Spin Structure with JLab 6 and 12 GeV

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4th Hadron Workshop / KITPC Program, Beijing, China, July, 2012

- Introduction
- Selected Results from JLab 6 GeV
  - Moments of Spin Structure Functions

    GDH/Bjorken Sum Rules, Spin Polarizabilities

    g_2/d_2: B-C Sum Rule, Color Lorentz Force (Polarizability)
- Planned experiments with JLab 12 GeV

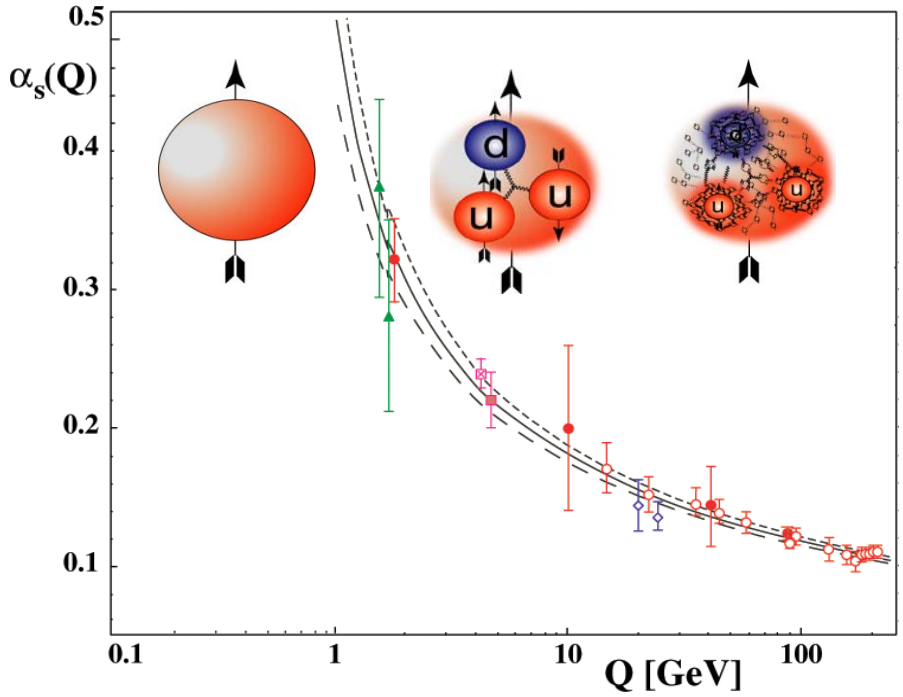
Strong Interaction and QCD

- **Strong interaction, running coupling ~1**
  -- asymptotic freedom (2004 Nobel)
  perturbation calculation works at high energy
  -- interaction significant at intermediate energy
  quark-gluon correlations
  -- interaction strong at low energy
  confinement
  -- gluons self interacting

- **A major challenge in fundamental physics:**
  -- Understand QCD in all regions, including strong (confinement) region

- **Fundamental degrees of freedom:**
  quarks, gluons
  Natural effective degrees of freedom:
  hadrons
- **Theoretical Tools:**
  pQCD (OPE), Lattice QCD, ChPT, …

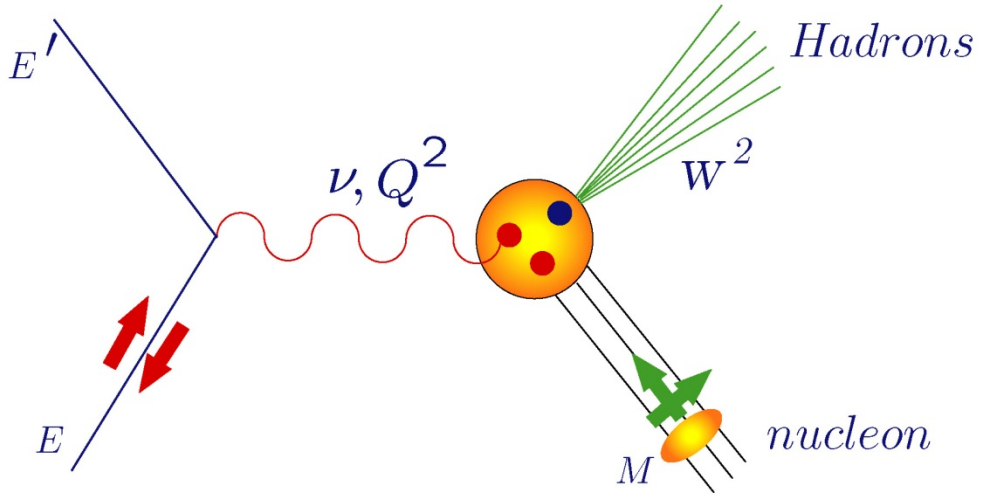
running coupling "constant"



Introduction

- Spin experiments provide fundamental information
  as well as insights into QCD dynamics
- Experiments: polarized beams(e, p), polarized targets (p, d, ^{3}He/n)
  longitudinal and transverse target polarization
  $A_{\parallel}$, $A_{\perp}$ → A_1, A_2
  $\Delta\sigma_{\parallel}$, $\Delta\sigma_{\perp}$ → Spin Structure Functions $g_1(x, Q^2)$, $g_2(x, Q^2)$
- Polarized PDFs $\Delta q(x)$
  LO, NLO,…, QCD evolution,
  Higher-twists
- Comparison with theories
  1. High-x
  2. Moments: sum rules/po larizabilities
- World data (CERN, SLAC, HERMES, RHIC-spin, JLab, …)
- JLab 6 GeV: high-x, low Q^2, high-precision.
- Future : JLab 12 GeV, (EIC)

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

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

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

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

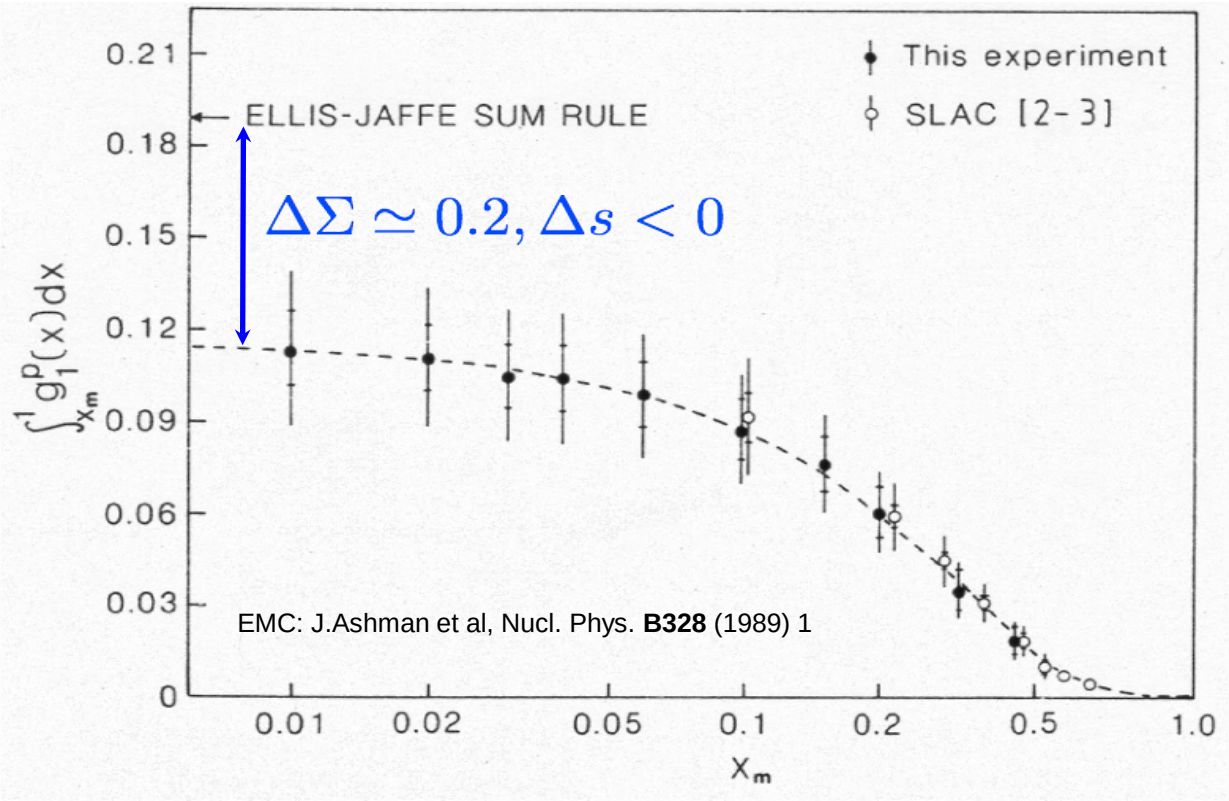
$q_i(x)$ quark momentum distributions of flavor i

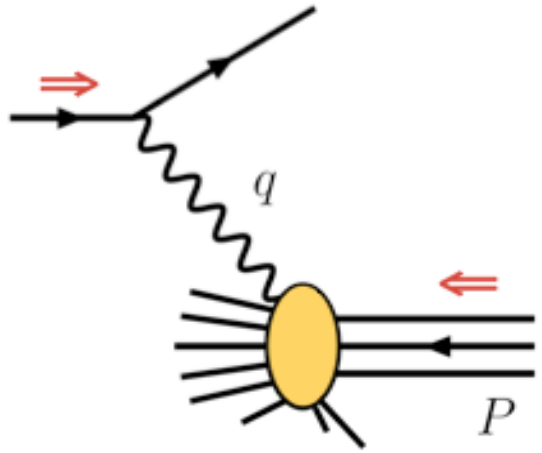
$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

$F_2 = 2xF_1$ $\qquad$ $g_2 = 0$ *(higher-twists)*

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

EMC/SLAC Polarized DIS – Spin "Crisis" or "Surprise"

