Spin Physics with CLAS

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for the CLAS Collaboration

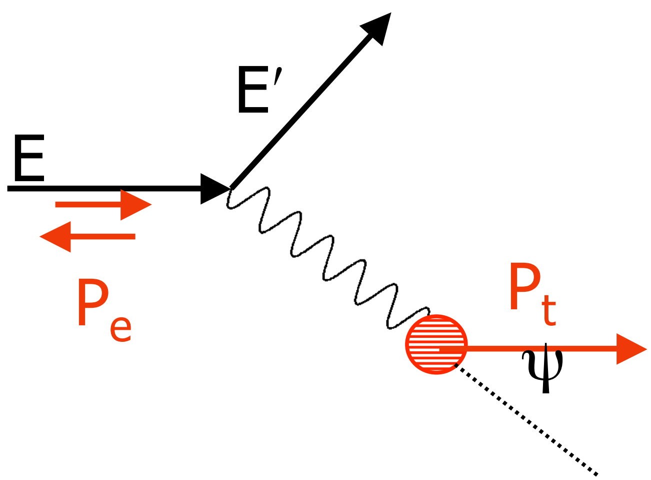
Outline

- Asymmetry measurements and spin structure functions
- EG1 Experiment
- A_1 at large Bjorken x
- Duality in spin structure functions
- Moments of Structure Functions
  - Low Q^2 behavior and comparison with χPT
- Transverse Structure of the Nucleon
- Future Plans

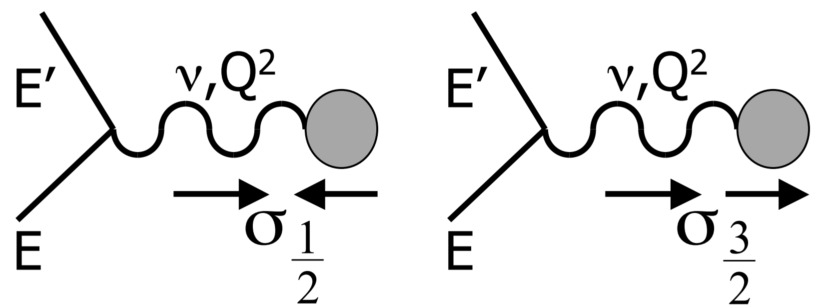
Asymmetry Measurements

The inclusive electron scattering cross section:

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



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



The structure functions A_1 and A_2 can be extracted from the measured asymmetries

$$A_{//} = D(A_1 + \eta A_2) \qquad A_\perp = d(A_2 - \zeta A_1)$$

where *D*, η, *d*, *and* ζ are functions of Q^2, *W*, *E*, *R*

Structure Functions

Unpolarized: $F_1(x,Q^2)$ and $F_2(x, Q^2)$; $x = Q^2/2M\nu$

Polarized: $g_1(x,Q^2)$ and $g_2(x, Q^2)$

dimensionless scaling variables

Parton model:

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x) \text{ and } F_2(x) = 2xF_1(x)$$

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x) \text{ and } g_2(x) = 0$$

i = quark flavor

e_i = quark charge

q = probability distribution

$\Delta q = q\uparrow - q\downarrow$

$$g_1(x,Q^2) = \frac{\tau}{1+\tau}\left(A_1 + \frac{1}{\sqrt{\tau}}A_2\right)F_1$$

$$g_2(x,Q^2) = \frac{\tau}{1+\tau}\left(\sqrt{\tau}A_2 - A_1\right)F_1$$

$$\tau = \frac{\nu^2}{Q^2}$$

Jefferson Lab
Newport News, Virginia, USA

6 GeV electron beam

Longitudinal polarization up to 85%

Halls: A B C

Hall B (EG1 collaboration)

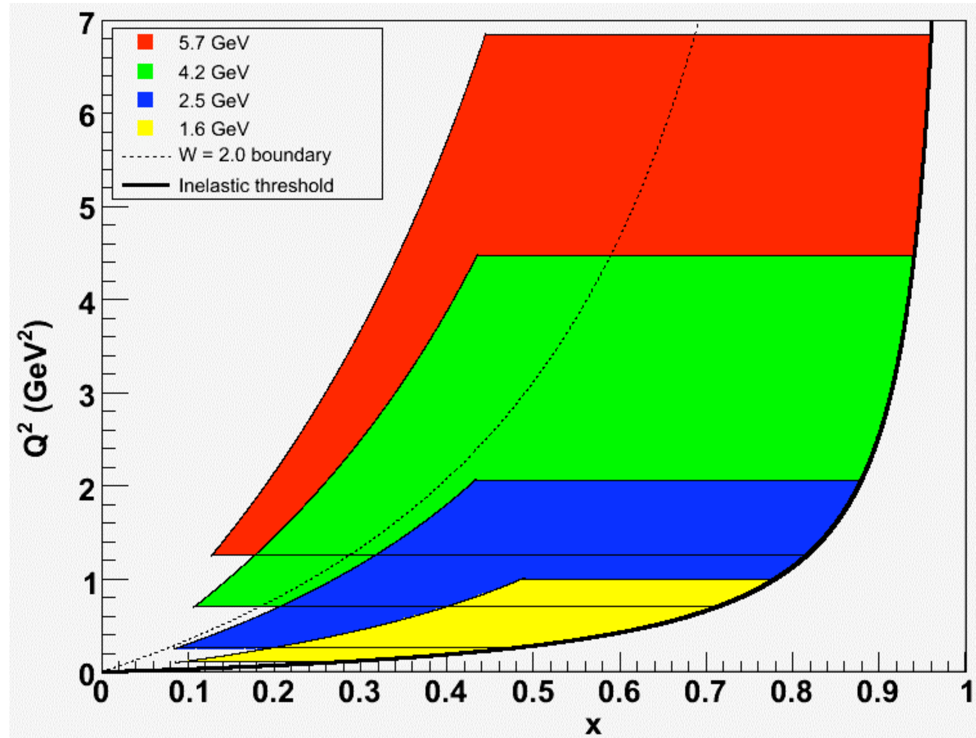
Time of Flight Scintillators

Drift Chambers

CEBAF Large Acceptance Spectrometer

Forward EM Calorimeter and Cerenkov Detectors not shown

2.5 and 4.2 GeV data are still being analyzed. They will fill in the intermediate Q^2 region.



Data presented today are results of the 1.6 and 5.7 GeV analyses

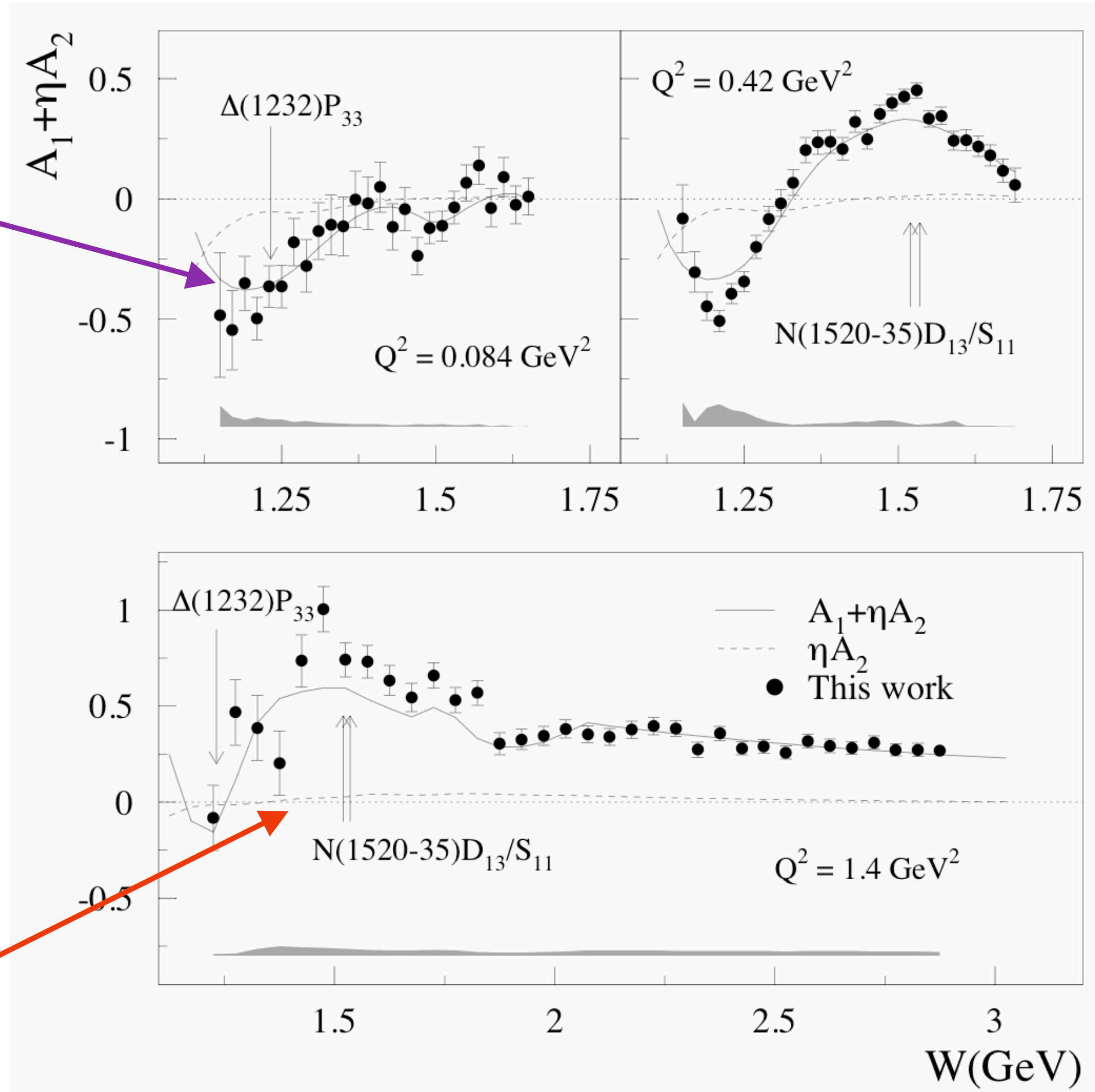
Good coverage of the resonance region

Some acceptance in the DIS region

Proton $A_1 + \eta A_2$

K.V. Dharmawardane *et al.*, Phys Lett B **641**, 11 (2006)

