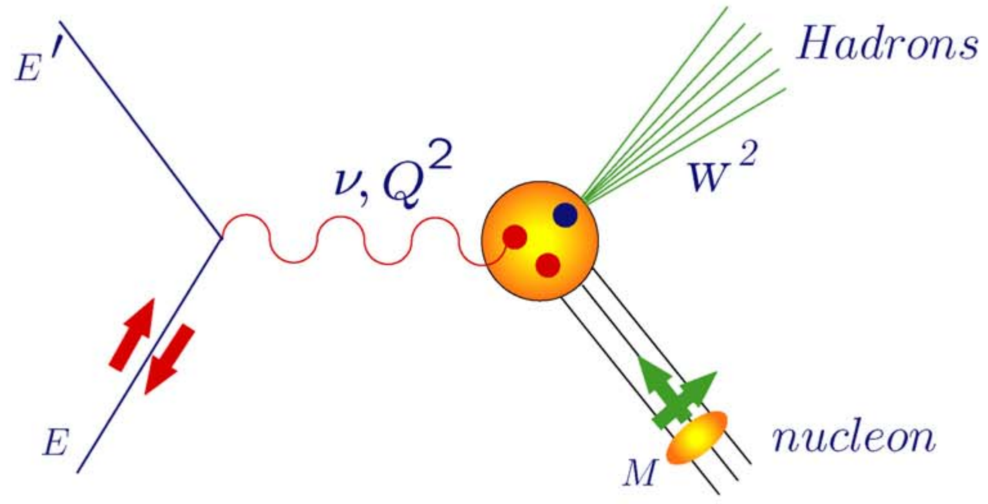
Spin Structure of the Nucleon

J. P. Chen, Jefferson Lab

Hirschegg Workshop, January 11-17, 2004

- Introduction
- Spin asymmetry at high x → valence quark spin distributions
- Sum rules, moments and polarizabilities
- Higher twist effects, quark-gluon correlations
- Quark-hadron duality
- SSA in semi-inclusive: transversity
- Summary

Polarized Deep Inelastic Electron Scattering



$x = \frac{Q^2}{2M\nu}$ 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

In the Bjorken scaling limit

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

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

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

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

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

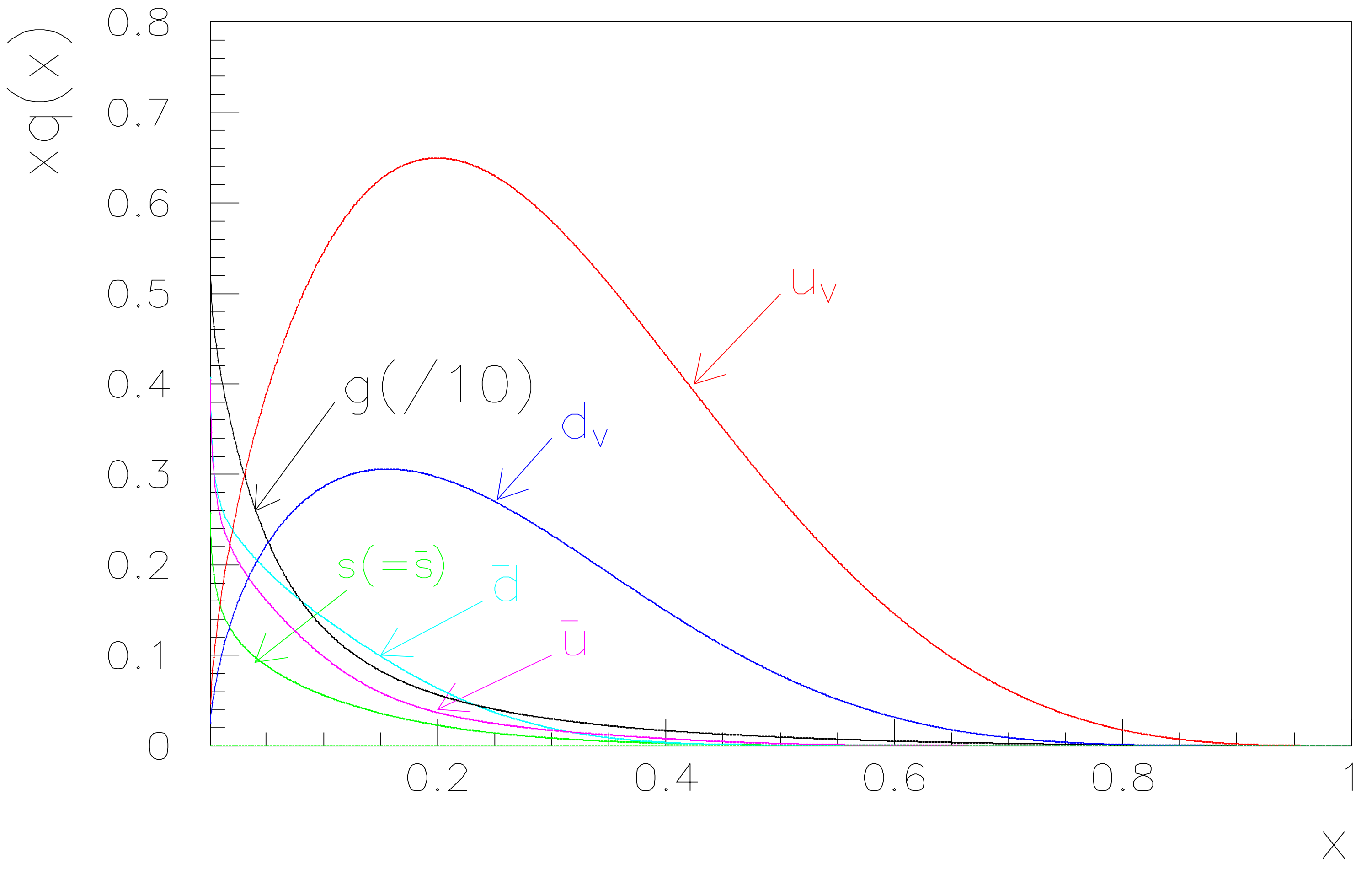
Observables of interest

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

$$R^{np}(x) = \frac{F_2^n(x)}{F_2^p(x)}$$

Parton Distributions

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



Status of Spin Structure Study

- What we've learned (before JLab)
  - Total quark contribution to nucleon spin: 20-30%
  - Gluon contribution is probably large
  - Quark orbital angular momentum is important
  - Bjorken Sum Rule verified to ~5%
  - Ellis-Jaffe Sum Rule violated
  - First dedicated g_2 experiment (SLAC E155x): higher twist?

- What to be learn
  - Gluon contribution (HERMES, COMPASS, RHIC-Spin, SLAC)
  - g_1 at very low x (RHIC-Spin, future ELIC)
  - Precision measurement of A_1 at high x
  - Precision measurement of g_2 (higher twists)
  - (Generalized) GDH Sum Rule, moments of g_1 and g_2, polarizabilities
  - Quark-hadron duality in g_1 and A_1

- Extend to semi-inclusive and exclusive
  - Spin-flavor decomposition
  - Transversity
  - Quark orbital angular momentum

Overview of Spin Structure Experiments

- High Q^2, DIS: SLAC, CERN, HERMES, RHIC-Spin
  - <Q^2> above 1 GeV^2, polarized p, d and ^3He
- Real Photon:
  - Mainz/Bonn, JLab, LEGS, GRAAL, TUNL, SPRING-8
- Low-Intermediate Q^2:
  - JLab Hall A: neutron with polarized ^3He
    - A_1^n at high x, valence quark spin structure, Q^2 range 3-5 GeV^2
    - GDH*, Q^2 range 0.02 - 1 GeV^2
      - g_2 at x~0.2, Q^2 from 0.5-1.5 GeV^2, higher twist
      - Spin Duality: Q^2 from 1-4 GeV^2
  - JLab Hall B: proton and deuteron, Q^2 range 0.2-2 GeV^2
  - JLab Hall C: proton and deuteron, <Q^2> ~ 1.3 GeV^2
- Semi-inclusive: HERMES, JLab

Valence Quark Spin Structure

A_1 at high x

Predictions for large x_{Bj}

Proton Wavefunction (Spin and Flavor Symmetric)

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

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

Physics Overview as x----> 1

Diquark Spin State	F^n_2/F^p_2	A^p_1	A^n_1
S=1 and S=0 equiprobable: SU(6)	2/3	5/9	0
	d/u=1/2	$\frac{\Delta u}{u}$ --->2/3	$\frac{\Delta d}{d}$ --->-1/3
S=1 suppressed, S=0 retained F. Close, Phys. Lett. 43B (1973) 422. F. Close, An introduction to Quarks and Partons (1979).	1/4	+1	+1
	d/u=0	$\frac{\Delta u}{u}$ --->1	$\frac{\Delta d}{d}$ --->-1/3
$S = 1, S_Z = 1$ suppressed $S = 1, S_Z = 0$ and $S = 0$ retained G. Farrar, D. Jackson, Phys. Rev. Lett. 35(1975)1416 G. Farrar, Phys. Lett. 70B (1977)346	3/7	+1	+1
	d/u=1/5	$\frac{\Delta u}{u}$ --->1	$\frac{\Delta d}{d}$ --->1
Instantons! N. Kochelev, hep-ph/9711226			~0

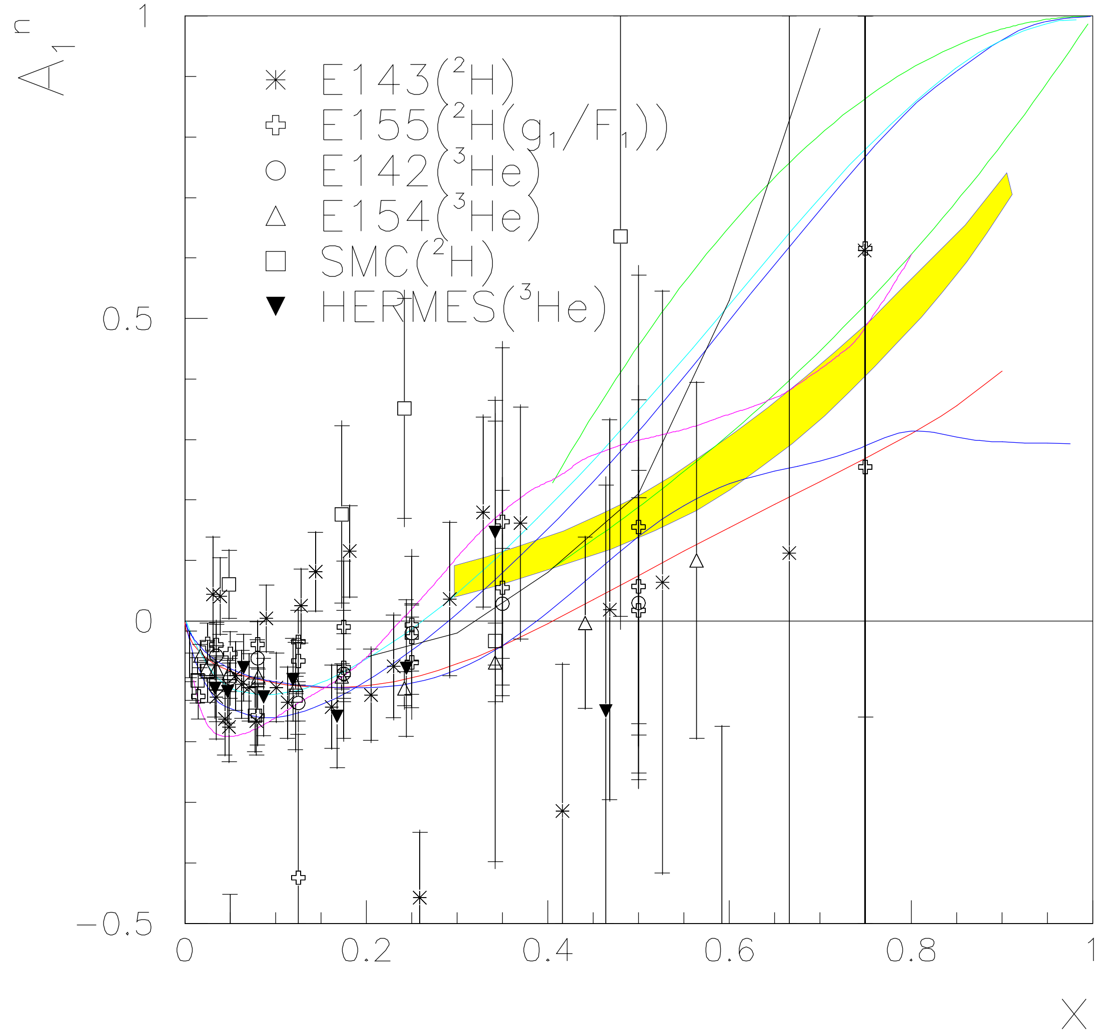
World Data on A_1^n and Models

- SU(6): $A_1^n=0$
- Valence quark models
- pQCD assuming HHC

(hadron helicity conservation)

- PDF fits (LSS)
- Statistical model
- Chiral Soliton model
- Local duality model
- Cloudy bag model

