SoLID TMDs Program

Solenoidal Large Intensity Device

ECT* Workshop on TMDs Physics
April 11 – 15, 2016

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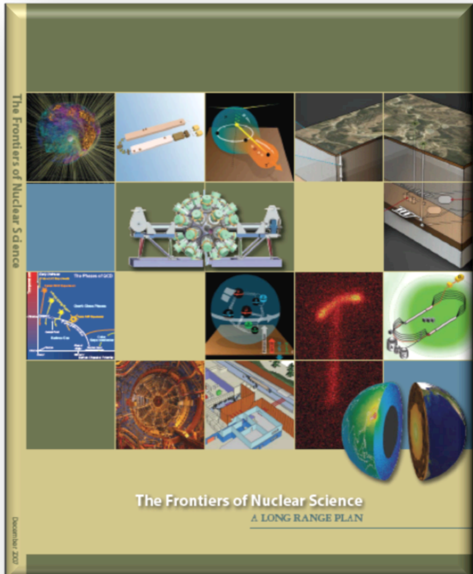
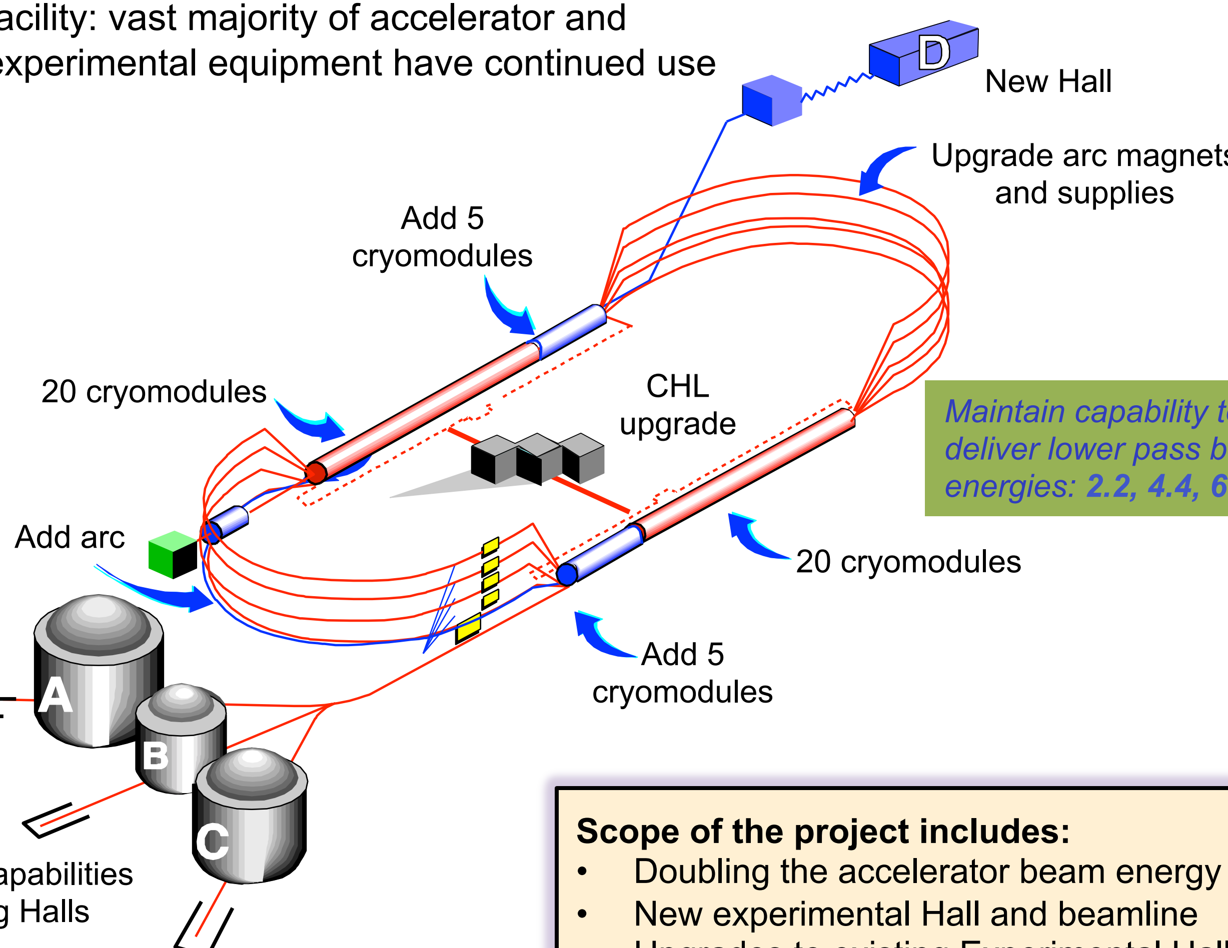
12 GeV Upgrade at JLab



Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



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

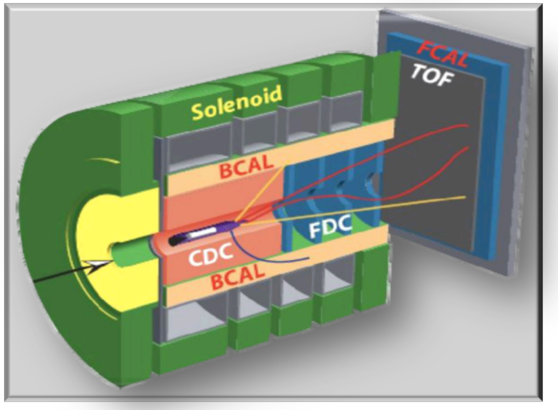
The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Scope of the project includes:

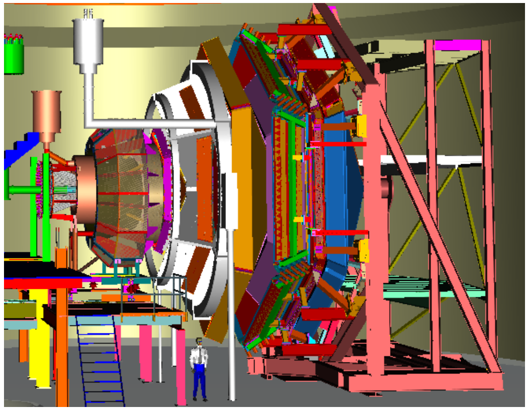
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

Solenoidal Large Intensity Device (SoLID) proposed for Hall A

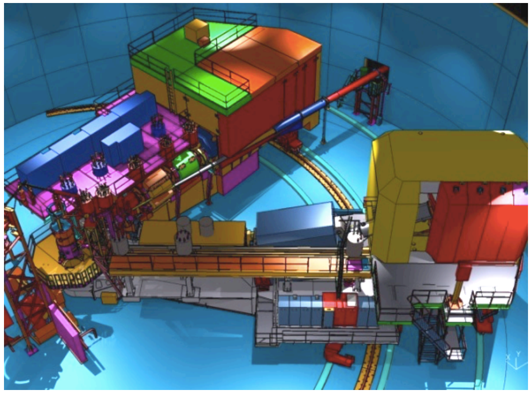
12 GeV Upgrade Physics Instrumentation



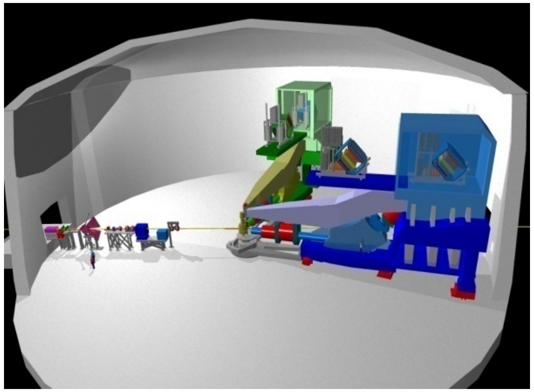
GLUEx (Hall D): exploring origin of confinement by studying hybrid mesons



CLAS12 (Hall B): understanding nucleon structure via generalized parton distributions



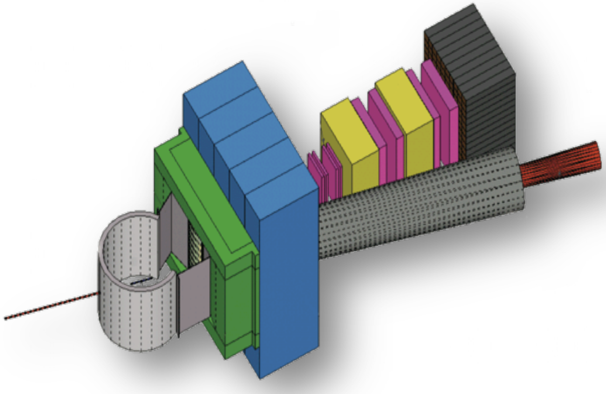
SHMS (Hall C): precision determination of valence quark properties in nucleons and nuclei



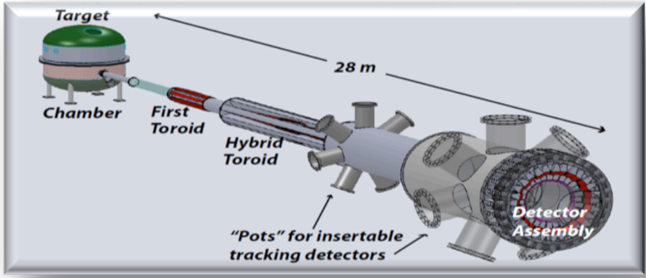
Hall A: nucleon form factors,
& future new experiments using new devices

Beyond 12 GeV Upgrade

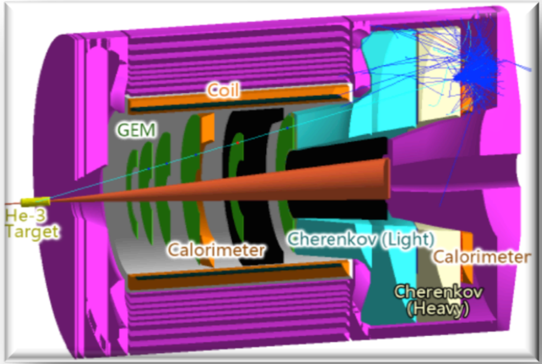
- **Super BigBite Spectrometer**
  (Approved for FY13-16 construction)
  - high Q^2 form factors
  - SIDIS



- **MOLLER experiment**
  - Standard Model Test

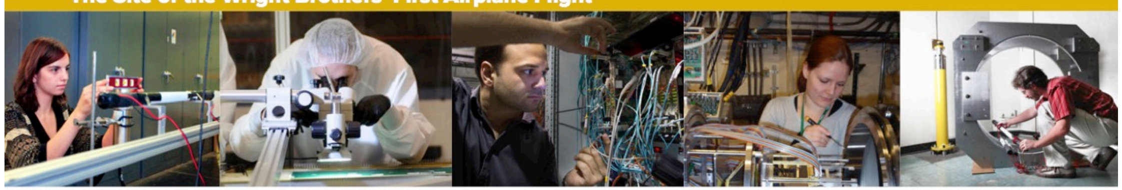


- **SoLID program**
  Chinese collaboration
  CLEO Solenoid



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight



The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

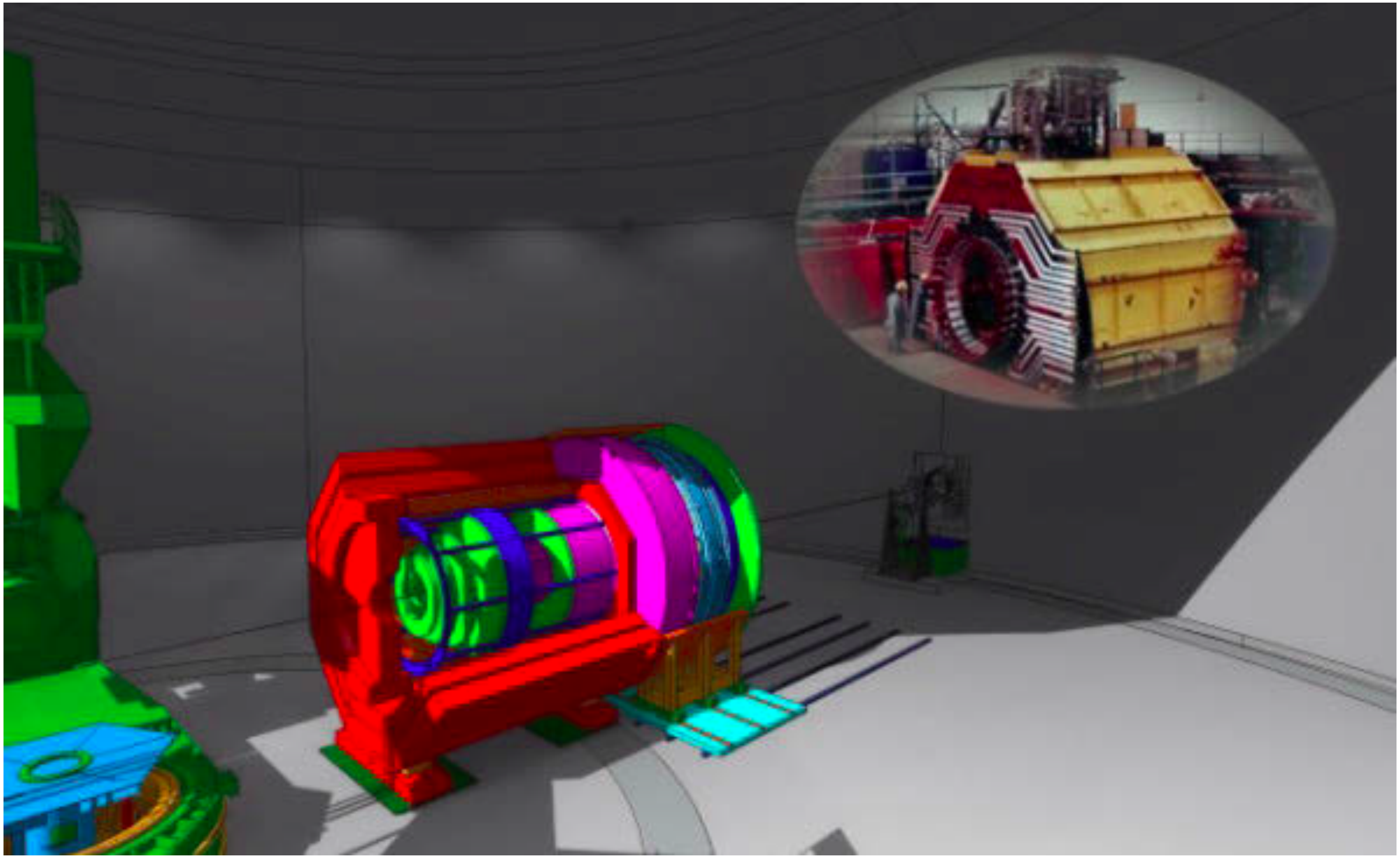


Figure 2.6: *The envisioned SoLID experiment in Hall A is centered around the CLEO-II magnet (insert) that will be relocated to JLab to enable a rich multipurpose science program. SoLID boasts large acceptance detection with operability at extremely high luminosities and offers unprecedented opportunities to provide precision 3D imaging of the motion of valence quarks in the nucleon and to probe the Standard Model.*