Full fit to world data



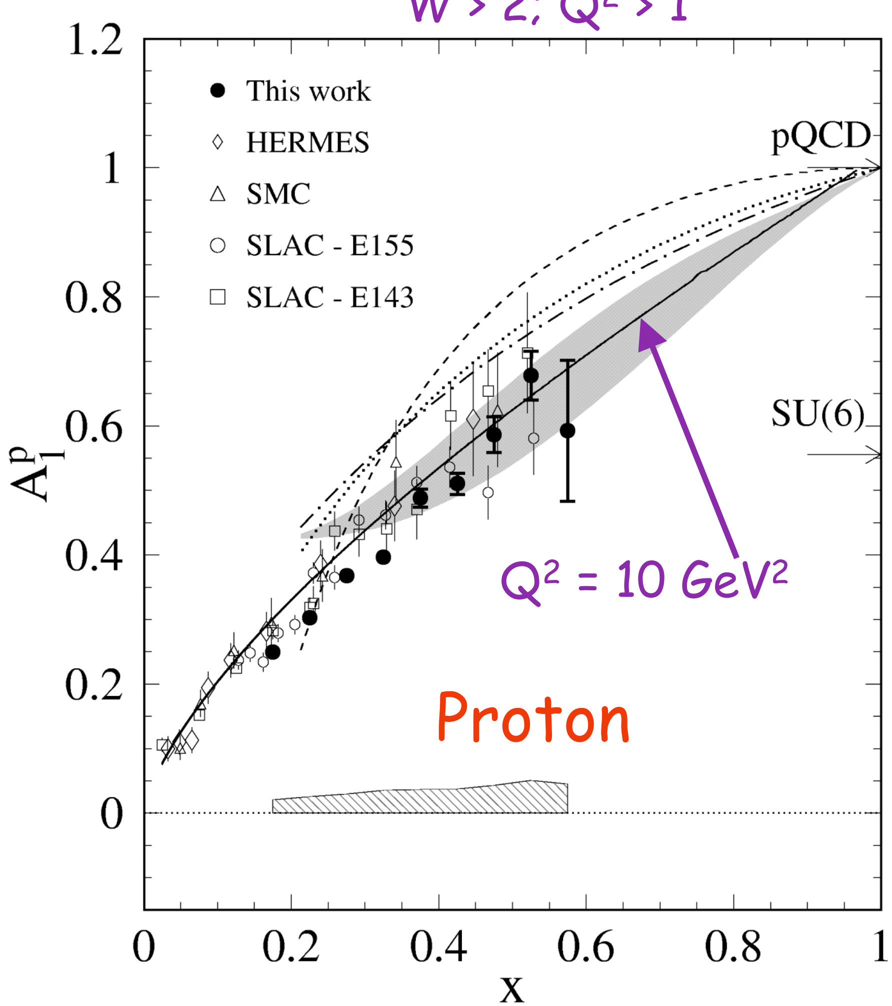
Dashed line is ηA_2

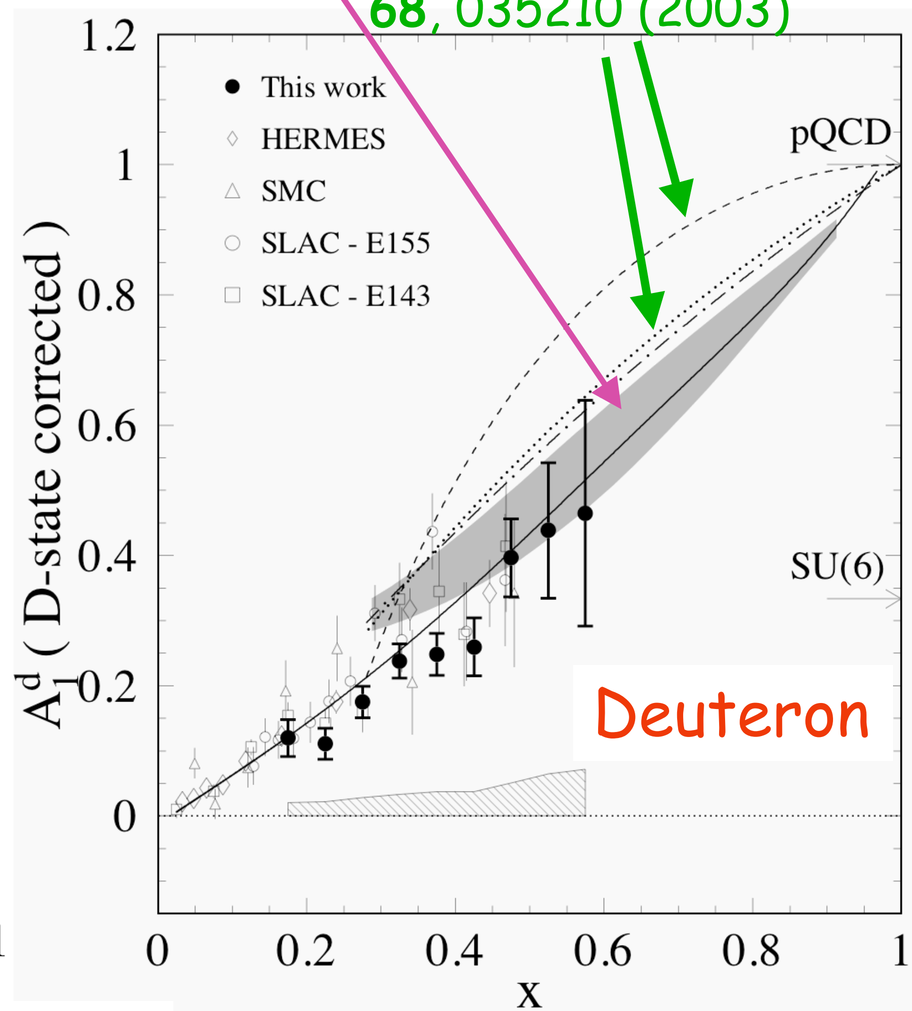
A_1 at large x - DIS data

Isgur, PRD **59**, 034013 (2003)

Close and Melnitchouk, PRC **68**, 035210 (2003)

W > 2; Q^2 > 1





Our data are consistent with an approach to A_1 = 1 as x → 1 as required by pQCD.

K.V. Dharmawardane *et al.*, Phys Lett B **641**, 11 (2006)

Δq/q

Assumptions:

- no sea quarks
- naïve parton model
- correction for deuteron D state and Fermi motion

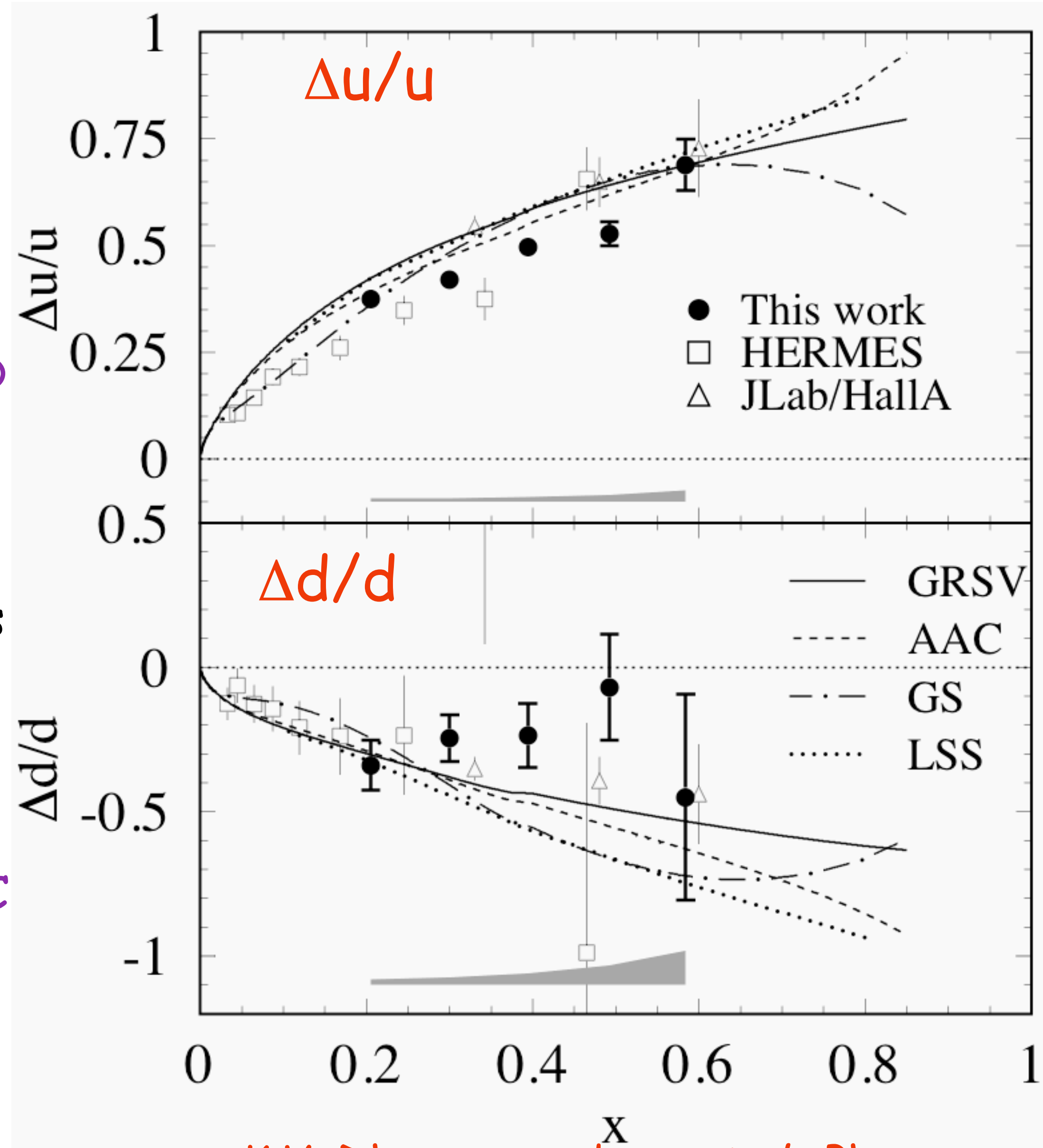
Δu/u:

- Statistically most precise
- Consistent with Δu/u→1 as x →1

Δd/d:

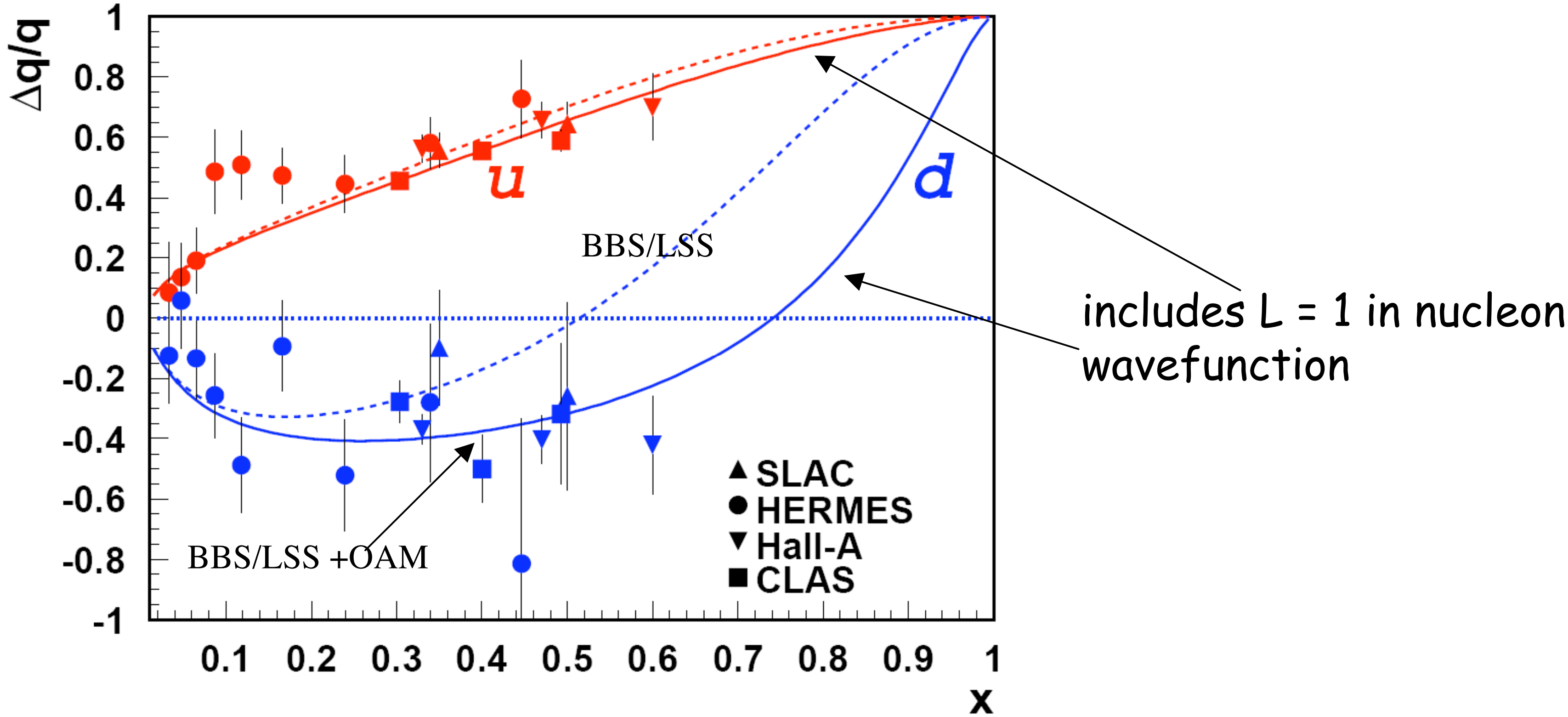
- Remains negative, in agreement with Hall A result: X. Zheng *et al.*, PRC **70**, 065207 (2004)

These data have improved the accuracy of NLO PDF fits.



K.V. Dharmawardane *et al.*, Phys Lett B **641**, 11 (2006)

The Effect of Orbital Angular Momentum



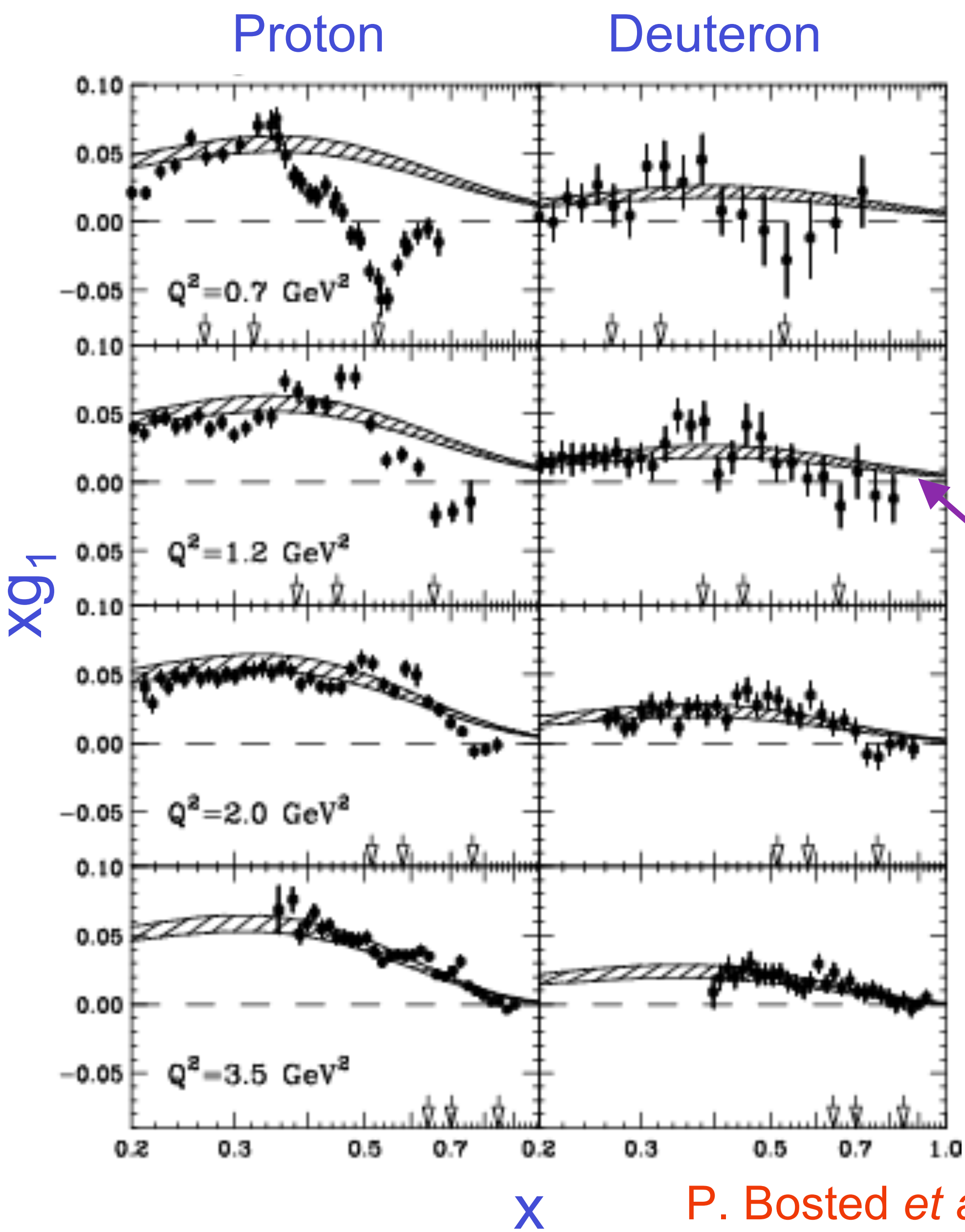
H. Avakian, S. Brodsky, A. Deur, F. Yuan
hep-ph/0705.1553

Quark-Hadron Duality

- The observation that nucleon resonances at low Q^2 average to the scaling curve measured in DIS
  - Bloom and Gilman, PRL **25**, 1140 (1970); PRD **4**, 2901 (1971)
- Observed with high precision in the unpolarized F_2^p structure function in Hall C, Jlab
  - I. Niculescu *et al.*, PRL **85**, 1182, 1186 (2000)
- Local duality also observed (*i.e.*, average over a smaller range in W)
- Related to the absence of higher twist strength in structure function moments
- Can we see these effects in spin structure functions?