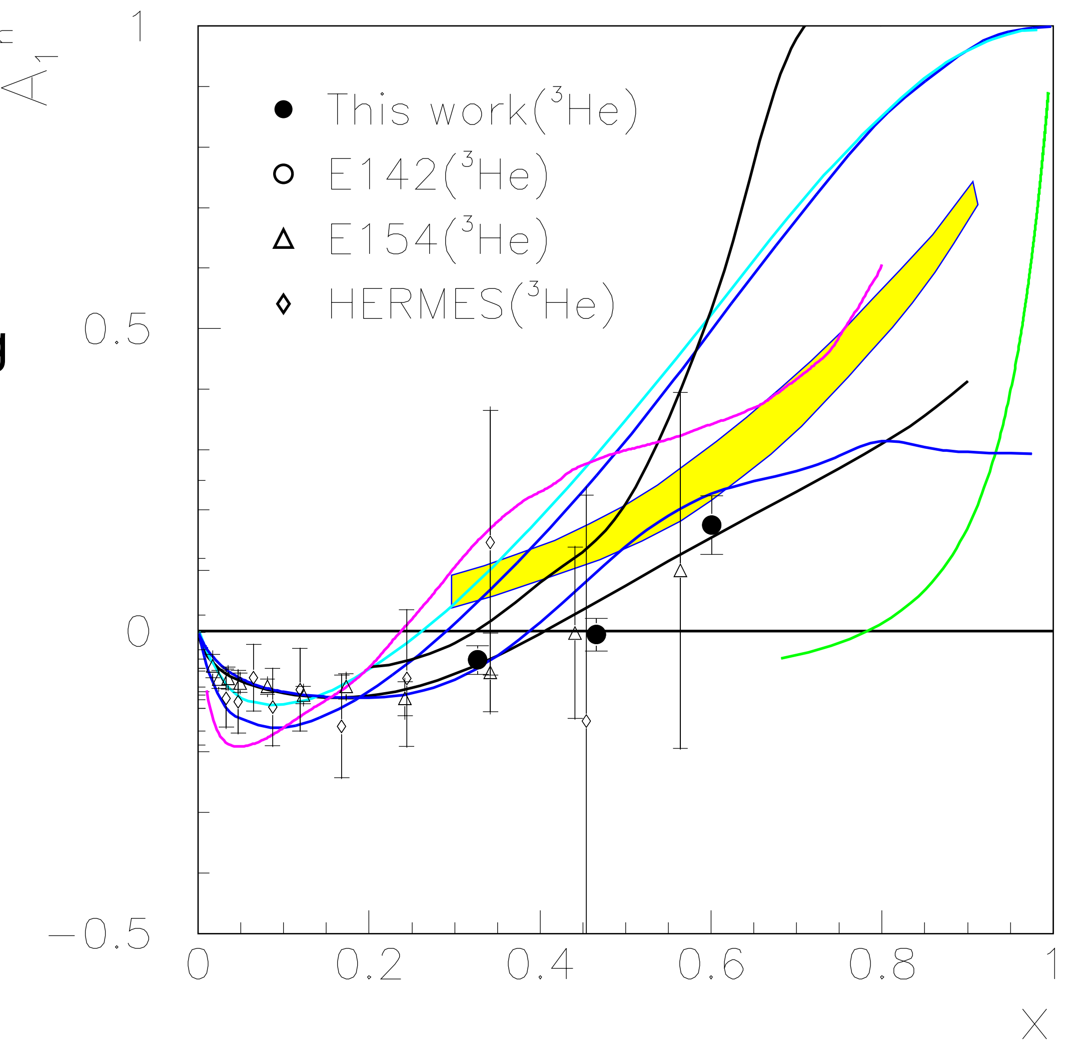
Need precision data at high x



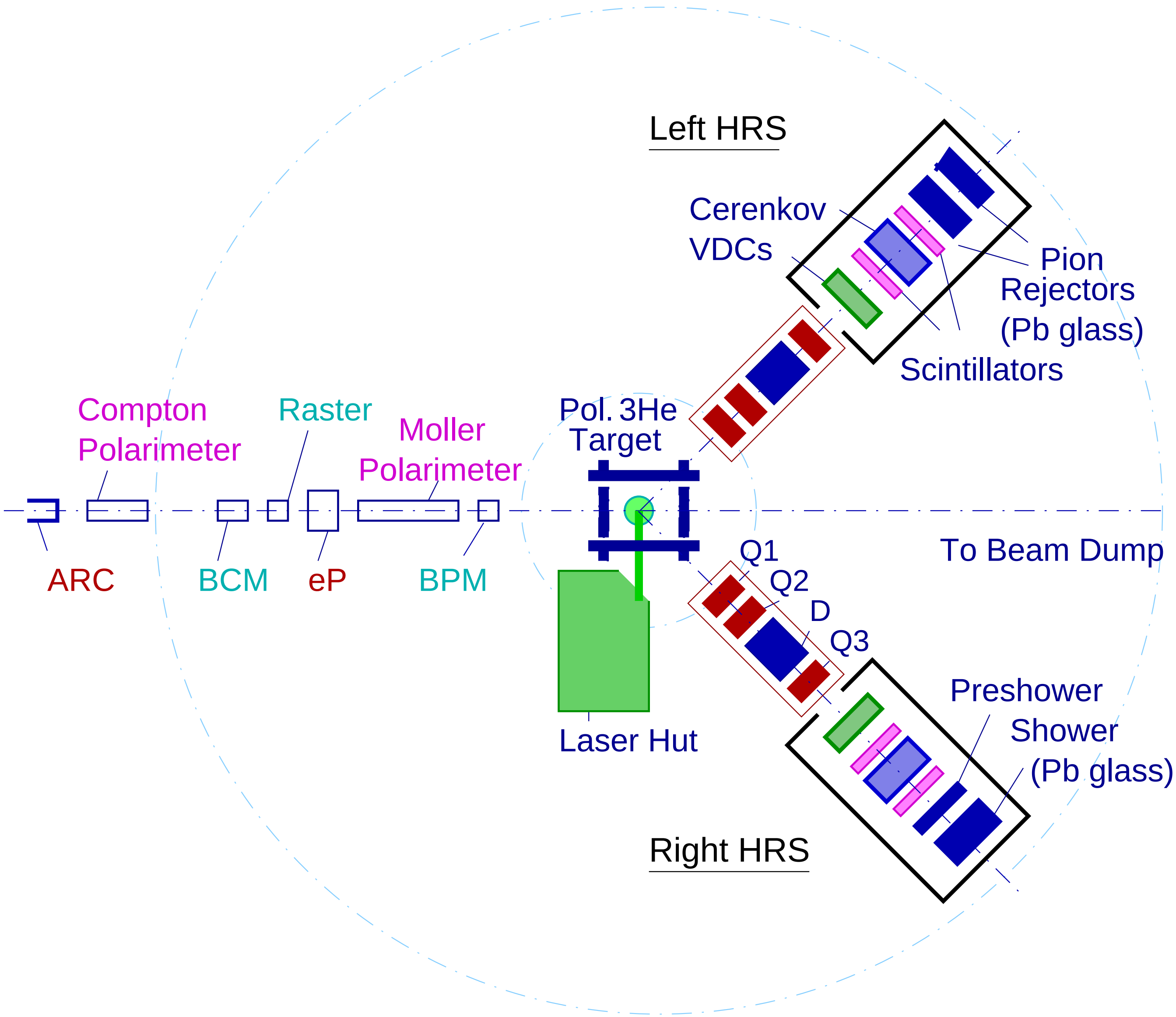
Precision Measurement of A_1^n at Large x

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

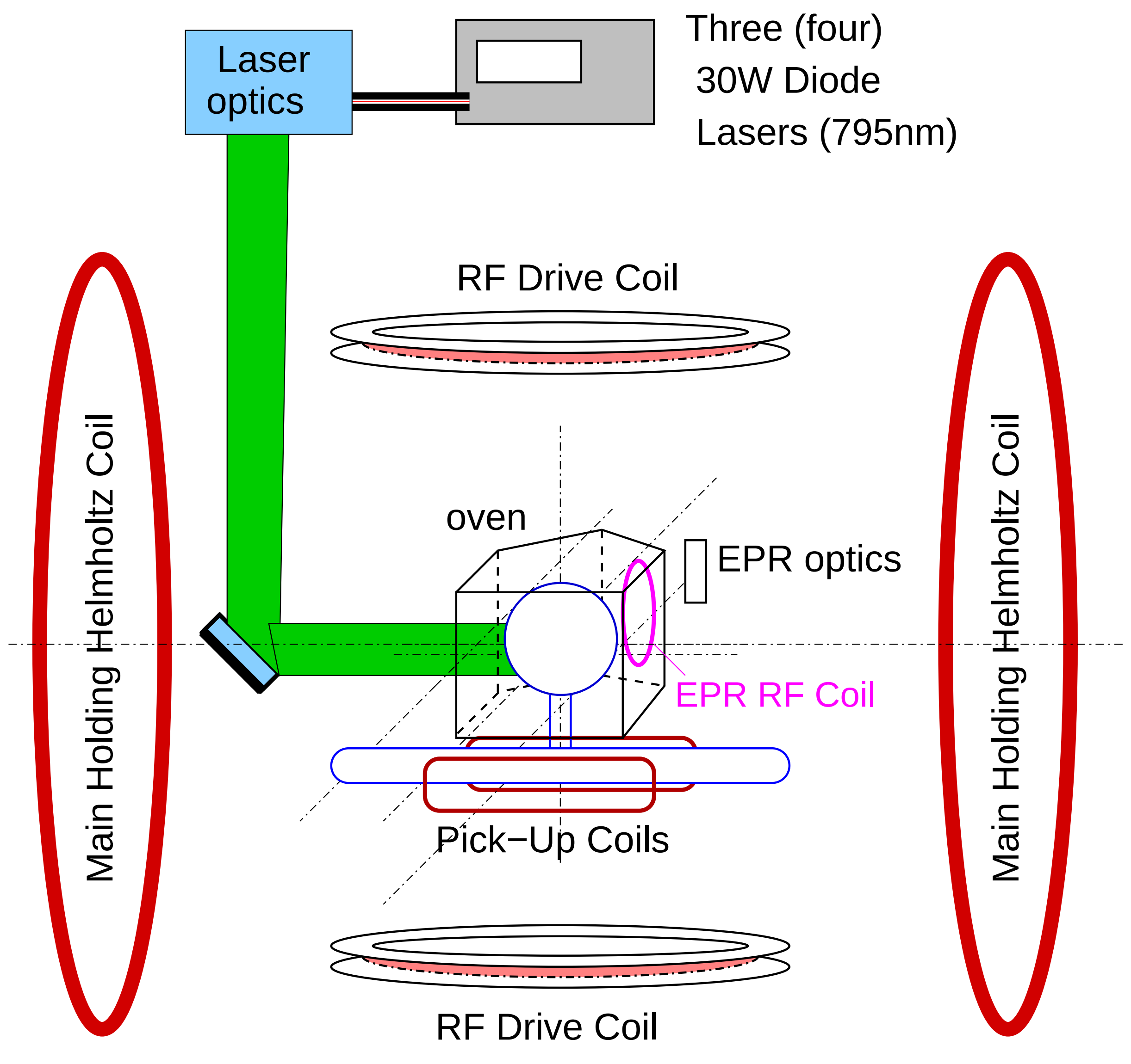
- First precision A_1^n data at high x
- Extracting valence quark spin distributions
- Test our fundamental understanding of valence quark picture
  - SU(6) symmetry
  - Valence quark models
  - pQCD (with HHC) predictions
  - Other models
- Quark orbital angular momentum
- Crucial input for pQCD fit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



JLab Hall A

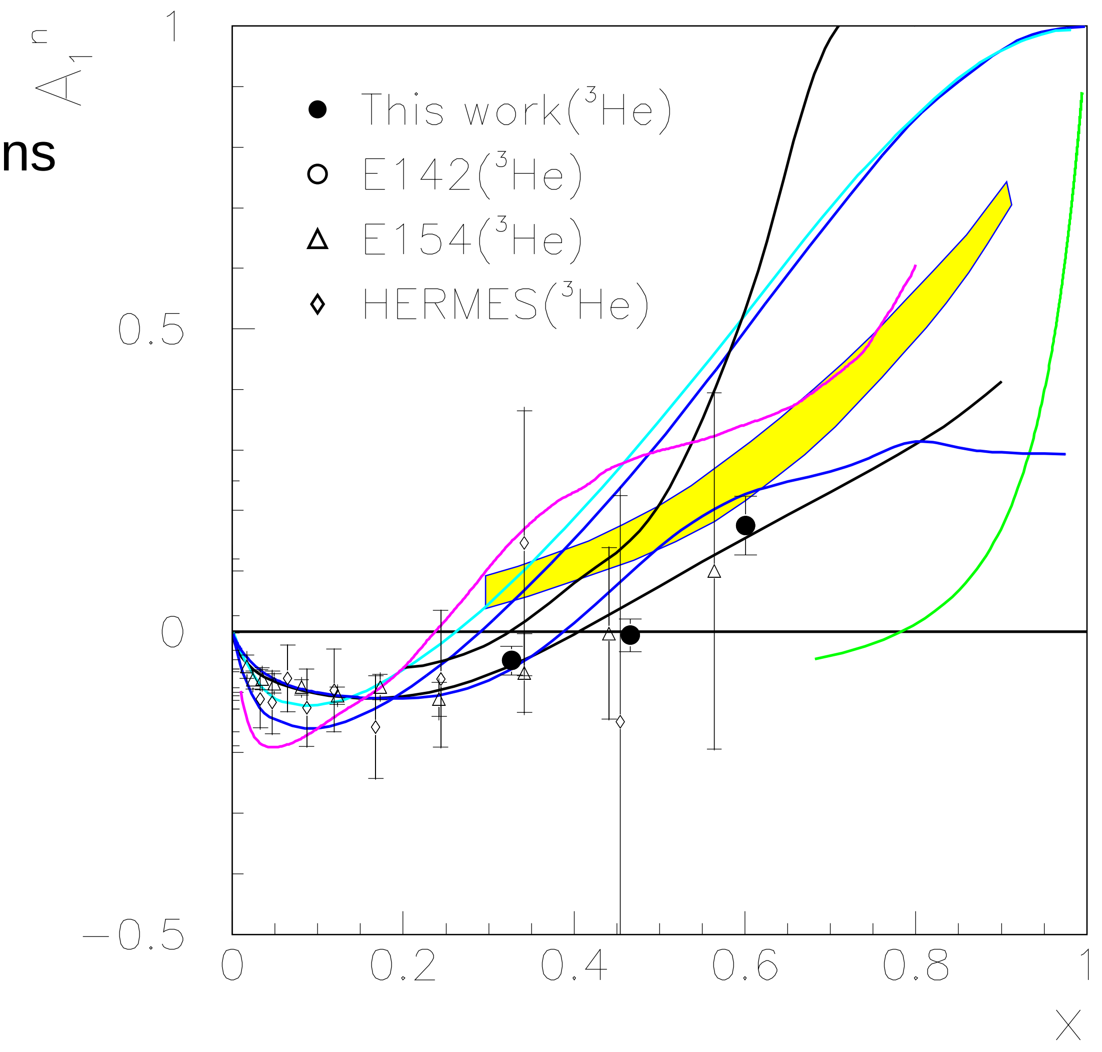

Left HRS
Cerenkov
VDCs
Pion
Rejectors
(Pb glass)
Scintillators
Compton
Polarimeter
Raster
Moller
Polarimeter
Pol. 3He
Target
ARC
BCM
eP
BPM
Q1
Q2
D
Q3
To Beam Dump
Laser Hut
Preshower
Shower
(Pb glass)
Right HRS

JLab Polarized ^{3}He Target



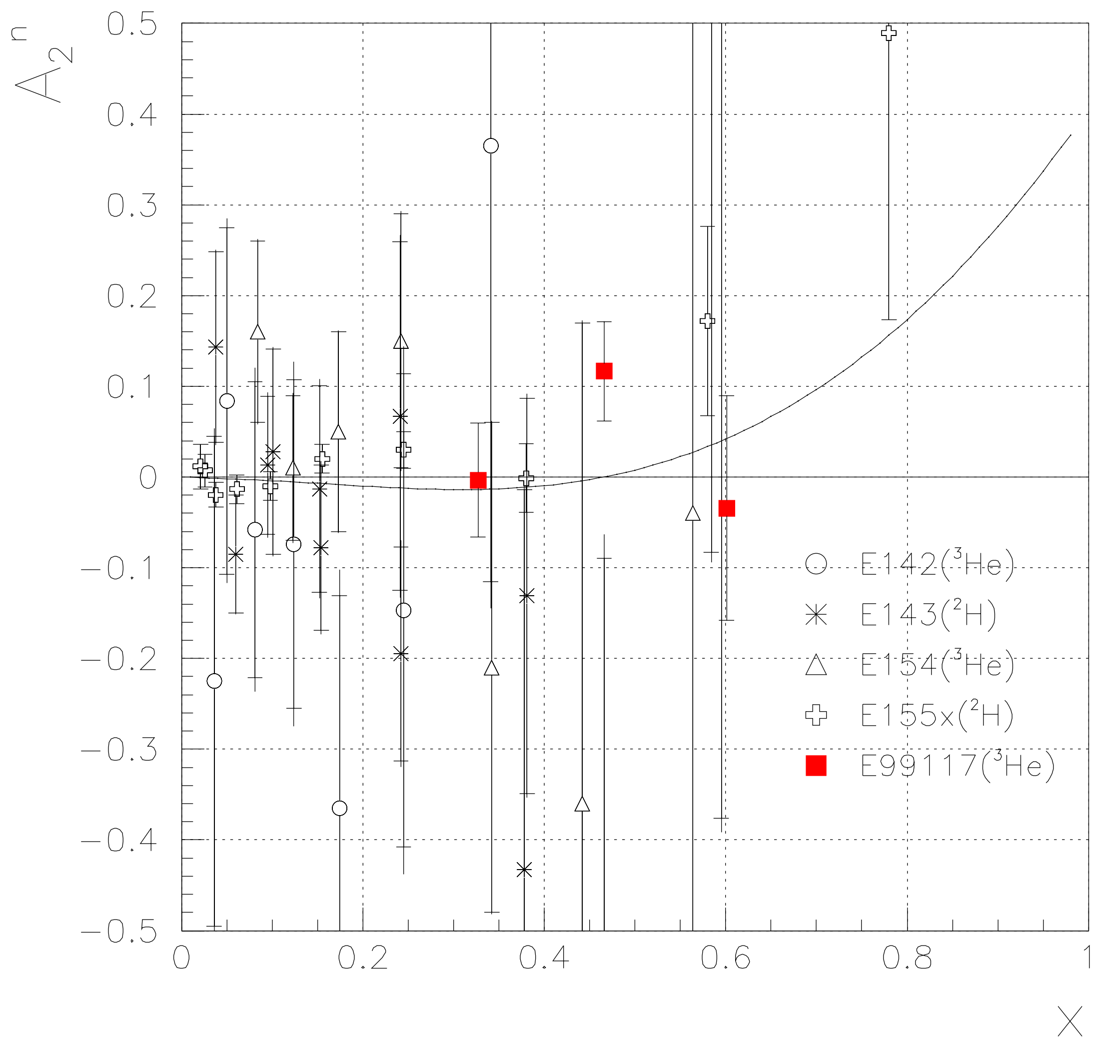
JLab E99-117 A_1^n Results

- First precision A_1^n data at $x > 0.3$
- Comparison with model calculations
  - SU(6) symmetry
  - Valence quark models
  - pQCD (with HHC) predictions
  - Other models
- Crucial input for pQCD fit to PDF
- PRL 92, 012004 (2004)