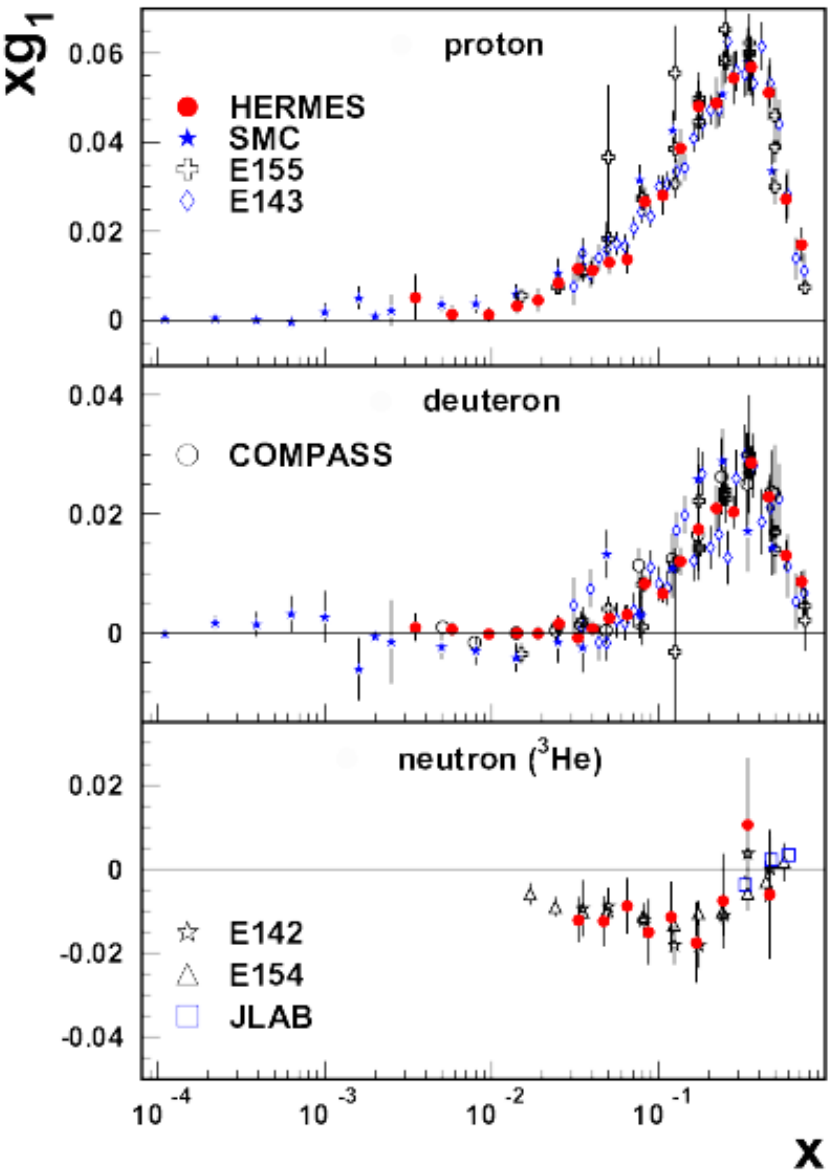


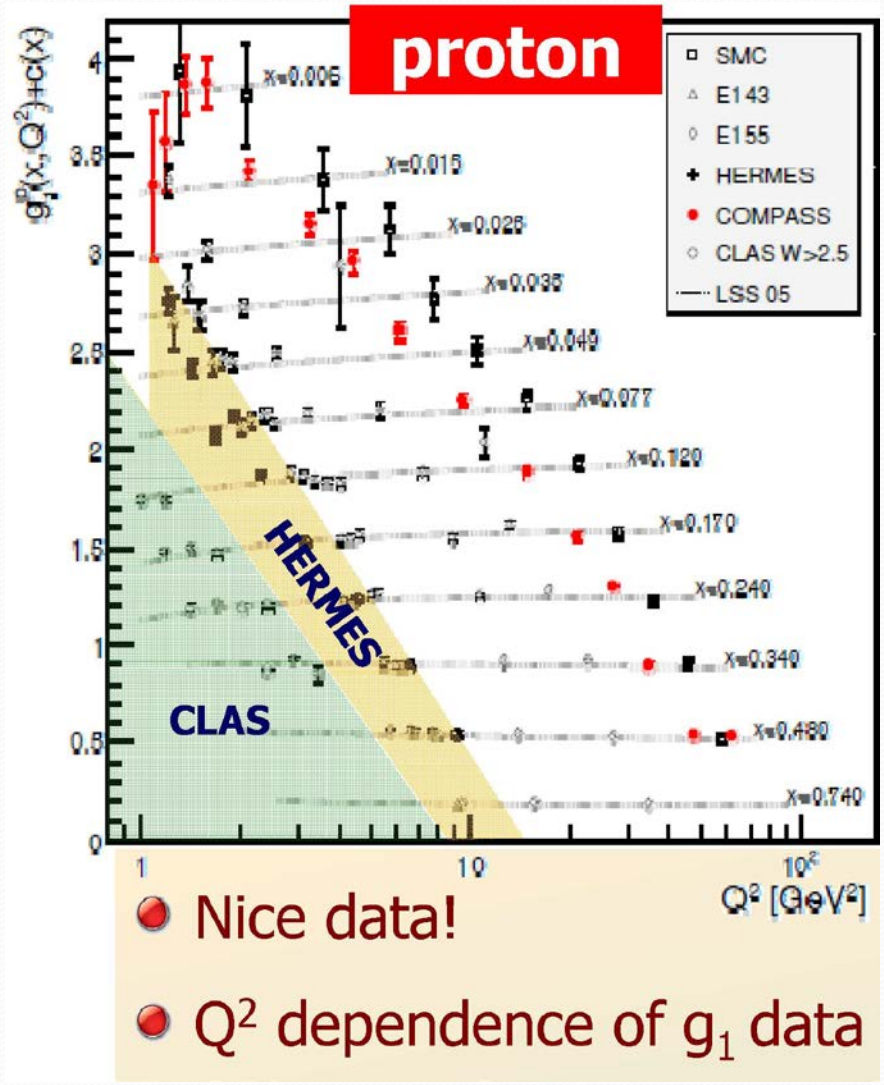


$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x, Q^2)}$$

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

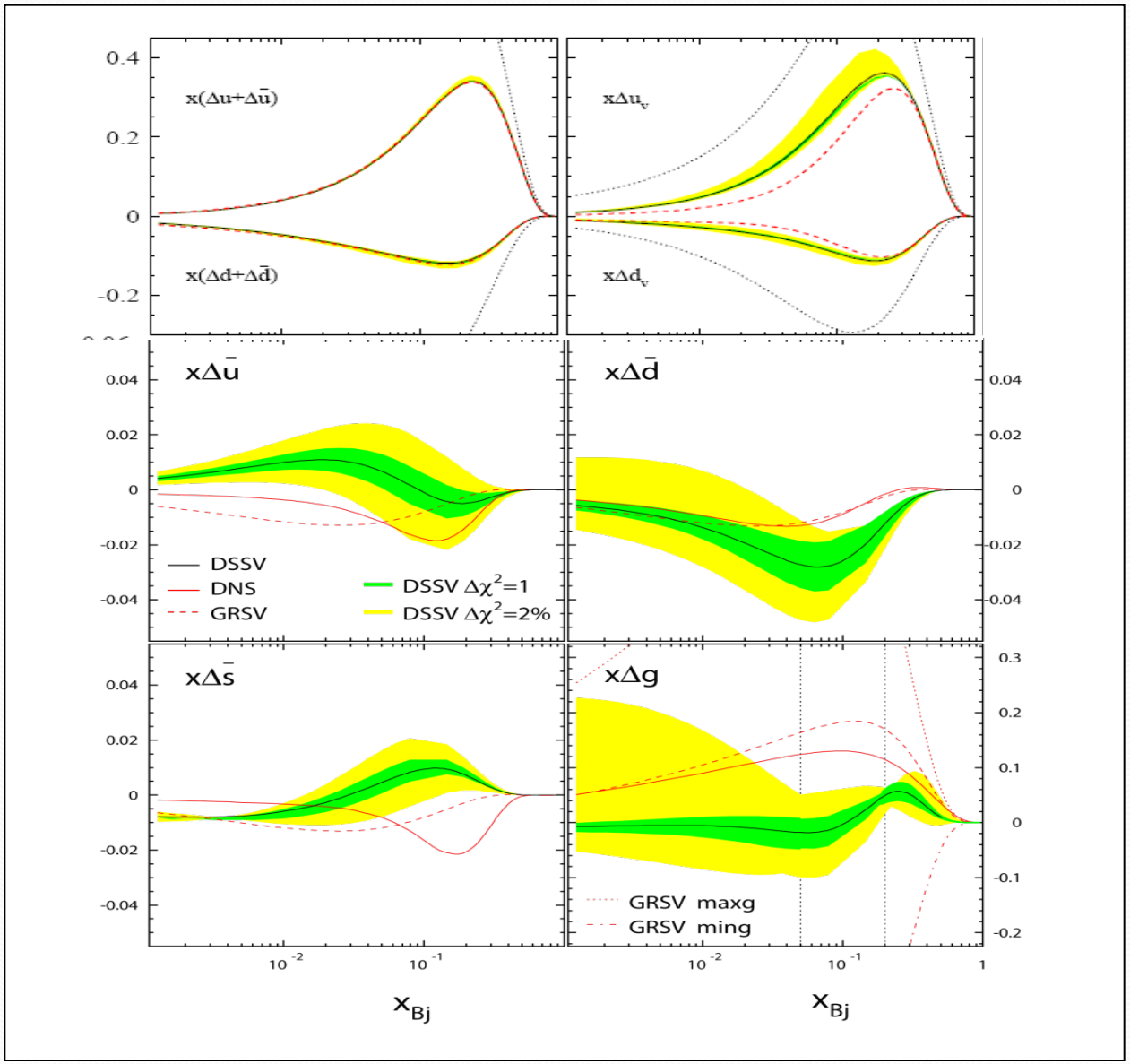
Polarized Structure functions





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

Polarized Parton Distributions



DSSV, PRL101, 072001 (2008)

Three Decades of Spin Structure Study

- 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 $(1/2)\Delta\Sigma + L_q + \Delta G + L_g = 1/2$ (Jaffe)

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

  Bjorken Sum Rule verified to <10% level

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

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

  New spin decomposition (X. Chen, *et. Al, Wakamatsu, …*)

  What observable directly corresponds to $L_z \sim b_x \times p_y$?

