Transverse Spin and Transverse Structure

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Beijing Hadron Workshop , July 27-30, 2010

- Deep-Inelastic Scattering: Parton Distributions
- Longitudinal Spin Structure: g_1 and moments
- Transverse Spin: g_2 and moments
- Transverse Spin and Transverse Structure:

  Transversity and TMDs
- Parity Violating Electron Scattering

Nucleon Structure

- Nucleon: proton =(uud) , neutron=(udd)
  + sea + gluons

- Global properties and structure
  - Mass: 99% of the visible mass in universe
    ~1 GeV, but u/d quark mass only a few MeV each!
  - Momentum: quarks carry ~ 50%
  - Spin: ½, but total quarks contribution only ~30%! — Spin Sum Rule?
  - Magnetic moment: large part is anomalous, >150%! — GDH Sum Rule
  - Axial charge — Bjorken Sum Rule
  - Tensor charge — Transverse Spin Sum Rule?
  - Polarizabilities (E, M, Spin, Color,)

Electron Scattering and Nucleon Structure

- Clean probe to study nucleon structure
  only electro-weak interaction, well understood

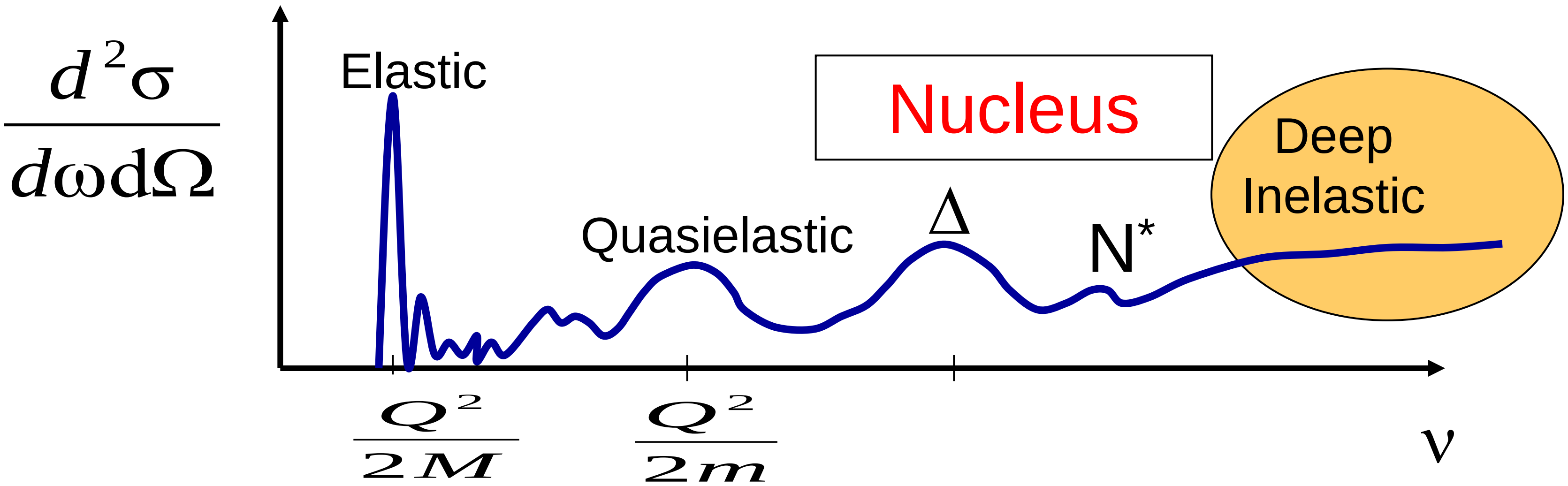
- Elastic Electron Scattering: Form Factors
  → 60s: established nucleon has structure (Nobel Prize)
  electrical and magnetic distributions

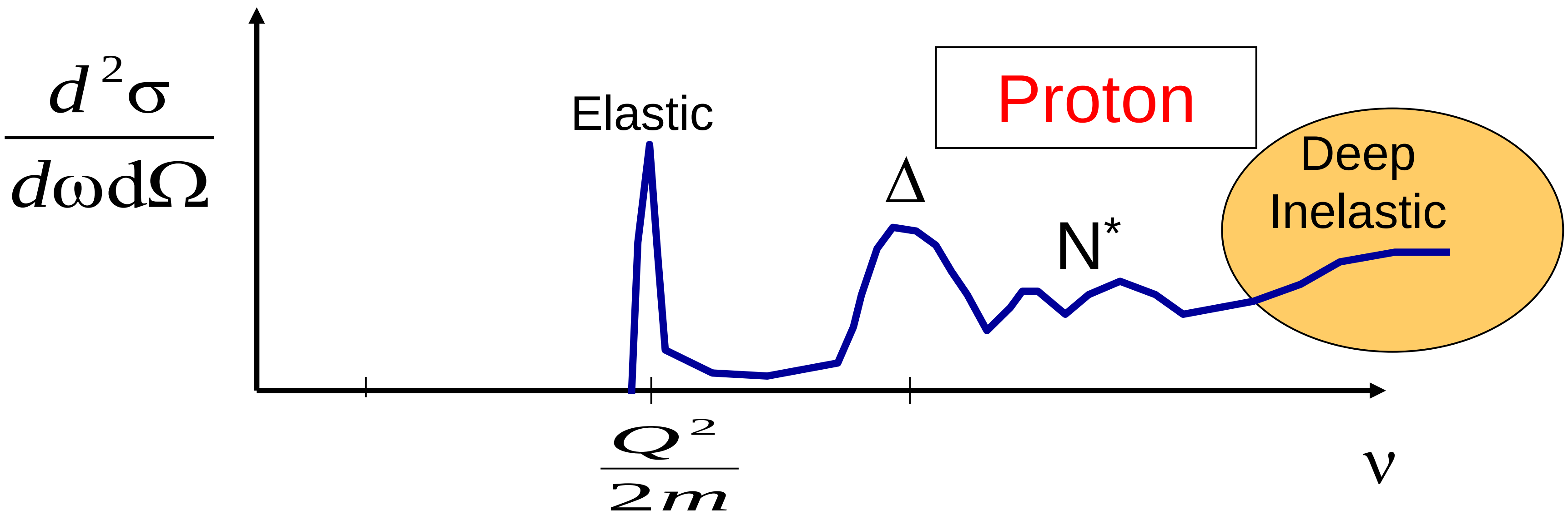
- Resonance Excitations

→ internal structure, rich spectroscopy
  constituent quark models

- Deep Inelastic Scattering
  → 70s: established quark-parton picture (Nobel Prize)
  parton distribution functions

Typical Electron Scattering Spectra at Fixed Q^2

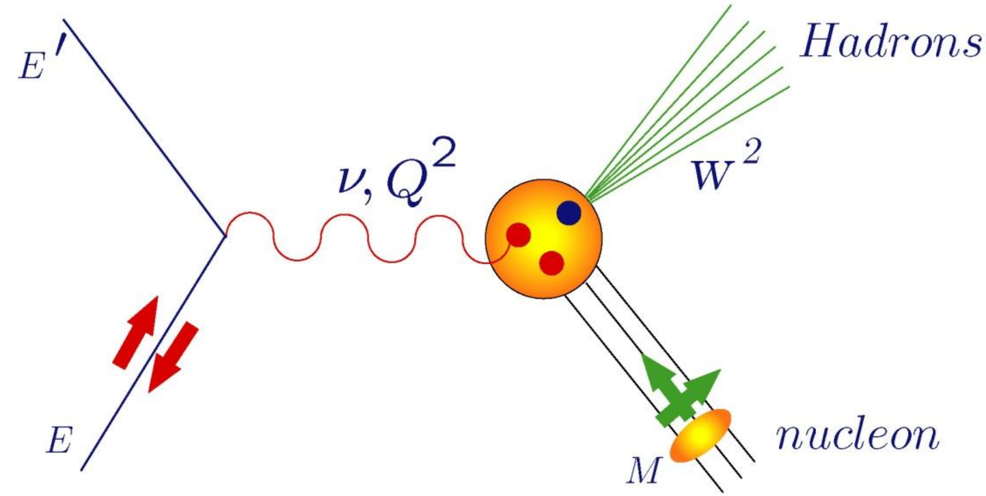




Deep-inelastics Scattering

Parton Distribution Functions

Polarized Deep Inelastic Electron Scattering



$x = \dfrac{Q^2}{2M\nu}$ Fraction of nucleon momentum carried by the struck quark

Q^2 = 4-momentum transfer of the virtual photon, ν = energy transfer, θ = scattering angle

- All information about the nucleon vertex is contained in

F_2 and F_1 the unpolarized (spin averaged) structure functions,

and

g_1 and g_2 the spin dependent structure functions

Quark-Parton Model

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

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

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

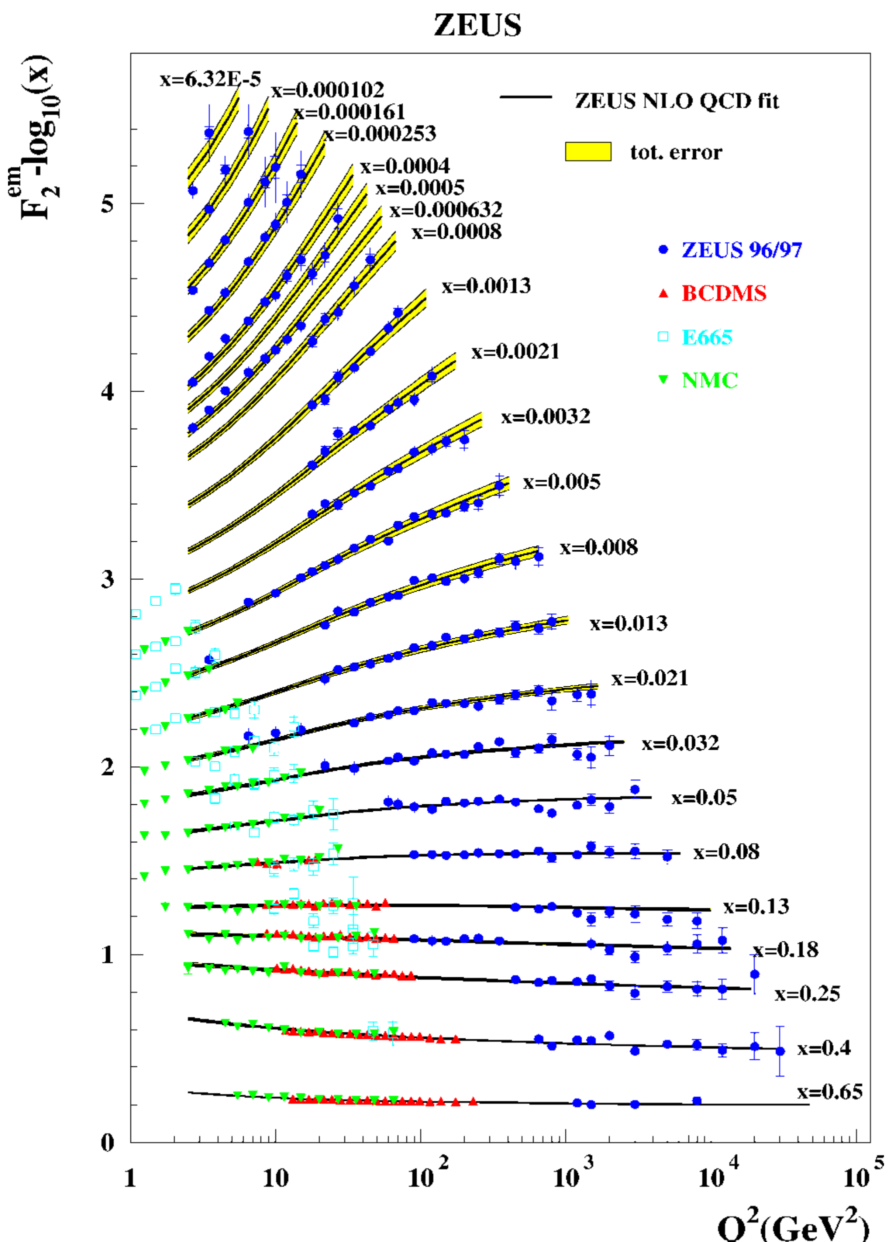
$q_i(x)$ quark momentum distributions of flavor i

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

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

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

Unpolarized and Polarized Structure functions



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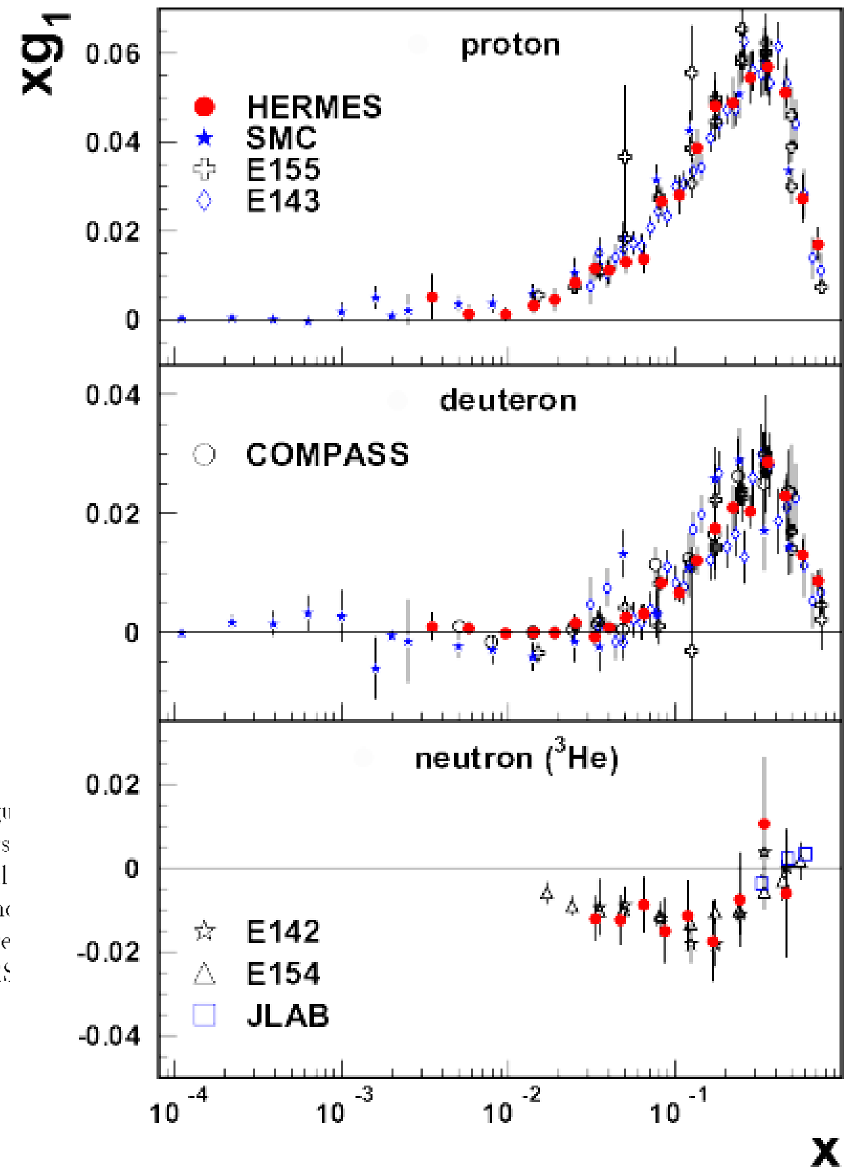

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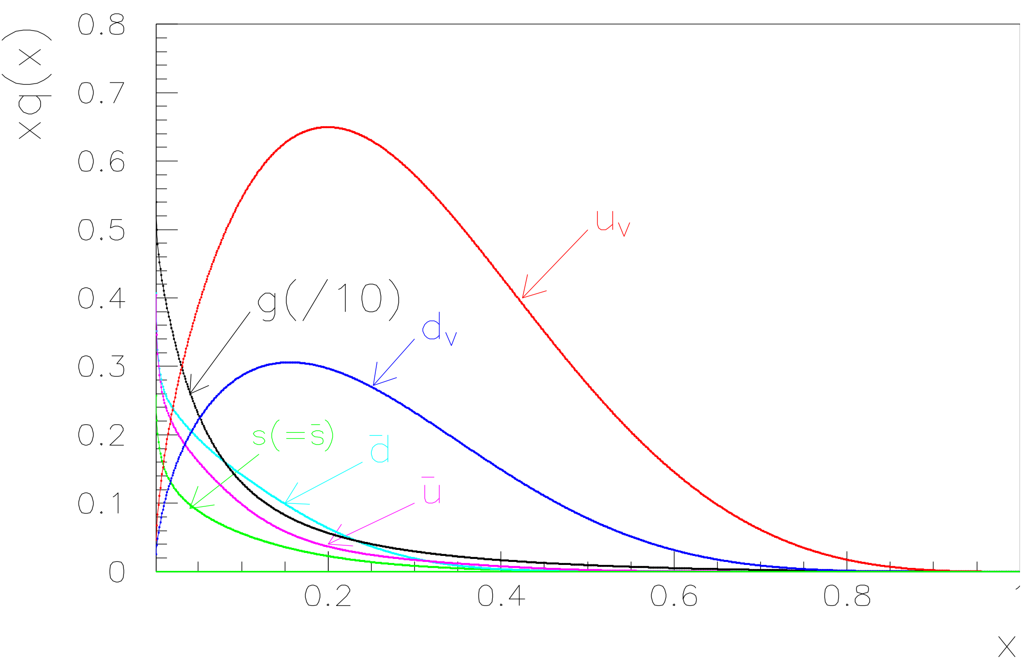
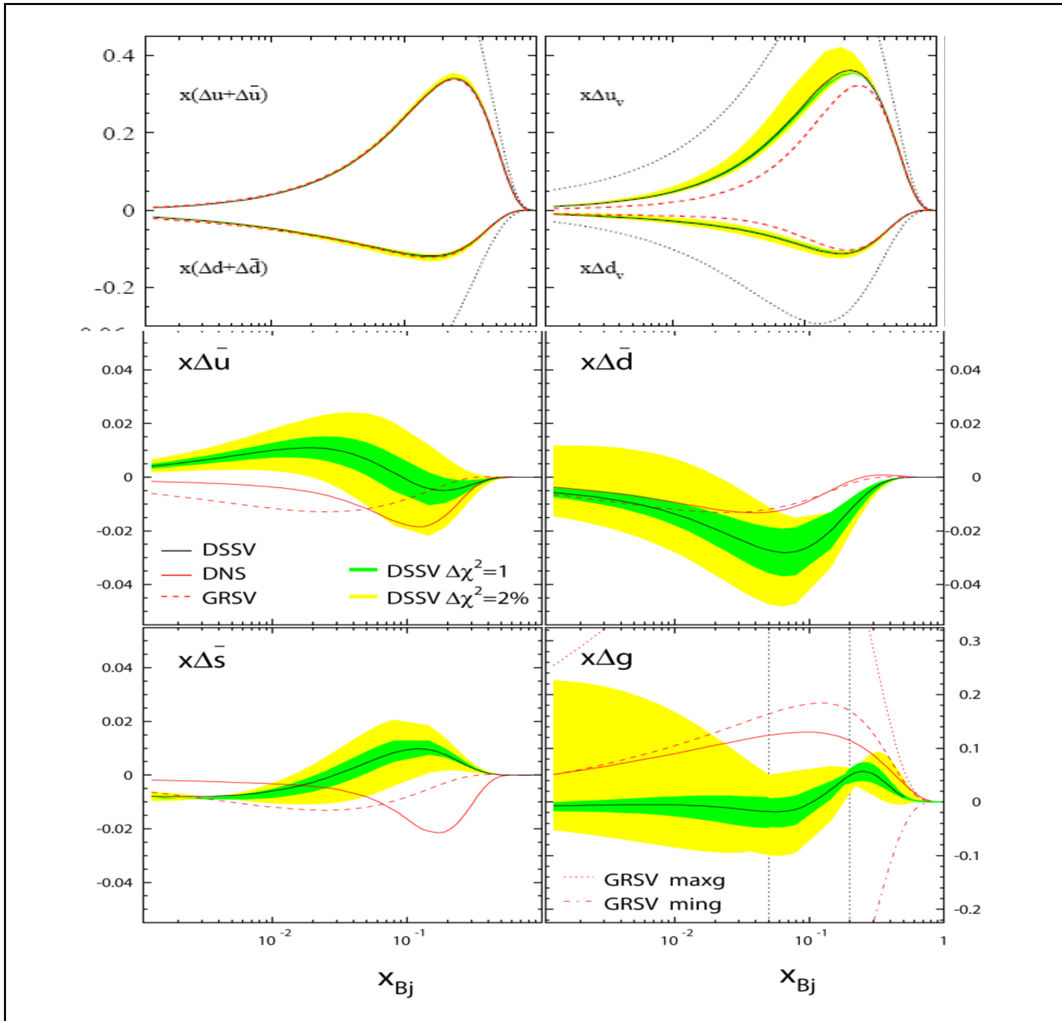
Parton Distributions (CTEQ6 and DSSV)

Unpolarized PDFs



CTEQ6, JHEP 0207, 012 (2002)

Polarized PDFs



DSSV, PRL101, 072001 (2008)

Nucleon Spin Structure

Spin Milestones

- Spin Milestones: (Nature)
  - 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)
  - 1971: Supersymmetry(13)
  - 1973: Magnetic resonance imaging(15)
  - 1980s: “Proton spin crisis”
  - 1990: Functional MRI (19)
  - 1997: Semiconductor spintronics (23)
  - 2000s: “New breakthrough in spin physics”?

