Nucleon Spin: Results and Challenges on both Longitudinal and Transverse Spin

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Seminar @ Los Alamos, February 19, 2009

- Introduction
- Highlights on JLab Longitudinal Spin Program:
  - Spin Sum Rules and Polarizabilities
  - Higher Twists: g_2/d_2
  - Quark-Hadron Duality
  - Spin Structure at High *x*: Valence Quark Distributions
- 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

  confinement

  spin and angular momentum

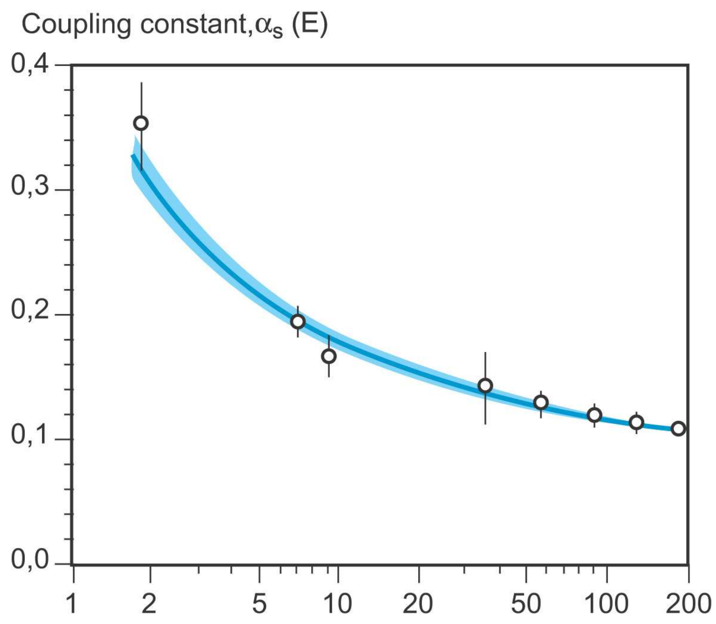
QCD and Nucleon Structure

- **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
  -- Chiral symmetry
  -- theoretical tools:
  pQCD, OPE, Lattice QCD, ChPT, …

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

- **Spin Structure Study:**
  -- study QCD and nucleon structure
  -- very rich program: 'crises' and 'puzzles'

α_s



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Nucleon Structure

- Nucleon: proton =(uud) and 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,)

- Sum rules: relate global property to integral of structure information

Spin and Magnetic Moment (of electron)

- 1921 Otto Stern and Walther Gerlach

  Ag molecular-beam passing through inhomogeneous magnetic field split into two beams

  - Ag atom has a magnetic moment

    Bohr magneton of the electron: $\mu_e = e\hbar/2m_e c$

- 1925 Uhlenbeck and Goudsmit
  - spin: internal property, like angular momentum

    electron spin $S_e = 1/2$ → two eigenstates +- 1/2

- Dirac:
  - relativistic effect: spin ←→ magnetic moment

- electron is point-like particle (no internal structure observed so far)

Anomalous Magnetic Moment (of Proton)

- 1933 Otto Stern

  Magnetic moment of the proton

  -- expected: $\mu_p = e\hbar/2m_p c$ (since $S_p = 1/2$)

  -- measured: $\mu_p = e\hbar/2m_p c(1+\kappa_p)$! first 'spin crisis'

  anomalous magnetic moment (a.m.m) $\kappa_p = 1.5 \pm 10\%$

- 1943 Nobel Prize awarded to Stern

  for 'development of the molecular beam method' and 'the discovery of the magnetic moment of protons'

  now: $\kappa_p = 1.792847386 \pm 0.000000063$

  and $\kappa_n = -1.91304275 \pm 0.00000045$

A.M.M and Its Implications

Anomalous magnetic moment is an evidence for an internal structure

→ finite size

- Finite size → Form factors

  Dirac form factor: normal relativistic effect

  Pauli form factor: relate to a.m.m. part

- Finite size ← → Excitation spectrum

- GDH Sum Rule

  relates a.m.m. to integral of excitation spectrum

A.M.M < -- > related to GPDs, TMDs (quark orbital angular momentum)

‘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)

  $\Delta\Sigma = 20\text{–}30\%$

  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

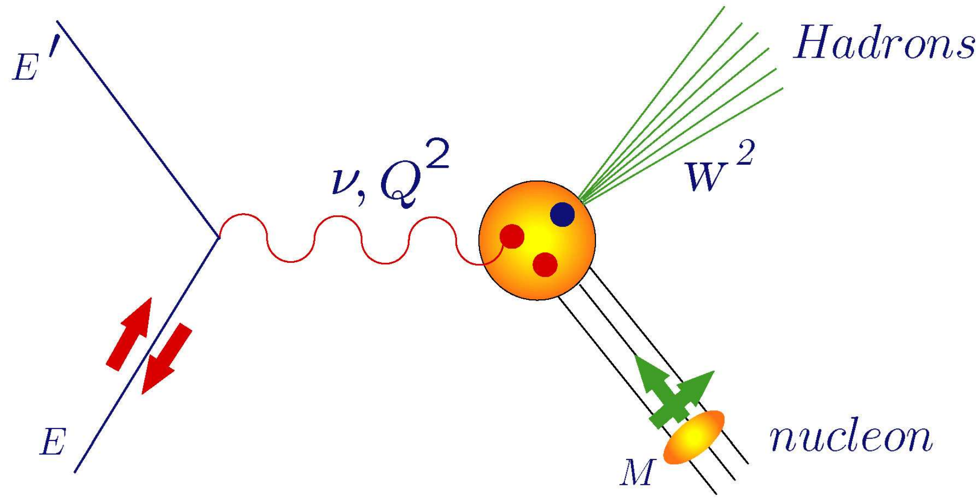
- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, … :

  $\Delta\Sigma \sim 30\%$; 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

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

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

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

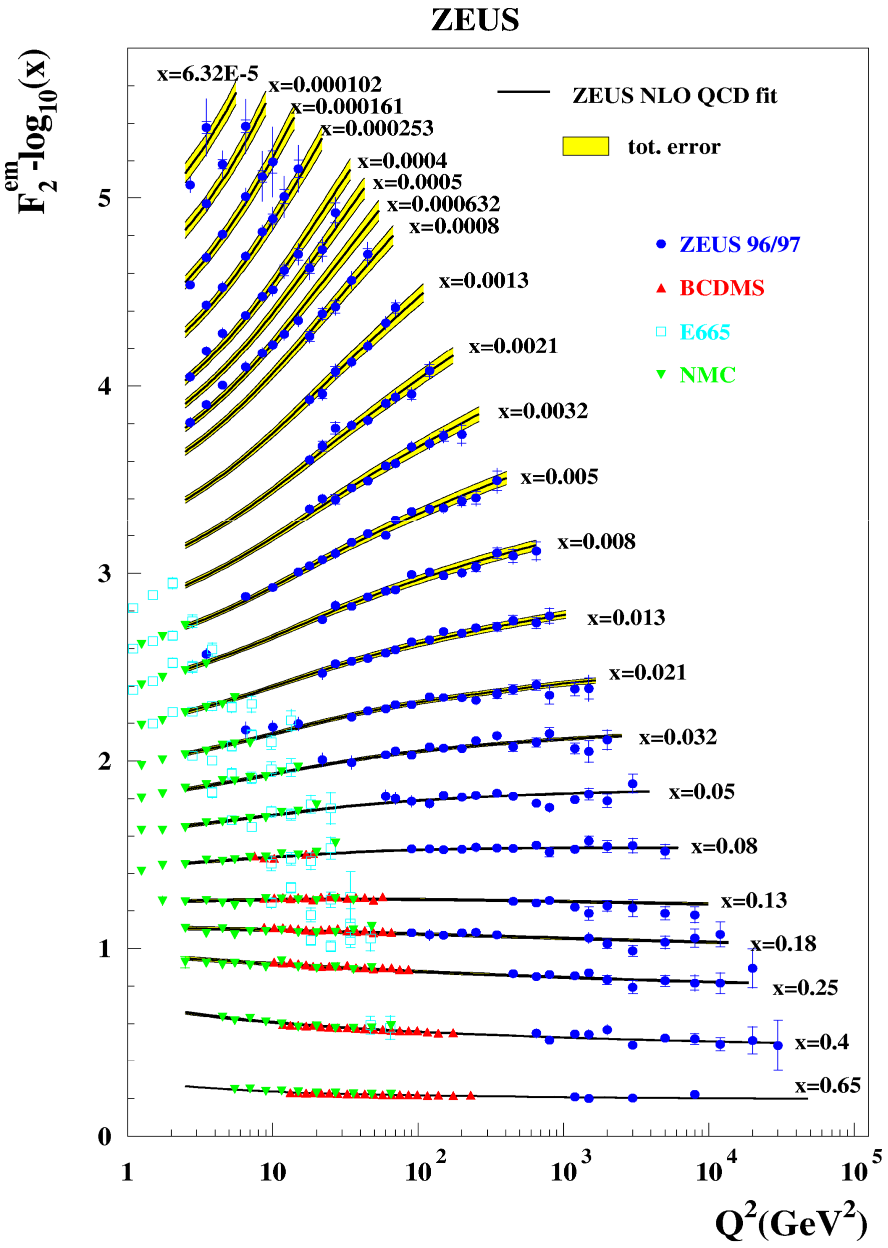
$q_i(x)$ quark momentum distributions of flavor i

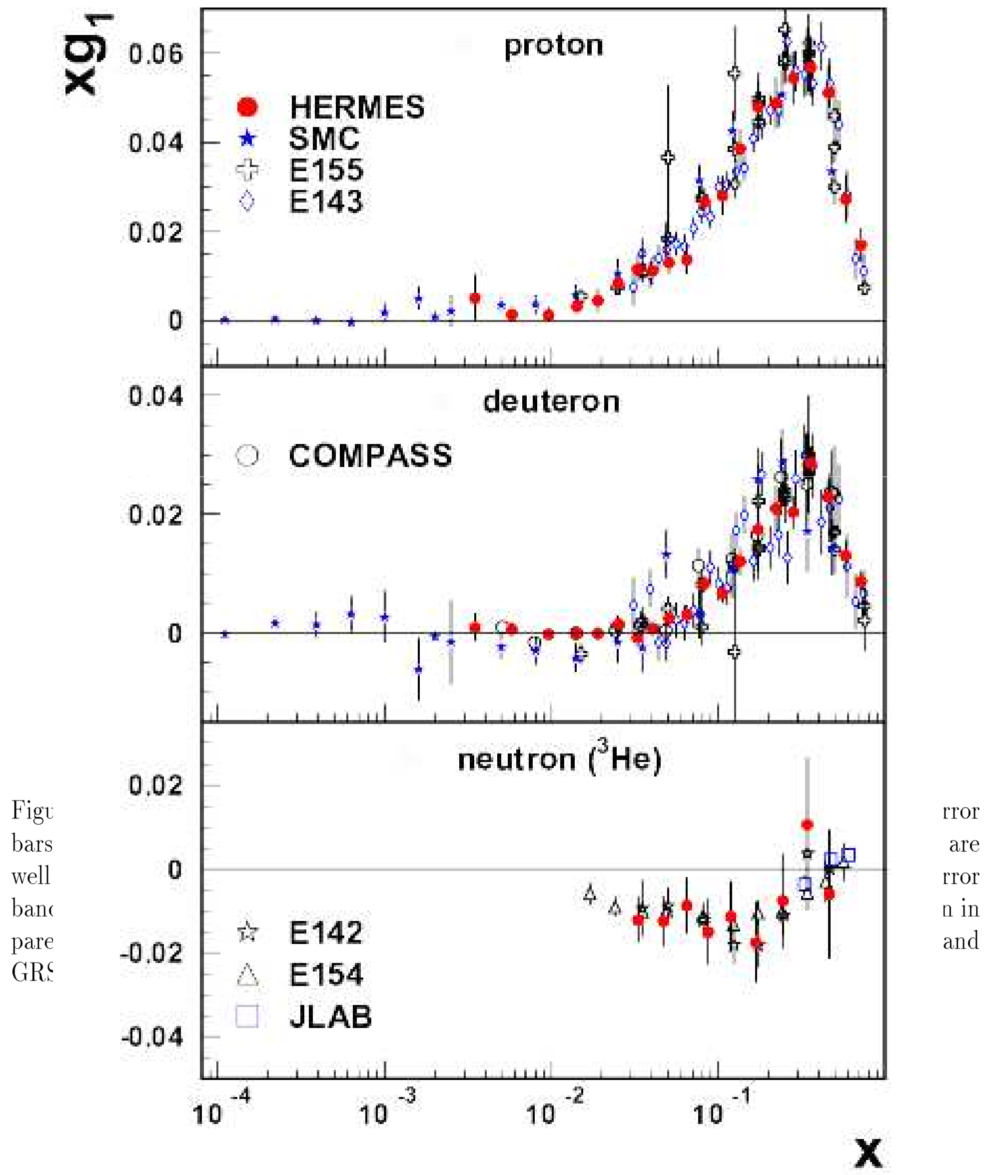
$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

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

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

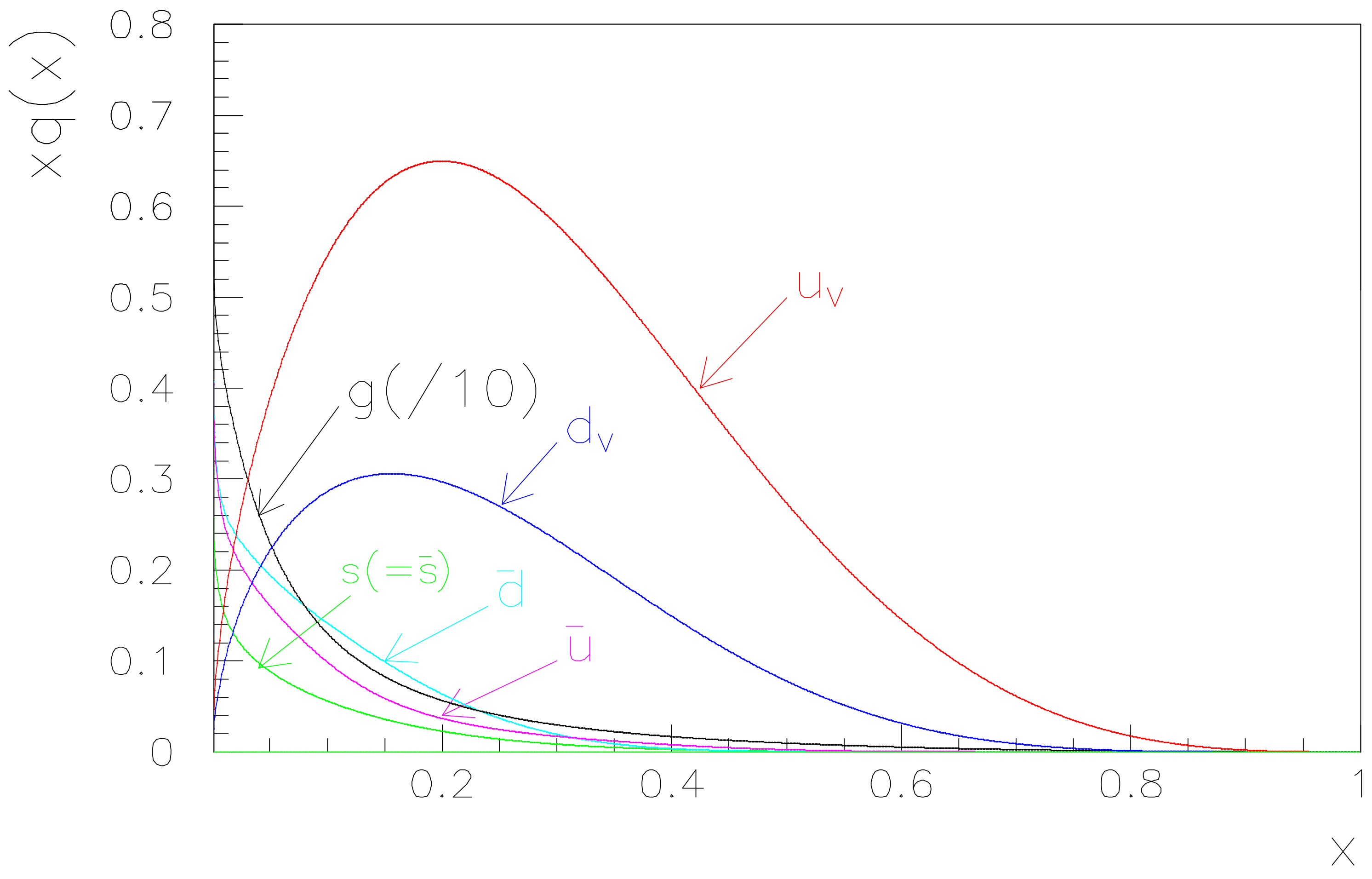
Unpolarized and Polarized Structure functions



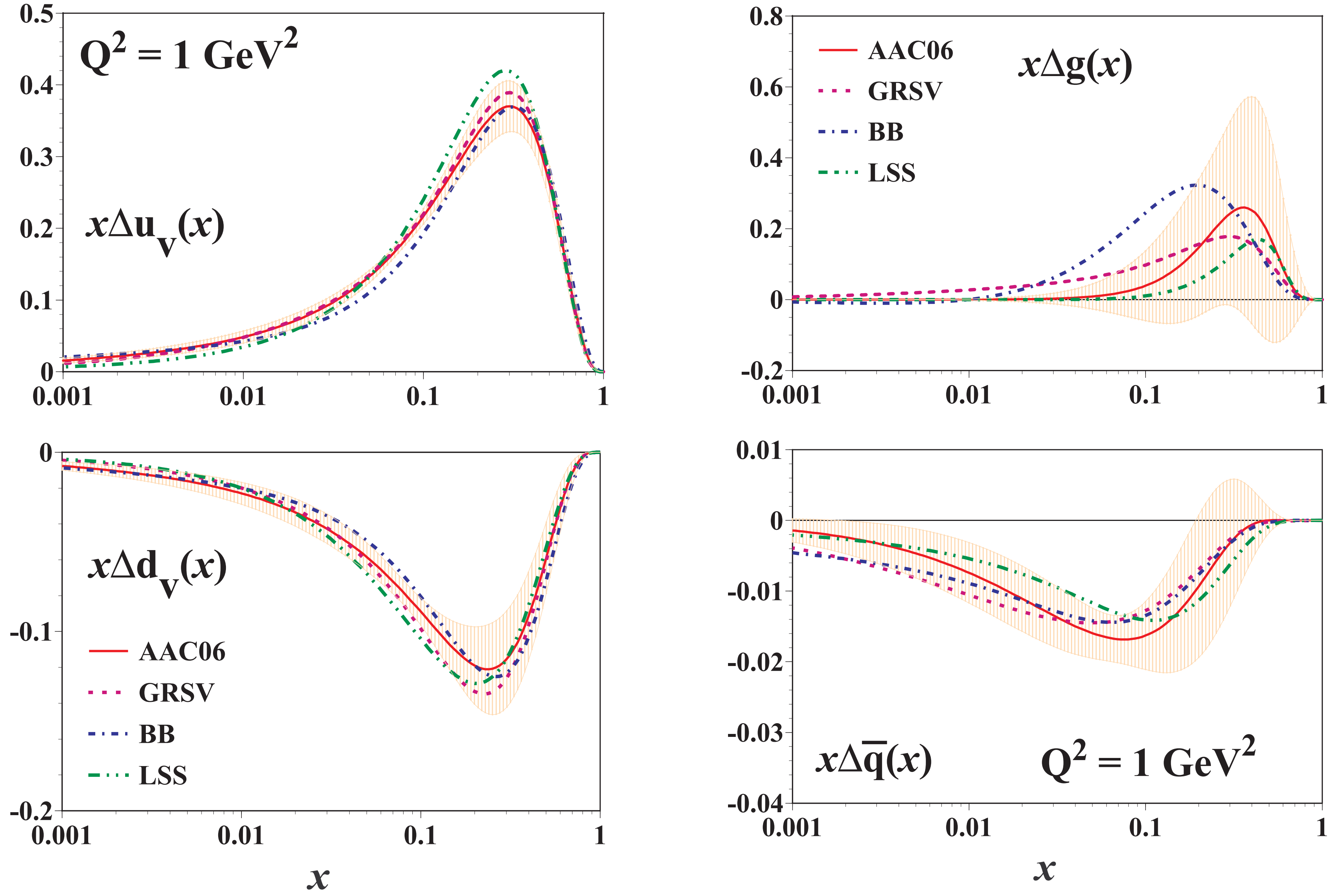


Unpolarized Parton Distributions (CTEQ6)

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

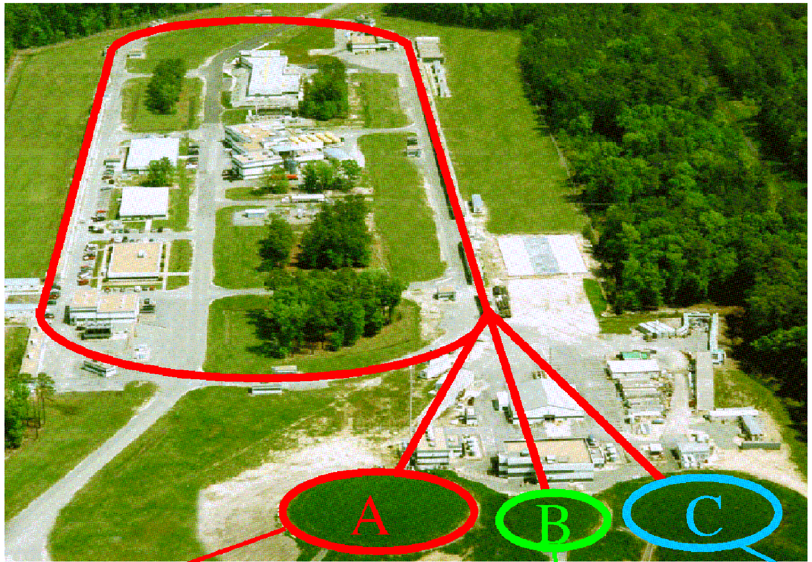


NLO Polarized Parton Distributions (AAC06)

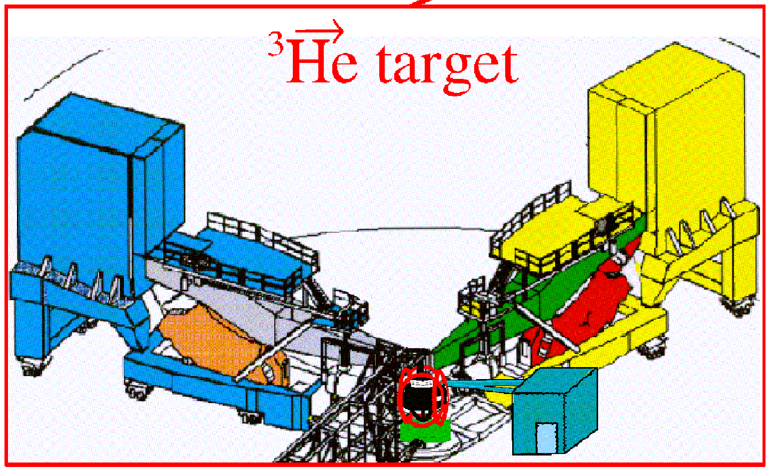


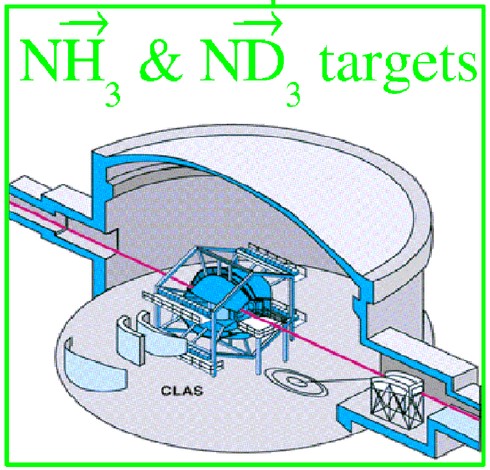
Jefferson Lab Experimental Halls

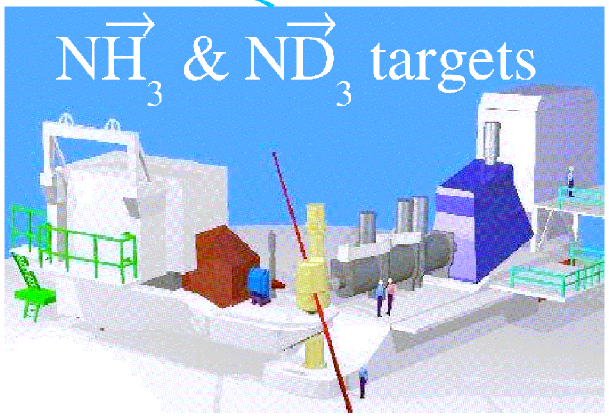
6 GeV polarized
CW electron beam
Pol=85%, 180μA