Both nucleons and nuclei are interesting

Duality in g_1



Curve represents range in g_1 from NLO parton distribution functions with target mass corrections applied and evolved to the Q^2 of the data:

AAC: PRD **69**, 054021 (2004)

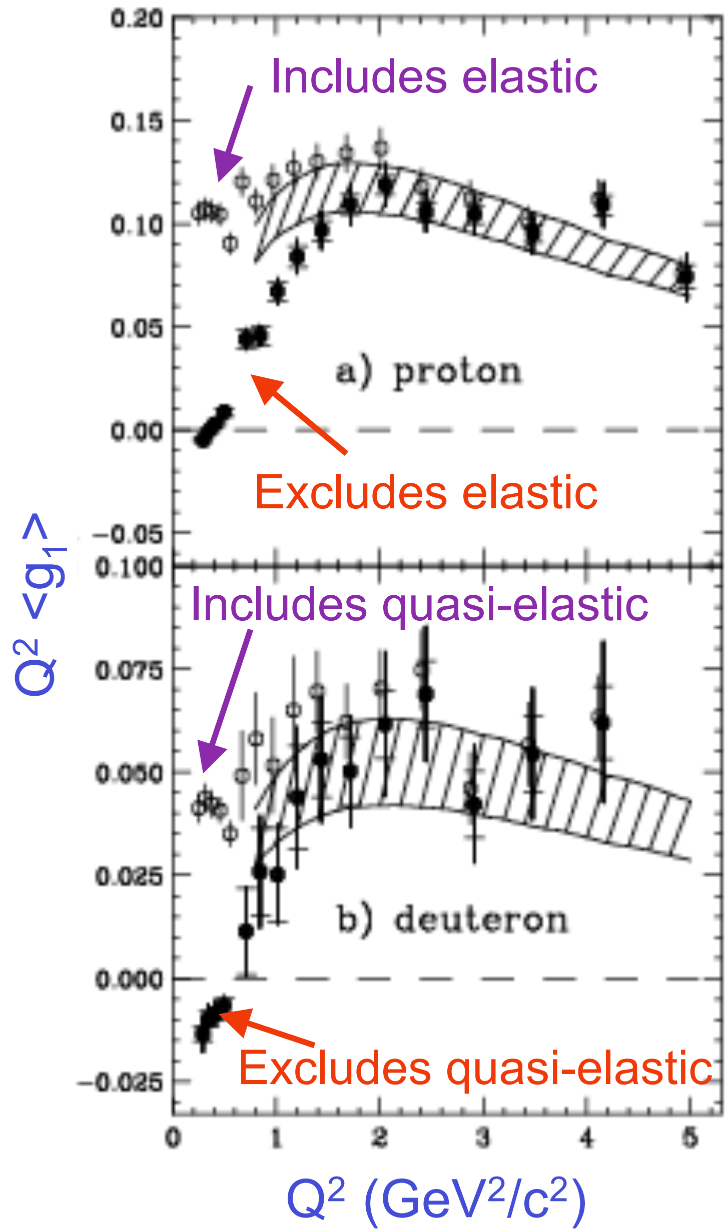
GRSV: PRD **63**, 094005 (2001)

As Q^2 increases the data begin to average to the PDF curve.

The Δ(1232) resonance lies below the DIS curve, as expected.

P. Bosted *et al.*,Phys. Rev C 75, 035203 (2007)

Average g_1 (W < 2 GeV)

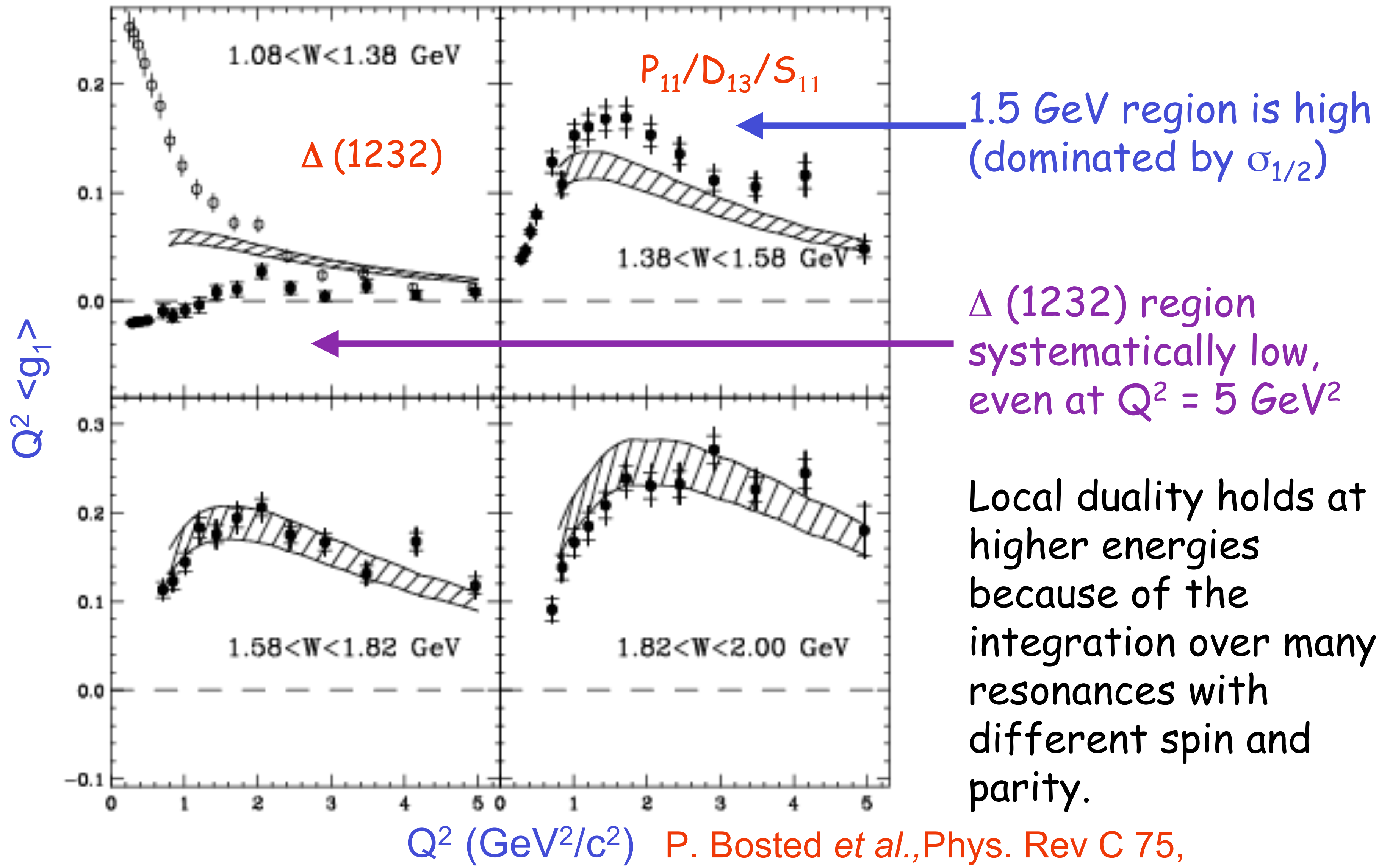


Good agreement with PDF fits (with TM corrections) down to about 1.7 GeV^2.

Power law (higher twist) deviations clear at lower Q^2. Adding the elastic peak improves the agreement with PDF, especially for the proton.

P. Bosted *et al.*,Phys. Rev C 75, 035203 (2007)

Local Duality for the Proton



Local duality holds at higher energies because of the integration over many resonances with different spin and parity.

P. Bosted *et al.*, Phys. Rev C 75, 035203 (2007)

First Moment of g_1

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

Generalized GDH Integral (all Q^2)

$$S_1(0,Q^2) = 4\int_{Q^2/2M}^{\infty} G_1(\nu,Q^2)\frac{d\nu}{\nu} = \frac{8}{Q^2}\Gamma(Q^2)$$

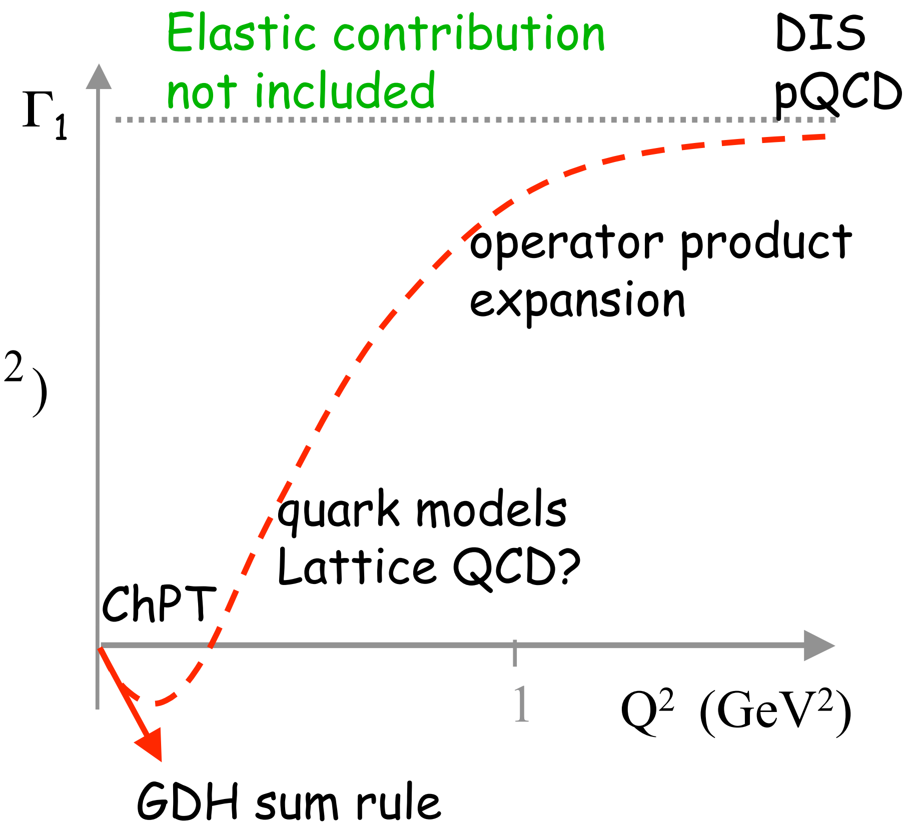
calculable

measurable

Ji and Osborne, J. Phys. G: Nucl. Part. Phys. **27** (2001) 127

Also useful:

