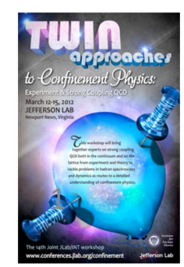
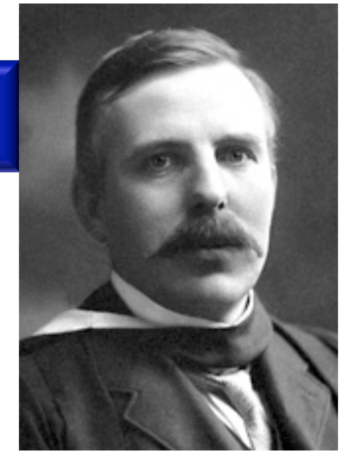
Experimental Variations on QCD Themes

Zein-Eddine Meziani
Temple University

- Preamble
- Elastic Form Factors and flavor decomposition
- Transversity and the tensor charge
- Lorentz color force
- Orbital momentum



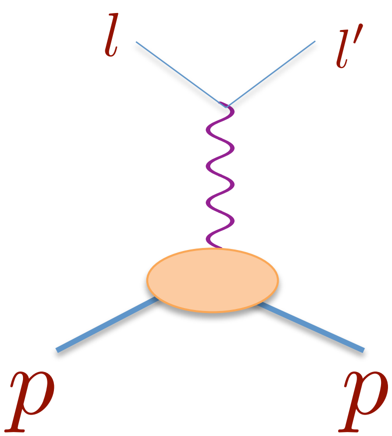
Experimental tools: Scattering

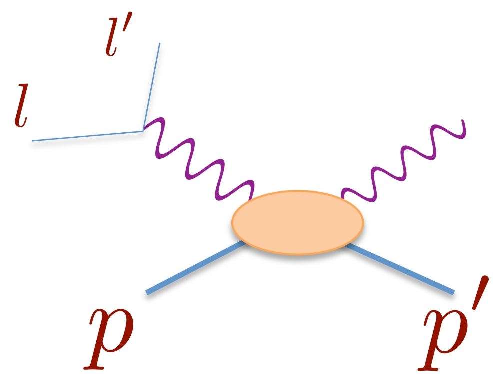


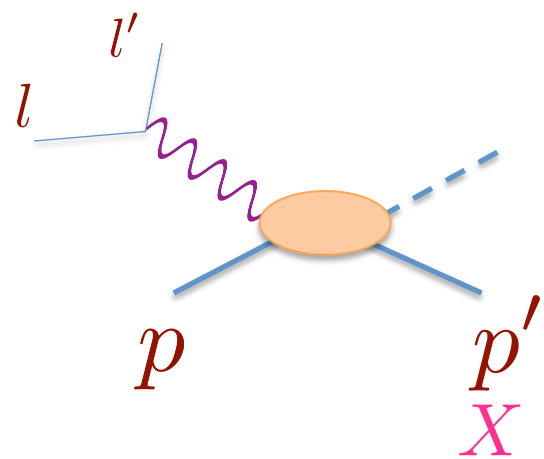
Rutherford, 1908, Chem. N.P.

- Use of lepton and hadron beams
  - Polarized beams of e-, e+, μ+, μ-, p
- Use of proton and nuclei targets
  - Targets in many cases are polarized (p, D, NH_3, ND_3, ^3He, HD)

- Electromagnetic probe: Compton scattering, real and virtual
  - Exclusive, semi-inclusive or inclusive (elastic scattering, inelastic scattering)





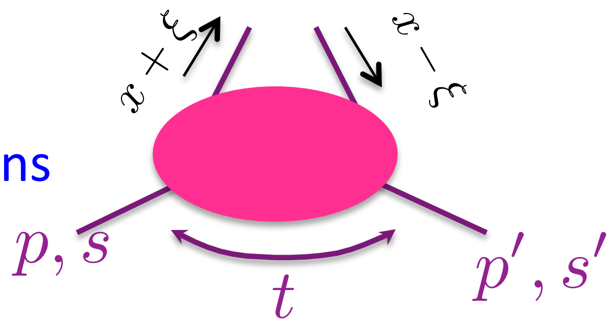


Compton, 1927, Phys. N.P.

A Framework in QCD

- Generalized Parton Distributions
  - Matrix elements of non-local operators with quarks and gluon field

$$\langle p|\mathcal{O}|p\rangle$$



  - Depend on two longitud. momentum fractions

$$x,\ \xi \text{ and } t = (p-p')^2$$

  - For unpolarized quarks we have two distributions:

H^q *conserves proton helicity*

E^q *flips proton helicity*

$$p = p' \Longrightarrow \qquad H^q(x,0,0) = \begin{cases} q(x) & \text{for } x>0 \\ -\bar{q}(x) & \text{for } x<0 \end{cases}$$

Elastic Form fators

- Integrating

$$\int dx\, x^n\, \mathsf{GPD}(x,\xi,t) \rightarrow \text{local operators} \rightarrow \text{form factors}$$

$$\sum_q e_q \int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1(t) \qquad \text{Dirac}$$

$$\sum_q e_q \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2(t) \qquad \text{Pauli}$$

STRINGS MICHIGAN THEORY

July 10-15, 2000 University of Michigan Ann Arbor

"Millennium Madness"

Physics Problems for the Next Millennium

In 1900 the world-renowned mathematician David Hilbert presented twenty-three problems at the

7. What are the fundamental degrees of freedom of M-theory (the theory whose low-energy limit is eleven-dimensional supergravity and which subsumes the five consistent superstring theories) and does the theory describe Nature?
   Louise Dolan, University of North Carolina, Chapel Hill
   Annamaria Sinkovics, Spinoza Institute
   Billy & Linda Rose, San Antonio College

8. What is the resolution of the black hole information paradox?
   Tibra Ali, Department of Applied Mathematics and Theoretical Physics, Cambridge
   Samir Mathur, Ohio State University

9. What physics explains the enormous disparity between the gravitational scale and the typical mass scale of the elementary particles?
   Matt Strassler, Institute for Advanced Study, Princeton

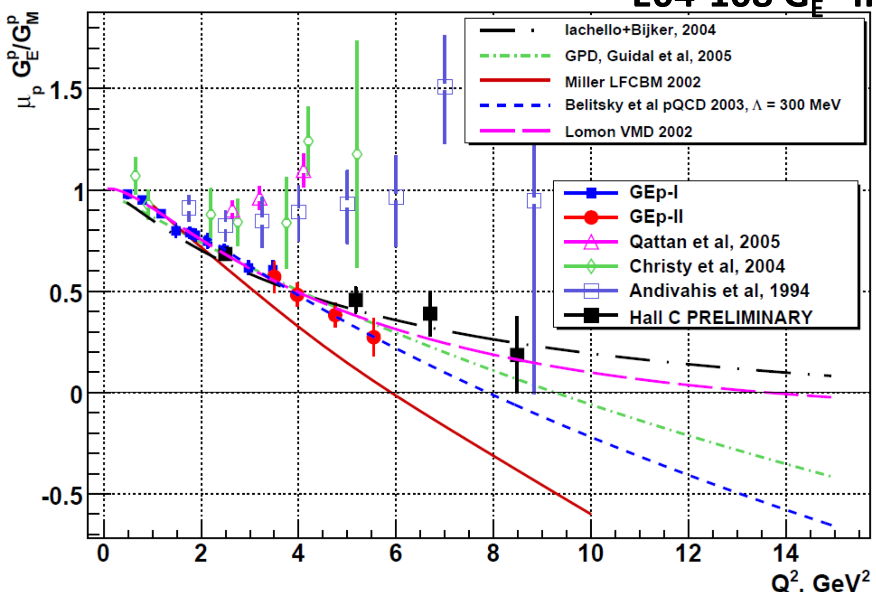
10. Can we quantitatively understand quark and gluon confinement in Quantum Chromodynamics and the existence of a mass gap?
    Igor Klebanov, Princeton University
    Oyvind Tafjord, McGill University

These ten questions were presented by David Gross at the closing of the conference on Saturday July 15, 2000.

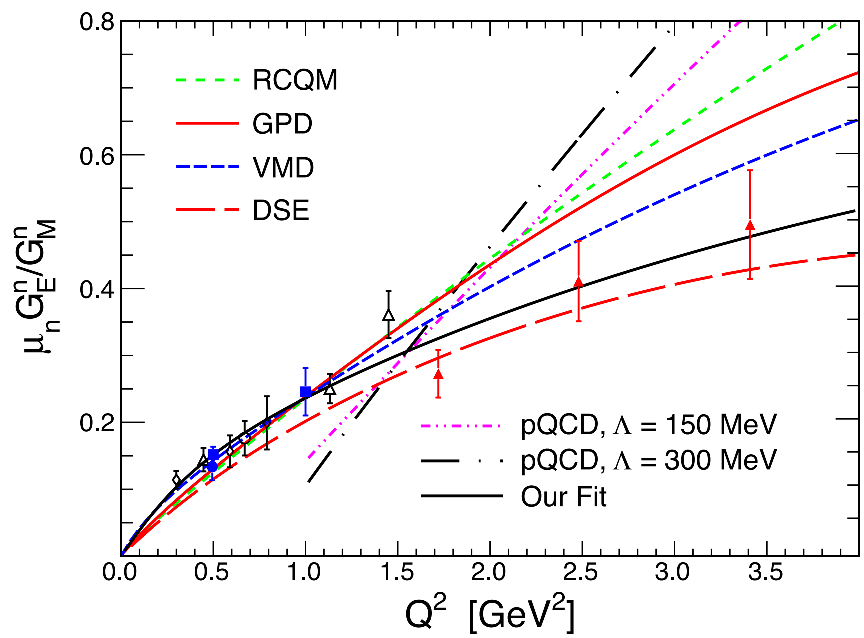
Nucleon Electromagnetic Form Factors

- Measurements of electromagnetic form factors used as a testing bed for models of the nucleon.
- Observables used to test our understanding of pQCD in the case of confined systems
- Leap forward with the new class of experiments from Jefferson Lab
- Flavor decomposition reveals separate information on the constituents and is a powerful discriminator between models

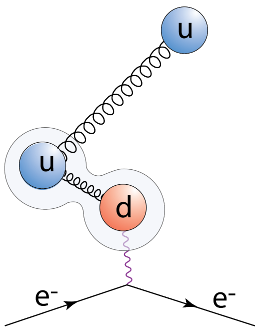
E04-108 G_E^P-III

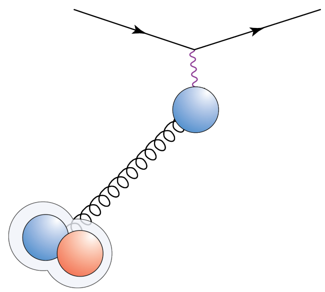


E02-013: G_E^N

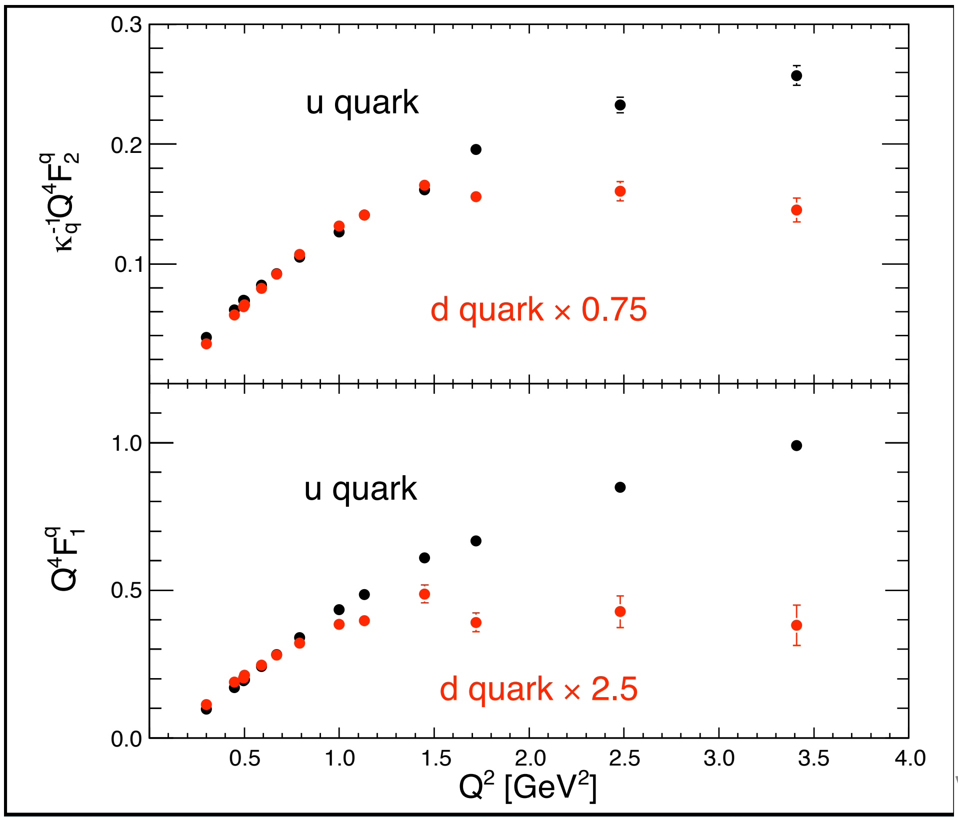


Flavor decomposition of Pauli and Dirac form factors → A di-quark picture unravels ?!





