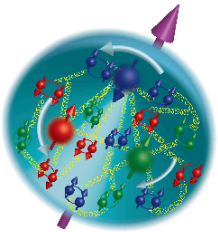
The TMD program at JLab

DIS2018
April 16 – 20, 2018

Haiyan Gao
Duke University and Duke Kunshan University

Nucleon Spin Decomposition



Proton spin puzzle

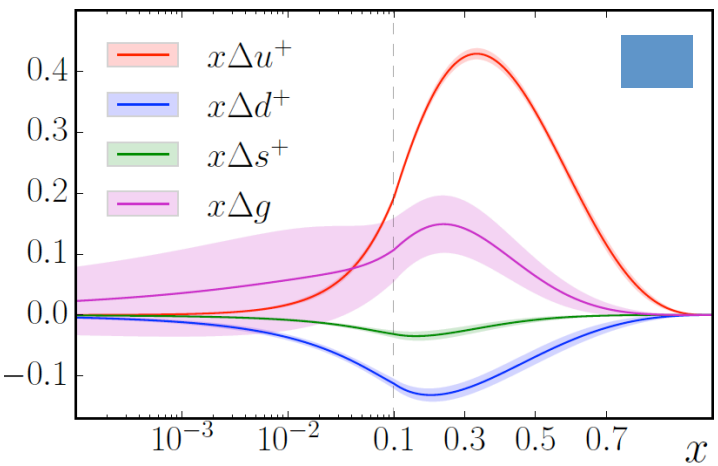
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

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

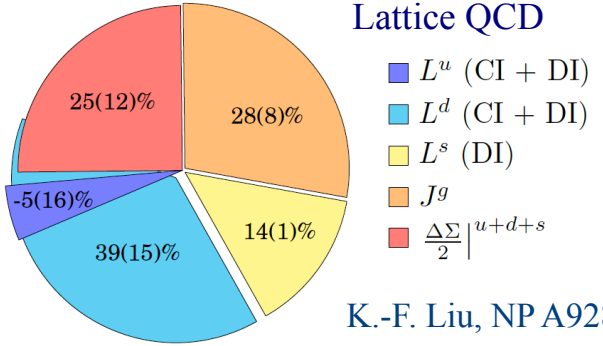
Spin decomposition

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



JAM Collaboration, PRD (2016).

Lattice QCD



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

Access to $L_{q/g}$

It is necessary to have transverse information.

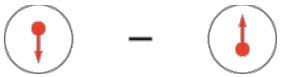
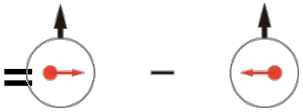
Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

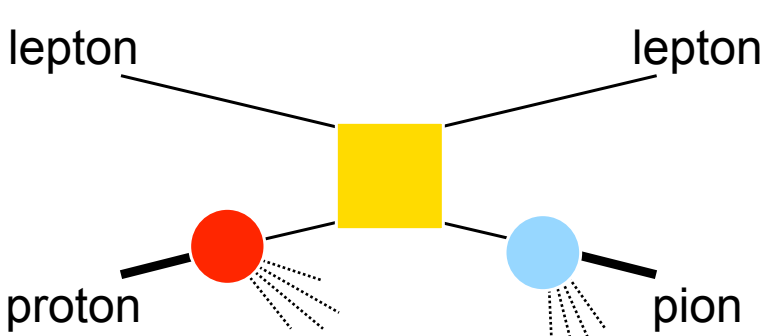
Gluon spin: STAR and PHENIX (pp collisions)
Lattice: Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017)

Leading Twist TMDs

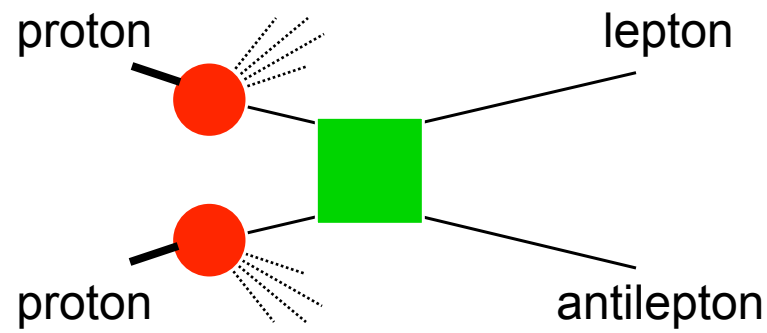
→ Nucleon Spin
→ Quark Spin

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

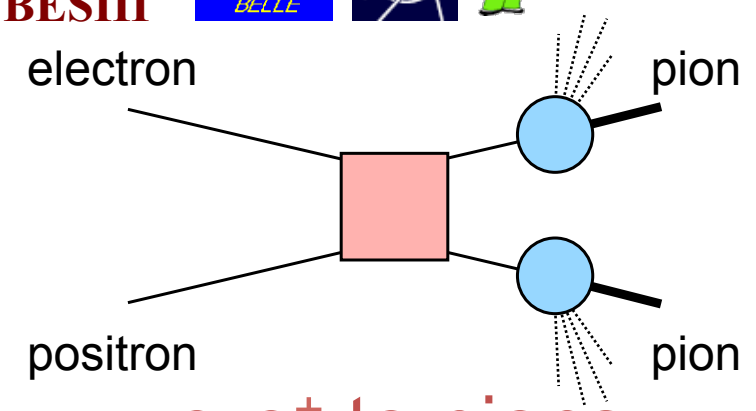
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

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

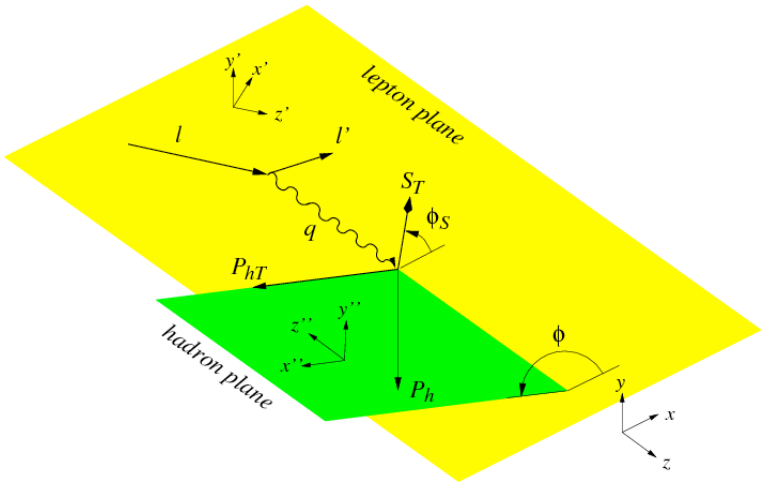
$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

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]

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

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

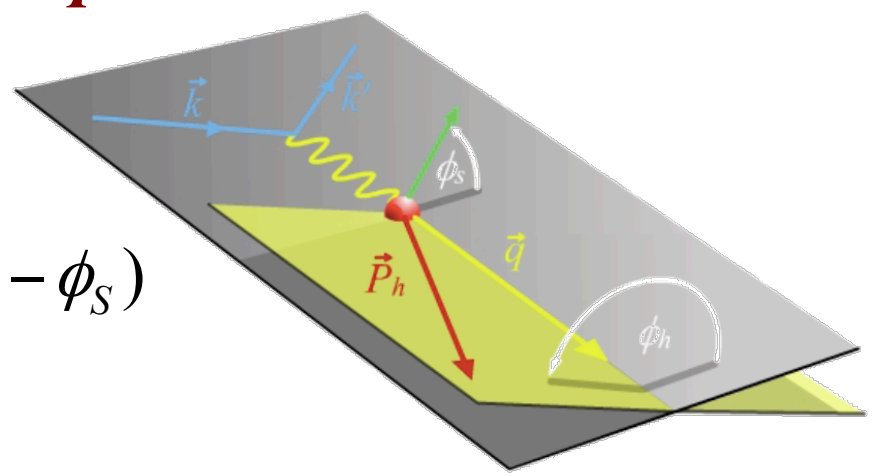
In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMDs.

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

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

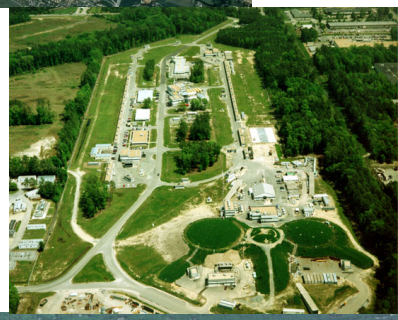
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

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

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.

Impressive experimental progress in QCD spin physics in the last 30 years

- **Inclusive spin-dependent DIS**
  - CERN: EMC, SMC, COMPASS
  - SLAC: E80, E142, E143, E154, E155
  - DESY: HERMES
  - JLab: Hall A, B and C
- **Semi-inclusive DIS**
  - SMC, COMPASS
  - HERMES, JLab
- **Polarized pp collisions**
  - BNL: PHENIX & STAR
  - FNAL: POL. DY
- **Polarized e+e- collisions**
  - KEK: Belle

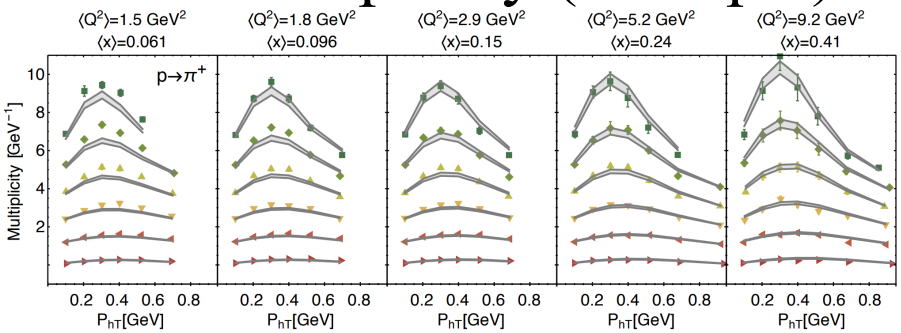


Z. Meziani

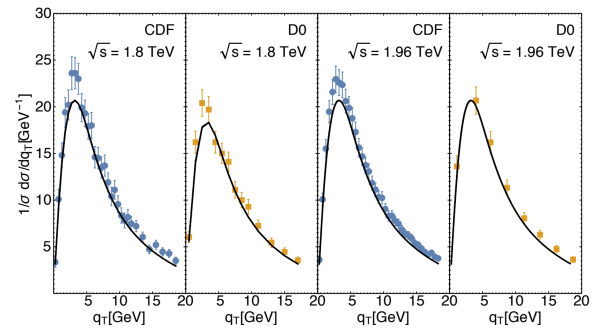
Global Analysis: Unpolarized TMD

Global analysis of semi-inclusive DIS, Drell-Yan and Z production data with TMD evolution

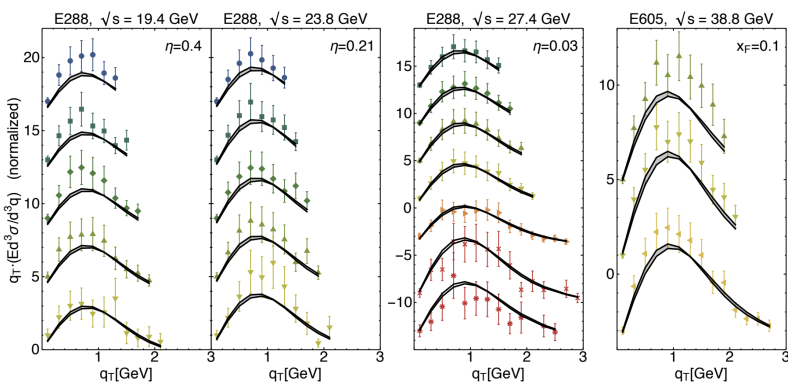
SIDIS multiplicity (example)