$$I_1 = \frac{2M^2}{Q^2}\Gamma_1 \qquad I_2 = \frac{2M^2}{Q^2}\Gamma_2$$

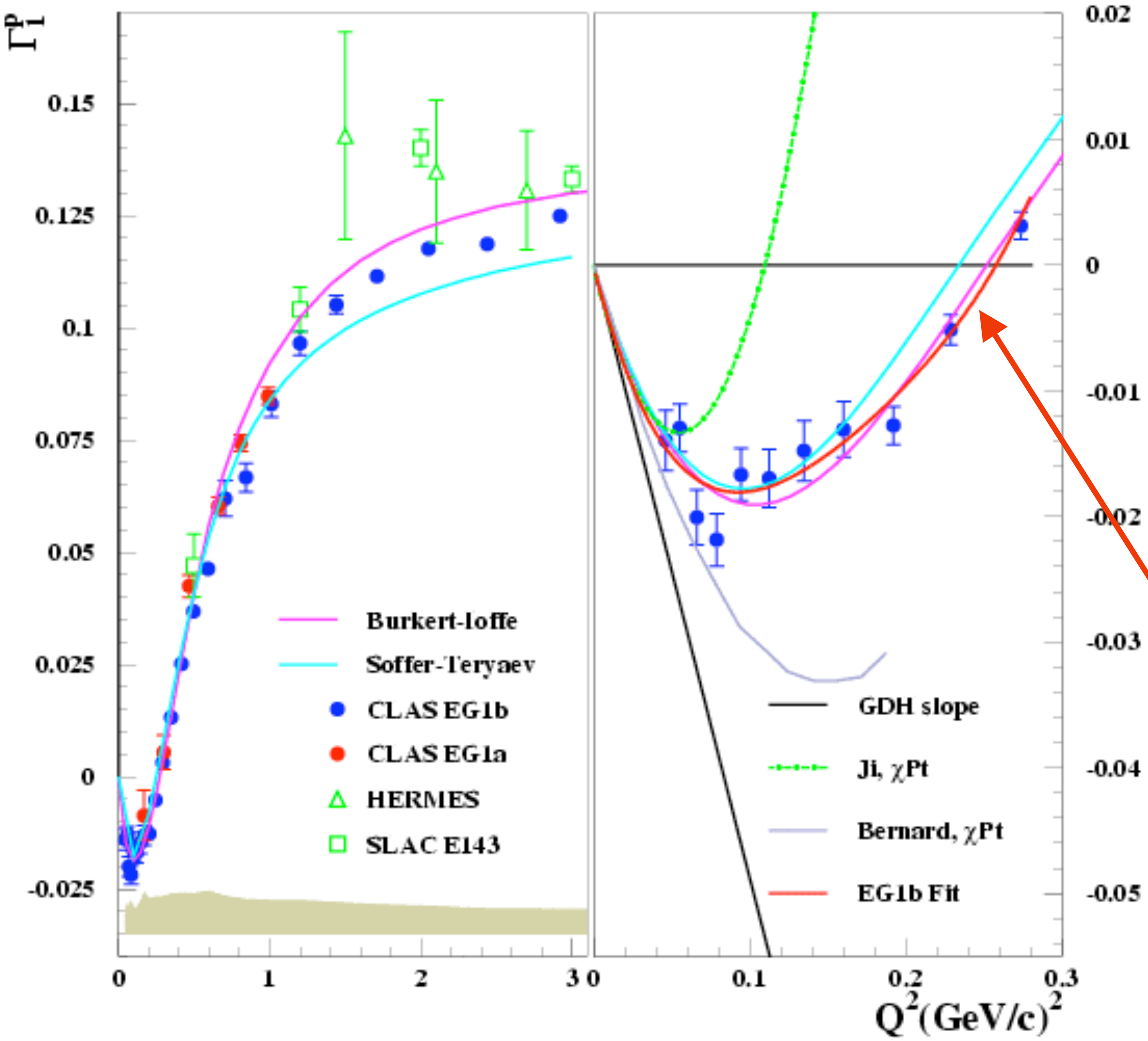


Interesting variation with Q^2

Hadron ⟶ Parton

Proton Integral $\Gamma_1 = \int g_1(x,Q^2)dx$

Ph.D. work: Y. Prok - UVa



Shows expected trend toward DIS result at high Q^2

At low Q^2 we observe a negative slope as expected from GDH Sum Rule.

Agreement with χPT at the lowest points.

Low Q^2 fit to data:

$$\Gamma_1 = -\frac{\kappa^2}{8M^2}Q^2 + bQ^4 + cQ^6 + dQ^8$$

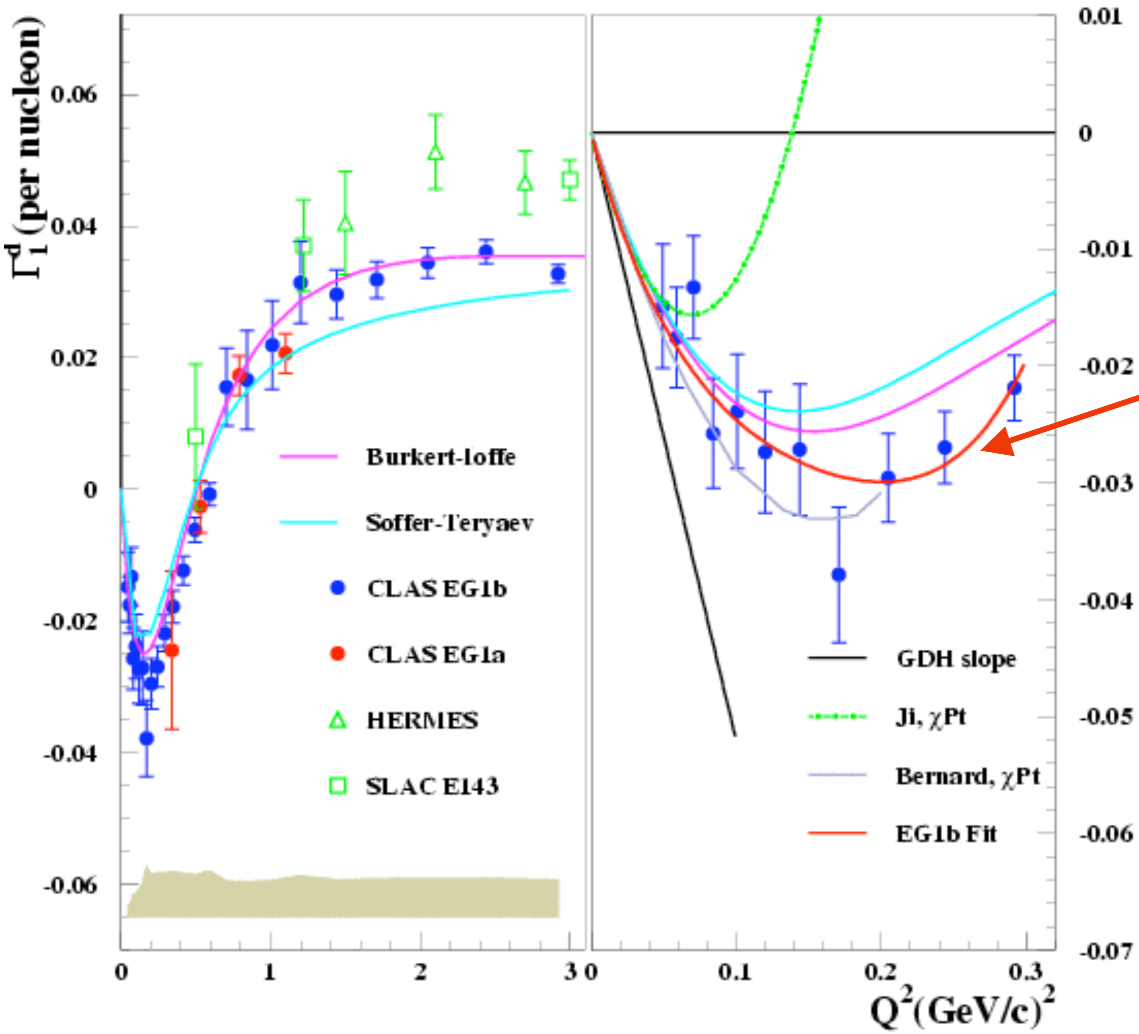
Ji predicts b = 3.89

Fit: b = 3.81±0.31 (stat) +0.44 - 0.57 (syst)

Y. Prok *et al.*,to be submitted to PRL

Deuteron: $\Gamma_1^d(Q^2)$ (per nucleon)

Ph.D. work: V. Dharmawardane – ODU



Like the proton, shows expected behavior at low and high Q^2

Agreement with χPT at the lowest points.

Low Q^2 fit to data:

$$\Gamma_1 = -\frac{\kappa^2}{8M^2}Q^2 + bQ^4 + cQ^6 + dQ^8$$

Ji predicts b = 3.26

Fit: b = 2.91 ± 0.52 (stat)
± 0.69 (syst)

Ji: PLB **472**, 1 (2000)

Bernard: PRD **67**, 078008 (2003)

Y. Prok *et al.*,to be submitted to PRL

Bjorken Sum

$$\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6} + Q^2 \text{ evolution}$$

Agreement with χPT up to higher Q^2

NNLO PQCD in reasonable agreement with the data

→ Higher twist is small even down to Q^2 = 0.5 GeV^2

Hall A data:

Amarian *etal.*, Phys. Rev. Lett. **89**, (2002) 242301

Amarian *etal.*, Phys. Rev. Lett. **92**, (2004) 022301

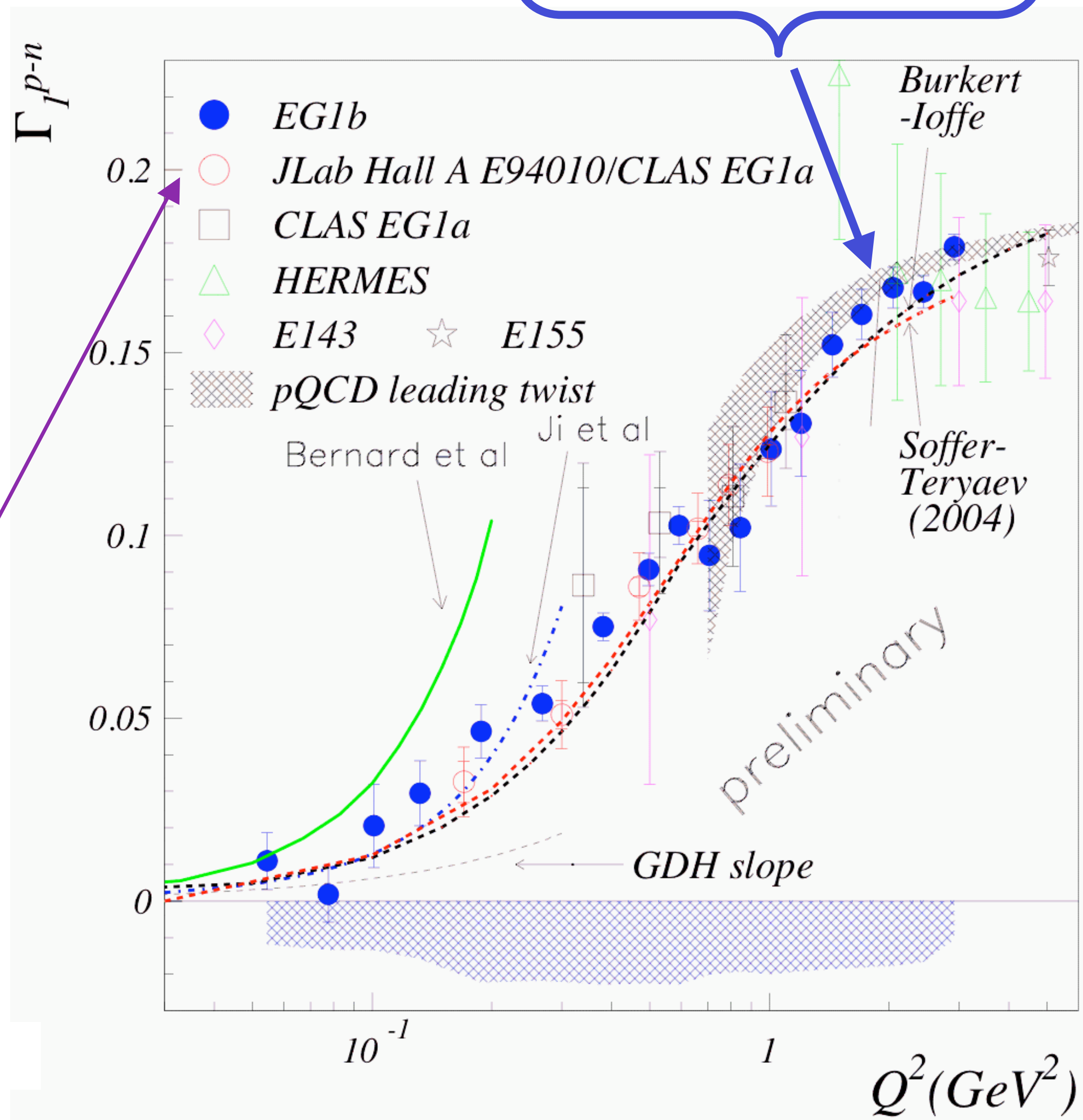


Figure from Alexandre Deur

Nucleon Polarizabilities

$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]dx$$

sensitive to resonances

$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]dx$$

insensitive to the Δ resonance

The integrals converge faster, minimizing the contribution from the unmeasured DIS part.

They can be calculated in χPT at low Q^2.

→They are a more stringent test of χPT than Γ_1 because they are not constrained at low Q^2.

Surprising disagreement between χPT and δ^n_{LT} seen in data from Hall A.

