Physics in Electron-Ion Collider Experiments
III: Nucleon Spin Structure

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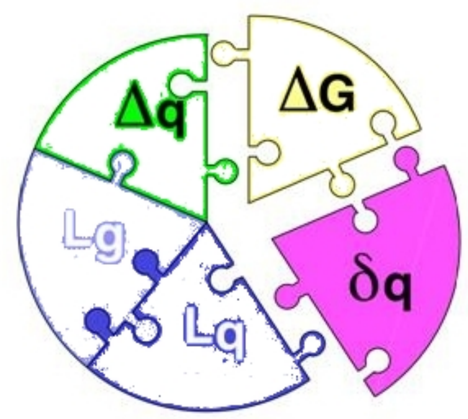
Huada School on QCD 2016: QCD in the EIC Era , May 23 – June 3, 2016

- Spin Milestone and "Spin Crisis"
- A_1 at high-x (valence quark region)
- Spin-flavor structure and gluon polarization
- Moments of spin structure: sum rules and polarizabilties
- g_2 and higher-twist effects (quark-gluon correlations)



Introduction

Spin Milestone and “Spin Crisis”

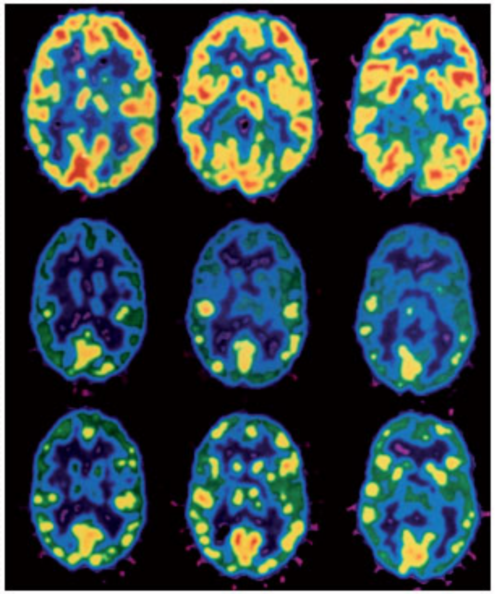
Spin Milestones (I)

- Nature: (www.nature.com/milestones/milespin)
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1932: Isospin(6)
  - 1935: Proton anomalous magnetic moment
  - 1940: Spin–statistics connection(7)
  - 1946: Nuclear magnetic resonance (NMR)(8)
  - 1950s: Development of magnetic devices (9)
  - 1950-51: NMR for chemical analysis (10)
  - 1951: Einstein-Podolsky-Rosen argument in spin variables(11)
  - 1964: Kondo Effect (12)
  - 1971: Supersymmetry(13)
  - 1972:Superfluid helium-3 (14)

Pauli and Bohr watch a spinning top

Spin Milestones (II)

- 1973: Magnetic resonance imaging(15)
- 1975-76:NMR for protein structure determination (16)
- 1978: Dilute magnetic semiconductors (17)
- 1980s: "Proton spin crisis or puzzle"
- 1988: Giant magnetoresistance(18)
- 1990: Functional MRI (19)
-             Proposal for spin field-effect transistor (20)
- 1991: Magnetic resonance force microscopy (21)
- 1996: Mesocopic tunnelling of magnetization (22)
- 1997: Semiconductor spintronics (23)
- (Spin-polarized suprecurrents for spintronics, 1/2011)
- 2000s: "Nucleon transverse spin puzzle"?
-    ?: More puzzles in nucleon spin?
- ……
-    ?: Breakthroughs in nucleon spin/nucleon structure study?
- ……
-    ?: Applications of nucleon spin physics?



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) κ_p= 1.5 +- 10%

- 1943 Nobel Prize awarded to Stern

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

now: κ_p=1.792847386 +- 0.000000063

and κ_n=-1.91304275 +- 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

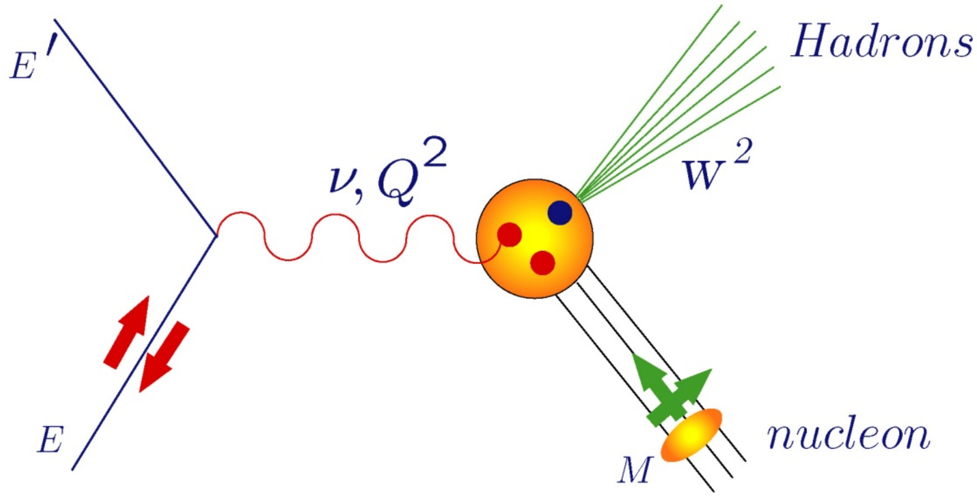
- Finite size ← → Excitation spectrum

- GDH Sum Rule

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

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

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

Cross Section & Spin Structure Functions

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left[\frac{F_2}{\nu} + 2\frac{F_1}{M}\tan^2\frac{\theta}{2}\right]$$

$$\frac{d^2\sigma}{dE' d\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1 - \frac{Q^2}{\nu}g_2\right]$$

$$\frac{d^2\sigma}{dE' d\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin\theta}{MQ^2}\frac{E'^2}{E}\frac{1}{\nu^2}(\nu g_1 + 2E g_2)$$

Quark-Parton Model

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

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

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

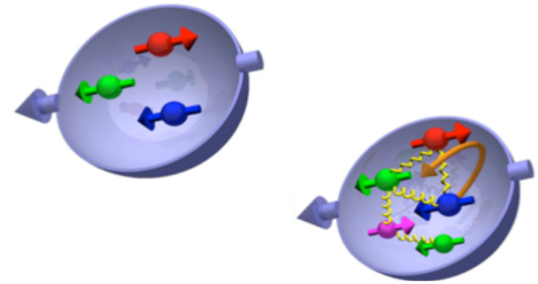
$q_i(x)$ quark momentum distributions of flavor i

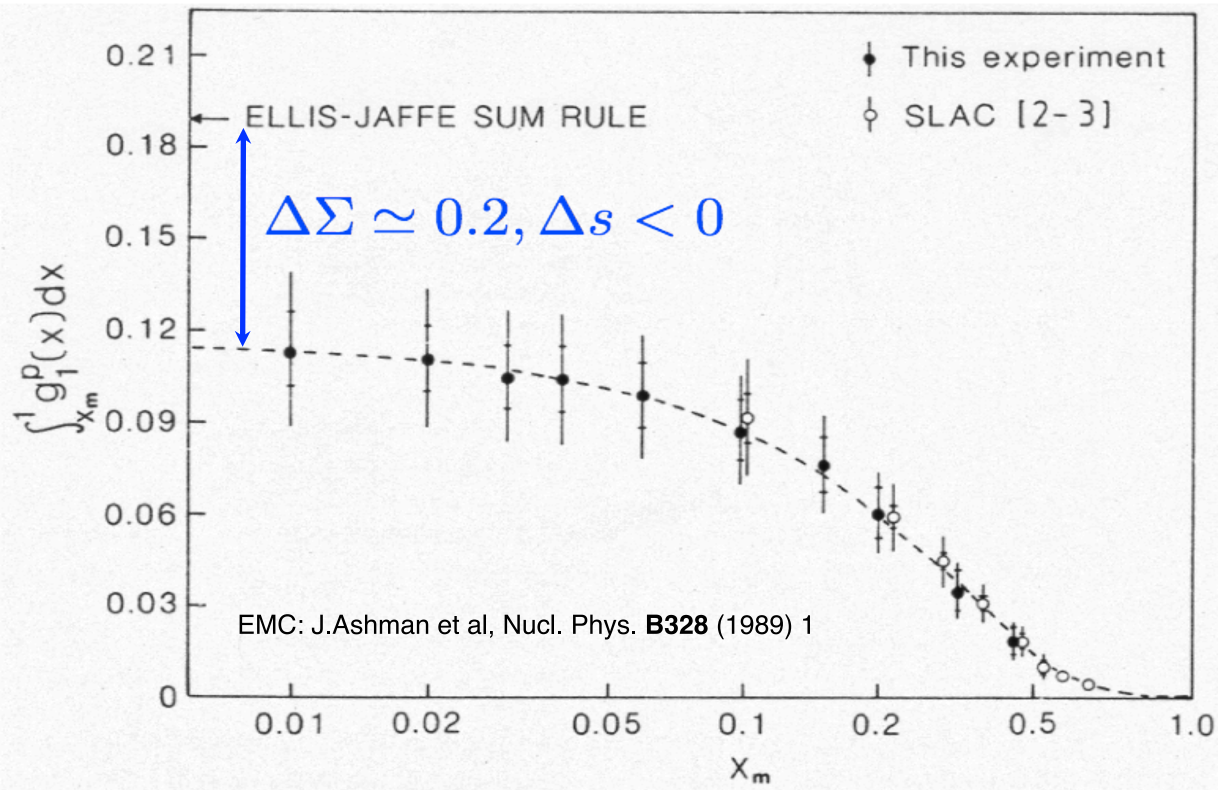
$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

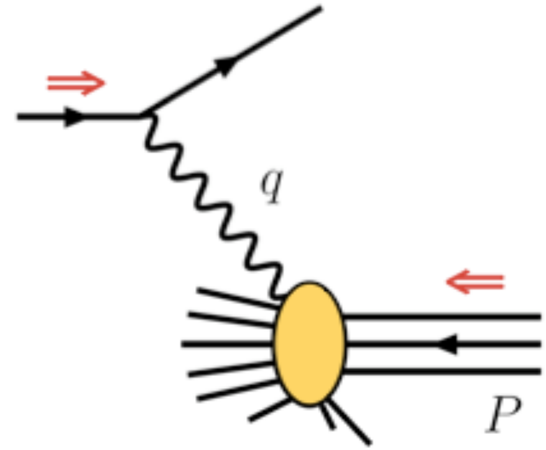
$F_2 = 2xF_1$ $\qquad g_2 = 0$

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

DIS - Surprises with Spin



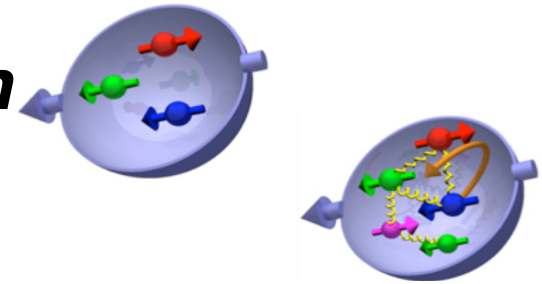




$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x,Q^2)}$$

The sum of Quark Spins contribute little to the proton spin, and strange quarks are negatively polarized.

DIS - Surprises with Spin



For the proton,

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x = \int_0^1 \left(\frac{1}{2}\sum e_q^2 \Delta q(x)\right)\mathrm{d}x = \frac{1}{2}\left(\frac{4}{9}\Delta_1 u + \frac{1}{9}\Delta_1 d + \frac{1}{9}\Delta_1 s\right)$$

$$= \frac{1}{12}(\Delta_1 u - \Delta_1 d) + \frac{1}{36}(\Delta_1 u + \Delta_1 d - 2\Delta_1 s) + \frac{1}{9}(\Delta_1 u + \Delta_1 d + \Delta_1 s)$$

Unique to DIS, $\Delta\Sigma$

Known from weak neutron to proton decay, combined with weak Σ to neutron decay

Known from weak neutron to proton decay

which becomes a prediction if $\Delta_1 s = 0$

Nucleon Spin Structure Study

- 1980s: EMC (CERN) + early SLAC

  quark contribution to proton spin is very small

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

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

  $\Delta\Sigma$ = 20-30%, the rest: gluon and quark orbital angular momentum

  $(½)\Delta\Sigma + L_q + \Delta G + L_G = 1/2$

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

  Bjorken Sum Rule verified to <10% level

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

  $\Delta\Sigma$ ~ 30%; ΔG contributes, orbital angular momentum significant

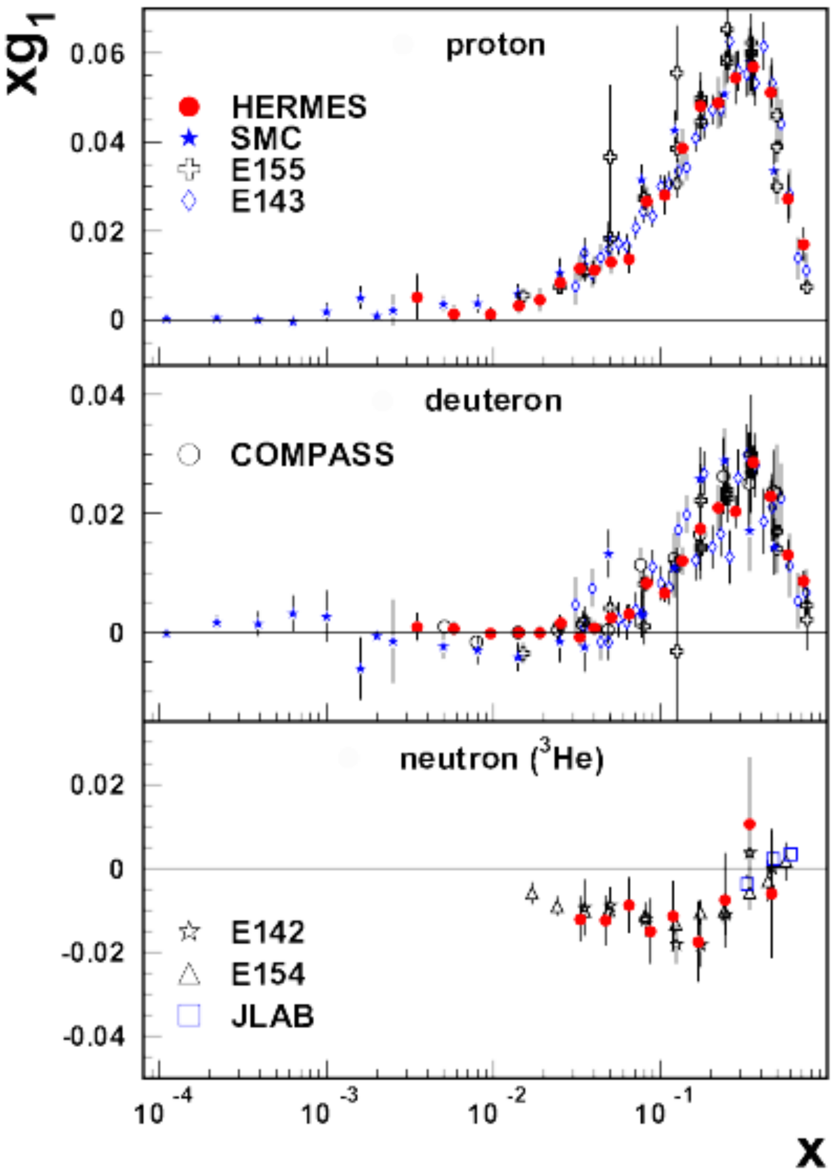
  Large-x (valence quark) behavior; Moments and sum rules

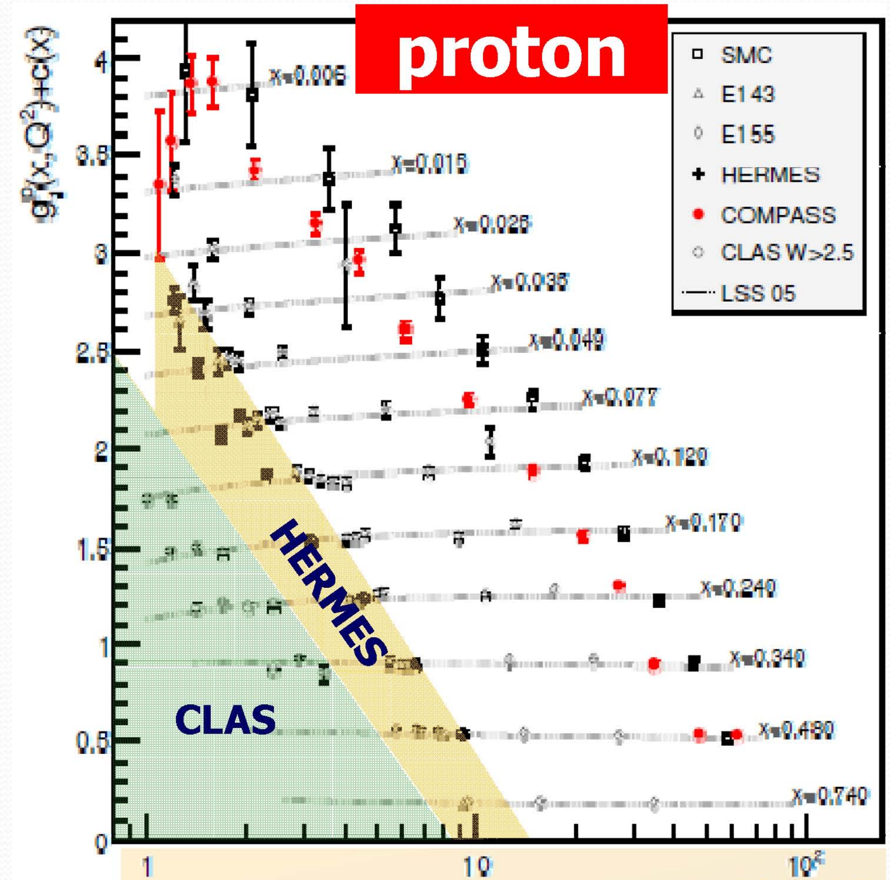
  Needs 3-d structure information to complete the proton spin puzzle

Reviews: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1;

J. P. Chen, arXiv:1001.3898, IJMPE 19 (2010) 1893

Polarized Structure functions

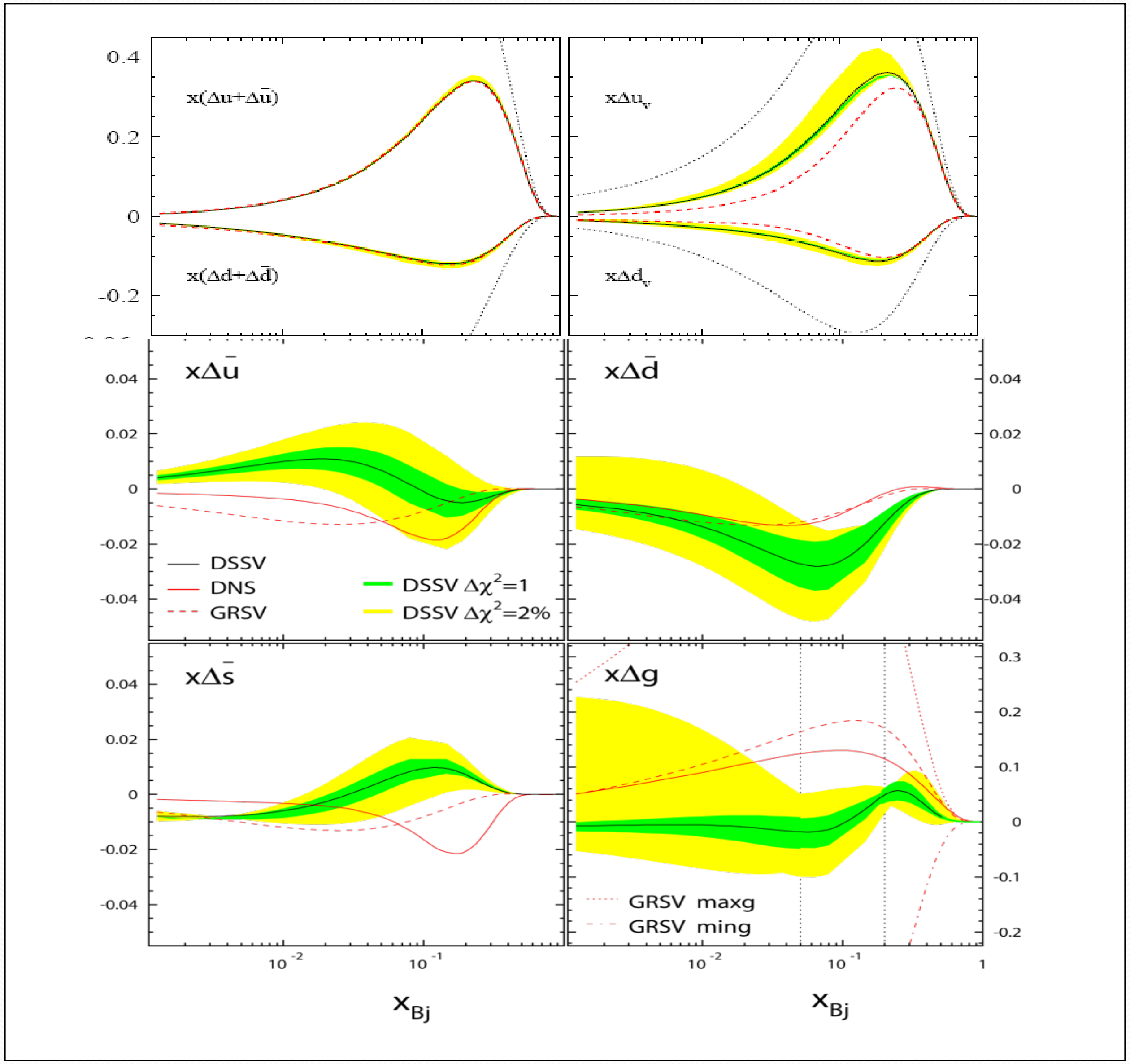




Q² [GeV²]

- Nice data!
- Q^2 dependence of g_1 data

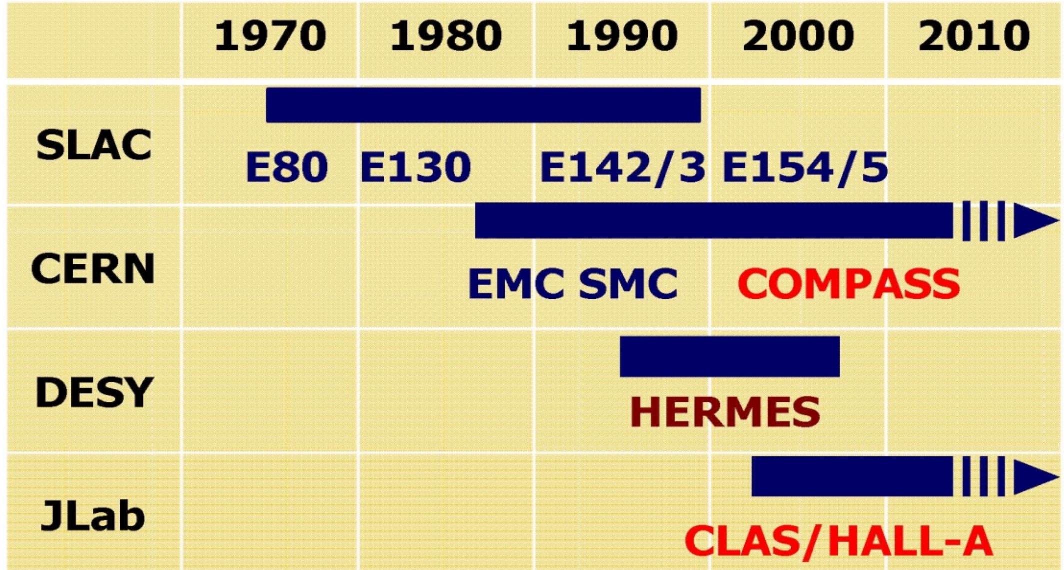
Polarized Parton Distributions



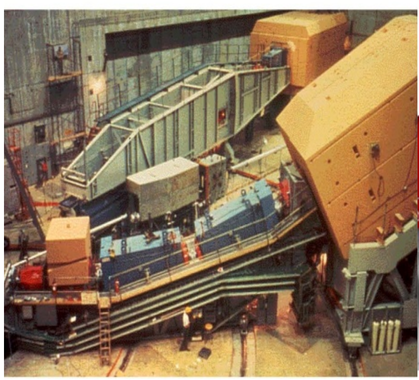
DSSV, PRL101, 072001 (2008)

