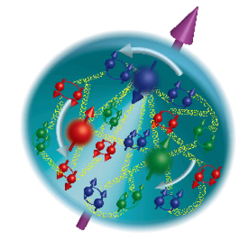
From 12 GeV to EIC: TMDs

Users Group Workshop and Annual Meeting
June 18 – 20, 2018

Haiyan Gao
Duke University and Duke Kunshan University

Nucleon Spin Decomposition



Proton spin puzzle

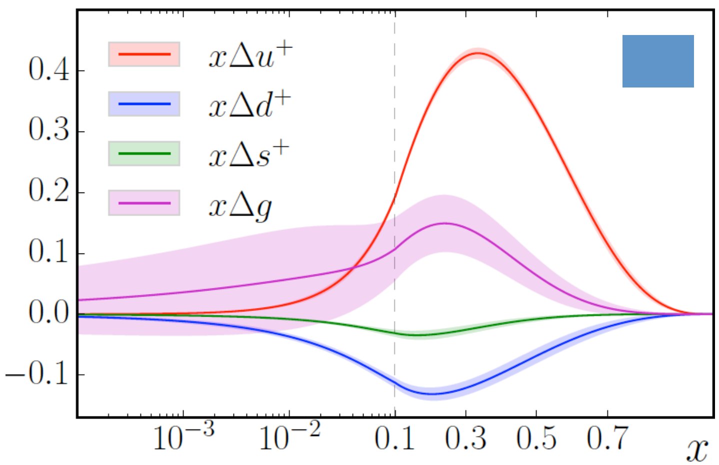
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

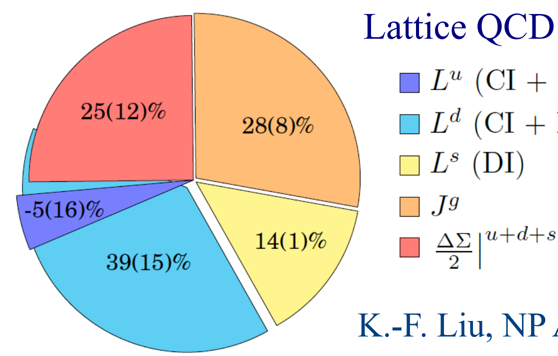
J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

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



JAM Collaboration, PRD (2016).



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

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

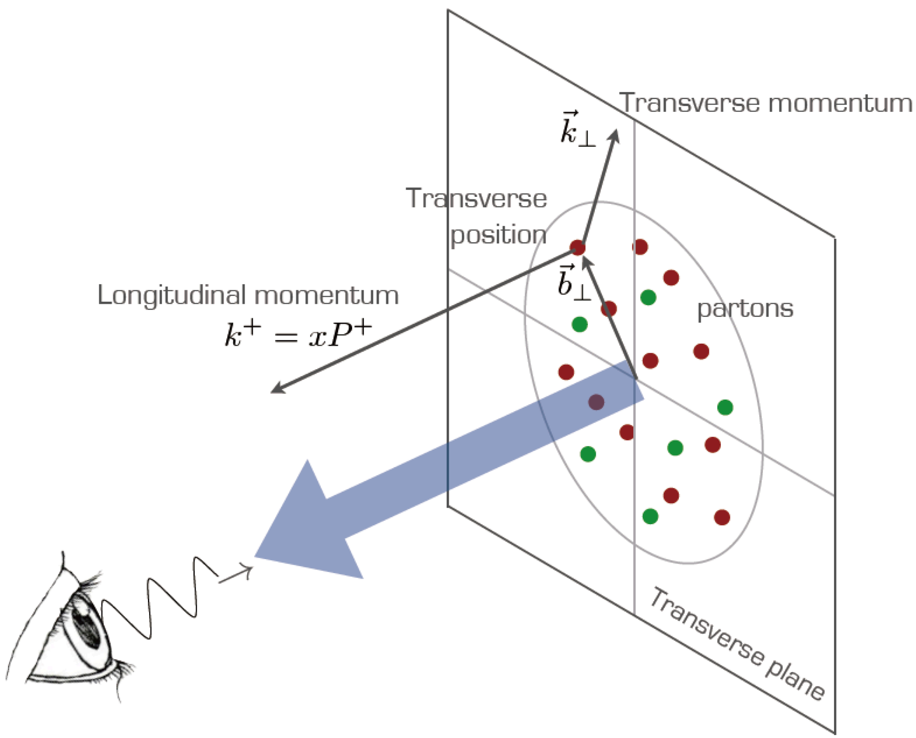
Access to $L_{q/g}$

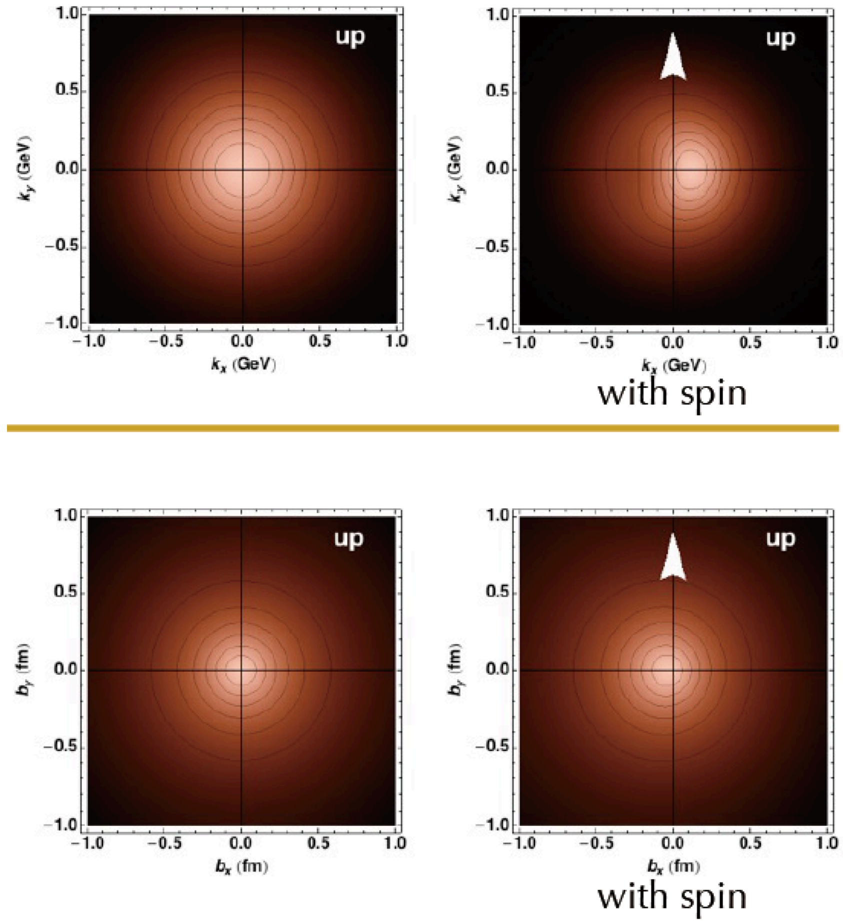
It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

Orbital motion - Nucleon Structure from 1D to 3D



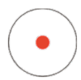
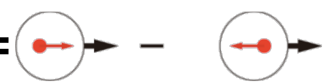
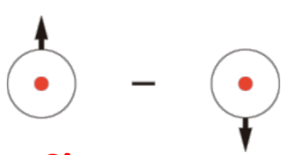
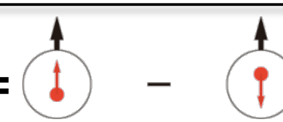


Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)

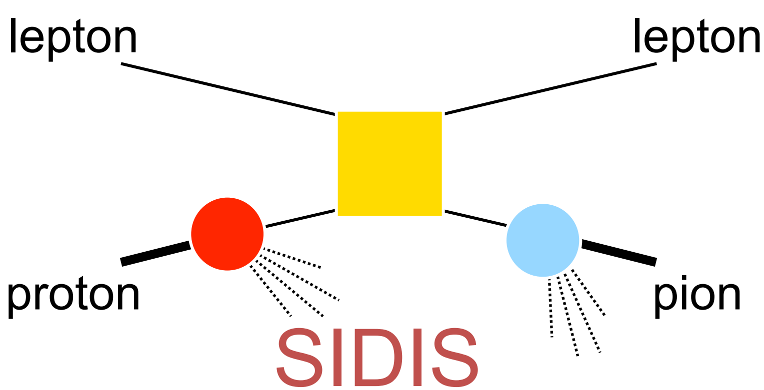
[Bacchetta's talk (2016)]