Will be upgraded to
12 GeV by ~2014

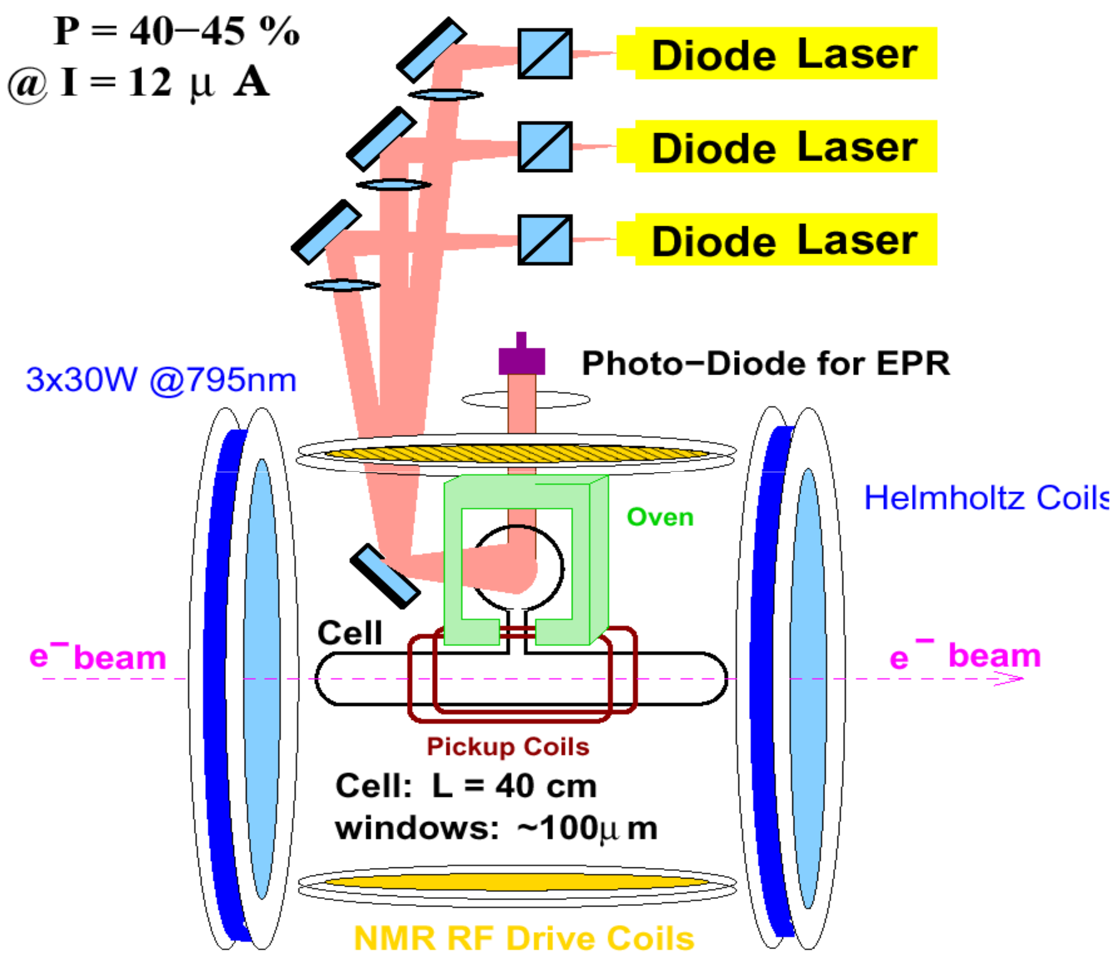






HallA: two HRS' **Hall B:CLAS** **Hall C: HMS+SOS**

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

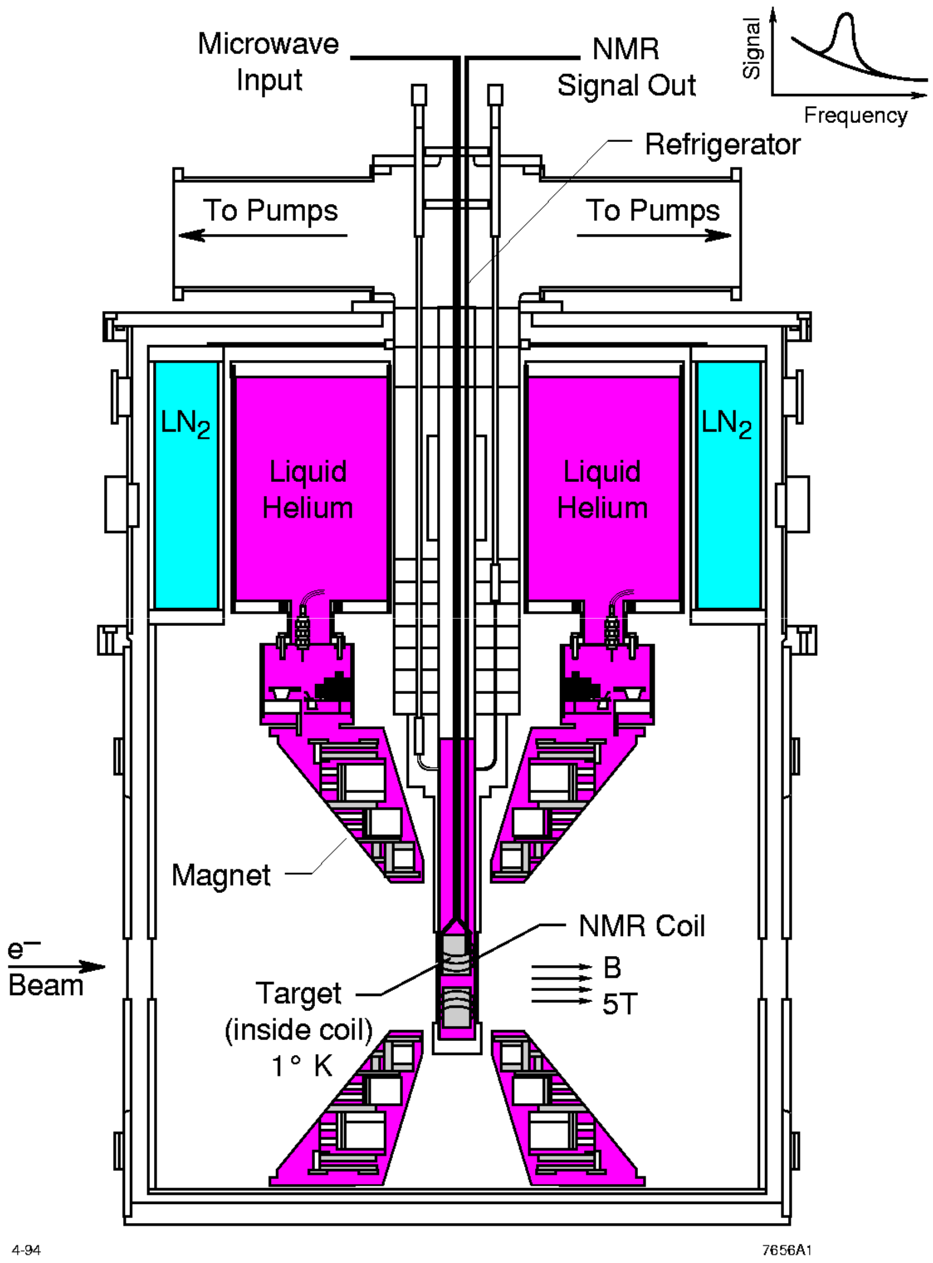
- Polarized NH_3/ND_3 targets
- Dynamical Nuclear Polarization

- 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

Spin Sum Rules and Polarizabilities

Moments of Spin Structure Functions

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

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

For v=0

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

Connecting GDH with Bjorken Sum Rules

- Q^2-evolution of GDH Sum Rule provides a bridge linking strong QCD to pQCD
  - Bjorken and GDH sum rules are two limiting cases

    High Q^2, Operator Product Expansion : $S_1(p\text{-}n) \sim g_A$ → Bjorken

    $Q^2 \to 0$, Low Energy Theorem: $S_1 \sim \kappa^2$ → GDH

  - High Q^2 (> ~1 GeV^2): Operator Product Expansion
  - Intermediate Q^2 region: Lattice QCD calculations
  - Low Q2 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

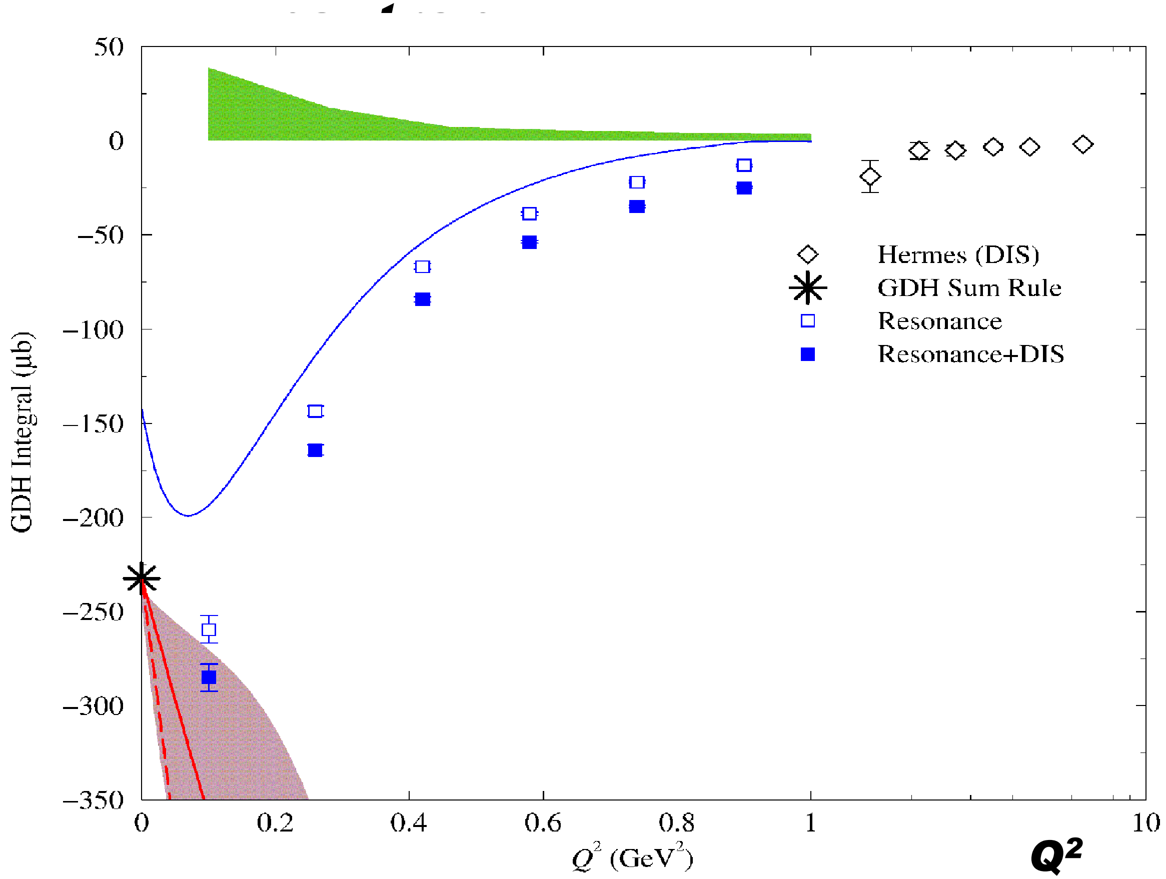
Spokespersons: G. Cates, J. P. Chen, Z.-E. Meziani

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



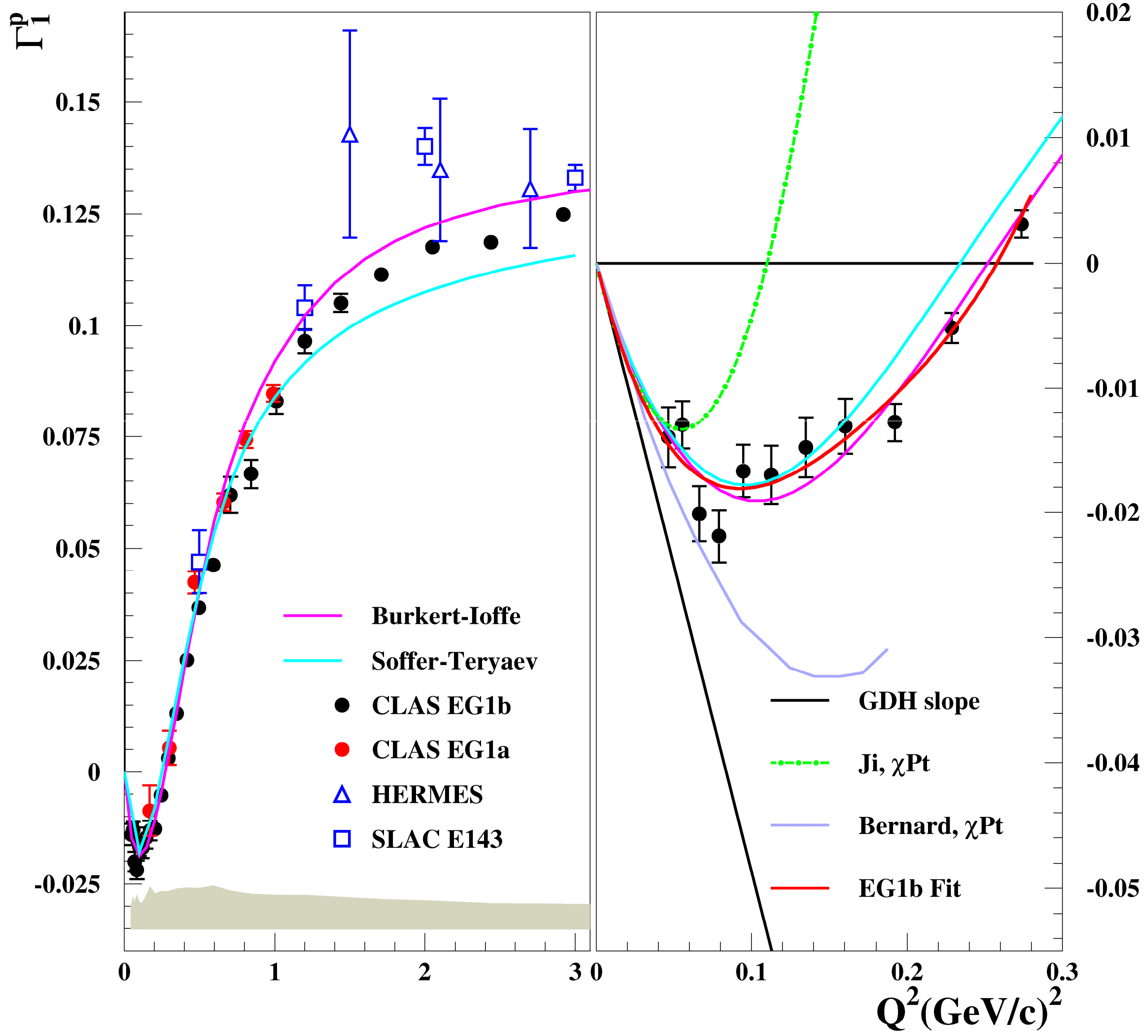
Q²

PRL 89 (2002) 242301

New Hall B EG1b Results: Γ_1^p

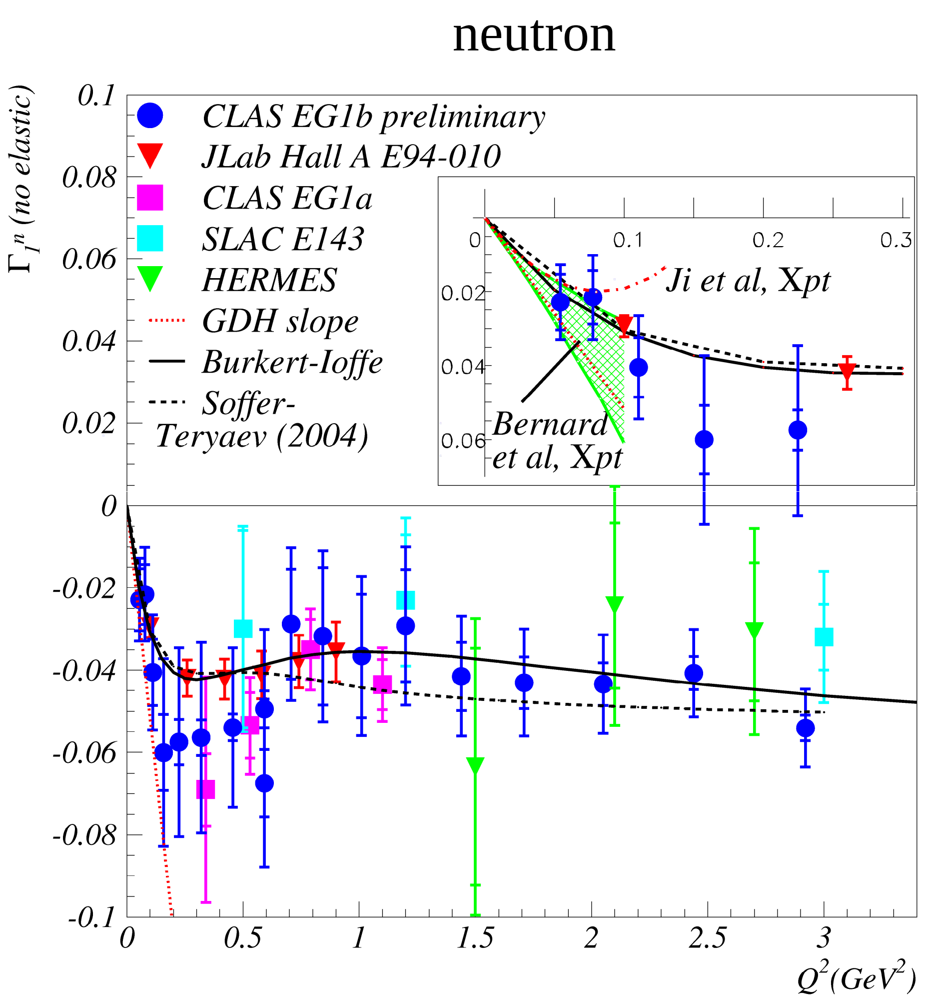
spokespersons: V. Burkert, D. Crabb, G. Dodge, S. Kuhn, R. Minehart, M. Taiuti

$\Gamma_1{}^p$

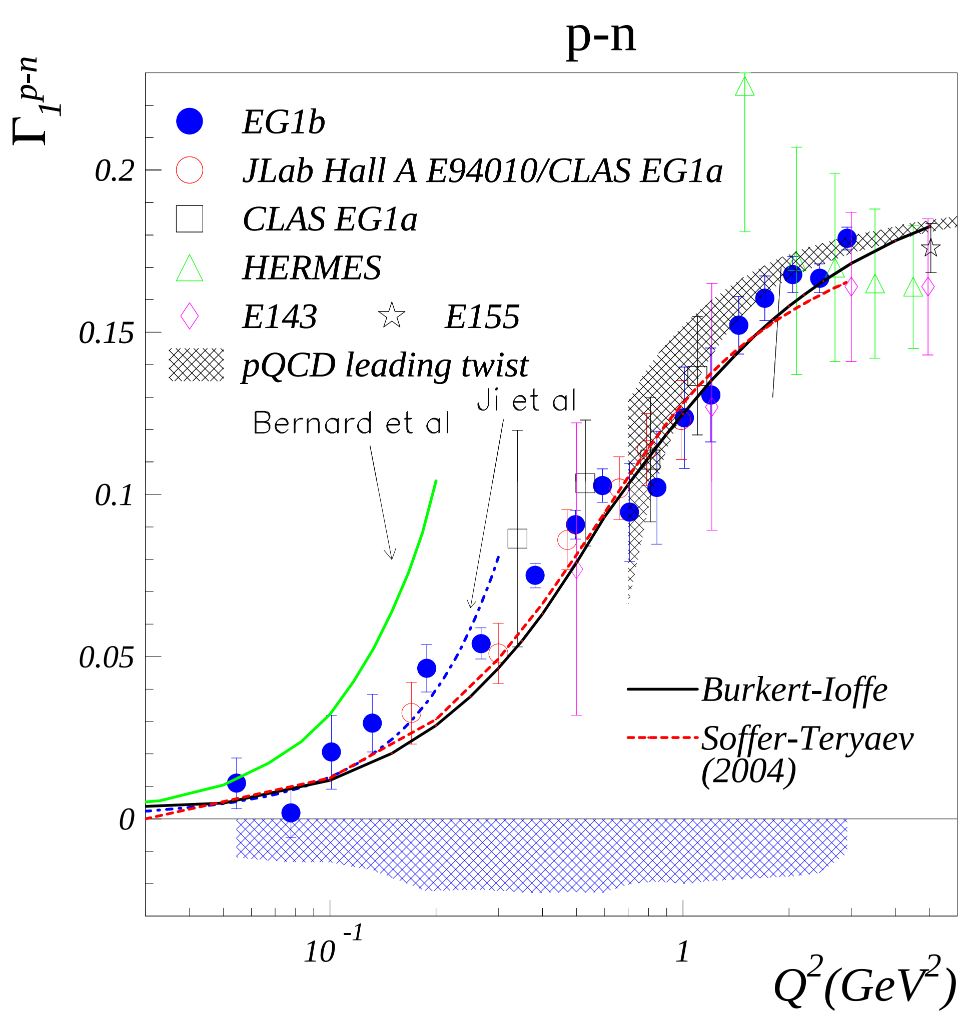


EG1b, Prok *et al.*
arXiv:0802.2232.
EG1a, PRL 91: 222002 (2003)

