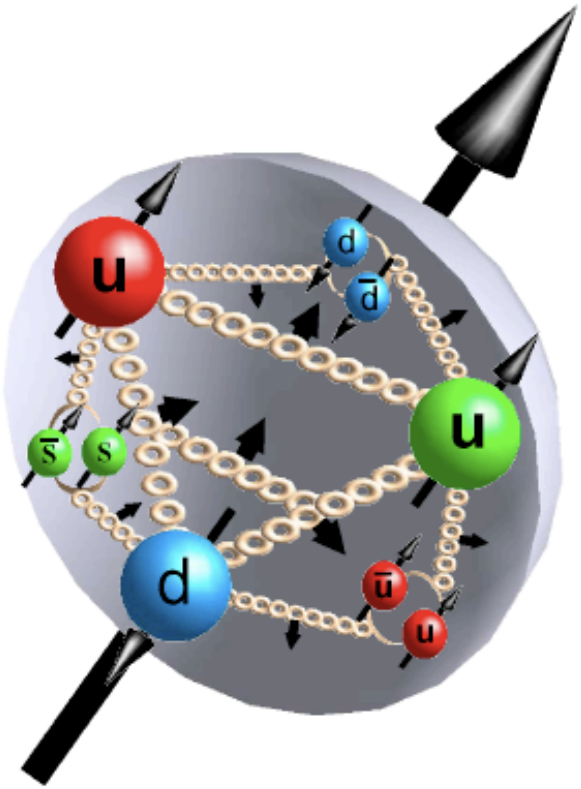
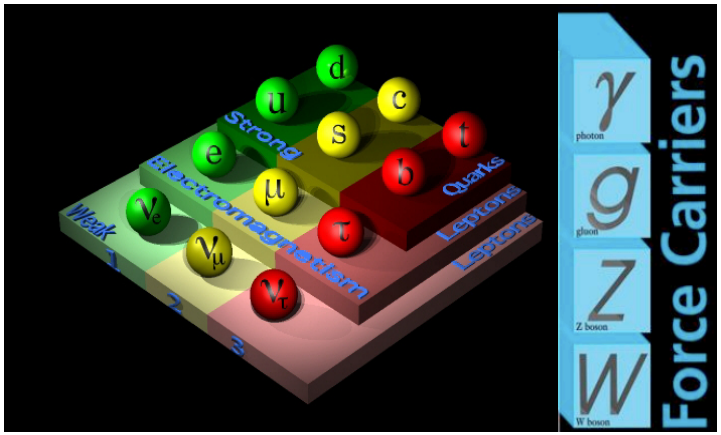
Spin Physics at Jefferson Lab



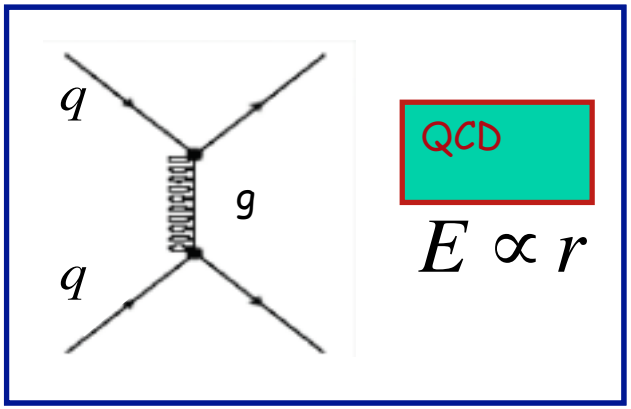
Yelena Prok
Old Dominion University
November 27 2012

University of Virginia Physics Seminar

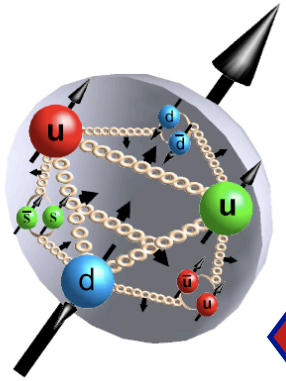
The Spin Puzzle → Key Question in **Standard Model QCD**



99.9% of mass of the visible universe composed of quarks and gluons - the building blocks of the nucleon

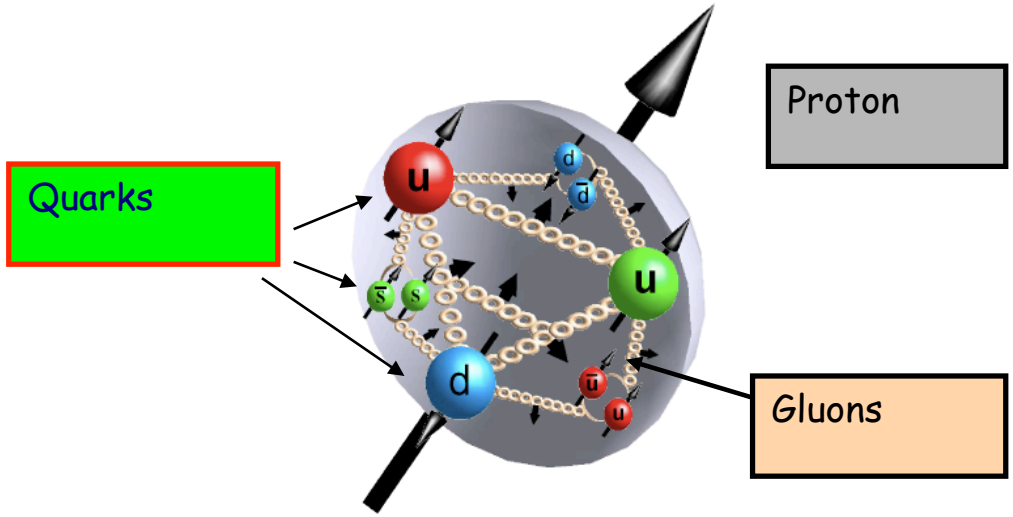


How do partonic degrees of freedom - mass, charge, color, **SPIN** - manifest as the nucleon degrees of freedom?



No access to free partons due to confinement! The proton is a stable and abundant source of partons

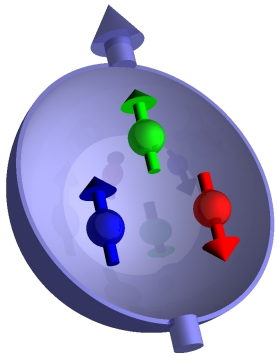
The Question: How do quarks and gluons combine to form hadronic angular momentum quantum numbers?



$$S_p = \frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta G + L_q + L_G$$

$$\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s} + \cdots)dx$$

Simple Quark Model



$\Delta\Sigma = \Delta u + \Delta d + \Delta s$ $\qquad$ $\Delta q = q\uparrow - q\downarrow$

- Quark spin contribution to the proton spin can be determined from the axial charges.
- The isovector axial charge (neutron decay const.)

$$\Delta u - \Delta d = g_A = 1.257$$

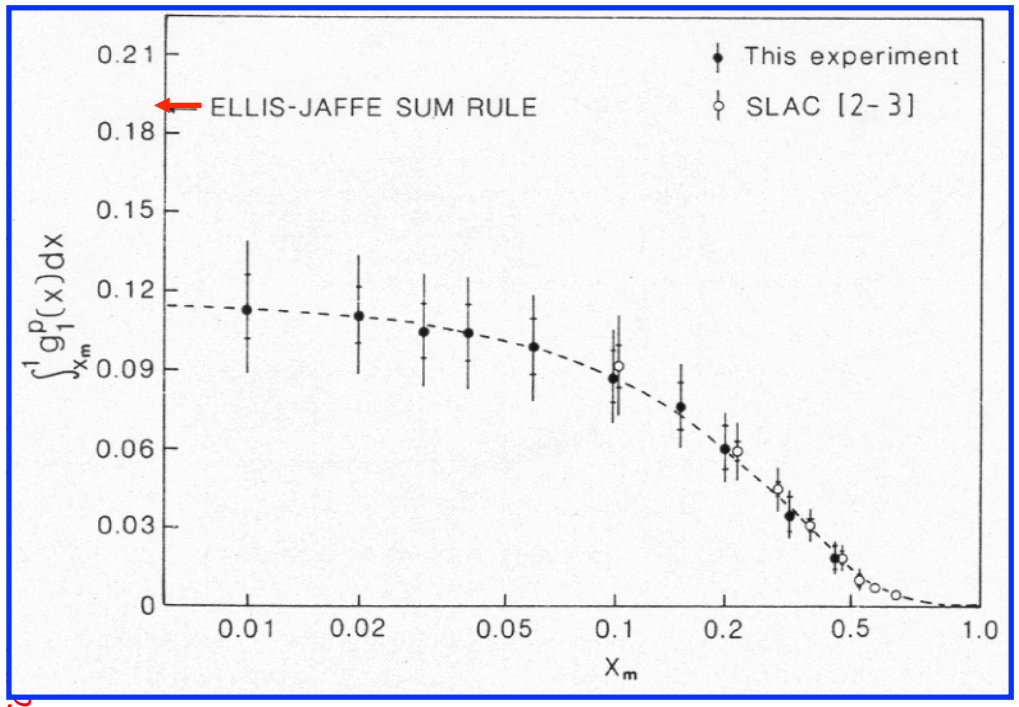
- The octet axial charge (hyperon β-decays+SU(3))

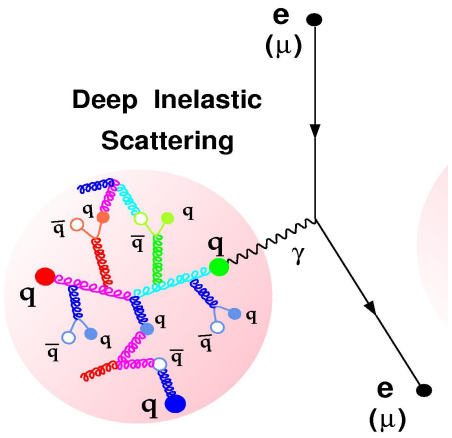
$$\Delta u + \Delta d - 2\Delta s = 0.585 \pm 0.025$$

- Ellis-Jaffe Sum Rule (no strange contribution)

$$\Delta\Sigma_{EJ} = 0.58 \pm 0.025$$

Early Measurements of $\Delta\Sigma=\Delta u+\Delta d+\Delta s$





- EMC → Deep Inelastic Scattering
- Requires Integration over all X
- Measurement is over a finite X
-

$\Delta\Sigma_{EJ} = 0.58 \pm 0.03$

$\Delta\Sigma_{EMC} = 0.12 \pm 0.10 \pm 0.14$

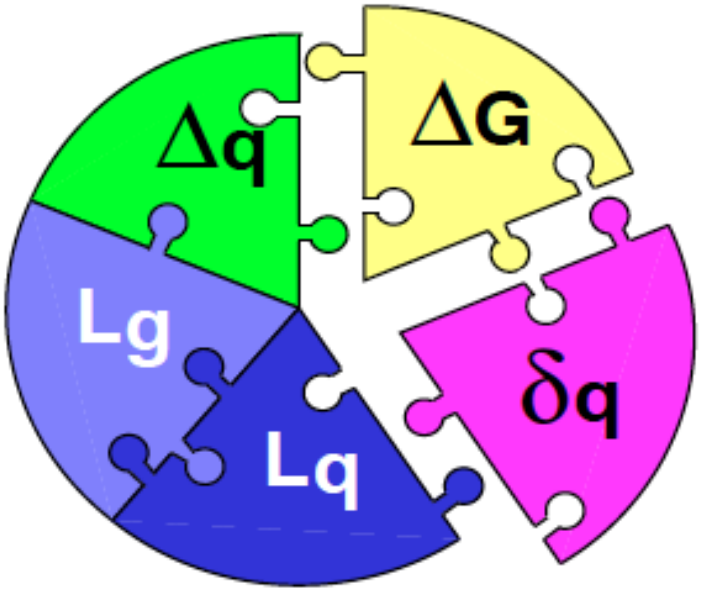
Measured quark distributions ≠ spin of the proton!

1. Could the missing spin be in the gluon? After all it contributes half total momentum/mass!
2. Could a large negative strange contribution - not included in theory but measured in data - cause discrepancy between EJ and data?
3. What about angular momentum?

The Spin Structure of the Proton

$$\tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$

- From NLO-QCD analysis of DIS measurements
  - $\Delta\Sigma \approx 0.2$
  - $\Delta G = 1.0 \pm 1.2$ → probably small?
- quark polarization $\Delta q(x)$
  - →first 5-flavor separation from HERMES
- transversity $\delta q(x)$
  - →a new window on quark spin
  - →azimuthal asymmetries from HERMES and JLab
  - →future: flavor decomposition
- gluon polarization $\Delta G(x)$
  - →RHIC-spin and COMPASS started providing answers!
- orbital angular momentum L
  - →how to determine?
  - → GPD's and TMD's

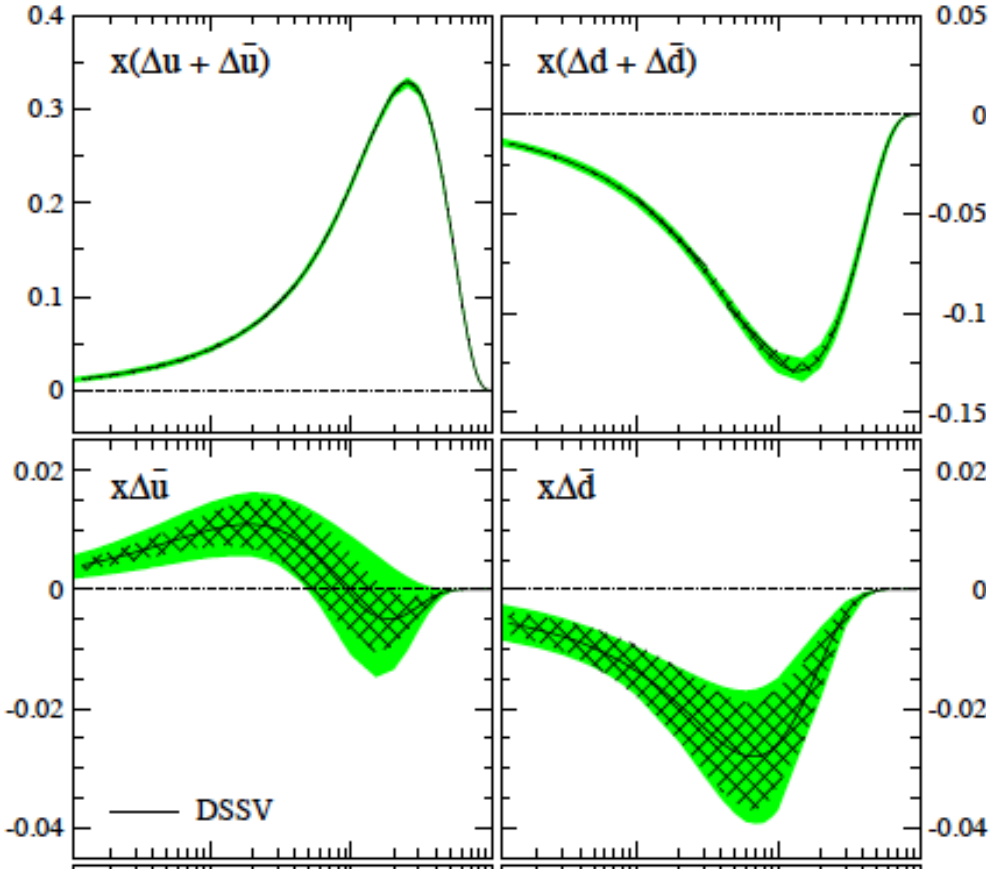


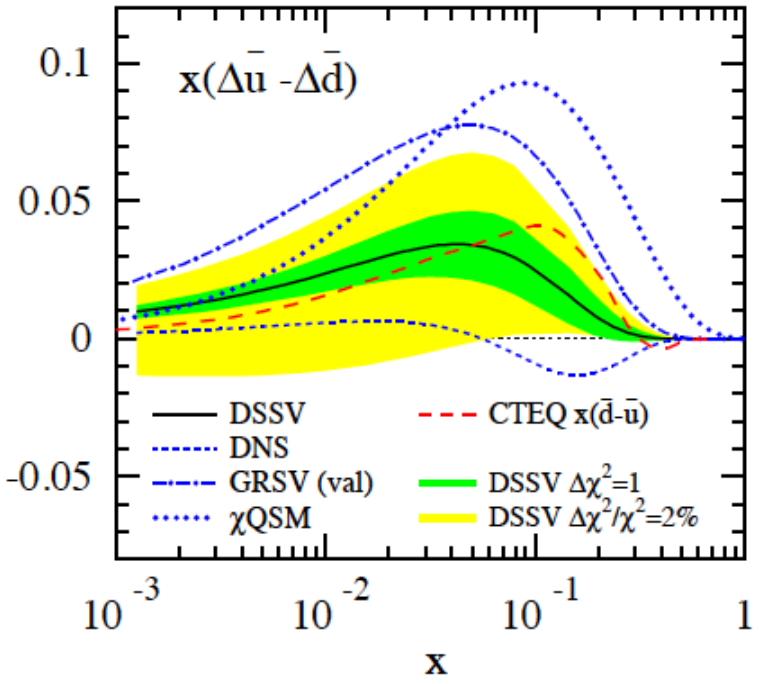
We want to solve this puzzle! → need large range in x and Q^2 and high luminosity for precision!

New Global Analysis with all World Data

DeFlorian, Sassot, Stratmann and Vogelsang, Phys. Rev. D 80, 034030 (2009)

Total up and down distributions





Good agreement with lattice QCD

New Global Analysis with all World Data

DeFlorian, Sassot, Stratmann and Vogelsang, Phys. Rev. D 80, 034030 (2009)

Strange quark distributions

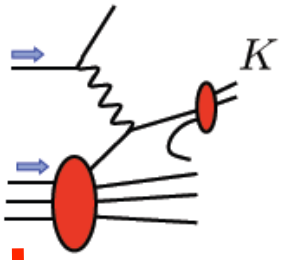
The integral of Δs can be extracted from the integral of g_1 using two other inputs (n decay, hyperon decay, SU(3))

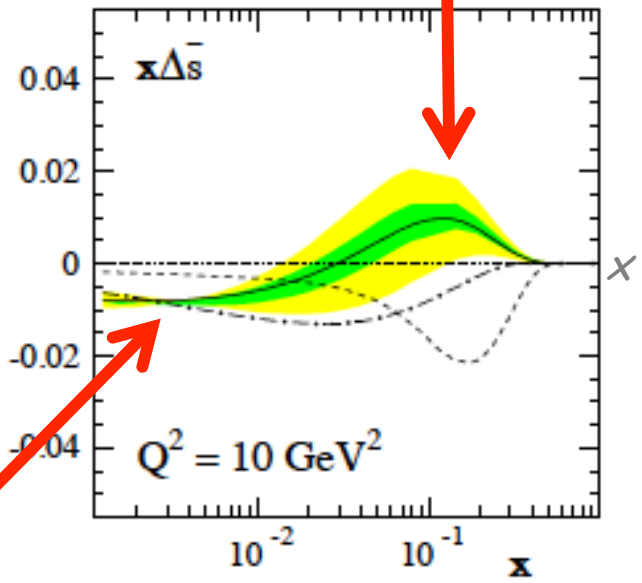
$\Delta\Sigma_s < 0$

• It can also be computed from Δs(x) measured from SIDIS data: kaon spin asymmetries, assuming FF known $\Delta\Sigma_s(x) \approx 0$

• Uncertainty in quark fragmentation functions ?
•SU(3) is broken ?

