Highlights and Perspectives of both Longitudinal and Transverse Spin Program at JLab

J. P. Chen, Jefferson Lab, Virginia

Seminar @ Los Alamos, February 19, 2009

- Introduction
- Highlights on JLab Longitudinal Spin Program:
  - Spin Structure at High *x*: Valence Quark Distributions
  - Spin Sum Rules and Polarizabilities
  - Higher Twists: g_2/d_2
- Transverse Spin and TMDs
- Outlook: 12 GeV Energy Upgrade

Introduction

- Structure and interactions
  - matter: atoms → nuclei → e+nucleons → quarks
  - interactions: strong, EM, weak, gravity

- Nucleon structure and strong interaction
  - energy and mass
  - spin and angular momentum

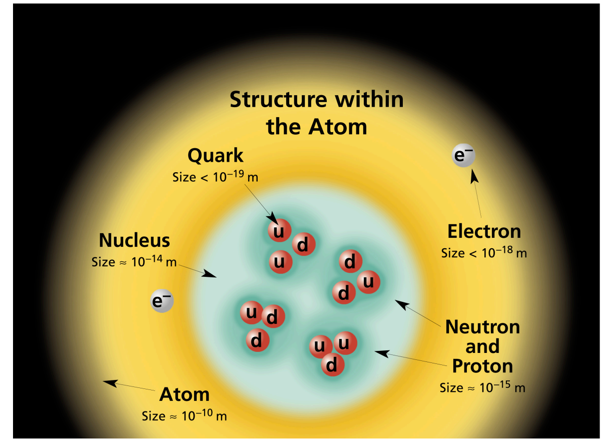
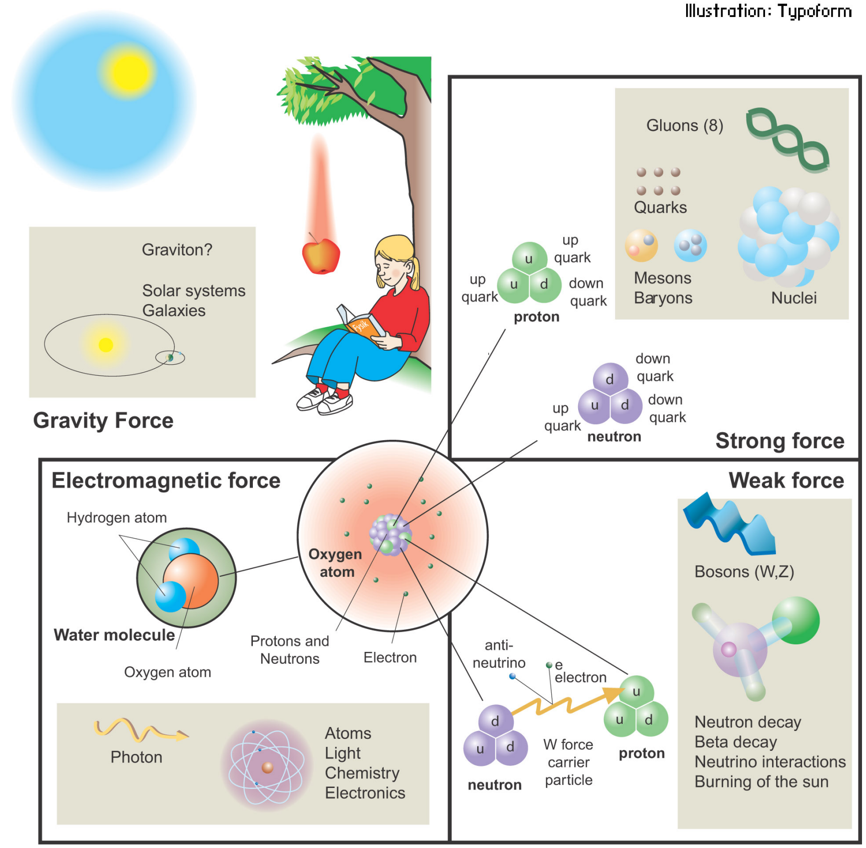


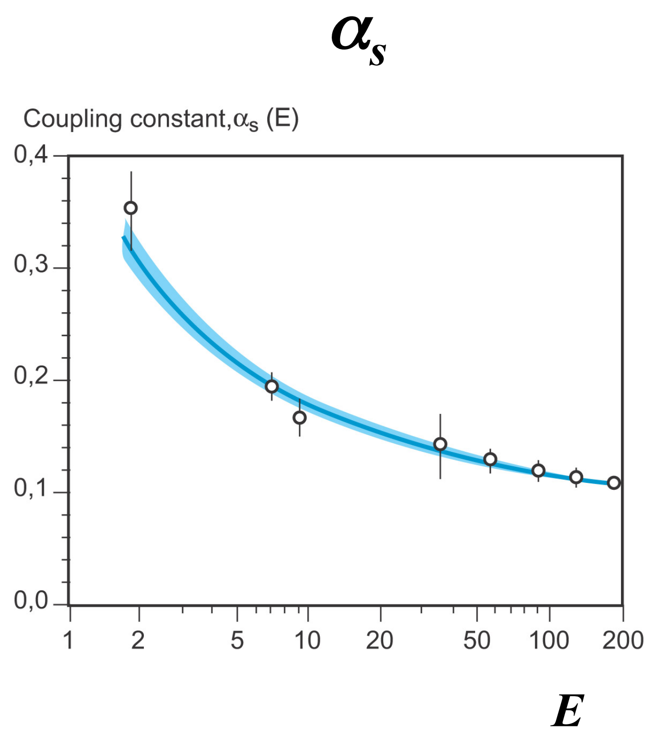
Illustration: Typoform



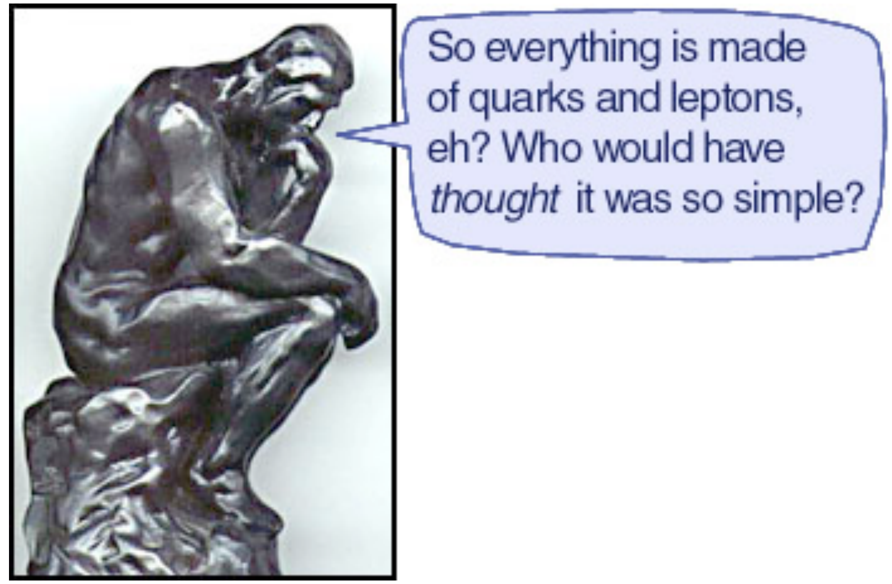
Strong Interaction and QCD

- **Strong interaction, running coupling ~1**
  -- QCD: accepted theory
  -- asymptotic freedom (2004 Nobel)
  perturbation calculation works at high energy
  -- interaction significant at intermediate energy
  quark-gluon correlations
  -- confinement
  interaction strong at low energy
- ❖ **theoretical tools:**
  pQCD, OPE, Lattice QCD, ChPT, …

- Major challenges:
  Understand QCD in strong interaction region
  → Study and understand nucleon structure



Nucleon Structure



- Nucleon: proton =(uud)
  neutron=(udd)
  + sea + gluons

- Global properties and structure
  Mass: 99% of the visible mass in universe
  ~1 GeV, but u/d quark mass only a few MeV each!
  Spin: ½, but total quarks contribution only ~30%! — Spin Sum Rule?
  Magnetic moment: large part is anomalous, >150%! — GDH Sum Rule
  Axial charge — Bjorken Sum Rule
  Tensor charge — Transverse Spin Sum Rule?
  Polarizabilities (E, M, Spin, Color,)

'Spin Crisis' or 'Spin Puzzle'

- 1980s: EMC (CERN) + early SLAC

  quark contribution to proton spin is very small

  $\Delta\Sigma = (12 +- 9 +- 14)\%$! 'spin crisis'

  (Ellis-Jaffe sum rule violated)

- 1990s: SLAC, SMC (CERN), HERMES (DESY)

  $\Delta\Sigma = 20-30\%$

  the rest: gluon and quark orbital angular momentum

  $A^+=0$ (light-cone) gauge $(½)\Delta\Sigma + L_q + \Delta G + L_g = 1/2$

  gauge invariant $(½)\Delta\Sigma + \mathcal{L}q + J_G = 1/2$

  Bjorken Sum Rule verified to 5-10% level

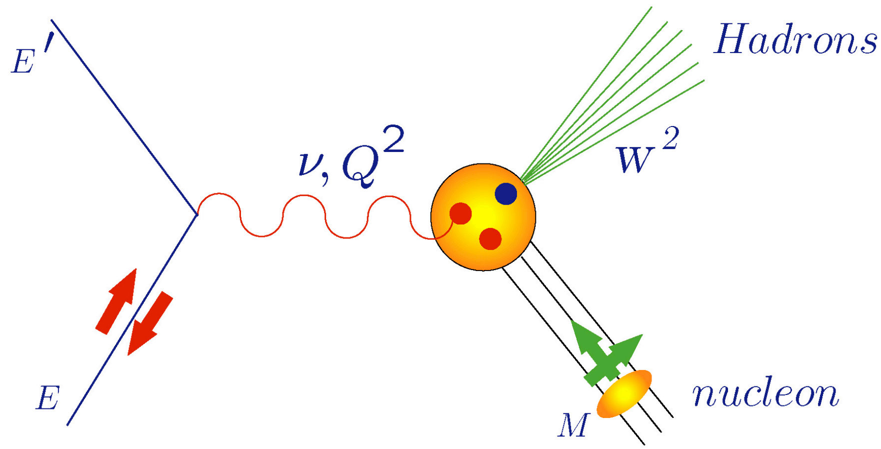
- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, … :

  $\Delta\Sigma \sim 30\%$; ΔG probably small

  orbital angular momentum probably significant

  Transversity, transverse momentum dependent distributions (TMDs)

Polarized Deep Inelastic Electron Scattering



$x = \dfrac{Q^2}{2M\nu}$ Fraction of nucleon momentum carried by the struck quark

Q^2 = 4-momentum transfer of the virtual photon, ν = energy transfer, θ = scattering angle

- All information about the nucleon vertex is contained in

F_2 and F_1 the unpolarized (spin averaged) structure functions,

and

g_1 and g_2 the spin dependent structure functions

Quark-Parton Model

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 f_i(x) \qquad g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

$$f_i(x) = q_i^{\uparrow}(x) + q_i^{\downarrow}(x)$$

$$\Delta q_i(x) = q_i^{\uparrow}(x) - q_i^{\downarrow}(x)$$

$q_i(x)$ quark momentum distributions of flavor i

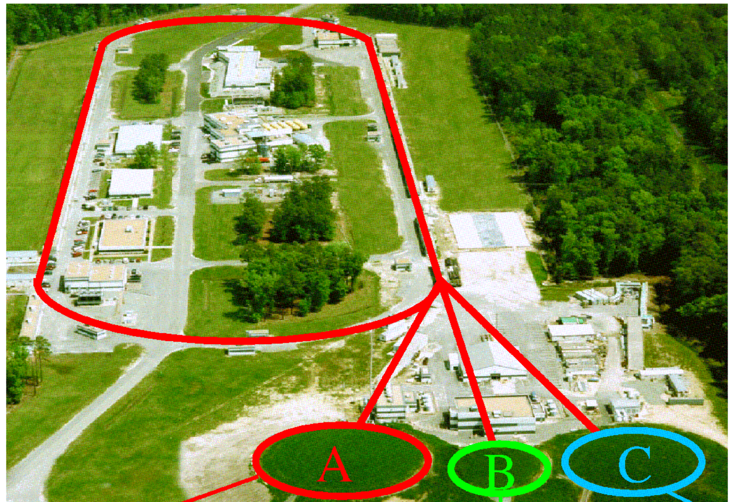
$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

$F_2 = 2xF_1$ $\qquad$ $g_2 = 0$

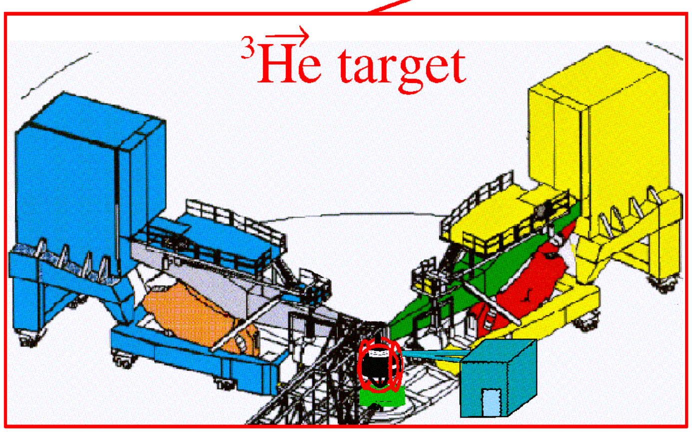
$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\Sigma \Delta q_i(x)}{\Sigma f_i(x)}$$

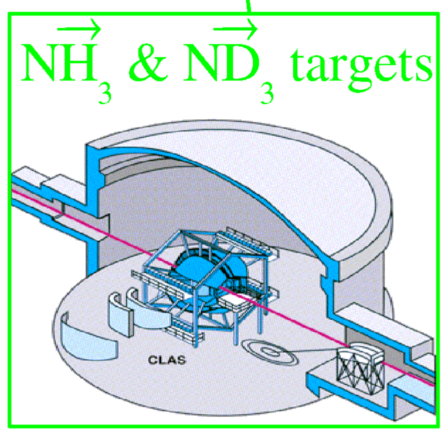
Jefferson Lab Experimental Halls

6 GeV polarized
CW electron beam
Pol=85%, 180µA



Will be upgraded to
12 GeV by ~2014



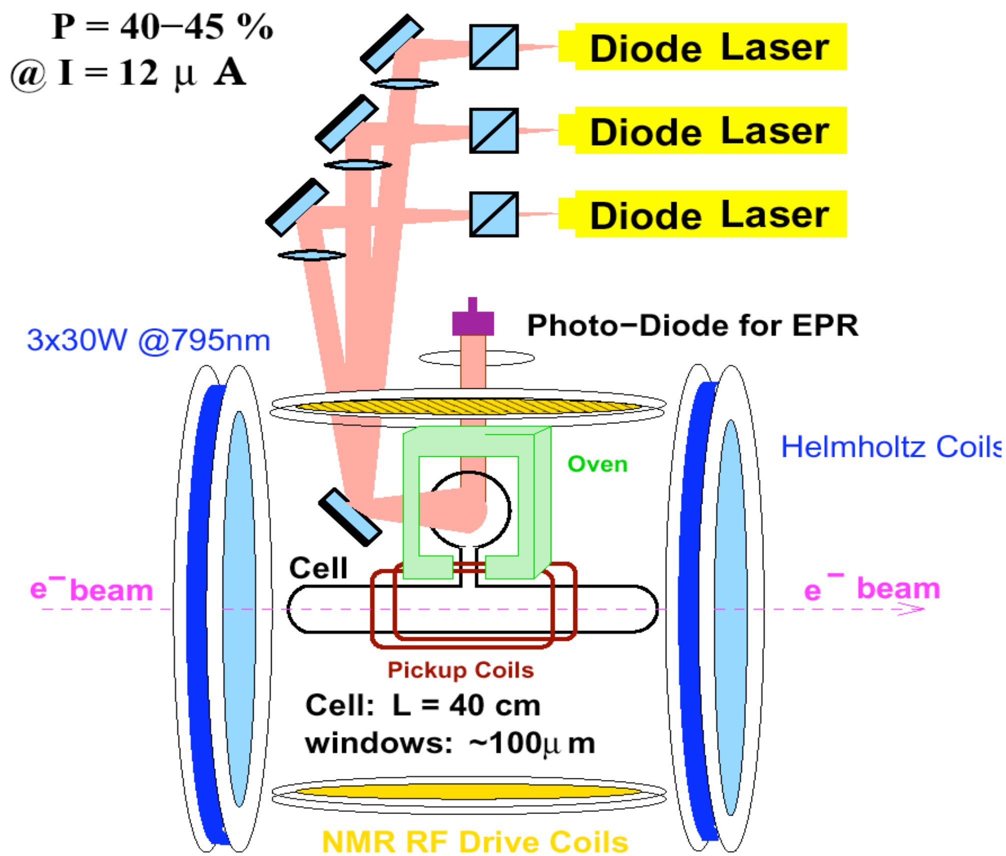


HallA: two HRS'

Hall B:CLAS

Hall C: HMS+SOS

Hall A polarized ^{3}He target



✓Both longitudinal, transverse and vertical

✓Luminosity=10^{36} (1/s) (highest in the world)

✓High in-beam polarization ~ 65%

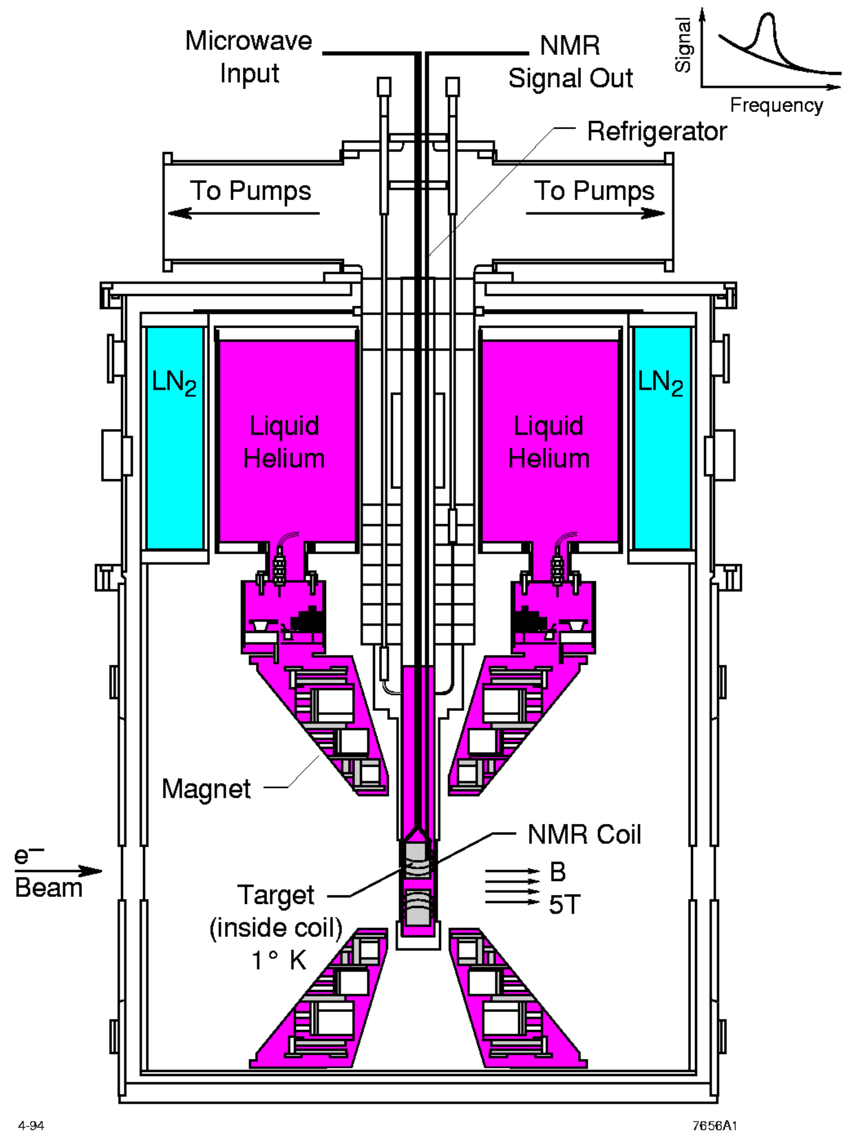
✓Effective polarized neutron target

✓9 completed experiments
4 are currently running
6 approved with 12 GeV (A/C)

Hall B/C Polarized proton/deuteron target

- Polarized NH_3/ND_3 targets
- Dynamical Nuclear Polarization

- In-beam average polarization
  - 70-80% for p
  - 30-40% for d
- Luminosity up to ~ 10^{35} (Hall C)
  ~ 10^{34} (Hall B)



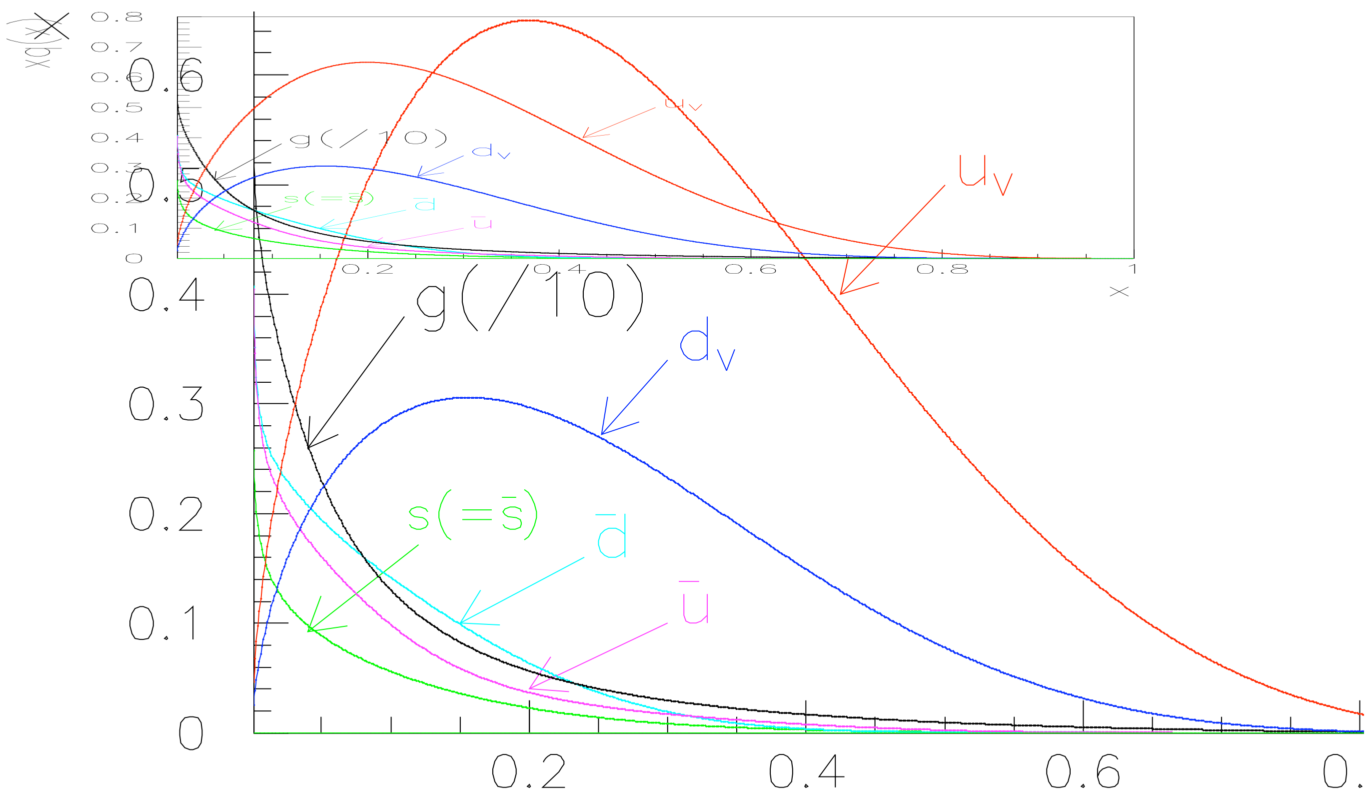
JLab Spin Structure Experiments

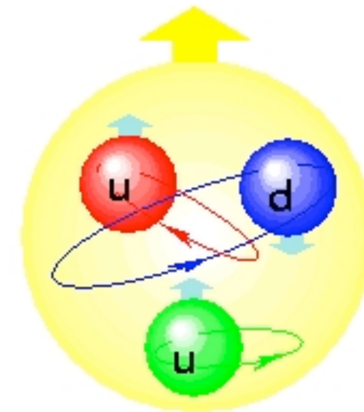
- Inclusive:
  - Moments: Spin Sum Rules and Polarizabilities, n (^{3}He), p and d
  - Higher twists: g_2/d_2, n and p
  - Valence Quark Structure: A_1 at high-x, n, p and d
  - Quark-Hadron duality in spin structure: n (^{3}He) and p
- Planned/On-going:
  - 6 GeV: g_2/d_2, p, n and d
  - 12 GeV: A_1/d_2, p, n and d
- Semi-inclusive:
  - transversity, TMDs, flavor decomposition,….