Overview of SoLID

Solenoidal **L**arge **I**ntensity **D**evice

- **SoLID is unique in that it provides equipment that combines**
  - **The capability to handle high luminosity ($10^{37\text{-}39}$)**
  - **A large acceptance detector with full ϕ coverage**

  → This allows a full exploitation of the JLab 12 GeV Upgrade
- SoLID takes advantage of the latest developments in detector and data acquisition technologies

- **SoLID is unique as evidenced by the approval of already 5 highly rated experiments, covering a wide range of important science topics:**
  - **Nucleon structure: transverse momentum imaging of valence quarks**
  - **Fundamental Symmetries: new physics in the 10-20 TeV region**
  - **QCD: constraining the conformal (trace) anomaly**

- **There is wide interest in SoLID science as evidenced by:**
  - More than 250 collaborators over 50 institutions and 13 countries
  - Already quite significant international contributions and potential further commitments, **particularly from China**
  - strong theoretical support

Overview on SoLID Physics

Rich, vibrant and important physics program to address some of the most fundamental questions in Nuclear and Particle Physics
500 PAC days (~ 5 years) of high-quality science program foreseen, both unique and multi-purpose

• **Unprecedented precision in three-dimensional imaging of the nucleon in momentum space *in the valence quark region (this workshop is mostly focused on)***

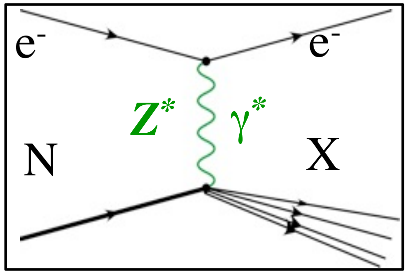
• **A search for new physics in the 10-20 TeV region, complementary to the reach at LHC, for example uniquely improving sensitivity to a *lepto-phobic Z'* of 100-200 GeV.**

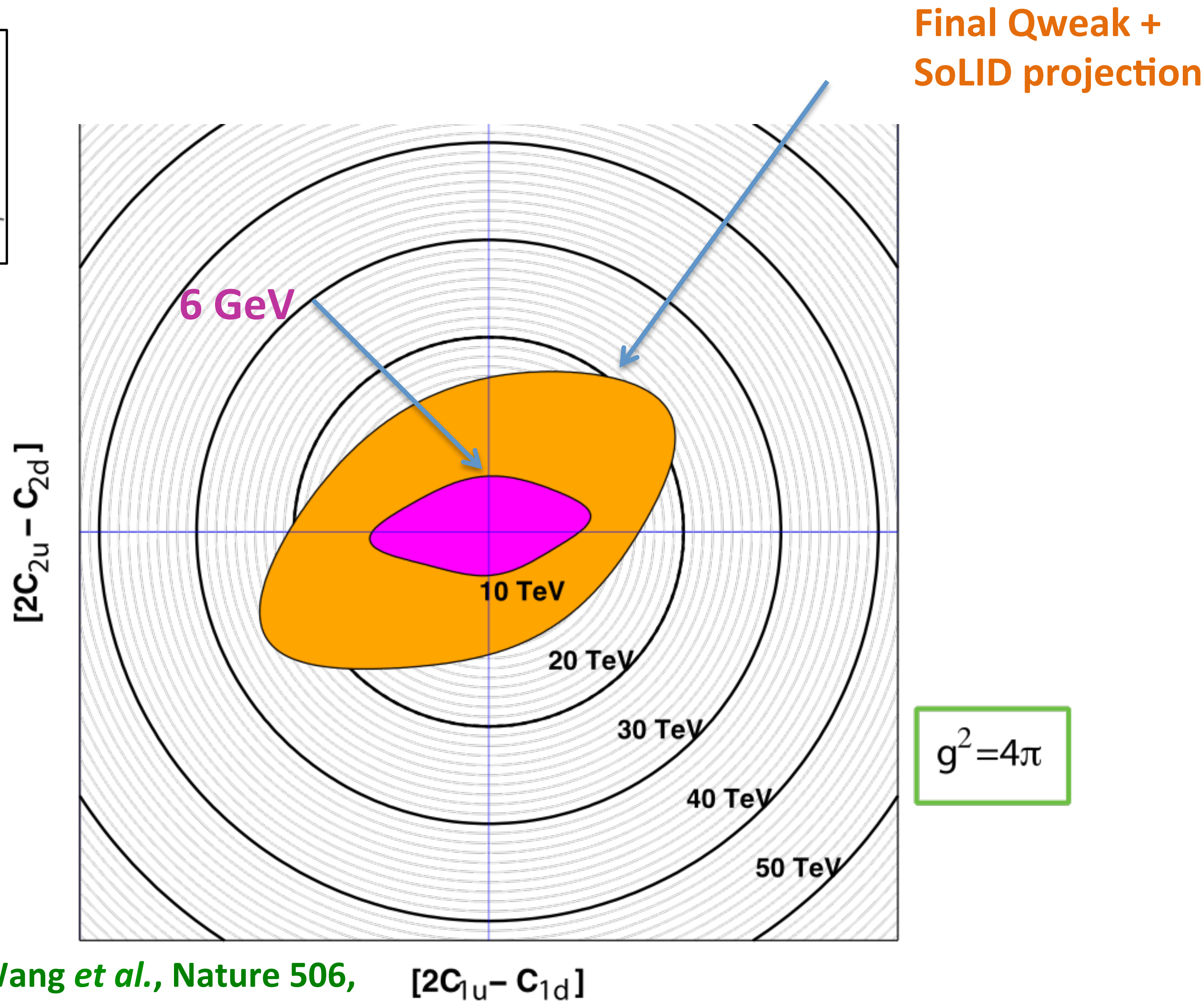
• **Allowing access to a completely unexplored kinematic region near the threshold of J/ψ production, allowing access to the QCD conformal anomaly *without competition for its precision***

SoLID will provide the community with a general-purpose solenoidal detector capable to operate at high luminosities while still maintain large acceptance. Much more physics is foreseen with such a device, such as **Di-Hadron Detection, inclusive Single-Spin Asymmetry measurements, Time-like Compton Scattering**, polarized DVCS, double DVCS, Nuclear Parity Violating Scattering, and much more!

12 GeV Upgrade: Extraordinary opportunity to do the ultimate PVDIS Measurement

PVDIS @ SoLID: unique impact

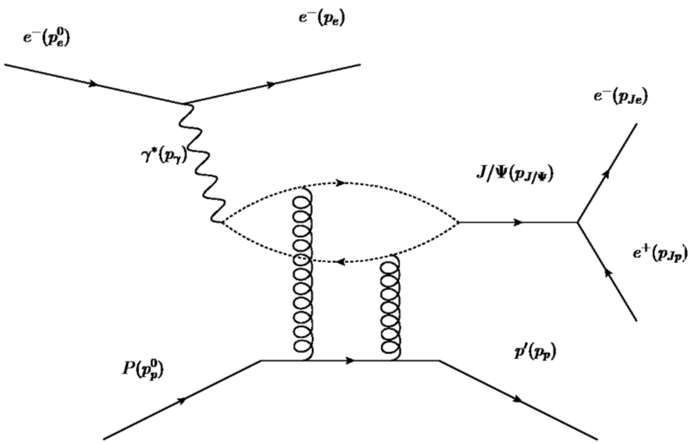


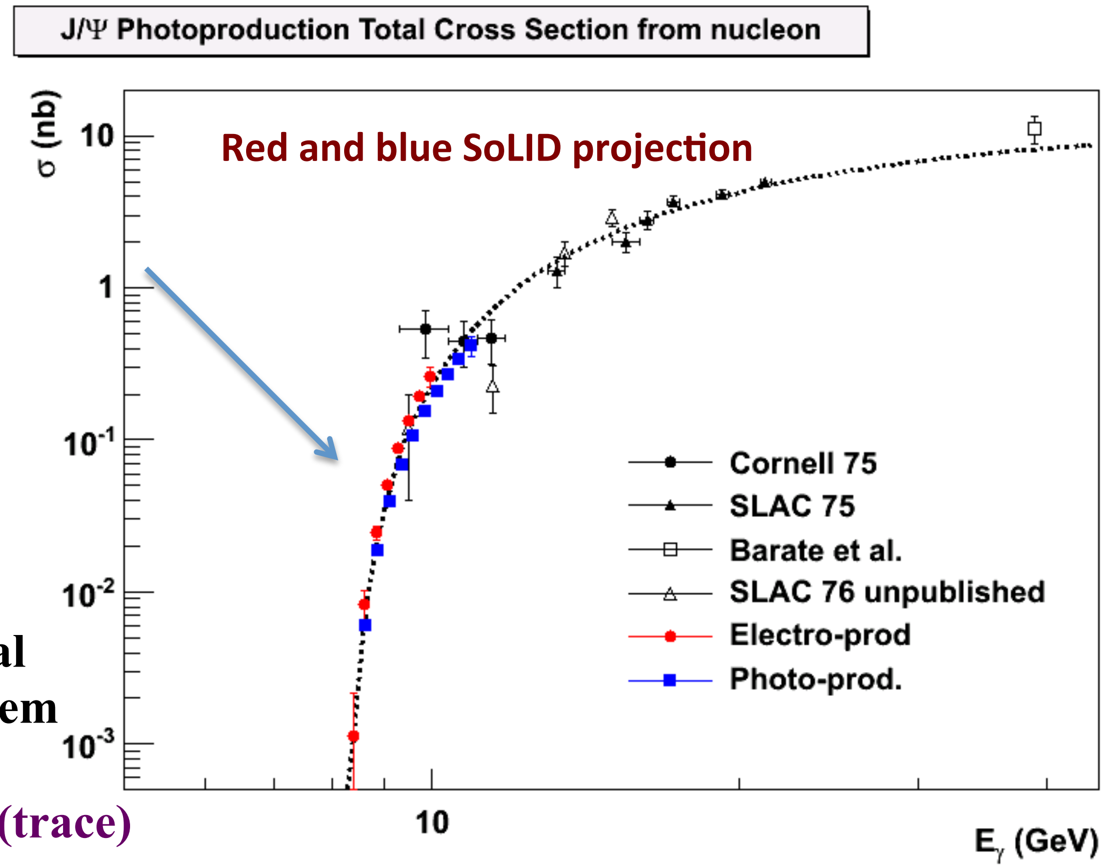


6 GeV PVDIS result, Wang *et al.*, Nature 506, No. 7486, 67 (2014)

J/ψ @ SoLID

$$\boxed{\gamma^* + N \rightarrow N + J/\psi}$$





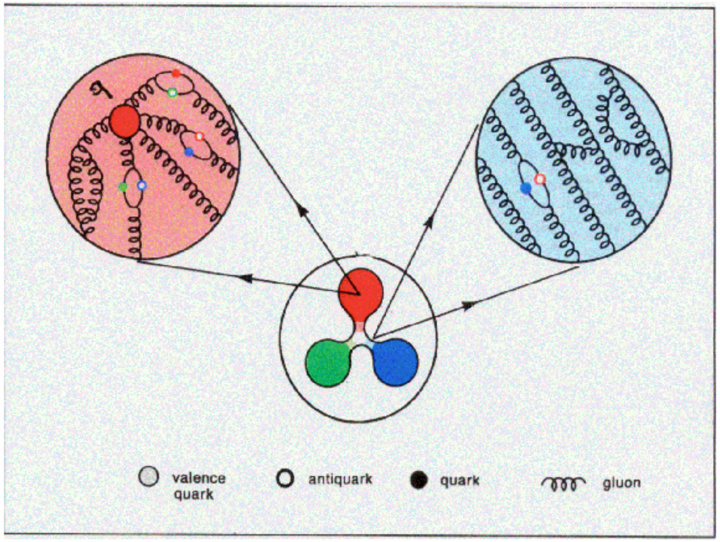
Imaginary part: related to the total cross section through optical theorem

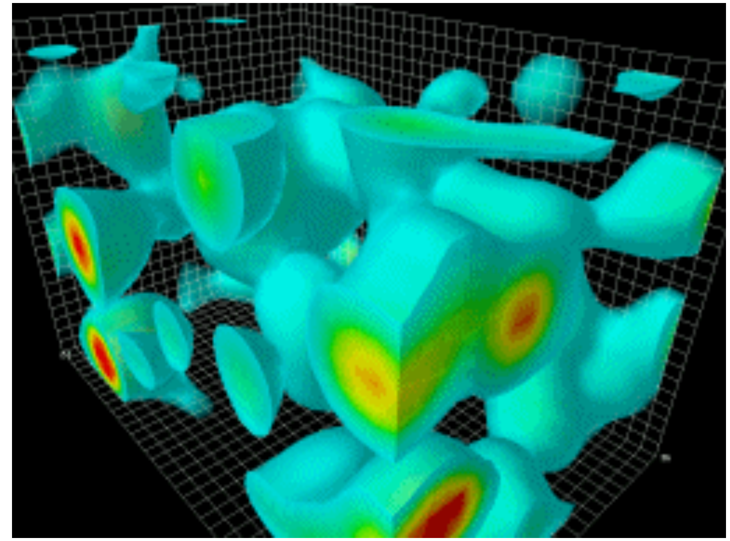
Real part: contains the conformal (trace) anomaly

