Nucleon Structure Study with JLab 12 GeV

Jian-ping Chen (陈剑平) , Jefferson Lab

Hadron-China2014, Lanzhou, China, July 21-24, 2014

- Form Factors, GPDs, …
- **Nucleon Spin Study: recent results and 12 GeV plan**
- **TMDs with 6 GeV JLab: Exploration,** Recent results
- **Plan at JLab 12 GeV for TMD study: Precision Multi-d Mapping**

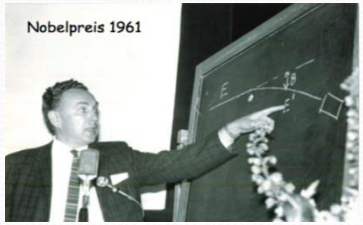
  SoLID Program on TMDs
- Long-term Future: Electron-Ion Colliders (EIC)

Electron Scattering and Nucleon Structure

- 1960s: Discovery: Proton Has Internal Structure

  elastic electron scattering

  Nucleon Form Factors -> EM Distributions

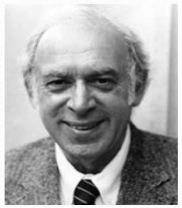


Robert Hofstadter,
Nobel Prize 1961

- 1970s: Discovery of Quarks (Partons)

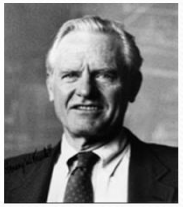
  inclusive deep-inelastic scattering (DIS)

  Structure Functions -> Parton Distributions



J.T. Friedman

R. Taylor



H.W. Kendall

Nobel Prize 1990

- 2004 Nobel prize for QCD

  ``asymptotic freedom''

- 1980s: "Spin Crisis"

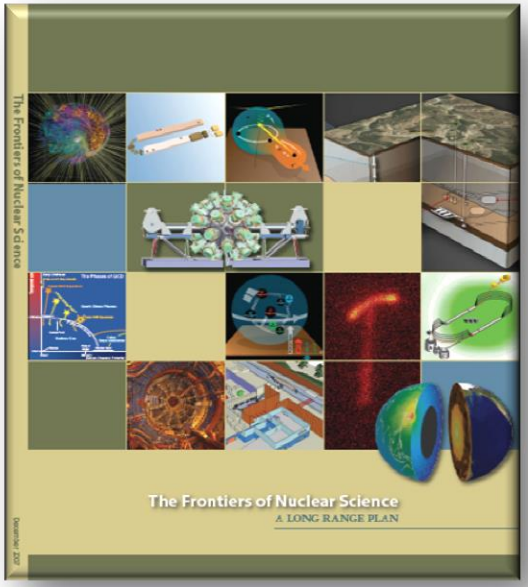
  Spin Distributions, Sum Rule, Gluon, Quark Orbital Angular Momentum

- 2000s: 3-d Structure: TMDs and GPDs

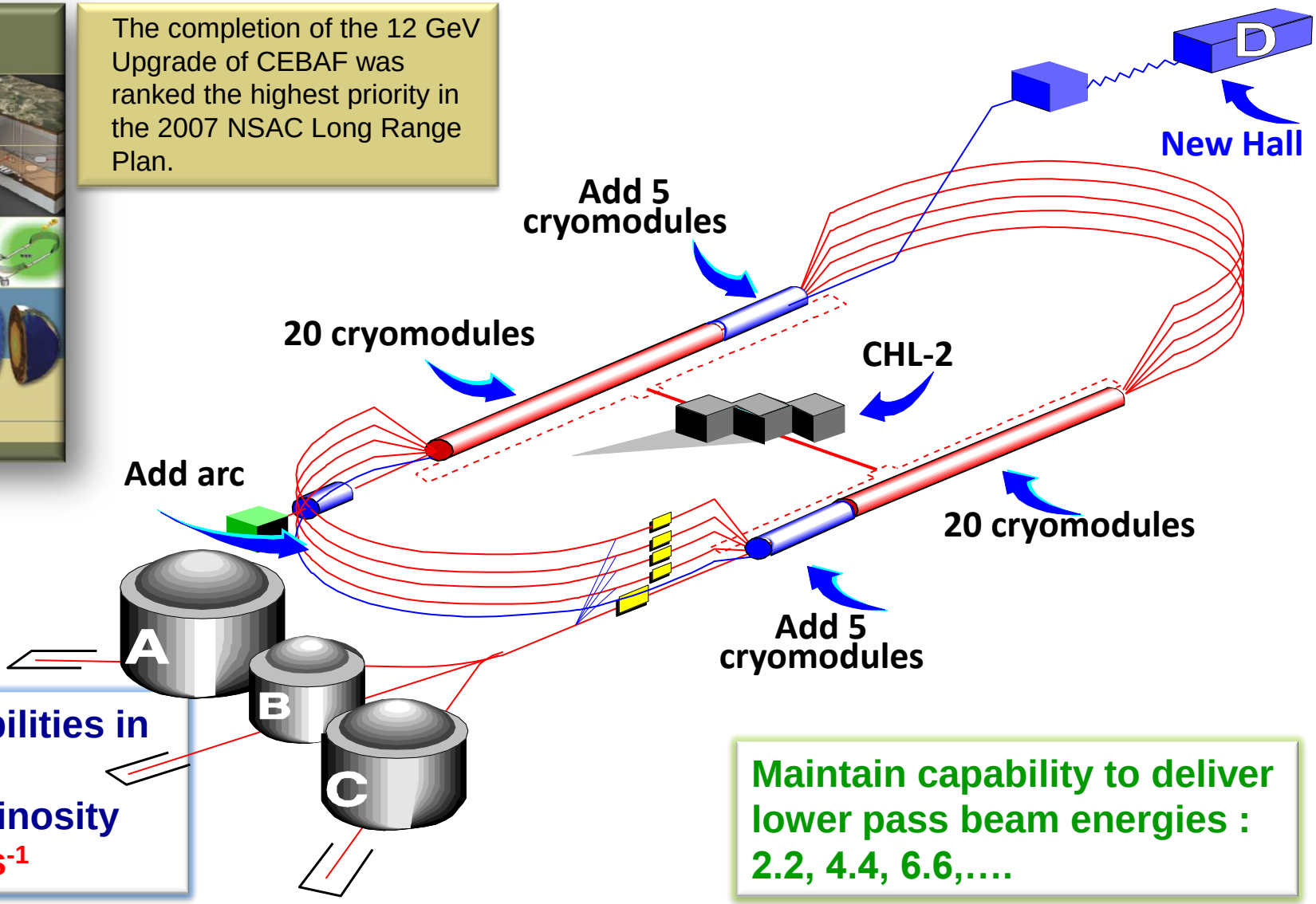
  QCD Dynamics, Non-perturbative region, Confinement

  Lattice QCD, Dyson-Schwinger, Ads/CFT: Holographic QCD

JLab 12 GeV Upgrade



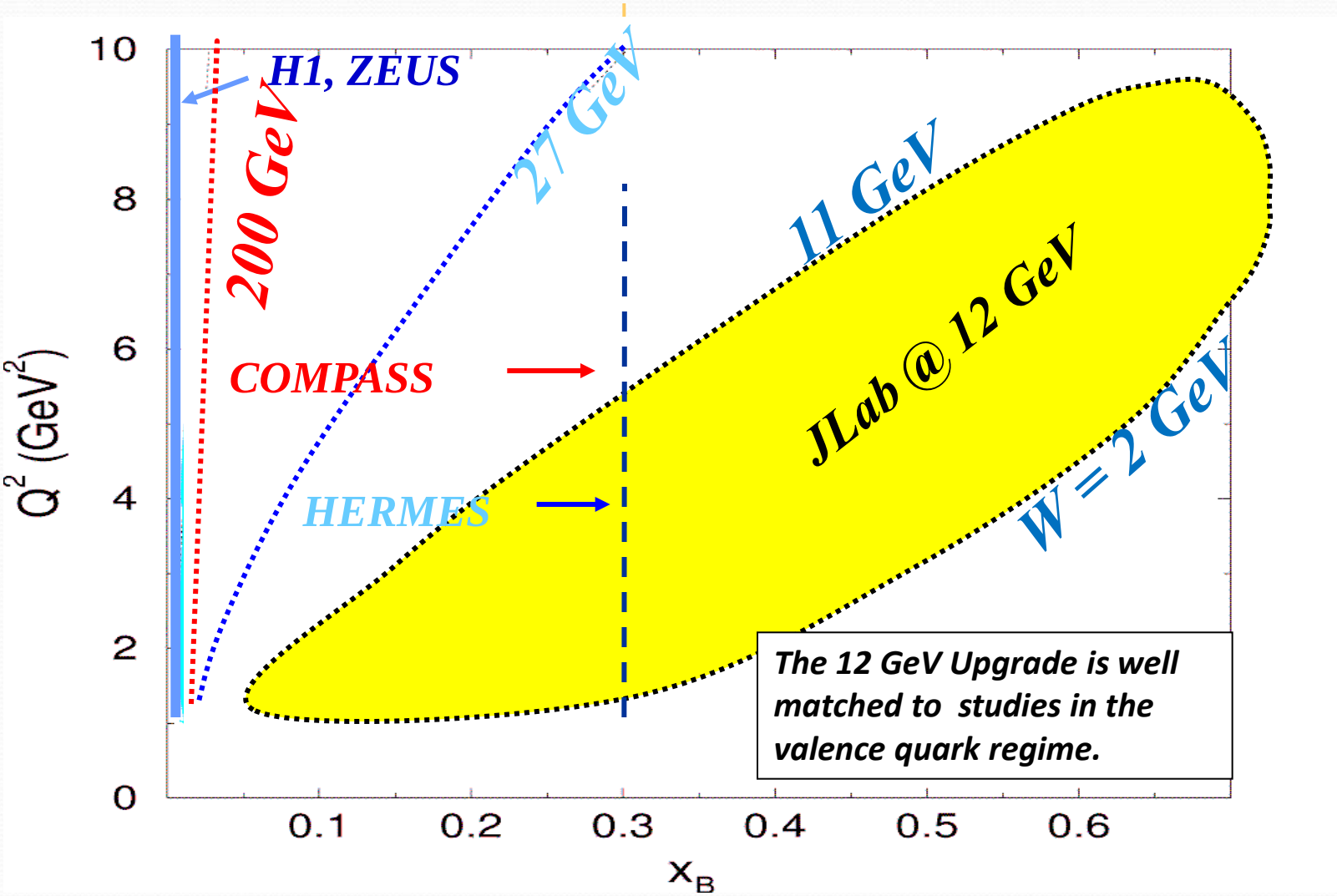
The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.



- **Enhanced capabilities in existing Halls**
- **Increase of Luminosity 10^{35} - ~10^{39} $cm^{-2}s^{-1}$**

Maintain capability to deliver lower pass beam energies : 2.2, 4.4, 6.6,….

Kinematics Coverage of the 12 GeV Upgrade



JLab Spin Program: Precision Measurements
Valance Quark Region
Moments: Spin Sum Rules/Polarizabilities
Higher-Twist: Quark-Gluon Correlations

A_1 and d_2 from JLab: Results and Plan

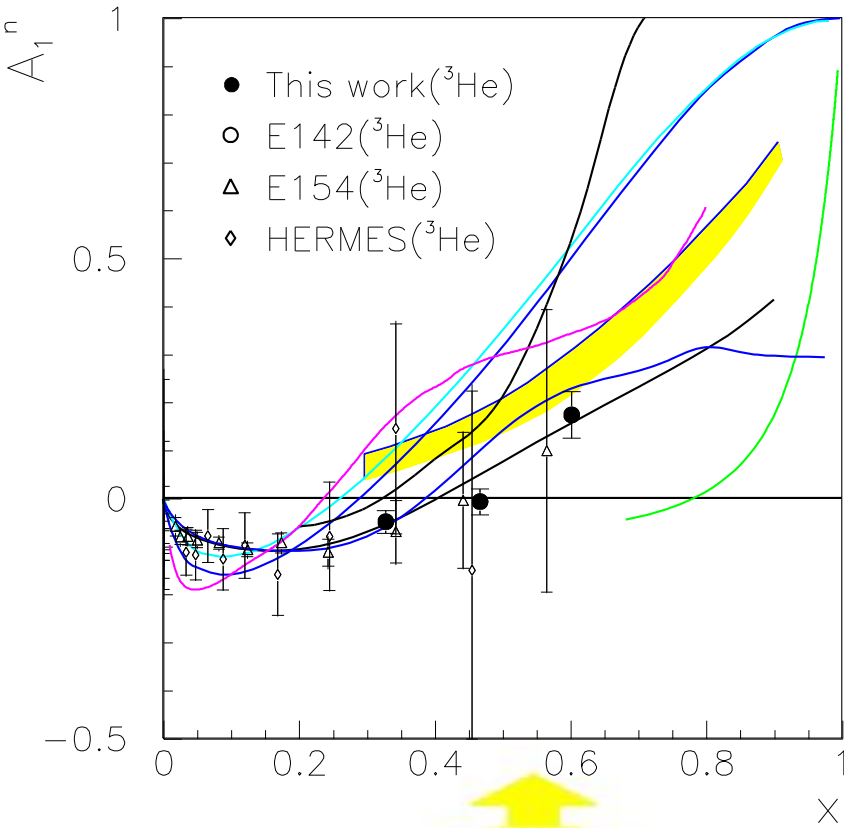
JLab Spin Experiments

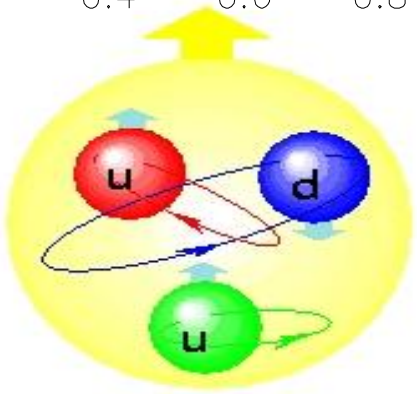
- High polarized luminosity → precision measurements
- Earlier JLab Spin Results
  - Spin Asymmetry **A_1 / g_1 in the Valence (High-*x*) Region**
  - Spin Moments: Spin Sum Rules and Polarizabilities,
  - Spin Structure in the Resonance Region
  - Reviews: S. Kuhn, J. P. Chen, E. Leader, Prog. Part. Nucl. Phys. 63, 1 (2009)
- Recent experiments with transversely polarized targets
  - **g_2 measurements to extract d_2 (SANE, d2n)**
  - Low Q^2: SAGDH, EG4, **g2p** **(Chao Gu's talk)**
- 12 GeV Program: **A1n (Hall A/C), A1p (Hall B), d2n (Hall C)**