SIDIS



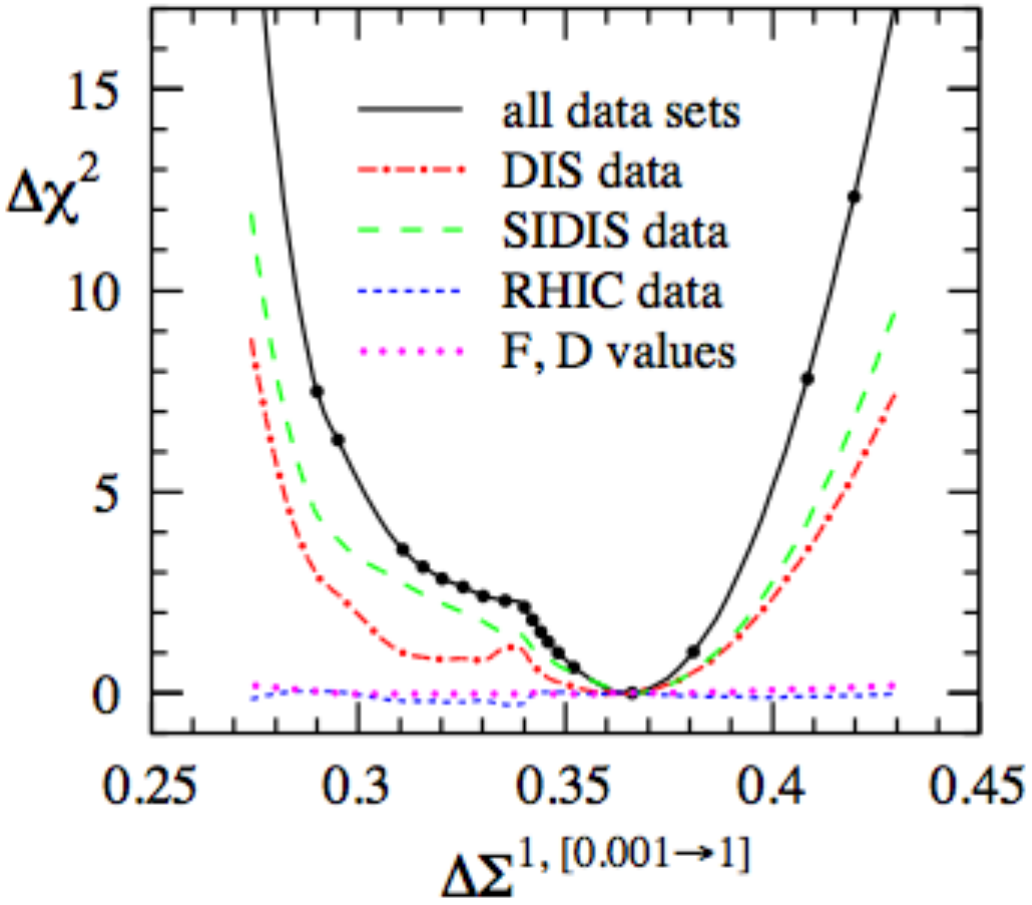


Driven by SU(3)

New Global Analysis with all World Data

DeFlorian, Sassot, Stratmann and Vogelsang, Phys. Rev. D 80, 034030 (2009)

Total quark and anti-quark spin contribution

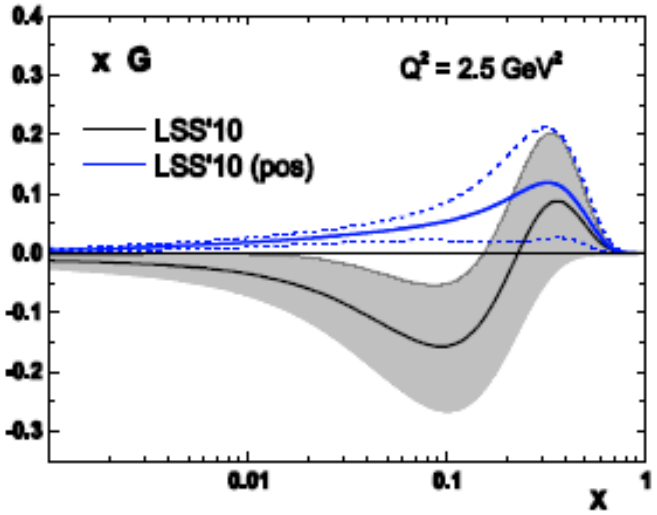


SU(3) broken:
$\Delta\Sigma \sim 0.36$

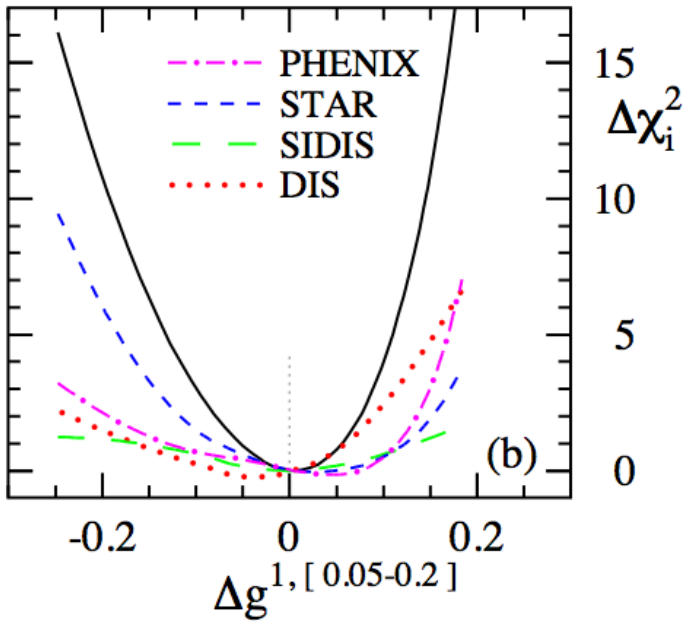
SU(3) holds:
$\Delta\Sigma \sim 0.24$

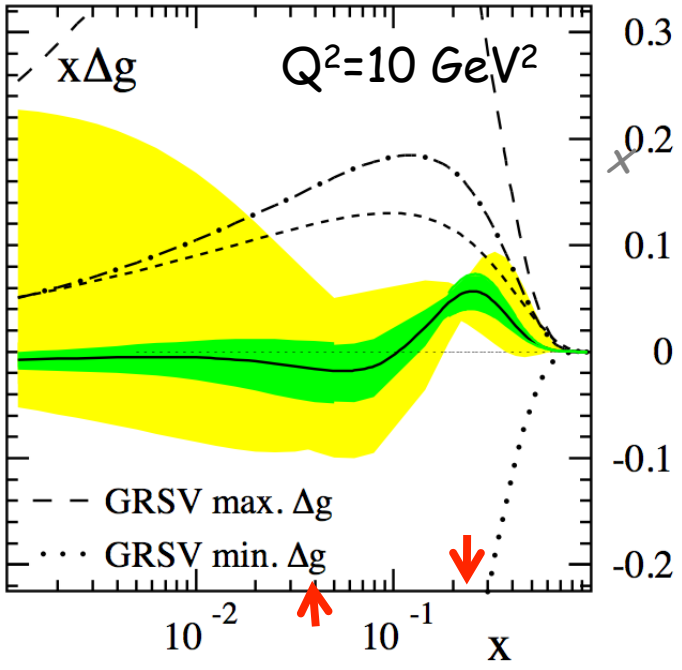
ΔG(x) from global QCD fits of polarized data

LSS '10
Only DIS & SIDIS data
Leader, Sidorov, Stamenov,
$\Delta G = -0.40 \pm 0.43$
$\Delta G = 0.25 \pm 0.19$



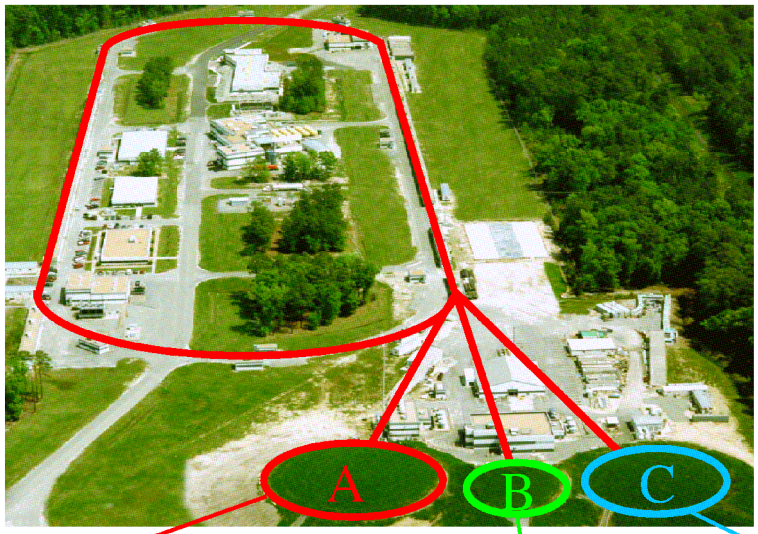
DSSV
DIS, SIDIS & p p
De Florian, Sassot, Stratmann, Vogelsang
PRL101 (2008)072001
$\Delta G = -0.08 \pm ?$

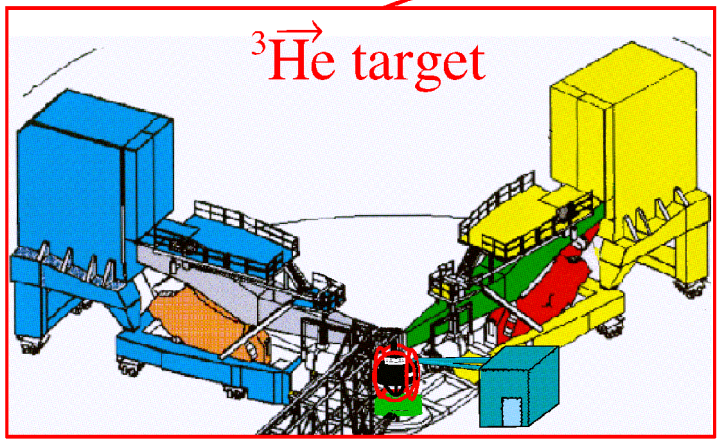


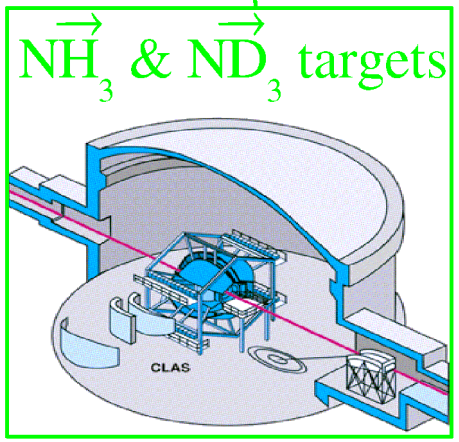


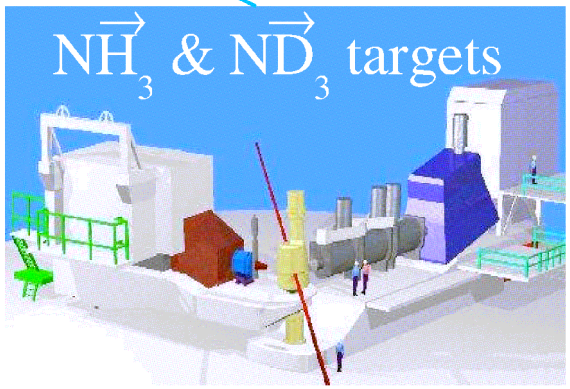
Jefferson Lab Experimental Halls

6 GeV pol. e beam
Pol=85%, 100μA





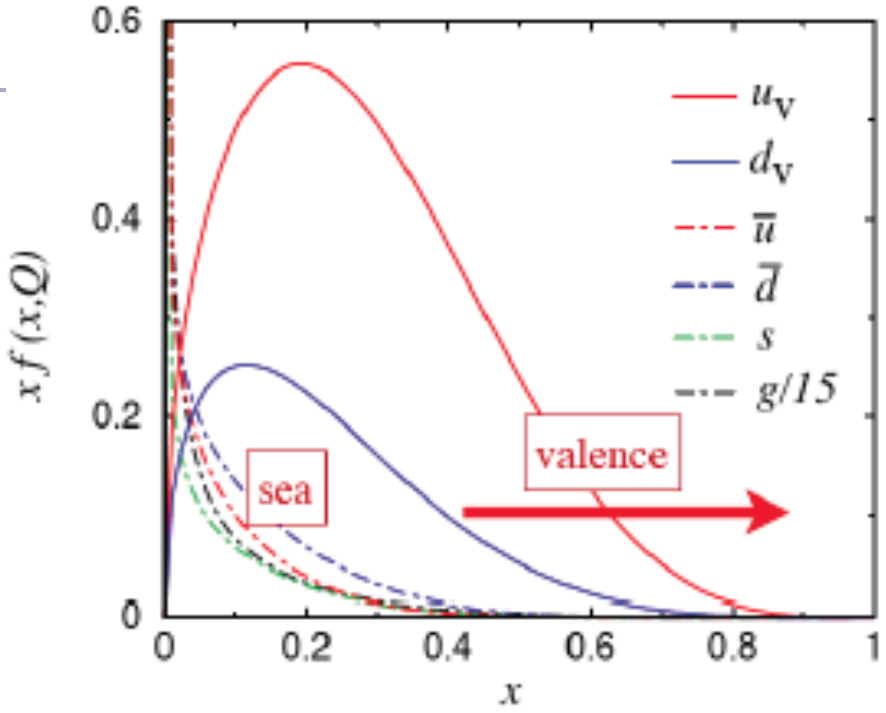




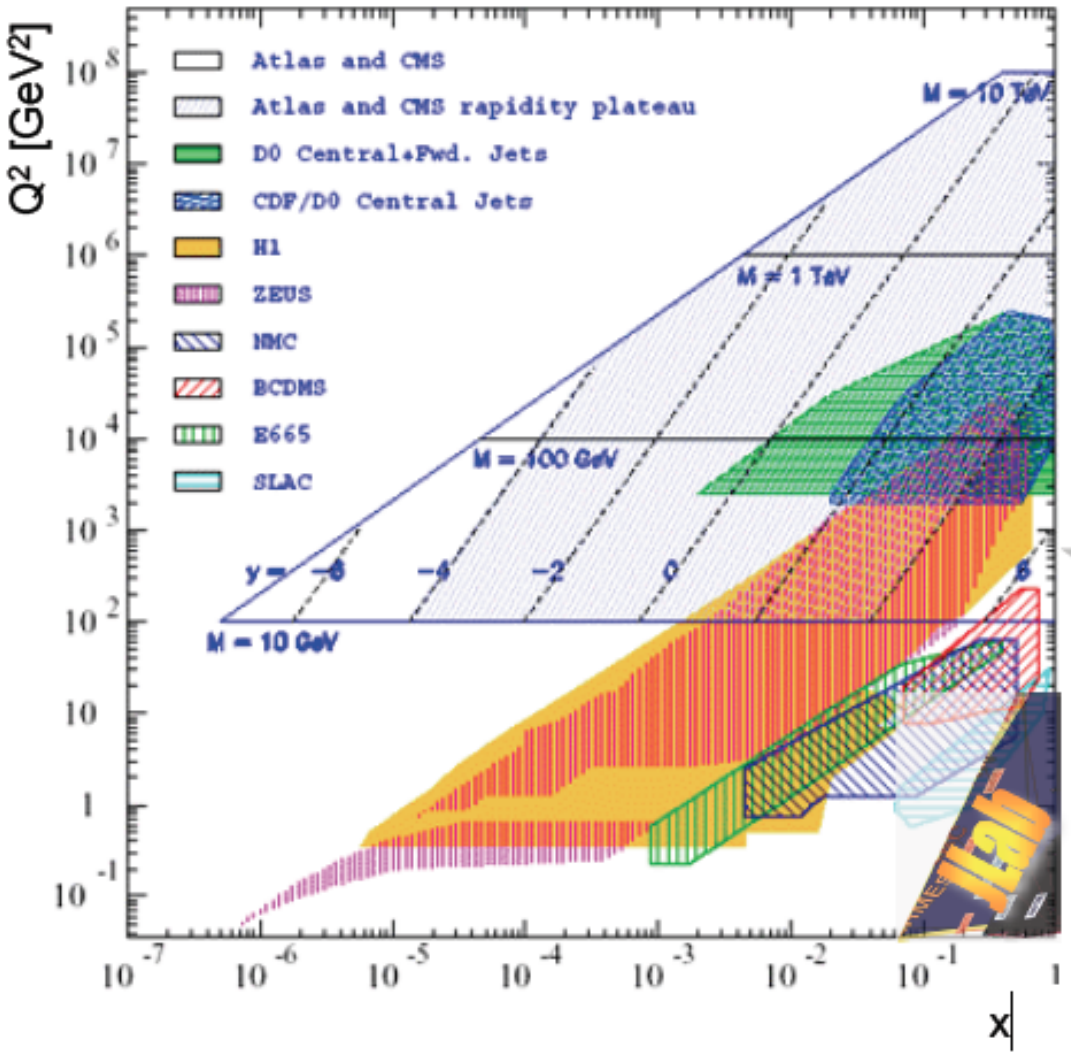
Hall A: two HRS' **Hall B:CLAS** **Hall C: HMS+SOS**

Topics Jefferson Lab Can Address

- Inclusive DIS
  - Spin structure functions
  - Valence PDFs at high Bjorken x
  - Sum Rules, OPE, higher twist
  - duality
- Semi-Inclusive DIS
  - Flavor tagged SSF
  - Transversity, TMD PDFs
- Exclusive Processes
  - DVCS
  - GPDs