Pauli and Bohr watch a spinning top

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

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'

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

  $\Delta\Sigma = 20\text{–}30\%$

  the rest: gluon and quark orbital angular momentum

  $A^+=0$ (light-cone) gauge $(½)\Delta\Sigma + L_q + \Delta G + L_g = 1/2$ (Jaffe)

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

  A new decomposition (X. Chen, F. Wang, *et. al*)

  Bjorken Sum Rule verified to $<10\%$ level

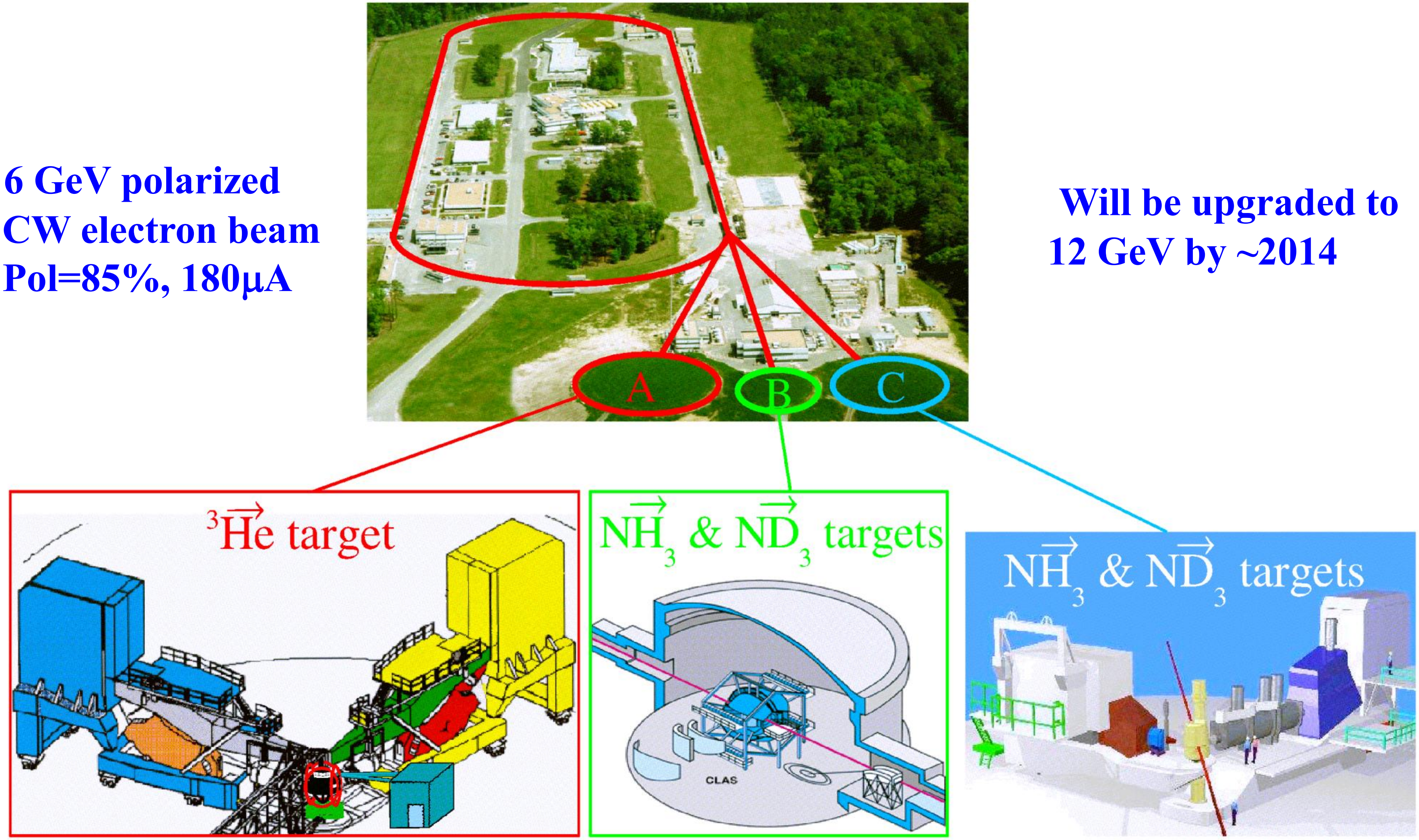
- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, … :

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

  Transversity, Transverse-Momentum Dependent Distributions

Jefferson Lab Experimental Halls

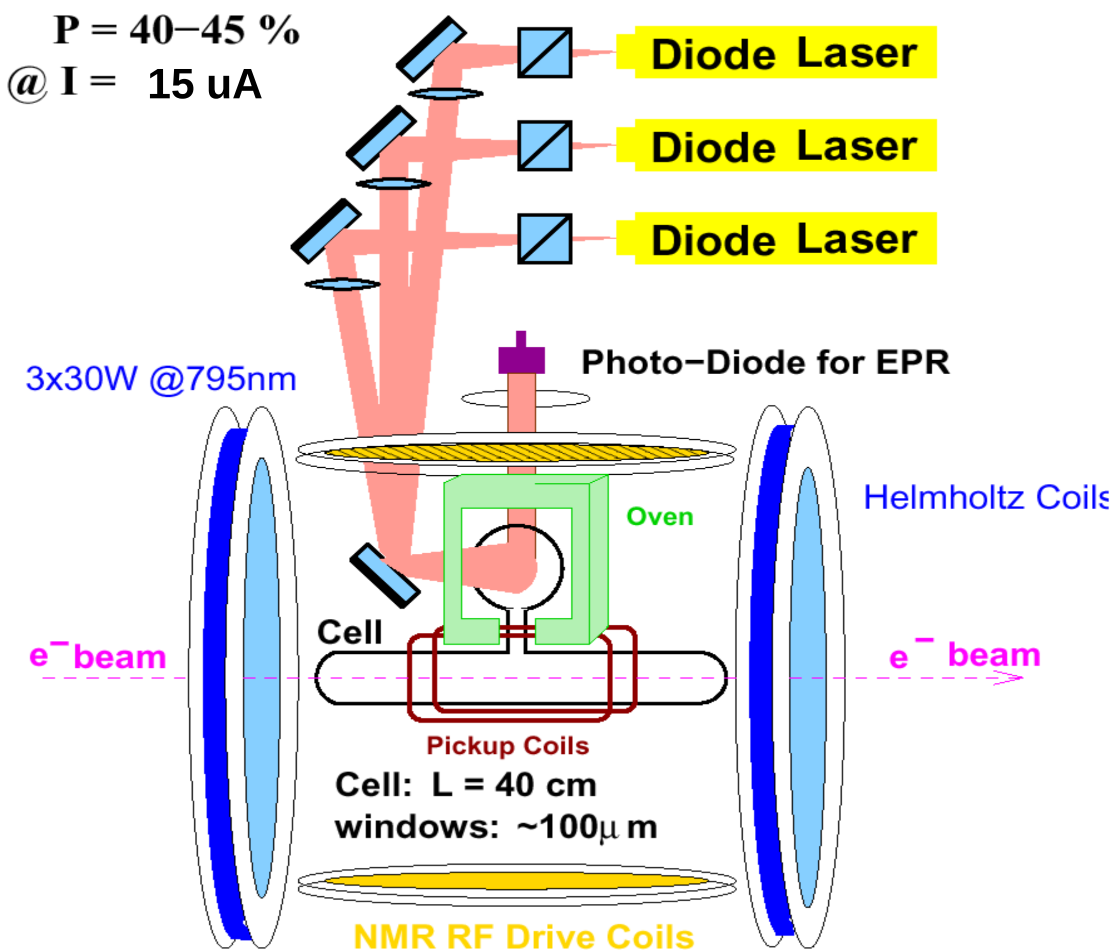
6 GeV polarized CW electron beam Pol=85%, 180μA



Will be upgraded to 12 GeV by ~2014

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

Hall A polarized ^{3}He target



✓longitudinal,
transverse and vertical

✓Luminosity=10^{36} (1/s)
(highest in the world)

✓High in-beam polarization
> 65%

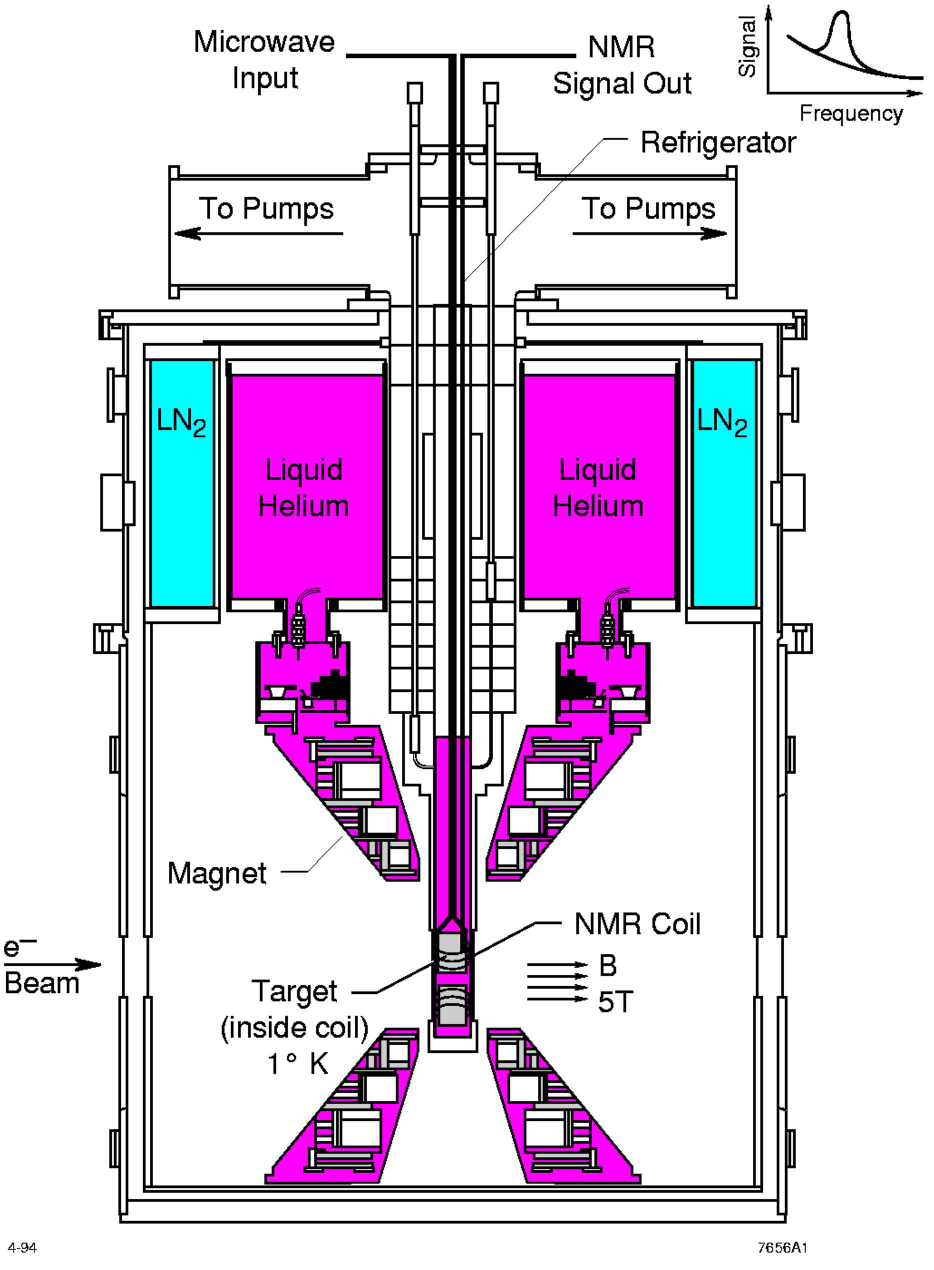
✓Effective polarized
neutron target

✓13 completed experiments
6 approved with 12 GeV (A/C)

Hall B/C Polarized proton/deuteron target

- Polarized NH_3/ND_3 targets
- Dynamical Nuclear Polarization

- In-beam average polarization
  - 70-90% for p
  - 30-40% for d
- Luminosity up to ~ 10^{35} (Hall C)
  - ~ 10^{34} (Hall B)

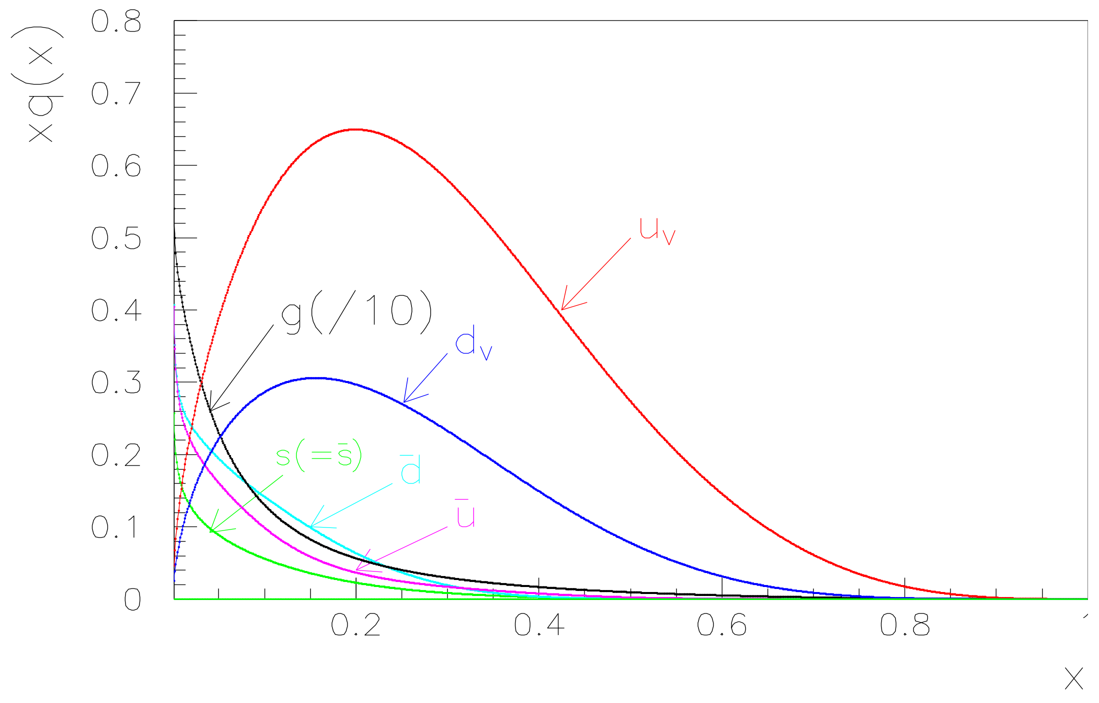


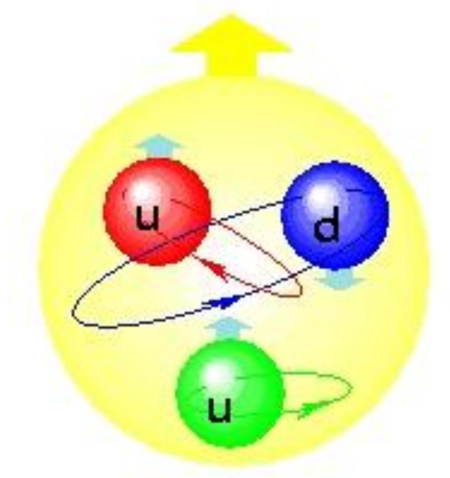
JLab Spin Experiments

- Results:
  - Spin in the valence (high-*x*) region
  - Moments: Spin Sum Rules and Polarizabilities
  - Higher twists: g_2/d_2
  - Quark-Hadron duality
  - Transversity (n)
- Completed:
  - d_2^p (SANE) and d_2^n
- Planned
  - g_2^p at low Q^2
- Future: 12 GeV
  - Inclusive: $A_1/d_{2,}$
  - Semi-Inclusive: Transversity, TMDs, Flavor-decomposition
- Review: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1

Valence Quark Spin Structure

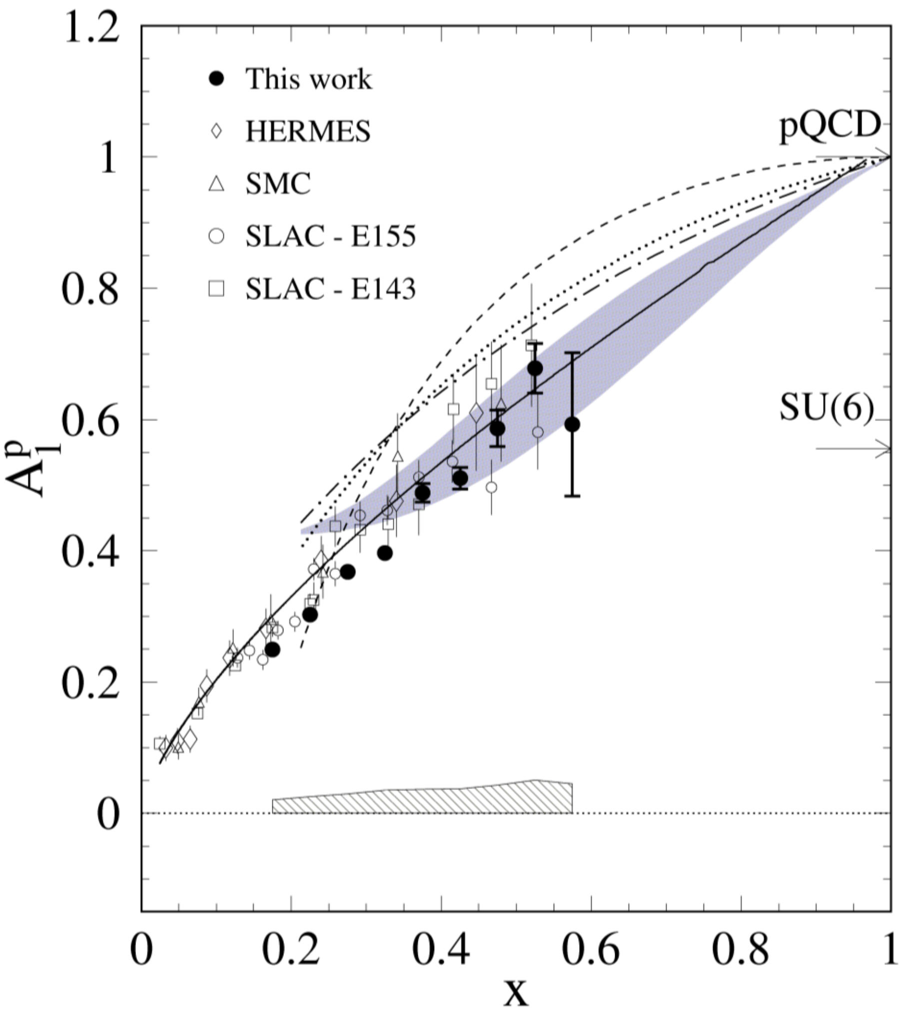
A_1 at high x and flavor decomposition



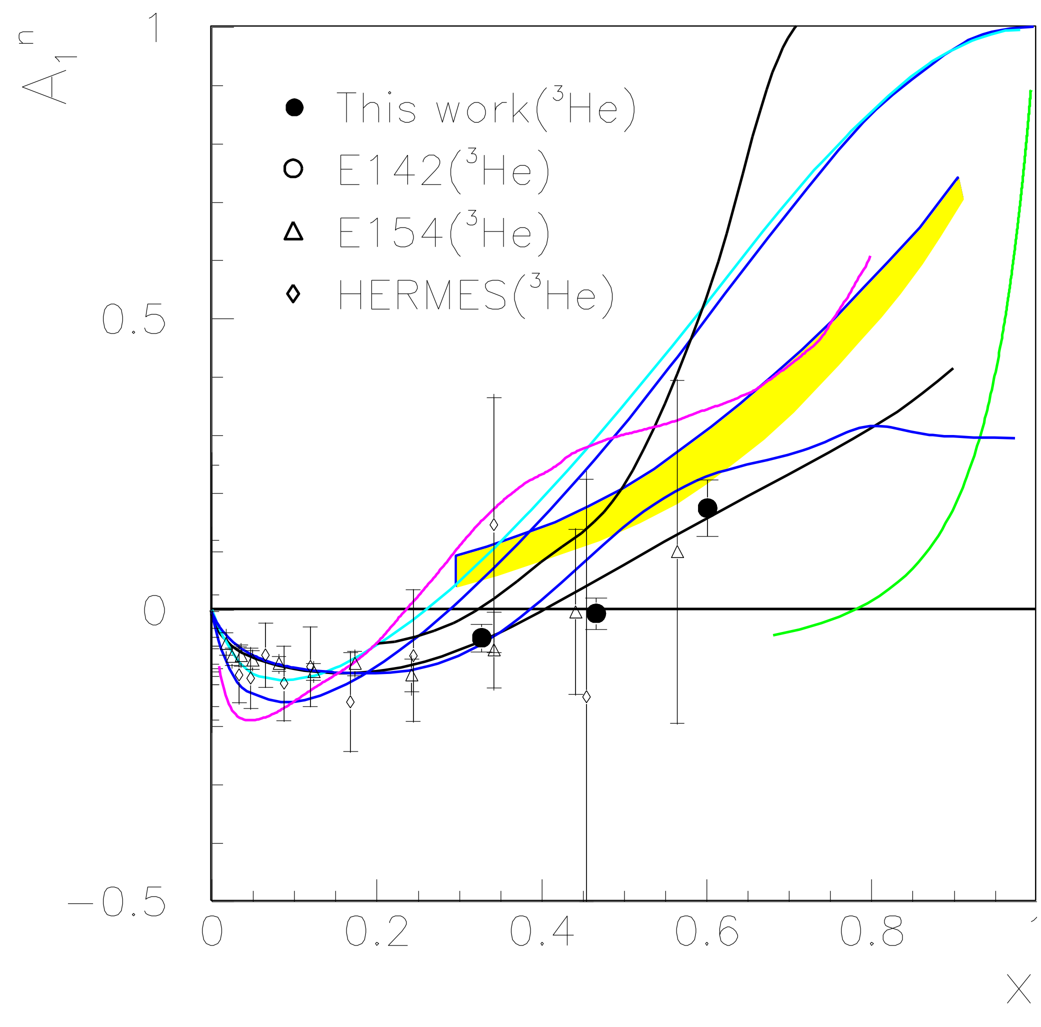


Valence (high-x) A_1^p and A_1^n results

Hall B CLAS, Phys.Lett. B641 (2006) 11

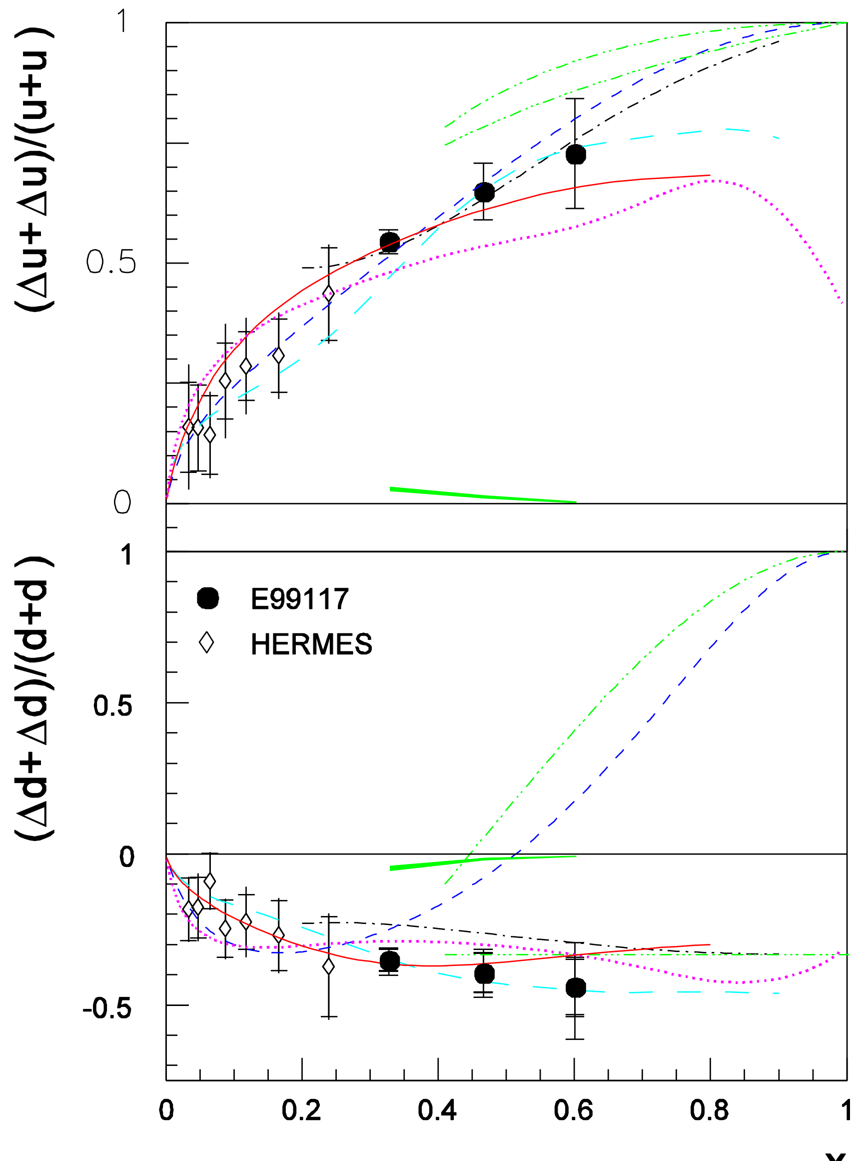


Hall A E99-117, PRL 92, 012004 (2004)
PRC 70, 065207 (2004)