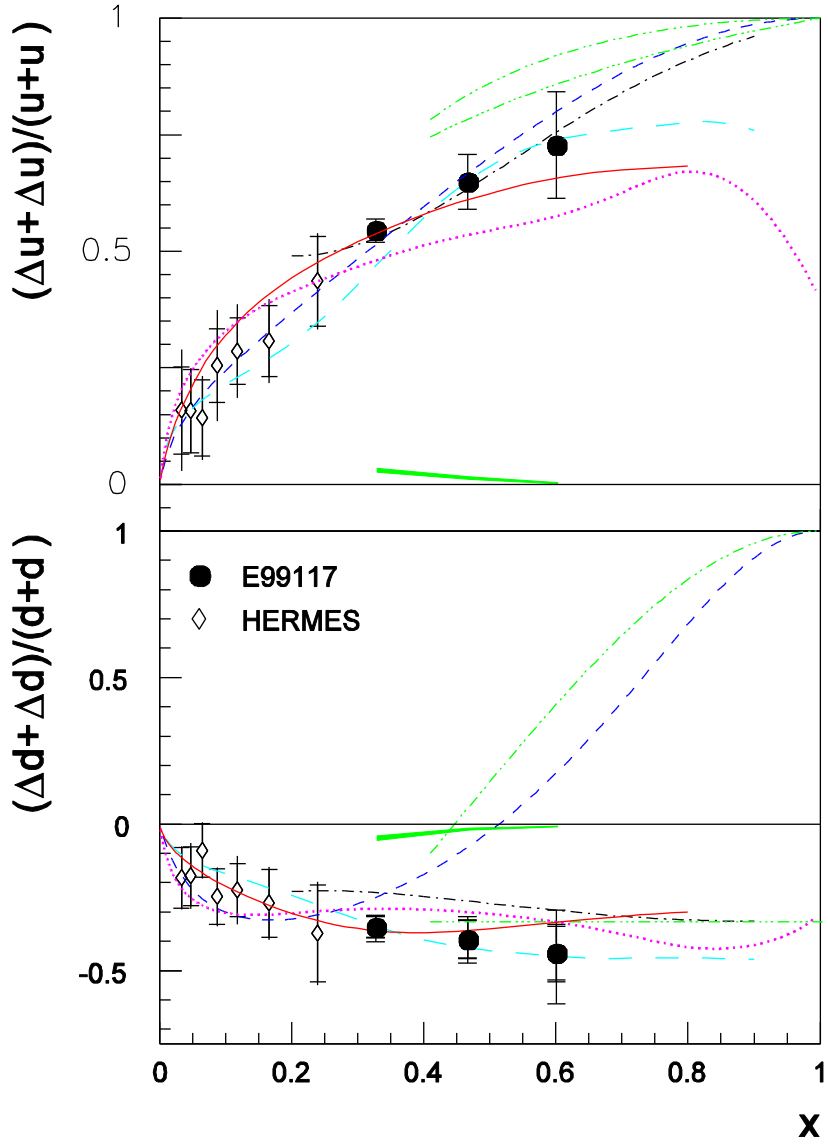
JLab E99117: *Precision Measurement of A_1^n at High-x*

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

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

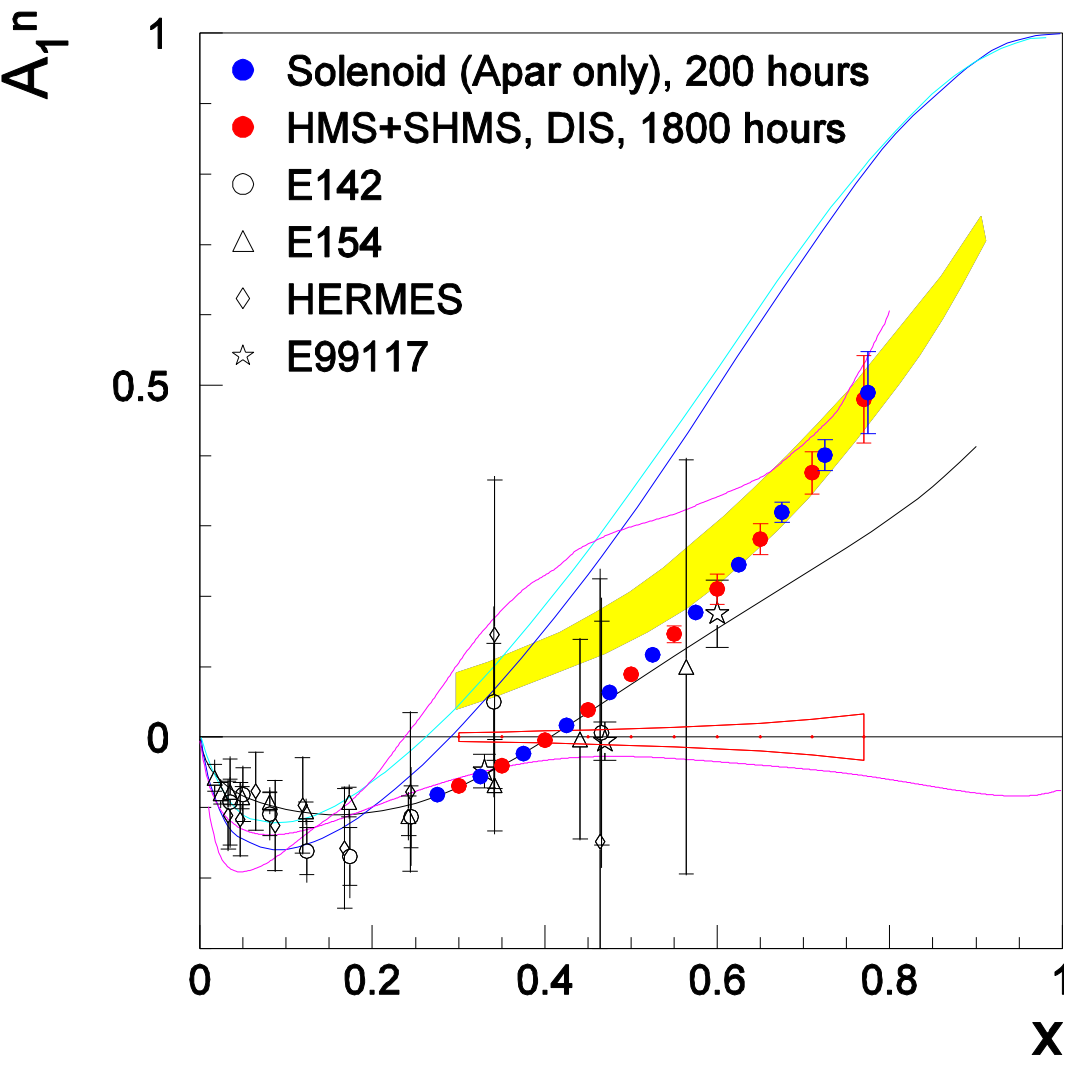




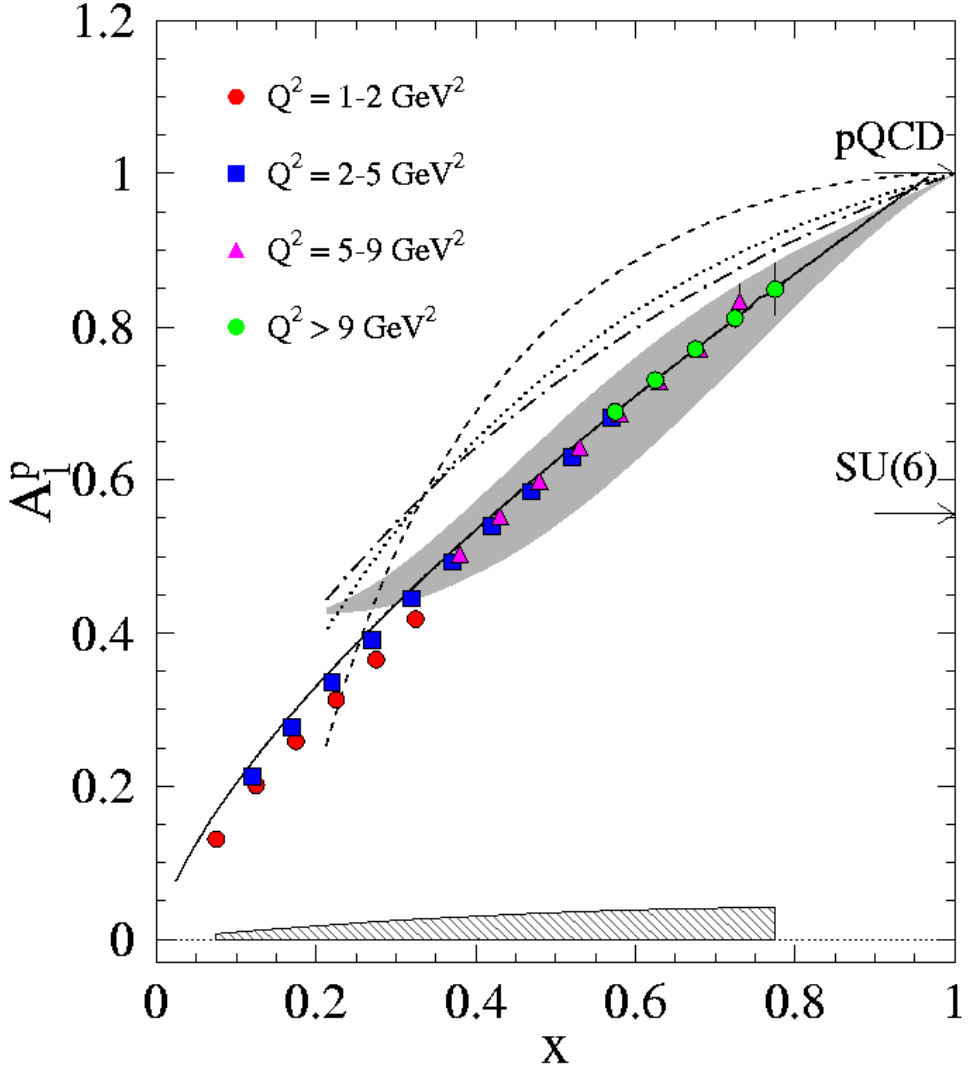


Projections for JLab at 11 GeV

A_1^n at 11 GeV



A_1^p at 11 GeV



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

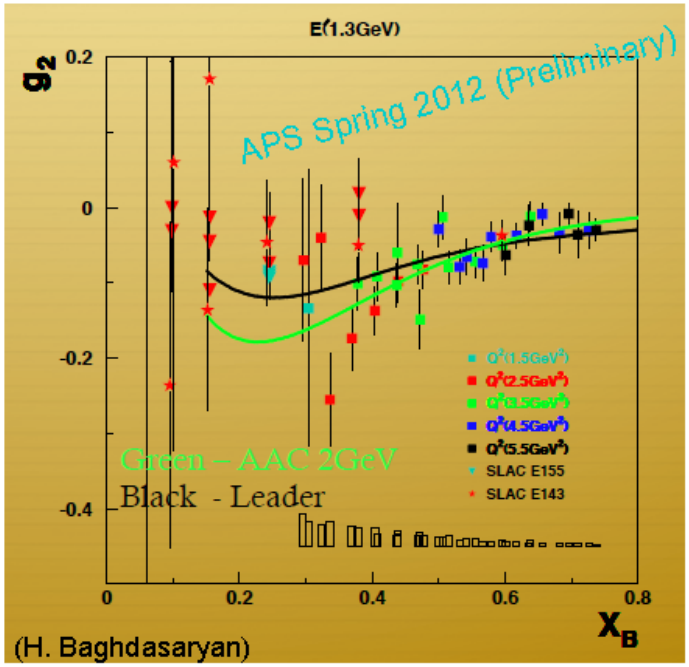
Provide a benchmark test of Lattice QCD at high Q^2