Threshold J/Ψ production, probing strong color field in the nucleon, conformal (trace) anomaly (has impact on understanding of the proton mass)

Proton: a fascinating many-body relativistic system

Higgs discovery almost irrelevant to proton mass





$$H_{QCD} = H_q + H_m + Hg + H_a$$

$H_q =$ Quark energy $\int d^3x\, \psi^\dagger (-i\mathbf{D}\cdot\alpha)\psi$

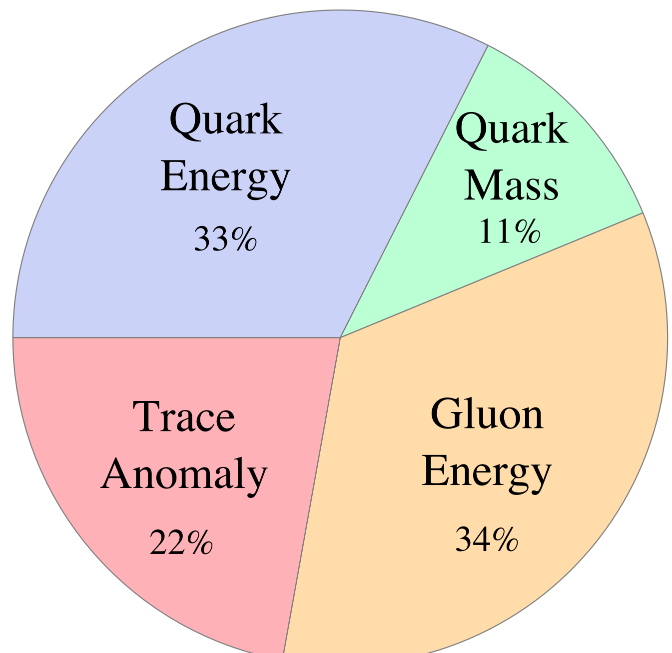
$H_m =$ Quark mass $\int d^3x\, \bar{\psi} m \psi$

$H_g =$ Gluon energy $\int d^3x\, \frac{1}{2}(\mathbf{E}^2 + \mathbf{B}^2)$

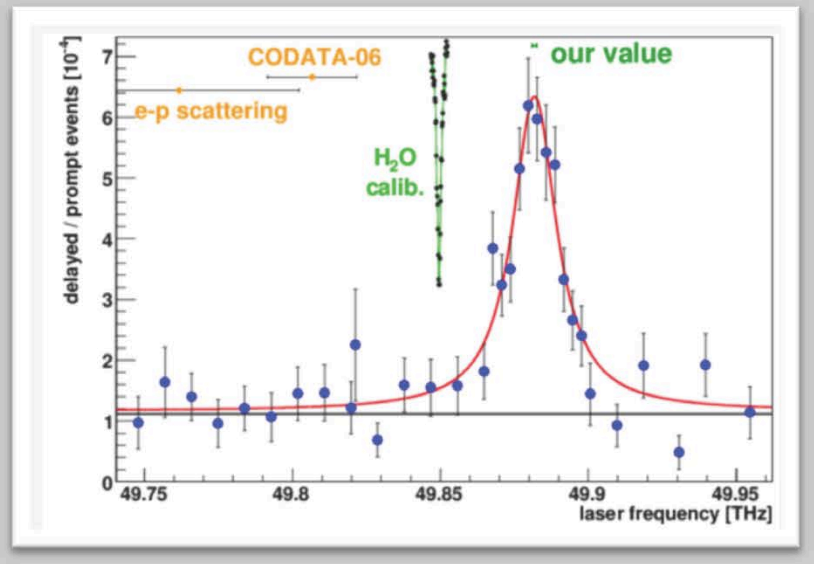
$H_a =$ Trace anomaly $\int d^3x\, \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2)$

Sets the scale for the Hadron mass!

X. Ji PRL 74 1071 (1995)



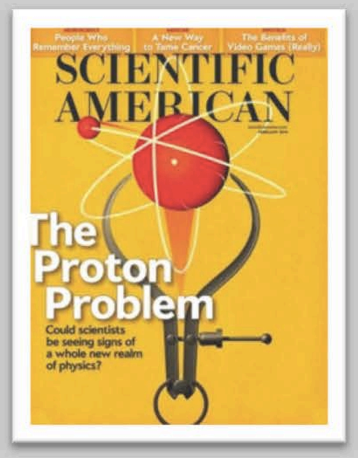
The Proton Size Puzzle



The New York Times

Süddeutsche Zeitung

DIE ZEIT



SPIEGEL ONLINE

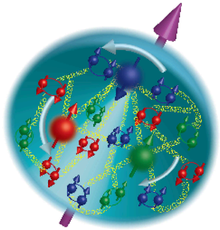
la Repubblica

Neue Zürcher Zeitung

NATIONAL GEOGRAPHIC

Los Angeles Times

Nucleon Spin Decomposition



Proton spin puzzle

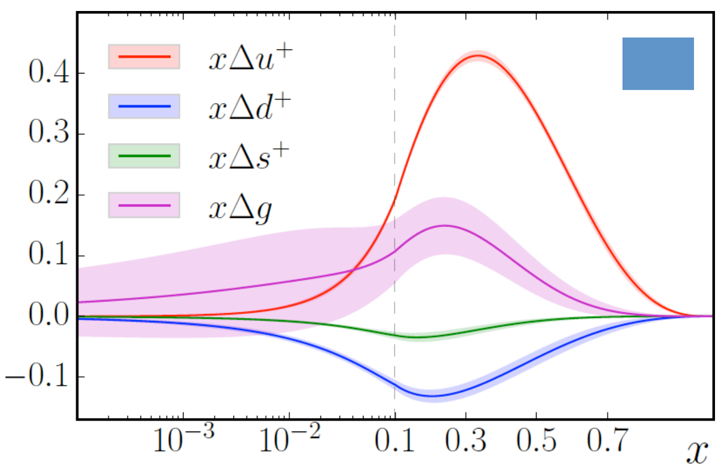
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

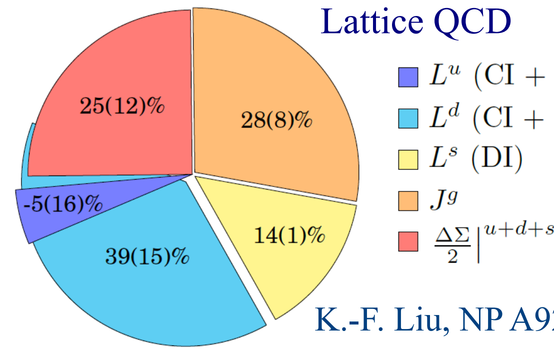
Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



JAM Collaboration, to appear in PRD (2016).

Lattice QCD



K.-F. Liu, NP A928, 99 (2014).

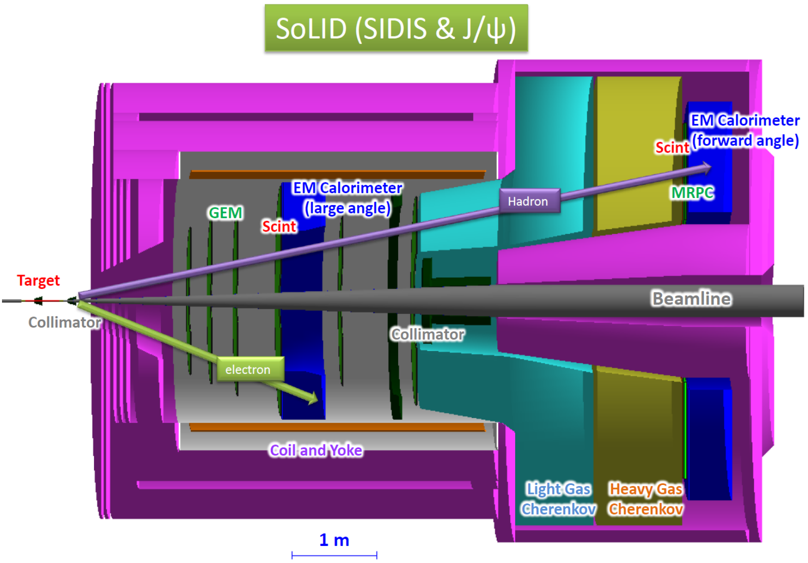
Access to $L_{q/g}$

It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV



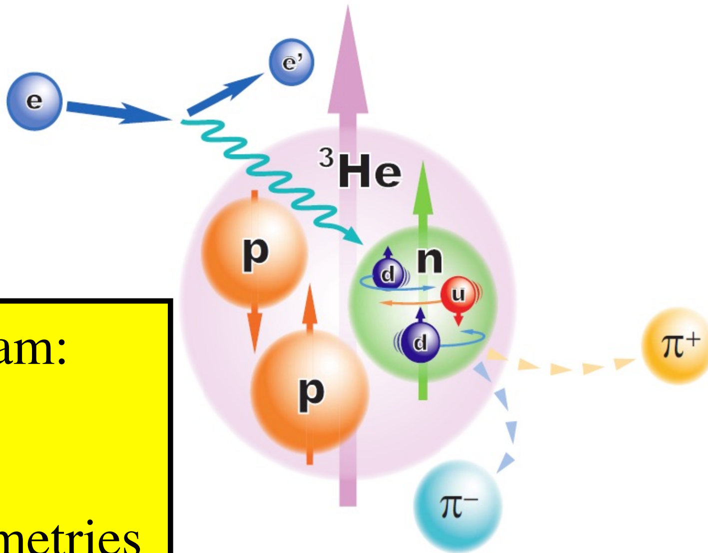
E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

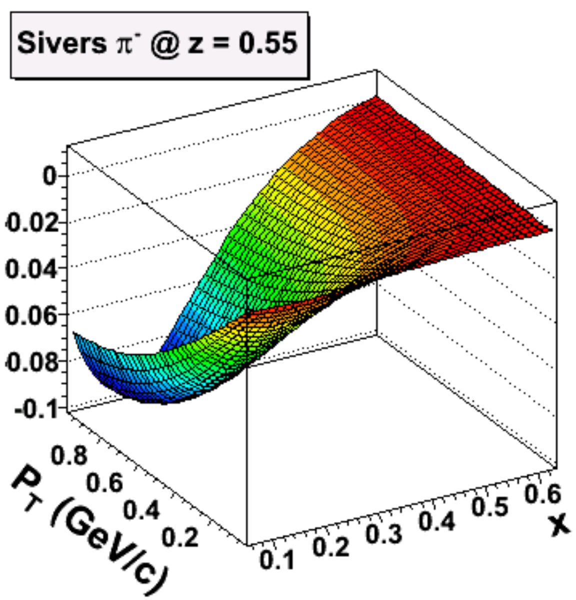
E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

Three run group experiments approved: TMDs, GPDs, and

Much more



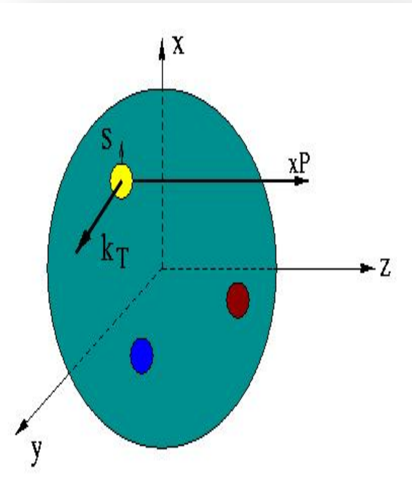


Key of SoLID-Spin program:
Large Acceptance
\+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

Unified View of Nucleon Structure

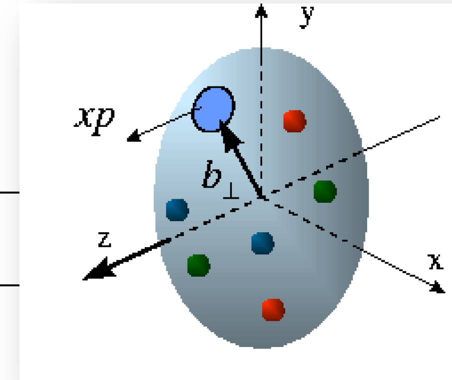
$W_p^u(x, k_T, \boldsymbol{r_T})$ Wigner distributions

5D Dist.