Γ_1 of neutron and p-n



EG1b (2008)
E94-010: PRL 92 (2004) 022301



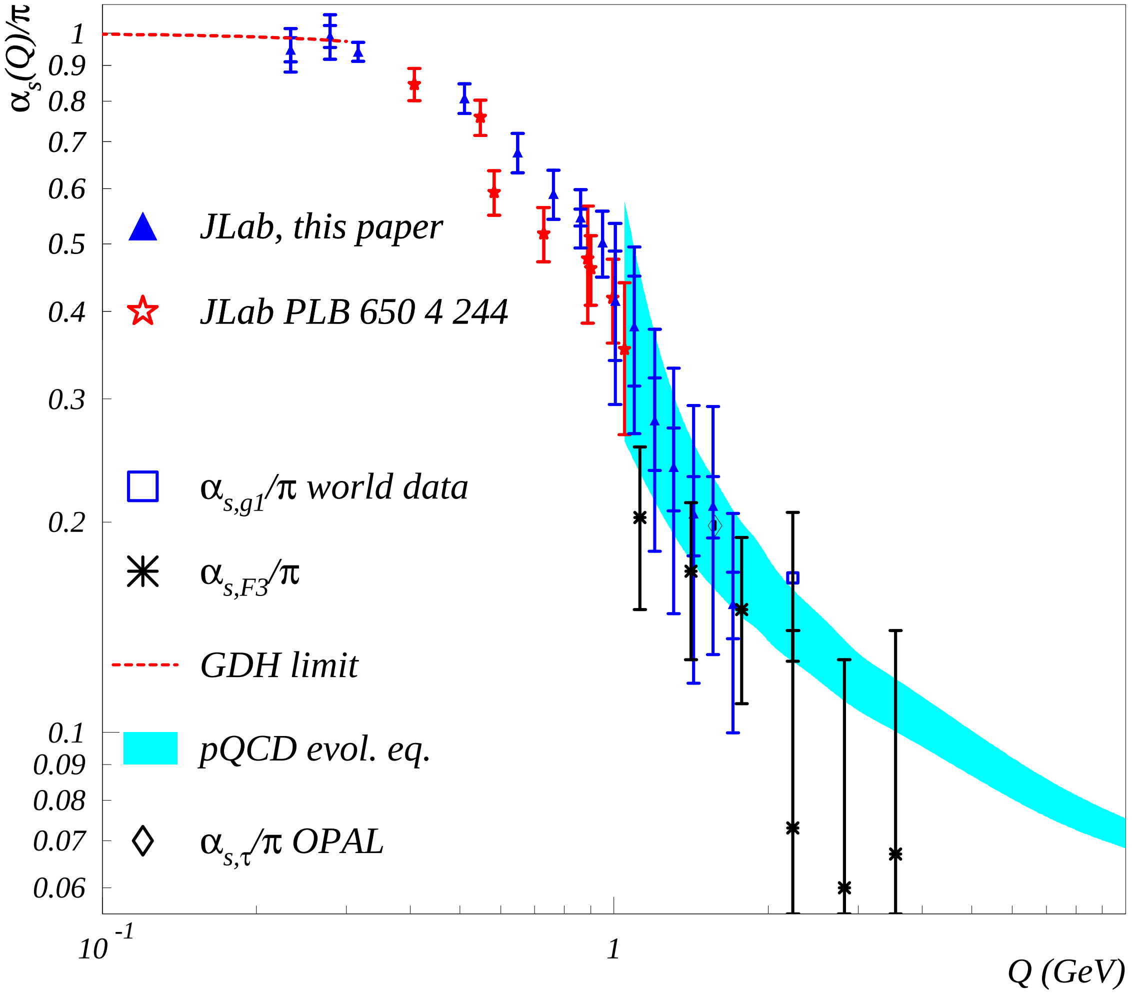
EG1b, PRD 78, 032001 (2008)
E94-010 + EG1a: PRL 93 (2004) 212001

Effective Coupling extracted from Bjorken Sum

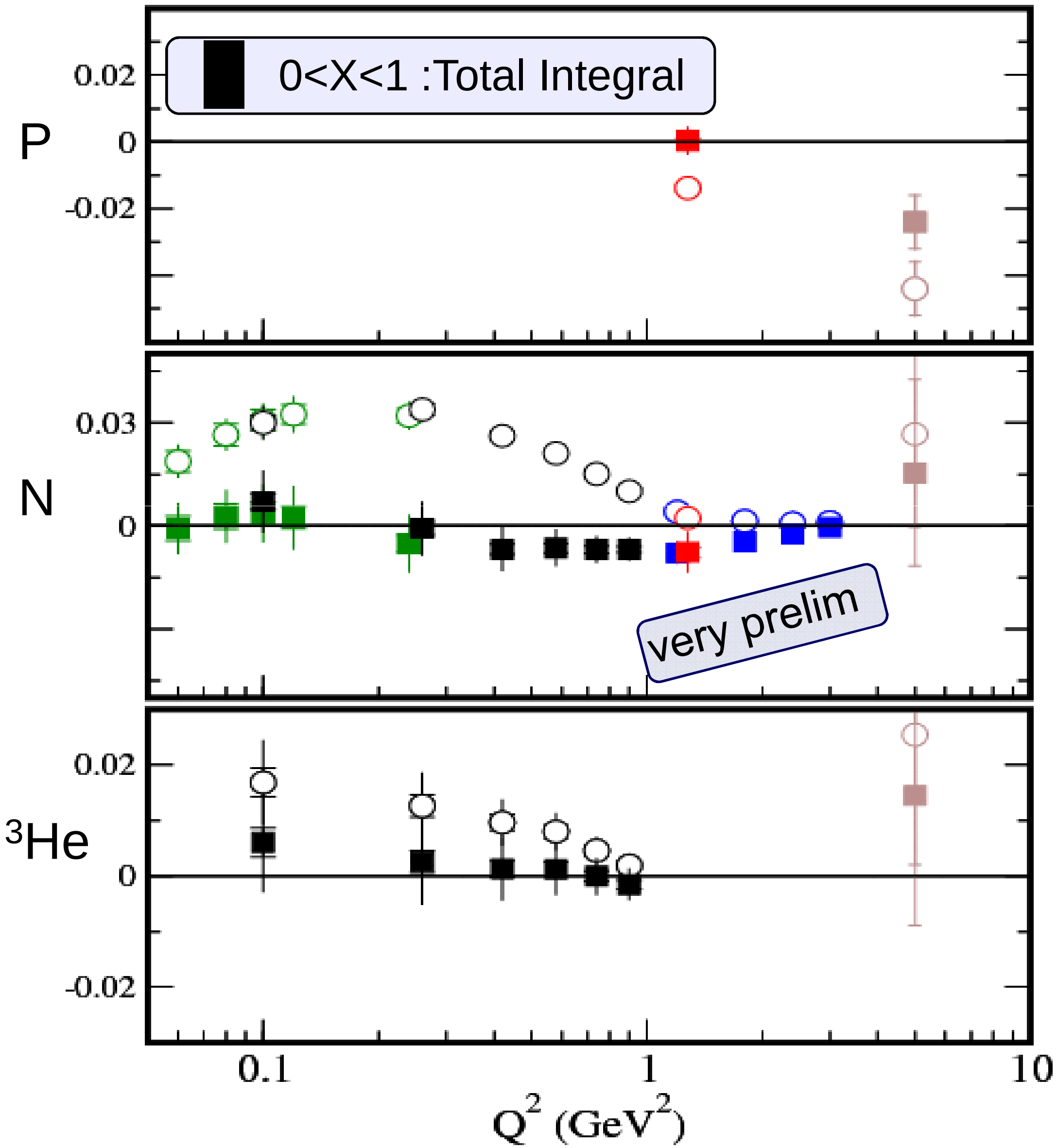
A. Deur, V. Burkert, J. P. Chen and W. Korsch

PLB 650, 244 (2007) and PLB 665, 349 (2008)

α_s/π



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)

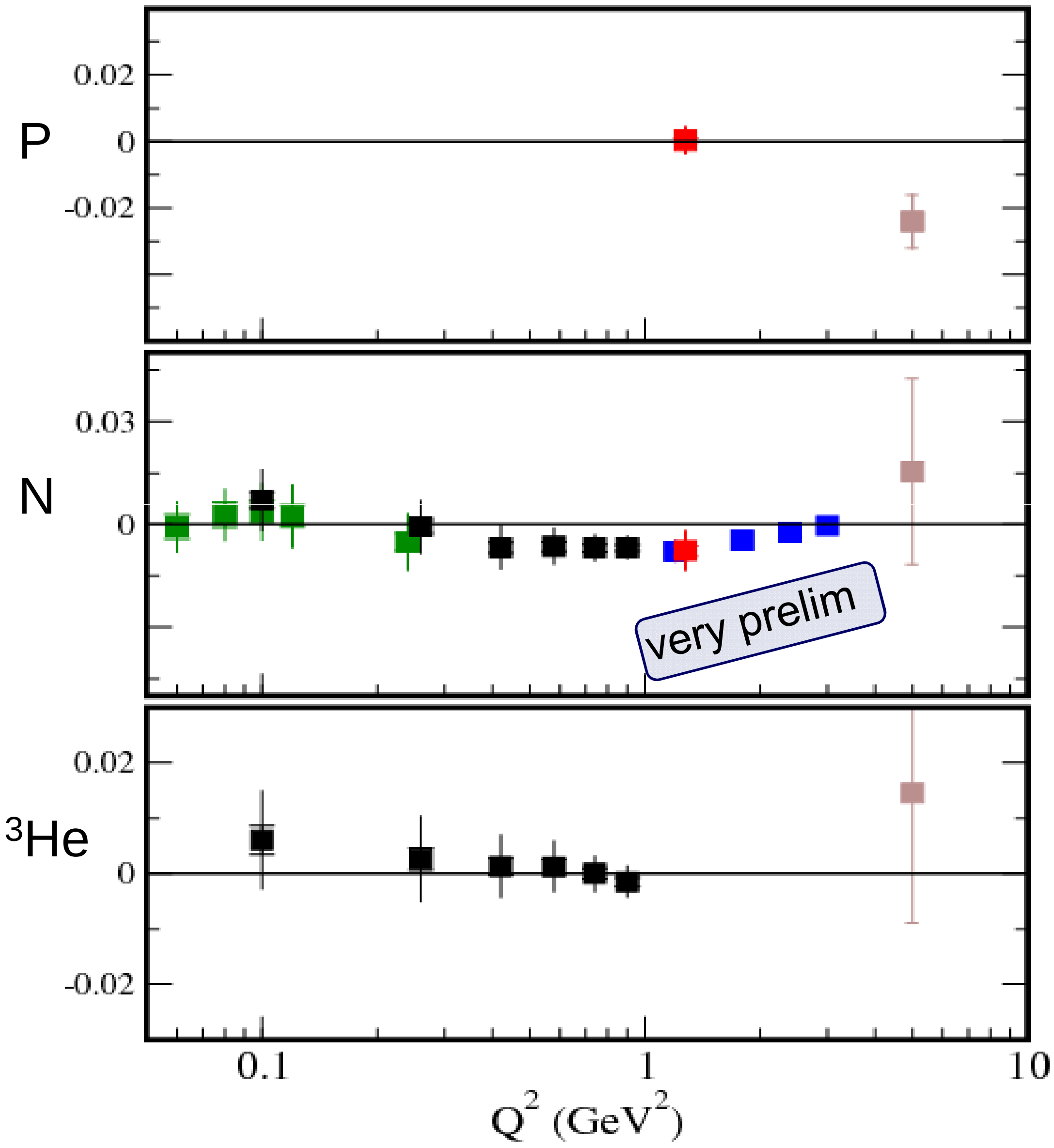
BC = Meas+low_*x*+Elastic

"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%)

BC Sum Rule



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 ^3He

2^{nd} Moments: Generalized Spin Polarizabilities

- **generalized forward spin polarizability γ_0**
  generalized L-T spin polarizability δ_{LT}

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

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

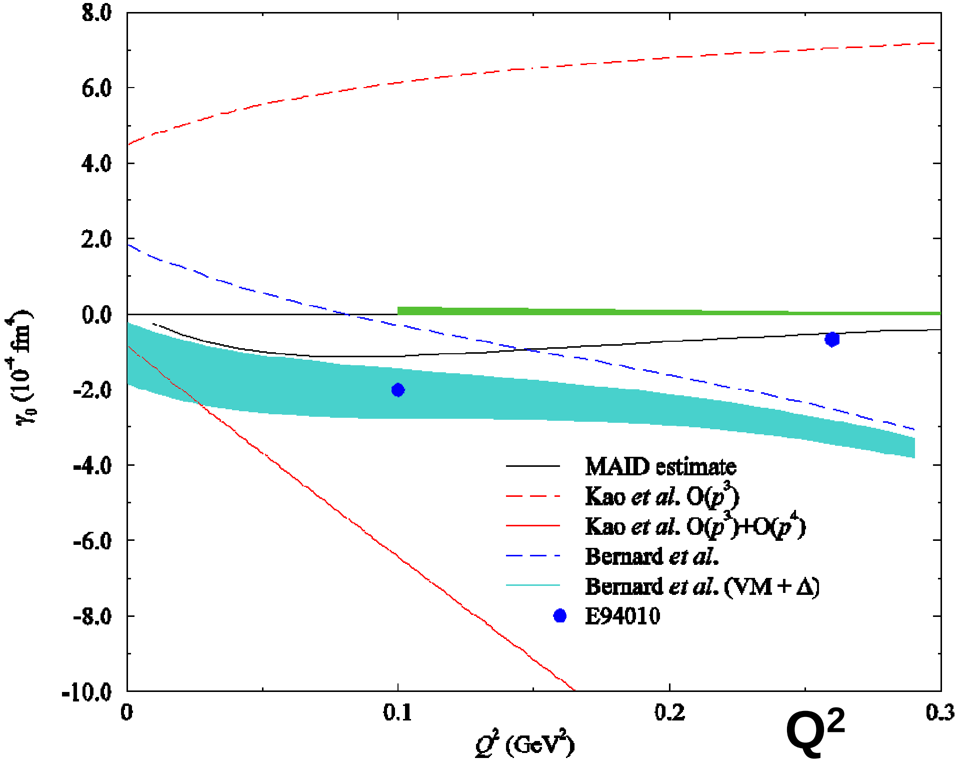
$$\delta_{LT}(Q^2) = \left(\frac{1}{2\pi^2}\right)\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu} \frac{\sigma_{LT}(Q^2,\nu)}{Q\nu^2} d\nu$$

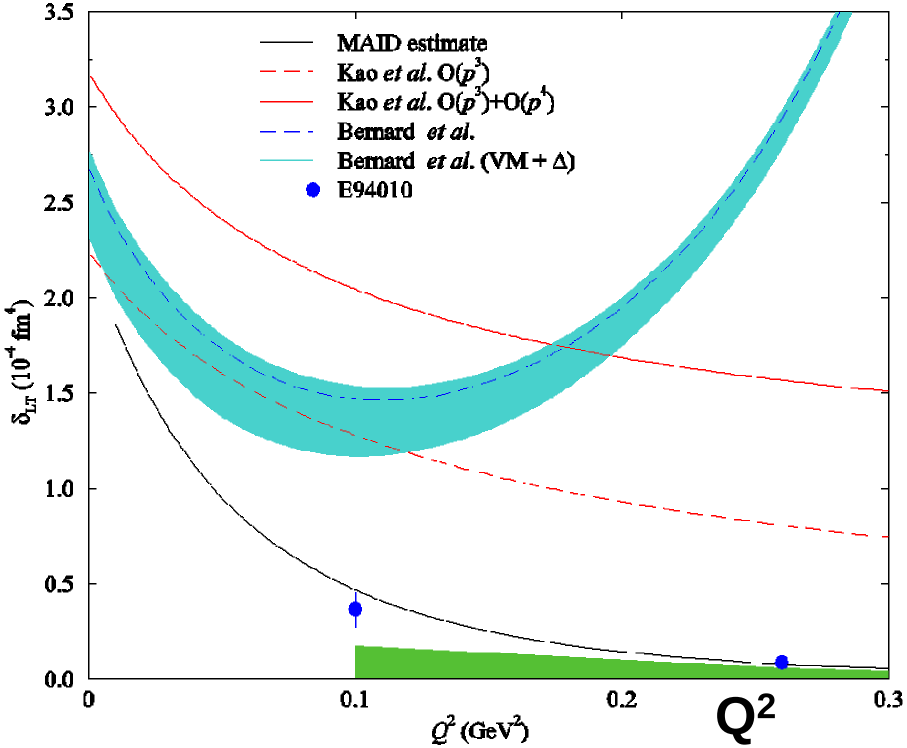
$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2 [g_1(Q^2,x) + g_2(Q^2,x) dx$$

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}





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	γ_0^{p-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	0.1
HBχPT	poor	poor	good	poor	good	good	good	bad	poor	bad	bad
RBχPT/Δ	good	fair	fair	fair	good	poor	fair	bad	good	bad	bad

Q^2 ~0.1 GeV^2 is too high for HBχPT? 0.05 is good?

RBχPT(NL) with Δ reasonable to Q^2 ~ 0.1?

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?

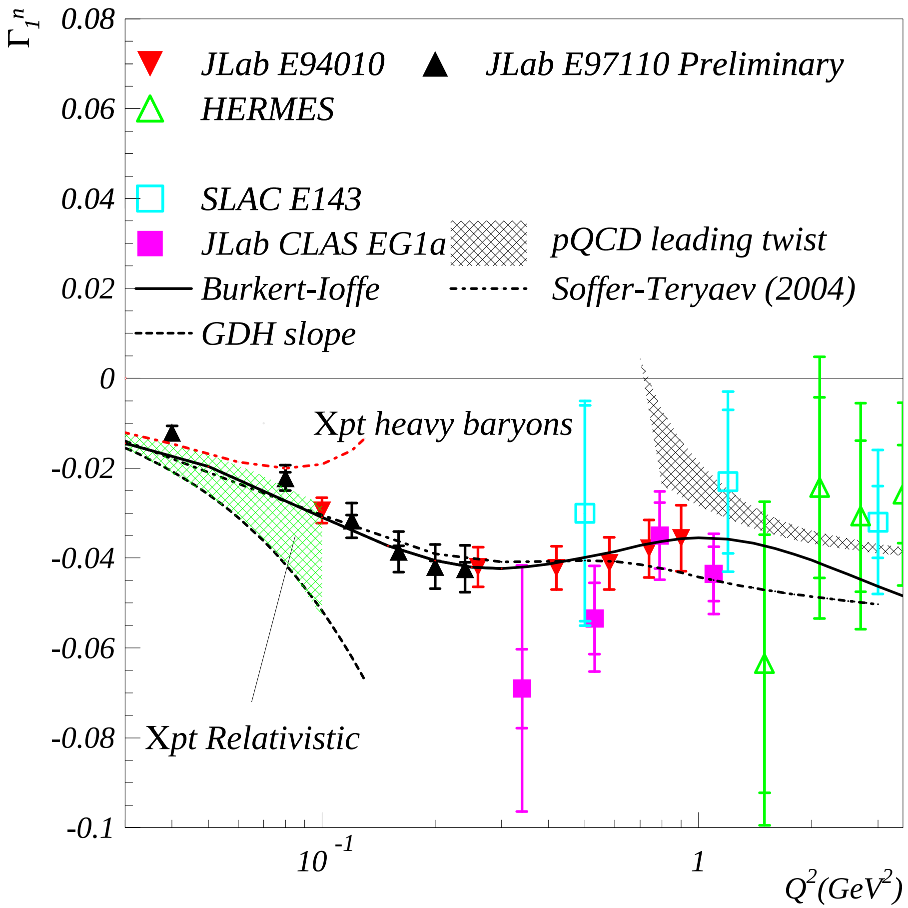
A challenge to χPT theorists.

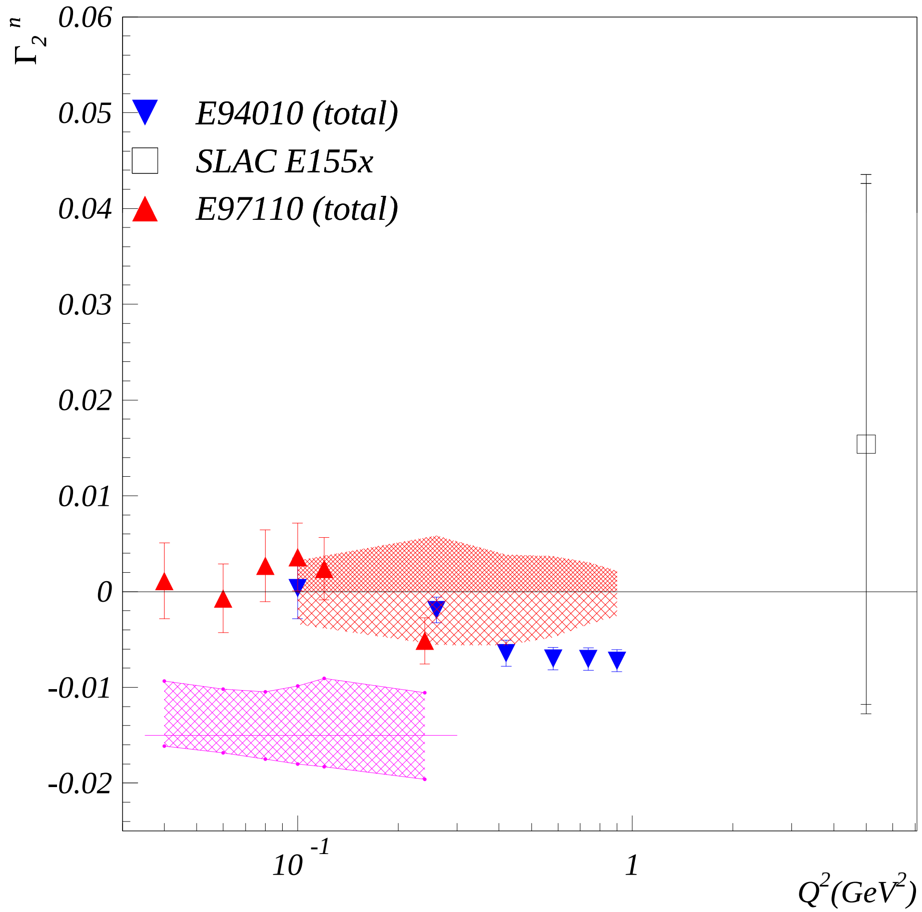
JLab E97-110: GDH Sum Rule and Spin Structure of ^{3}He and Neutron with Nearly Real Photons