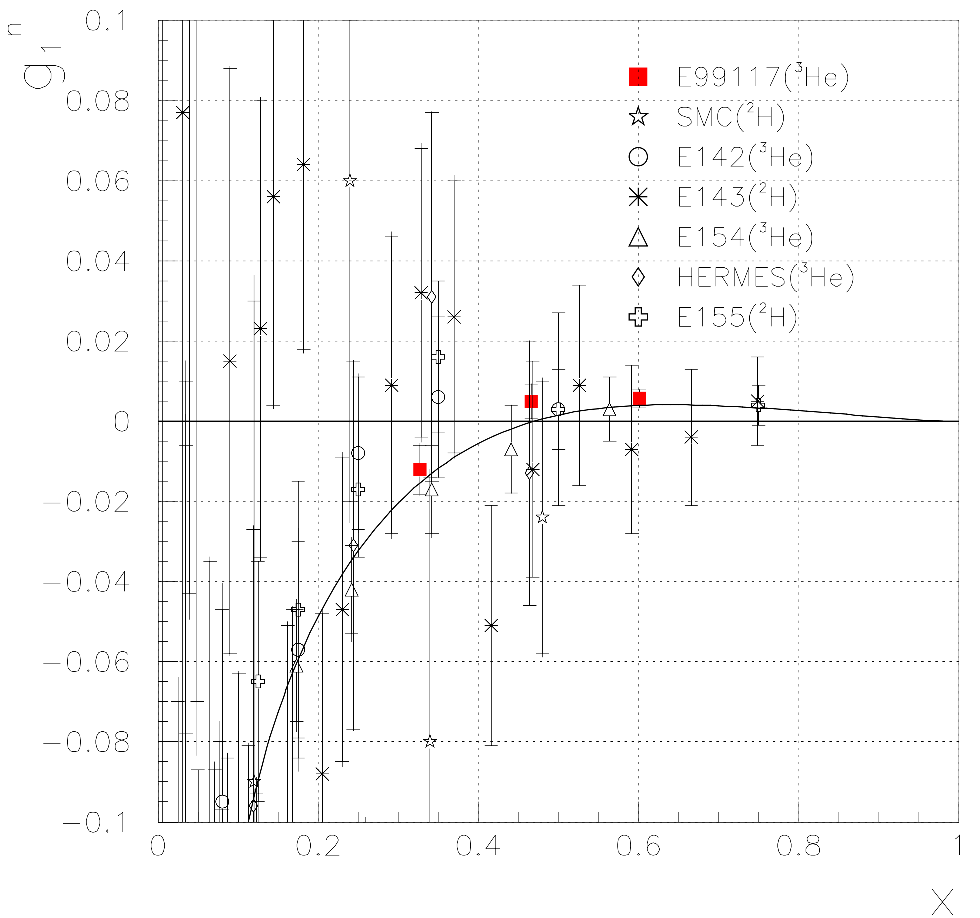


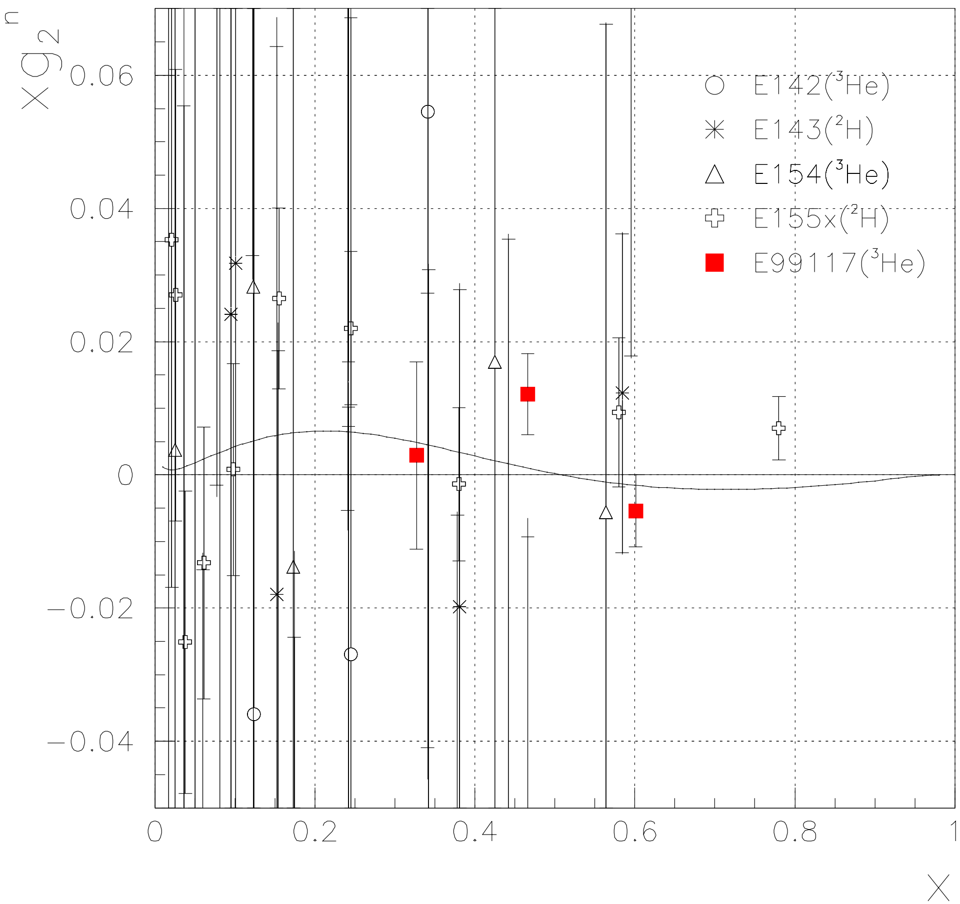
A_2^n results

- Obtained as a by-product
- Precision as good as the world best results



Precision g_1^n and g_2^n results



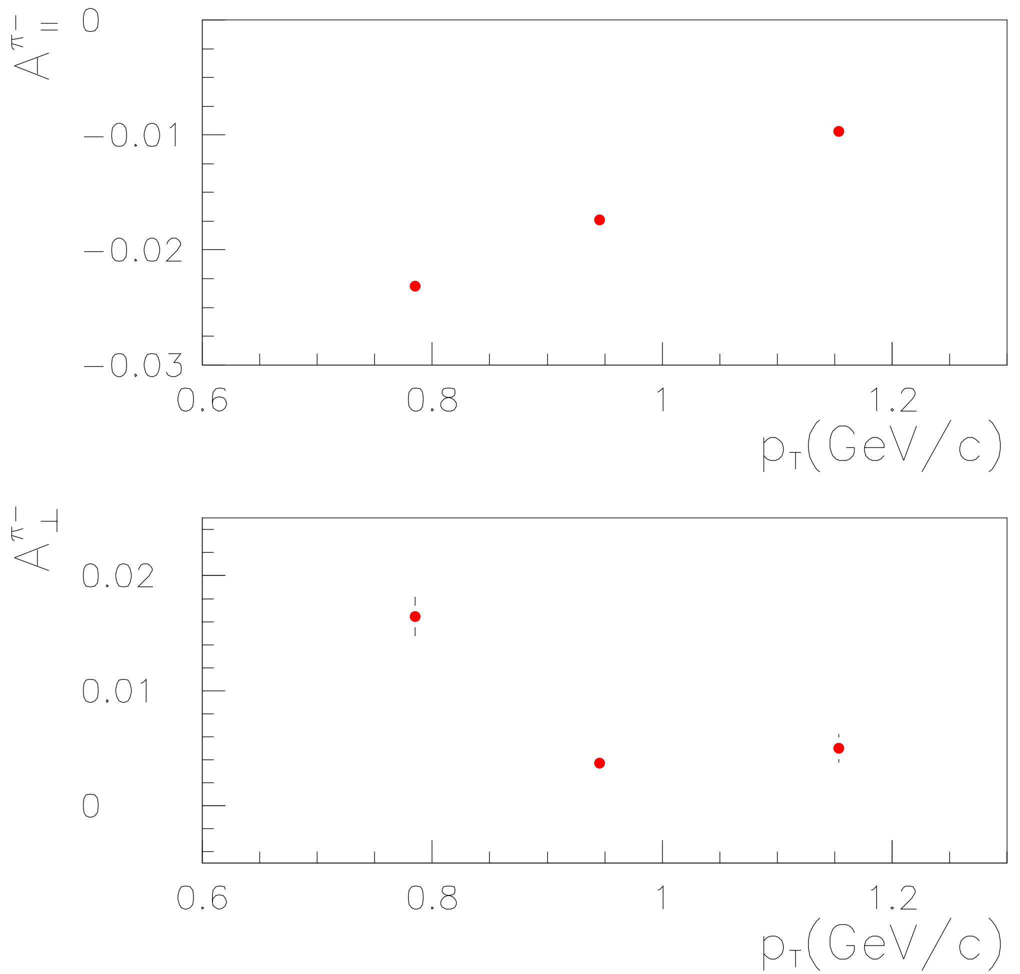


Pion Asymmetry

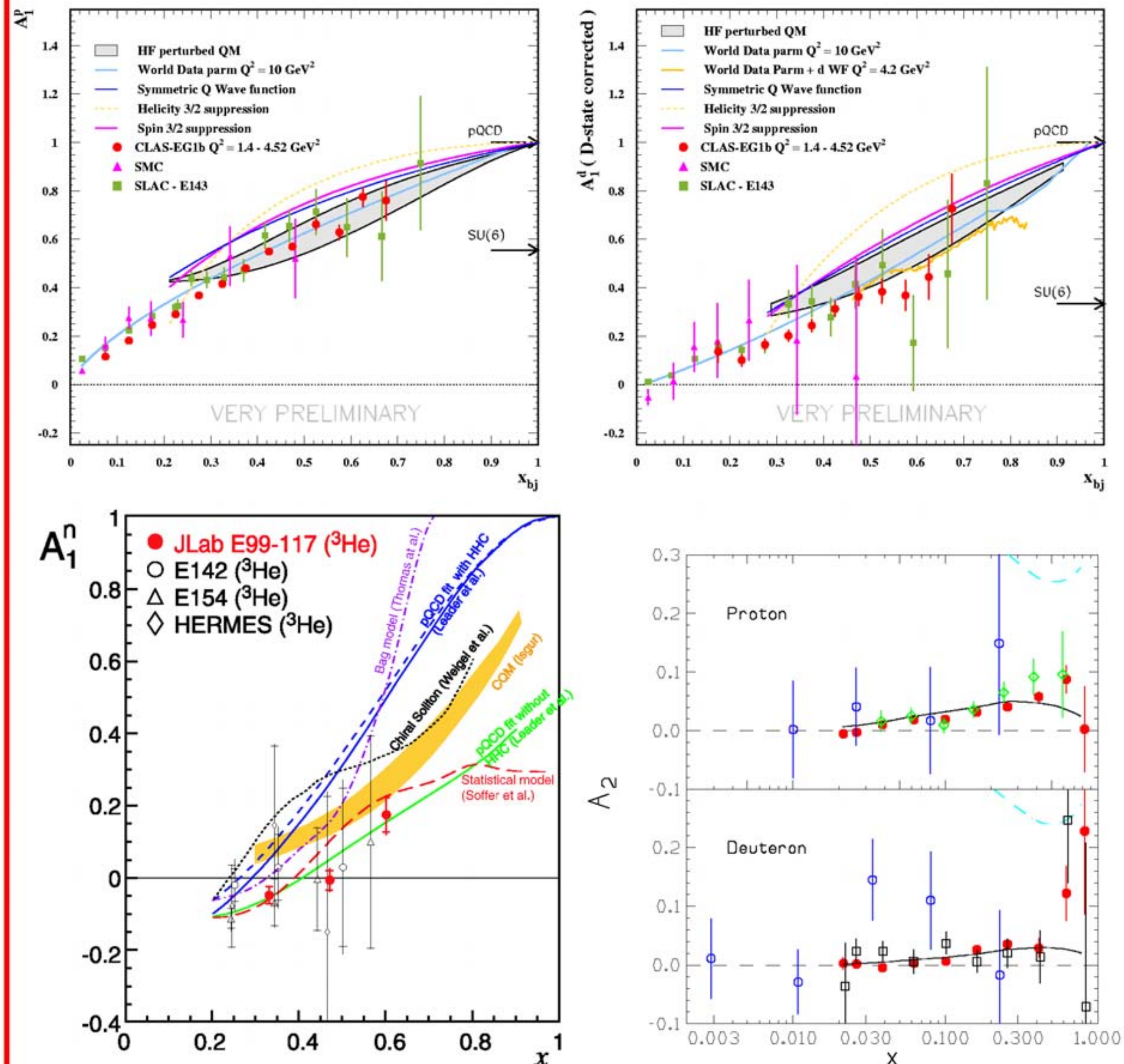
- Another by-product
  Inclusive pion asymmetry
- Dominated by photon production

- Awaiting theoretical calculations

  (J. M. Laget, …)