Dirac and Pauli form factors for up and down quarks

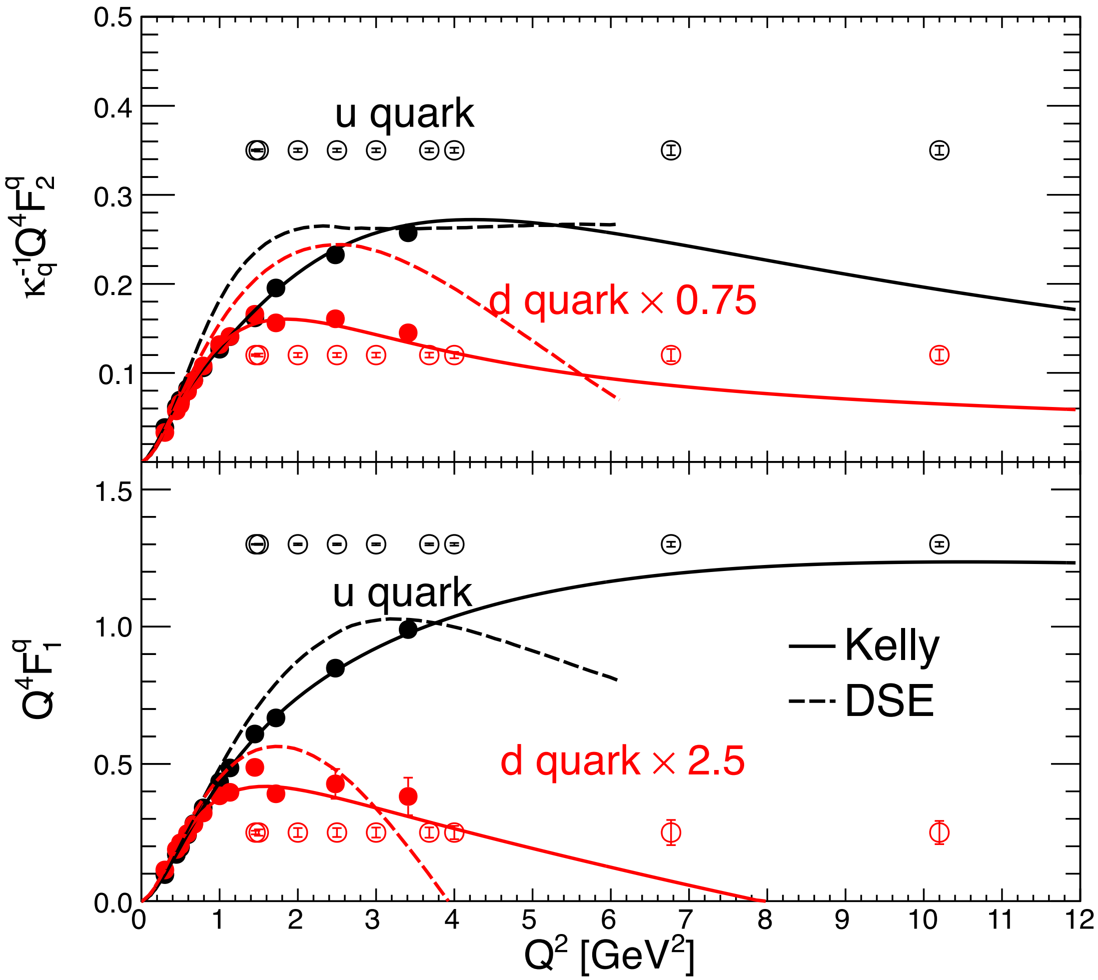


- Using proton and neutron world data including JLab 6 GeV data a flavor decomposition has been performed
- Q^2 dependence hints at a di-quark picture at some scale.

Cates, de Jager, Riordan Wojtsekhowski
Phys.Rev.Lett. 106 (2011) 252003

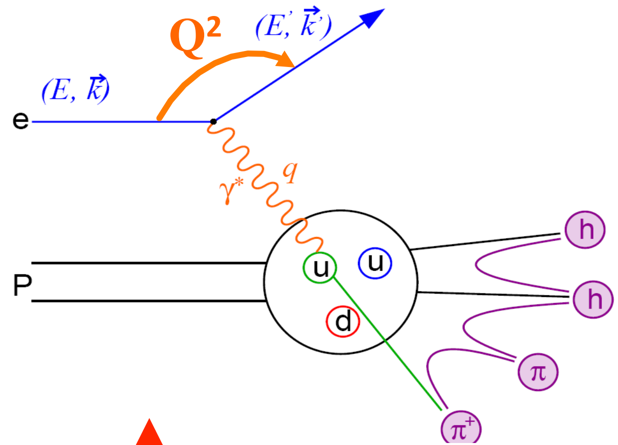
12 GeV reach (Dirac and Pauli form factors)

- 12 GeV upgrade reach is critical
- Is there a regime where this exclusive process can be described in pQCD?



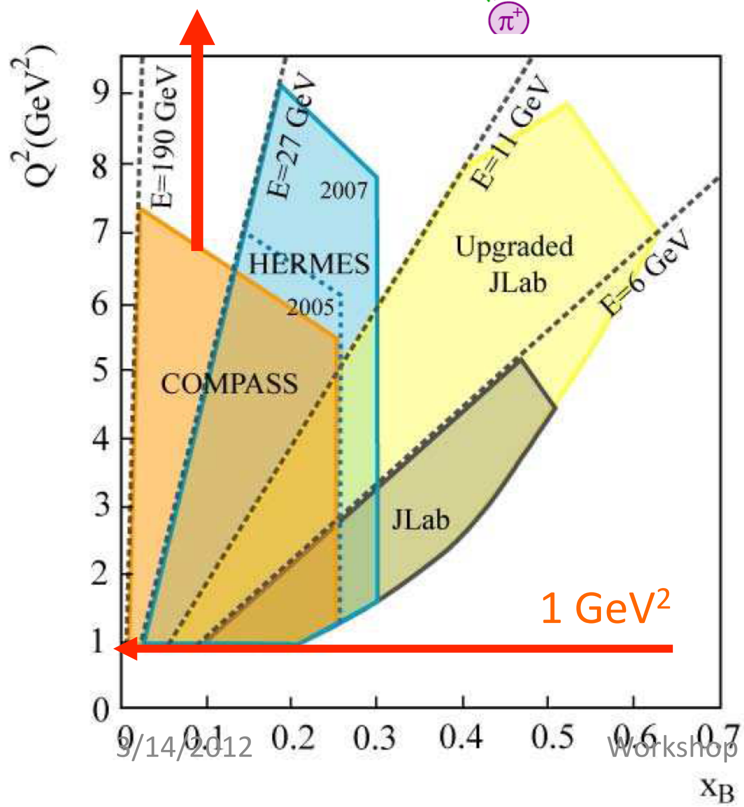
Courtesy of B. Wojtsekhowski

Semi-Inclusive Deep-Inelastic Scattering

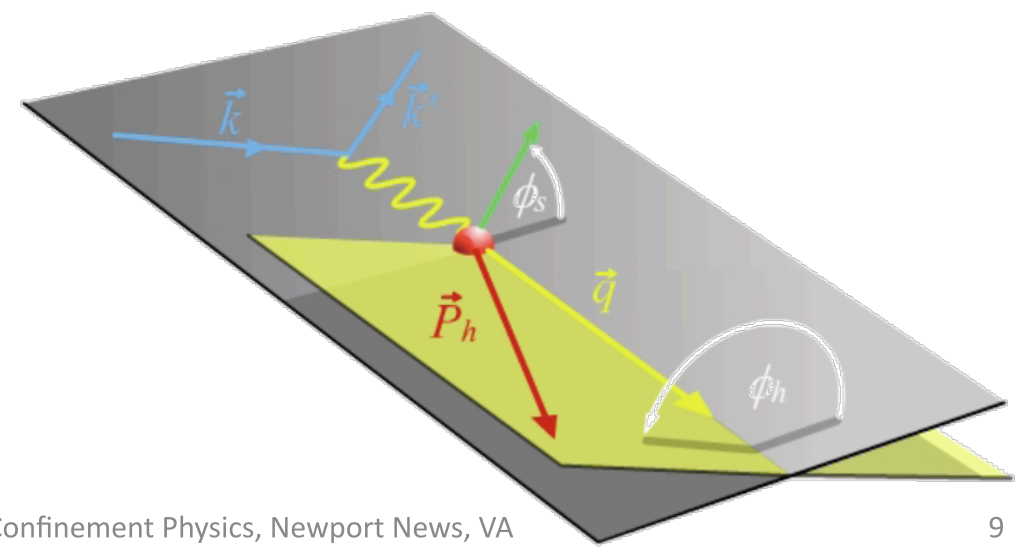


Factorization

$$\sigma^h_{l,S} \propto \sum_f \sigma^{q_f} \otimes pdf(x) \otimes frag^{q_f, g \to h}(z)$$



- Beam polarized
- Target polarized transverse (T) or longitudinal (L)



Transversity distribution

- Quark transverse polarization in a transversely polarized nucleon:

h_{1T} =

- ➥ Can be probed in Semi-Inclusive DIS, Drell-Yan processes.

$$\sigma_{UT} : \sin(\phi_h - \phi_s) f_{1T}^{\perp} \otimes D_1, \qquad \cos(\phi_h + \phi_s) h_1 \otimes H_1^{\perp}$$

- ➥ Does not mix with gluons, has valence like behavior.
- ➥ Nucleon tensor charge can be extracted from the lowest moment of h_1 and compared to LQCD calculation:

Tensor Charge

$$\langle PS \bar{\psi} \sigma^{\mu\nu} \psi PS \rangle = \int_0^1 dx \, [\delta q(x) - \delta \bar{q}(x)]$$

Transversity and the Tensor Charge

Bjorken Sum rule

$$\int_0^1 \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] dx = \frac{1}{6} g_A$$

GDH sum rule

$$\int_{thr}^{\infty} \left[\frac{\sigma_{3/2} - \sigma_{1/2}}{\nu}\right] d\nu = \frac{2\pi^2\alpha}{M^2}\kappa^2$$