Polarized Quark Distributions

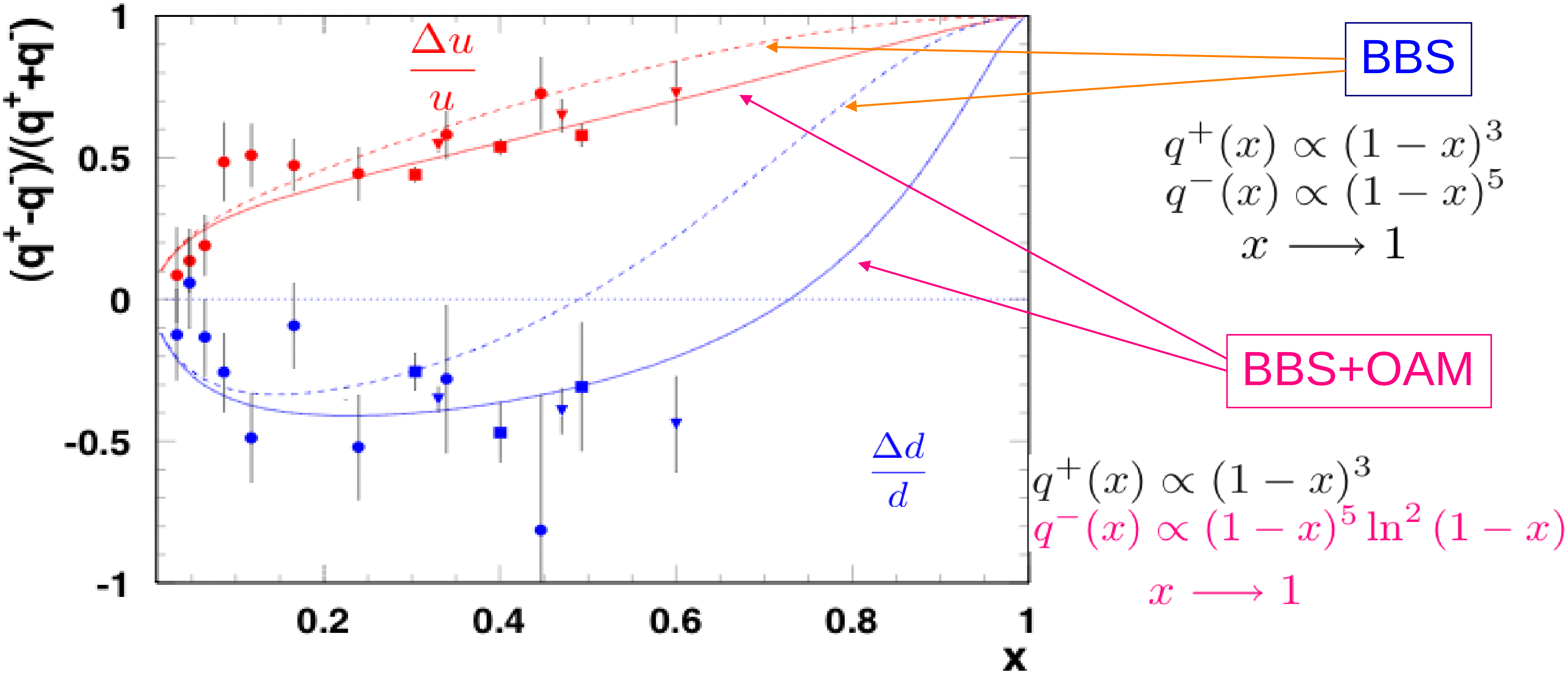
- Combining A_1^n and A_1^p results
- Valence quark dominating at high x
- u quark spin as expected
- d quark spin stays negative!
  - Disagree with pQCD model calculations assuming HHC (hadron helicity conservation)
  - Quark orbital angular momentum
- Consistent with valence quark models and pQCD PDF fits without HHC constraint



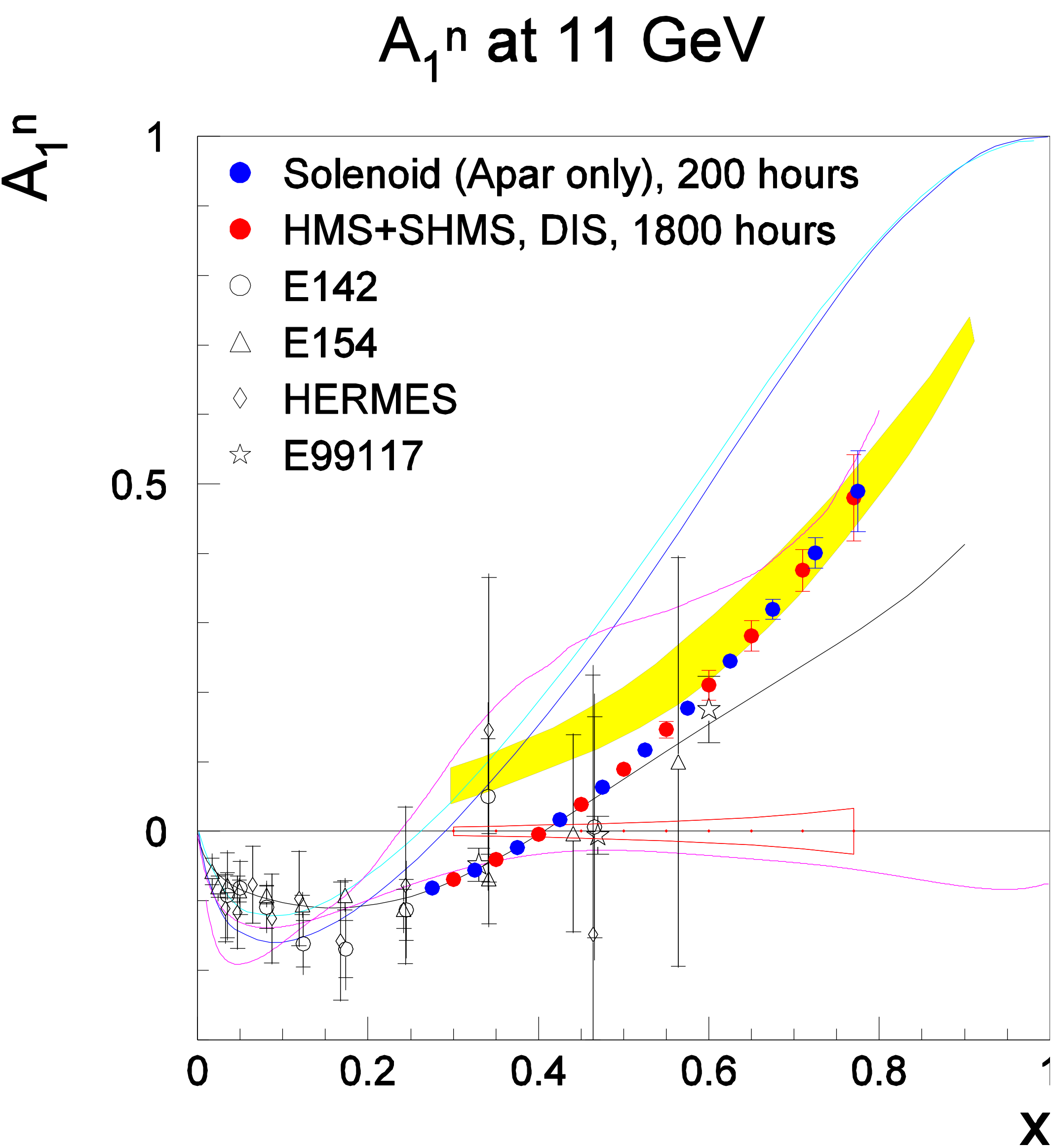
pQCD with Quark Orbital Angular Momentum

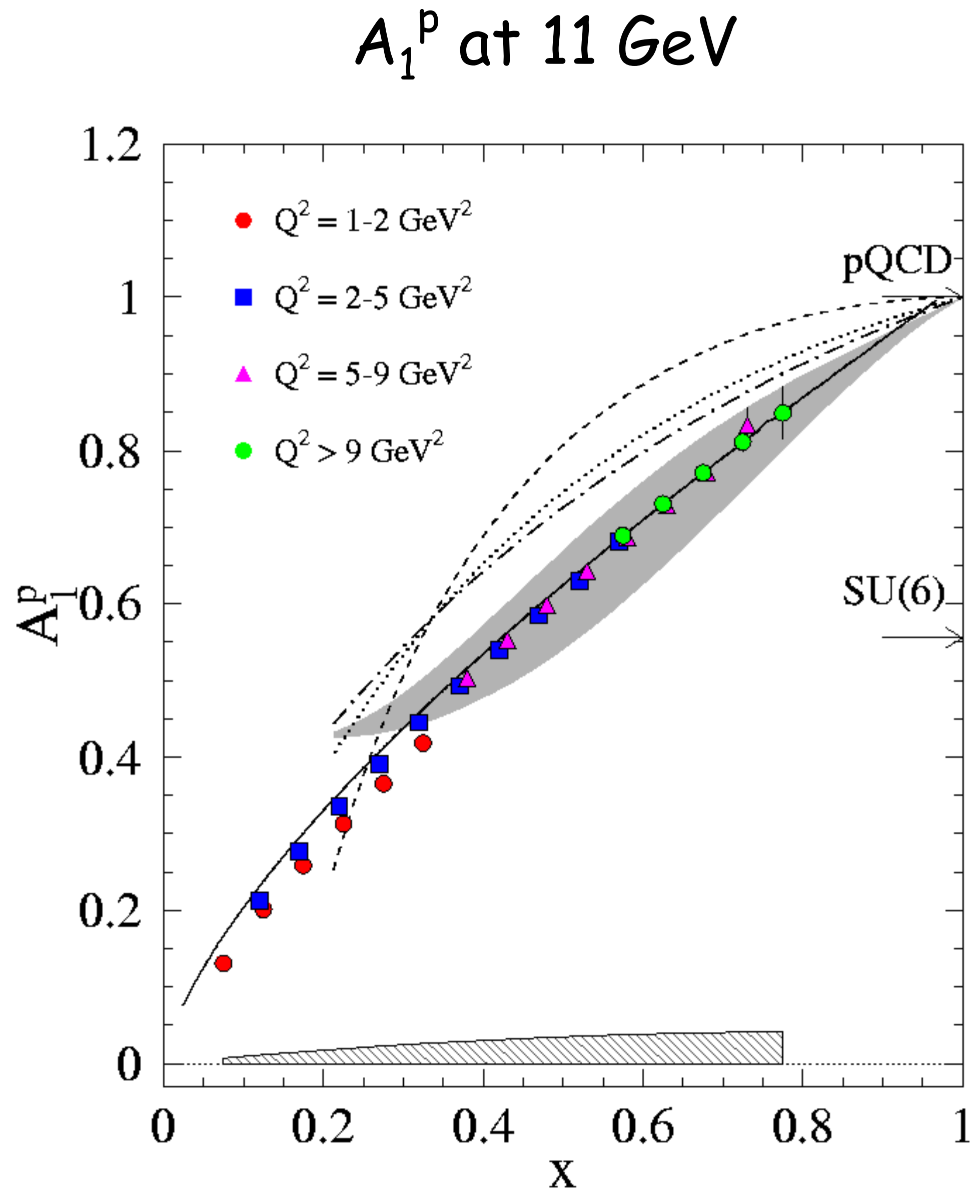
F. Yuan, H. Avakian, S. Brodsky, and A. Deur, arXiv:0705.1553

Inclusive Hall A and B and Semi-Inclusive Hermes



Projections for JLab at 11 GeV





Spin Sum Rules: First Moments

Sum Rules

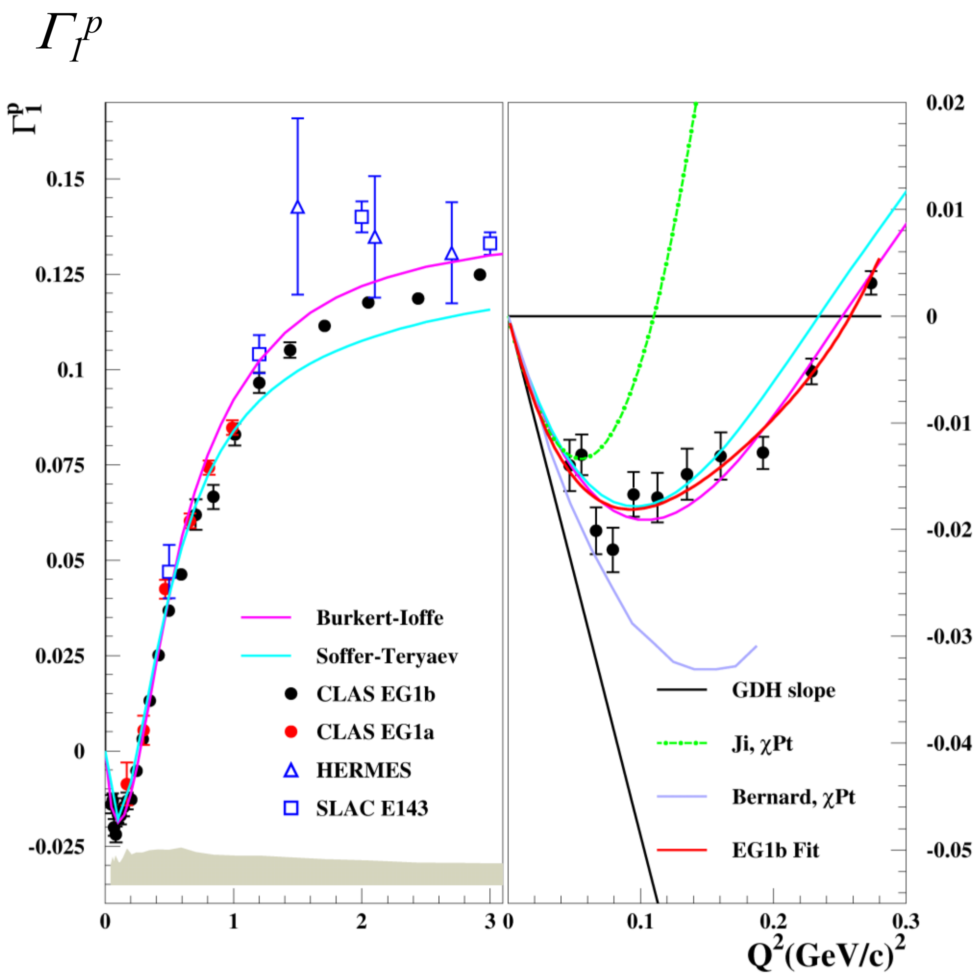
Moments of Spin Structure Functions → Global Property

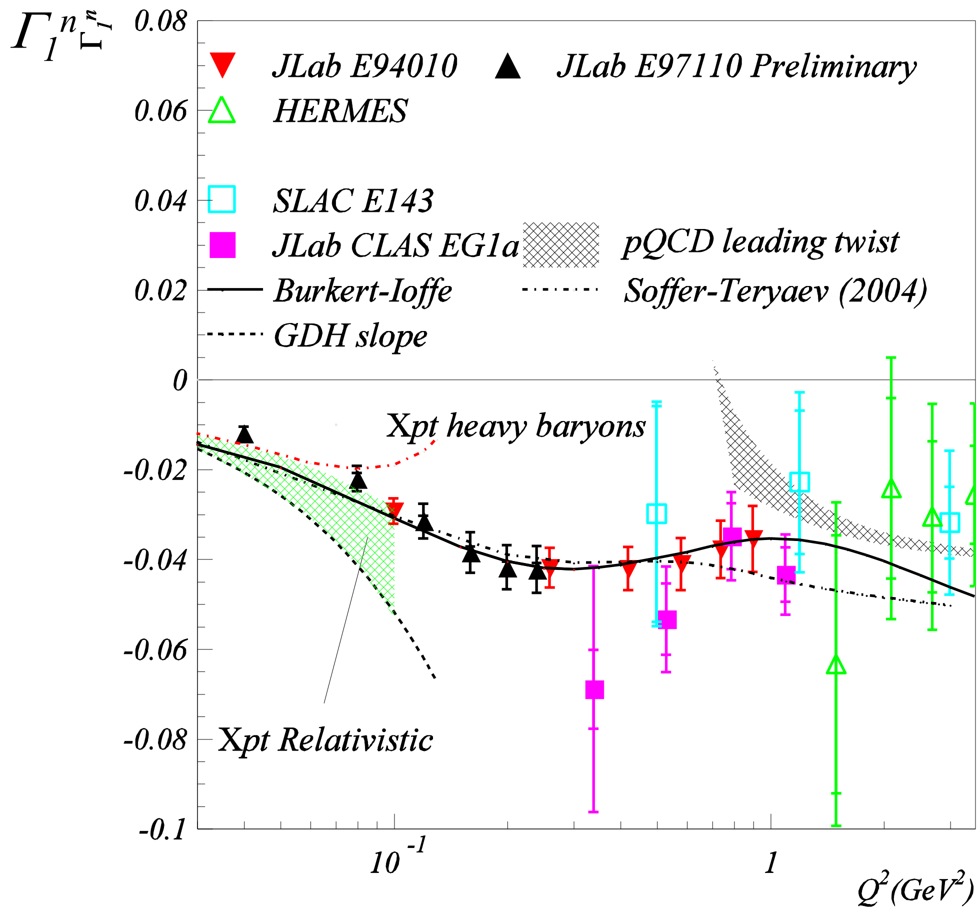
First Moment of g_1^p and g_1^n : Γ_1^p and Γ_1^n