Jefferson Lab in Perspective



JLab DIS

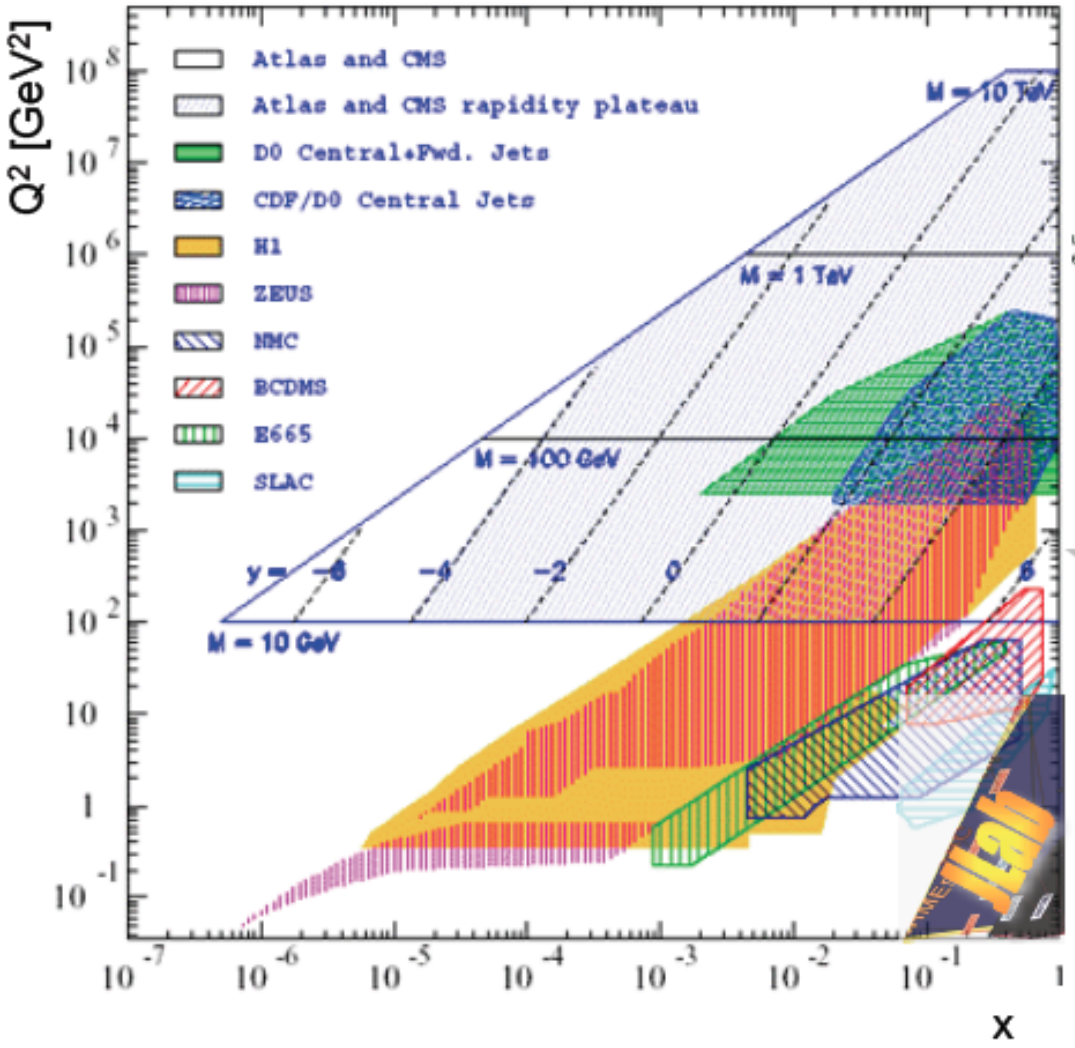
Present: 6 GeV

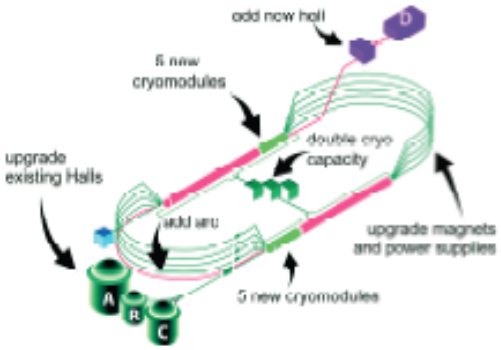
Q^2 = 1…6 GeV²

x = 0.1…0.6

W = 0.94…3 GeV

Jefferson Lab in Perspective





JLab DIS

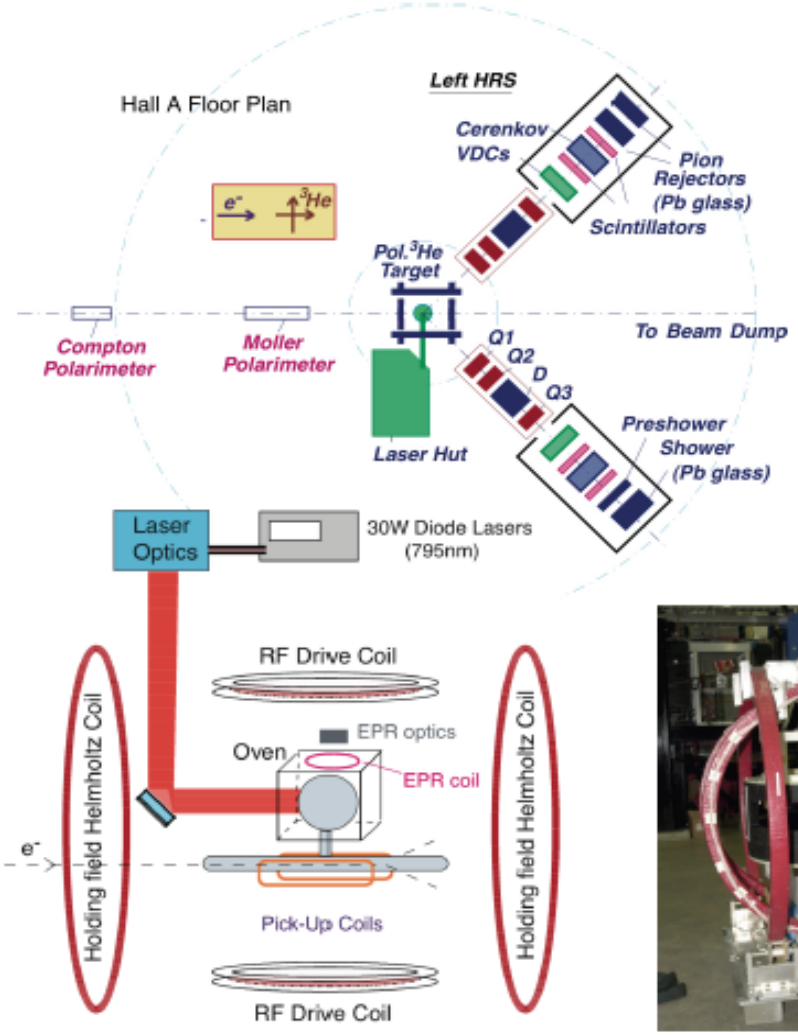
Future: 12 GeV

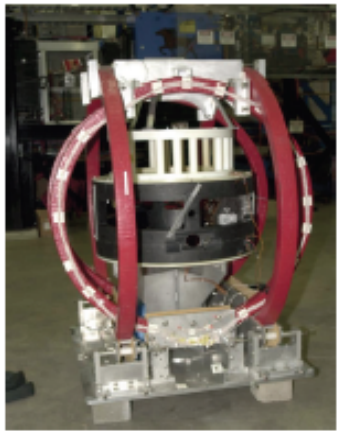
Q^2 = 1…13 GeV^2

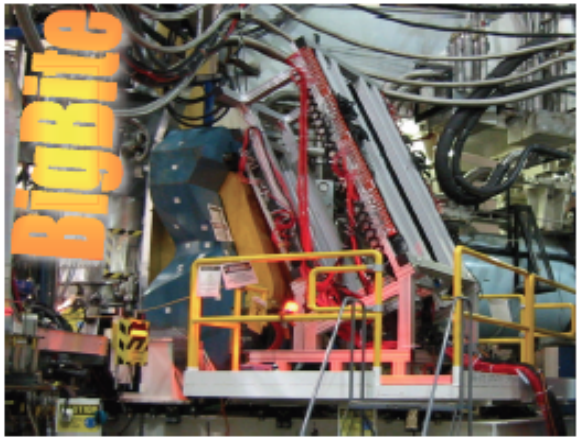
x = 0.06…0.8

W = 0.94…4 GeV

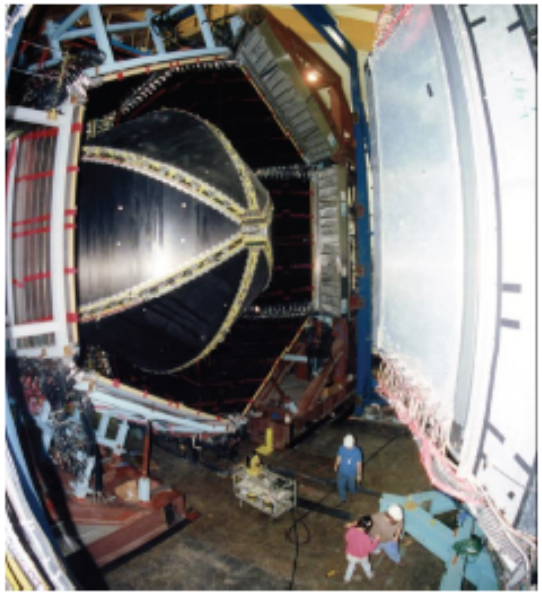
Experimental Hall A

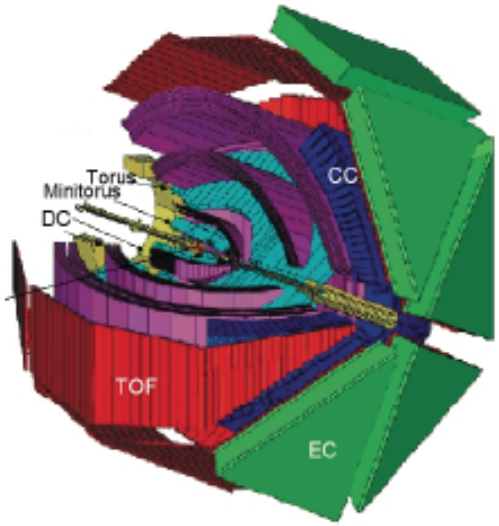


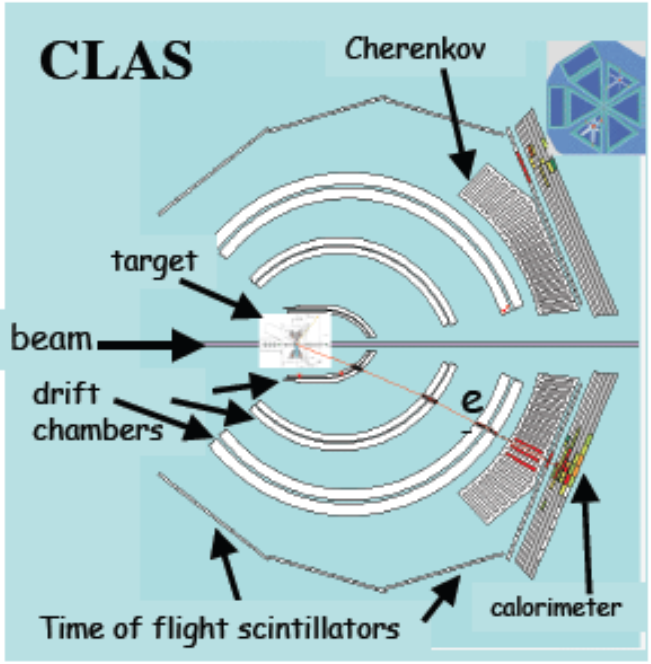


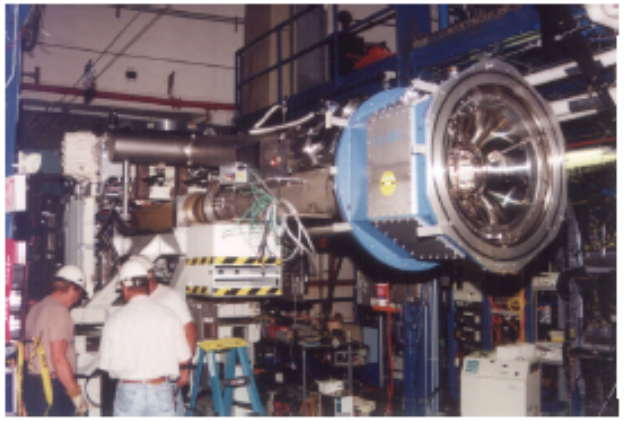


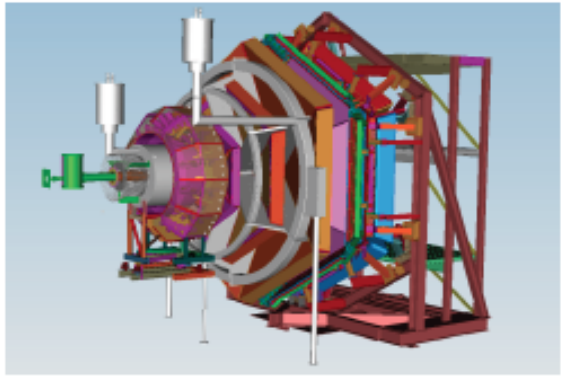
Experimental Hall B



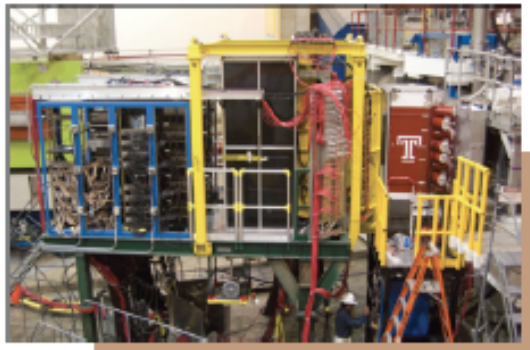




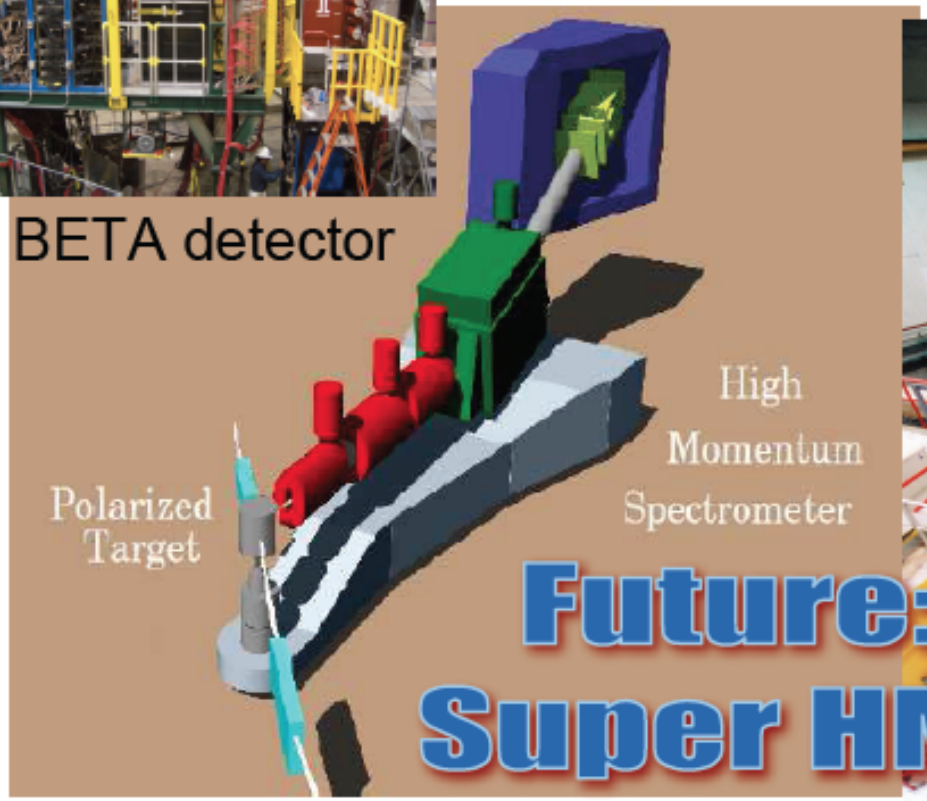




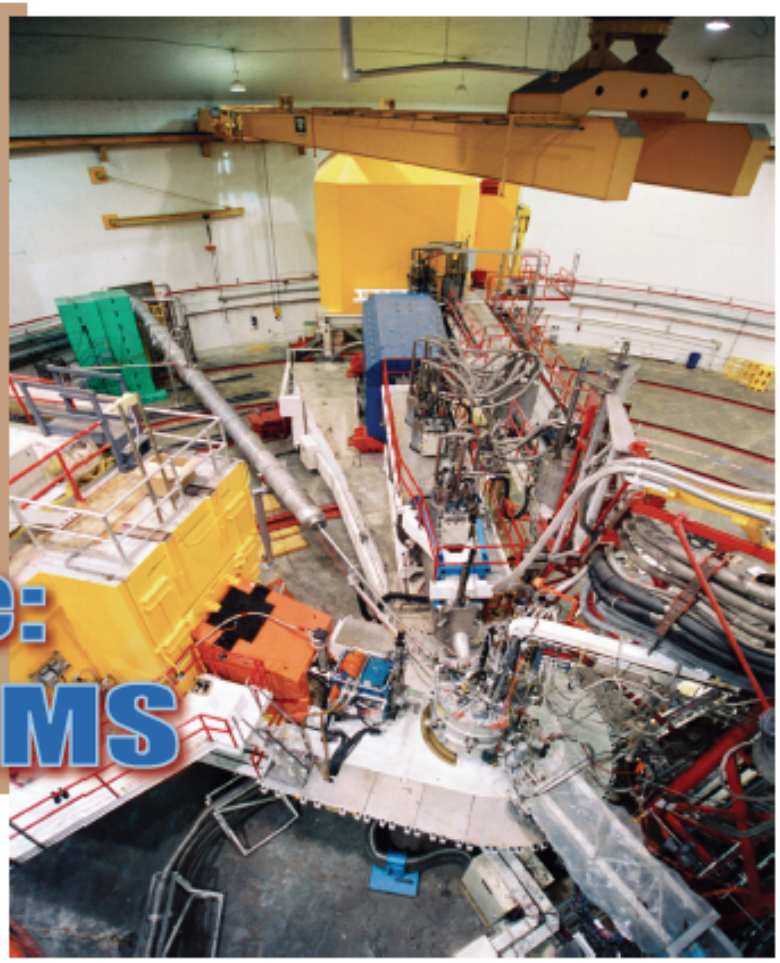
Experimental Hall C

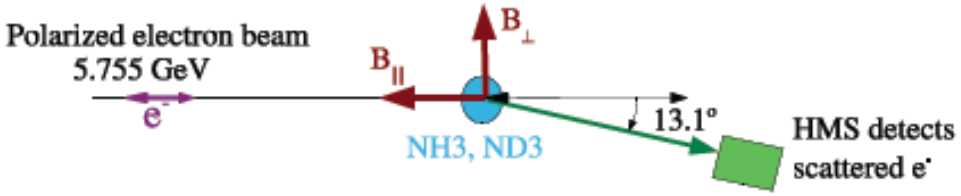


BETA detector

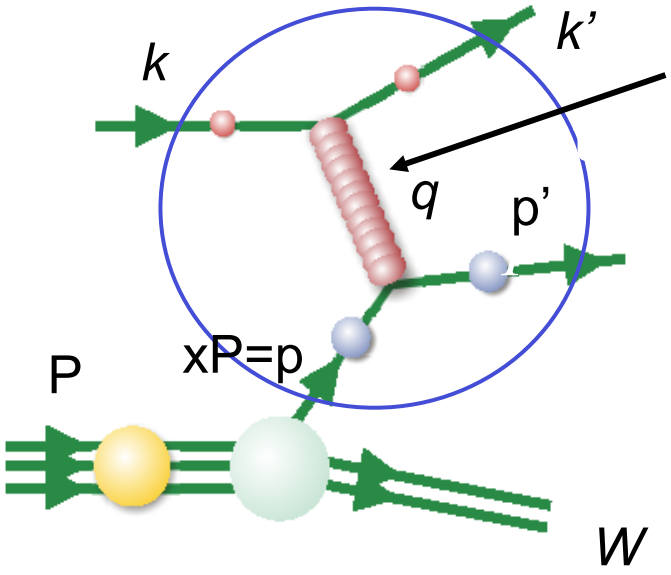


Future: Super HMS





Inclusive DIS of lepton off nucleon



Virtual photon probes the structure

Important variables:

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

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

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

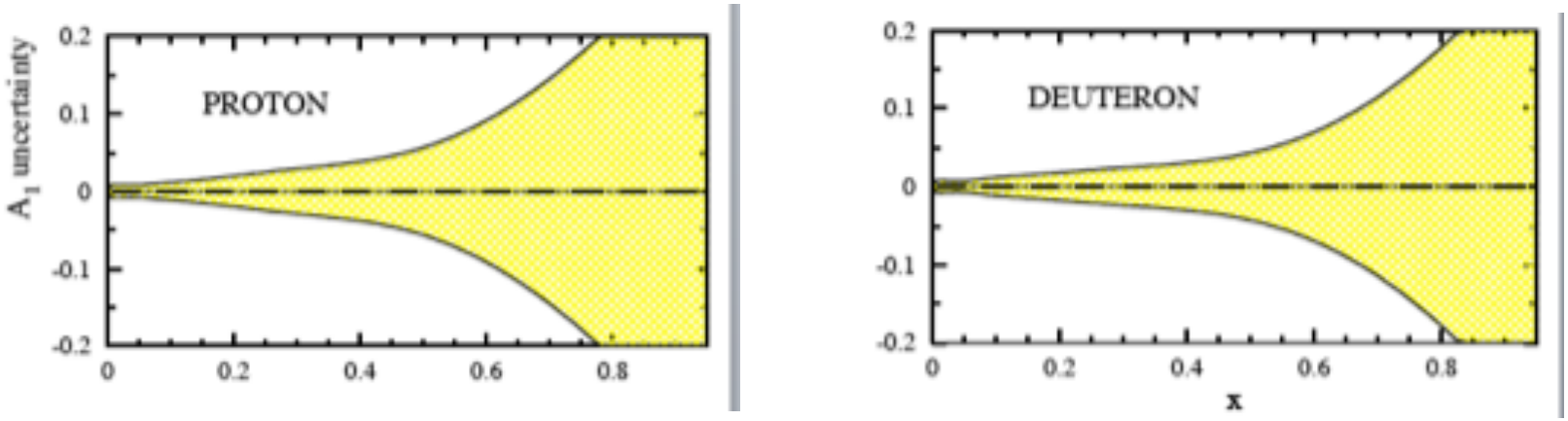
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{\nu E Q^2}\left[(E + E'\cos\theta)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$

Large-x behavior of the A_1 asymmetry

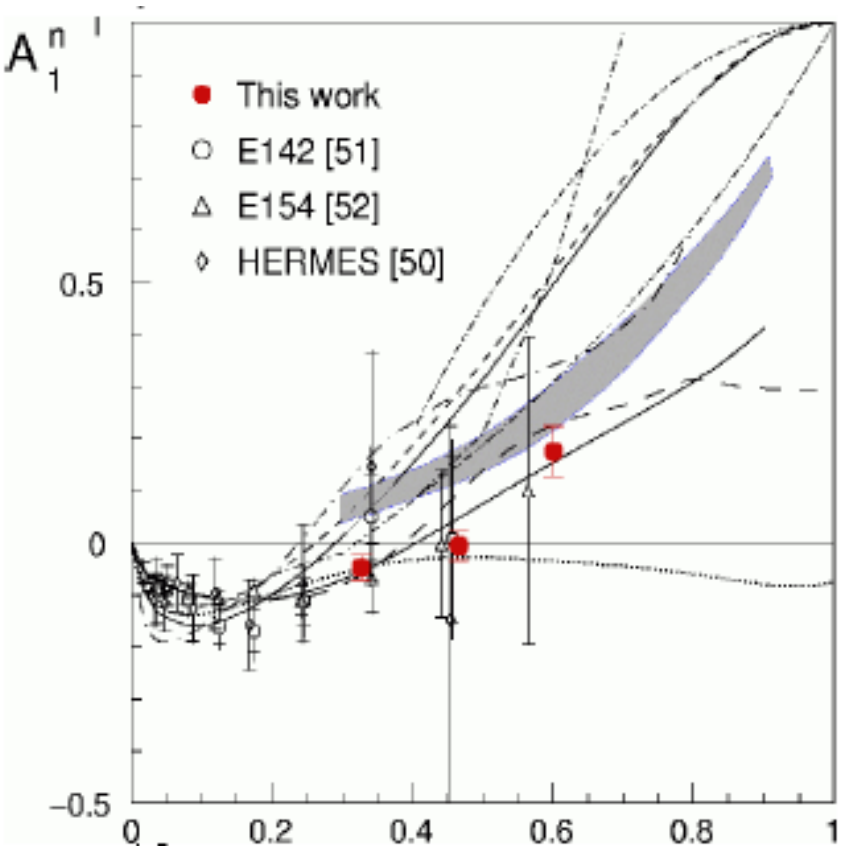
Large x region dominated by valence quarks→ can test quark models