- Review: Sebastian, Chen, Leader, arXiv:0812.3535, to appear on PPNP

Valence Quark Spin Structure

A_1 at high *x* and flavor decomposition





Why Are PDFs at High *x* Important?

- Valence quark dominance: simpler picture
  - -- direct comparison with nucleon structure models
    SU(6) symmetry, broken SU(6), diquark
- $x \rightarrow 1$ region amenable to pQCD analysis
  - -- hadron helicity conservation?
- Clean connection with QCD, via lattice moments
- Input for search for physics beyond the Standard Model at high energy collider
  - -- evolution: high x at low $Q^2 \rightarrow$ low x at high Q^2
  - -- small uncertainties amplified
  - -- example: HERA 'anomaly' (1998)
- Input to nuclear, high energy and astrophysics calculations

Predictions for High *x*

Proton Wavefunction (Spin and Flavor Symmetric)

$$\left|p\uparrow\right\rangle = \frac{1}{\sqrt{2}}\left|u\uparrow(ud)_{S=0}\right\rangle + \frac{1}{\sqrt{18}}\left|u\uparrow(ud)_{S=1}\right\rangle - \frac{1}{3}\left|u\downarrow(ud)_{S=1}\right\rangle - \frac{1}{3}\left|d\uparrow(uu)_{S=1}\right\rangle - \frac{\sqrt{2}}{3}\left|d\downarrow(uu)_{S=1}\right\rangle$$

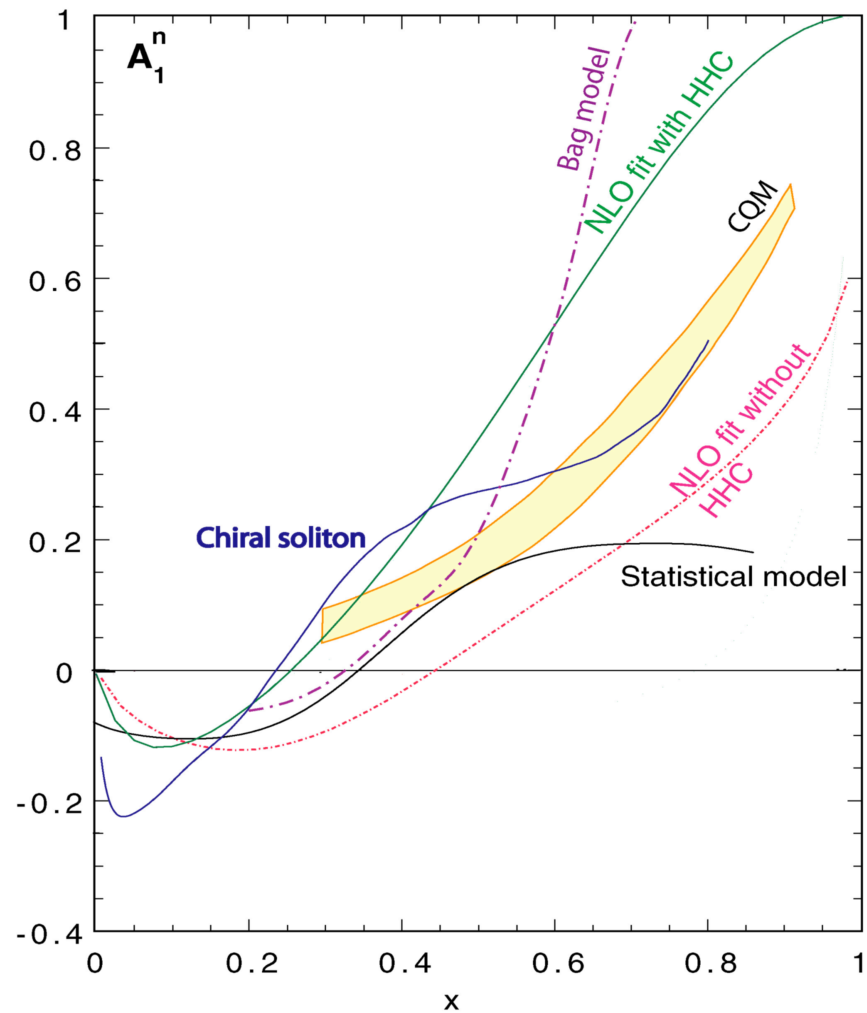
Nucleon Model	F_2^n/F_2^p	d/u	$\Delta u/u$	$\Delta d/d$	A_1^n	A_1^p
SU(6)	2/3	1/2	2/3	-1/3	0	5/9
Scalar diquark	1/4	0	1	-1/3	1	1
pQCD	3/7	1/5	1	1	1	1

Polarized quarks as x--> 1

- SU(6) symmetry:
  - $A_1^p = 5/9$ $A_1^n = 0$ $d/u=1/2$
  - $\Delta u/u = 2/3$ $\Delta d/d = -1/3$
- Broken SU(6) via scalar diquark dominance
  - $A_1^p \to 1$ $A_1^n \to 1$ $d/u \to 0$
  - $\Delta u/u \to 1$ $\Delta d/d \to -1/3$
- Broken SU(6) via helicity conservation
  - $A_1^p \to 1$ $A_1^n \to 1$ $d/u \to 1/5$
  - $\Delta u/u \to 1$ $\Delta d/d \to 1$

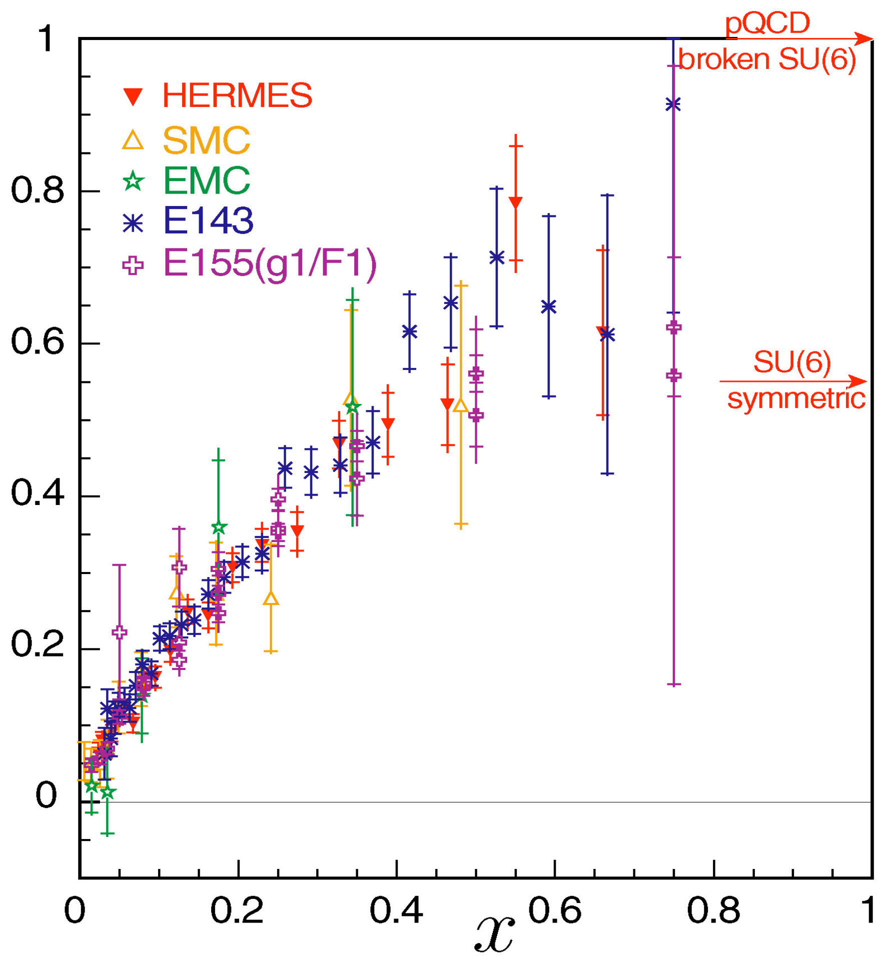
$q^{\uparrow}(x \to) \equiv (1-x)^3$ $q^{\downarrow}(x \to) \equiv (1-x)^5$

Note that $\Delta q/q$ as x--> 1 is more sensitive to spin-flavor symmetry breaking effects than A_1

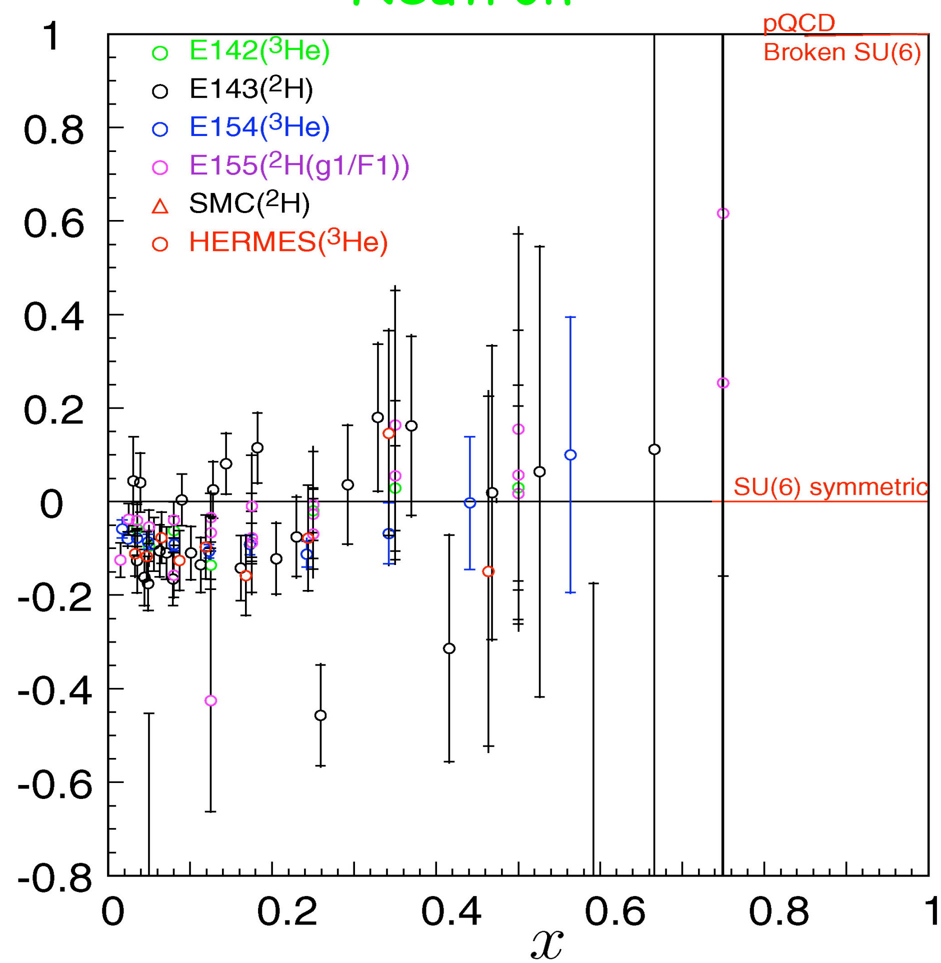


World data for A_1

Proton



Neutron

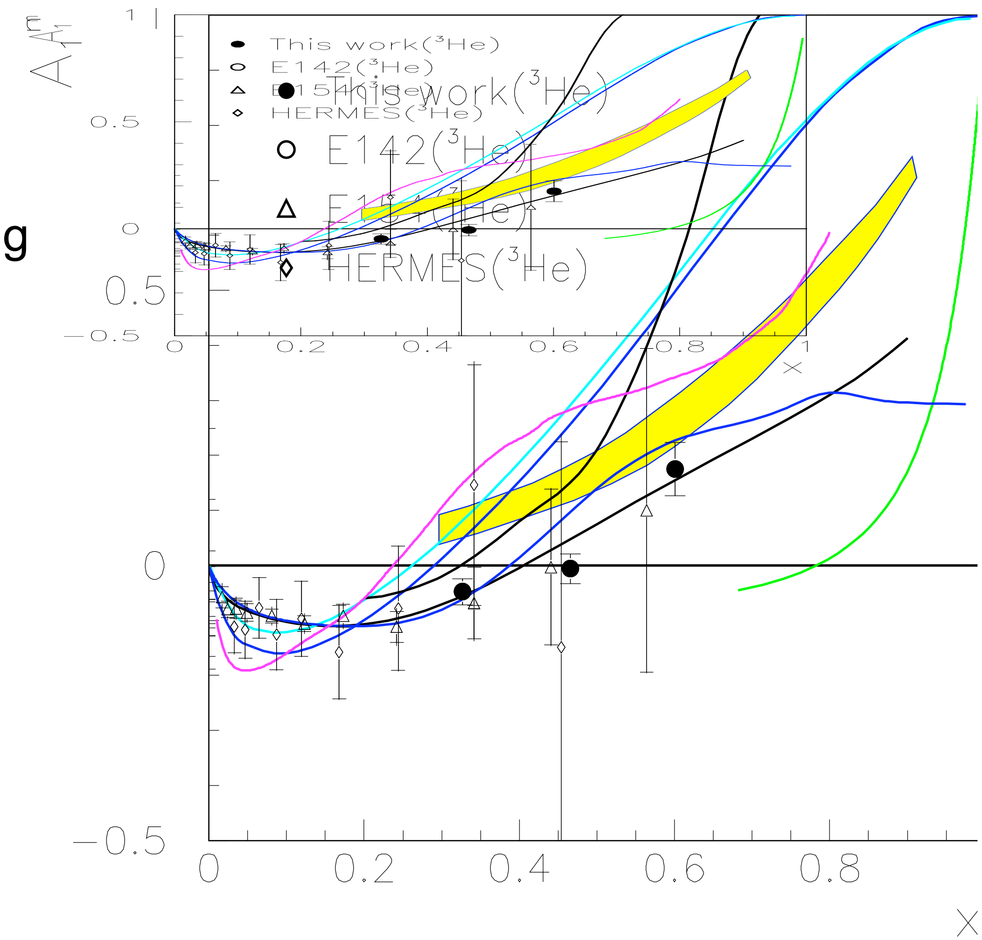


JLab E99-117

Precision Measurement of A_1^n at Large *x*

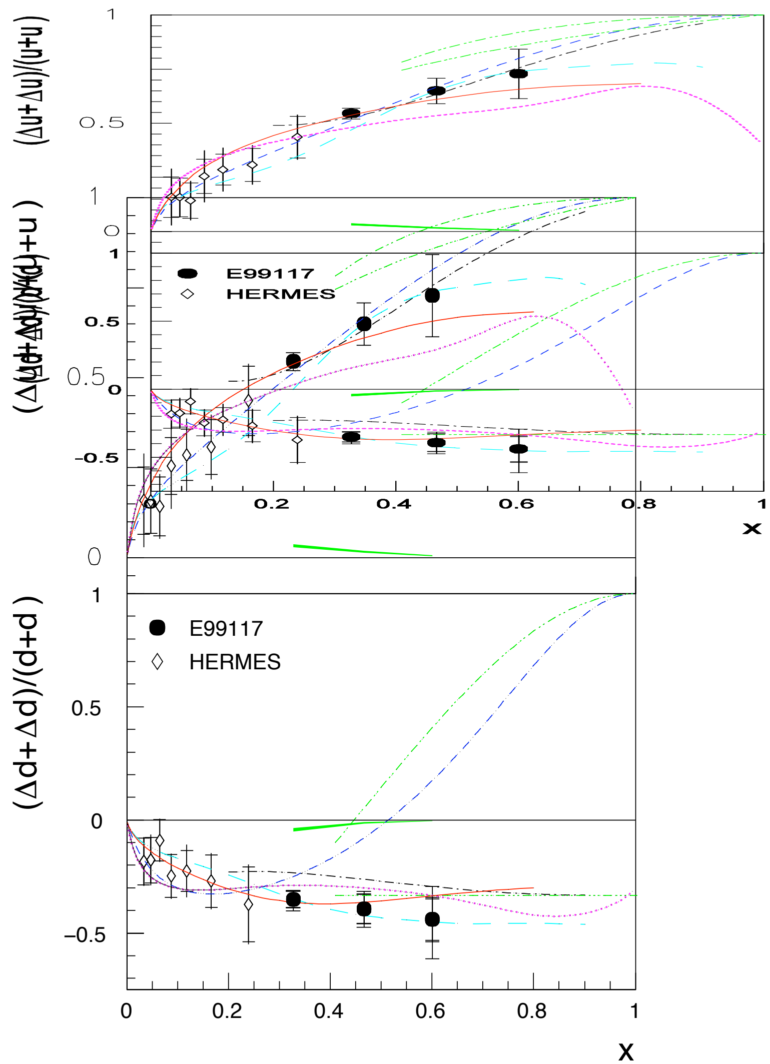
Spokespersons: J. P. Chen, Z. -E. Meziani, P. Souder, PhD Student: X. Zheng

- First precision A_1^n data at high x
- Extracting valence quark spin distributions
- Test our fundamental understanding of valence quark picture
  - SU(6) symmetry
  - Valence quark models
  - pQCD (with HHC) predictions
- Quark orbital angular momentum
- Crucial input for pQCD fit to PDF
- **PRL 92, 012004 (2004)**
- **PRC 70, 065207 (2004)**



Polarized Quark Distributions

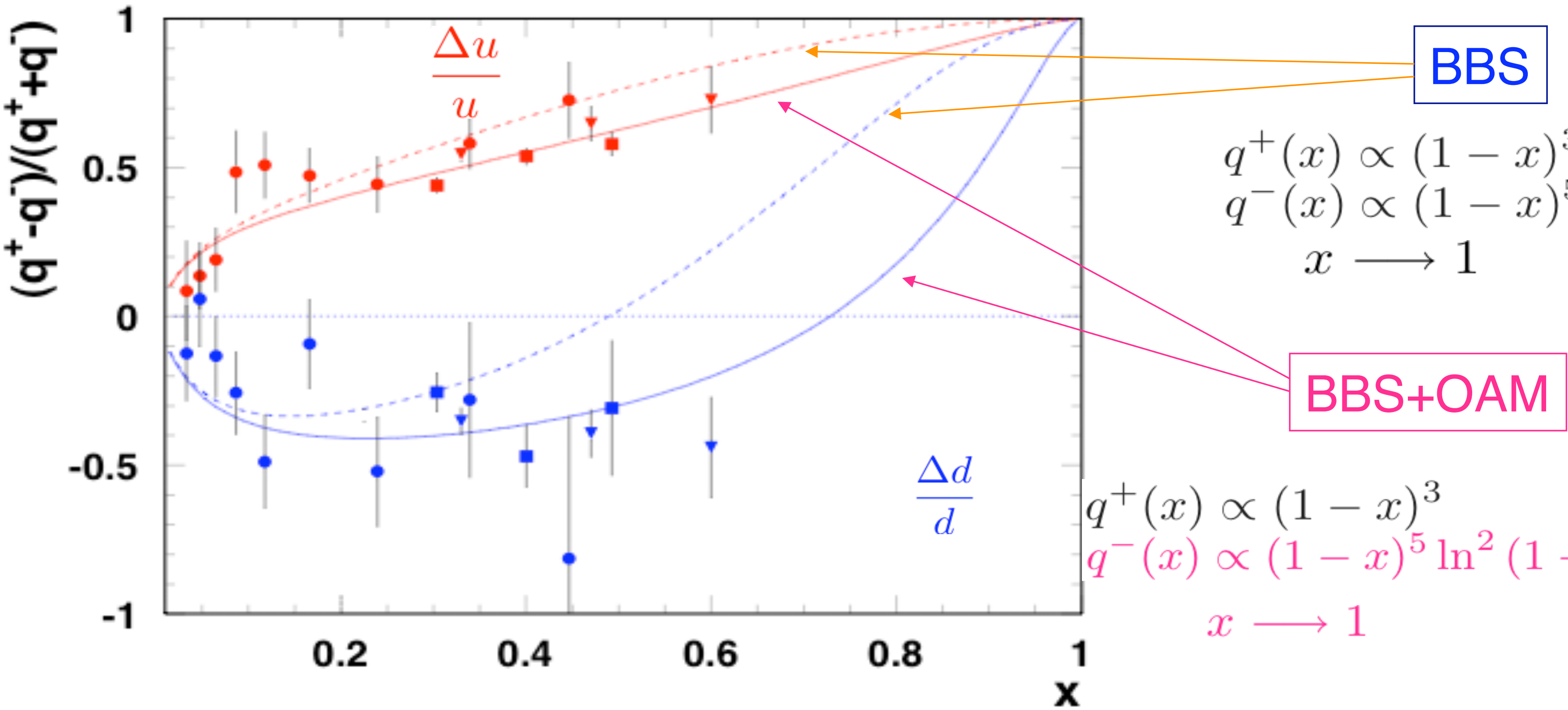
- Combining A_1^n and A_1^p results
- Valence quark dominating at high *x*
- u quark spin as expected
- d quark spin stays negative!
  - Disagree with pQCD model calculations assuming HHC (hadron helicity conservation)
  - Quark orbital angular momentum
- Consistent with valence quark models and pQCD PDF fits without HHC constraint