  Valence Quark Spin Distributions

  Sum Rules at low Q^2, Higher-Twists

  Transversity, TMDs, GPDs, multi-d structure

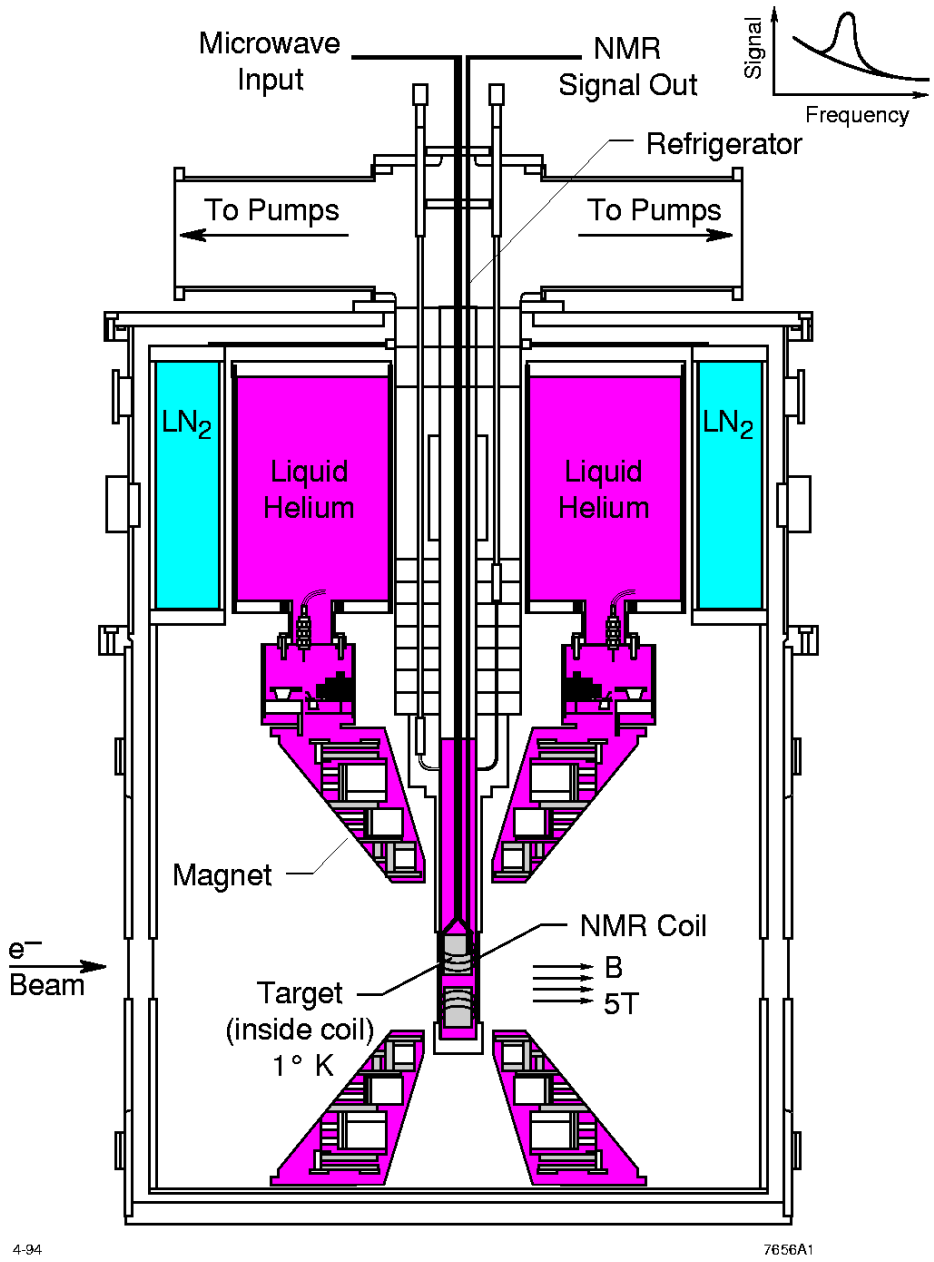
JLab Spin Experiments

- Results: Published and Preliminary/Upcoming
  - Spin in the Valence (High-*x*) Region
  - Spin (g_1/g_2) Moments: Spin Sum Rules and Polarizabilities,
  - Color Polarizability/Lorentz Force: d_2
  - ...
- Just completed data taking
  - g_2^p at low Q^2
- Future: 12 GeV
  - Inclusive: A_1/d_2,
  - Semi-Inclusive:, Flavor-decomposition, Transversity ,TMDs,
  - GPDs
- Reviews: S. Kuhn, J. P. Chen, E. Leader, Prog. Part. Nucl. Phys. 63, 1 (2009)

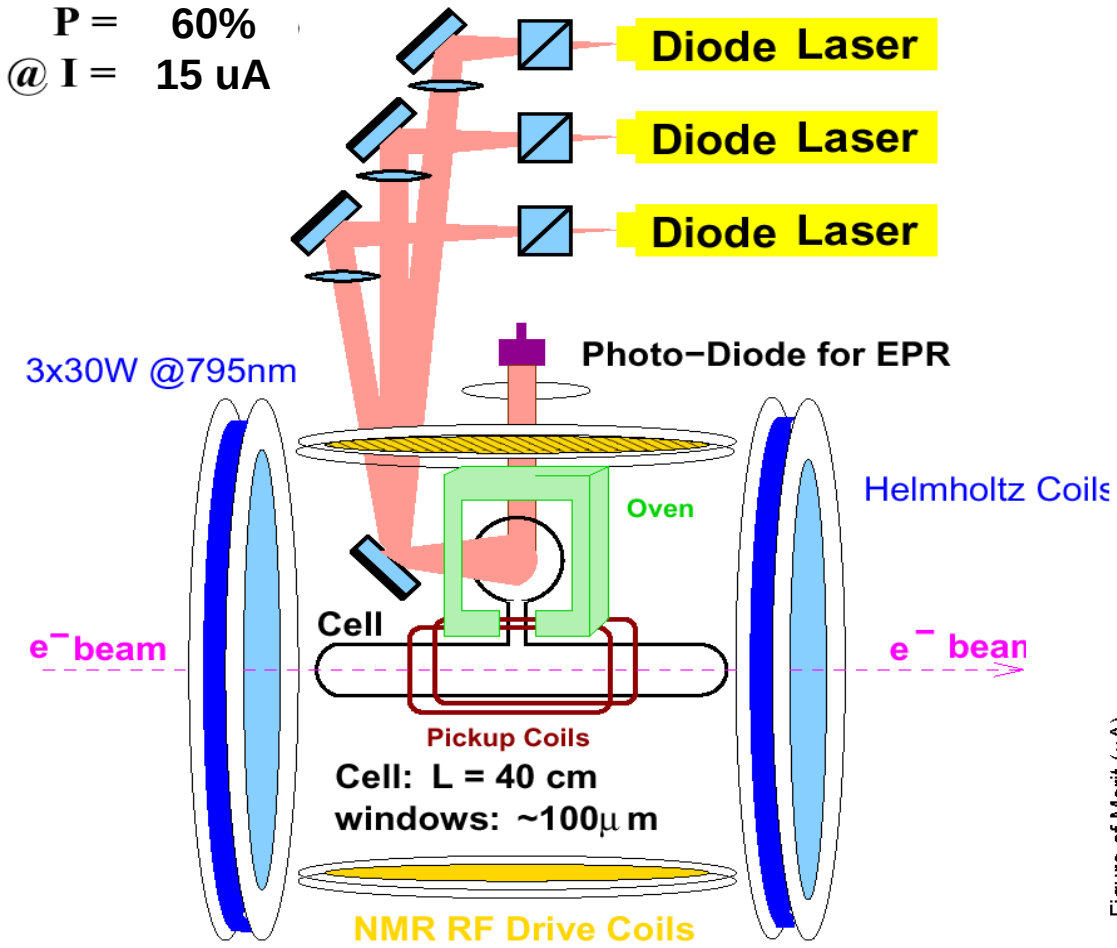
JLab Polarized Proton/Deuteron Target

- Polarized NH_3/ND_3 targets
- Dynamical Nuclear Polarization

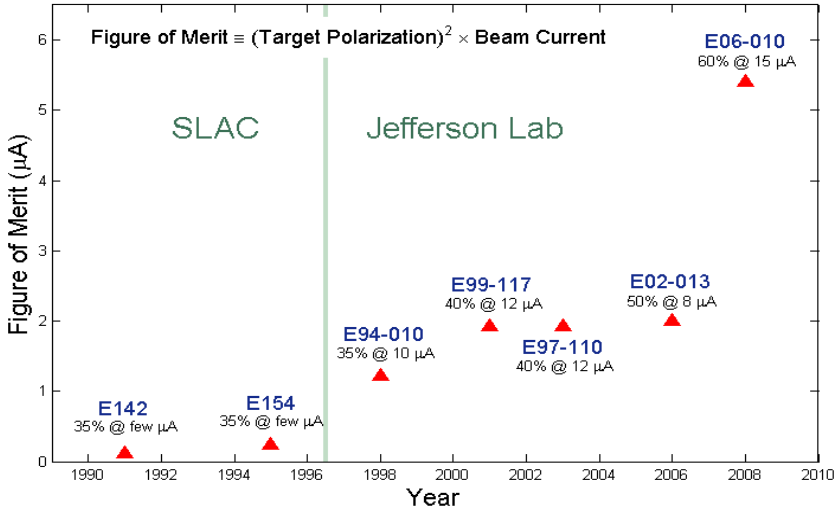
- In-beam average polarization
  - 70-90% for p
  - 30-50% for d
- Luminosity ~ 10^{35} (Hall C/A)
  - ~ 10^{34} (Hall B)



JLab Polarized ^{3}He Target



- ✓**longitudinal, transverse and vertical**
- ✓**Luminosity=10^{36} (1/s) (highest in the world)**
- ✓**Record high pol ~ 60%**