Spin Structure Experiments

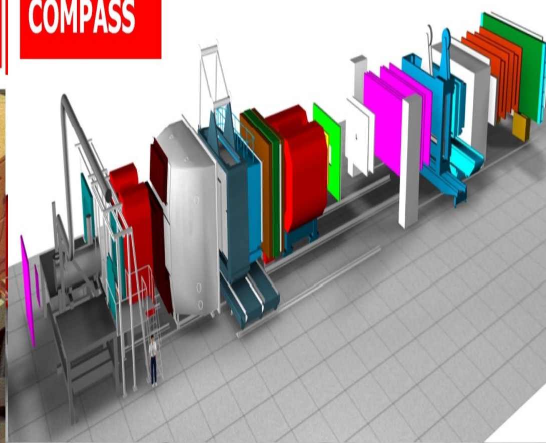
E80, E130	$\vec{e}\ \vec{p}$	≤ 20 GeV
EMC	$\vec{\mu}\ \vec{p}$	100–200 GeV
E142, 143	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	≤ 28 GeV
SMC	$\vec{\mu}\ \vec{p}, \vec{d}$	100, 190 GeV
E154, 155	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	≤ 50 GeV
HERMES	$\vec{e}\ \vec{p}, \vec{n}, \vec{d}$	27.5 GeV
COMPASS	$\vec{\mu}\ \vec{p}, \vec{d}$	160 GeV
HALL A	$\vec{e}\ \vec{n}$	6 GeV
CLAS	$\vec{e}\ \vec{p}, \vec{d}$	6 GeV



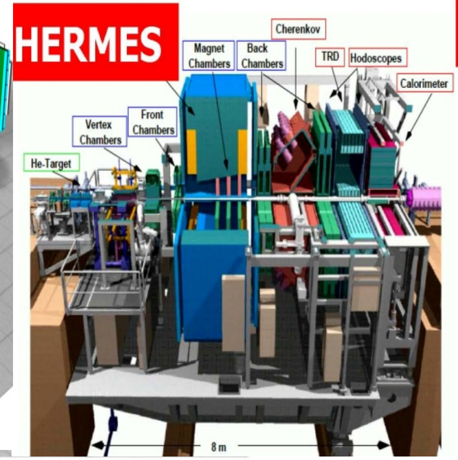
SLAC - End Station A



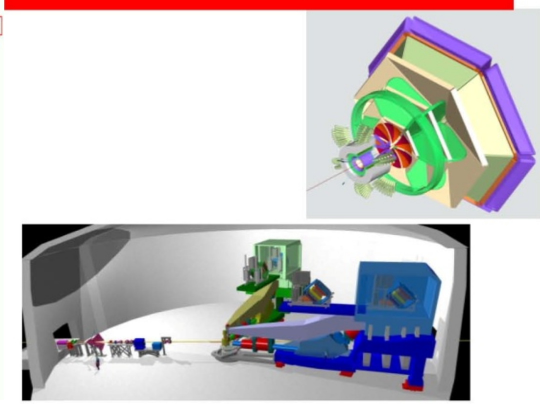
COMPASS



HERMES



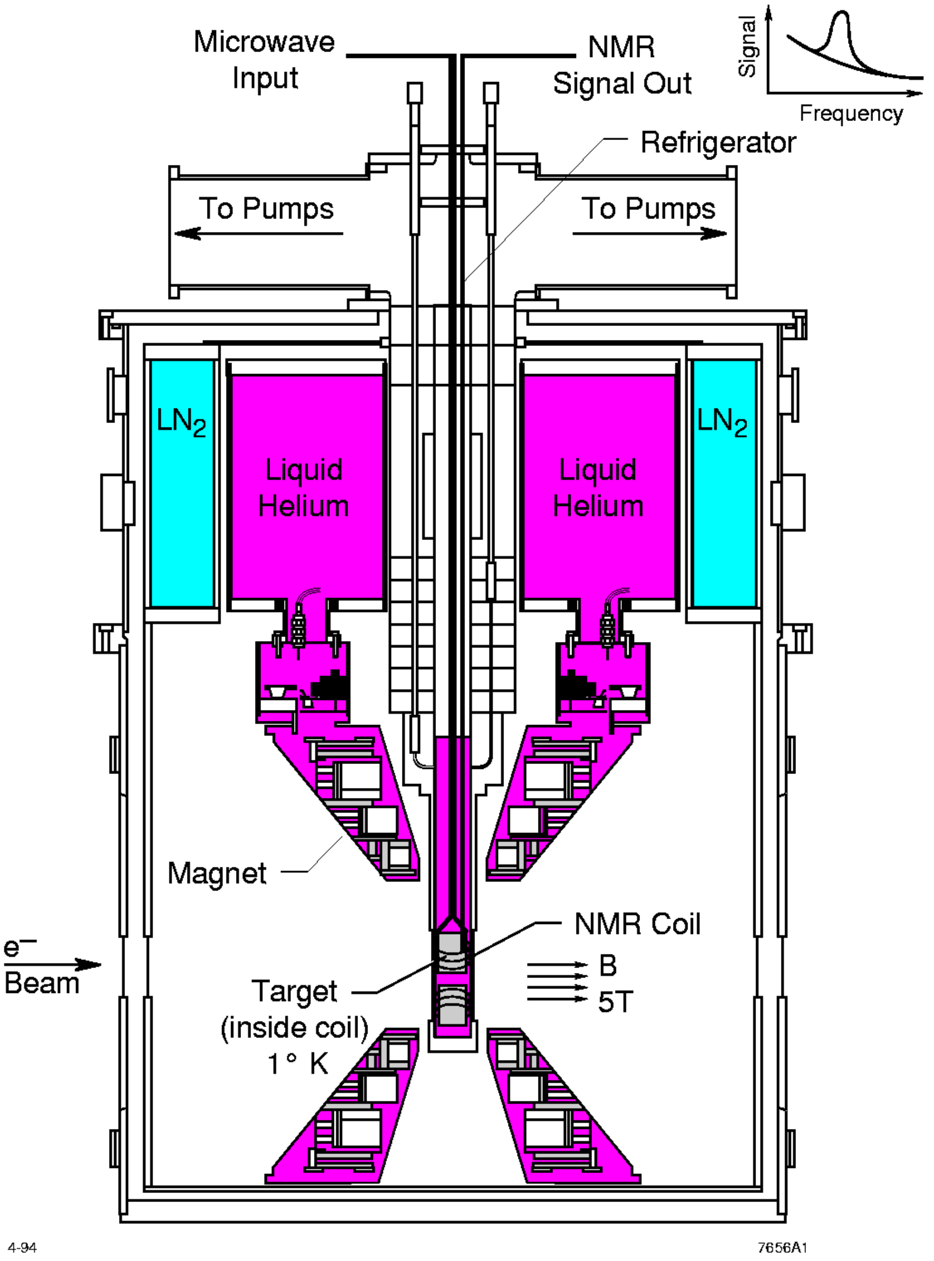
Jlab - CLAS, Hall A



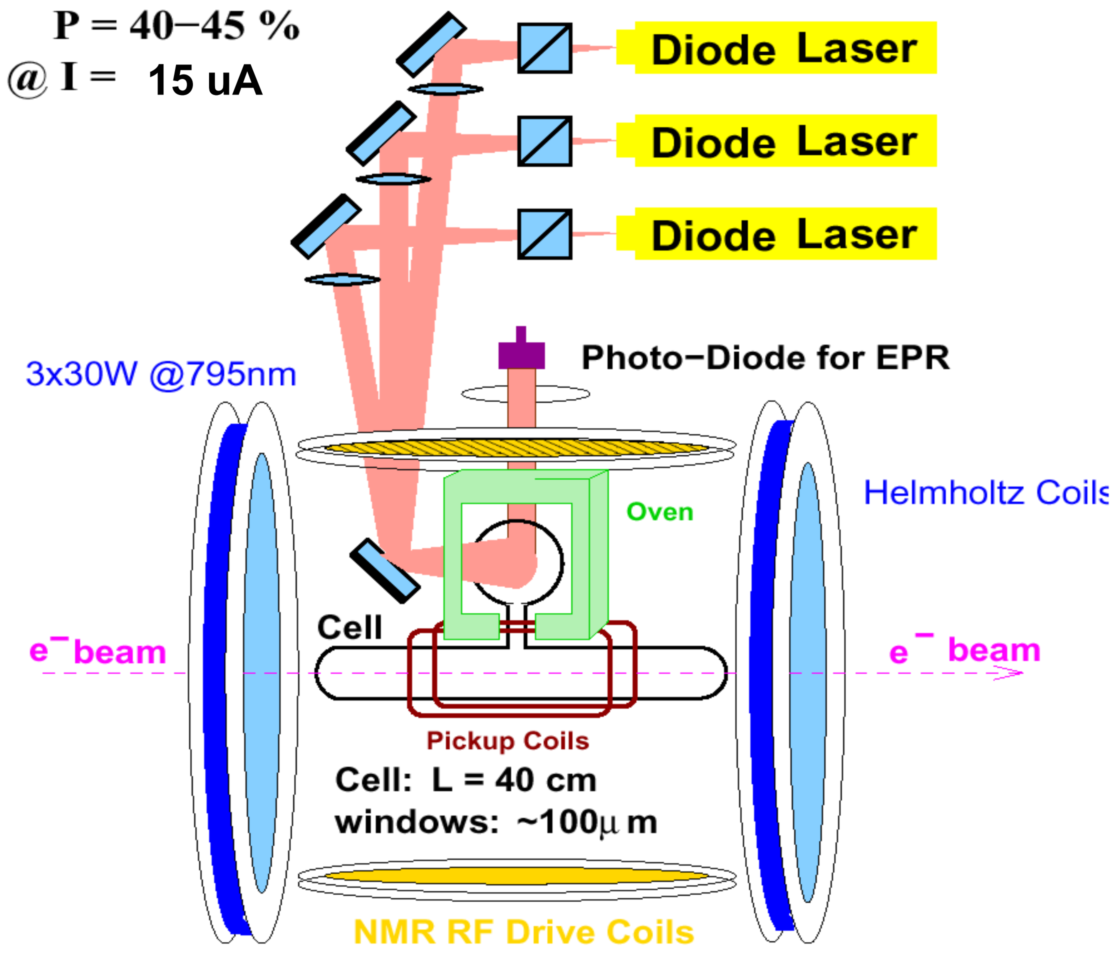
Polarized proton/ deuteron target

- Polarized NH_3/ND_3 targets
- Used in Hall B and Hall C (also at SLAC)
- Dynamical Nuclear Polarization

- ~ 90% for p
  ~ 40% for d
- Luminosity ~ 10^{35}

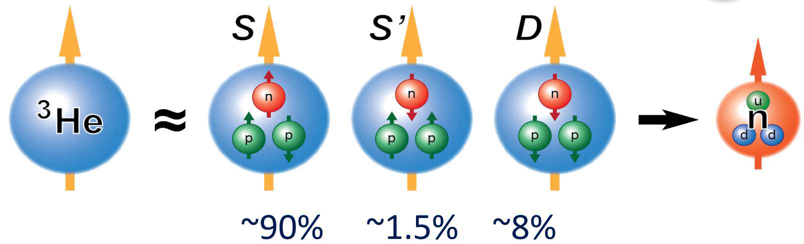


JLab polarized ^{3}He target

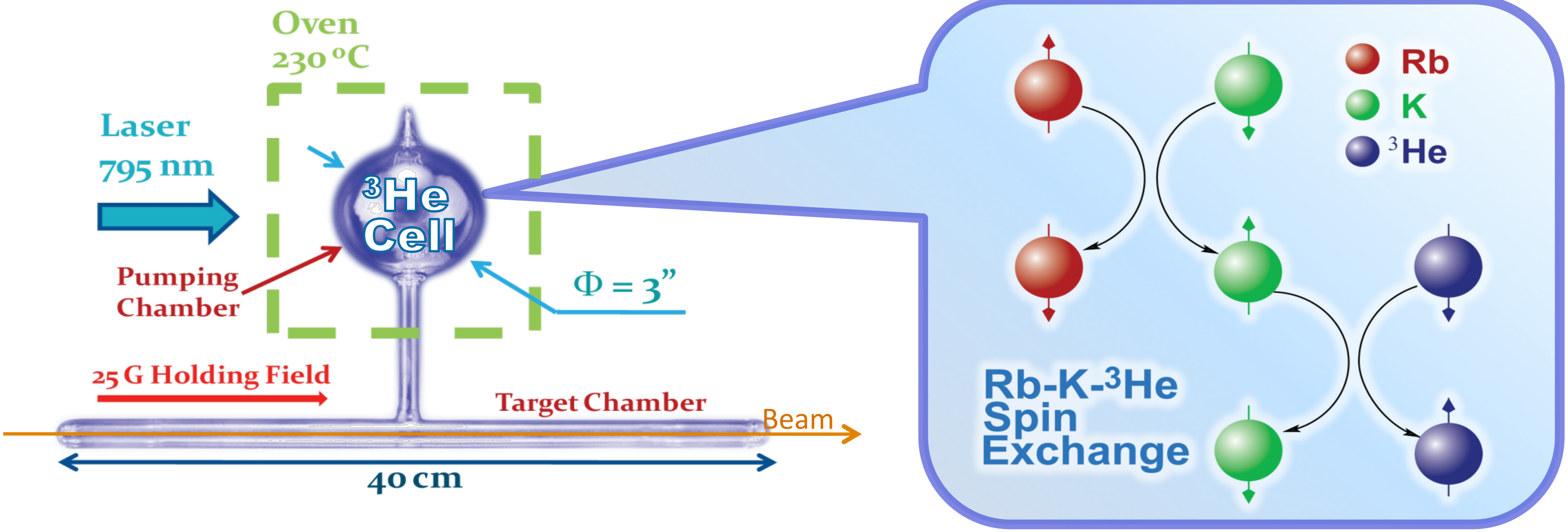


- ✓longitudinal, transverse and vertical
- ✓Luminosity=10^{36} (1/s) (highest in the world)
- ✓High in-beam polarization ~ 60%
- ✓Effective polarized neutron target
- ✓13 completed experiments
  7 approved with 12 GeV (A/C)

Polarized ^{3}He Target

- 

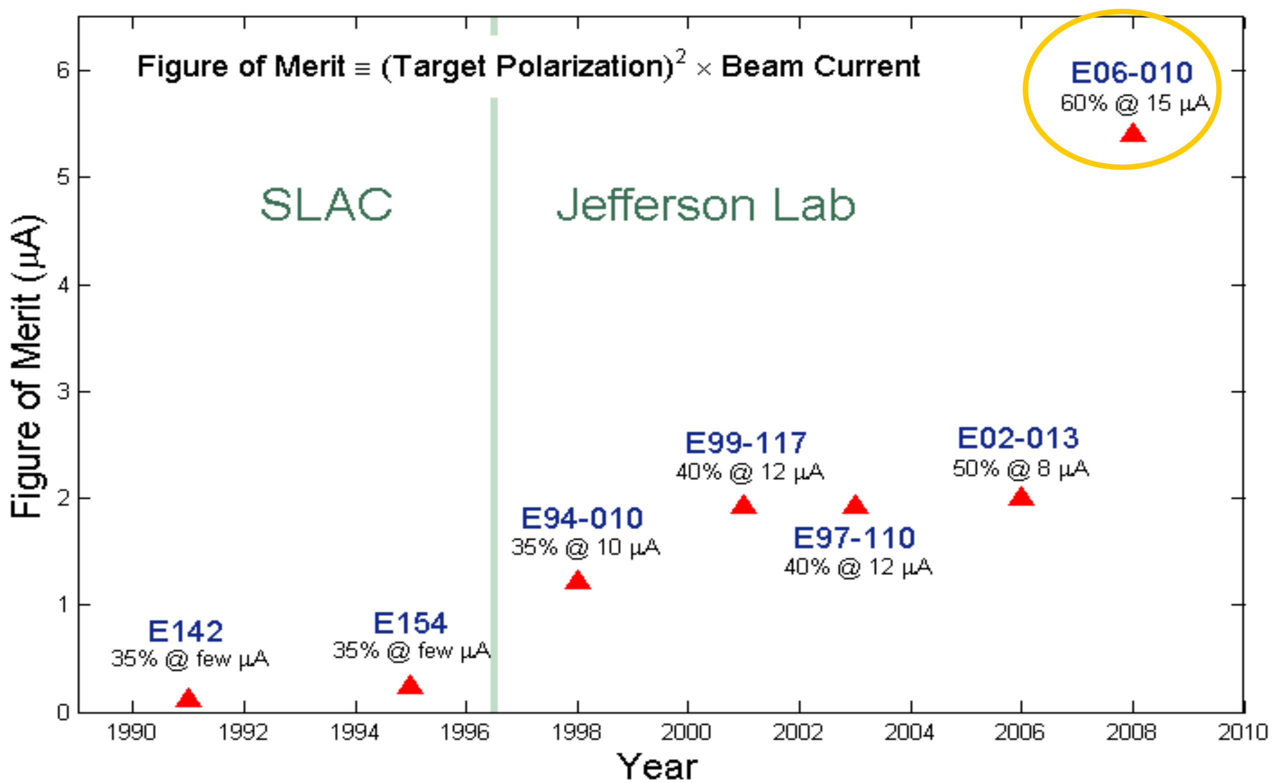
- High Luminosity polarize target: $L(n) = 10^{36}$ cm^{-2} s^{-1}(achieved), 10^{37} cm^{-2} s^{-1} (R&D)
- Compact size: No cryogenic support needed
- Proton dilution measured experimentally



Performance of ^{3}He Target

- High luminosity: $L(n) = 10^{36}$ cm^{-2} s^{-1} (being upgraded to 10^{37})
- Polarization in all 3 directions (L, T, V)
- **Record high in-beam ~ 60% polarization**
- Fast spin flip (every 20 minutes)

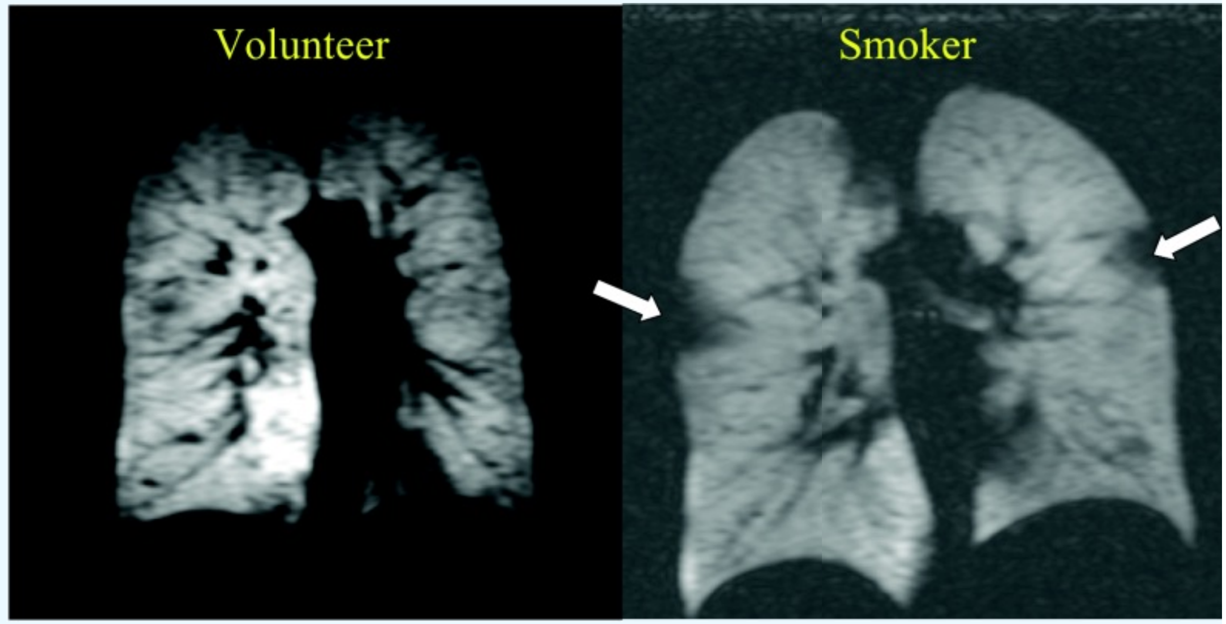
History of Figure of Merit of Polarized ^{3}He Target



Medical Imaging

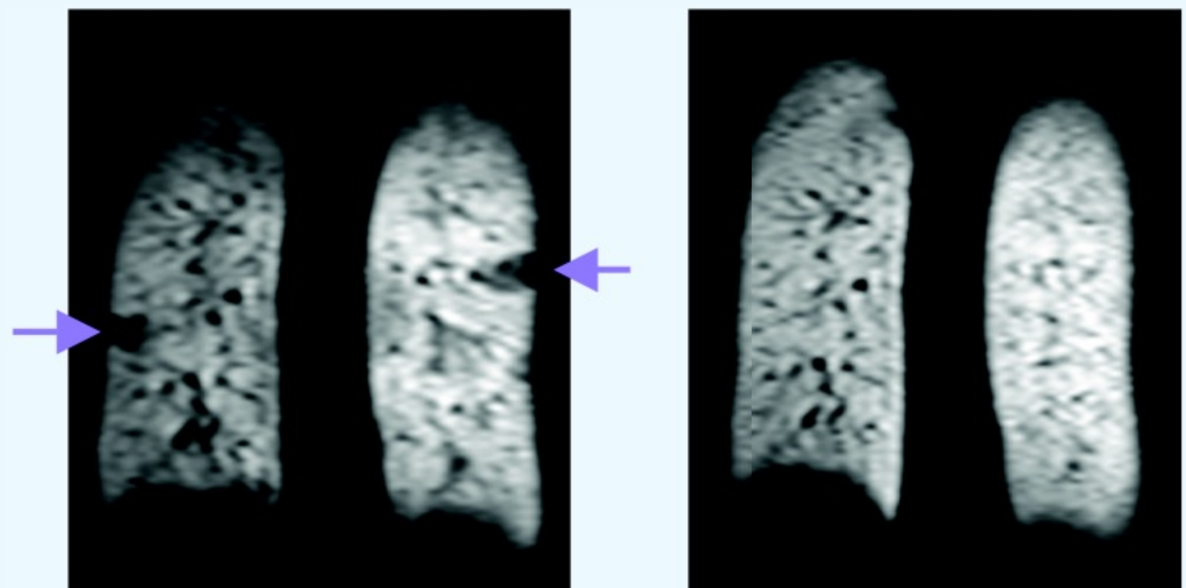
- ^{3}He Spin density MRI

Courtesy of W. Heil, Univ. Mainz



Courtesy of T. Altes et al., University of Virginia

Inhaled Bronchodilator
Asymptomatic Asthmatic



Experiment Summary ($Q^2 > 0$)