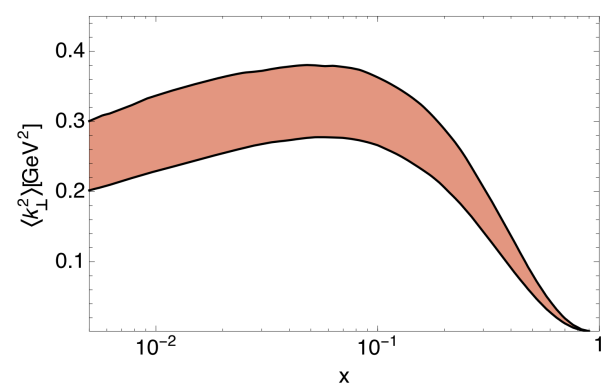
Z production



Drell-Yan cross section

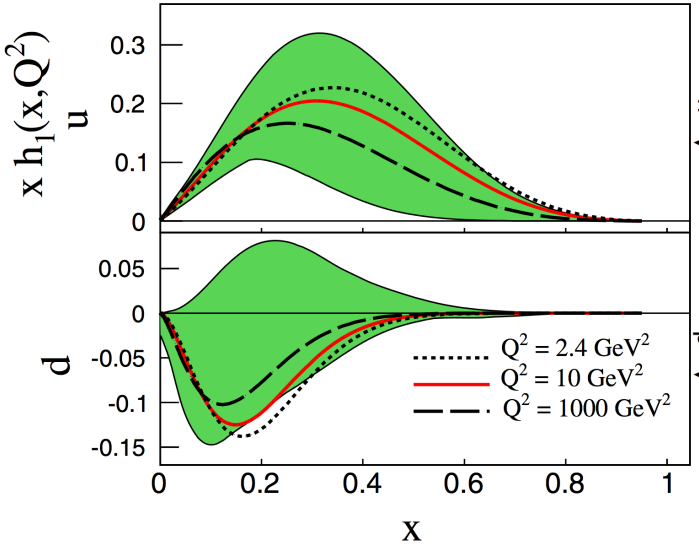


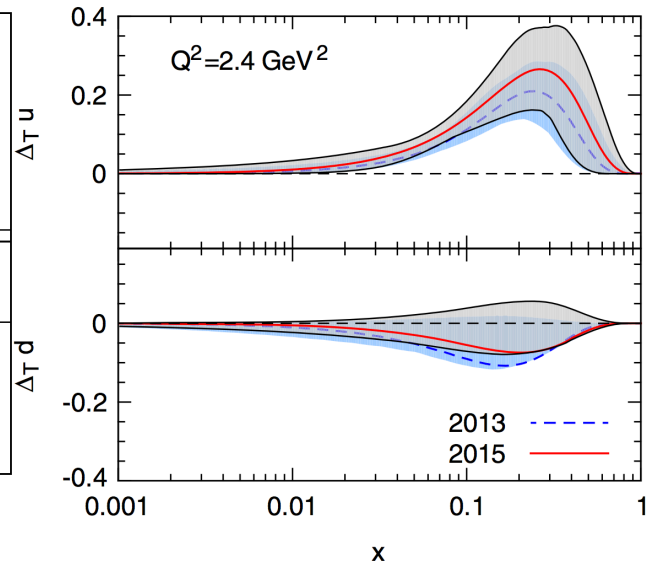
Transverse momentum distribution

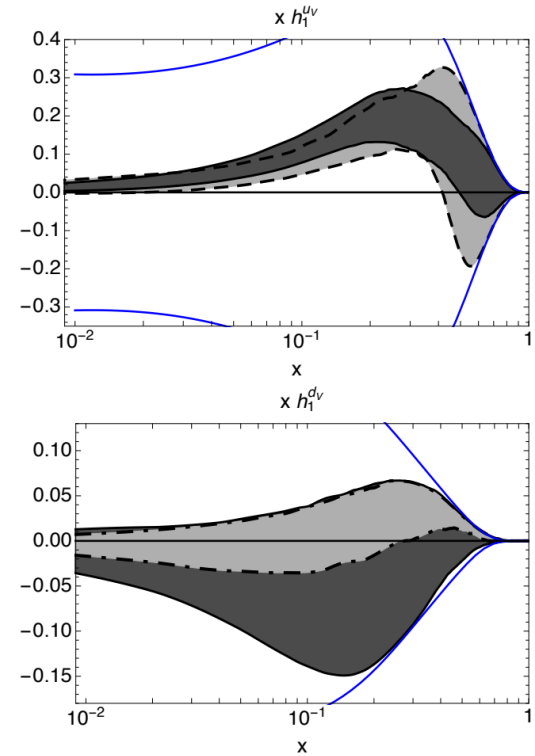


A. Bacchetta *et al.*, J. High Energy Phys. 06 (2017) 081.

Global Analysis: Transversity







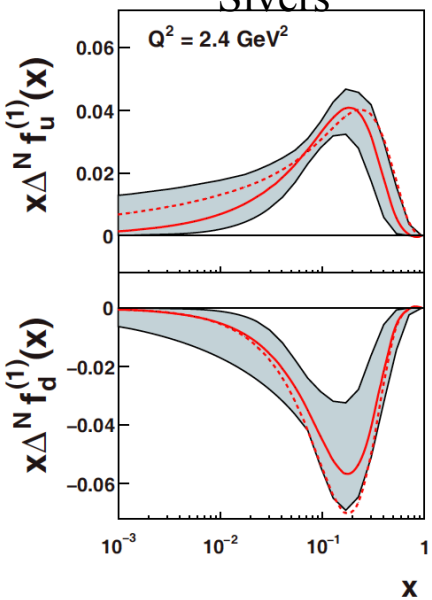
Z.-B. Kang et al., Phys. Rev. D 93, 014009 (2016).

M. Anselmino et al., Phys. Rev. D 92, 114023 (2015).

M. Radici and A. Bacchetta, arXiv: 1802.05212[hep-ph]

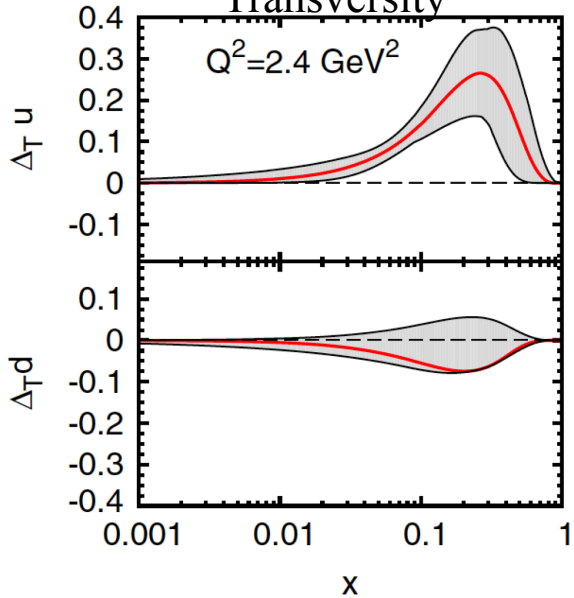
Present Status On TMD Extractions

Sivers



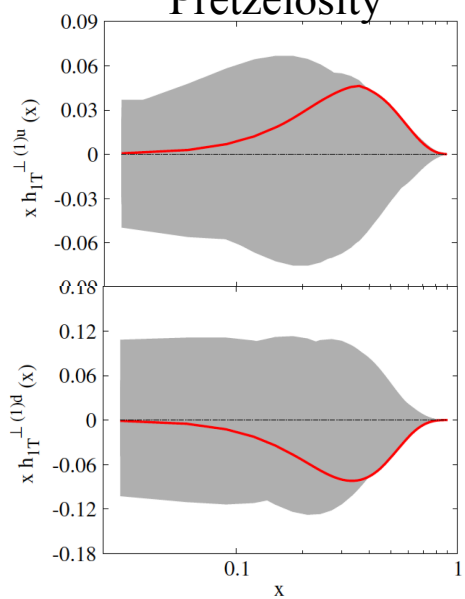
Anselmino et al, EPJA39, 89 (2009)

Transversity



Anselmino et al, PRD92, 114023 (2015)

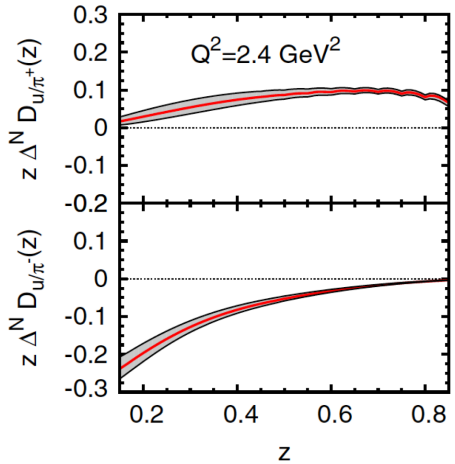
Pretzelosity

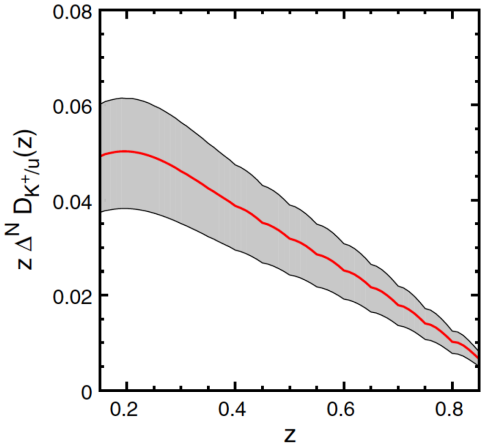


Lefky et al, PRD91, 034010 (2015)

Collins fragmentation

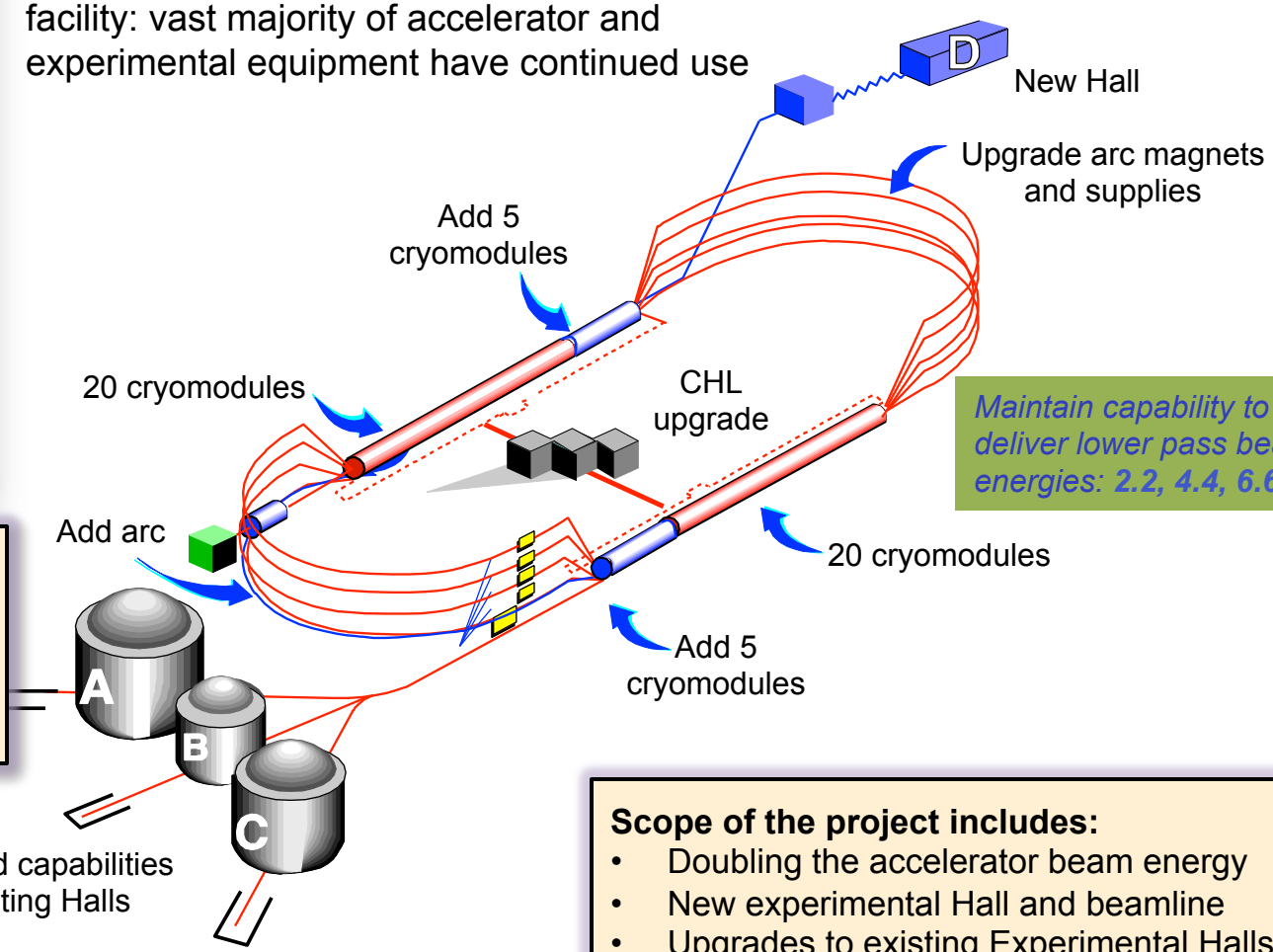
Anselmino et al, PRD92, 114023 (2015)
PRD93, 034025 (2016)