Moments of Spin Structure Functions

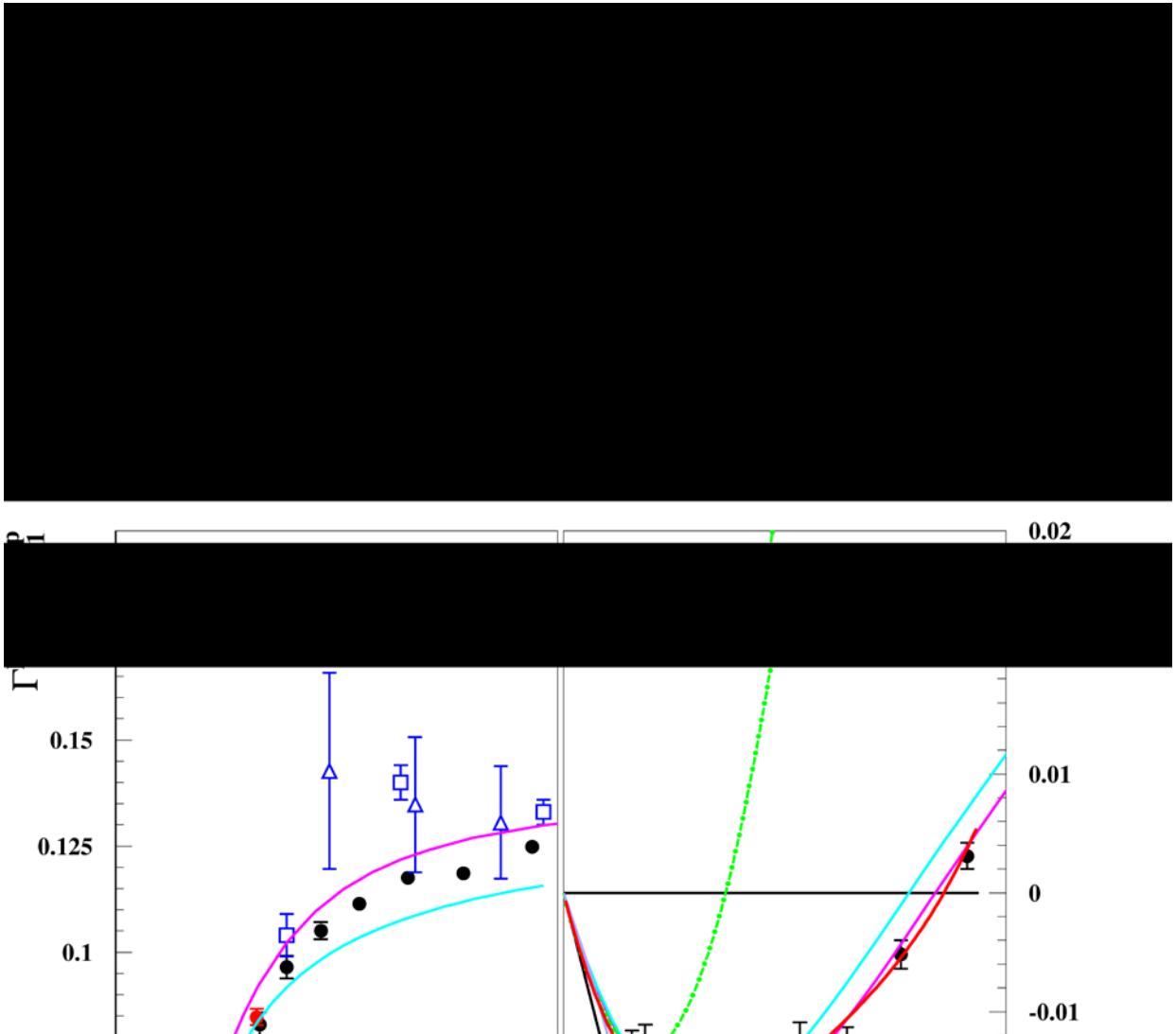
Sum Rules, Polarizabilities

First Moment of g_1^p : Γ_1^p

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

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

Γ_1^p



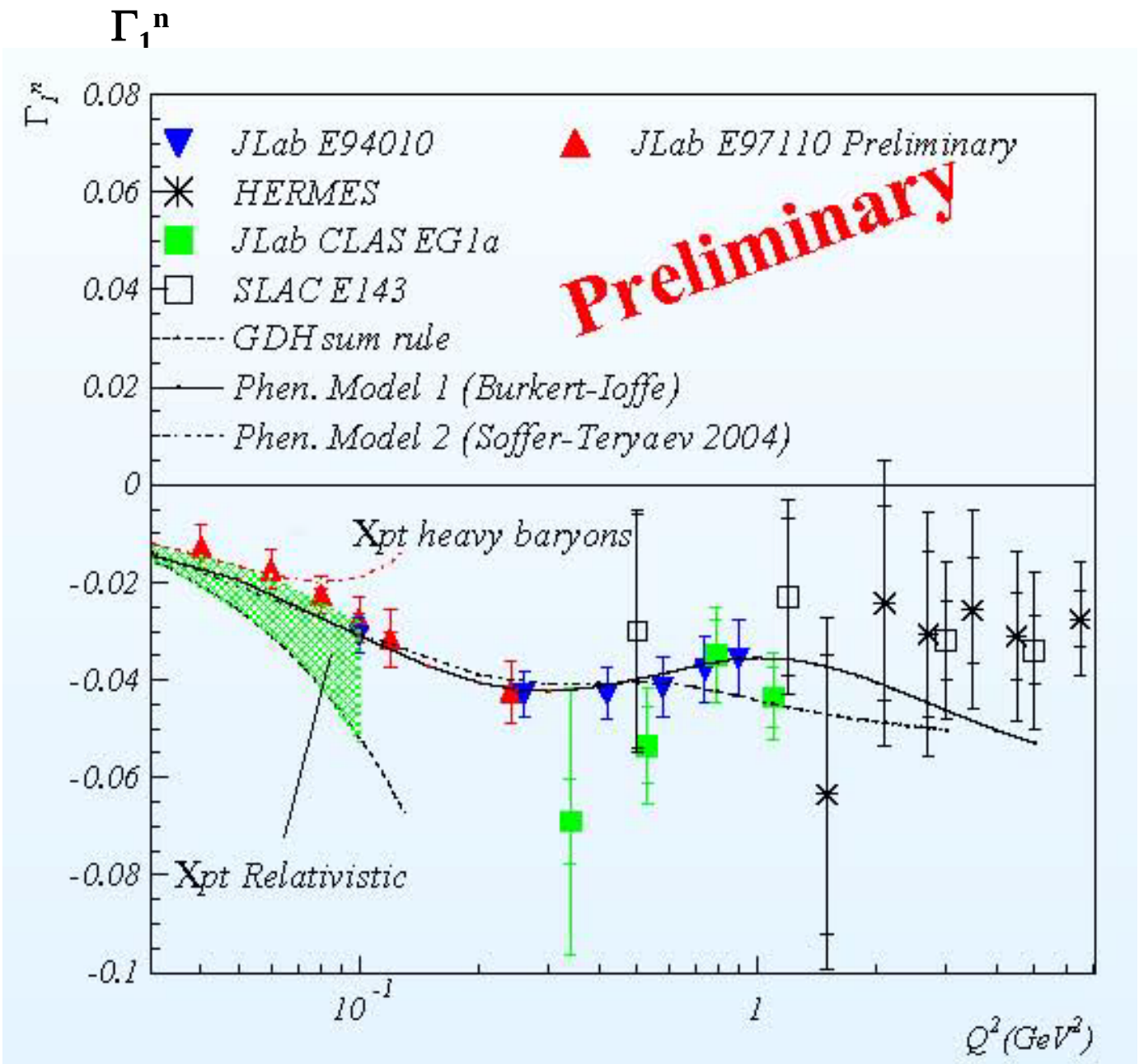
EG1b, arXiv:0802.2232
EG1a, PRL 91, 222002 (2003)
Spokespersons: V. Burkert,
D. Crabb, G. Dodge,