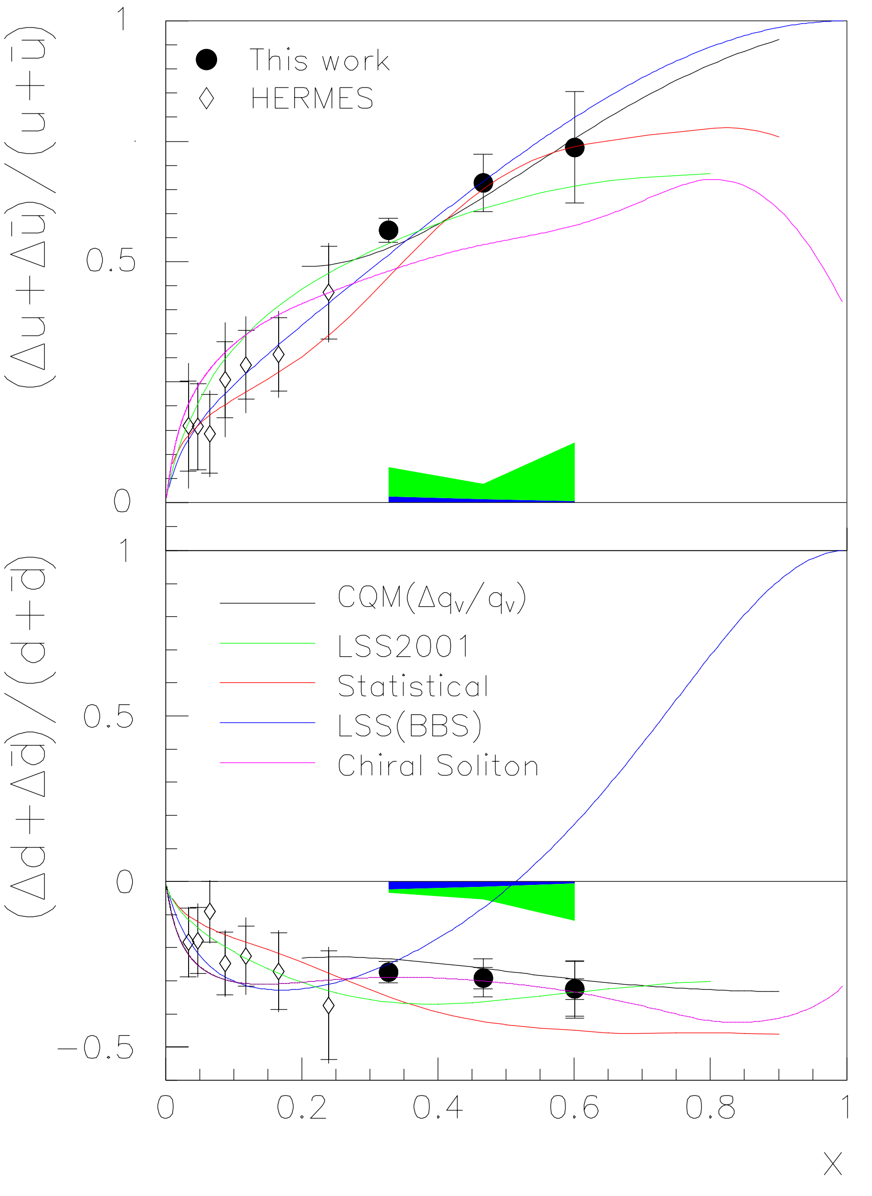


A_1 and A_2 vs. x


HF perturbed QM
World Data parm Q² = 10 GeV²
Symmetric Q Wave function
Helicity 3/2 suppression
Spin 3/2 suppression
CLAS-EG1b Q² = 1.4 - 4.52 GeV²
SMC
SLAC - E143
pQCD
SU(6)
VERY PRELIMINARY
x_bj
World Data Parm + d WF Q² = 4.2 GeV²
A_1^d (D-state corrected)
JLab E99-117 (³He)
E142 (³He)
E154 (³He)
HERMES (³He)
Bag model (Thomas at al.)
pQCD fit with HHC (Leader et al.)
Chiral Soliton (Weigel et al.)
CQM (Isgur)
pQCD fit without HHC (Leader et al.)
Statistical model (Soffer et al.)
Proton
Deuteron
A 2
x

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 or pQCD PDF fits



Discussion

- First precision data of A_1^n and g_1^n at high x (up to 0.6)
- A_1^n positive above x=0.5
- Extracted $\Delta u/u$ and $\Delta d/d$
  - $\Delta d/d$ stays negative!
- Provide important input for pQCD fit to spin PDF

- Consistent with pQCD fit of spin PDF to previous data
- Consistent with SU(6) breaking valence quark models
- Disagree with leading order pQCD model
  - Hadron Helicity conservation assumption in question
  - Quark orbital angular momentum important

The results published in PRL 92, 012004 (2004), and also in the news:

AIP Physics News Update

Science online (Science Now)

Science News

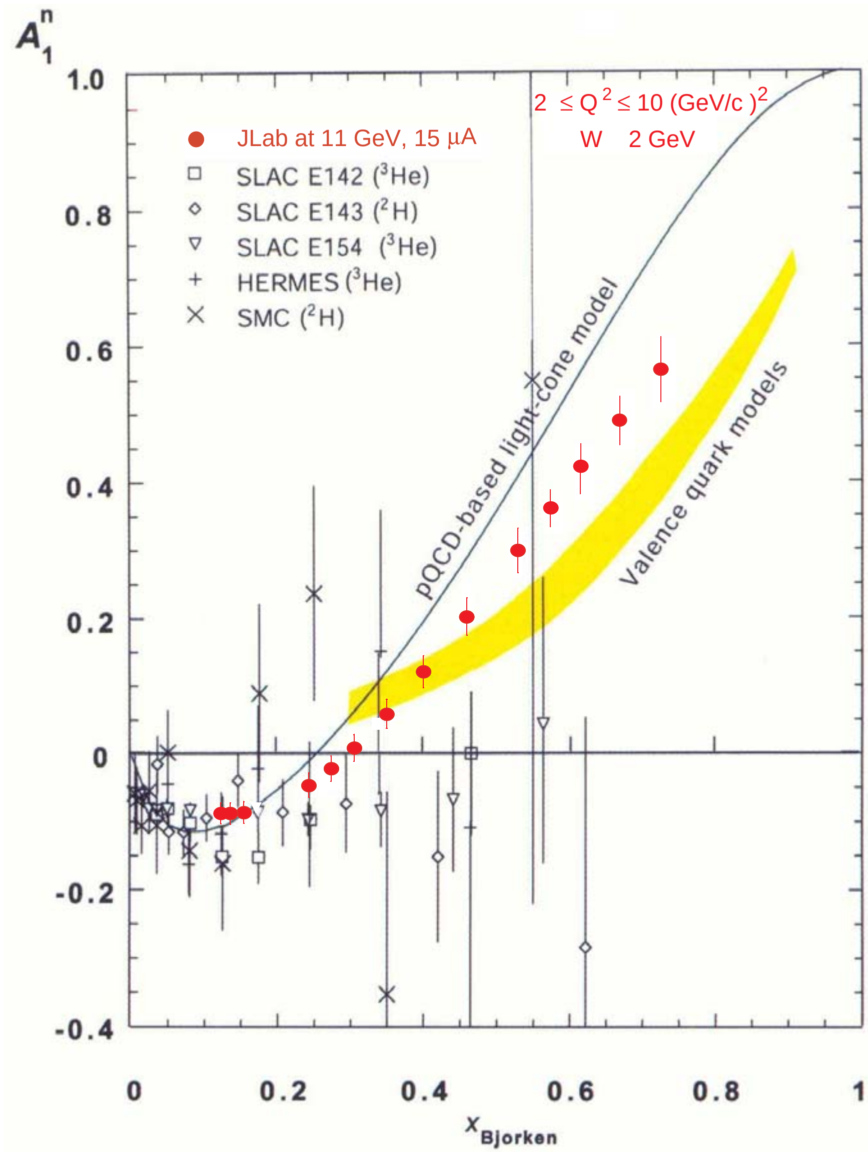
A_1^n with 12 GeV Upgrade

One of the flagship experiments:

complete a chapter on the valence quark structure

use $^3\overrightarrow{He}$ target and 15 μA beam

use a new medium (wide) acceptance spectrometer for e detection



Generalized GDH Sum Rule

Moments and
Polarizabilities

Gerasimov-Drell-Hearn Sum Rule

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

- A fundamental relation between the nucleon spin structure and its anomalous magnetic moment
- Based on general physics principles
  - Lorentz invariance, gauge invariance, unitarity
  - unsubtracted dispersion relation applied to forward Compton amplitude
- First measurement on proton up to 800 MeV (Mainz) and up to 3 GeV (Bonn)
- Results agree with sum rule with assumptions for higher energy contributions
- Next: Mainz, GRAAL, SPring-8, LEGS, HIGS, JLab, SLAC
- The neutron

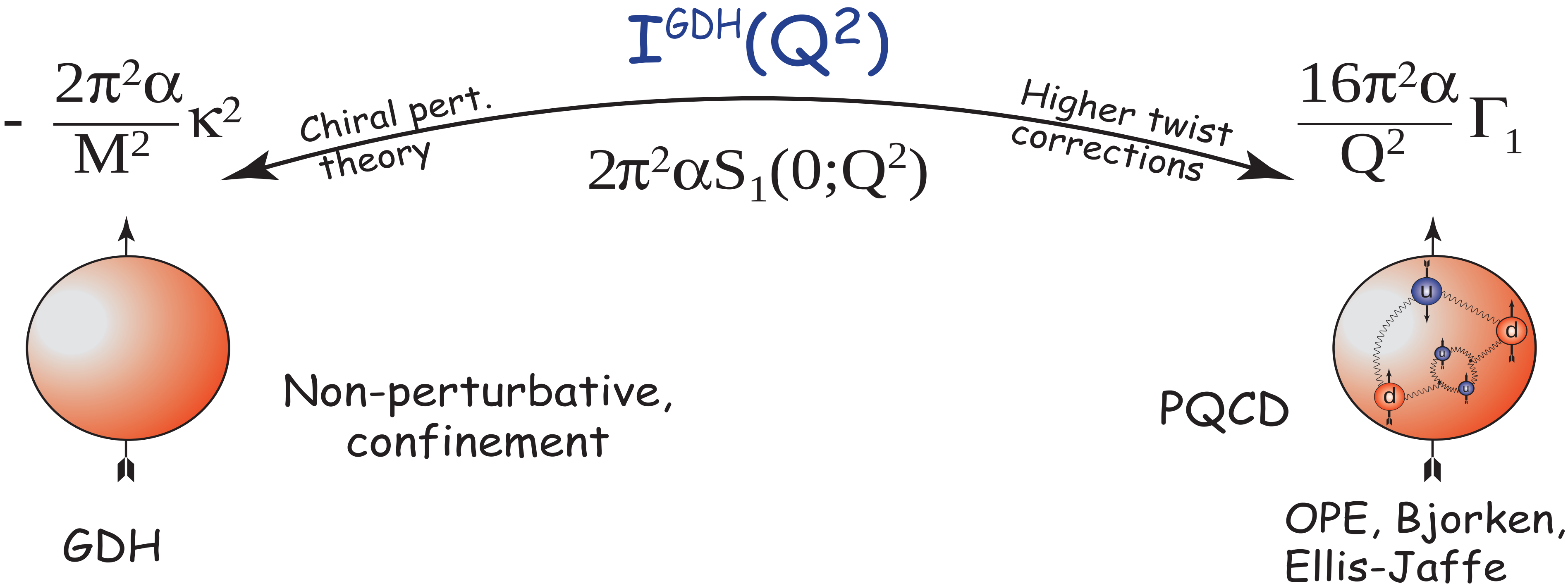
Generalized GDH Sum Rule

- Dispersion relations on Virtual Compton Scattering lead to Generalized GDH sum rule valid at all Q^2 (Ji and Osborne)

- Q^2-evolution of GDH Sum Rule provides a bridge linking strong QCD to pQCD
  - Bjorken and GDH sum rules are two limiting cases
  - Operator Product Expansion of higher twists: > 1 GeV^2
  - Chiral Perturbation Theory: < 0.1 GeV^2
  - Intermediate region: Lattice QCD calculations

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

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



Many of the underlying assumptions are the same as those being tested in high-energy spin-structure tests

Moments of g_1, g_2

At large Q^2, twist expansion (OPE):

$$\Gamma_1(Q^2) = a_0 + \frac{M^2}{9Q^2}(a_2 + 4d_2 - 4f_2) + O\left(\frac{M}{Q}\right)^4$$

a_0: leading twist, a_2: target mass term, d_2 and f_2 related to color E-M polarizibilities

Define d_2 to be

$$d_2(Q) = \int_0^1 x^2[2g_1(x, Q^2) + 3g_2(x, Q^2)]dx = 3\int_0^1 x^2[g_2(x, Q^2) - g_2^{WW}(x, Q^2)]dx$$

at large Q^2, d_2 is the twist 3 term as in OPE

Wanndzura-Wilczek term

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

Burkhardt-Cottingham(B-C) sum rule

$$\Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2)dx = 0$$

Generalized Forward Spin Polarizabilities

Nucleon Forward Spin Polarizabilities:

$$\gamma_0(Q^2) = \frac{1}{2\pi^2}\int_{\nu_0}^{\infty}\frac{K}{\nu}\frac{\sigma_{TT}(\nu, Q^2)}{\nu^3}d\nu = \frac{16\alpha M^2}{Q^6}\int_0^{x^0} x^2\left\{g_1(x, Q^2) - \frac{4M}{Q^2}x^2 g_2(x, Q^2)\right\}dx$$

$$\delta_{LT}(Q^2) = \frac{1}{2\pi^2}\int_{\nu_0}^{\infty}\frac{K}{\nu}\frac{\sigma_{LT}(\nu, Q^2)}{Q\nu^2}d\nu = \frac{16\alpha M^2}{Q^6}\int_0^{x^0} x^2\{g_1(x, Q^2) + g_2(x, Q^2)\}dx$$

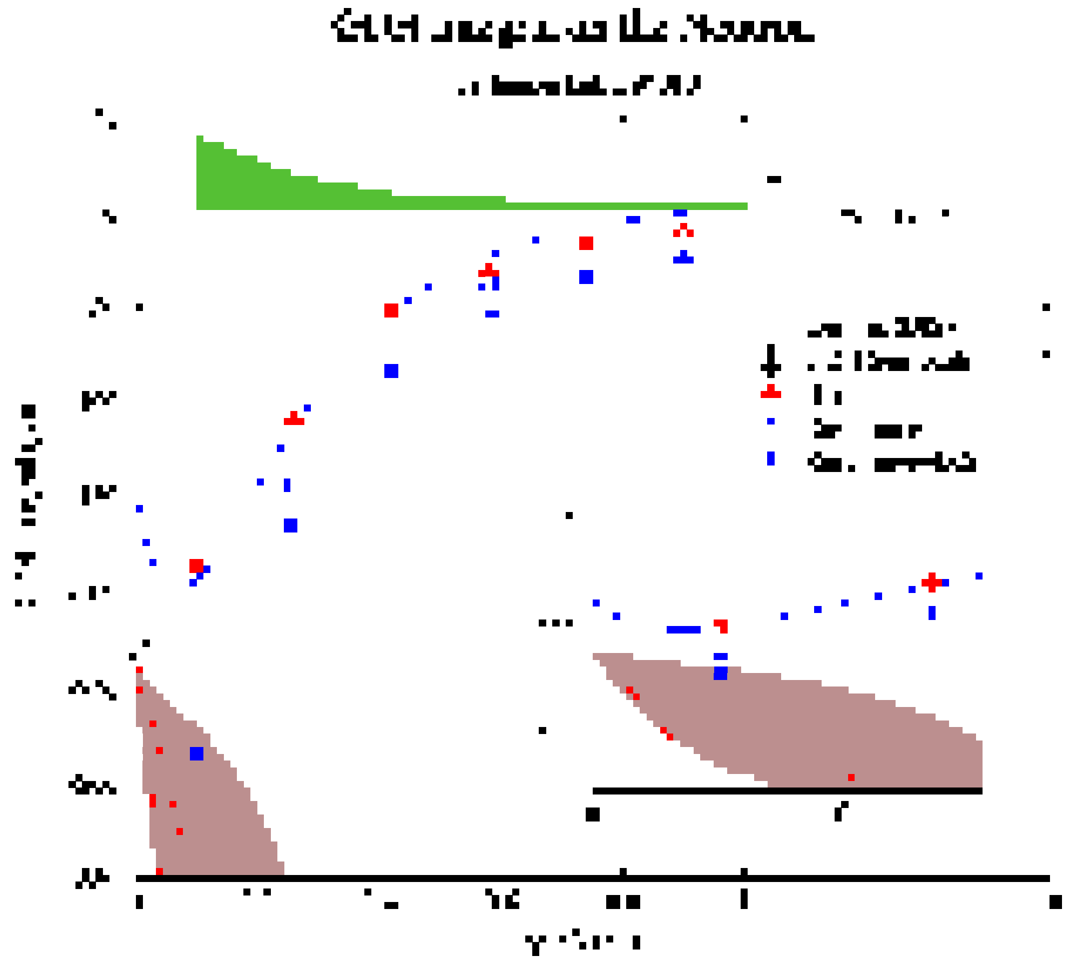
-- With x^2 weighting, the integration mostly from low energy part