pQCD with Quark Orbital Angular Momentum

F. Yuan, H. Avakian, S. Brodsky, and A. Deur, arXiv:0705.1553

Inclusive Hall A and B and Semi-Inclusive Hermes



$q^+(x) \propto (1-x)^3$

$q^-(x) \propto (1-x)^5$

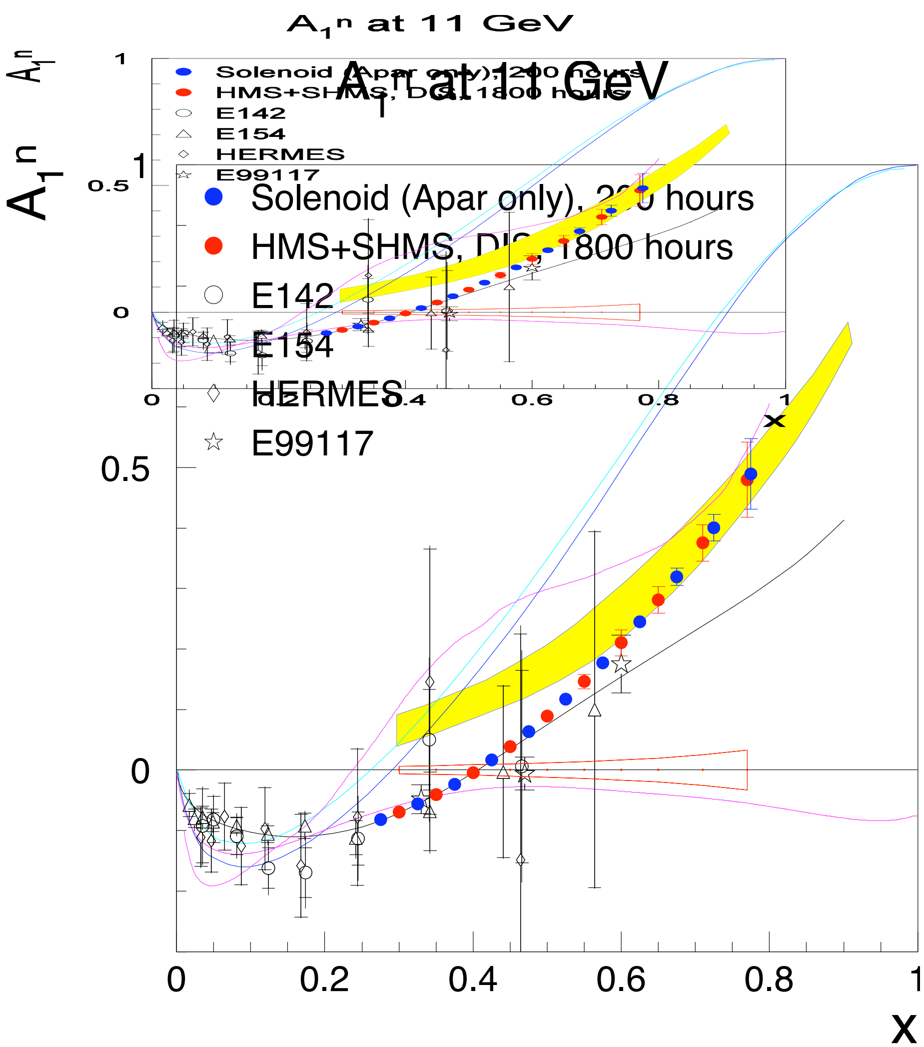
$x \longrightarrow 1$

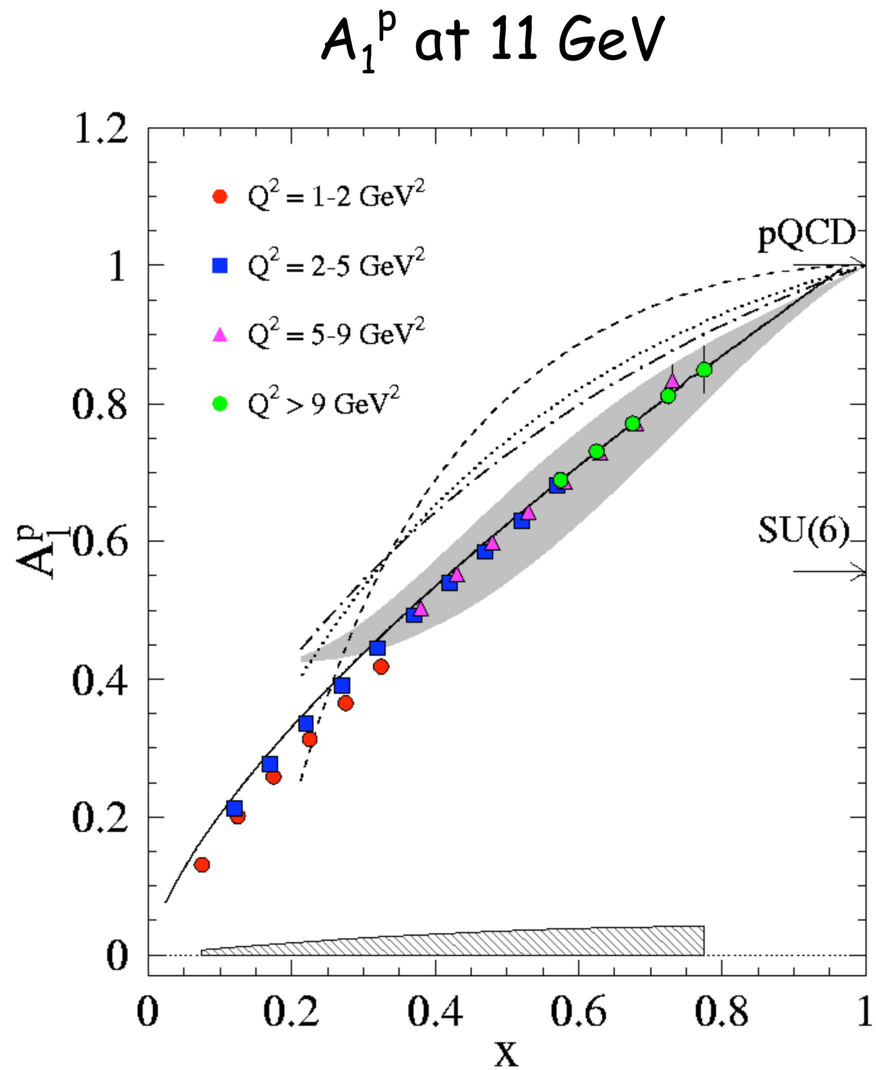
$q^+(x) \propto (1-x)^3$

$q^-(x) \propto (1-x)^5 \ln^2(1-x)$

$x \longrightarrow 1$

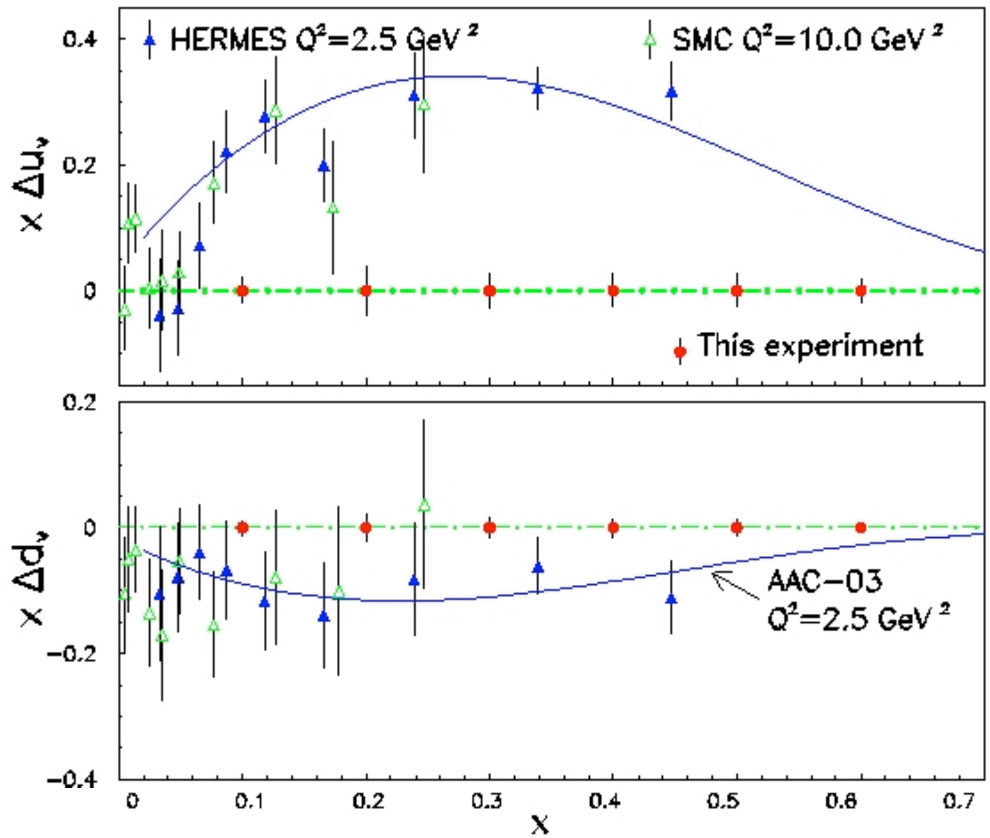
Projections for JLab at 11 GeV



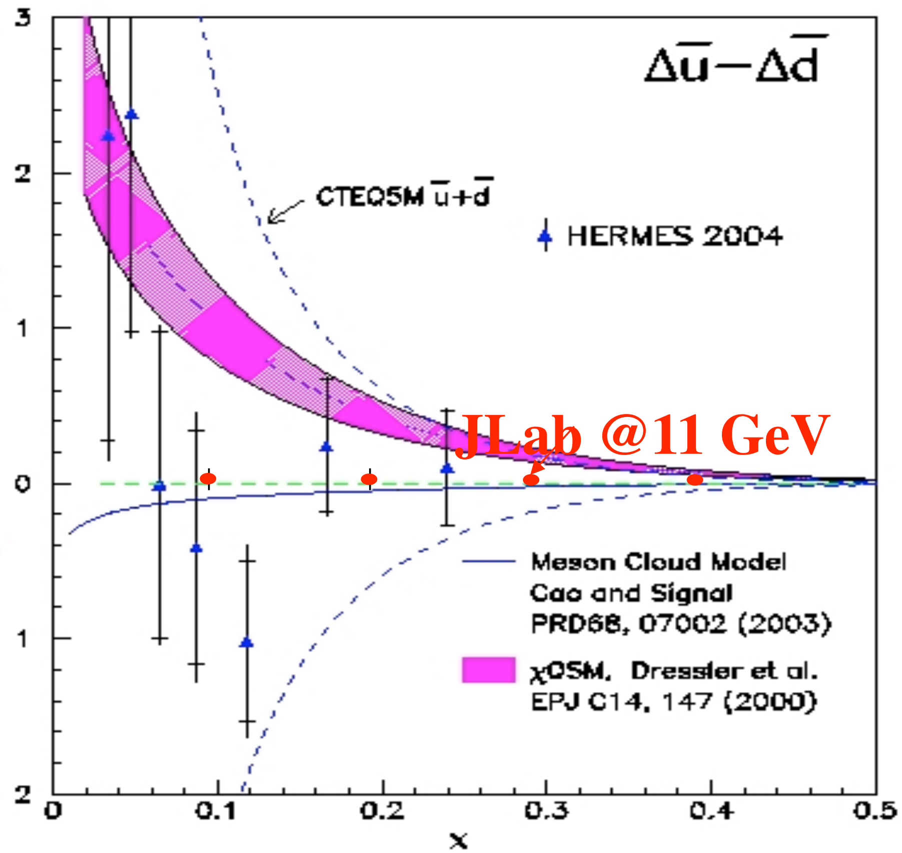


Flavor decomposition with SIDIS

Δu and Δd at JLab 11 GeV

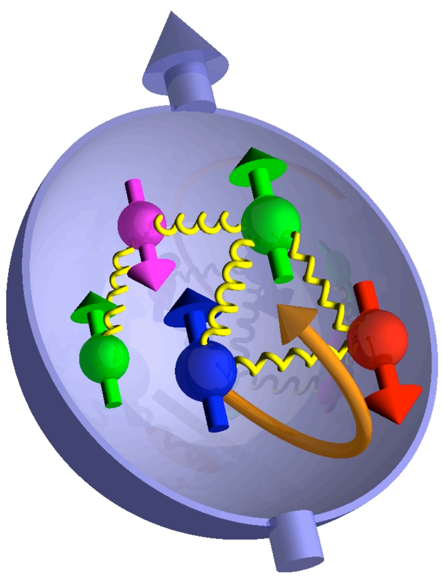


Polarized Sea



Spin Sum Rules and Polarizabilities

Moments of Spin Structure Functions



Sum Rules

➔

Generalized GDH Sum Rule

- Generalized GDH Sum Rule provides a bridge linking strong QCD to pQCD
  - Bjorken (large Q^2) and GDH (Q^2=0) sum rules are two limiting cases
  - High Q^2 (> ~1 GeV^2): Operator Product Expansion
  - Intermediate Q^2 region: Lattice QCD calculations
  - Low Q^2 region (< ~0.1 GeV^2): Chiral Perturbation Theory

  Calculations: RBχPT with Δ, Bernard, Hemmert, Meissner;

  HBχPT, Ji, Kao, Osborne; Kao, Spitzenberg, Vanderhaeghen

Reviews: Theory: Drechsel, Pasquini, Vanderhaeghen, Phys. Rep. 378,99 (2003)

Experiments: Chen, Deur, Meziani, Mod. Phy. Lett. A 20, 2745 (2005)

JLab E94-010

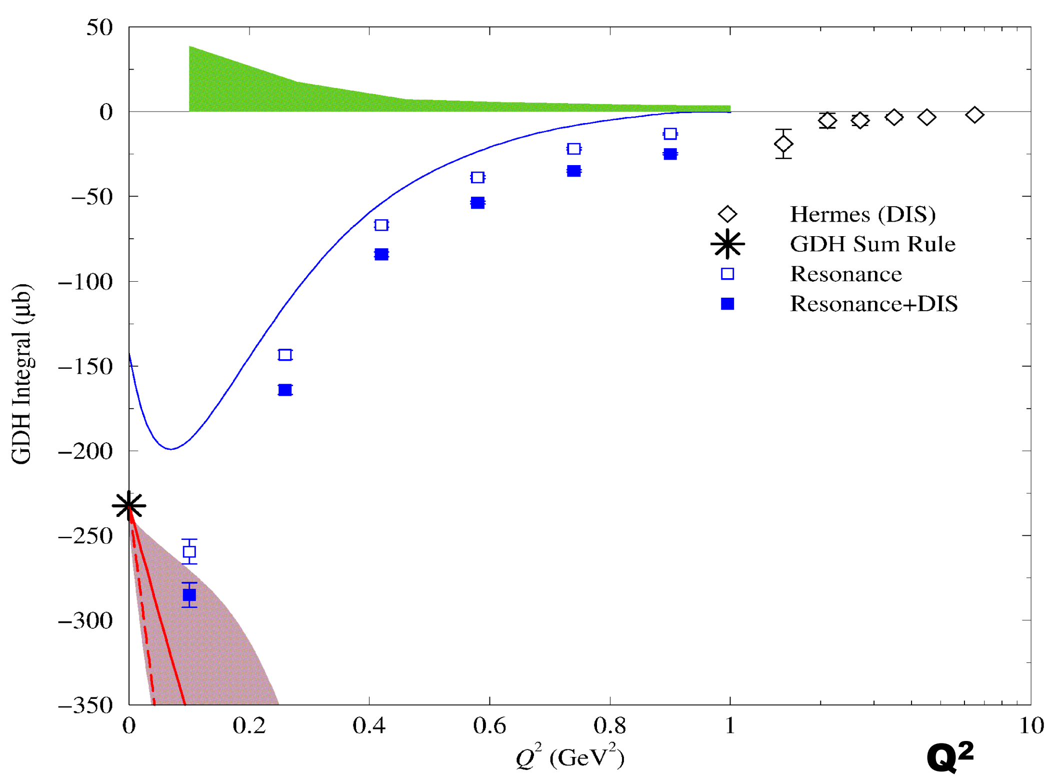
Neutron spin structure moments and sum rules at Low Q^2

Spokespersons: G. Cates, J. P. Chen, Z.-E. Meziani

PhD Students: A. Deur, P. Djawotho, S. Jensen, I. Kominis, K. Slifer

- Q^2 evolution of spin structure moments and sum rules
  (generalized GDH, Bjorken and B-C sum rules)
- transition from quark-gluon to hadron
- Test χPT calculations
- Results published in several PRL/PLB's
- New results on ^{3}He

GDH integral on

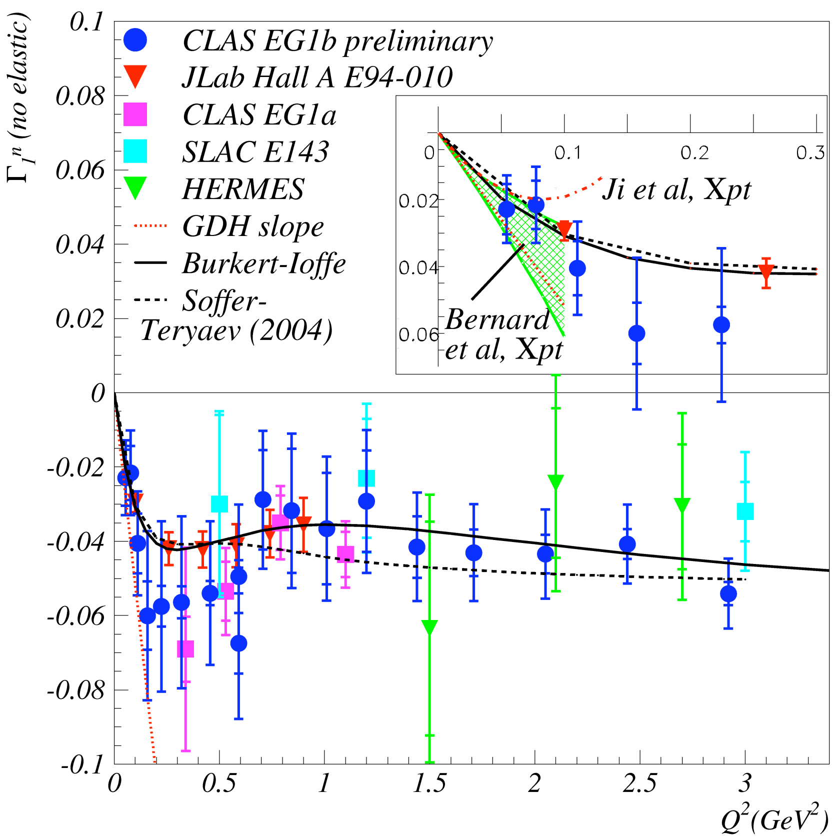


PRL 89 (2002) 242301

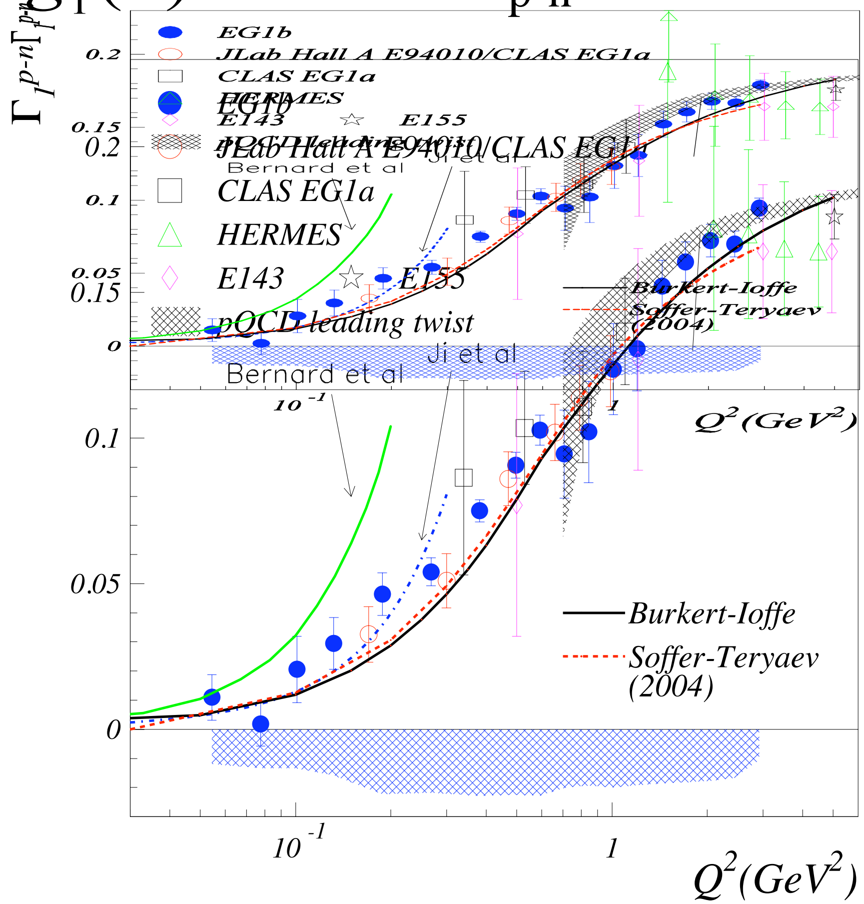
Γ_1 of neutron and p-n

$$\Gamma_1 = \int_0^{1-} g_1(x)dx$$

neutron



p-n



E94-010: PRL 92 (2004) 022301
EG1b (d-p)

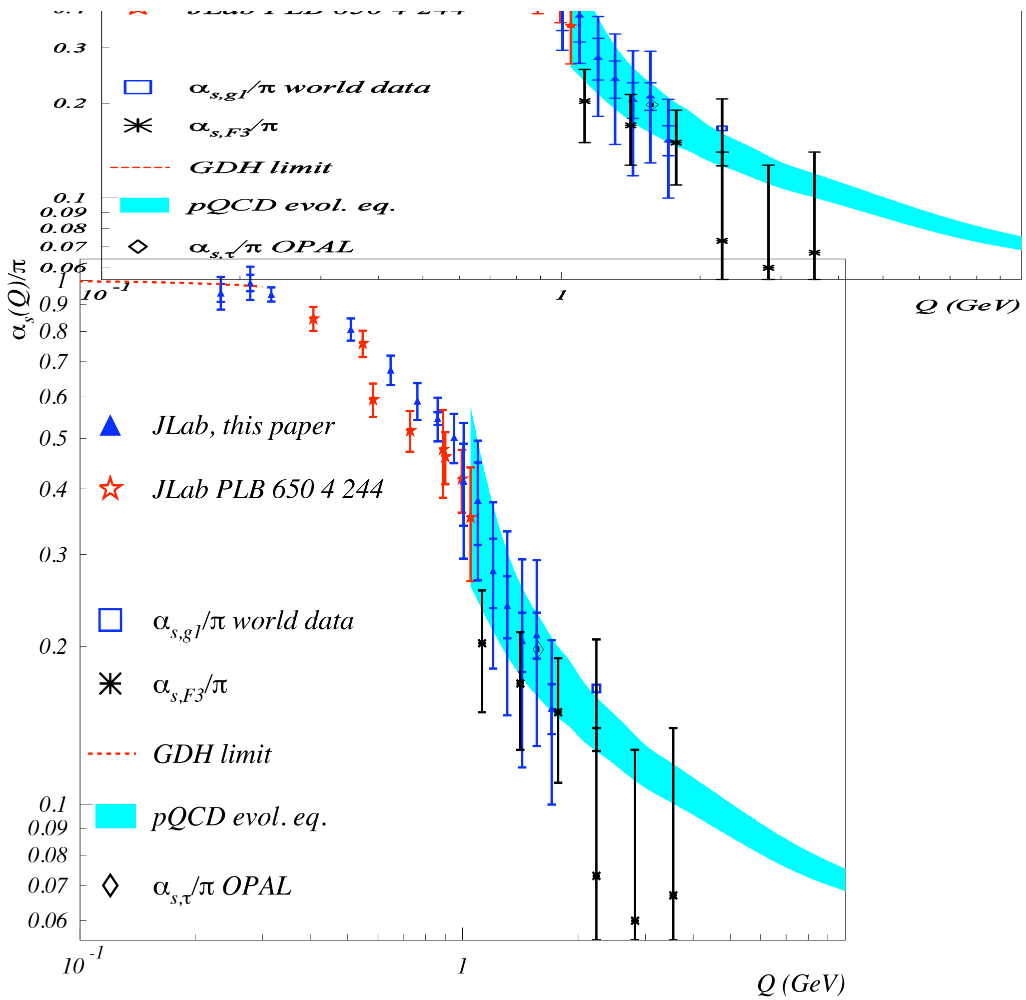
EG1b, PRD 78, 032001 (2008)
E94-010 + EG1a: PRL 93 (2004) 212001

Effective Coupling extracted from Bjorken Sum

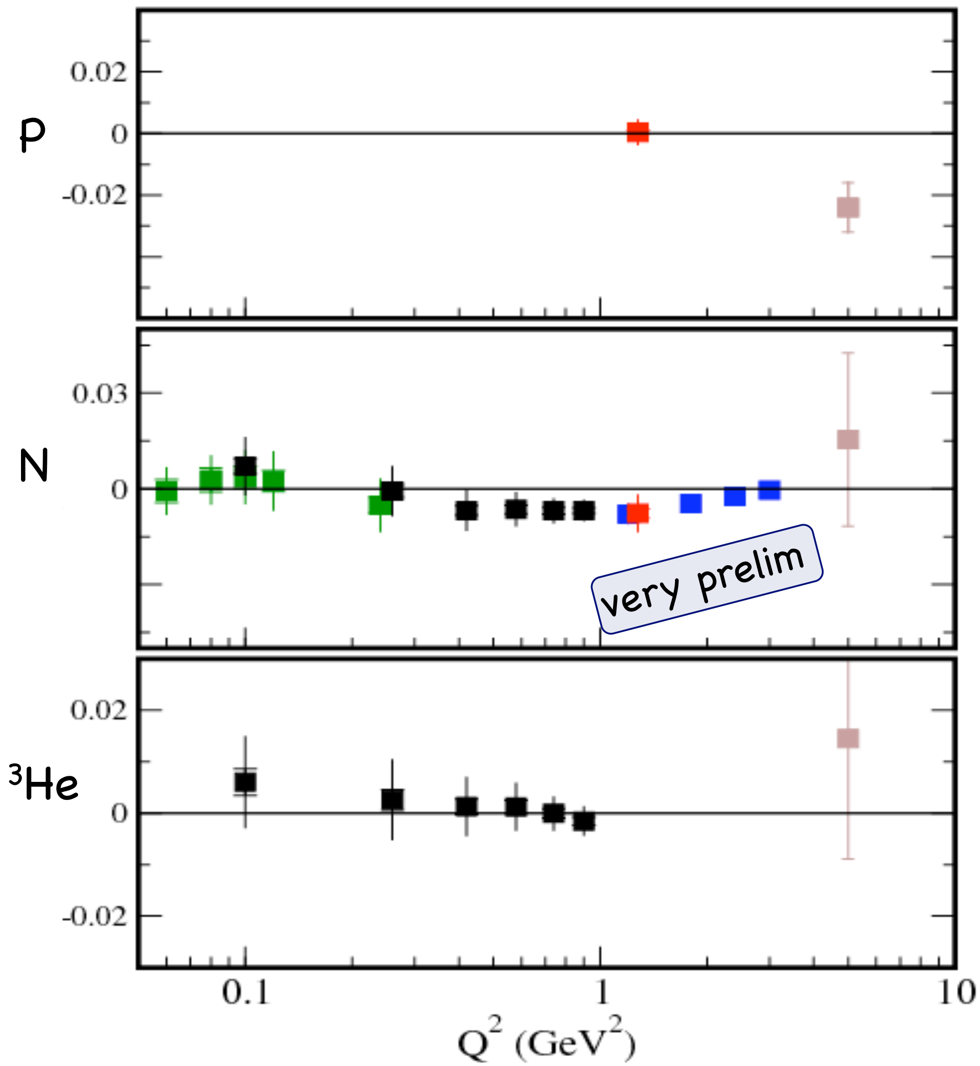
A. Deur, V. Burkert, J. P. Chen and W. Korsch