Axial Charge

And

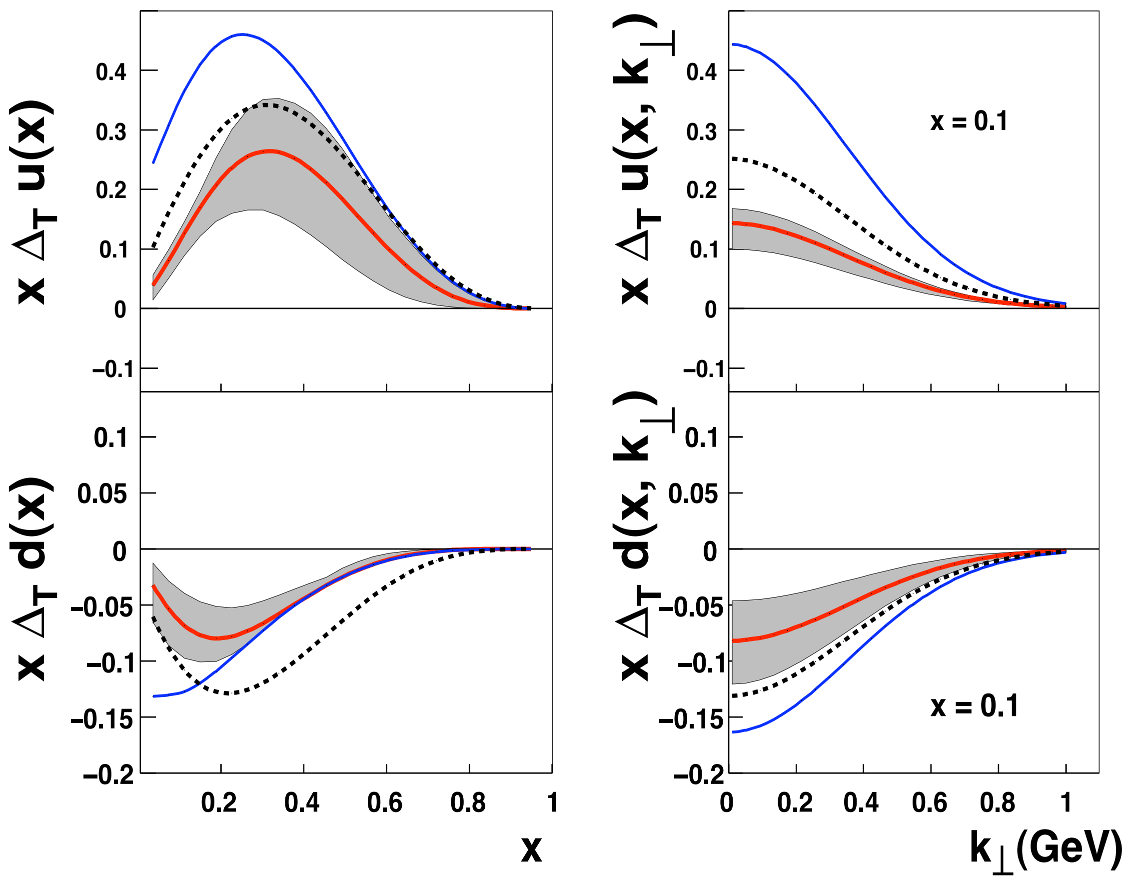
Vector Charge

$$\langle PS \bar{\psi} \sigma^{\mu\nu} \psi PS \rangle = \int_0^1 dx \left[\delta q(x) - \delta \bar{q}(x)\right]$$

Tensor Charge

Transversity using COMPASS and HERMES SIDIS data and the Belle data $e^+e^- \to H_1 H_2 X$ $eN^\uparrow \to eHX$

- A good start, good agreement with models
- Soffer bound imposed in the extraction
- What happens if it is not imposed. Is the Soffer bound violated?
- Soft gluon emission should reduce the extracted quantity by a factor of 2 ?! (Boer, 2008)

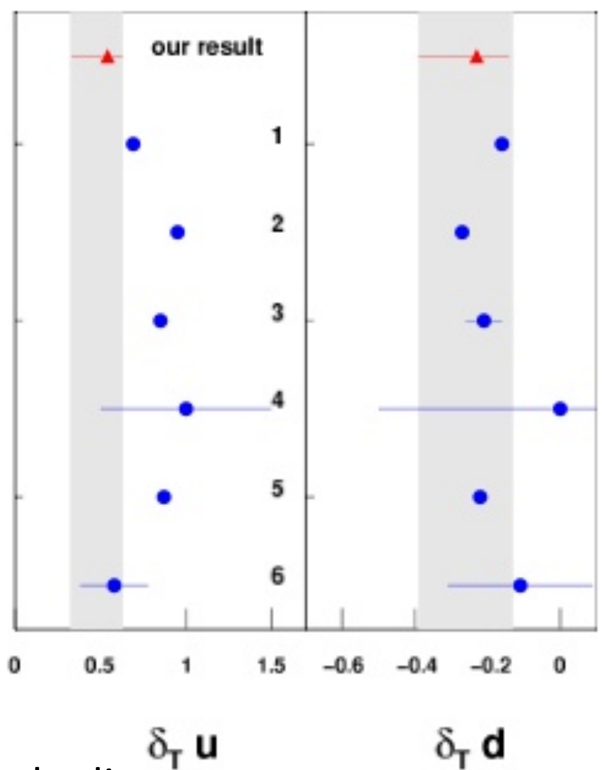


Anselmino et al. 2008

Tensor charges

$$\delta_T q = \int_0^1 dx\,(h_{1q} - h_{1\bar{q}}) = \int_0^1 dx\, h_{1q}$$

$$\delta_T u = 0.54^{+0.09}_{-0.22},\ \delta_T d = -0.23^{+0.09}_{-0.16} \text{ at } Q^2 = 0.8 \text{ GeV}^2$$



Courtesy of Prokudin

1. Quark-diquark model:
   Cloet, Bentz and Thomas
   PLB **659**, 214 (2008), $Q^2 = 0.4$ GeV^2
2. CQSM:
   M. Wakamatsu, PLB **653** (2007) 398.
   $Q^2 = 0.3$ GeV^2
3. Lattice QCD:
   M. Gockeler et al.,
   Phys.Lett.B627:113-123,2005 ,
   $Q^2 = 4$ GeV^2
4. QCD sum rules:
   Han-xin He, Xiang-Dong Ji,
   PRD 52:2960-2963,1995, $Q^2 \sim 1$ GeV^2
5. Constituent quark model:
   B. Pasquini, M. Pincetti, and S. Boffi,
   PRD72(2005)094029 and PRD76(2007)034020,
   $Q^2 \sim 0.8$ GeV^2
6. Spin-flavour SU(6) symmetry
   L. Gamberg, G. Goldstein,
   Phys.Rev.Lett.87:242001,2001 $Q^2 \sim 1$ GeV^2

Parton Distributions Functions at Large x

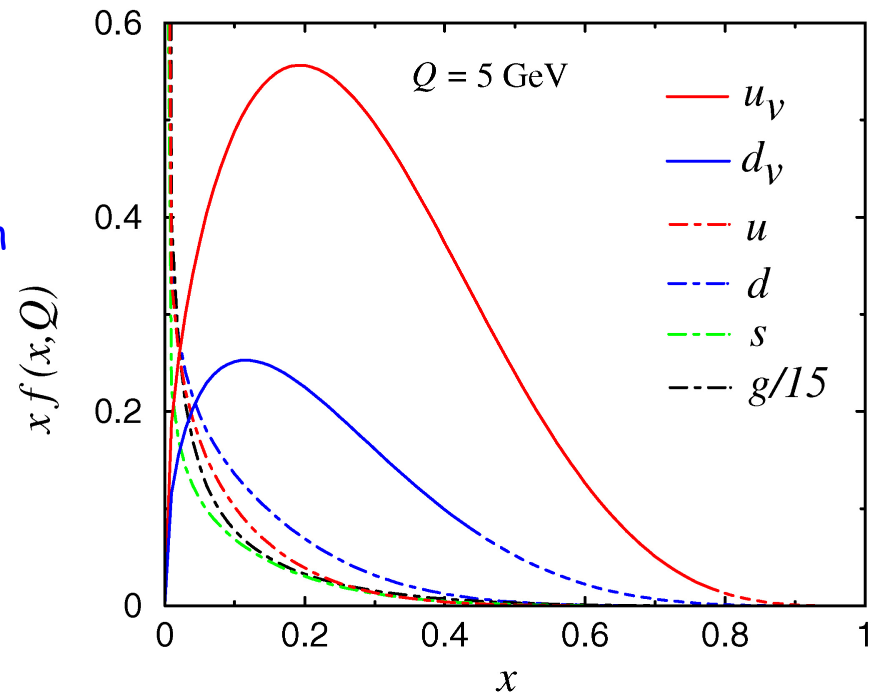
Understand the nucleon structure in the valence quark region

◉ What is required?

- Complete knowledge of parton distribution functions (PDFs).

At Large x

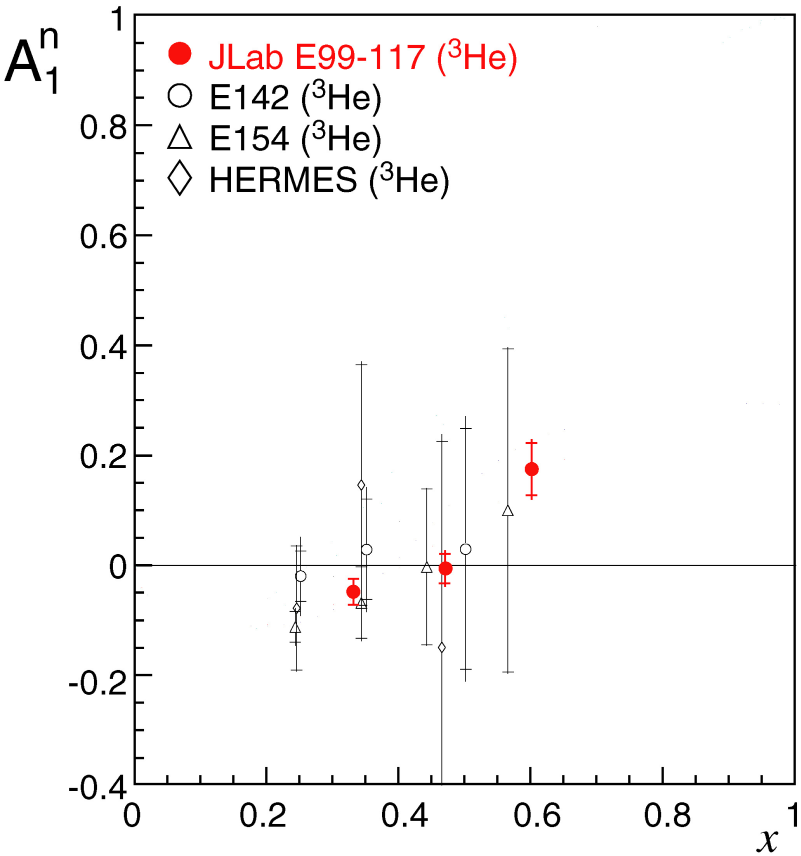
- large x exposes valence quarks
  - free of sea effects
- no explicit hard gluons to be included
- x->1 behavior – sensitive test of spin-flavor symmetry breaking
- important for higher moments of PDFs - compare with lattice QCD
- intimately related with resonances, quark-hadron duality

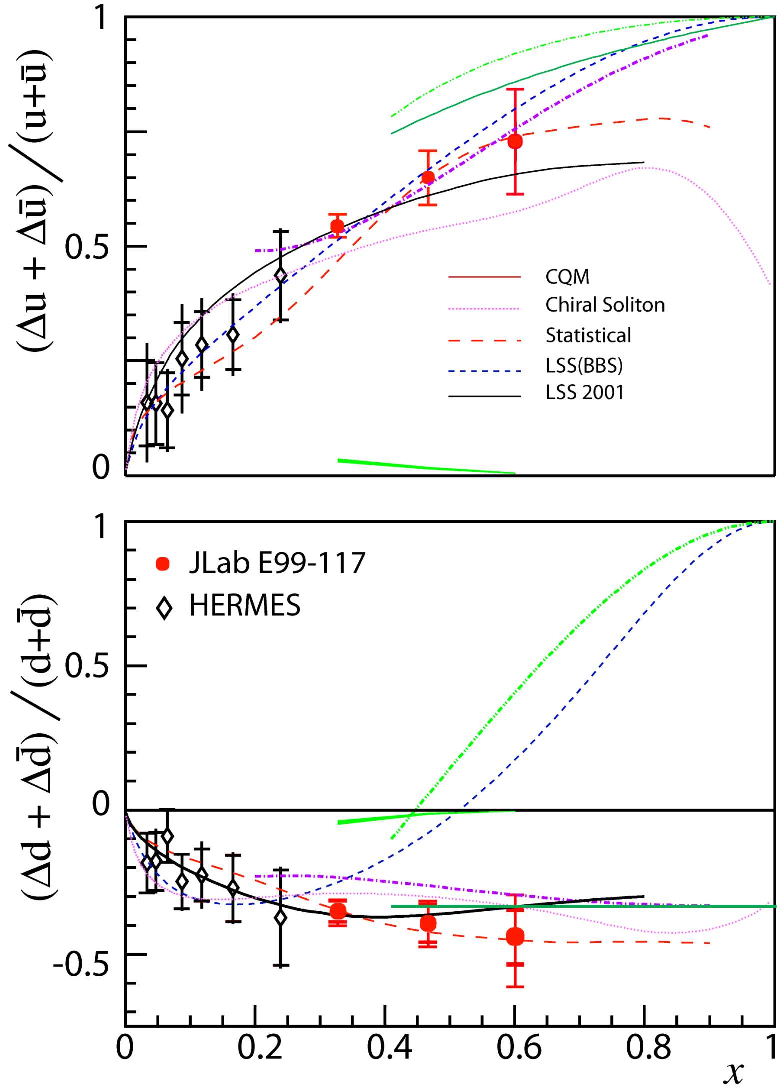


$$M_n(Q^2) = \int_0^1 dx\; x^{n-2}\; F_2(x, Q^2) \qquad n = 2,4,...$$

$$M_n(Q^2) = \int_0^1 dx\; x^{n-1}\; g_1(x, Q^2), \qquad n = 1,3,5...$$

A_1^n and Helicity-Flavor Decomposition





$$\frac{\Delta u + \Delta\bar{u}}{u} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4 + R^{du}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1 + 4R^{du})$$

$$\frac{\Delta d + \Delta\bar{d}}{d} = \frac{4}{15}\frac{g_1^n}{F_1^n}(4 + \frac{1}{R^{du}}) - \frac{1}{15}\frac{g_1^p}{F_1^p}(1 + 4\frac{1}{R^{du}})$$