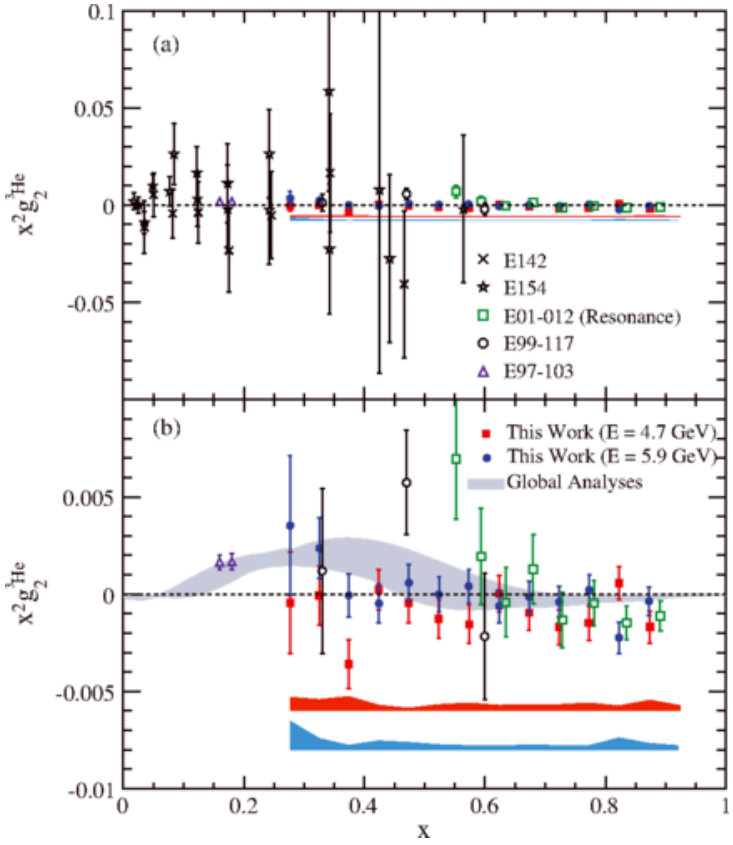
Avoid issue of low-*x* extrapolation

Related to Sivers Function?

SANE (p) and d2n (n) Experiments

g_2 in DIS and Resonance Region



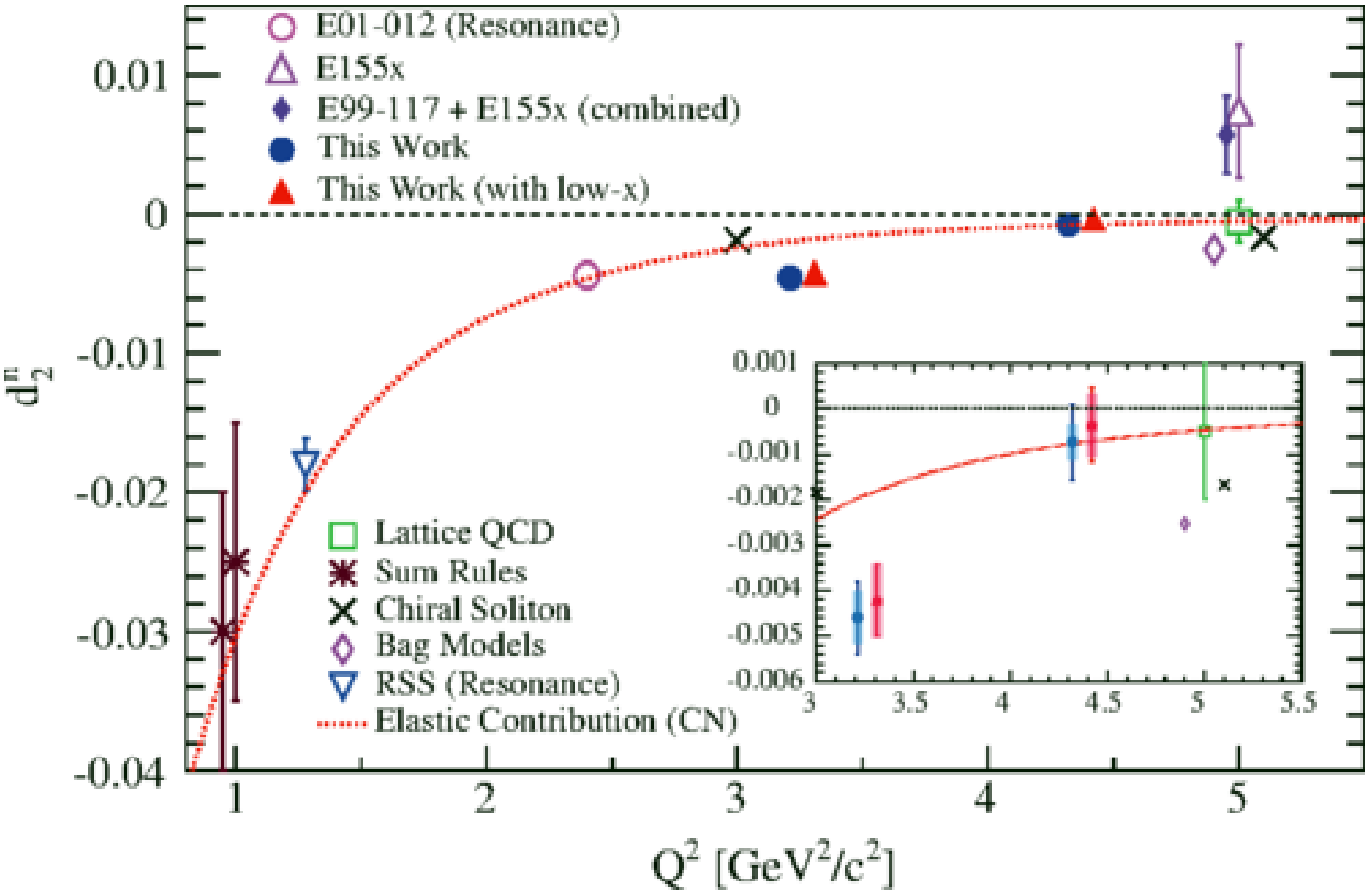


- Proton (NH_3)
  - Hall C SANE (E07-003)
  - $0.3 < x < 0.8 \quad 2.5 < Q^2 < 6.5$

n and ^{3}He **(PRL 113, 022002 (2014))**
Hall A d2n (E06-014)
4.7 and 5.9 GeV Beam Energy

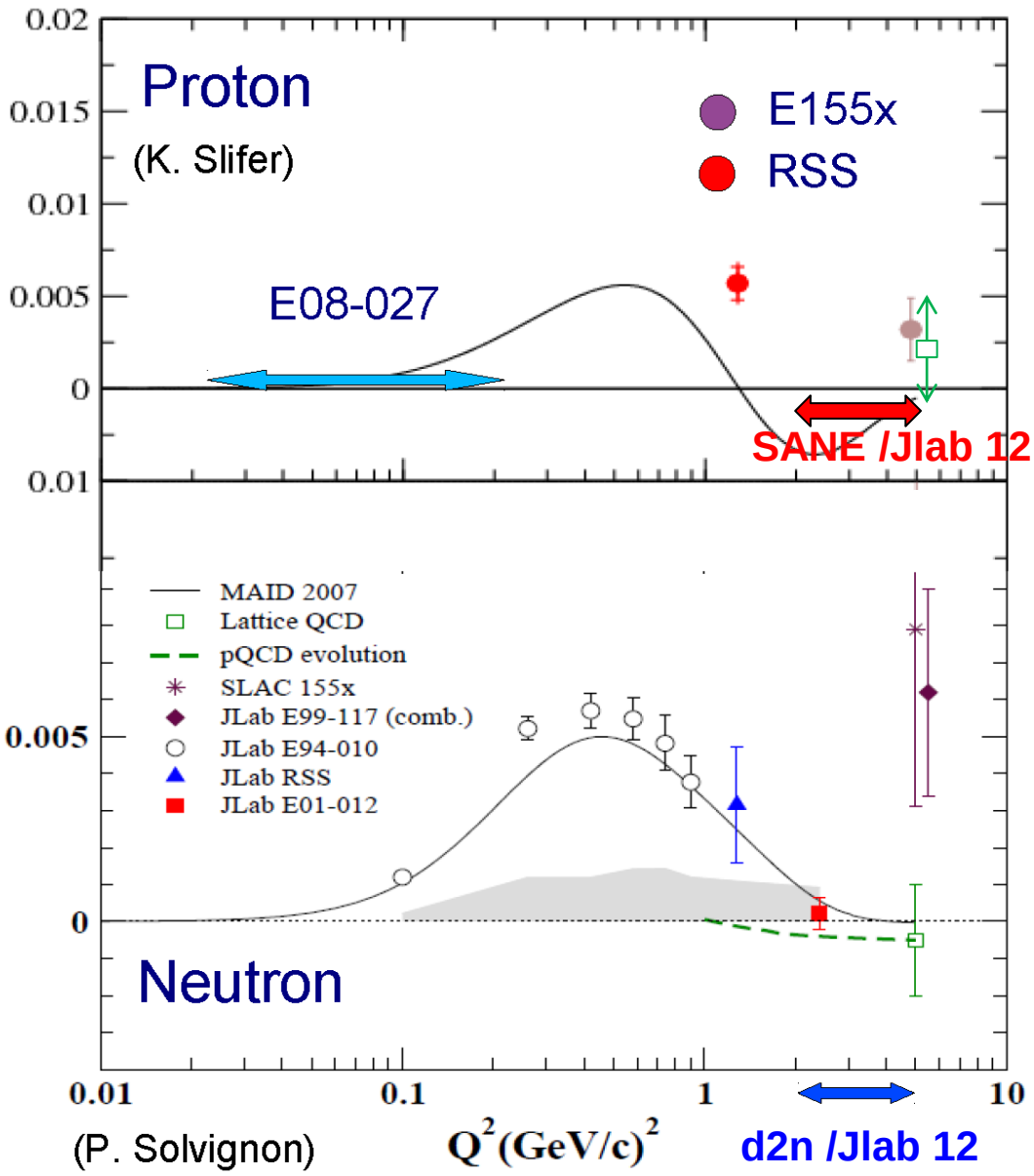
Hall A d_{2n} Results
(PRL 113, 022002 (12014))

- d2n from JLab and world
- Bench mark test of LQCD at high Q^2
- Elastic contribution significant at low Q^2, but well known
- Contributions from unmeasured Low x region usually not significant due to x^2 weighting



d_2 Measurements and Projections

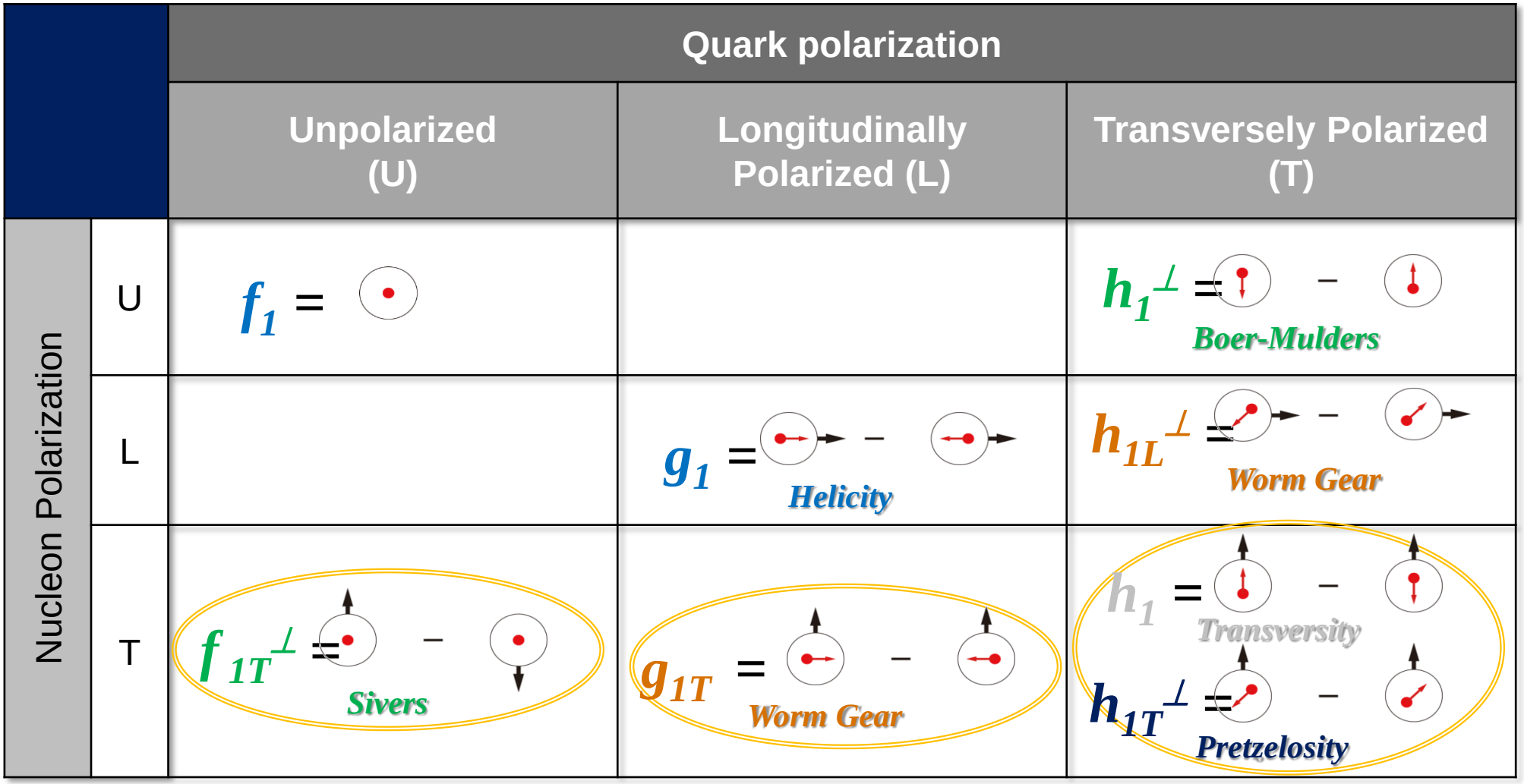
- d_2 moments for
  p (E155x, RSS, SANE, JLab12)
  n (E155x, E01-012, d2n, JLab12)
- Benchmark test of LQCD
- Only contributions from the measurement region
- Elastic not included (only important for $Q^2 < 2$ GeV^2)