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

γ_0 from EG1 data

$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} A_1 F_1 x^2 dx$$

F_1 from fit to world data

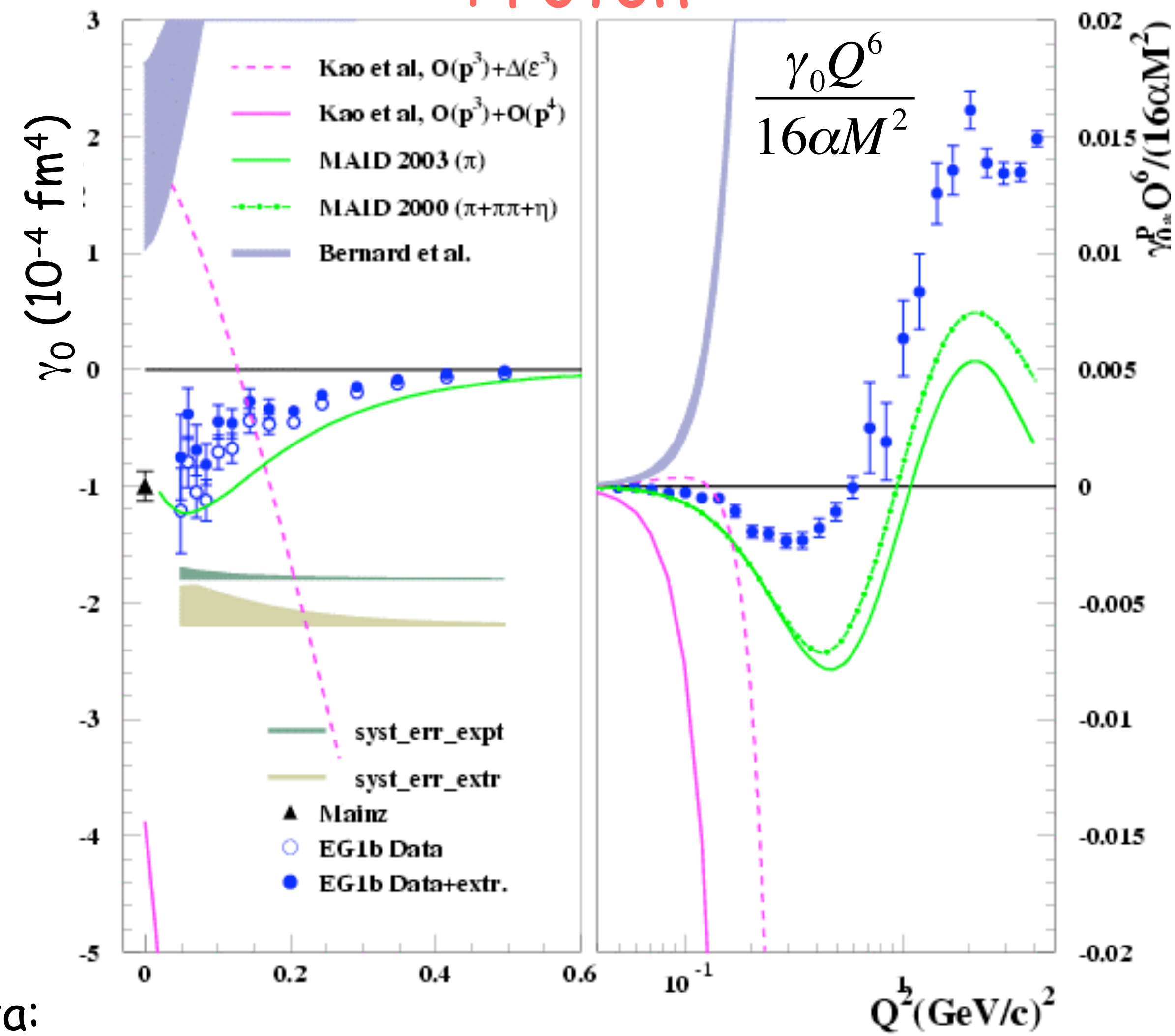
Discrepancy with MAID is primarily due to parametrizations of F_1.

No agreement with χPT, even at $Q^2 = 0.05$ GeV^2

We see evidence of expected Q^6 scaling at $Q^2 \approx 1.5$ GeV^2

MAID - phenomenological parametrization of world data: Nucl. Phys. **A645**, 145 (1999)

Proton



Y. Prok *et al.*,to be submitted to PRL

γ_0 (proton - neutron)

Calculated using γ_0^p from EG1 and γ_0^n from Hall A (E94010).

Minimizes the effect of the $\Delta(1232)$ resonance

Discrepancy with MAID at low Q2 probably due to non-resonance terms.

χPT Calculations disagree in magnitude and trend

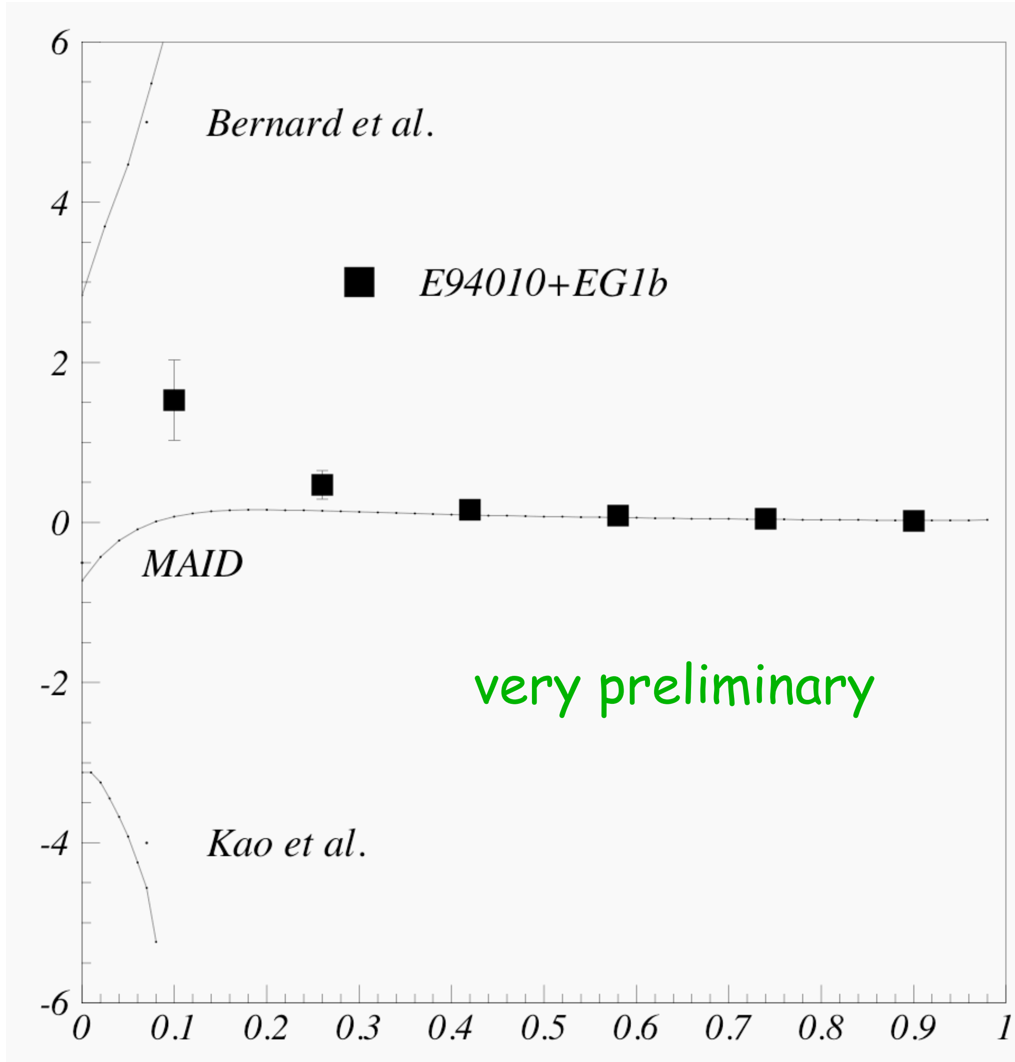


Figure from Alexandre Deur

γ_0 (proton + neutron)

Calculated using γ_0^p from EG1 and γ_0^n from Hall A (E94010).

Emphasizes the $\Delta(1232)$ resonance

Much better agreement with MAID at low Q^2, indicating that MAID gets the $\Delta(1232)$ correct, as expected

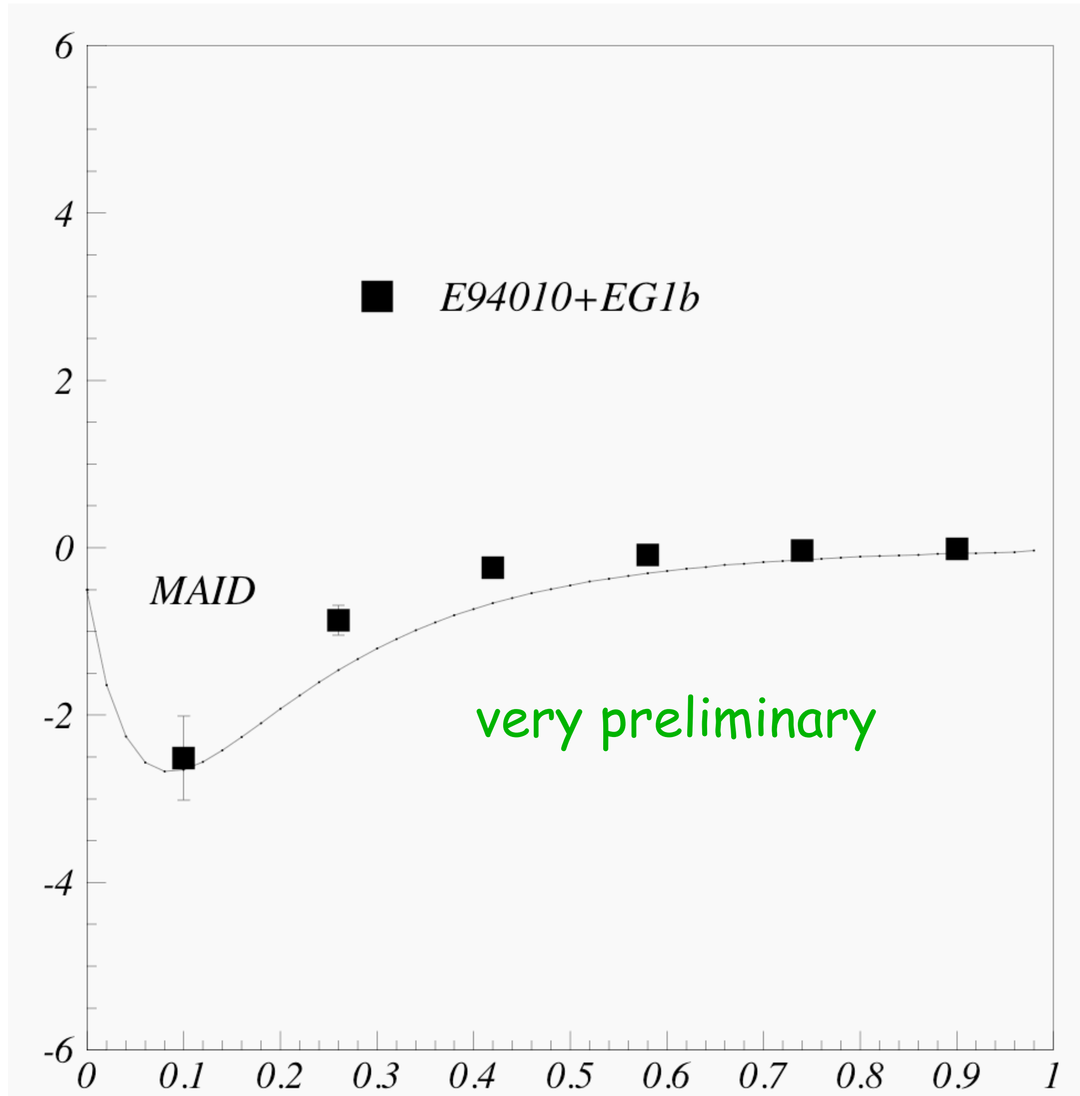
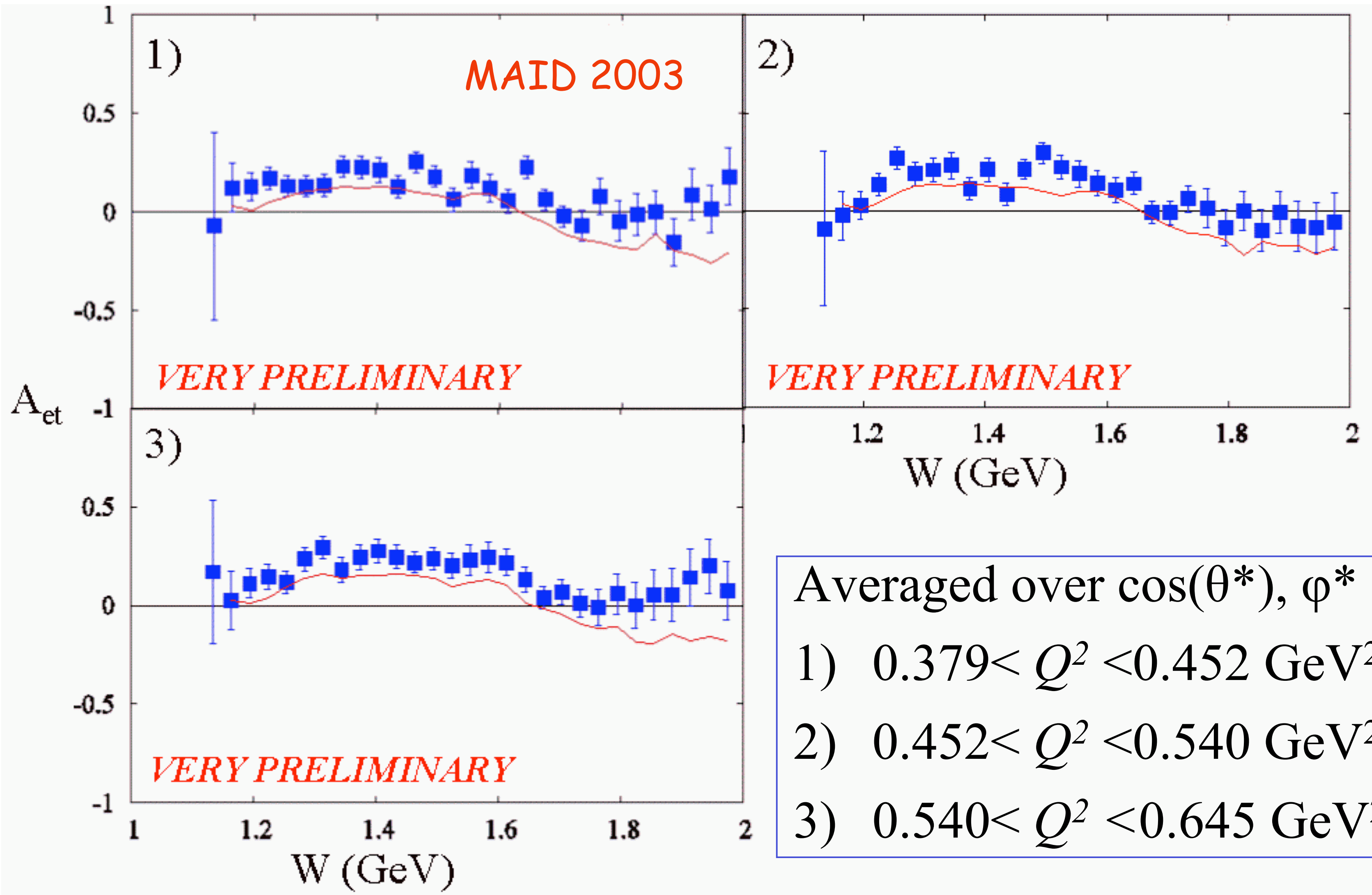