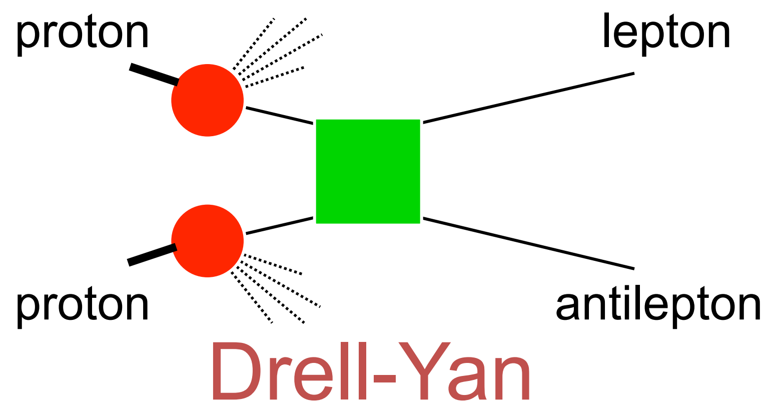
Leading Twist TMDs

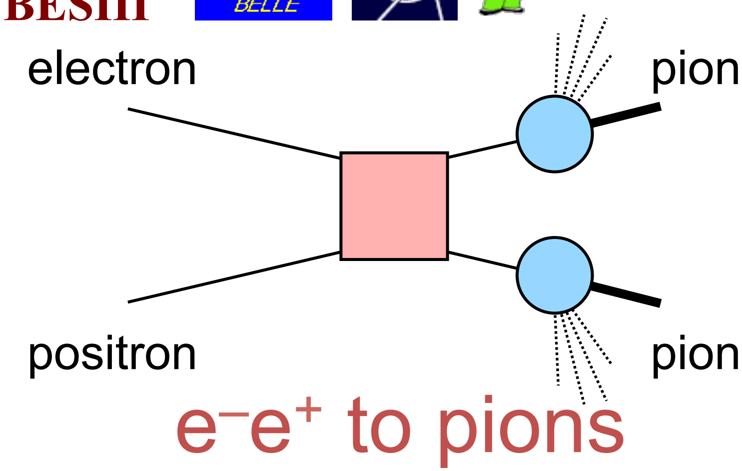
→ Nucleon Spin
→ Quark Spin

		Quark polarization		
		Un-Polarized	**Longitudinally Polarized**	**Transversely Polarized**
Nucleon Polarization	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







Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

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

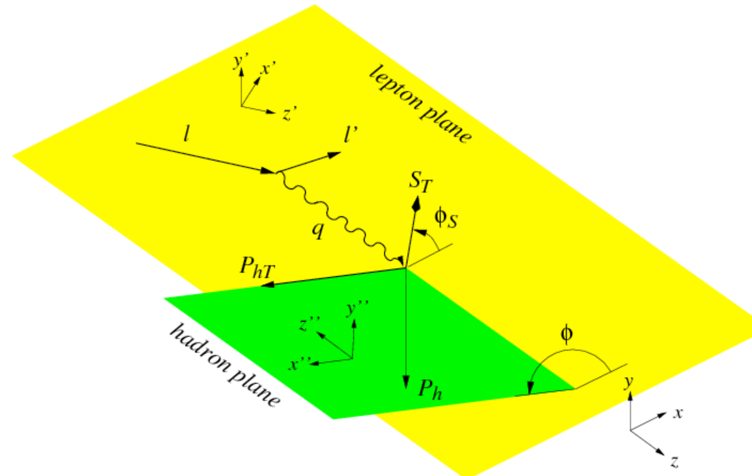
$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

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]

$$\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S}$$

$$= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\times \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+ S_L\left[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + \lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

$$+ S_T\Big[\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)$$

$$+ \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$

$$+ \lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)$$

$$+ \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}$$

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

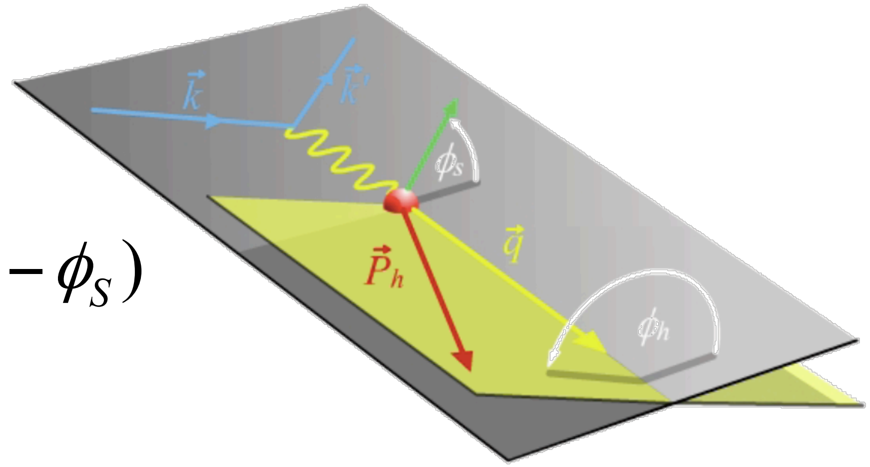
In parton model, F(x, z, Q^2, P_T)s are expressed as the convolution of TMDs.

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

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

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

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

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

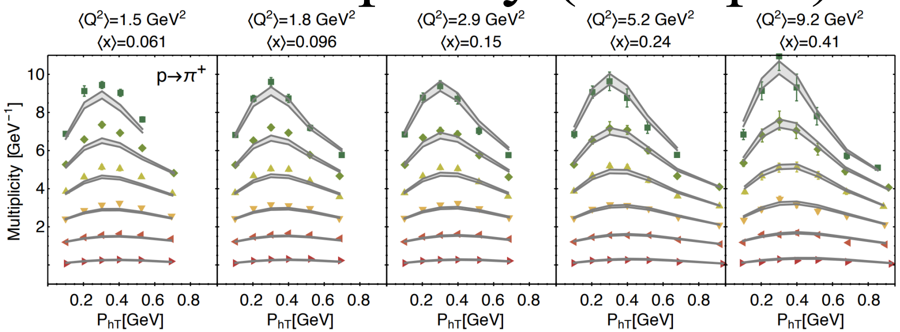
- ## Polarized pp collisions
  - BNL: PHENIX & STAR
  - FNAL: POL. DY

- ## Polarized e+e- collisions
  - KEK: Belle

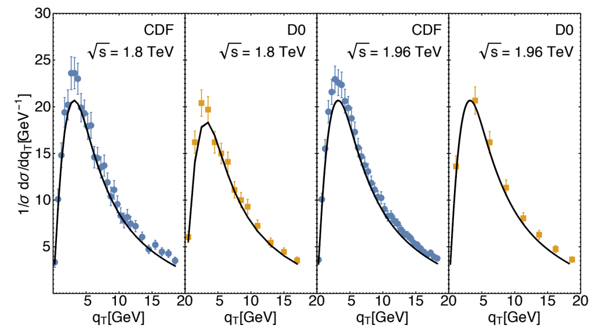
Global Analysis: Unpolarized TMD

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

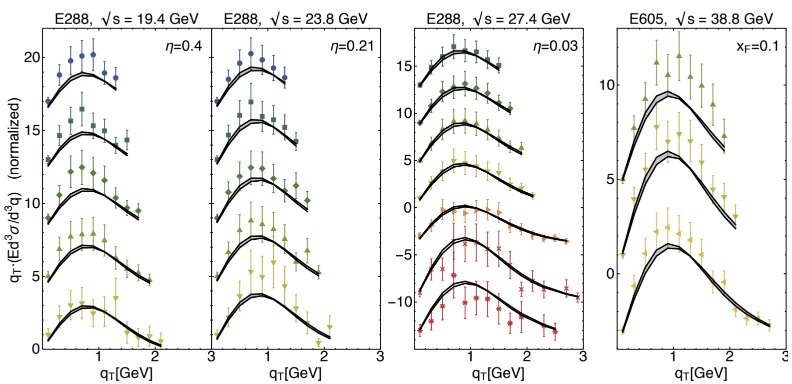
SIDIS multiplicity (example)