PLB 650, 244 (2007) and arXiv:0803.4119

α_s/π



BC Sum Rule



$$\Gamma_2 = \int_0^1 g_2(x)dx = 0$$

BC satisfied w/in errors for JLab Proton
2.8σ violation seen in SLAC data

BC satisfied w/in errors for Neutron
(But just barely in vicinity of Q^2=1)

BC satisfied w/in errors for ^{3}He

2^{nd} Moments: Generalized Spin Polarizabilities

- generalized forward spin polarizability γ_0

  generalized L-T spin polarizability δ_{LT}

$$\gamma_0(Q^2) = (\frac{1}{2\pi^2})\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu} \frac{\sigma_{TT}(Q^2,\nu)}{\nu^3} d\nu$$

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

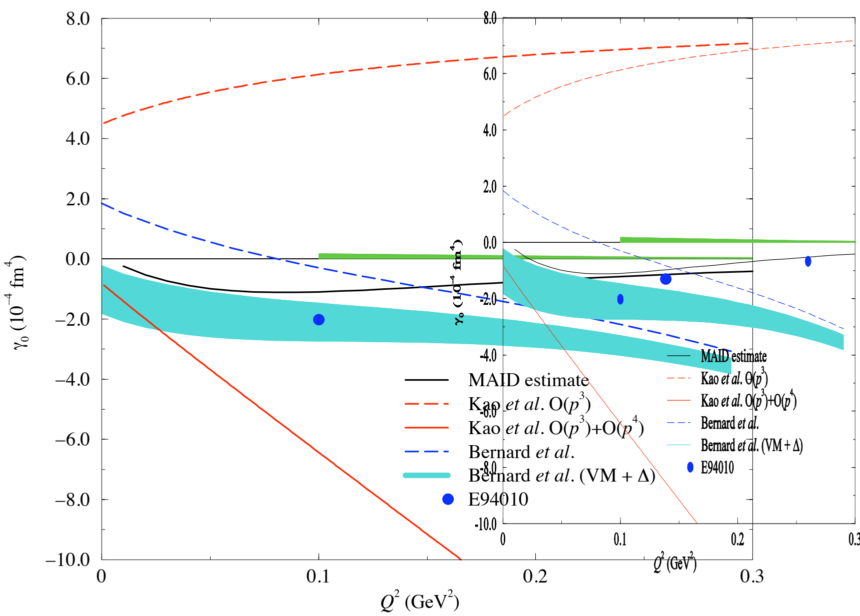
$$\delta_{LT}(Q^2) = (\frac{1}{2\pi^2})\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu} \frac{\sigma_{LT}(Q^2,\nu)}{Q\nu^2} d\nu$$

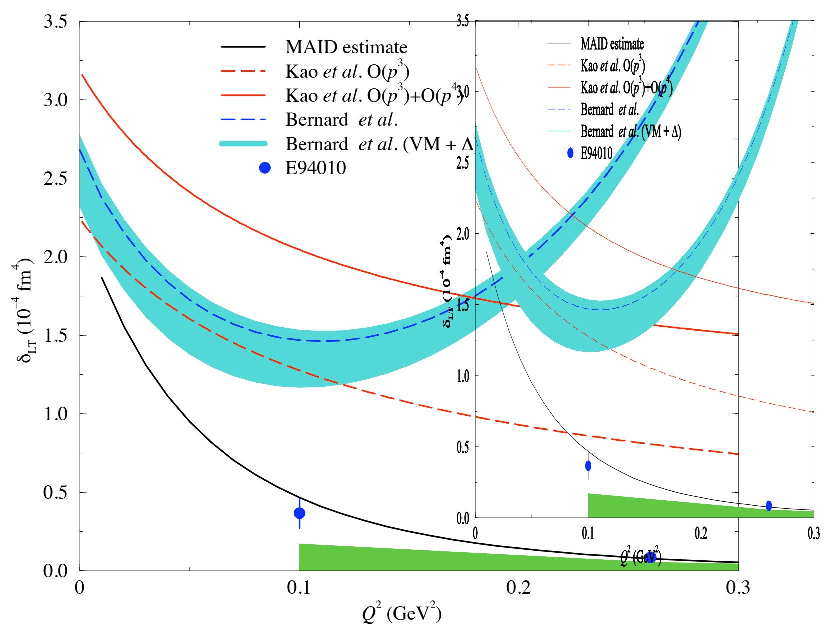
$$= \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2[g_1(Q^2,x) + g_2(Q^2,x)dx$$

Neutron Spin Polarizabilities

- δ_{LT} insensitive to Δ resonance
- RB ChPT calculation with resonance for γ_0 agree with data at Q^2=0.1 GeV^2
- Significant disagreement between data and both ChPT calculations for δ_{LT}
- Good agreement with MAID model predictions

γ_0 E94-010, PRL 93 (2004) 152301 δ_{LT}





Q^2 **Q^2**

Summary of Comparison with χPT

	I_A^n	Γ_1^P		Γ_1^n		Γ_1^{p-n}		γ_0^p	γ_0^n	δ_{LT}^n
Q^2 (GeV^2)	0.1	0.1	0.05	0.1	0.05	0.16	0.05	0.05	0.1	0.1
HBχPT	poor	poor	good	poor	good	good	good	bad	poor	bad
RBχPT/Δ	good	fair	fair	fair	good	poor	fair	bad	good	bad

- Q^2 range when χPT works: 0.05 is good, or 0.1 GeV^2?
- δ_{LT} puzzle: δ_{LT} not sensitive to Δ, one of the best quantities to test χPT, it disagrees with neither calculations by several hundred %!
- Very low Q^2 data on n(^{3}He), p and d available soon (E97-110, EG4)
- Need NNL O(P^5)? Kao *et al.* are working on that
- Other reasons?

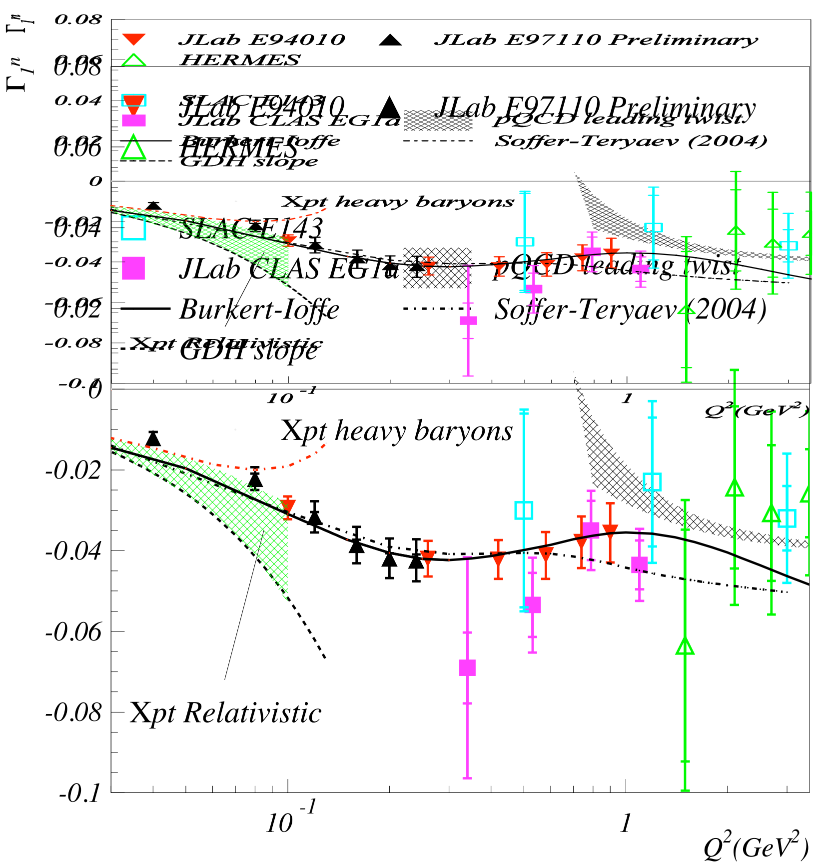
A challenge to χPT theorists.

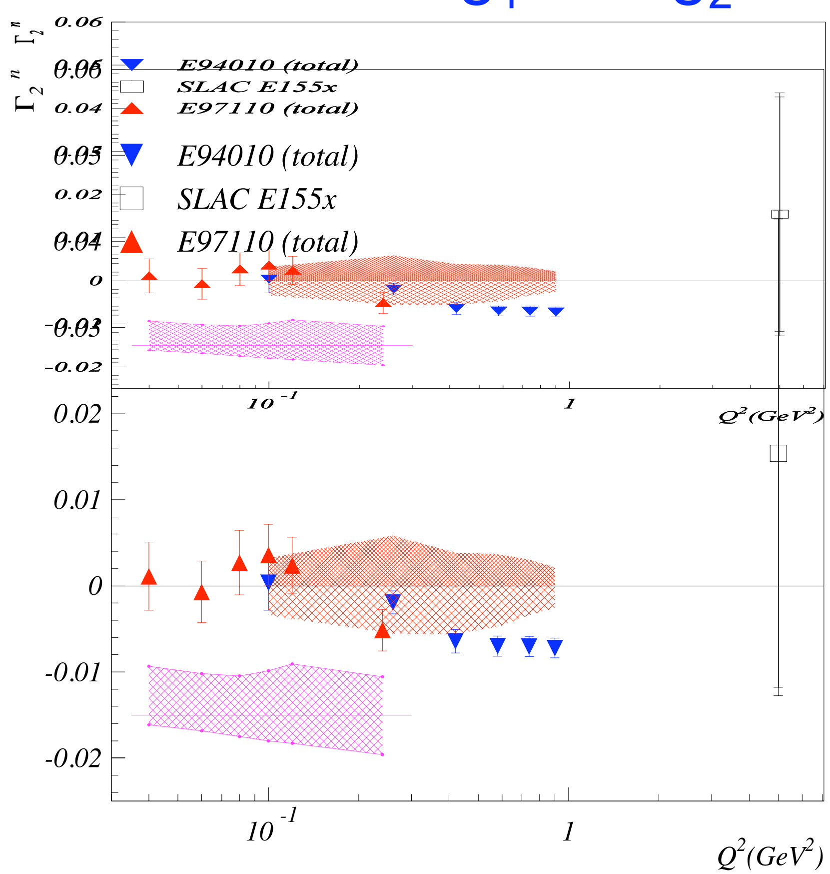
JLab E97-110: GDH Sum Rule and Spin Structure of ^{3}He and Neutron with Nearly Real Photons

Spokespersons: J. P. Chen, A. Deur, F. Garibaldi;

PhD Students: J. Singh, V. Sulkosky, J. Yuan

Preliminary Results: zeroth moments of g_1 and g_2



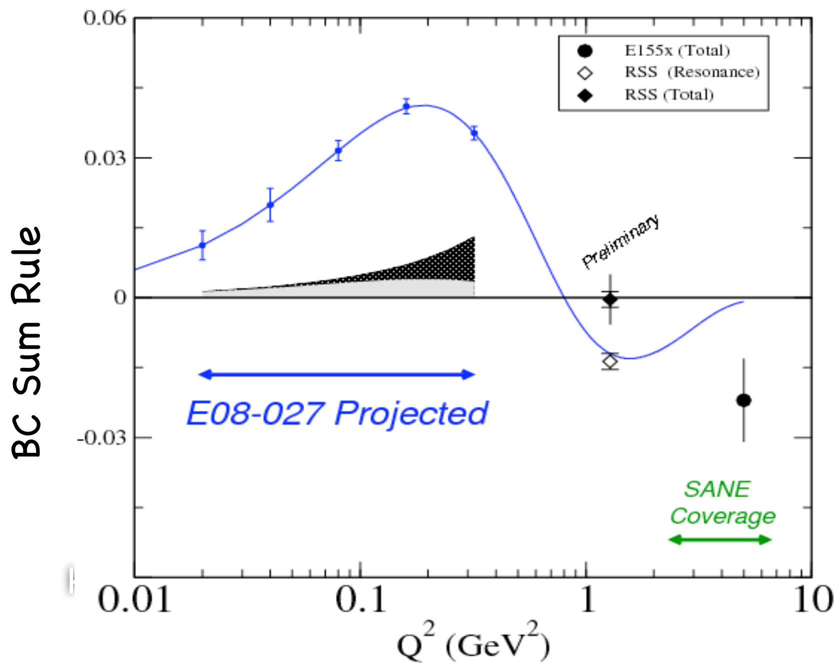


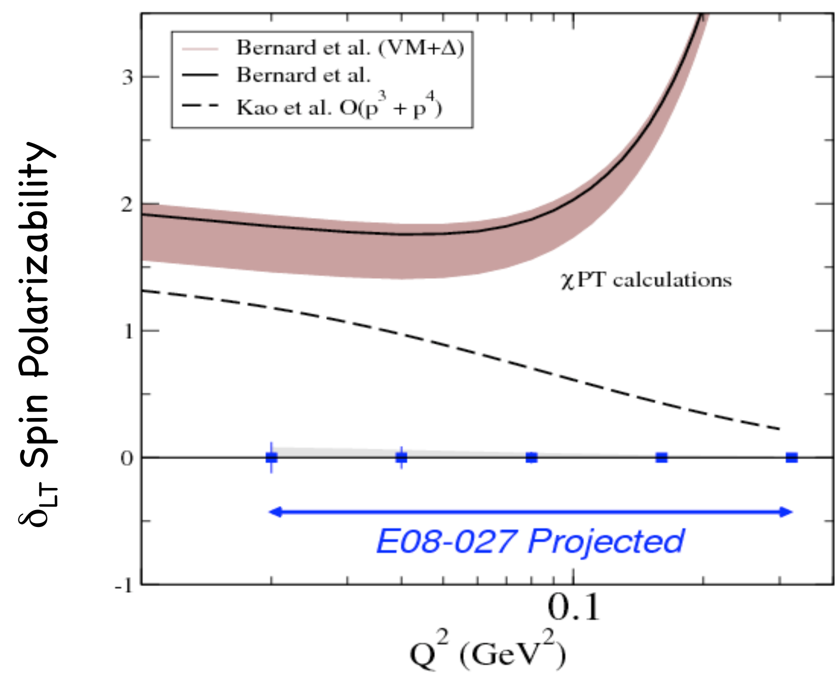
Planed: E08-027: Proton g_2 and δ_{LT}

J.P Chen, A. Camsonne, K. Slifer

g_2^p : central to knowledge of Nucleon Structure but remains unmeasured at low Q^2

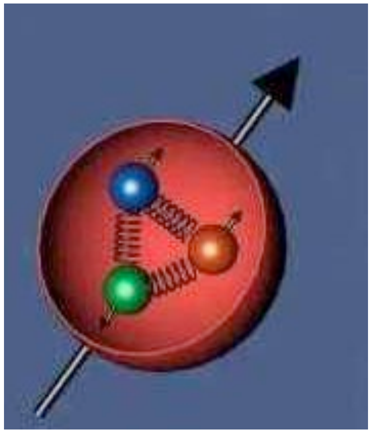
—Critical input to Hydrogen Hyperfine Calculations
—Violation of BC Sum Rule suggested at^n large Q^2
—State-of-Art χPT calcs fail dramatically for δ_{LT}





g_2, d_2: Higher Twists

Quark-gluon Correlations
and Color Polarizabilities



g_2: twist-3, *q-g* correlations

- experiments: transversely polarized target

  SLAC E155x, (p/d)

  JLab Hall A (n), Hall C (p/d)

- g_2 leading twist related to g_1 by Wandzura-Wilczek relation

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

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

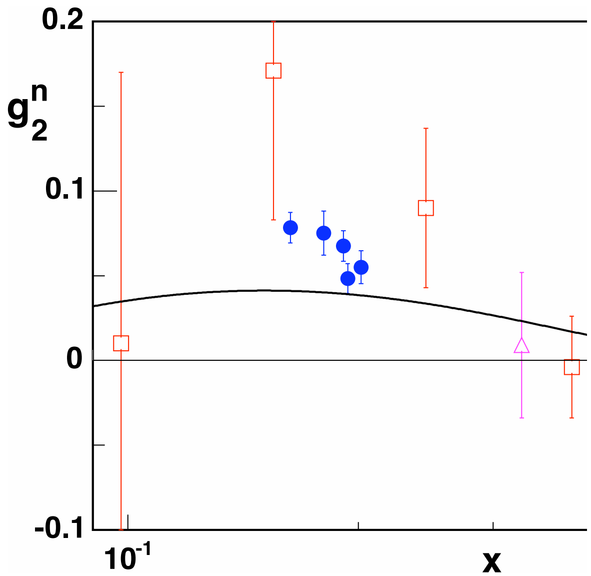
- $g_2 - g_2^{WW}$: a clean way to access twist-3 contribution

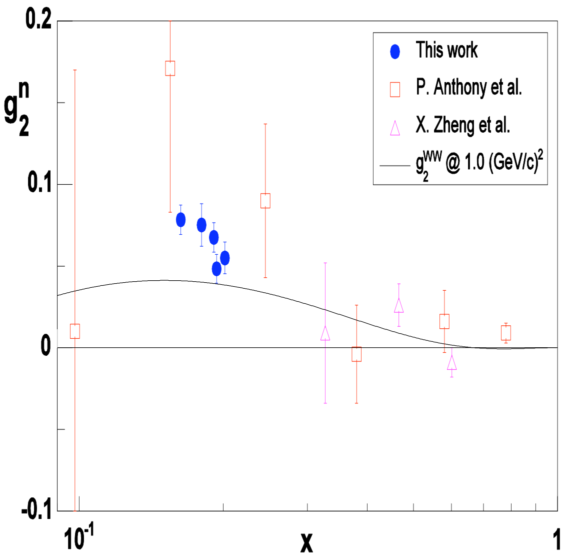
  quantify *q-g* correlations

Jefferson Lab Hall A E97-103

Precision Measurement of $g_2^n(x,Q^2)$: Search for Higher Twist Effects

T. Averett, W. Korsch (spokespersons) **K. Kramer (Ph.D. student)**





- Improve g_2^n precision by an order of magnitude.
- Measure higher twist → quark-gluon correlations.
- Hall A Collaboration, K. Kramer *et al.*, PRL 95, 142002 (2005)

Color Polarizability: d_2 (twist-3)

- 2^{nd} moment of g_2-g_2^{WW}

  d_2: twist-3 matrix element

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

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

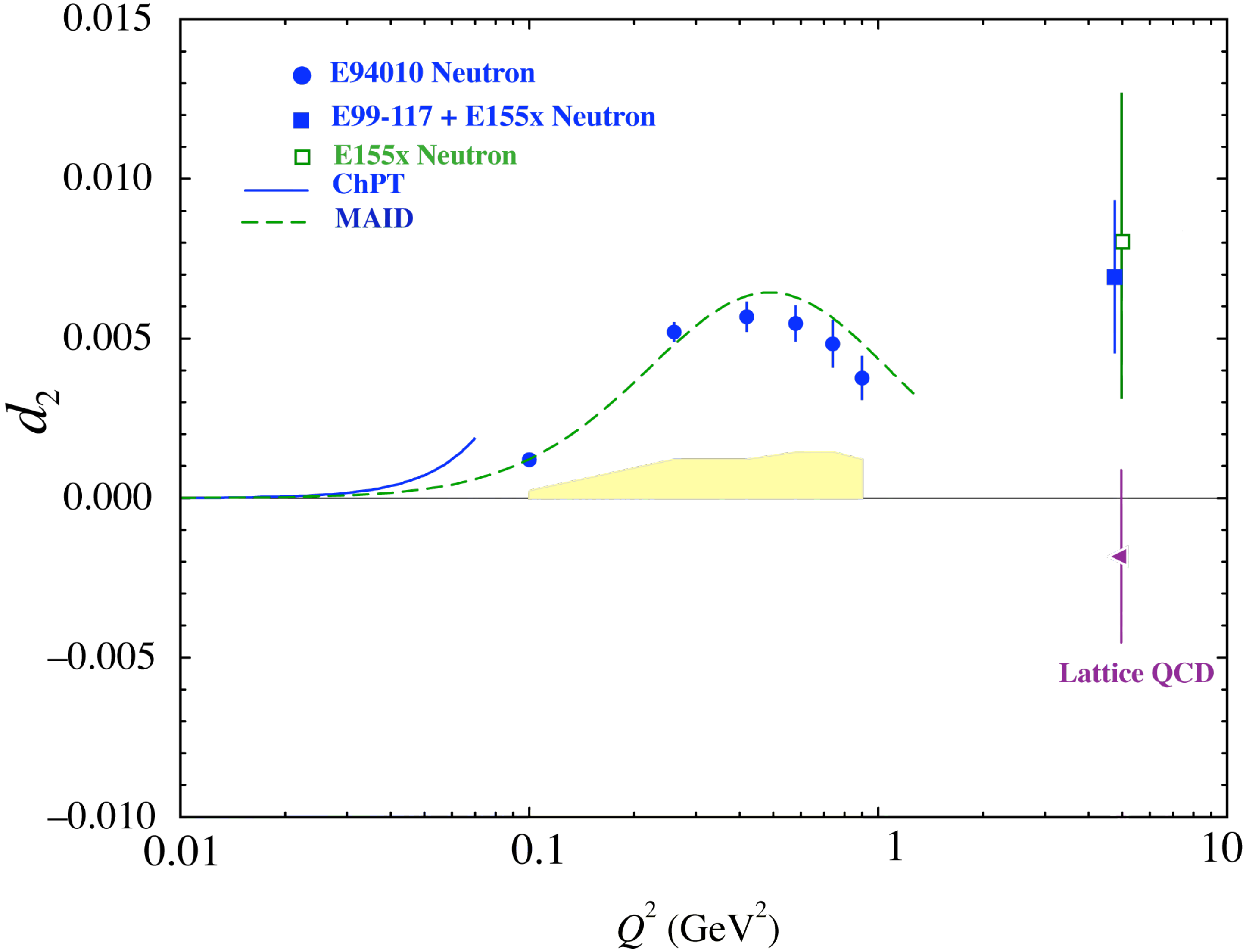
d_2 and g_2-g_2^{WW}: clean access of higher twist (twist-3) effect: *q*-*g* correlations

Color polarizabilities χ_E,χ_B are linear combination of d_2 and f_2

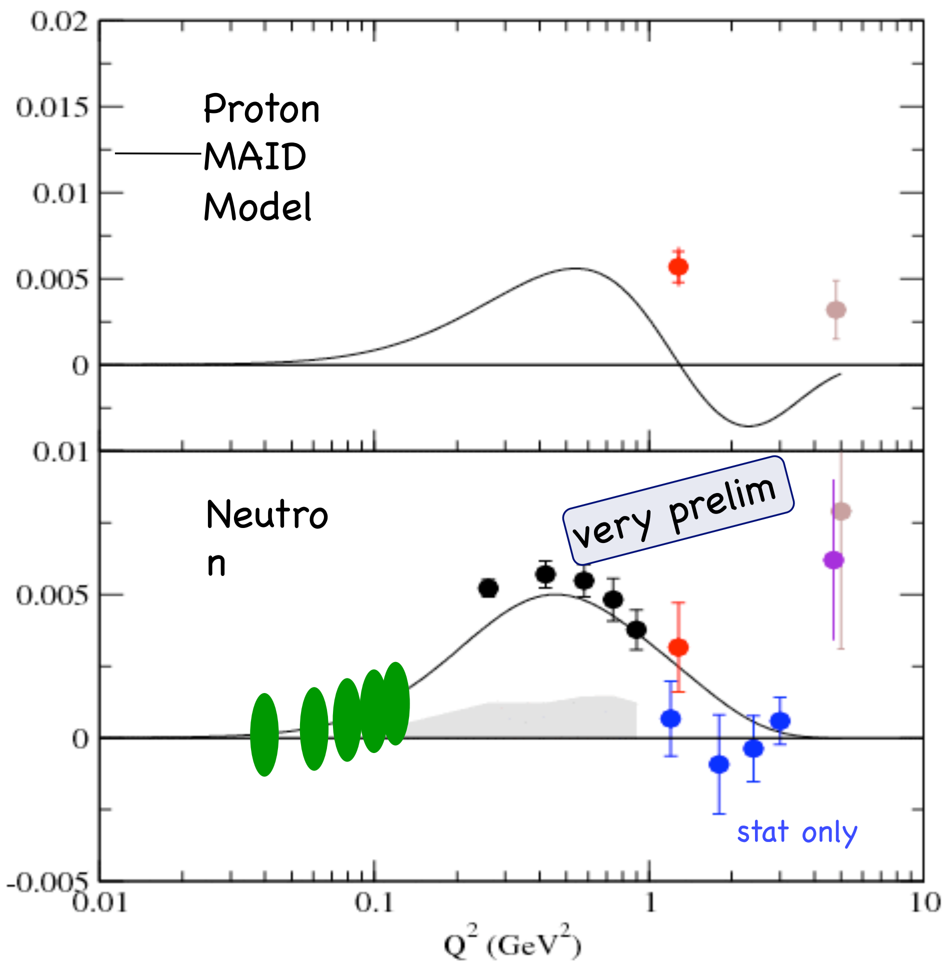
Provide a benchmark test of Lattice QCD at high Q^2

Avoid issue of low-*x* extrapolation

Measurements on neutron: d_2^n (Hall A and SLAC)



$d_2(Q^2)$



BRAND NEW DATA!