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





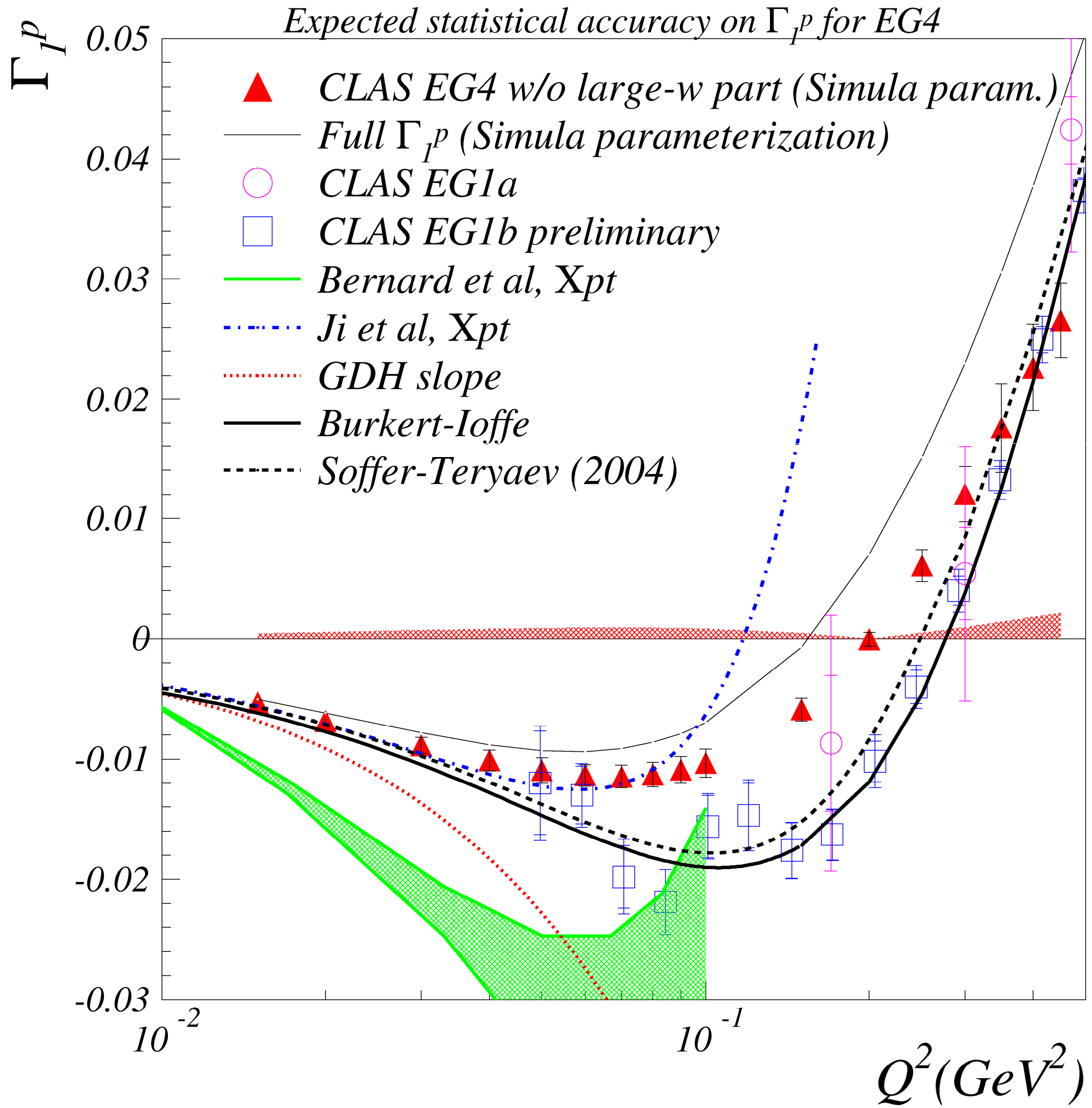
Hall B EG4 Projected Results

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



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

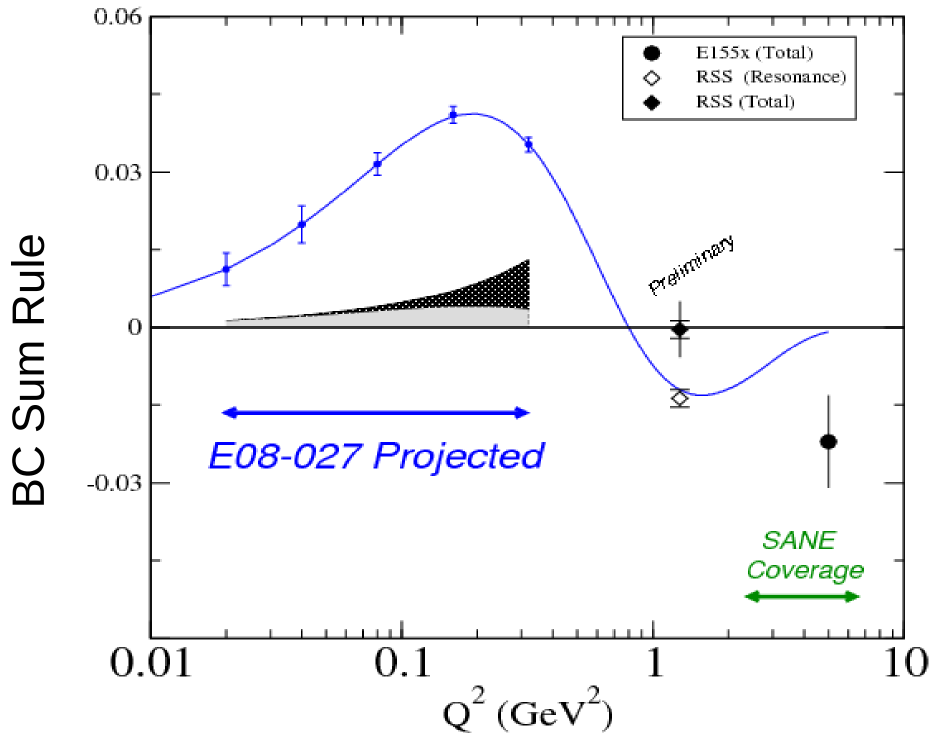
E08-027: Proton g_2 and δ_{LT}

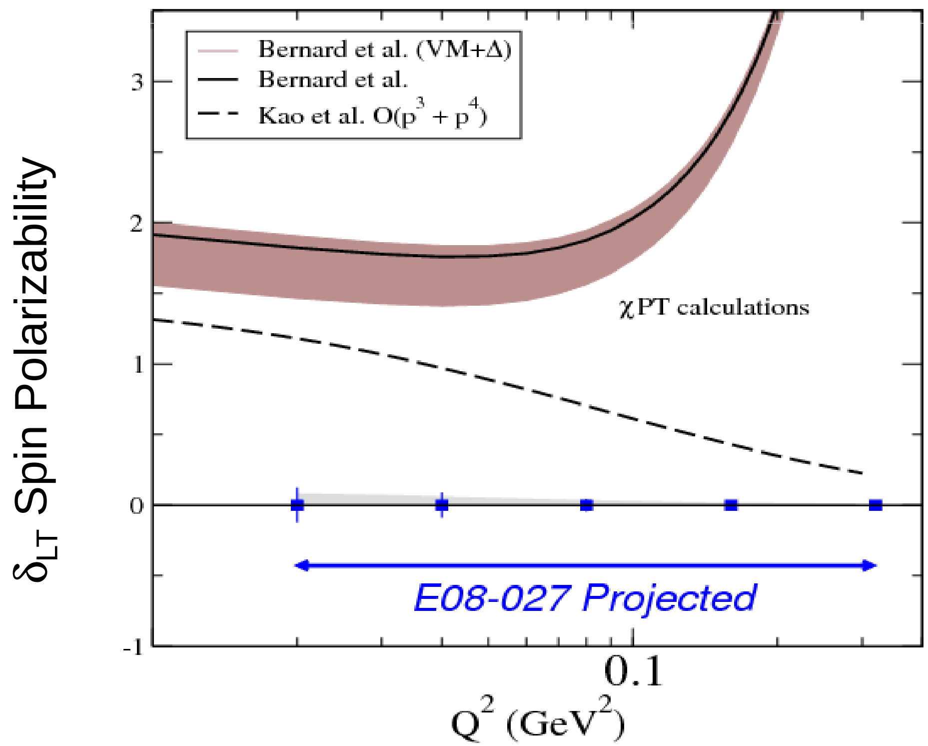
J.P. Chen, A. Camsonne, K. Slifer

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 large Q^2
—State-of-Art χPT calcs fail dramatically for δ_{LT}

Septa Magnets for low Q^2
Polarized Proton Target





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

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

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

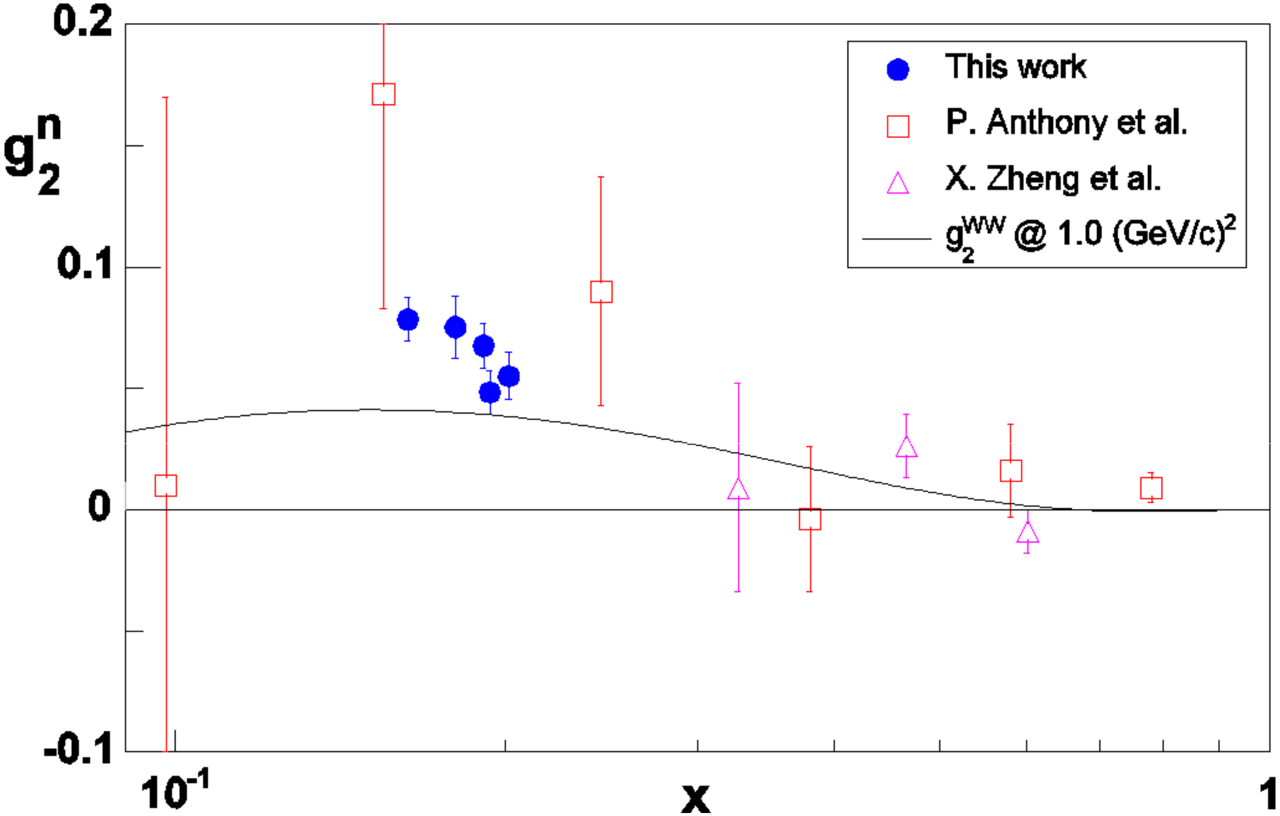
- $g_2 - g_2^{WW}$: a clean way to access twist-3 contribution

  quantify *q-g* correlations

Jefferson Lab Hall A E97-103

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

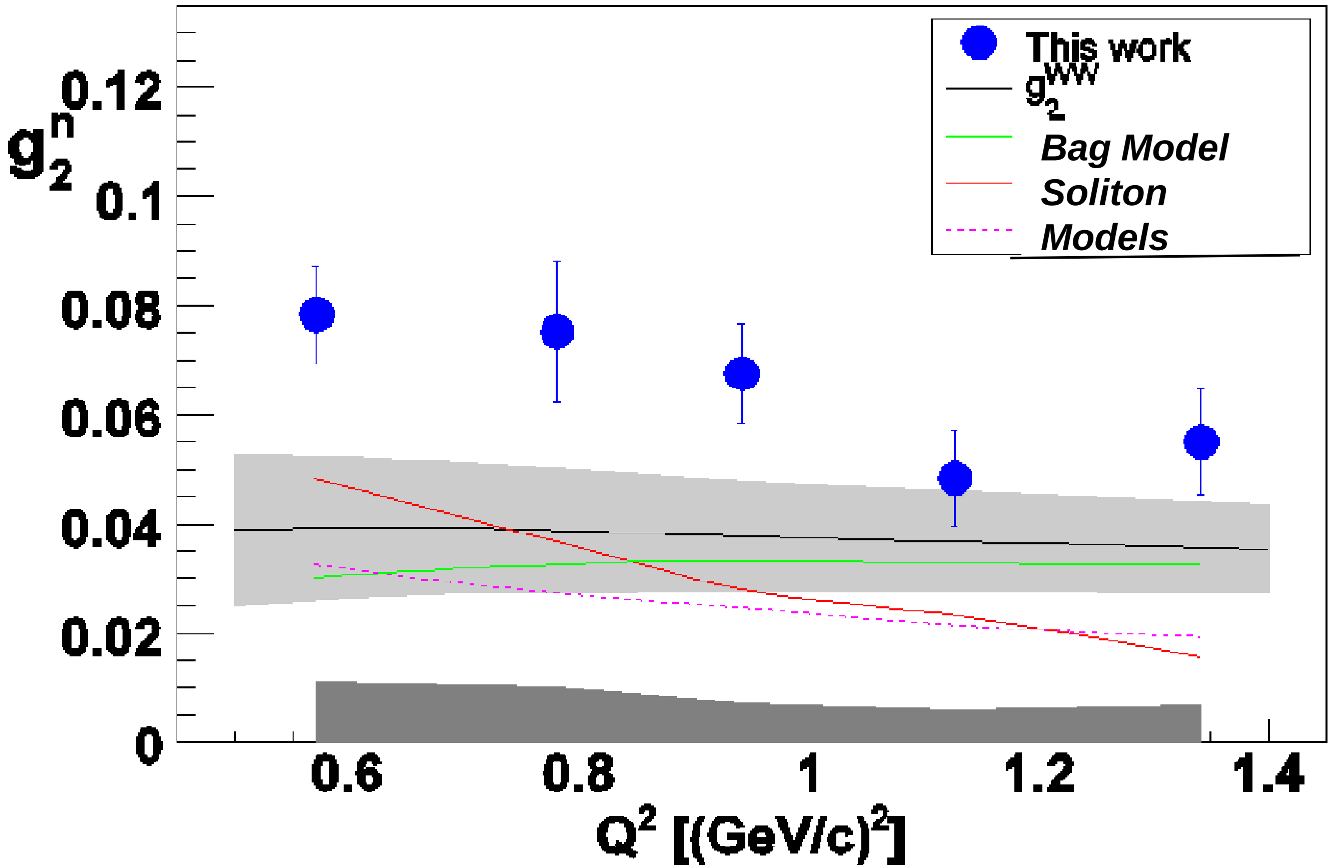
T. Averett, W. Korsch (spokespersons) **K. Kramer (Ph.D. student)**



- 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)

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



Color Polarizability: d_2 (twist-3)

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

  d_2: twist-3 matrix element

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

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

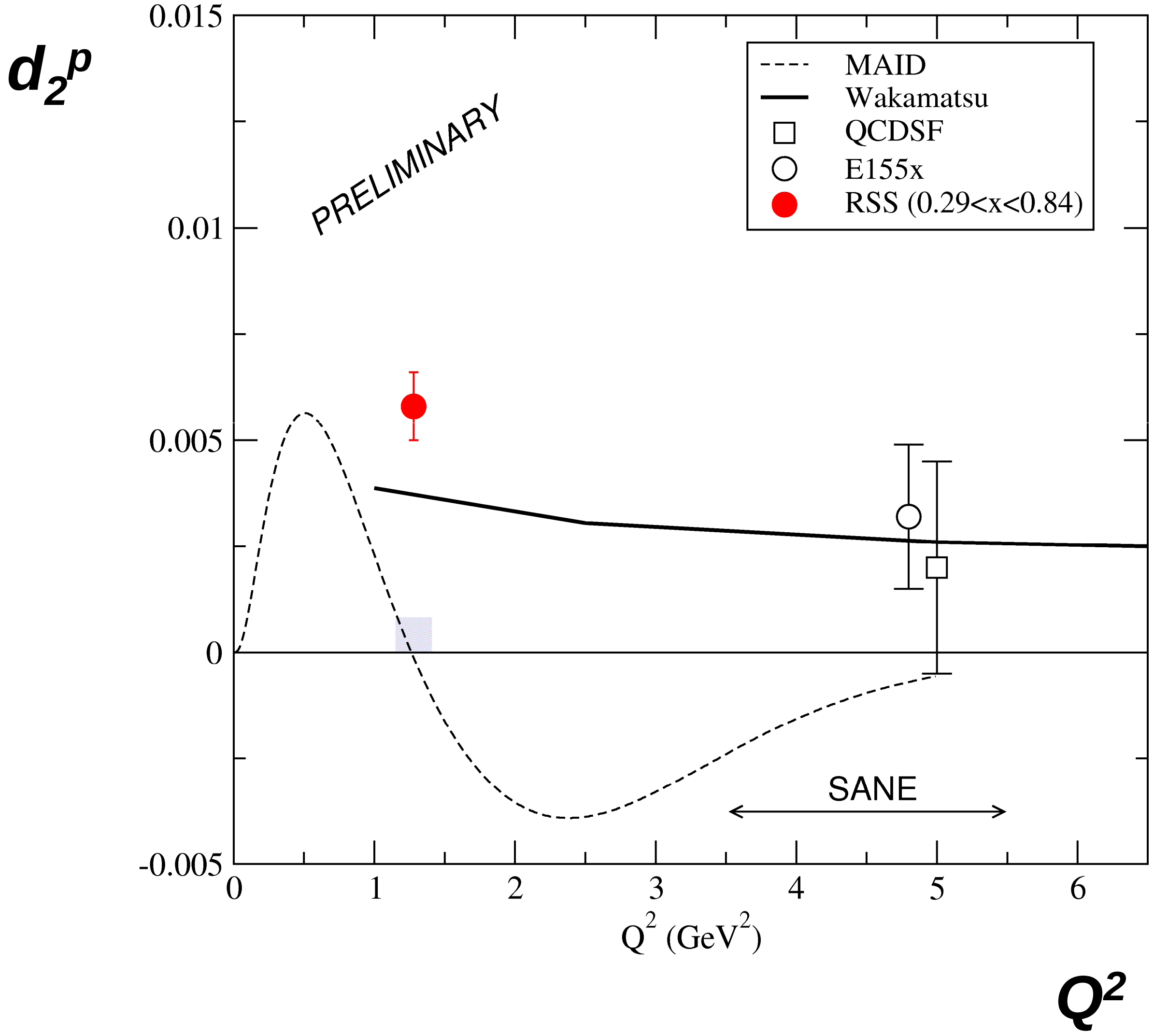
d_2 and g_2-g_2^{WW}: clean access of higher twist (twist-3) effect: *q*-*g* correlations

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

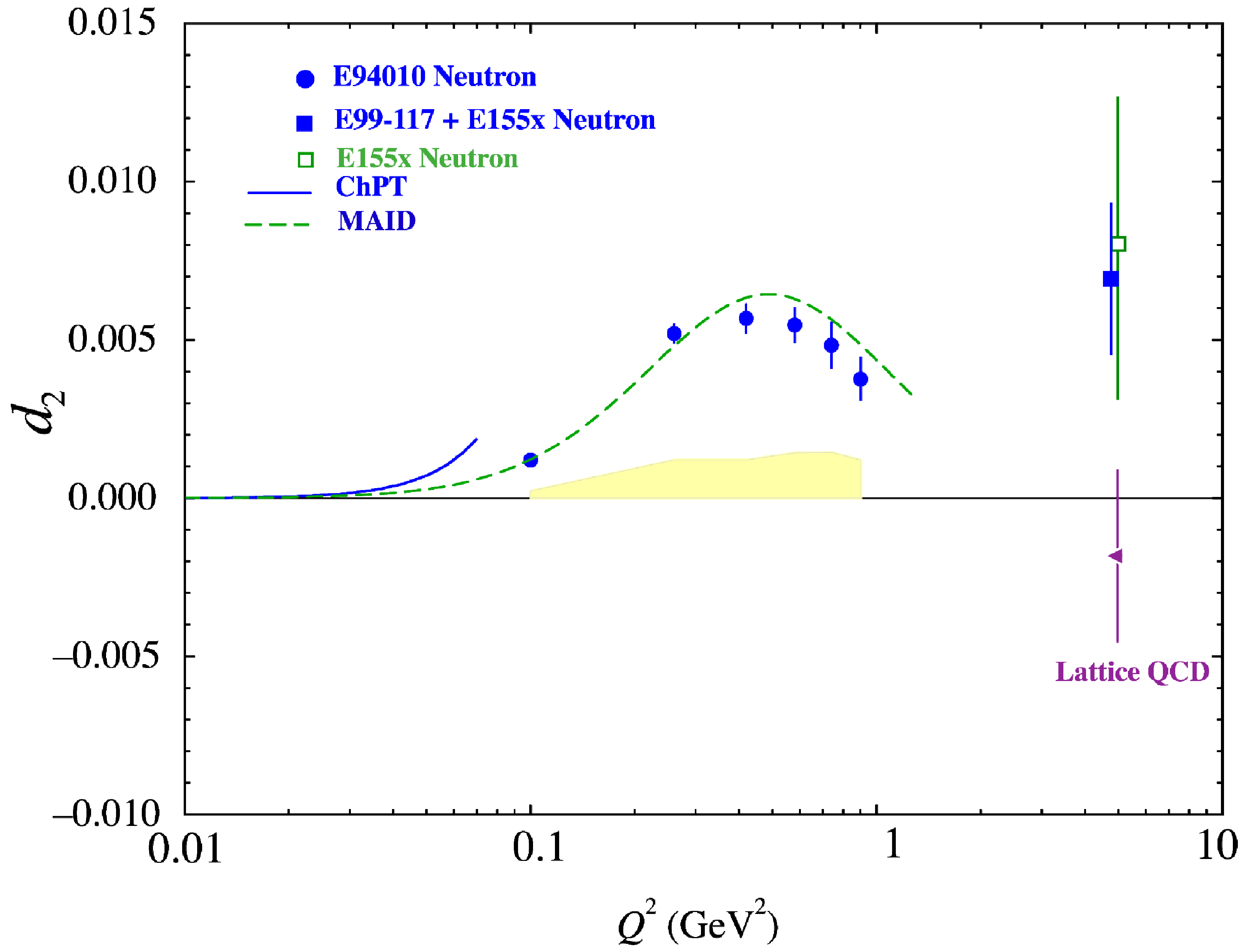
Provide a benchmark test of Lattice QCD at high Q^2

Avoid issue of low-*x* extrapolation

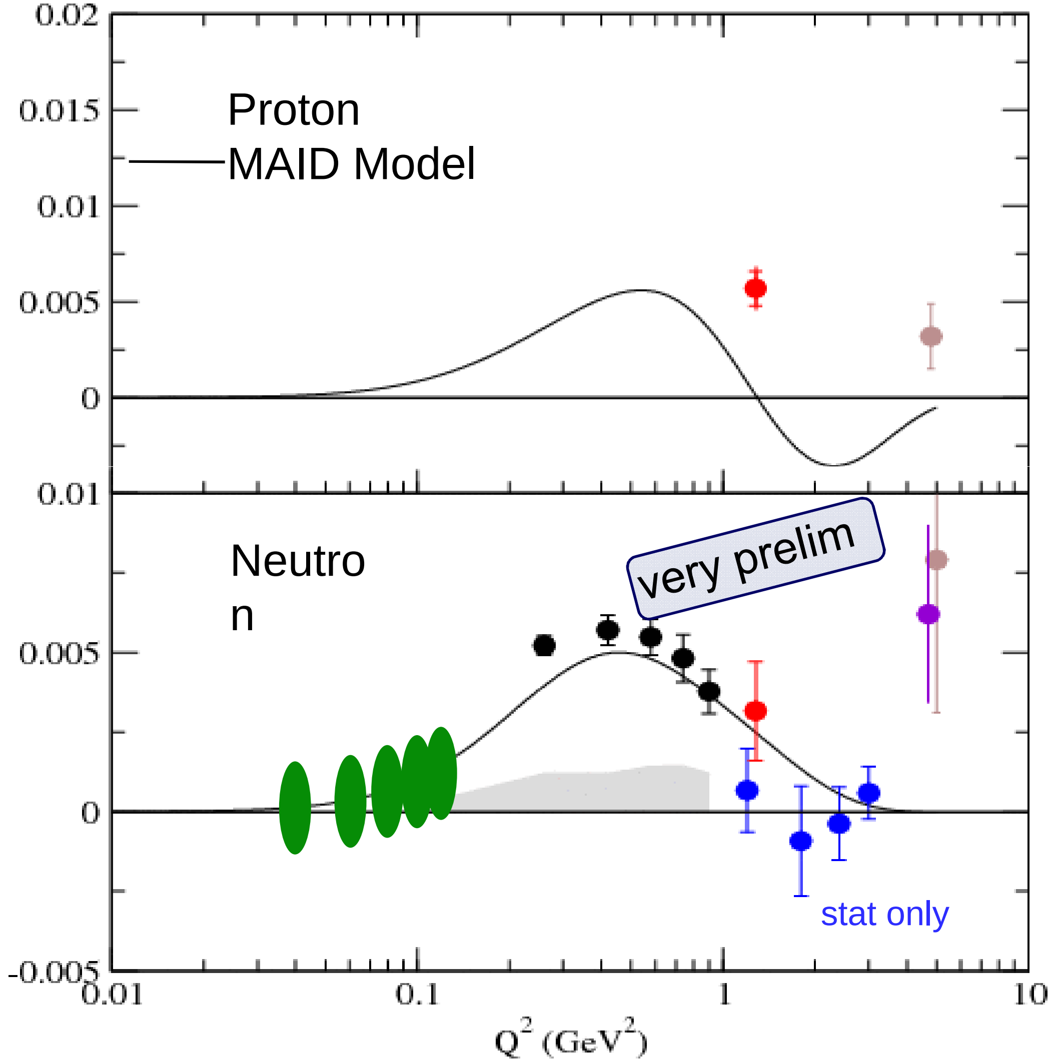
Measurement on proton: d_2^p (Hall C and SLAC)
RSS and SANE: O. Rondon *et al.*



