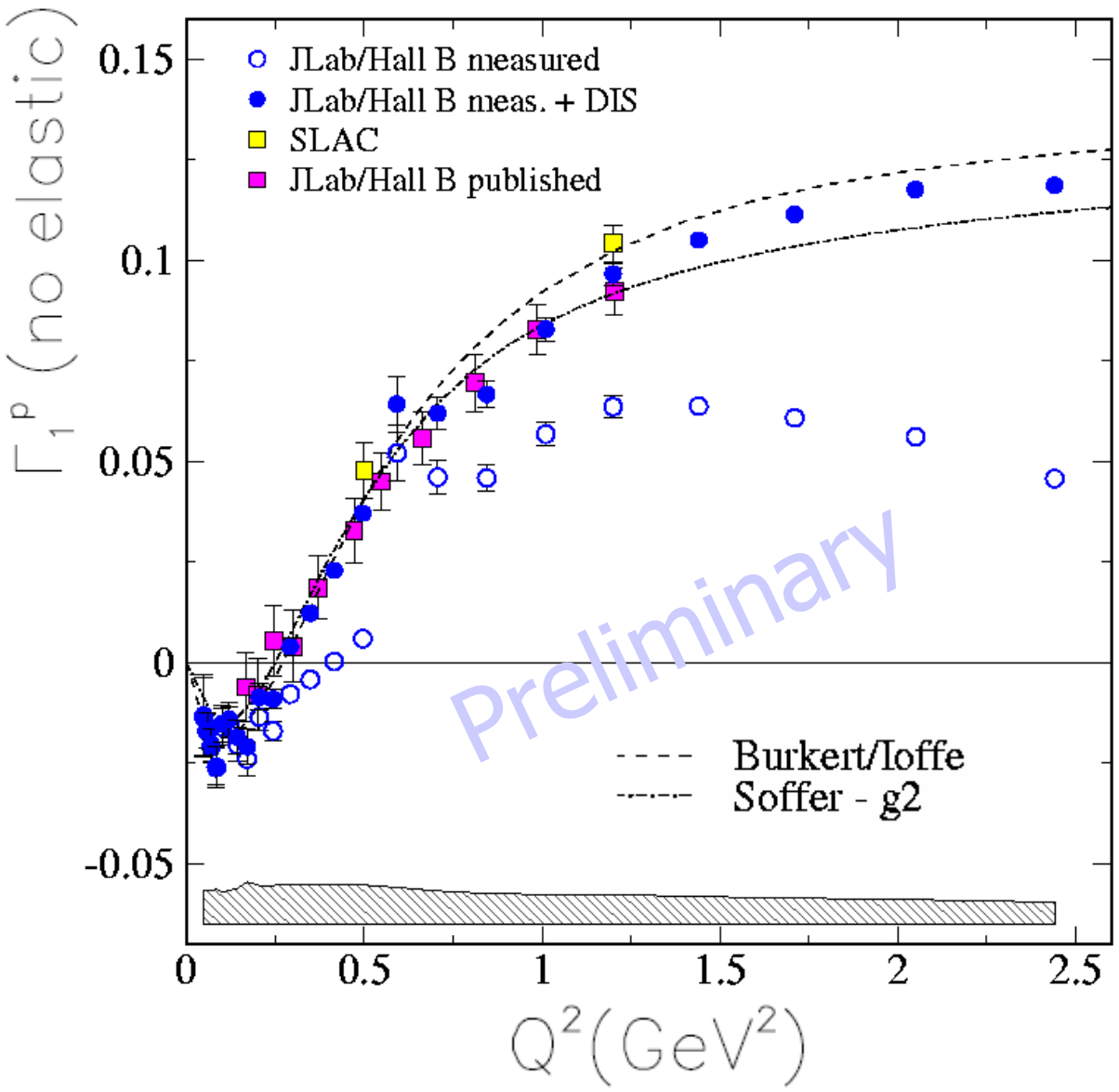
Generalized GDH Integral

A generalization of the GDH sum rule has been suggested by Ji and Osborne by relating the virtual-photon forward Compton amplitude S_1 to the nucleon structure function Γ_1