Observable	H target	D target	^{3}He target
g_1, g_2, Γ_1 & Γ_2 at high Q^2	SLAC JLAB SANE	SLAC	SLAC JLAB E97-117 JLAB E01-012 JLAB E06-014
g_1 & Γ_1 at high Q^2 COMPASS RHIC-Spin	SMC HERMES JLAB EG1	SMC HERMES JLAB EG1	HERMES
Γ_1 & Γ_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
Γ_1 at low Q^2	SLAC HERMES JLAB EG1	SLAC HERMES JLAB EG1	HERMES
$\Gamma_1, Q^2 << 1$ GeV^2	JLab EG4	JLab EG4	JLab E97-110
$\Gamma_2, Q^2 << 1$ GeV^2	JLab E08-027		JLab E97-110

Q^2=0 **Mainz, Bonn, LEGS, HIGS**

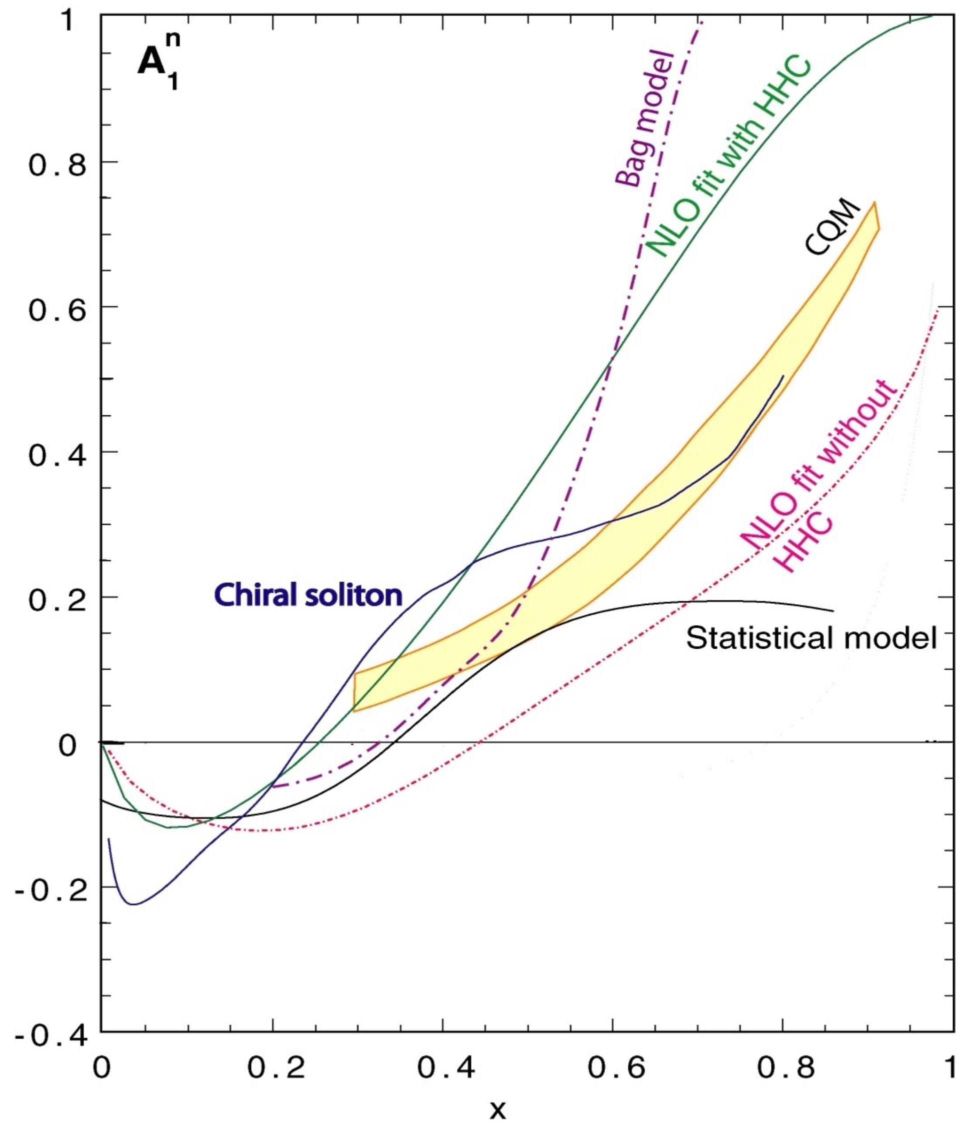
Select Highlights in Nucleon Spin Study I

g_1/A_1 at High-x: Valence Quark

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
  - $A_1^p \to 1$ $A_1^n \to 1$ $d/u \to 1/5$
  - $\Delta u/u \to 1$ $\Delta d/d \to 1$

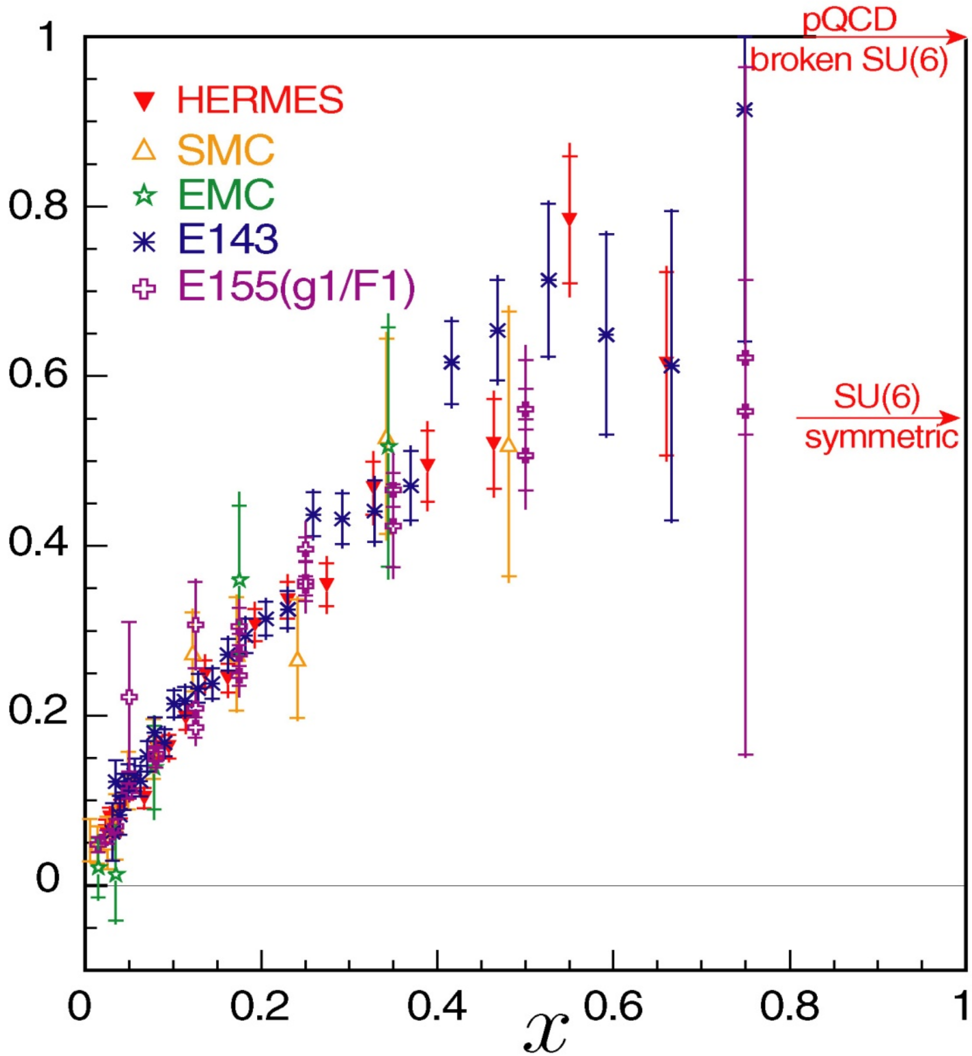
$q^{\uparrow}(x \to) \equiv (1-x)^3$ $q^{\downarrow}(x \to) \equiv (1-x)^5$



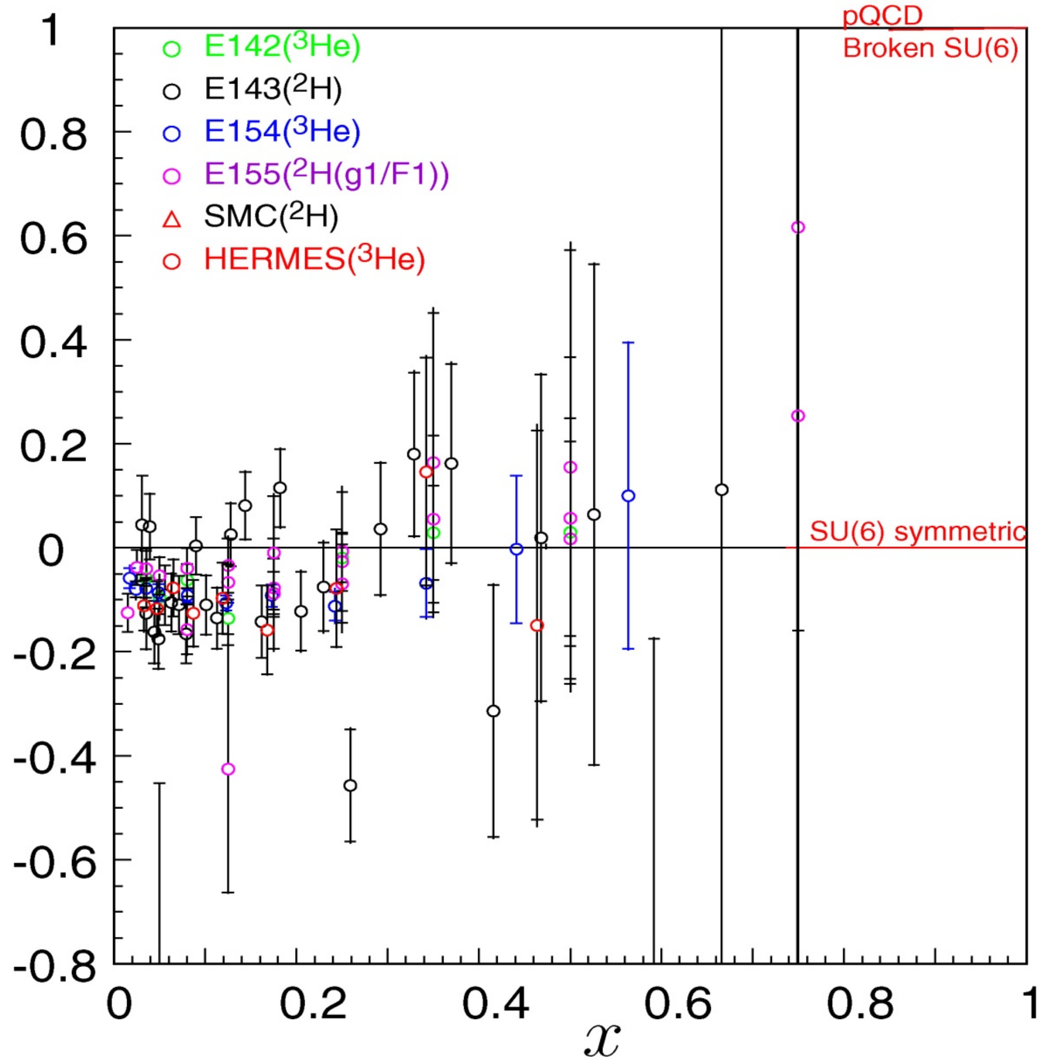
Note that $\Delta q/q$ as x--> 1 is more sensitive to spin-flavor symmetry breaking effects than A_1

World data for A_1

Proton



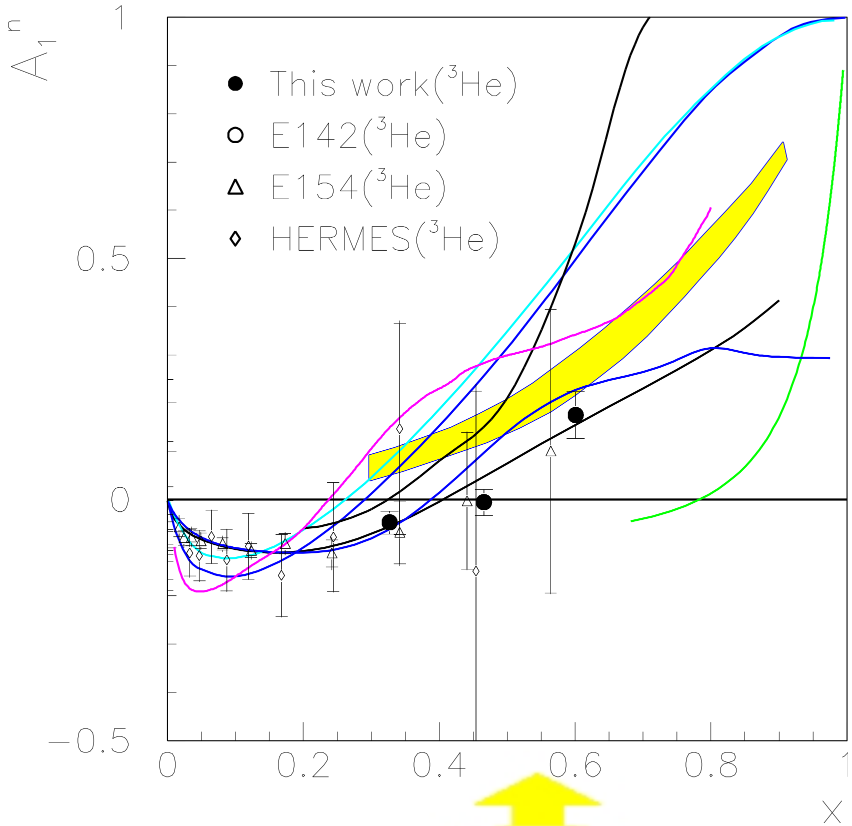
Neutron

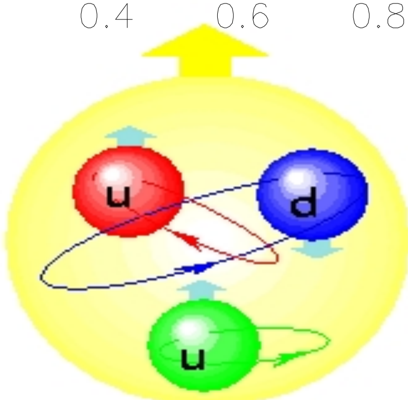


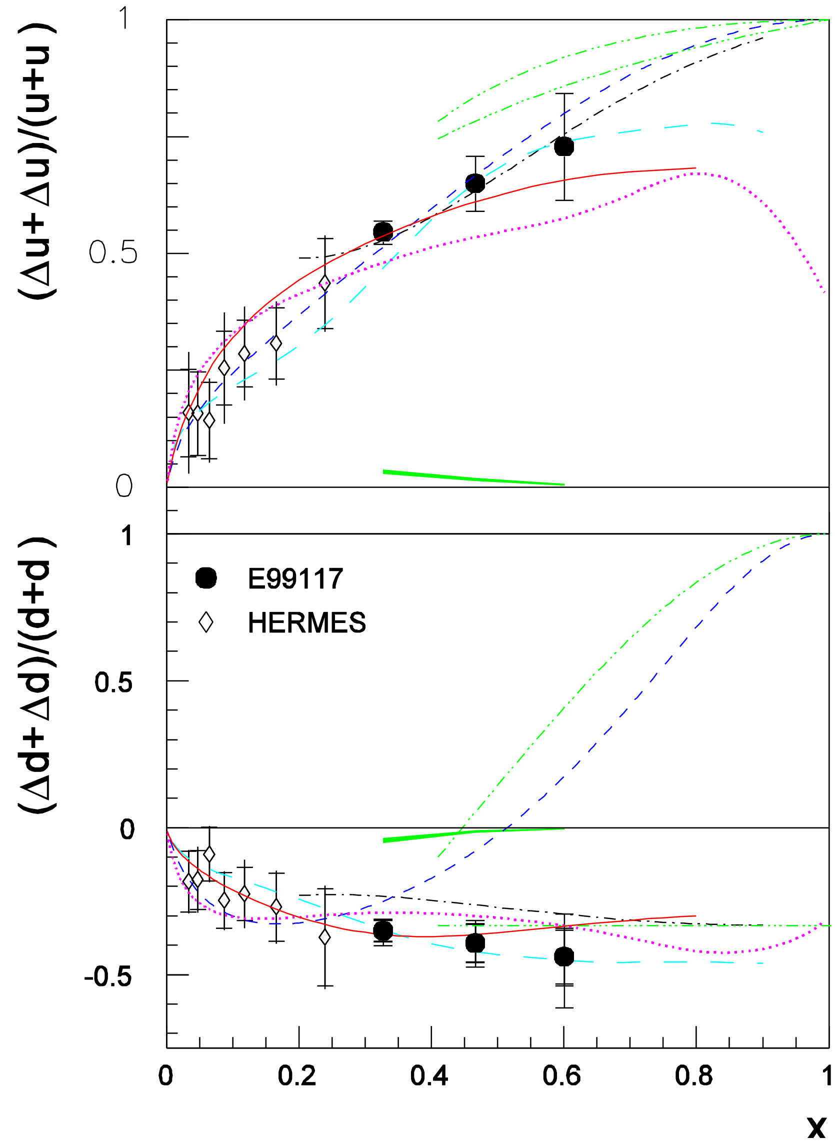
JLab E99117: *Precision Measurement of A_1^n at High-x*

PRL 92, 012004 (2004) , PRC 70, 065207 (2004)

Physics News Update, Science Now
Science News, Physics Today Update

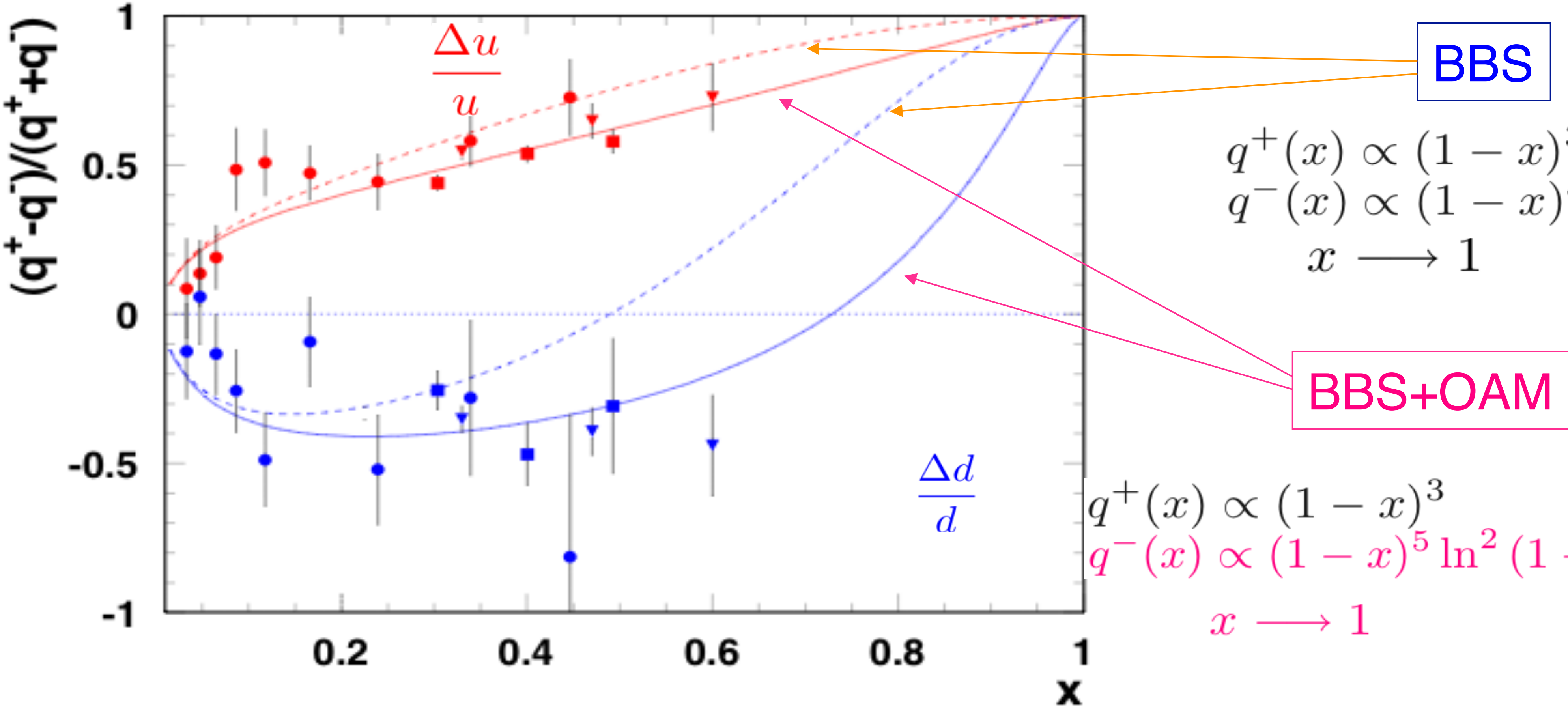






pQCD with Quark Orbital Angular Momentum

Inclusive Hall A and B and Semi-Inclusive Hermes

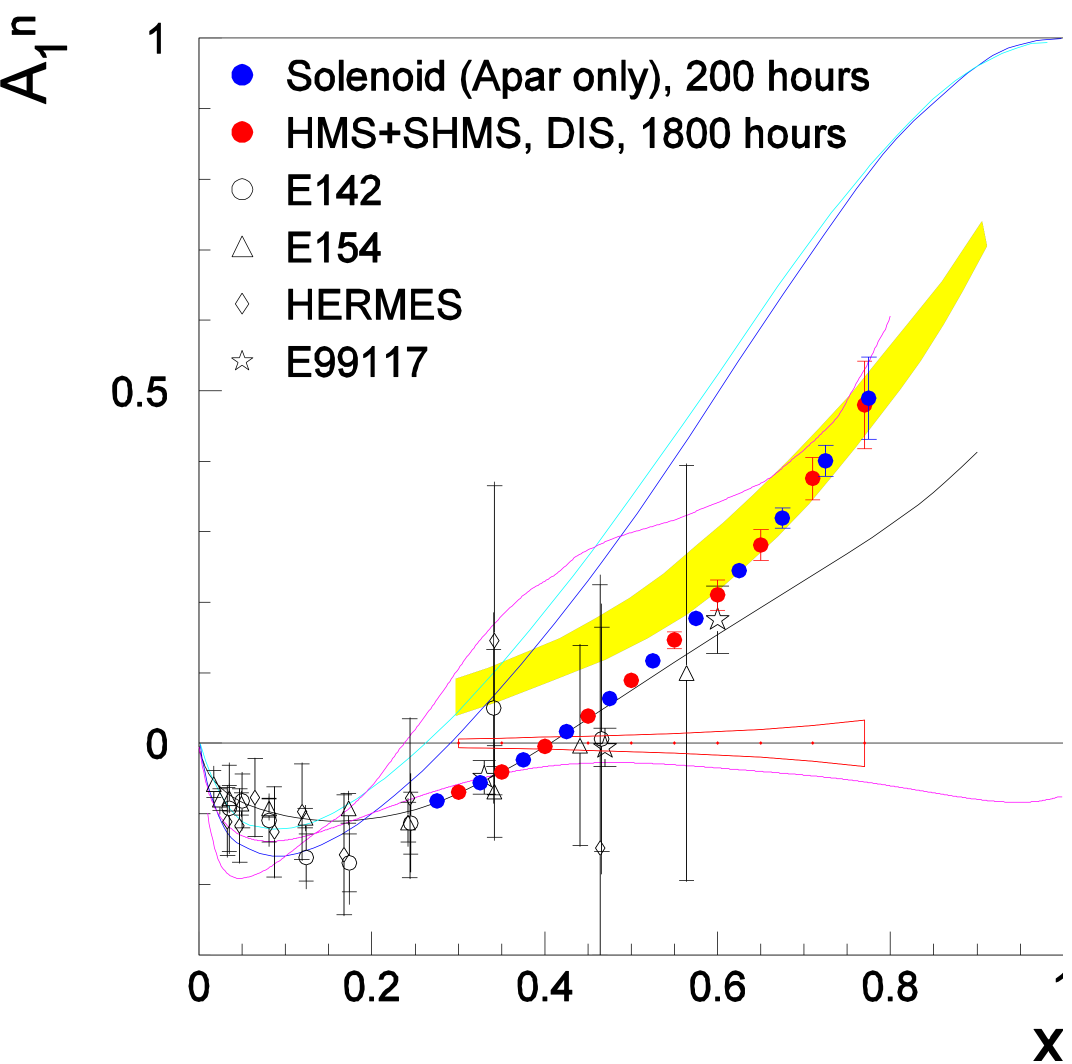


$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5$$
$$x \longrightarrow 1$$