Test fundamental understanding

ChPT at low Q^2, Twist expansion at high Q^2, Future Lattice QCD

1st period data analysis: H. Lu





EG1b, arXiv:0802.2232

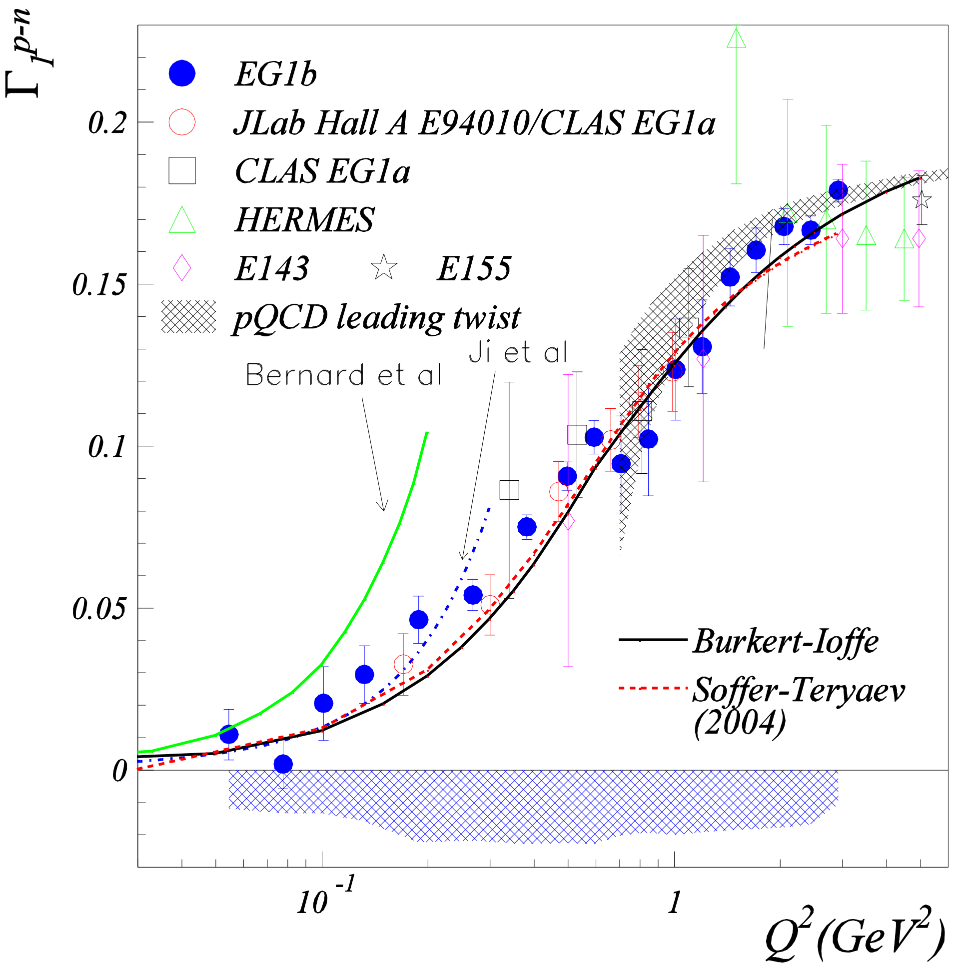
EG1a, PRL 91, 222002 (2003)

E94-010, from ^3He, PRL 92 (2004) 022301

E97-110, from ^3He, preliminary

EG1a, from d-p

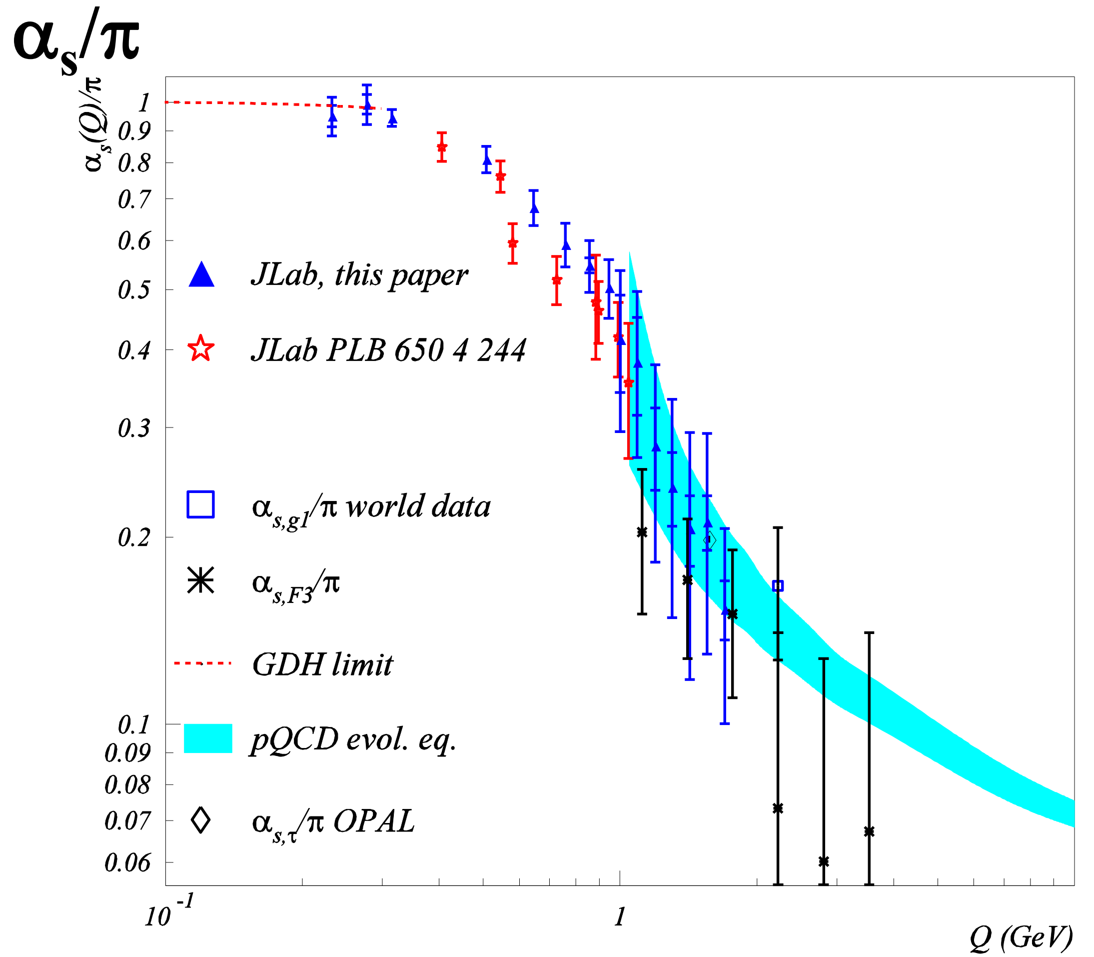
Γ_1 of p-n



EG1b, PRD 78, 032001 (2008)

E94-010 + EG1a: PRL 93 (2004) 212001

Effective Coupling



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

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

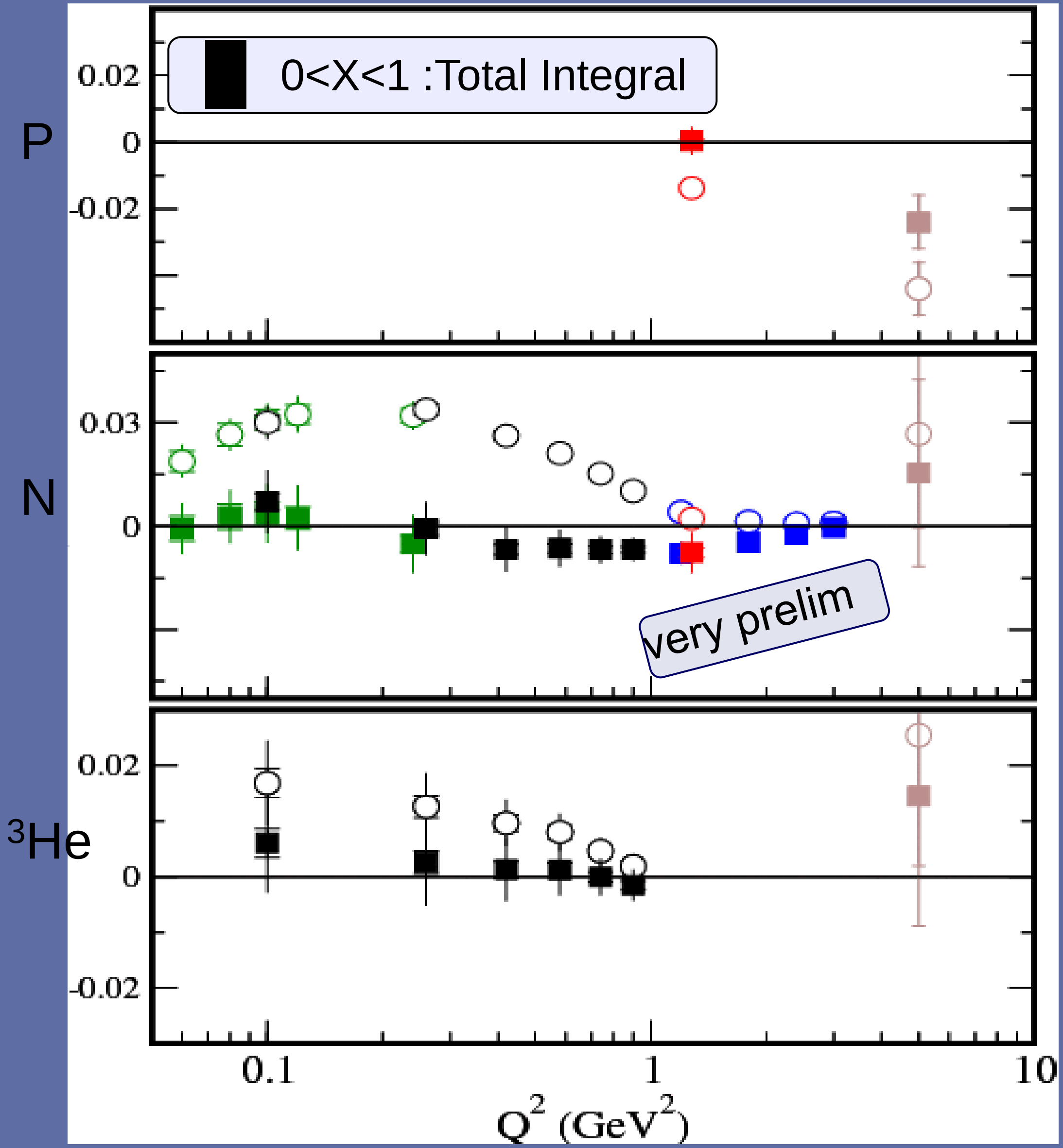
Transverse Spin (I): Inclusive

Moments of g_2 Structure Function:

Burkhardt - Cottingham Sum Rule

Spin and Color Polarizabilities

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 (very preliminary)

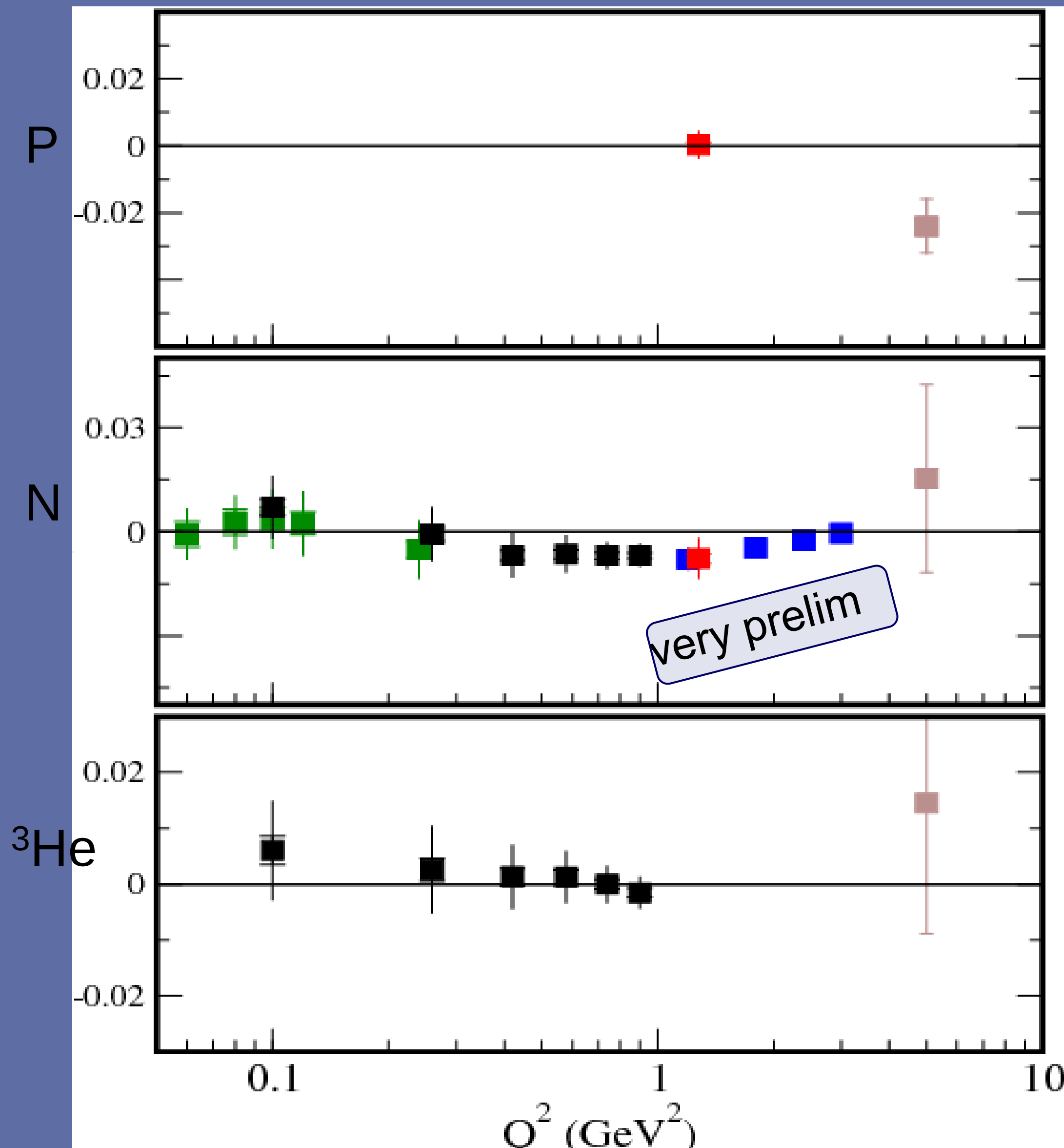
BC = Meas+low_*x*+Elastic

"Meas": Measured x-range

"low-*x*": refers to unmeasured low x part of the integral.
Assume Leading Twist Behaviour

Elastic: From well know FFs (<5%)

BC Sum Rule



BC satisfied w/in errors for JLab Proton
2.8σ violation seen in SLAC data

BC satisfied w/in errors for Neutron
(But just barely in vicinity of Q^2=1!)

BC satisfied w/in errors for ^{3}He

Higher Moments: Generalized Spin Polarizabilities

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

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

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

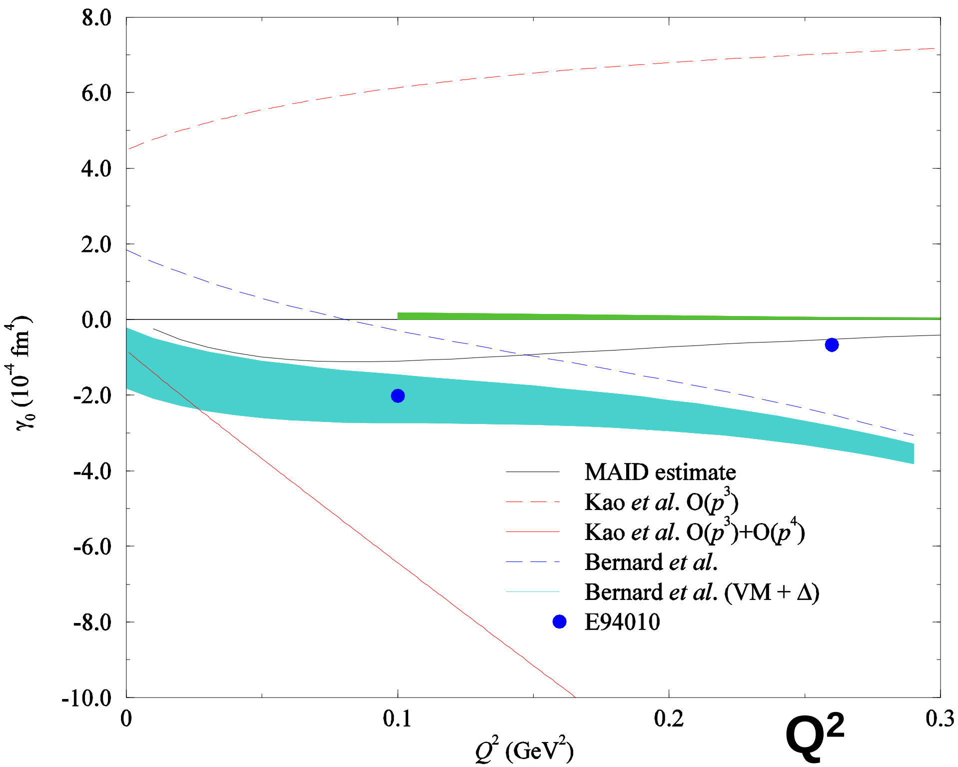
$$\delta_{LT}(Q^2) = \left(\frac{1}{2\pi^2}\right)\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu}\frac{\sigma_{LT}(Q^2,\nu)}{Q\nu^2}d\nu$$

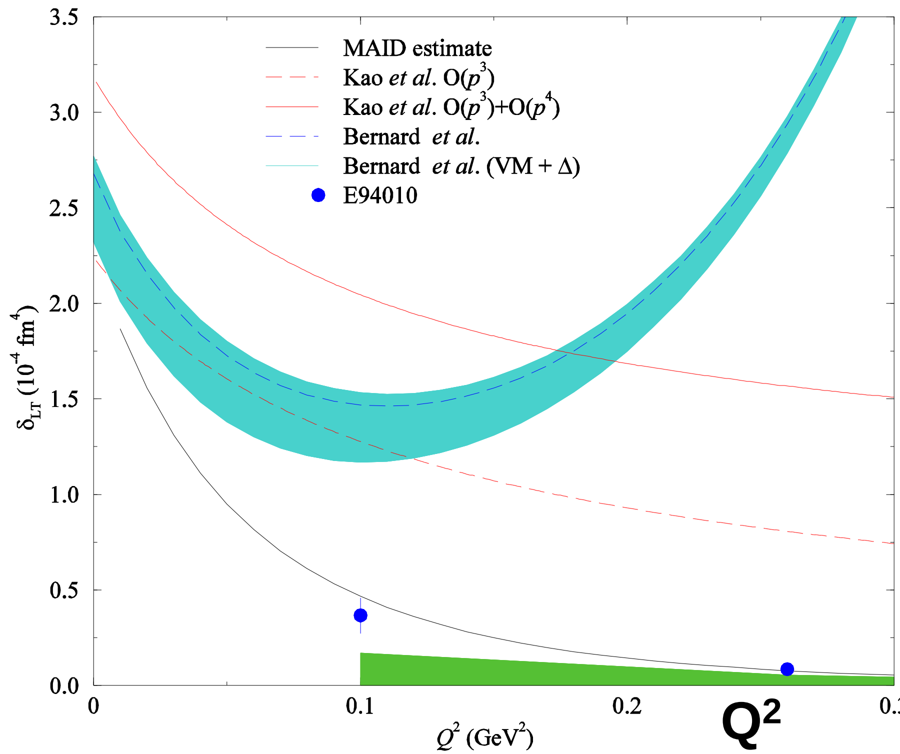
$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2[g_1(Q^2,x) + g_2(Q^2,x)dx$$

Neutron Spin Polarizabilities

- δ_{LT} insensitive to Δ resonance
- RB ChPT calculation with resonance for γ_0 agree with data at Q^2=0.1 GeV^2
- Significant disagreement between data and both ChPT calculations for δ_{LT}
- Good agreement with MAID model predictions

γ_0 E94-010, PRL 93 (2004) 152301 δ_{LT}





Planned 6 GeV Experiment: Proton g_2 and δ_{LT}

g_2^p : central to knowledge of Nucleon Structure
but remains unmeasured at low Q^2

—Critical input to Hydrogen Hyperfine Calculations
—Violation of BC Sum Rule suggested at large Q^2
—State-of-Art χPT calcs fail dramatically for δ_{LT}^n