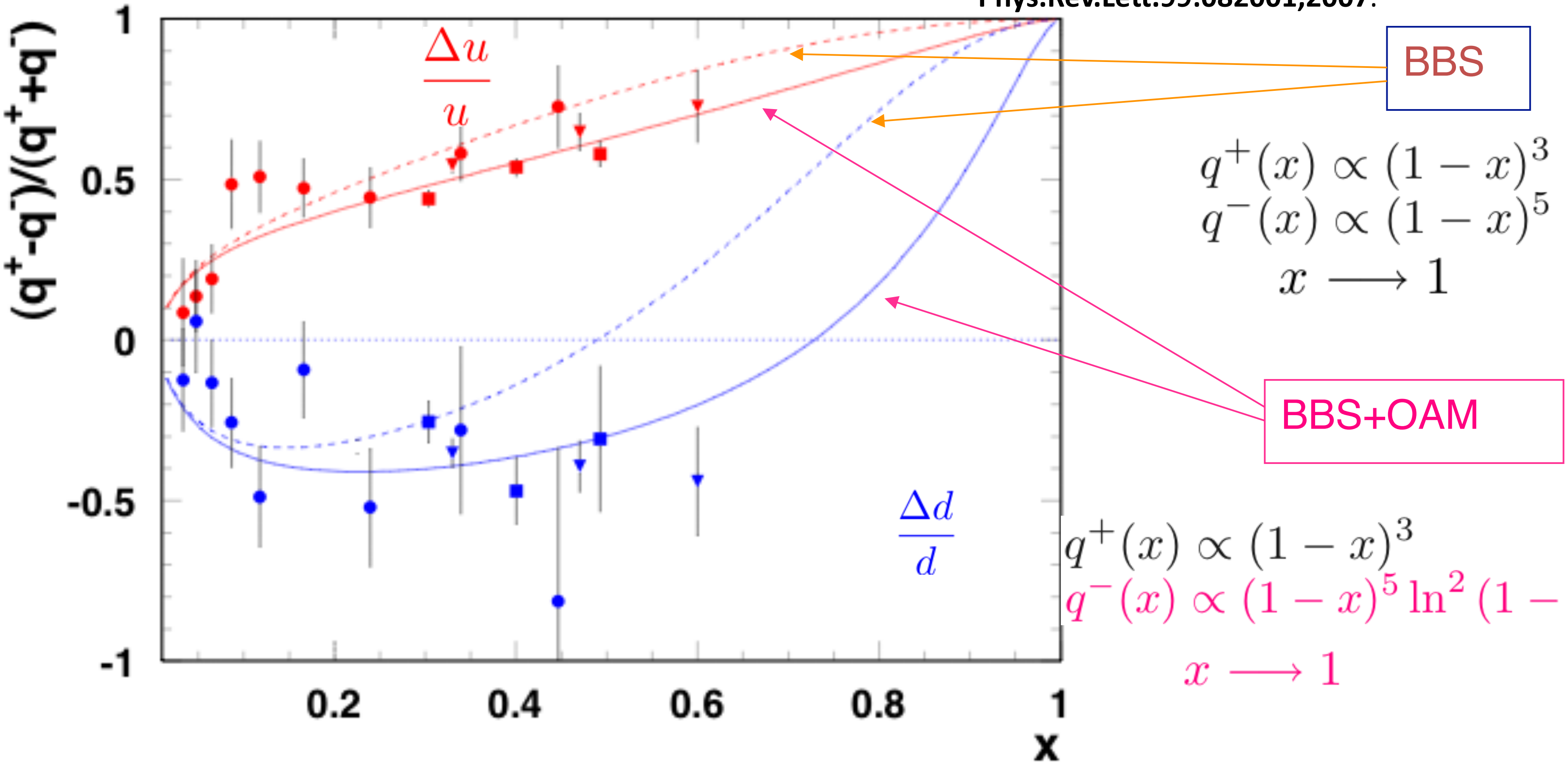
$$R^{du} = \frac{d + \bar{d}}{u + \bar{u}}$$

JLab E99-117

Effect of considering transverse momentum of quarks in the nucleon

Inclusive Hall A and B and Semi-Inclusive Hermes

Avakian, Brodsky, Deur and Yuan
Phys.Rev.Lett.99:082001,2007.



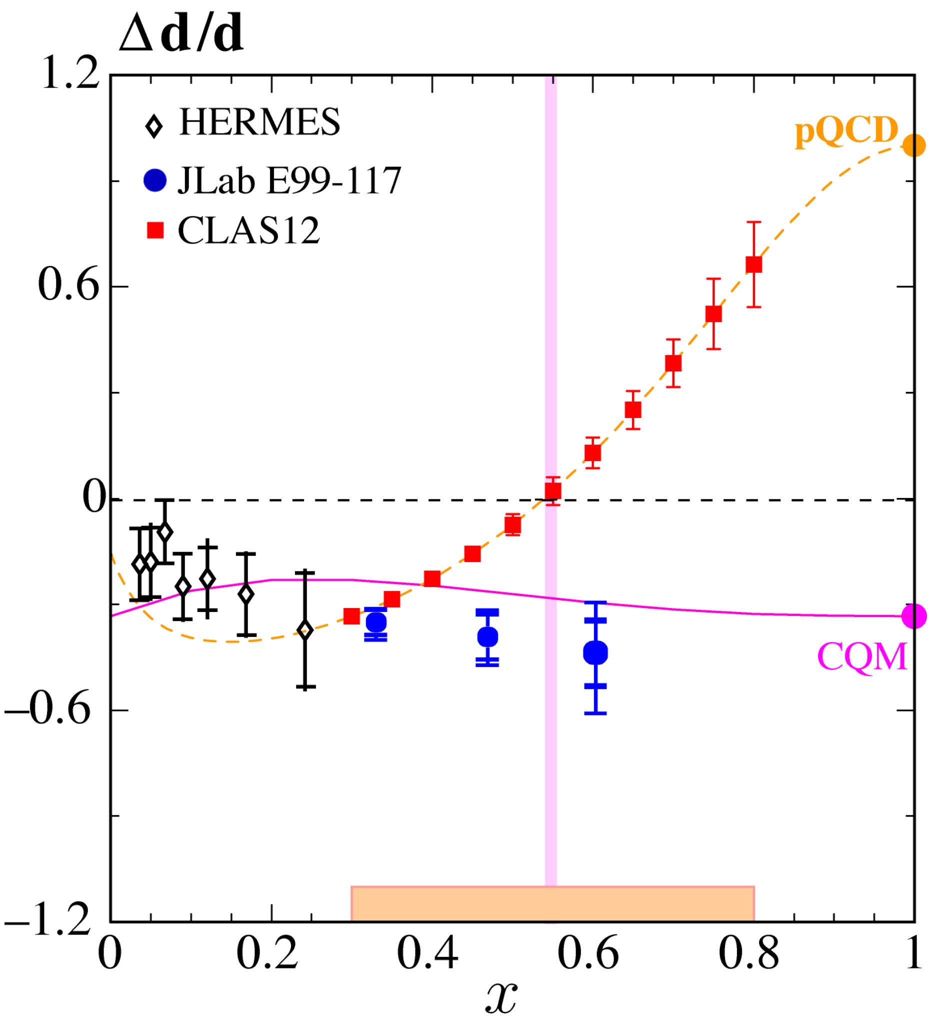
$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5$$
$$x \longrightarrow 1$$

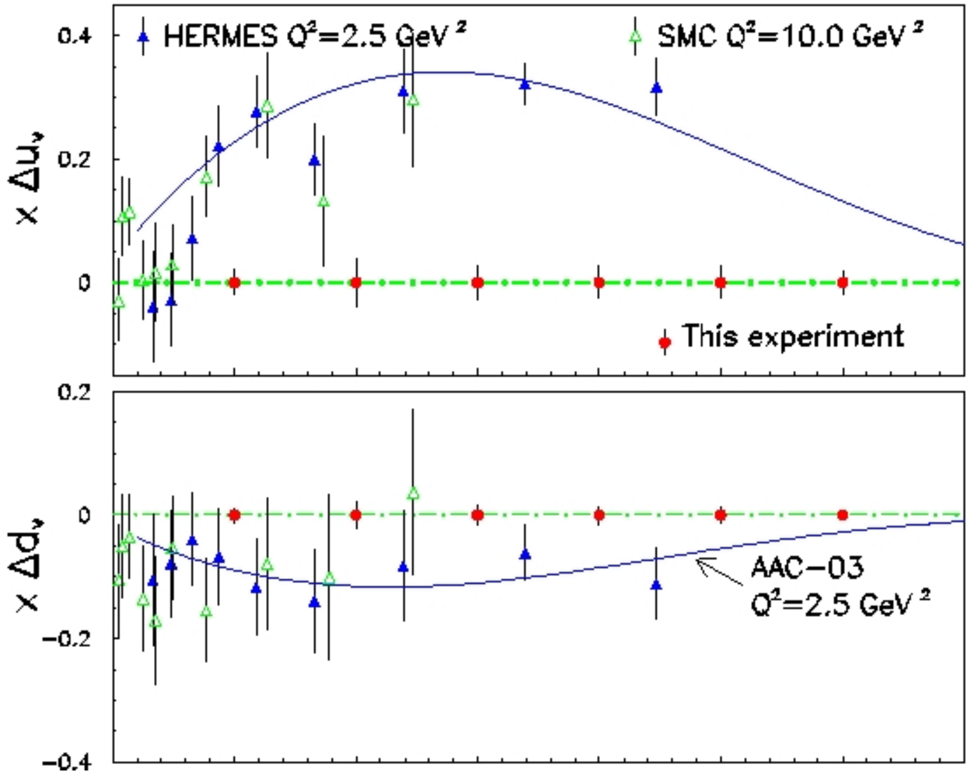
$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5 \ln^2(1-x)$$
$$x \longrightarrow 1$$