Model for x --> 1	A_1^p	A_1^n	d/u	Δu/u	Δd/d
SU(6)	5/9	0	1/2	2/3	-1/3
w/ hyperfine ($E_{S=0} < E_{S=1}$)	1	1	0	1	-1/3
One gluon exchange	1	1	0	1	-1/3
Suppressed symmetric WF	1	1	0	1	-1/3
S=1/2 dominance	1	1	1/14	1	1
$\sigma_{1/2}$ dominance	1	1	1/5	1	1
pQCD (conserved helicity)	1	1	1/5	1	1



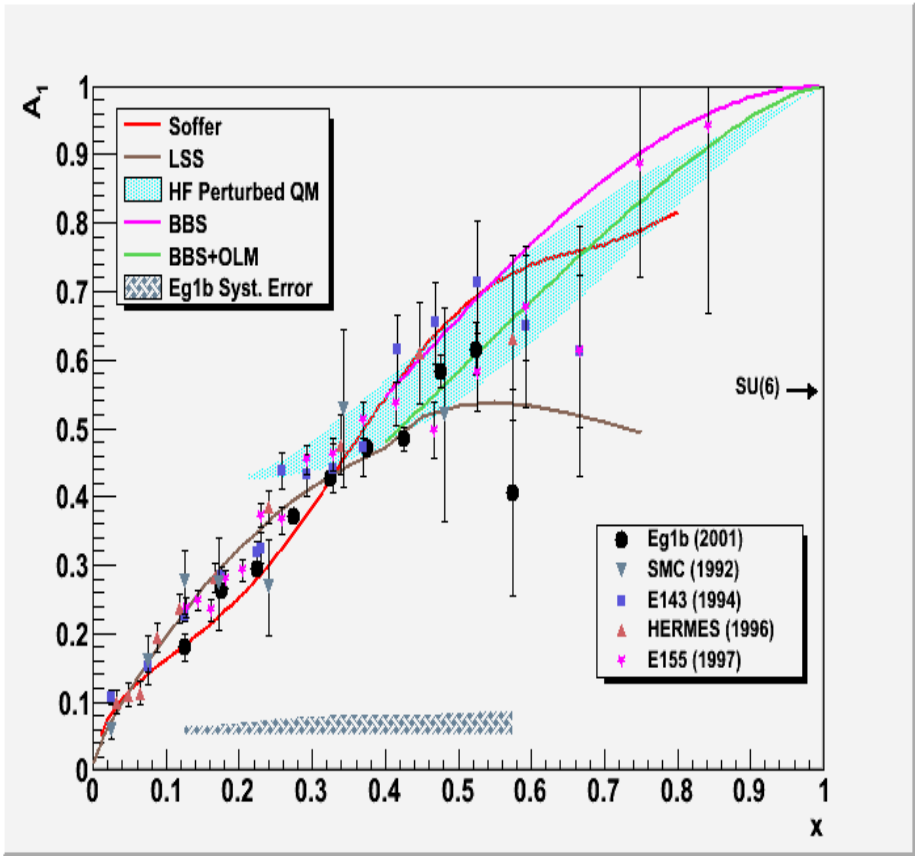
Large-x behavior of the A_1 asymmetry

Hall A, neutron

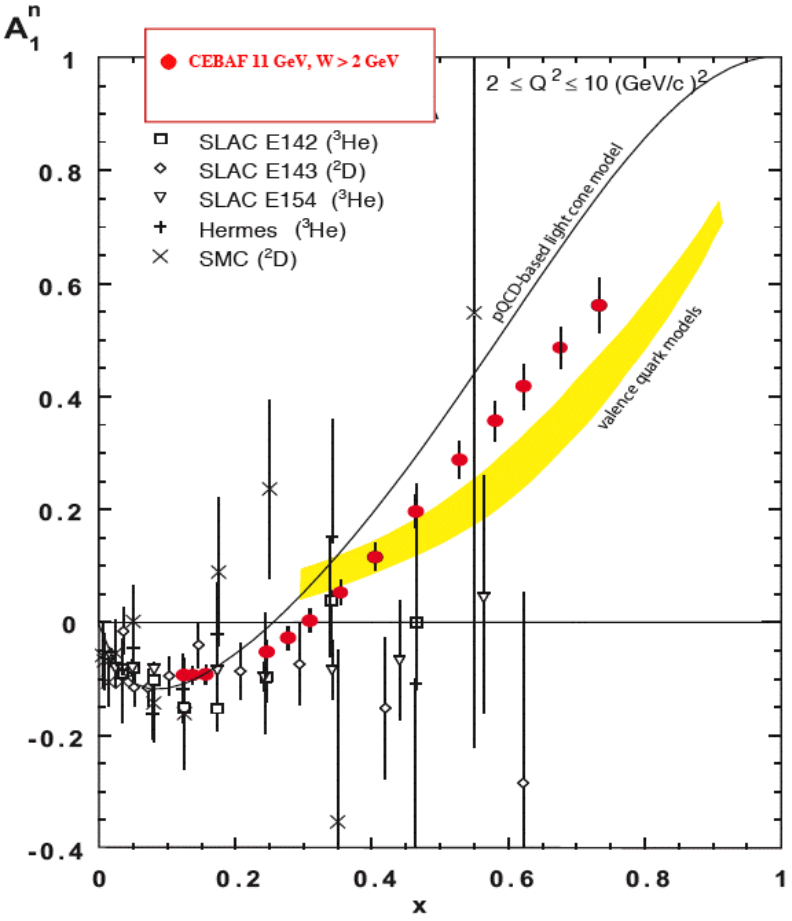


X. Zheng, *et al.* Phys.Rev. C70 (2004) 065207

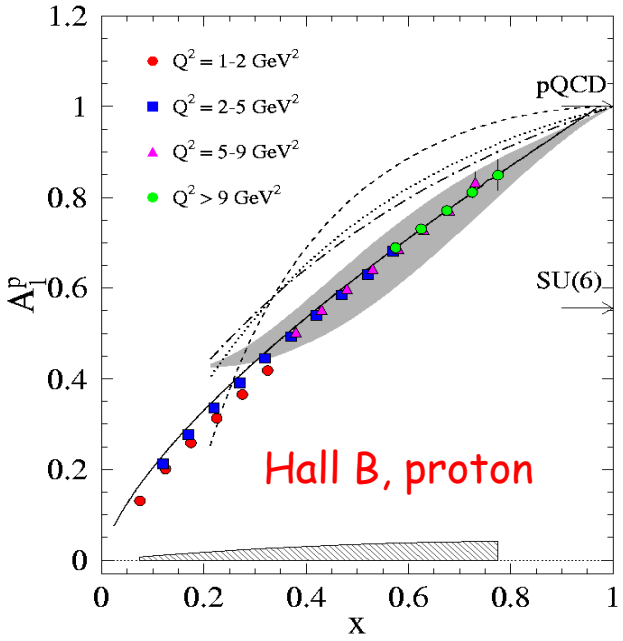
Hall B, proton

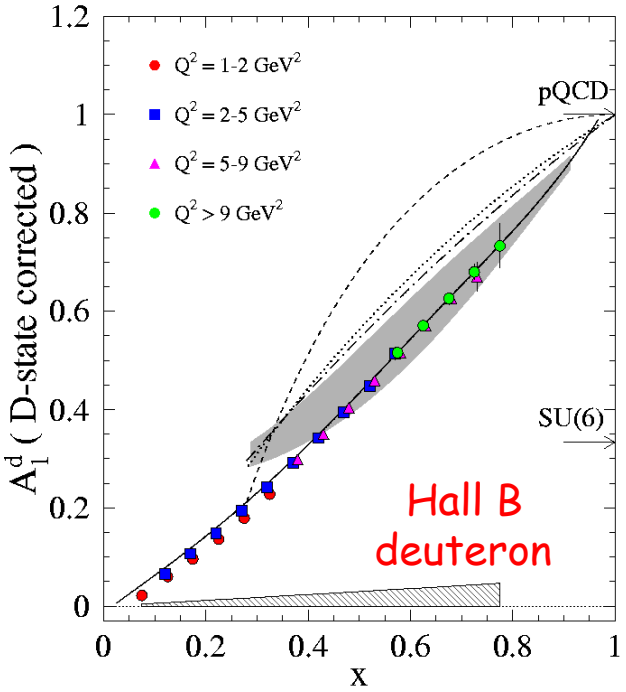


A_1 at large x : Future



Halls A, C neutron

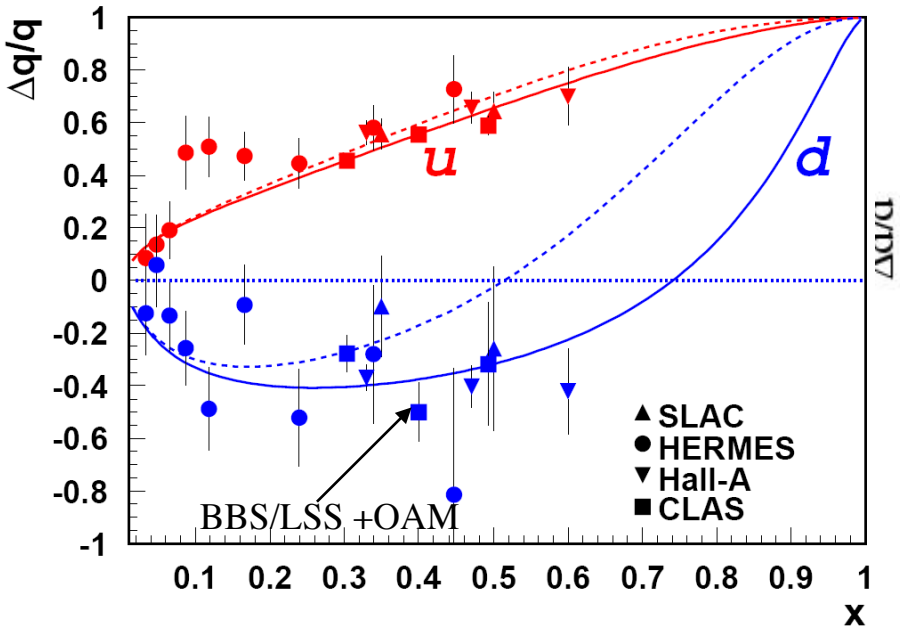




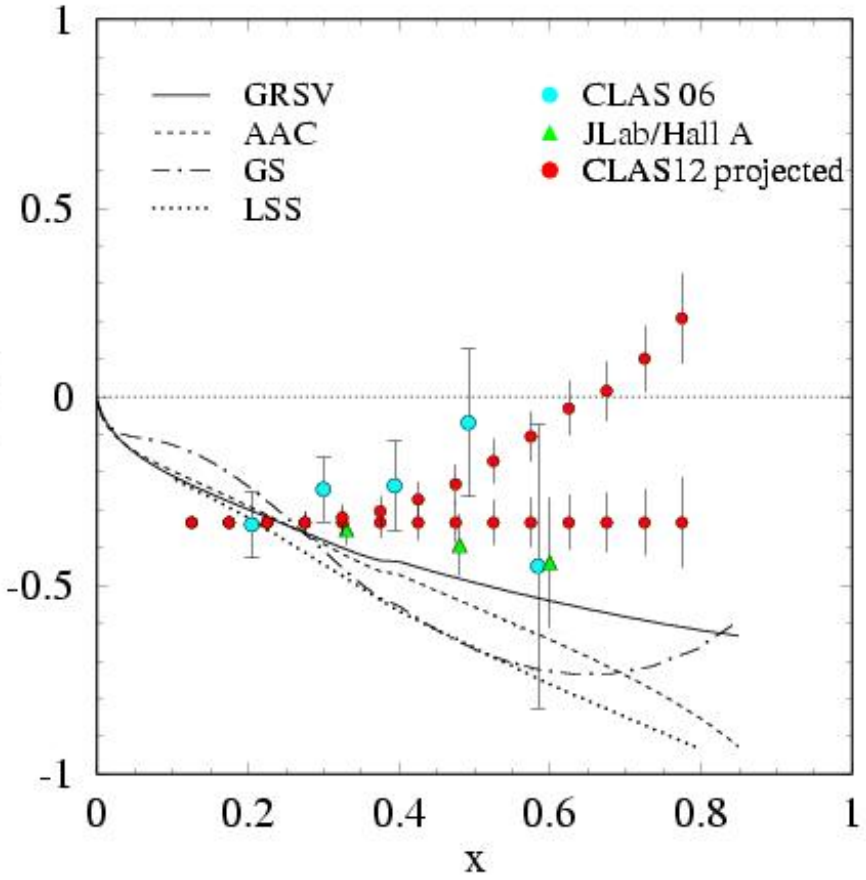
Quark polarization in the valence region

$$A_1(x,Q^2) = \frac{\sum e_i^2 \Delta q_i(x,Q^2)}{\sum e_i^2 q_i(x,Q^2)}$$

Existing Data

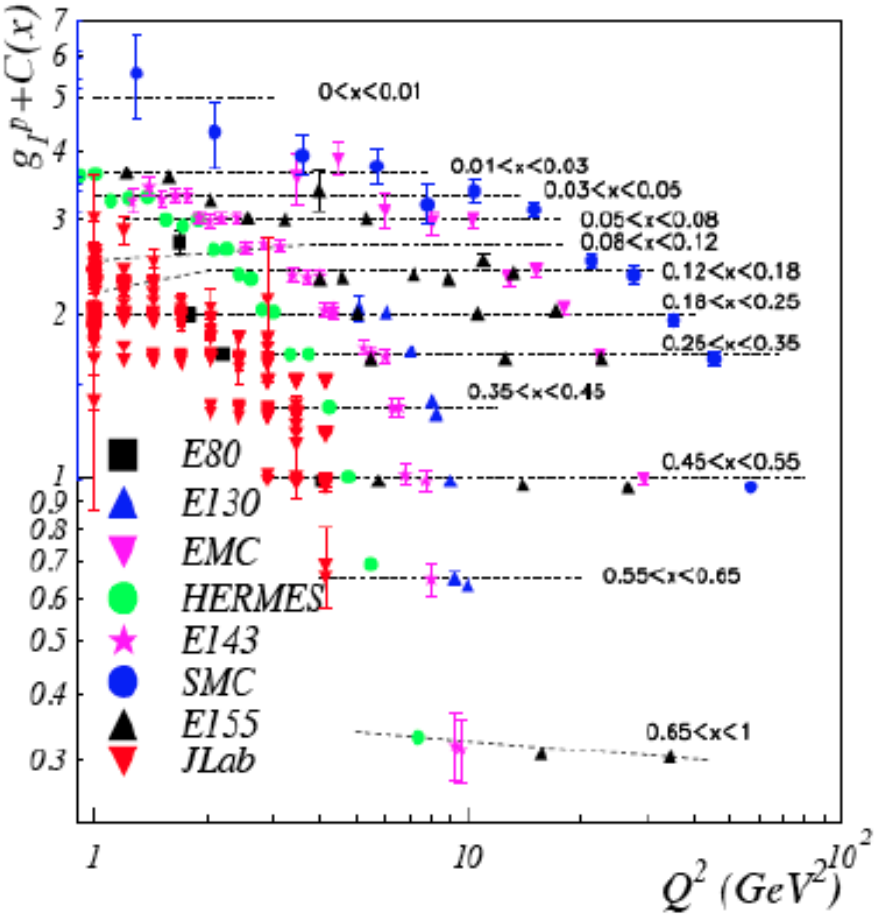


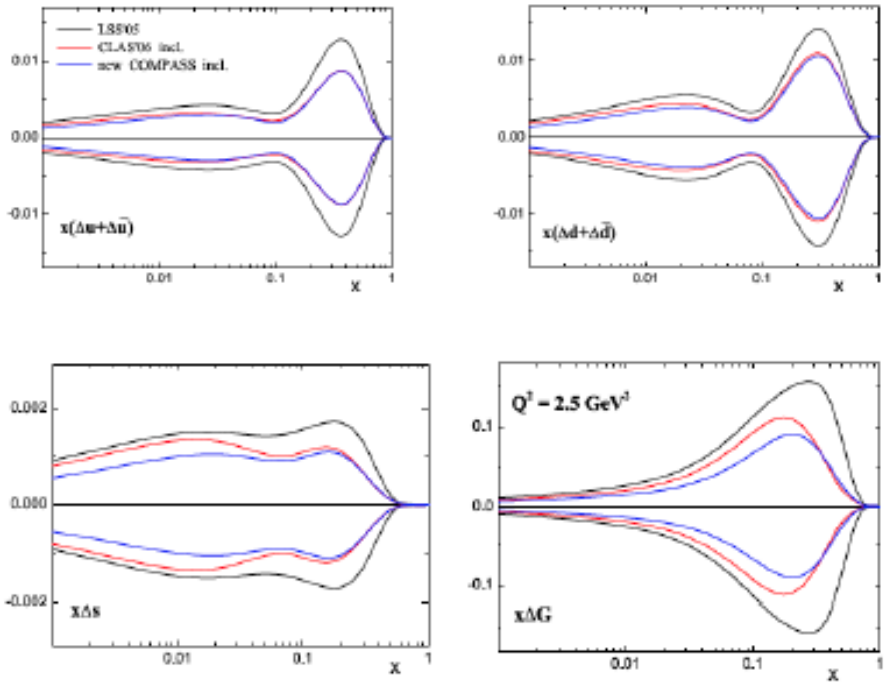
Simulated Data for EG12
Extracted from A_1^p, A_1^d and d/u



Effect of JLAB data on NLO fits of PDFs

$$g_1(x,Q^2)_{pQCD}=\frac{1}{2}\sum_q^{N_f} e_q^2[(\Delta q+\Delta\bar{q})\otimes(1+\frac{\alpha_s(Q^2)}{2\pi}\delta C_q)+\frac{\alpha_s(Q^2)}{2\pi}\Delta G\otimes\frac{\delta C_G}{N_f}]$$