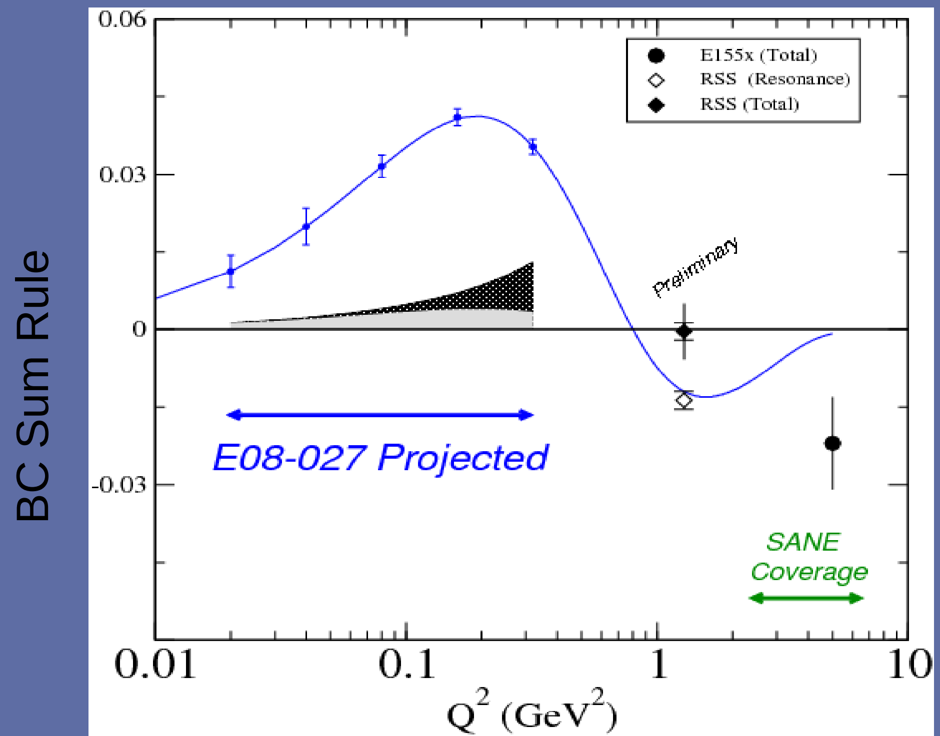
E08-027 : A⁻ rating by PAC33

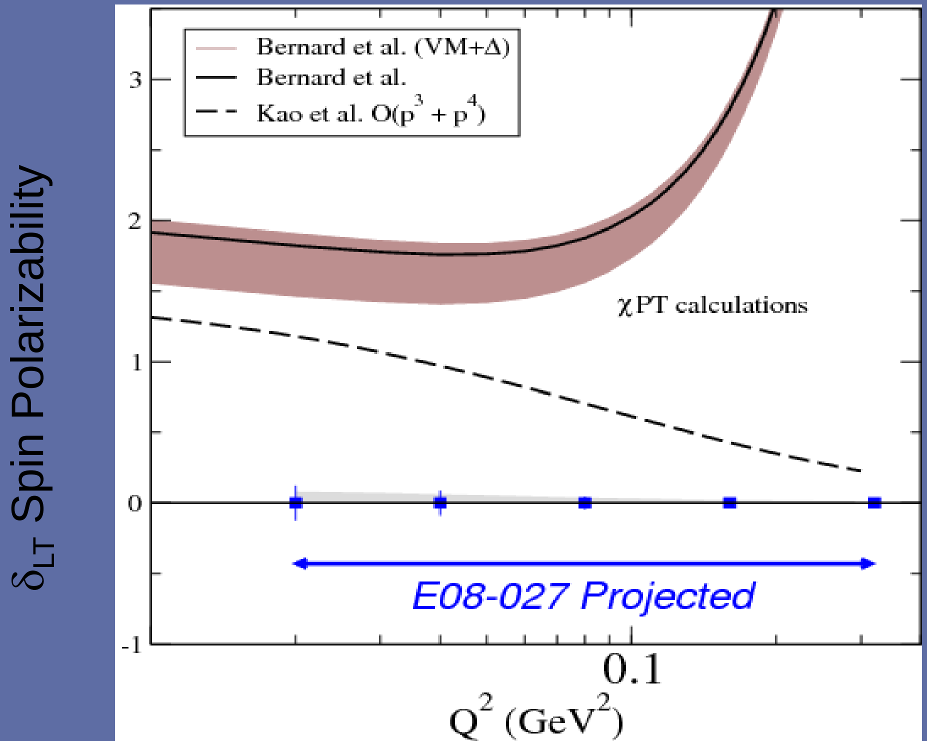
K. Slifer, A. Camsonne, ,J. P. Chen

PhD students: **P. Zhu (USTC)**, 7 total

Septa Magnets for low Q^2

Transverse Polarized Proton Target





Color Polarizability (or 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

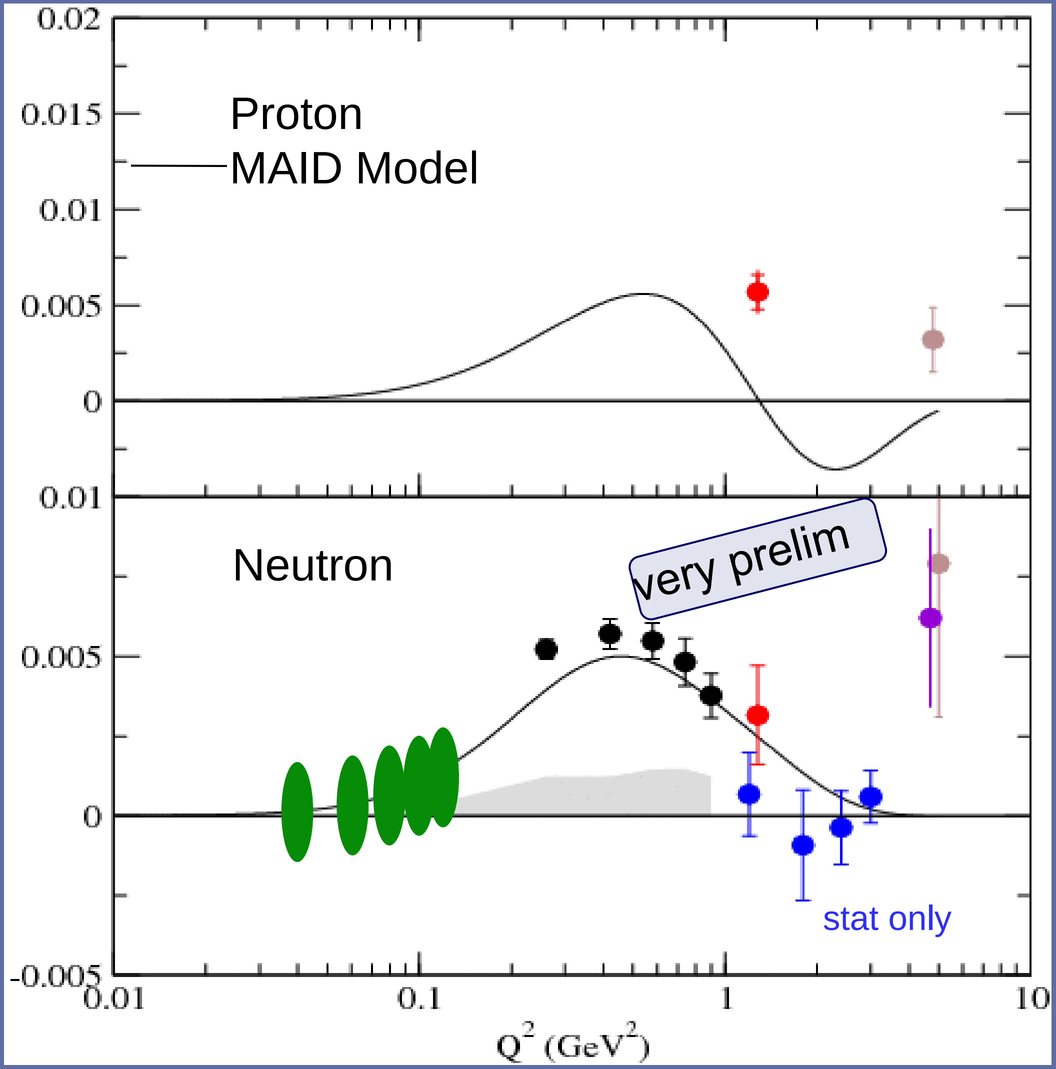
Color polarizabilities χ_E, χ_B are linear combination of d_2 and f_2

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

Avoid issue of low-*x* extrapolation

Relation to Sivers and other TMDs?

$d_2(Q^2)$



NEW DATA!

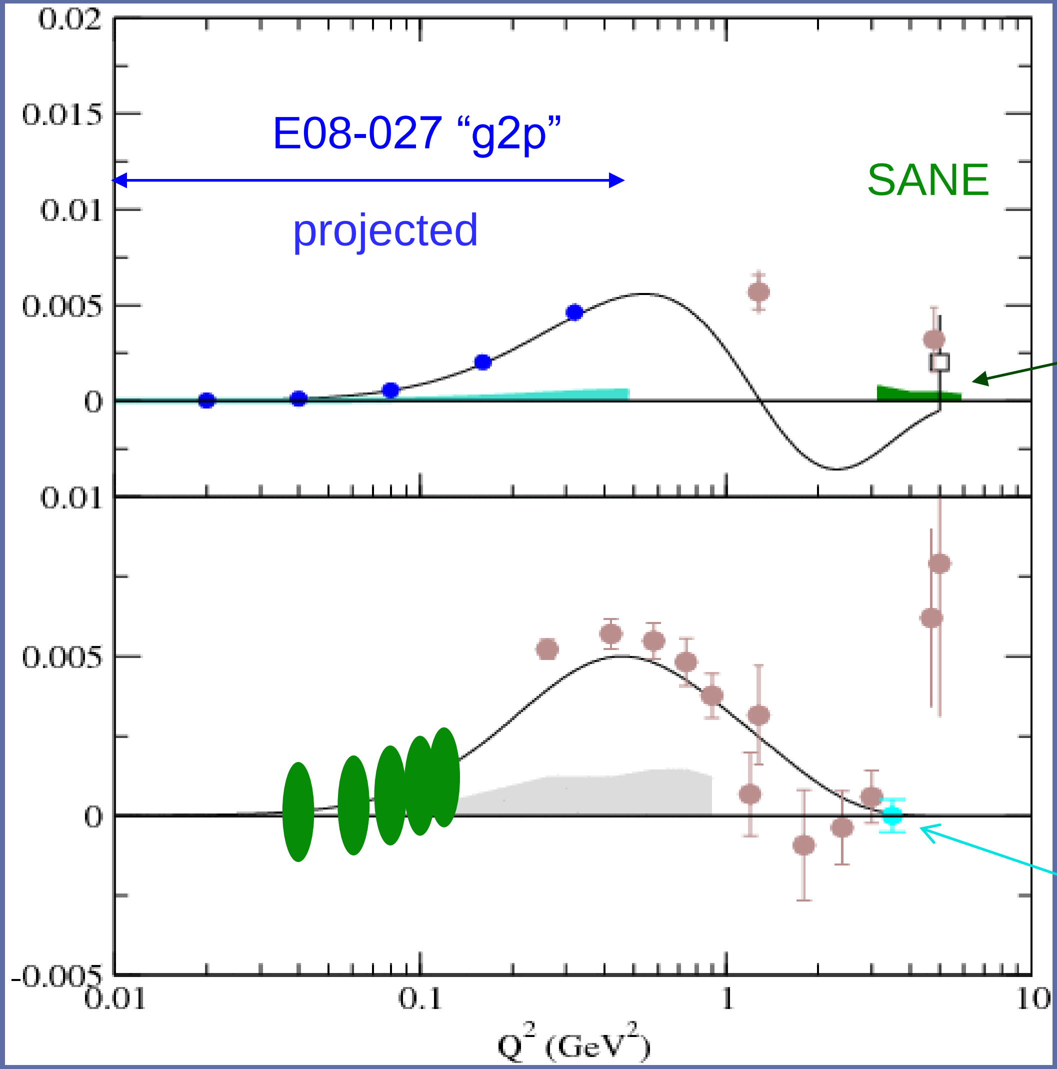
Very Preliminary

RED : RSS. (Hall C, NH_3,ND_3)

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

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

$d_2(Q^2)$



6 GeV Experiments

Sane: just completed in Hall C

"g2p" in Hall A, 2011

"d2n" just completed in Hall A

Transverse Spin (II): Single Spin Asymmetries in SIDIS

Transversity and TMDs

Transversity

- Three twist-2 quark distributions:
  - Momentum distributions: $q(x,Q^2) = q^{\uparrow}(x) + q^{\downarrow}(x)$
  - Longitudinal spin distributions: $\Delta q(x,Q^2) = q^{\uparrow}(x) - q^{\downarrow}(x)$
  - Transversity distributions: $\delta q(x,Q^2) = q^{\perp}(x) - q_{\top}(x)$
- It takes two chiral-odd objects to measure transversity
  - Semi-inclusive DIS

    Chiral-odd distributions function (transversity)

    Chiral-odd fragmentation function (Collins function)
- TMDs: (without integrating over P_T)
  - Distribution functions depends on x, $k_\perp$ and Q^2 : $\delta q,\ f_{1T}^{\perp}(x,k_\perp,Q^2), \ldots$
  - Fragmentation functions depends on z, $p_\perp$ and Q^2 : $D,\ H_1(x,p_\perp,Q^2)$
  - Measured asymmetries depends on x, z, $P_\perp$ and Q^2 : *Collins, Sivers, …*

    ($k_\perp$, $p_\perp$ and $P_\perp$ are related)

"Leading-Twist" *TMD* Quark Distributions

Quark \ Nucleon	Unpol.	Long.	Trans.
Unpol.	$f_1 =$		$f_{1T}^{\perp} = \quad - $
Long.		$g_{1L} = \quad - $	$g_{1T} = \quad - $
Trans.	$h_1^{\perp} = \quad - $	$h_{1L}^{\perp} = \quad - $	$h_{1T} = \quad - $ $h_{1T}^{\perp} = \quad - $

Multi-dimensional Distributions

$W_p^u(k,r_T)$ “Mother” Wigner distributions

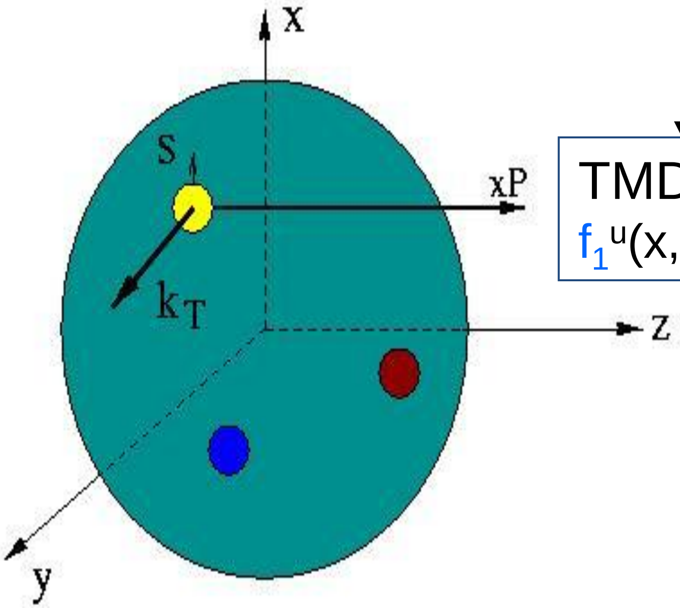
↓ d^2r_T ↓ d^2k_T

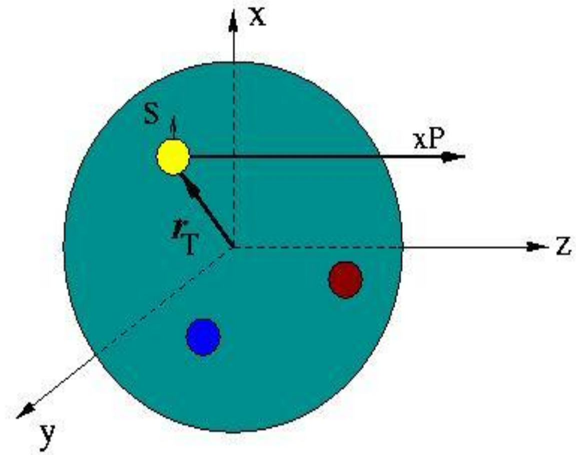
TMDs
$f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

GPDs/IPDs
$H(x,r_T)$,$E(x,r_T)$,..

↓ d^2k_T ↓ d^2r_T

PDFs $f_1^u(x)$, .. $h_1^u(x)$

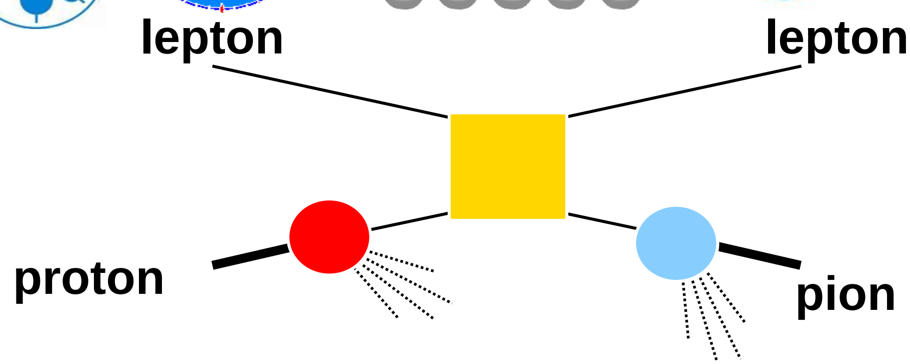




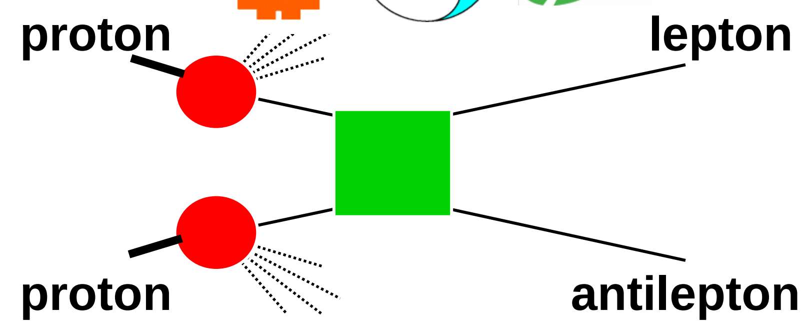
quark polarization

- Gauge invariant definition (Belitsky,Ji,Yuan 2003)
- Universality of k_T-dependent PDFs (Collins,Metz 2003)
- Factorization for small k_T. (Ji,Ma,Yuan 2005)

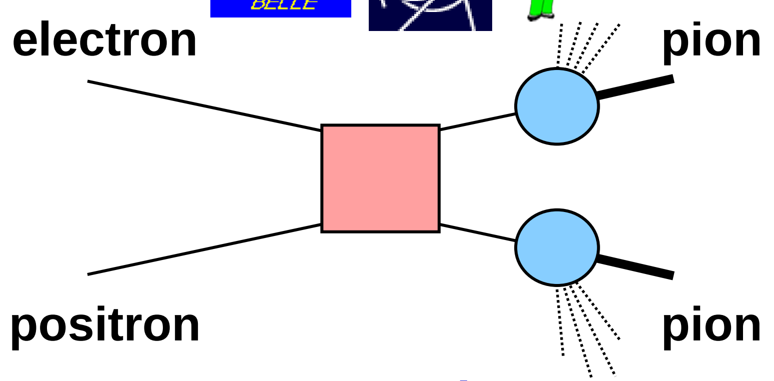
Access TMDs through Hard Processes



SIDIS



Drell-Yan



$e^{-}e^{+}$ to pions

Partonic scattering amplitude

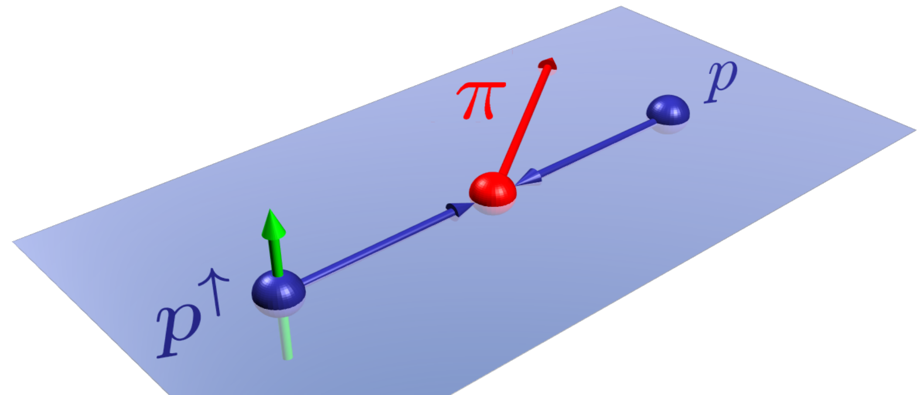
Fragmentation amplitude

Distribution amplitude

$$f_{1T}^{\perp q}(SIDIS) = -f_{1T}^{\perp q}(DY)$$

Single Spin Asymmetries in $p_\uparrow + p \rightarrow \pi + X$

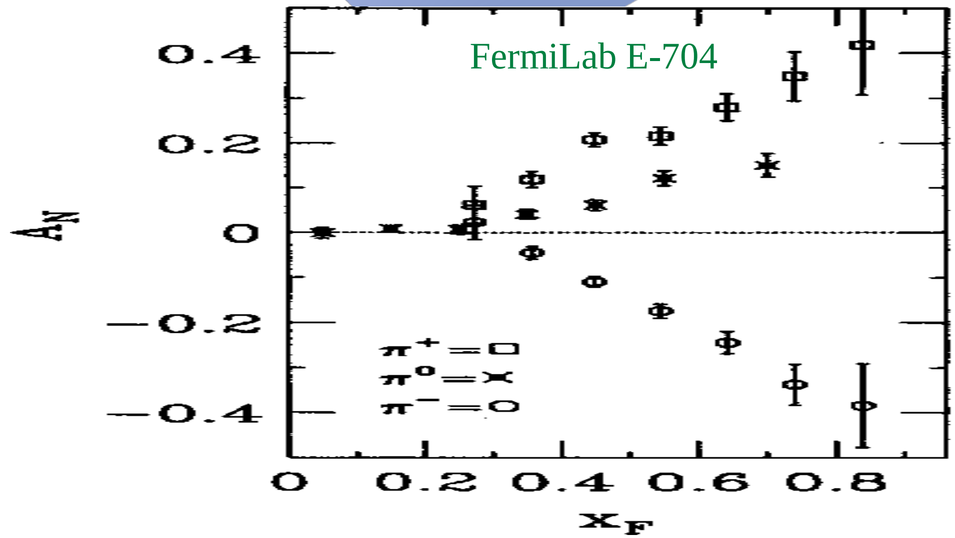
$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$



$\sqrt{s}$=20 GeV, p_T=0.5-2.0 GeV/c

π^0 – E704, PLB261 (1991) 201.

$\pi^{+/-}$ - E704, PLB264 (1991) 462.



Large transverse single-spin effects were observed at RHIC, at much higher CM energies.

- In collinear picture, the QCD predict small SSAs with transversely polarized protons colliding at high energies.