12 GeV Upgrade at JLab

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



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

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

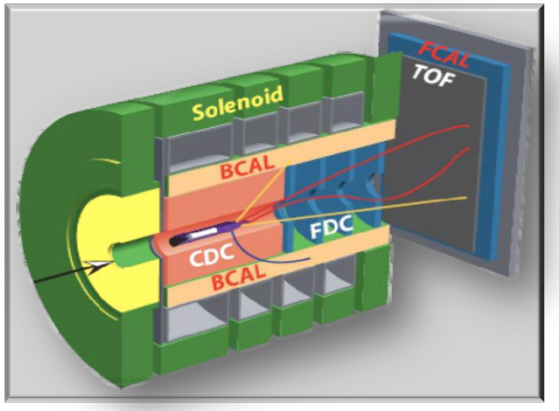
Scope of the project includes:

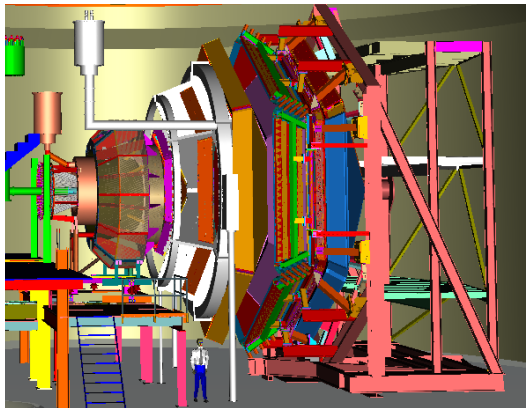
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

Solenoidal Large Intensity Device (SoLID) proposed for Hall A

12 GeV Upgrade Physics Instrumentation

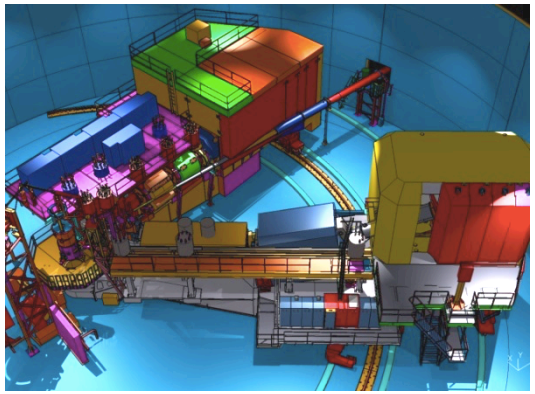
GLUEx (Hall D): **exploring origin of confinement by studying hybrid mesons**

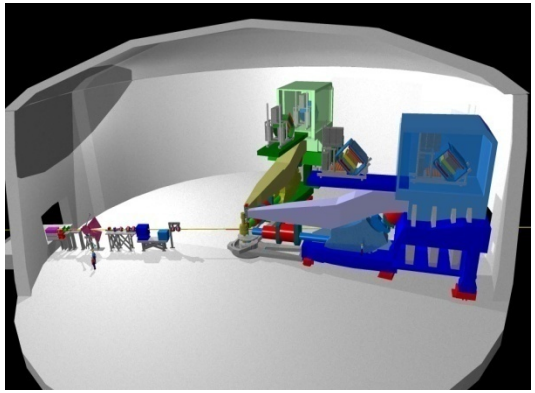




CLAS12 (Hall B): **understanding nucleon structure via generalized parton distributions**

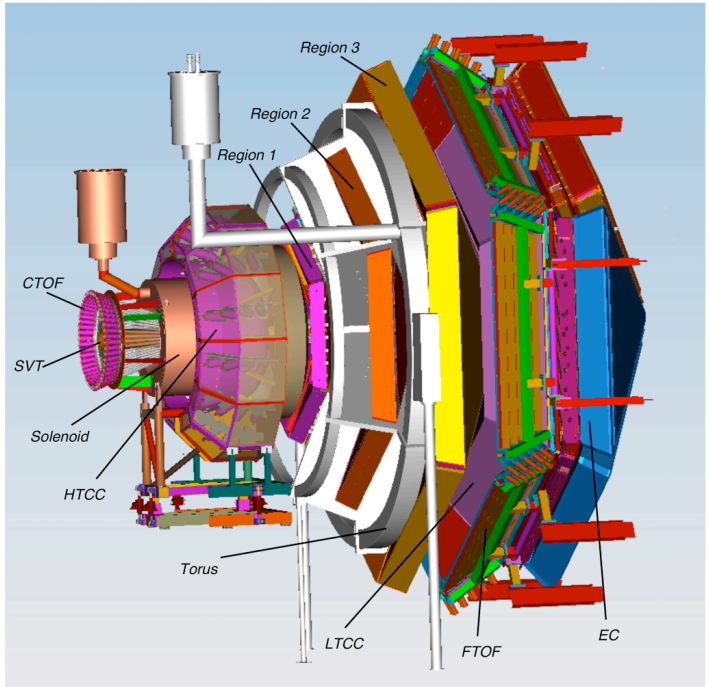
SHMS (Hall C): **precision determination of valence quark properties in nucleons and nuclei**

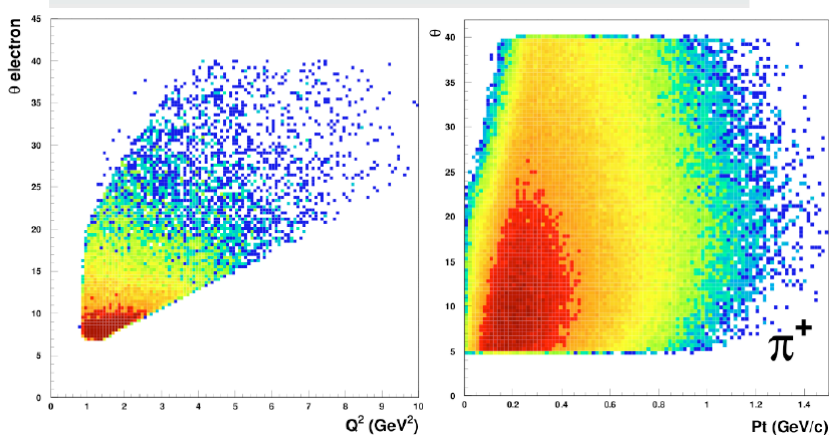




Hall A: **nucleon form factors,**
& future new experiments using new devices

CLAS 12

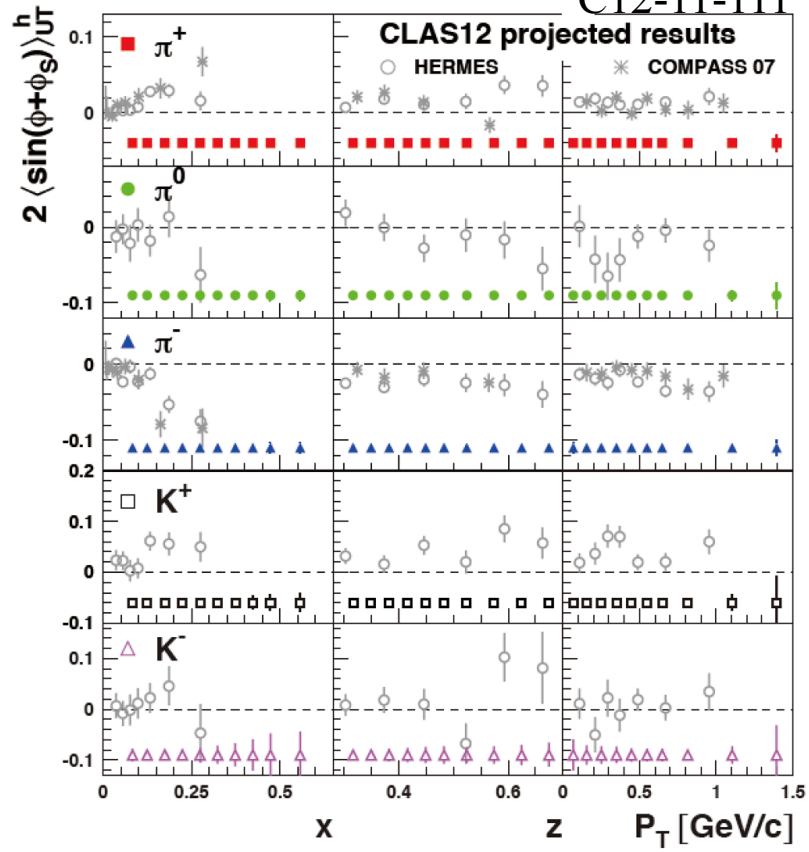




E12-09-007, E12-09-008
E12-09-009, E12-07-107

NH_3 and ND_3 targets

C12-11-111



Hall C SIDIS Program (typ. x/Q^2 ~ constant)

[R. Ent, DIS2016]