Figure from Alexandre Deur

Exclusive Channels: $ep \rightarrow e' \pi^+ n$
Double Spin Asymmetry



Averaged over cos(θ*), φ*

1) $0.379 < Q^2 < 0.452$ GeV^2

2) $0.452 < Q^2 < 0.540$ GeV^2

3) $0.540 < Q^2 < 0.645$ GeV^2

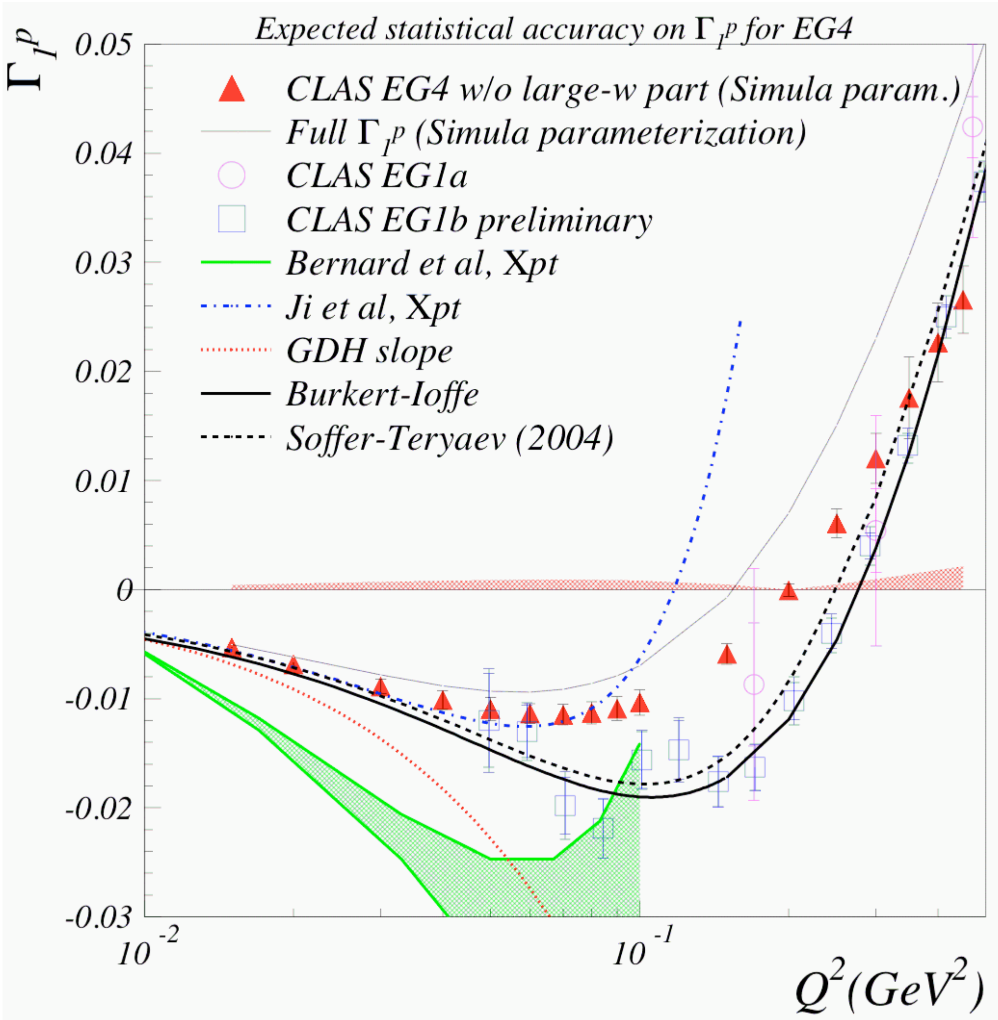
New Low Q^2 CLAS Experiment: EG4
(ran in Spring 2006)

NH_3 and ND_3 targets

Measure g_1^p, g_1^d down to Q^2 = 0.015 GeV^2; extract Γ_1

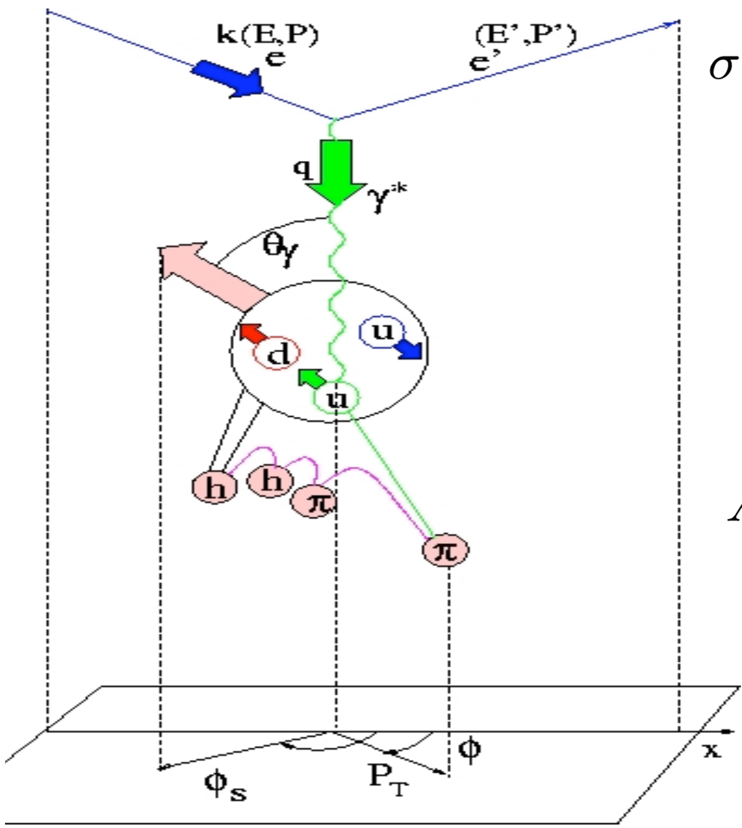
Goals:

- Test χPT at lower Q^2
- Extract Γ_1^n, γ_0 and Bjorken Sum
- Extrapolate Γ_1^n to Q^2 = 0 to test χPT and/or GDH Sum rule on the neutron.
- Study nuclear corrections in extraction of g_1^n through comparison with Hall A low Q^2 experiment using ^{3}He



data analysis underway

Semi-inclusive DIS: Transverse Structure of the Nucleon



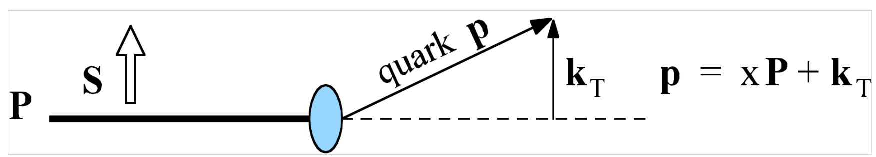
$$\sigma = \sigma_{UU} + P_B \sigma_{LU} \sin\phi + P_T \sigma_{UL} \sin 2\phi + \ldots$$

P_B, P_T

U unpolarized
L long. polarized
T trans. polarized

$$A_{UL}^{\sin 2\phi} = \frac{\sigma_{UL}}{\sigma_{UU}}$$

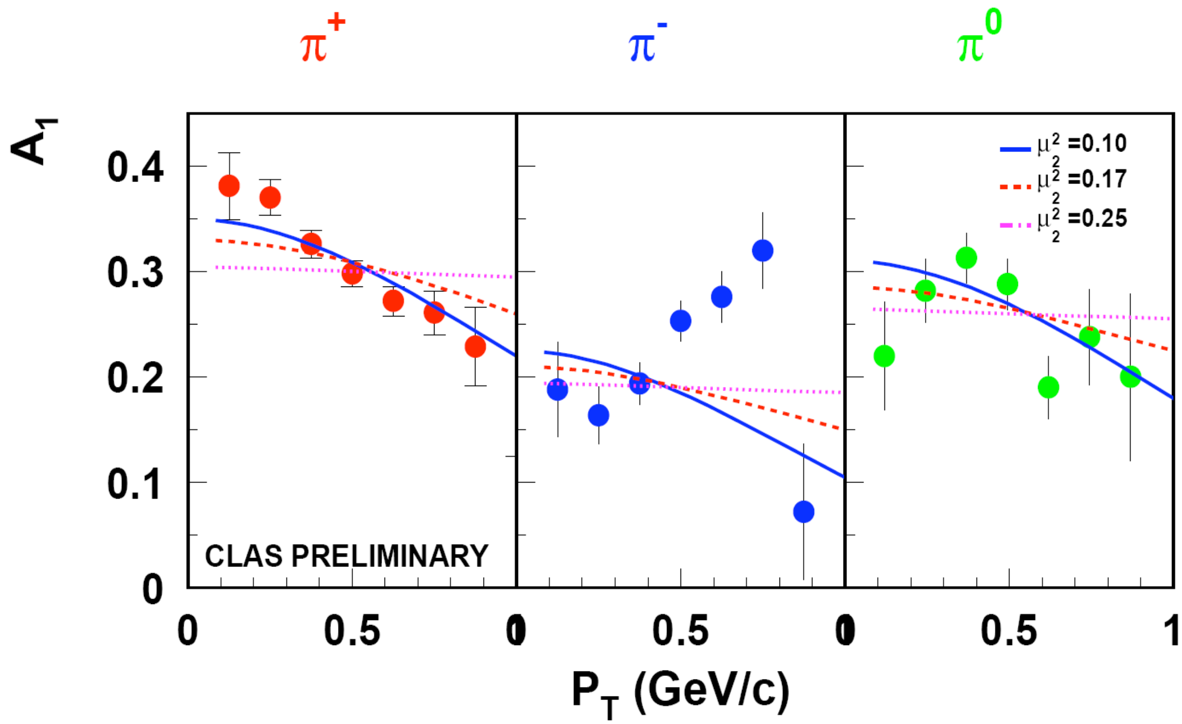
sin2ϕ moment of the cross section for unpolarized beam and longitudinal target



A_1 P_T-dependence in SIDIS

$$A_{LL}^{\pi} = \frac{\sigma_{LL}}{\sigma_{UU}} \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

M.Anselmino et al
PRD 74, 074015 (2006)



$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

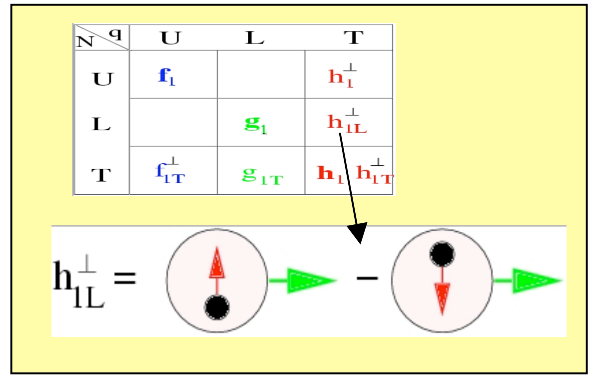
$\mu_0^2 = 0.25$ GeV^2
$\mu_D^2 = 0.20$ GeV^2

π+ A_1 can be explained in terms of broader k_T distributions for f_1 compared to g_1
π^- A_1 may require non-Gaussian P_T-dependence for different helicities and flavors

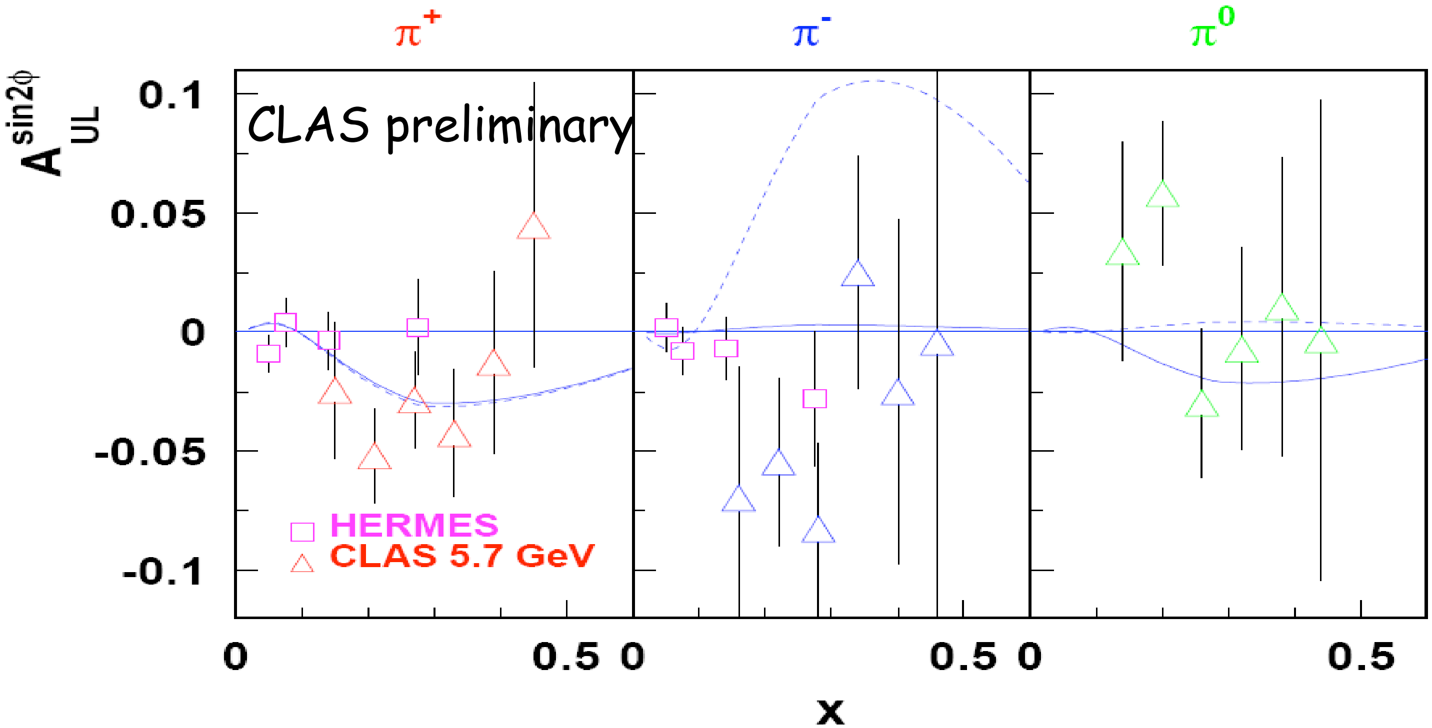
Figure from Harut Avakian

Collins fragmentation:
Longitudinally polarized target

$$A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} H_1^{\perp} \sin 2\phi$$