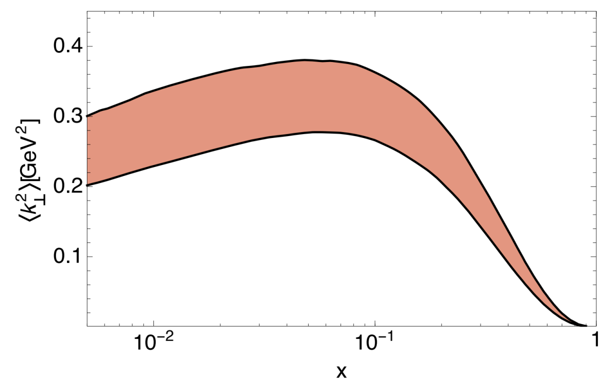
Z production



Drell-Yan cross section

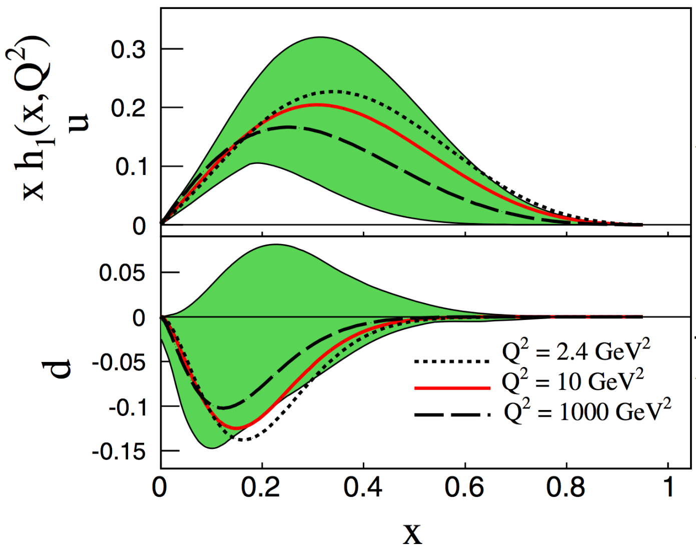


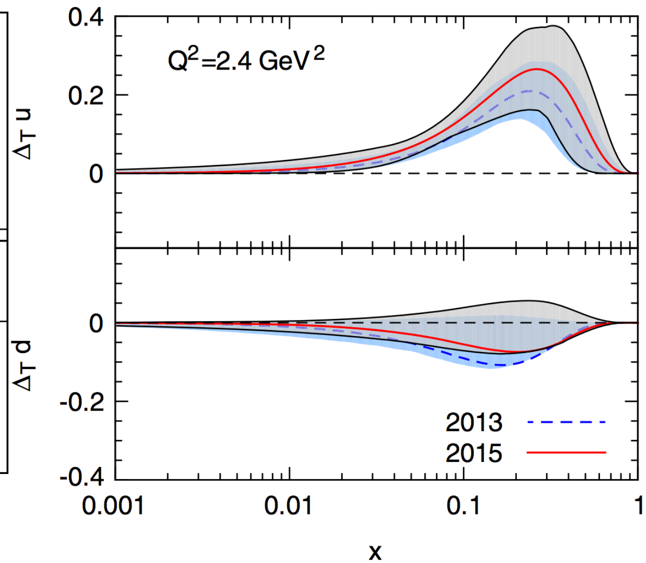
Transverse momentum distribution

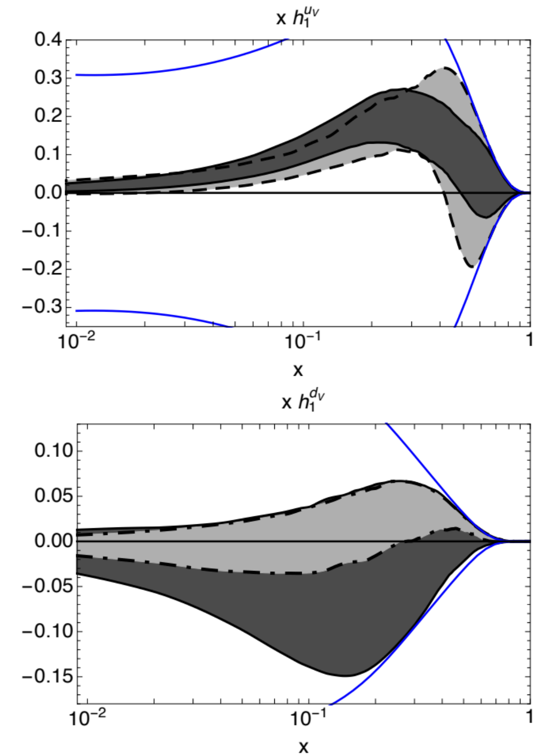


A. Bacchetta *et al.*, J. High Energy Phys. 06 (2017) 081.

Global Analysis: Transversity







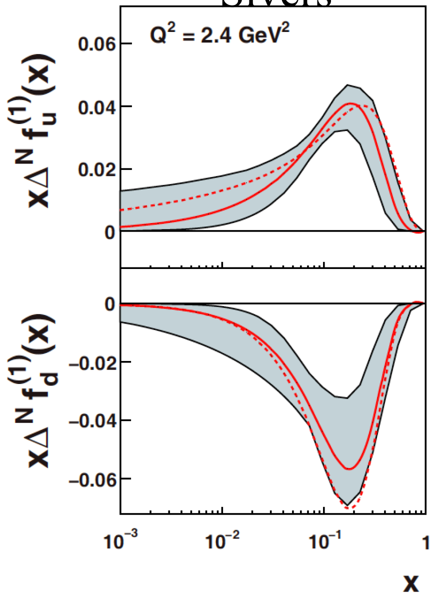
Z.-B. Kang et al., Phys. Rev. D 93, 014009 (2016).

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

M. Radici and A. Bacchetta: Phys. Rev. Lett. 120, 192001 (2018) SIDIS + pp (pion pairs)

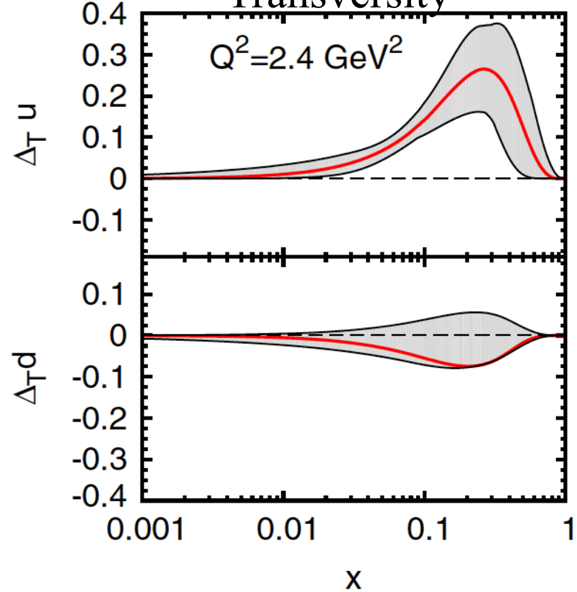
Present Status On TMD Extractions

Sivers



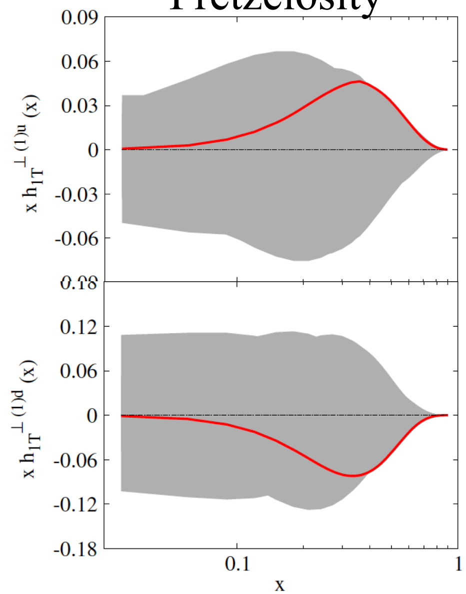
Anselmino et al, EPJA39, 89 (2009)

Transversity



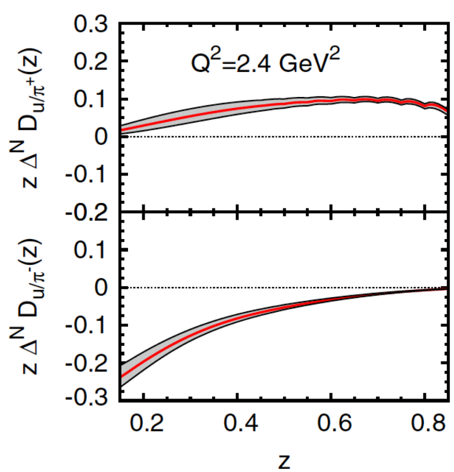
Anselmino et al, PRD92, 114023 (2015)

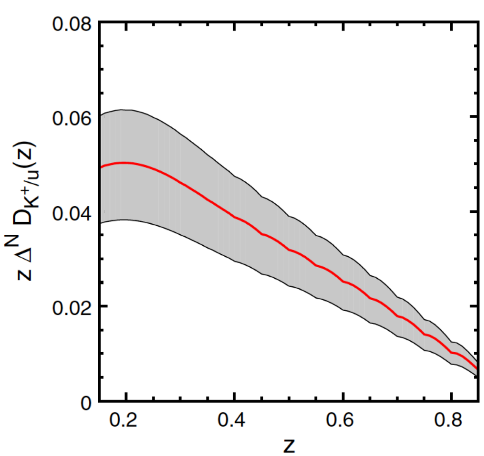
Pretzelosity



Lefky et al, PRD91, 034010 (2015)