$d^2\boldsymbol{r_T}$

d^2k_T



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

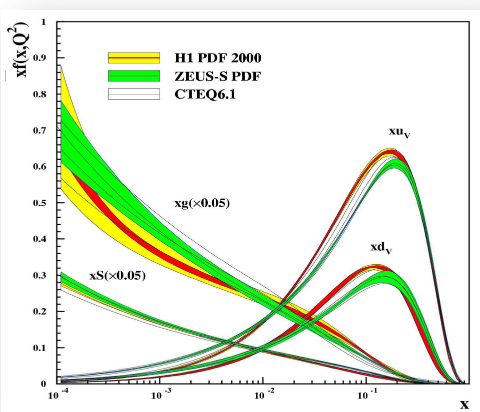
GPDs/IPDs

3D imaging

d^2k_T

d^2r_T

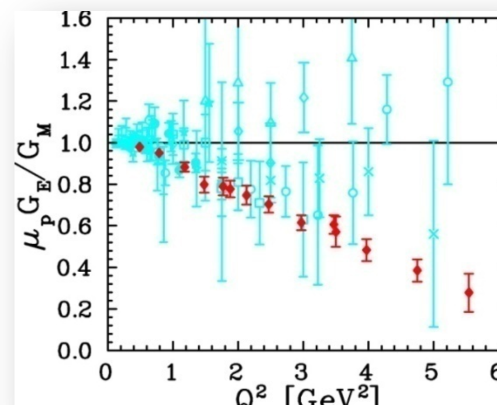
dx &
Fourier Transformation



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

1D

Form
Factors
$G_E(Q^2)$,
$G_M(Q^2)$

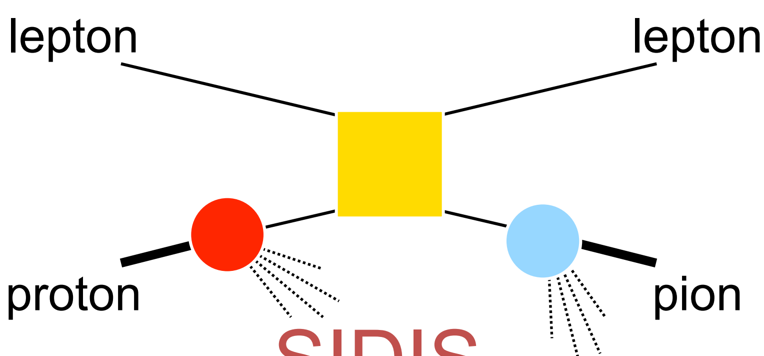


Leading Twist TMDS

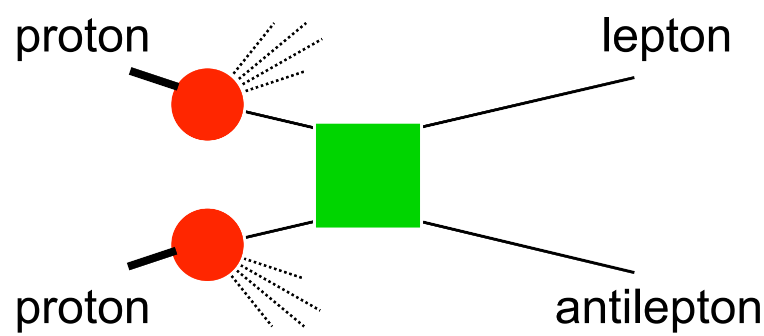
→ Nucleon Spin
→ Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 =$		$h_1^{\perp} = \quad - \quad$ Boer-Mulder
	L		$g_1 = \quad - \quad$ Helicity	$h_{1L}^{\perp} = \quad - \quad$
	T	$f_{1T}^{\perp} = \quad - \quad$ Sivers	$g_{1T}^{\perp} = \quad - \quad$	$h_{1T} = \quad - \quad$ Transversity $h_{1T}^{\perp} = \quad - \quad$ Pretzelosity

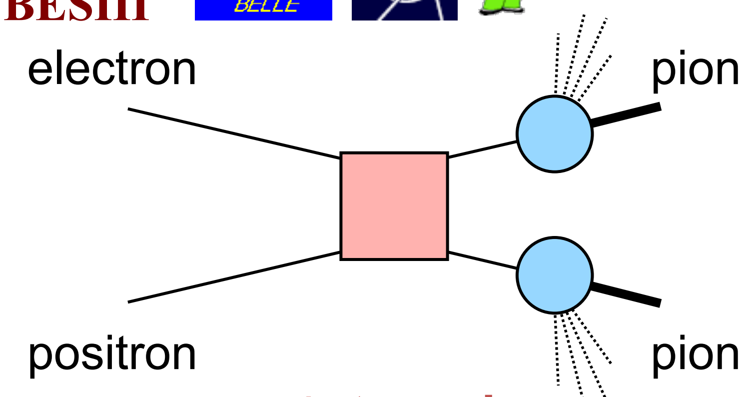
Access TMDs through Hard Processes



SIDIS



Drell-Yan



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

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

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

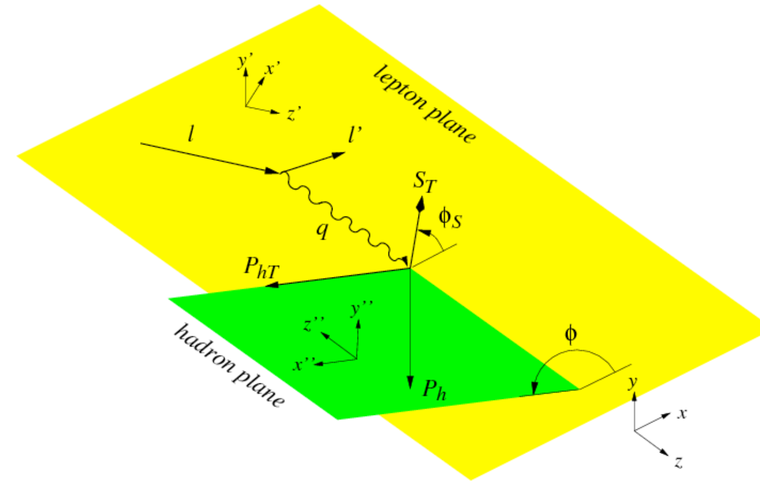
$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

Drell-Yan Programs

SIDIS and Structure Functions

SIDIS differential cross section

18 structure functions $F(x, z, Q^2, P_T)$,
model independent. (one photon exchange approximation)



[Diehl&Sapeta EPJC2005]

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} \\
&= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
&\times \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\,F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\,F_{LU}^{\sin\phi_h}\sin\phi_h \\
&+ S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\,F_{UL}^{\sin\phi_h}\sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\Big] + \lambda_e S_L\Big[\sqrt{1-\epsilon^2}\,F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\,F_{LL}^{\cos\phi_h}\cos\phi_h\Big] \\
&+ S_T\Big[\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)\sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\
&\qquad + \sqrt{2\epsilon(1+\epsilon)}\,F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\epsilon(1+\epsilon)}\,F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big] \\
&+ \lambda_e S_T\Big[\sqrt{1-\epsilon^2}\,F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
&\qquad + \sqrt{2\epsilon(1-\epsilon)}\,F_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\epsilon(1-\epsilon)}\,F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}
\end{aligned}
$$

SoLID:
4D bins in (x, z, Q^2, P_T)

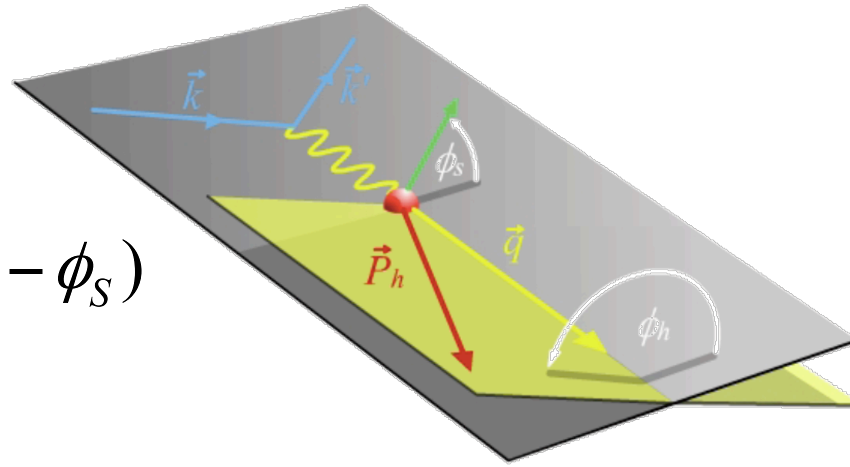
In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMDs.

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

Collins frag. Func. from e$^+$e$^-$ collisions

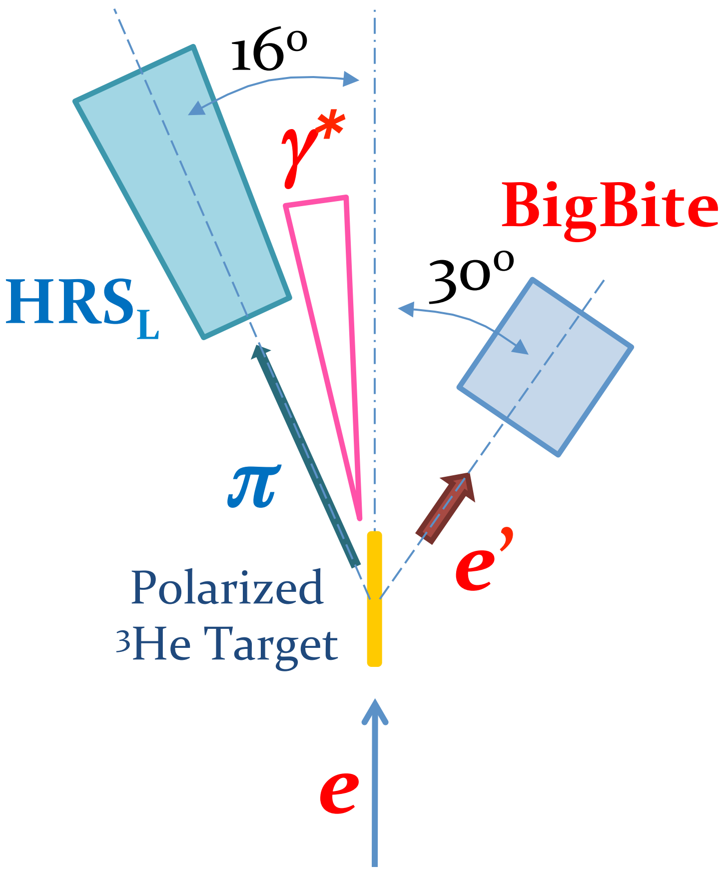
$$A_{UT}^{Sivers} \propto \left\langle \sin(\phi_h-\phi_S)\right\rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

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

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P$_T$)

Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

E06-010: neutron $A_{(U/L)T}(\pi^+/K^+, \pi^-/K^-)$

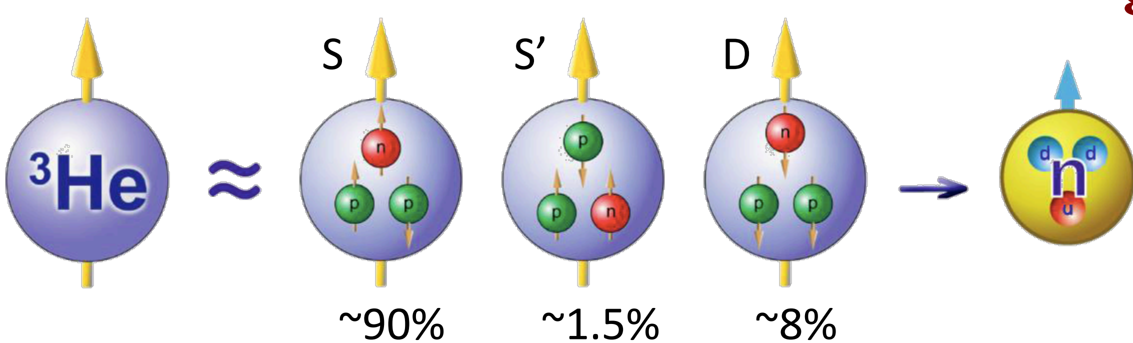


- ***First*** **neutron** data in SIDIS SSA&DSA
  - Similar Q^2 as HERMES experiment
- Disentangle Collins/Sivers effects

- Electron beam: $\boldsymbol{E}$ = 5.9 GeV
- High luminosity L ~ 10^{36} $cm^{-2}s^{-1}$
  - 40 cm transversely polarized ^{3}He target
  - Average beam current 12 uA (max: 15 uA as in proposal)

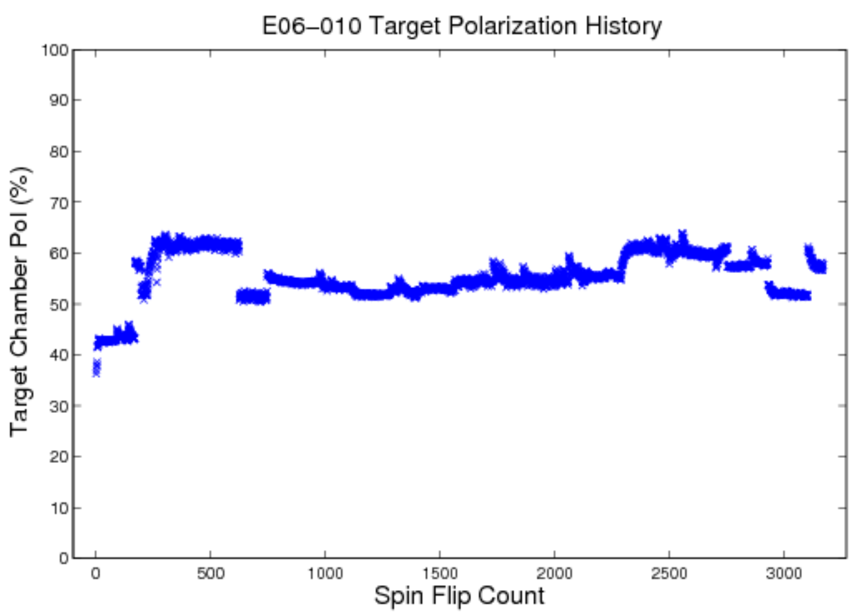
- BigBite at 30^o as **electron** arm:
  $\boldsymbol{P_e}$ = 0.6 ~ 2.5 GeV/*c*
- HRSL at 16^o as **hadron** arm: $\boldsymbol{P_h}$ = 2.35 GeV/*c*

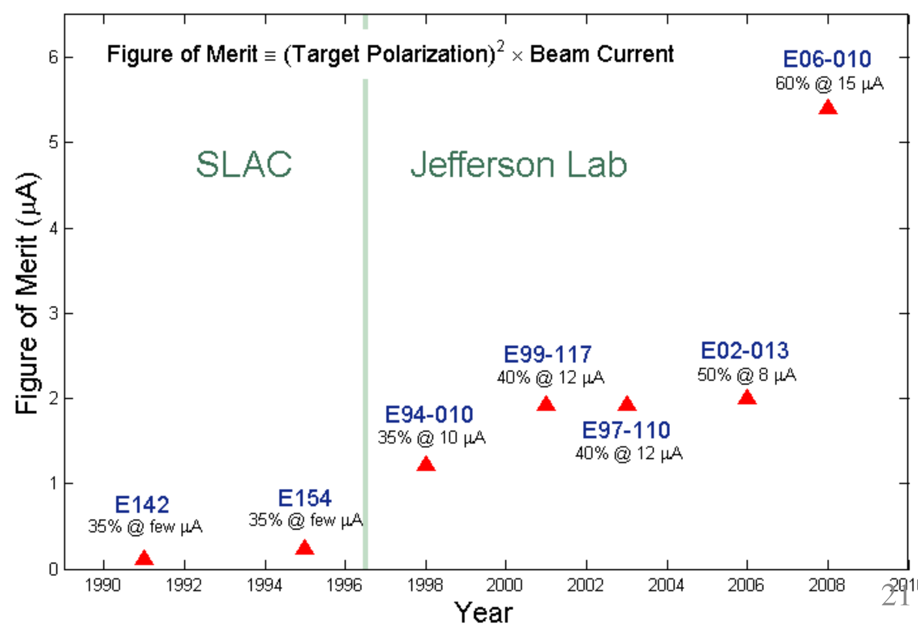
Polarized ^{3}He Target



Effective Polarized Neutron Target!