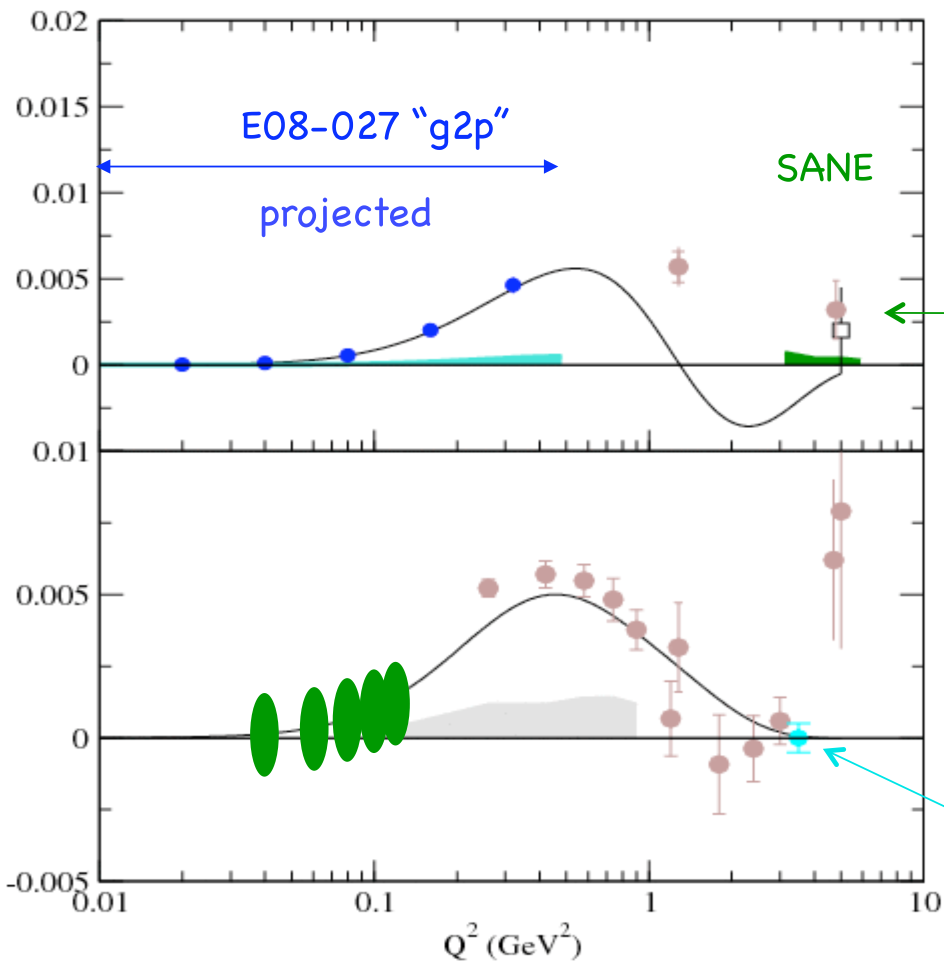
Very Preliminary

RED : RSS. (Hall C, NH_3,ND_3)

BLUE: E01-012. (Hall A, ^3He)

GREEN: E97-110. (Hall A, ^3He)

$d_2(Q^2)$



Upcoming 6 GeV Experiments

SANE in Hall C, taking data

$2.3 < Q^2 < 6$ GeV2

"g2p" in Hall A, 2011

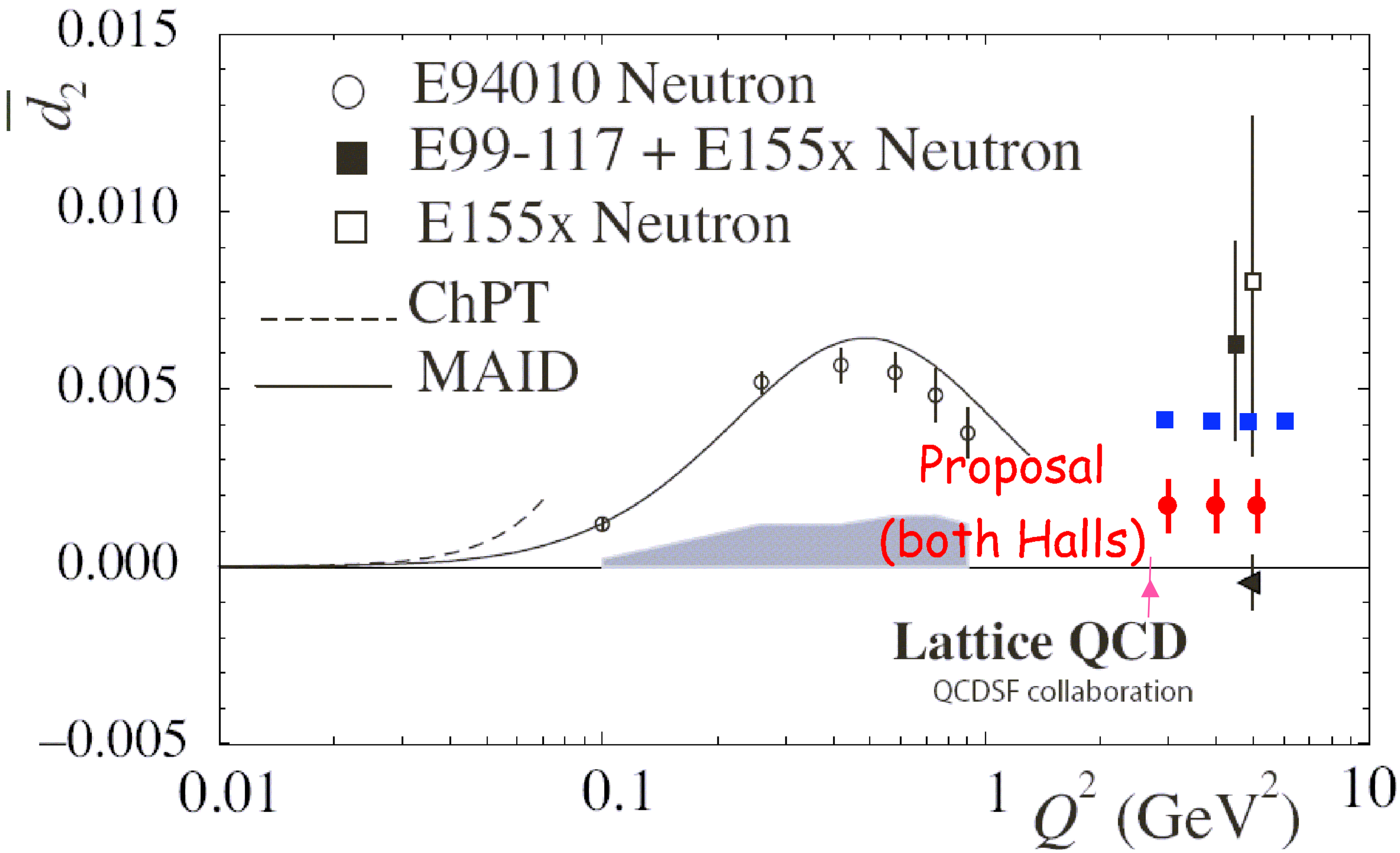
$0.015 < Q^2 < 0.4$ GeV^2

"d2n" in Hall A, taking data

$Q^2 = 3$ GeV^2

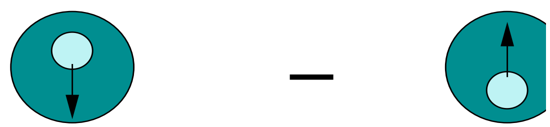
Planned d_2^n with JLab 6 GeV and 12 GeV

- Projections with planned 6 GeV and 12 GeV experiments
- Improved Lattice Calculation (QCDSF, hep-lat/0506017)



Semi-inclusive Deep Inelastic Scattering *N(e,e'π)x*

Transversity and TMDs

$h_1^{\perp} =$ 

Transversity

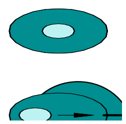
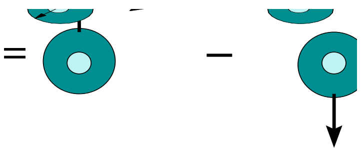
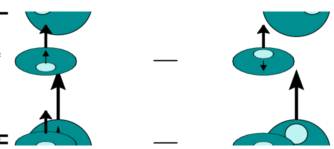
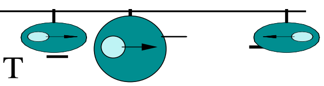
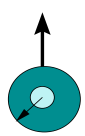
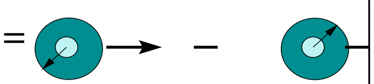
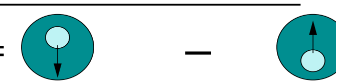
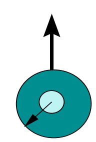
- Three twist-2 quark distributions:
  - Momentum distributions: $q(x,Q^2) = q^{\uparrow}(x) + q^{\downarrow}(x)$
  - Longitudinal spin distributions: $\Delta q(x,Q^2) = q^{\uparrow}(x) - q^{\downarrow}(x)$
  - Transversity distributions: $\delta q(x,Q^2) = q^{\perp}(x) - q_{\top}(x)$
- It takes two chiral-odd objects to measure transversity
  - Semi-inclusive DIS

    Chiral-odd distributions function (transversity)

    Chiral-odd fragmentation function (Collins function)
- TMDs: (without integrating over P_T)
  - Distribution functions depends on x, $k_\perp$ and Q^2 : $\delta q,\ f_{1T}^{\perp}(x,k_\perp,Q^2),\ \ldots$
  - Fragmentation functions depends on z, $p_\perp$ and Q^2 : $D,\ H_1(x,p_\perp,Q^2)$
  - Measured asymmetries depends on x, z, $P_\perp$ and Q^2 : *Collins, Sivers, …*

    ($k_\perp$, $p_\perp$ and $P_\perp$ are related)

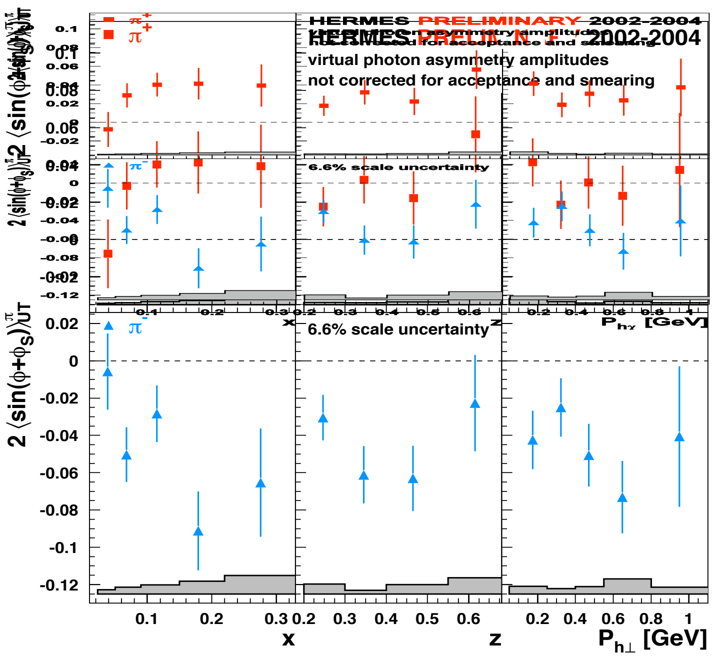
“Leading-Twist” *TMD* Quark Distributions

Nucleon / Quark	Unpol.	Long.	Trans.
Unpol.	f_1 = 		$f_{1T}^{\perp}$ = 
Long.		g_{1L} − h_{1T} = − $h_{1L}^{\perp}$ = − 	g_{1T} = g_{1T} − 
Trans.	$h_{1T}^{\perp}$ =  −	$h_{1L}^{\perp}$ =  −	$h_1^{\perp}$ =  − $h_{1T}^{\perp}$ =  −

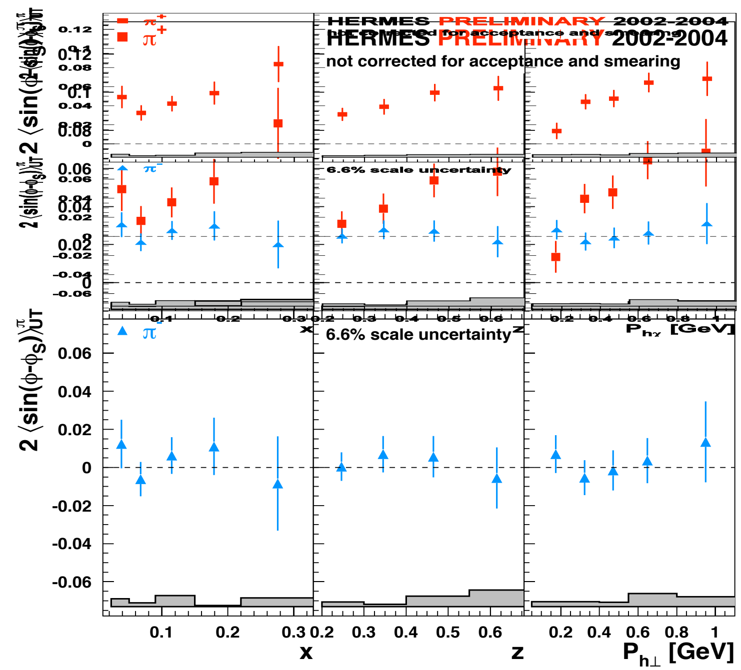
$A_{UT}^{\sin(\phi)}$ from transv. pol. H target

Simultaneous fit to $\sin(\phi + \phi_s)$ and $\sin(\phi - \phi_s)$

`Collins' moments



`Sivers' moments



- Non-zero Collins asymmetry
- Assume $\delta q(x)$ from model, then

  H_1_unfav ~ -H_1_fav

- Need independent H_1 (BELLE)

- Sivers function nonzero (π^+)→ orbital angular momentum of quarks
- Regular flagmentation functions

Current Status

- Large single spin asymmetry in pp->πX
- Collins Asymmetries

  - sizable for proton (HERMES and COMPASS)

    large at high x, π^- and π+ has opposite sign

    unfavored Collins fragmentation as large as favored (opposite sign)?

  - consistent with 0 for deuteron (COMPASS)

- Sivers Asymmetries
  - non-zero for π^+ from proton (HERMES), consistent with zero (COMPASS)?
  - consistent with zero for π^- from proton and for all channels from deuteron
  - large for K^+ ?

- Very active theoretical and experimental study

  RHIC-spin, JLab (Hall A 6 GeV, CLAS12, HallA/C 12 GeV), Belle, FAIR (PAX)

- Global Fits/models by Anselmino *et al., Yuan et al.* and …
- First neutron measurement from Hall A 6 GeV (E06-010)
- Solenoid with polarized ^{3}He at JLab 12 GeV

  Unprecedented precision with high luminosity and large acceptance

E06-010/06-011 **Single Target-Spin Asymmetry in Semi-Inclusive *n↑(e,e'π+/-)* Reaction on a Transversely Polarized ^{3}He Target**

Spokespersons:

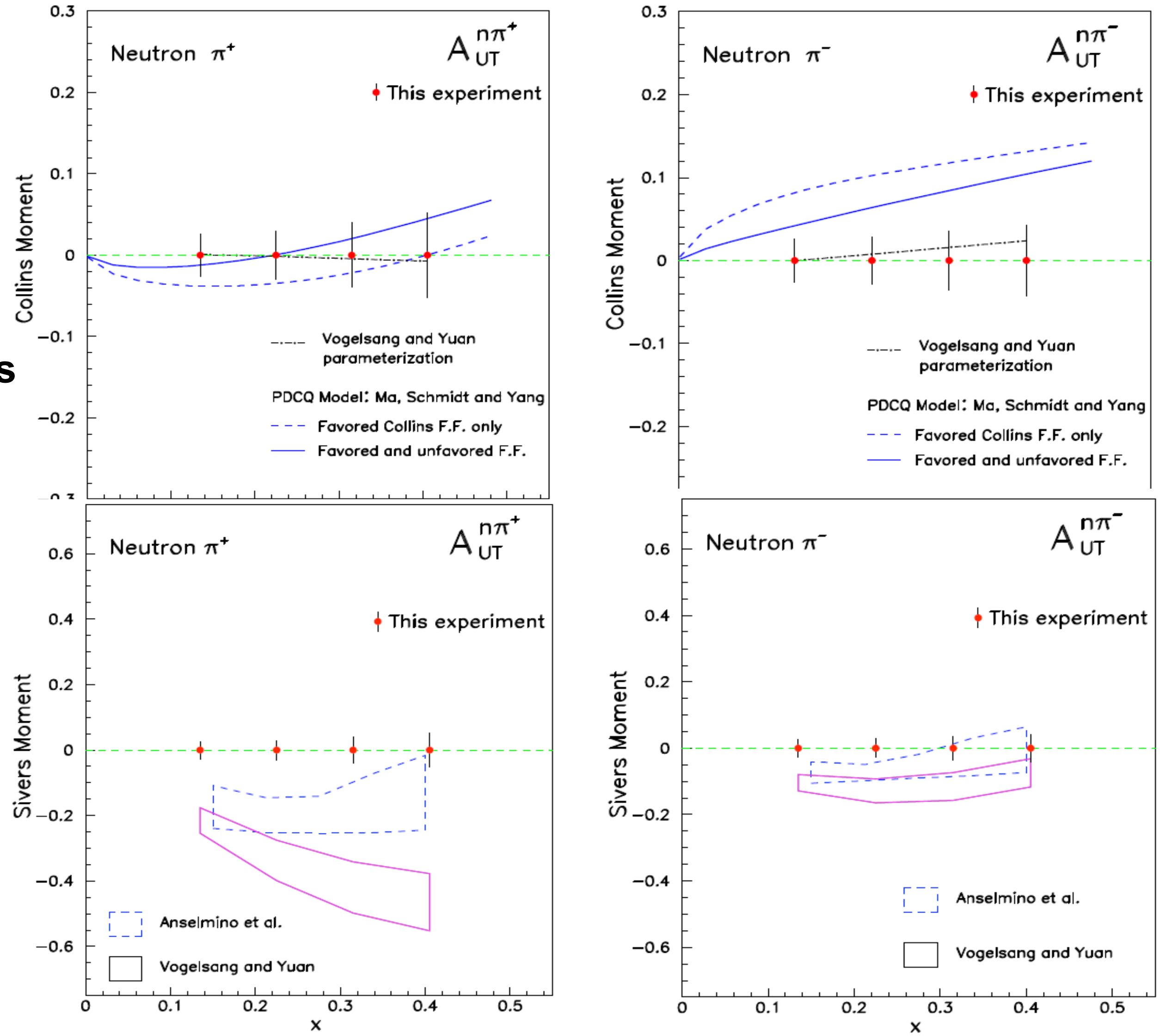
X. Jiang,
J. P. Chen,
E. Cisbani,
H. Gao,
J.-C. Peng

7 PhD Students:

Successfully Completed data taking, exceeded PAC approved goal

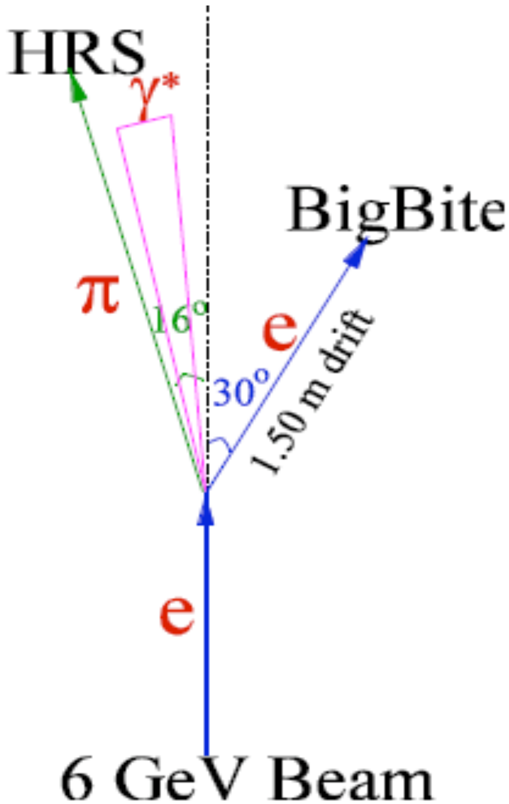
Collins

Sivers

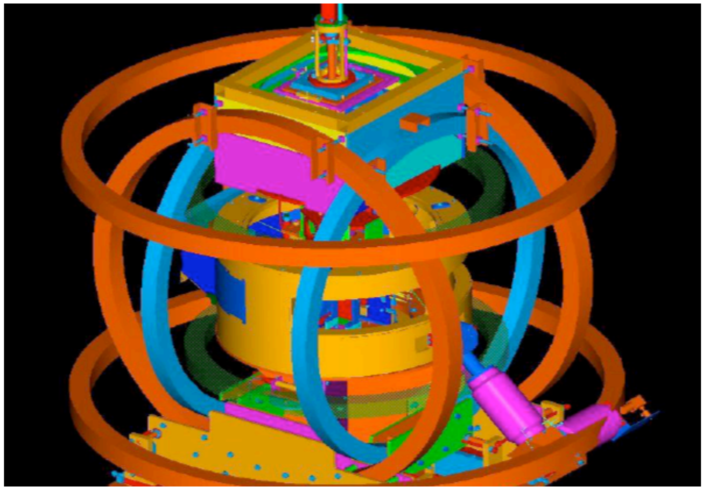


Hall-A Transversity:

en→e'πX
en→e'KX



Polarized 3He: effective polarized neutron target
World highest polarized luminosity: 10^{36}
New record in polarization: >70% without beam
~65% in beam and with spin-flip (proposal 42%)



HRSL for hadrons (p+- and K+-), new RICH commissioned

BigBite for electrons, 64 msr, detectors performing well

Precision Study of Transversity and *TMDs*

- From exploration to precision study
- Transversity: fundamental *PDF*s, tensor charge
- *TMD*s provide 3-d structure information of the nucleon
- Learn about quark orbital angular momentum
- Multi-dimensional mapping of *TMD*s
  - 3-d ($x, z, P_\perp$)
  - Q^2 dependence
  - multi facilities, global effort
- Precision → high statistics
  - high luminosity and large acceptance