First Moment of g_1^n : Γ_1^n

E94-010, PRL 92 (2004) 022301

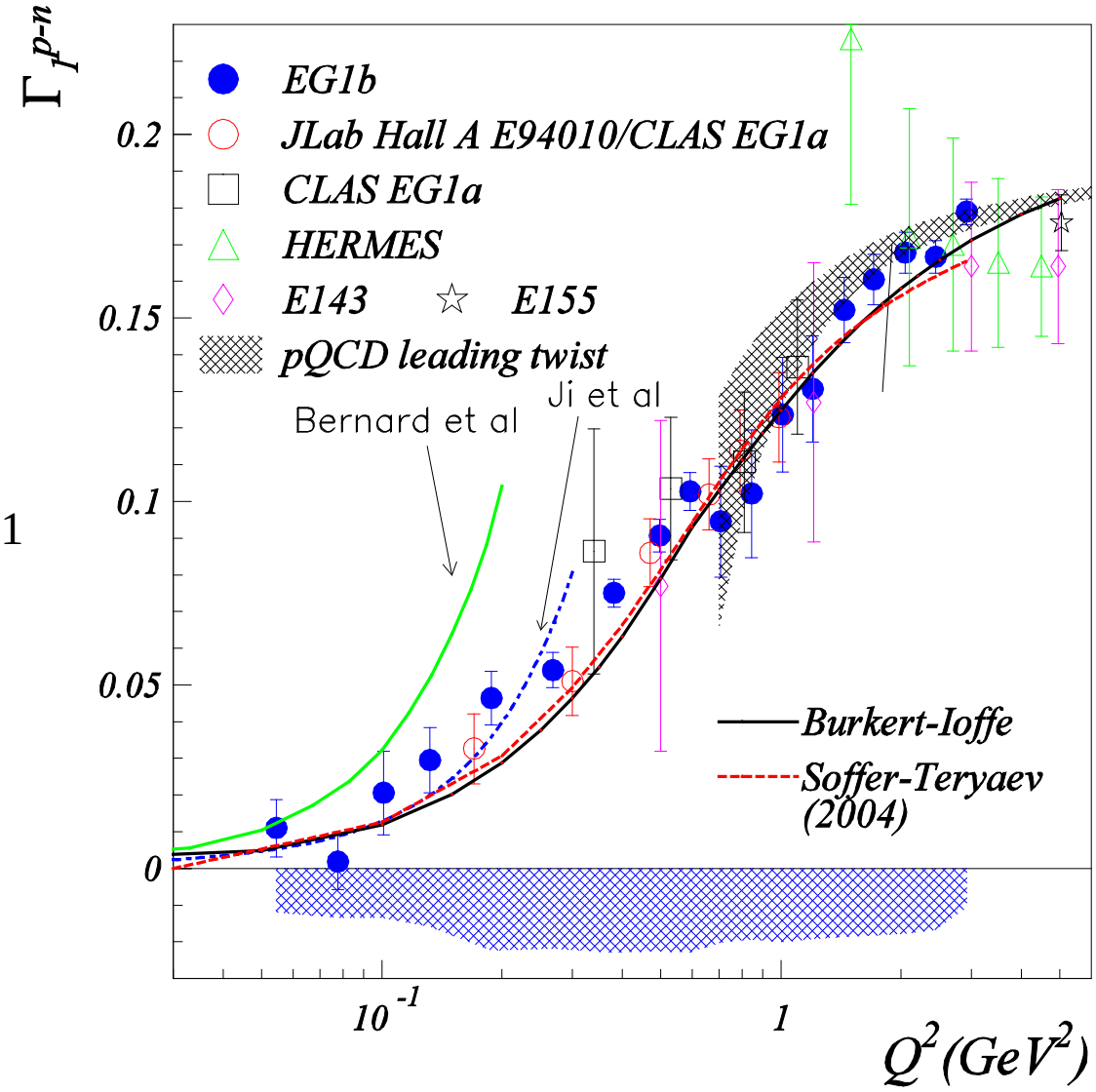
E97-110, preliminary

EG1a, from *d-p*



Γ_1 of *p-n*

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

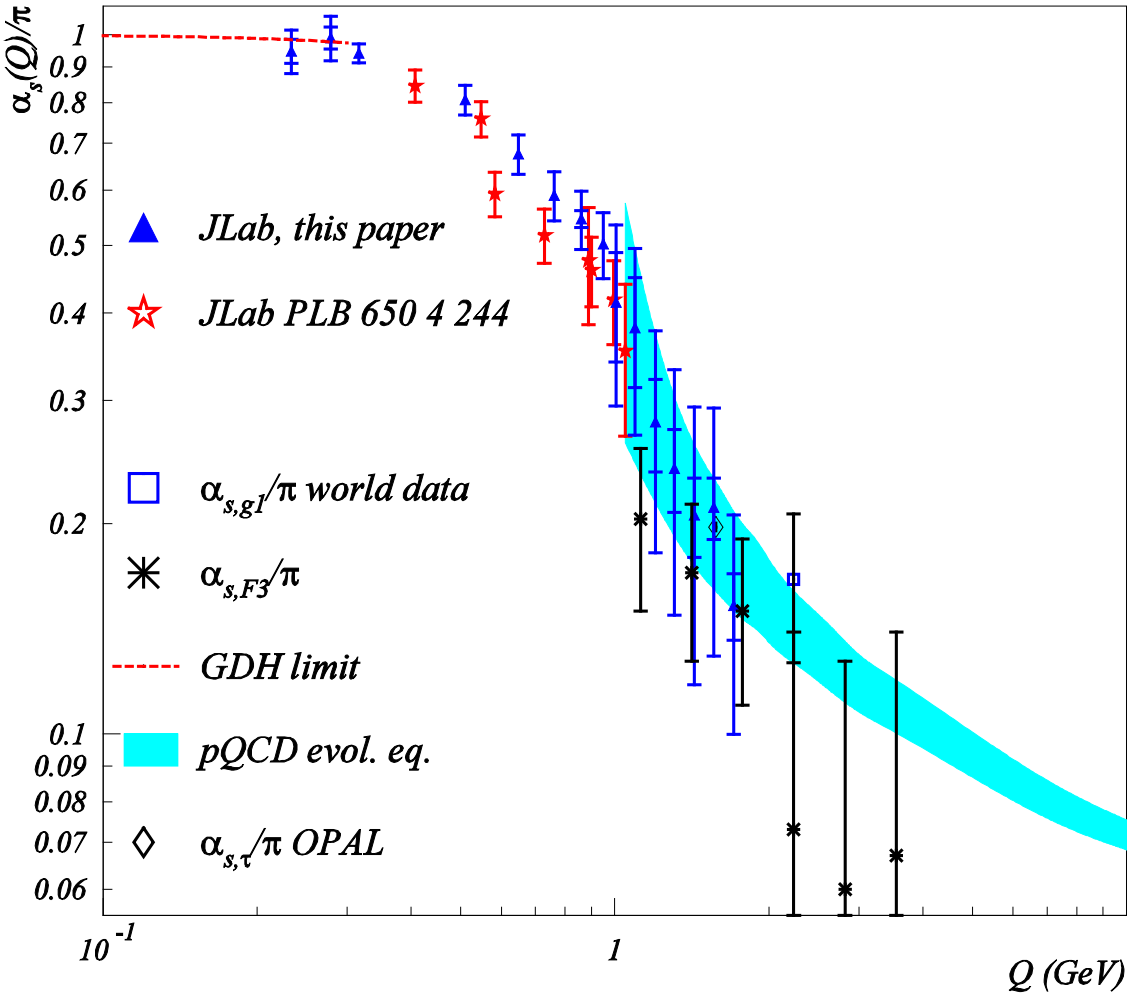


Effective Coupling Extracted from Bjorken Sum

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

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

α_s/π



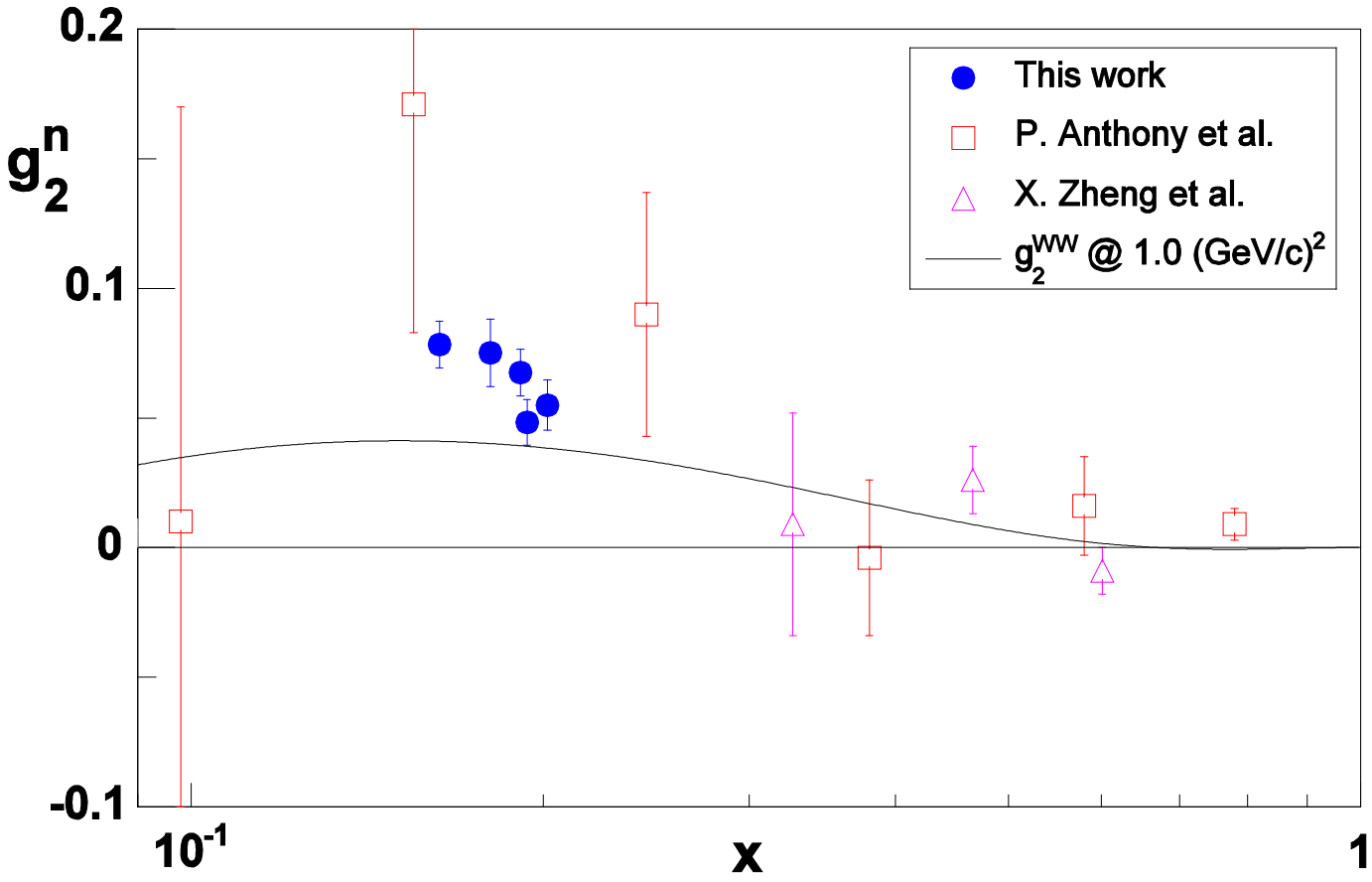
Second Spin Structure Function g_2

Burkhardt - Cottingham Sum Rule

d_2: Color Lorentz Force (Polarizability)

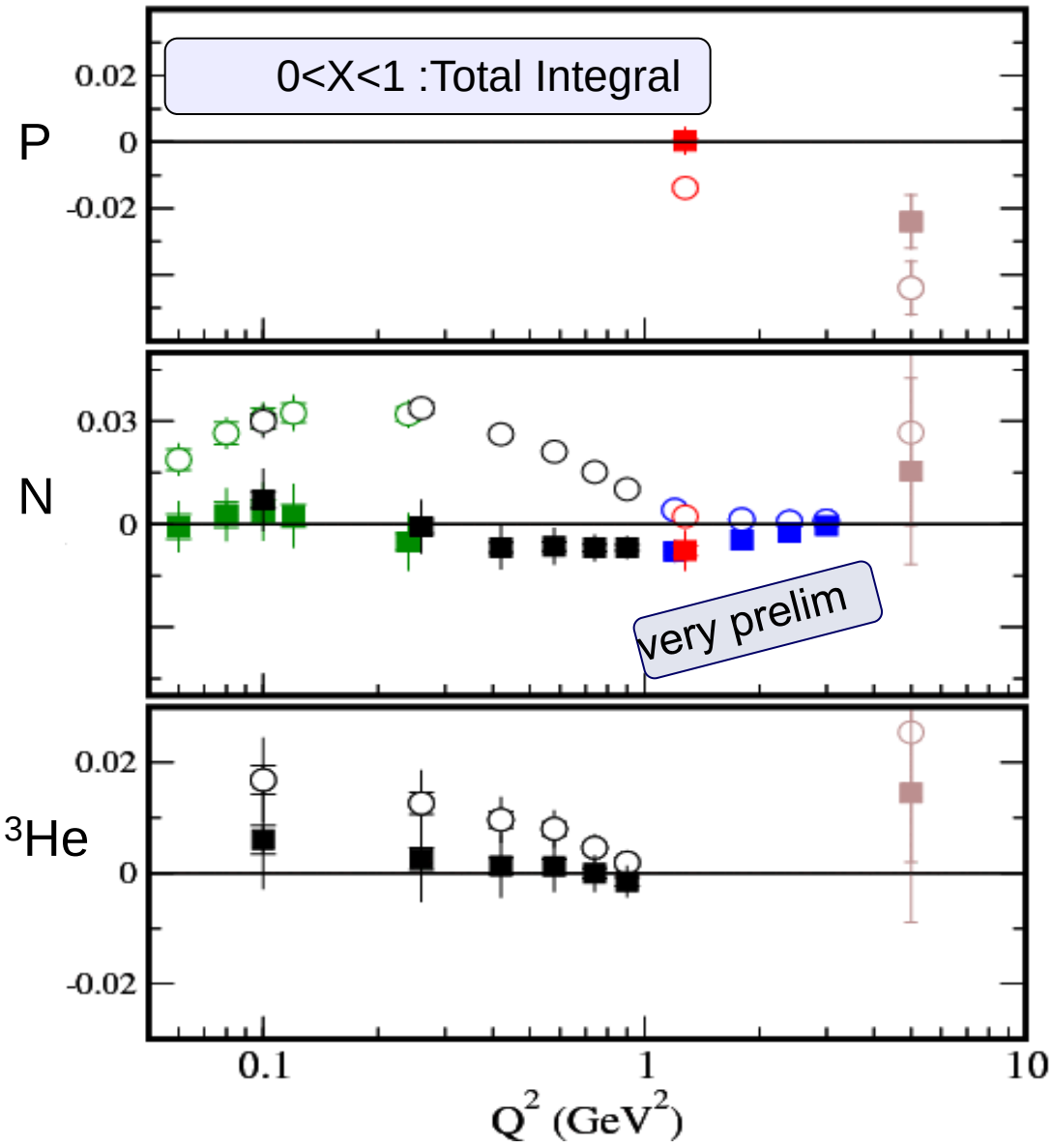
Spin Polarizabilities

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



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

Brawn: SLAC E155x
Red: Hall C RSS
Black: Hall A E94-010
Green: Hall A E97-110 (preliminary)
Blue: Hall A E01-012 (spokespersons: N. Liyanage, former student, JPC) (preliminary)