Transverse Momentum Dependent Distributions
6 GeV Results

Results from JLab Hall A E06-010

Leading-Twist TMD PDFs



Nucleon Spin

Quark Spin

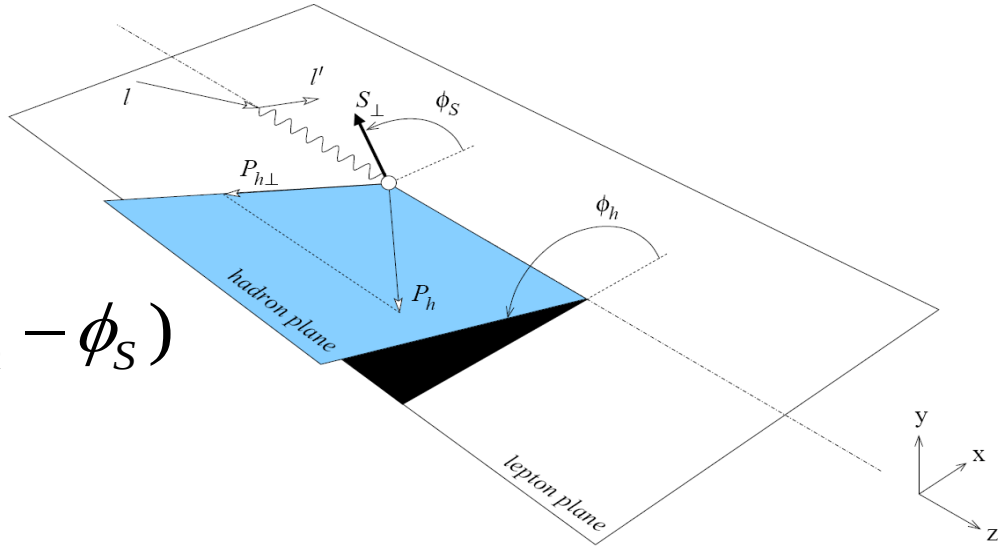
: Probed with transversely pol target
HERMES, COMPASS, JLab E06-010

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



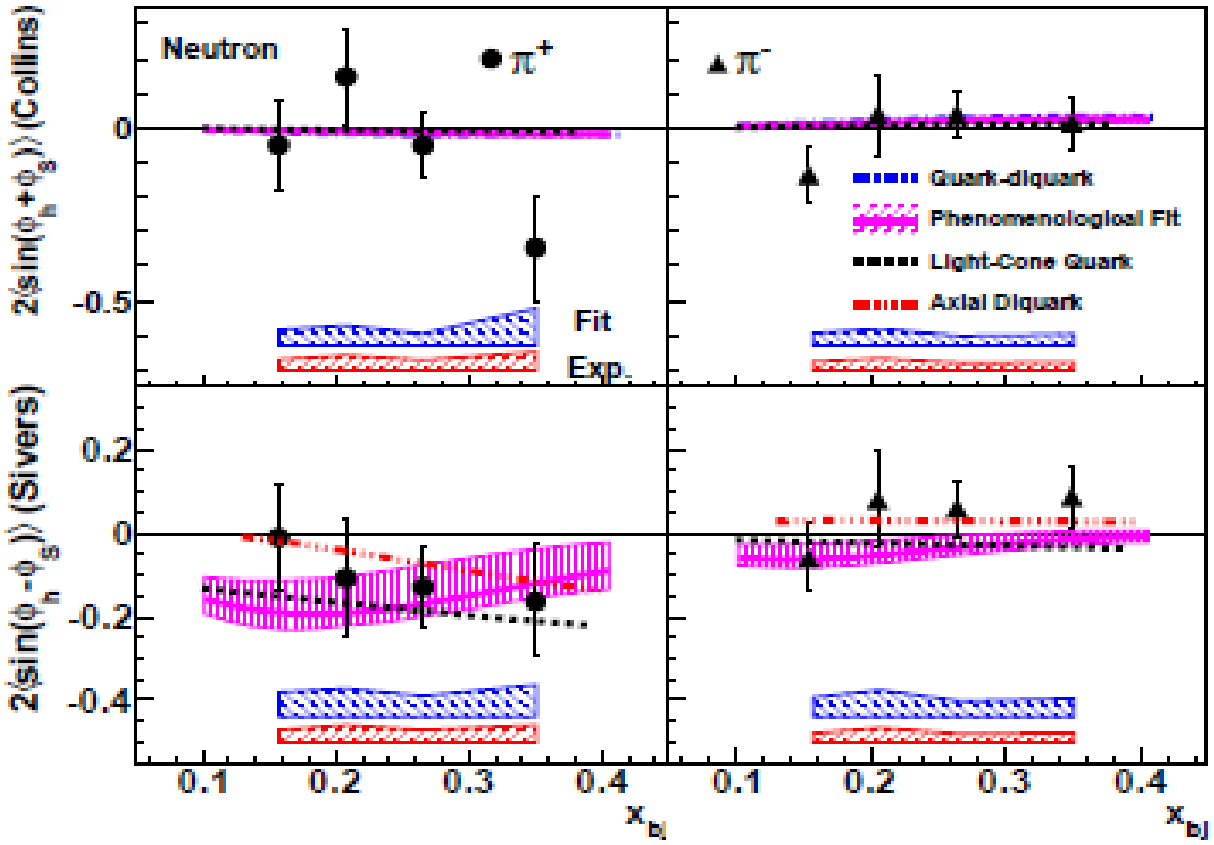
$$A_{UT}^{Collins} \propto \left\langle \sin(\phi_h + \phi_S) \right\rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

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

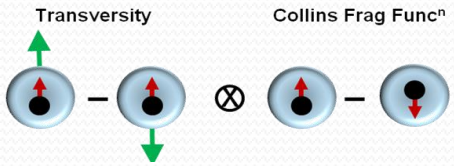
$$A_{UT}^{Pretzelosity} \propto \left\langle \sin(3\phi_h - \phi_S) \right\rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

E06-010: Collins/Sivers on Neutron (^{3}He)

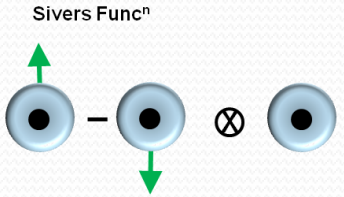
X. Qian, *et al.*, PRL 107 072003 (2011)



Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

- 

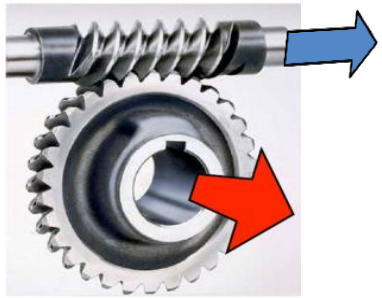
Collins asymmetries ->
  - -- Transversity
  - – Tensor charge: LQCD
  - – **Data are limited by stat. Needs more precise data!**



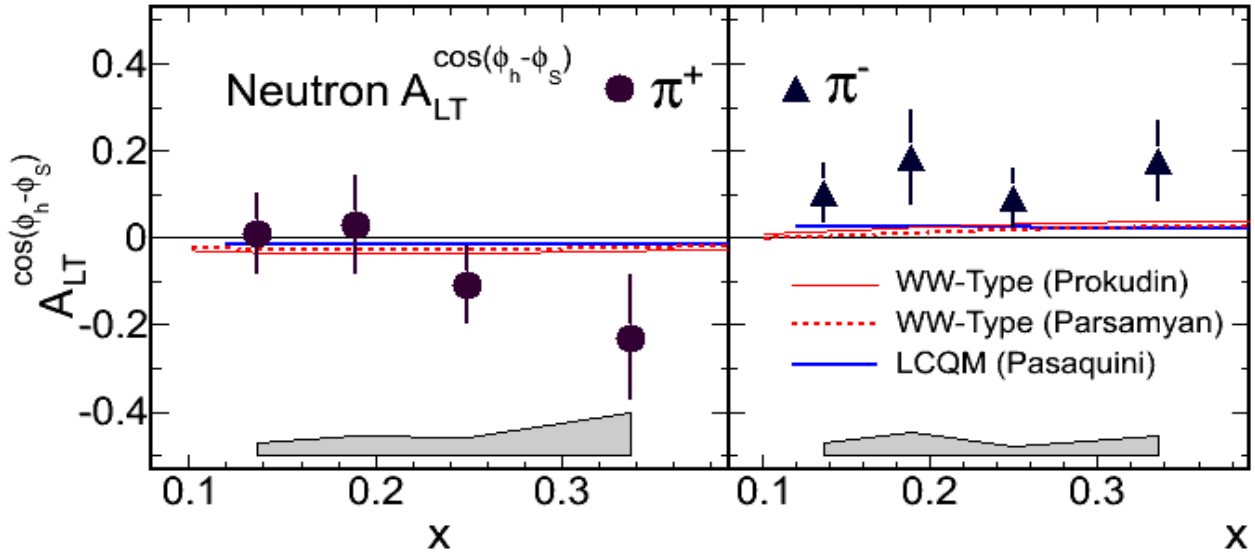
- Negative Sivers π^+ Asymmetry
  - – Consistent with HERMES/COMPASS
  - – **Independent demonstration of negative d quark Sivers function.**

E06-010: Neutron A_{LT}

J. Huang et al., PRL. 108, 052001 (2012).



- $$A_{\mathrm{LT}}^{n} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$
  - Dominated by L=0 and L=1 interference
- Consist w/ model in signs, suggest larger asymmetry



E06-010: Pretzelosity Results on Neutron

Y. Zhang et al. submitted to PRC, arXiv: 1312.3047

Pretzelosity: L=0 and 2 Interference

Pretzelosity Asymmetries,

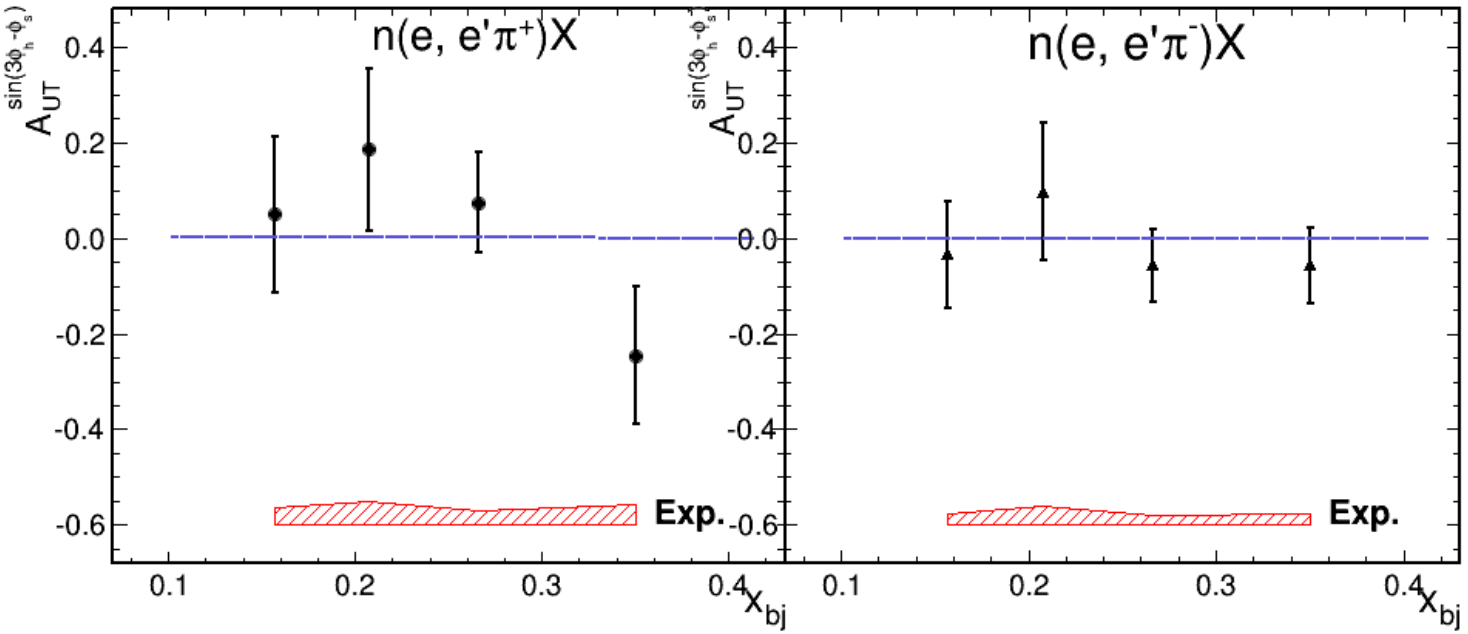
$A_{UT}\sin(\varphi_h - \varphi_s)$, on the neutron