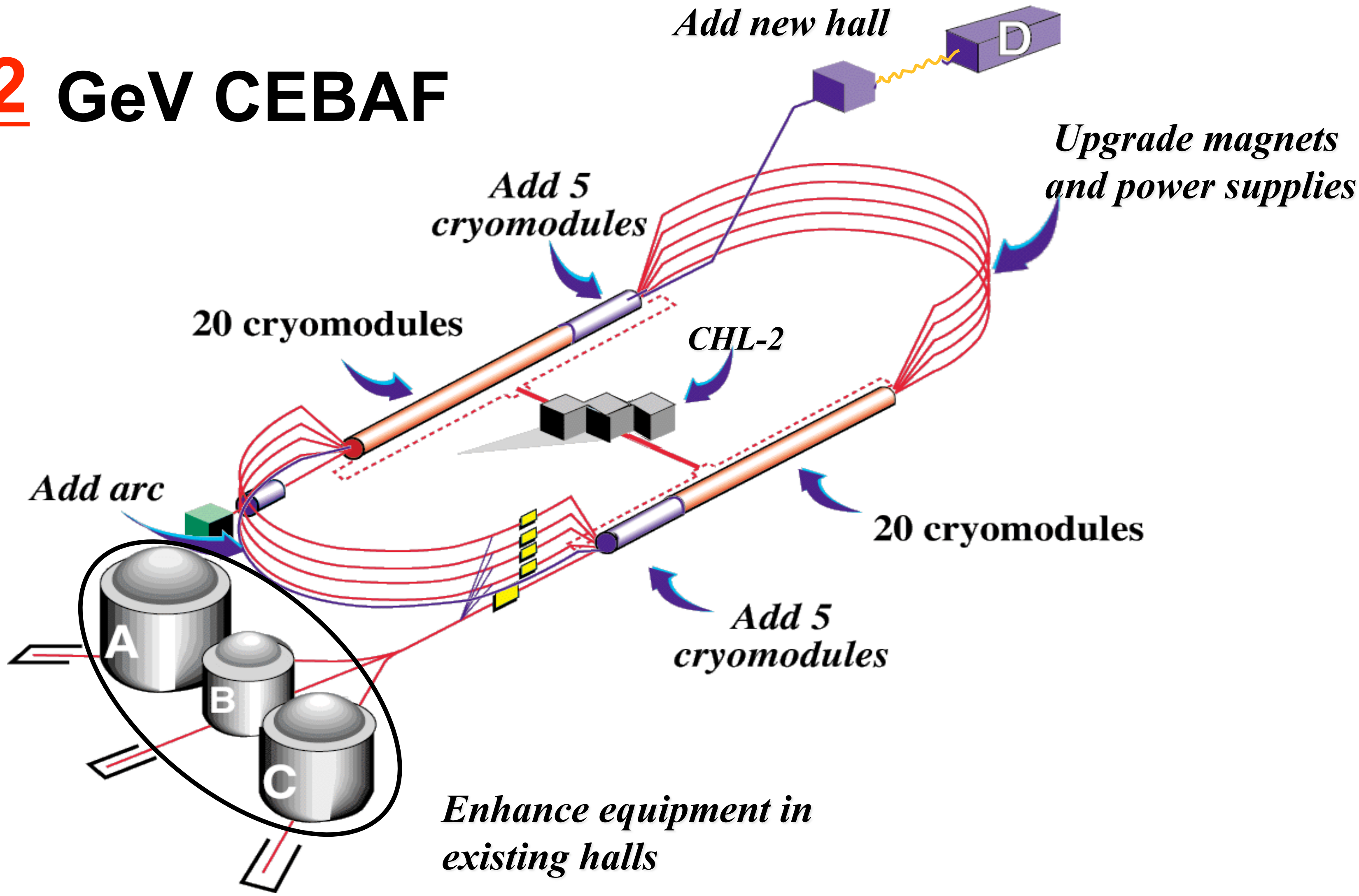
Measurement of Tensor Charge

- Tensor charge is a fundamental quantity; *LQCD* prediction
- A plan for a measurement of the tensor charge
  - As much model independent as possible
  - Valence phenomena: *u* and *d* quarks dominant
  - To determine δu, δd, H_1^u, H_1^d
    - Need at least 4 measurements at each kinematical point
      → *SIDIS* of π^{+-} on both proton and neutron
  - Kinematical region: most contributions in $0.1 < x < 0.5$
  - 12 GeV JLab idea for this measurement
    - CLAS12 with proton and a new Solenoid with polarized neutron (^{3}He)

- Issues: factorization, Q^2 evolution, *NLO*, higher-twists, sea quarks

  e+e- (Belle), pp (RHIC, FAIR,…), ep (EIC) → global fit

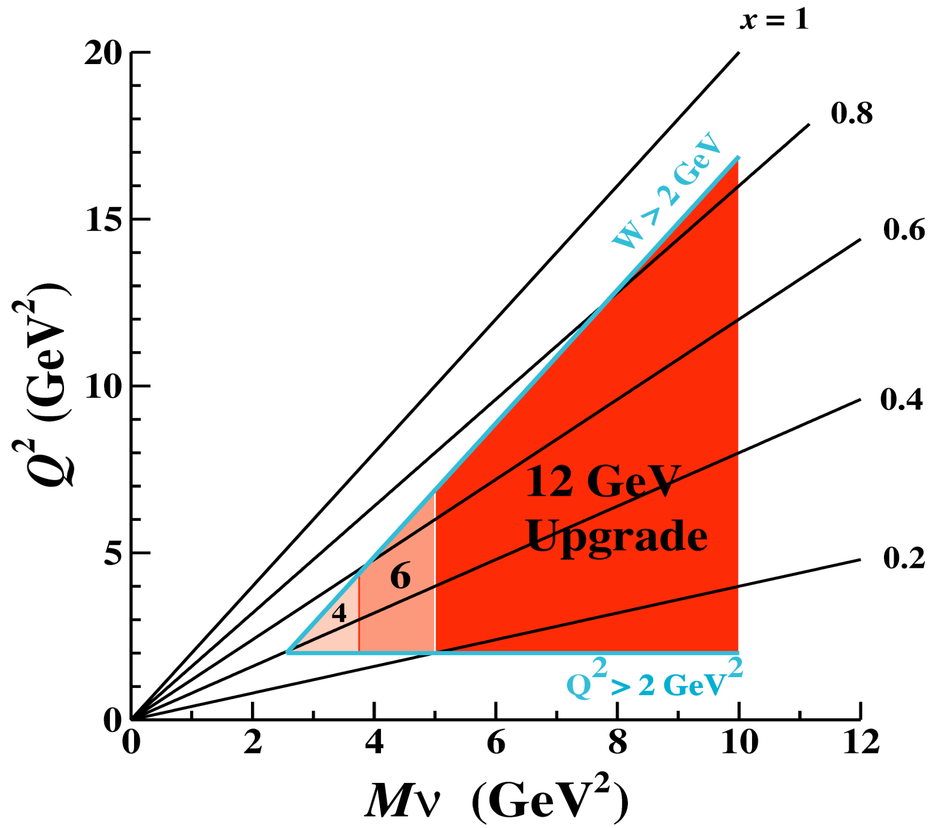
12 GeV CEBAF



Add new hall
D
Upgrade magnets
and power supplies
Add 5
cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5
cryomodules
A
B
C
Enhance equipment in
existing halls

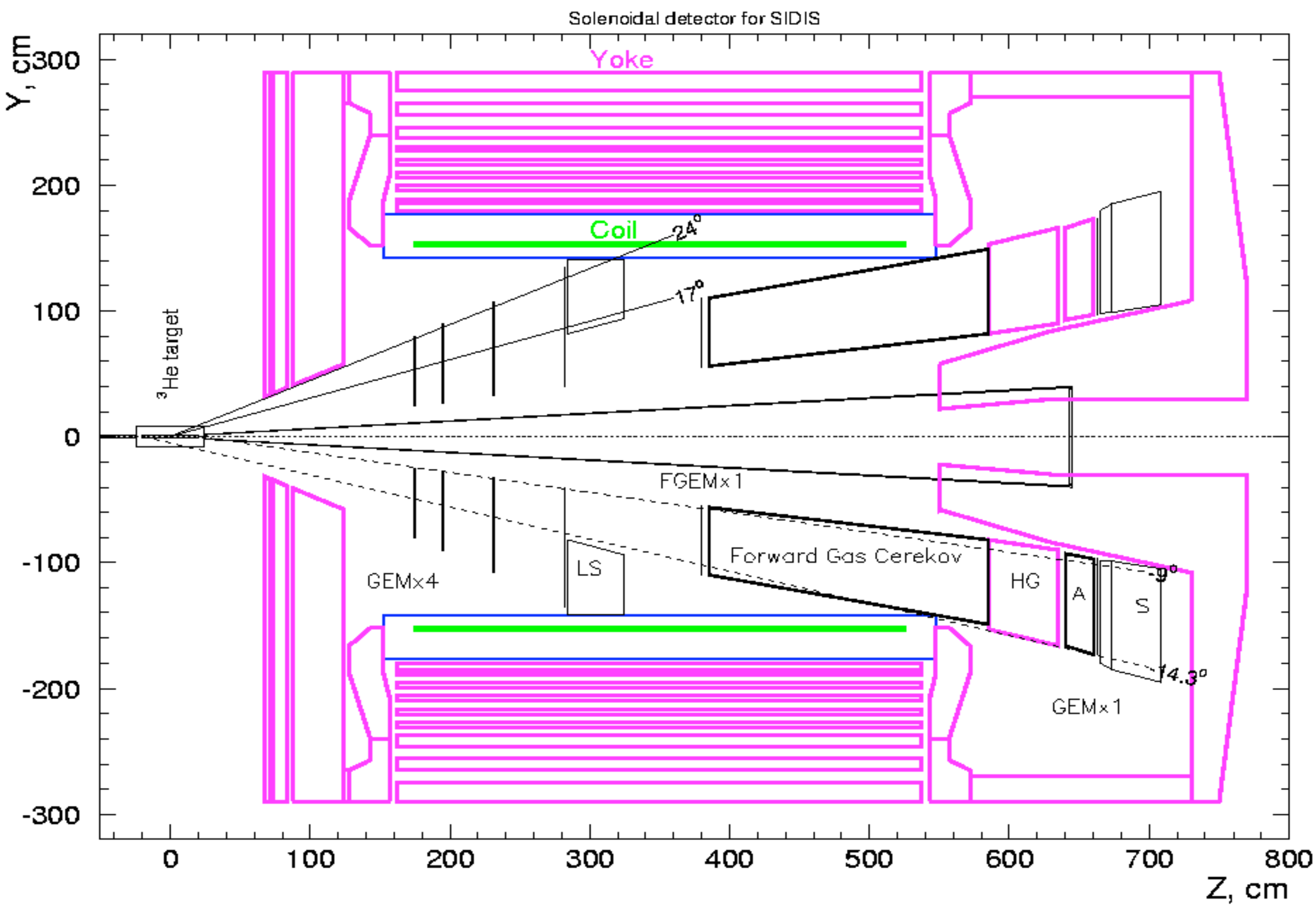
12 GeV Upgrade Kinematical Reach

- Reach a broad DIS region
- Precision SIDIS for transversity and TMDs
- Experimental study/test of factorization
- Decisive inclusive DIS measurements at high-*x*
- Study GPDs



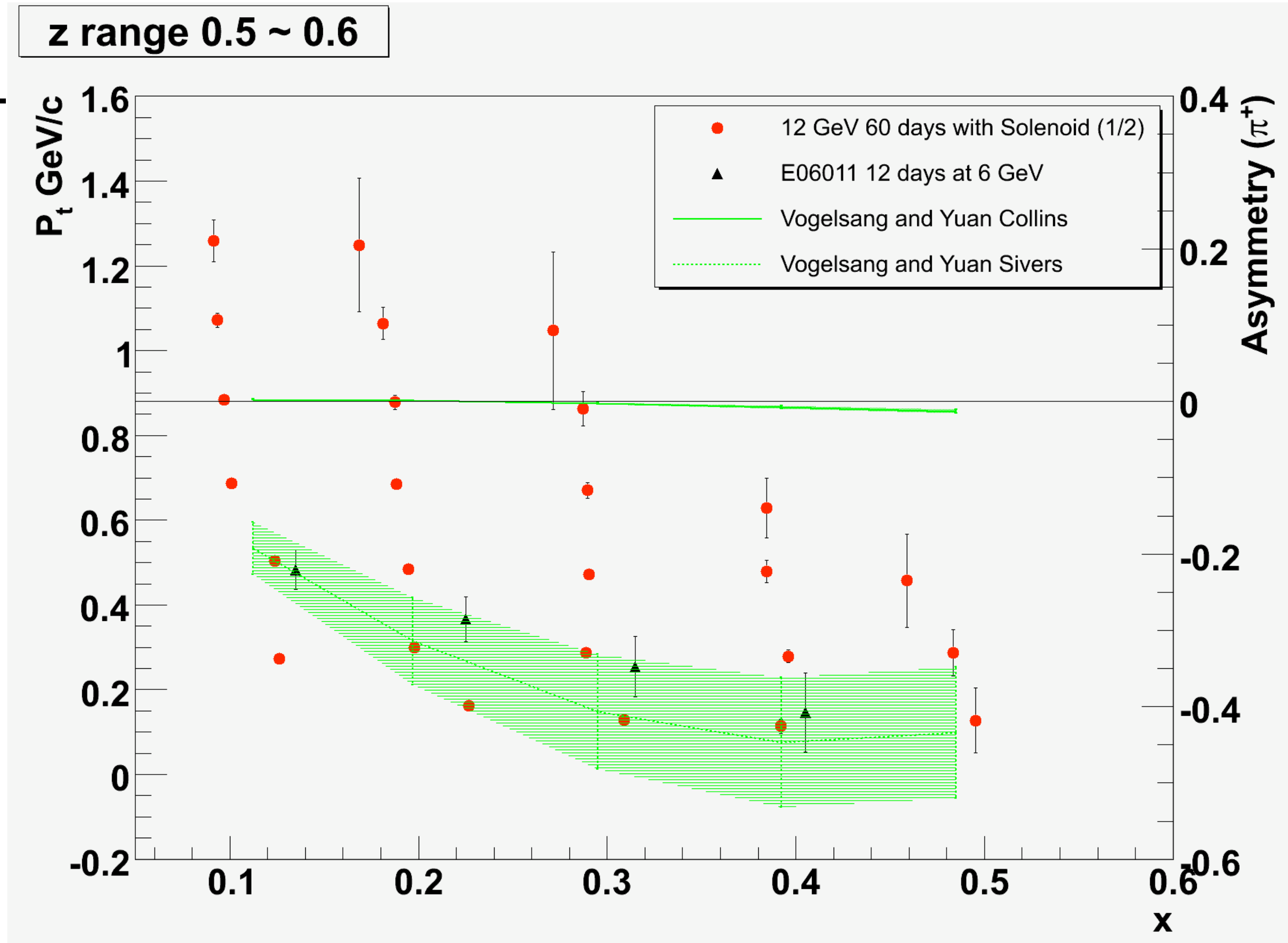
Solenoid detector for SIDIS at 11 GeV

Proposed for PVDIS at 11 GeV

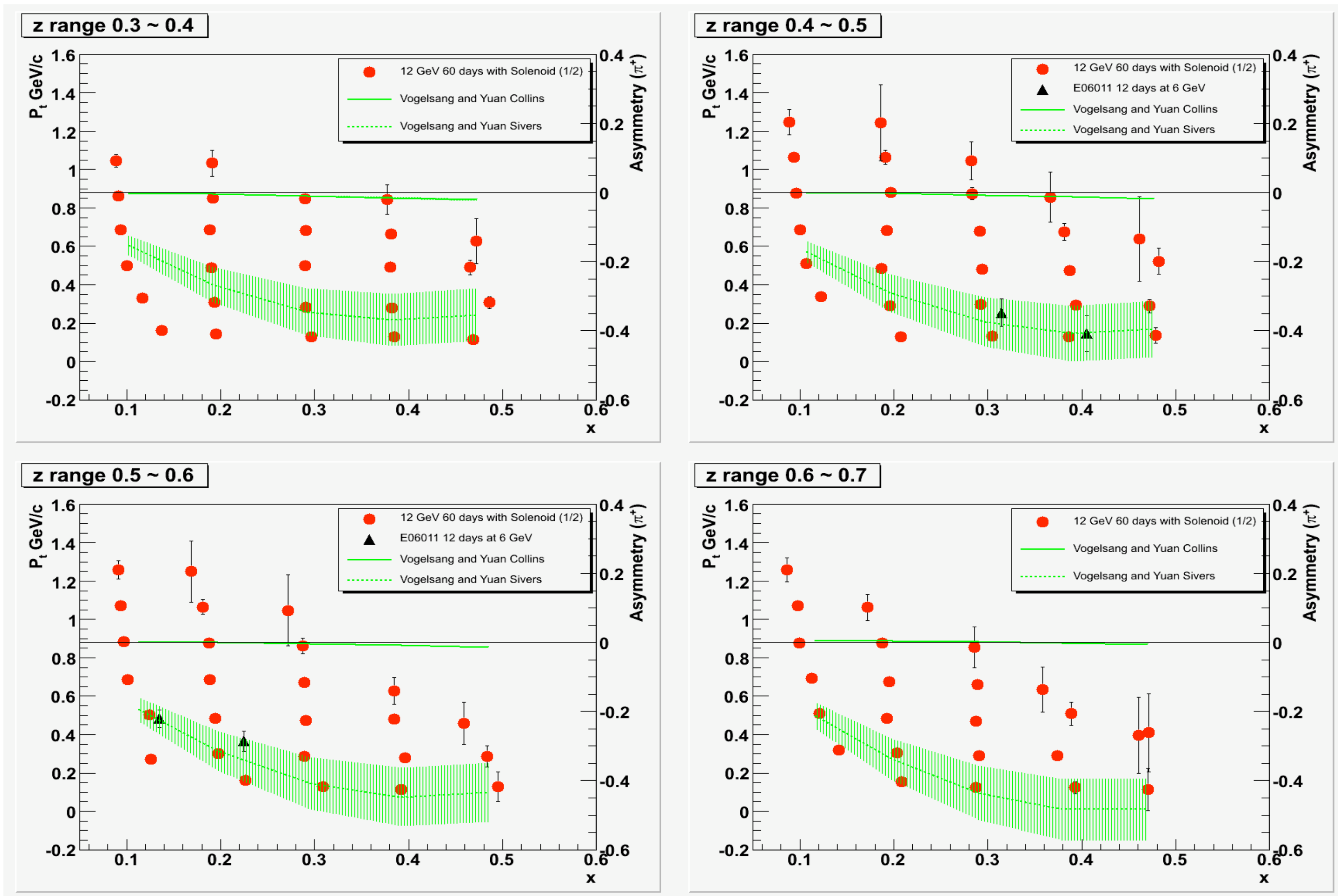


3-D Mapping of Collins/Siver Asymmetries at JLab 12 GeV With A Large Acceptance Solenoid Detector

- Both π+ and π-
- For one z bin (0.5-0.6)
- Will obtain 4 z bins (0.3-0.7)
- Upgraded PID for K+ and K-



3-D Projections for Collins and Sivers Asymmetry (π^+)



Discussion

- Unprecedented precision *3-d* mapping of SSA
  - Collins and Sivers
  - π^+, π^- and K^+, K^-
- Study factorization with x and z-dependences
- Study P_T dependence
- Combining with CLAS12 proton and world data
  - extract transversity and fragmentation functions for both *u* and *d* quarks
  - determine tensor charge
  - study TMDs for both valence and sea quarks
  - study quark orbital angular momentum
- Combining with world data, especially data from high energy facilities
  - study Q^2 evolution
- Global efforts (experimentalists and theorists), global analysis
  - much better understanding of 3-d nucleon structure and QCD

Spin Structure with the Solenoid at JLab 12 GeV

- Program on neutron spin structure with polarized ^{3}He and solenoid
  - **Polarized ^{3}He target**
    - effective polarized neutron
    - highest polarized luminosity: 10^{36}
  - **A solenoid with detector package (GEM, EM calorimeter+ Cherenkov**
    - large acceptance: ~700 msr for polarized (without baffles)

→ high luminosity and large acceptance

  - **Inclusive DIS: improve by a factor of 10-100**
    - A_1 at high-x: high precision
    - d_2 at high Q^2: very high precision
    - parity violating spin structure g_3/g_5 : first significant measurement
  - **SIDIS: improve by a factor of 100-1000**
    - transversity and TMDs,
    - spin-flavor decomposition (~2 orders improvement)
- Unpolarized luminosity: $5x10^{38}$, acceptance ~ 300 msr (with baffles)
  - **Parity-Violating DIS**
  - **Boer-Mulders function**

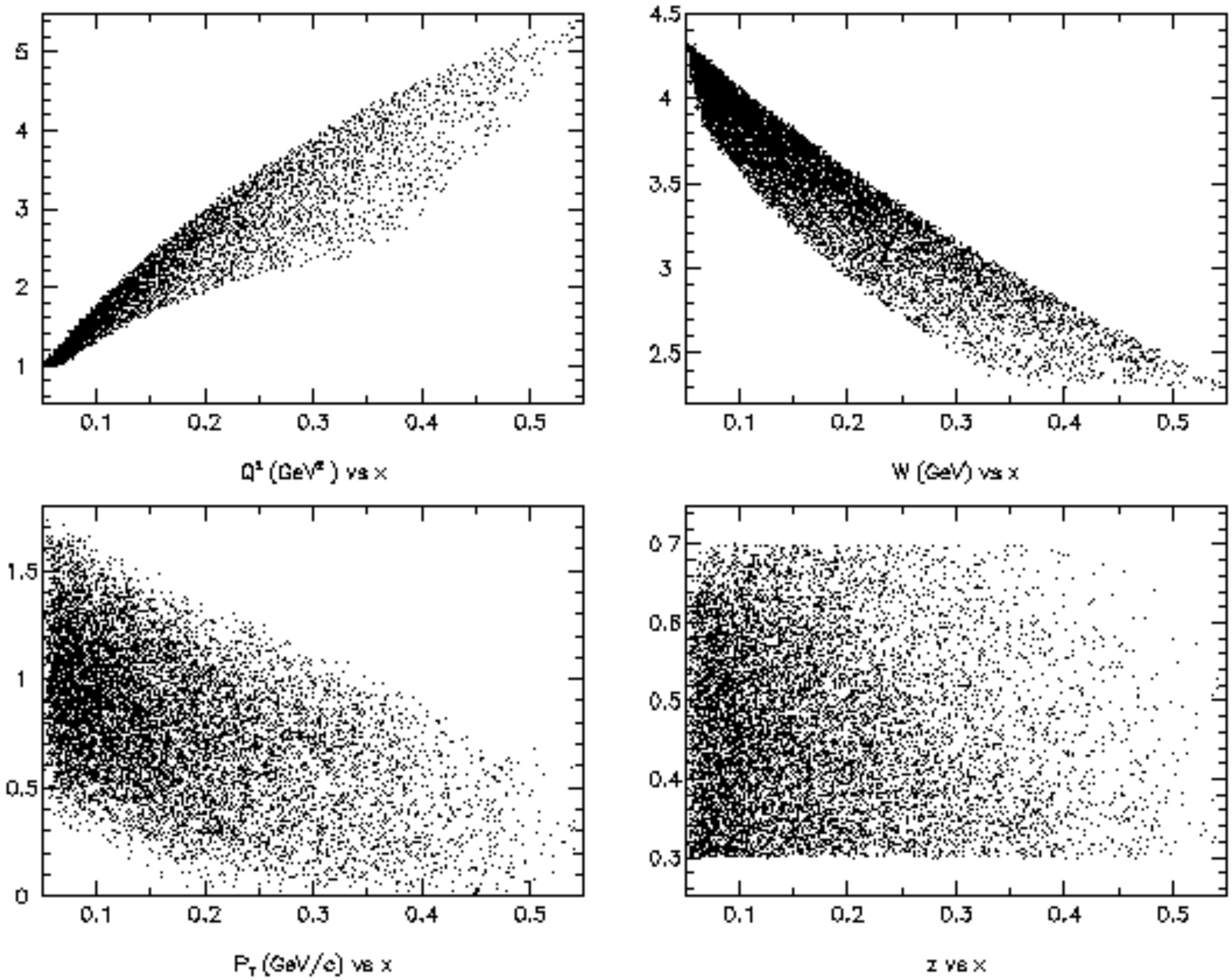
Summary

- Spin structure study full of surprises and puzzles
- A decade of experiments from JLab: exciting results
  - A_1 at high-x: valence structure, flavor decomposition, quark OAM
  - Spin sum rules and polarizabilities: test χPT calculations
  - g_2/d_2: higher-twist effects and q-g correlations, *L*QCD
- Bright future
  - Complete a chapter in longitudinal spin structure study
  - Transversity and TMDs: new dimensions
  - Upgrades (12 GeV, large acceptance) greatly enhance our capability
- Together with other world facilities, experiments and theoretical efforts will lead to breakthrough in our understanding of STRONG QCD.