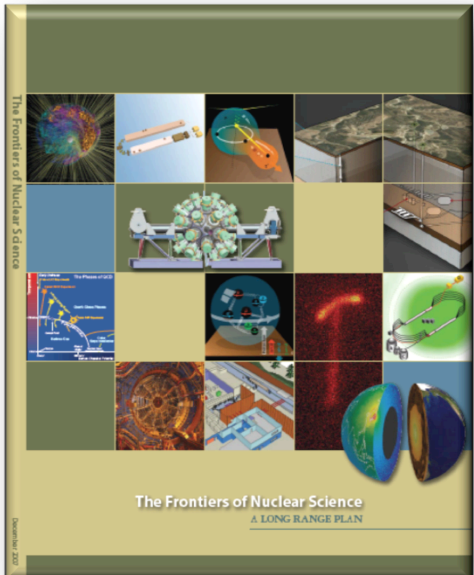
Collins fragmentation



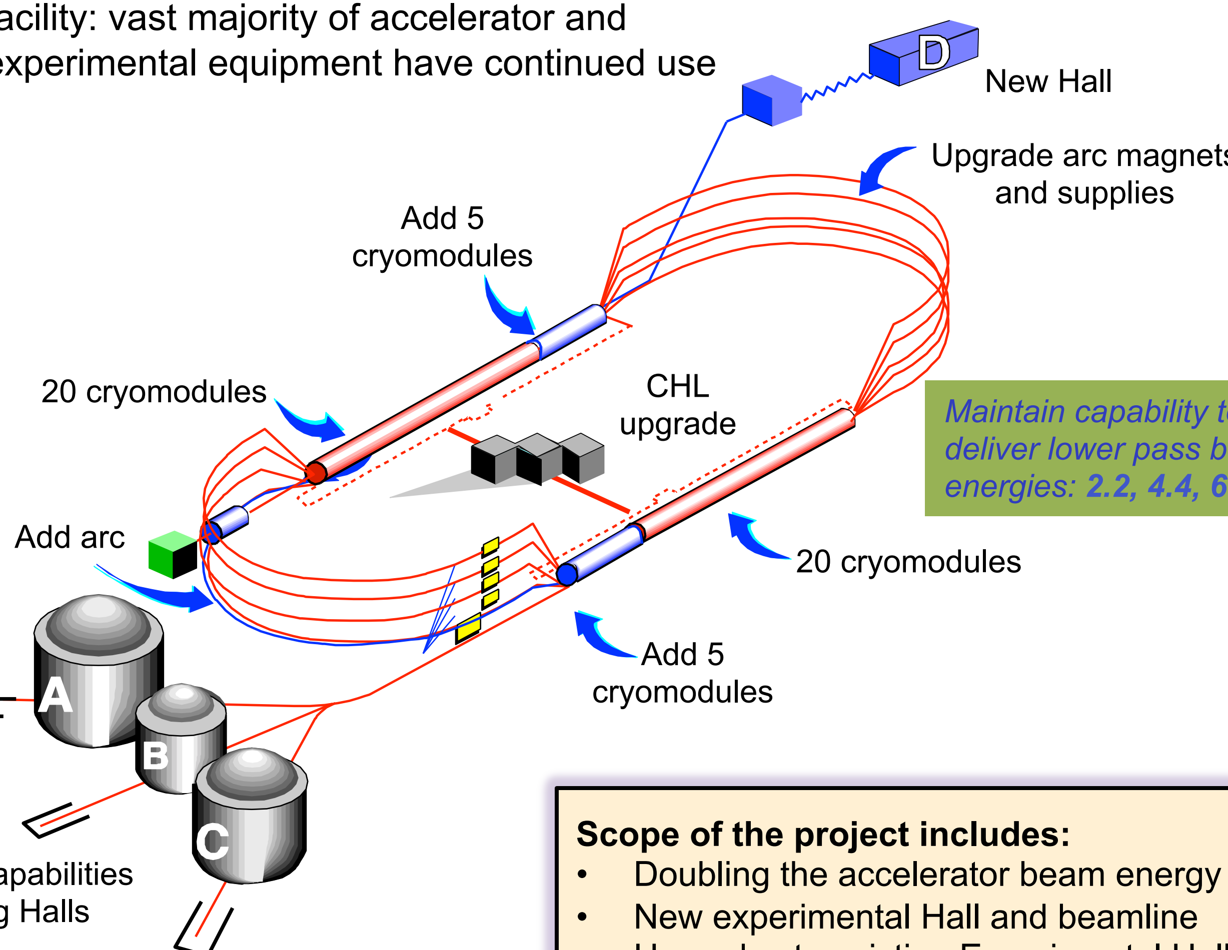


Anselmino et al, PRD92, 114023 (2015)
PRD93, 034025 (2016)

12 GeV Upgrade at JLab



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



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

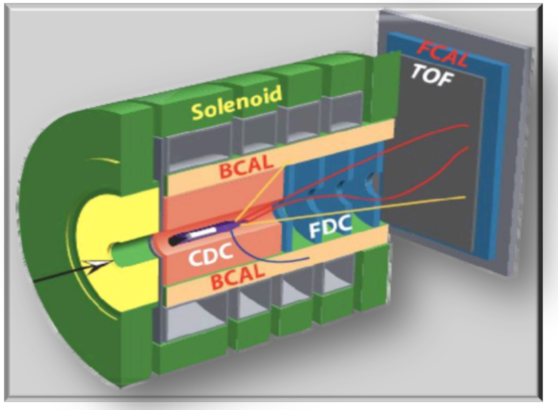
The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Scope of the project includes:

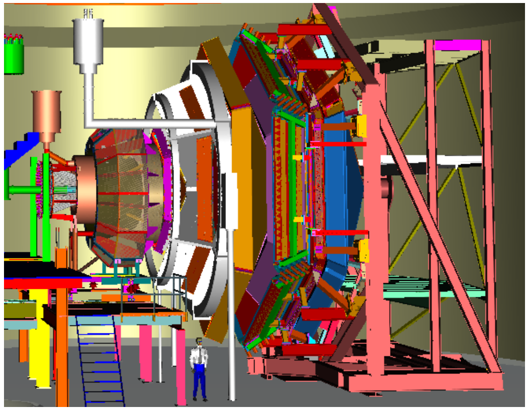
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

Solenoidal Large Intensity Device (SoLID) proposed for Hall A

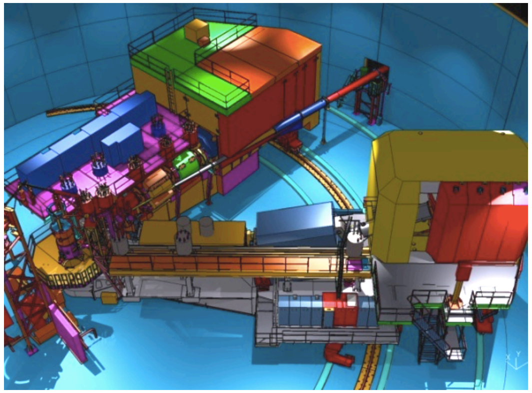
12 GeV Upgrade Physics Instrumentation



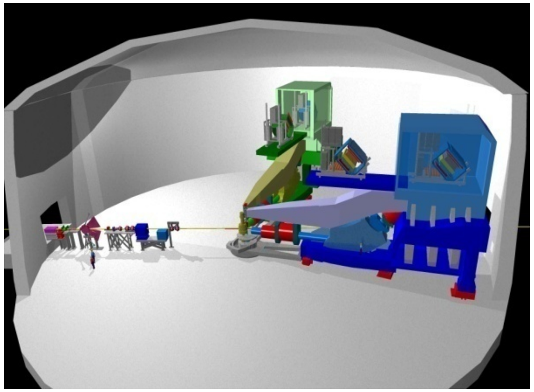
GLUEx (Hall D): exploring origin of confinement by studying **hybrid mesons**



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



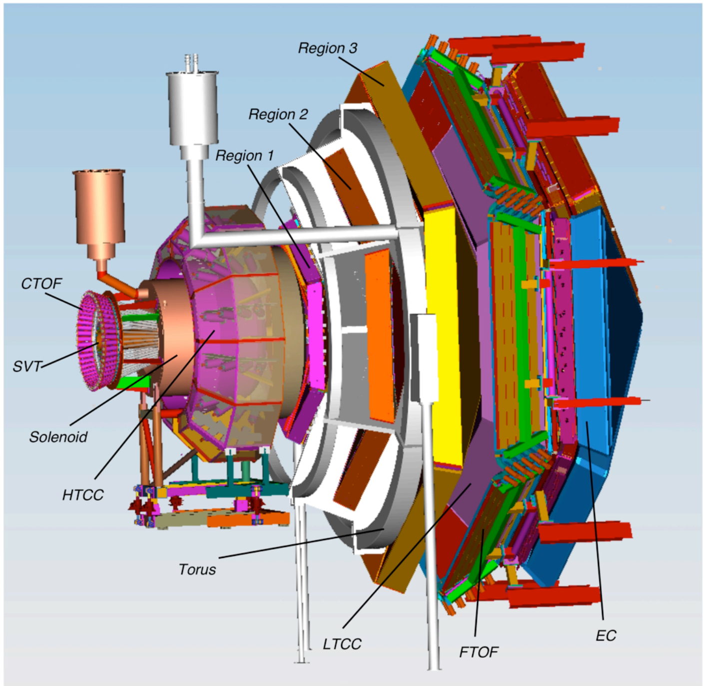
SHMS (Hall C): precision determination of **valence quark properties** in nucleons and nuclei