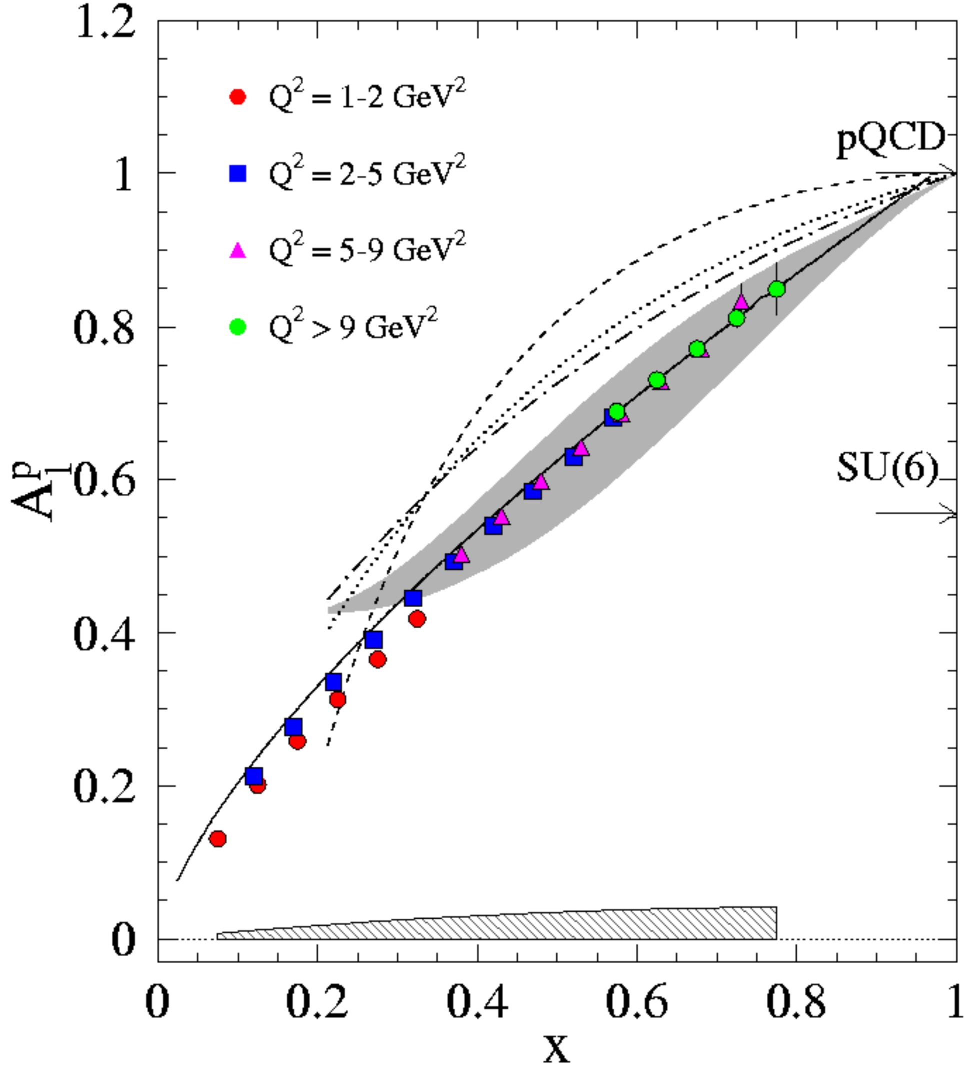
$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5 \ln^2(1-x)$$
$$x \longrightarrow 1$$

Projections for JLab at 11 GeV

A_1^n at 11 GeV



A_1^p at 11 GeV



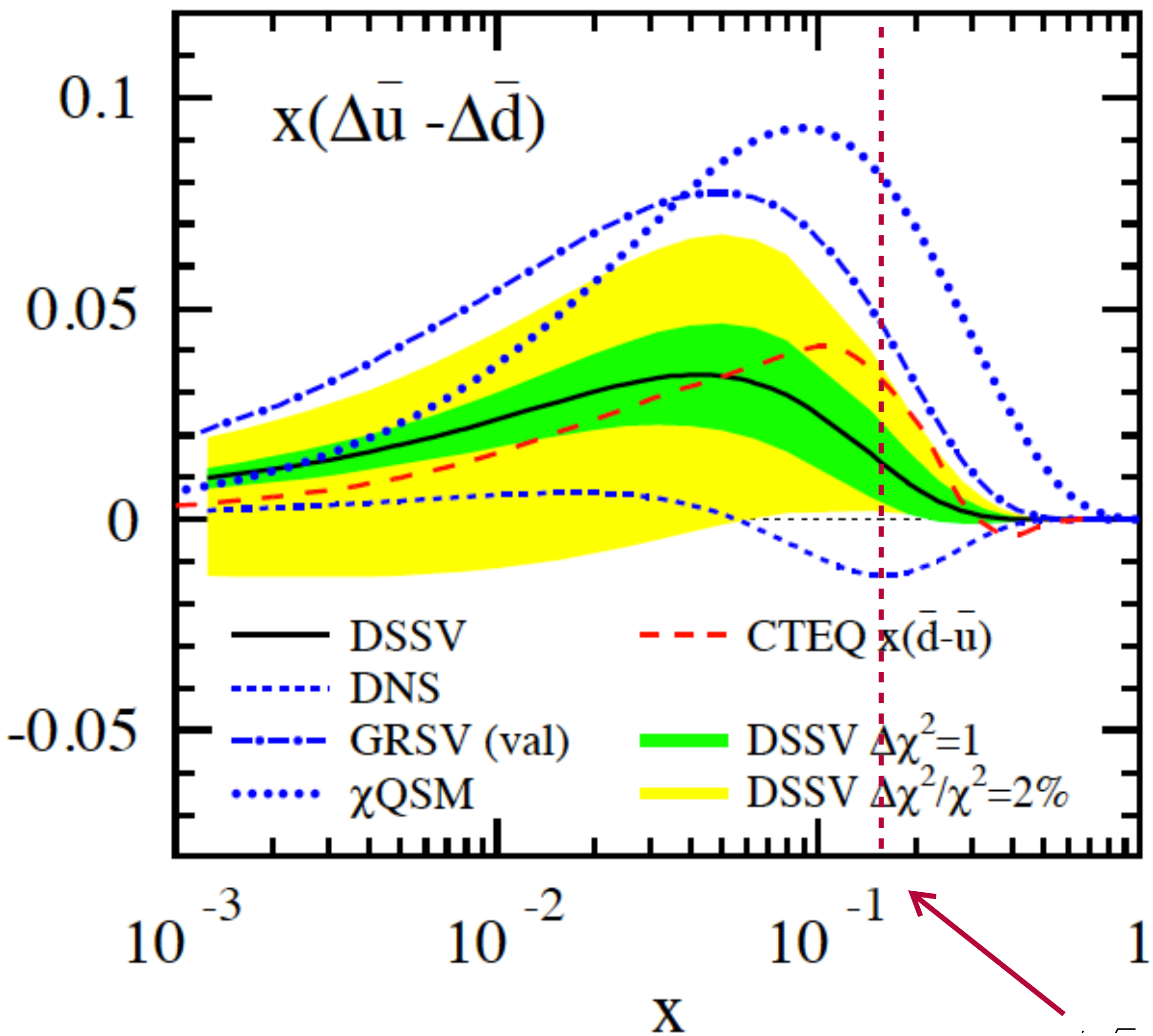
Select Highlights in Nucleon Spin Study II

Spin-Flavor Structure
Gluon Polarization

RHIC-Spin W program: Polarized Sea Quark

- Impact of new DSSV global fit result

D. de Florian et al., Phys. Rev. Lett. 101 (2008) 072001



RHIC Spin Collaboration (2012)

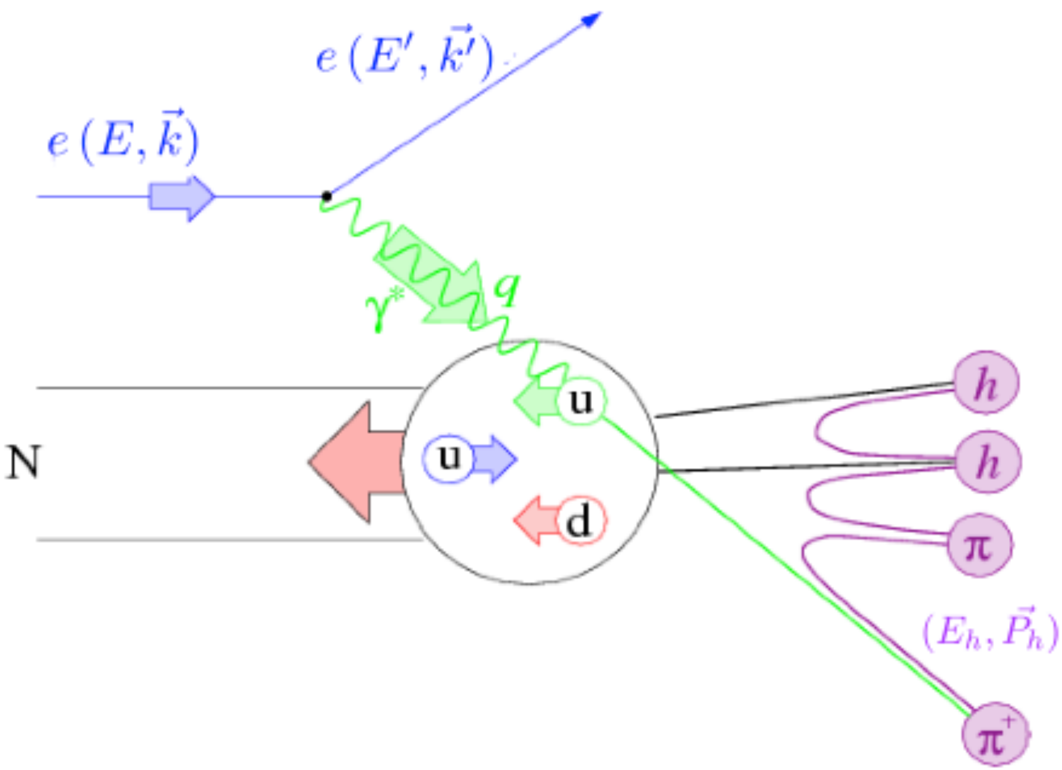
- From recent DSSV++ result incl. STAR A_L data:

$$\int_{0.05}^{1} \Delta\bar{u}(x,Q^2)dx \approx 0.02$$

$$\int_{0.05}^{1} \Delta\bar{d}(x,Q^2)dx \approx -0.05$$

Tagging the quark flavor

semi-inclusive deep-inelastic scattering



$$Q^2 \equiv -q^2$$

$$\nu \equiv \frac{Pq}{M} \stackrel{lab}{=} E - E'$$

$$y \equiv \frac{Pq}{Pk} \stackrel{lab}{=} \frac{\nu}{E}$$

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

$$x_B \equiv \frac{Q^2}{2Pq}$$

$$z \equiv \frac{PP_h}{Pq} \stackrel{lab}{=} \frac{E_h}{\nu}$$

$$P_{h\perp} = \frac{|\vec{q} \times \vec{P}_h|}{|\vec{q}|}$$

$$\sigma^{ep\to eh} = \sum_q DF^{p\to q}(x_B, p_T^2, Q^2) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z, k_T^2, Q^2)$$

distribution function (DF): distribution of quarks in nucleon
p_T : transverse momentum of struck quark

fragmentation function (FF): fragmentation of struck quark into final-state hadron
k_T : transverse momentum of fragmenting quark

Quark helicity distribution

$$A_1^h \simeq \frac{\overset{\Rightarrow}{\overset{\Leftarrow}{\sigma}} - \overset{\Rightarrow}{\overset{\Rightarrow}{\sigma}}}{\overset{\Rightarrow}{\overset{\Leftarrow}{\sigma}} + \overset{\Rightarrow}{\overset{\Leftarrow}{\sigma}}}$$

$$\propto \sum_q e_q^2 \Delta q(x_B, Q^2) D_q^h(z, Q^2)$$

proportional to square of quark electric charge

favored fragmentation

$u \rightarrow \pi^+ = |u\bar{d}>$

$d \rightarrow \pi^- = |\bar{u}d>$

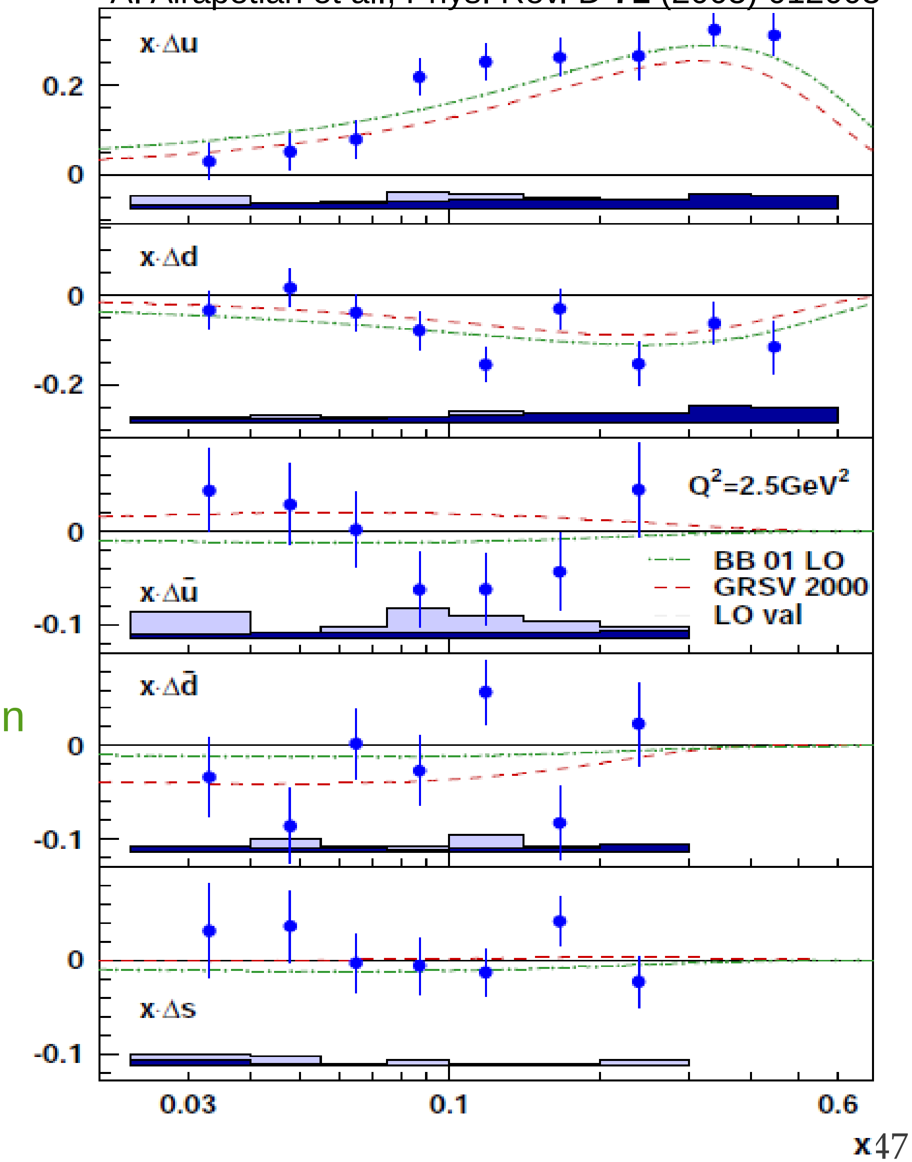
unfavored fragmentation

$d \rightarrow \pi^+ = |u\bar{d}>$

$u \rightarrow \pi^- = |\bar{u}d>$

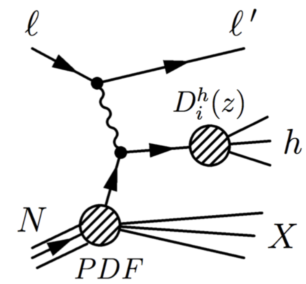
A. Airapetian et al., Phys. Rev. Lett. **92** (2004) 012005

A. Airapetian et al., Phys. Rev. D **71** (2005) 012003



hermes

FF in the collinear case



$$\int d^2\mathbf{k}_\perp f_1^q(x,k_\perp) = f_1^q(x)$$

$$\int d^2\mathbf{p}_\perp D_1^q(z,p_\perp) = D_1^q(z)$$

Very good knowledge of PDFs and FFs is a key element for a precise determination of polarized quantities, e.g. polarization of quarks in

- Longitudinally polarized nucleon

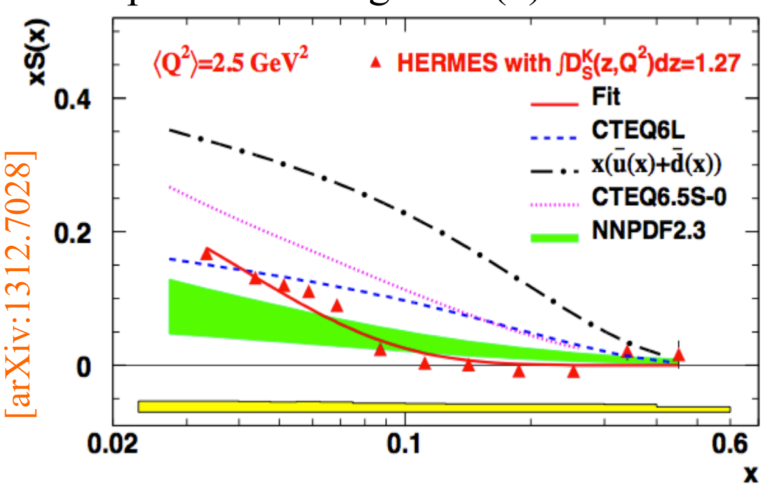
$$A_{LL}^h(x,z) = \frac{\sum_f \Delta q_f(x) D_{q_f}^h(z)}{\sum_f q_f(x) D_{q_f}^h(z)}$$

Large uncertainties in the strange sector

unpolarized PDF

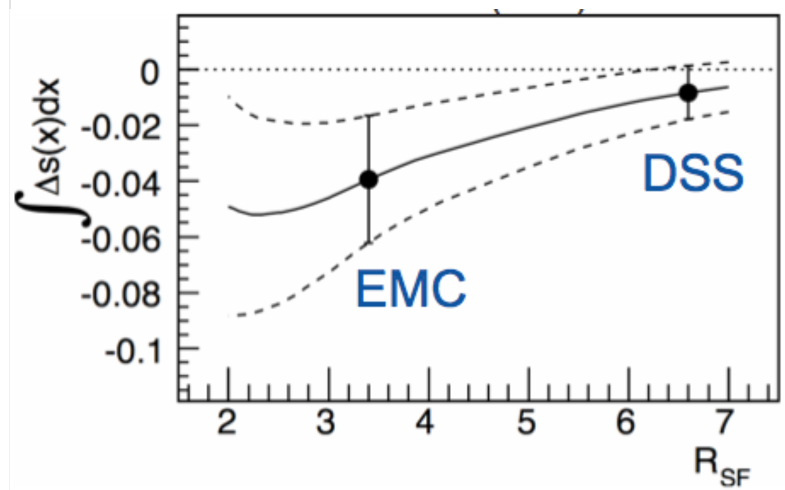
polarized PDF

poor knowledge of S(x)



[arXiv:1312.7028]

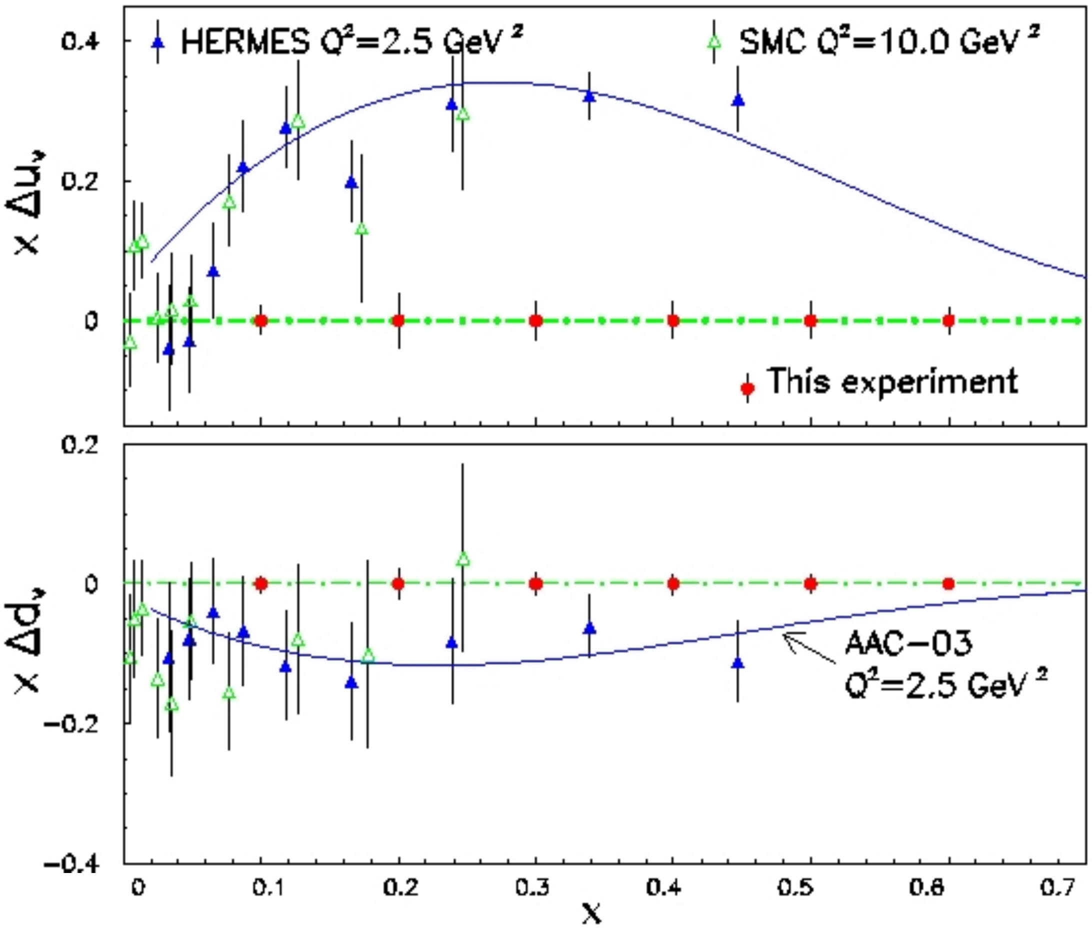
strong dependence of ΔS on FFs parameterizations