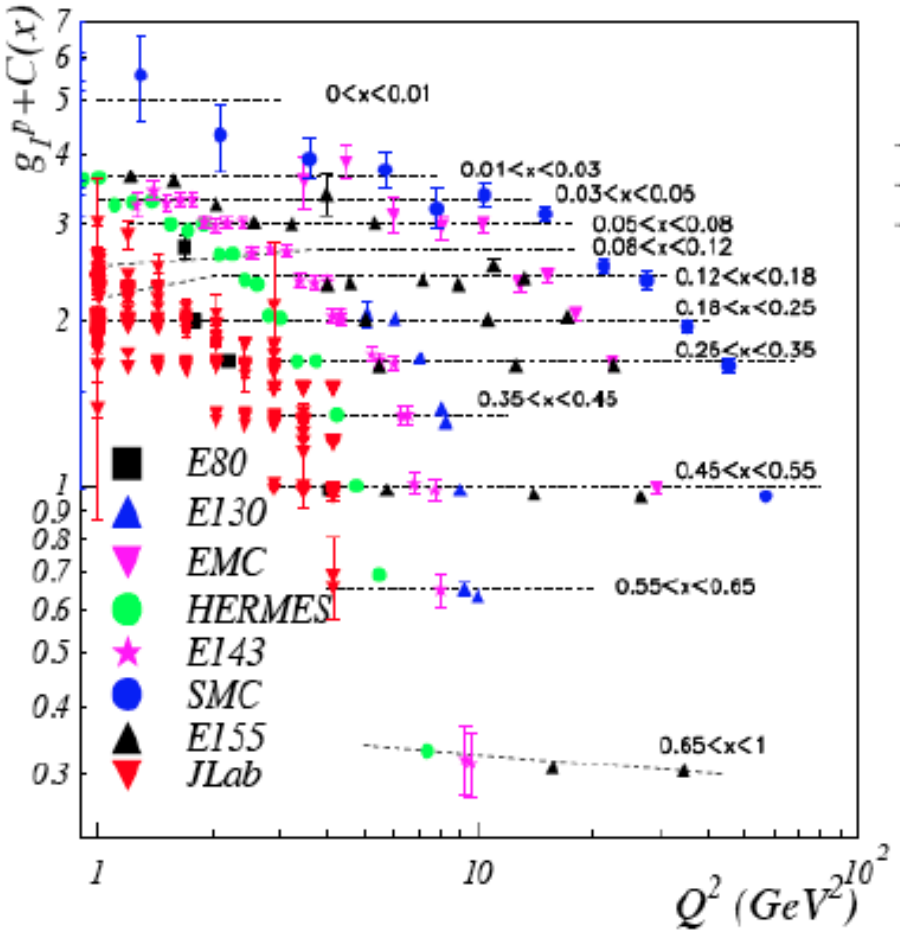


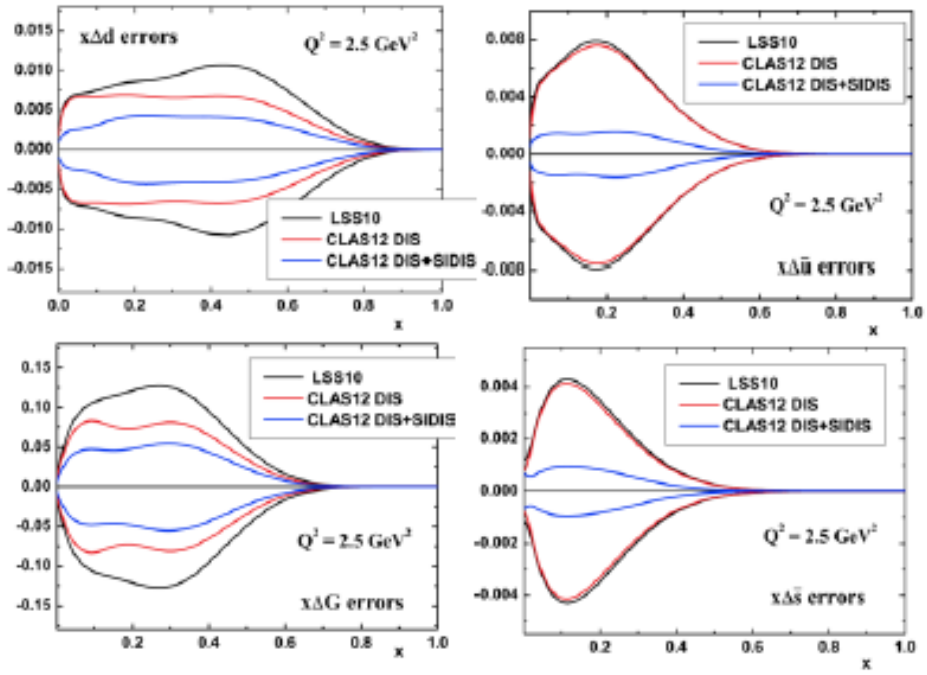


NLO fit by Leader, Stamenov and Siderov, including both CLAS data and new COMPASS data on the deuteron

Effect of JLAB data on NLO fits of PDFs

$$g_1(x,Q^2)_{pQCD} = \frac{1}{2}\sum_q^{N_f} e_q^2 [(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \frac{\delta C_G}{N_f}]$$





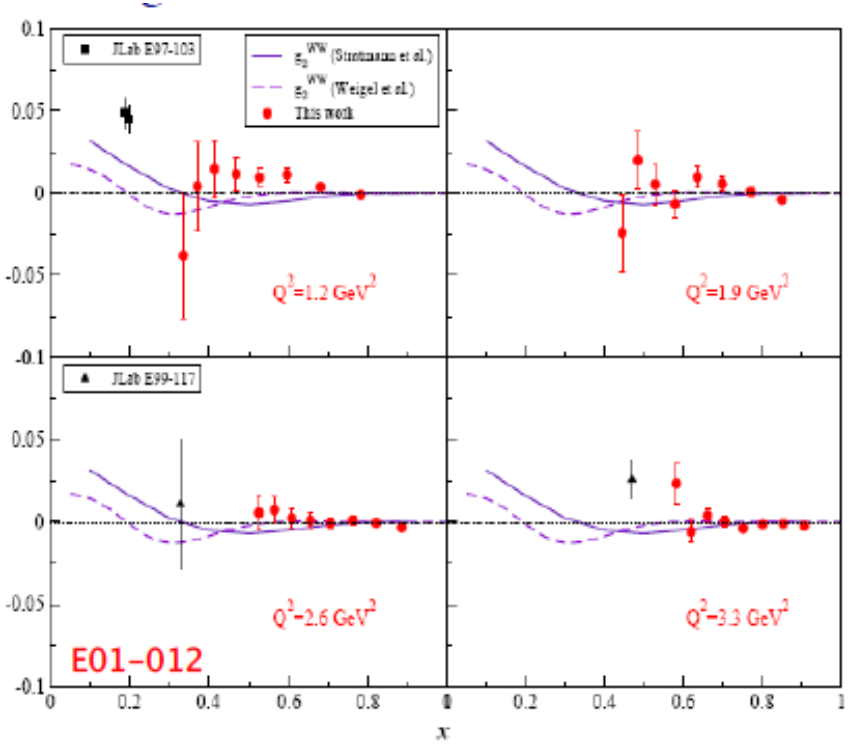
NLO fit by Leader, Stamenov and Siderov, including both CLAS data and new COMPASS data on the deuteron

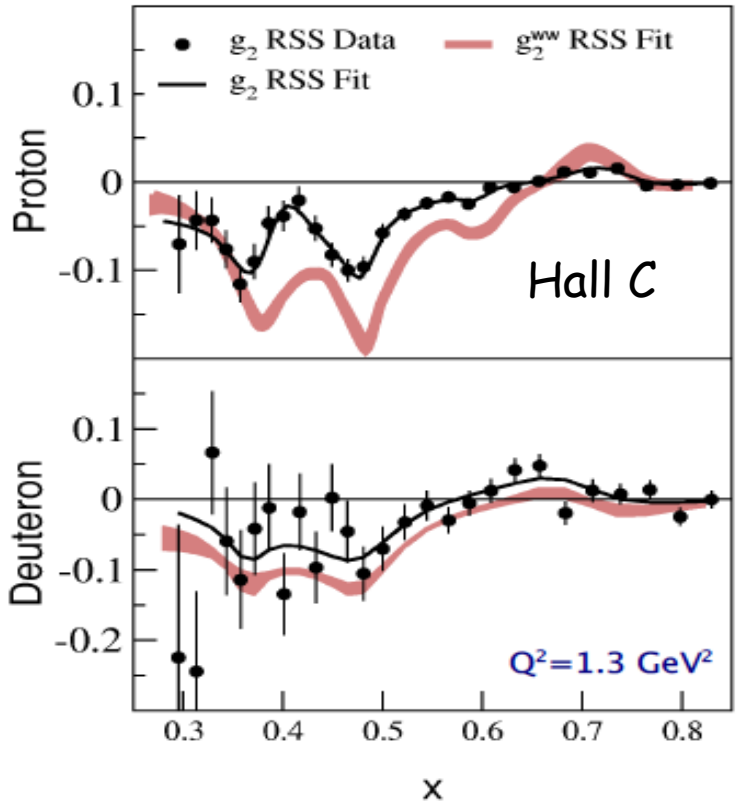
The spin structure function g_2

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

$$= -g_1(x,Q^2) + \int_x^1 \frac{dx'}{x'} g_1(x',Q^2) - \int_x^1 \frac{dx'}{x'} \frac{\partial}{\partial x'} \left[\frac{m}{M} h_T(x',Q^2) + \xi(x',Q^2) \right]$$

Hall A, neutron

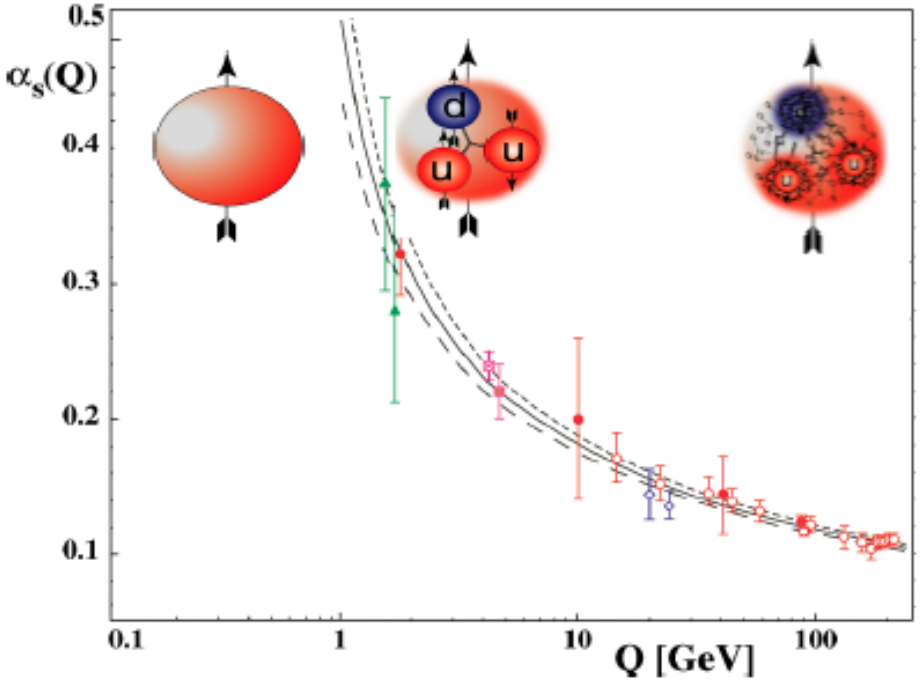




Quark-Hadron Duality

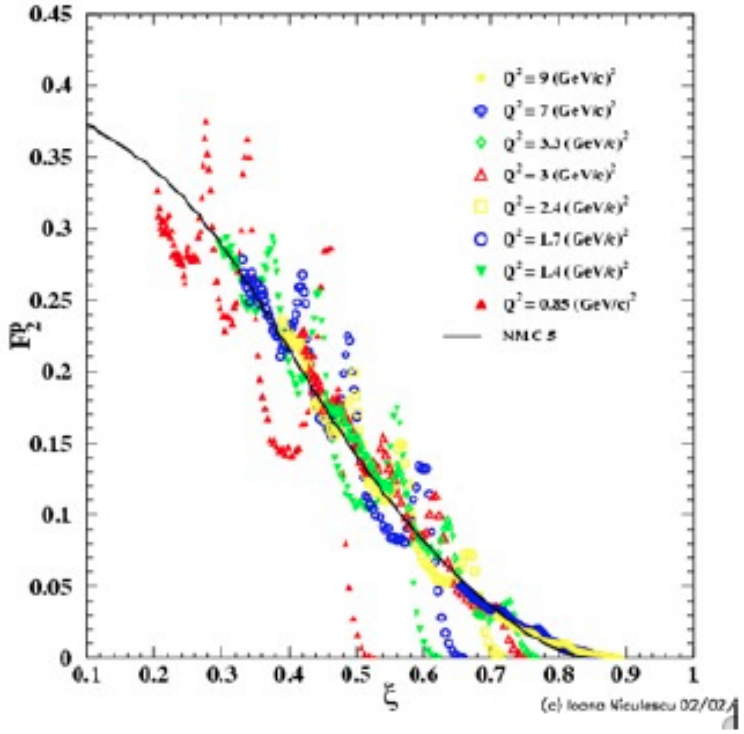
SFs averaged over (part of) resonance region ≈ DIS SFs

Long Distance Physics:
hadronic observables

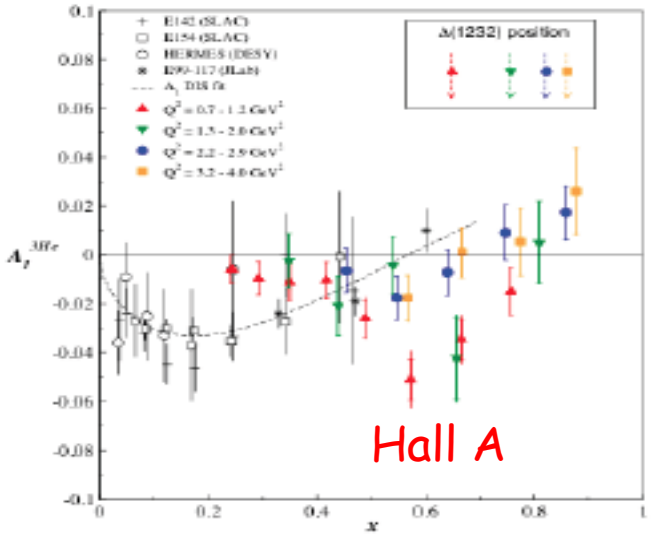


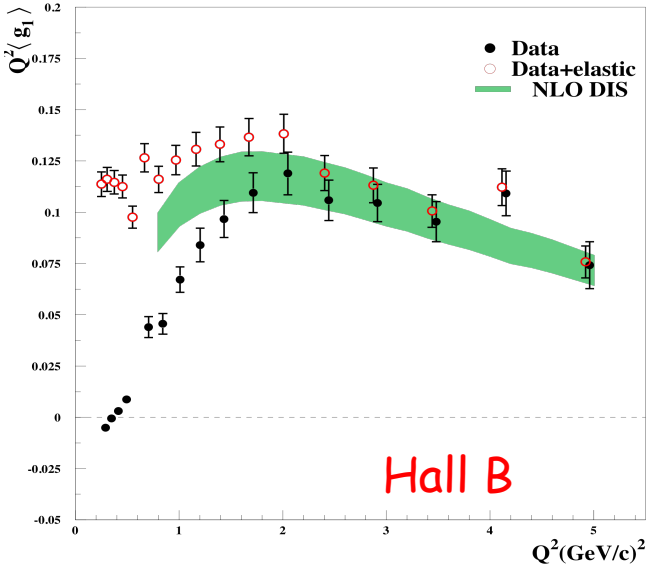
Asymptotically Free Quarks:
regime of pQCD