Hall A: nucleon form factors,

& future new experiments using new devices

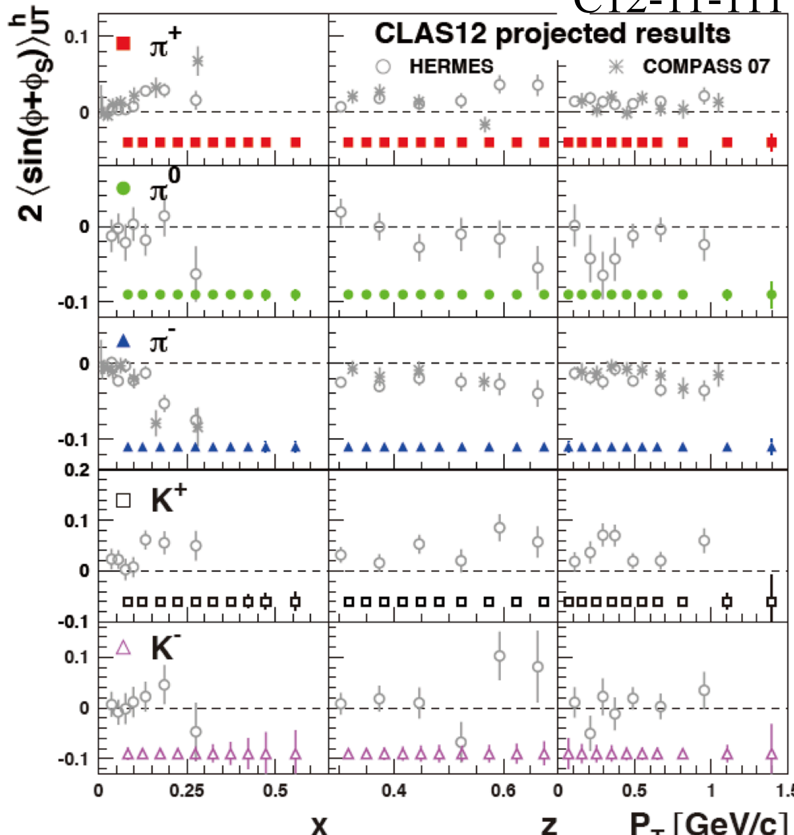
CLAS 12

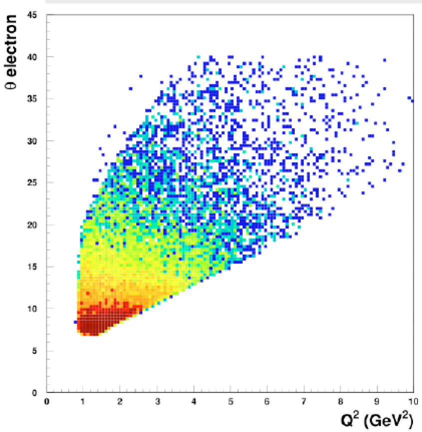


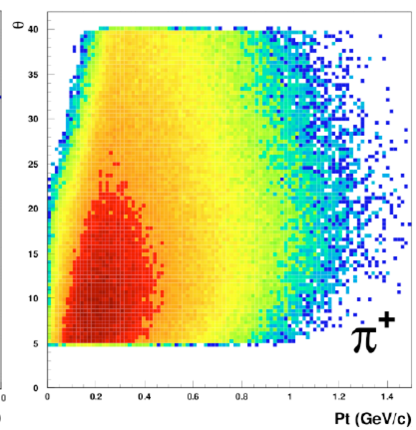
E12-09-007, E12-09-008
E12-09-009, E12-07-107

NH_3 and ND_3 targets

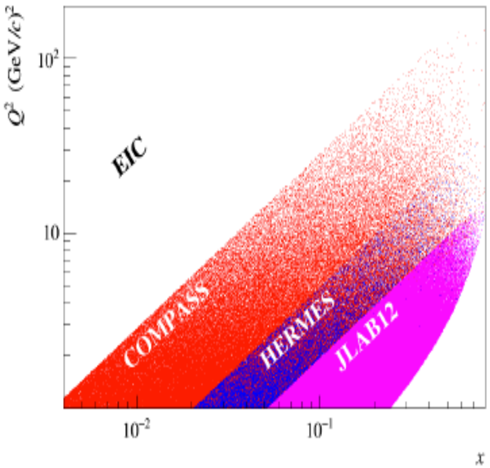
C12-11-111

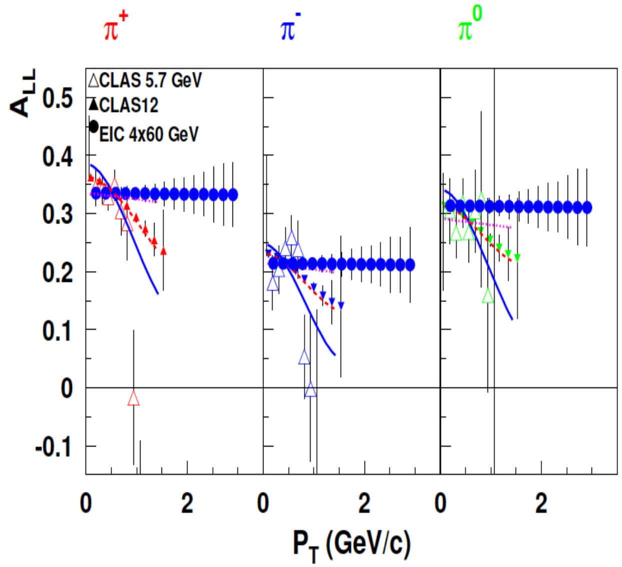


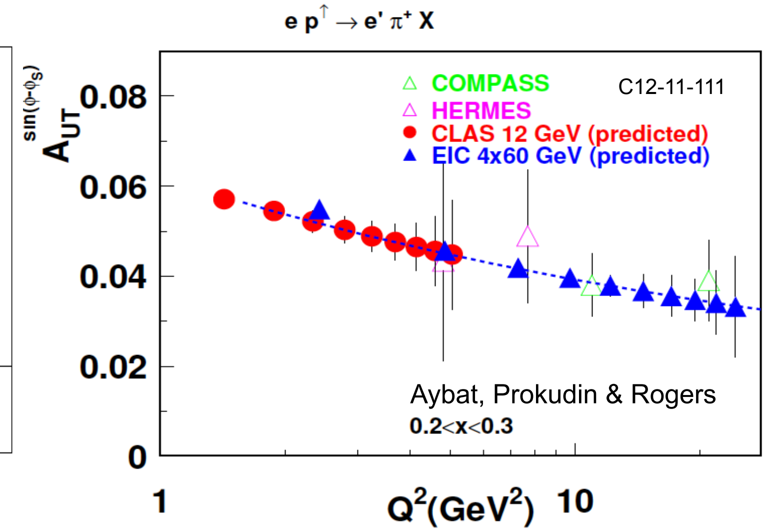




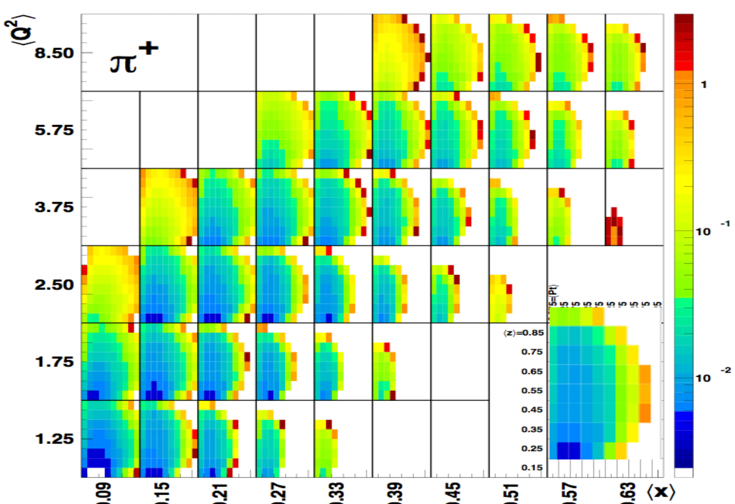
CLAS12: Evolution and k_T-dependence of TMDs







CLAS12 kinematical coverage k_T-dependence of $g_1(x, k_T)$ Q^2-dependence of Sivers, $f_1^\perp(x, k_T)$



- Large acceptance of CLAS12 allows studies of P_T and Q^2-dependence of SSAs in a wide kinematic range
- Comparison of JLab12 data with HERMES, COMPASS (and EIC) will pin down transverse momentum dependence and the non-trivial Q^2 evolution of TMD PDFs in general, and Sivers function in particular.