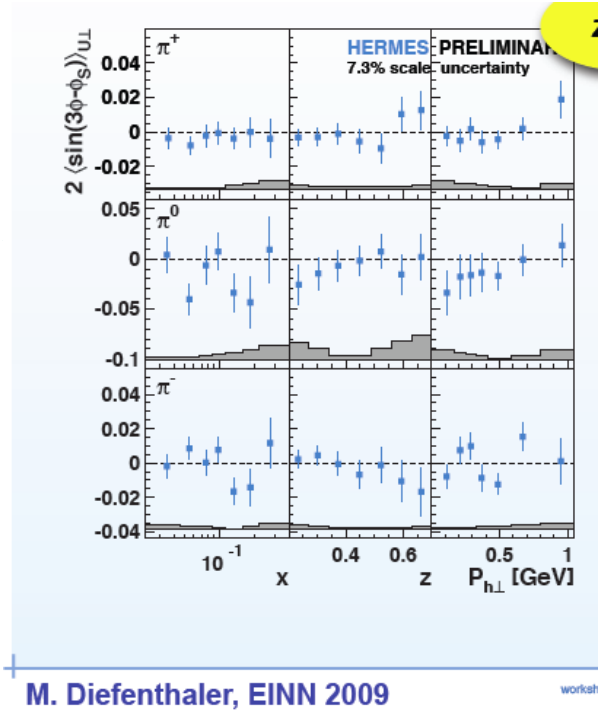
For both π+ and π-,

consistent with zero within uncertainties

.

Preliminary Results



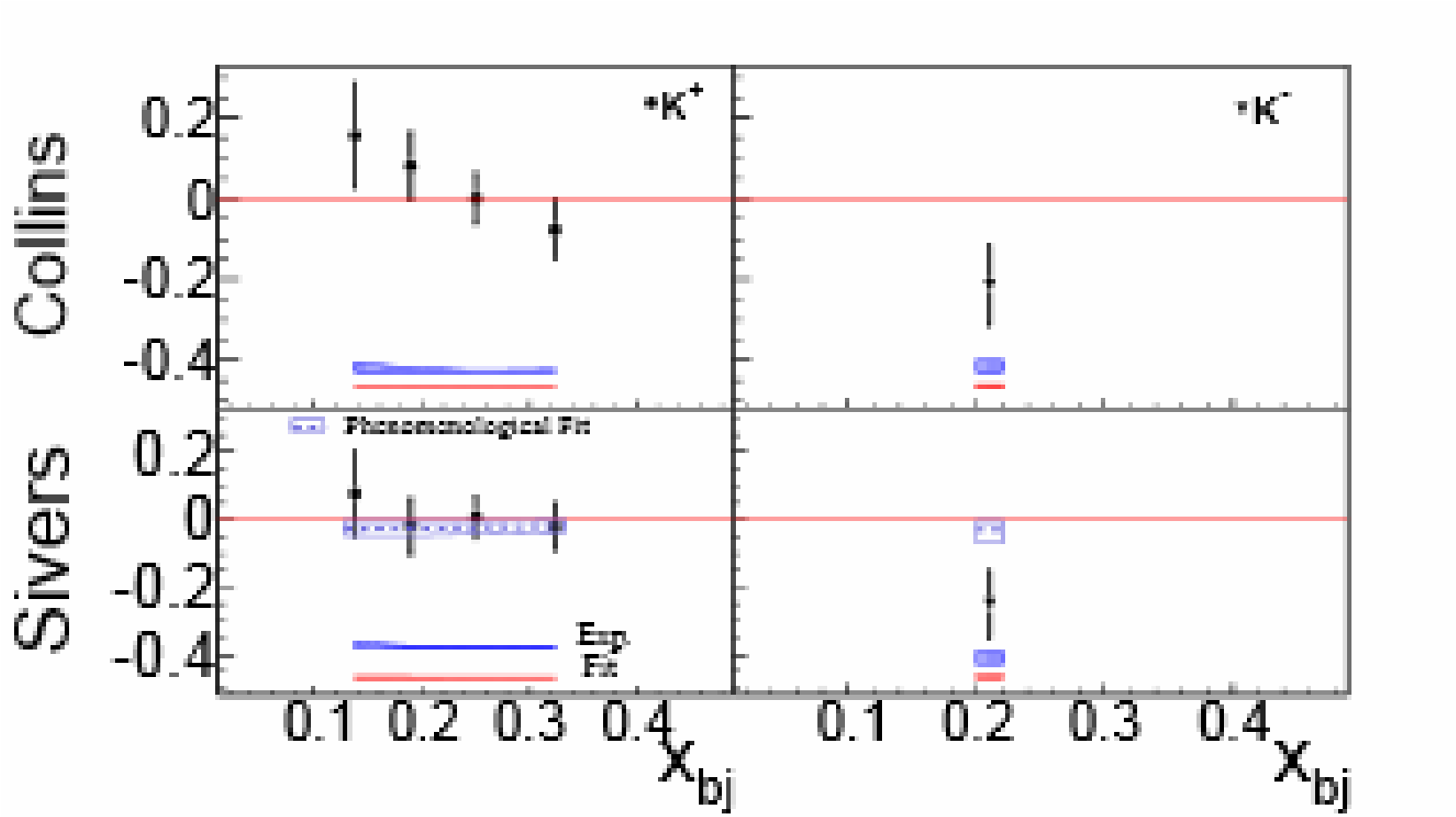


HERMES

E06-010: K+/K- Collins and Sivers on ^{3}He

Y. Zhao et al, submitted to PRC (arXiv:1404.7204)

Large negative K^- Asymmetries

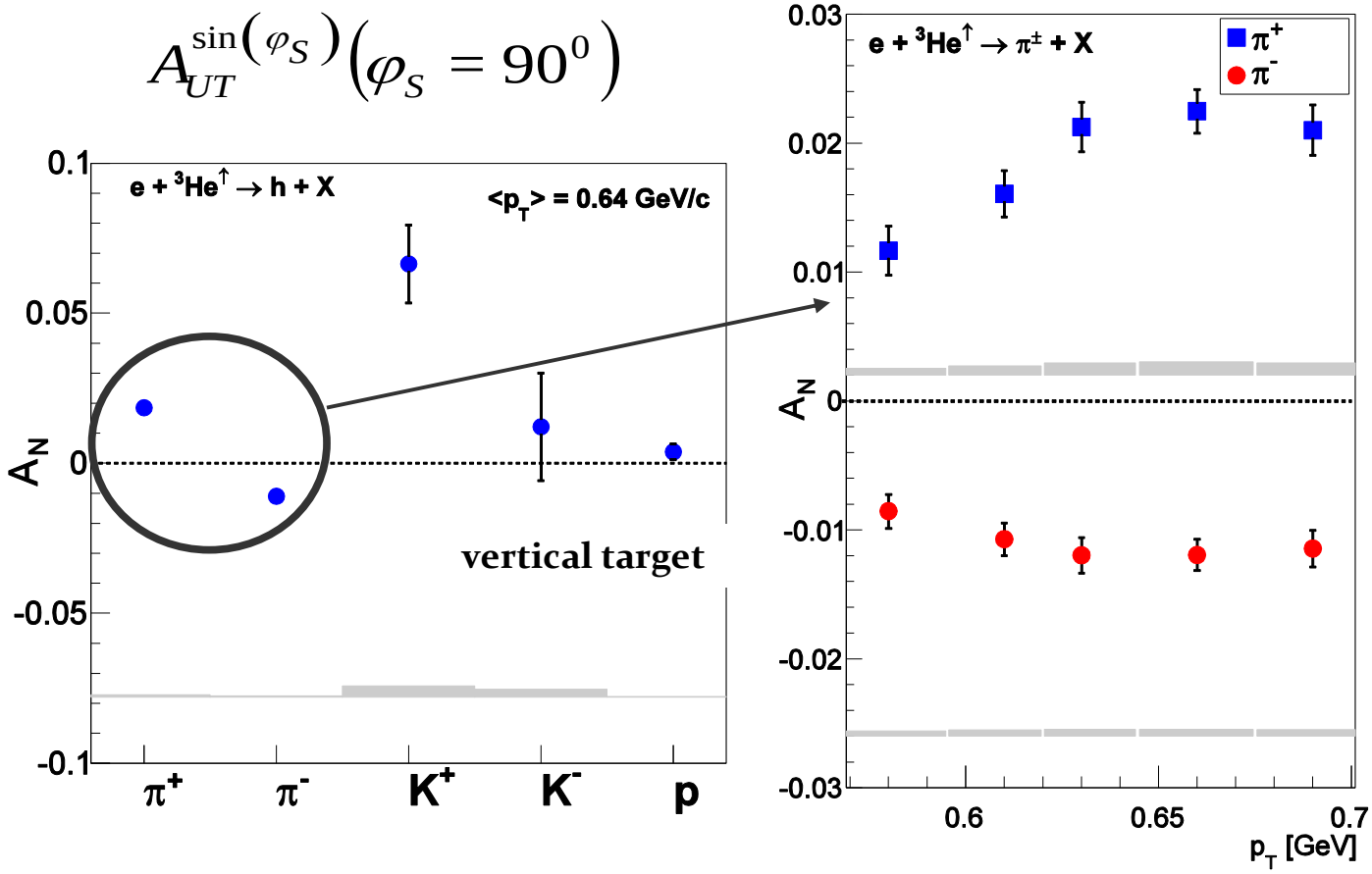


E06-010: Inclusive Hadron SSA (A_N)

K. Allada, Y. Zhao, et al., PRC. 89, 042201, 2014.

- **Clear non-zero target SSA**
- **Opposite sign for π^+ and π^-**
- **A_N at low p_T not very well understood**
- **Results consistent with predictions based on Sivers mechanism (valid at high p_T)**

$$A_{UT}^{\sin(\varphi_S)}\left(\varphi_S = 90^0\right)$$



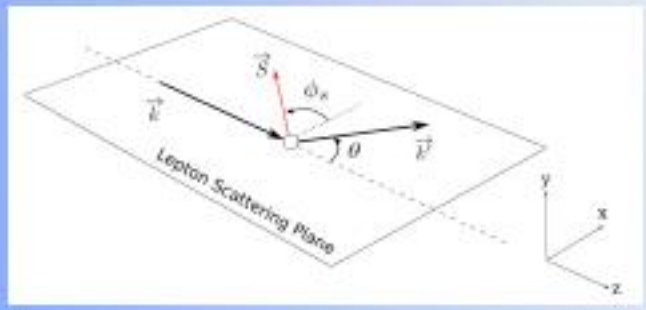
Jefferson Lab
Thomas Jefferson National Accelerator Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

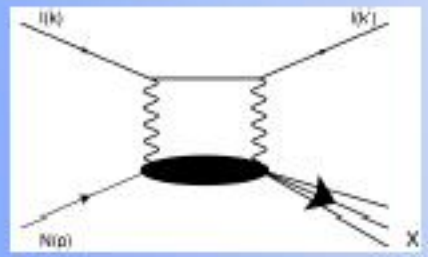
First Observation of a Non-Zero Target-Normal Single-Spin Asymmetry

Jefferson Lab E07-013, Hall A, Polarized ^{3}He Collaboration,
J. Katich *et al.*, Phys. Rev. Lett. **113**, 022502 (2014)

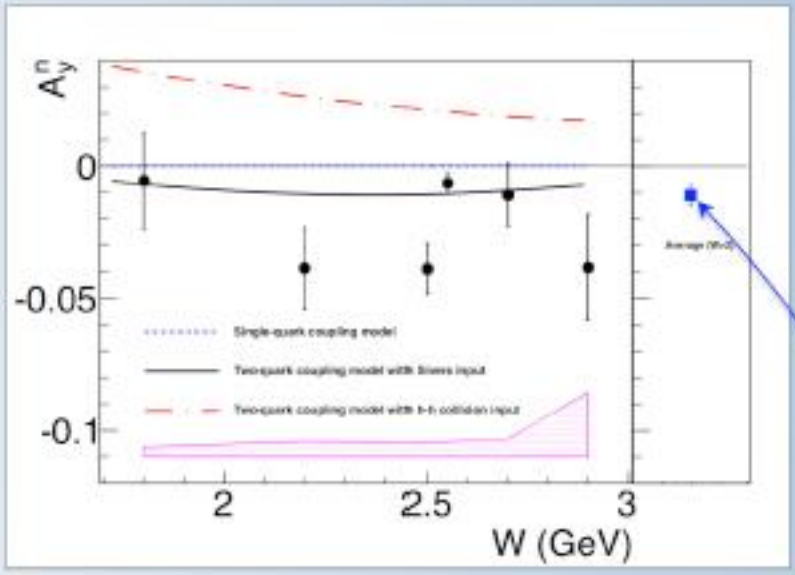
- Un-polarized electrons, transversely polarized target, inclusive DIS reaction $^3\mathrm{He}^{\uparrow}(e,e')X$
- No Born contribution due to time-reversal invariance
- Direct access to nucleon dynamics through two-photon processes
- Parton model predictions $A_y^n \approx 10^{-2}$ *to* 10^{-4}, sign not known
- Predictions have opposite signs using input from SIDIS vs. hadron-hadron collisions



$$A_{UT}(\phi_S) = \frac{d\sigma(\phi_S) - d\sigma(\phi_S + \pi)}{d\sigma(\phi_S) + d\sigma(\phi_S + \pi)} = A_y \sin\phi_S$$