Longitudinal Double Spin Asymmetry in SIDIS

At JLab 12 GeV with SIDIS

E_e =11 GeV **NH_3 and ^3He**

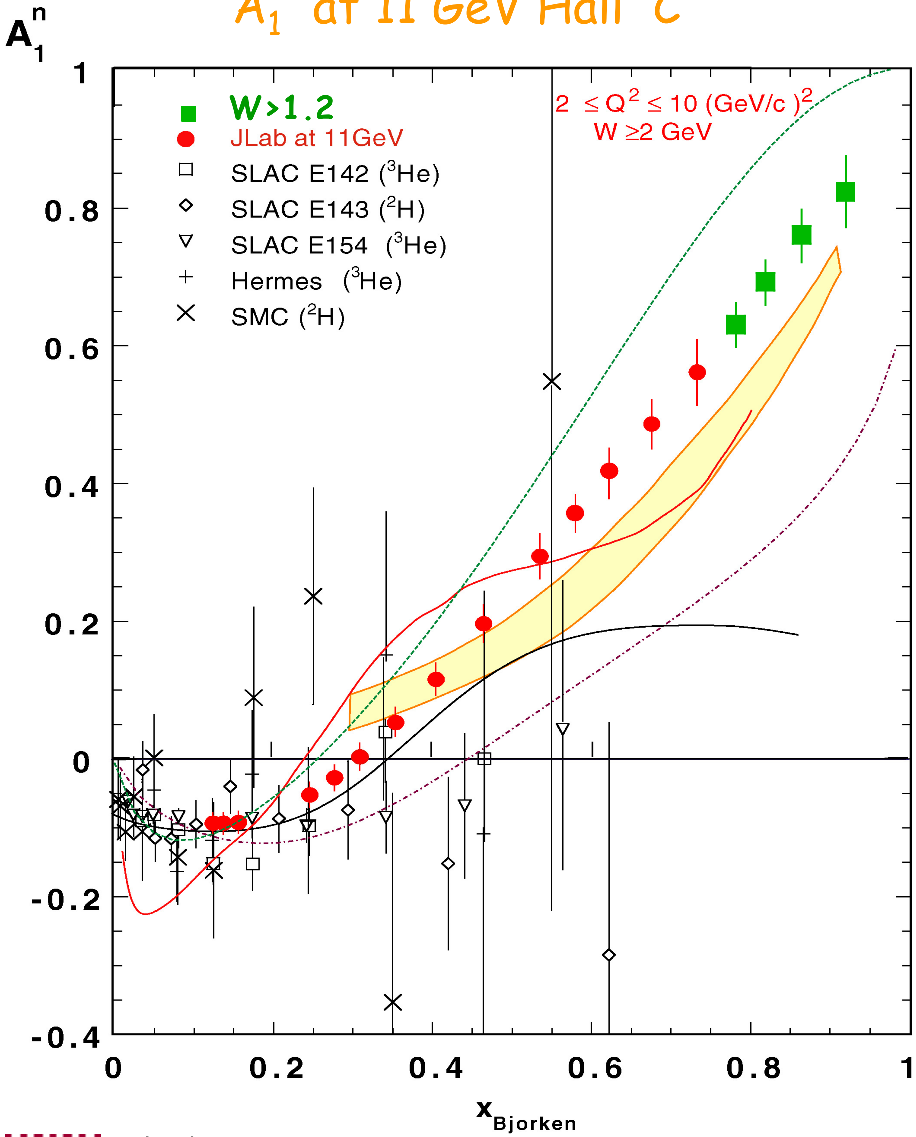




- Asymmetry measurements with different hadrons (π+,π−) and targets (p,n) allows for flavor separation

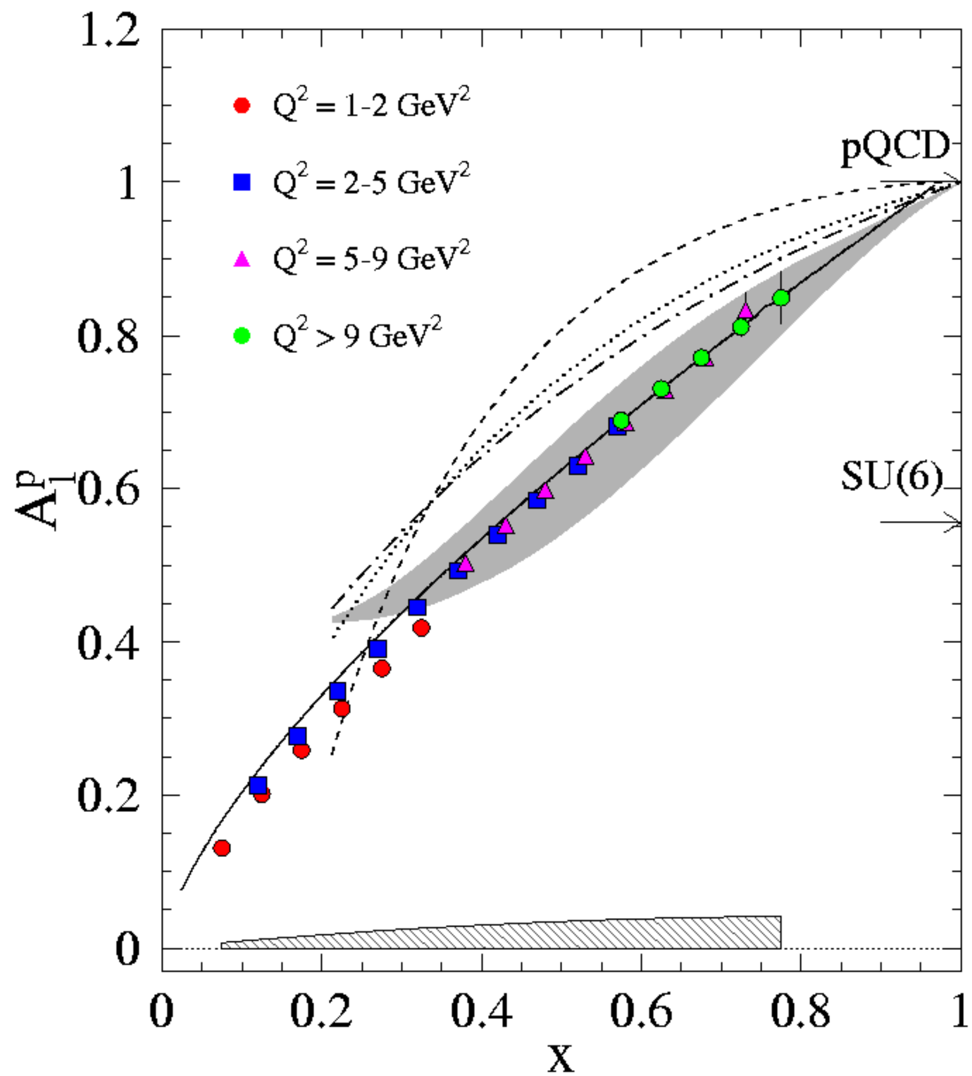
Inclusive double spin asymmetries using 12 GeV

A_1^n at 11 GeV Hall C



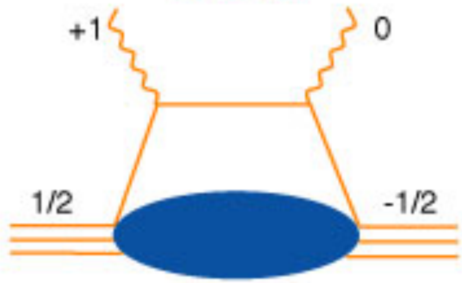
CLAS12

Proton



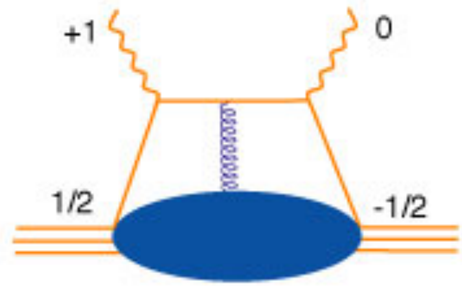
Quark Gluon Correlations

twist-2



Carry one unit of orbital angular momentum

twist-3



Couple to a gluon

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

- a twist-2 term (Wandzura & Wilczek, 1977):

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

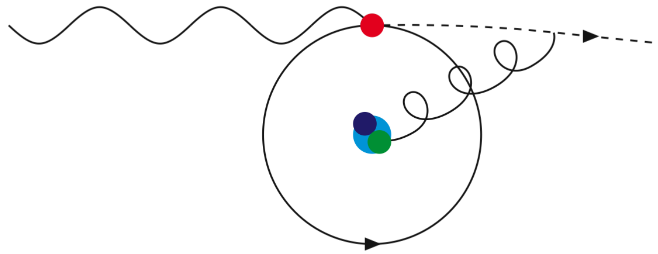
- a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 92):

$$\bar{g}_2(x, Q^2) = -\int_x^1 \frac{\partial}{\partial y} \left(\frac{m_q}{M} h_T(y, Q^2) + \xi(y, Q^2) \right) \frac{dy}{y}$$

transversity (→ h_T) quark-gluon correlation (→ ξ)

Average Color Lorentz Force (M. Burkardt)

$$\int dx x^2 \bar{g}_2(x) = \frac{1}{3} d_2 = \frac{1}{6MP^{+2}S^x} \langle P,S \left| \bar{q}(0) g G^{+y}(0) \gamma^+ q(0) \right| P,S \rangle$$



↪ d_2 a measure for the **color Lorentz force** acting on the struck quark in SIDIS in the instant **after being hit by the virtual photon**

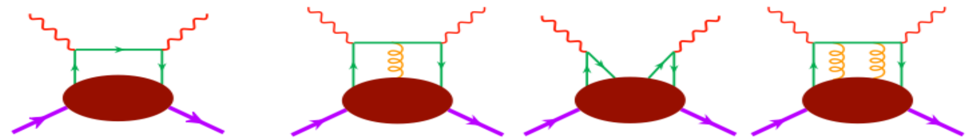
$$\langle F^y(0) \rangle = -M^2 d_2 \qquad \text{(rest frame; } S^x = 1\text{)}$$

- Interpretation of d_2 with the transverse FSI force in DIS also consistent with $\langle k_\perp^y \rangle \equiv \int_0^1 dx \int d^2 k_\perp \, k_\perp^2 \, f_{1T}^\perp(x, k_\perp^2)$ in SIDIS (Qiu, Sterman)

$$\langle k_\perp^y \rangle = -\frac{1}{2p^+} \left\langle P,S \left| \bar{q}(0) \int_0^\infty dx^- g G^{+y}(x^-) \gamma^+ q(0) \right| P,S \right\rangle$$

semi-classical interpretation: average $k_\perp$ in SIDIS obtained by correlating the quark density with the transverse impulse acquired from (color) Lorentz force acting on struck quark along its trajectory to (light-cone) infinity

Moments of Structure Functions



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

$$= \Gamma_1^{\mathrm{twist-2}}(Q^2) + \frac{M_N^2}{9\,Q^2}\left[a_2(Q^2) + 4\,d_2(Q^2) + 4\,f_2(Q^2)\right] + \mathcal{O}\left(\frac{M_N^4}{Q^4}\right)$$

$$a_2(Q^2) \equiv 2\int_0^1 dx\, x^2\, g_1^{\mathrm{twist-2}}(x, Q^2)$$ → target mass correction term

$d_2(Q^2)$ → dynamical twist-3 matrix element

$$d_2(Q^2) \equiv \int_0^1 dx\, x^2\, \{3\,g_2(x, Q^2) + 2\,g_1(x, Q^2)\}$$

$f_2(Q^2)$ → dynamical twist-4 matrix element

- Both d_2 and f_2 are required to determine the color polarizabilities
- To extract f_2, d_2 needs to be determined first.