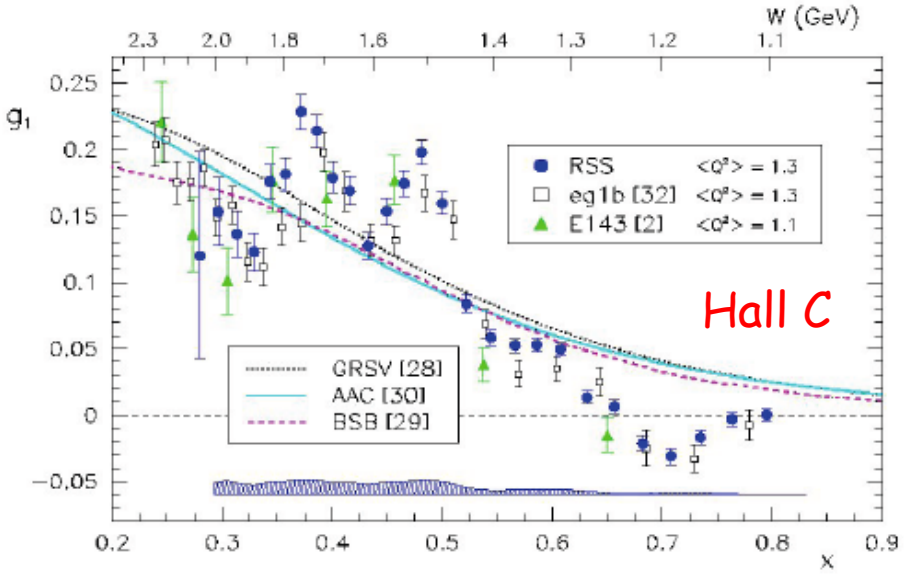
Hall C Data

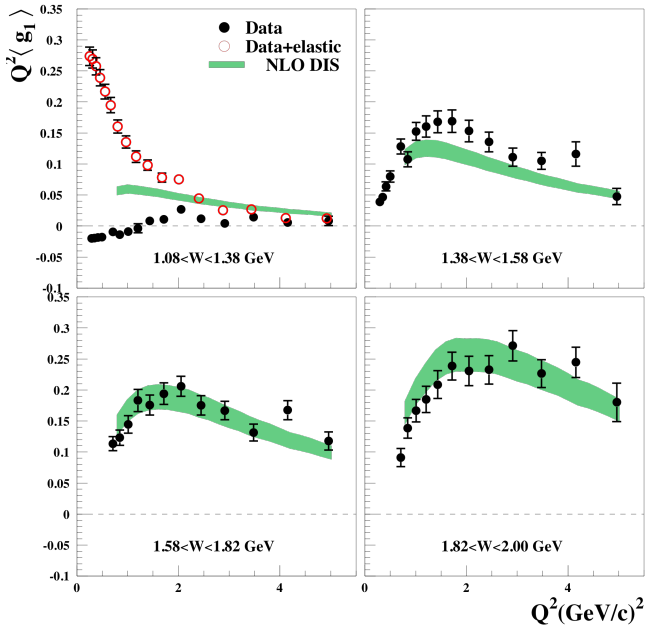


Quark-Hadron Duality in g_1

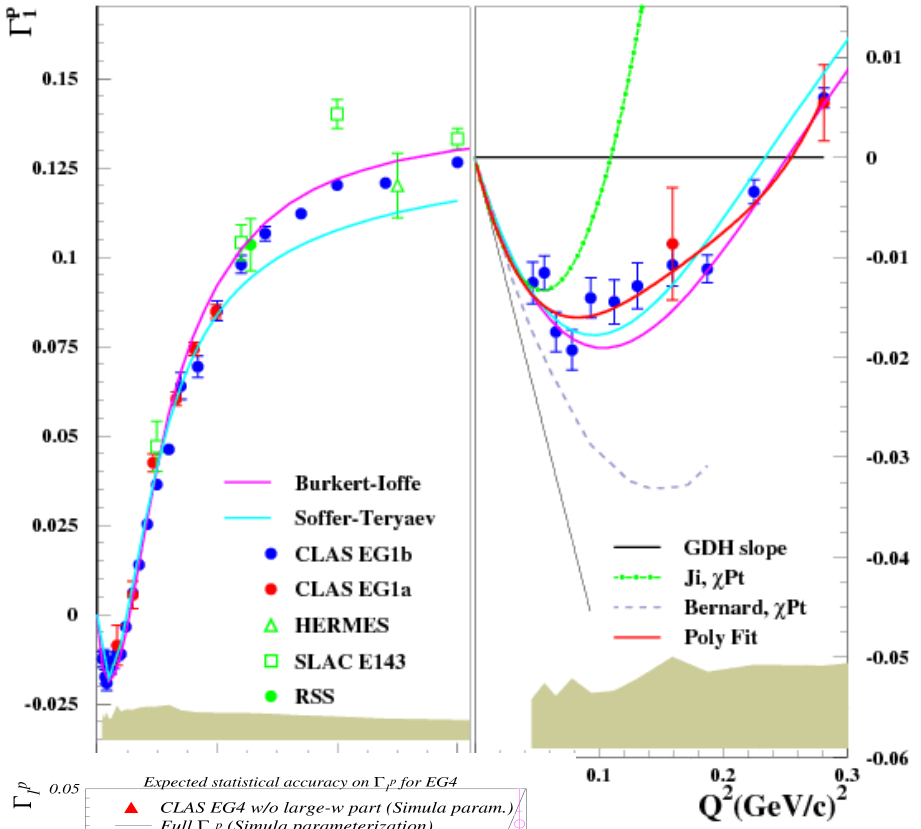


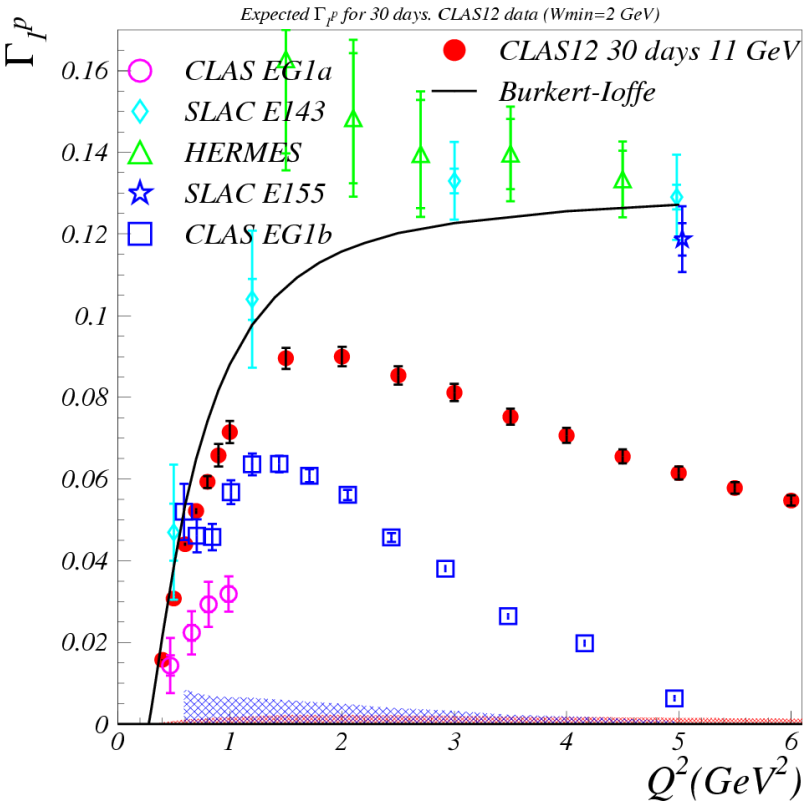


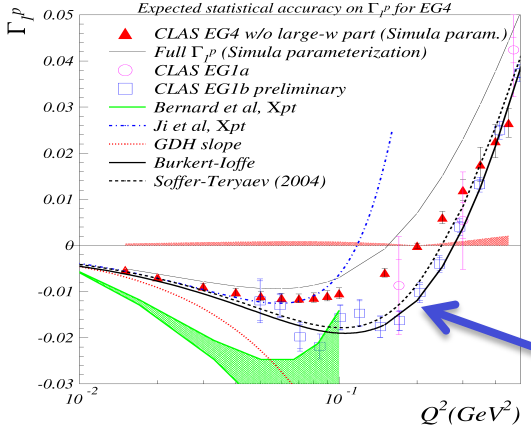




Sum Rules



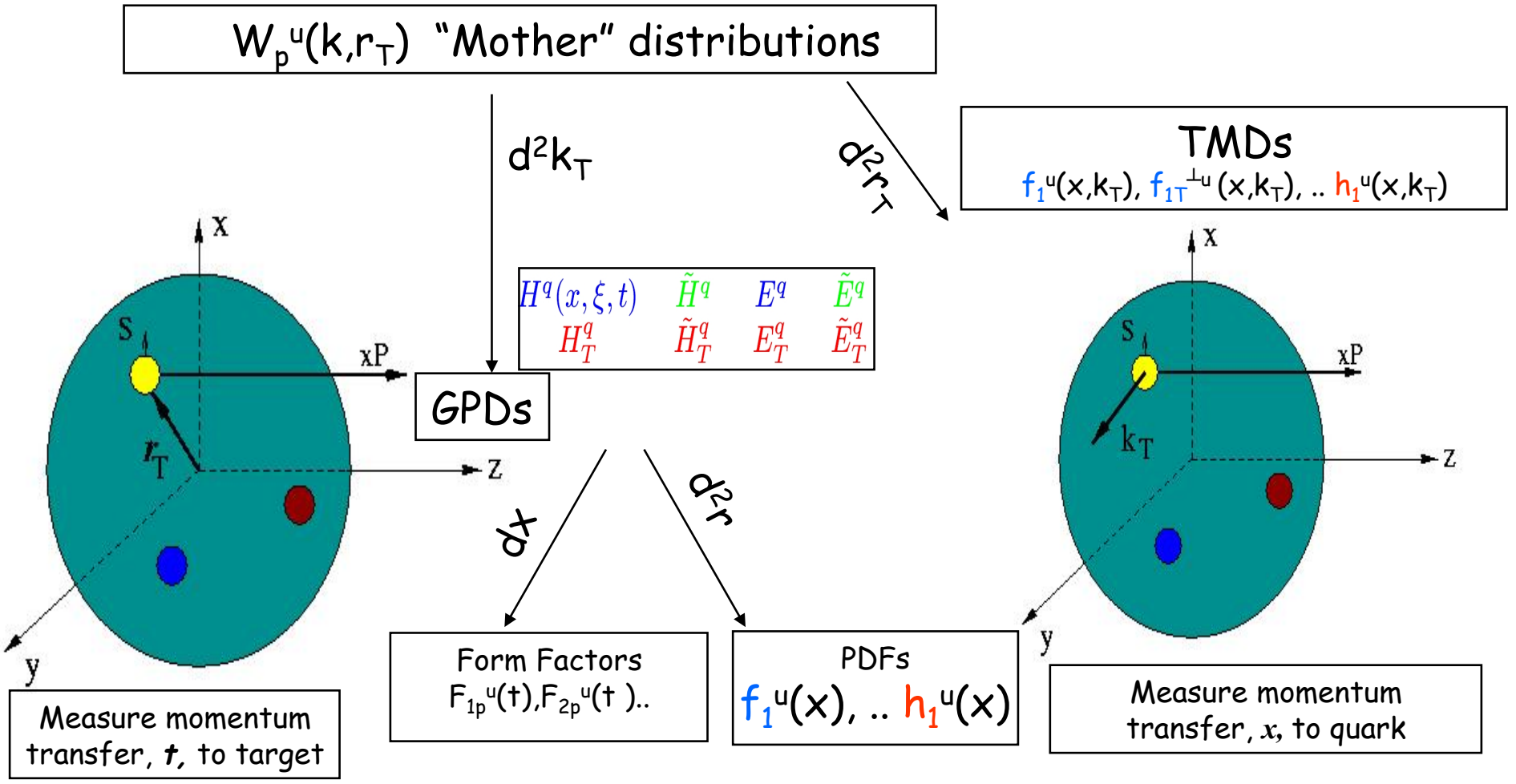




At low Q^2 we observe a negative slope as expected from GDH Sum Rule.

Extends to very low Q^2 of 0.015 GeV^2 both proton and deuteron

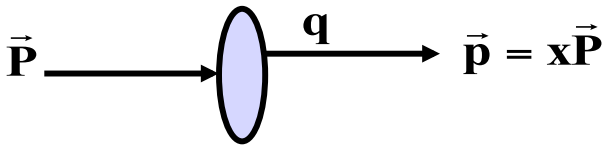
Towards the 3 dimensional picture..



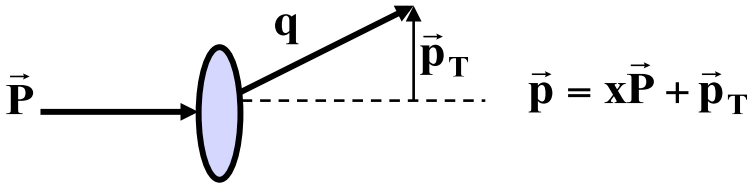
Hard exclusive and semi-inclusive measurements provide complementary information about the transverse structure of the nucleon

TMDs measured in SIDIS

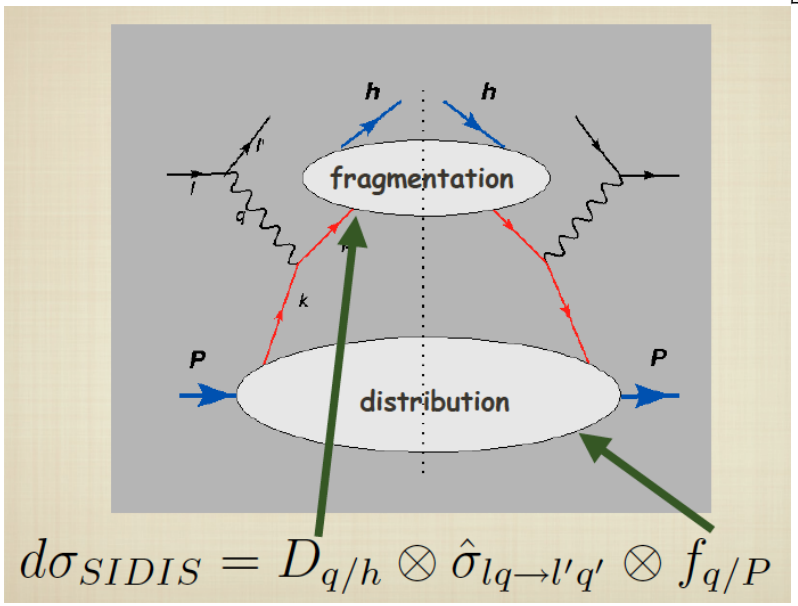
In the collinear approximation:



Parton transverse momentum

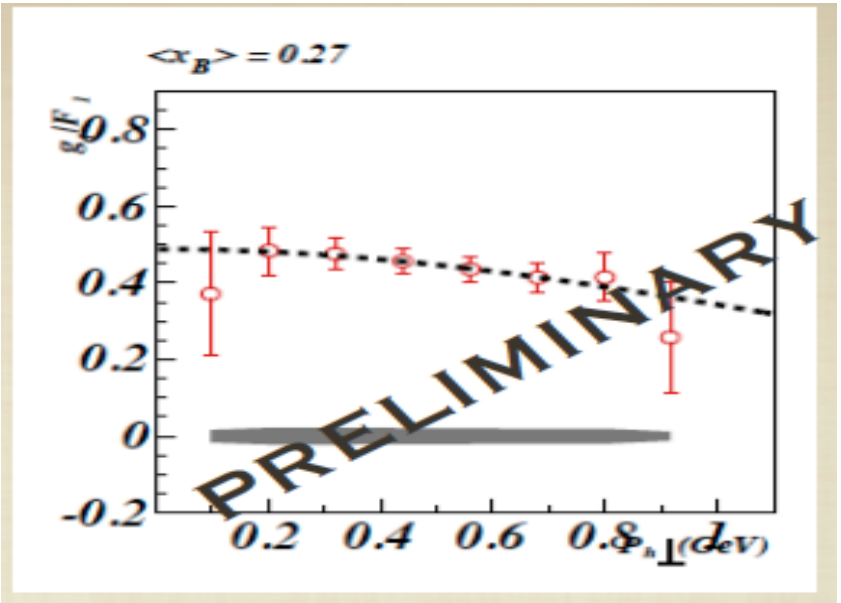


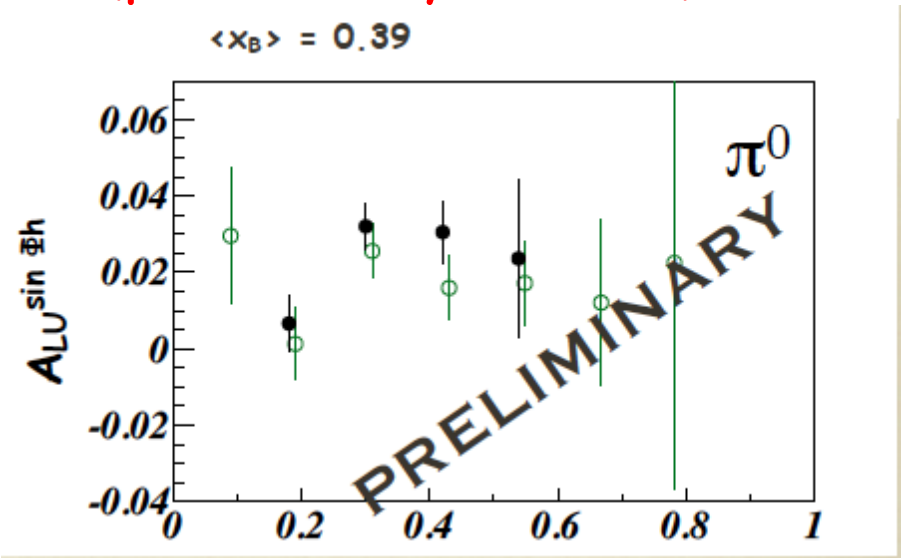
nucleon \ quark	U	L	T
U	f1		$h_1^\perp$
L		g1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h1, $h_{1T}^\perp$

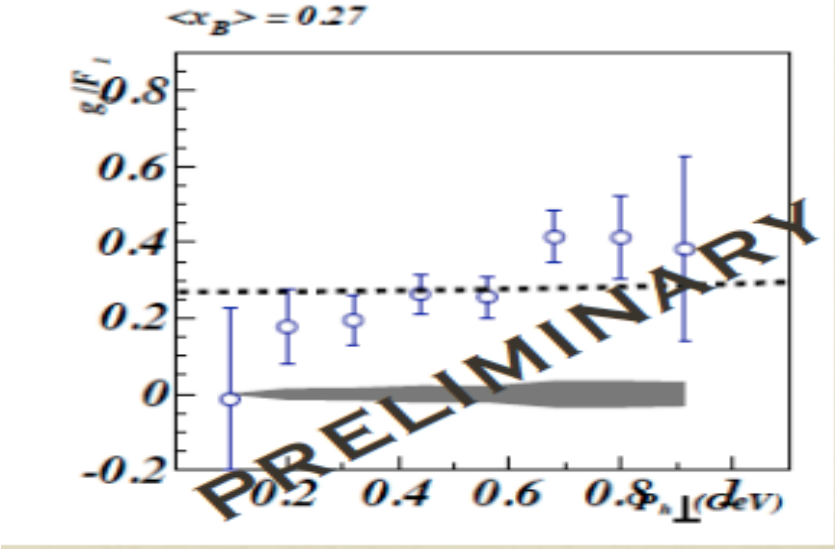


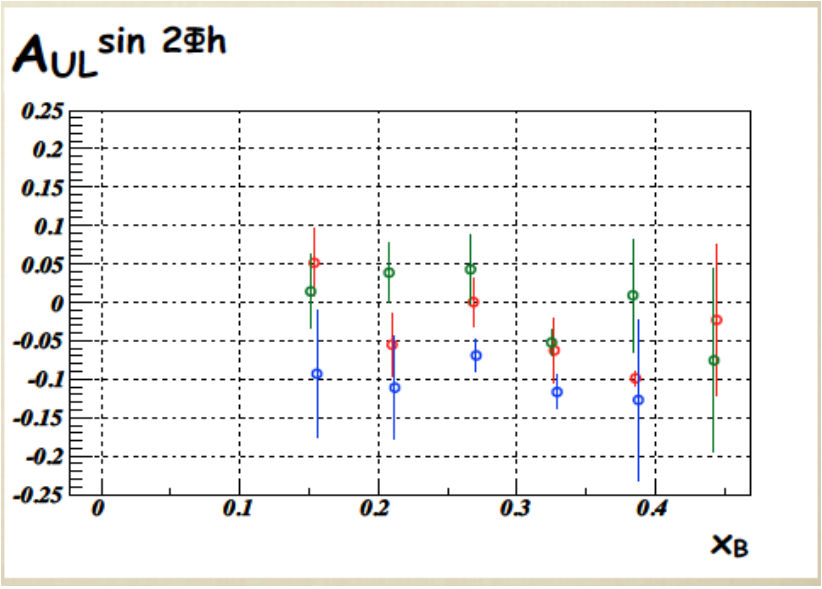
- Measure A_{UL}, A_{LU}, A_{LL}
- Different hadron species
- Spin-momentum correlations (Sivers function, Boer-Mulders function, "pretzelosity")
- New fragmentation functions (Collins)

Hall B: SIDIS asymmetries with longitudinally polarized NH_3 and ND_3 targets (preliminary results)







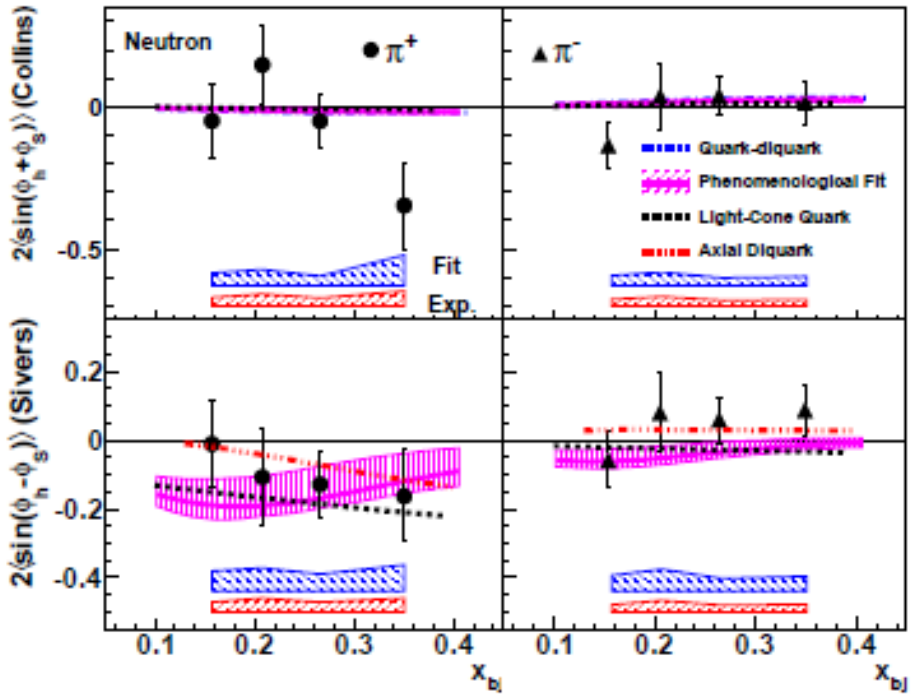


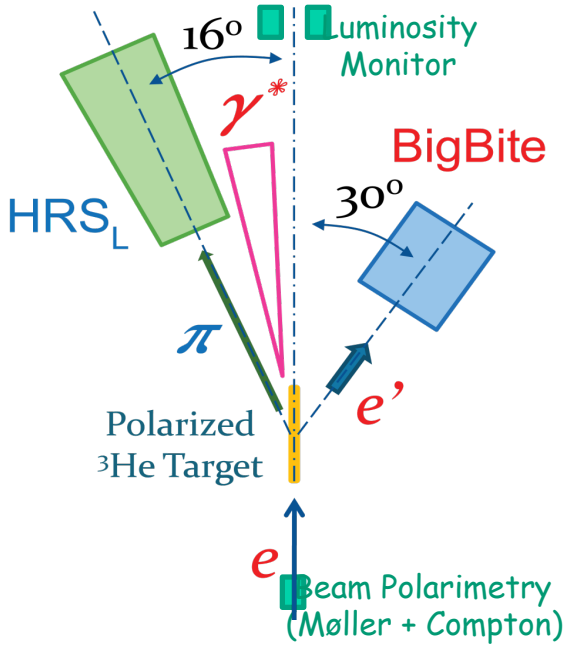
Hall A: Target Single-Spin Asymmetry in SIDIS Reaction on a Transversely Polarized 3He Target

$$A_{UT}(\phi_h^l, \phi_S^l) = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$A_{UT}^{Collins} \propto \left\langle \sin\left(\varphi_h + \varphi_s\right)\right\rangle_{UT} \propto h_1 \otimes H_1^\perp$$

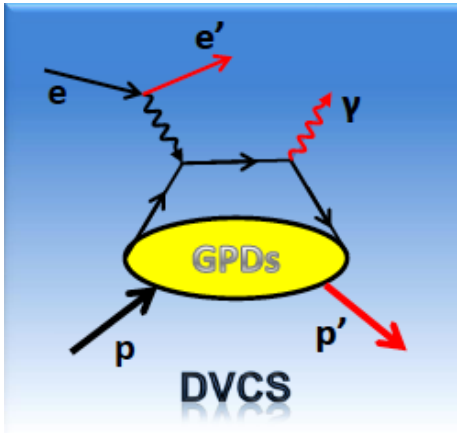
$$A_{UT}^{Sivers} \propto \left\langle \sin\left(\varphi_h - \varphi_s\right)\right\rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$



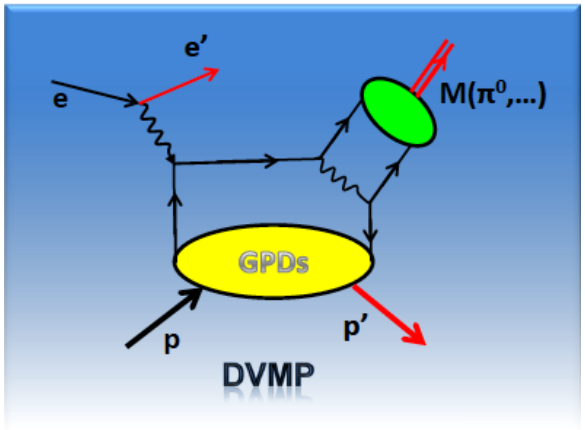


Collins:
asymmetries are not large, except at x=0.34

Silvers:
π^- is consistent with zero; however, π^+ favor negative values



GPDs through DVCS and DVMP



DVCS:

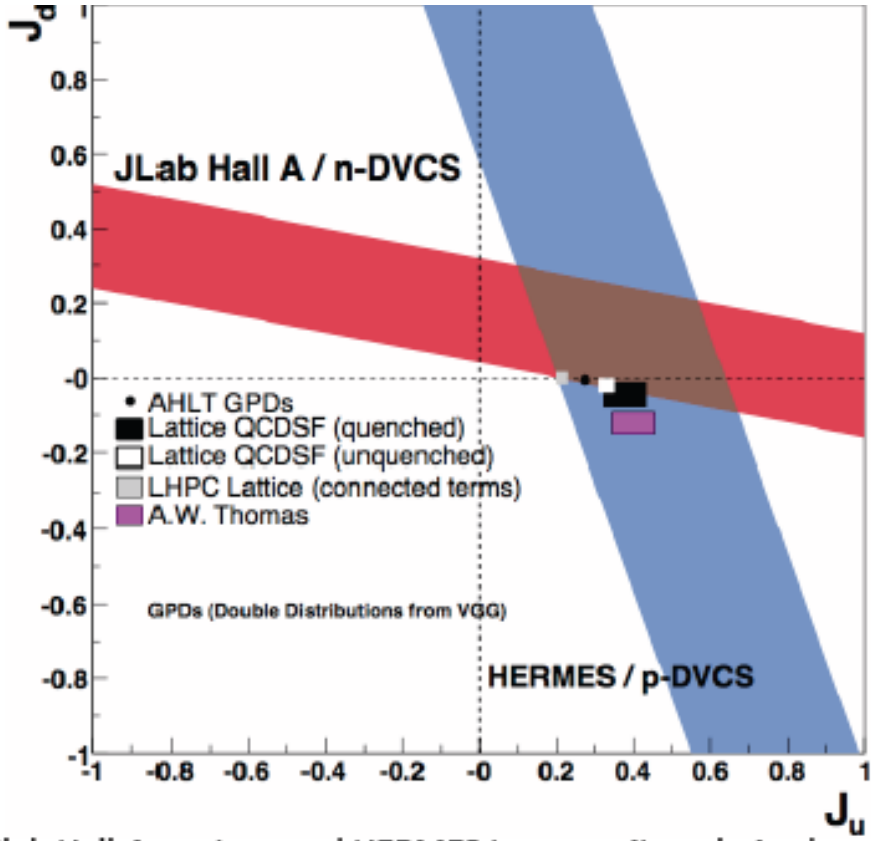
- the clearest way to access the GPDs
- Only γ_T photons participate in DVCS
- Interference with BH process

DVMP:

- Factorization proven only for σ_L
  $\sigma_T/\sigma_L \sim 1/Q^2$
- Meson distribution amplitude
- Gluon exchange required
- Vector and pseudoscalar meson production allows to separate flavor and separate the helicity-dependent GPDs form helicity independent.