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

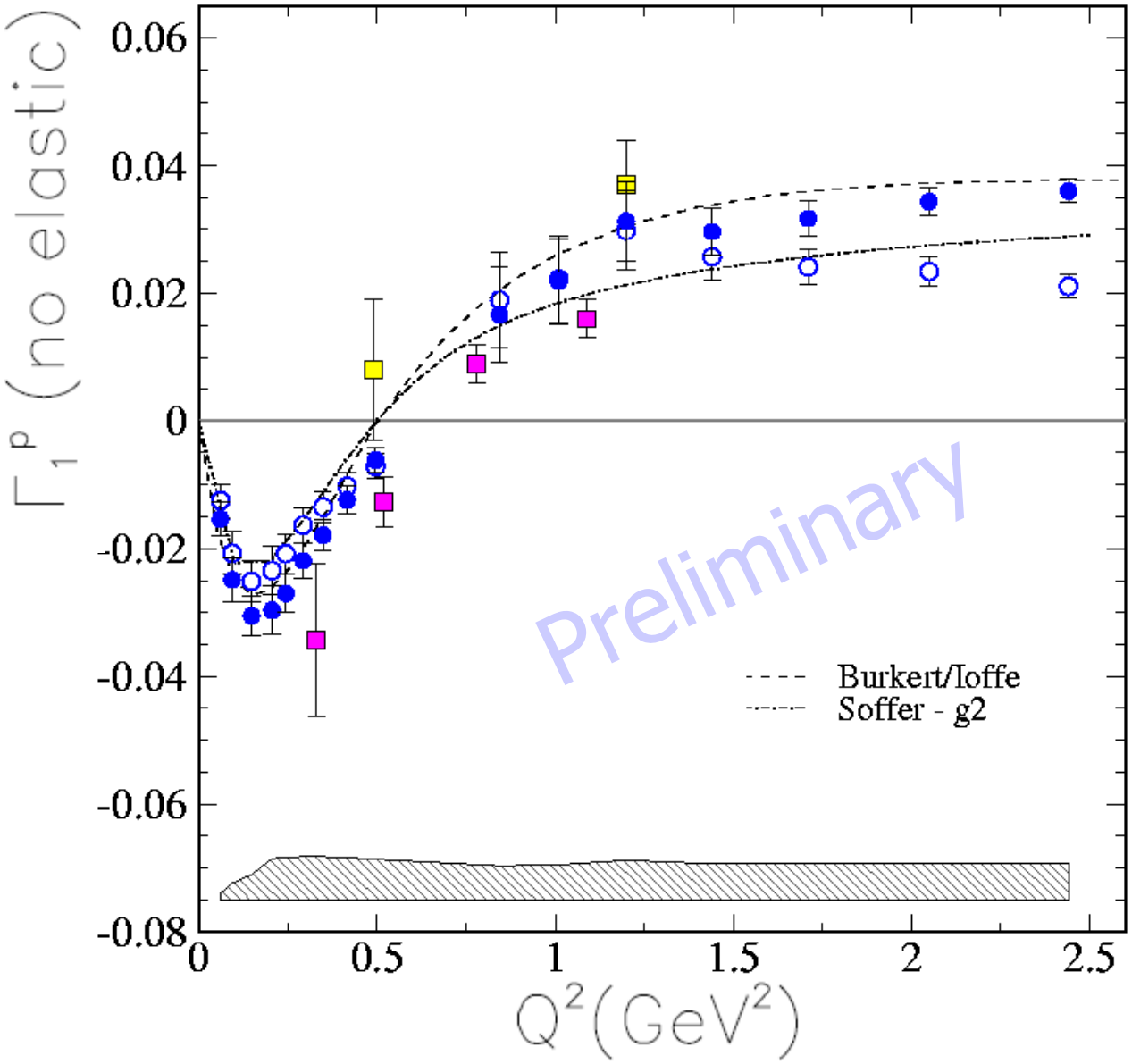


Integral of g_1 on the Proton



- the integral is consistent with previous SLAC data
- shows strong Q^2 dependence varying from negative to positive values as Q^2 increases
- change in slope occurs at 0.15 GeV^2