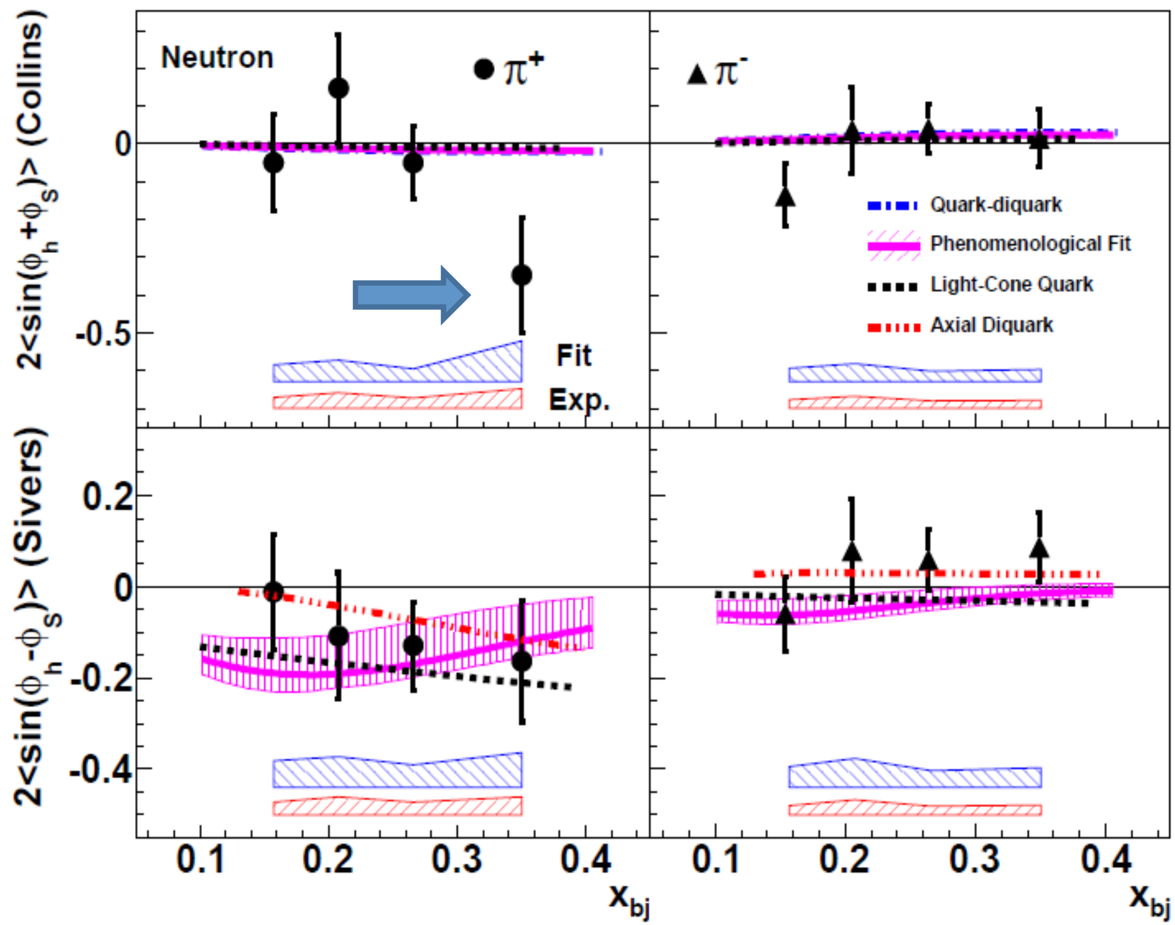
- Polarized ^{3}He ran reliably throughout the experiment, and the following three experiments.
- Reached **55%-60%** polarization with 15 μA beam and 20 minute spin flip! **A NEW RECORD!**





Results on Neutron

- Sizable Collins π^+ asymmetries at x=0.34?
  - Sign of violation of Soffer's inequality?
  - **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.**



Model (fitting) uncertainties shown in blue band.

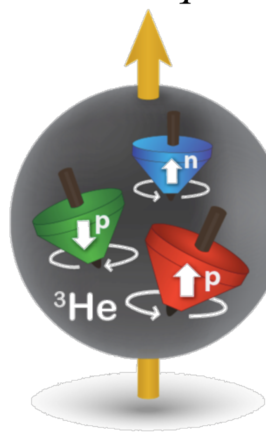
Experimental systematic uncertainties: red band

X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011)

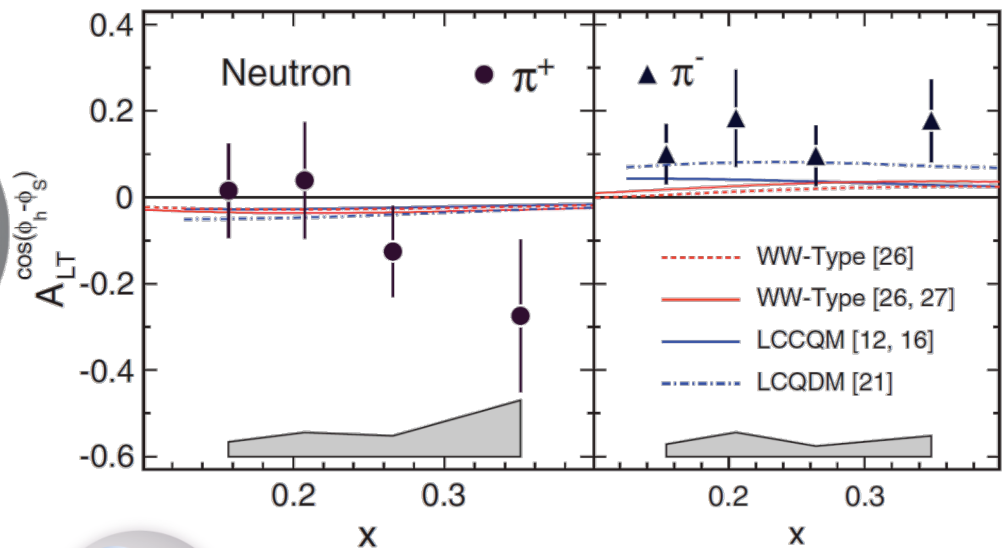
New Observable Reveals Interesting Behaviors of Quarks

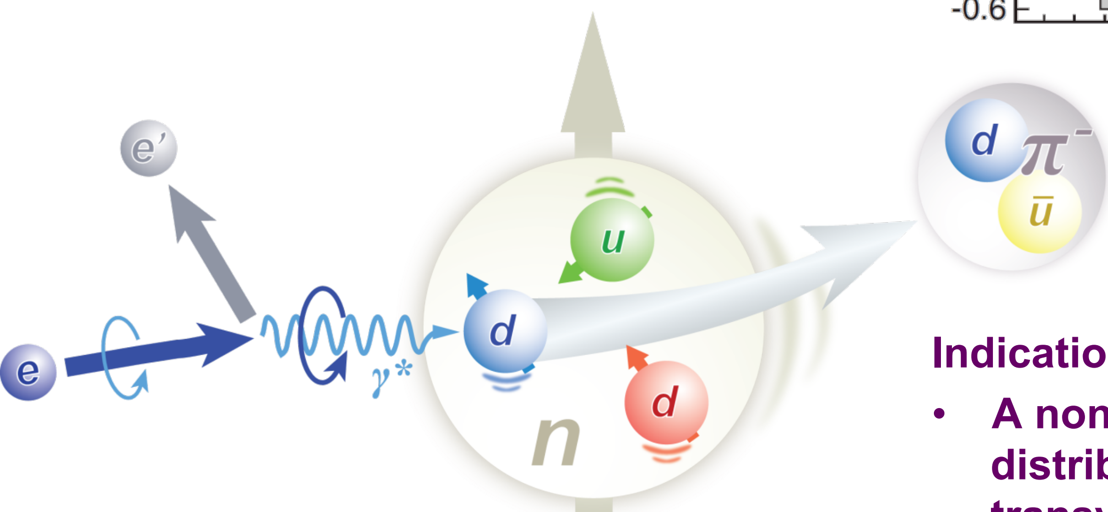
$$A_{\mathrm{LT}}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

Target:
polarized ^3He => polarized neutron



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





First measurement of A_{LT}
beam-target double-spin asymmetry

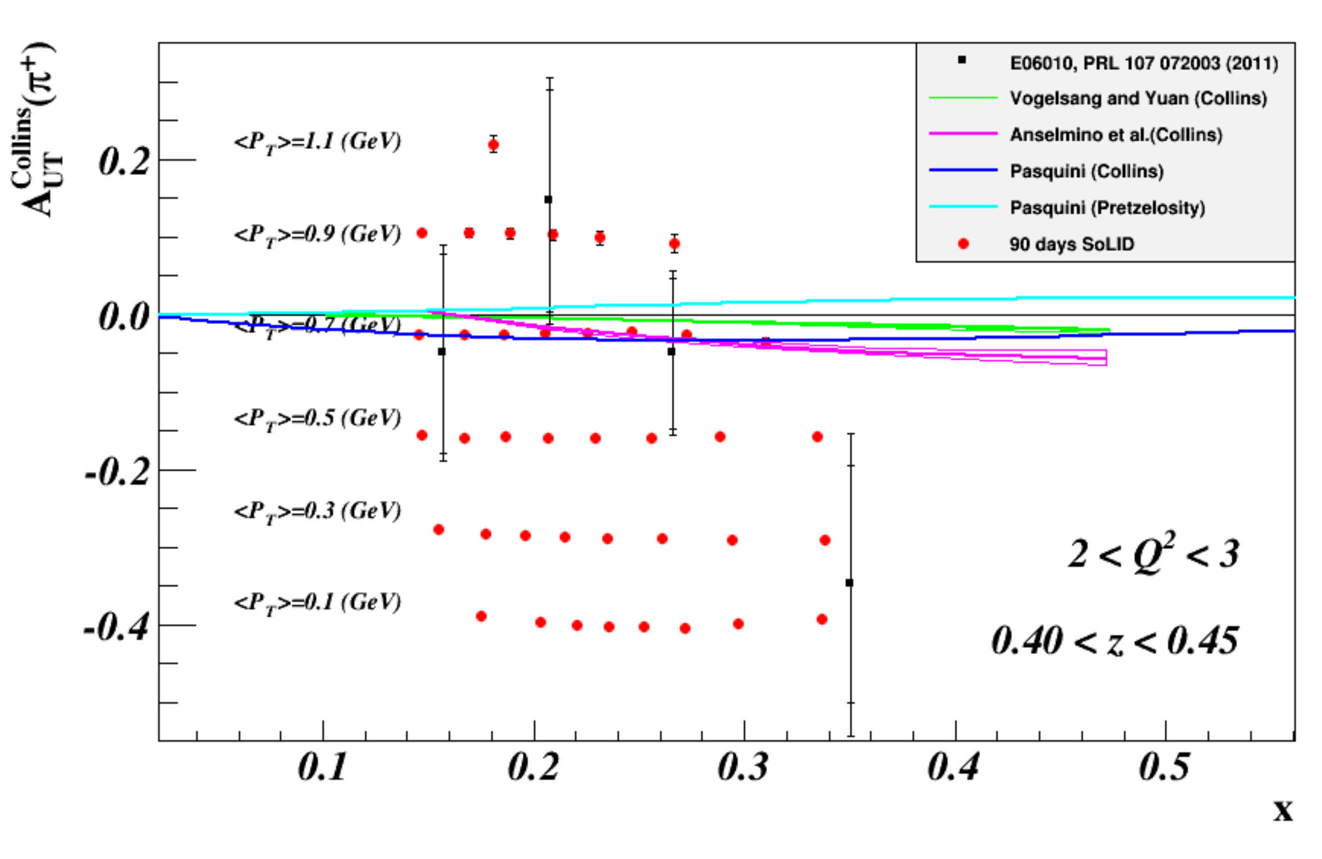
Indications:

- **A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction**
- **Quark orbital motions**

Hermes showed preliminary results from the proton

J. Huang et al., PRL108, 052001 (2012)

Projected Data (E12-10-006)



- Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.
- z ranges from 0.3 ~ 0.7, only one z and Q^2 bin of 11/8.8 GeV is shown here.