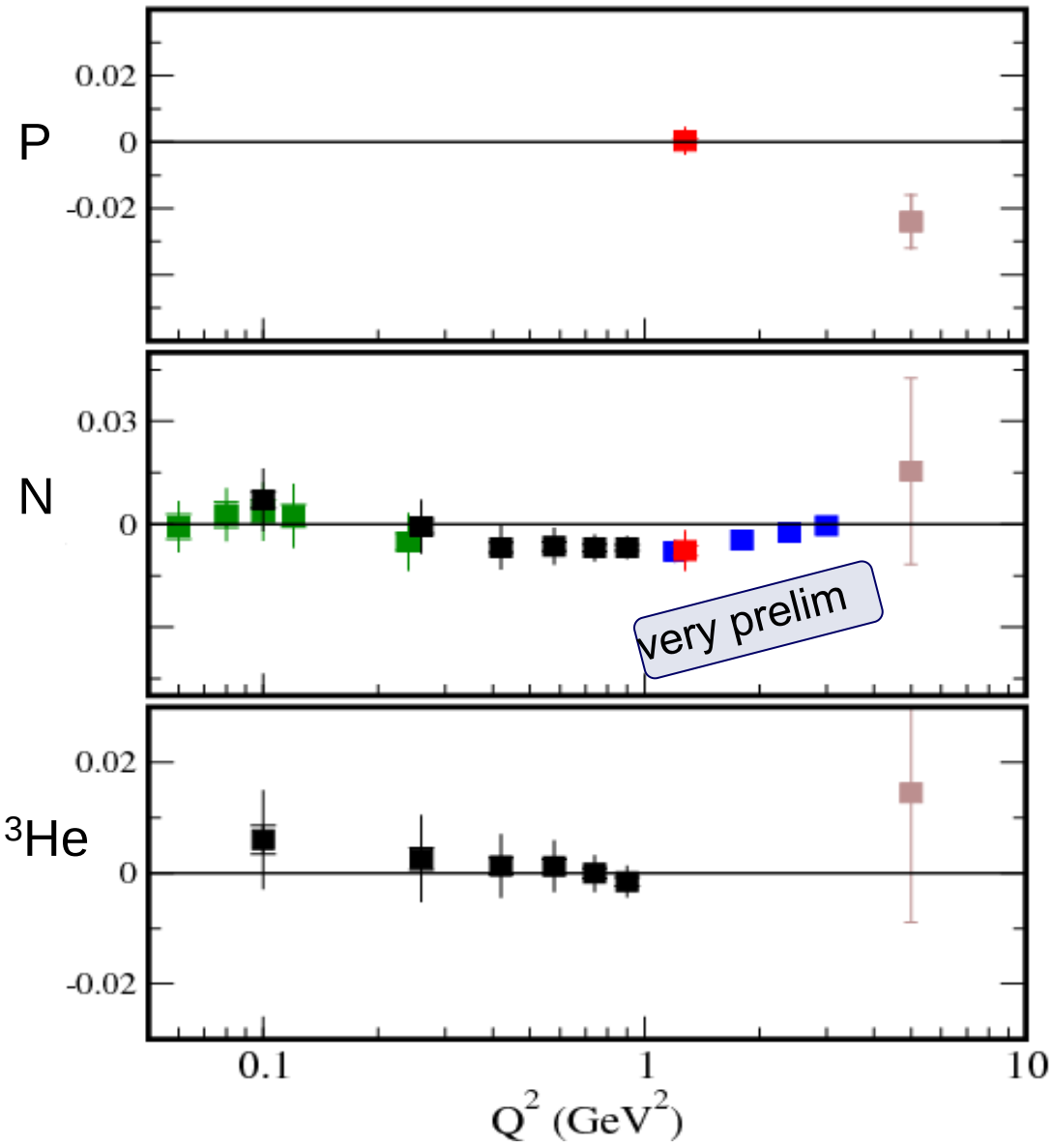
BC = Meas+low_*x*+Elastic

"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 ^{3}He

Color Lorentz Force (Polarizability): d_2

- 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

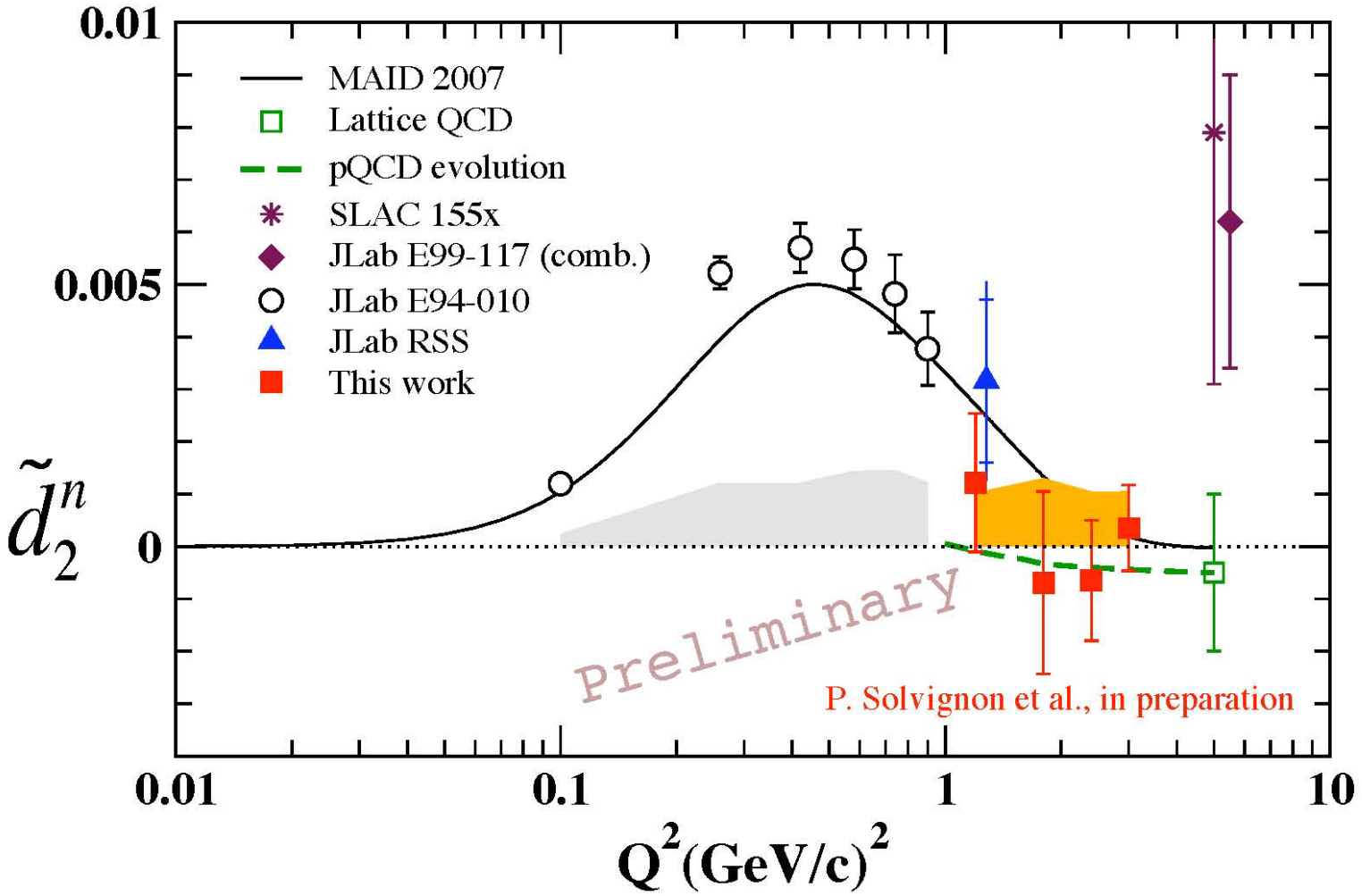
Provide a benchmark test of Lattice QCD at high Q^2