-- δ_{LT} is not sensitive to the Delta and should be converging fast in ChPT

Measurement of Neutron (^{3}He) Spin Structure Function at Low Q^2, a Connection between Bjorken and GDH Sum Rules

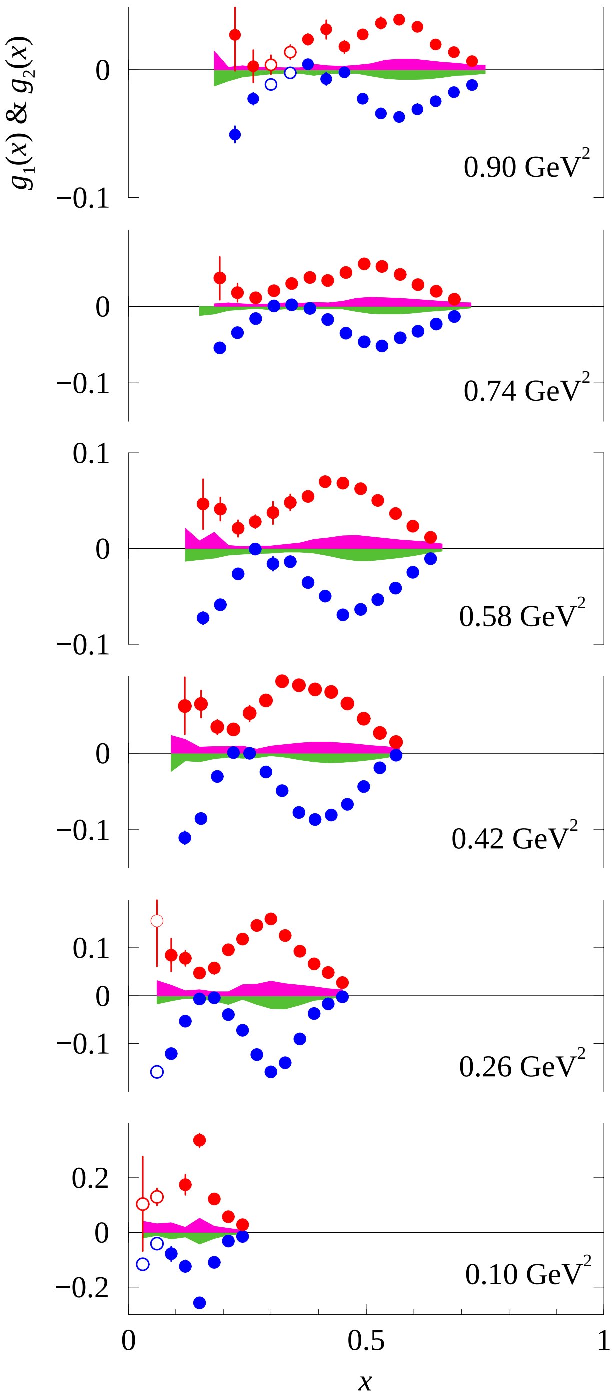
Spokespersons: G. Cates, J. P. Chen, Z.-E. Meziani
PhD Students: A. Deur, P. Djawotho, S. Jensen, I. Kominis K. Slifer

- Investigate Q^2 evolution of Spin Structure Functions
- Investigate Q^2 evolution of GDH and Bjorken sum rules
- Study GDH integral over transition from perturbative regime to non-perturbative regime
- First results (GDH) published in PRL89,242301 (2002)
- Second results (moments) accepted for publication in PRL



Hall A $g_1^{^3He}$ and $g_2^{^3He}$

- First JLab experiment using polarized ^{3}He target to study neutron spin structure functions
- Parallel and perpendicular asymmetries and cross section measurements → precision g_1 and g_2
- $g_2 \sim -g_1$ in the Δ resonance region (i.e. $\sigma_{LT} \sim 0$)



First Moment of g_1^n

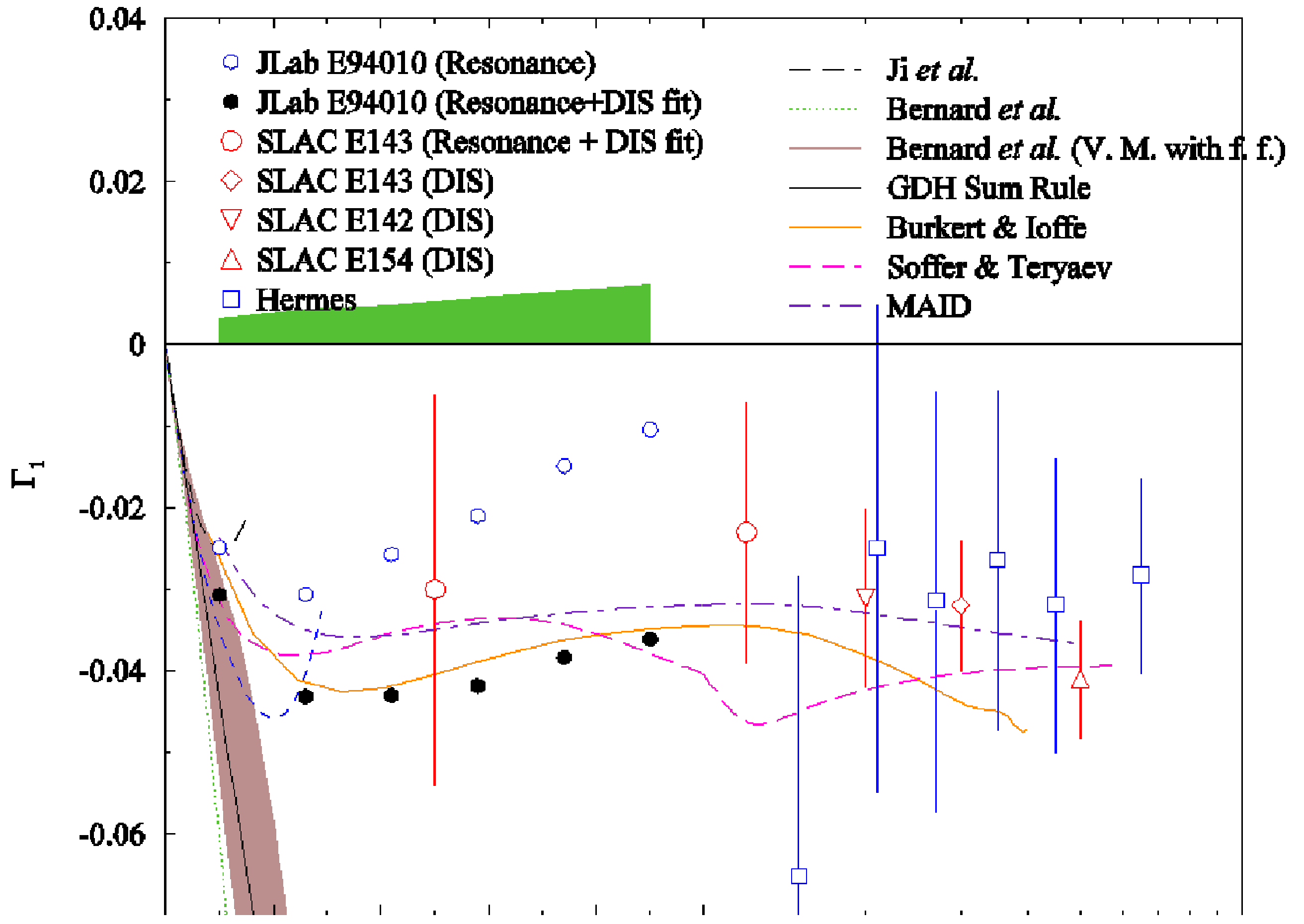
- High precision data
- Resonance contributions to the first moment significant
- Smooth transition
- Test fundamental understanding

ChPT at low Q^2

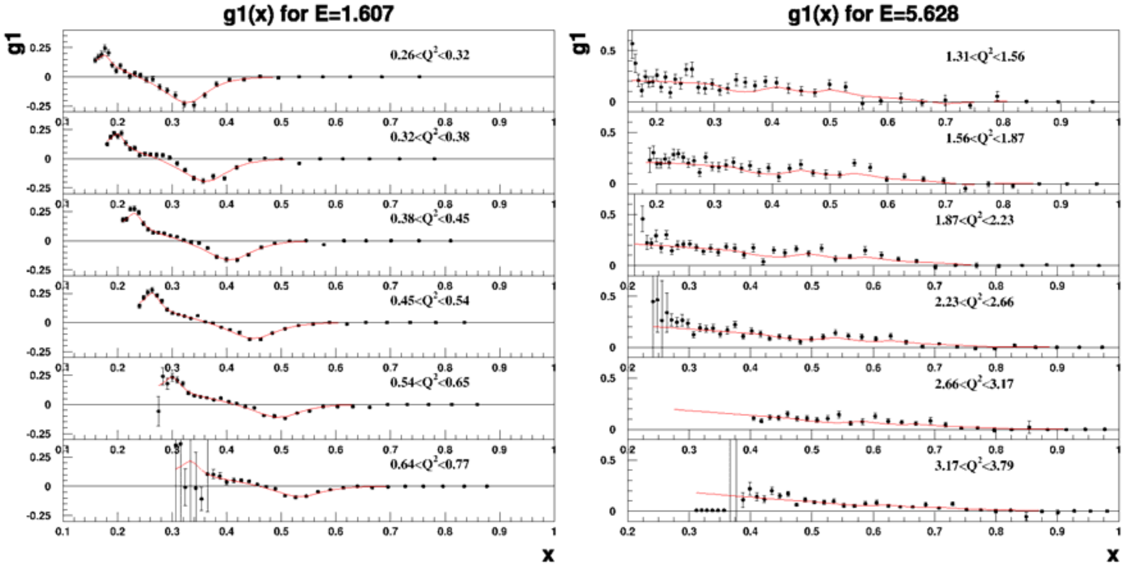
Twist expansion at high Q^2

Models

Future Lattice QCD



CLAS (eg1b) g_1^p vs. x



- Additional CLAS data have been taken at lower and higher energies for more complete kinematic coverage.
- For the 5.6 GeV data, g_1 is positive.
- The Δ drives the 1.6 GeV data negative.
- The newer data generally extend to lower x, and require less extrapolation when calculating moments.

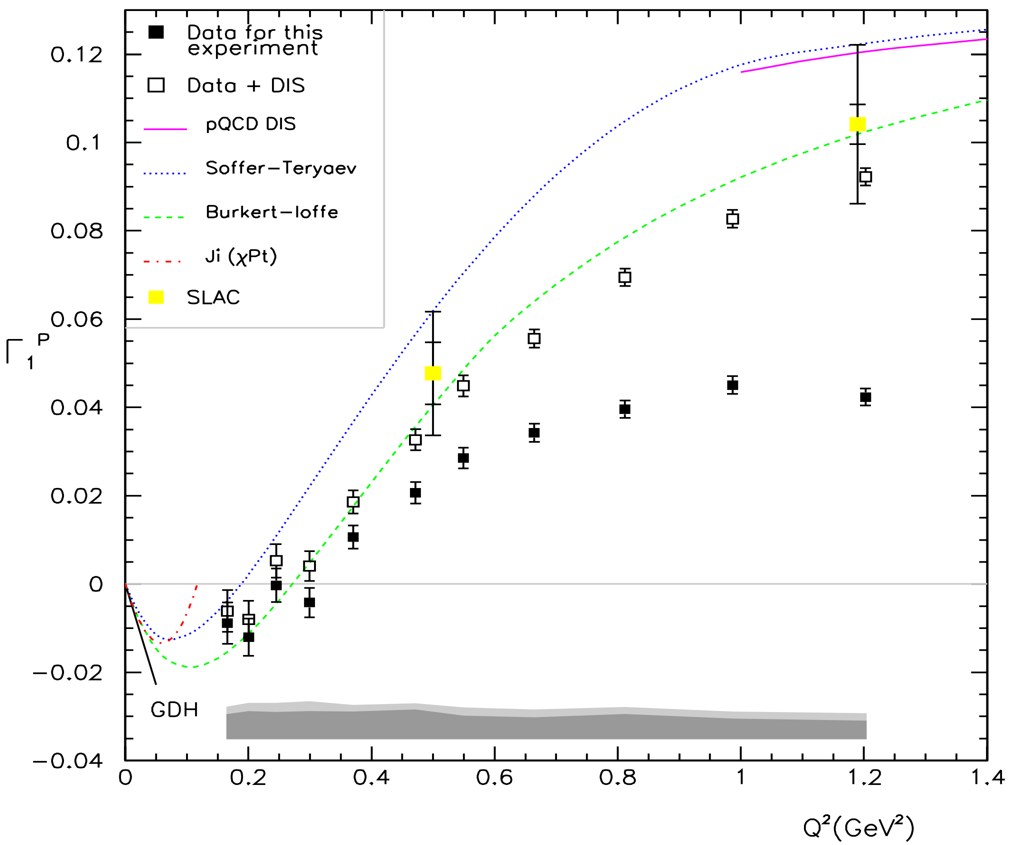
Moments of g_1^p-g_1^n

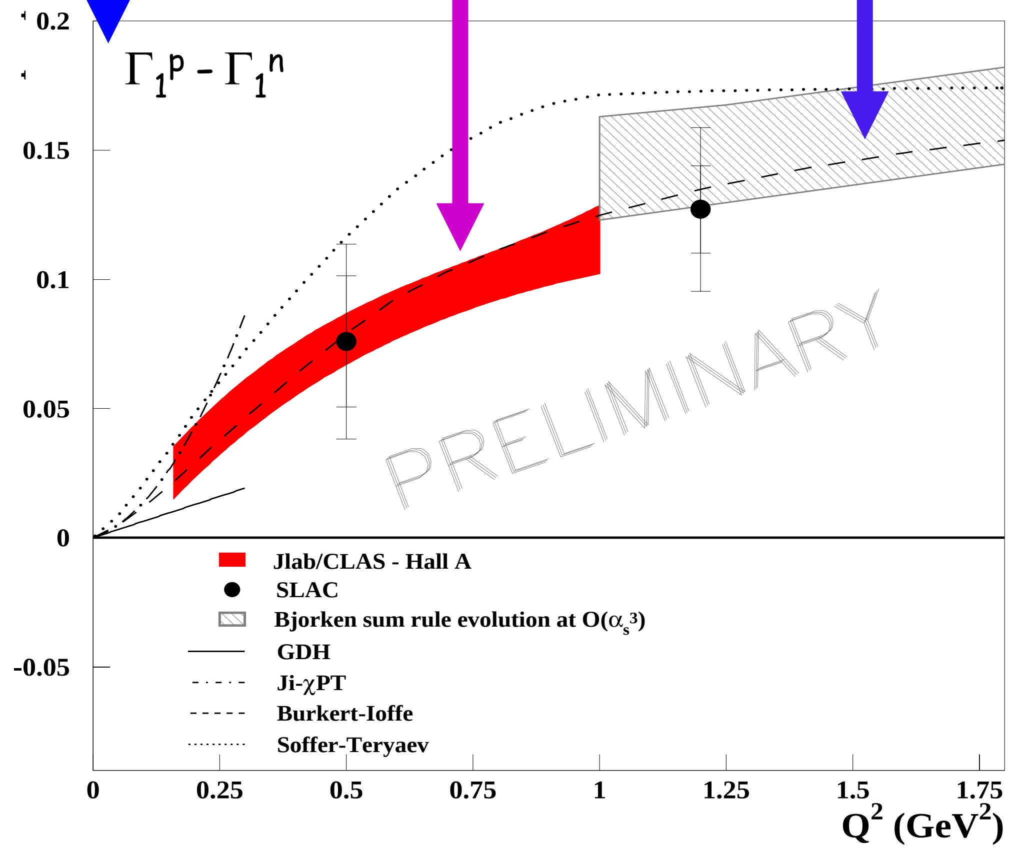
Hall B results of moment Γ_1^p
- Resonance significant contribution
- Zero crossing