Integral of g_1 on the Deuteron

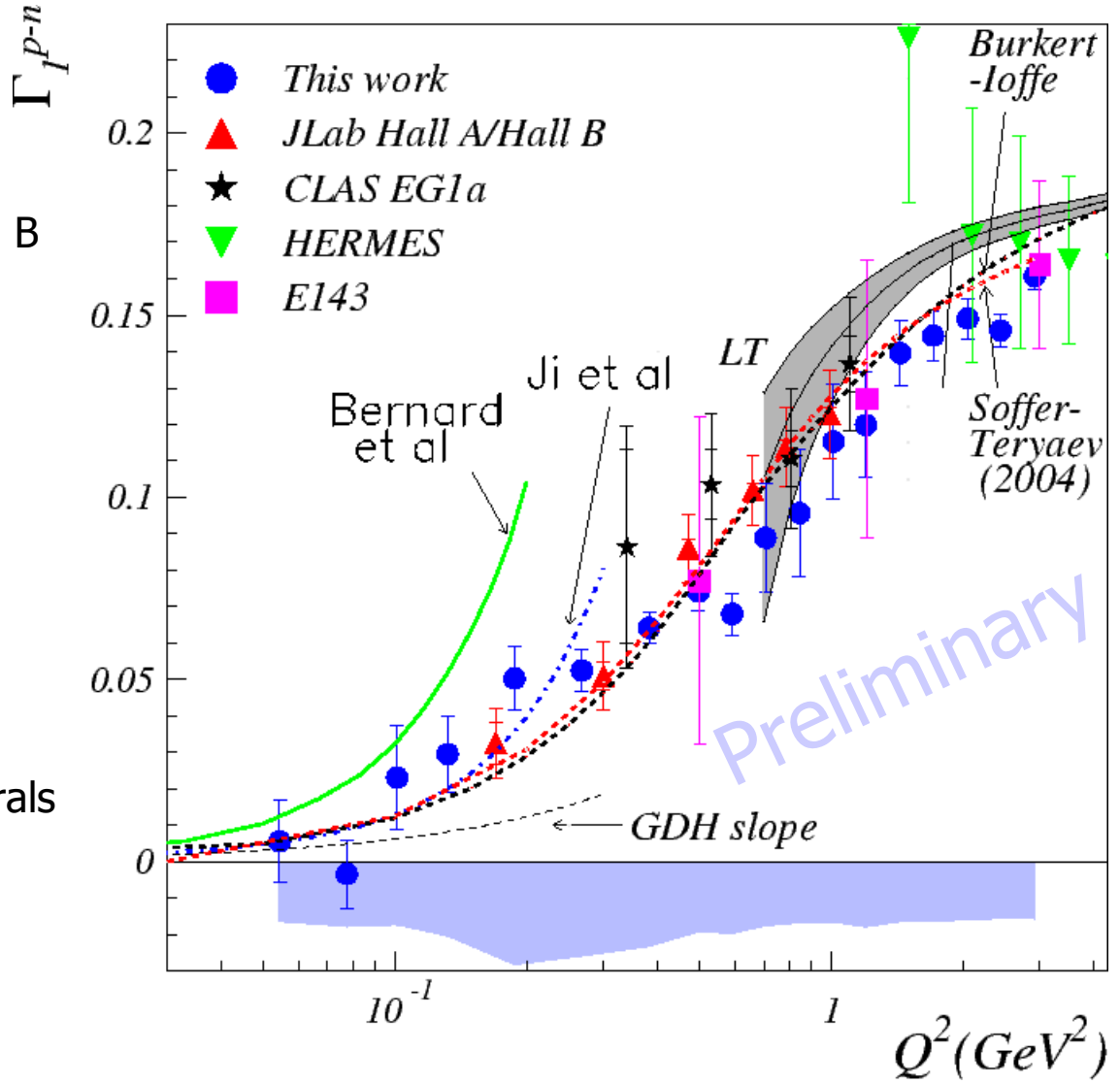


- consistent with previous SLAC data
- slower transition than for the proton
- change in slope occurs at 0.2 GeV^2

Bjorken Sum Rule

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

- combined analysis of Hall A and Hall B measurements
  A. Deur et al., PRL 93 212001(2004)
  and new preliminary analysis
  (A. Deur et al.)
- 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



Moments and Higher Twists

◆ New global extraction of g1 structure functions and analysis in terms of OPE

➔ Higher Twist extraction

M. Osipenko et al., PRD 71, 054007(2005); PLB 609, 259(2005)

Nachtmann moments
(Leading twist is incorporating correctly kinematic twists)

$$M_1(Q^2) = \int_0^1 dx \, \frac{\xi^2}{x^2} \left\{ g_1(x,Q^2) \left(\frac{x}{\xi} - \frac{1}{9} \frac{M^2 x \xi}{Q^2} \right) - g_2(x,Q^2) \frac{4}{3} \frac{M^2 x^2}{Q^2} \right\}$$

$$M_1(Q^2) = \mu_2(Q^2) + \frac{\mu_4(Q^2)}{Q^2} + \frac{\mu_6(Q^2)}{Q^4} + \cdots$$

$$\mu_2(Q^2) = C_s(Q^2) \frac{a_0^{\rm inv}}{9} + C_{\rm ns}(Q^2) \left(\frac{a_3}{12} + \frac{a_8}{36} \right)$$

$$\mu_4(Q^2) = 4 f_2(Q^2)/9M^2$$

$$f_2(Q^2)\, M^2 S^\mu = \frac{1}{2} \sum_q e_q^2 \, \langle N | g \, \bar{\psi}_q \, \tilde{G}^{\mu\nu} \gamma_\nu \, \psi_q | N \rangle$$