Avoid issue of low-*x* extrapolation

Relation to Sivers and other TMDs

Preliminary results on neutron from E01-012

Spokespersons: J. P. Chen, S. Choi, N. Liyanage, plots by P. Solvignon

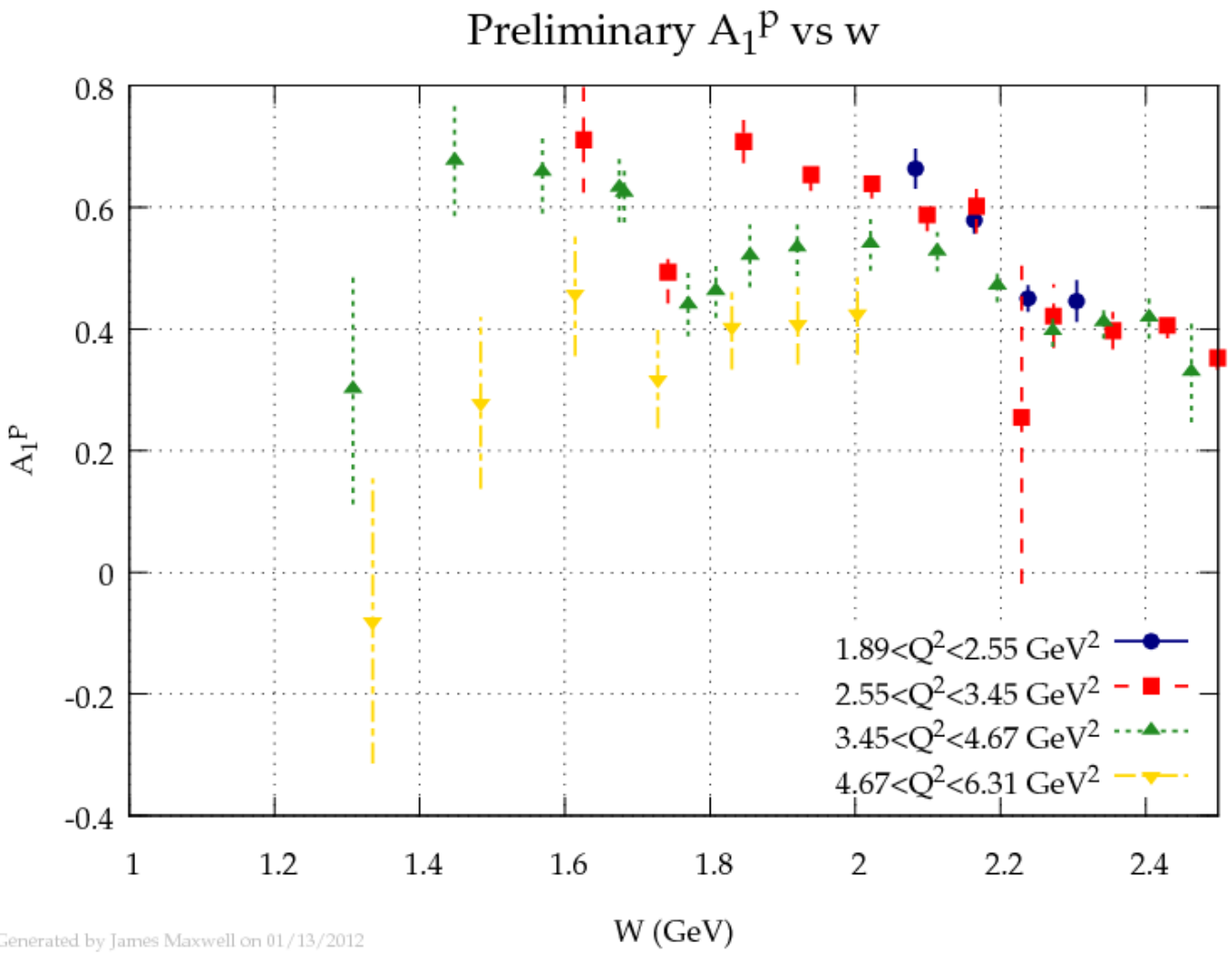


Moments from E01-012 and E94-010 include the resonance region only

Preliminary $A_1(p)$ Results, Hall C SANE

Spokespersons: S. Choi, M. Jones, Z. Meziani and O. Rondon

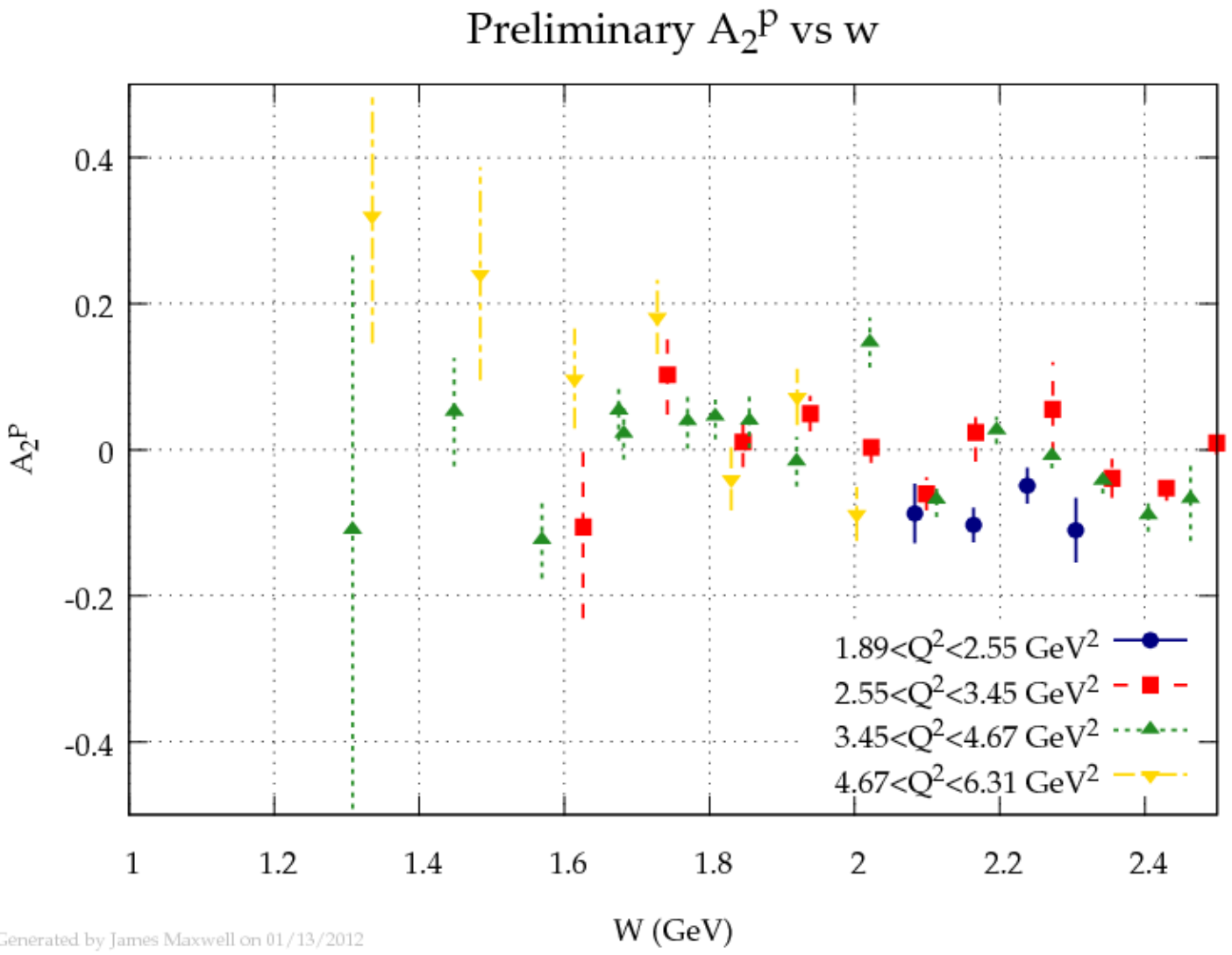
Courteous of O. Rondon



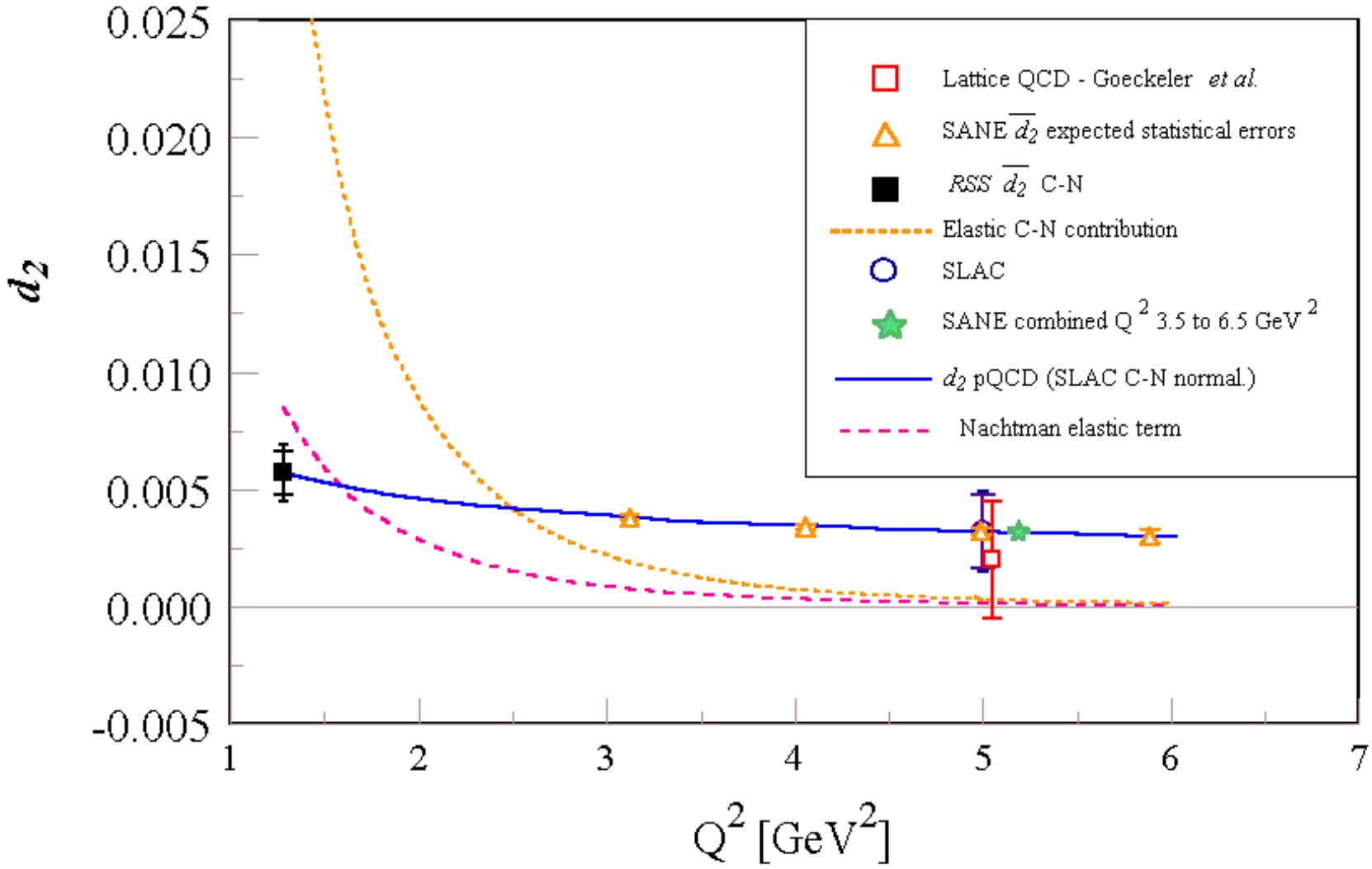
Preliminary $A_2(p)$ Results, Hall C SANE

Spokespersons: S. Choi, M. Jones, Z. Meziani and O. Rondon

Courteous of O. Rondon



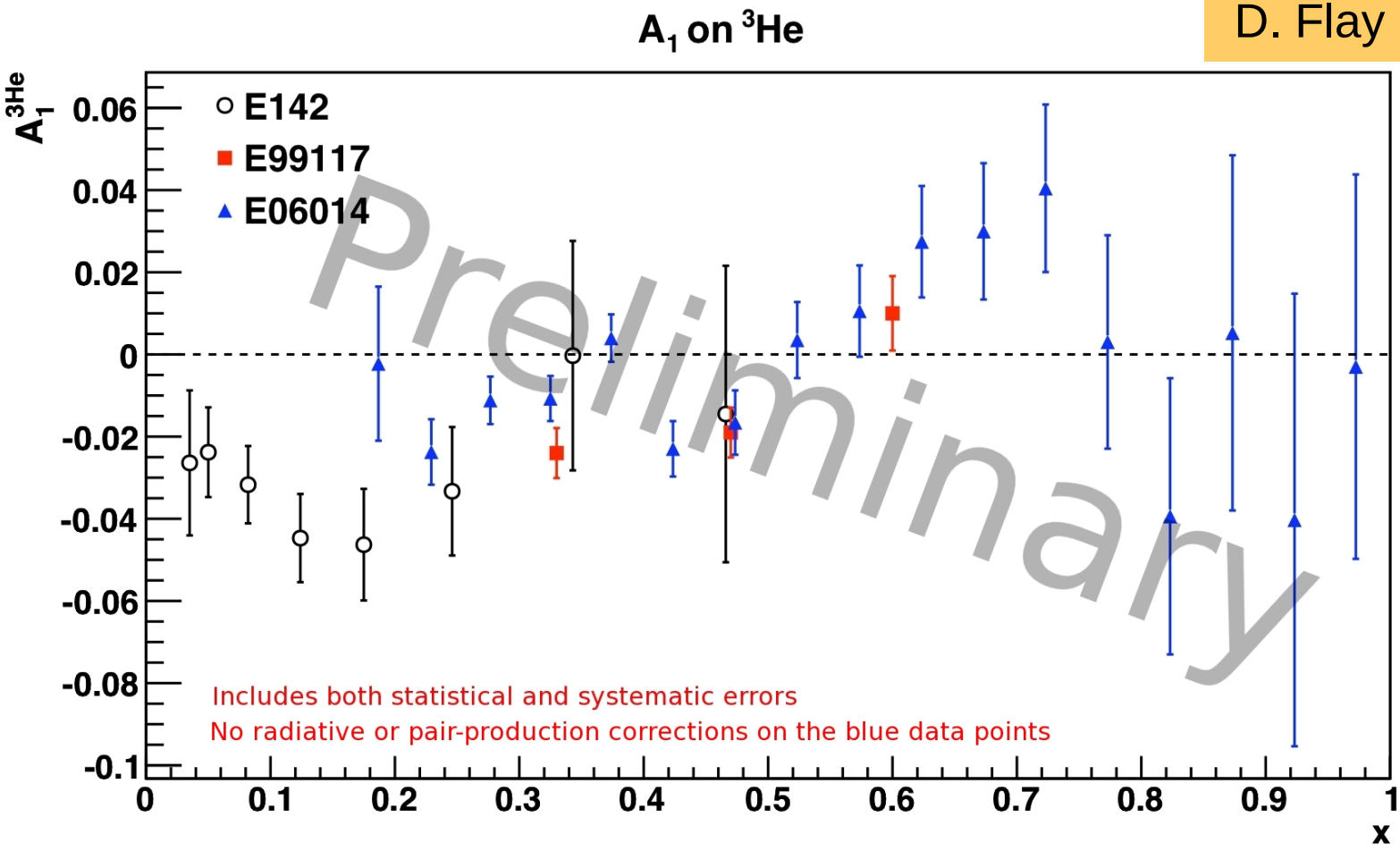
Projection on d2p from Hall C SANE



Preliminary $A_1(^3He)$ Results, Hall A E06-014

Spokespersons: S. Choi, Z. Meziani, X. Jiang and B. Sawasky

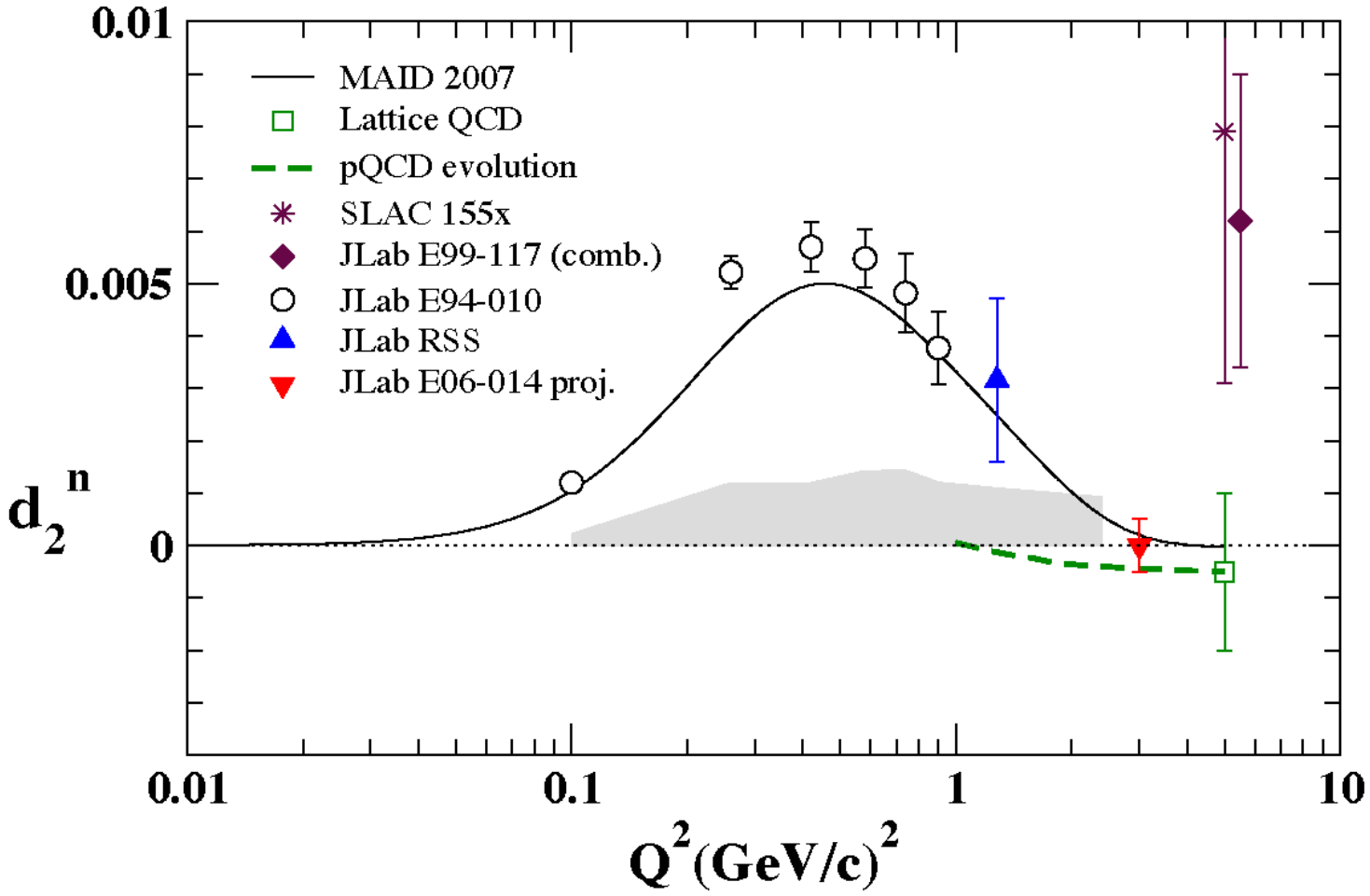
Courteous of D. Flay



Projection on Hall A E06-014 (d_2^n)