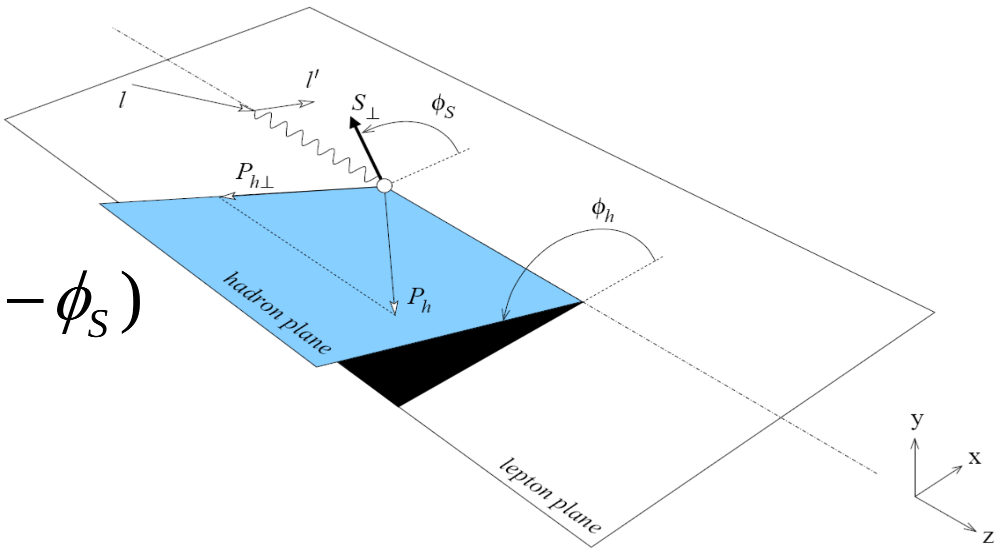
Kane, Pumplin, Repko ‘78

Separation of Collins, Sivers and pretzelocity effects through angular dependence in SIDIS

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$



$$A_{UT}^{Collins} \propto \left\langle \sin(\phi_h + \phi_S) \right\rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

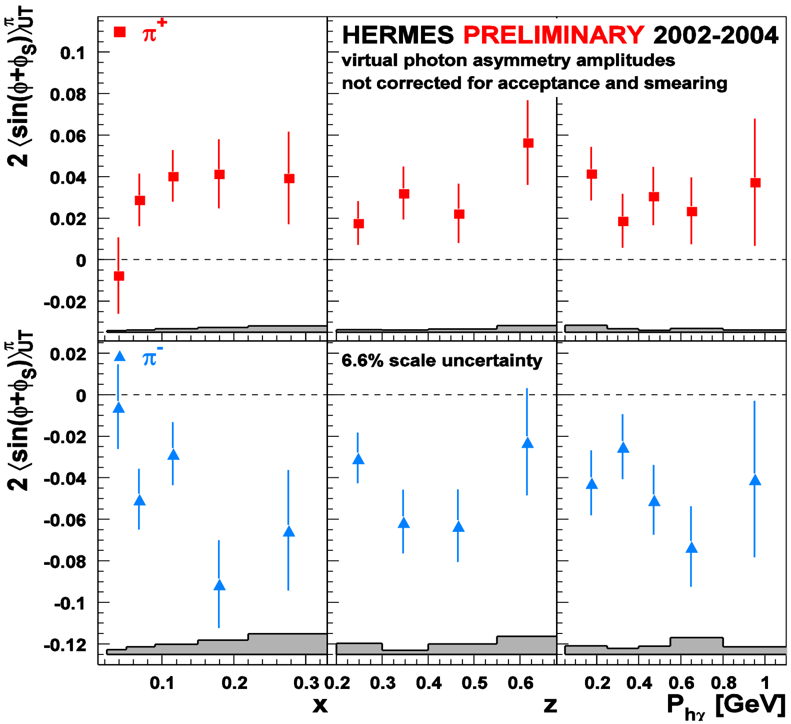
$$A_{UT}^{Sivers} \propto \left\langle \sin(\phi_h - \phi_S) \right\rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \left\langle \sin(3\phi_h - \phi_S) \right\rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

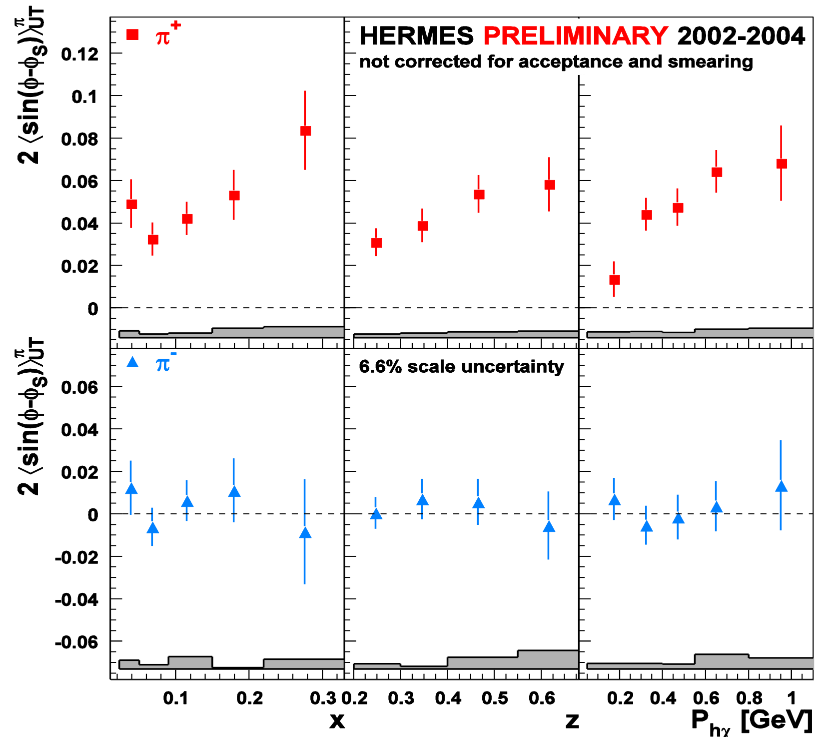
$A_{UT}^{\sin(\phi)}$ from transv. pol. H target

Simultaneous fit to $\sin(\phi + \phi_s)$ and $\sin(\phi - \phi_s)$

`Collins' moments



`Sivers' moments



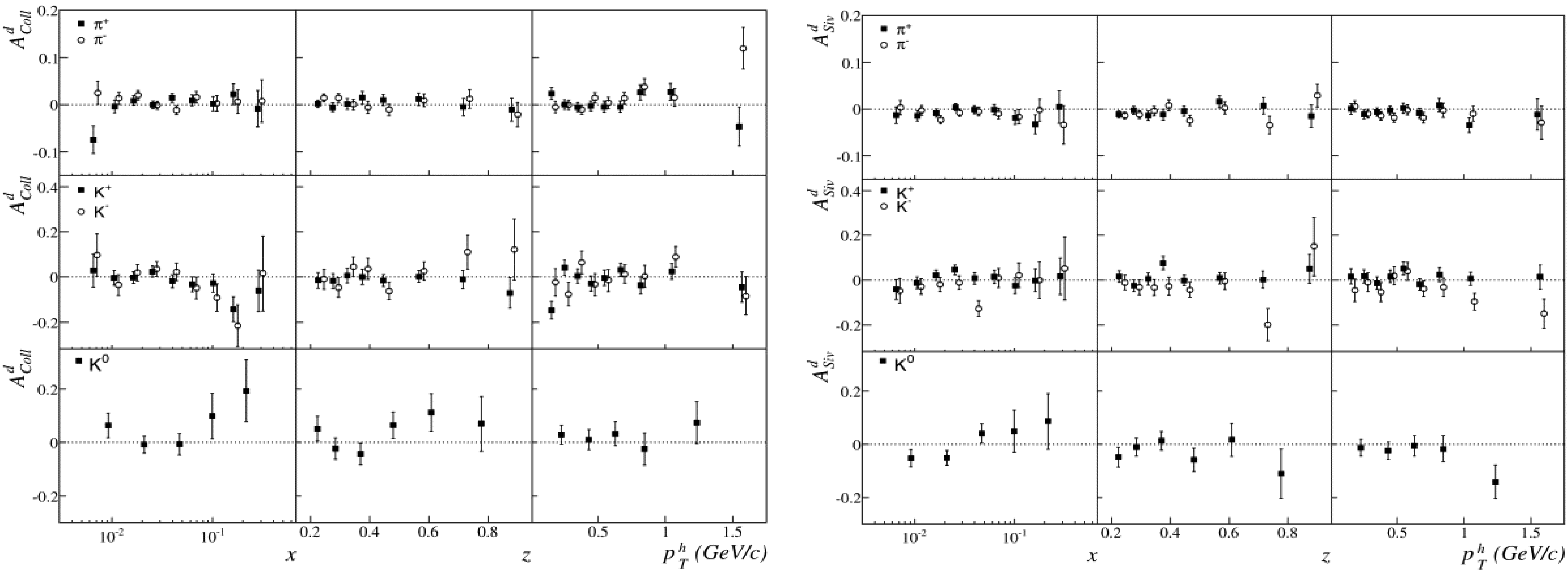
- Non-zero Collins asymmetry
- Assume $\delta q(x)$ from model, then

  H_1_unfav ~ -H_1_fav

- Need independent H_1 (BELLE)

- Sivers function nonzero (π^+)$\rightarrow$ orbital angular momentum of quarks
- Regular flagmentation functions

Collins/Sivers asymmetries from COMPASS deuteron



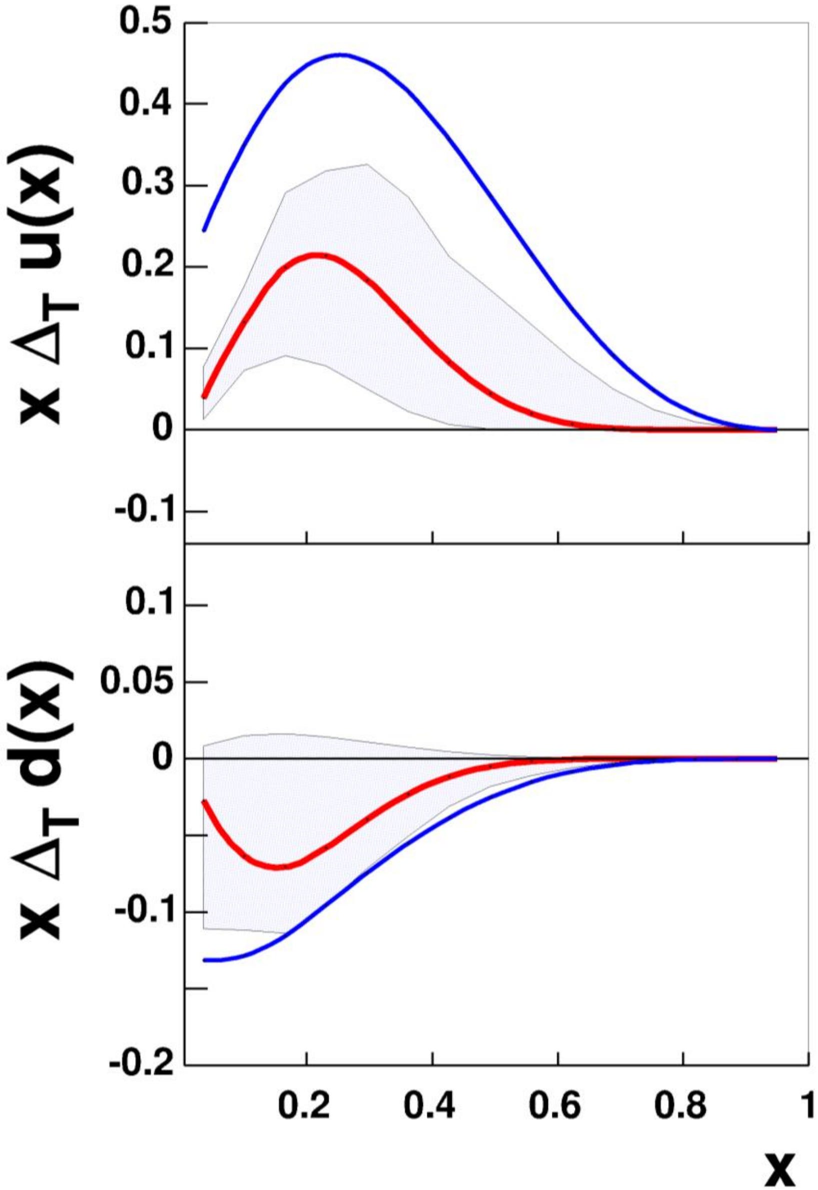
Phys. Lett. B 673 (2009) 127-135

u and d cancellation?

Transversity Distributions

A global fit to the **HERMES p, COMPASS d** and **BELLE e+e-** data by the Torino group (Anselmino *et al.).*

PRD 75, 054032 (2007)



Current Status

- Large single spin asymmetry in pp->πX
- Collins Asymmetries

  - sizable for proton (HERMES and COMPASS)

    large at high x, π^- and $\pi+$ has opposite sign

    unfavored Collins fragmentation as large as favored (opposite sign)?

  - consistent with 0 for deuteron (COMPASS)

- Sivers Asymmetries

  - non-zero for π^+ from proton (HERMES), smaller for COMPASS?
  - consistent with zero for π^- from proton and for all channels from deuteron
  - large for K^+ ?

- Very active theoretical and experimental study

  RHIC-spin, JLab (Hall A 6 GeV, CLAS12, HallA/C 12 GeV), Belle, FAIR (PAX)

- Global Fits/models by Anselmino *et al.*, *Yuan et al.* and …
- First neutron measurement from Hall A 6 GeV (E06-010)
- Solenoid with polarized ^{3}He at JLab 12 GeV

  Unprecedented precision with high luminosity and large acceptance

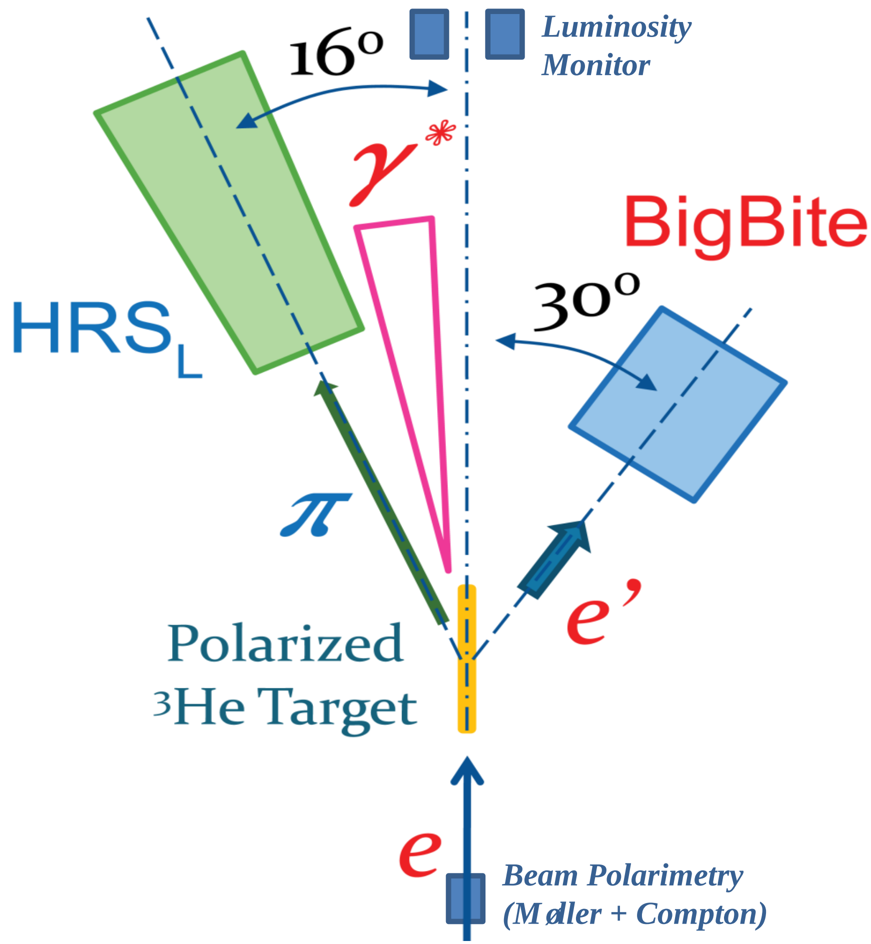
JLab E06-010

7 PhD Students, Y. Zhang (Lanzhou)

en→e'πX

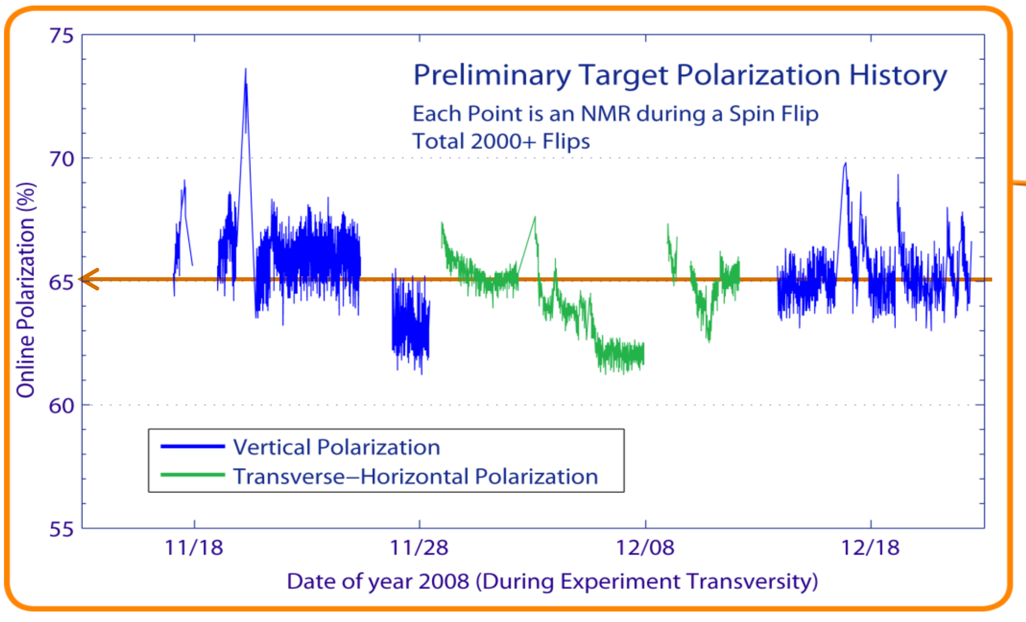
en→e'KX

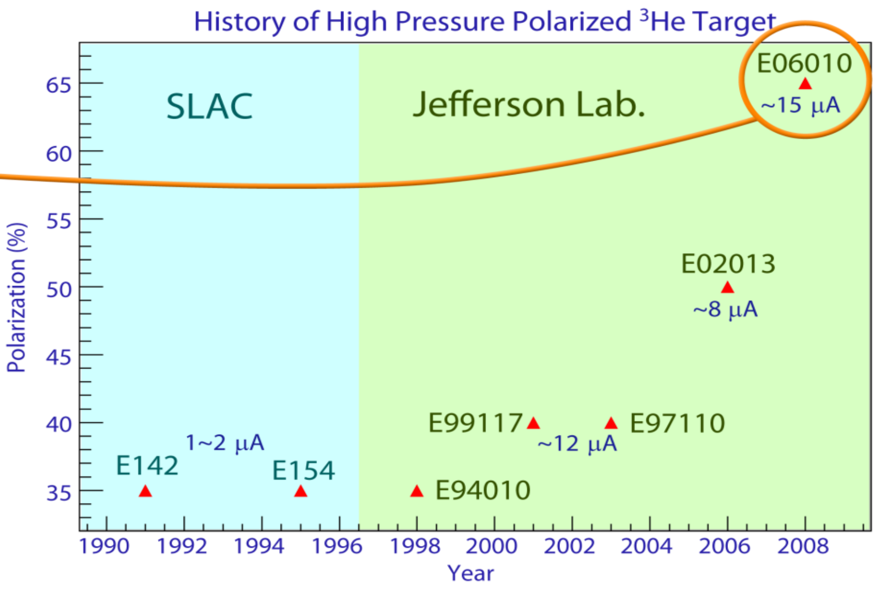
- Polarized ^{3}He Target
- Polarized Electron Beam
  - ~80% Polarization
  - Fast Flipping at 30Hz
  - PPM Level Charge Asymmetry controlled by online feed back
- BigBite at 30º as Electron Arm
  - $P_e = 0.7 \sim 2.2$ GeV/c
- HRS_L at 16º as Hadron Arm
  - $P_h = 2.35$ GeV/c



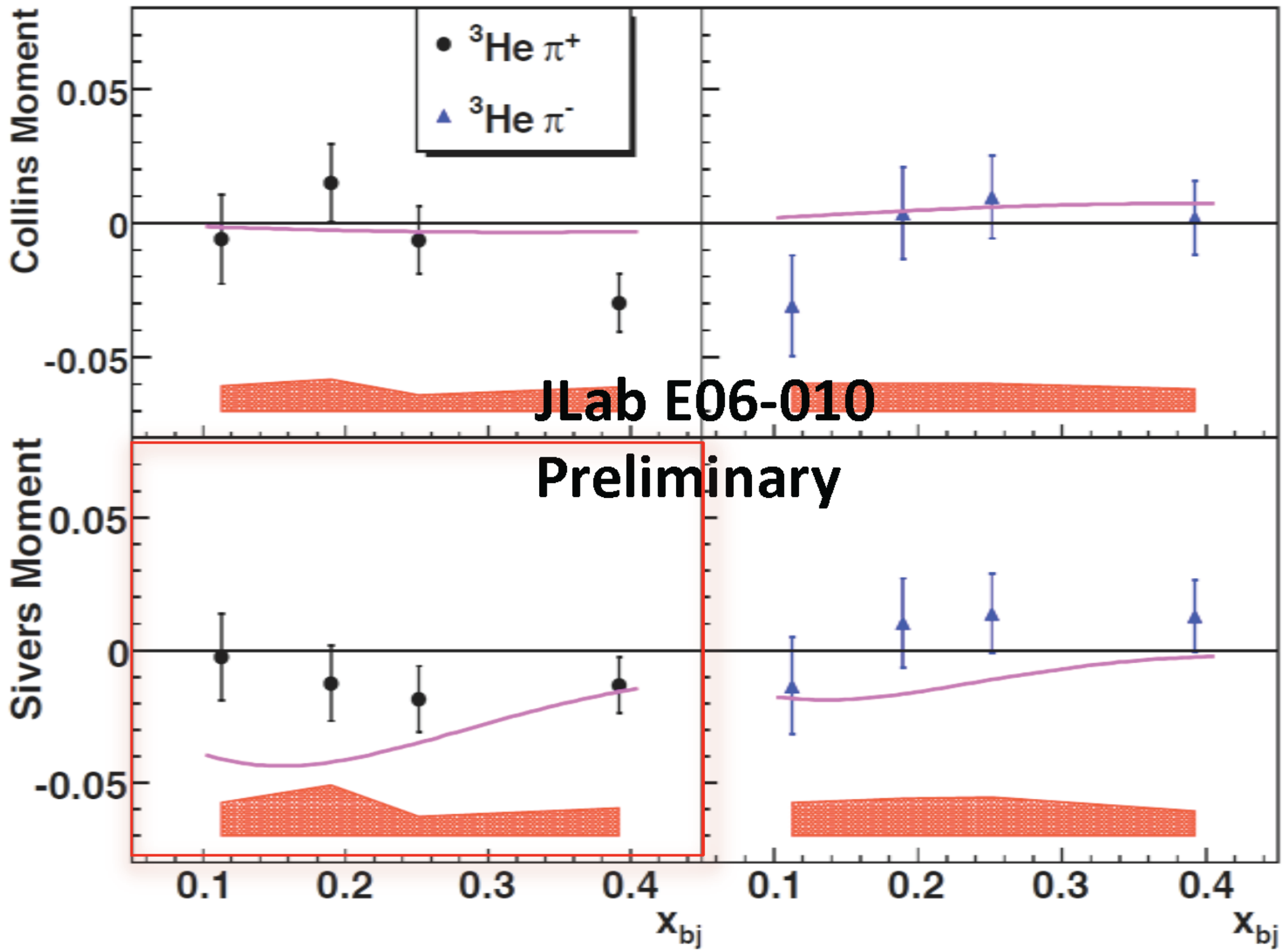
Performance of ^{3}He Target

- High luminosity: L(n) = 10^{36} cm^{-2} s^{-1}
- Record high 65% polarization (preliminary) in beam with automatic spin flip / 20min