- Two-photon exchange asymmetry
  - -- zero for non-interacting quarks
  - -- non-zero with qgq, qγq correlations



- First measurement of target single-spin asymmetry for neutrons
- First non-zero measurement (3σ) of target single-spin asymmetry
- Consistent with model using SIDIS Sivers input
- Result: $A_y^n = (-1.09 \pm 0.38) \times 10^{-2}$ ($W > 2$ GeV)

Future: TMD study with SoLID at 12 GeV JLab Hall A

Precision 4-D mapping of TMD asymmetries
with Polarized ^{3}He (Neutron) and Proton

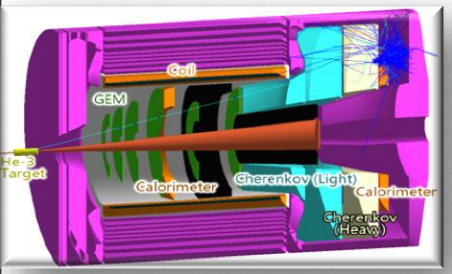
JLab 12 GeV Era: Precision Study of *TMD*s

- From exploration to precision study with 12 GeV JLab
- Transversity: fundamental *PDF*s, tensor charge, LQCD
- *TMD*s: 3-d momentum structure of the nucleon
- → Quark orbital angular momentum
  - LC Quark Models: Worm-Gear (L=1), Pretzelosity (L=2)
  - Sivers ~ GPD (E), QCD Lensing
- Multi-dimensional mapping of *TMD*s
  - 4-d ($x,z,P_{\perp},Q^2$)
  - Multi-facilities, global effort
- Precision → high statistics
  - high luminosity and large acceptance

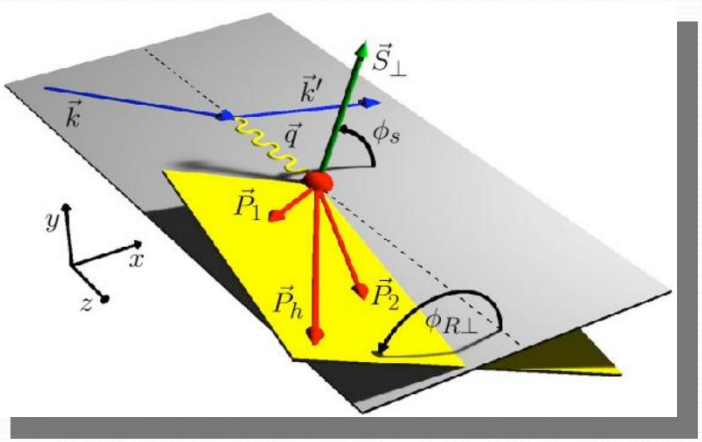
JLab 12: Multi-Halls TMD Program

Hall A/SBS
High x - Q^2, 2-3D

Hall A/SOLID
High Lumi and acceptance – 4D

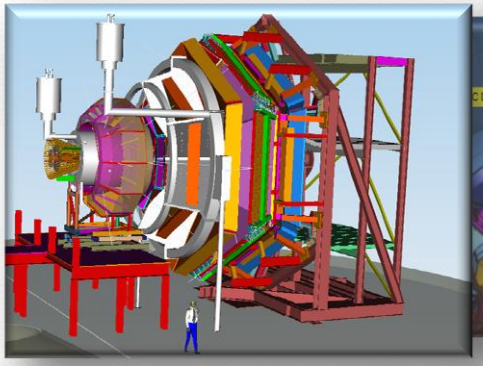


^{3}He, NH_3



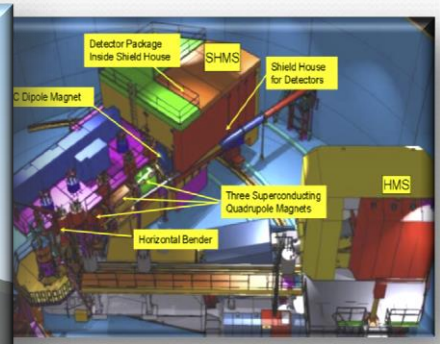
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall B/CLAS12
General survey, medium luminosity



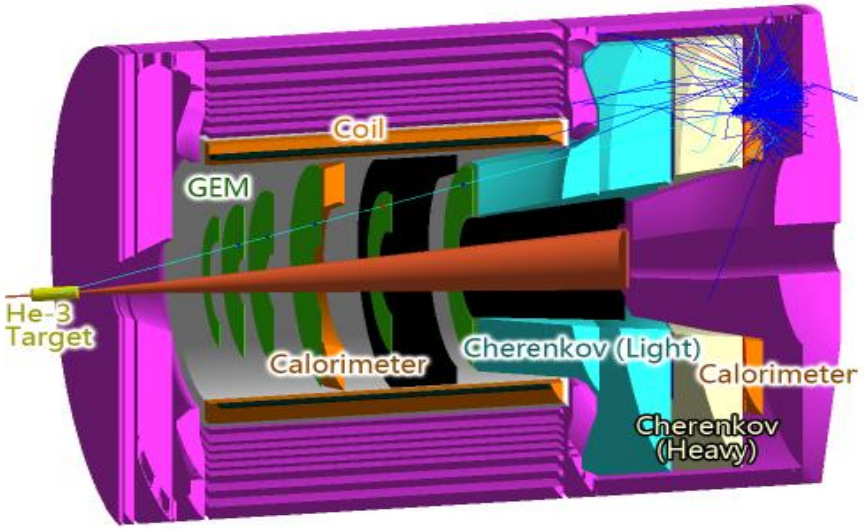
H_2/D_2, NH_3/ND_3, HD

Hall C/SHMS
L-T studies, precise π^+/π^- ratios



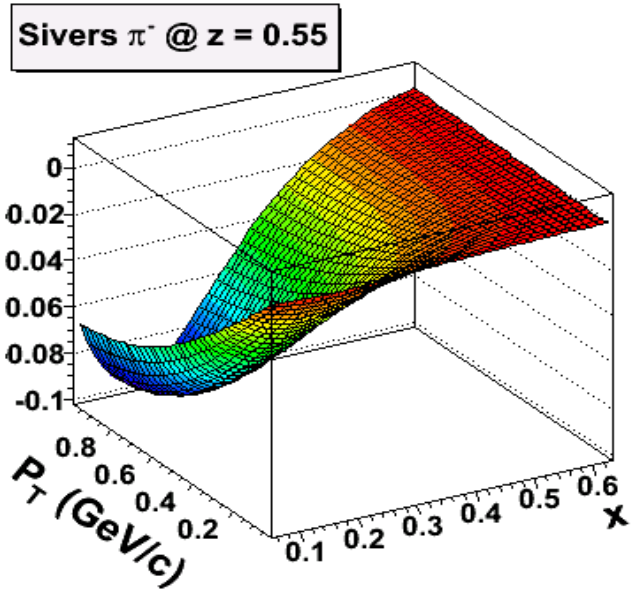
H_2 D_2

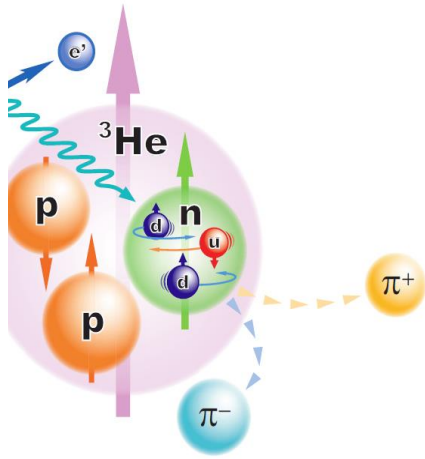
Nucleon Structure (TMDs) with SoLID



Solenoidal Large Intensity Device (SoLID)

Semi-inclusive Deep Inelastic Scattering program:
Large Acceptance + High Luminosity
+ Polarized targets
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Orbital Motion





International collaboration (9 countries, 50+ institutes and 200+ collaborators)

- Large Chinese collaboration

(USTC, CIAE, PKU, Tsinghua U, Lanzhou, IMP,+)

- large GEM trackers
- MRPC-TOF
- EM Calorimeter

3 A rated SIDIS experiments approved for SoLID with 2 having Chinese collaborators as co-spokesperson (Li from CIAE and Yan from USTC)

New di-hadron proposal, co-spokesperson (Xiao from Tsinghua)

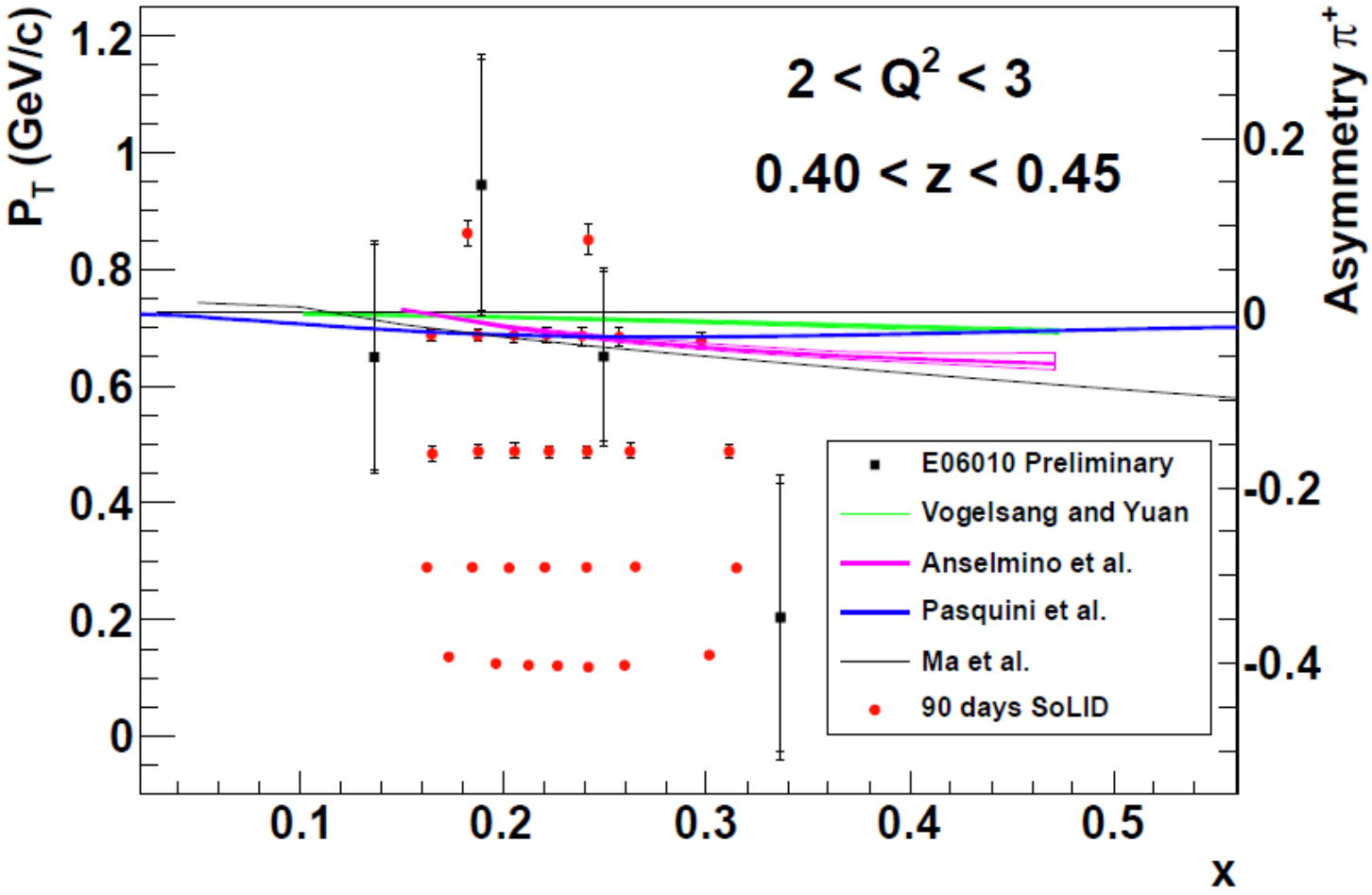
E12-10-006/E12-11-108, Both Approved with "A" Rating

Mapping of Collins(Sivers) Asymmetries with SoLID

E12-10-006 3He(n), Spokespersons: J. P. Chen, H. Gao, X. Jiang, J-C. Peng, X. Qian
E12-11-007(p) , Spokespersons: K. Allda, J. P. Chen, H. Gao, X. Li, Z-E. Mezinai