Hall A d_2^n and Hall C SANE experiments
Neutron and Proton

Spokespeople:
B. Sawatzky, S. Choi, X. Jiang and Z.-E.M

Students:
D. Flay, D. Parno, M. Posik

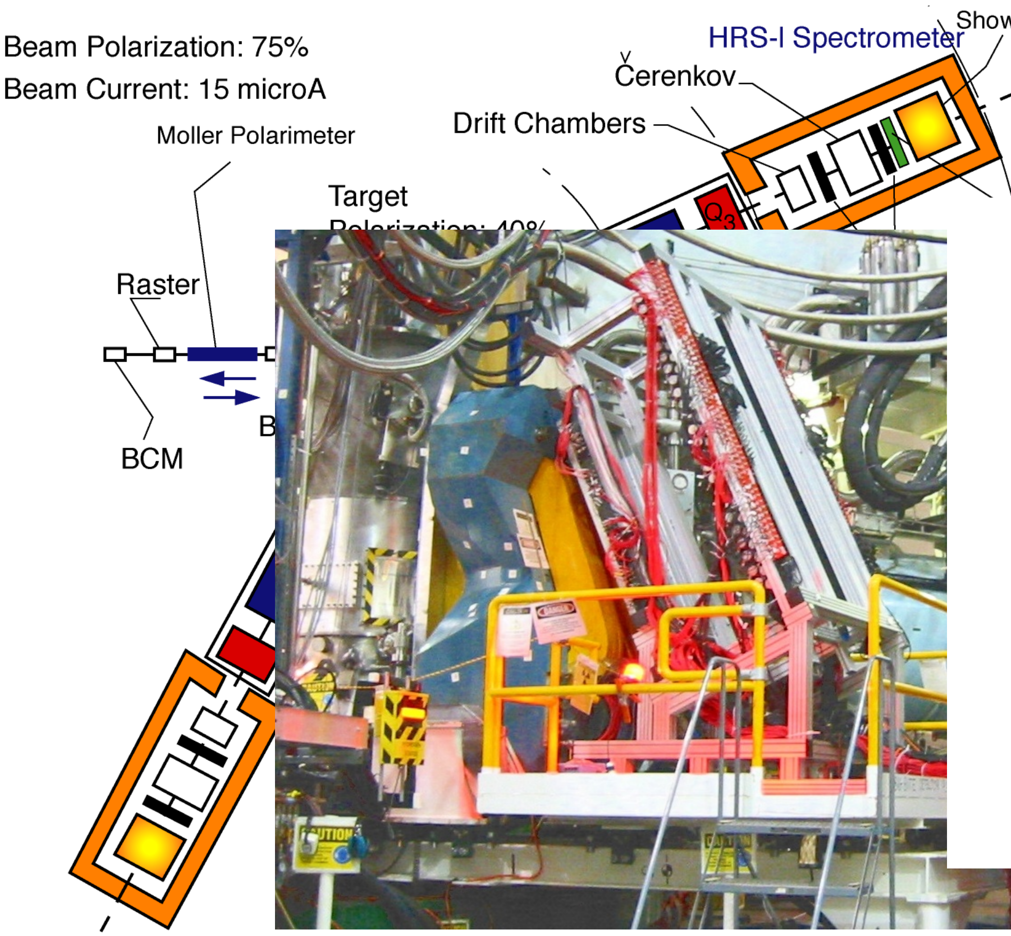
and the Hall A collaboration

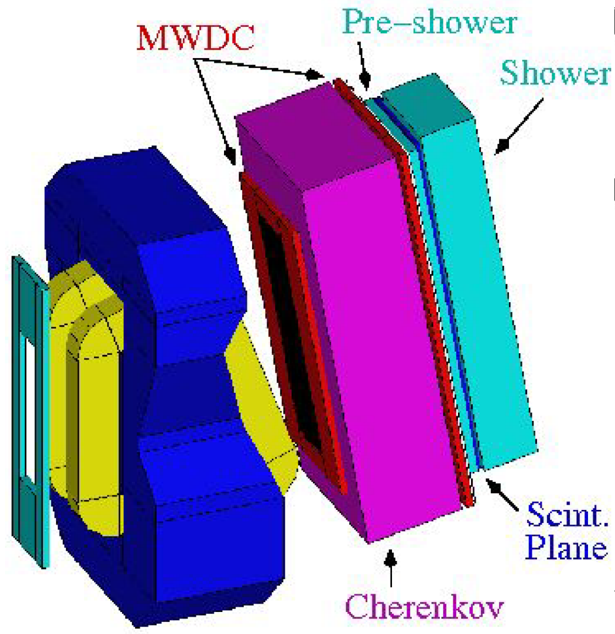
Spokespeople:
O. Rondon, S. Choi, M. Jones,, Z.-E. M

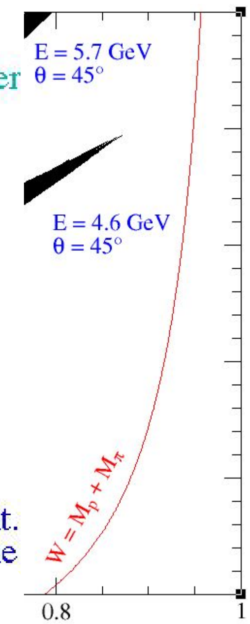
Students:
W. Armstrong, H. Kang, A. Liyanage, J. Maxwell, J. Mulholland

and the Hall C collaboration

Experiment E06-114 (d_2^n) in Hall A



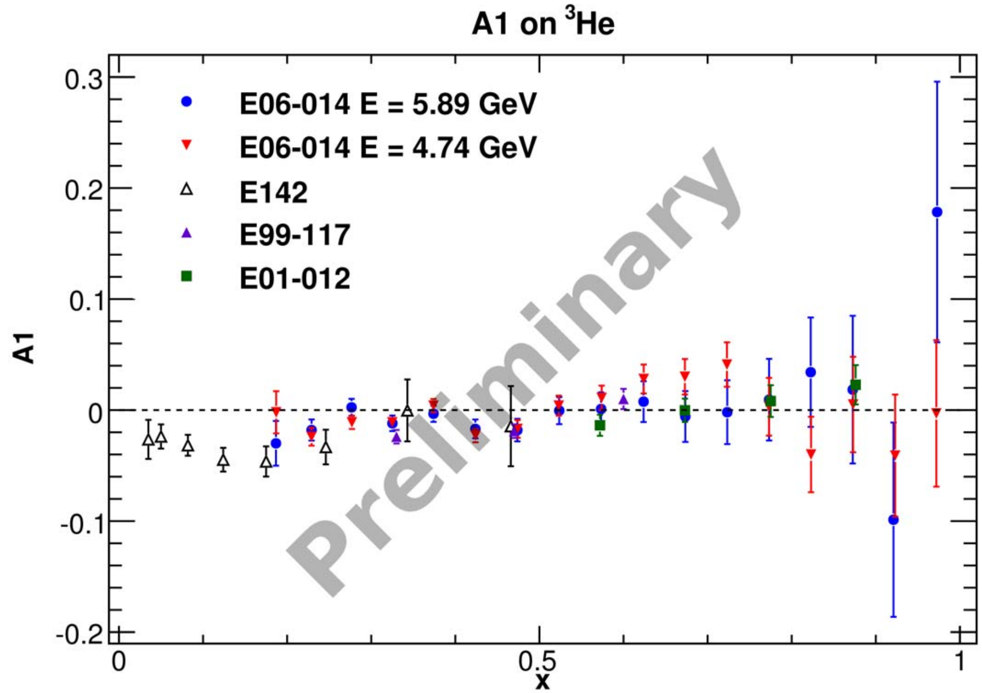




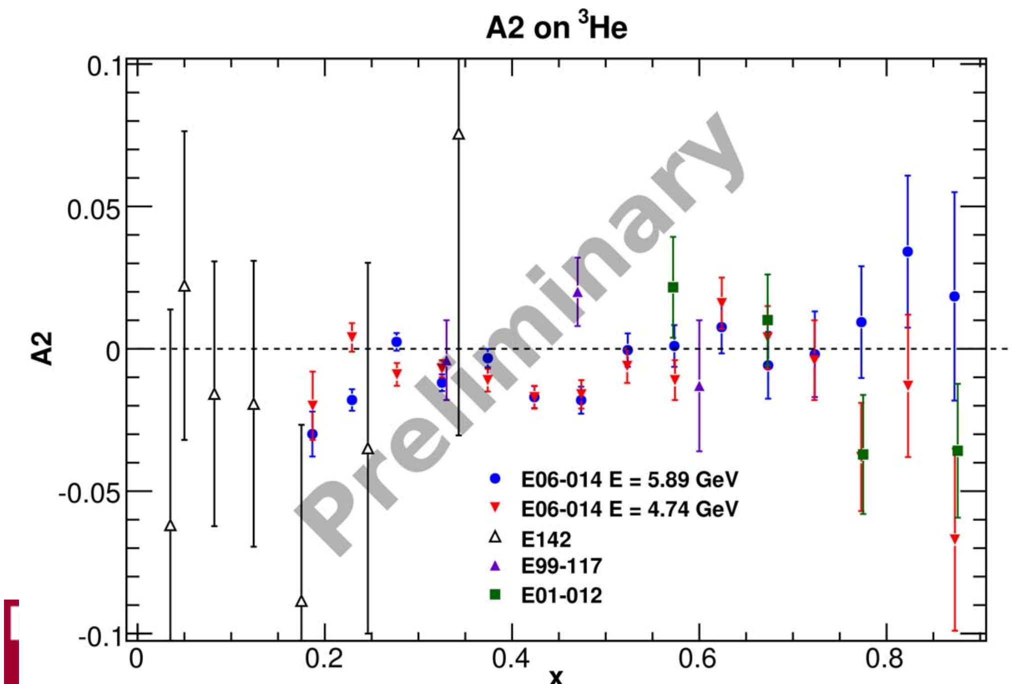
Two beam energies 4.7 and 5.89 GeV
(4 pass, 5 pass)

BigBite fixed at single scattering angle (θ=45°)
(data divided into 10 bins during analysis)