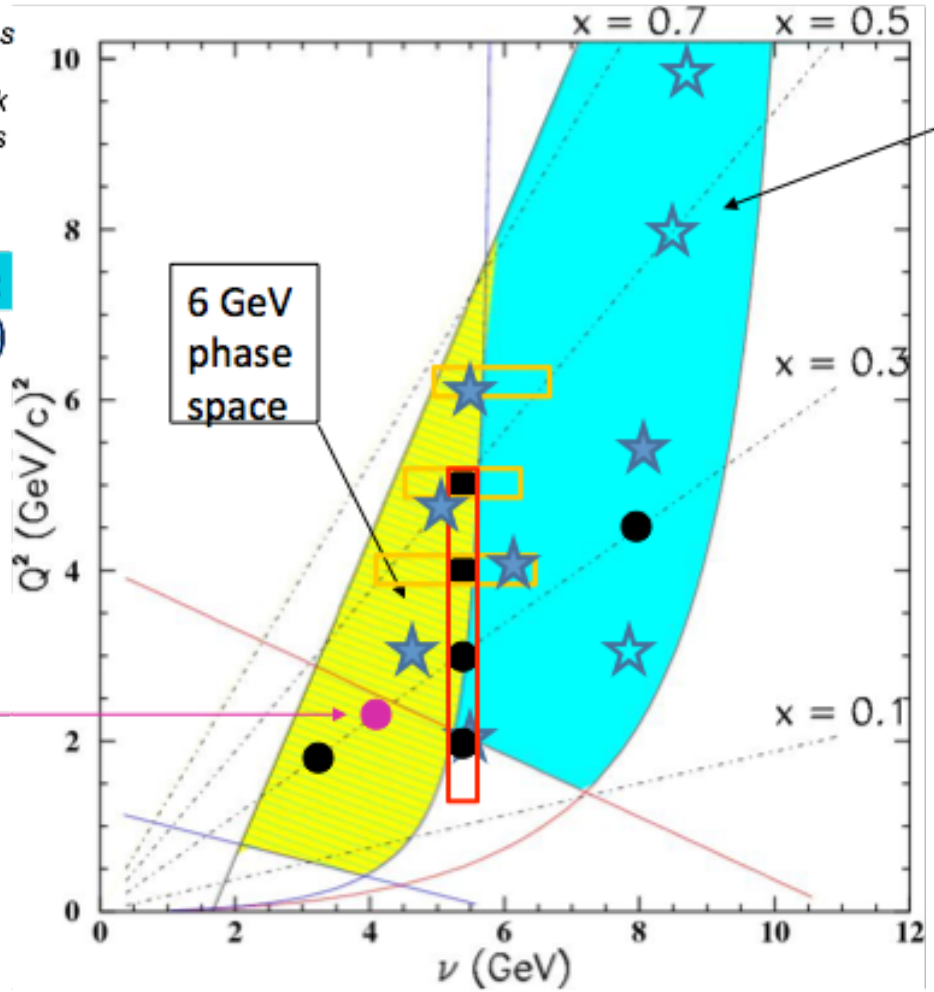
HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007
Neutral pions:
Scan in (x,z,P_T)
Overlap with E12-09-017 & E12-09-002

Parasitic with E12-13-010

E00-108 (6 GeV)



Charged pions:

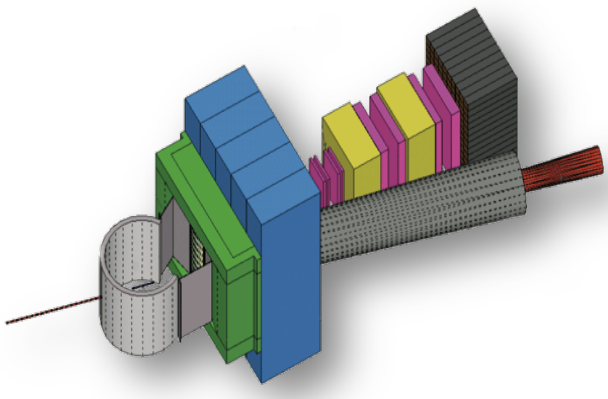
E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

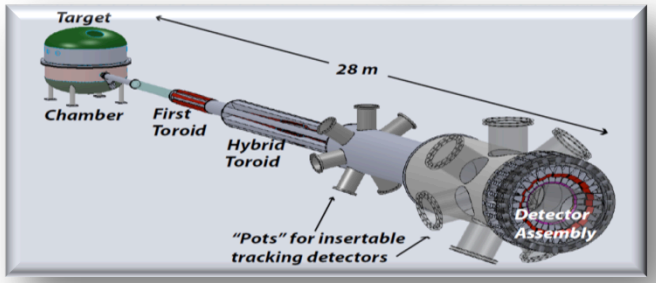
E12-09-002
+ scans in z

Beyond 12 GeV Upgrade

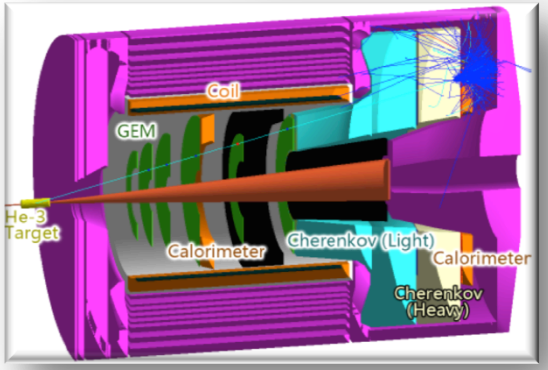
- **Super BigBite Spectrometer**
  (Approved for FY13-16 construction)
  - **high Q^2 form factors**
  - **SIDIS**



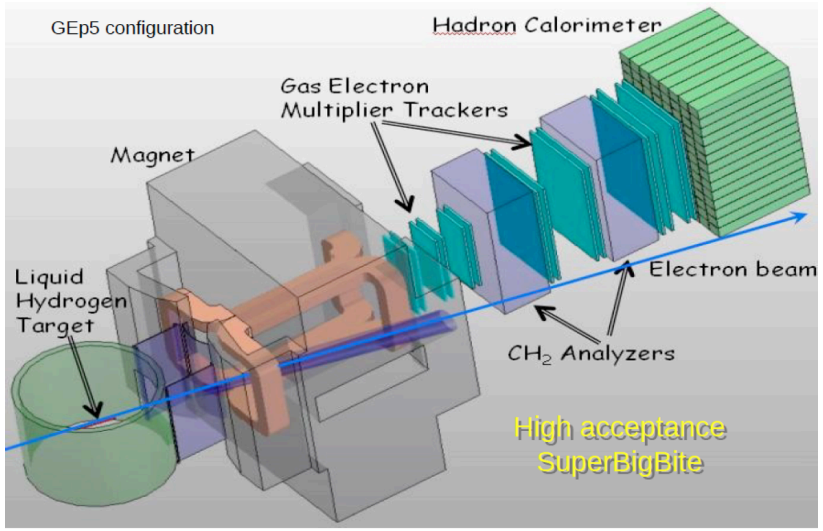
- **MOLLER experiment**
  (MIE – FY20-24?)
  - **Standard Model Test**



- **SoLID program**
  Chinese collaboration
  CLEO Solenoid
  Proton mass, spin and
  Standard Model Test

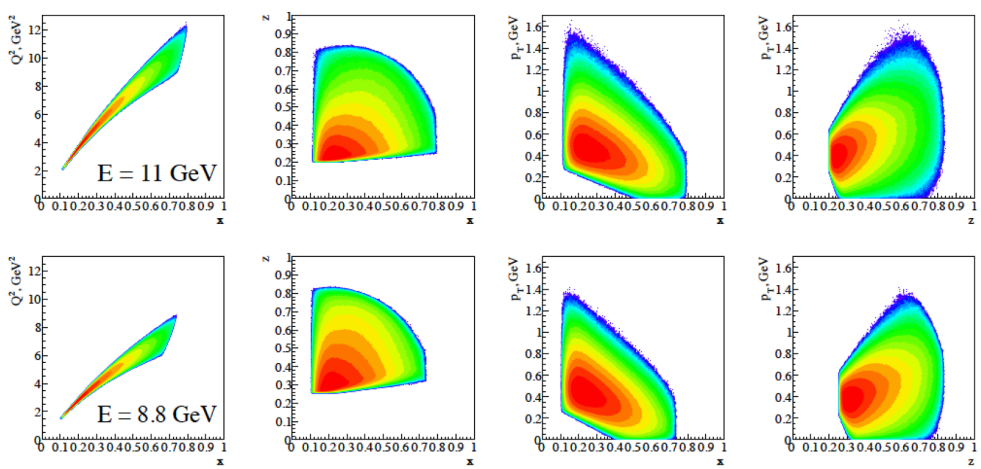


SuperBigbite Spectrometer

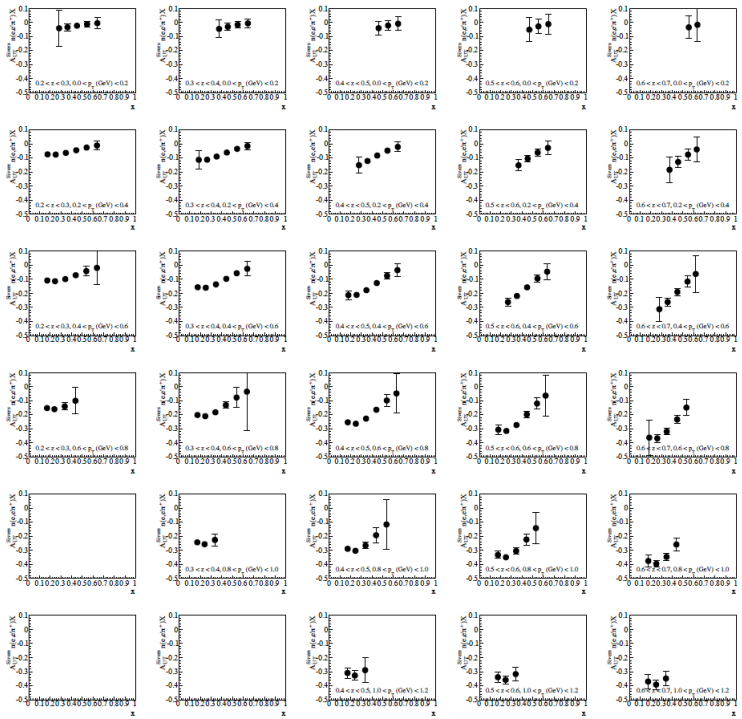


E12-09-018: 64 days

neutron (^{3}He) target



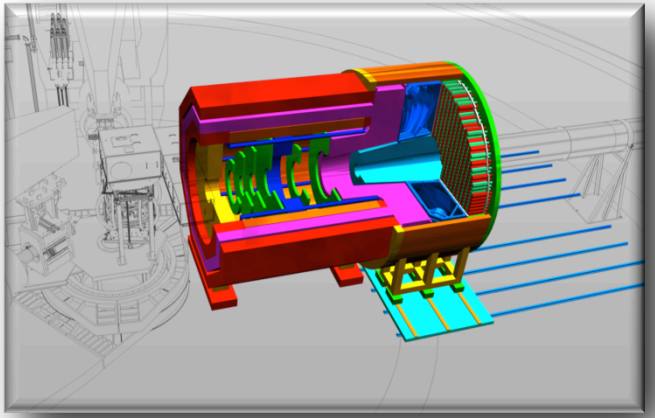
3D mapping example



Solenoidal Large Intensity Device (SoLID) Physics

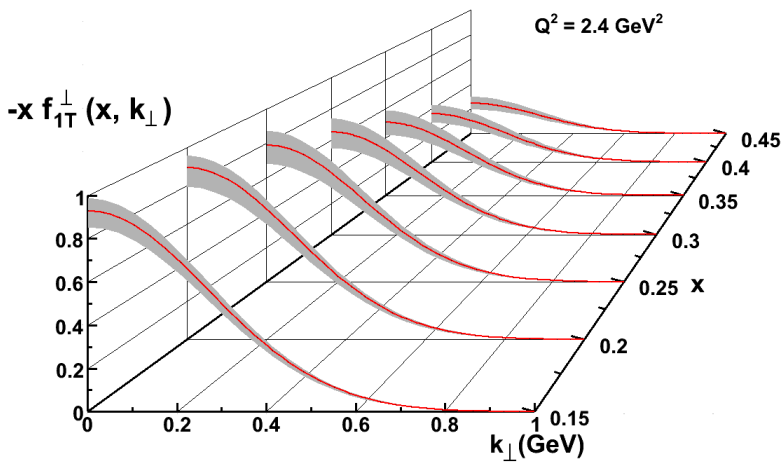
SoLID provides unique capability:

- ✓ high luminosity ($10^{37\text{-}39}$)
- ✓ large acceptance with full ϕ coverage