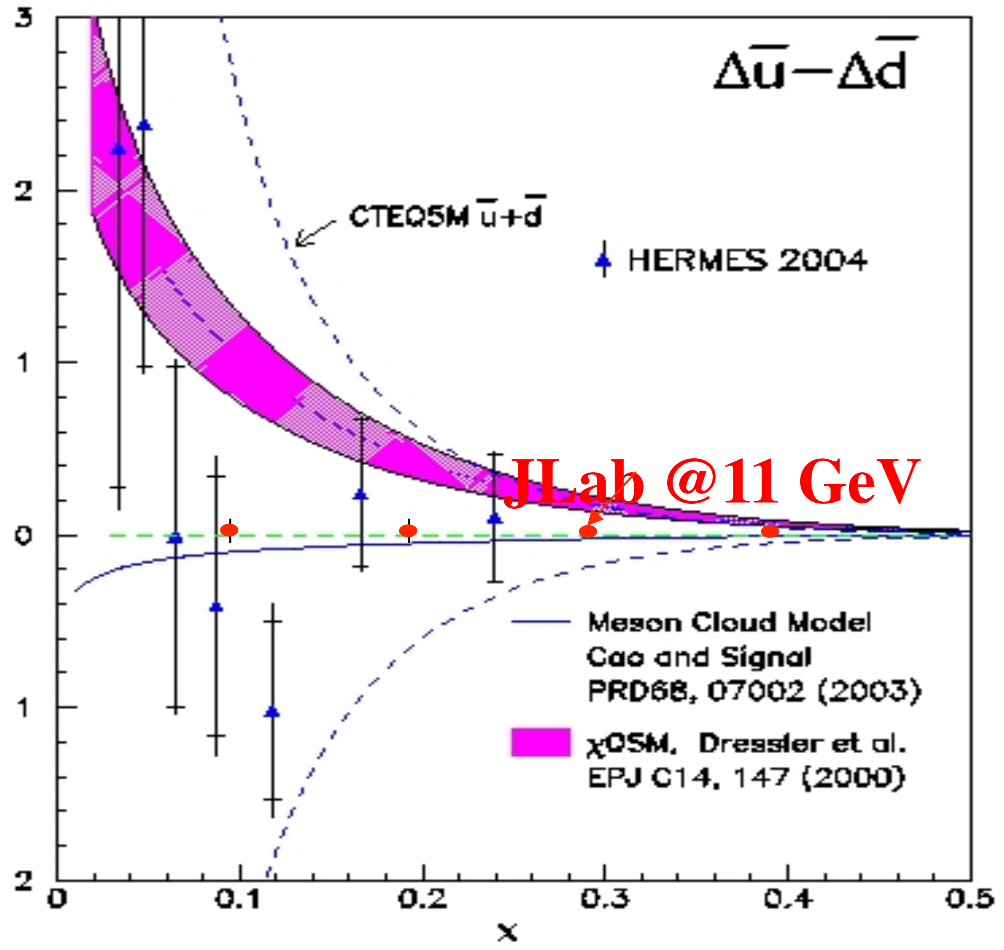
PLB 693 (2010) 227–235

Flavor decomposition with SIDIS

Δu and Δd at JLab 11 GeV



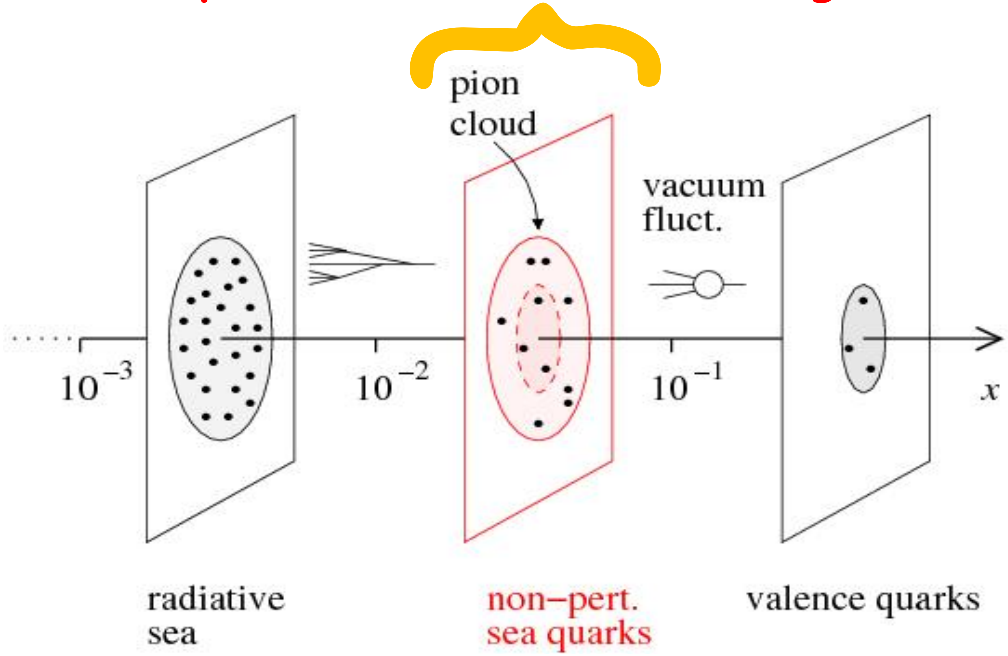
Polarized Sea



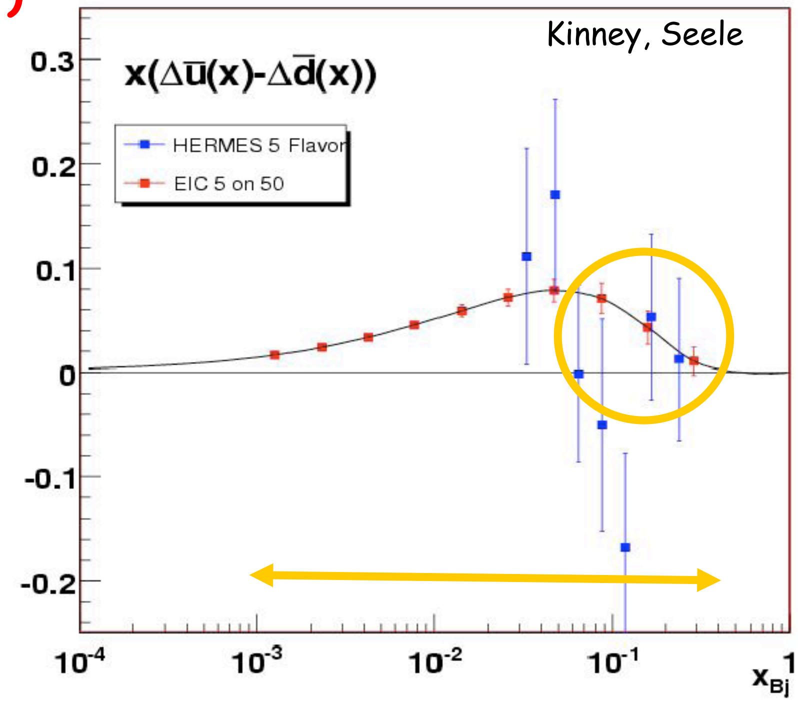
Sea Quark Polarization

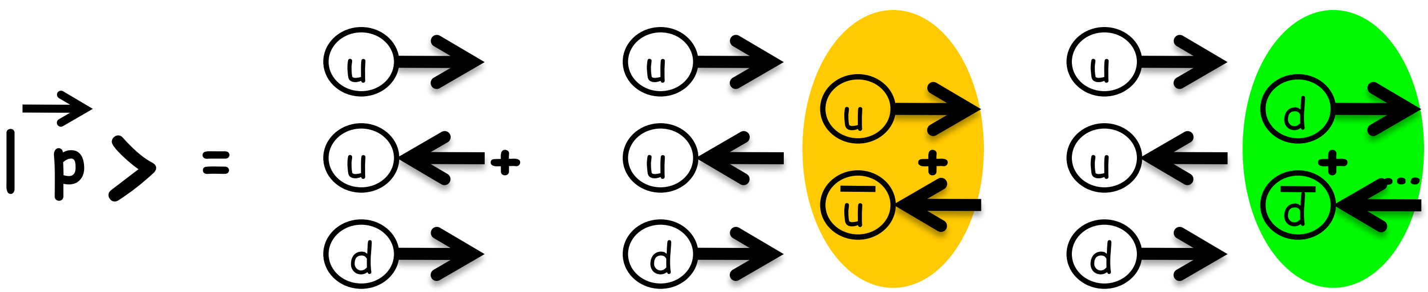
- Spin-Flavor Decomposition of the Light Quark Sea

Access requires s ~ 100-1000 (and good luminosity)



100 days, L $=10^{33}$, s = 1000



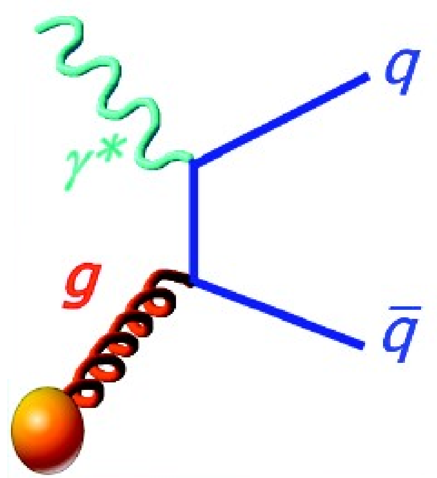


Many models predict $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

Gluon helicity distribution

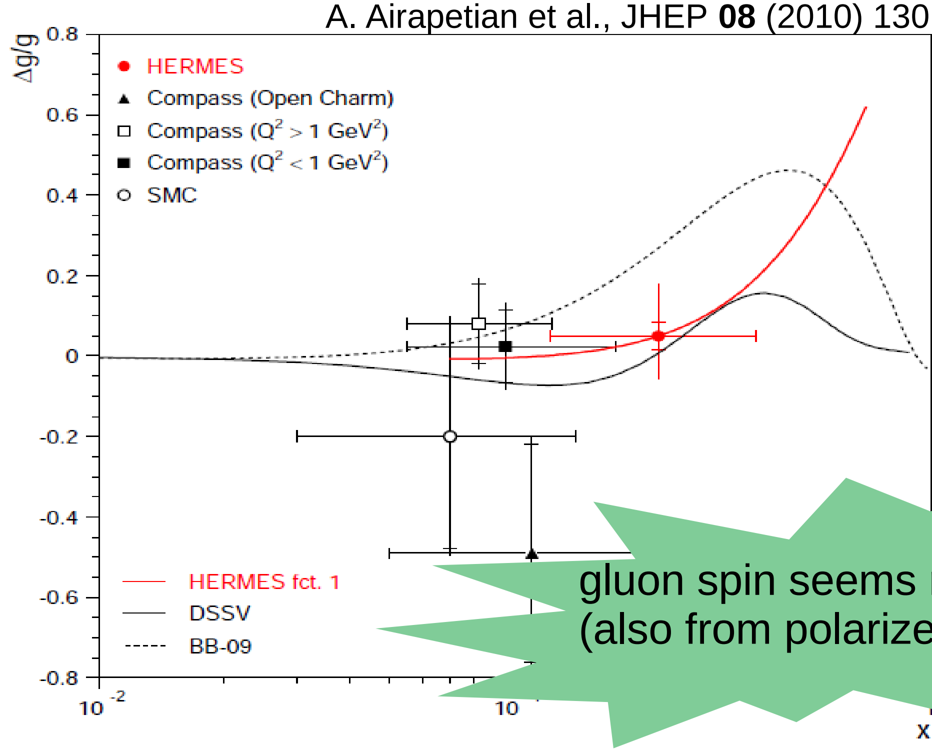
$$A_1^h \simeq \frac{\overset{\Rightarrow}{\overset{\Leftarrow}{\sigma}} - \overset{\Rightarrow}{\overset{\Rightarrow}{\sigma}}}{\overset{\Rightarrow}{\overset{\Leftarrow}{\sigma}} + \overset{\Rightarrow}{\overset{\Leftarrow}{\sigma}}} \propto \frac{\Delta g(x_B, Q^2)}{g(x_B, Q^2)}$$

select high-$P_{h\perp}$ hadrons



photon-gluon fusion

A. Airapetian et al., JHEP **08** (2010) 130

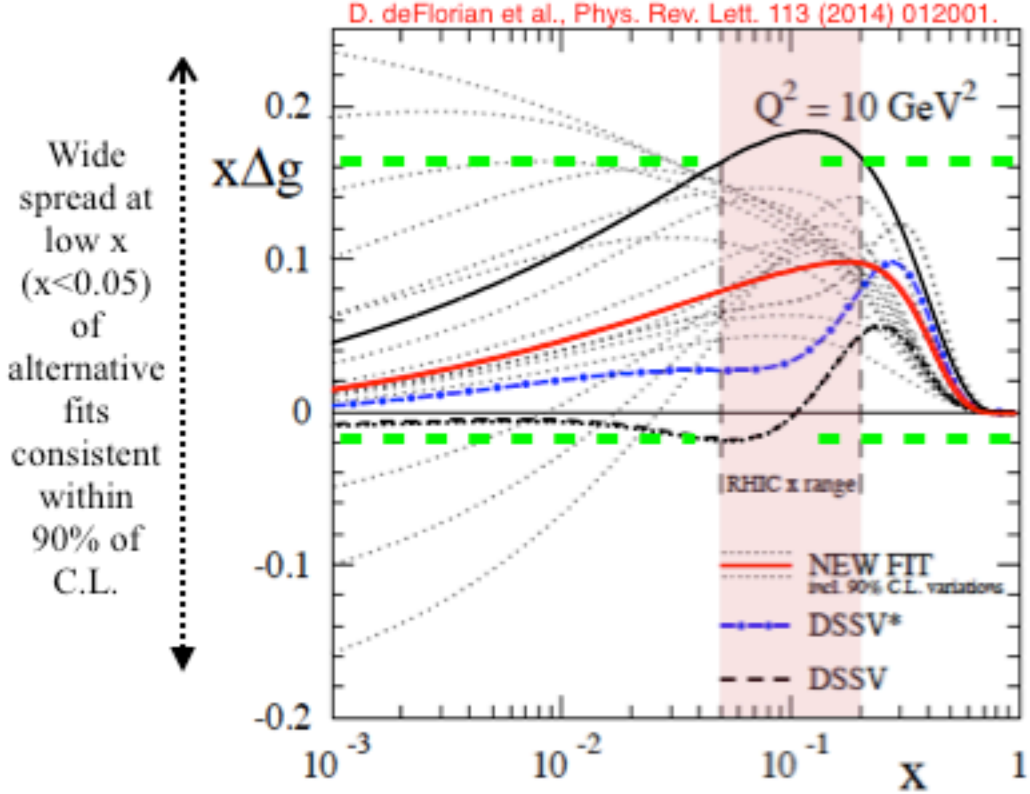


gluon spin seems rather small
(also from polarized pp data)

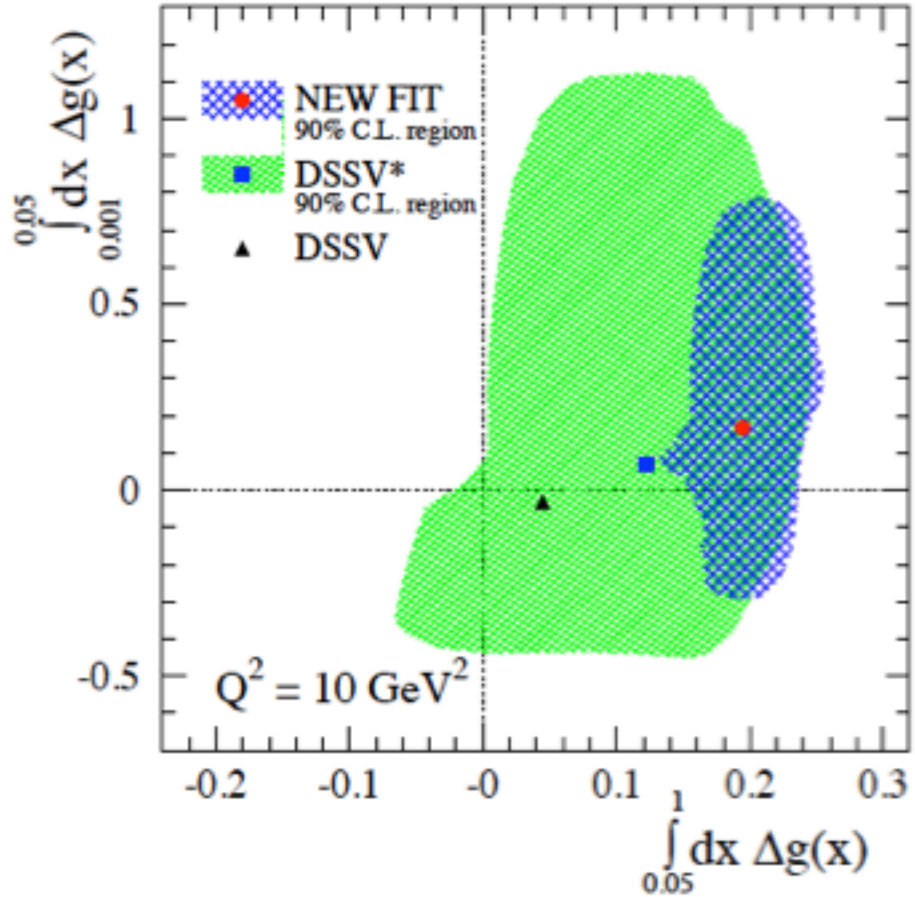
RHIC-Spin: Gluon Polarization

- Impact on Δg from RHIC data

D. deFlorian et al., Phys. Rev. Lett. 113 (2014) 012001.



D. deFlorian et al., Phys. Rev. Lett. 113 (2014) 012001.

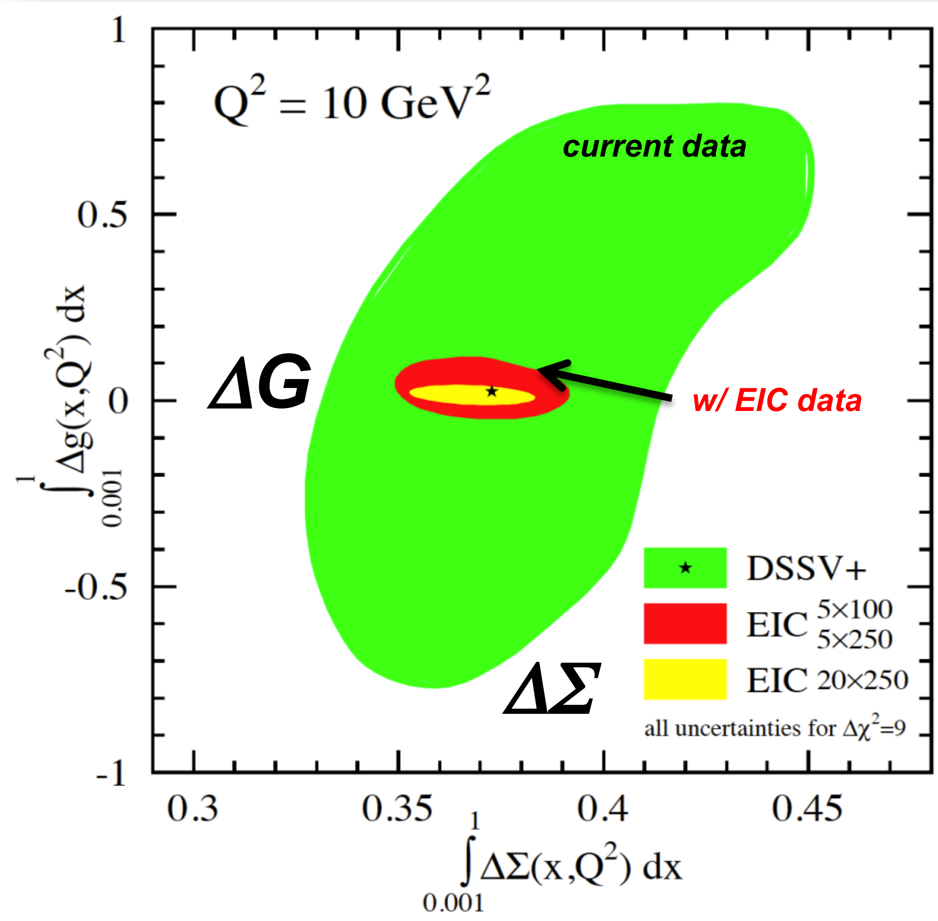


- DSSV: Original global analysis incl. first RHIC results (Run 5/6)
- DSSV*: New COMPASS inclusive and semi-inclusive results in addition to Run 5/6 RHIC updates
- DSSV - NEW FIT: Strong impact on $\Delta g(x)$ with RHIC run 9 results: $0.20^{+0.06}_{-0.07}$ 90% C.L. for $0.05 < x$
- Similar conclusion by independent global analysis of NNPDF: $0.23^{+0.07}_{-0.07}$ for $0.05 < x < 0.5$

E. R. Nocera et al., Nucl. Phys. B887 (2014) 276.

"...better small-x probes are badly needed."

EIC: Are the Gluons Polarized?