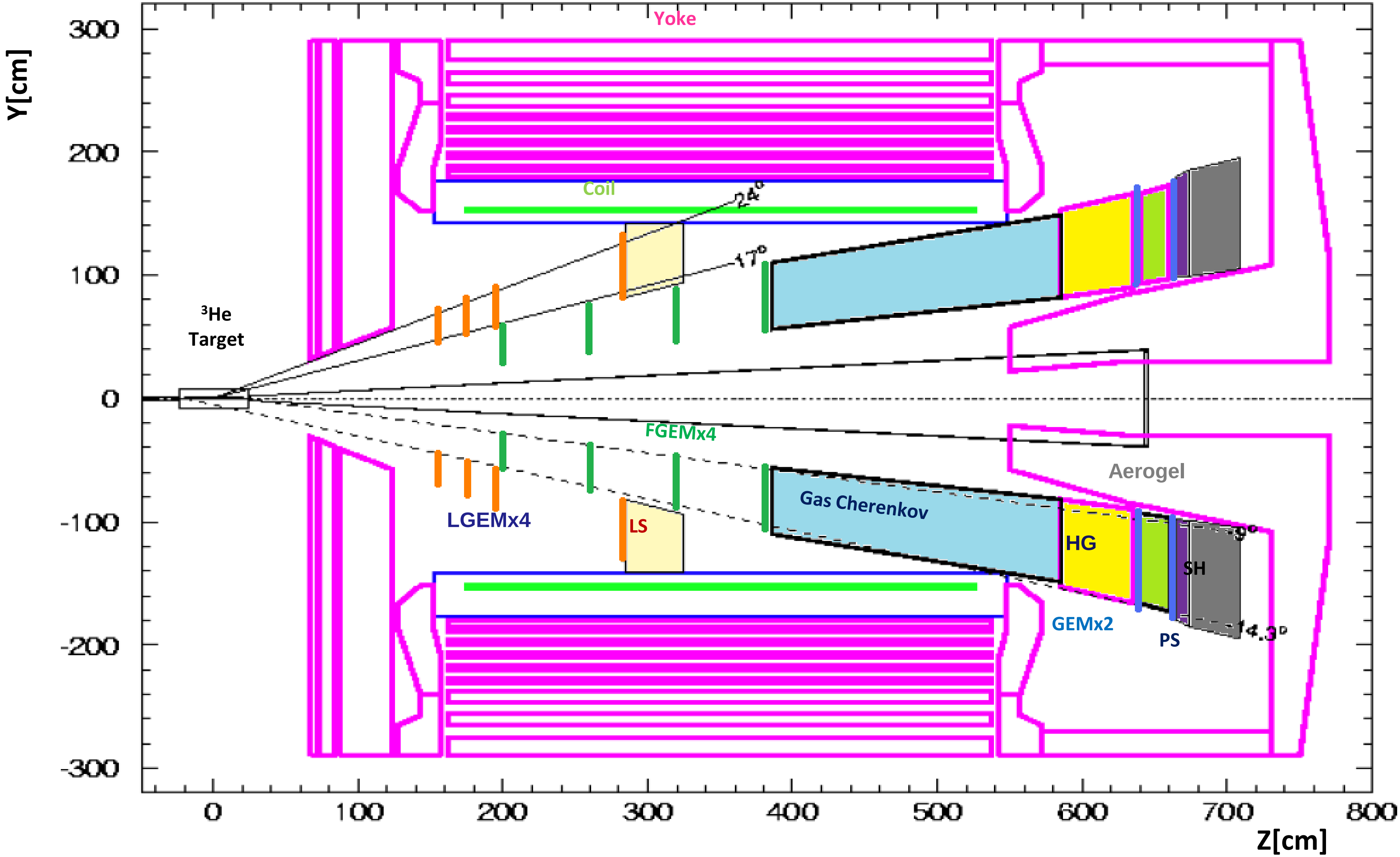
^{3}He Target Single-Spin Asymmetry in SIDIS: JLab E06-010



Precision Study of Transversity and *TMDs*

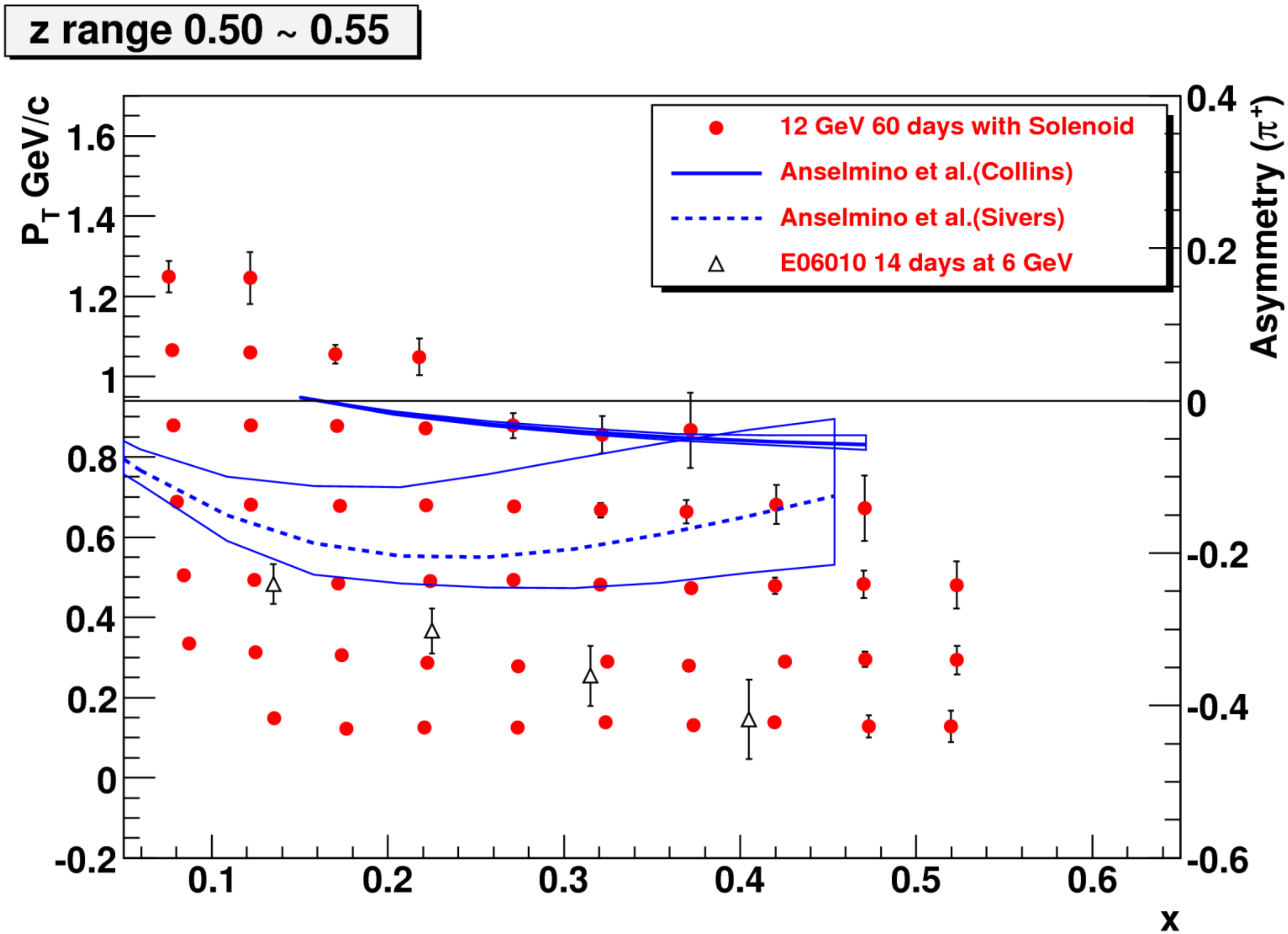
- From exploration to precision study
- Transversity: fundamental *PDFs*, tensor charge
- *TMDs* provide multi-d structure information of the nucleon
- Spin-orbit correlations: quark orbital angular momentum
- Multi-parton correlations: QCD dynamics
- Multi-dimensional mapping of *TMDs*
  - 4-d ($x, z, P_{\perp}, Q^2$)
  - Multi-facilities, global effort
- Precision → high statistics
  - high luminosity and large acceptance

Solenoid detector for SIDIS at 11 GeV



4-d Mapping of Collins/Sivers Asymmetries 12 GeV With SOLID (L=10^{36})

- Both π+ and π-
- For one z bin (0.5-0.55)
- Will obtain 8 z bins (0.3-0.7)
- Haiyan Gao's talk



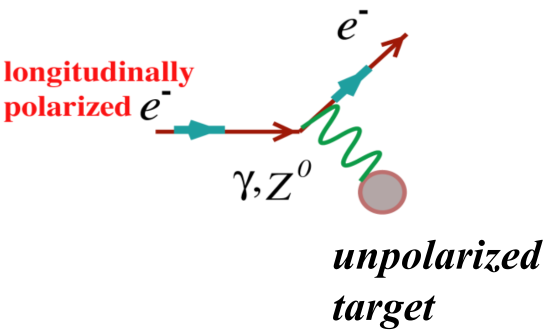
Discussion

- Unprecedented precision *4-d* mapping of SSA
  - Collins and Sivers
  - π^+, π^- and K^+, K^-
- Study factorization with *x* and *z*-dependences
- Study P_T dependence
- With similar quality SIDIS data on the proton and data from e+e-
  - extract transversity and fragmentation functions for both *u* and *d* quarks
  - determine tensor charge
  - study TMDs for valence quarks
  - study quark orbital angular momentum
- Combining with world data, especially data from high energy facilities (future EIC)
  - study Q^2 evolution (need theoretical development)
  - sea and gluon TMDs (more surprises are waiting?)
- Global efforts (experimentalists and theorists), global analysis
  - Precision information on multi-dimension nucleon structure

Particty Violating Electron Scattering

Strange Form Factors

Parity-Violating (PV) Electron Scattering



$$\sigma \;\alpha\; | A_\gamma + A_{weak} |^2 \sim |A_{EM}|^2 + 2 A_{EM} A^*_{weak} + \ldots$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\, g$$

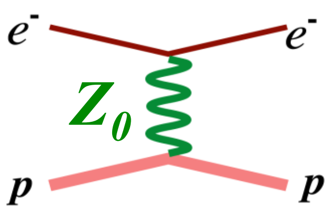
Leading contribution to parity-violating scattering asymmetry from interference of EM and weak amplitudes

$$g = g_A^e g_V^T + \beta g_V^e g_A^T$$

$A_{PV} \sim 10^{-5} \cdot Q^2$ ***to*** $10^{-4} \cdot Q^2$

- ***g_V^e and g_A^e are function of $\sin^2\theta_W$***
- ***β is a kinematic factor***
- ***g^T: nucleon structure (QCD)***

Elastic Electroweak Scattering

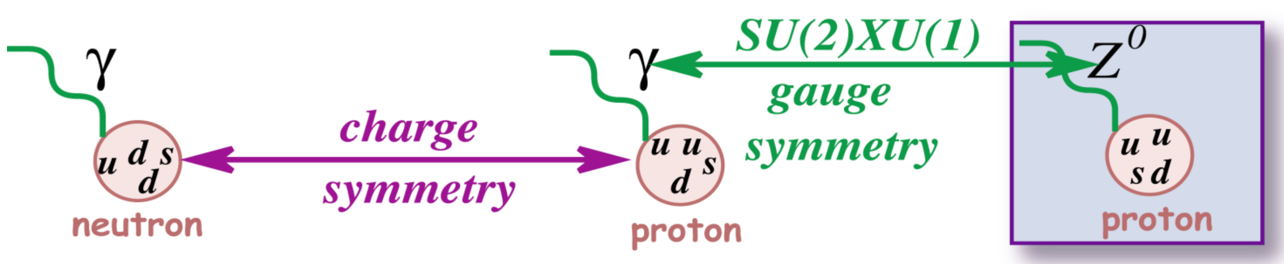


A_{PV} for elastic e-p scattering:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

$$A_E = \varepsilon G_E^p G_E^Z, \qquad A_M = \tau G_M^p G_M^Z, \qquad A_A = -\left(1-4\sin^2\theta_W\right)\varepsilon' G_M^p G_A^e$$

Forward angle ... ***Backward angle***

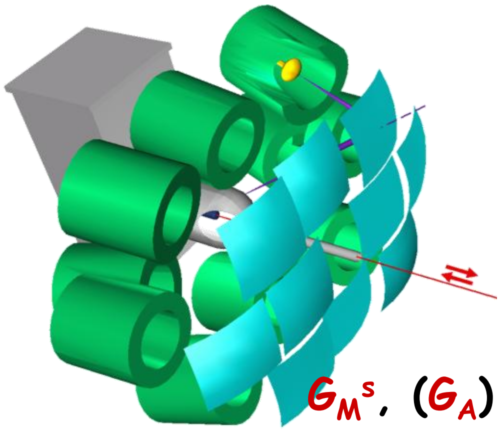


$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2),\ G_M^s(Q^2)$

$Q^2 \rightarrow 0,$ $\Rightarrow$ $\rho_s,\ \mu_s$

Overview of Experiments

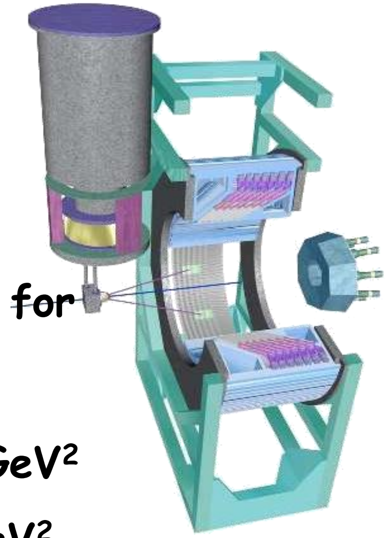


SAMPLE

open geometry, integrating

G_M^s, (G_A) at Q^2 = 0.1 GeV^2

A4



Open geometry

Fast counting calorimeter for background rejection

G_E^s + 0.23 G_M^s at Q^2 = 0.23 GeV^2

G_E^s + 0.10 G_M^s at Q^2 = 0.1 GeV^2

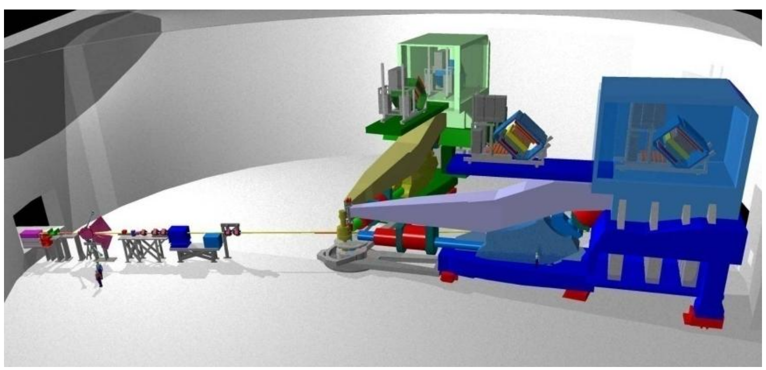
G_M^s, G_A^e at Q^2 = 0.1, 0.23, 0.5 GeV^2

HAPPEX

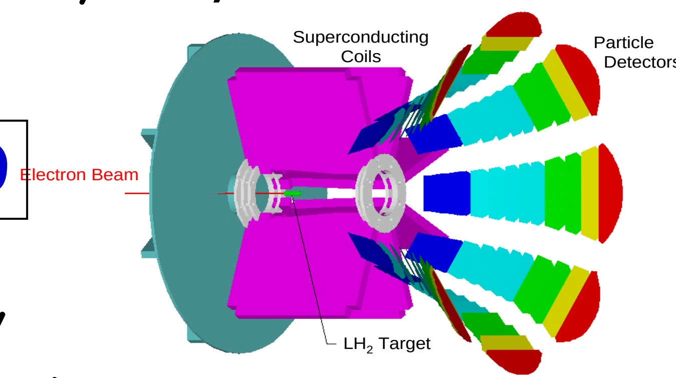
G_E^s + 0.39 G_M^s at Q^2 = 0.48 GeV^2

G_E^s + 0.08 G_M^s at Q^2 = 0.1 GeV^2

G_E^s at Q^2 = 0.1 GeV^2 (^{4}He)



G0



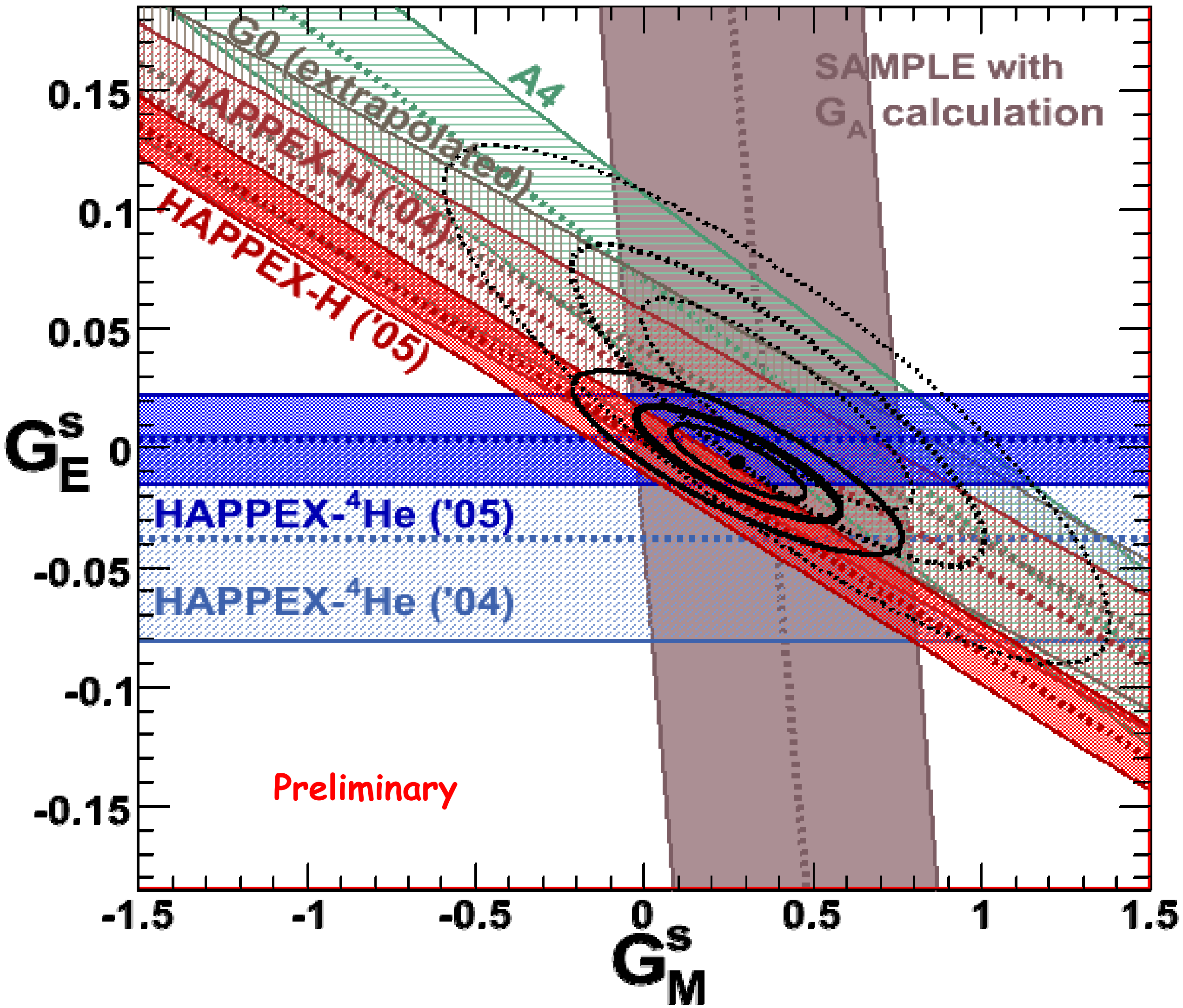
Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