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)

K. Slifer, O. Rondon *et al*. in preparation

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

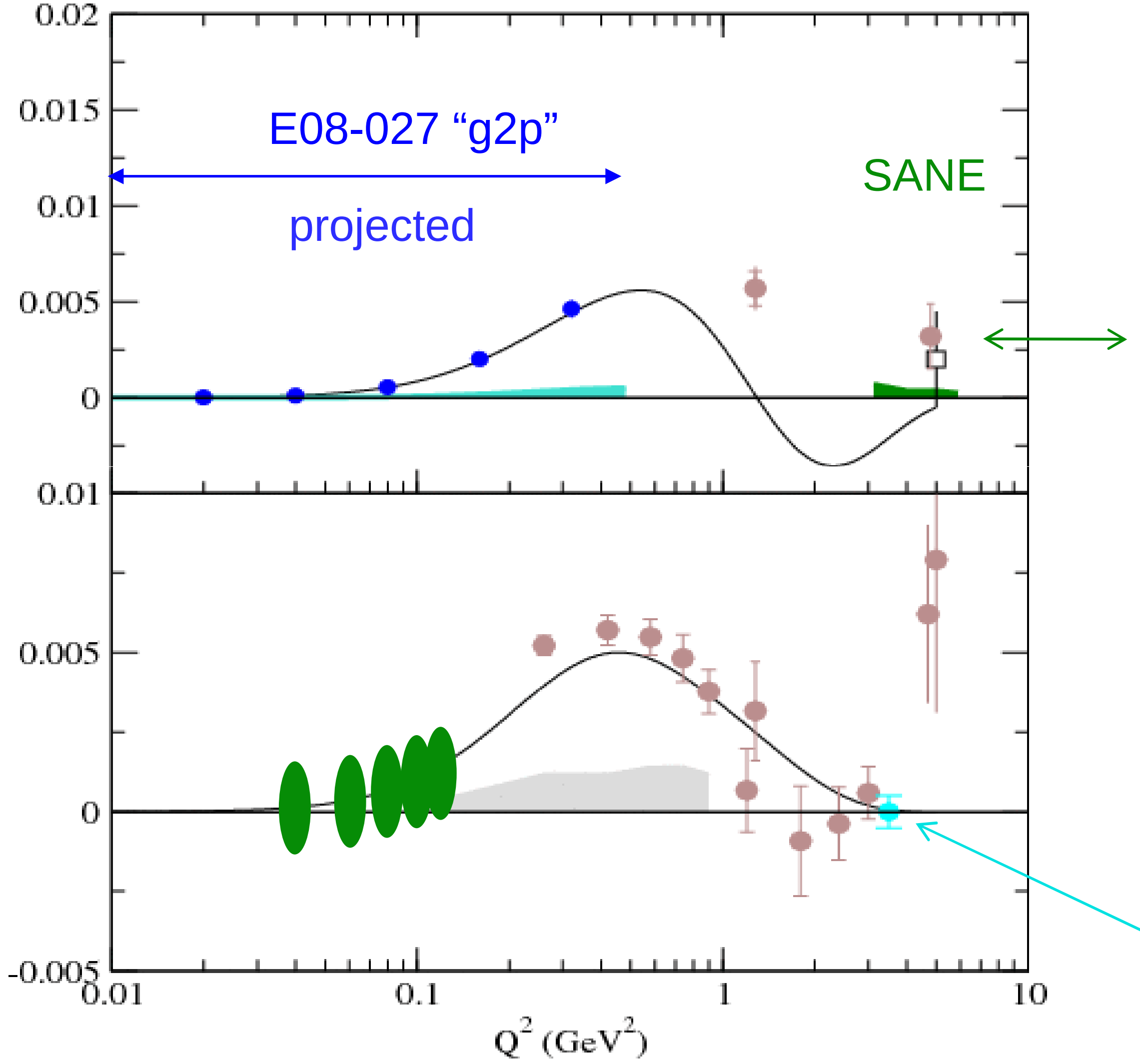
courtesy of **P. Solvignon**

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

courtesy of **V. Sulkosky**

Thanks also to the spokesmen of these experiments!
RSS: Mark Jones, Oscar Rondon
E01-012: N. Liyanage, J.P.Chen, Seonho Choi
SaGDH: J.P. Chen, A. Deur, F. Garabaldi

$d_2(Q^2)$



Upcoming 6 GeV Experiments

Sane: Fall 2008

$2.3 < Q^2 < 6$ GeV2

“g2p” in Hall A, 2011

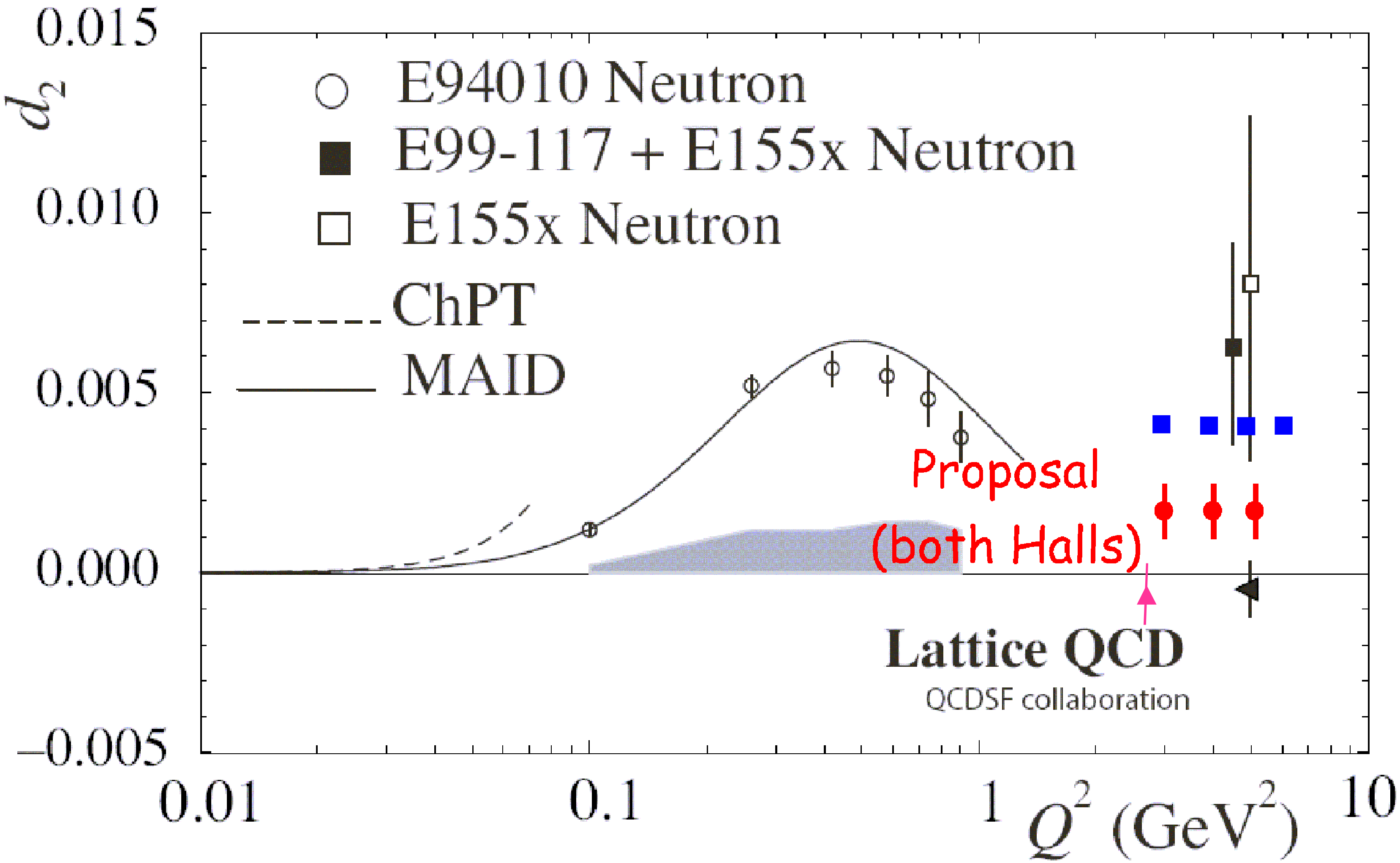
$0.015 < Q^2 < 0.4\ \text{GeV}^2$

“d2n” in Hall A, 2009

$Q^2 = 3\ \text{GeV}^2$

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)



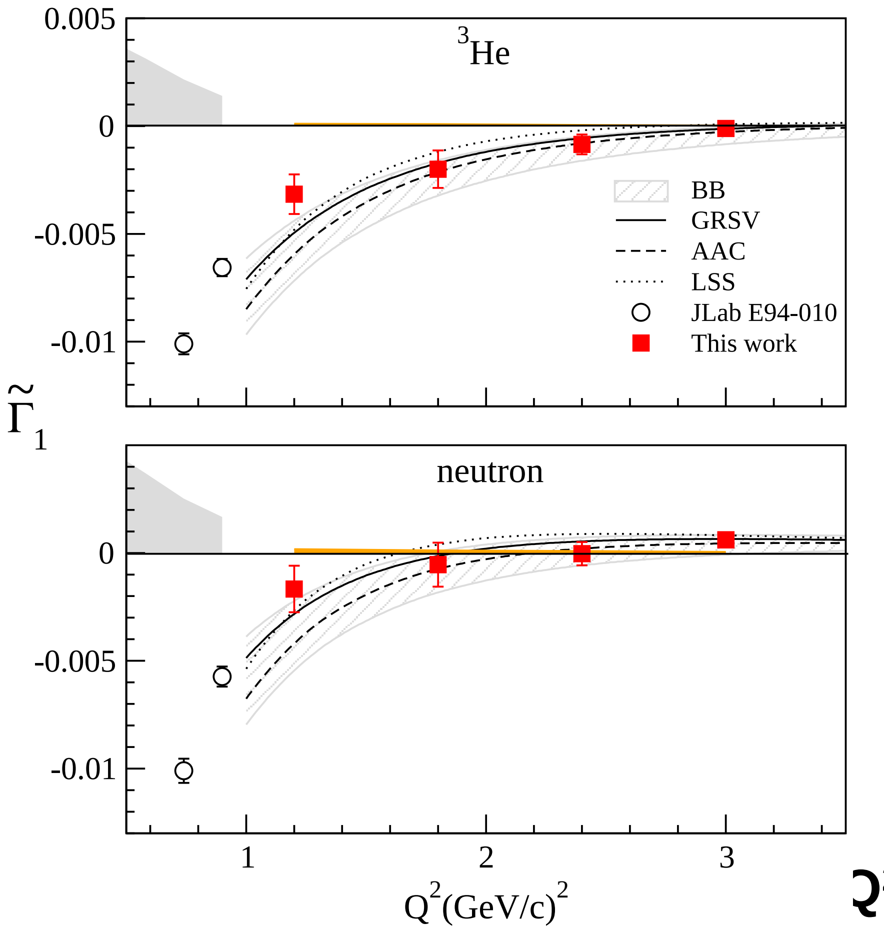
Quark-hadron Duality in Spin Structure

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

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

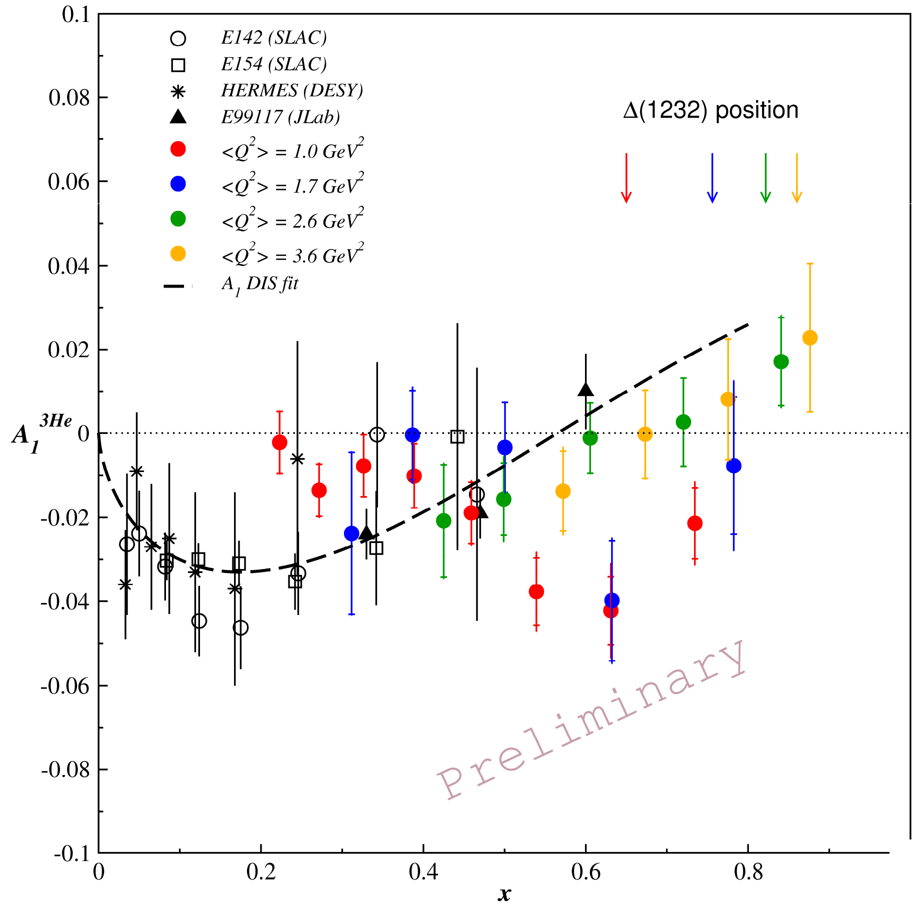
- g_1/g_2 and A_1/A_2 (^{3}He/n) in resonance region, $1 < Q^2 < 4$ GeV^2
- Study quark-hadron duality in spin structure.
- PRL 101, 1825 02 (2008)

Γ_1 resonance vs. pdfs



Q^2

A_1^{3He} (resonance vs DIS)



x

Valence Quark Spin Structure

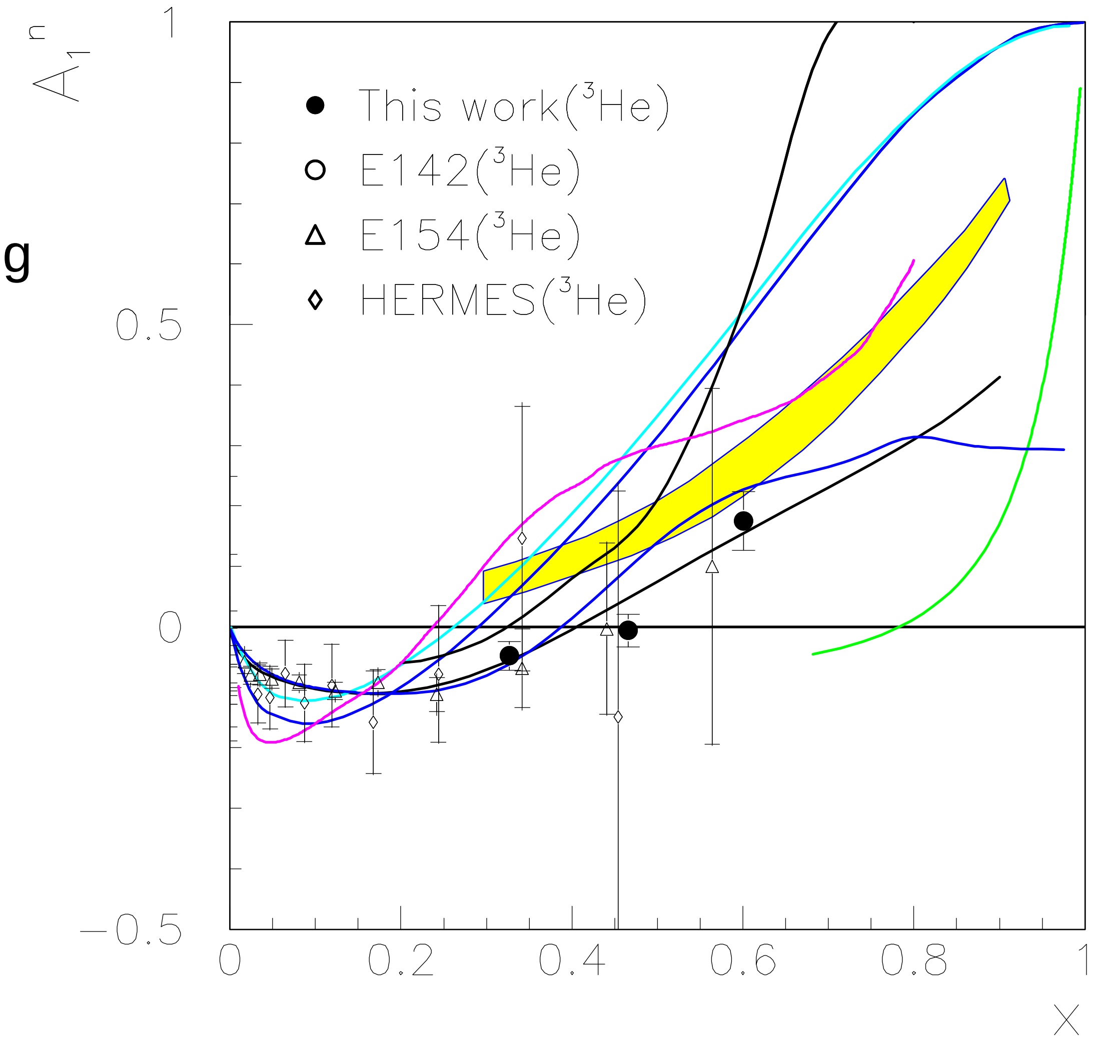
A_1 at high x and flavor decomposition

JLab E99-117

Precision Measurement of A_1^n at Large *x*

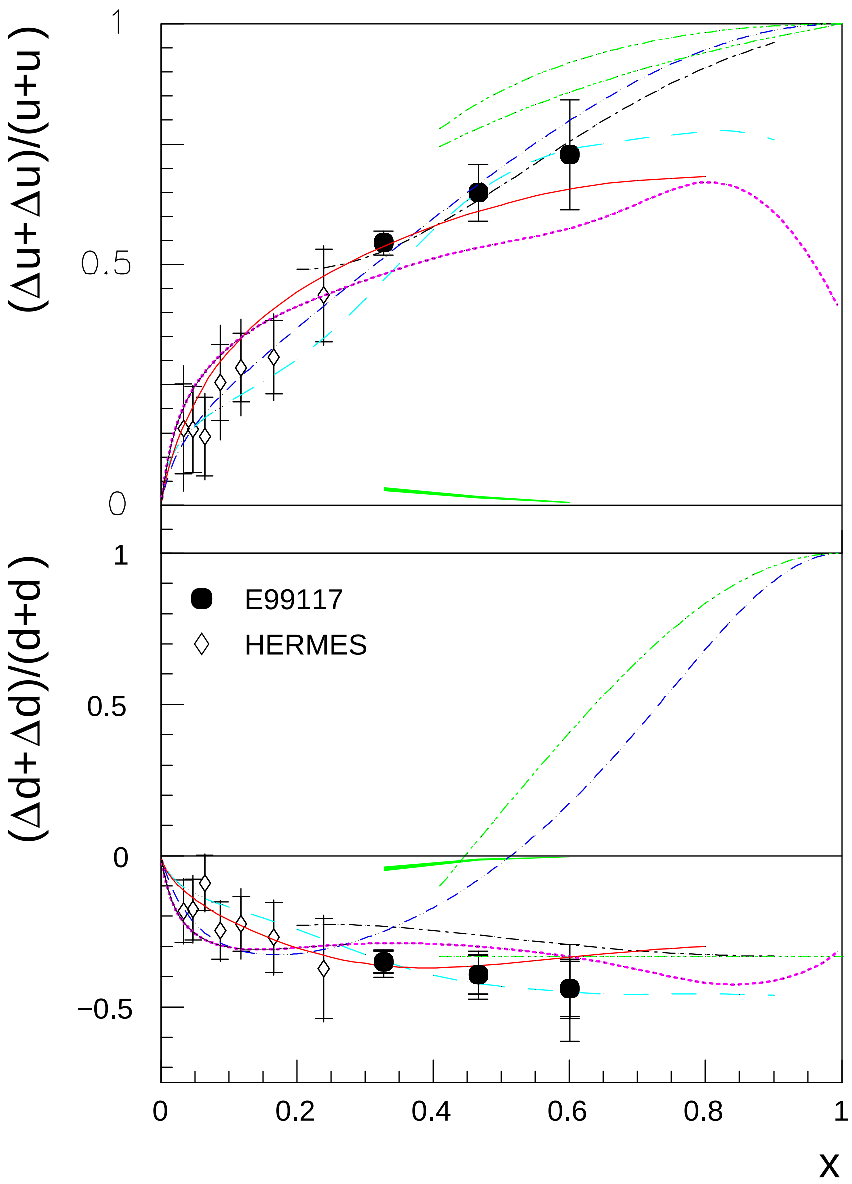
Spokespersons: J. P. Chen, Z. -E. Meziani, P. Souder, PhD Student: X. Zheng