A Polarized EIC:

- ***Tremendous improvement on ΔG***
- ***Also improvement in ΔΣ***
- ***Spin Flavor decomposition of the Light Quark Sea***

Select Highlights of Nucleon Spin Study III: Spin Sum Rules and Moments of SSFs

Sum Rules

Moments of Spin Structure Functions ➔ Global Property

Bjørken Sum Rule

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \int \{g_1^p(x,Q^2) - g_1^n(x,Q^2)\}dx = \frac{1}{6} g_A C_{NS}$$

g_A: axial vector coupling constant from neutron β-decay
C_{NS}: Q^2-dependent QCD corrections (for flavor non-singlet)

- A fundamental relation relating an integration of spin structure functions to axial-vector coupling constant
- Based on Operator Product Expansion within QCD or Current Algebra
- Valid at large Q^2 (higher-twist effects negligible)
- Data are consistent with the Bjørken Sum Rule at 5-10 % level

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

  New measurements on p, d and ^{3}He from LEGS, MAMI(2), …

Generalized GDH Sum Rule

- Many approaches: Anselmino, Ioffe, Burkert, Drechsel, …
- Ji and Osborne (J. Phys. G27, 127, 2001):

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

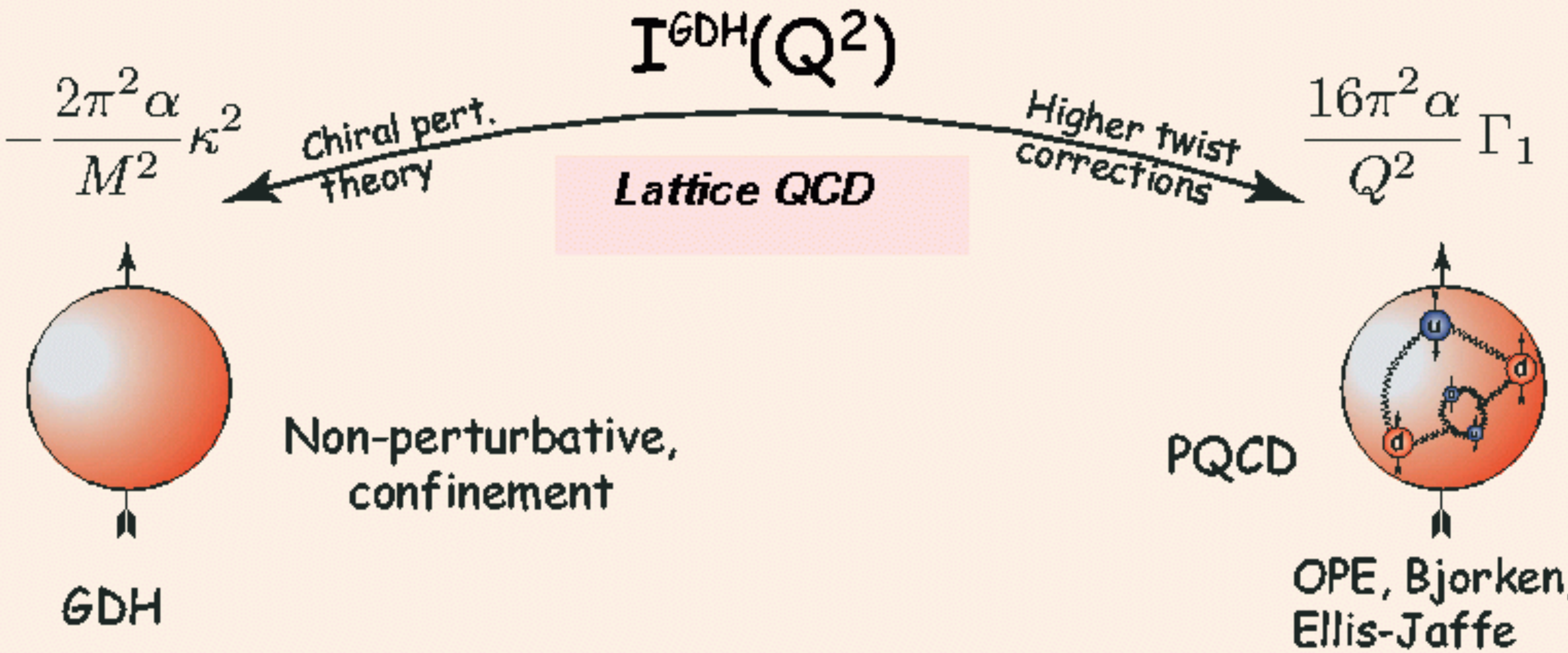
  Same assumptions: no-subtraction dispersion relation
  optical theorem
  (low energy theorem)

- Generalized GDH Sum Rule

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

Why is $I^{GDH}(Q^2)$ is interesting?

One of the few opportunities to "zoom out" from tiny length scales (DIS) to large length scales



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

    $Q^2 \rightarrow 0$, 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 Q^2 region (< ~0.1 GeV^2): Chiral Perturbation Theory

Calculations: HBχPT: Ji, Kao, Osborne, Spitzenberg, Vanderhaeghen

RBχPT: Bernard, Hemmert, Meissner

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

Chen, Int. J. Mod. Phys. E19, 1893 (2010).

Moments of g_1^p : Γ_1^p (Before EG4)

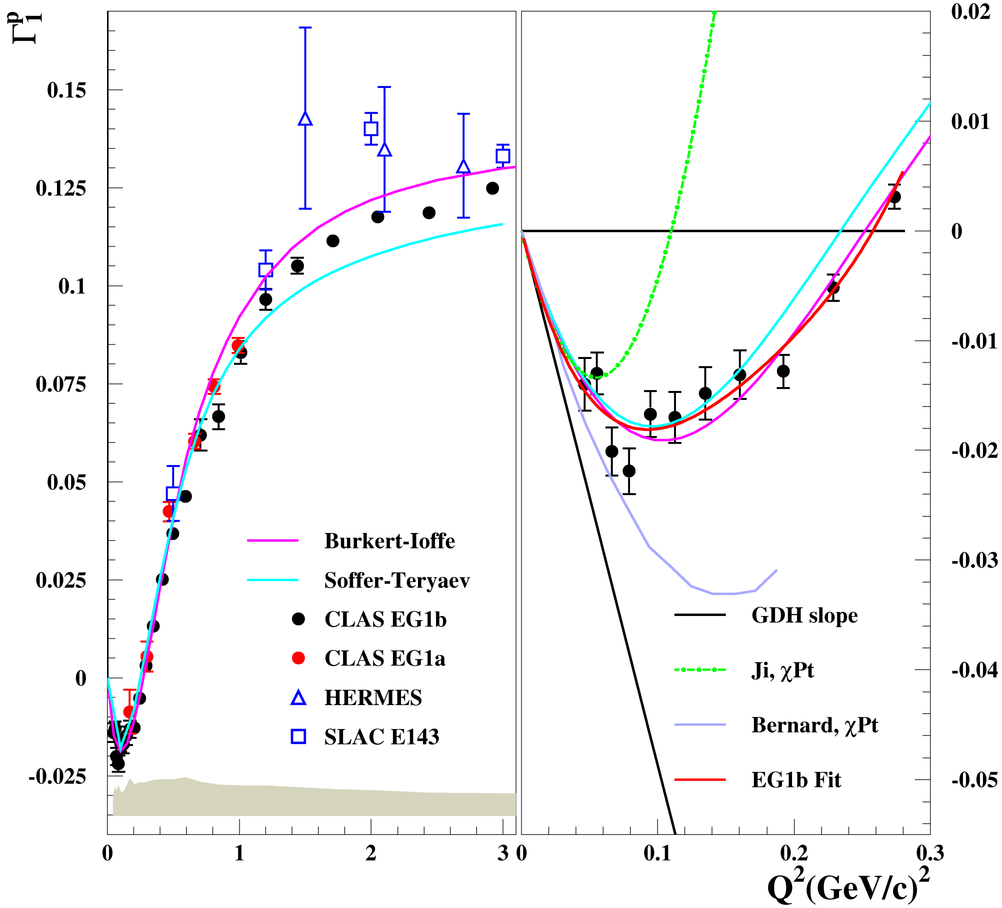
Total Quark Contribution to Proton Spin (at high Q^2)

Twist expansion at intermediate Q^2, LQCD, ChPT at low Q^2

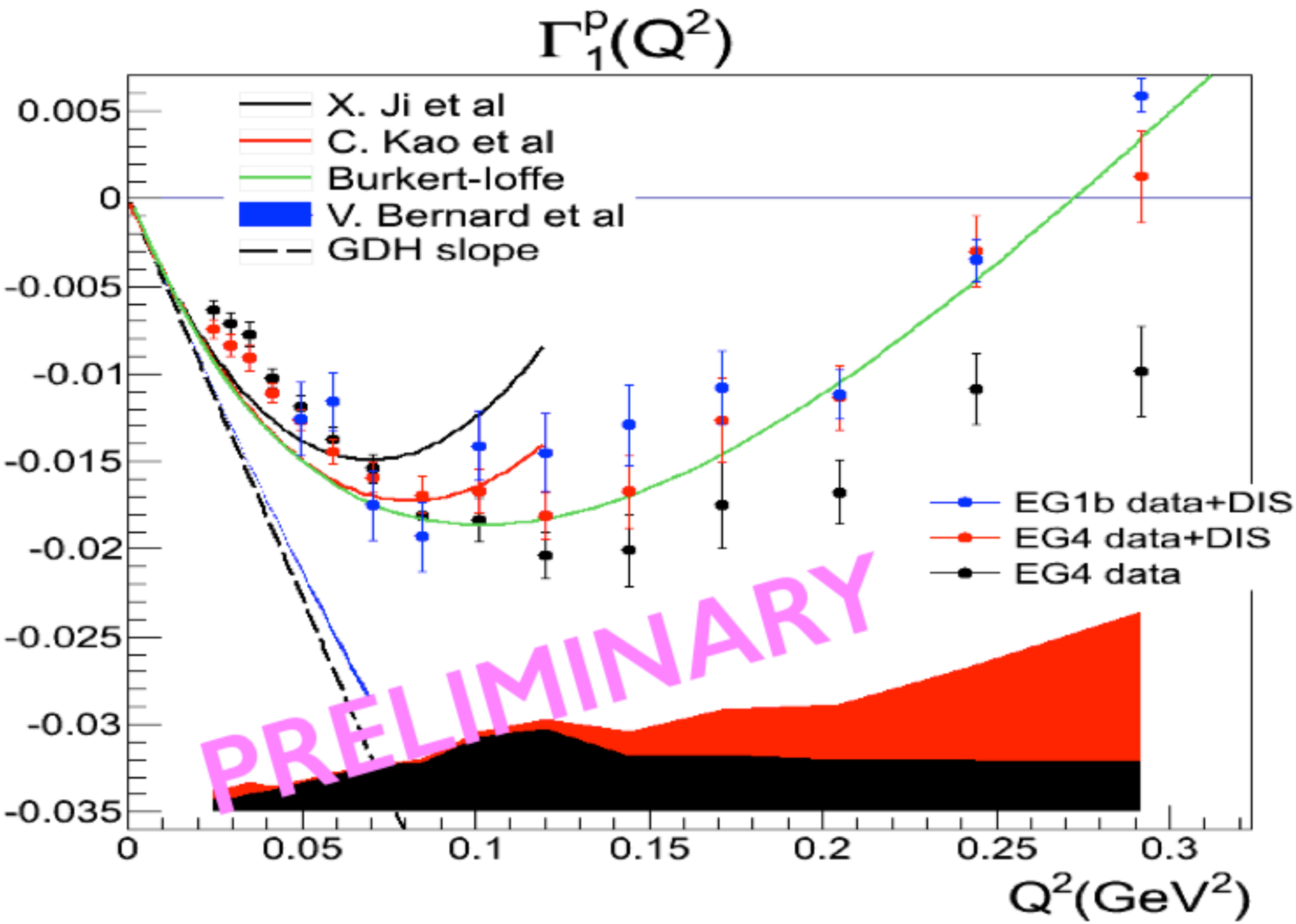
EG1b, Phys.Lett. B672, 12 (2009) , EG1a, PRL 91, 222002 (2003)

Spokespersons: V. Burkert, D. Crabb, G. Dodge,

Γ_1^p



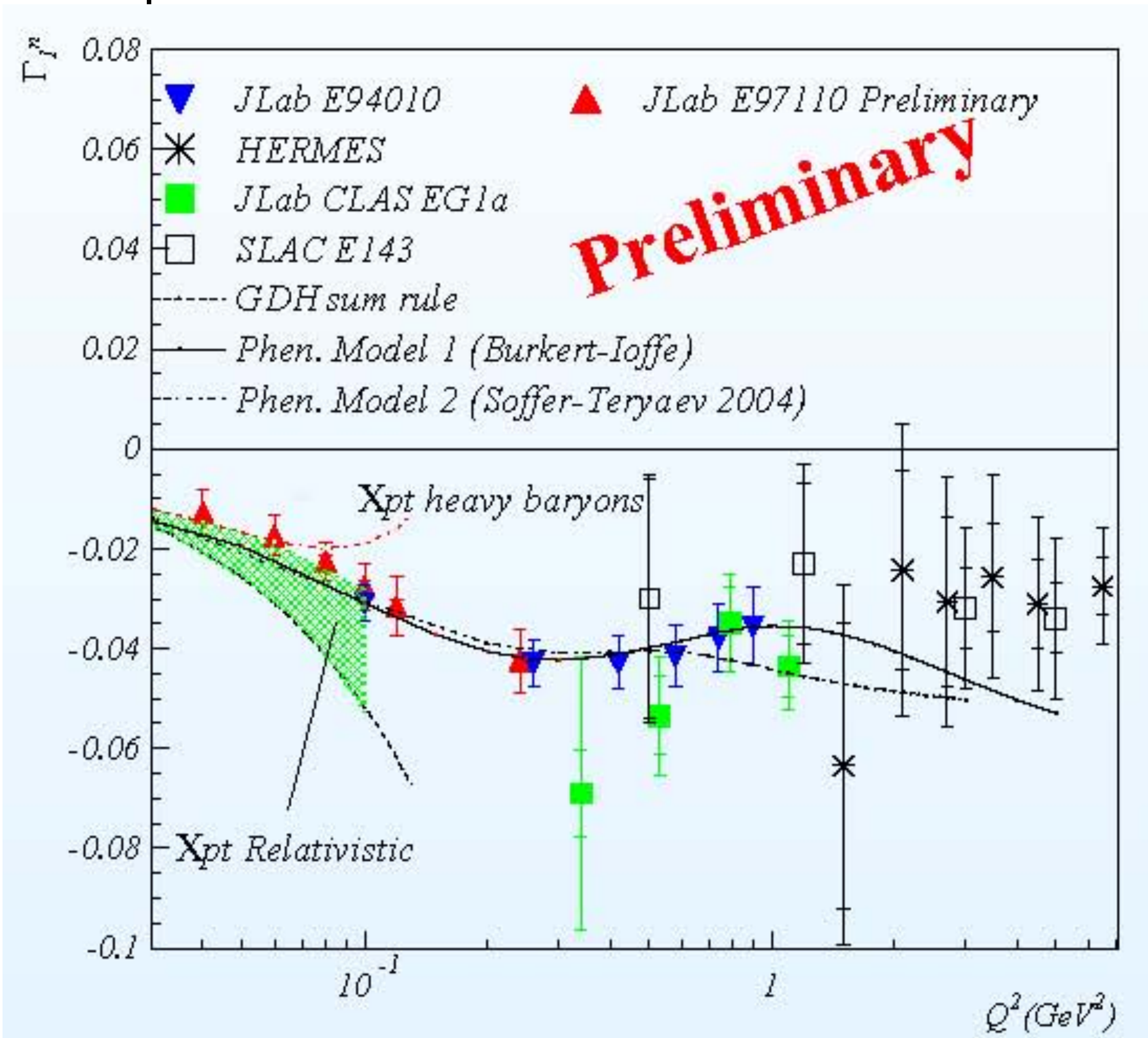
EG4 Preliminary Results on Proton g_1 Moment



First Moment of g_1^n : Γ_1^n

E94-010, PRL 92 (2004) 022301
E97-110, preliminary
EG1a, from d-p

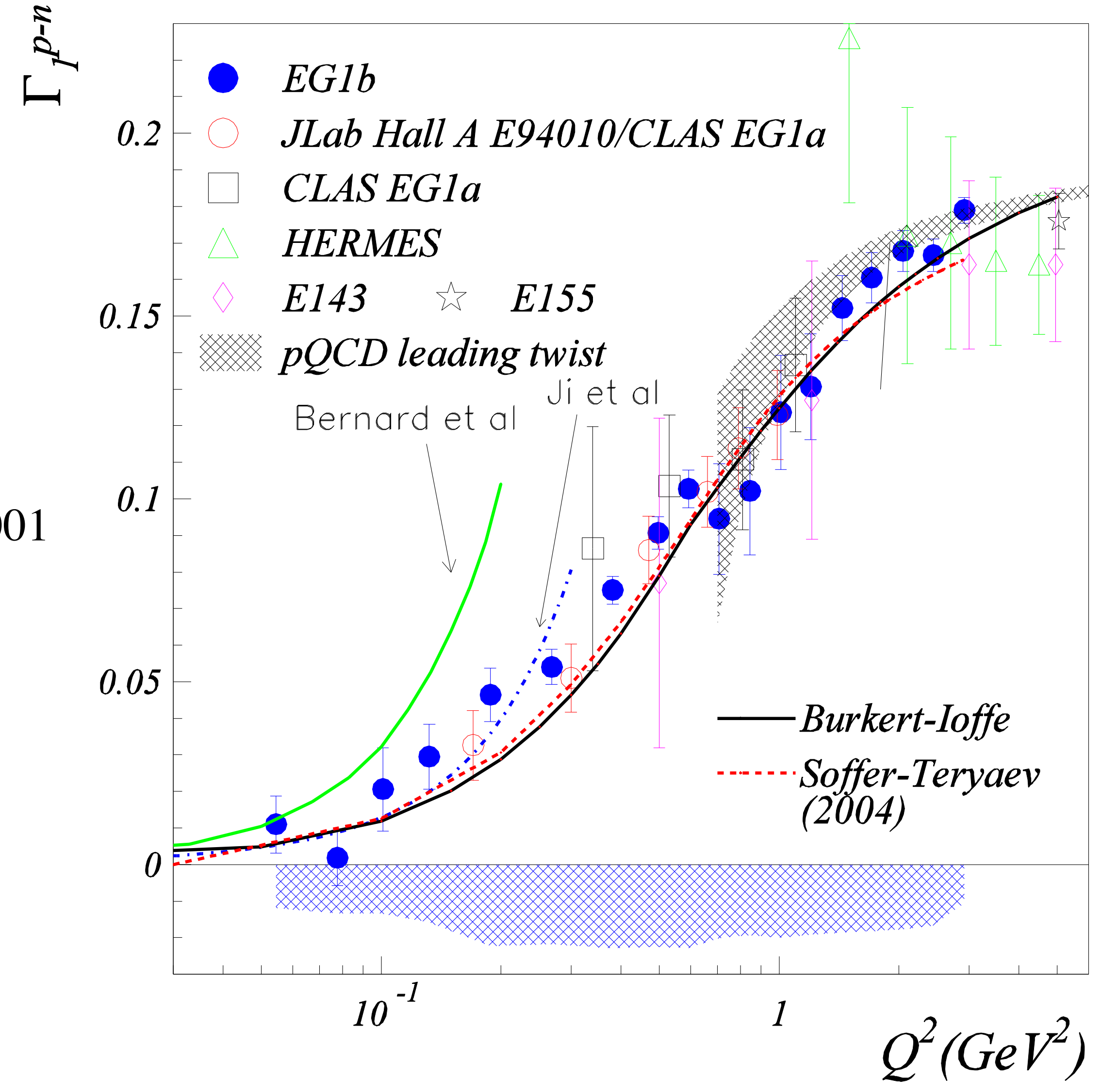
Γ_1^n



Bjorken Sum: Γ_1 of *p-n*

A. Deur, *et al.*

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

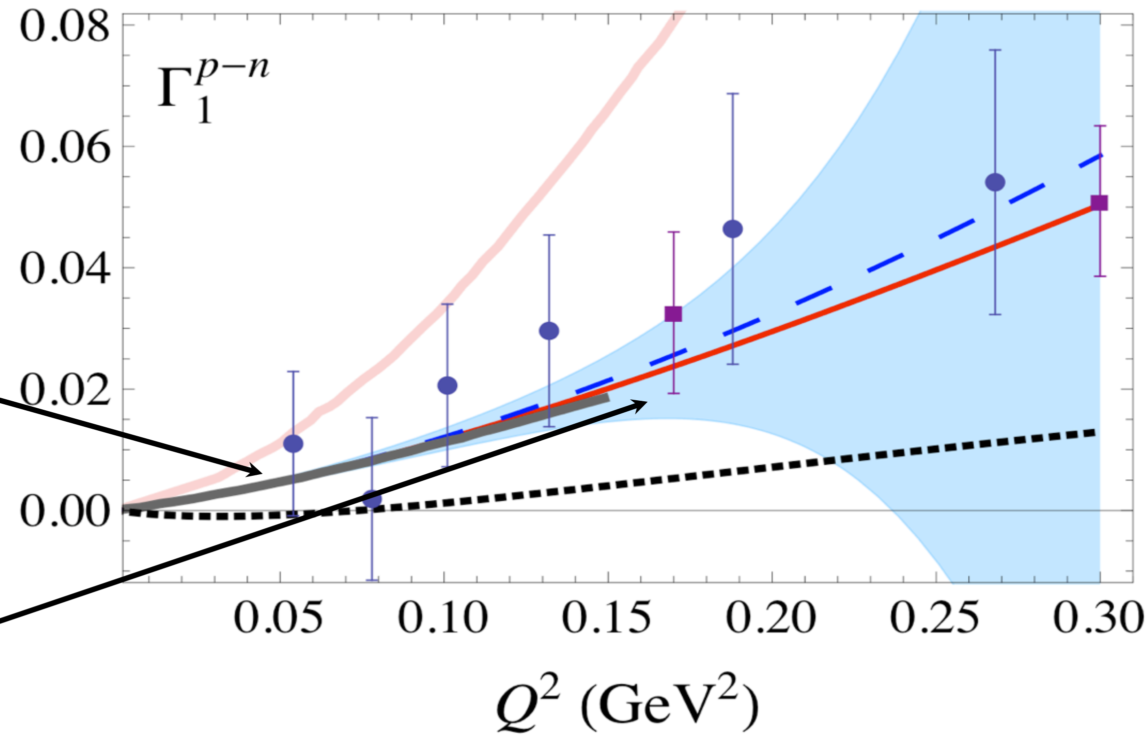


Bjorken Sum (p-n)

- Low Q^2: test of χpt calculations

Recent calculations from Bernard et al., PRD 87 (2013)

Lensky, Alarcon & Pascalutsa PRC 90 055202 (2014)