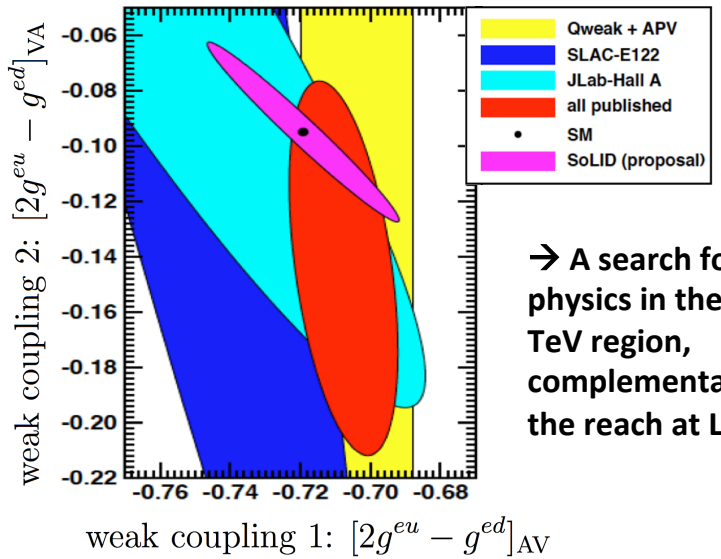


→ multi-purpose program to maximize the 12-GeV science potential

1) Precision in 3D momentum space imaging of the nucleon

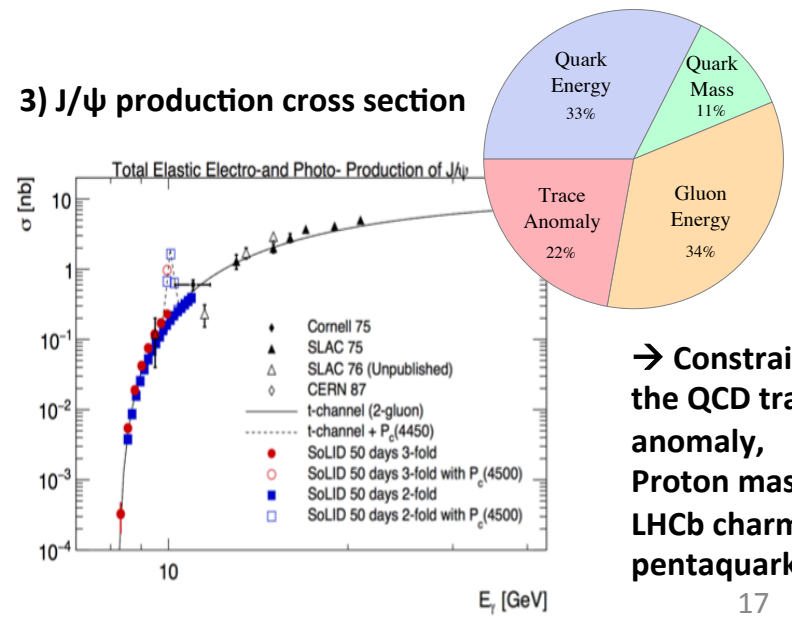


2) Precise determination of the electroweak couplings



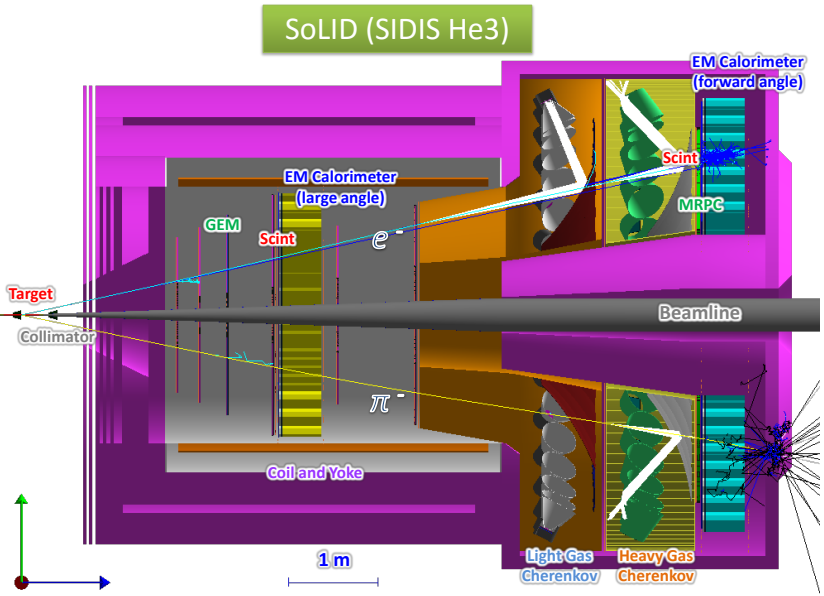
→ **A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.**

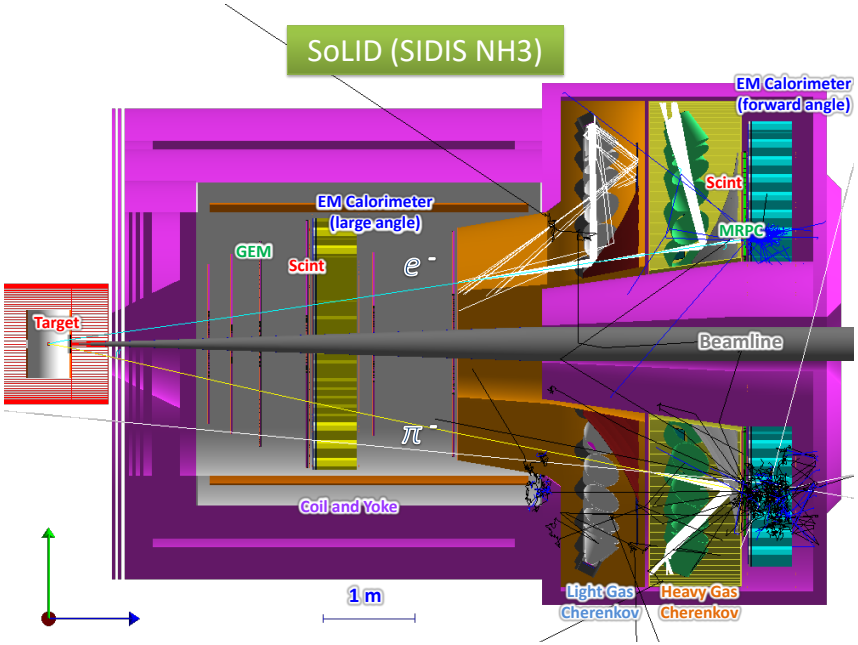
3) J/ψ production cross section



→ **Constrain the QCD trace anomaly, Proton mass , LHCb charmed pentaquark**

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**

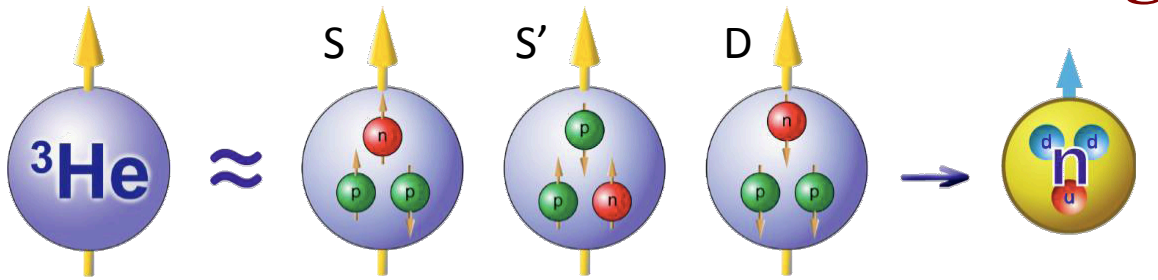
E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

Three run group experiments approved: TMDs, GPDs, and

much more

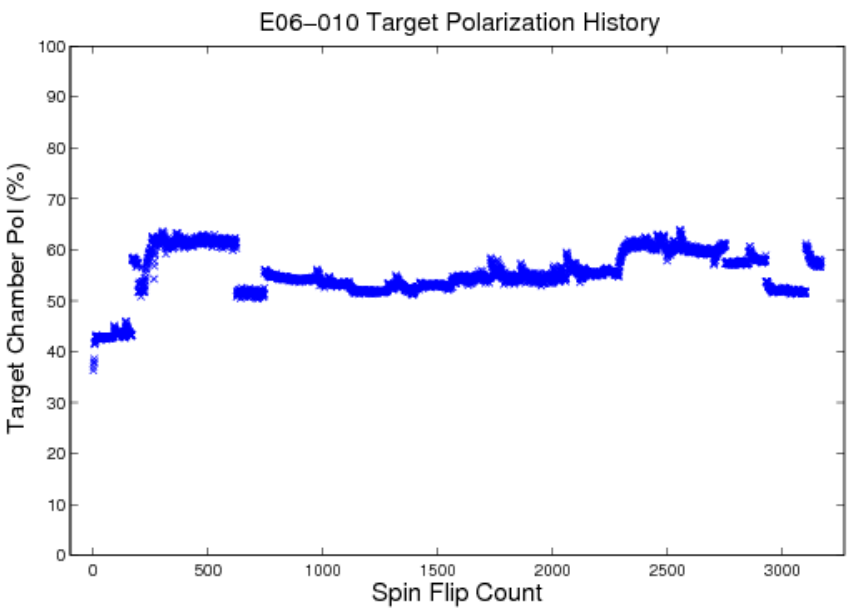
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

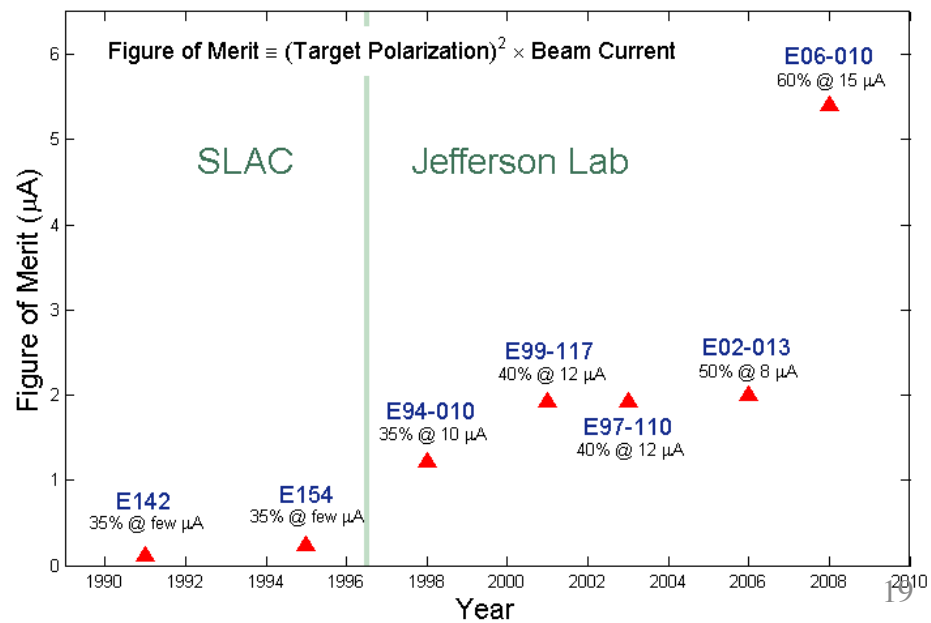
Polarized ^{3}He Target



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!**

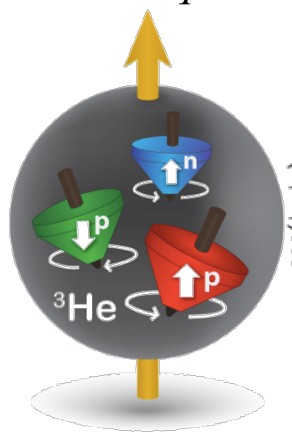




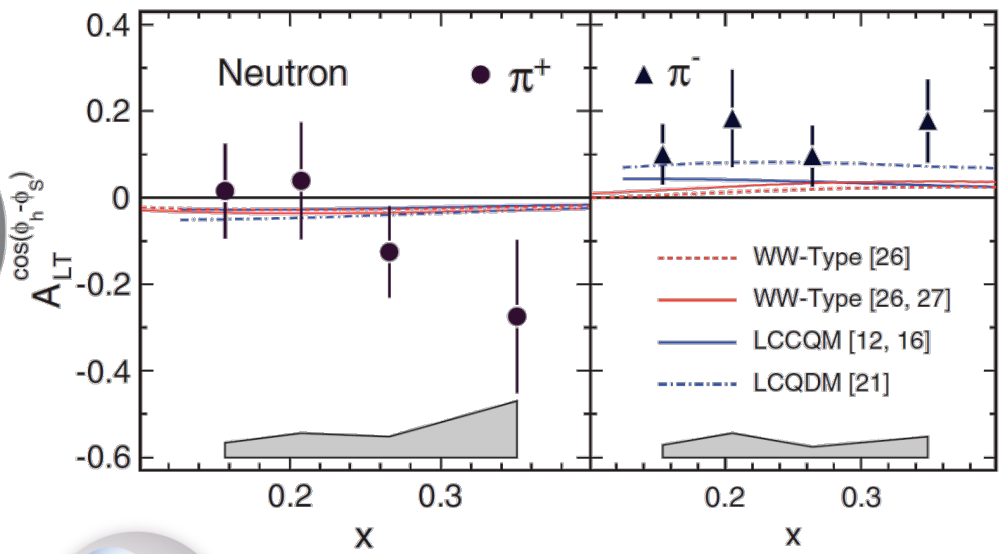
New Observable Reveals Interesting Behaviors of Quarks