Kotzinian-Mulders Asymmetry (1996)



Curves: χQSM Efremov et al., Czech. J. Phys. 55, A189 (2005); hep-ph/0412420

Figure from Harut Avakian

12 GeV upgrade at Jefferson Lab

- Upgrade is the highest priority for nuclear physics in the United States
- Project Engineering & Design underway
- Construction expected to begin in Oct. 2008

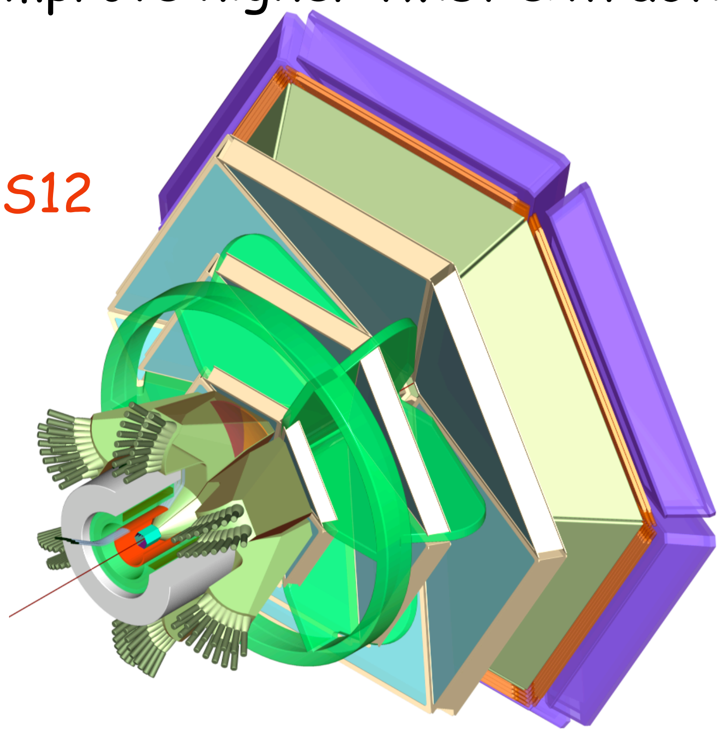
We welcome new collaborators!

Jefferson Lab 12 GeV Upgrade
Approved Experiment EG12 with CLAS12

Provide data on g_1 over a larger range in x at low and moderate Q^2,

- –extend coverage in x and Q^2
- –reduce systematic uncertainties on integrals
- –higher moments will benefit from higher x
- –improve higher twist extraction

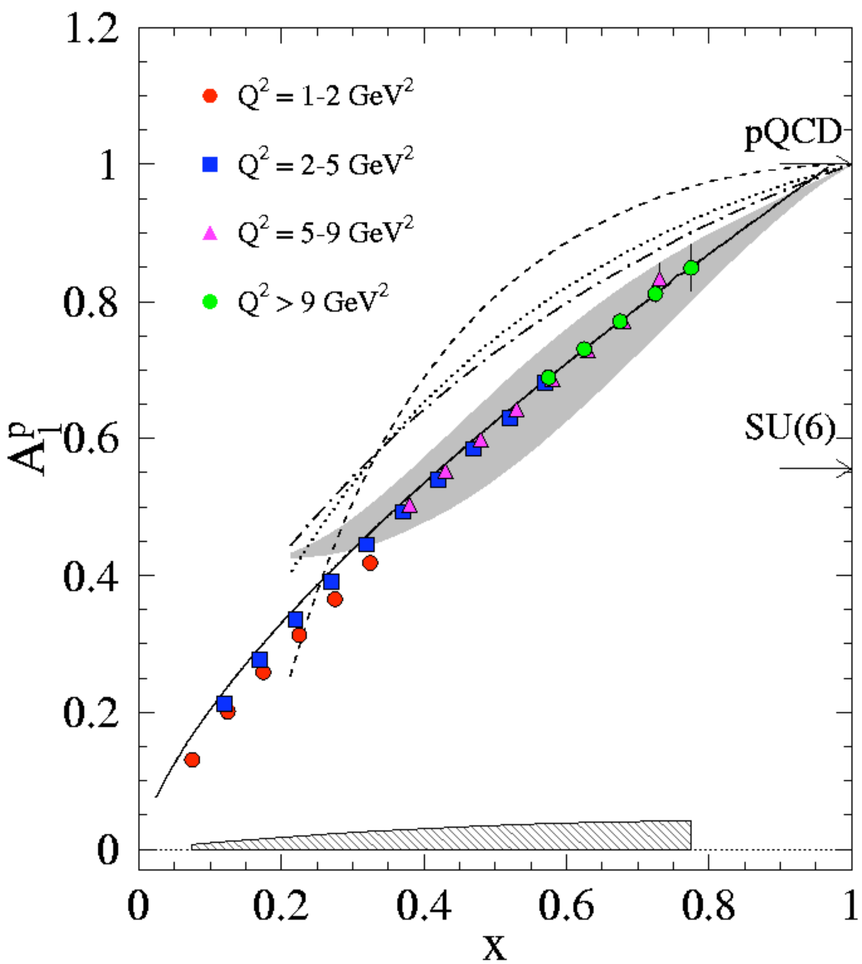
CLAS12

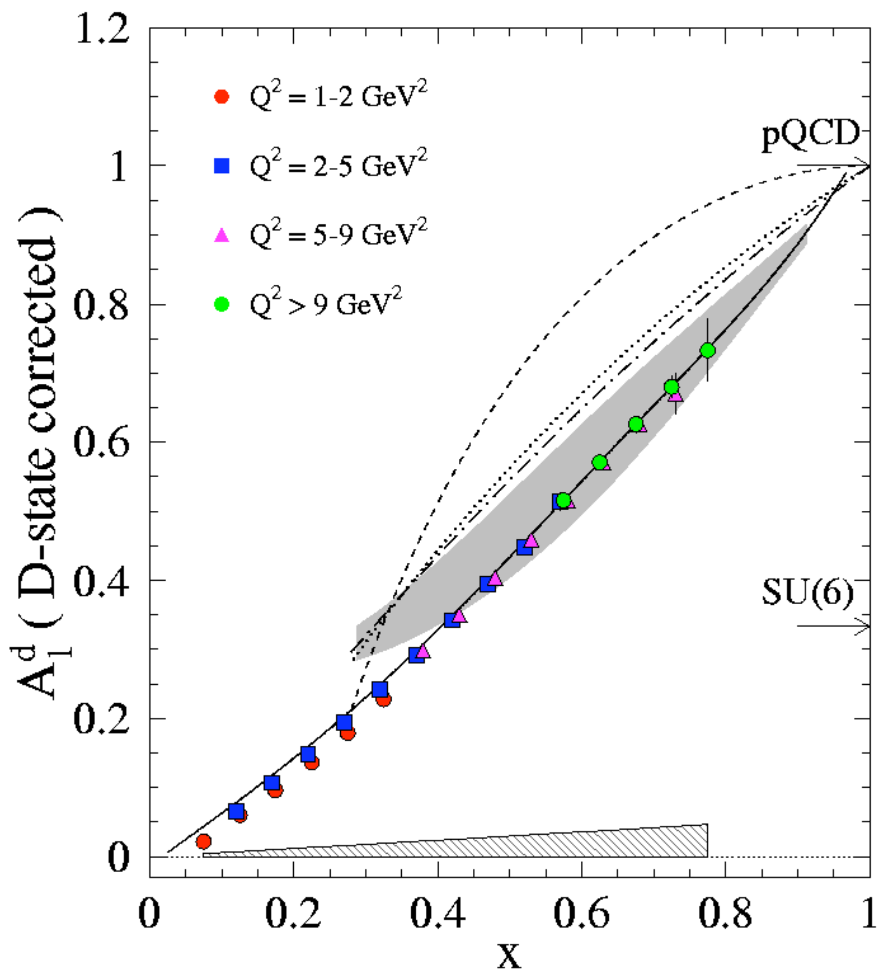


- E_{beam} = 11 GeV
- L = 2 x 10^{35} /cm^2/s
- CLAS12 acceptance
- p and d targets
- P_b=85% P_t=80(40)% p(d)
- 80 days of beam time
- Stat ~ syst errors at high *x*