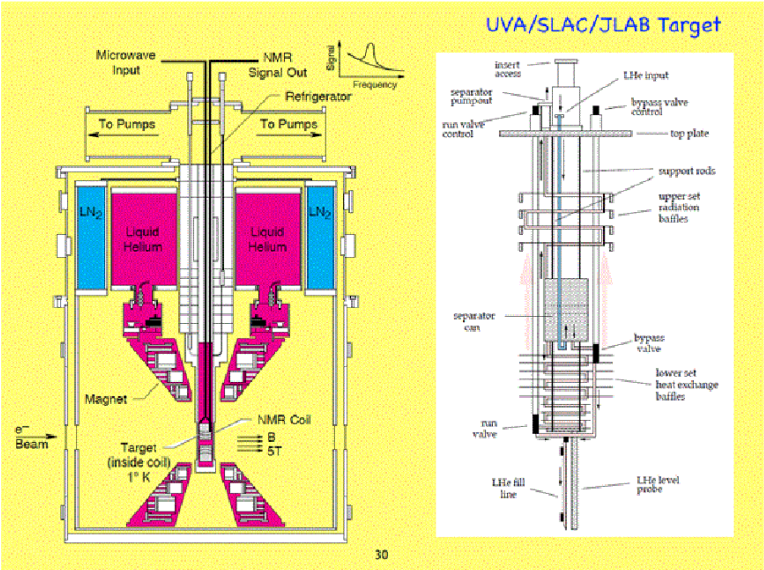
  π^+ projections are shown, similar to the π^- .

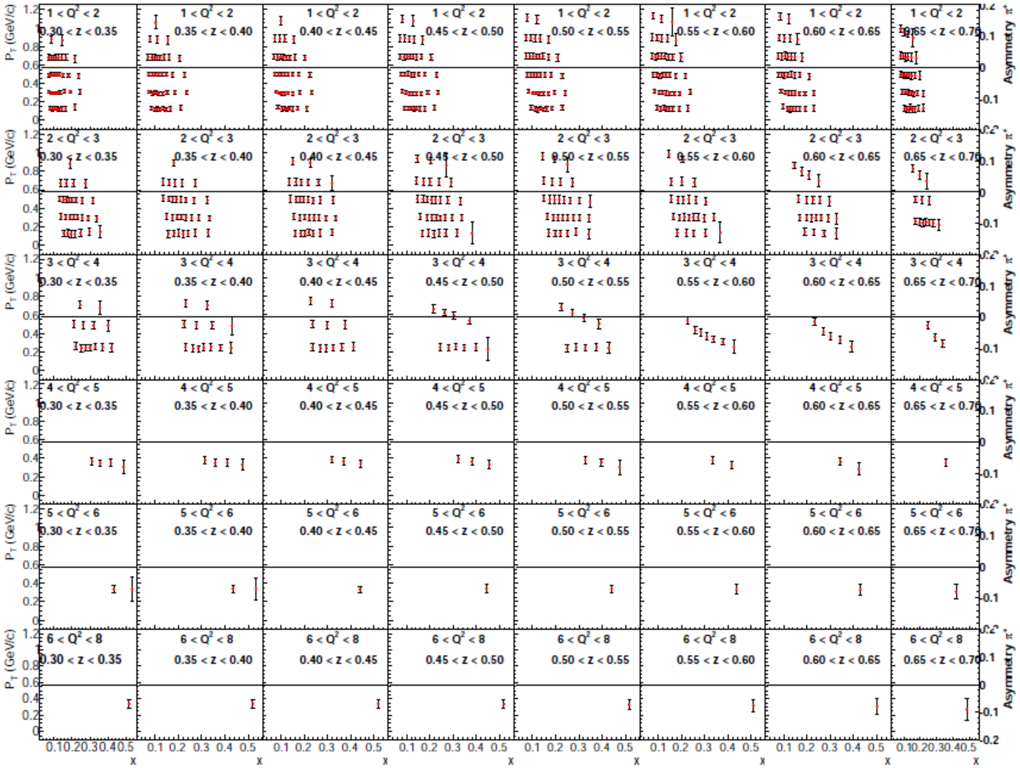
E12-10-006 Spokespersons: Chen, Gao (contact), Jiang, Qian and Peng

X. Qian et al in PRL 107, 072003

Experiment E12-11-108

Target Single Spin Asymmetry in SIDIS *(e, eπ$^{\pm}$)* Reaction on a Transversely Polarized Proton Target and SoLID





$Q^2 = 1$ - 8 GeV^2

Z = 0.3 – 0.7

- Use similar detector setup as that of two approved ^{3}He SoLID expts.
- Use JLab/UVa polarized NH_3 target with upgraded design of the magnet
- Target spin-flip every two hours with average in-beam polarization of 70%
- Polarized luminosity with 100nA current: 10^{35} cm^{-2}s^{-1}
- Beamline chicane to transport beam through 5T target magnetic field (already used for g2p expt.)

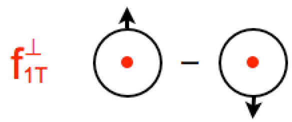
Spokespersons:

K. Allada (Jlab), J. P. Chen (Jlab), Haiyan Gao (Contact), Xiaomei Li (CIAE), Z-E. Meziani (Temple)

Unpolarized Quark in p↑

$$f_{q/p\uparrow}(x,\mathbf{k}_\perp) = f_1^q(x,k_\perp) - f_{1T}^{\perp q}(x,k_\perp)\frac{\hat{\mathbf{P}}\times\mathbf{k}_\perp\cdot\mathbf{S}}{M}$$

Sivers distribution



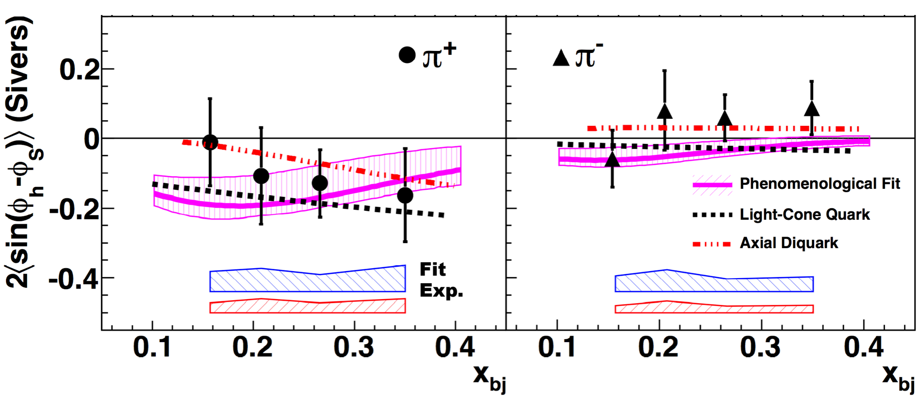
naively time-reversal odd.

$$f_{1T}^{\perp q}(x,k_\perp)\Big|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x,k_\perp)\Big|_{\text{DY}}$$

Measurement in SIDIS

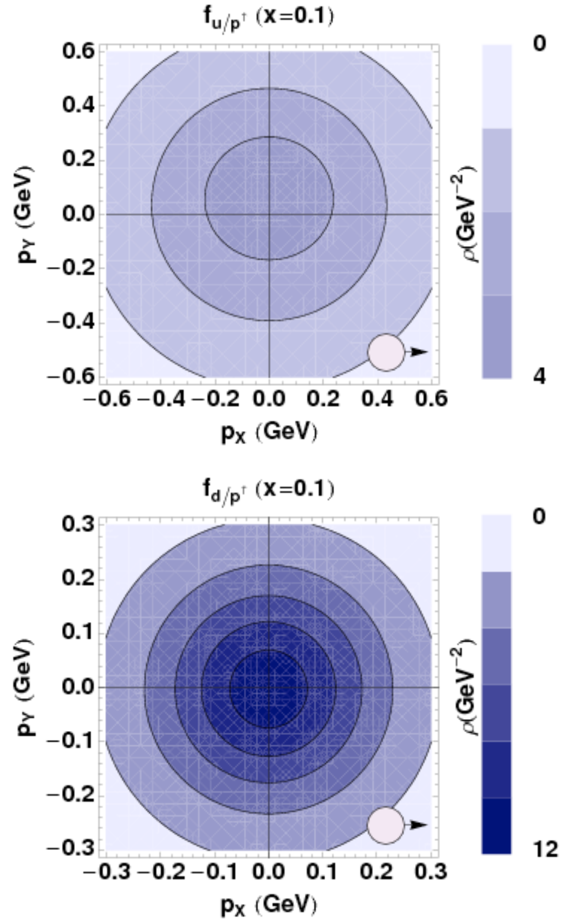
Single spin asymmetry (Sivers asymmetry)

$$A_{UT}^{\sin(\phi_h-\phi_S)} \sim f_{1T}^{\perp}(x,k_\perp)\bigotimes D_1(z,p_\perp)$$



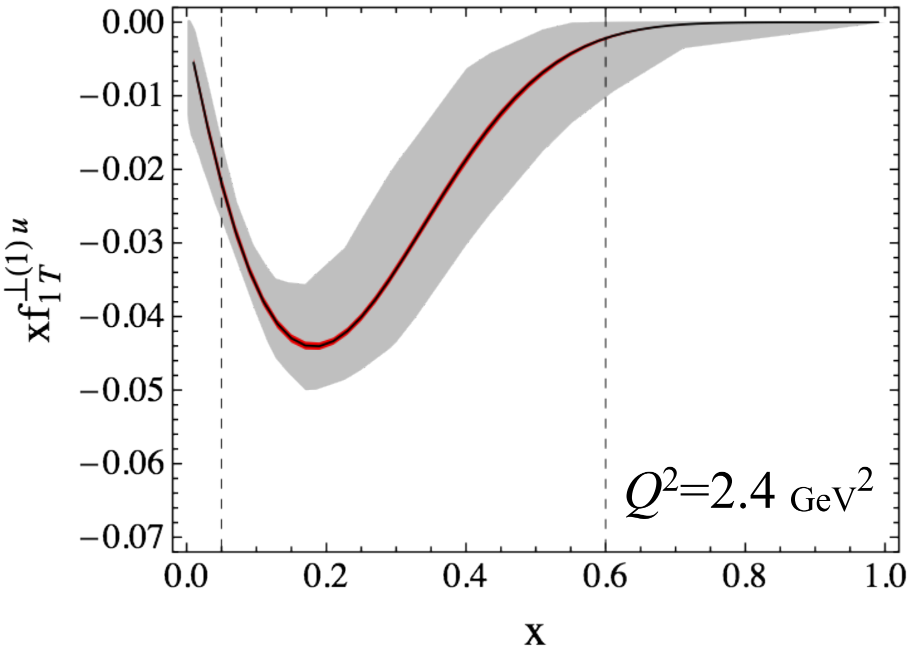
6 GeV JLab E06-010, X. Qian et al., PRL 107, 072003 (2011).

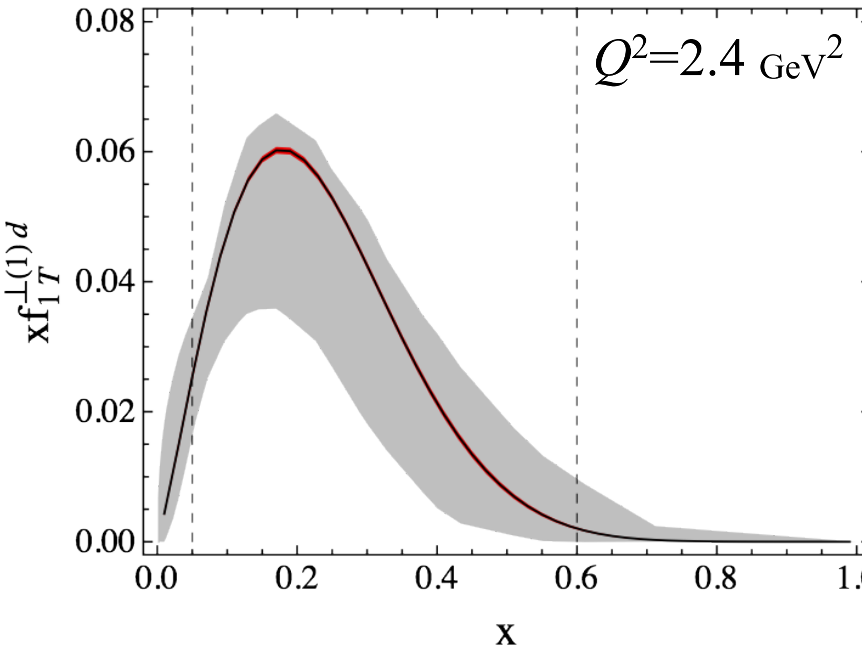
Model Calculation



Bacchetta, Conti, Radici
PR D 78, 074010 (2008).