	Meson	GPD flavor composition
$\widetilde{H}, \widetilde{E}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d$
H, E	ρ^0	$2u + d$
	ρ^+	$u - d$
	ω	$2u - d$

Constraints on J_u and J_d



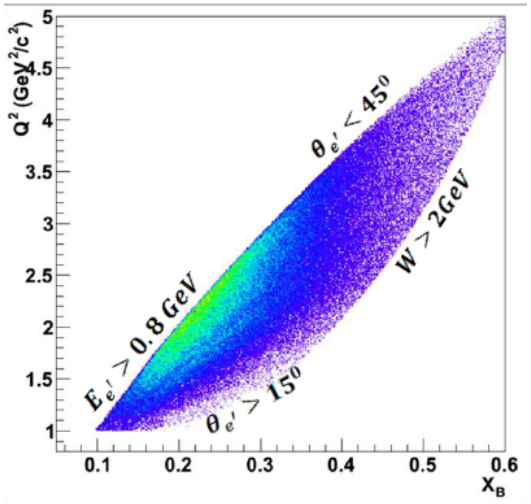
Helicity-dependent Jlab Hall-A neutron and HERMES transversity polarized proton data constrain in ***a model dependent way*** on the total up and down quark contributions to the proton spin.

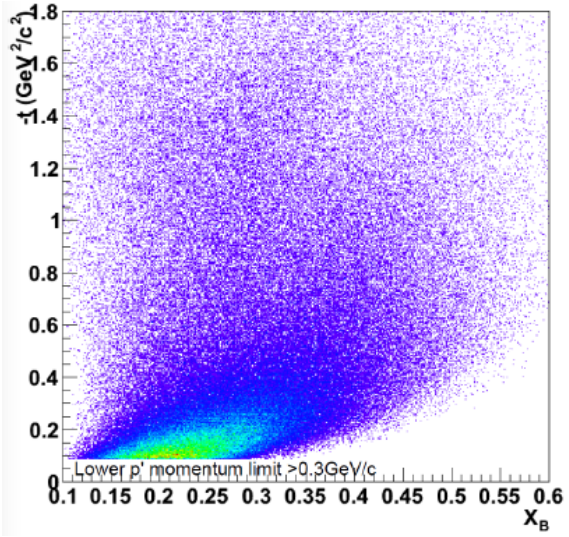
$$J_q = \frac{1}{2}\Delta\Sigma_q + L_q = \frac{1}{2}\int_{-1}^{1} x[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)]dx$$

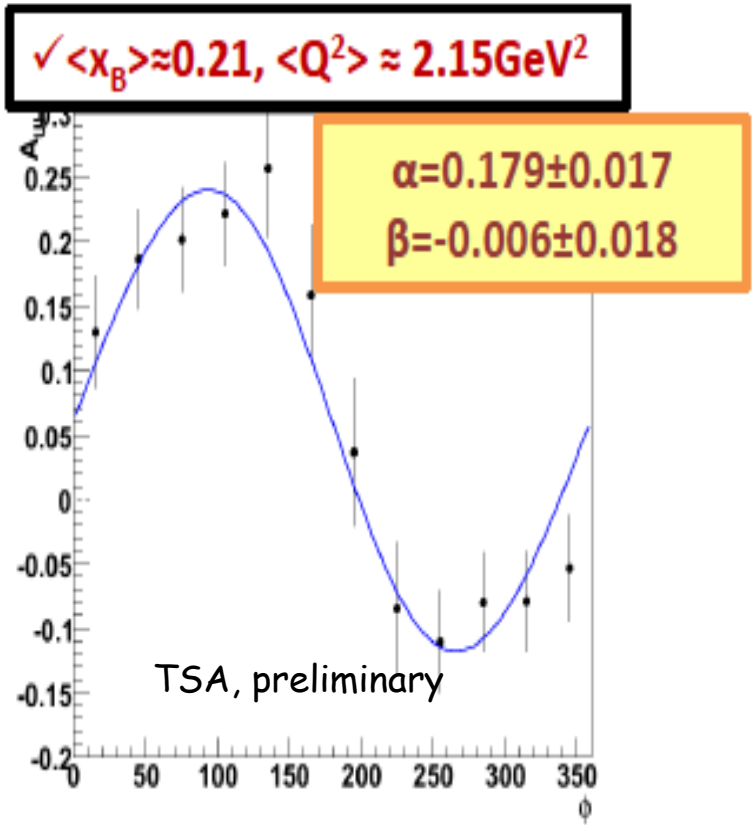
6 GeV Experimental Results

Hall A: Proton DVCS, helicity dependent and independent cross sections were measured at
Q2=(1.5, 1.9,2.3) GeV^2, -t=(0.17, 0.23, 0.28, 0.33) GeV^2, x_B=0.36
Neutron DVCS, helicity dependent cross section on deuterium

Hall B: Proton and deuterium DVCS and DVMP, helicity dependent and independent

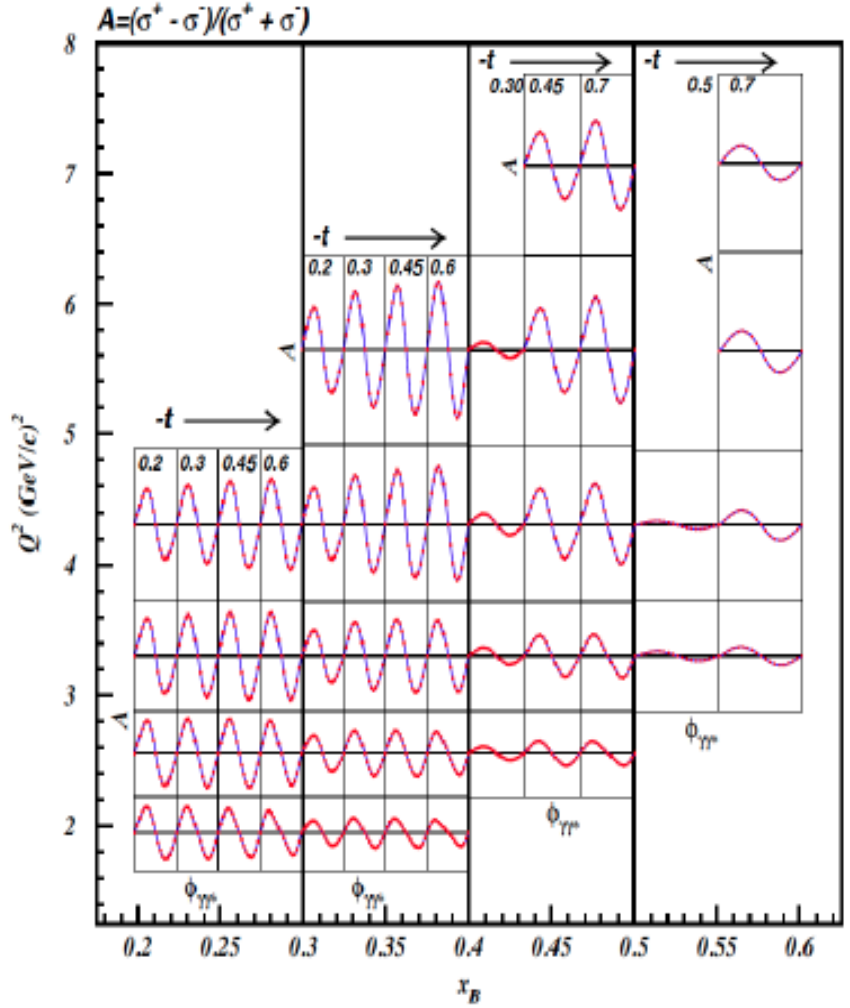




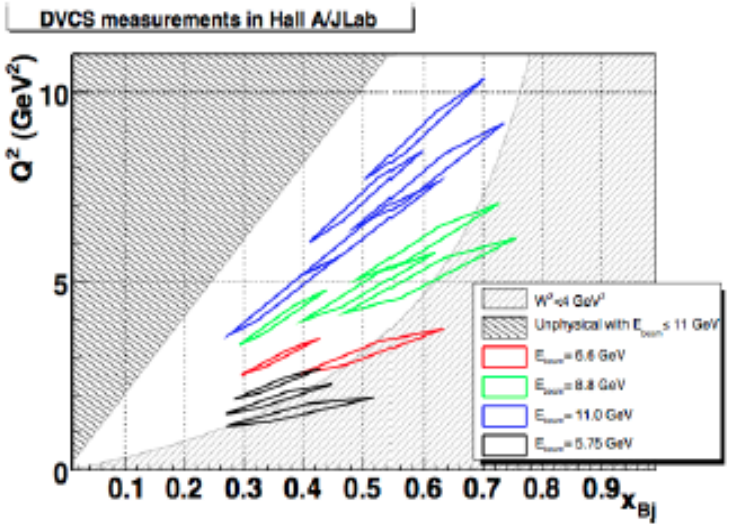


Future of GPD measurements at 12 GeV

CLAS12: A comprehensive map



Hall A: Detailed Precision Measurements



Plus:

Asymmetries with respect to beam helicity, target polarization (longitudinal and transverse), and beam charge (potential for positron source) ⇒ Constrain all 4 GPDs

Conclusions

- Jefferson Lab has produced a multitude of precision data on polarized structure functions, PDFs , *GPDs, and TMDs, moments, higher* twist and duality..

•Study of the spin-structure of the nucleon is one of the main driving forces behind the upgrade of Jefferson Lab

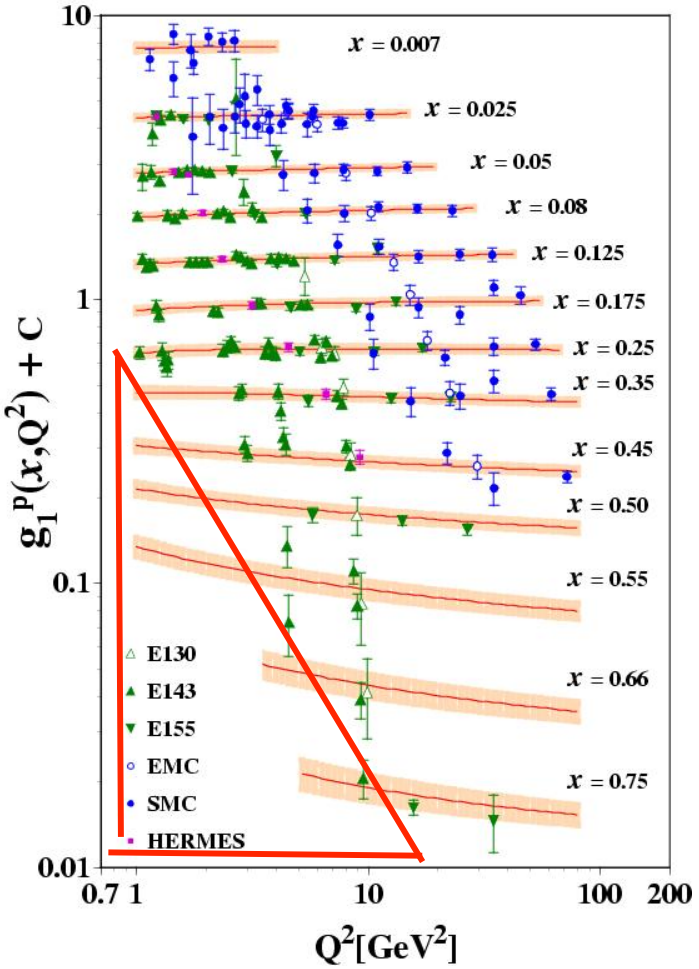
- Jefferson Lab at 12 GeV will complete the 3-dimensional quark picture of the nucleon for $x > 0.1$

Extra slides

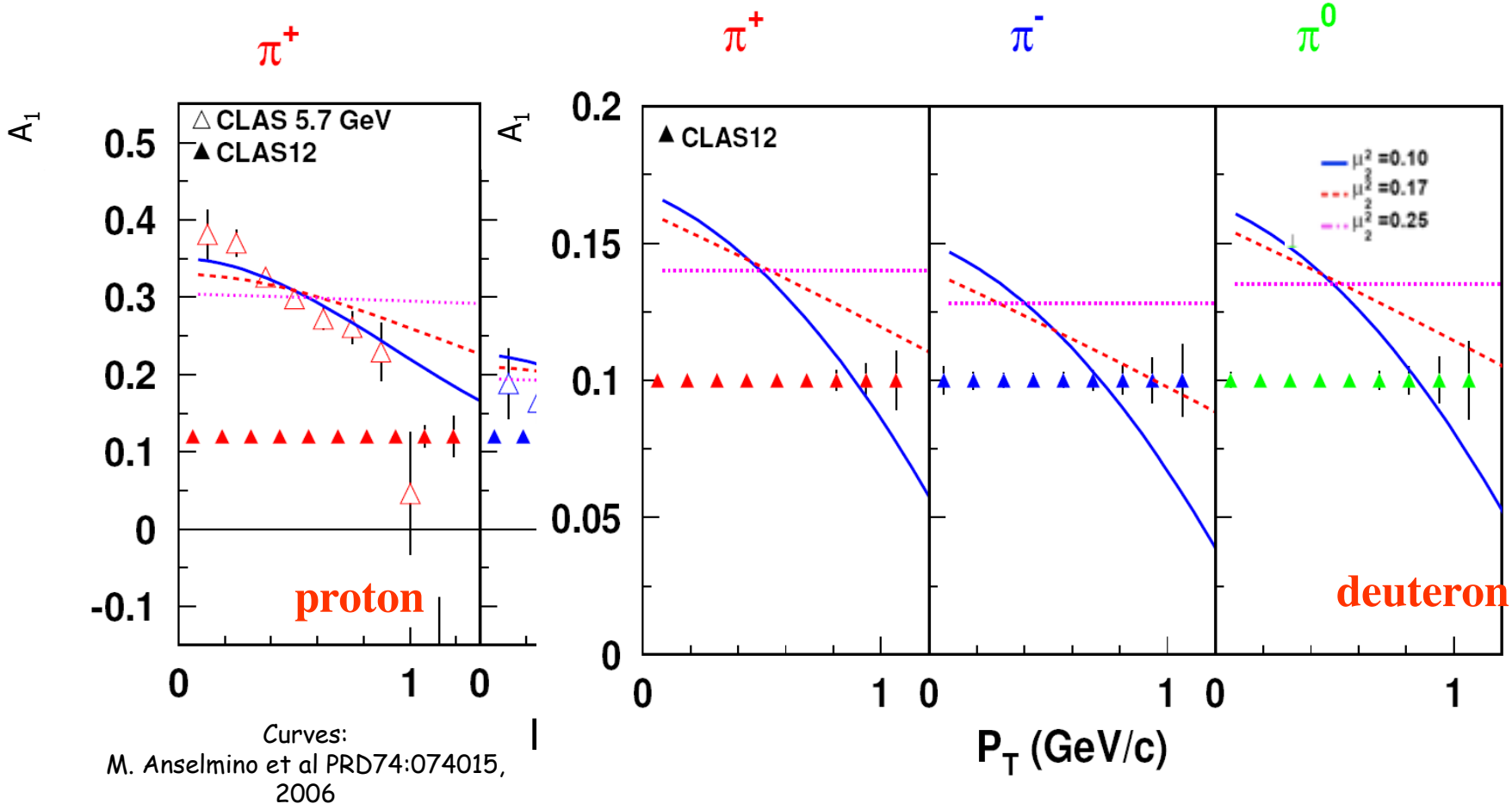
Status of $g_1(x,Q^2)$

$$g_1^{NLO}(x,Q^2) = g_1^{LO} + \frac{1}{2}\left\langle e^2 \right\rangle \sum_q e_q^2 \left[\Delta q(x,Q^2) \otimes C_q + \Delta g(x,Q^2) \otimes C_g\right]$$

- Data mostly for DIS and low :
- Remains to be done:
  - ΔG (RHIC,COMPASS)
  - ΔL (DVCS: COMPASS, HERMES,Jlab)
  - Transversity(HERMES, Jlab, RHIC)
  - Large x precision measurements (Jlab)
  - Measurement in non-perturbative region (Jlab)



A_1 – P_T dependence @ 12 GeV

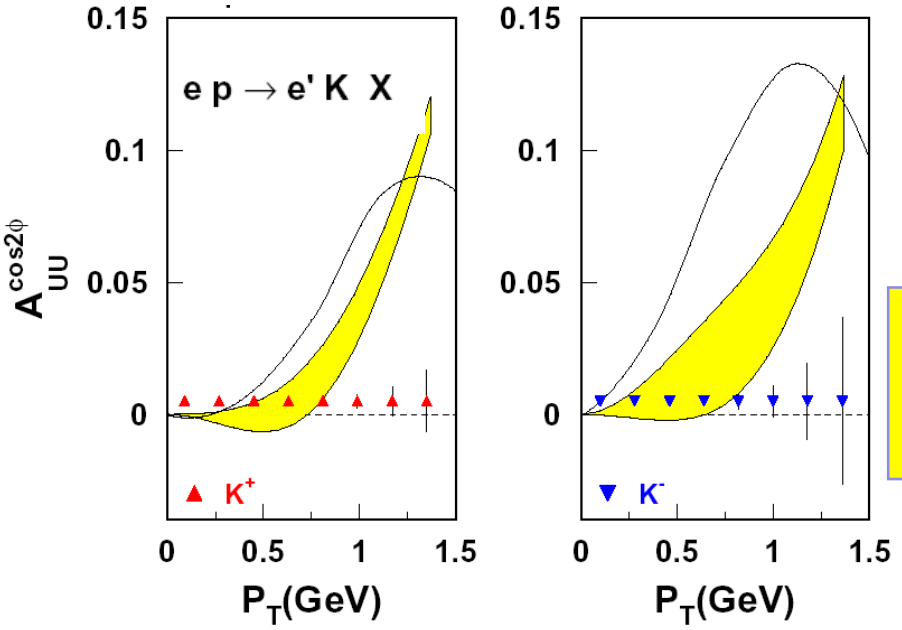


Curves:
M. Anselmino et al PRD74:074015, 2006

A_1 P_T-dependence provides access to helicity dependence of k_T-distributions of quarks

Deuteron and hydrogen data required for P_T-dependent flavor decomposition.