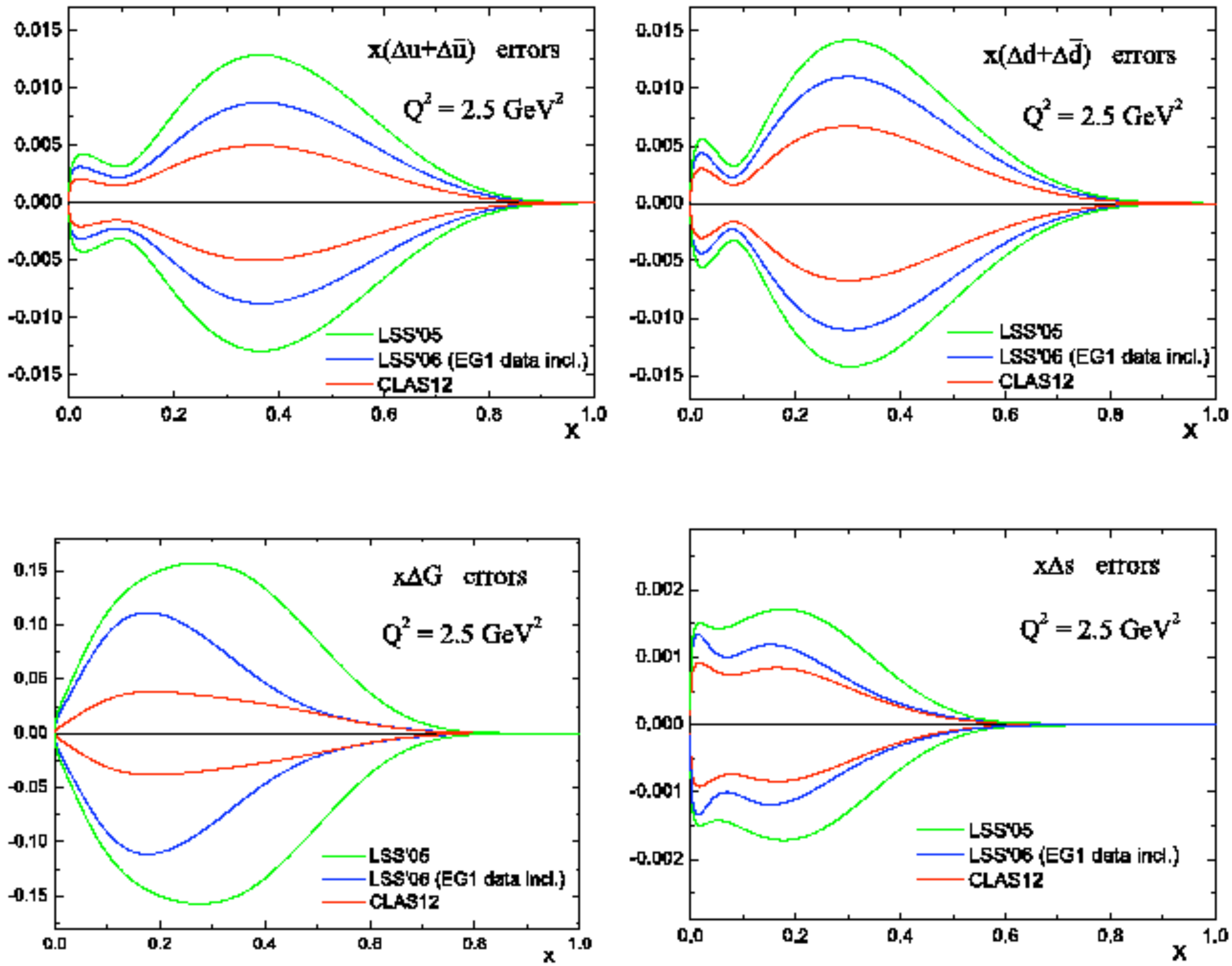
Predicted Data with CLAS12

Proton W > 2; Q^2 > 1 Deuteron



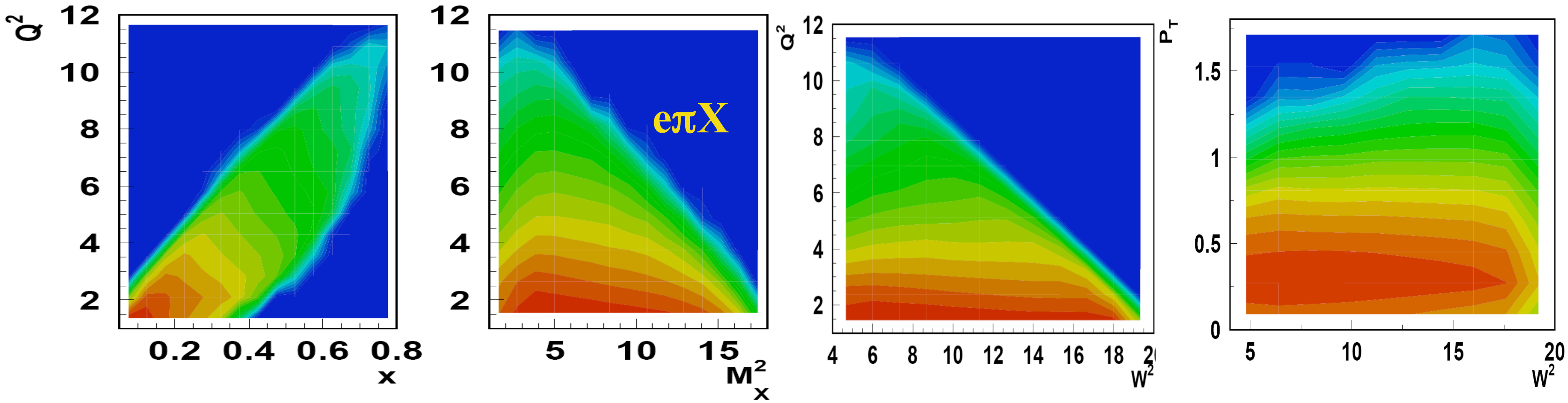


Improvements in Δu, Δd, ΔG, Δs



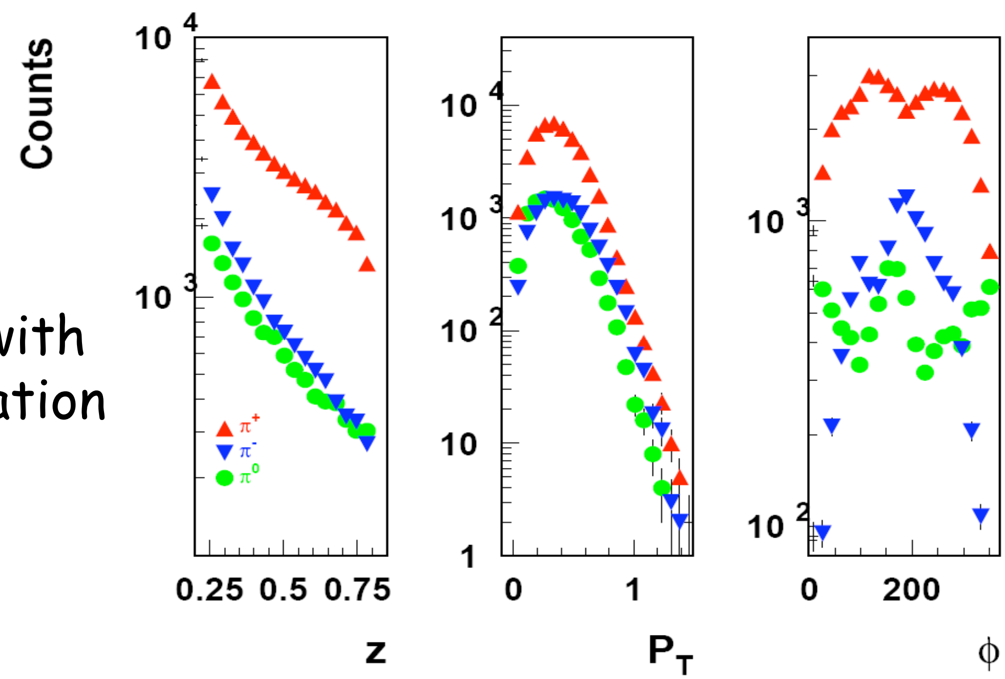
Gail Do

CLAS12: Kinematical coverage



SIDIS kinematics

$Q^2 > 1$ GeV^2
$W^2 > 4$ GeV^2
$y < 0.85$
$M_X > 2$ GeV



Large Q^2, M_X, and P_T accessible with CLAS12 are important for separation of Higher Twist contributions

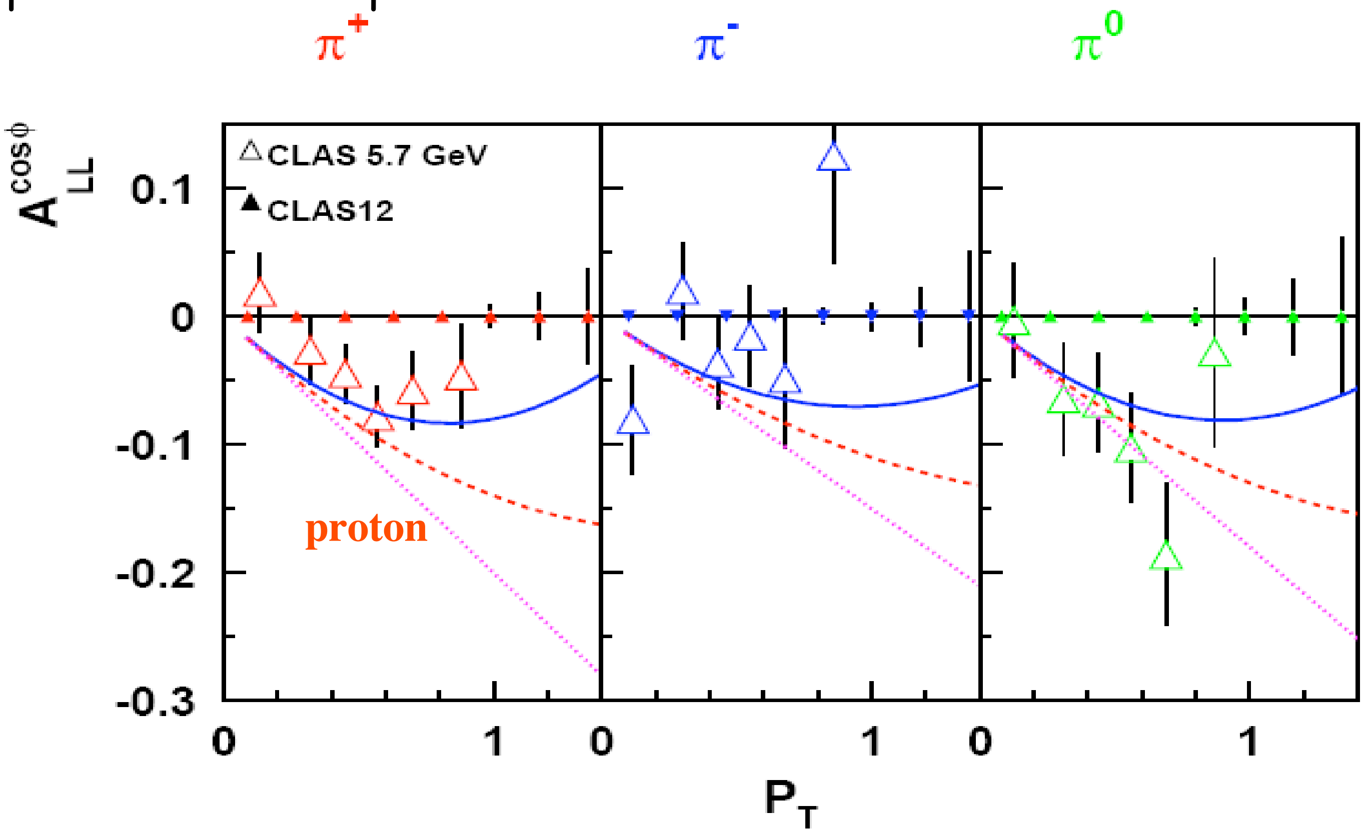
Gail Dodge, Old Dominion University

SIDIS ($\gamma^*p\rightarrow\pi X$): LL x-section subleading moment

$$A_{LL}^{\cos\phi} \propto A_{LL}(P_T)\frac{1}{Q}\frac{zP_T\mu_2^2}{\mu_D^2 + z^2\mu_2^2}$$

M.Anselmino et al
Phys.Rev.D74:074015,2006

Azimuthal moment of A_{LL} most sensitive to the difference of widths in polarized and unpolarized distributions.



Summary

We have extracted $g_1(x,Q^2)$ from NH_3 and ND_3 targets over a wide kinematical range in and above the resonance region with good statistical precision.

- Our data are consistent with an approach to $A_1 = 1$ as $x \to 1$ as required by pQCD.
- We observe global duality in the proton and the deuteron above Q2 ≈ 1.7 GeV^2 and local duality above W = 1.58 GeV.

Nucleon polarizability γ_0 is a more stringent test of χPT than Γ_1. χPT fails to describe γ_0^p, even as low as $Q^2 = 0.05$ GeV^2. We observe scaling with Q^6 above $Q^2 \approx 1.5$ GeV^2.

MAID describes γ_0^{p+n} reasonably well, but disagrees significantly with γ_0^{p-n} at low Q^2, suggesting a problem with the non-resonant terms.

SIDIS: interesting behavior observed in $A_{LL}(\pi^-)$

Jefferson Lab upgrade will allow us to begin a third generation of spin structure studies.

World data on polarized structure function $g_1(x,Q^2)$

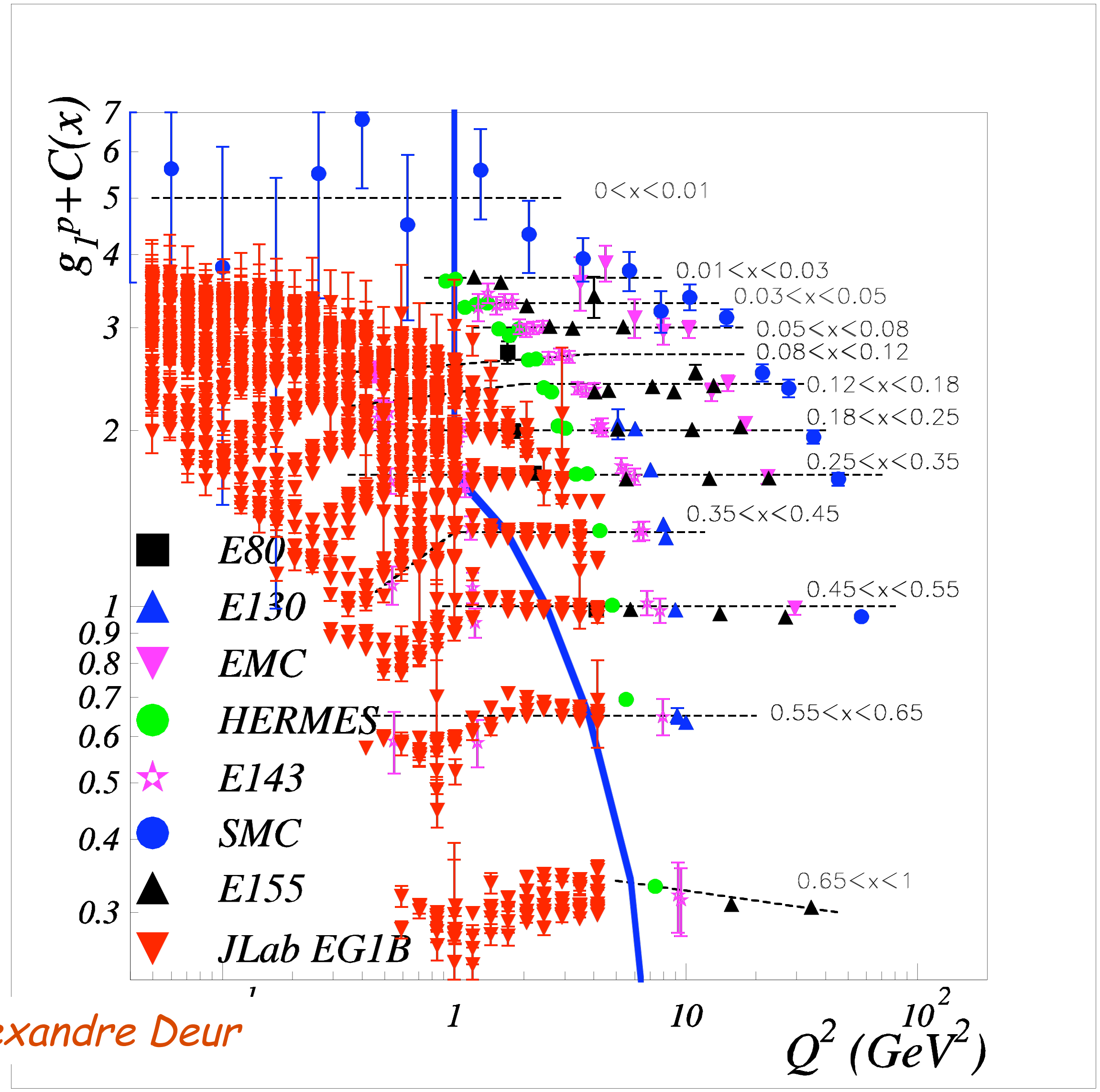


Figure from Alexandre Deur