SoLID Impact on Sivers



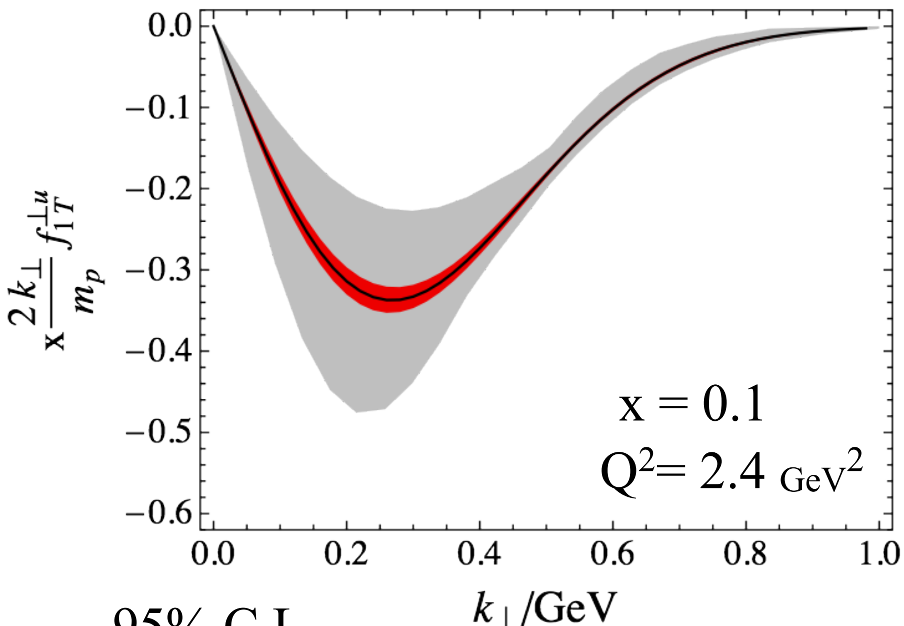


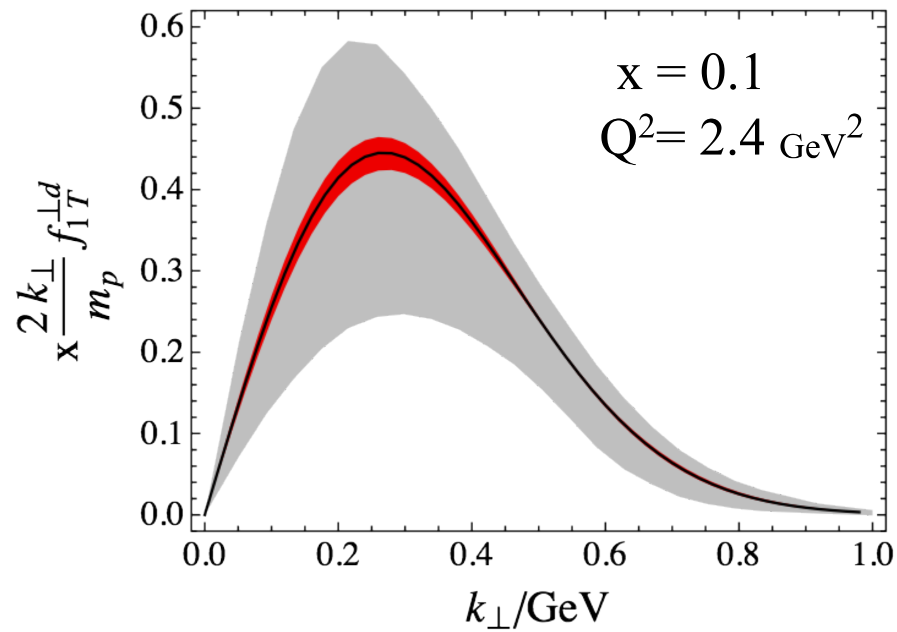
95% C.L.

Gray: parametrization by M. Anselmino *et al*., EPJ A 39, 89 (2009).

Red: SoLID projection with transversely polarized neutron/proton data.

Quark Transverse Momentum in p↑





95% C.L.

(grey) parametrization by M. Anselmino et al., EPJ A 39, 89 (2009).

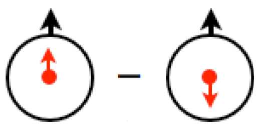
(red) SoLID projection with transversely polarized neutron and proton data.

$$\langle \mathbf{k}_\perp \rangle = -M \int \mathrm{d}x f_{1T}^{\perp(1)}(x)\,(\mathbf{S}\times\hat{\mathbf{P}})$$

	$\langle k_\perp \rangle^u$	$\langle k_\perp \rangle^d$
(grey)	96^{+60}_{-28} MeV	-113^{+45}_{-51} MeV
(red)	$96^{+2.8}_{-2.4}$ MeV	$-113^{+1.3}_{-1.7}$ MeV

Transverse Spin Structure

Transversity

h_1  (Collinear & TMD)

A transverse counter part to the longitudinal spin structure: helicity g_{1L}

They are NOT the same due to relativity.

Chiral-odd

Unique for the quarks.
No mixing with gluons.
Simpler evolution effect.

NOT accessible via inclusive DIS process.
Must couple to another chiral-odd function.
(*e.g.* Collins function $H_1^{\perp}$)

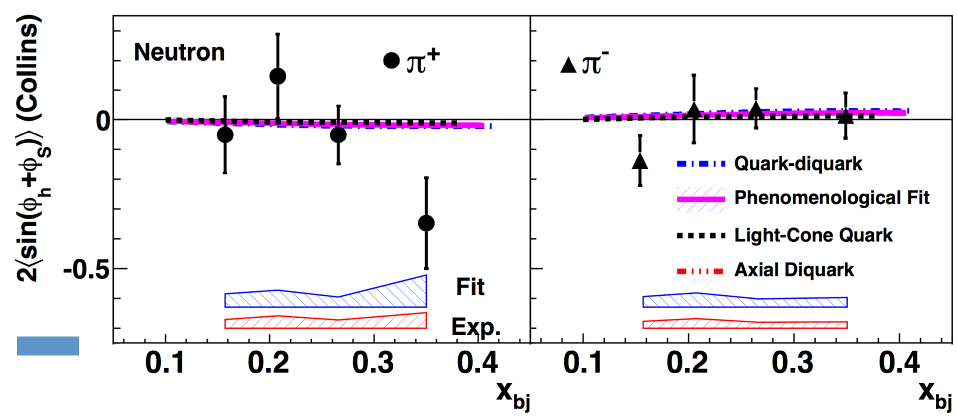
Measured via
SIDIS (E12-10-006, E12-11-008), Drell-Yan
Di-hadron (approved as run group with E12-10-006)

Measurement in SIDIS

Single spin asymmetry
(Collins asymmetry)

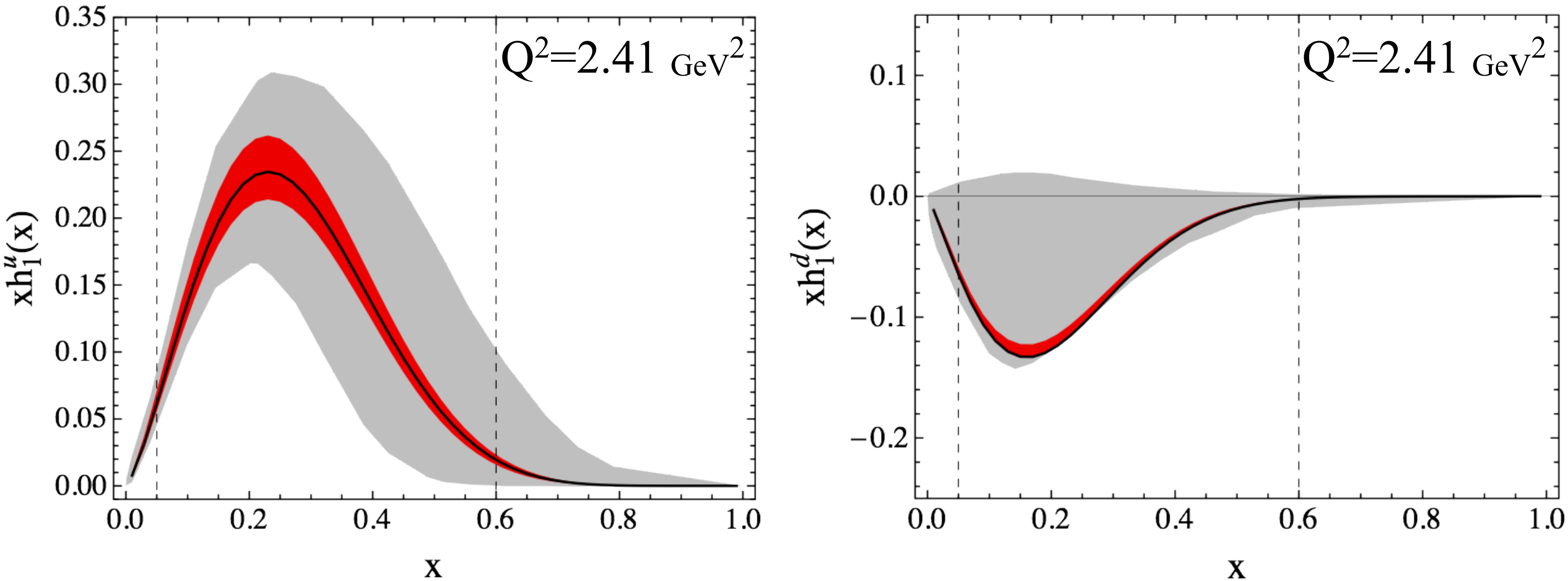
$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1(x,k_\perp) \bigotimes H_1^{\perp}(z,p_\perp)$$

$H_1^{\perp}(z,p_\perp)$ Collins fragmentation function



6 GeV JLab E06-010, X. Qian et al., PRL 107, 072003 (2011).

SoLID Impact on Transversity

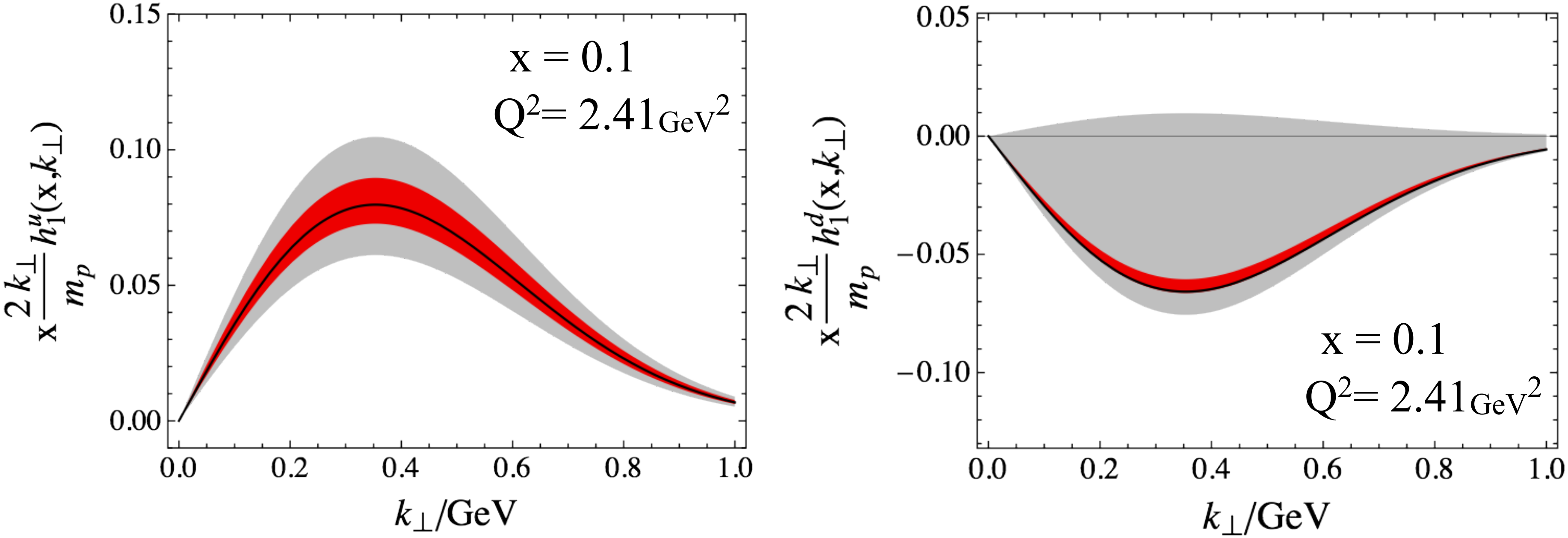


95% C.L.

parametrization by M. Anselmino et al., PR D 87, 094019 (2013).

SoLID projection with transversely polarized neutron and proton data.

SoLID Impact on Transversity TMD



95% C.L.

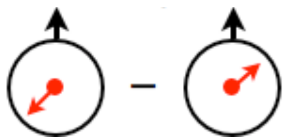
parametrization by M. Anselmino et al., PR D 87, 094019 (2013).

SoLID projection with transversely polarized neutron and proton data.

Pretzelosity

Pretzelosity distribution

$h_{1T}^{\perp}$



Chiral-odd. NO gluon analogy.
Interference of light-front wave functions differing by ΔL = 2.
Measuring the difference between helicity and transversity, and hence relativistic effects. (spherically symmetric models)

Relation to OAM (canonical)

$$L_z^q = -\int \mathrm{d}x \mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int \mathrm{d}x h_{1T}^{\perp(1)q}(x) \qquad \text{(model dependent)}$$

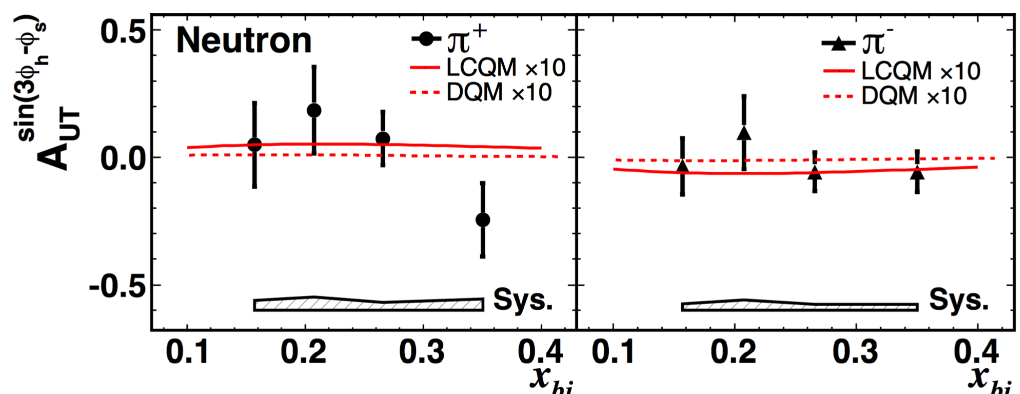
Measurement in SIDIS

Single spin asymmetry

$$A_{UT}^{\sin(3\phi_h - \phi_S)} \sim h_{1T}^{\perp}(x, k_\perp) \bigotimes H_1^{\perp}(z, p_\perp)$$