- 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)**



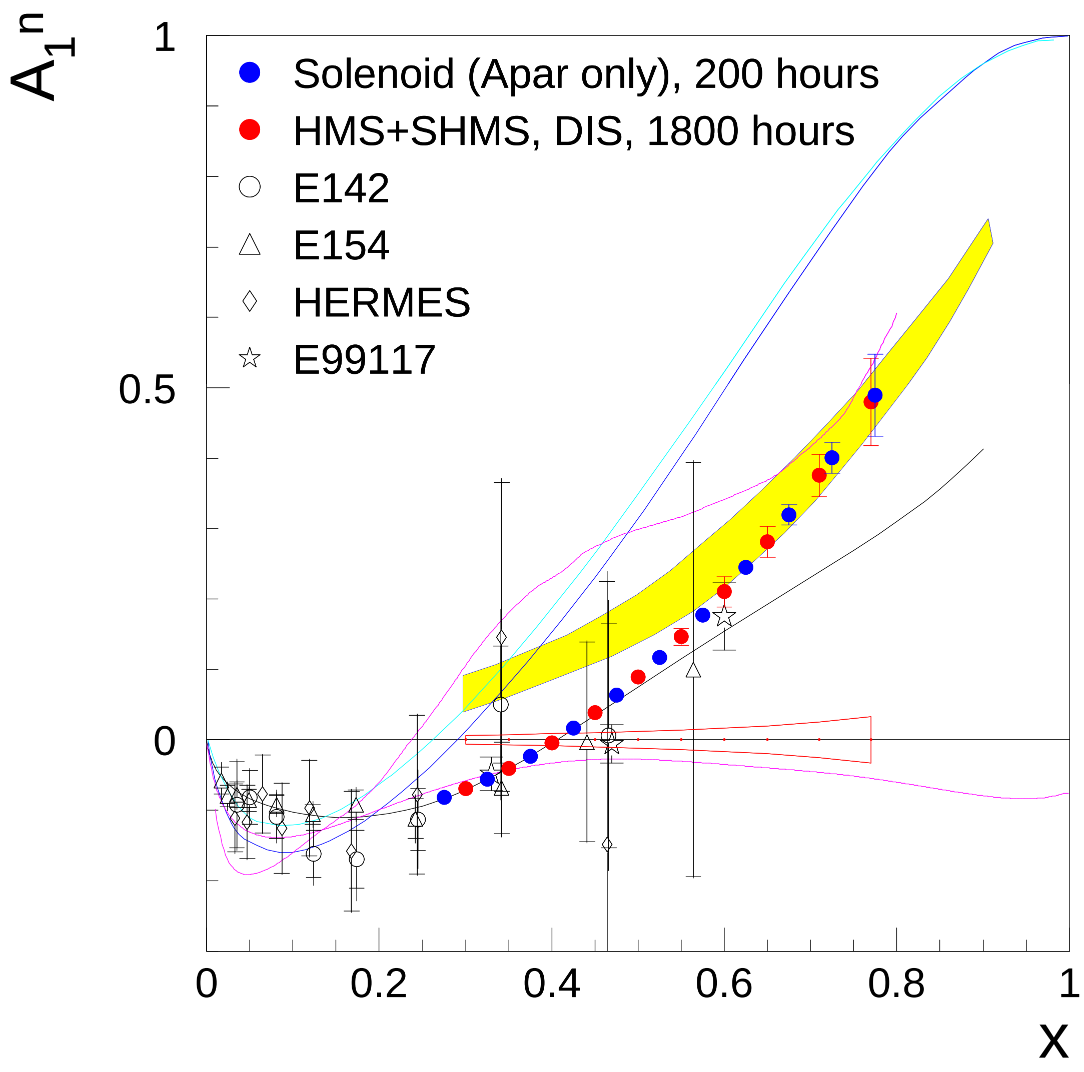
Polarized Quark Distributions

- 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

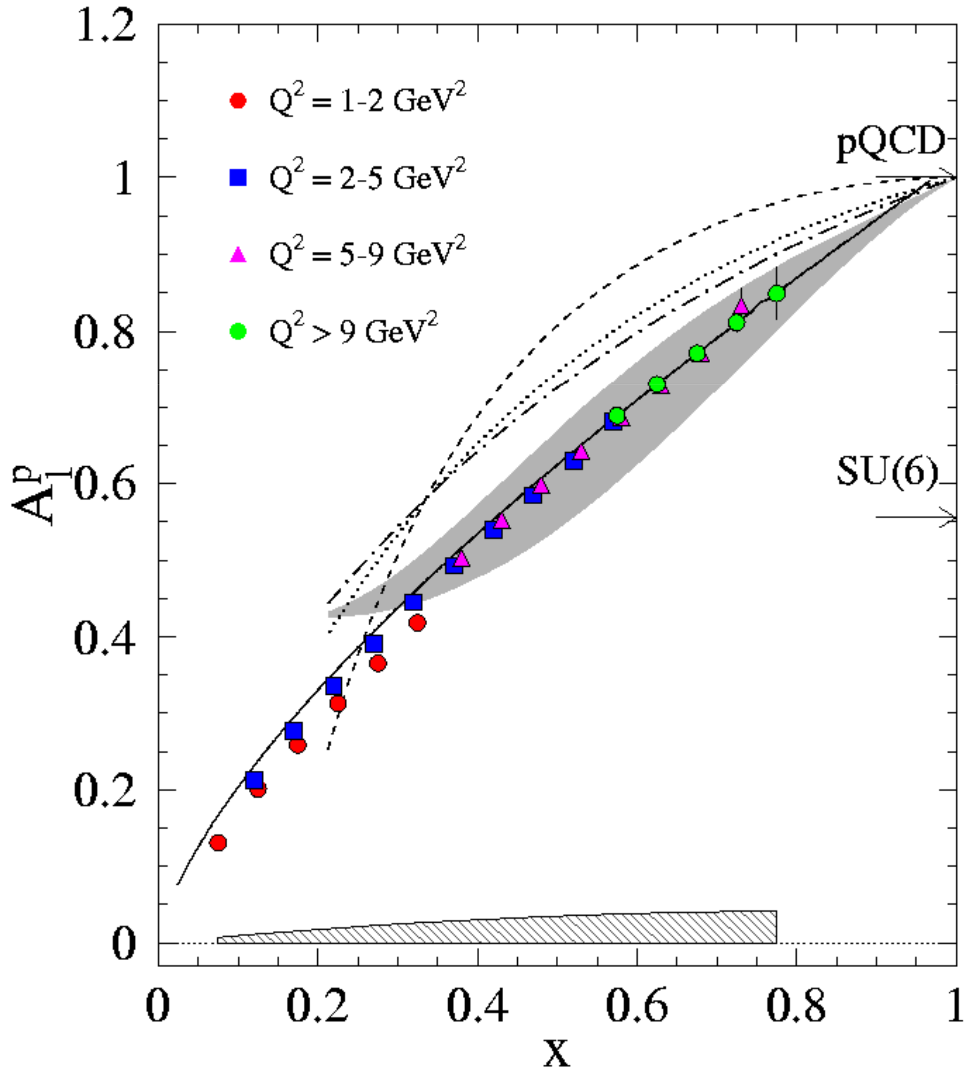


Projections for JLab at 11 GeV

A_1^n at 11 GeV



A_1^p at 11 GeV



Semi-inclusive Deep Inelastic Scattering $N(e,e'\pi)x$

Transversity and TMDs

Transversity and TMDs

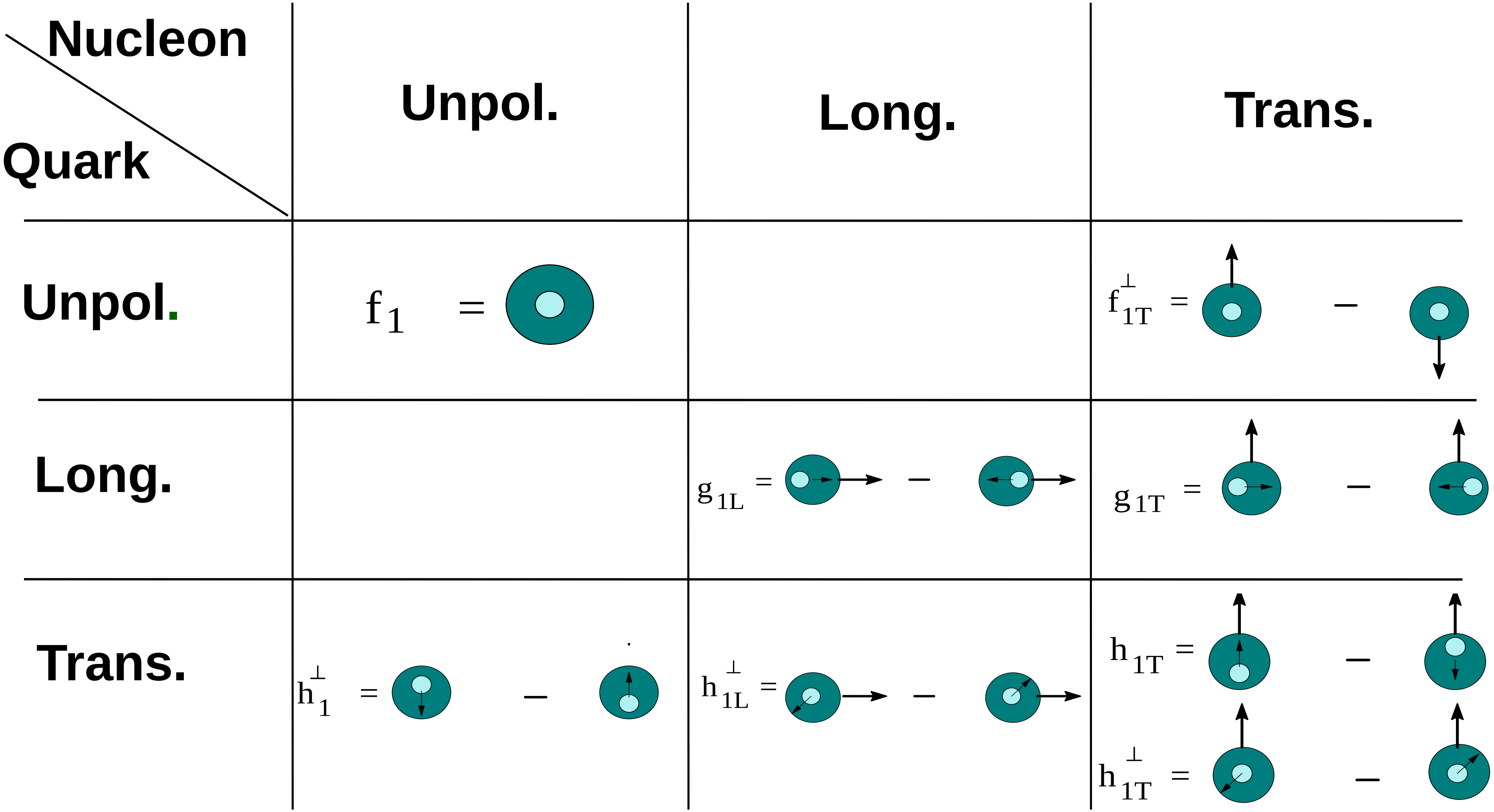
- Three twist-2 quark distributions:
  - Momentum distributions: $q(x,Q^2) = q^{\uparrow}(x) + q^{\downarrow}(x)$
  - Longitudinal spin distributions: $\Delta q(x,Q^2) = q^{\uparrow}(x) - q^{\downarrow}(x)$
  - Transversity distributions: $\delta q(x,Q^2) = q^{\perp}(x) - q_{\top}(x)$
- It takes two 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 : δq, $f_{1T}^{\perp}(x,k_\perp,Q^2)$, …
  - 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)

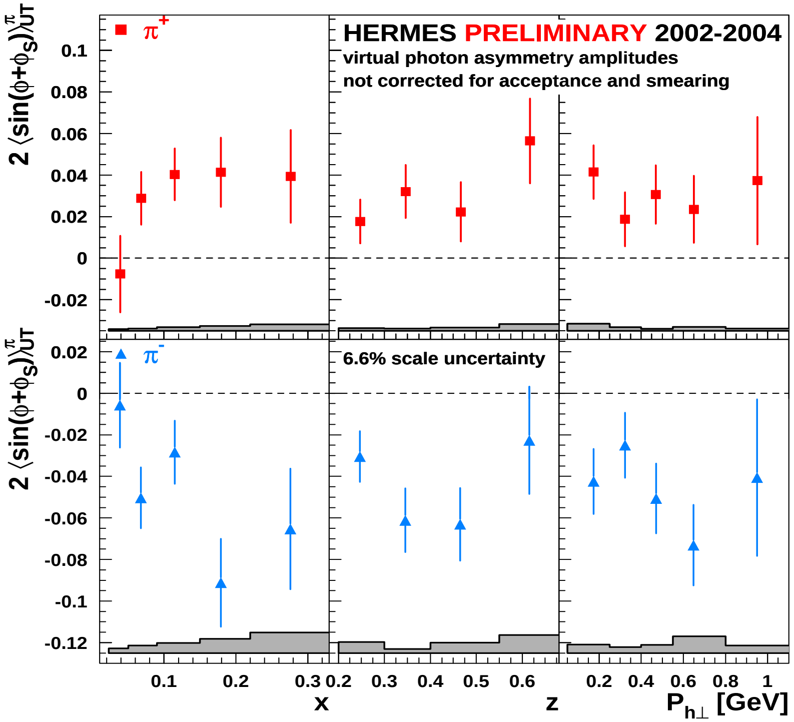
“Leading-Twist” *TMD* Quark Distributions



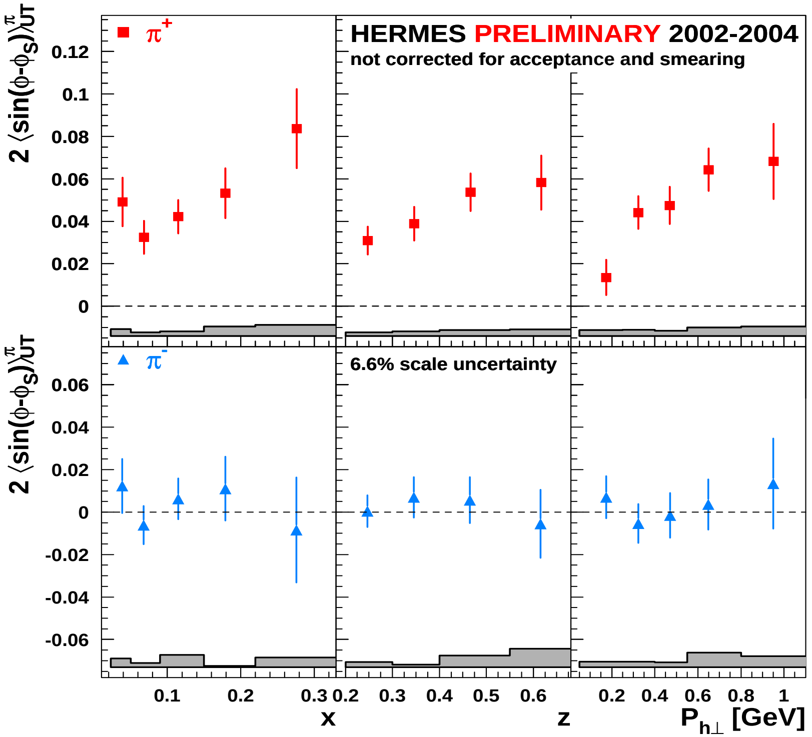
$A_{UT}^{\sin(\phi)}$ from transv. pol. H target

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^+)$\rightarrow$ 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, large for π^-

    π^- and $\pi+$ 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

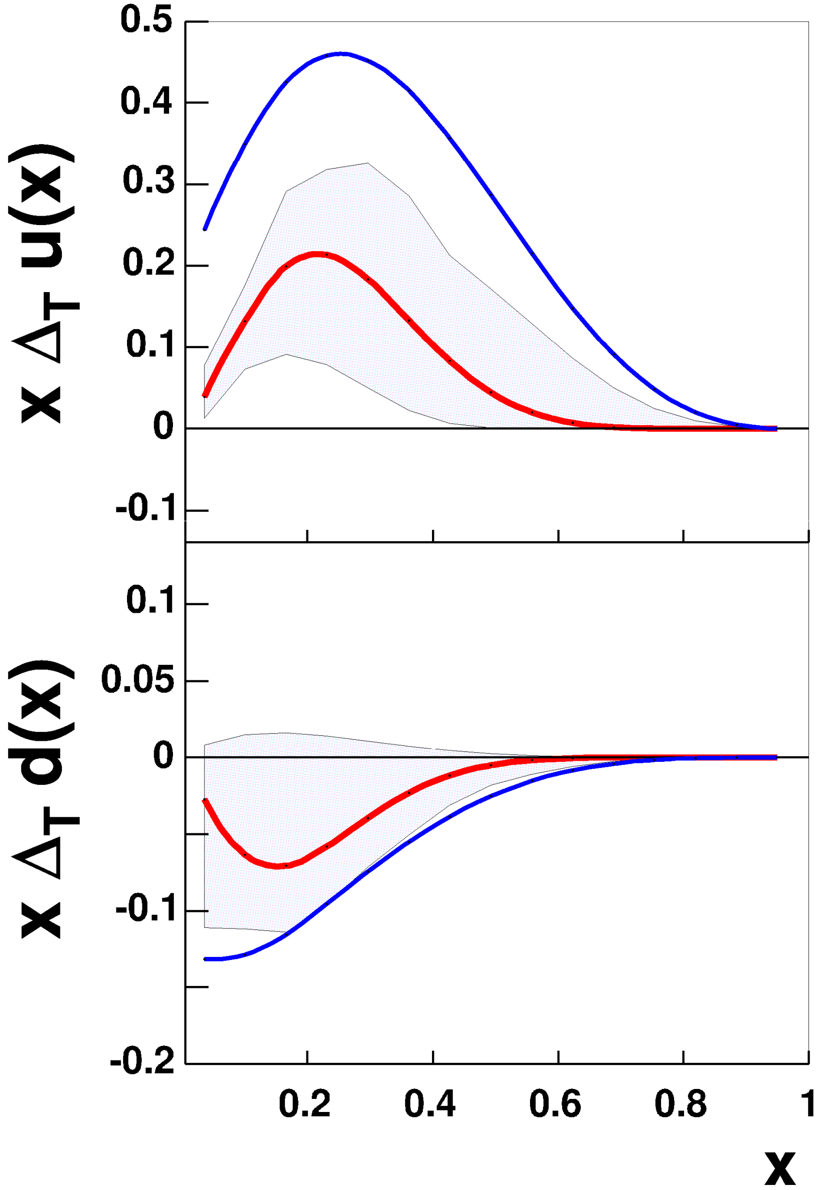
  Unprecedented precision with high luminosity and large acceptance

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.

Need precision multi-dimension data.



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

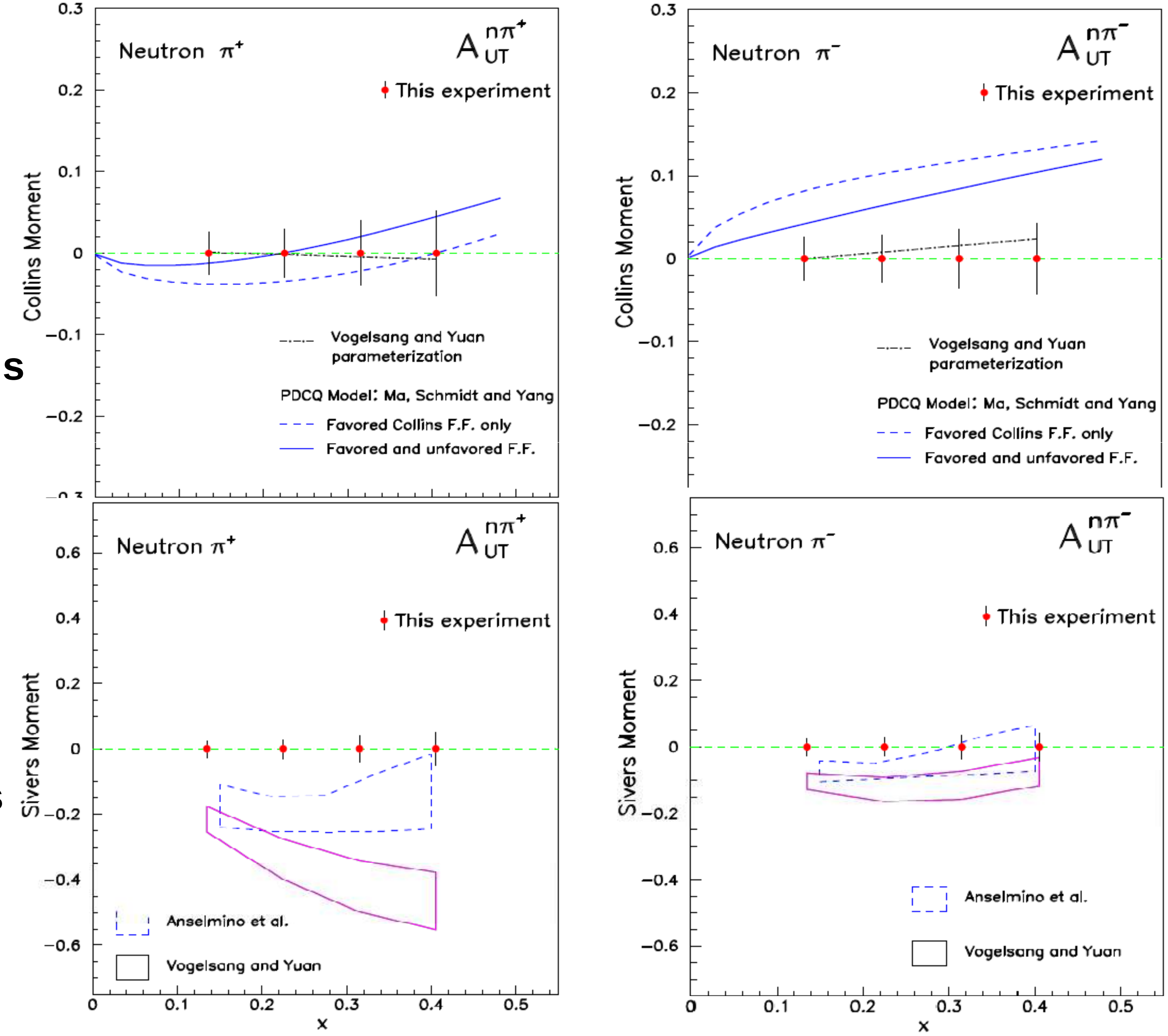
Spokespersons:
X. Jiang,
J. P. Chen,
E. Cisbani,
H. Gao,
J.-C. Peng

7 PhD Students:

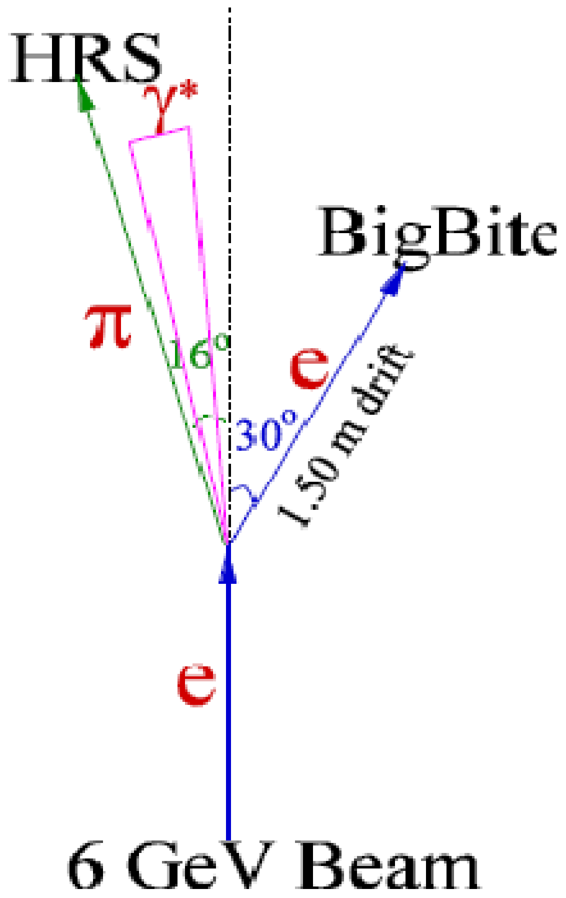
Successfully Completed data taking, exceeded PAC approved goal