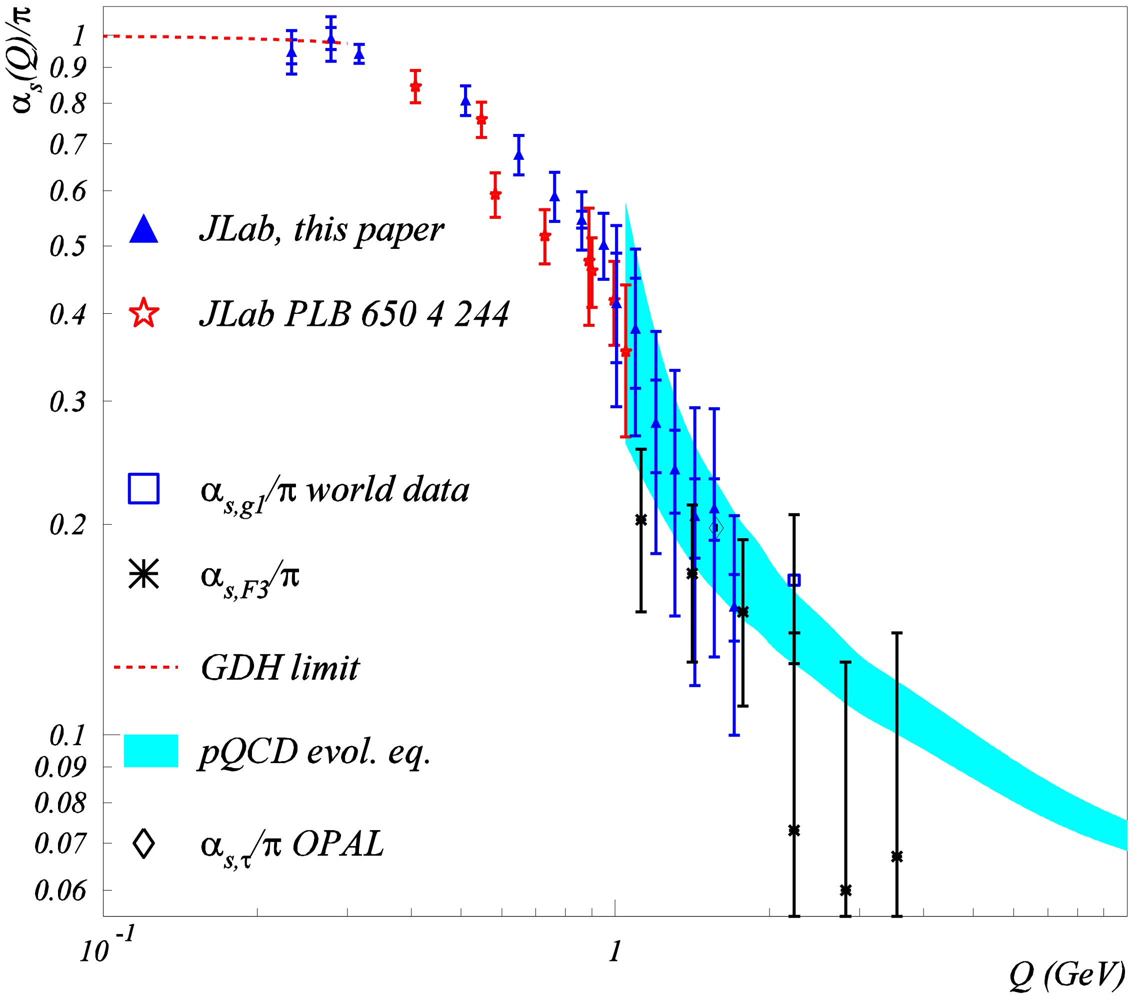


Effective Coupling Extracted from Bjorken Sum

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

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

α_s/π



Select Highlights of Nucleon Spin Study IV: Second Spin Structure Function g2

g_2 Moments: Burkhardt - Cottingham Sum Rule

Higher moments: d_2, Color Polarizability

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

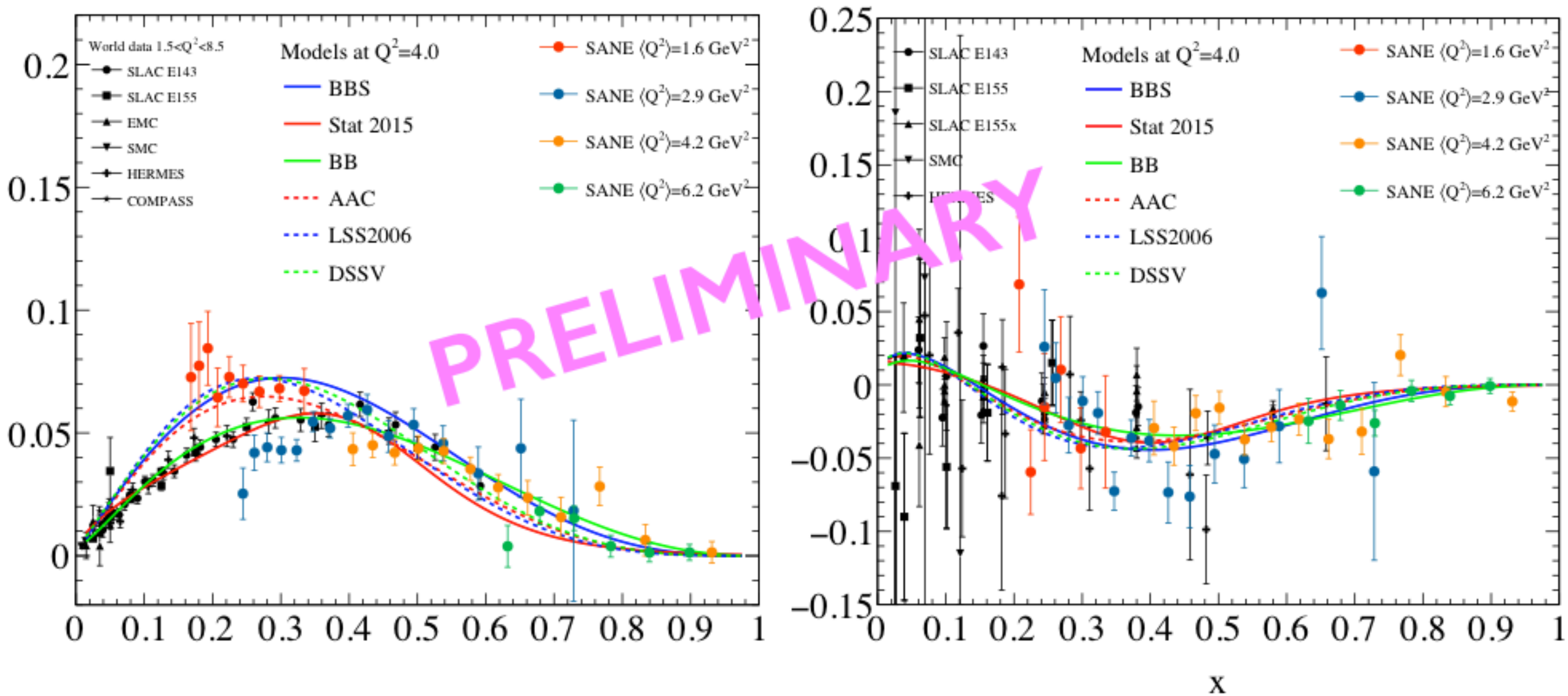
$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

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

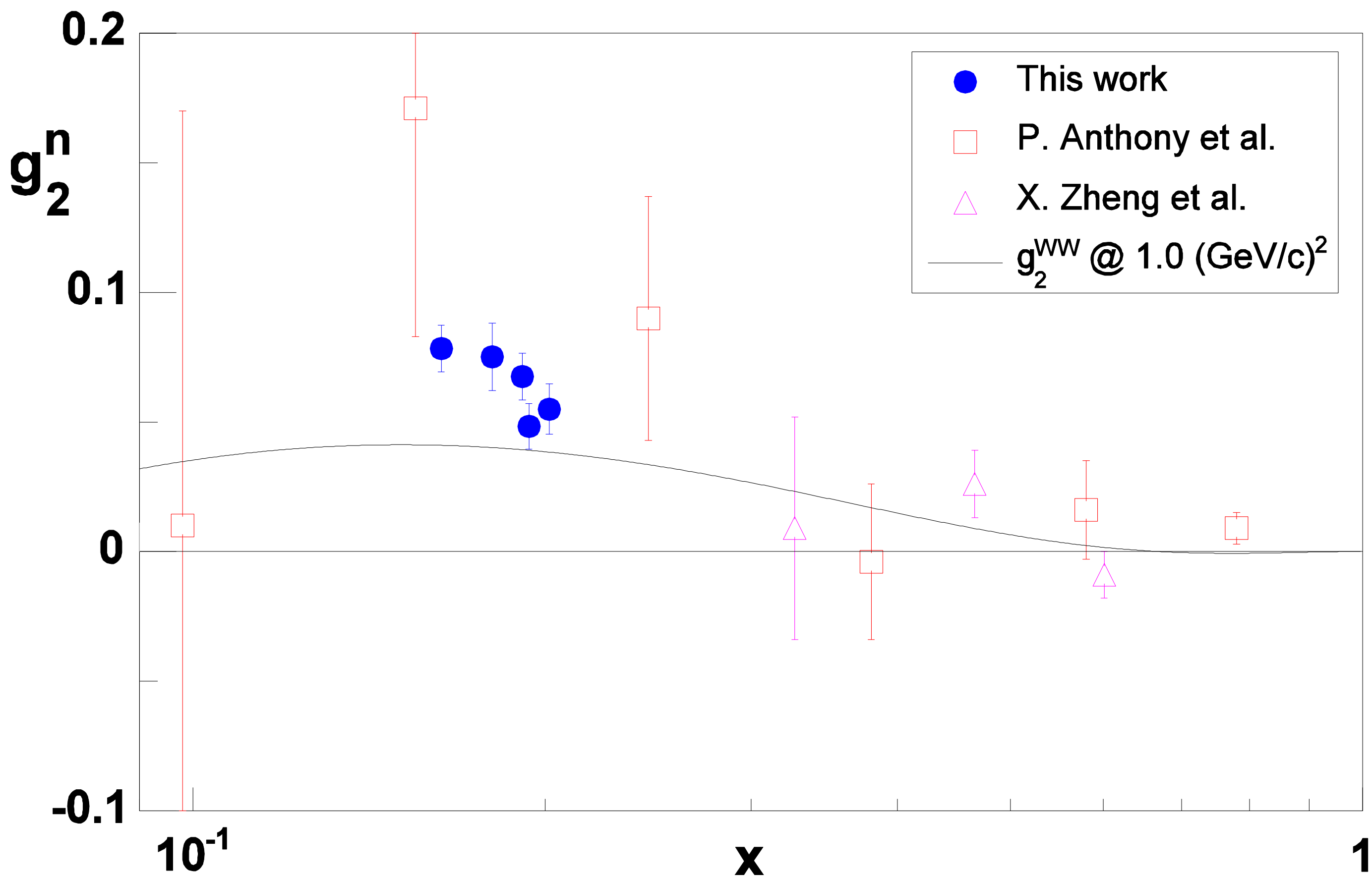
- $g_2 - g_2^{WW}$: a clean way to access twist-3 contribution

  quantify *q-g* correlations

Proton g_1 and g_2

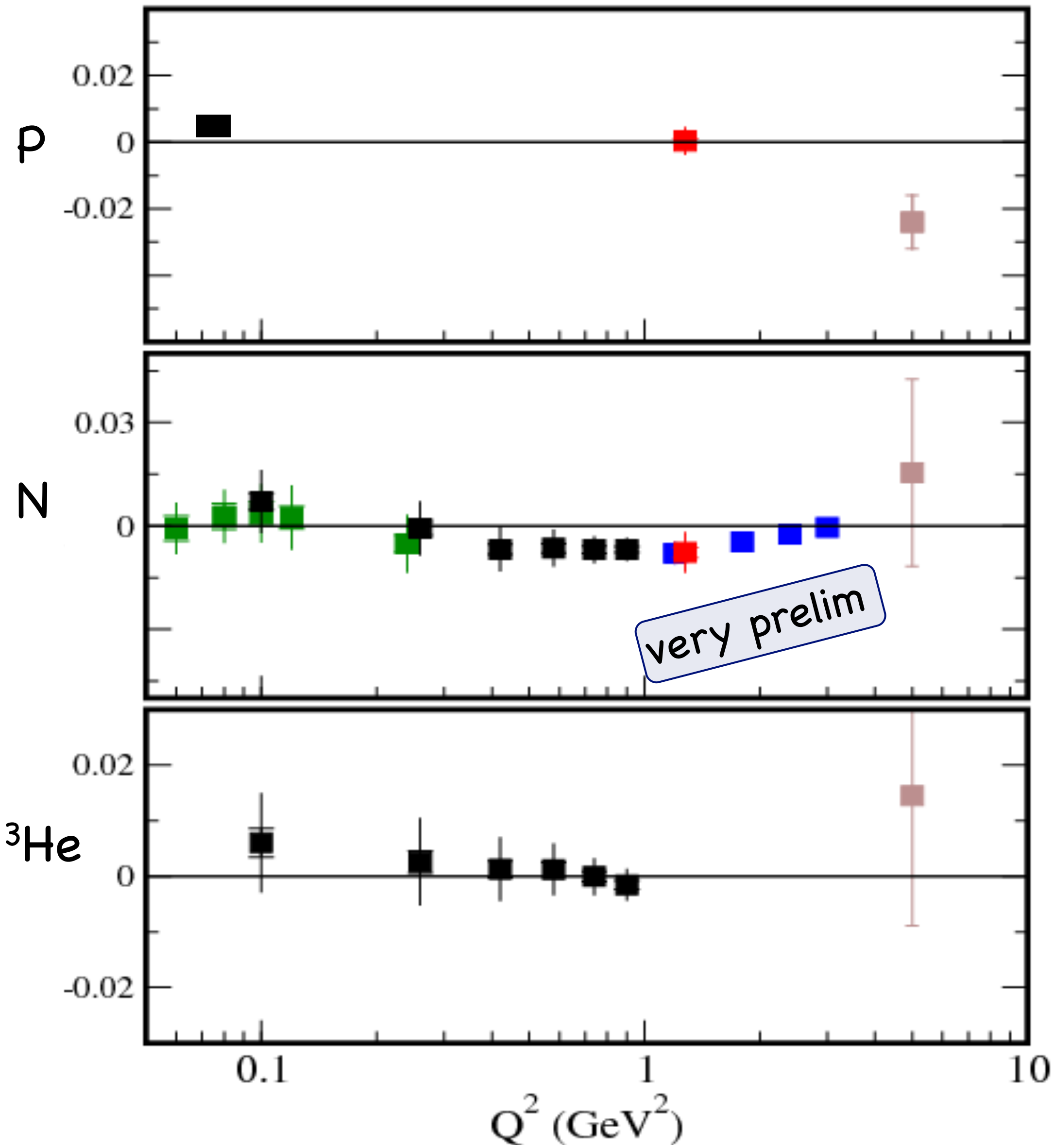


Precision Measurement of $g_2^n(x,Q^2)$: Search for Higher Twist Effects



- Measure higher twist → quark-gluon correlations.
- Hall A Collaboration, K. Kramer *et al.*, PRL 95, 142002 (2005)

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

Color Polarizability (Lorentz Force): d_2

- 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

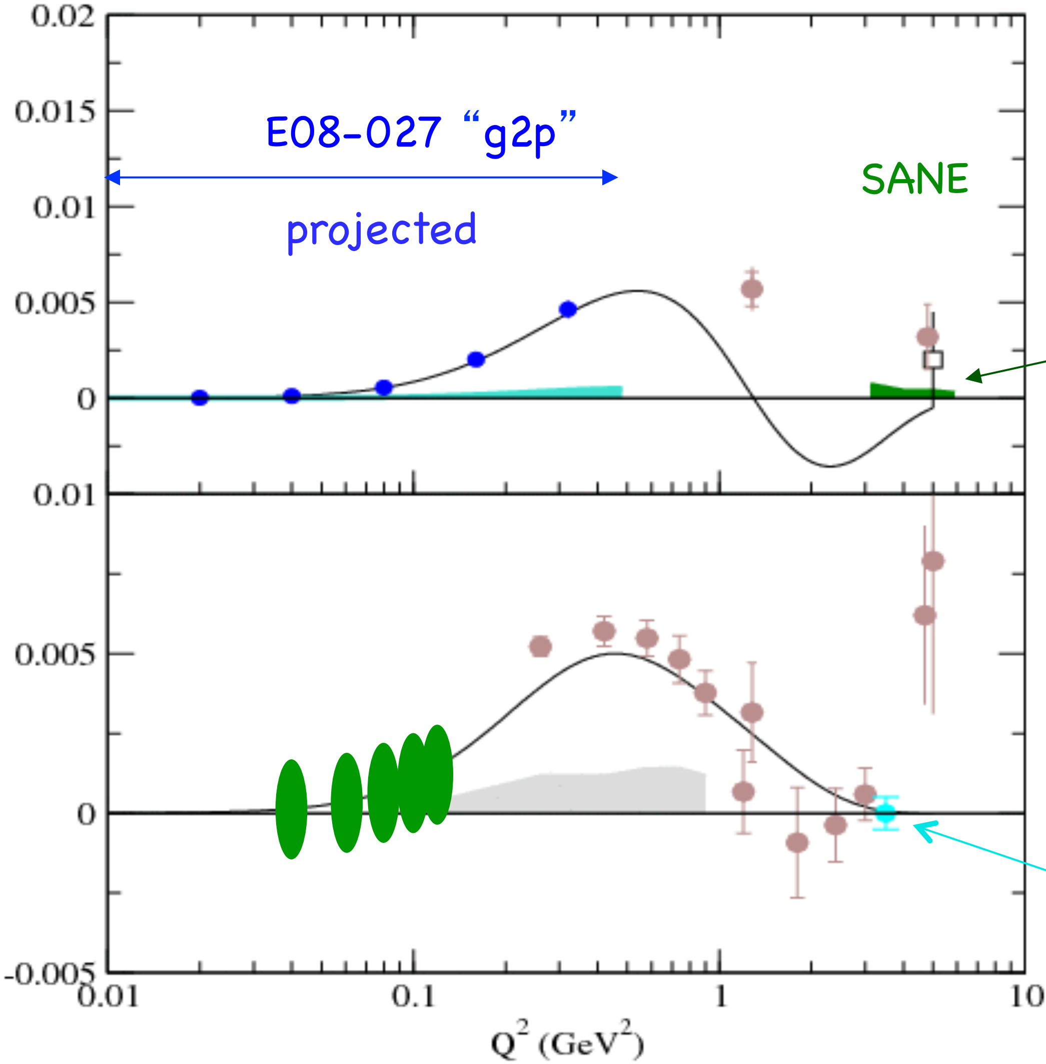
Color polarizabilities χ_E,χ_B are linear combination of d_2 and f_2