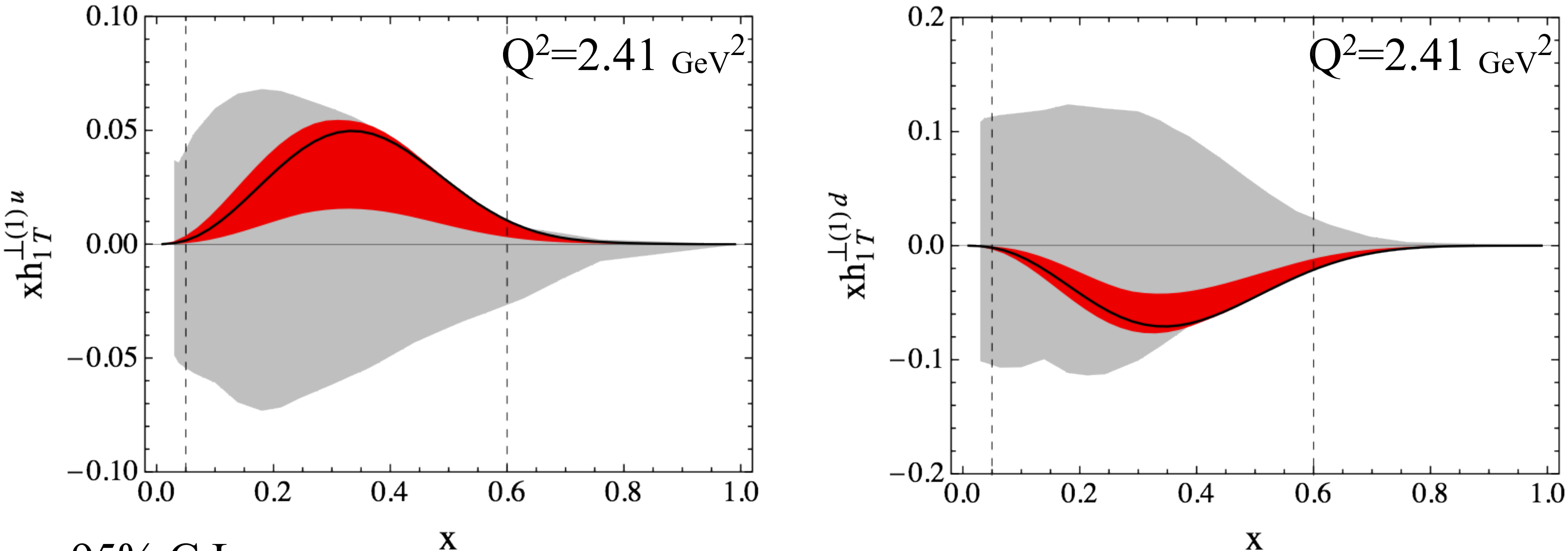
A global fit to 175 data from COMPASS, HERMES, and JLab found comparable with null signal hypothesis at 72% C.L..

C. Lefky, A. Prokudin, PR D 91, 034010 (2015).



6 GeV JLab E06-010, Y. Zhang et al., PR C 90, 055209 (2014).

SoLID Impact on Pretzelosity



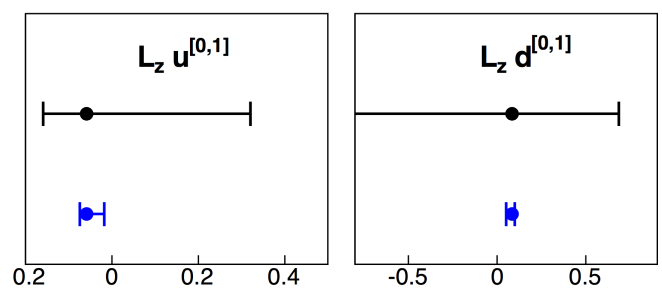
95% C.L.

parametrization by C. Lefky et al., PR D 91, 034010 (2015).

SoLID projection with transversely polarized neutron and proton data.

OAM:

$$L_z^q = -\int \mathrm{d}x\mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x,k_\perp) = -\int \mathrm{d}x h_{1T}^{\perp(1)q}(x)$$



Lefky et al. (2015)

SoLID projection

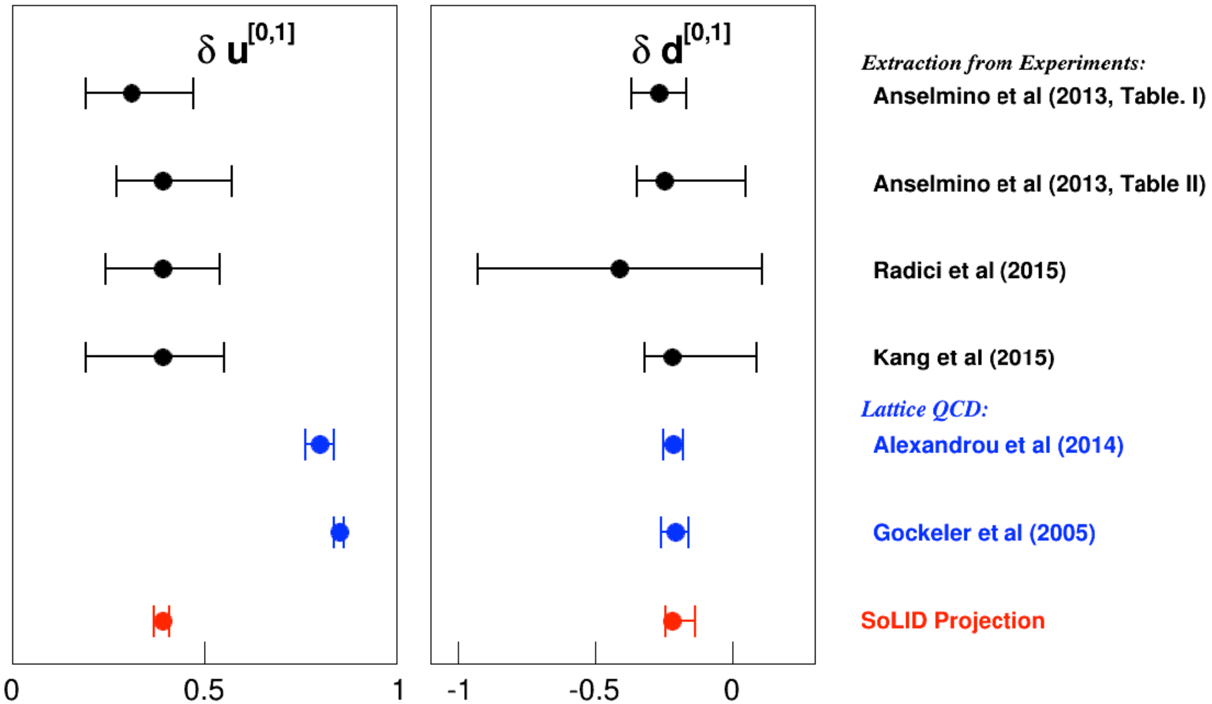
Tensor Charge

Definition

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = \delta_T q\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S) \quad \delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] \mathrm{d}x$$

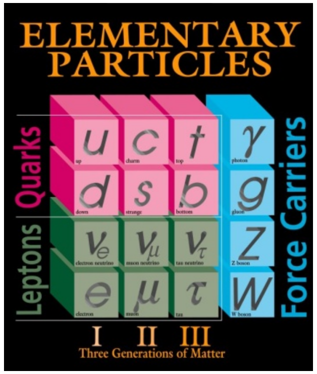
A fundamental QCD quantity. Matrix element of local operators.
Moment of transversity distribution. Valence quark dominant.
Calculable in lattice QCD.

SoLID impact



SoLID projection by A. Prokudin, N. Sato, K. Allada, and Z. Ye (on-going).

CP violation in the Standard Model



- Flavor changing weak current

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

$$J^\mu = \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} \frac{\gamma_\mu (1-\gamma^5)}{2} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass eigenstates

- 3 mixing angles and 1 complex phase δ_{CKM}
  - $\delta_{CKM} \neq 0$, CP violation

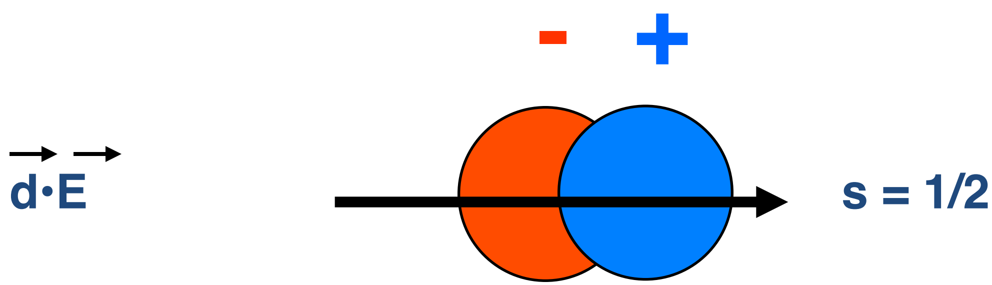
- **The θ term in QCD lagrangian**

$$L_{QCD} = -\frac{1}{4} G^\alpha_{\mu\nu} G^{\alpha\mu\nu} - \sum \bar{\psi}_n [i\gamma^\mu \partial_\mu + g\gamma^\mu G^\alpha_\mu T^\alpha + m_n] \psi_n + \theta \frac{g^2}{32\pi^2} G^{\alpha\mu\nu} \tilde{G}^\alpha_{\mu\nu}$$

- If $\theta \neq 0$, $G^{\alpha\mu\nu} \tilde{G}^{\alpha}_{\mu\nu}$ violates P & T $\quad \tilde{G}^\alpha_{\mu\nu} \equiv \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} G^{\alpha\rho\sigma}$

Neutron Electric Dipole Moment (EDM)

Current limit (10^{-26} θ) e.cm , next generation of experiments aim at (10^{-28} θ) e.cm



- If neutron possesses EDM, in an electric field, Hamiltonian $H = -d_n \vec{\sigma} \bullet \vec{E}$
  – changes sign under T (P) symmetry operation
- d_n is more sensitive to θ than to δ_{CKM}
- Neutron EDM ~ O(10^{-16} θ) e.cm (various model predictions)

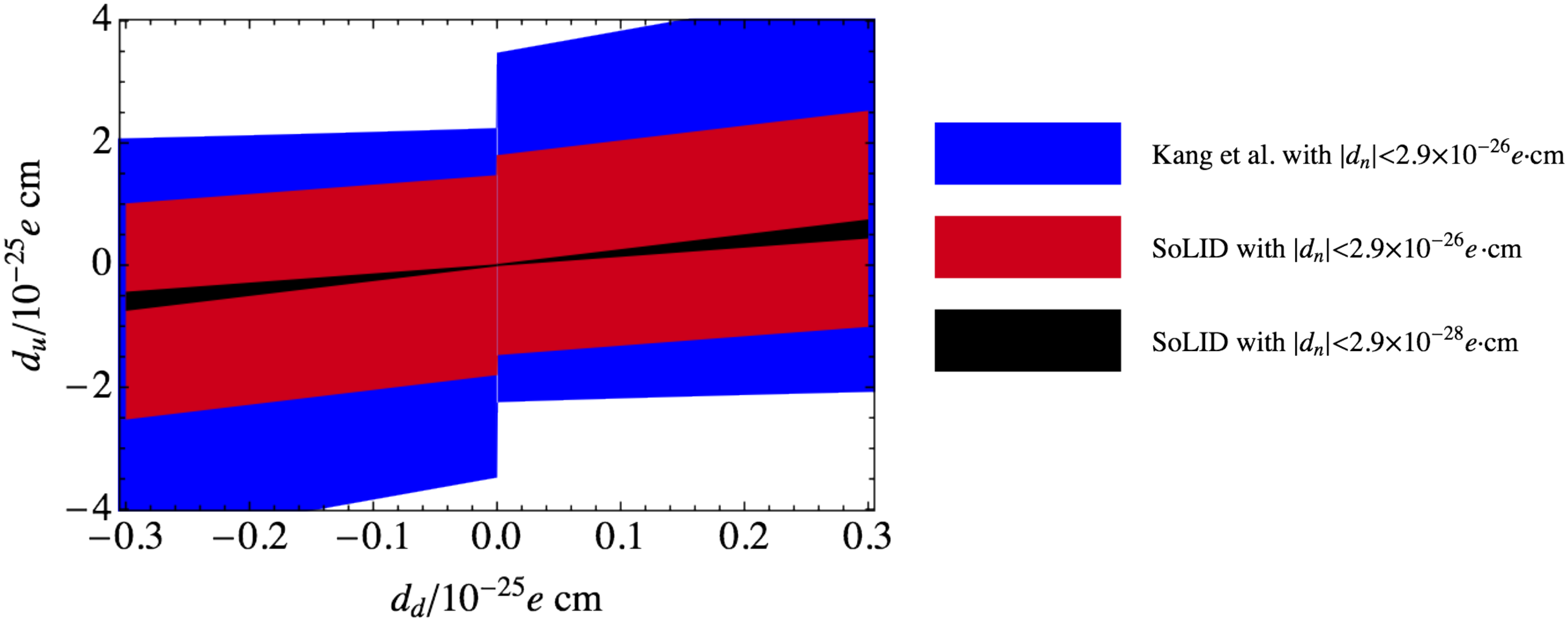
Quark EDM appears only at the three-loop level

Tensor Charge and Neutron EDM

Electric Dipole Moment

Tensor charge and EDM

$$d_n = \delta_T u \, d_u + \delta_T d \, d_d + \delta_T s \, d_s$$



current neutron EDM limit $|d_n| < 2.9 \times 10^{-26}\, e \cdot \mathrm{cm}$

Summary

- Spin remains important and puzzling for nucleon
- Three-dimensional imaging of nucleon helps solve the remaining puzzle to the proton spin, and uncovers the rich dynamics of QCD
- Rich SoLID Physics program at 12-GeV JLab
  - SIDIS program with unprecedented precision on TMDs
  - Flavor separation of tensor charge with high precision - impact on lattice QCD calculations, neutron EDM experiments, ….
  - SoLID SIDIS kaon detection being investigated
  - Promising GPD program with SoLID, complementary to the SoLID TMD program

Thanks to K. Allada, J.-P Chen, T.-B. Liu, Z.-E. Meziani, A. Prokudin, N. Sato, P. Souder, Z. Ye, X.F. Yan, and Z. Zhao

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