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

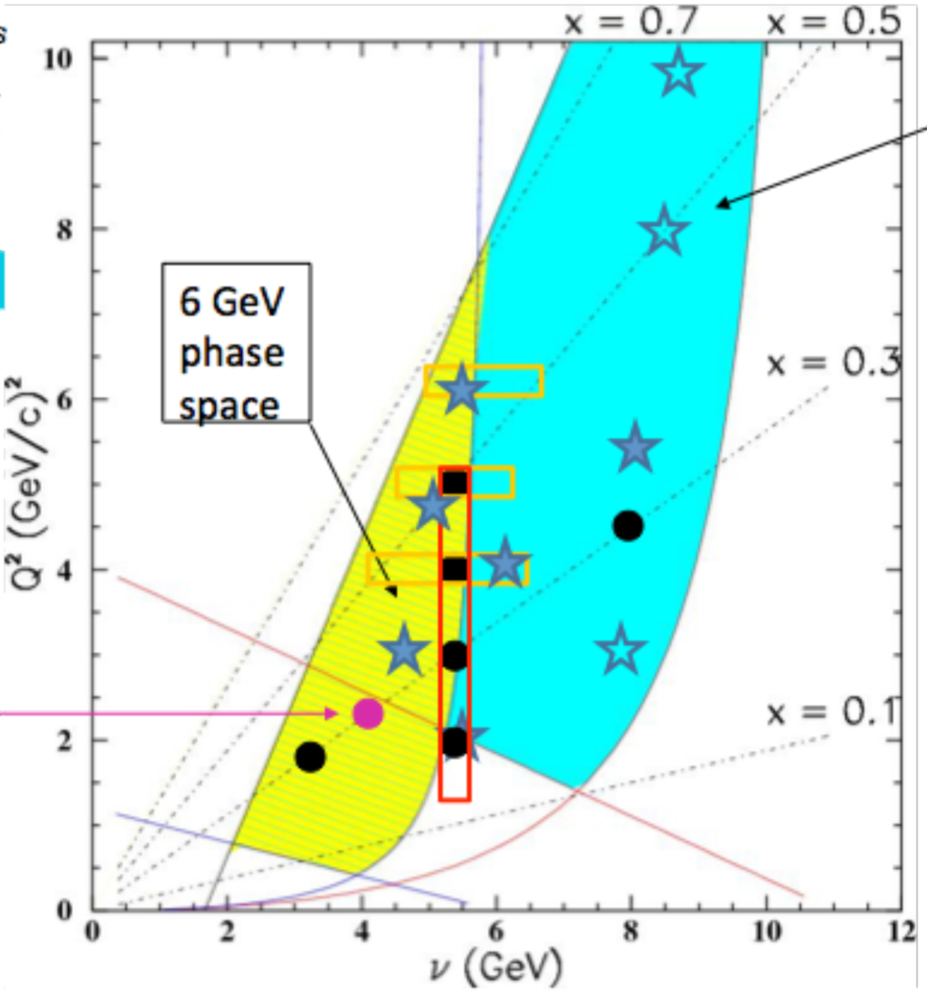
[R. Ent, DIS2016]

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



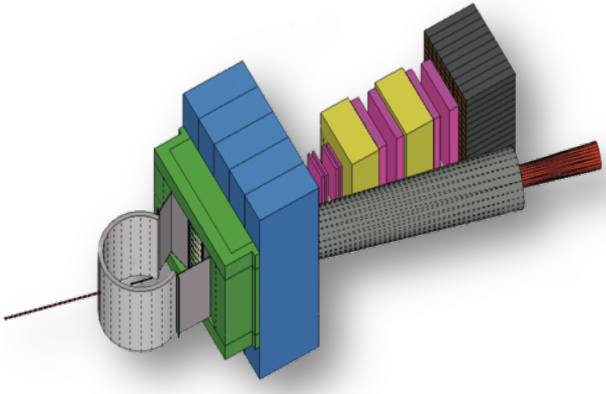
Charged pions:

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

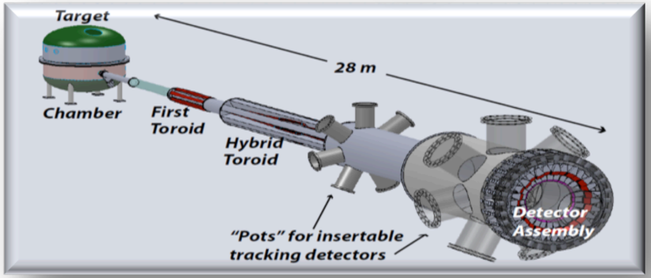
● E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