Combine Hall A g_1^n with Hall B g_1^p data

Chiral Perturbation Theory (χPT)

Bjorken Sum Rule (Verification of QCD)

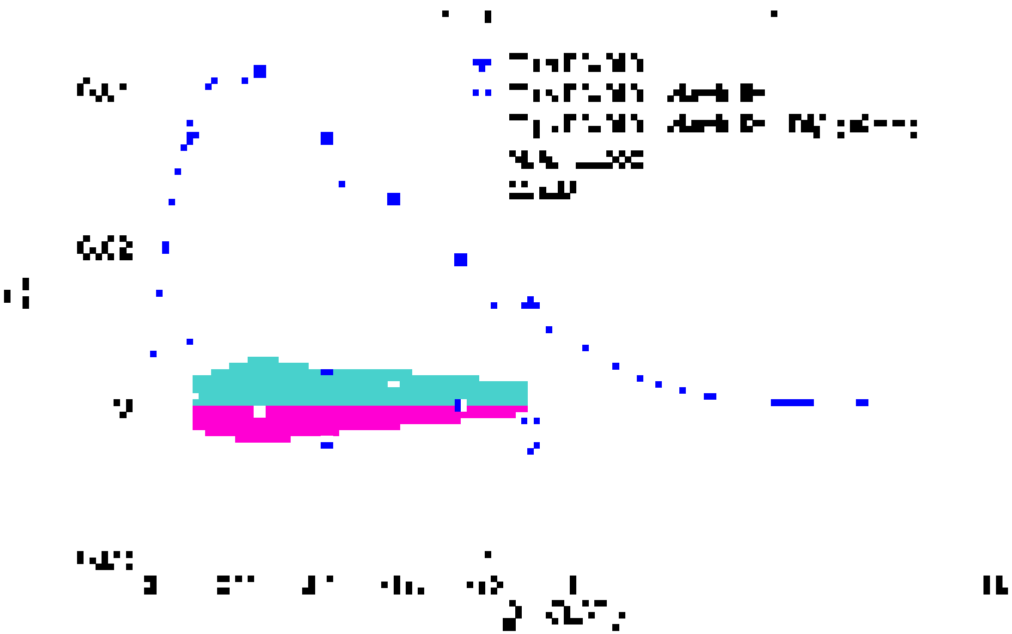




Moments of g_2^n

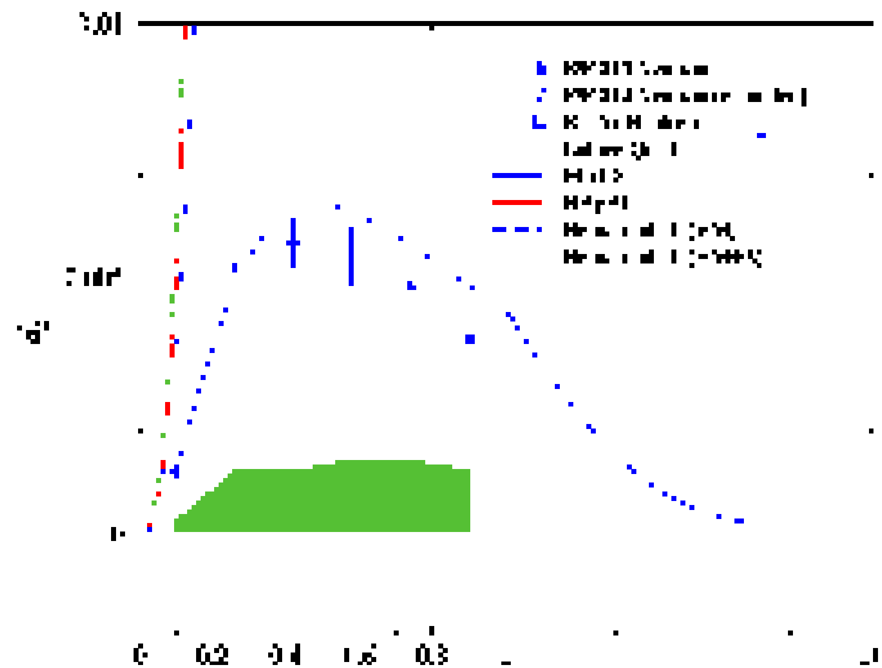
- First moment:

  Burkhardt-Cottingham sum rule
- Same assumptions as GDH, with super-convergence
- Elastic and high energy contributions
- B-C sum rule satisfied within uncertainties



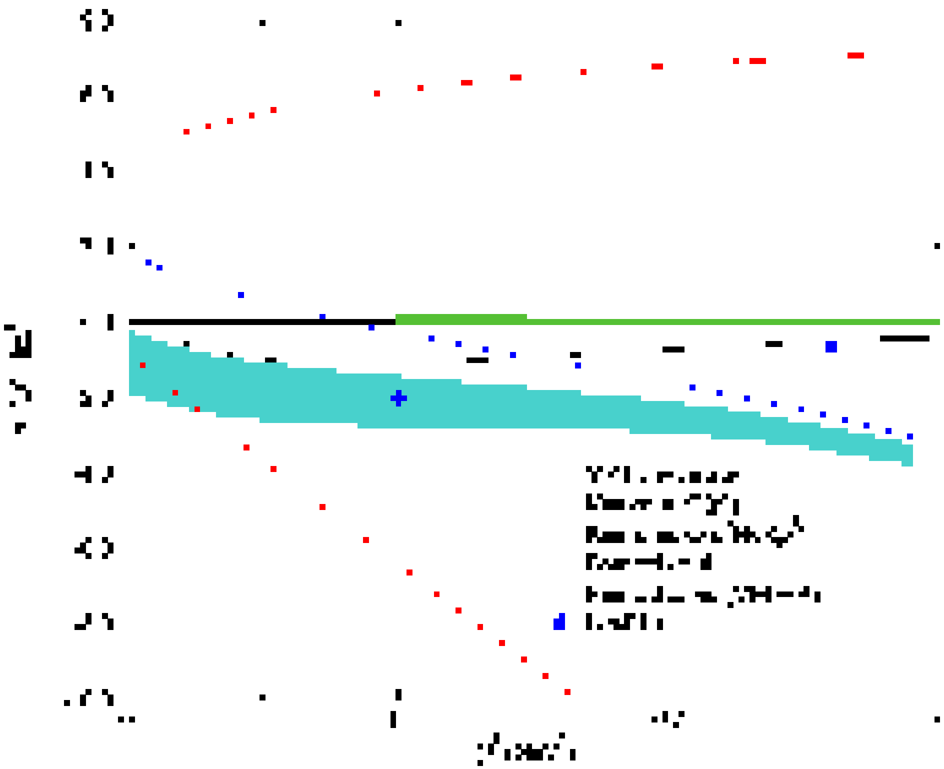
- Second moment d_2

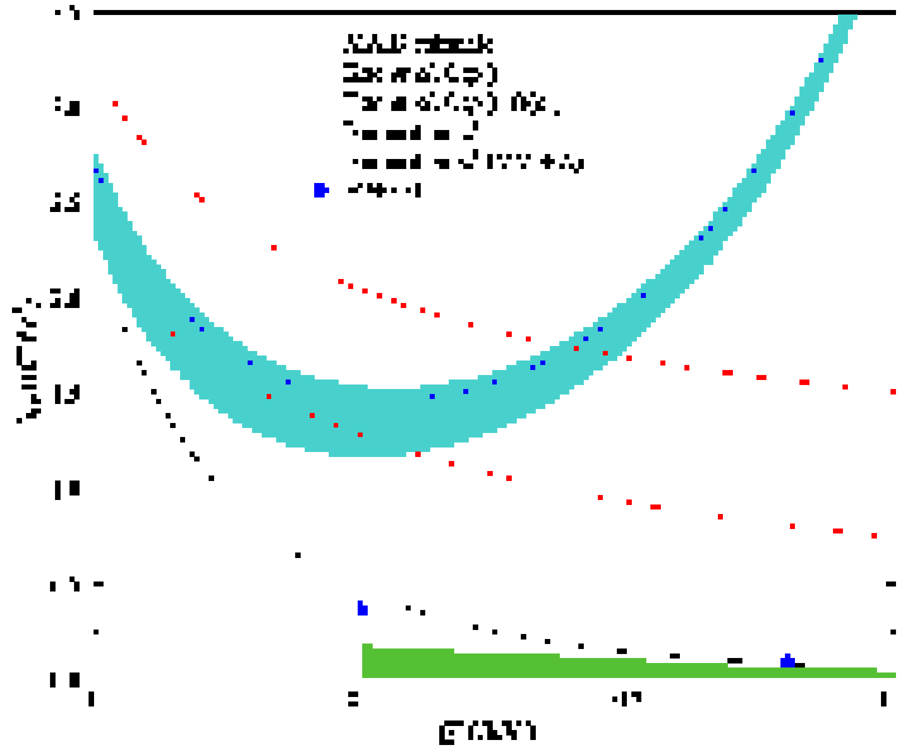
  Twist-3 matrix element
- Color polarizabilities
- ChPT (low Q^2), MAID model and Lattice QCD (high Q^2)
- Need intermediate Q^2 data



Forward Spin Polarizabilities

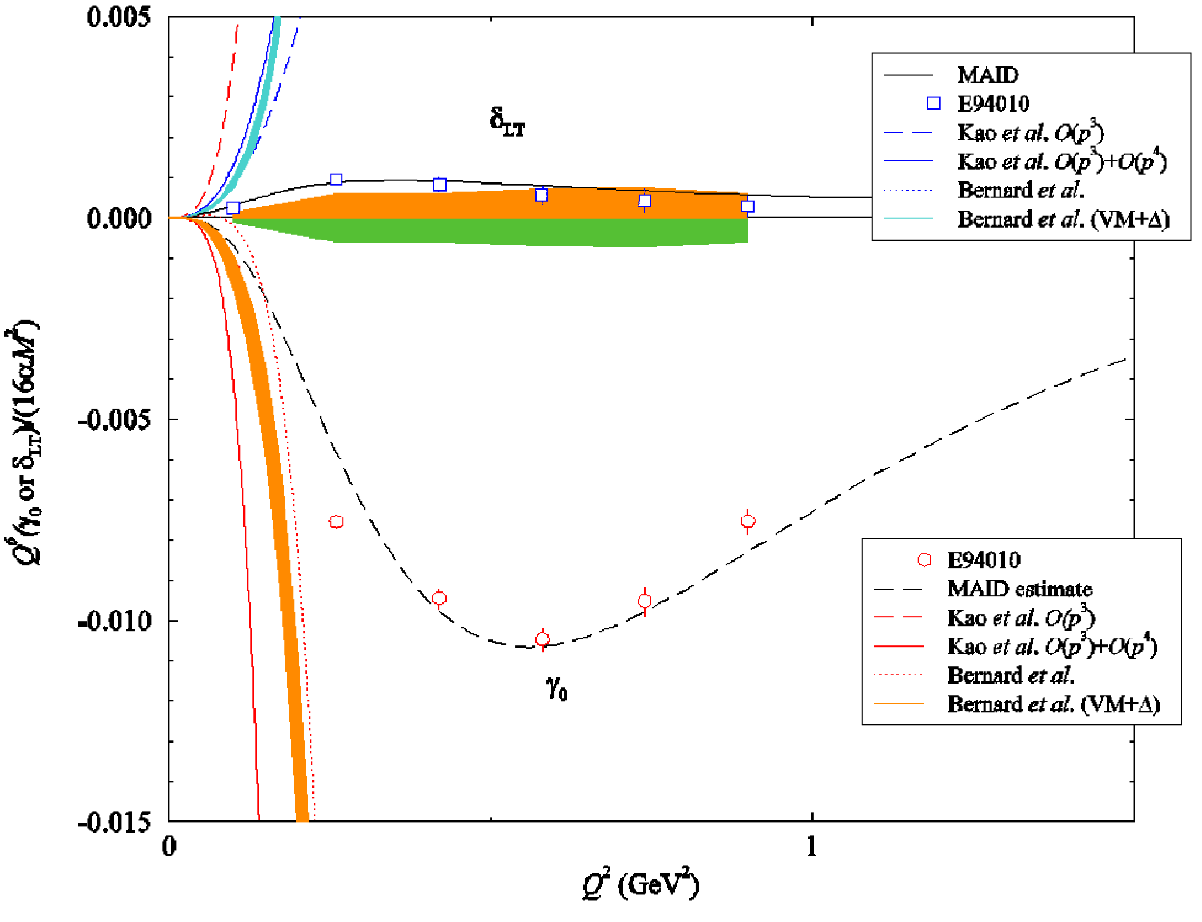
- ChPT expected to work at low Q^2 (up to 0.1-0.2 GeV^2?)
  - γ_0 sensitive to resonance
  - δ_{LT} insensitive to Δ resonance
- Comparison with two group's ChPT calculations
- Good agreement with MAID model predictions





Forward Spin Polarizabilities

- Expected to scale at high Q^2
- Reasonable agreement with MAID model pedictions