a_3, a_8 taken from β decay

More in talk by W. Melnitchouk

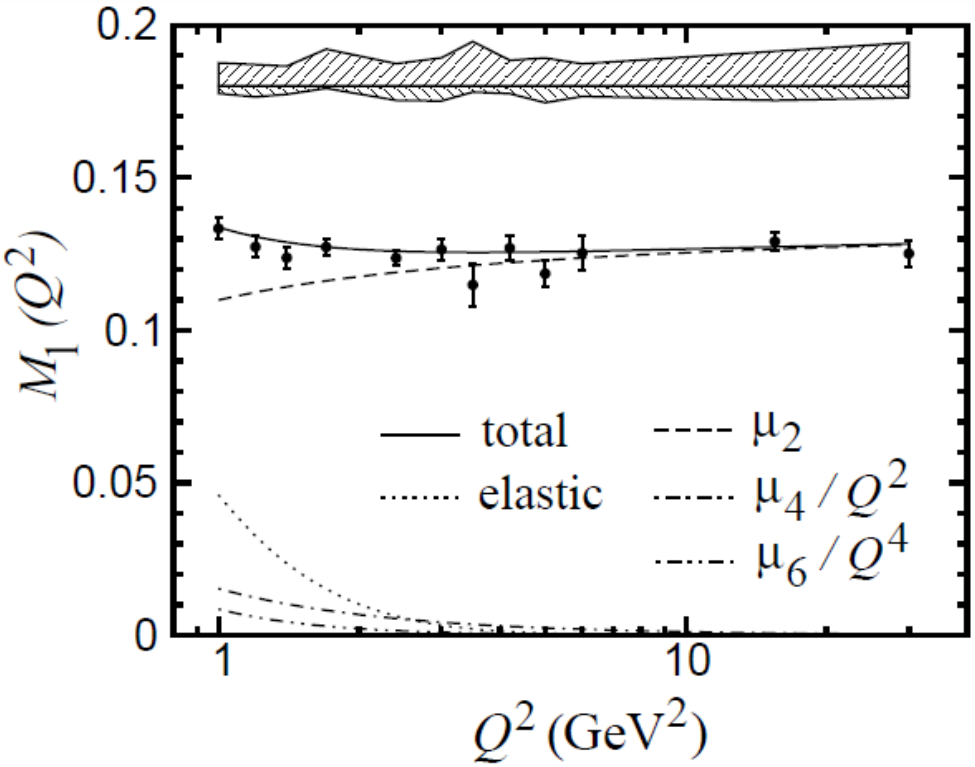
First moment and HT

High Q^2 fit

$$a_0^{\rm inv} = 0.145 \pm 0.018\,(\text{stat.}) \pm 0.103\,(\text{sys.}) \pm 0.041\,(\text{low } x) \pm {}^{0.006}_{0.010}\,(\alpha_s)$$

Low Q^2 fit

$$f_2 = 0.039 \pm 0.022\,(\text{stat.}) \pm {}^{0.000}_{0.018}\,(\text{sys.}) \pm 0.030\,(\text{low } x) \pm {}^{0.007}_{0.011}\,(\alpha_s)$$



➔ **Higher twists small…**

Color polarizabilities

$$\chi_E = \frac{2}{3}(2d_2 + f_2)$$
$$\chi_B = \frac{1}{3}(4d_2 - f_2)$$

$$d_2(Q^2) = \int_0^1 dx\, x^2 \left[2g_1(x,Q^2) + 3g_2(x,Q^2)\right]$$

$$\chi_E = 0.026 \pm 0.015\ (\text{stat.}) \pm {}^{0.021}_{0.024}\ (\text{sys.})$$
$$\chi_B = -0.013 \mp 0.007\ (\text{stat.}) \mp {}^{0.010}_{0.012}\ (\text{sys.})$$

- Disagrees with QCD sum rules, instanton vacuum model
- Consistent with MIT bag model

New low Q^2 measurement

New Experiments

New completed experiment:

E-03-006 **The GDH Sum Rule with nearly real photons and the proton g1 structure function at low momentum transfer**

New Proposals:

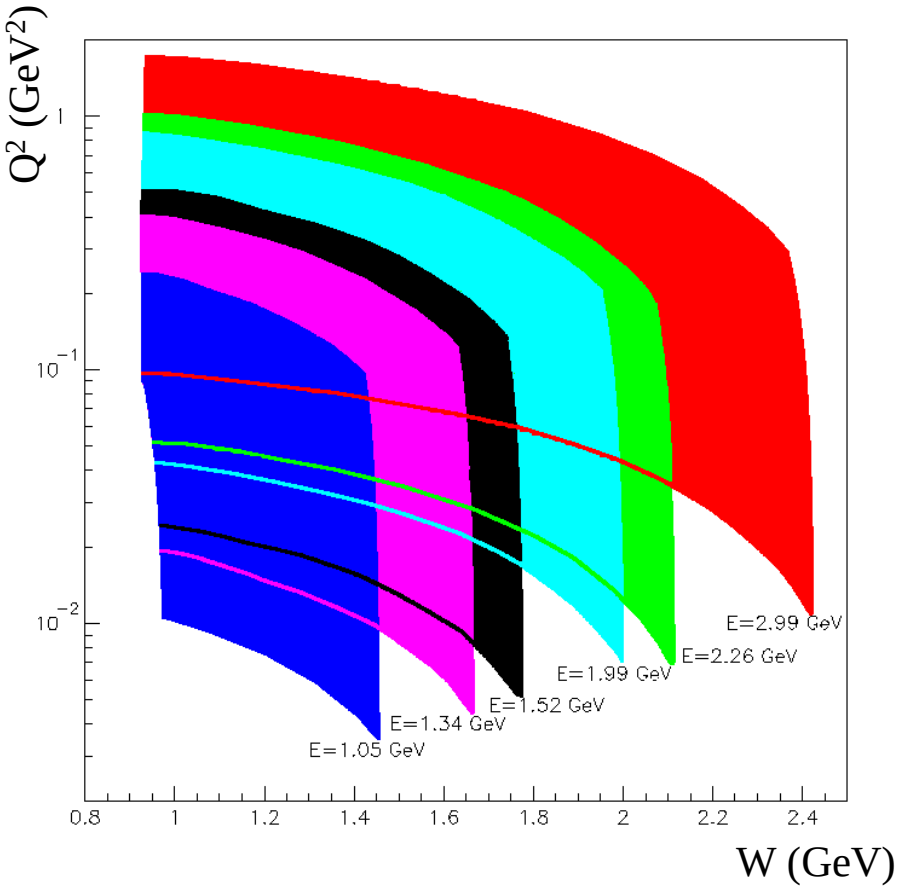
P-05-111 ***Measurement of the Gerasimov-Drell-Hearn Integral at low Q^2 on the Neutron and Deuteron***