Collins Asymmetry

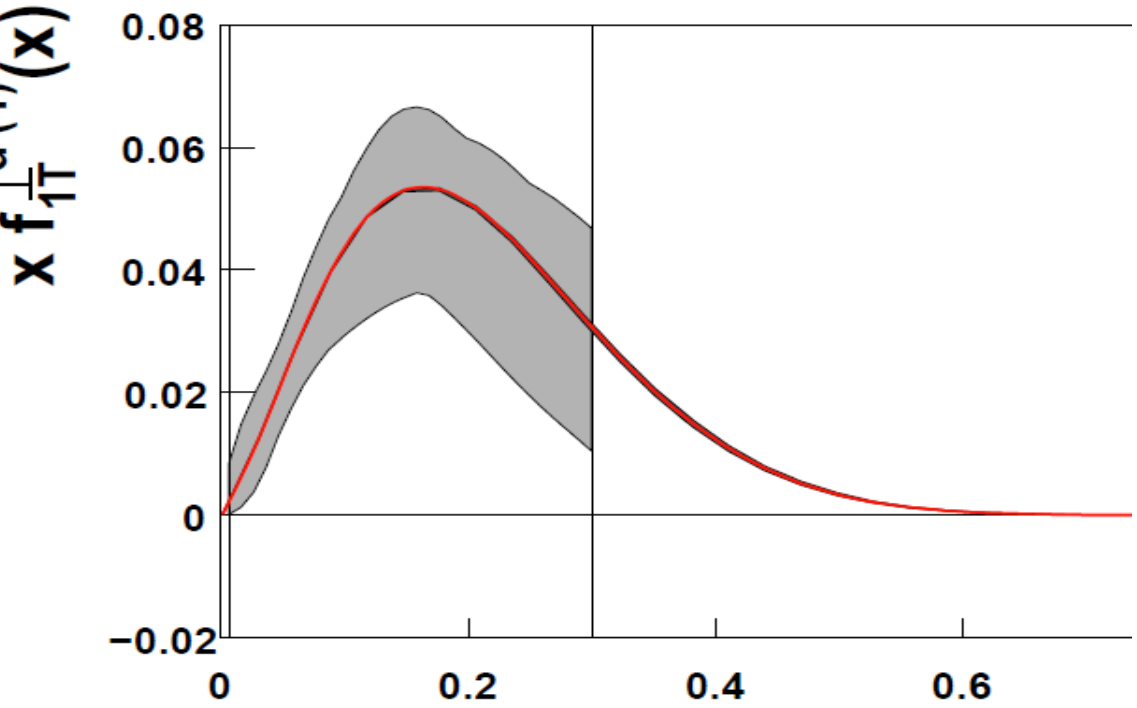
- Both π+ and π-
- Precision Map in region
  x(0.05-0.65)
  z(0.3-0.7)
  Q^2(1-8)
  P_T(0-1.6)
- <10% tensor charge

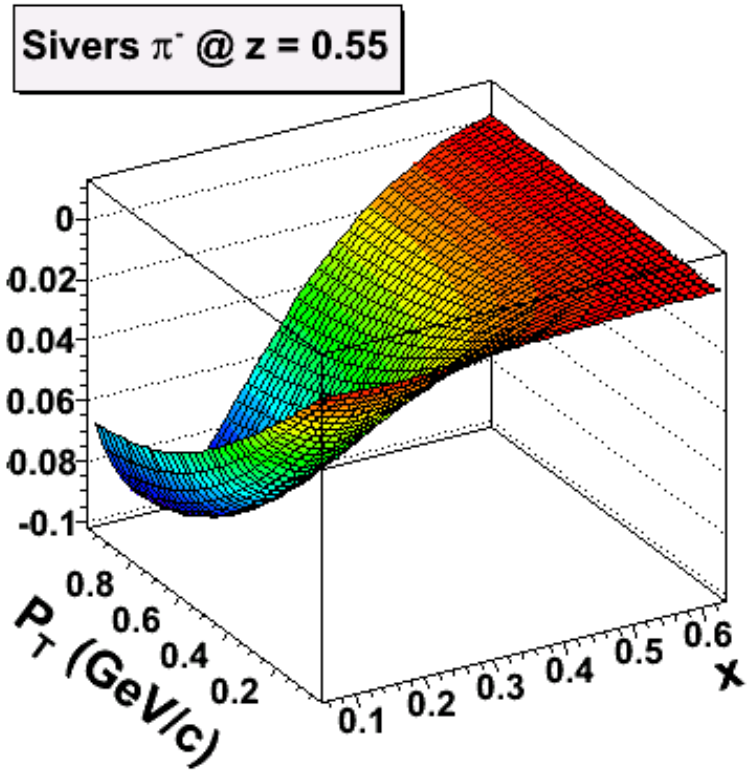


Expected Improvement: Sivers Function

$f_{1T}^{\perp}$ = 

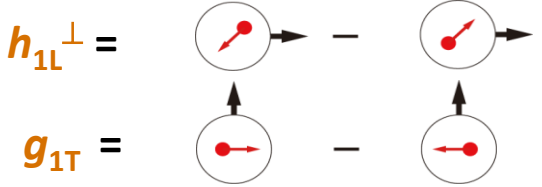
- Significant Improvement in the valence quark (high-x) region
- Illustrated in a model fit (from A. Prokudin)



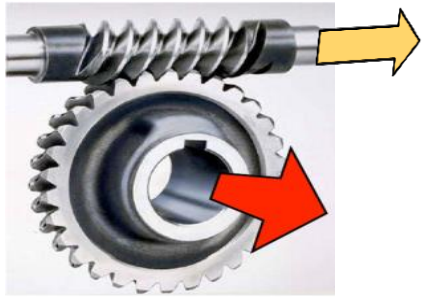


E12-11-107: Worm-gear functions ("A' rating:)

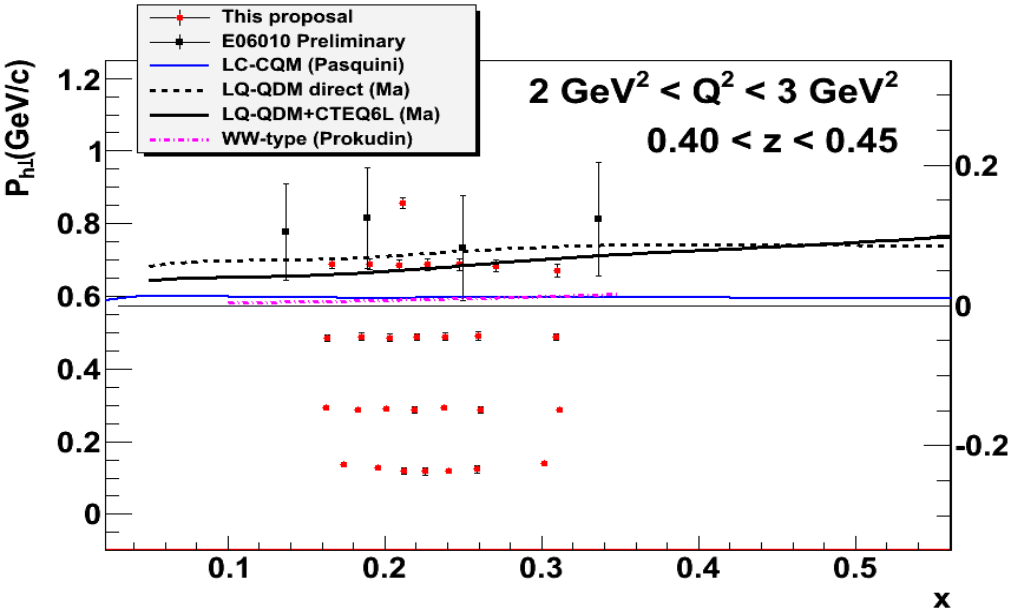
Spokespersons: J. P. Chen/J. Huang/Y. Qiang/ W. Yan

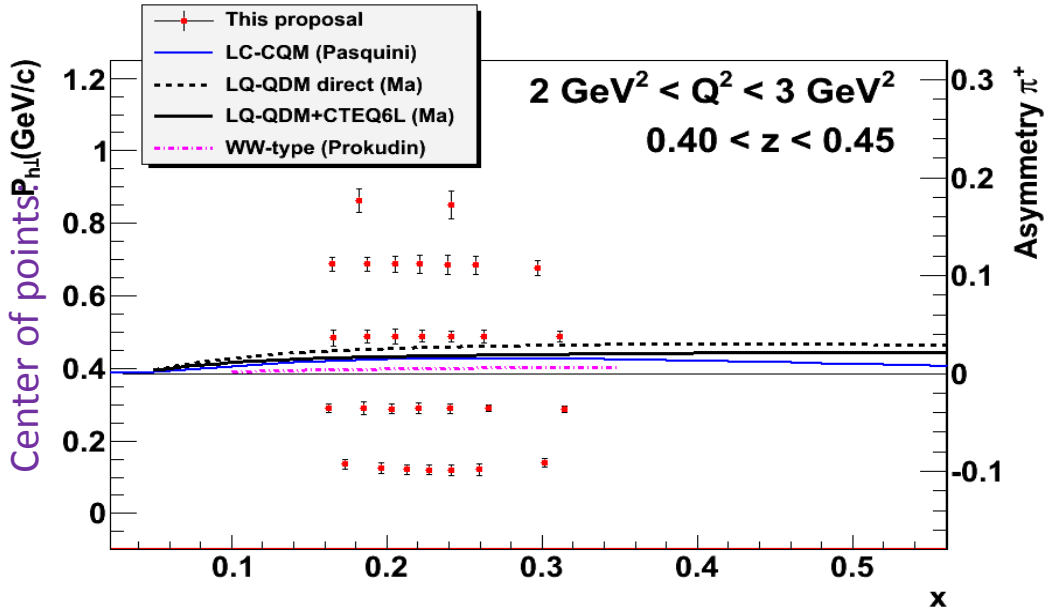


- Dominated by real part of interference between L=0 (S) and L=1 (P) states
- No GPD correspondence
- Lattice QCD -> Dipole Shift in mom. space.
- Model Calculations -> $h_{1L}^{\perp}$ =? $-g_{1T}$.



Longi-transversity
Trans-helicity





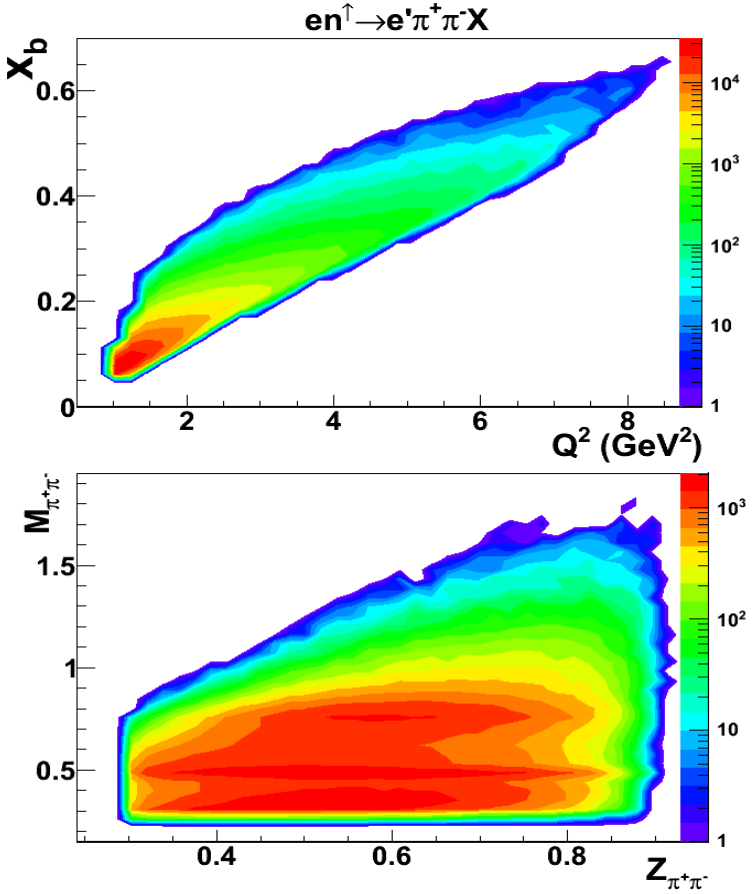
$$A_{LT} \sim g_{1T}(x)D_1(z)$$

$$A_{UL} \sim h^{\perp}{}_{1L}(x)H^{\perp}{}_1(z)$$

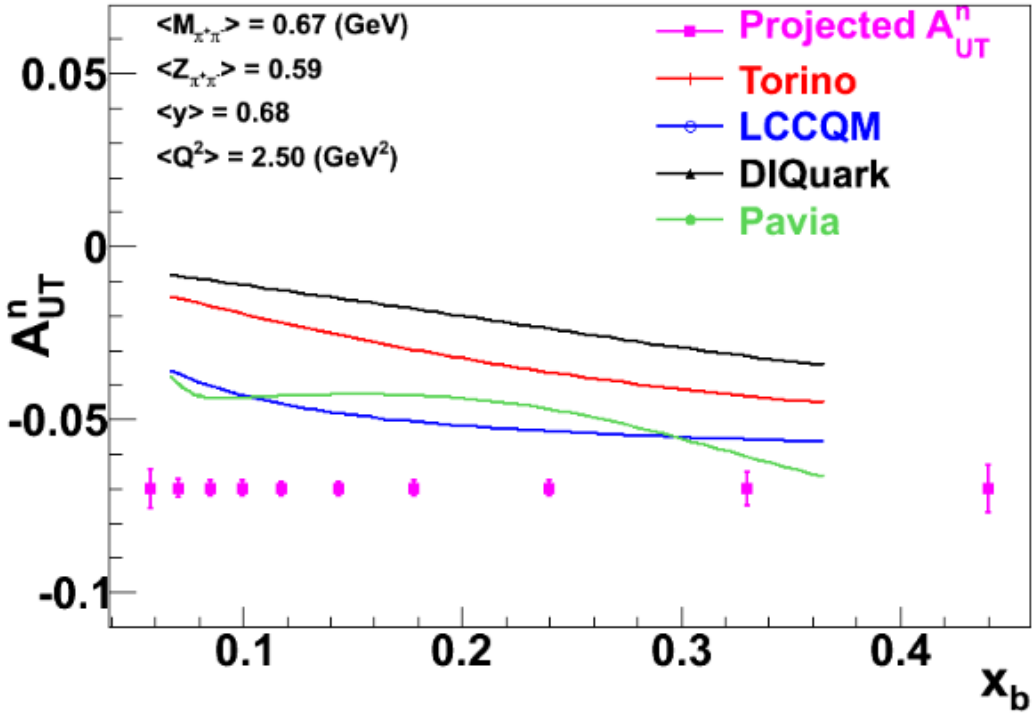
Measure Transversity via Dihadron with SoLID

New Proposal, J. Zhang, J. P. Chen, A. Courtoy, H. Gao, Z. Xiao

- Precision dihadron (π+/π-) production on a transversely polarized ^{3}He (n)
- Extract transversity on neutron
- Provide crucial inputs for flavor separation of transversity



Wide x_b and Q^2 coverages



Projected Statistics error for one ($M_{\pi\pi}$,$z_{\pi\pi}$) bin, integrated over all y and Q^2.