Spokespersons: S. Choi, Z. Meziani, X. Jiang and B. Sawasky

Courteous of D. Flay

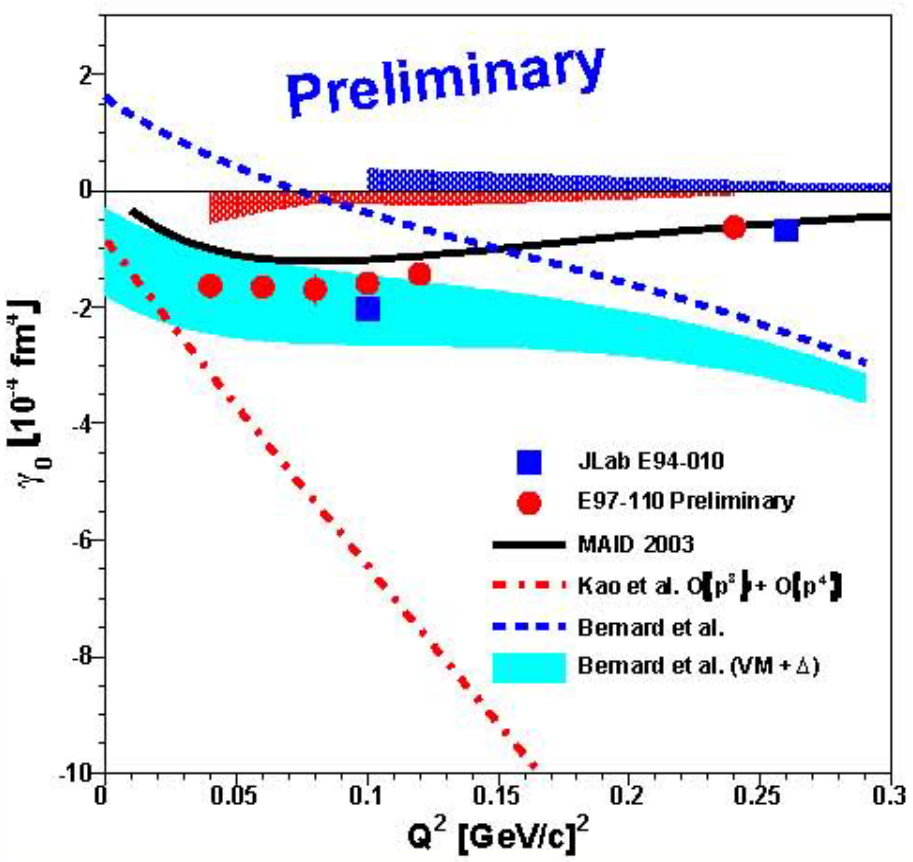


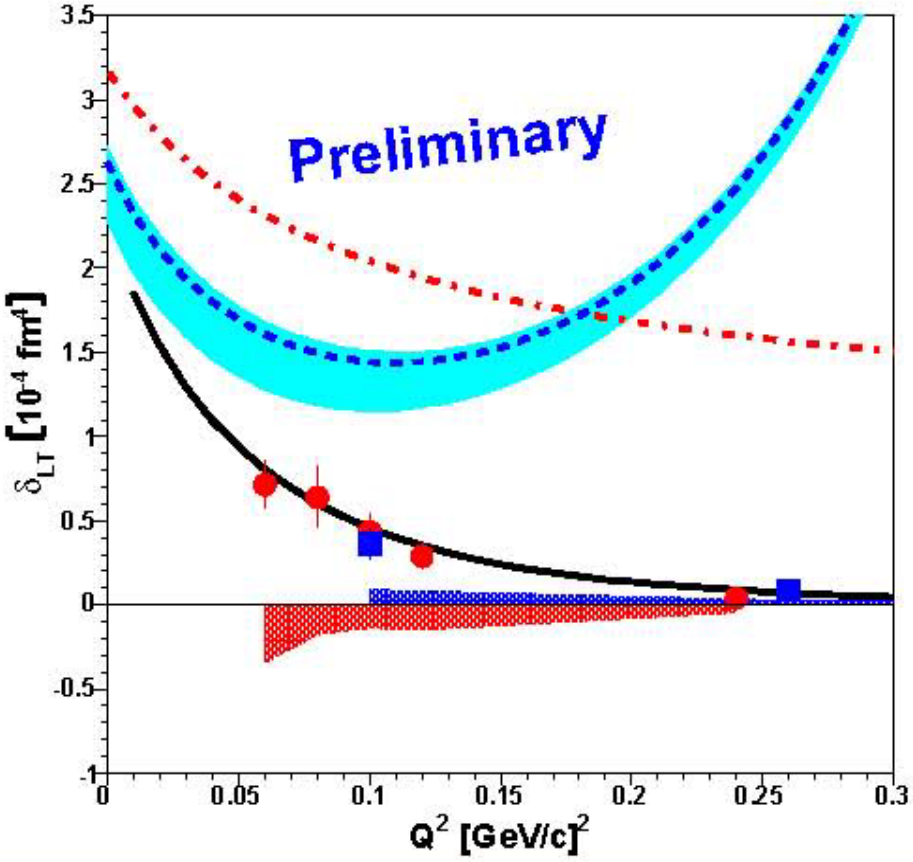
Spin Polarizabilities

Preliminary E97-110 (and Published E94-010)

Spokesperson: J. P. Chen, A. Deur, F. Garibaldi, plots by V. Sulkosky

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





Q^2 Q^2

E08-027 : Proton g_2 Structure Function

Fundamental spin observable has never been measured at low or moderate Q^2

Spokespersons: A. Camsonne, J. P. Chen, D. Crabb, K. Slifer, 7 PhD students

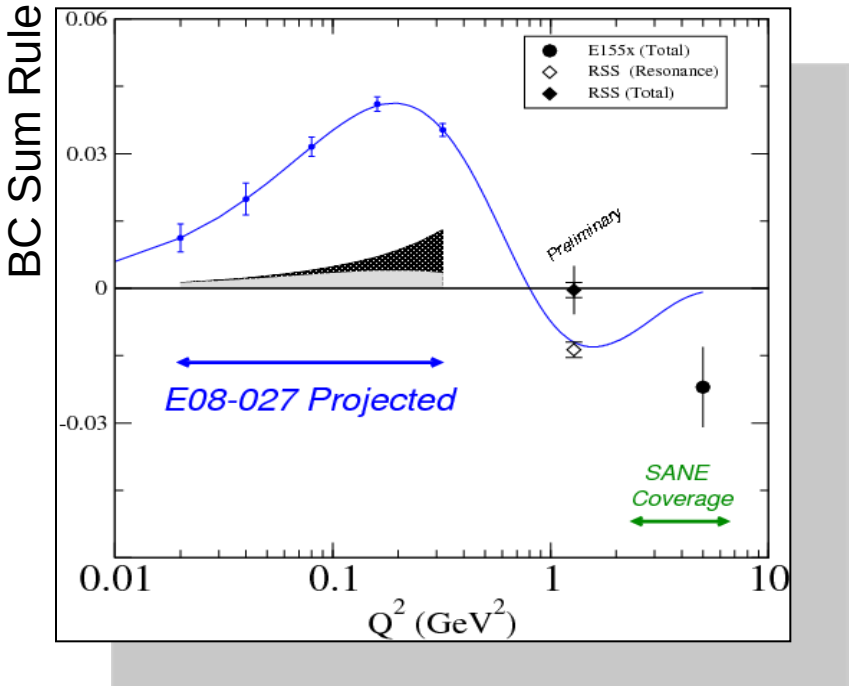
BC Sum Rule : violation suggested for proton at large Q^2, but found satisfied for the neutron & ^{3}He.

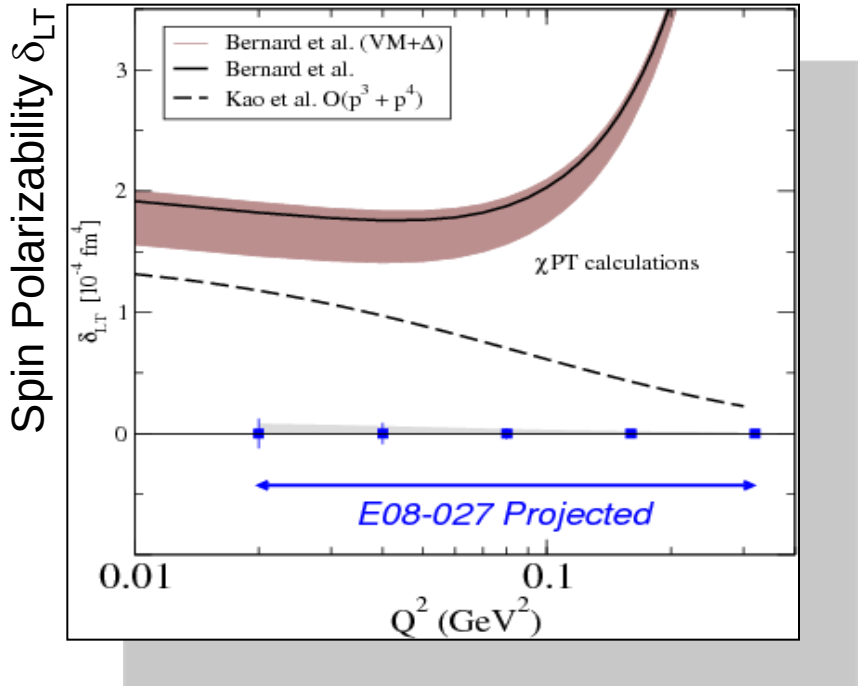
Spin Polarizability : Major failure (>8σ) of χPT for neutron δ_{LT}. Need g_2 isospin separation to solve.

Hydrogen HyperFine Splitting : Lack of knowledge of g_2 at low Q^2 is one of the leading uncertainties.

Proton Charge Radius : also one of the leading uncertainties in extraction of $<R_p>$ from μ–H Lamb shift.

Completed data taking (5/2012)





Summary

- Spin structure study full of surprises and puzzles
- A decade of experiments from JLab: exciting results
  - precision measurements of moments of spin structure functions
    - spin sum rules and polarizabilities
    - g_2/d_2: high-twist effects (twist-3), quark-gluon correlations
  - …
- Bright future
  - 12 GeV Upgrade will greatly enhance our capability
    - Precision determination of the valence quark spin structure
      flavor separation
    - Precision measurements of g_2/d_2
    - Precision extraction of transversity/tensor charge
  - EIC: Precision Study of Gluons and Sea
    - Precision ΔG and Sea Quarks, Δs
    - 3-D: TMDs, GPDs