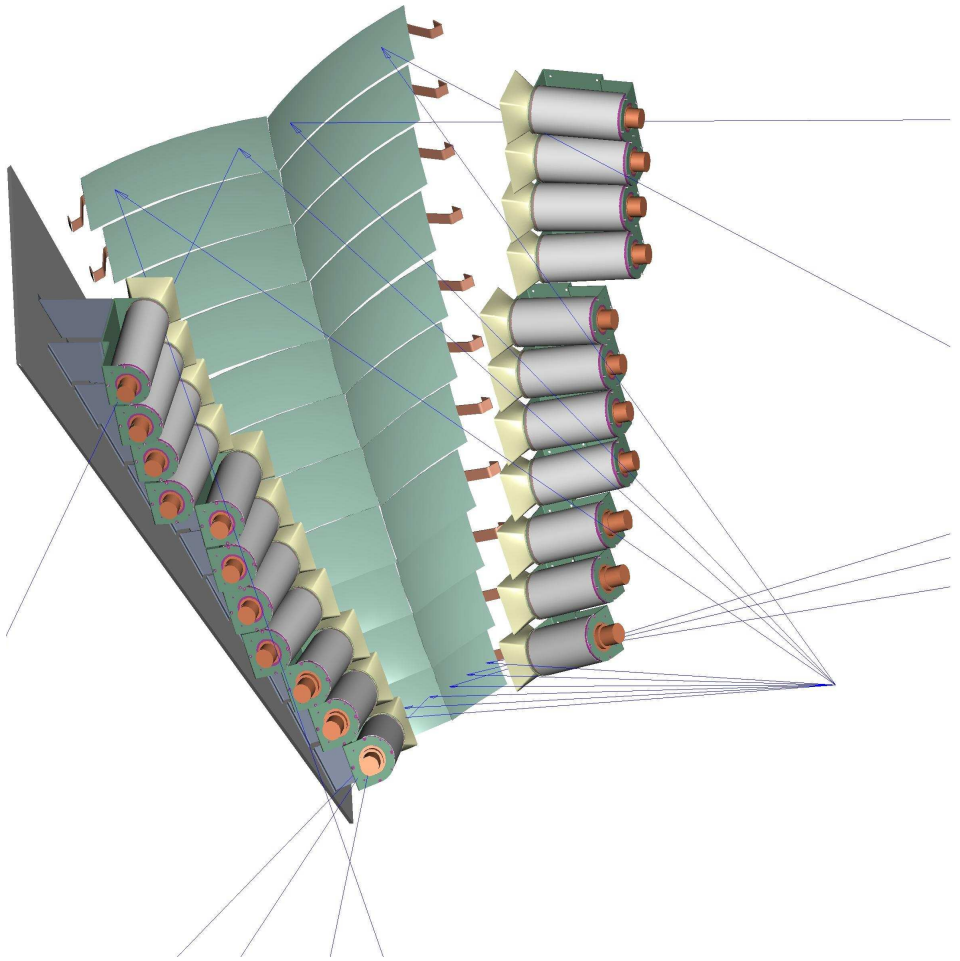
P-05-113 ***Semi-Inclusive Pion Production with a Longitudinally Polarized Target at 6 GeV***

P-05-114 ***Deeply Virtual Compton Scattering at 6 GeV with polarized target and polarized beam using the CLAS detector***

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 down to ~ 6 deg. (INFN-Genova)