Collins

Sivers



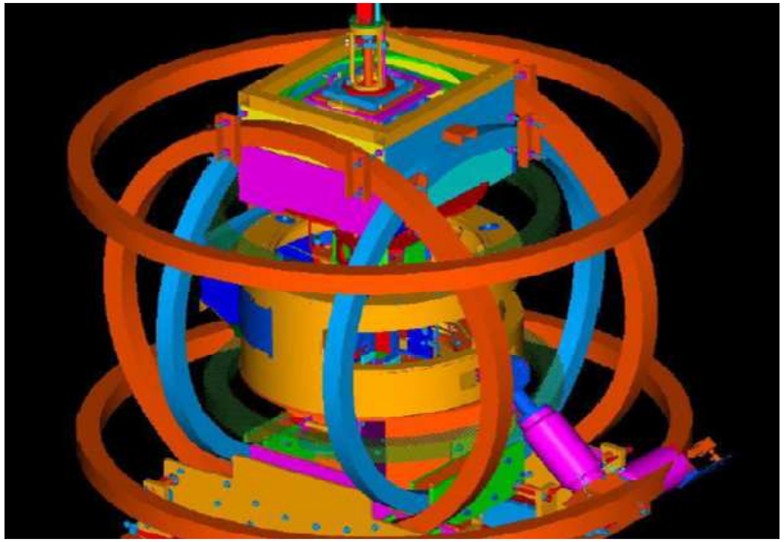
Hall-A Transversity: $en \to e'\pi X$ $en \to e'KX$



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
- Laboratory to study *QCD*
- 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

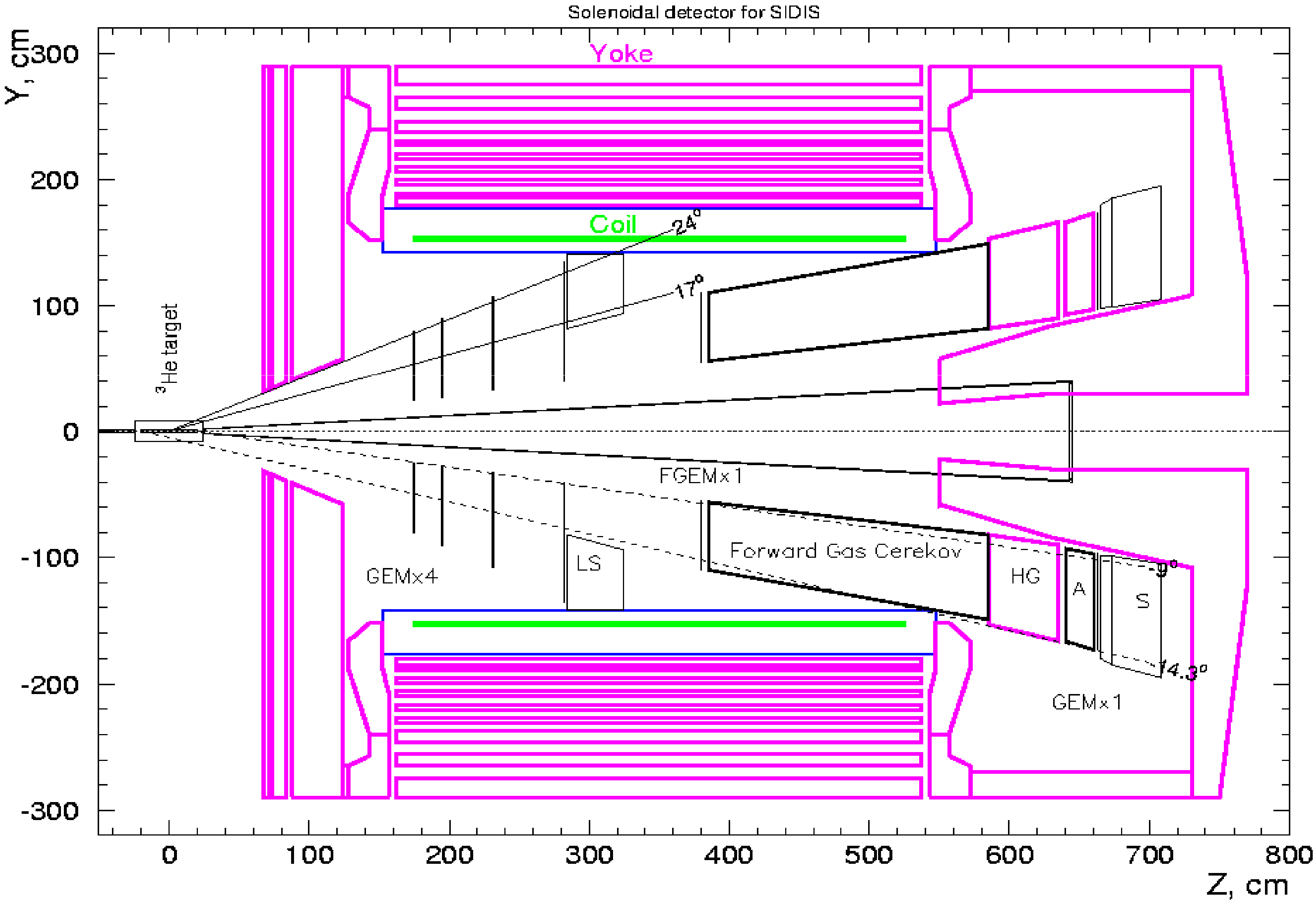
      → *SIDIS* of π^{+-} on both proton and neutron
  - Kinematical region: most contributions in $0.1 < x < 0.5$
  - 12 GeV JLab idea for this measurement
    - CLAS12 with proton and a new Solenoid with polarized neutron (^{3}He)

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

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

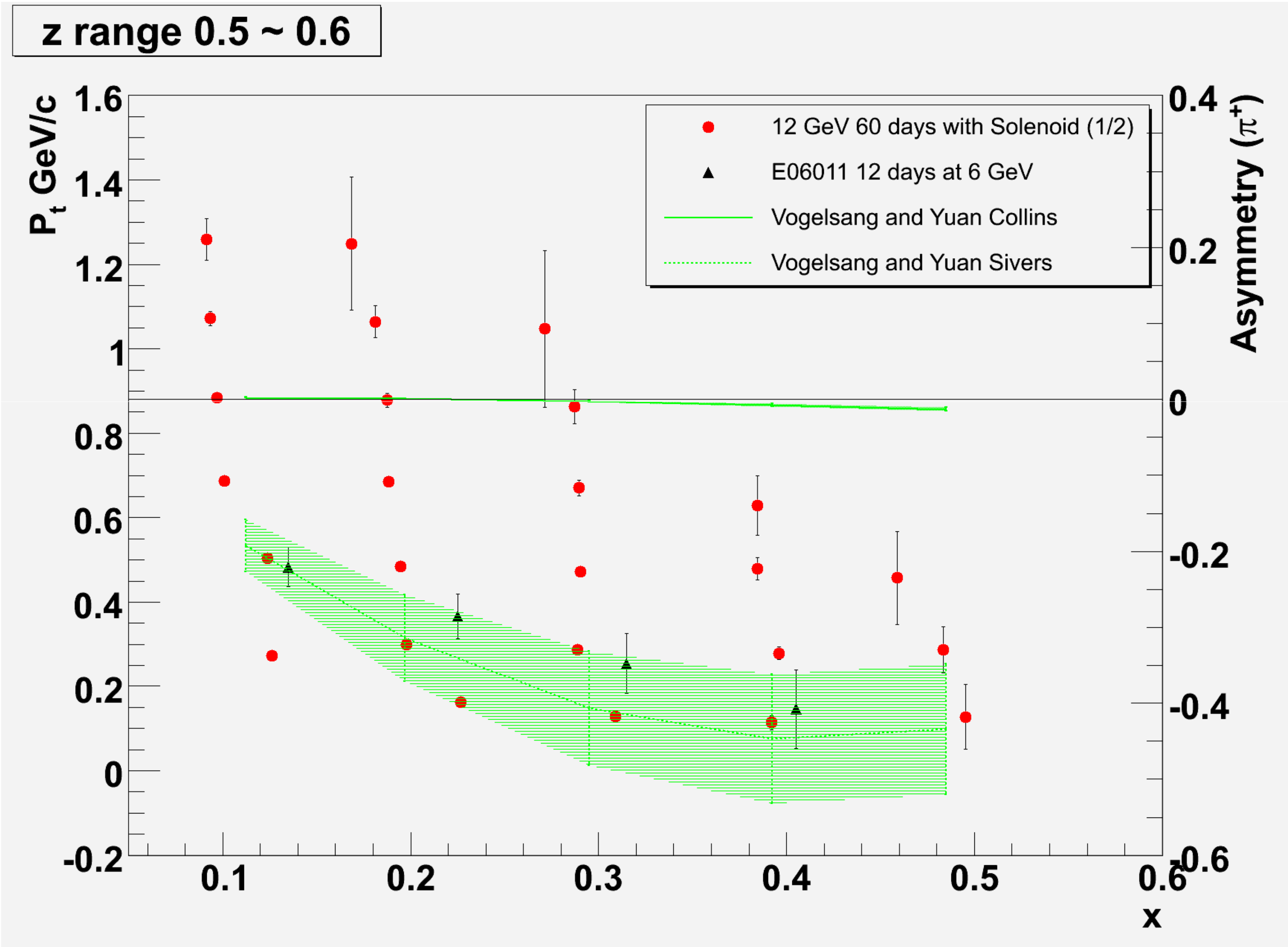
Solenoid detector for SIDIS at 11 GeV

Proposed for PVDIS at 11 GeV

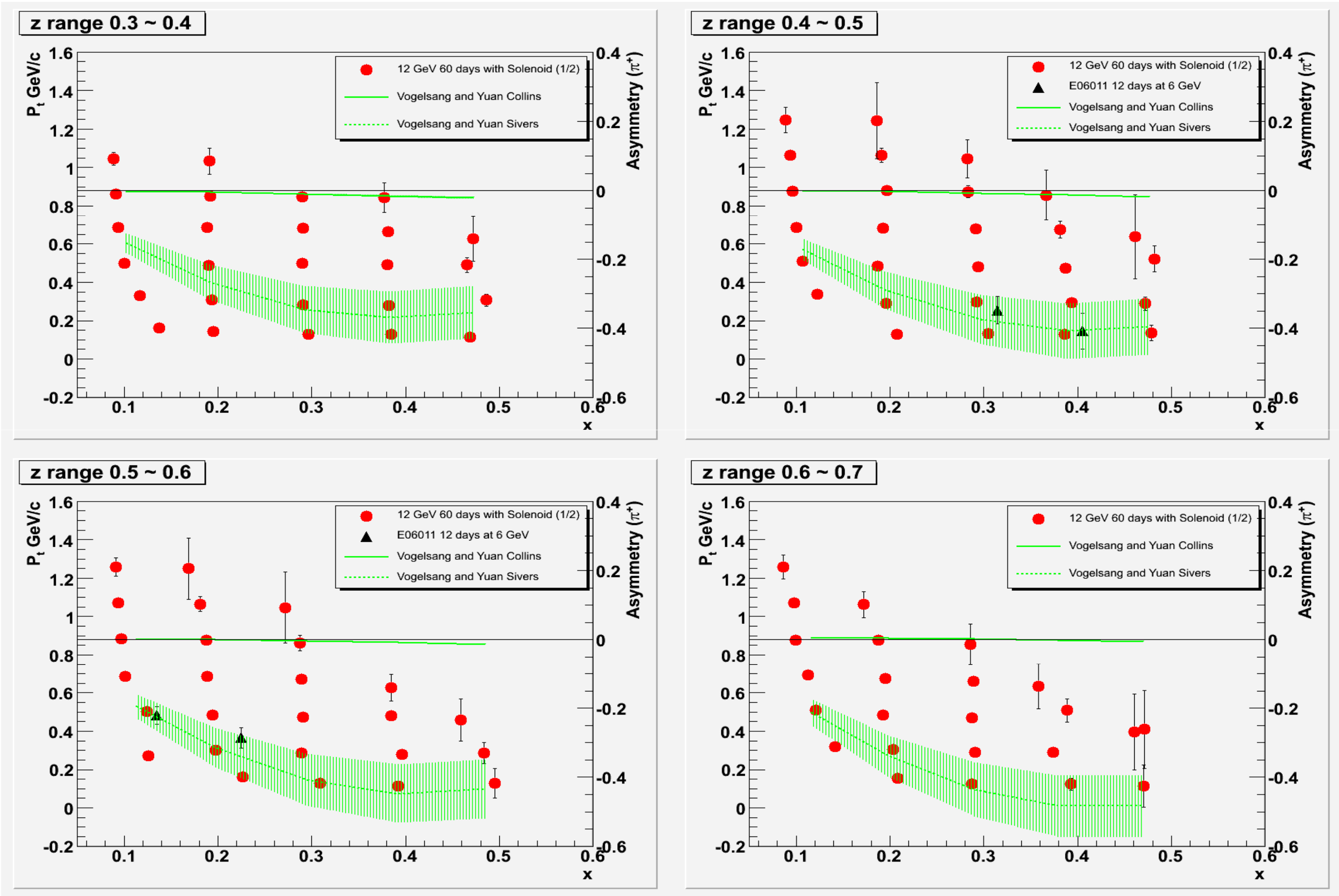


3-D Mapping of Collins/Siver Asymmetries at JLab 12 GeV With A Large Acceptance Solenoid Detector

- 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

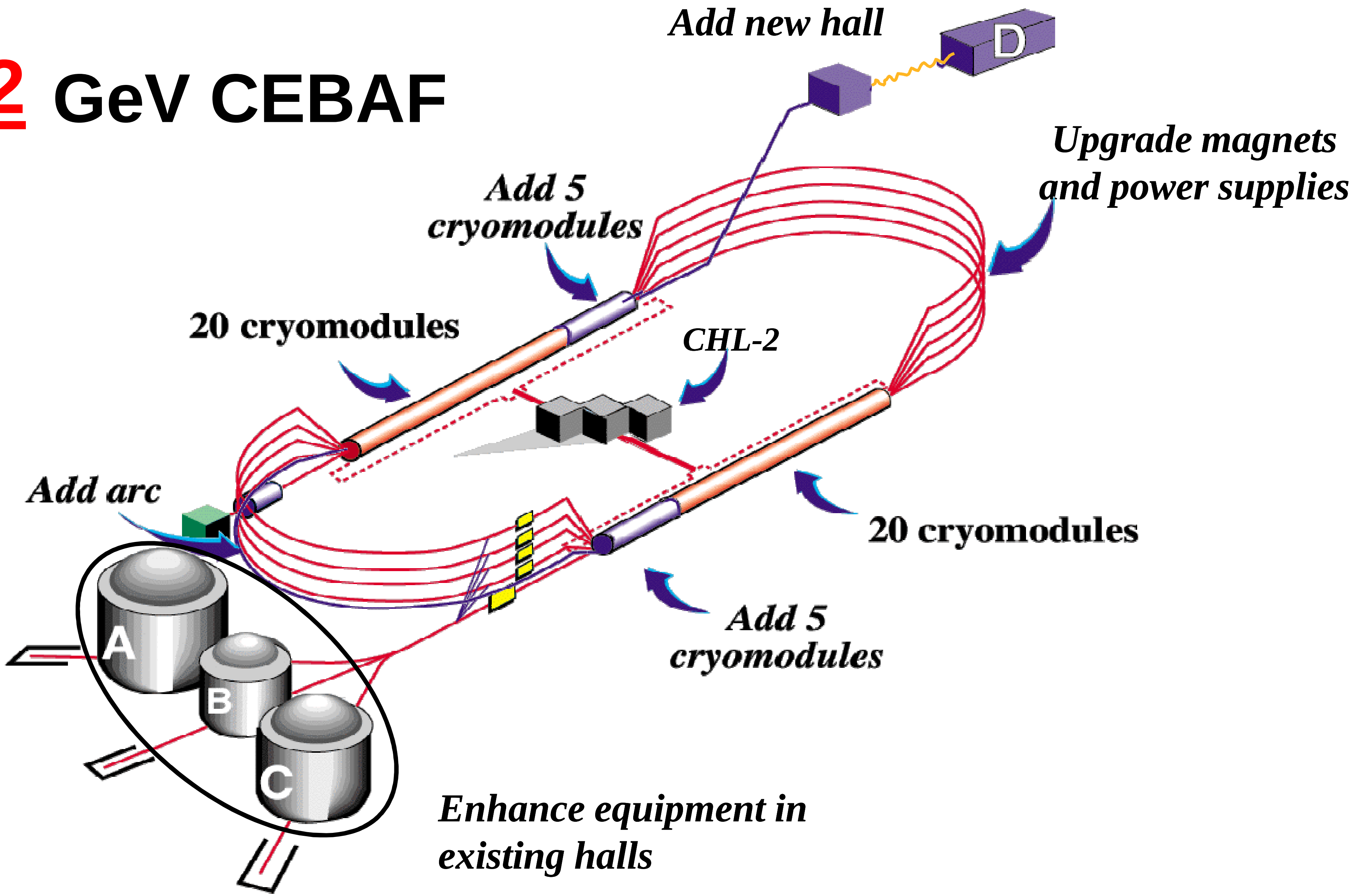
- Unprecedented precision *3-d* mapping of SSA
  - Collins and Sivers
  - π^+, π^- and K^+, K^-
- Study factorization with x and z-dependences
- Study P_T dependence
- Combining with CLAS12 proton and world data
  - extract transversity and fragmentation functions for both u and d quarks
  - determine 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

Summary

- Spin structure study full of surprises and puzzles
- A decade of experiments from JLab: exciting results
  - Spin sum rules and polarizabilities: test χPT calculations

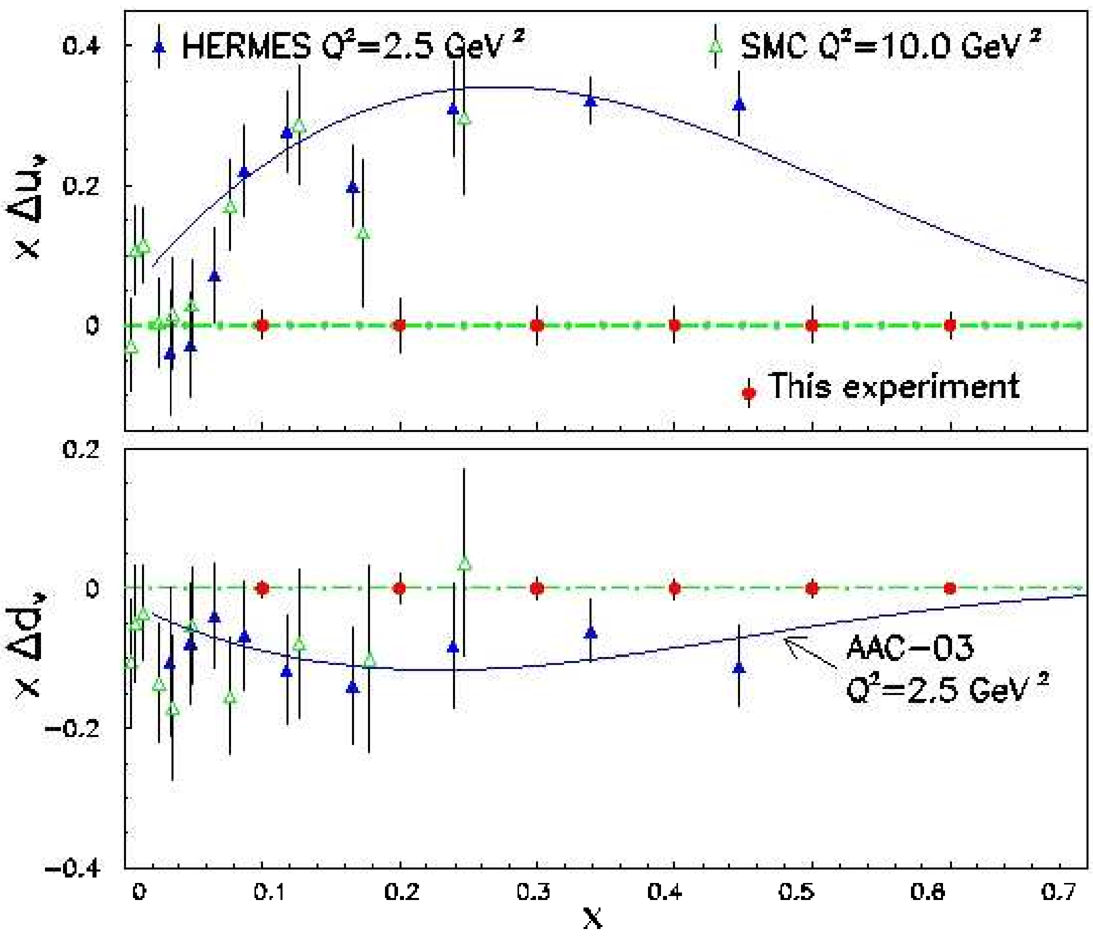
  → 'δ_{LT} puzzle'
  - g_2/d_2: higher-twist effects and q-g correlations, *L*QCD
  - Spin-duality: transition and link between hadrons and quark-gluons
  - A_1 at high-x: valence structure, flavor decomposition, quark OAM
- Bright future
  - Complete a chapter in longitudinal spin structure study
  - 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.