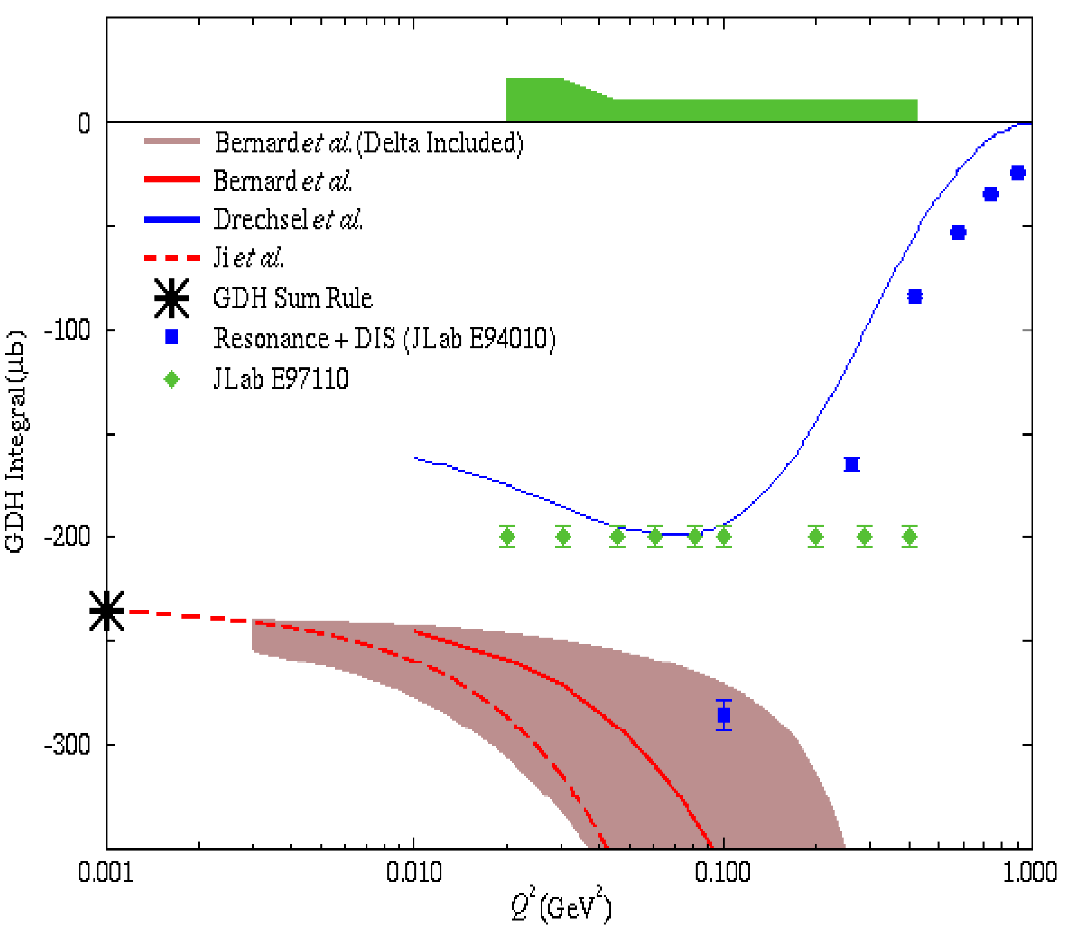
JLab E97-110

GDH Sum Rule and Spin Structure of ^{3}He and Neutron with Nearly Real Photons

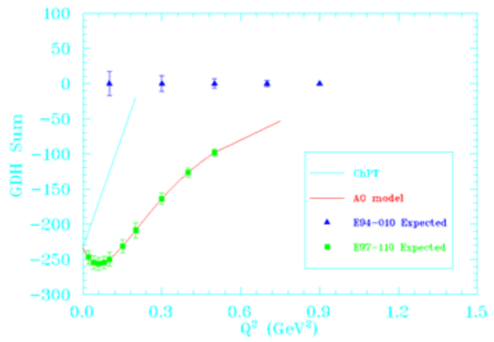
Spokespersons: J. P. Chen, A. Deur, F. Garibaldi; PhD Students: J. Singh, V. Sulkosky, J. Yuan

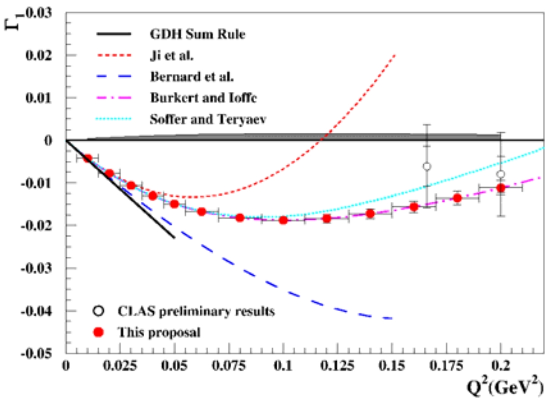
- Measured generalized GDH at Q^2 near zero for ^{3}He and neutron
  - Slope of GDH sum rule at Q^2 ~ 0
  - Check ChPT
  - Extrapolation to real photon point
  - Constraints on resonance models
- Overlap with previous Hall A GDH experiment E94-010 (PRL89, 242301 (2002))
- Data acquisition completed
- Analysis underway

E97110 Expected Results



Future GDH Measurements





- Hall A will extend its polarized neutron structure function measurements to low Q^2 by using a septum magnet to get down to 6° scattering angles (left graph).
- Hall B will extend its polarized proton structure function measurements to low Q^2 by using a new small-angle Cherenkov counter (right graph).
- Together, these experiments will map out the approach to the Gerasimov-Drell-Hearn (GDH) limit.
- GDH extrapolation shows $\Gamma_1 \to -\kappa^2 Q^2/8M^2$ as $Q^2 \to 0$.

Higher Twists:
Quark-gluon Correlations

Quark-hadron Duality

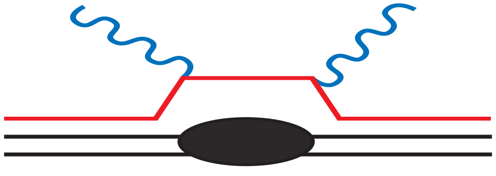
Transversity

Quark-Gluon Correlations

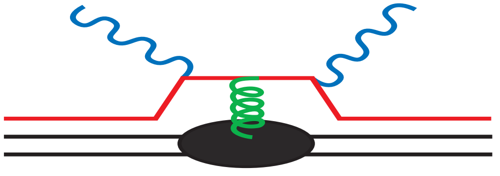
$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

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

- In simple partonic picture $g_2(x)=0$
- Wandzura and Wilczek have shown that g_2 can be written in two parts:
  - twist-2 contributions given by g_1
  - the other originating from quark-gluon correlations (twist-3)



Twist–2



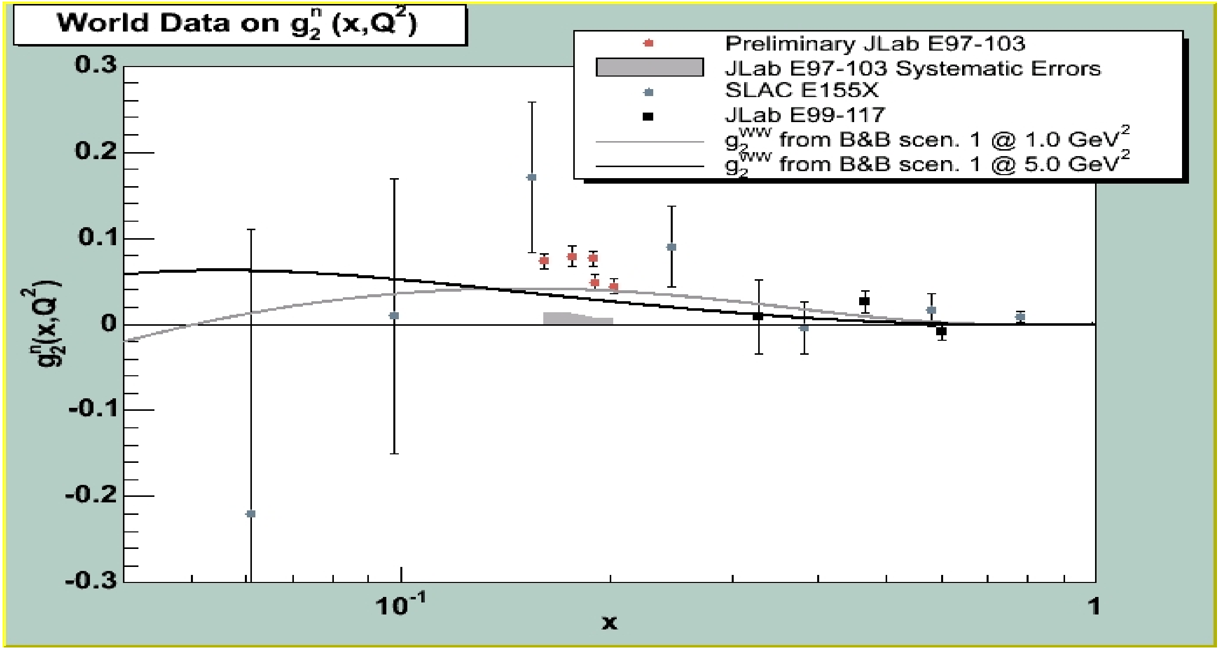
Twist–3

$$d_2^n(Q^2) = \int_0^1 x^2\left[2g_1^n(x,Q^2) + 3g_2^n(x,Q^2)\right]dx \qquad d_2 = (2\chi_B + \chi_E)/3$$

Jefferson Lab Hall A Experiment E97-103

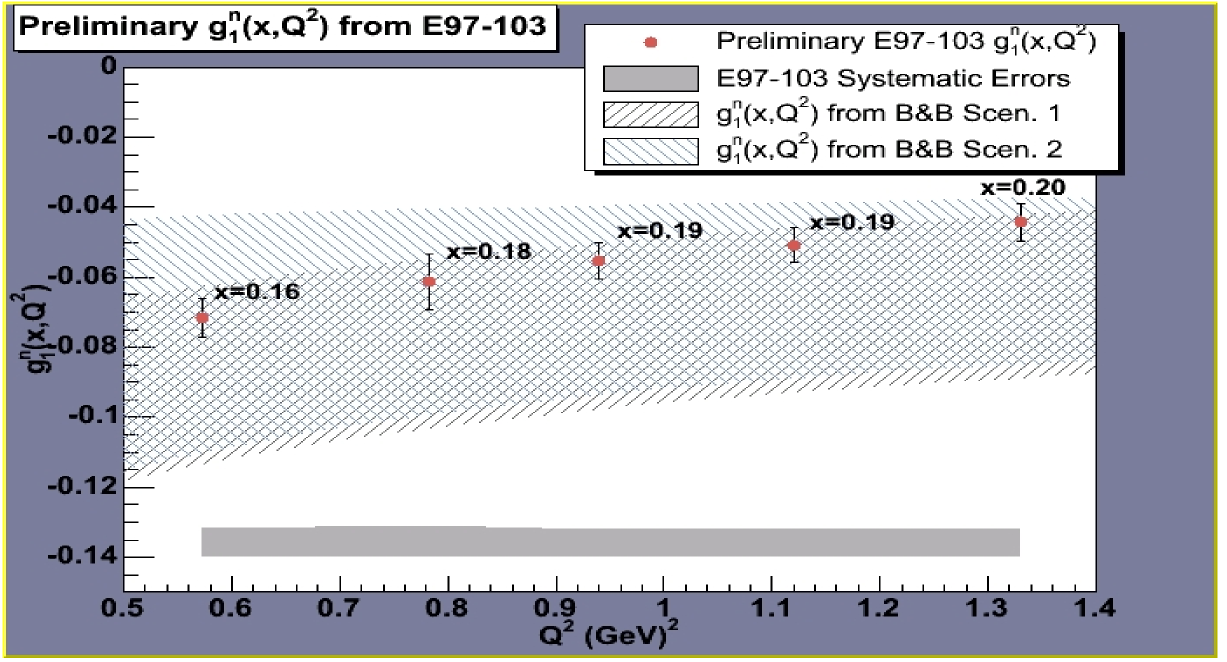
Precision Measurement of the Neutron Spin Structure Function $g_2^n(x,Q^2)$: A Search for Higher Twist Effects

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

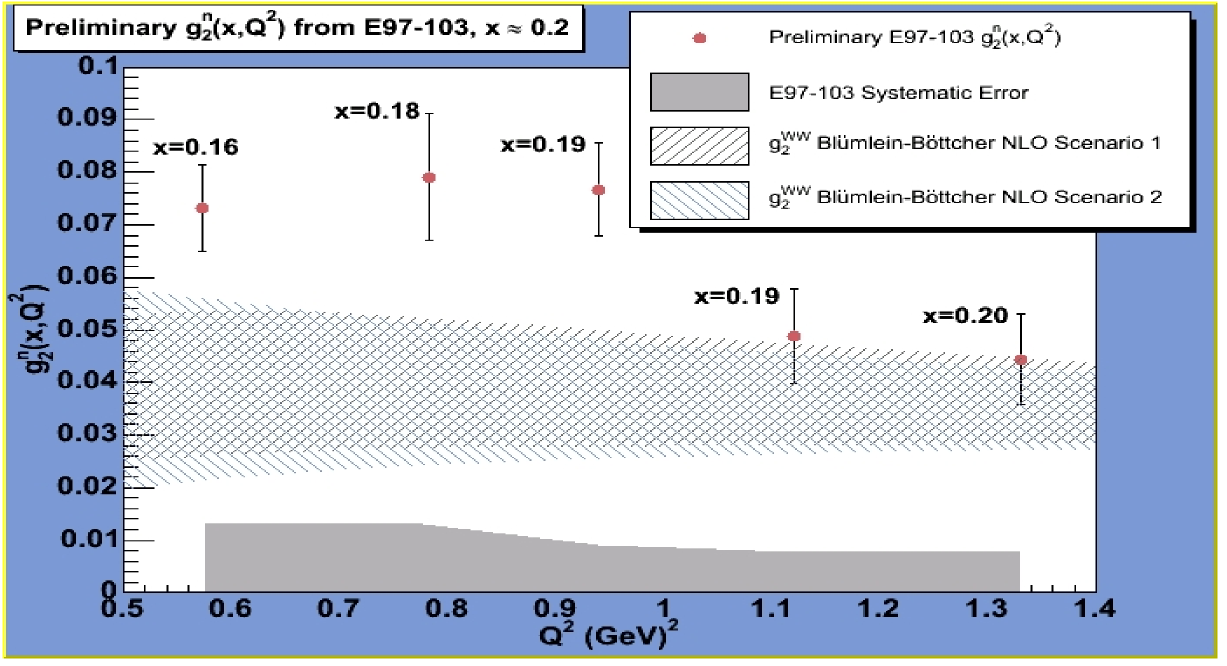


- Inclusive DIS of polarized electrons from a polarized ^{3}He target.
- Precision g_2^n data covering $0.57 < Q^2 < 1.34$ GeV^2 at $x \sim 0.2$.
- Direct comparison to *twist-2* g_2^{ww} prediction using world g_1^n data.
- Quantitative measurement of higher twist effects provides information on nucleon structure beyond simple parton model (e.g. quark-gluon correlations.

Jefferson Lab E97-103 Preliminary Results



- Measured g_1^n agree with NLO fit to world data, evolved to our Q^2.



- Measured g_2^n consistently higher than g_2^{ww} at low Q^2.

- E97-103 improved precision of g_2^n by an order of magnitude.