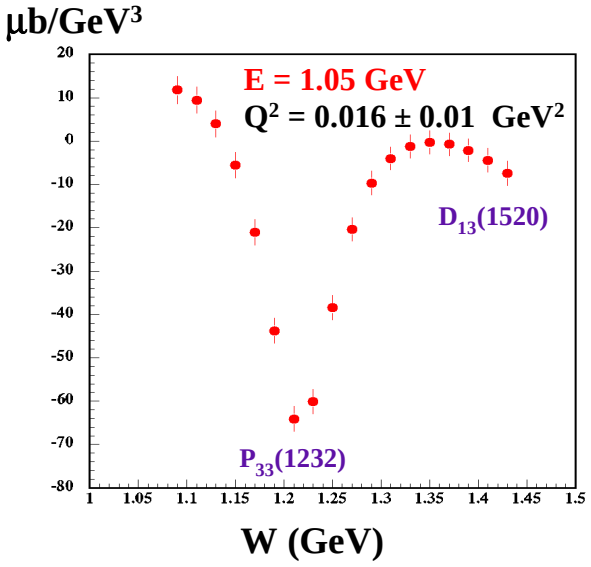


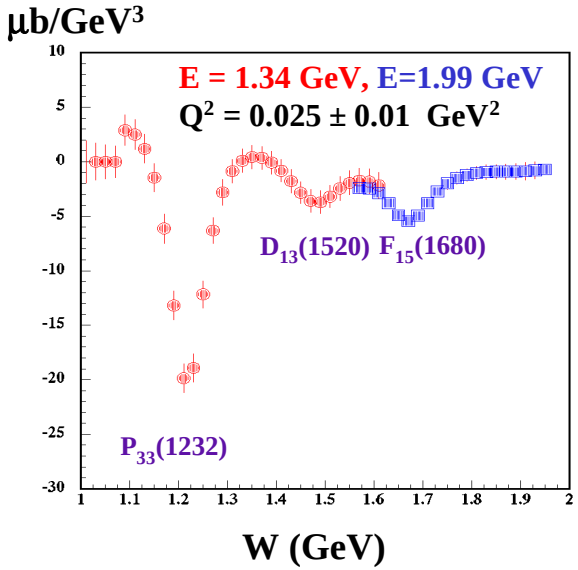


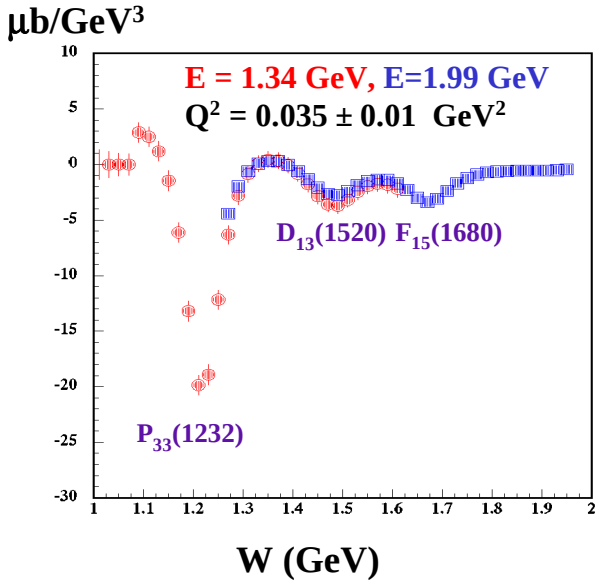
Proton Structure Function at Very Low Q^2

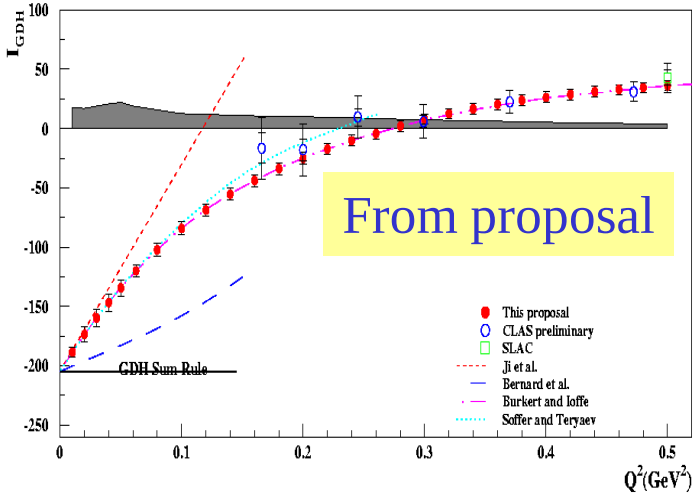
expected results for statistical errors
on top of THEORETICAL cross section difference
based on S. Simula's parameterization,
S. Simula et al., PRD 65, 034017 (2002)