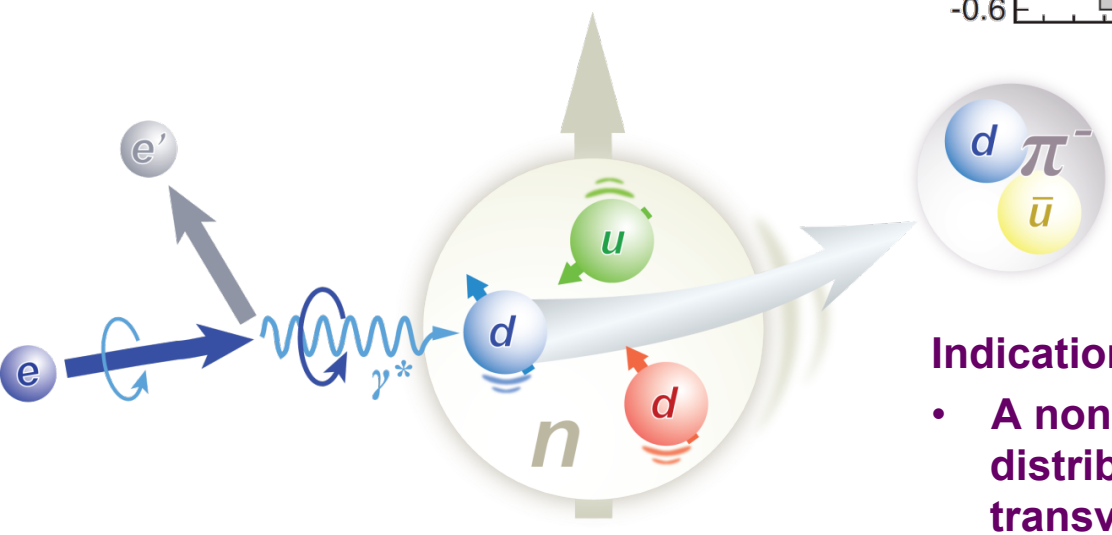
$$A_{\mathrm{LT}}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

Target:
polarized ^{3}He => 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**

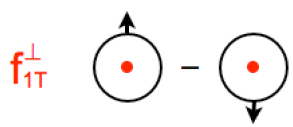
Hermes showed preliminary results from the proton

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

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



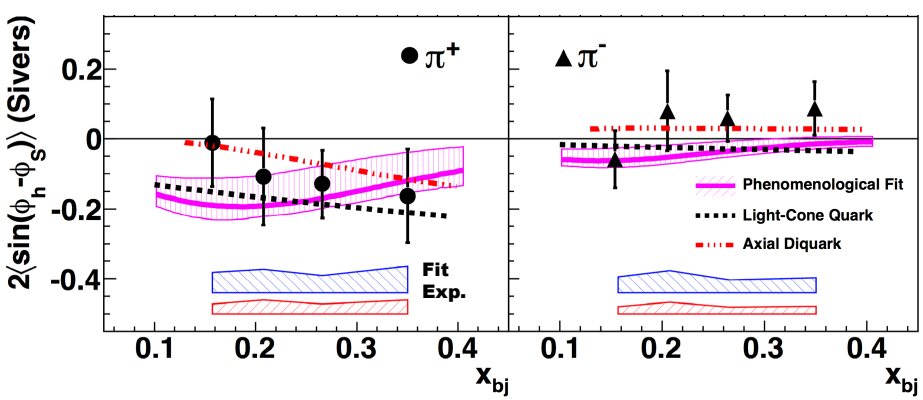
naively time-reversal odd.

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

Measurement in SIDIS

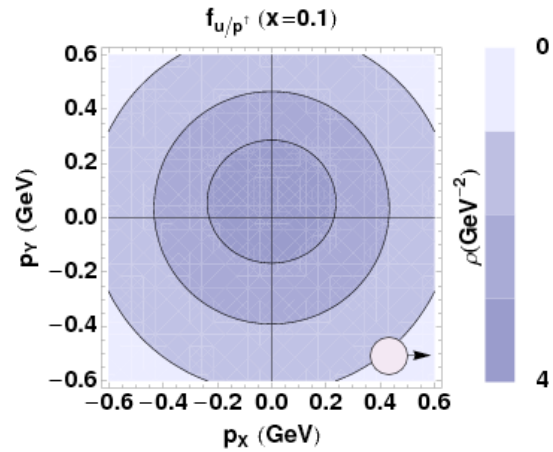
Single spin asymmetry (Sivers asymmetry)

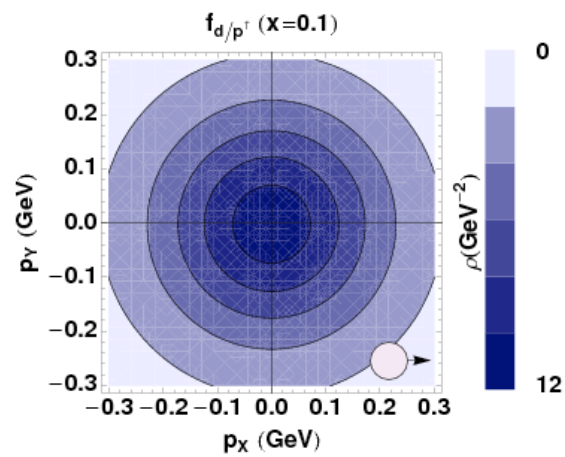
$$A_{UT}^{\sin(\phi_h - \phi_S)} \sim f_{1T}^{\perp}(x, k_\perp) \otimes D_1(z, p_\perp)$$



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

Model Calculation





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

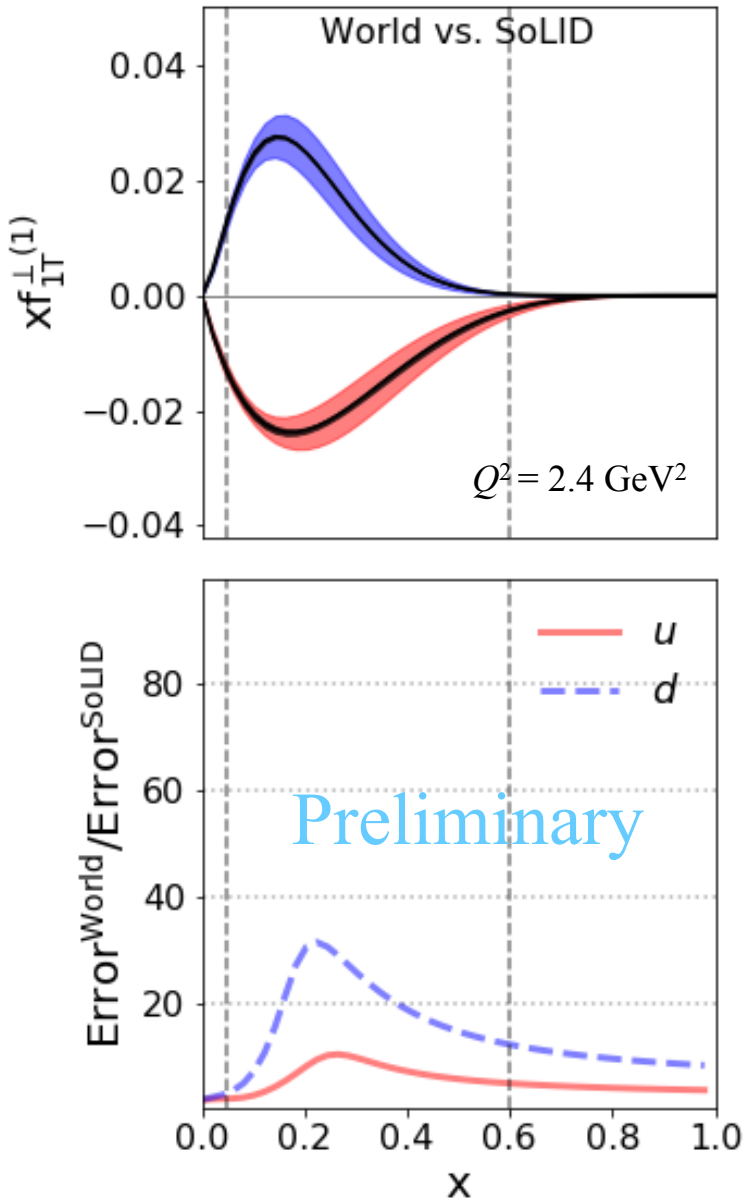
SoLID Impact on Sivers

Fit SIDIS Sivers asymmetries data from HERMES, COMPASS and Jlab-6 GeV

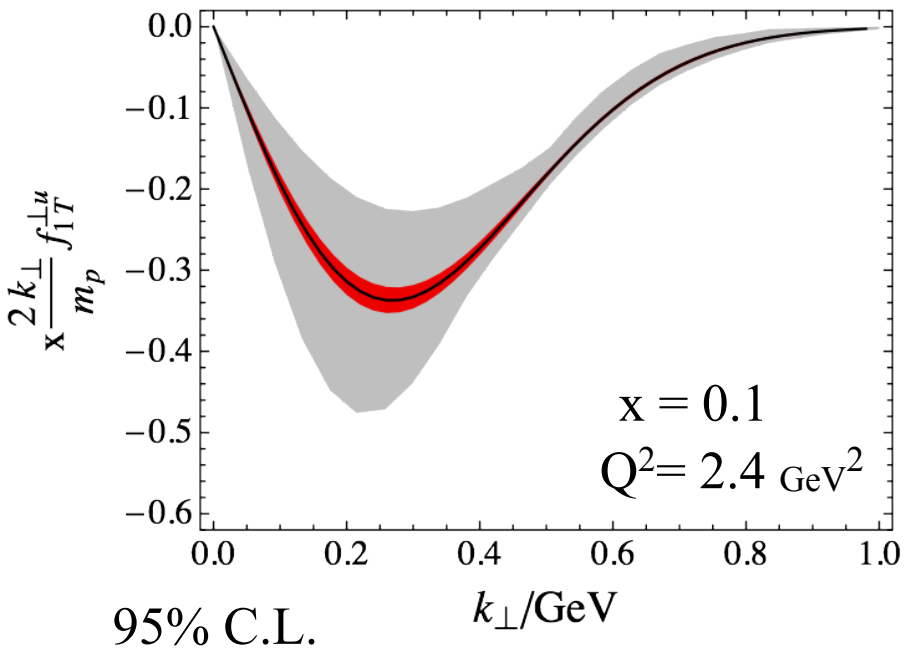
Monte Carlo method with nested sampling algorithm is applied