JLab E01-012

Measurement of neutron (^3He) spin structure functions in the resonance region

Spokespersons: J. P. Chen, S. Choi, N. Liyanage;   PhD student: P. Solvignon

- Measured g_1^n and A_1^n in the resonance region for $1.0 < Q^2 < 4.0$ GeV^2

- Combined with DIS measurements:

  provide a first test of spin-flavor dependence of quark-hadron duality

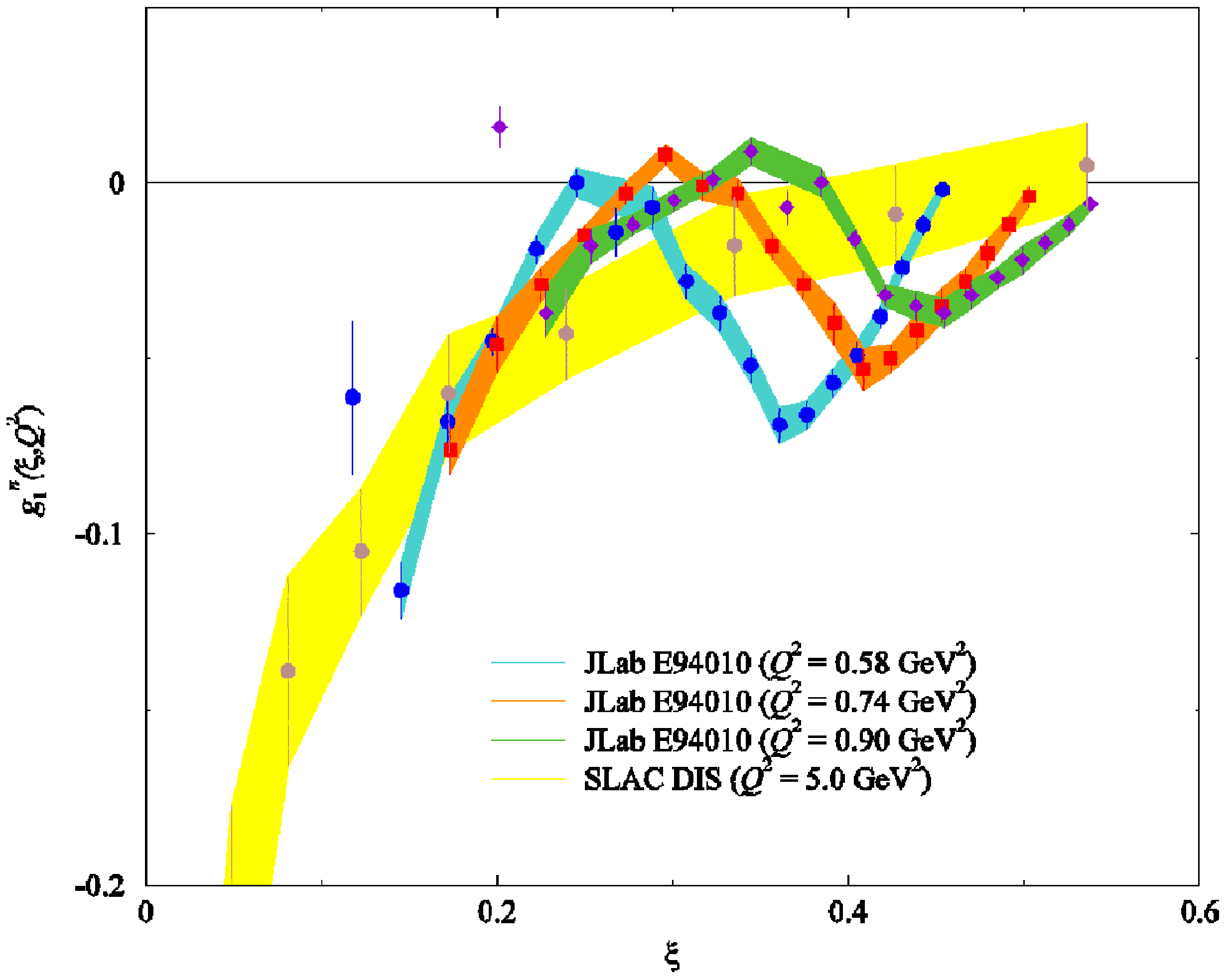
- Quark-hadron duality: scaling curve seen at high Q^2 is an accurate average over the resonance bumps at lower Q^2 (observed for F_2^p)

- g_1^n at $Q^2 \sim 1$ GeV^2 from E94-010 shows hints of duality

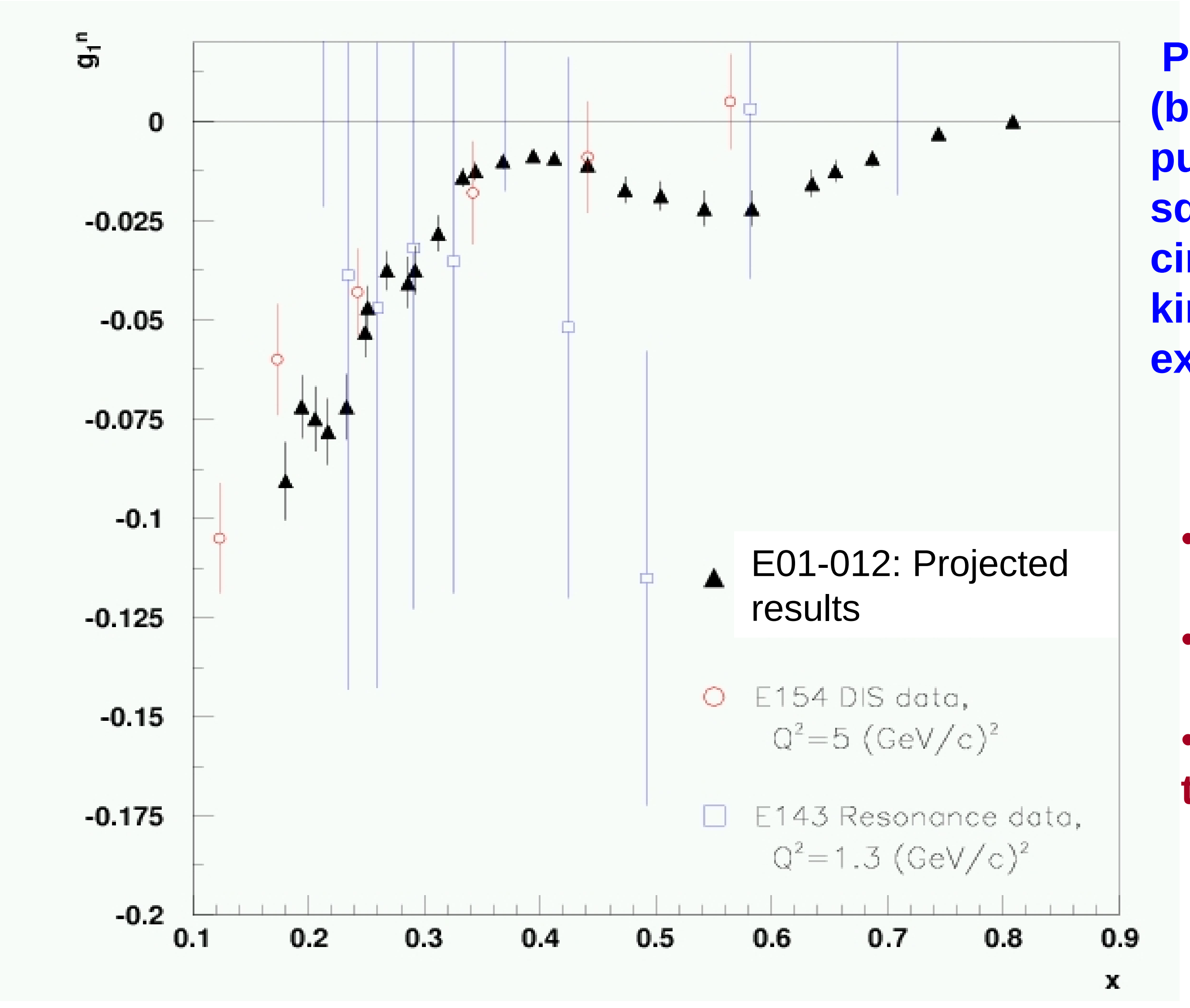
- If duality established
  - Powerful tool to study very high ***x*** behavior

Hint from E94-010 data: approaching duality

- E94-010 resonance g_1 data, Q^2 from 0.58 to 0.9 GeV^2
- Comparing with SLAC DIS g_1 data, Q^2 = 5 GeV^2
- First hint of approaching quark-hadron duality



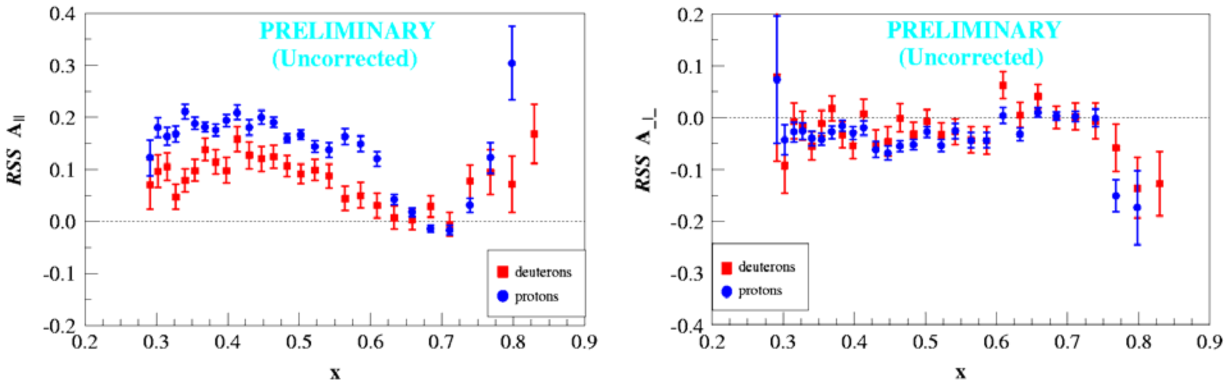
E01-012: Projected results



Projected results shown here (black triangles), compared to published resonance data (blue squares) and DIS data (red circles), are from one of the four kinematic settings of the experiment.

- **Data taken early 2003**
- **Data analysis in progress**
- **Preliminary results expected this Spring.**

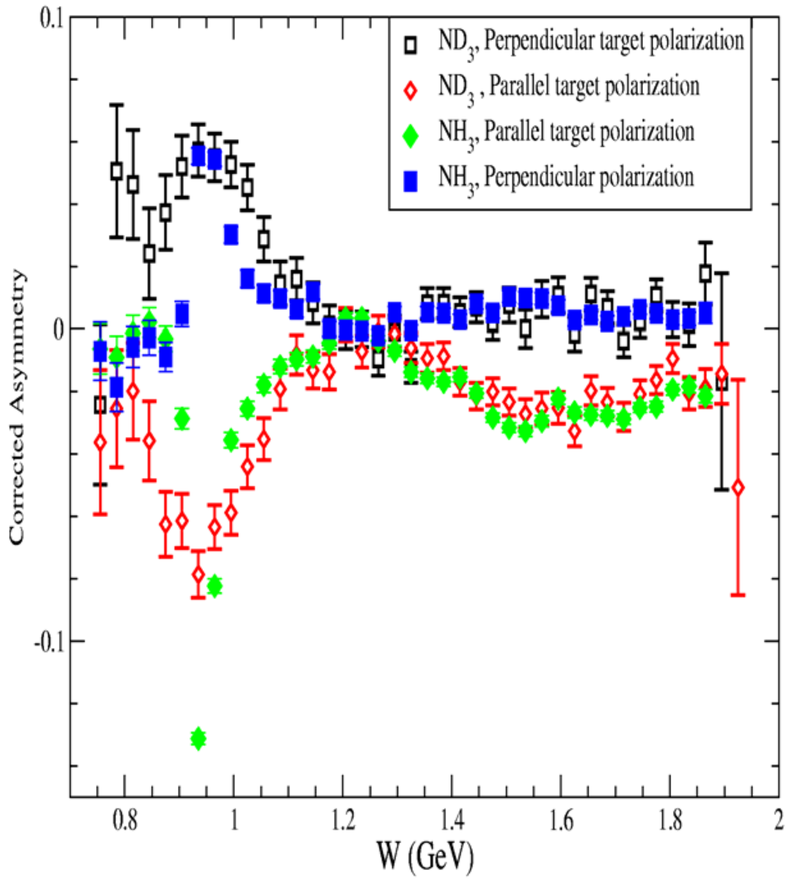
Hall C E01-006
Resonance Spin Structure



- Beam energy 5.755 GeV.
- HMS spectrometer at 13.08°.
- $< Q^2 >= 1.3$ GeV^2.
- First JLab measurement using ammonia targets to measure $\perp$ configuration.

Comparison of NH_3 and ND_3 Asymmetries

Replay by Frank Wesselmann



JLab E03-004

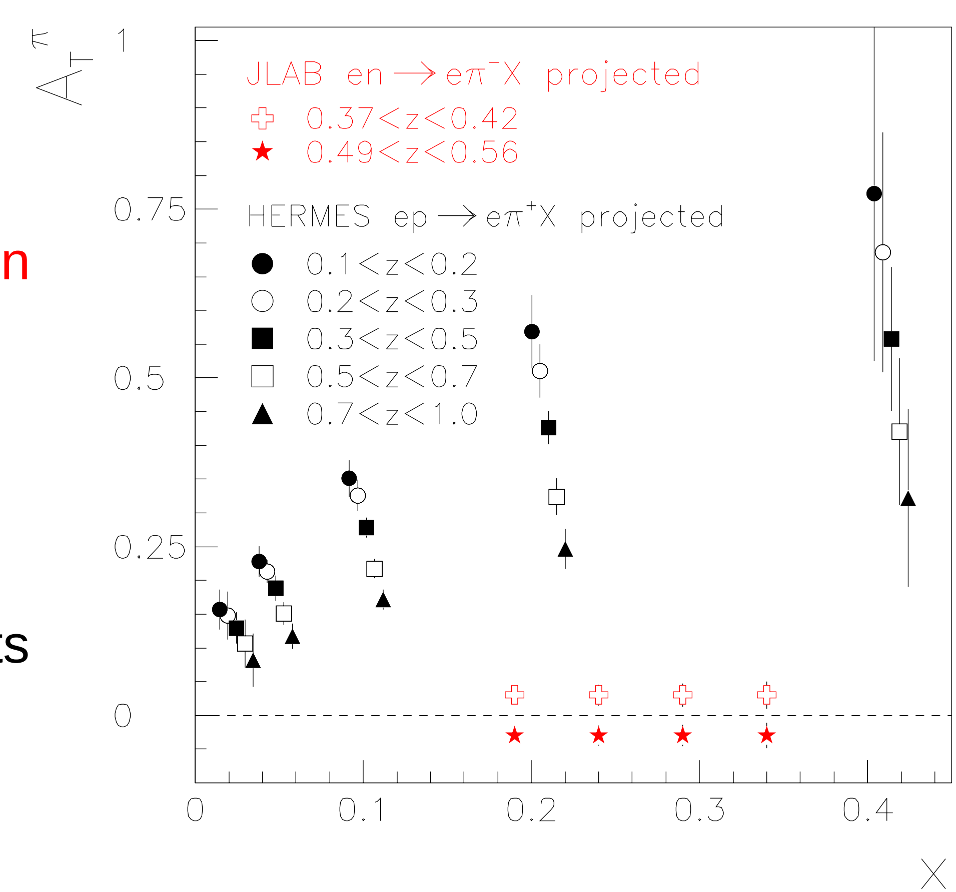
Neutron Transversity through ^{3}He(e,e'π)

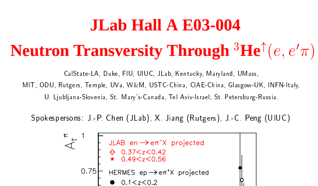
Spokespersons:J.-P. Chen, X. Jiang, J.-C. Peng

Transverse target single spin asymmetry
n(e,e'π)X

First transversity measurement on neutron

- high polarized luminosity
- x: 0.19-0.34, Q^2: 1.8-2.7 GeV^2,
  W: 2.5-2.9 GeV
- separation of Collins and Sivers effects
- complementary to the proton data of HERNES run-II





Summary

- JLab precision spin structure data
  - A_1 at high x: valence quark spin distributions
    - A_1^n went to positive above x=0.5 → SU(6) breaking,
    - □ $\Delta d/d$ stays negative → quark orbital angular momentum
  - GDH* sum rule, moments, polarizabilities
    - Bridge linking strong QCD to pQCD
    - ChPT, OPE twist expansion, and Lattice QCD
  - Higher twister: q-g correlations
  - Quark-hadron duality
  - Transversity
- Outlook: even more exciting
  - Near term: several experiments planned
  - Long term: 12 GeV upgrade (Friday 1/16 talk by J. P. Chen)