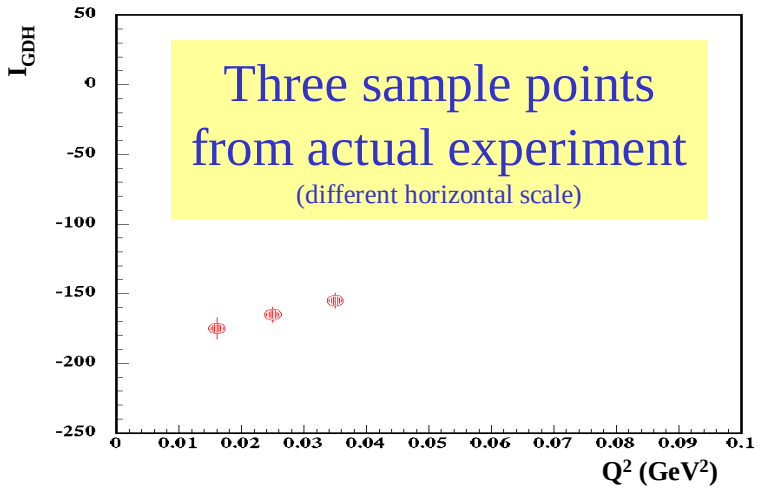
$$\frac{d\sigma^{\rightarrow\Leftarrow}}{d\Omega dE'} - \frac{d\sigma^{\rightarrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{ME\nu Q^2}\left[(E - E'\cos\vartheta)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$