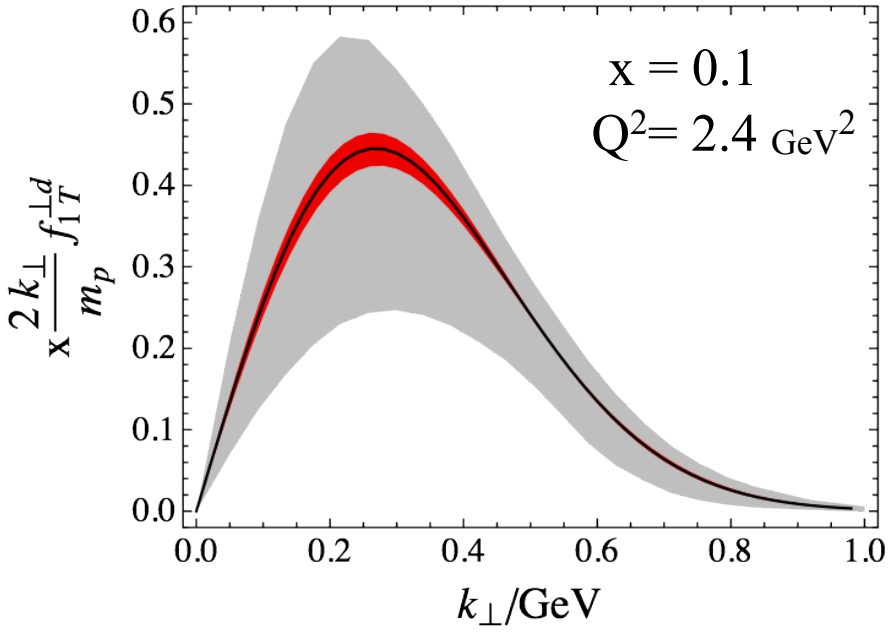
TMD evolution is not included

Both statistical and systematic uncertainties are included



Quark Transverse Momentum in p↑





95% C.L.

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

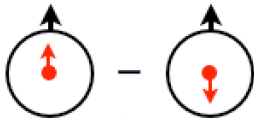
SoLID projection with transversely polarized neutron and proton data.

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

	$\langle k_\perp \rangle^u$	$\langle k_\perp \rangle^d$
	96^{+60}_{-28} MeV	-113^{+45}_{-51} MeV
	$96^{+2.8}_{-2.4}$ 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.

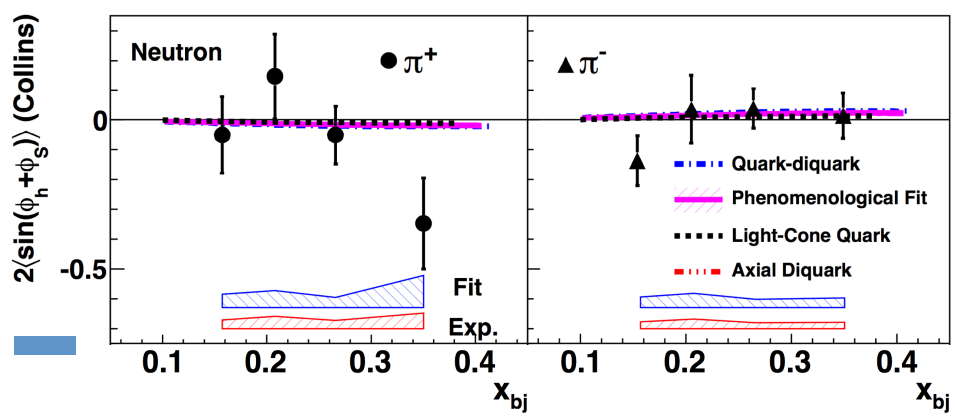
NOT accessible via inclusive DIS process.
Must couple to another chiral-odd function.
(*e.g.* Collins function $H_1^{\perp}$)
Measured via
SIDIS (E12-10-006, E12-11-008), Drell-Yan
Di-hadron (approved as run group with E12-10-006)

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

Fit Collins asymmetries in SIDIS and e^+e^- annihilation

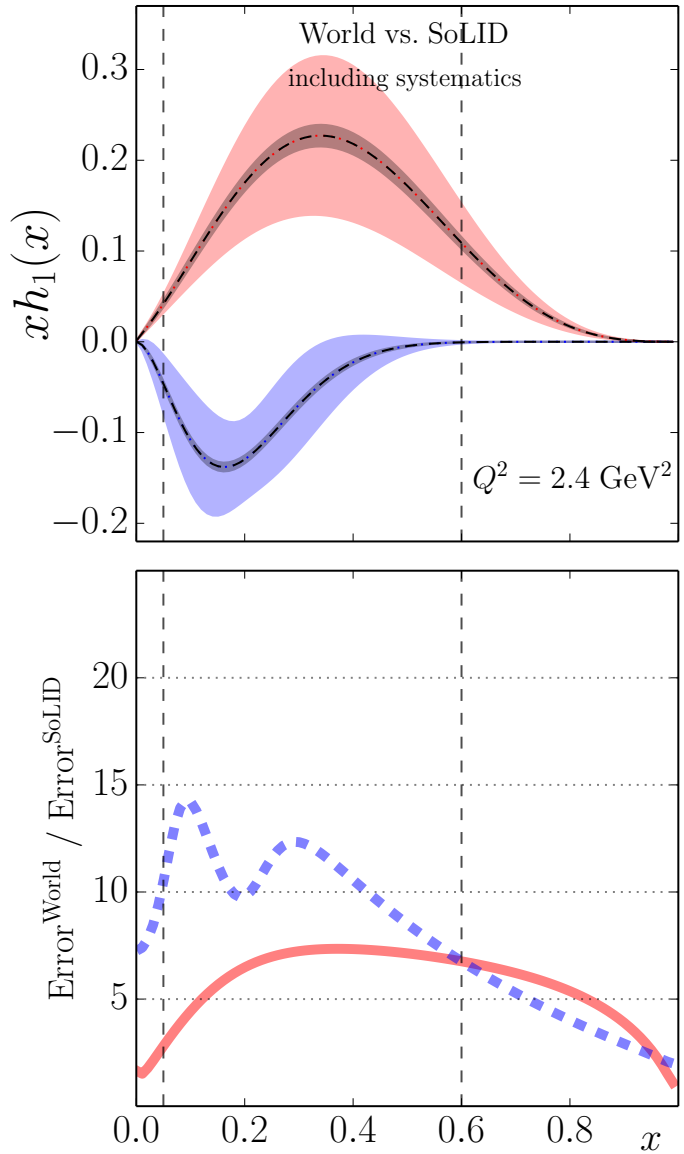
SIDIS data from HERMES, COMPASS and JLab-6 GeV

e^+e^- data from BELLE and BABAR

TMD evolution is included

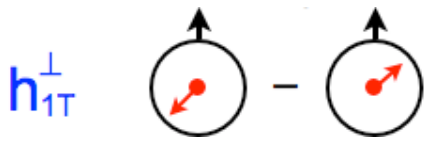
Both statistical and systematic uncertainties are included

About one order of magnitude improvement



Pretzelosity

Pretzelosity distribution



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)

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

(model dependent)

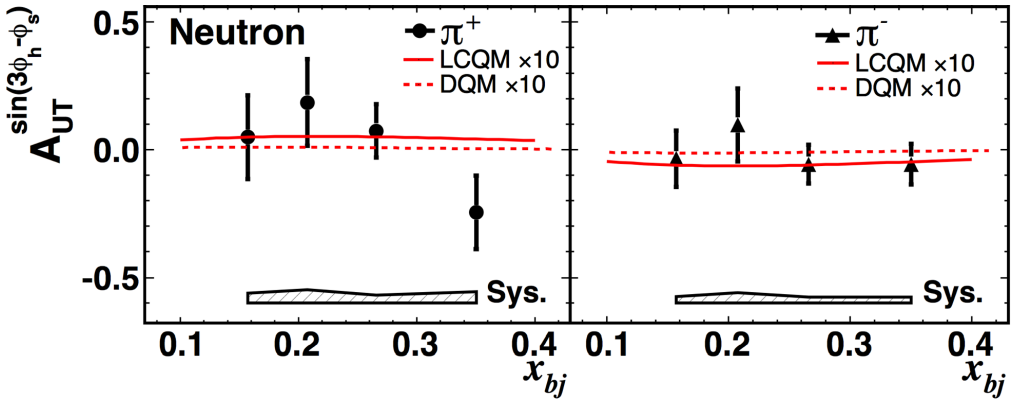
Measurement in SIDIS

Single spin asymmetry

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

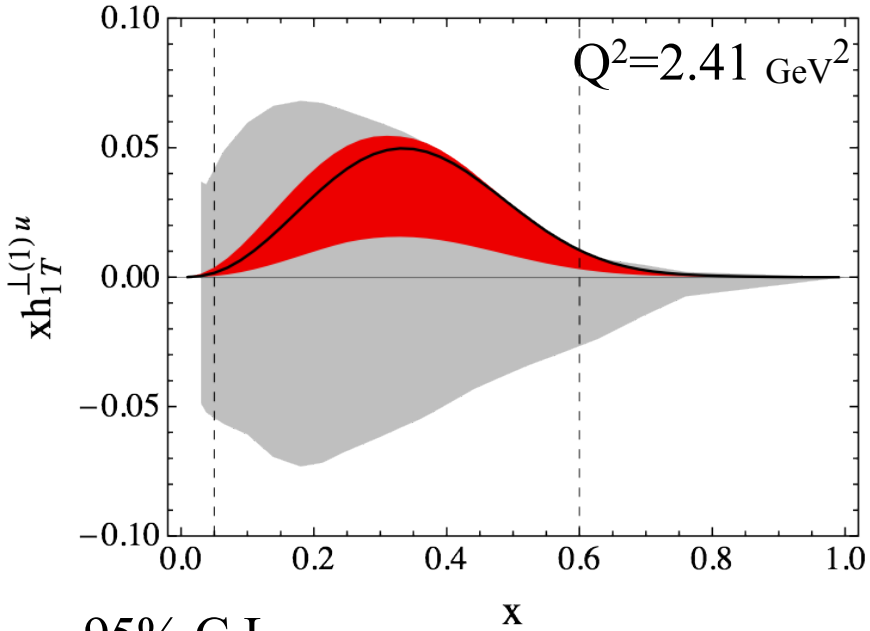
A global fit to 175 data from COMPASS, HERMES, and JLab found comparable with null signal hypothesis at 72% C.L..

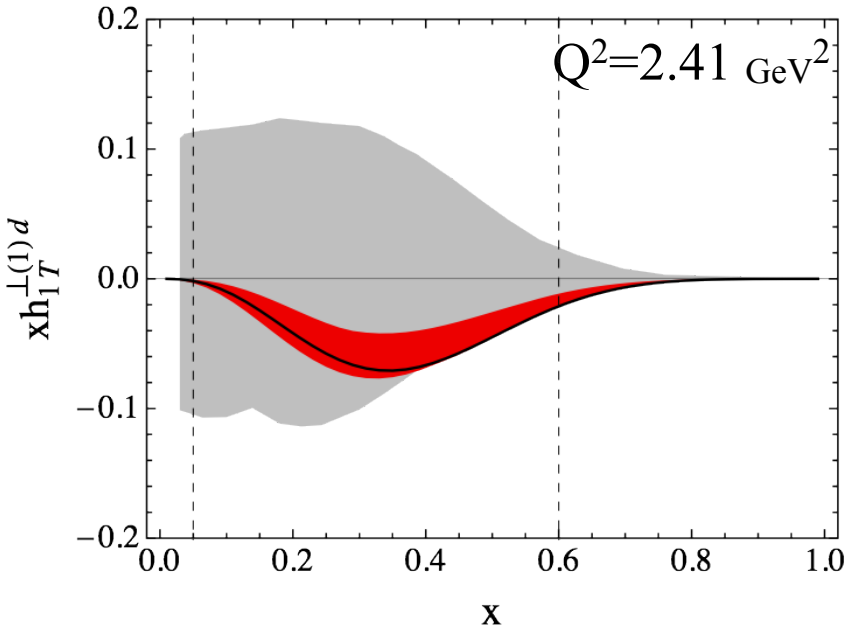
C. Lefky, A. Prokudin, PR D 91, 034010 (2015).