E12-09-002
+ scans in z

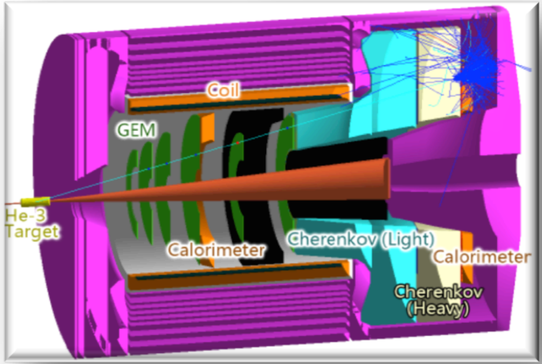
Beyond 12 GeV Upgrade



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

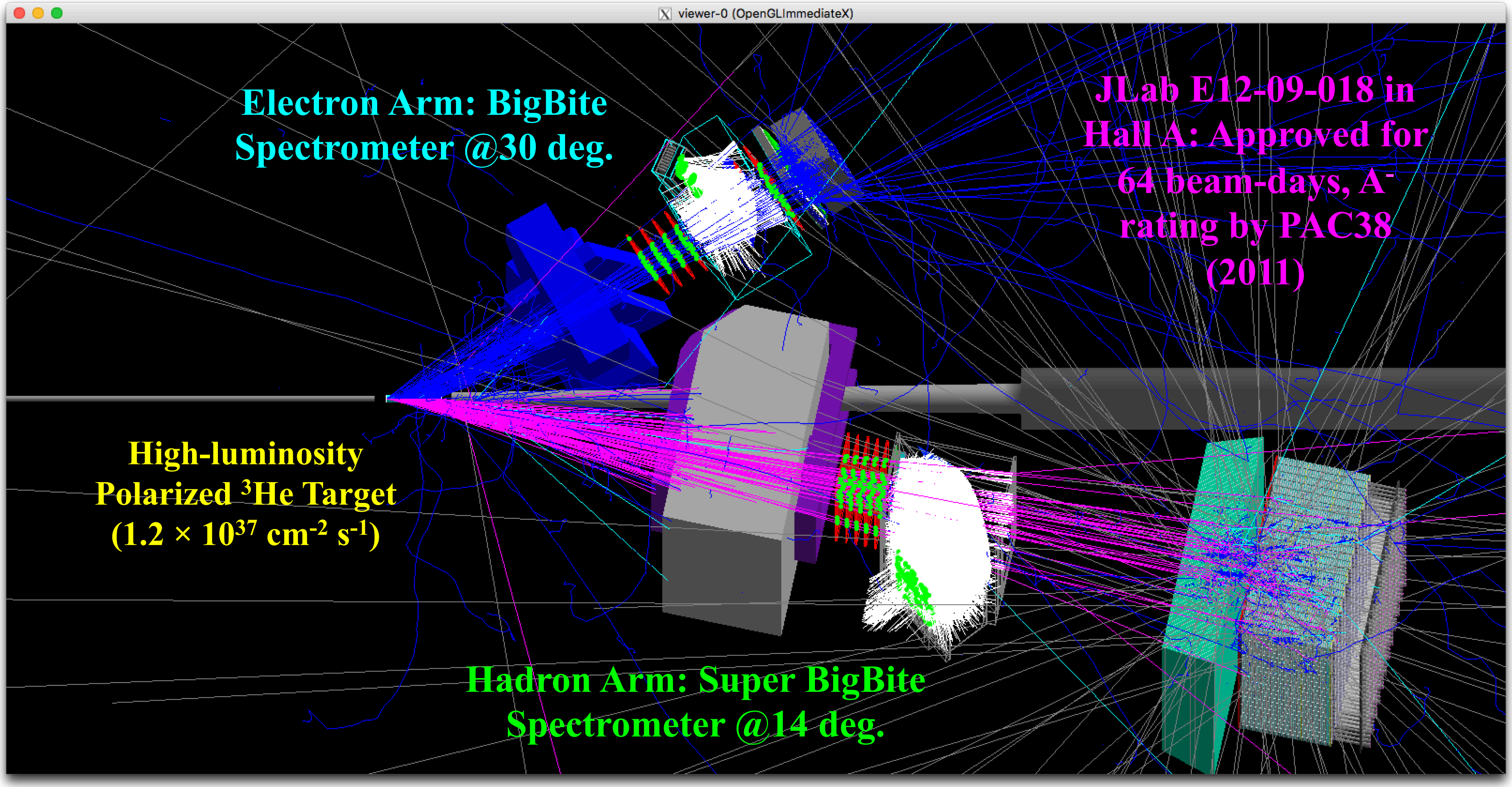


- MOLLER experiment
  (MIE – FY20-24?)
  - Standard Model Test



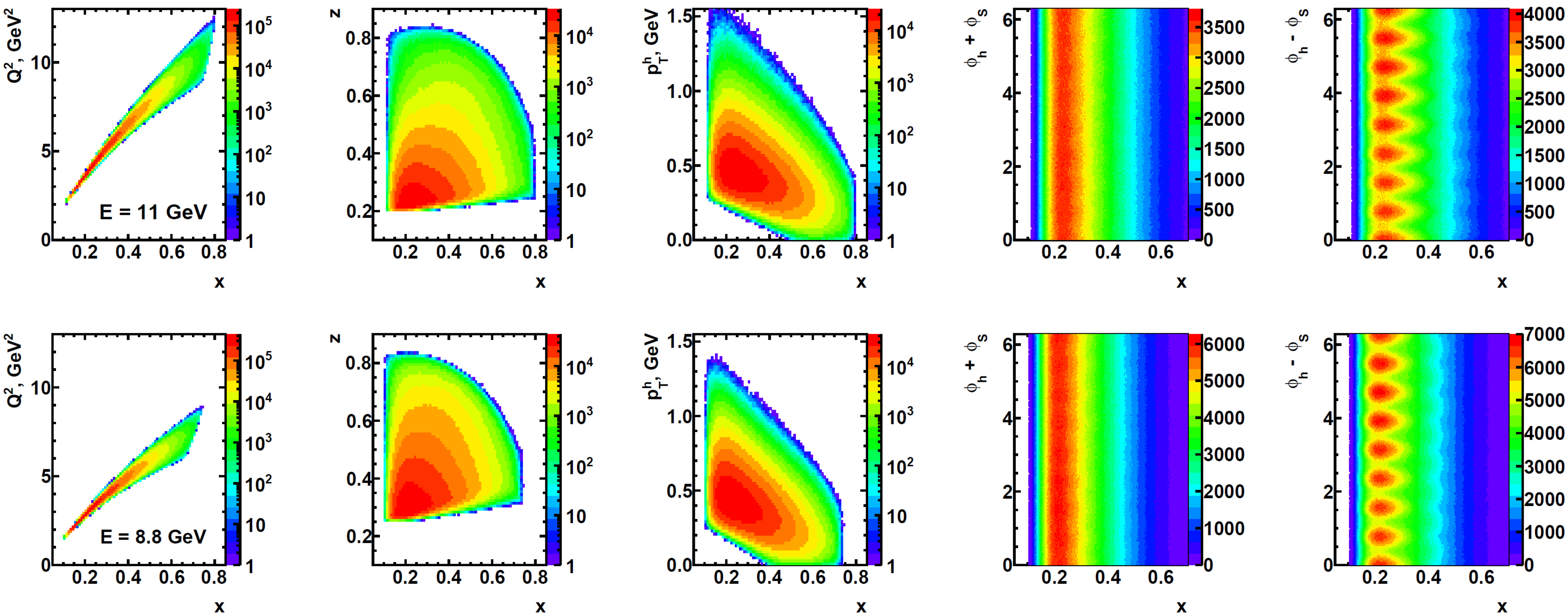
- SoLID program
  Chinese collaboration
  CLEO Solenoid
  Proton mass, spin and
  Standard Model Test

E12-09-018—Transversely Polarized



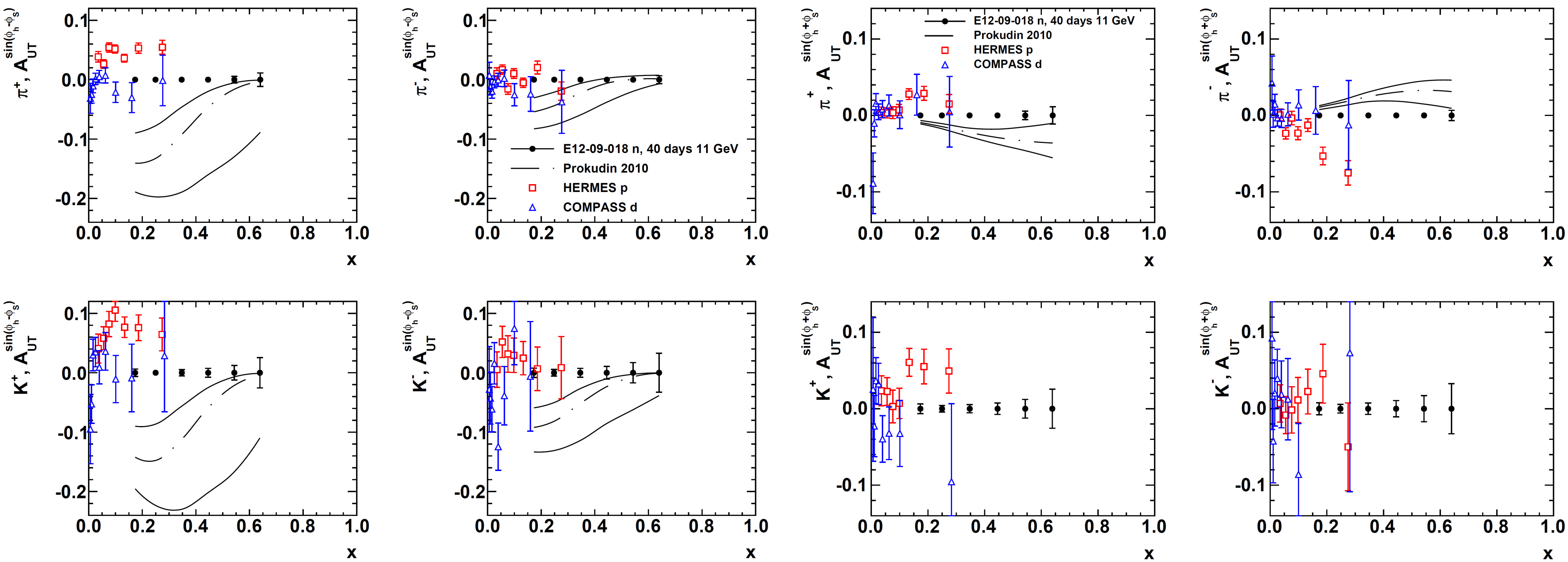
- **E12-09-018** in Hall A: transverse spin physics with high-luminosity polarized ^{3}He.
- 40 (20) days production at E = 11 (8.8) GeV—significant Q^2 range at fixed x
- Collins, Sivers, Pretzelosity, A_{LT} for n(e,e'h)X, h = $\pi^+/\pi^-/\pi^0/K^+/K^-$
- Re-use HERMES RICH detector for charged hadron PID
- Reach high x (up to ~0.7) and high statistical FOM (~1,000X Hall A E06-010 @6 GeV)

SIDIS Kinematic Coverage in



- Wide, independent coverage of x, z, p_T, $\phi_h \pm \phi_S$ in a single kinematic configuration.
- At least four (preferably 8) target spin directions to achieve full ϕ_S coverage
- Q^2, x strongly correlated due to dimensions of BigBite magnet gap.
- Data at E = 11, 8.8 GeV provide data for significantly different Q^2 at same x
- Systematics control → independent spectrometers, detectors in field-free regions, straight-line tracking, simple, well-defined (but adequately large) acceptance, etc.

SBS+BB Projected Results: Collins and Sivers SSAs



Projected A_{UT}^{Sivers} vs. x (11 GeV data only)

Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)

- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than E06-010 neutron data.
- Kaon and neutral pion data will aid flavor decomposition, and understanding of reaction-mechanism effects.

3D and "4D" extraction of SIDIS SSAs with SBS

Example result for 3D binning (x,z,p_T)

- E = 11 GeV, 40 days

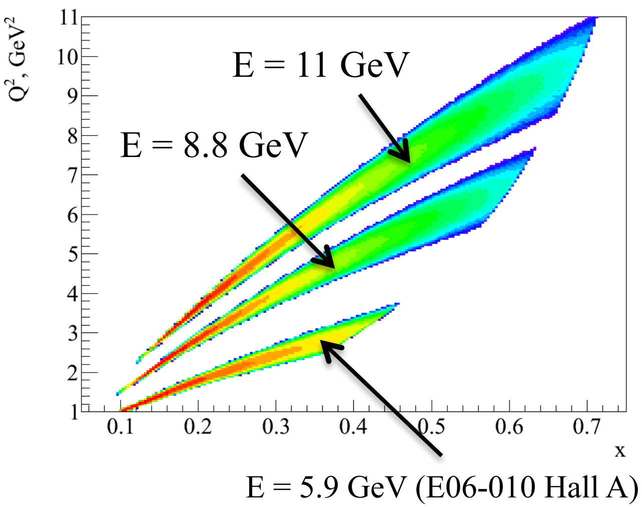
$$A_{UT}^{\sin(\phi_h-\phi_S)} \text{ for } \mathbf{n}(e,e'\pi^+)X :$$