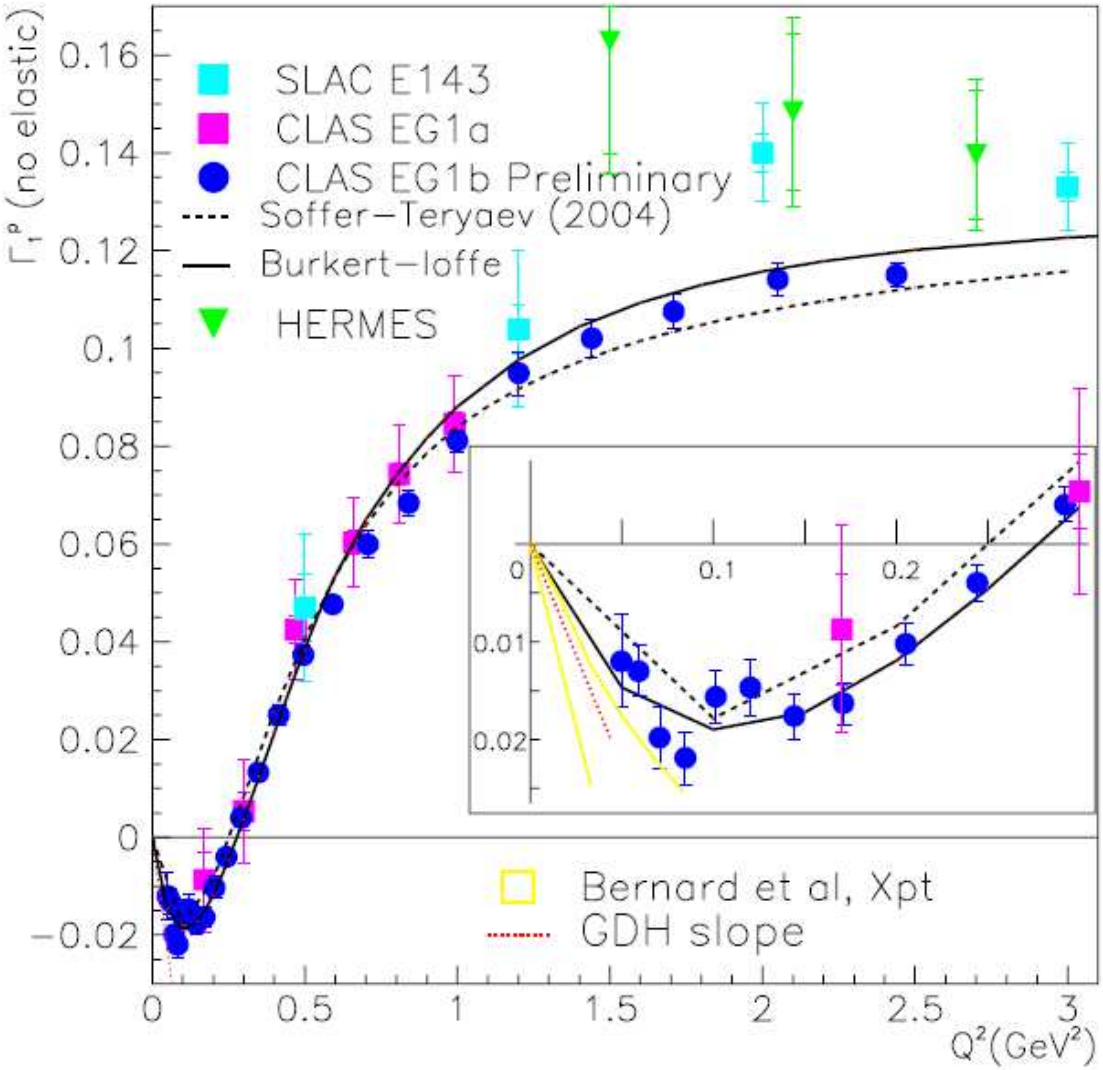




Summary

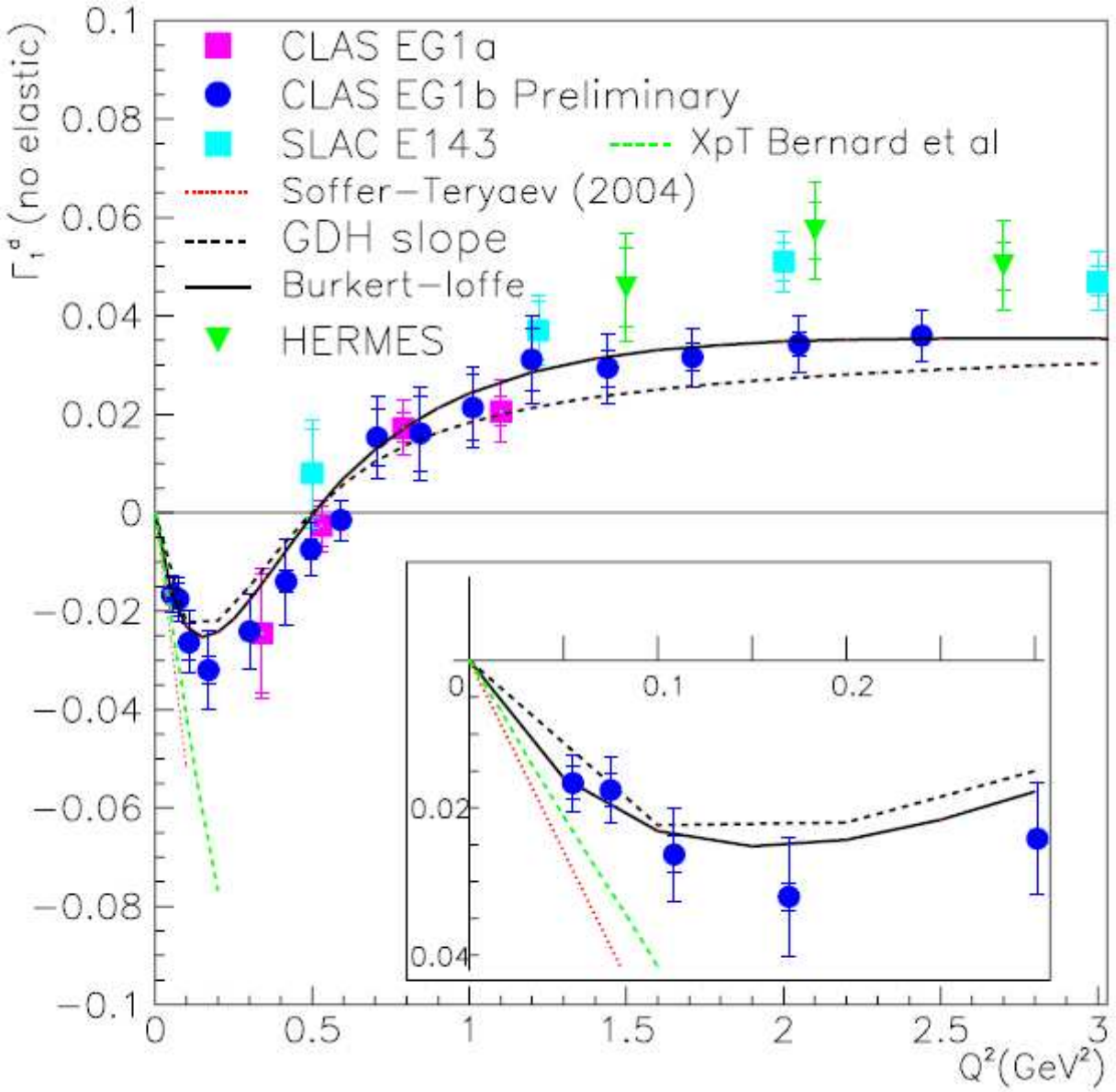
- A wealth of new data on the nucleon spin structure in the non-perturbative regime has been produced in Hall B at Jefferson Lab as part of a broad spin physics program, still in progress
- These measurements provide new information for understanding the transition between hadronic and partonic degrees of freedom by investigating spin structure functions, related sum rules and moments, asymmetries, …
- A new measurement to cover the very low momentum transfer region and provide a bridge to the GDH sum rule at the photon point has just been successfully completed

Integral of g_1 on the Proton



- the integral is consistent with previous SLAC data
- shows strong Q^2 dependence varying from negative to positive values as Q^2 increases
- change in slope occurs at 0.15 GeV^2

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