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

Avoid issue of low-x extrapolation

Relation to Sivers and other TMDs

$d_2(Q^2)$



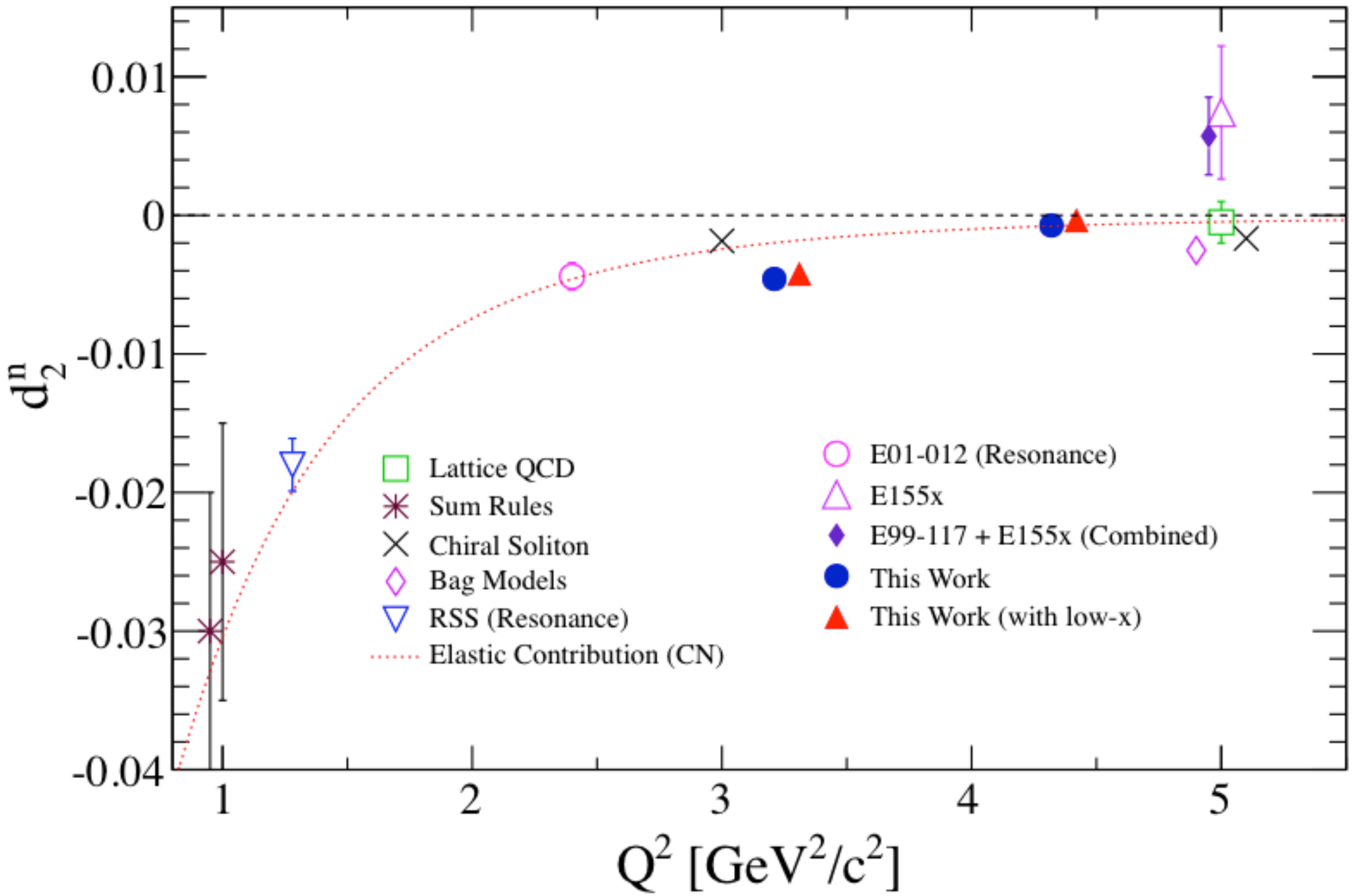
6 GeV Experiments

Sane: new in Hall C

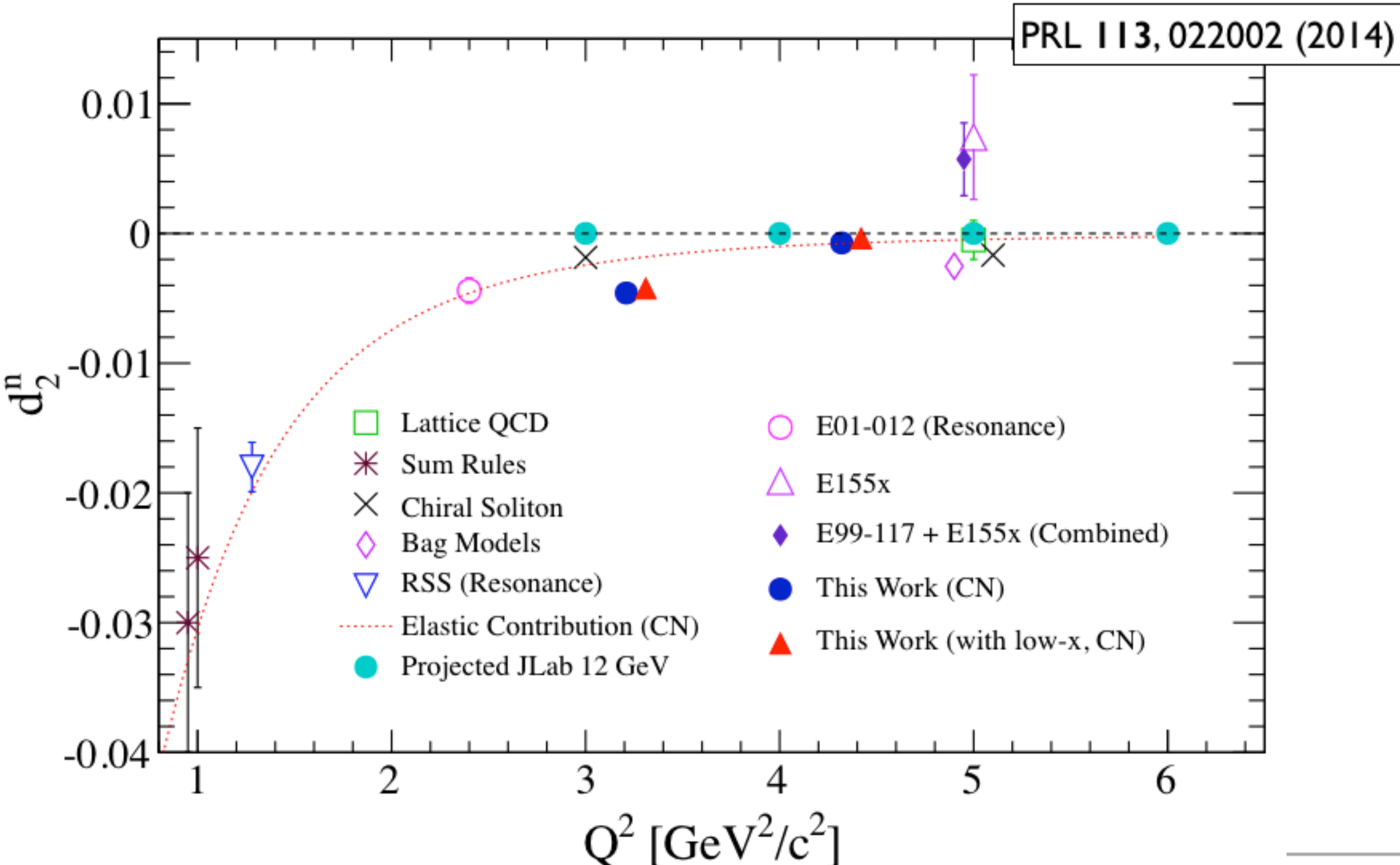
"g2p" in Hall A, 2011

"d2n" new in Hall A

d_2^n Result from JLab E06-014



JLab 12 Projection of d_2^n



Higher Moments @ low Q^2: Generalized Spin Polarizabilities

- generalized forward spin polarizability γ_0

  generalized L-T spin polarizability δ_{LT}

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

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

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

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

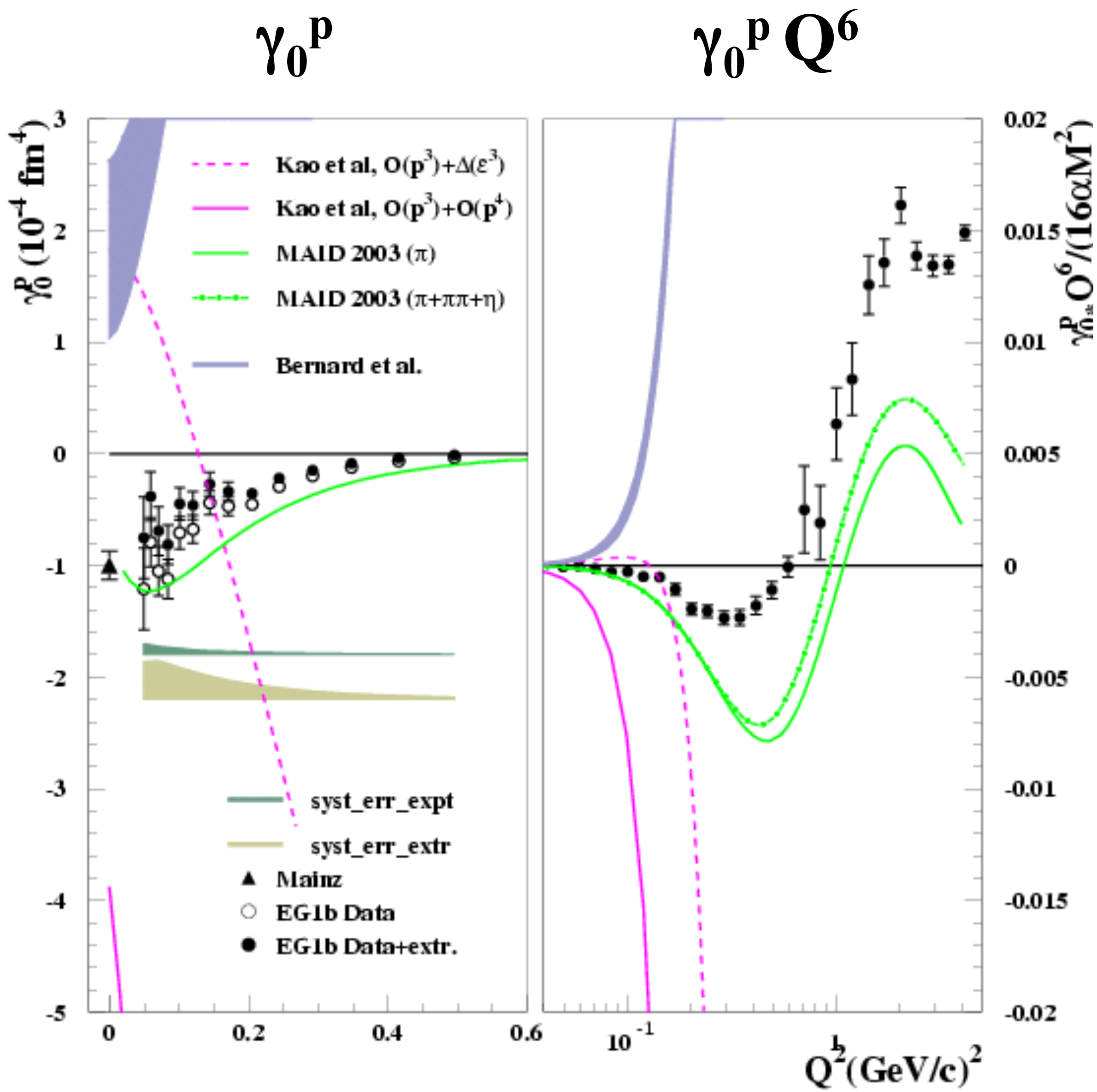
CLAS Proton Spin Polarizability γ_0^p

- EG1b, Prok *et al.*
  PLB 672,12 (2009)

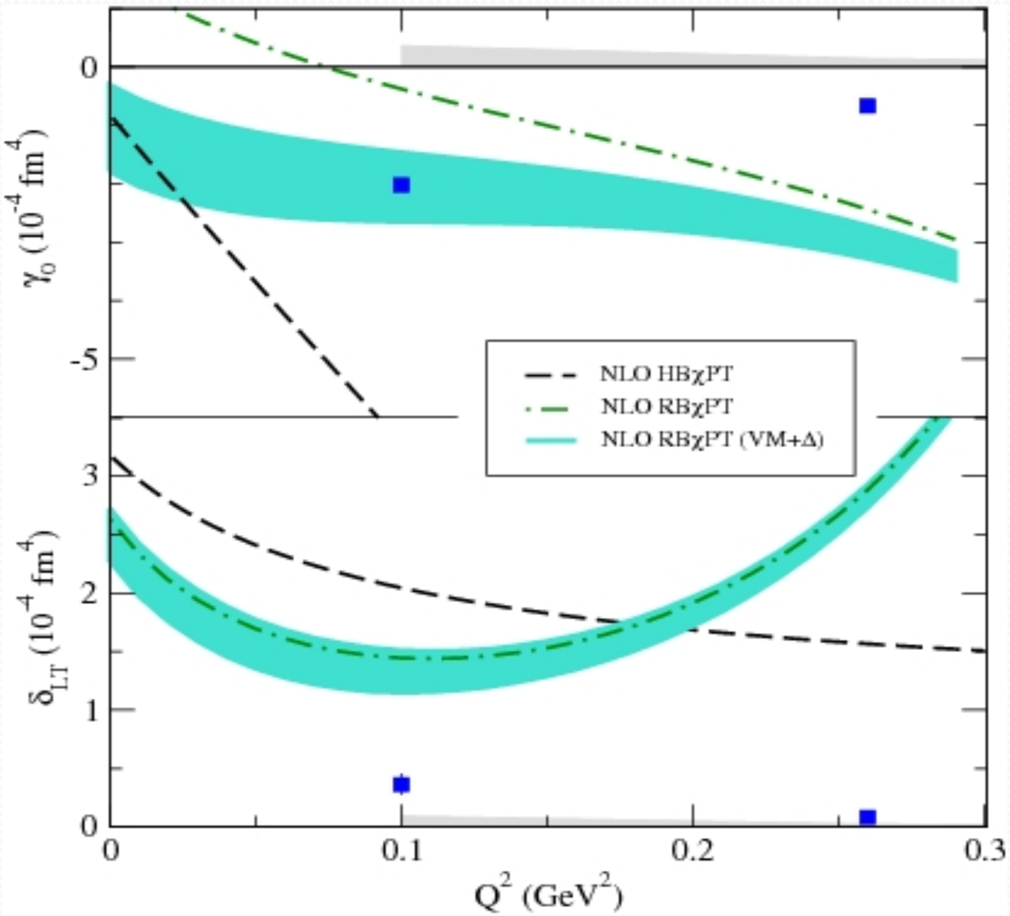
  Large discrepancies with ChPT

  Only longitudinal data, model for transverse (g_2)

  γ_0 sensitive to resonance



Neutron Spin Polarizabilities and the δ_{LT} Puzzle



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

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

δ_{LT} not sensitive to Δ,
one of the best quantities to test χPT

E94-010, PRL 93: 152301 (2004)

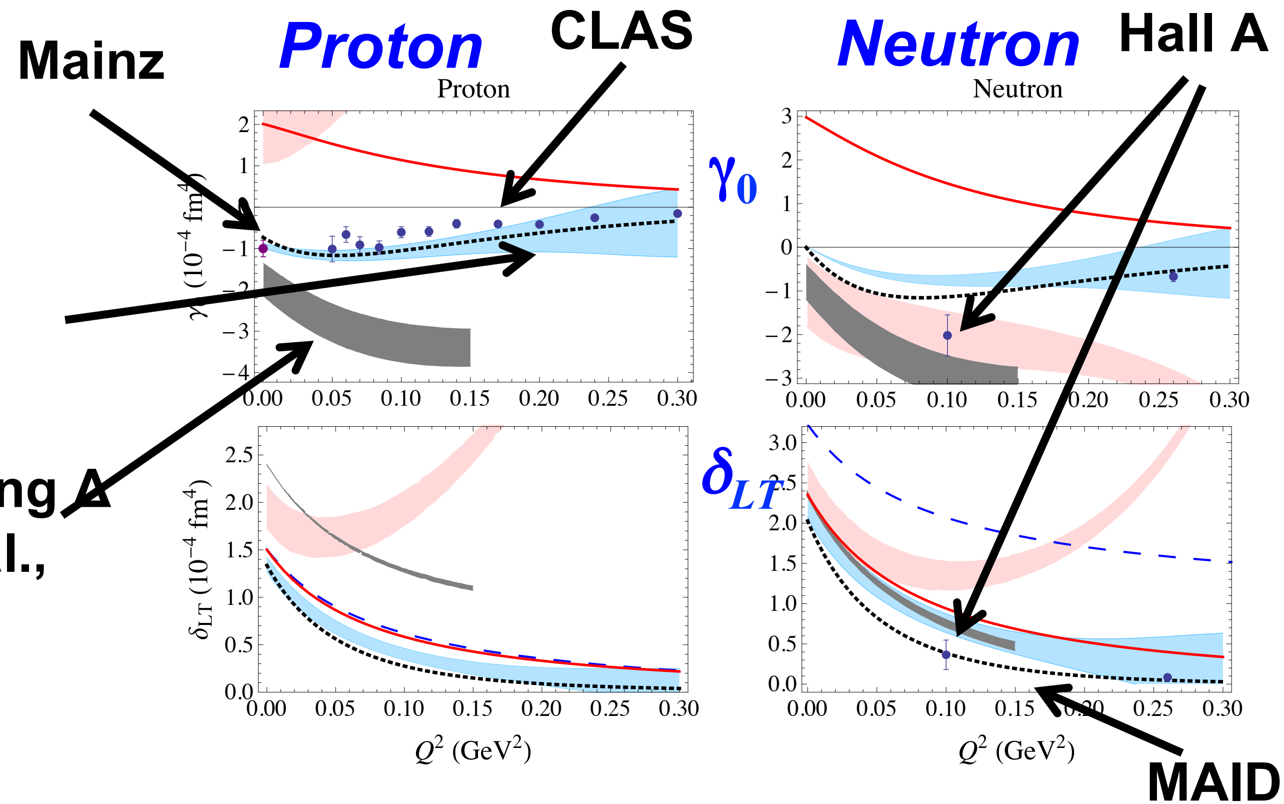
Failure of χPT?

Heavy Baryon χPT Calculation
Kao, Spitzenberg, Vanderhaeghen
PRD 67:016001(2003)

Relativistic Baryon χPT
Bernard, Hemmert, Meissner
PRD 67:076008(2003)

Theoretical Developments and the δ_{LT} Puzzle

- **HBχPT: recent: Lensky, Alarcon & Pascalutsa, PRC 90 055202 (2014)**
- **RB χ PT: properly including Δ contribution, Bernard et al., PRD 87 (2013)**

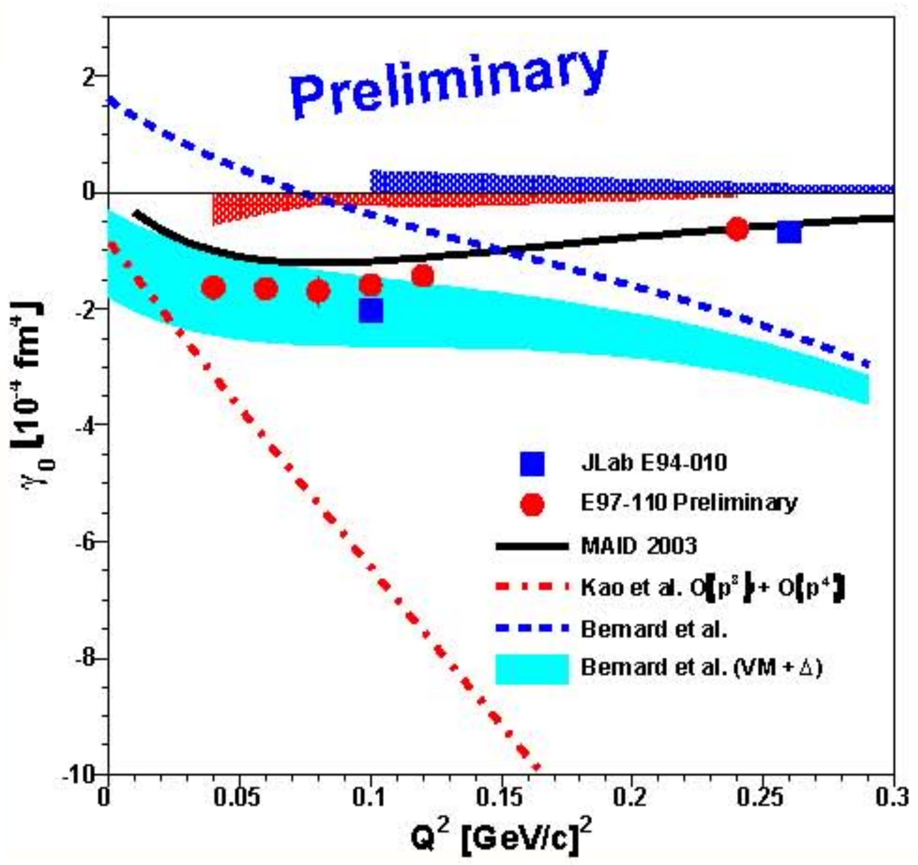


δ_{LT}

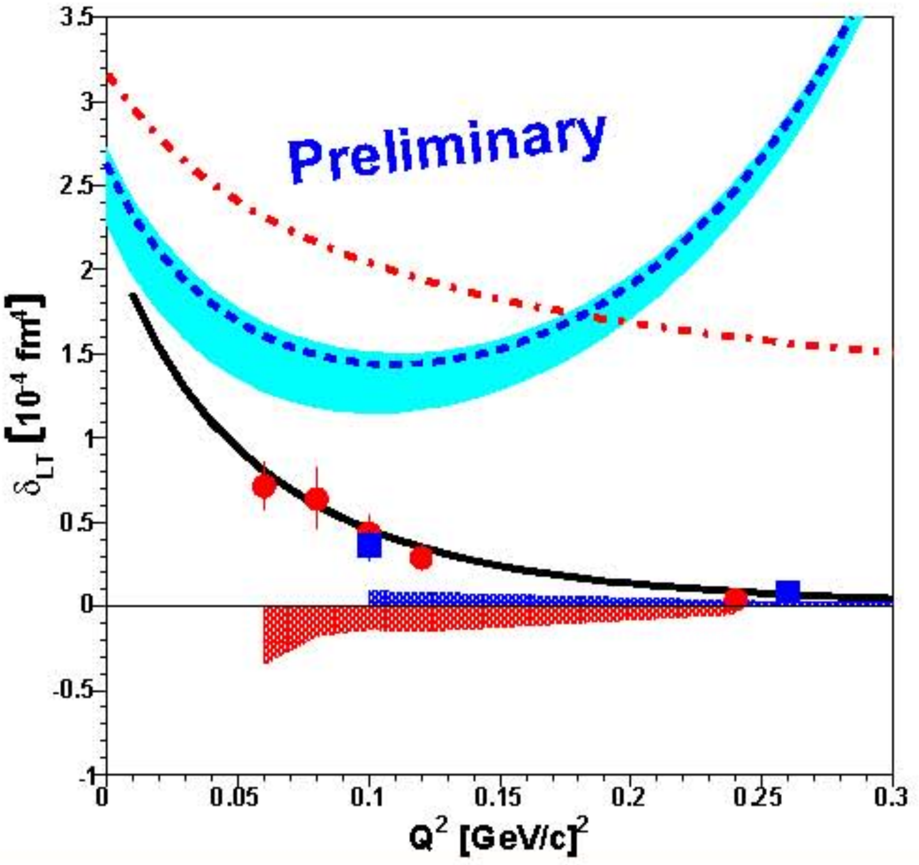
Spin Polarizabilities : E97-110 and E94-010 results

- Significant disagreement between data and both ChPT calculations for δ_{LT}
- Good agreement with MAID model predictions

γ_0

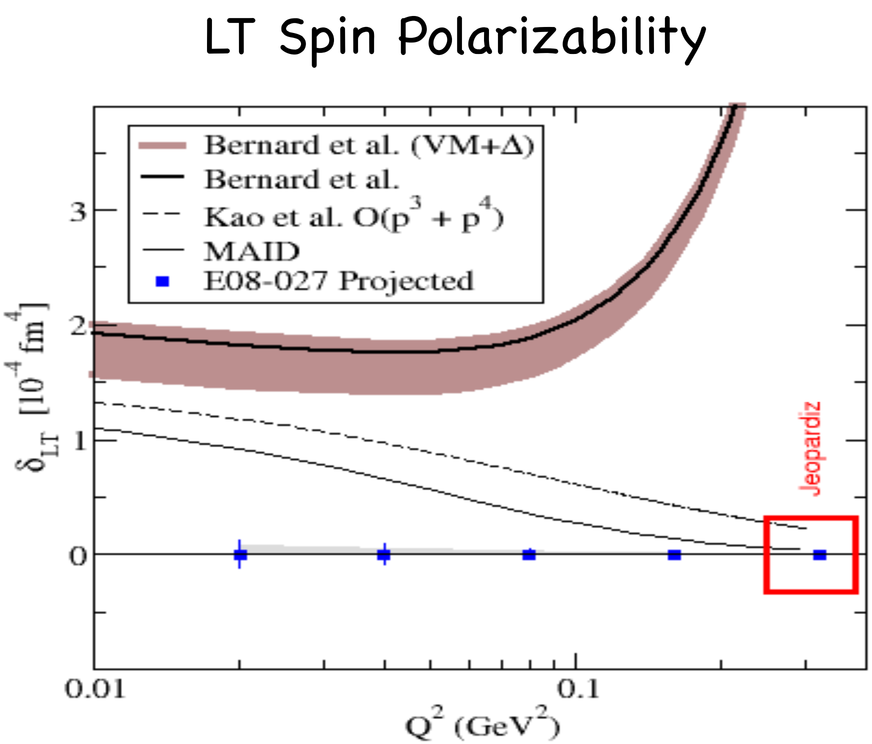


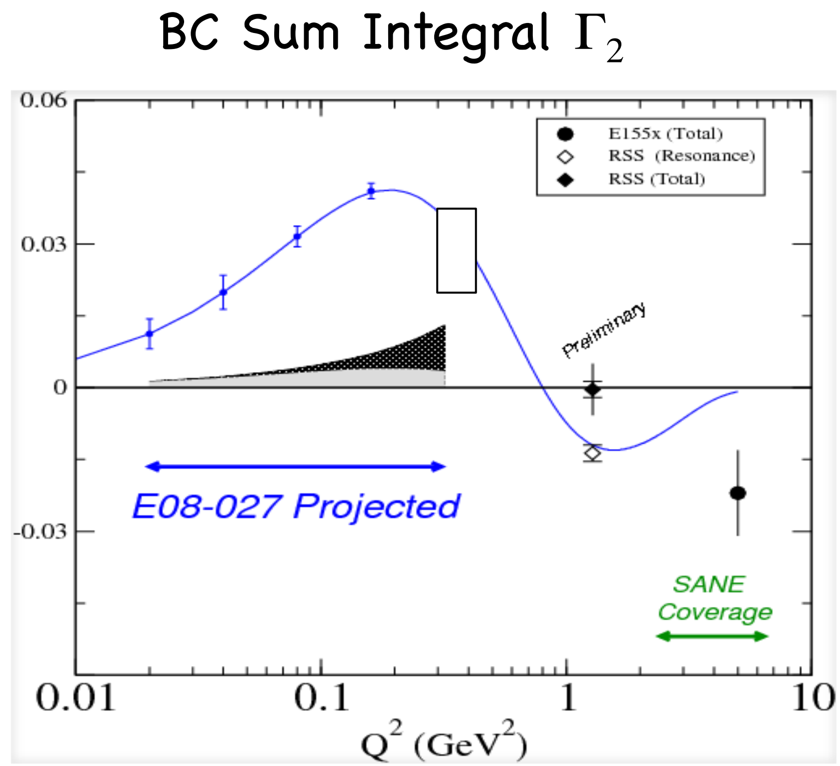
δ_{LT}



Q^2 Q^2

E08-027: g_2^p at low Q^2





Main goals:

1) Test Chiral PT calculations: large discrepancy for neutron δ_{LT}
2) BC Sum Rule: violation suggested for proton at large Q^2, ok for neutron
3) Input to Hydrogen Hyper Fine Splitting/ Proton Radius

Last Experiment @ JLab6 (2012). Analysis underway.

Summary

- Spin structure study full of surprises and puzzles

- A decade of experiments from JLab: exciting results
  - precision A_1 measurements at high-x: valence spin structure
  - spin-flavor: sea quark polarization, gluon polarization
  - precision measurements of g_2/d_2: high-twist
  - spin sum rules and polarizabilities
  - test χPT calculations, → 'δ_{LT} puzzle'

- Bright future
  - complete a chapter in spin structure study with 6 GeV JLab
  - 12 GeV Upgrade will greatly enhance our capability
    - Precision determination of the valence quark spin structure
  - EIC: precision determination of polarized sea and gluon and multi-d