Experiment ran Jan.-Mar. 09

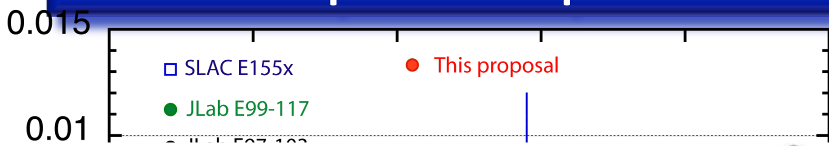


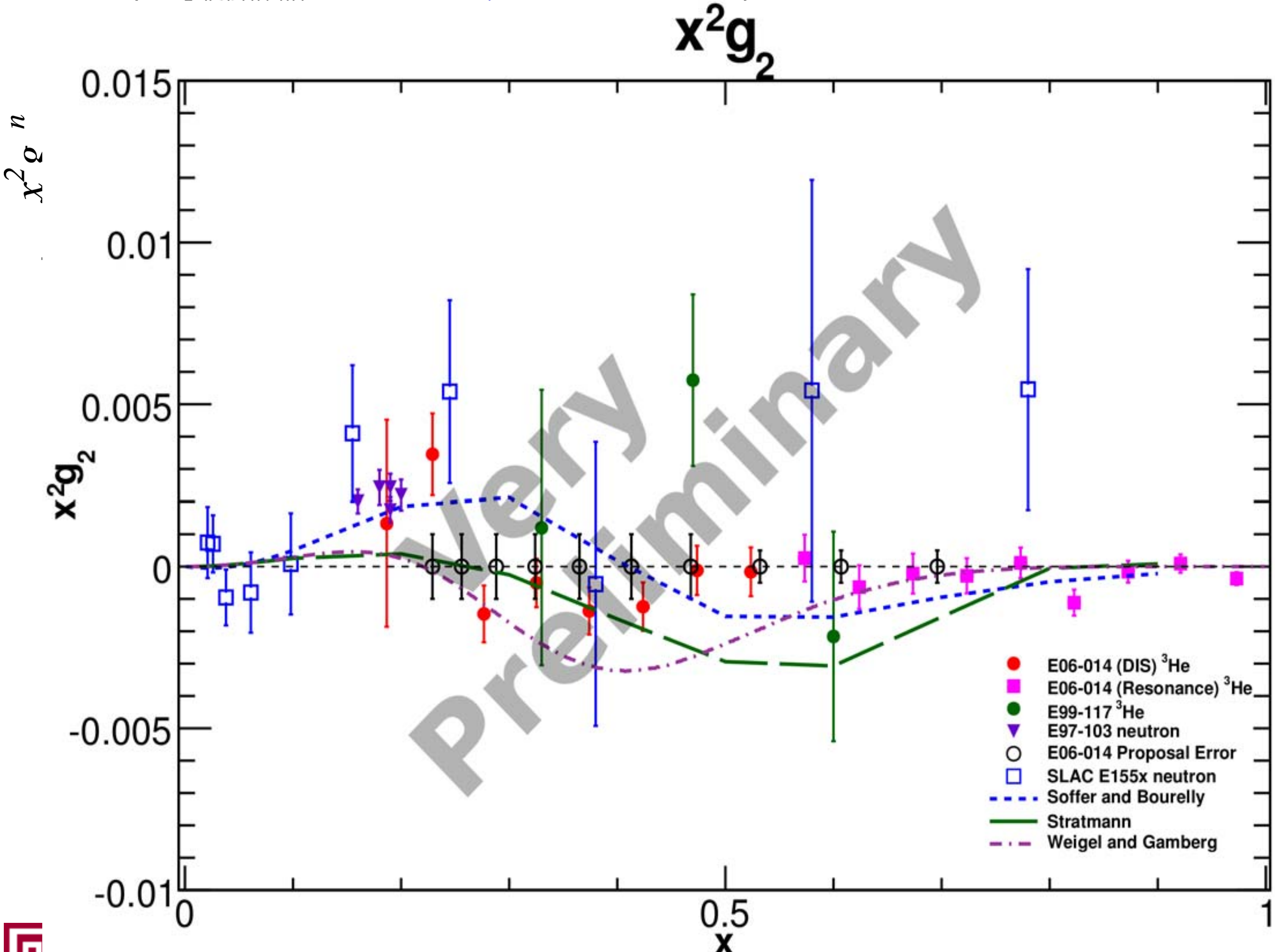
A_1 He3 at 4.7 and 5.89 GeV beam energy



A_2 He3 at 4.7 and 5.89 GeV beam energy

Expected precision in Experiment E06-114





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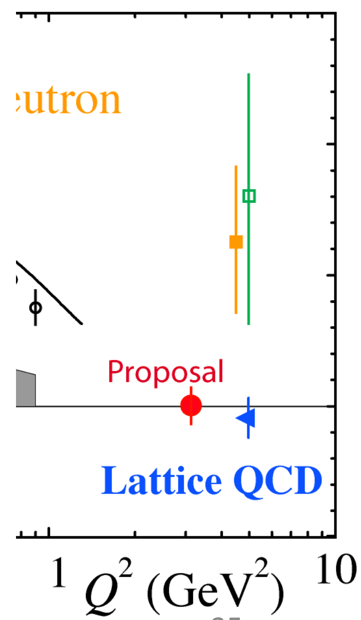
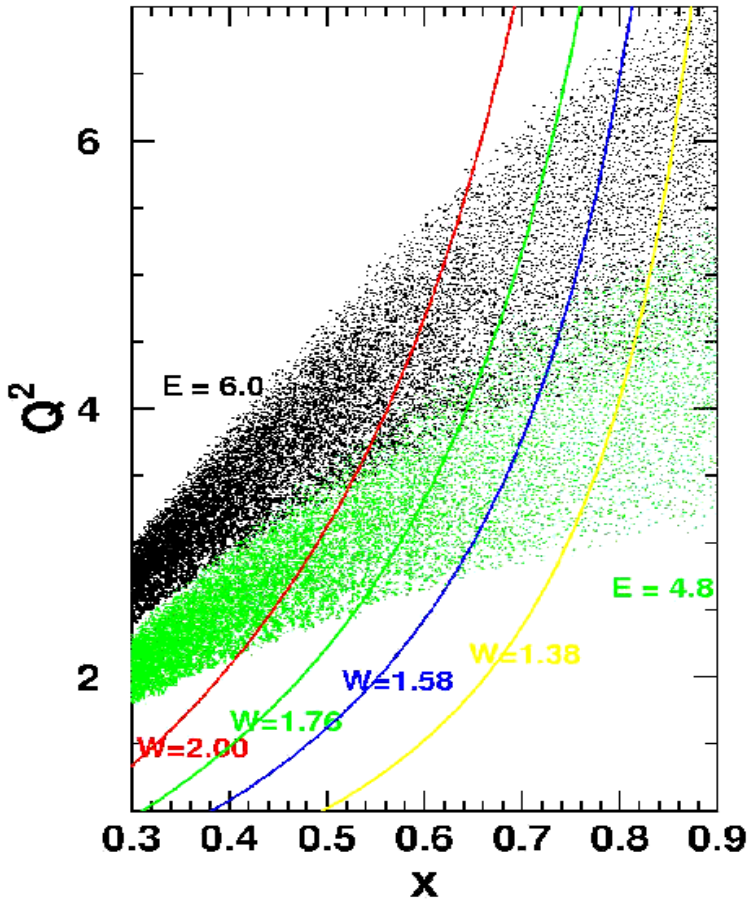
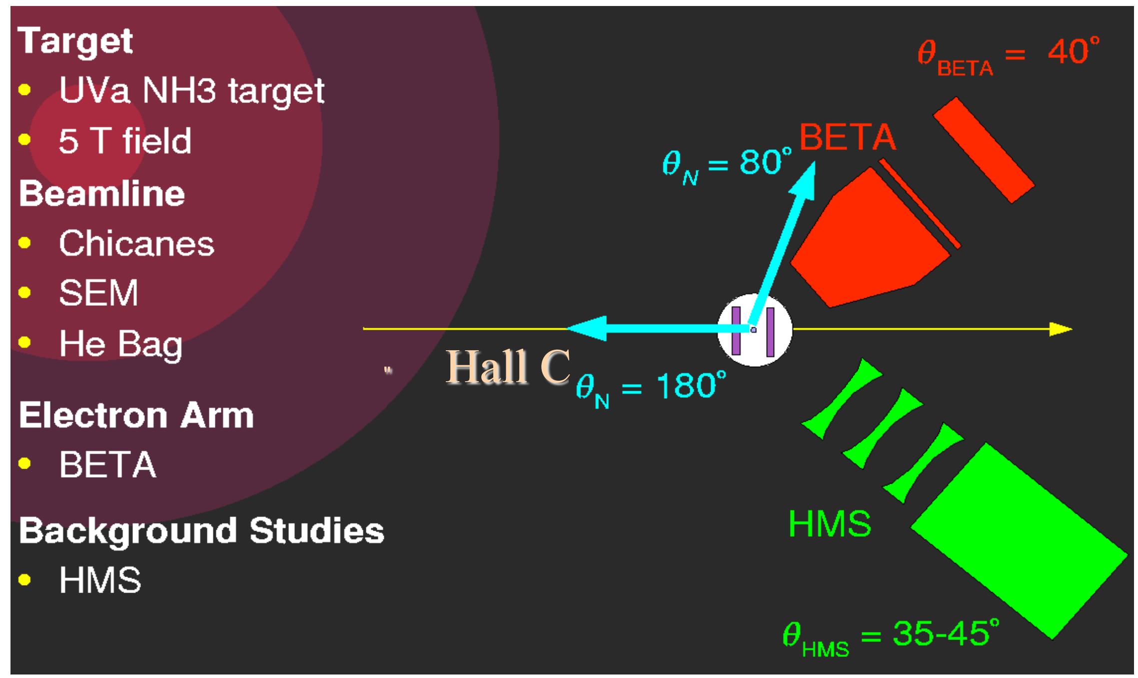


SANE experiment in Hall C





CEBAF polarized beam

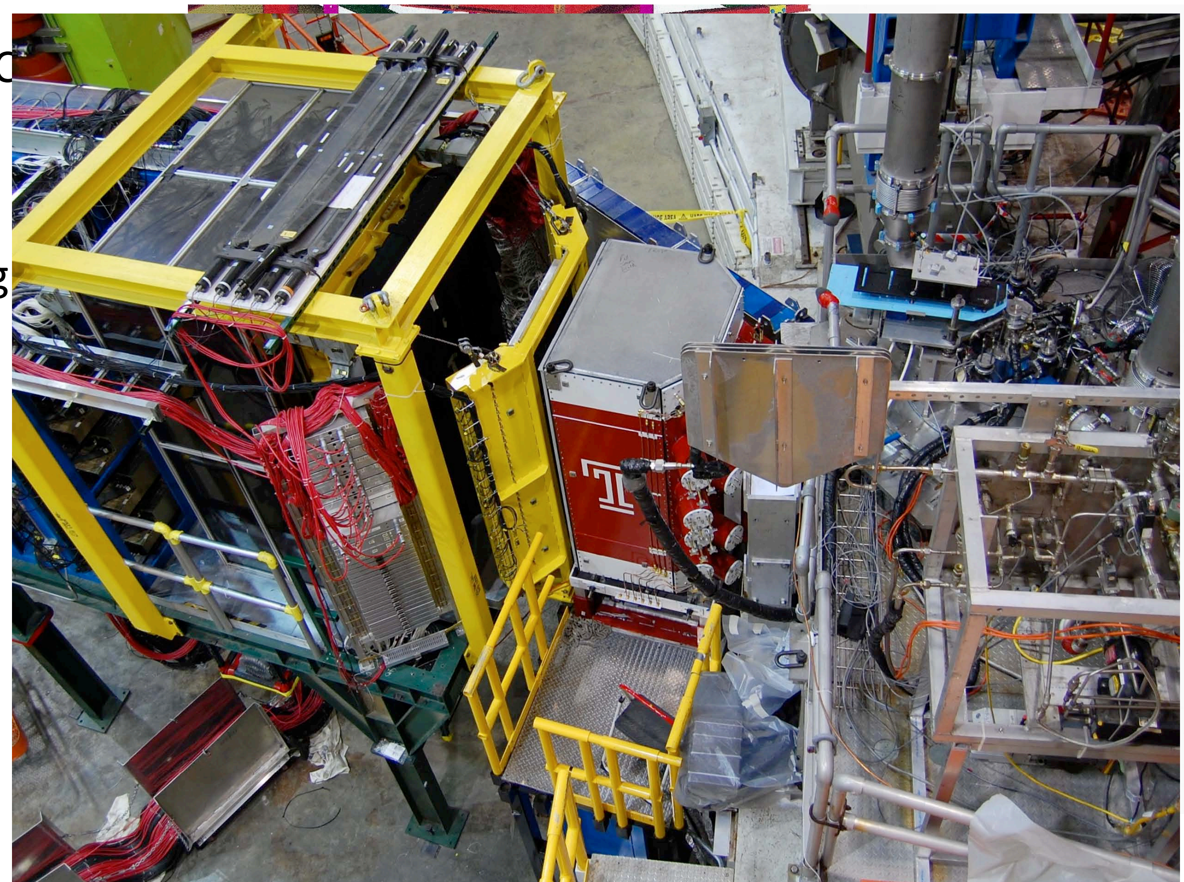
- 85 nA
- 75% beam polarization

- Two beam energies:
  - **6.0 GeV (black)**
  - **4.8 GeV (green)**

Experiment Ran January-March 09

BETA detector

- Three subsystems:
  - Lead glass calorimeter BigC Energy Measurement
  - Gas Cherenkov: e- identification
  - Lucite hodoscope: tracking
  - Front tracker: tracking
- Target field sweeps low *E* background
- Characteristics
  - Effective solid angle (with cuts) = 0.194 sr
  - Energy resolution 5%/√*E* *(GeV)*
  - *angular resolution = 2°*
  - *1000:1 pion rejection*