SIDIS Kinematical with the Solenoid (10^o-17^o)

Q^2* vs *x

W* vs *x



P_T* vs *x

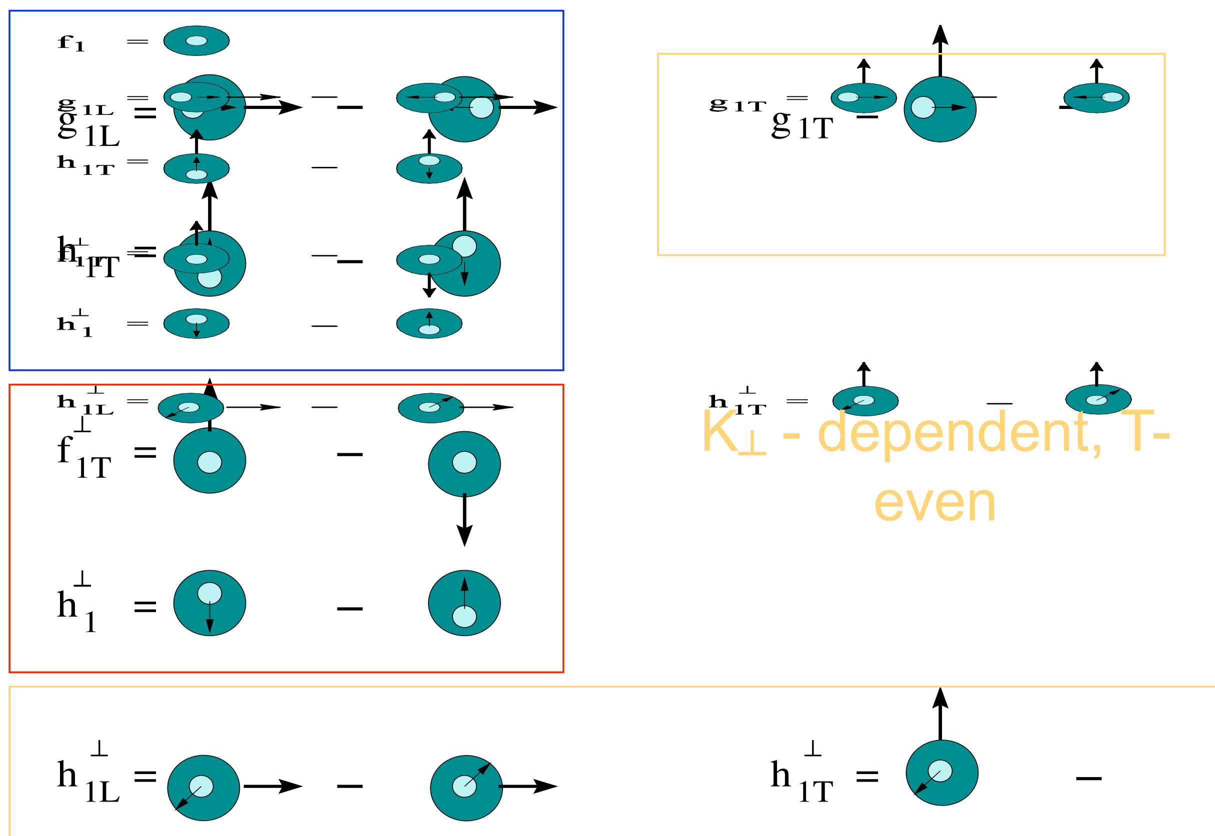
z* vs *x

Leading-Twist Quark Distributions

(A total of eight distributions)

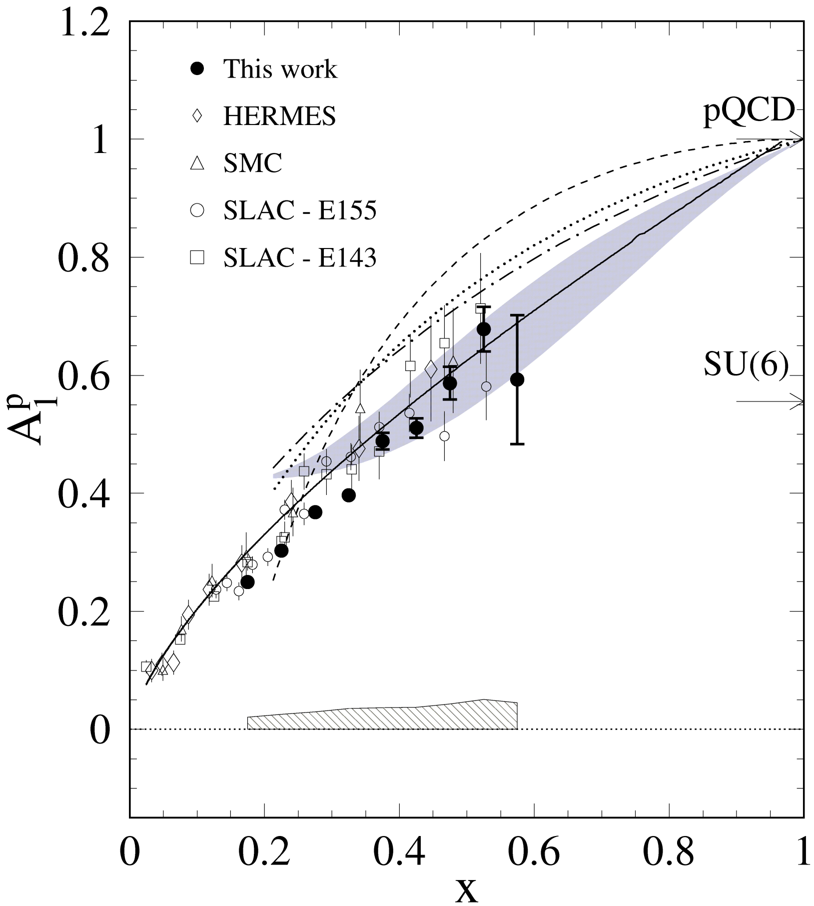
No K⊥ dependence

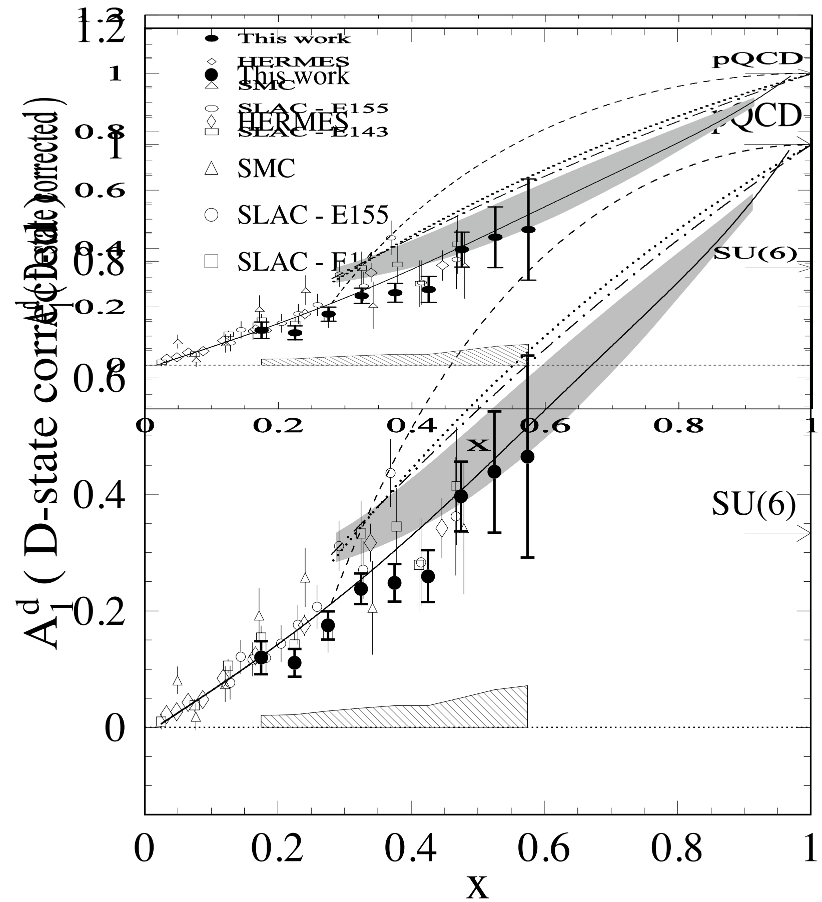
K⊥ - dependent, T-odd



CLAS A_1^p and A_1^d results

CLAS collaboration, Phys.Lett. B641 (2006) 11

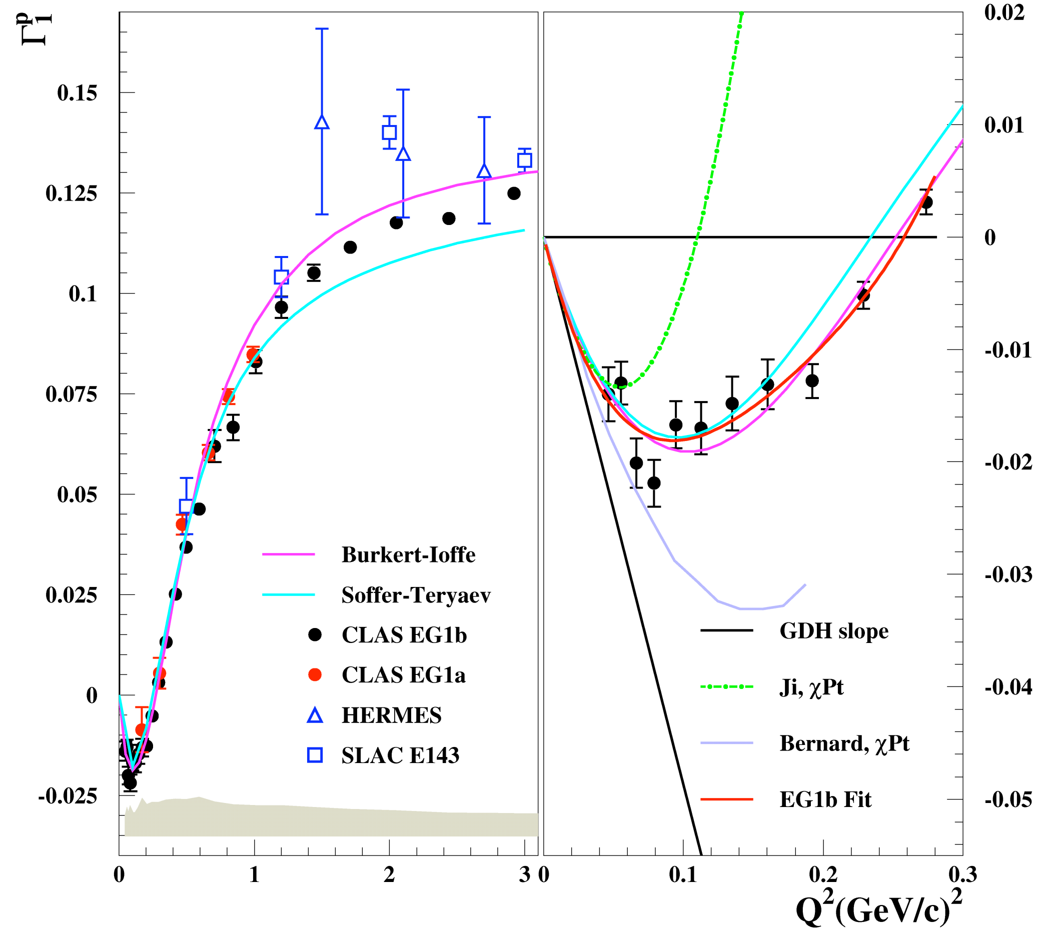




Hall B EG1b Results: Γ_1^p

spokespersons: V. Burkert, D. Crabb, G. Dodge, S. Kuhn, R. Minehart, M. Taiuti

$\Gamma_1{}^p$



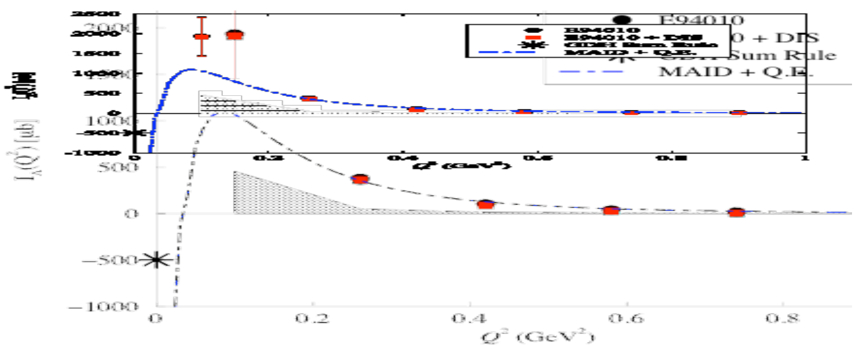
EG1b, Prok *et al.*
arXiv:0802.2232.
EG1a, PRL 91: 222002 (2003)

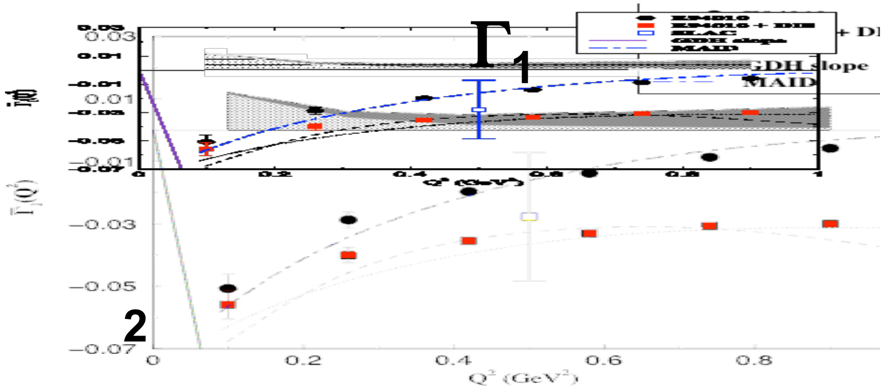
New Hall A ^{3}He Results

- Q^2 evolution of moments of ^{3}He spin structure functions
- Test Chiral Perturbation Theory predictions at low Q^2
- need χPT calculations for ^{3}He

K. Slifer, *et al.*,PRL 101, 022303 (2008)

GDH integral I_A





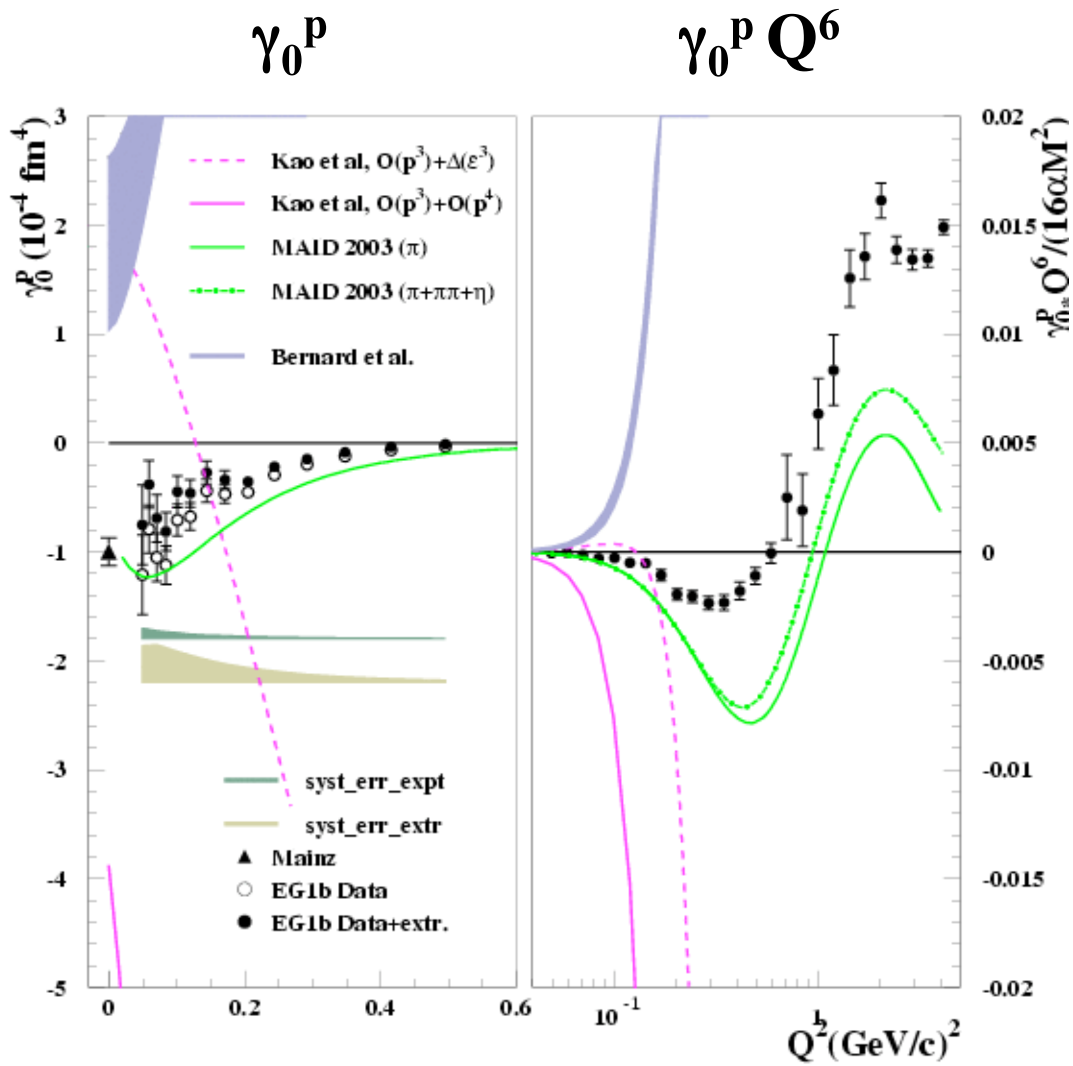
CLAS Proton Spin Polarizability

- EG1b, Prok *et al.* *arXiv:0802.2232*

Large discrepancies with ChPT!

Only longitudinal data, model for transverse (g_2)

γ_0 sensitive to resonance



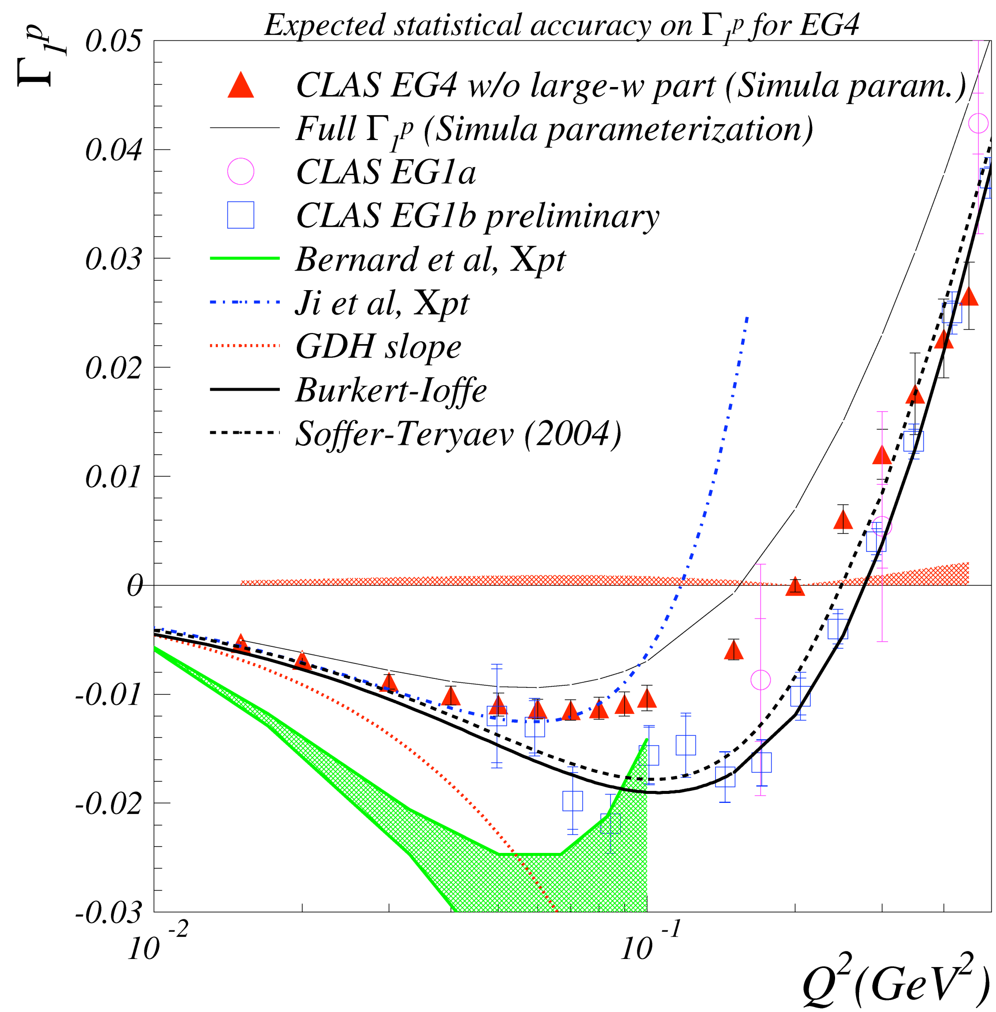
Hall B EG4 Projected Results

Spokespersons: M. Battaglieri, R. De Vita, A. Deur, M. Ripani

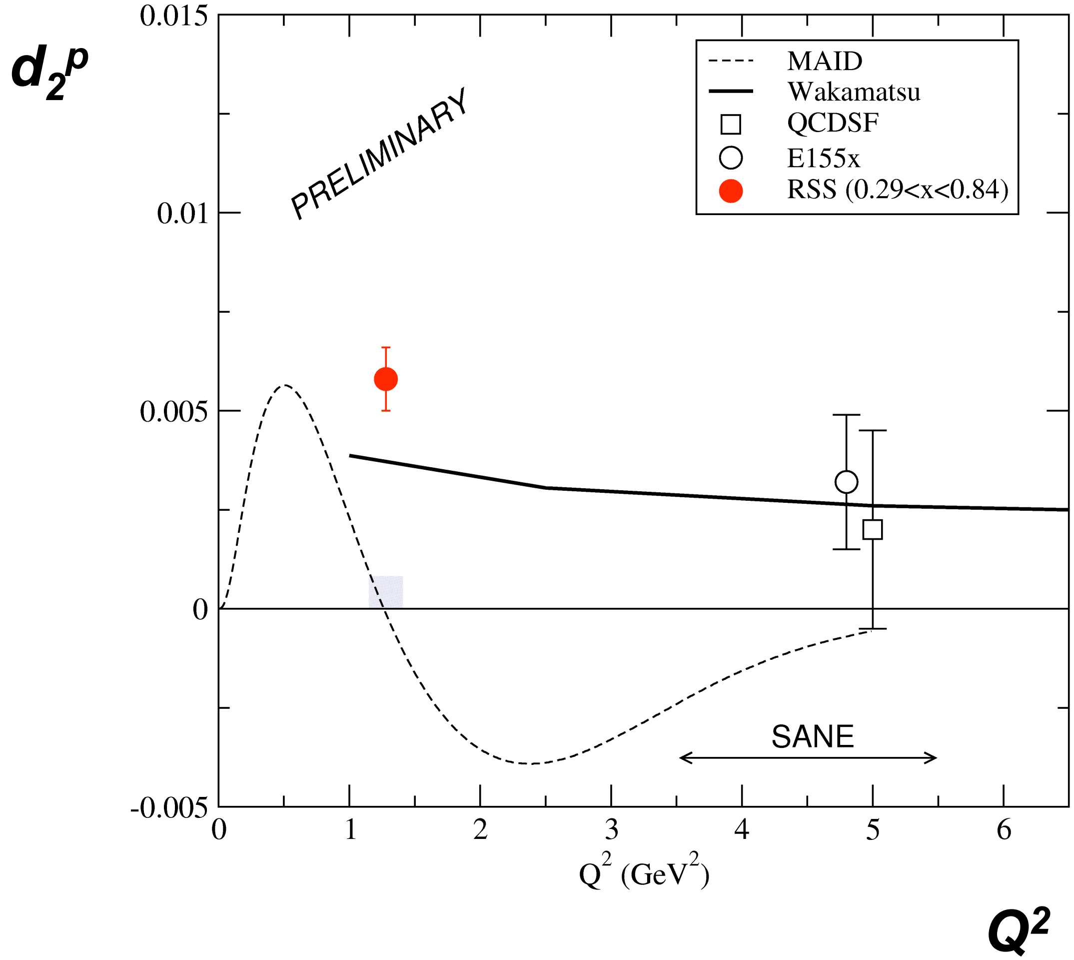
- Extend to very low Q^2 of 0.015 GeV^2
- Longitudinal polarization