12 GeV CEBAF

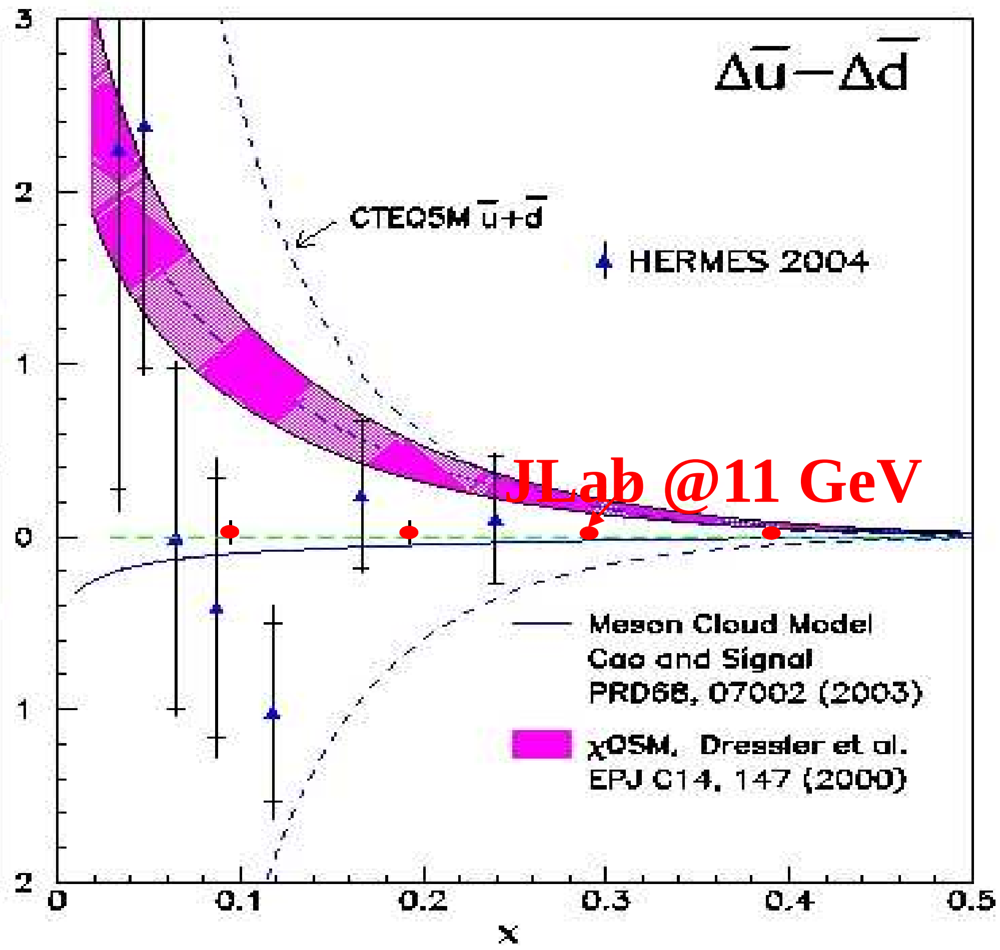

Add new hall
D
Upgrade magnets
and power supplies
Add 5
cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5
cryomodules
A
B
C
Enhance equipment in
existing halls

Flavor decomposition with SIDIS

Δu and Δd at JLab 11 GeV



Polarized Sea

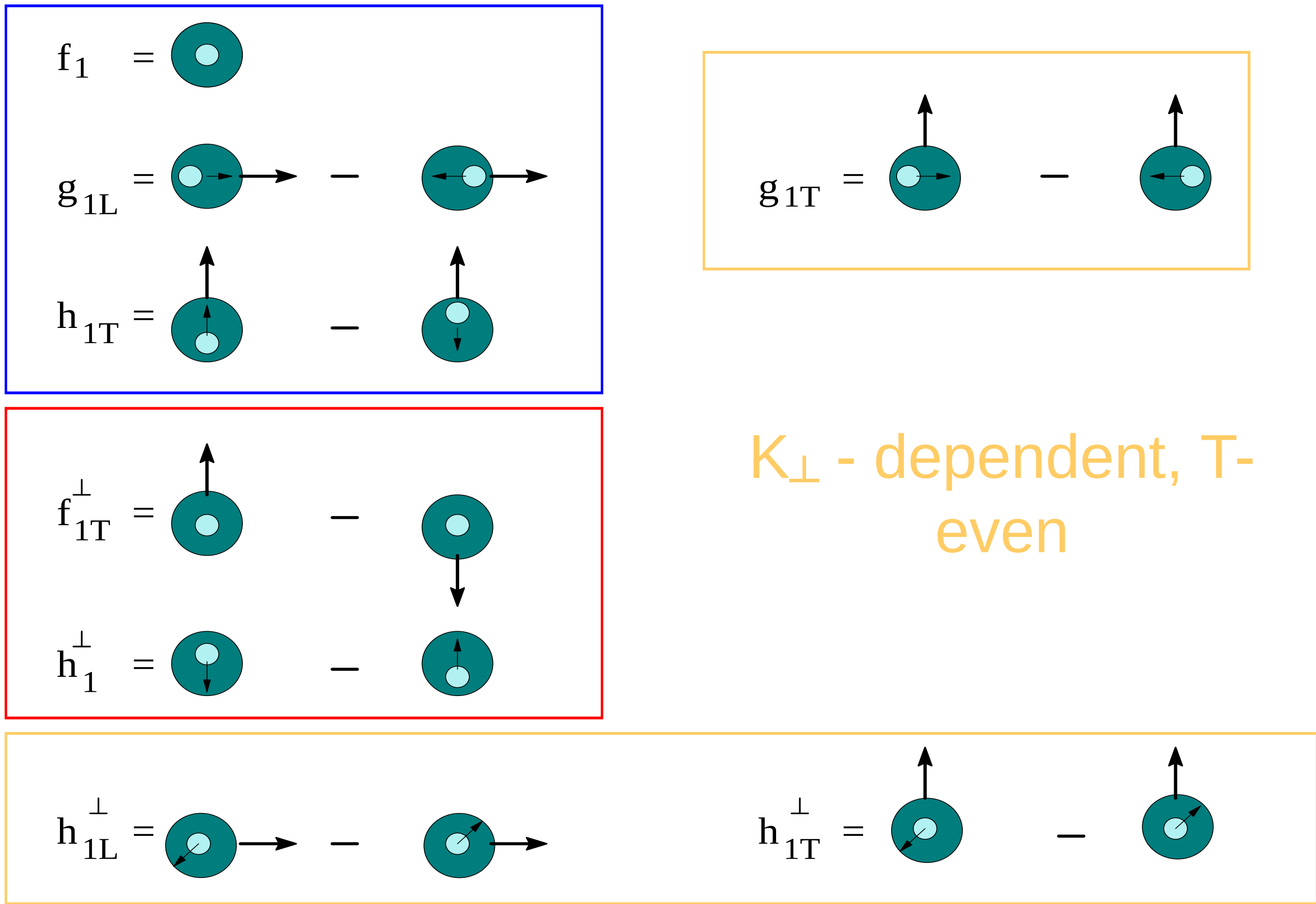


Leading-Twist Quark Distributions

(A total of eight distributions)

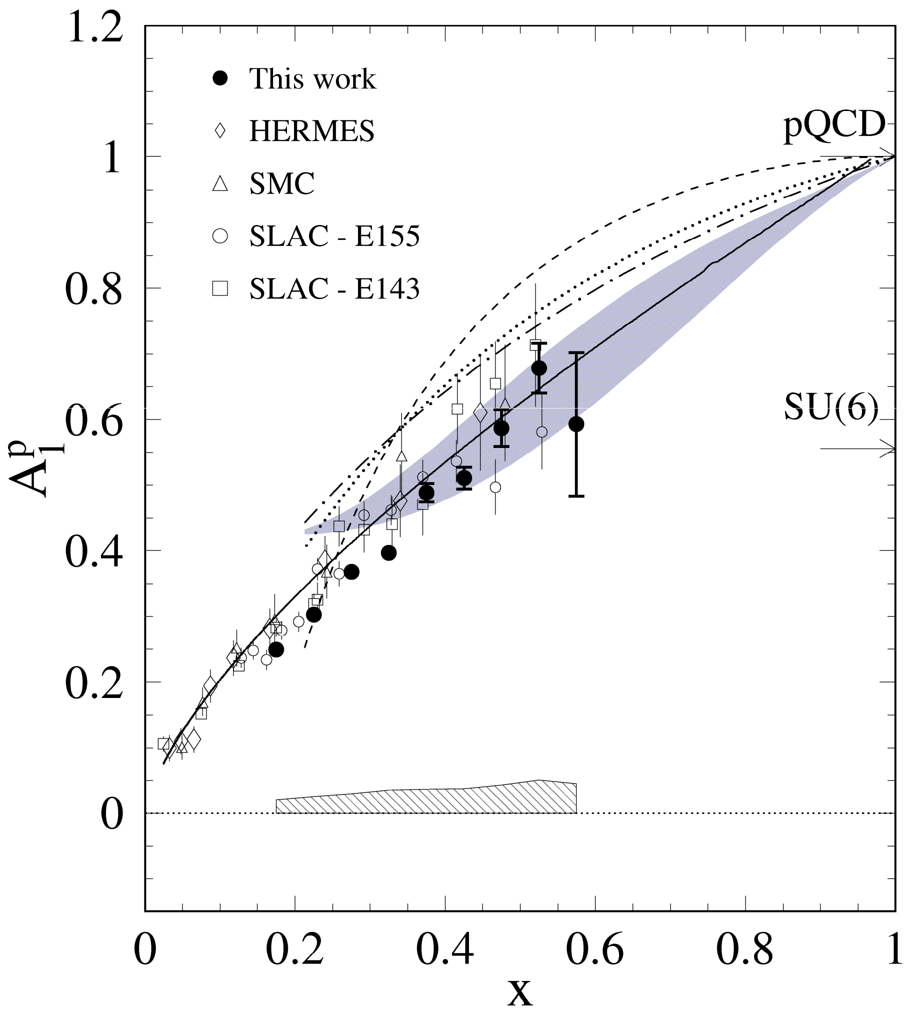
No $K_\perp$ dependence

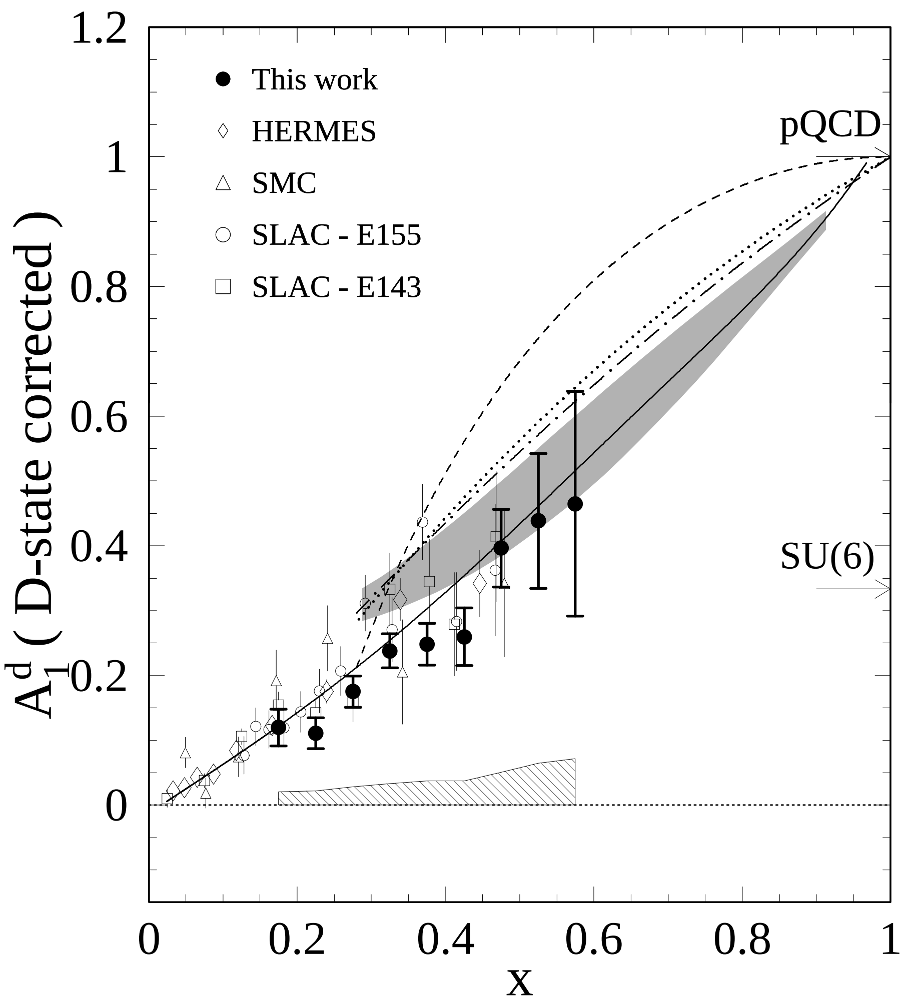
$K_\perp$ - dependent, T-odd



CLAS A_1^p and A_1^d results

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

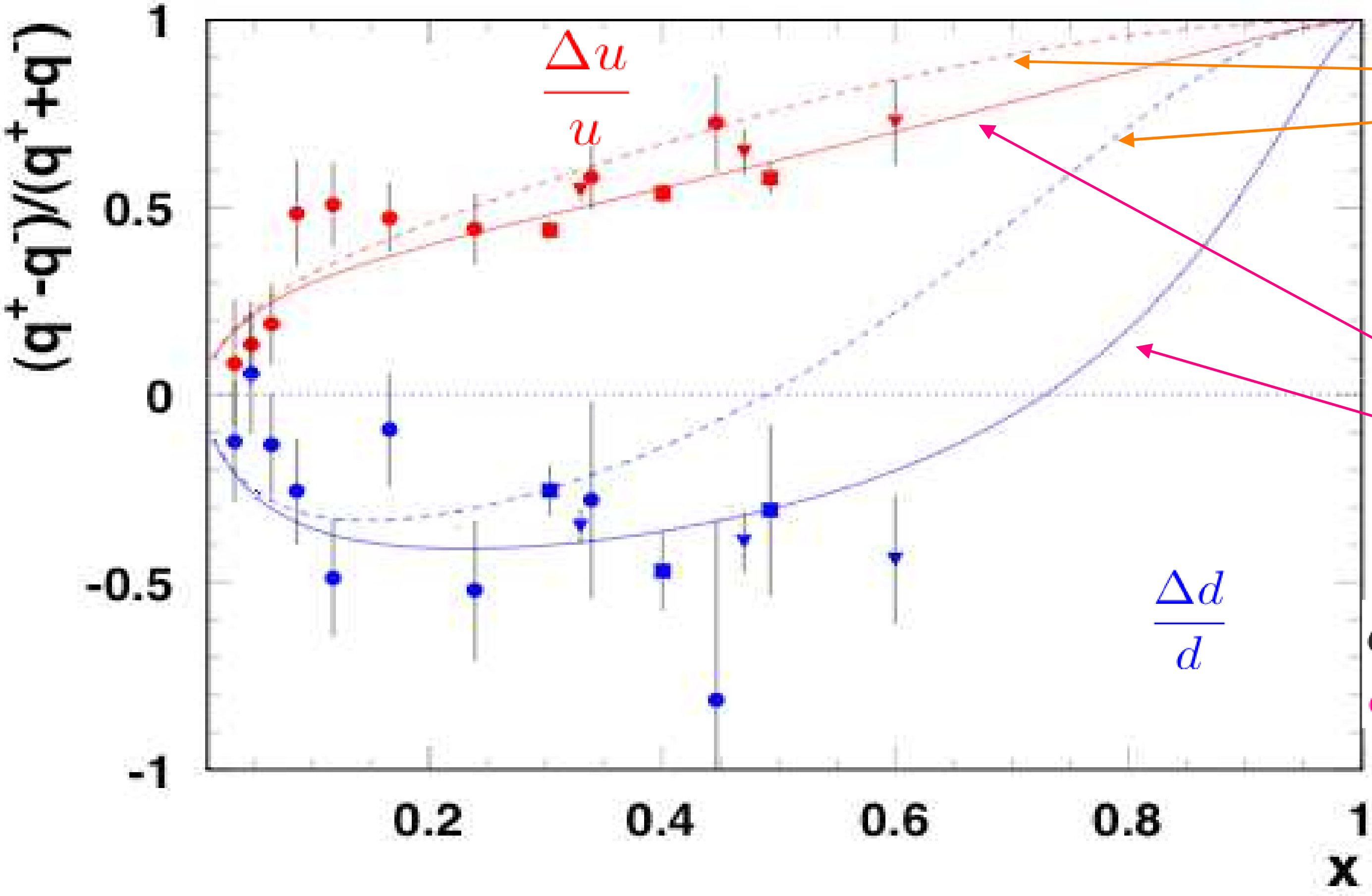




pQCD with Quark Orbital Angular Momentum

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

Inclusive Hall A and B and Semi-Inclusive Hermes



BBS

$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5$$
$$x \longrightarrow 1$$

BBS+OAM

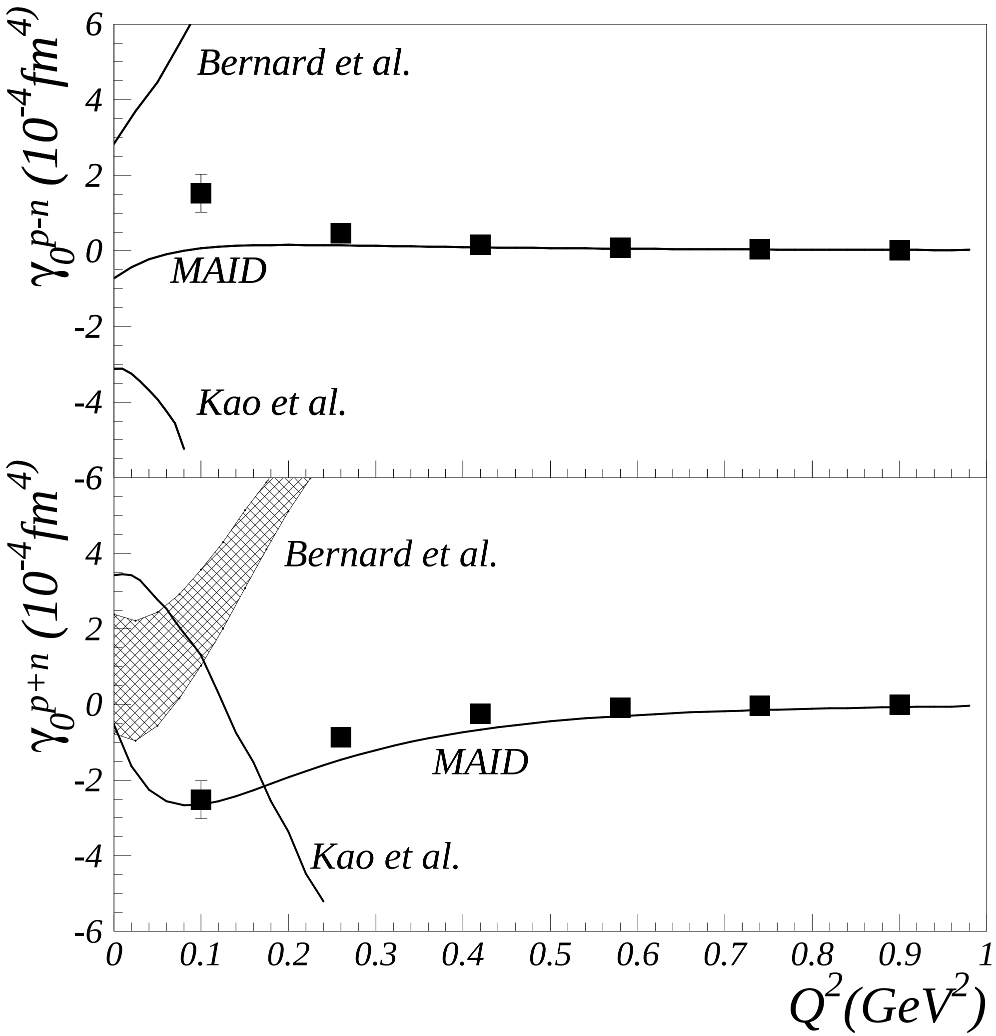
$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5 \ln^2(1-x)$$
$$x \longrightarrow 1$$

Spin Polarizability γ_0: Isospin Separation

- Deur *et al.* *arXiv:0802.2232*

- γ_0 sensitive to resonance, but p-n not sensitive to Δ

Still large discrepancy with ChPT



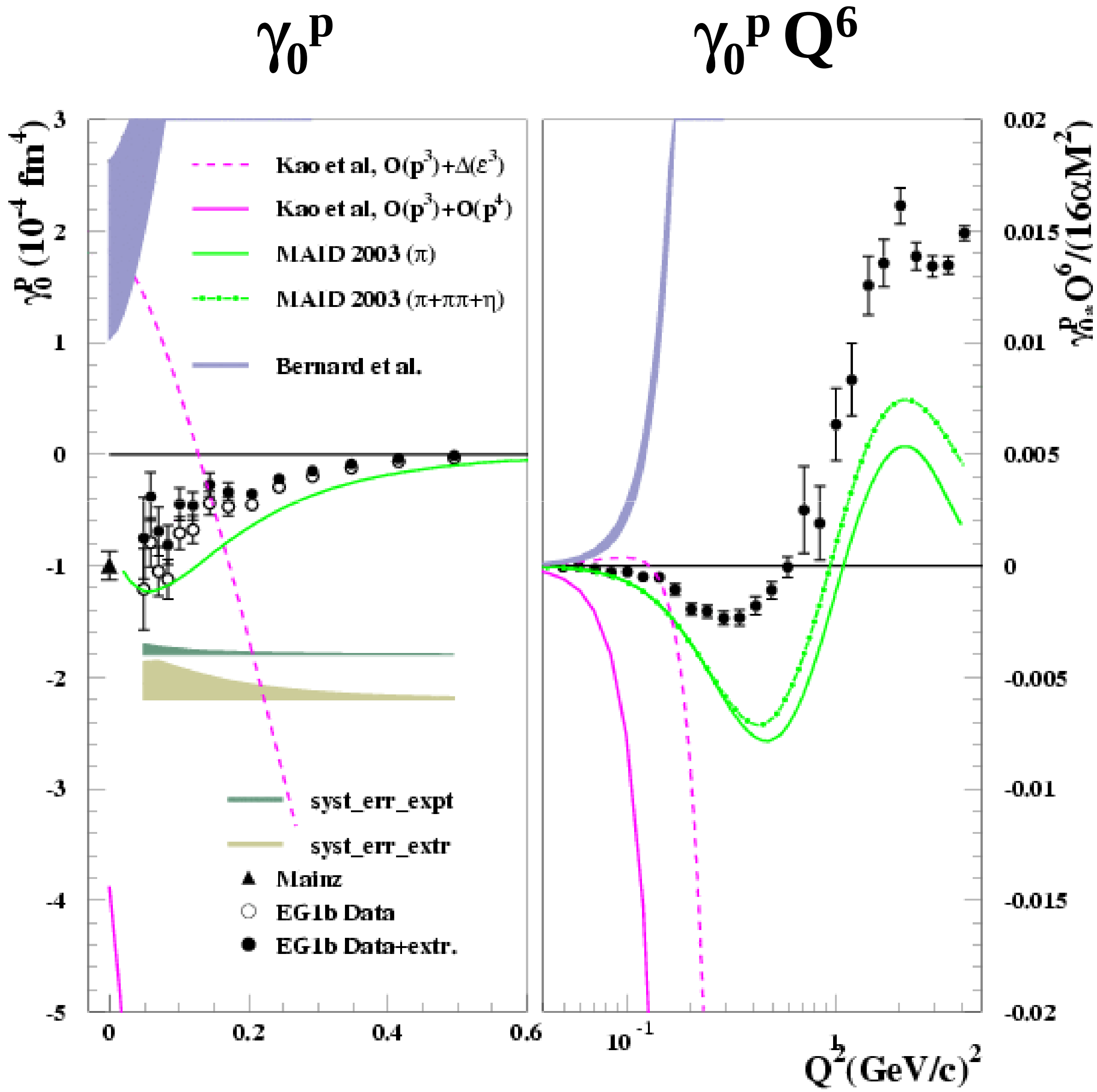
CLAS Proton Spin Polarizability

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

Large discrepancies with ChPT!

Only longitudinal data, model for transverse (g_2)

γ_0 sensitive to resonance

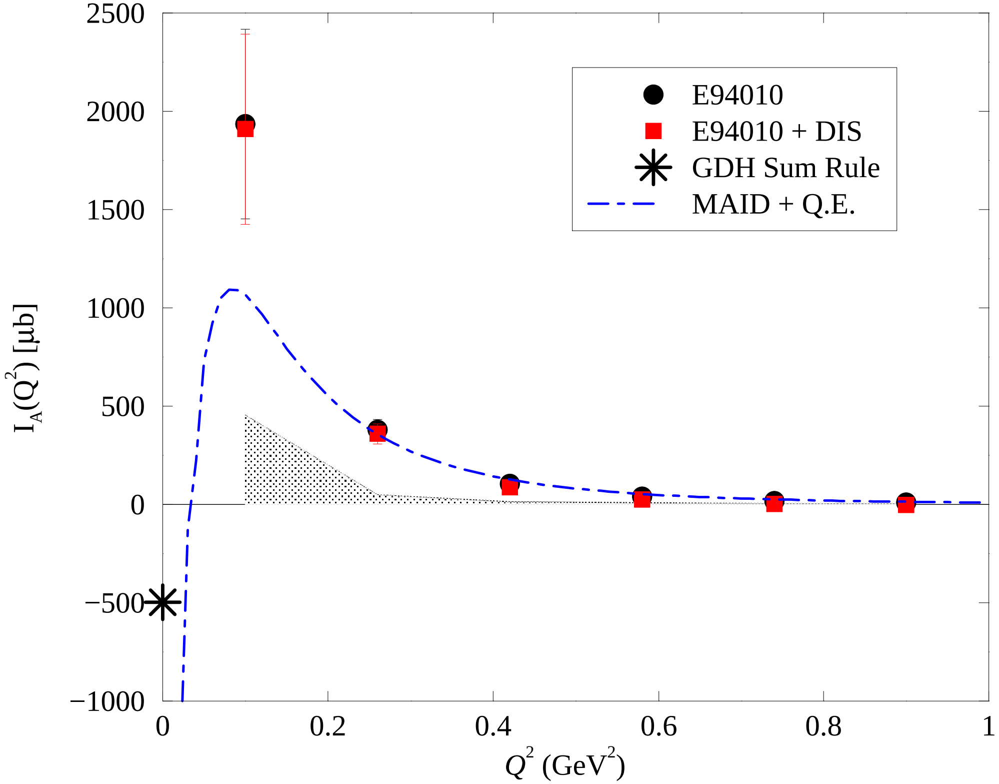


New Hall A ^{3}He Results

- 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



Γ_1