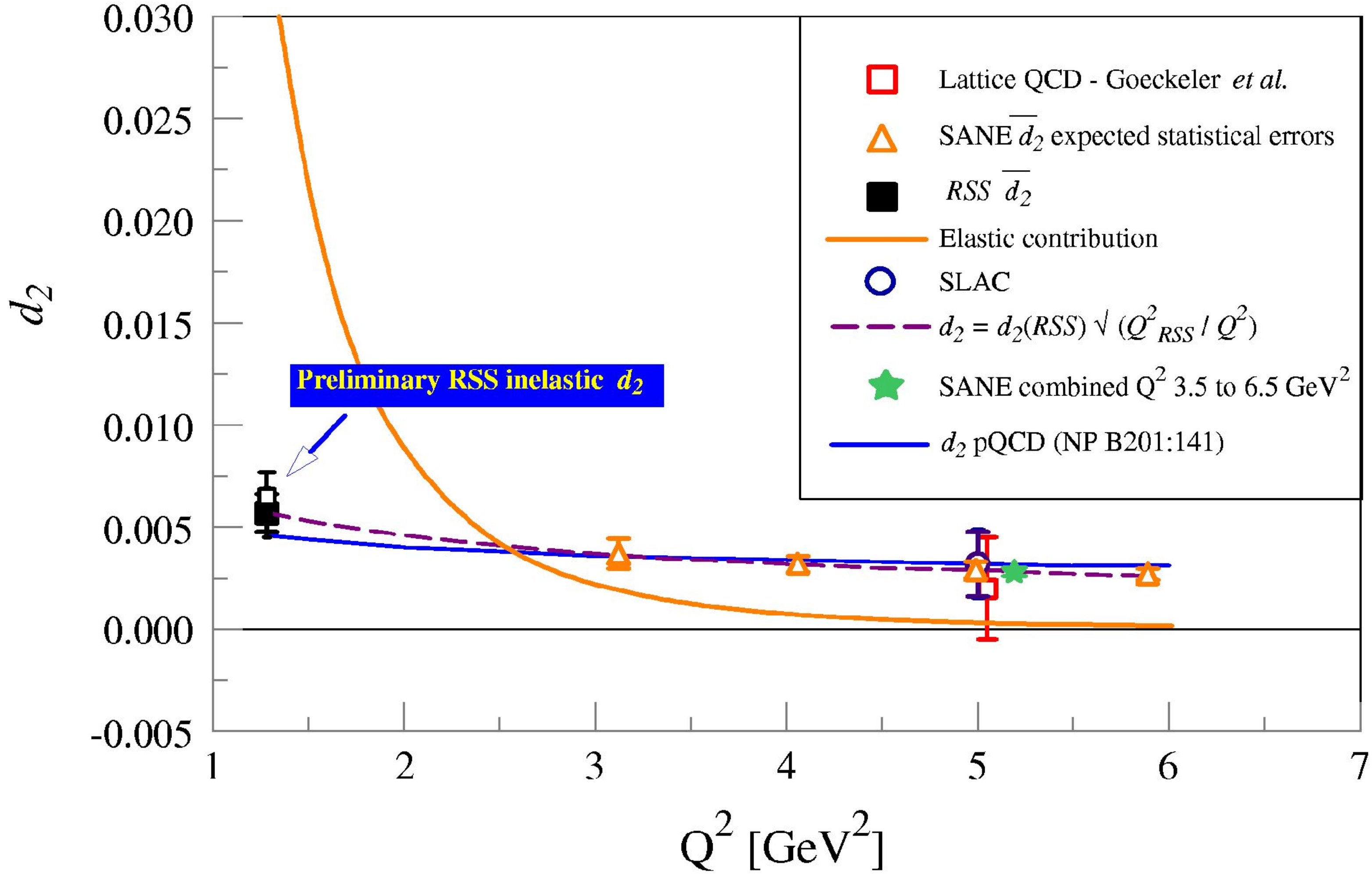


Lead Glass Calorimeter

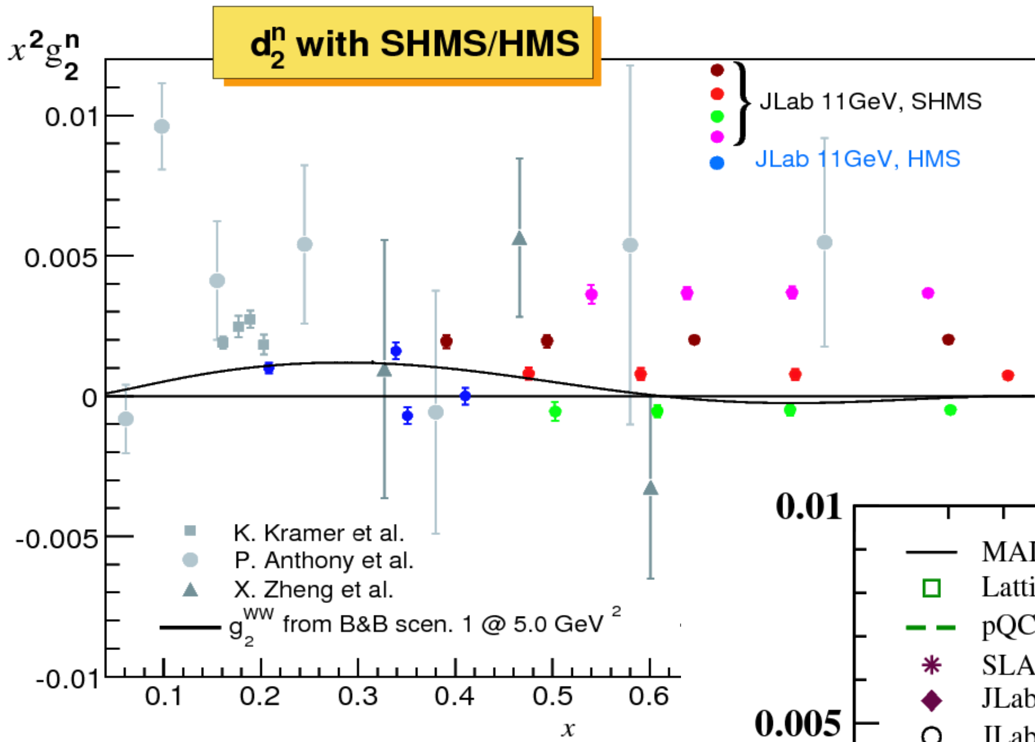
Lucite Hodoscope

d_2^p RSS and SANE d_2^p projection in Hall C

RSS spokesperons: M. Jones, O. Rondon
SANE spokespersons: S. Choi, M. Jones, O. Rondon, Z.-E. M

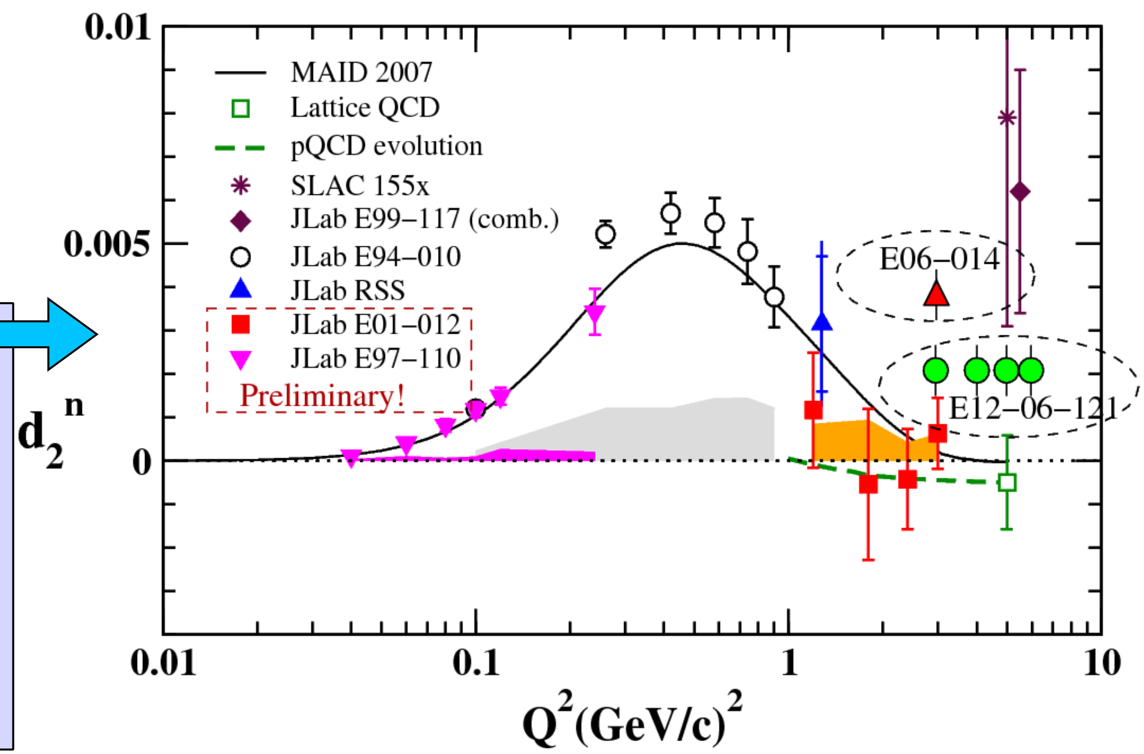


12 GeV Projected results for g2n and d2n



Projected g_2^n points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5—7 GeV^2.

- g_2 for ^3He is extracted directly from L and T spin-dependent cross sections measured within the same experiment.
- Strength of SHMS/HMS: nearly constant Q^2 (but less coverage for x < 0.3)



Nucleon Spin Sum Rule

$$\frac{1}{2} = J^q(\mu) + J^g(\mu)$$

Ji Sum rule (1997)

$$J^q = \int dx x \left[H^q + E^q\right]$$

$$J^g = \int dx \left[H^g + E^g\right]$$

$$J^q(\mu) = \frac{1}{2}\Delta\Sigma + L^q(\mu)$$

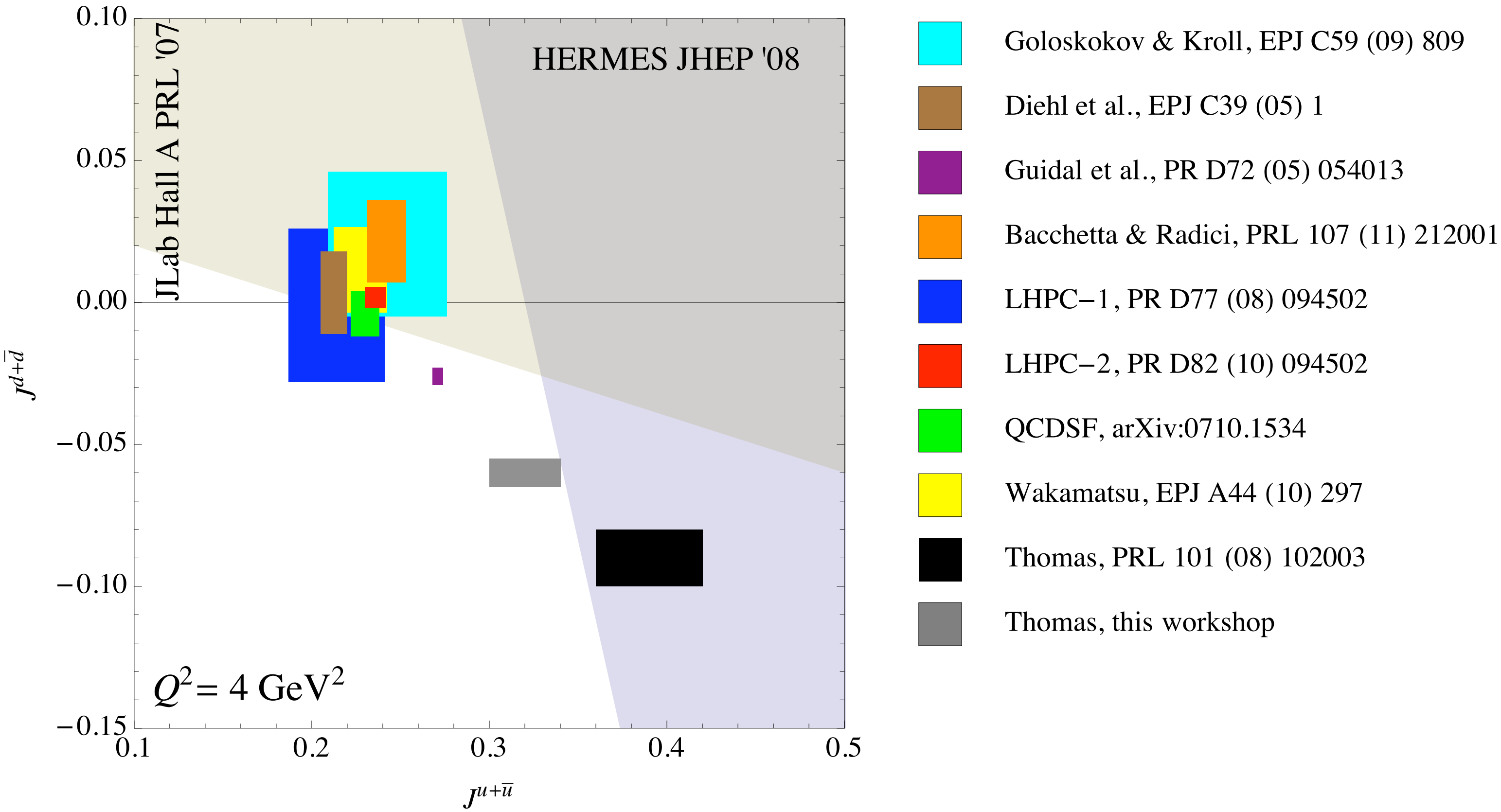
Total angular momentum of gluons

Spin of quarks Contribution: Measured in DIS

Orbital angular momentum of quarks: Input from Lattice and measurements at JLab 12 GeV

- Through the momentum sum rule and HERA DVMP with J/Psi data we have a glimpse on GPD H^g
- Nothing is known about GPD E^g

Extractions and lattice QCD



Extraction using SIDIS Sivers data from Hermes, Compass and JLab

Bachetta INT 2012

Summary

- There are important observables that tell a "story" about the constituents of the nucleon but need to be measured with precision.

- Theoretical tools to interpret the measurements are rapidly improving allowing the investigation of the structure of the nucleon as well as the dynamics of the constituents in the valence region.

- An EIC would be a natural extension for the investigation of the sea and the glue in a confined nucleon.