Summary on SoLID TMD Program

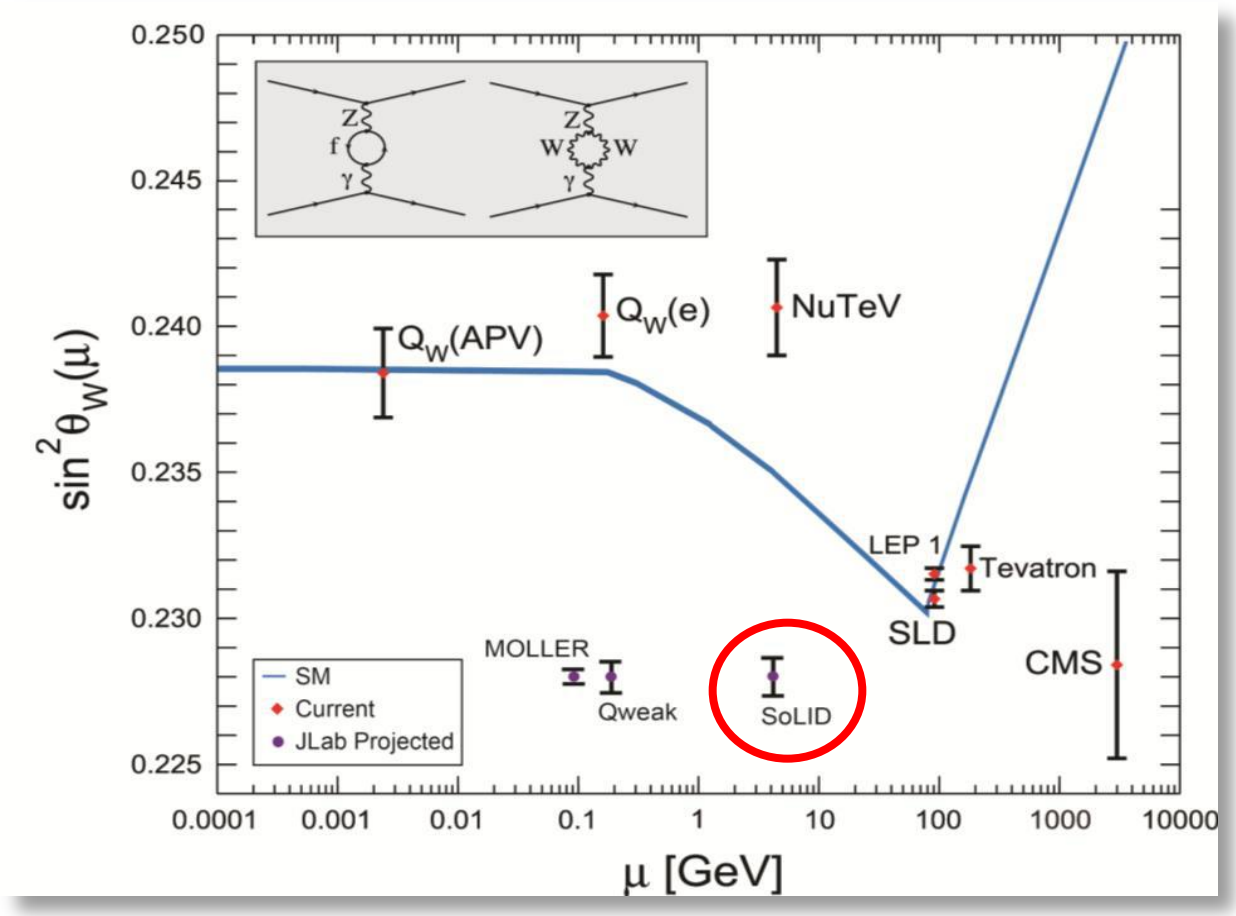
- Unprecedented precision *4-d* mapping of SSA
  - Collins, Sivers, Pretzelosity and Worm-Gear
- Both polarized ^{3}He (n) and polarized proton with SoLID
- Three “A” rated experiments approved. New Proposal: di-hadron.
- Study factorization with *x* and *z*-dependences
- Study P_T dependence
- Combining with the world data
  - extract transversity and tensor charge for both *u* and *d* quarks
  - Most precise extraction of TMDs in valence region, just starts to reach sea
  - learn quark orbital motion and quark orbital angular momentum
  - study Q^2 evolution
- Global efforts (experimentalists and theorists), global analysis
  - much better understanding of multi-d nucleon structure and QCD
- Welcome new collaborators
- Future: EIC to precision study sea and gluon

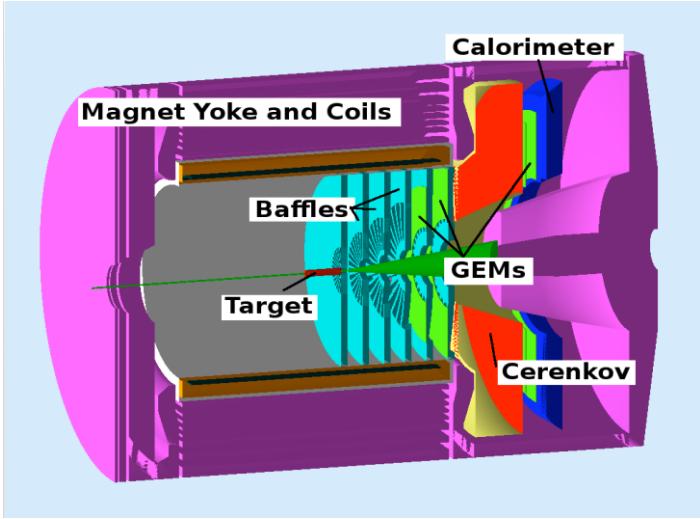
PVDIS with SoLID

E12-10-007: Contact Person: P. Souder

6 GeV PVDIS results published in

Nature, 506, 7486, 67-70 (2014)





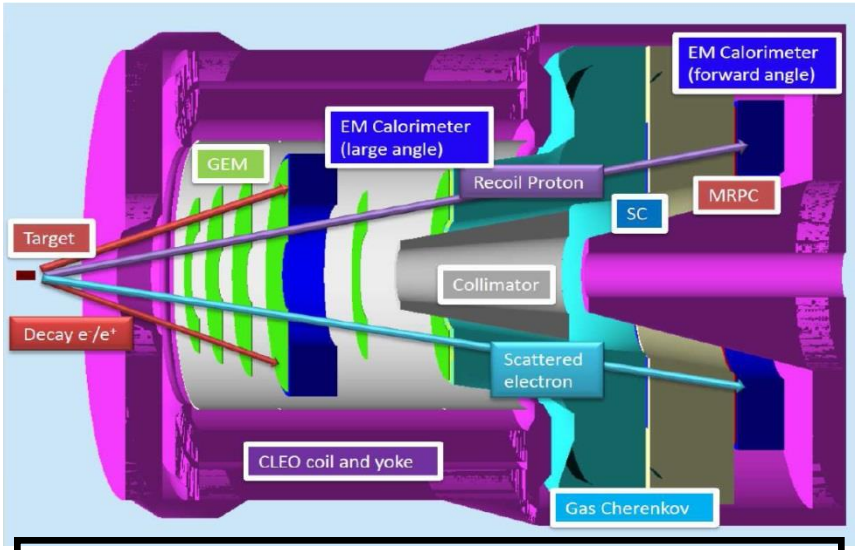
- High Luminosity on LD2 and LH2
- Better than 1% errors for small bins over large range kinematics
- Test of Standard Model
- Quark structure:
  - charge symmetry violation
  - quark-gluon correlations
  - d/u at large-x

SoLID-J/ψ: Study Non-Perturbative Gluons

J/ψ: ideal probe of non-perturbative gluon

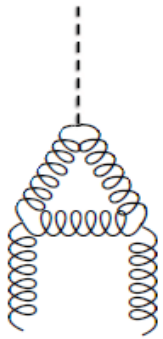
The high luminosity & large acceptance capability of SoLID enables a unique "precision" measurement near threshold

- **Search for threshold enhancement**
- **Shed light on the conformal anomaly**

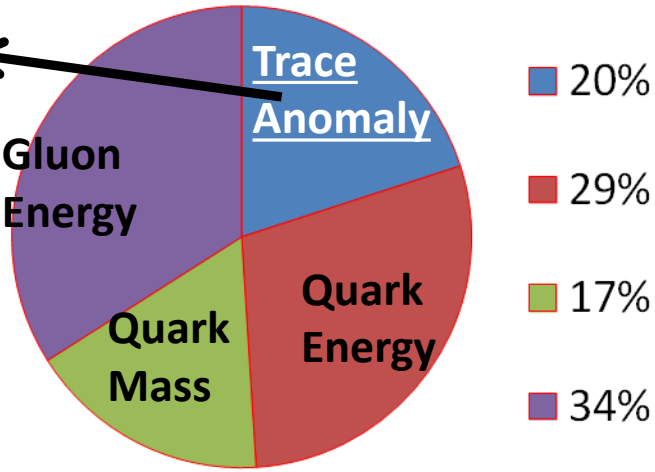


$$\gamma^* + N \rightarrow N + J/\psi$$

$$G^{\alpha\beta\gamma} G_{\gamma}^{\alpha\beta}$$

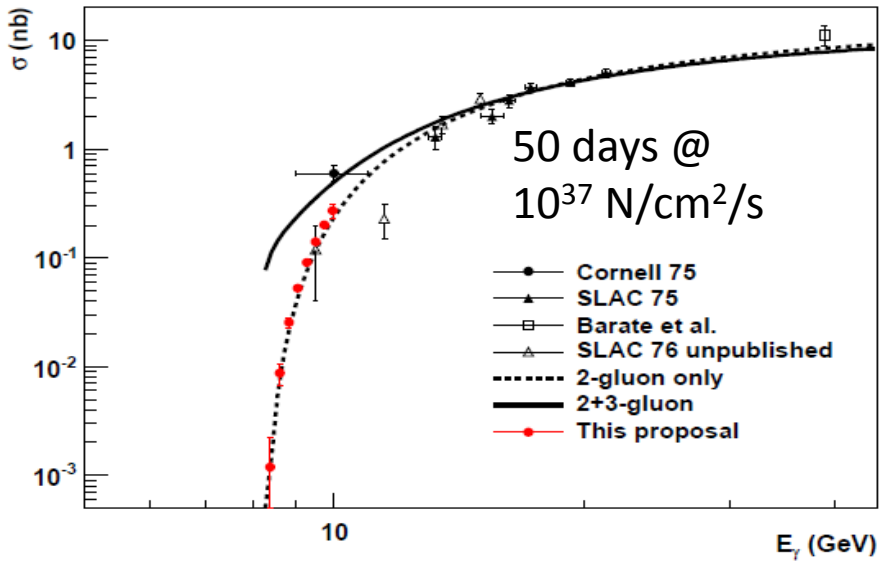


Proton Mass Budget



X. Ji PRL 74 1071 (1995)

J/Ψ Photoproduction Total Cross Section from nucleon



Summary

- Nucleon Spin and TMD study have been exciting and fruitful
- Recent Results and JLab 12 Plan on Spin Structure Study A_1, g_2 / d_2
- Recent results on TMD from JLab
- **JLab 12 GeV**

  Planned SoLID program with JLab12

  Precision 4-d mapping of TMD asymmetries
- Longer-term future: EIC in US and China

  Exciting new opportunities

Precision experimental data + development in theory for Nucleon Spin/TMD +…

➢ lead to breakthrough in understanding QCD