→ g_1^p, g_1^d

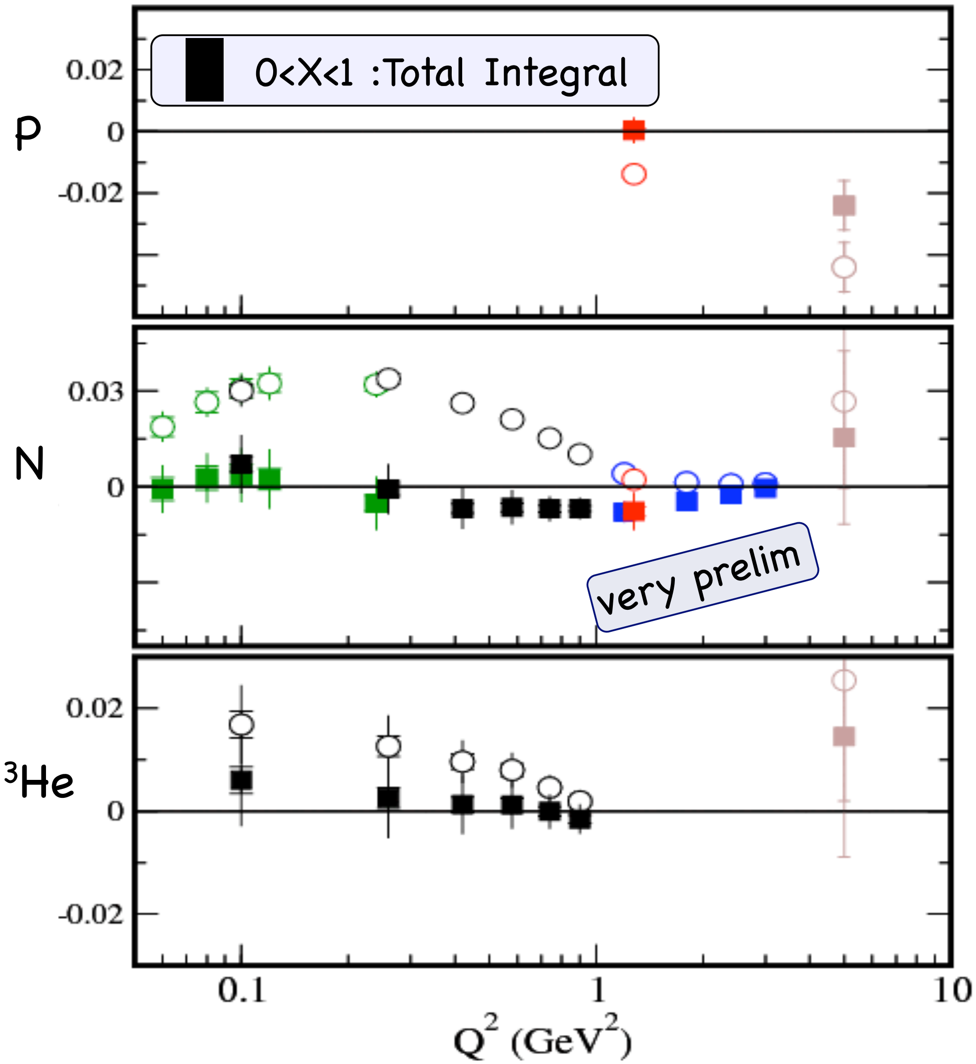
- Data taking in 2006
- Analysis progress well



Measurement on proton: d_2^p (Hall C and SLAC) RSS and SANE: O. Rondon *et al.*



BC Sum Rule



$$\Gamma_2 = \int_0^1 g_2(x)dx = 0$$

Brawn: SLAC E155x
Red: Hall C RSS
Black: Hall A E94-010
Green: Hall A E97-110 (very preliminary)
Blue: Hall A E01-012 (very preliminary)

<u>BC = Meas+low_x+Elastic</u>

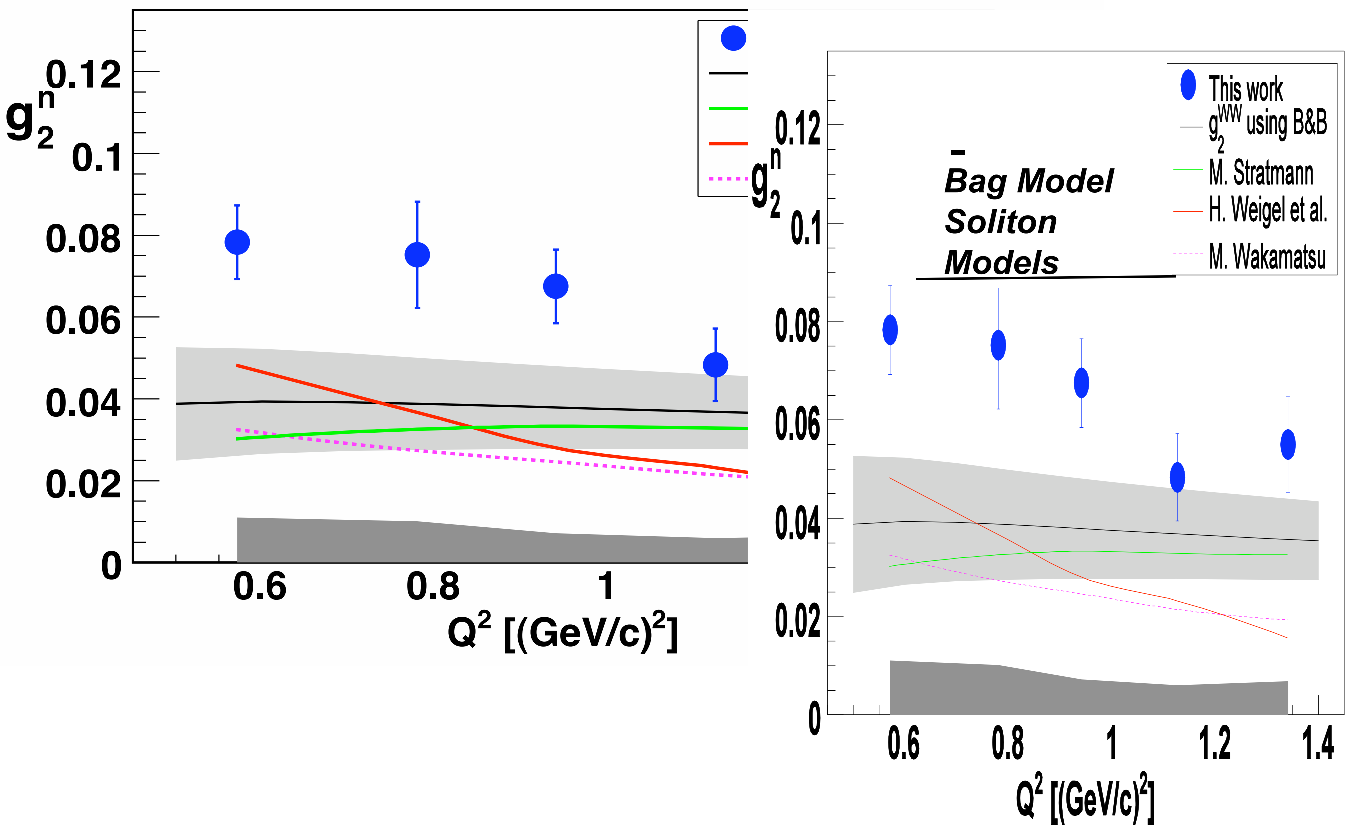
"Meas": Measured x-range

"low-x": refers to unmeasured low x part of the integral.
Assume Leading Twist Behaviour

Elastic: From well know FFs (<5%)

E97-103 results: g_2^n vs. Q^2

- measured g_2^n consistently higher than g_2^{ww}: positive twist-3
- higher twist effects significant below Q^2=1 GeV^2
- Models (color curves) predict small or negative twist-3



Gerasimov-Drell-Hearn Sum Rule

Circularly polarized photon on longitudinally polarized nucleon

$$\int_{\nu_{in}}^{\infty} \left(\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)\right)\frac{d\nu}{\nu} = -\frac{2\pi^2\alpha_{EM}}{M^2}\kappa^2$$

- A fundamental relation between the nucleon spin structure and its anomalous magnetic moment

- Based on general physics principles
  - Lorentz invariance, gauge invariance → low energy theorem
  - unitarity → optical theorem
  - casuality → unsubtracted dispersion relation applied to forward Compton amplitude

- First measurement on *proton* up to 800 MeV (Mainz) and up to 3 GeV (Bonn) agree with GDH with assumptions for contributions from un-measured regions

Generalized GDH Sum Rule

- Many approaches: Anselmino, Ioffe, Burkert, Drechsel, …

- Ji and Osborne:

  Forward Virtual-Virtual Compton Scattering Amplitudes: $S_1(Q^2,\nu)$, $S_2(Q^2, \nu)$

  (or alternatively, $g_{TT}(Q^2,\nu)$, $g_{LT}(Q^2,\nu)$)

  Same assumptions: no-subtraction dispersion relation

  optical theorem

  (low energy theorem)

- Generalized GDH Sum Rule

$$S_1(Q^2,v) = 4\int_{el}^{\infty}\frac{G_1(Q^2,v')v'\,dv'}{v'^2-v^2}$$

For v=0

$$S_1(Q^2) = 4\int_{el}^{\infty}\frac{G_1(Q^2,v)dv}{v}$$

δ_{LT} Puzzle

- Possible reasons for δ_{LT} puzzle: discussions with theorists

  Consensus: A real challenge to (χPT) theorists!

  Speculations: Short range effects beyond πN?

  t-channel axial vector meson exchange?

  Isoscalar in nature?

  An effect of QCD vacuum structure?

- To help solve the puzzle and to understand the nature of the problem, more information needed, including isospin separation

  → need measurement on proton

  Does the δ_{LT} discrepancy also exists for proton?

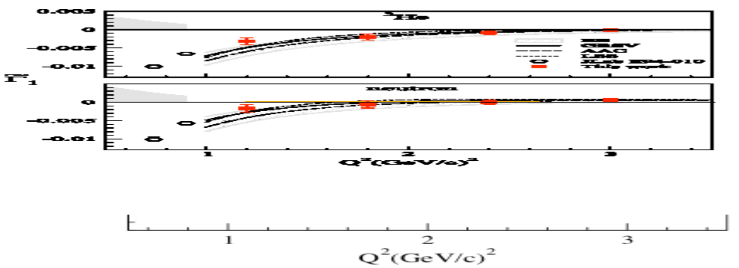
  E08-027 approved to measure g_2^p and δ_{LT} on proton

Duality in Spin-Structure: Hall A E01-012 Results

Spokesperson: **N. Liyanage, J. P. Chen, S. Choi;** PhD Student: **P. Solvignon**

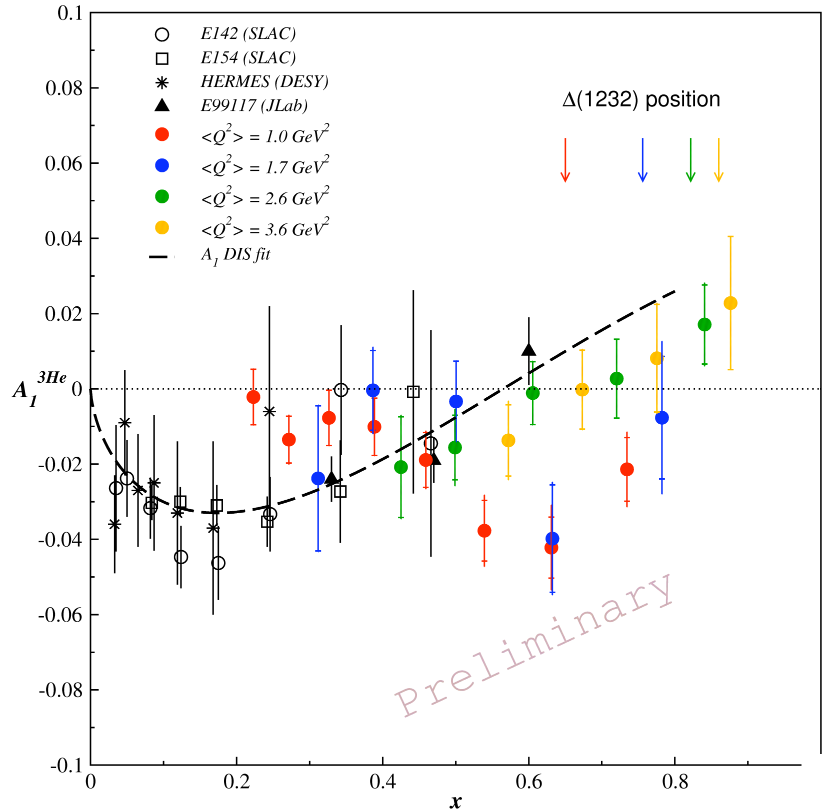
- g_1/g_2 and A_1/A_2 ($^3He/n$) in resonance region, $1 < Q^2 < 4$ GeV^2
- Study quark-hadron duality in spin structure.
- PRL 101, 1825 02 (2008)

Γ_1 resonance vs. pdfs



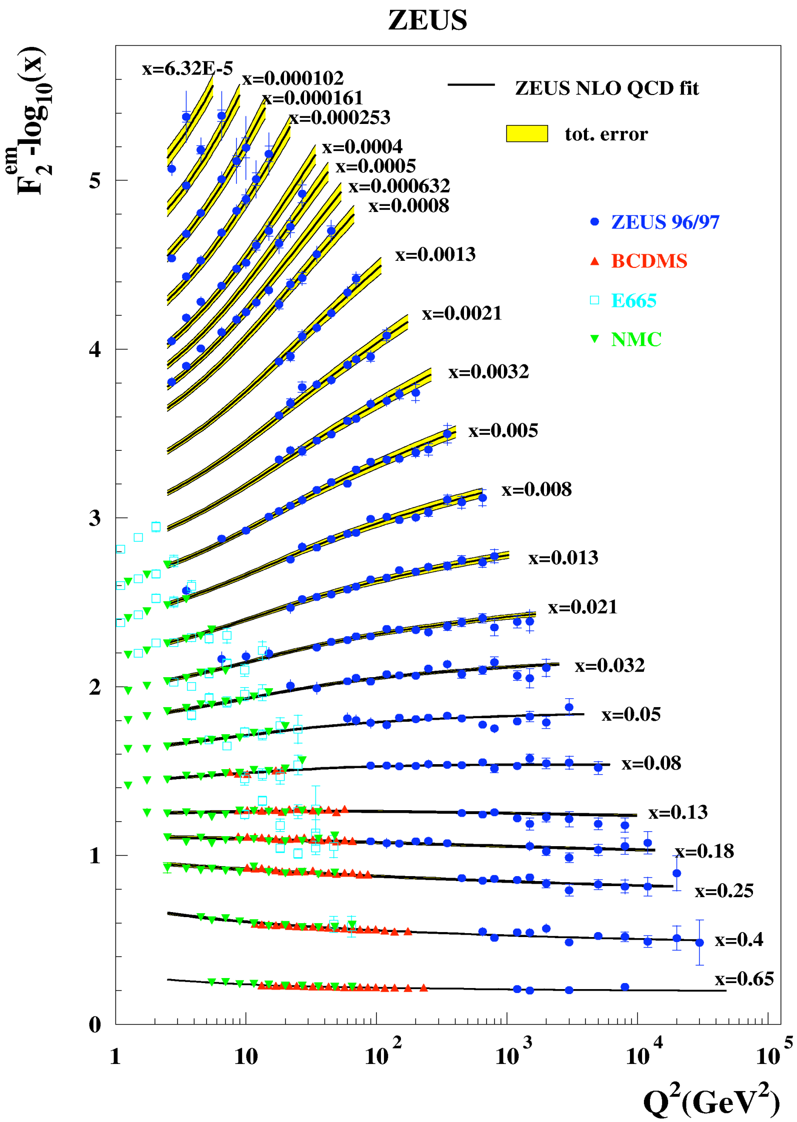
Q²

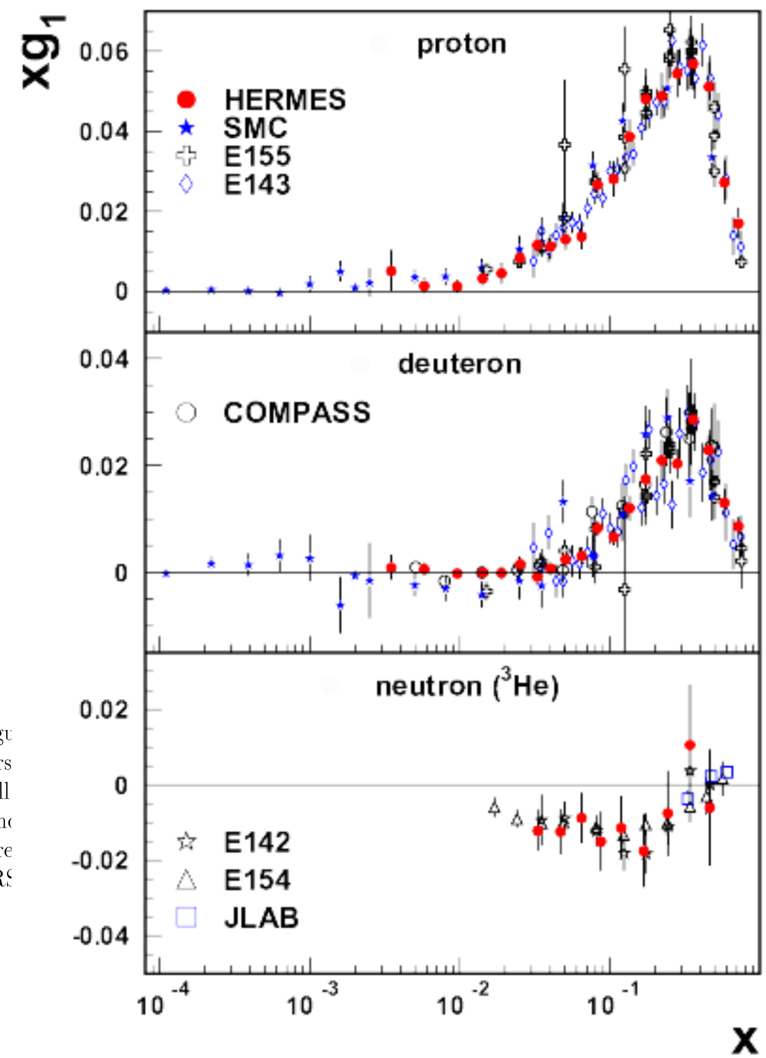
A_1^{3He} (resonance vs DIS)



x

Unpolarized and Polarized Structure functions





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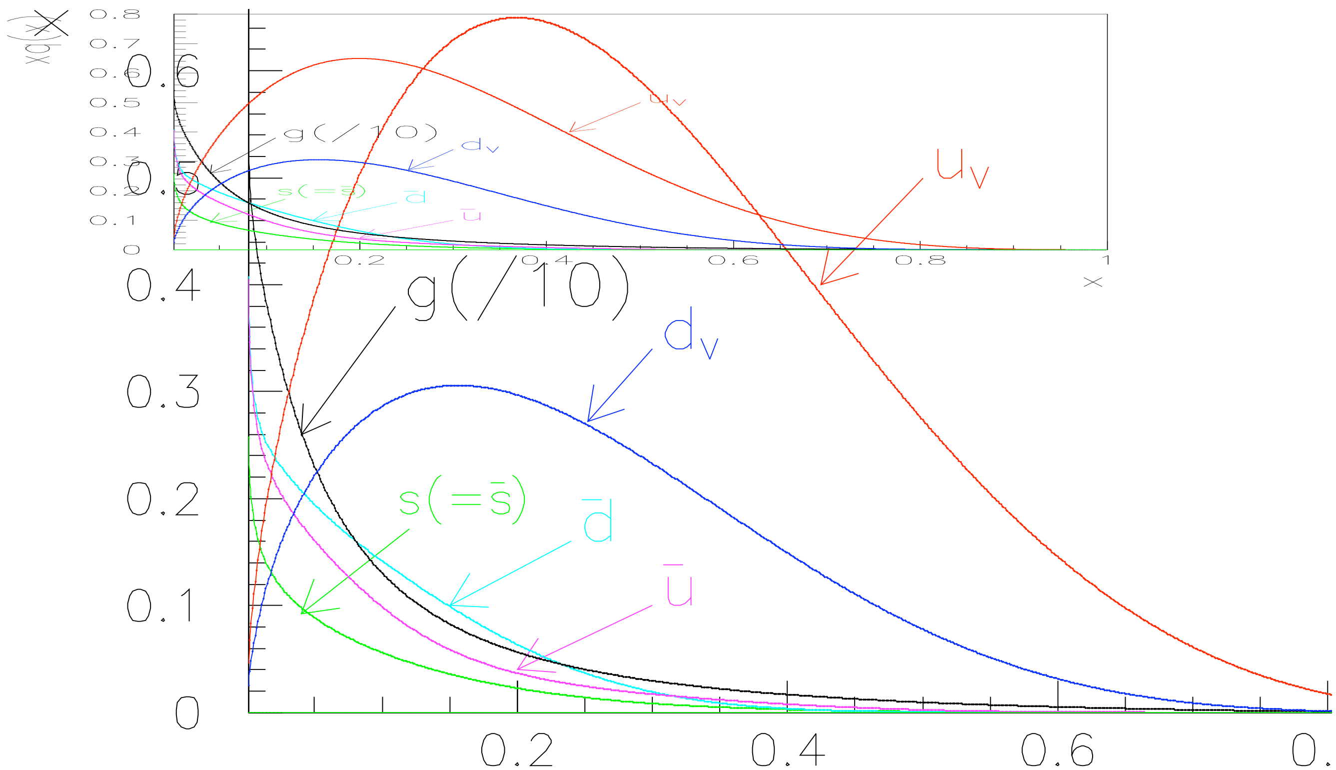
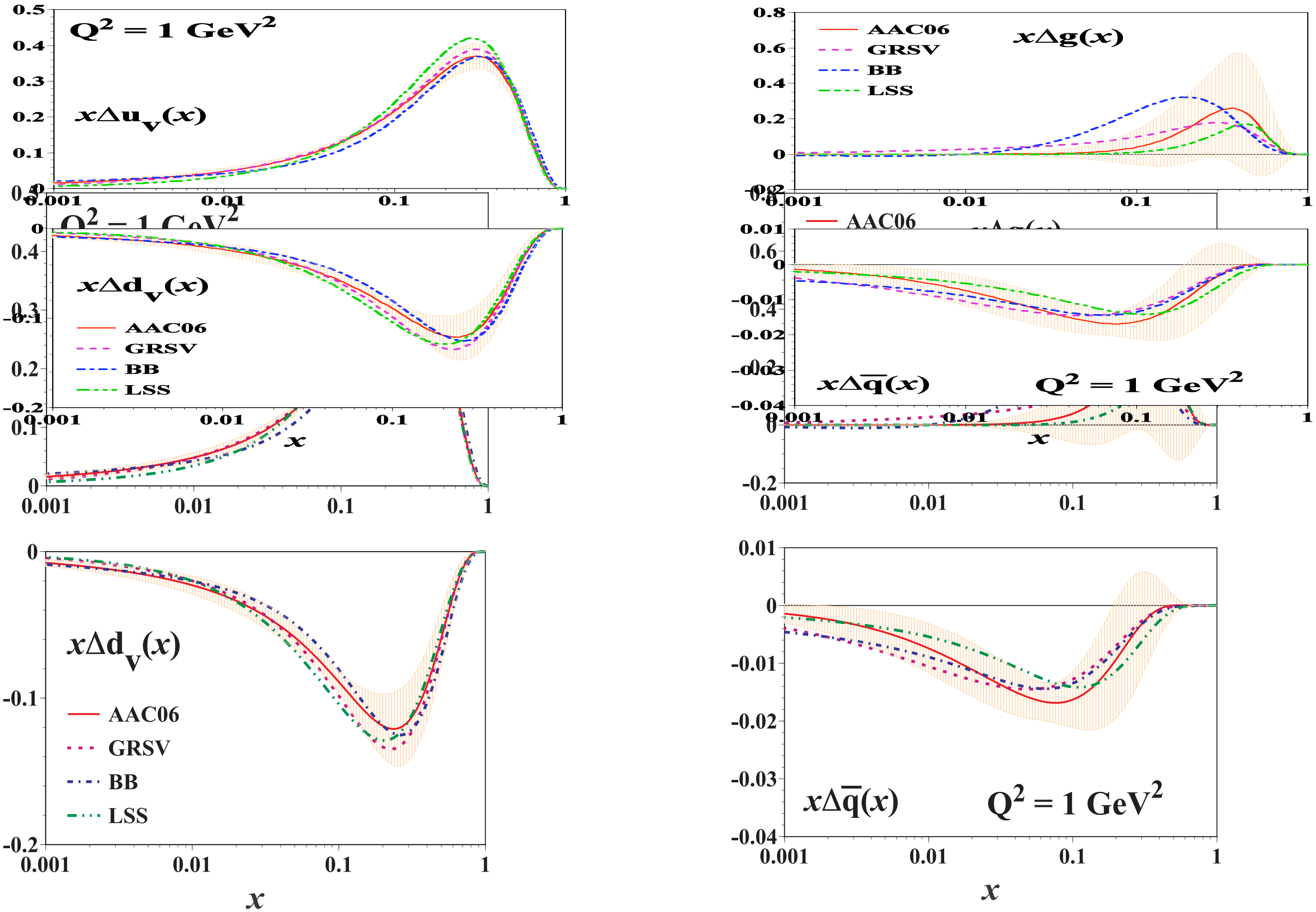
Unpolarized Parton Distributions (CTEQ6)

- After 40 years DIS experiments, unpolarized structure of the nucleon reasonably well understood.
- High *x* → valence quark dominating



NLO Polarized Parton Distributions (AAC06)



Transversity Distributions

A global fit to the HERMES p, COMPASS d and BELLE e+e- data by the Torino group (Anselmino *et al.).*

Need neutron data.