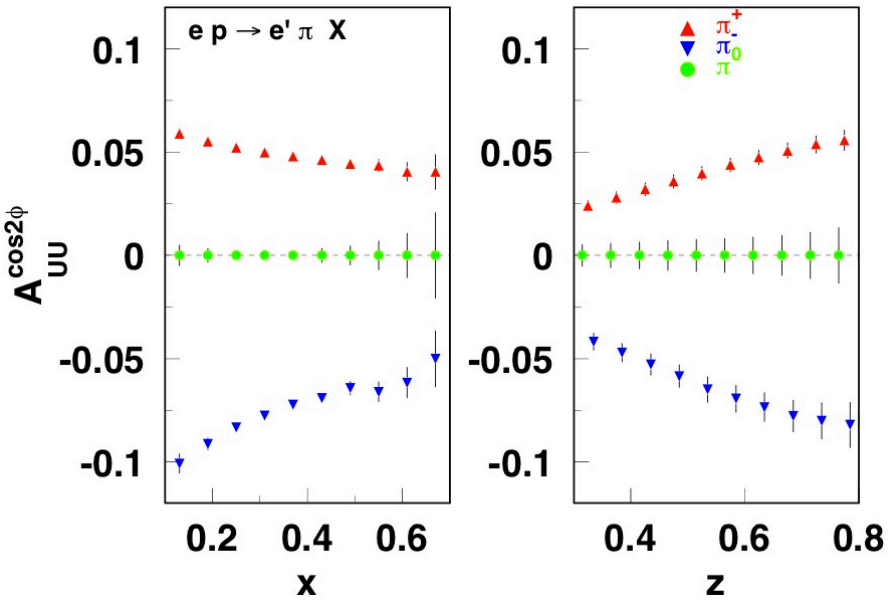
Boer-Mulders asymmetry @ CLAS12

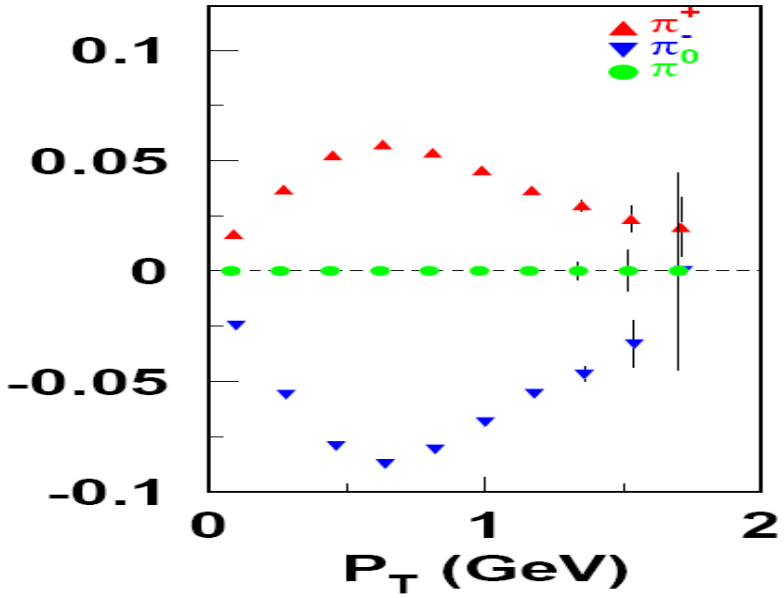


$$F_{UU} \propto \begin{cases} f_1 D_1 \\ h_1^{\perp} H_1^{\perp} \cos(2\phi) \end{cases}$$

π/K measurement with CLAS12 will provide a more detailed knowledge of spin-orbit correlations in hadronization

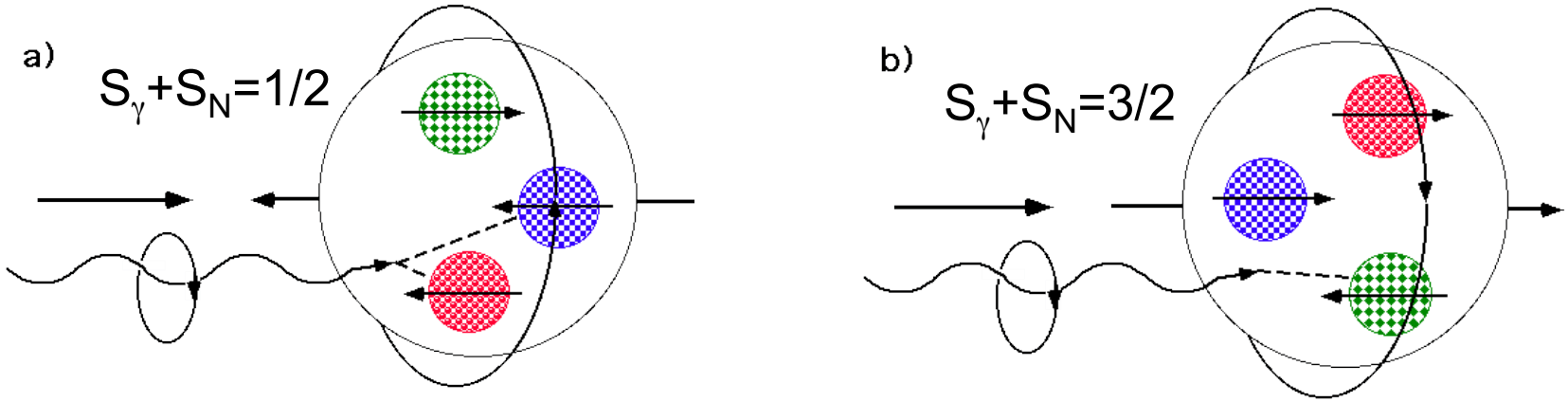
56 days at $L=1\times10^{35}$ cm^{-2}s^{-1}





Spin Structure Function g_1

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x) + \Delta\bar{q}(x)\right]$$

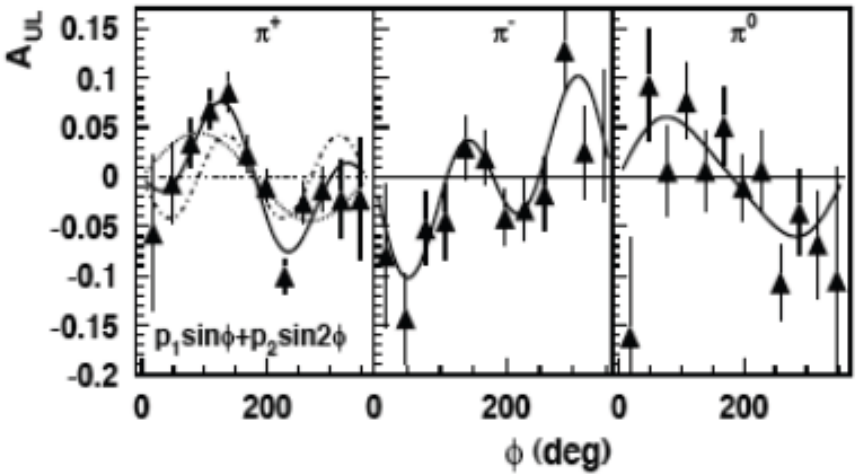


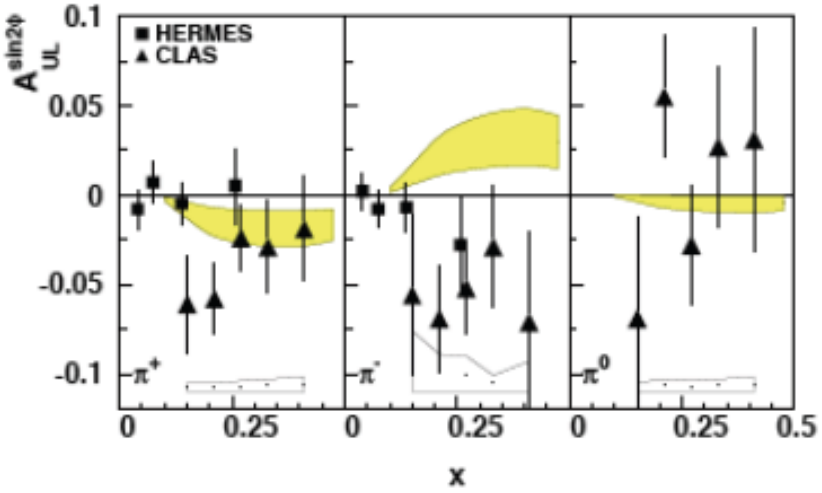
$\sigma_{1/2} \approx q^+(x)$ $\sigma_{3/2} \approx q^-(x)$

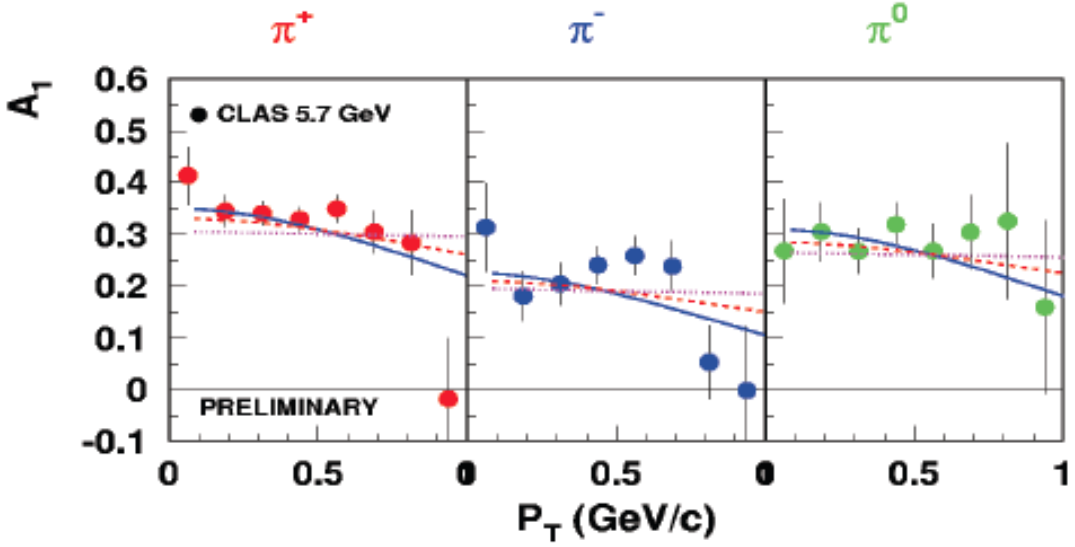
Virtual photon couples to quarks of opposite helicity

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

Semi-inclusive DIS:







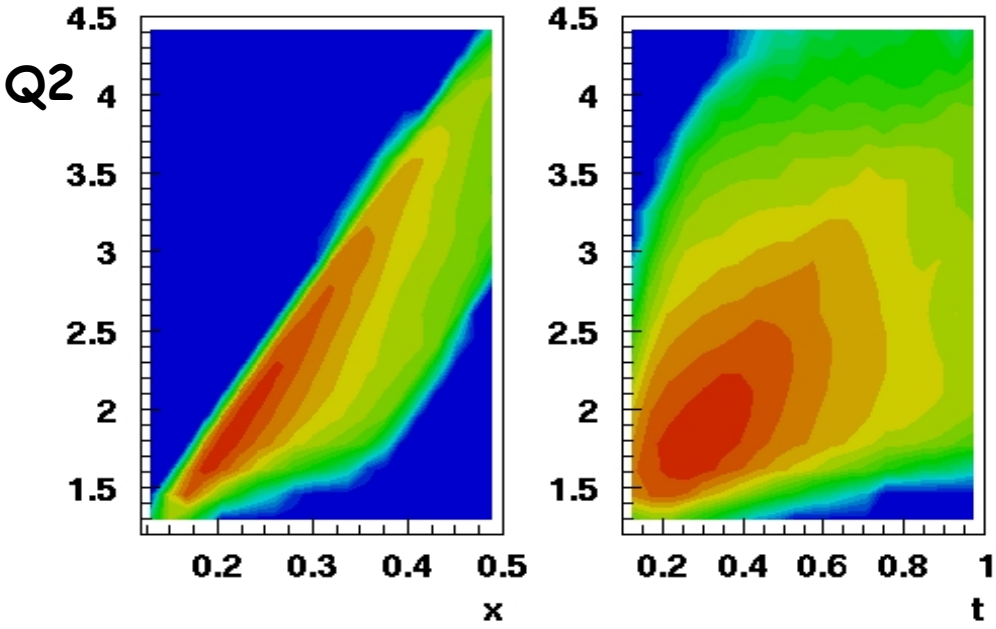
p_T dependence of π A_{LL} can be explained by broader k_T distributions for f_1 compared to g_1

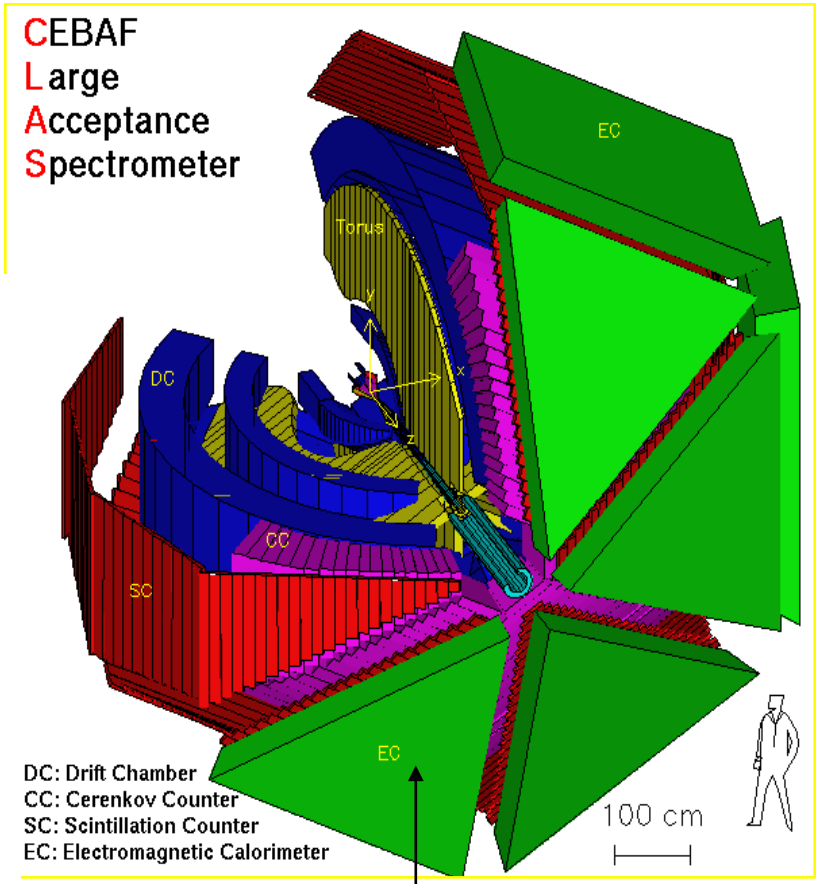
$$A_1 \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

The CLAS Detector

- High luminosity, polarized CW beam
- Wide physics acceptance, including exclusive, semi-inclusive processes, current and target fragmentation
- Wide geometric acceptance, allowing detection of multi-particle final states

~ 200 physicists
37 institutions





Forward CALO

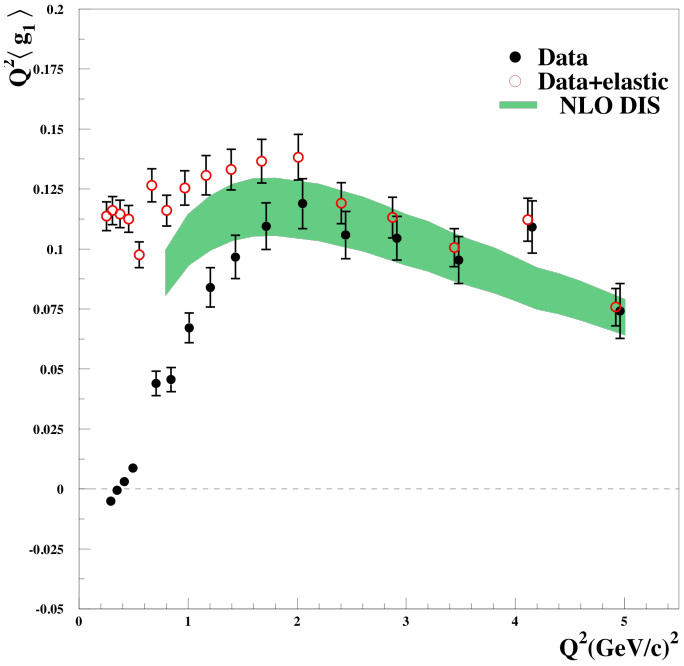
Quark-Hadron Duality in g_1

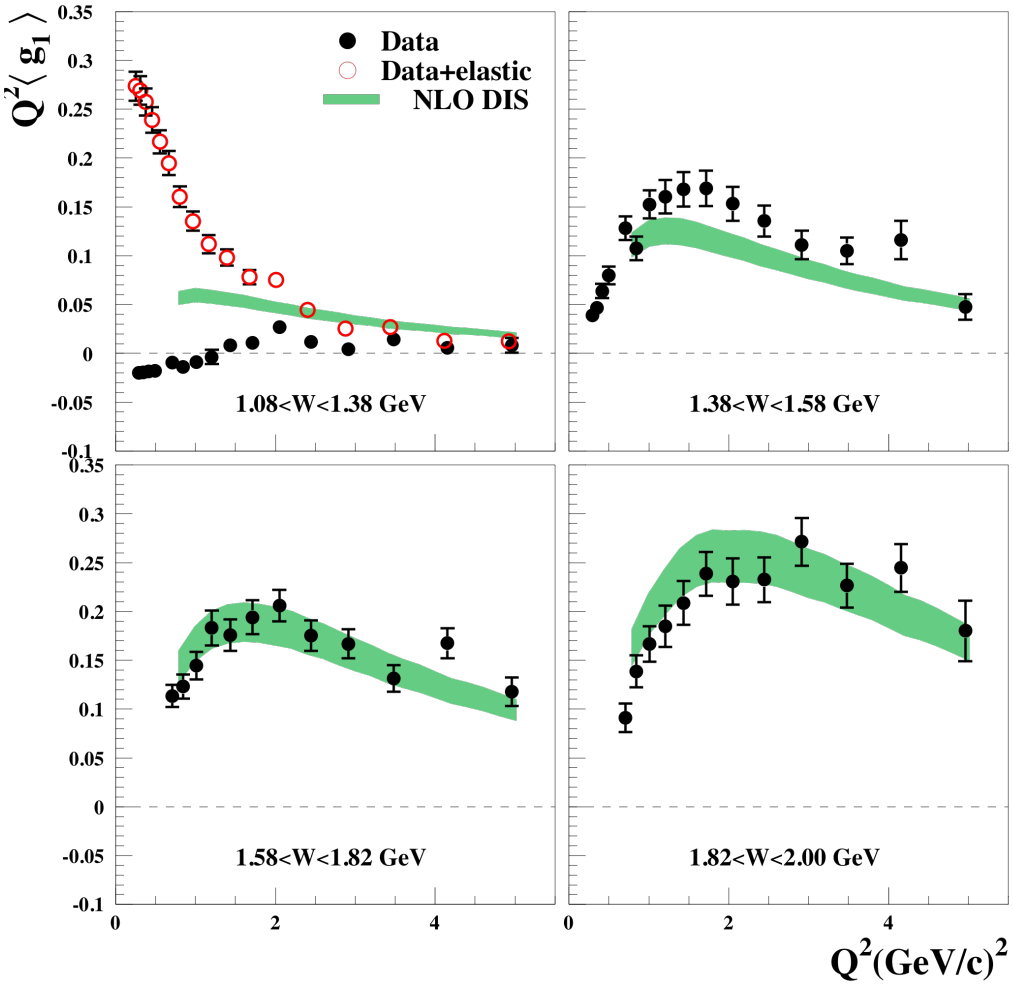
Valid for spin structure functions?

Not so obvious - can change in sign:

$$A_1^{DIS}(x \to 1) \to 1$$

$$A_1^{\Delta}(\text{low } Q^2) \approx -\frac{1}{2} \quad \left(\sigma_{\frac{3}{2}} > \sigma_{\frac{1}{2}}\right)$$





Existing Data from CLAS

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

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