G_E^s + η G_M^s over Q^2 = [0.12,1.0] GeV^2

G_M^s, G_A^e at Q^2 = 0.23, 0.62 GeV^2

World Data near Q^2 ~0.1 GeV^2



G_M^s = 0.28 +/- 0.20

G_E^s = -0.006 +/- 0.016

~3% +/- 2.3% of proton magnetic moment

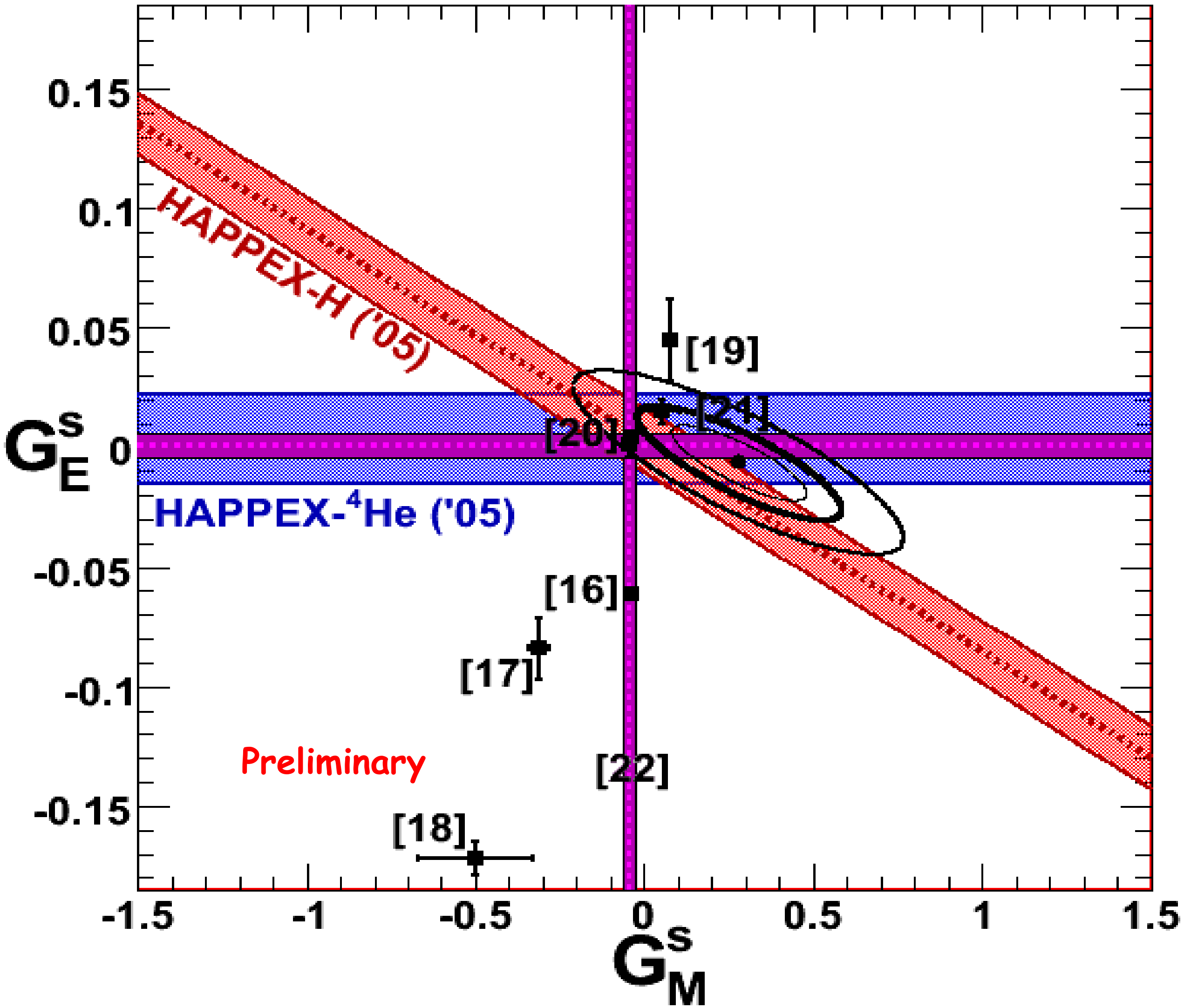
~0.2 +/- 0.5% of electric distribution

HAPPEX-only fit suggests something even smaller:

G_M^s = 0.12 +/- 0.24

G_E^s = -0.002 +/- 0.017

World data consistent with state of the art theoretical predictions



16. **Skyrme Model** - N.W. Park and H. Weigel, Nucl. Phys. *A* **451**, 453 (1992).

17. **Dispersion Relation** - H.W. Hammer, U.G. Meissner, D. Drechsel, Phys. Lett. B **367**, 323 (1996).

18. **Dispersion Relation** - H.-W. Hammer and Ramsey-Musolf, Phys. Rev. *C* **60**, 045204 (1999).

19. **Chiral Quark Soliton Model** - A. Sliva *et al.*, Phys. Rev. D **65**, 014015 (2001).

20. **Perturbative Chiral Quark Model** - V. Lyubovitskij *et al.*, Phys. Rev. *C* **66**, 055204 (2002).

21. **Lattice** - R. Lewis *et al.*, Phys. Rev. D **67**, 013003 (2003).

22. **Lattice + charge symmetry** -Leinweber et al, Phys. Rev. Lett. **94**, 212001 (2005) & hep-lat/0601025

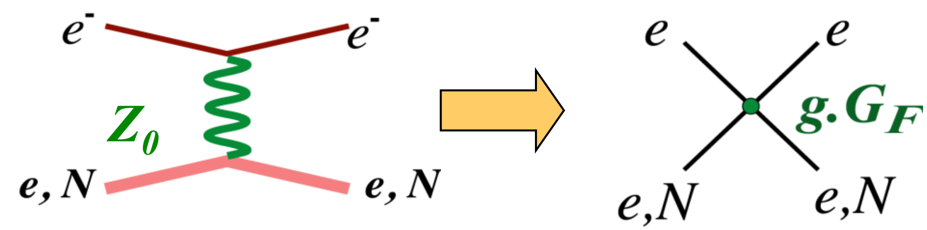
Particty Violating Electron Scattering

Standard Model Tests,

Charge Symmetry Breaking, …

Weak Neutral Current (WNC) Interactions

Low energy Weak NC interactions ($Q^2 << M_Z^2$)

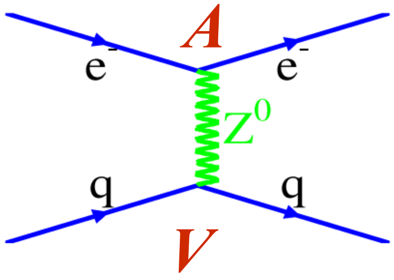


Historical Context:

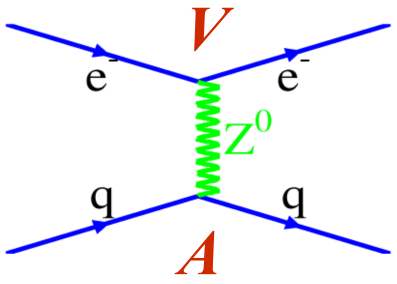
- **1960s: An Electroweak Model of Leptons (and quarks)**
  - **$SU(2)_L$ X $U(1)_Y$ gauge theory predicted the Z boson**
- **1973: antineutrino-electron scattering**
  - **First weak neutral current observation**
- **Mid-70s: first e-d DIS parity violation experiment at SLAC: *$Q^2 \sim 1\ (GeV)^2$***
  - **Central to establishing $SU(2)_L$ X $U(1)_Y$**

•Established experimental technique: $\delta(A_{PV}) < 10$ ppm
•Cleanly observed weak-electromagnetic interference
•$\sin^2\theta_W = 0.224 \pm 0.020$: same as in neutrino scattering

Electron-Quark Phenomenology



$$C_{1i} \equiv 2g_A^e g_V^i$$



$$C_{2i} \equiv 2g_V^e g_A^i$$

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) \approx -0.19$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) \approx 0.35$$
$$C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) \approx -0.04$$
$$C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$

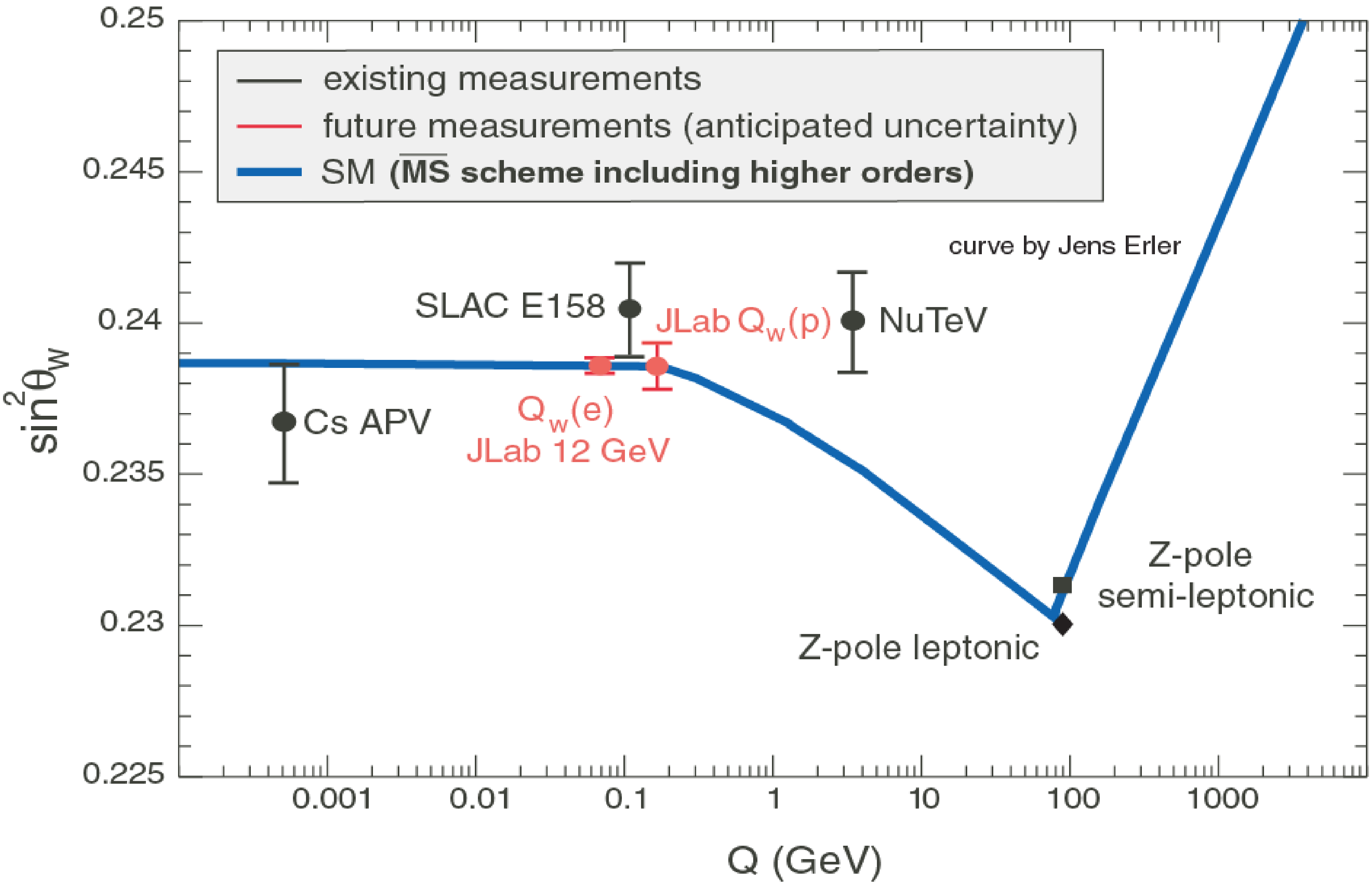
C_{1u} and C_{1d} will be determined to high precision by Q_{weak}, Cs

C_{2u} and C_{2d} are small and poorly known:
one combination can be accessed in PV DIS

New physics such as compositeness, leptoquarks:
Deviations to C_{2u} and C_{2d} might be fractionally large

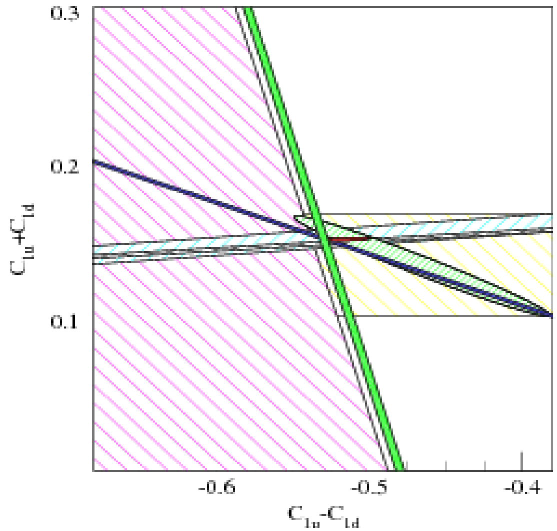
Low Energy Tests of the Standard Model

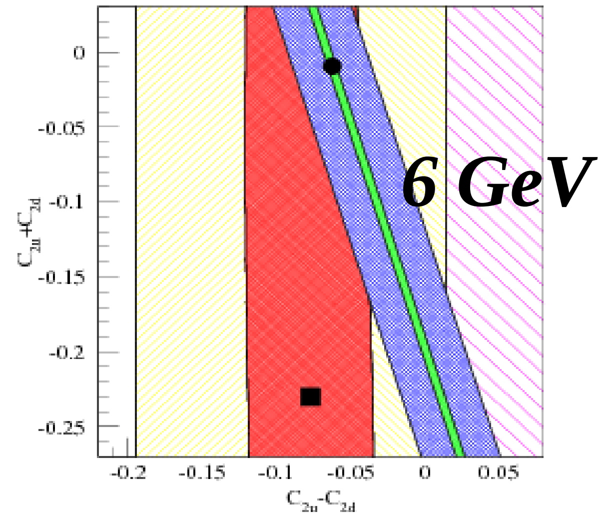
K. Kumar's talk



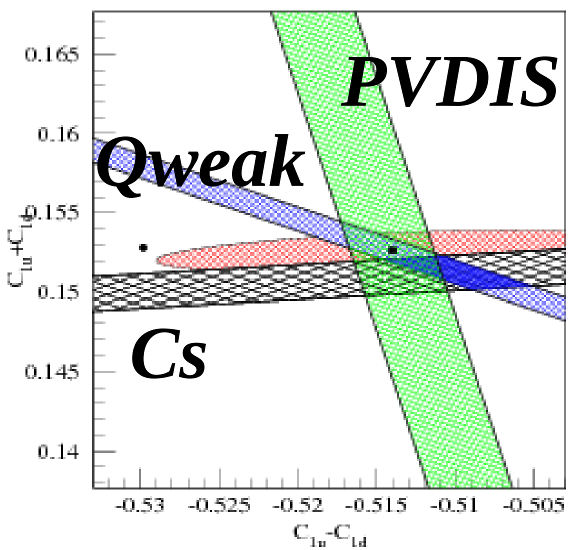
Sensitivity: C_1 and C_2 from PVDIS/Qweak

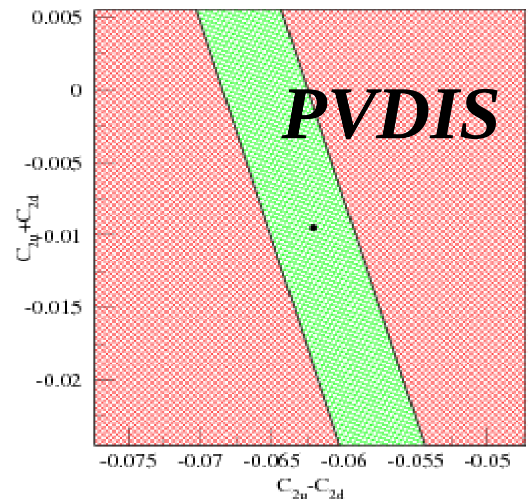
World's data





Precision Data

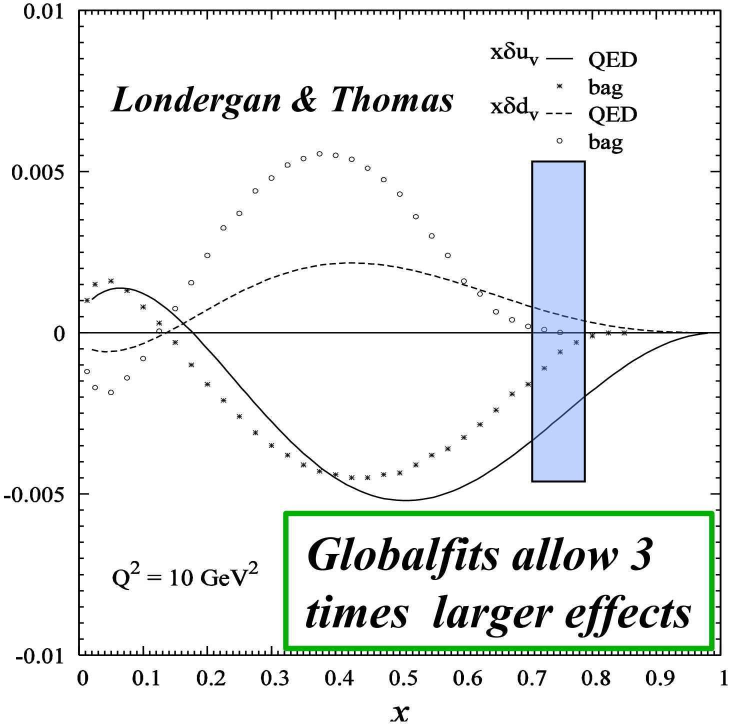




P. Souder's talk

Precision Hadronic Physics with DIS PV

- *Charge Symmetry Violation (CSV) at High x: clean observation possible?*



$$\delta u(x) = u^p(x) - d^n(x)$$

$$\delta d(x) = d^p(x) - u^n(x)$$

$$\frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.3\,\frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

- *Direct observation of parton-level CSV: exciting!*
- *Implications for high energy collider pdfs*
- *Could explain significant portion of the NuTeV anomaly*

Londergan & Thomas, B. Ma,…

- *d(x)/u(x) at as $x \to 1$*

  Longstanding QCD prediction

  Needs high precision without nuclear effects

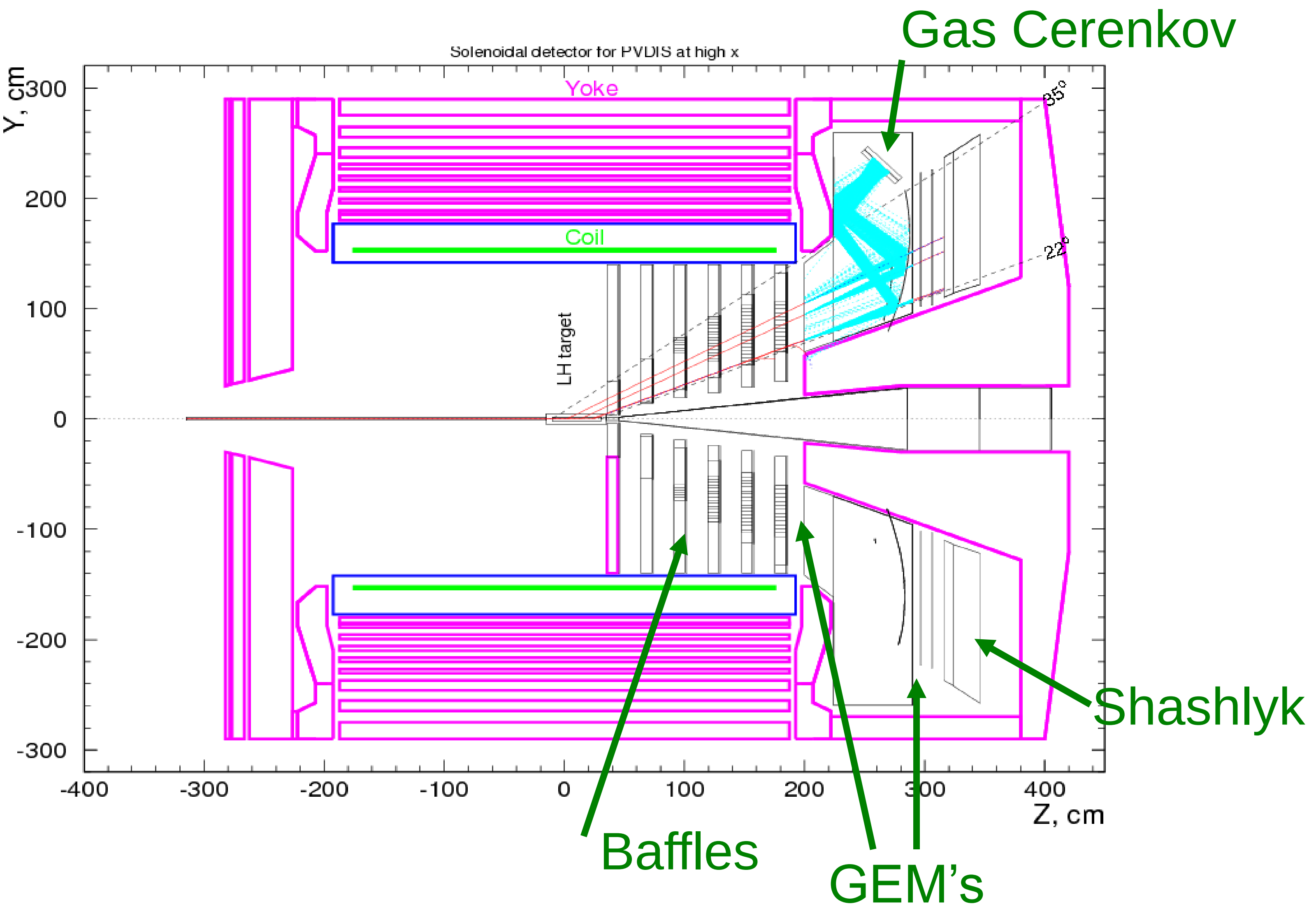
- *Higher Twist*

  Quark-gluon correlations

  Difficult to extract from DIS structure functions

  DIS PV: 'clean' extraction of twist-4

SoLID Spectrometer



Summary

- DIS: probe quark-gulon structure of the nucleon, PDFs
- Spin structure study full of surprises and puzzles
- A decade of experiments from JLab: exciting results
    - valence spin structure
    - spin sum rules and polarizabilities
    - test χPT calculations, → 'δ_{LT} puzzle'
    - precision measurements of g_2/d_2: high-twist
- Transversity and TMDs: spin-orbit and multi-parton correlations
    - first neutron transversity measurement
    - precision 4-d mapping with SOLID at 12 GeV
- Parity violating electron scattering
    - Strangeness form factors
    - Standard model test
    - Precision tool to study hadron structure