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

SoLID Impact on Pretzelosity





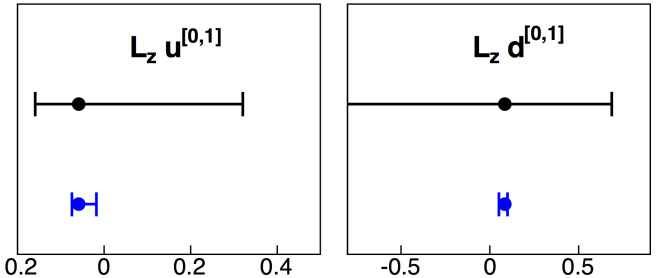
95% C.L.

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

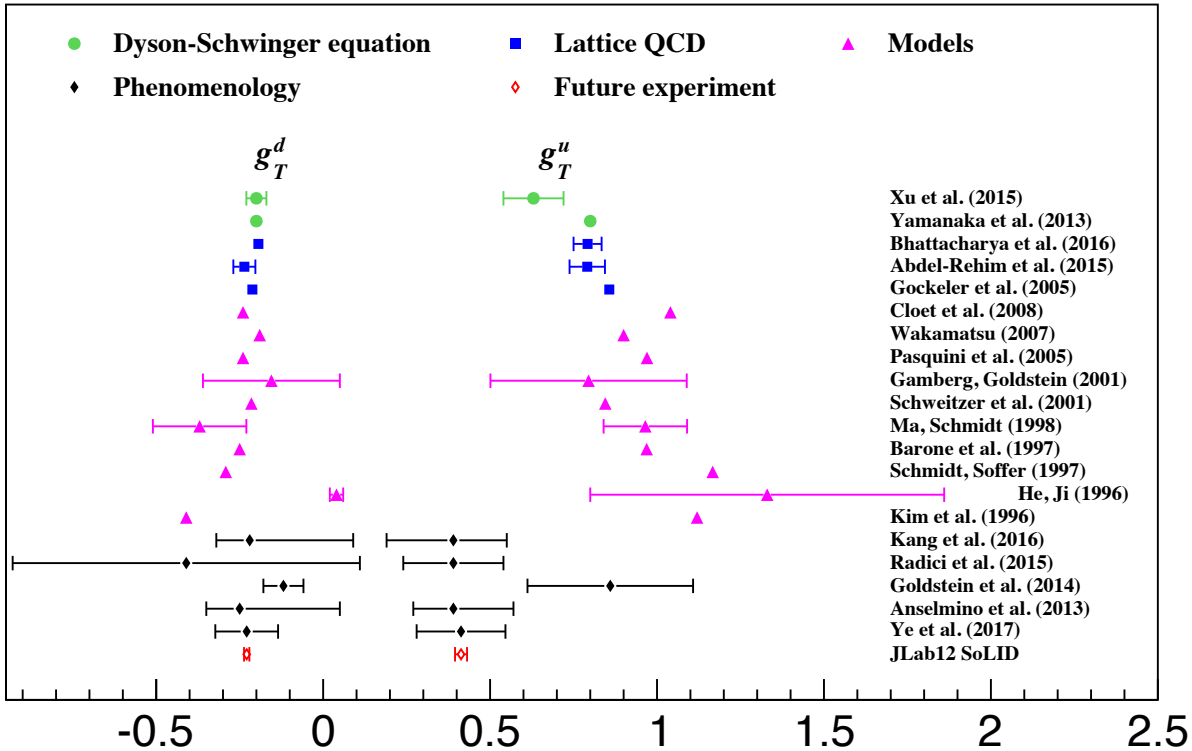
$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = g_T^q\,\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S) \qquad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

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

SoLID impact

Z. Ye et al., PLB 767, 91 (2017)

SoLID projection based on Kang et al 2015 parameterization.



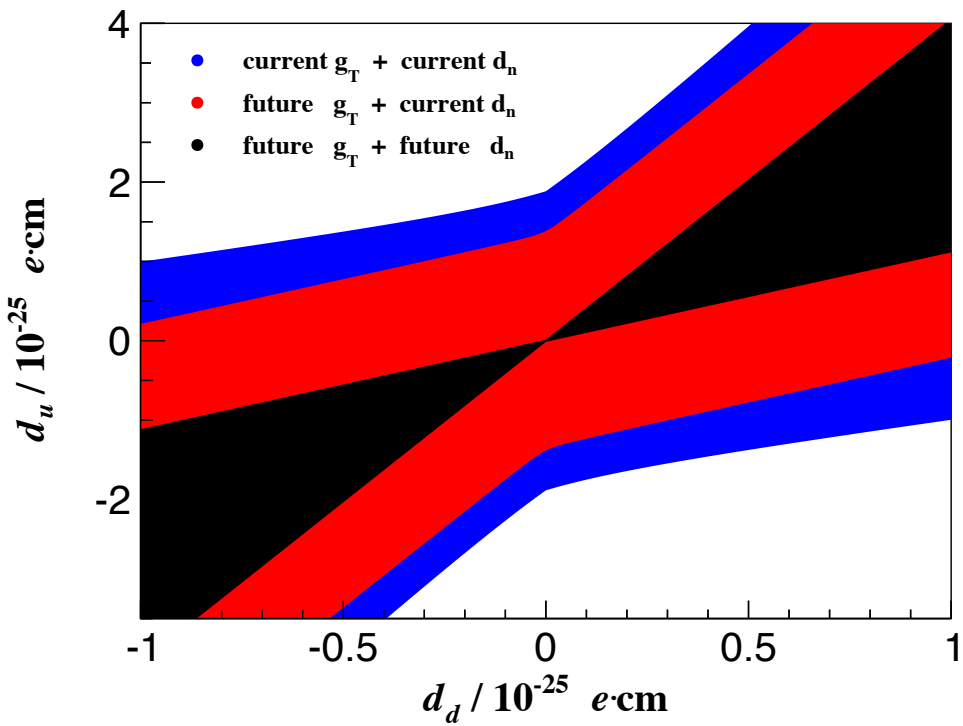
Constraint on Quark EDMs

Current upper limit on the neutron EDM

$$3.0 \times 10^{-26}\, e\,\mathrm{cm} \quad (90\%\ \mathrm{CL})$$

J.M. Pendlebury et al., Phys. Rev. D 92, 092003 (2015). [Re-analysis]
C.A. Baker et al., Phys. Rev. Lett. 97, 131801 (2006).

Constraint on quark EDMs with tensor charge



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

Using g_T^s from lattice calculation

- Future g_T: SoLID projected tensor charge
- Future d_n: $3.0\times10^{-28} e$ cm

H. Gao, T. Liu, Z. Zhao, arXiv:1704.00113, to appear in PRD

Constraint on Quark EDMs

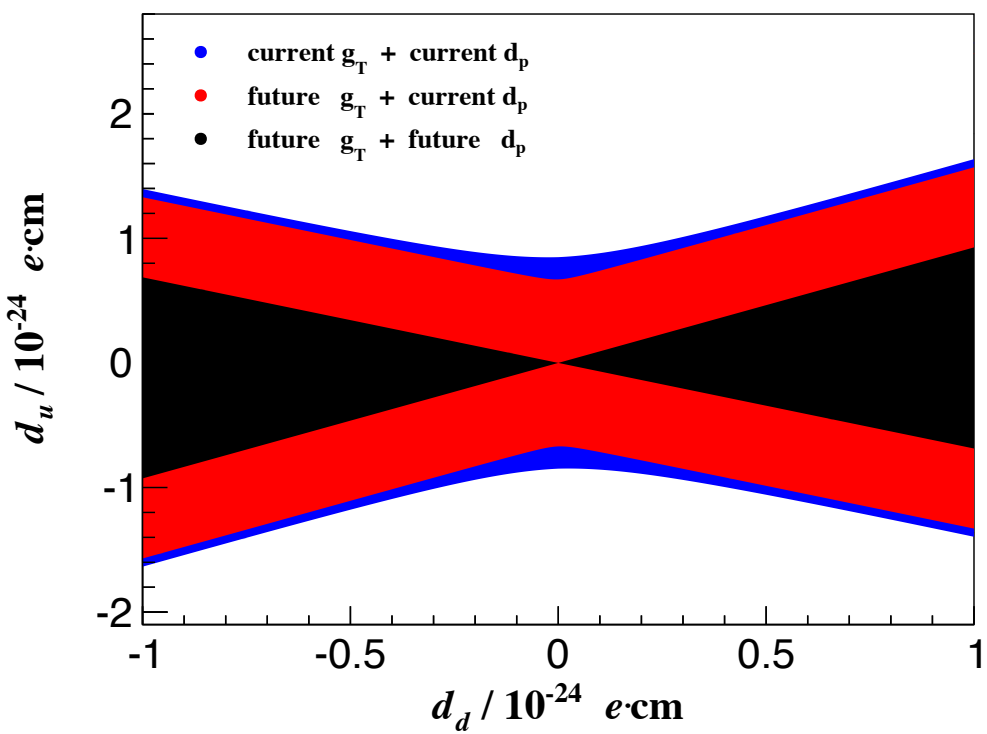
Current upper limit on the proton EDM

- Mercury atom EDM limit: $7.4 \times 10^{-30}\, e\,\mathrm{cm}$ (95% CL)
- Derived proton EDM limit: $2.6 \times 10^{-25}\, e\,\mathrm{cm}$

B. Graner et al., Phys. Rev. Lett. 116, 161601 (2016).

Schiff moment method including the uncertainty among different theoretical models

Constraint on quark EDMs with tensor charge



$$d_p = g_T^u\, d_u + g_T^d\, d_d + g_T^s\, d_s$$

Using g_T^s from lattice calculation

- Future g_T: SoLID projected tensor charge
- Future d_p: $2.6\times10^{-29} e$ cm

H. Gao, T. Liu, Z. Zhao, arXiv:1704.00113, to appear in PRD

Constraint on Quark EDMs (III)

Constraint on quark EDMs with combined proton and neutron EDMs

	d_u upper limit	d_d upper limit
Current g_T + current EDMs	$1.27\times10^{-24}e$ cm	$1.17\times10^{-24}e$ cm
SoLID g_T + current EDMs	$6.72\times10^{-25}e$ cm	$1.07\times10^{-24}e$ cm
SoLID g_T + future EDMs	$1.20\times10^{-27}e$ cm	$7.18\times10^{-28}e$ cm

Include 10% isospin symmetry breaking uncertainty

Sensitivity to new physics

$$d_q \sim \bar{e} m_q/(4\pi\Lambda^2)$$

Three orders of magnitude improvement on quark EDM limit → Probe to 30 ~ 40 times higher scale

Current quark EDM limit: $10^{-24}e$ cm → ~ 1 TeV

Future quark EDM limit: $10^{-27}e$ cm → 30 ~ 40 TeV

H. Gao, T. Liu, Z. Zhao, arXiv: 1704.00113, to appear in PRD

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 TMD Physics program at 12-GeV JLab
  - CLAS12, SBS, and Hall C
  - SoLID SIDIS program with unprecedented precision on TMDs
  - Flavor separation of tensor charge with high precision - impact on lattice QCD calculations, neutron EDM experiments, ….

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

Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231