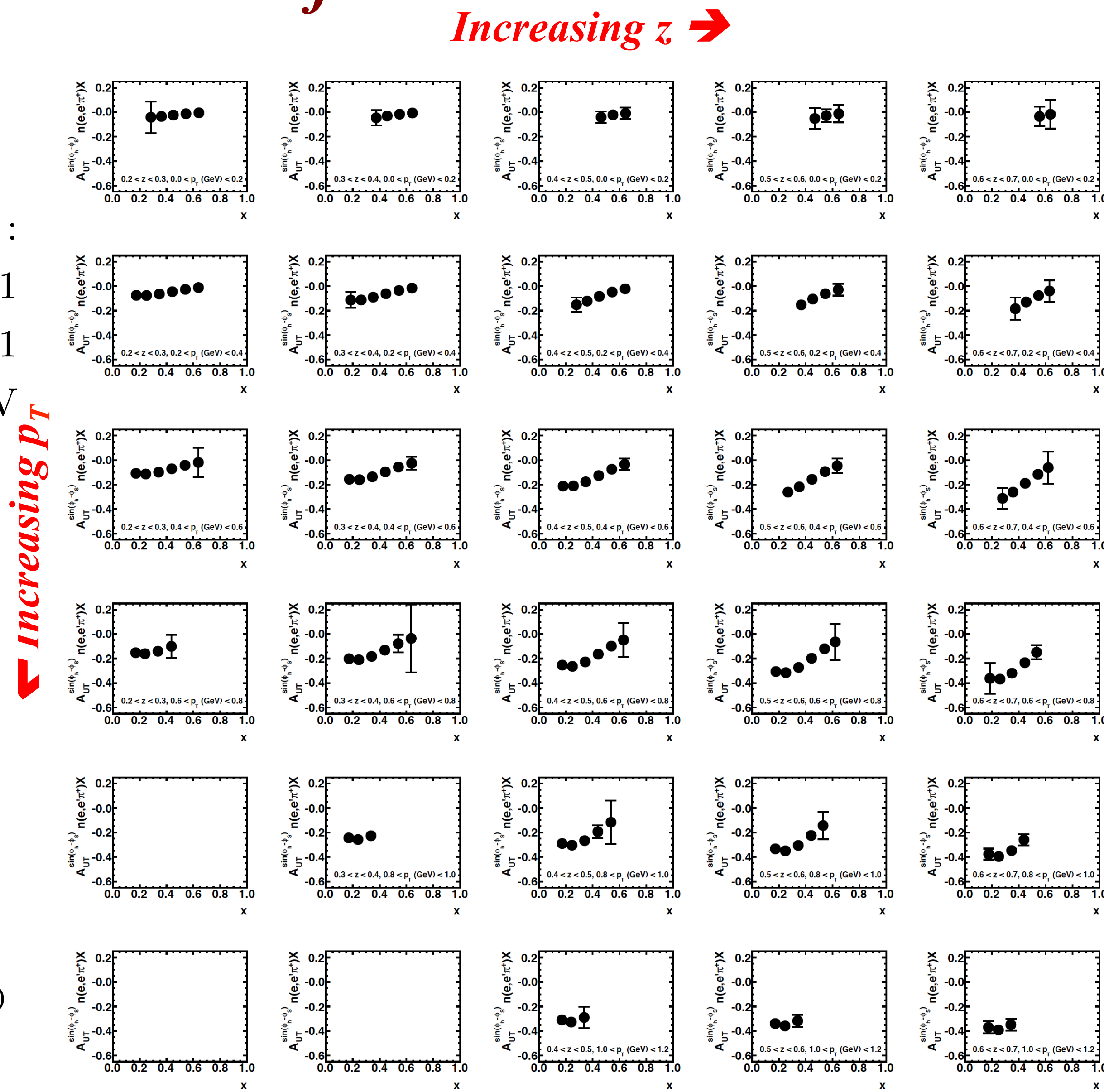
$$0.1 \leq x \leq 0.7, \Delta x = 0.1$$

$$0.2 \leq z \leq 0.7, \Delta z = 0.1$$

$$0 \leq p_T(\text{GeV}) \leq 1.2, \Delta p_T = 0.2 \text{ GeV}$$

- "4D" with Q^2 dependence from 20 days at 8.8 GeV:

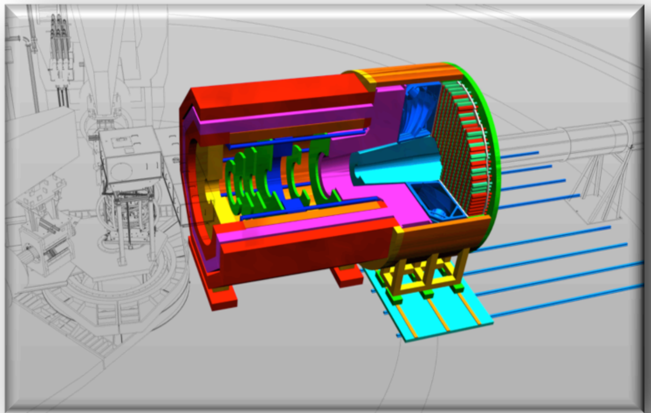




Solenoidal Large Intensity Device (SoLID) Physics

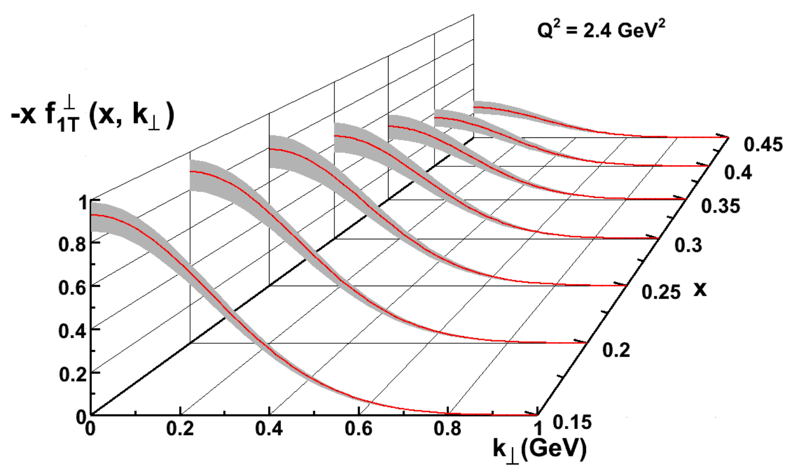
SoLID provides unique capability:

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

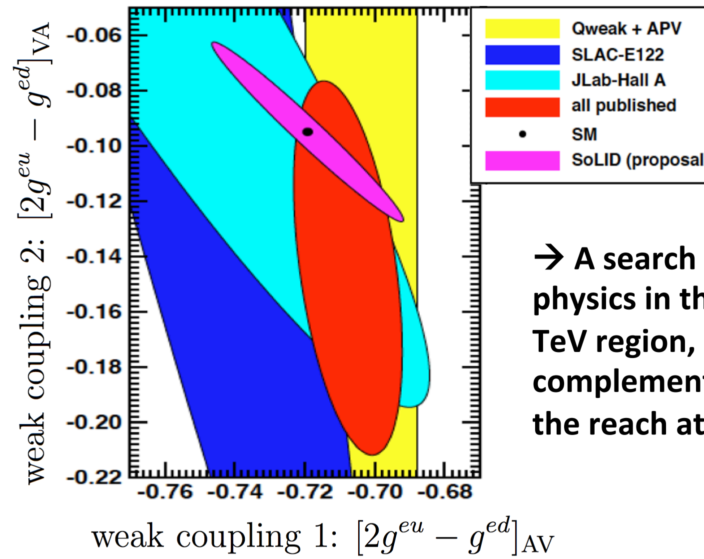


→ multi-purpose program to maximize the 12-GeV science potential

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

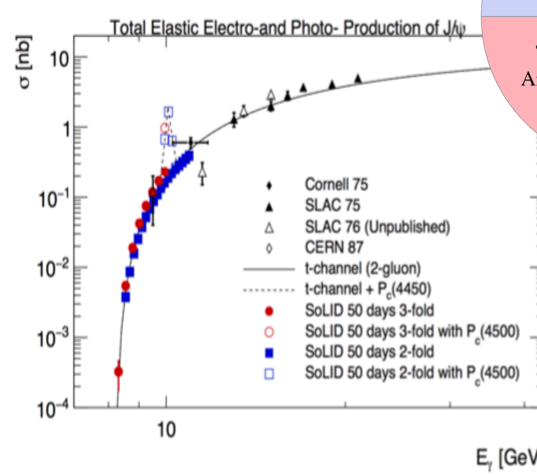


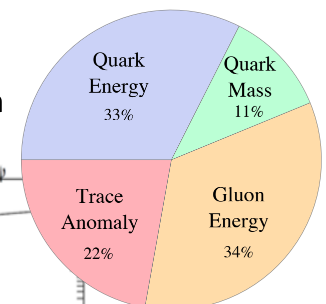
2) Precise determination of the electroweak couplings



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

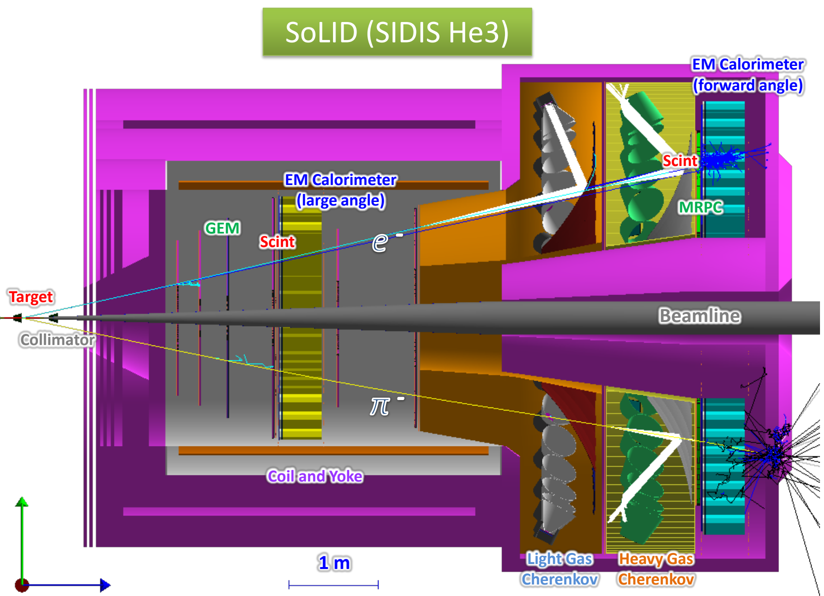
3) J/ψ production cross section

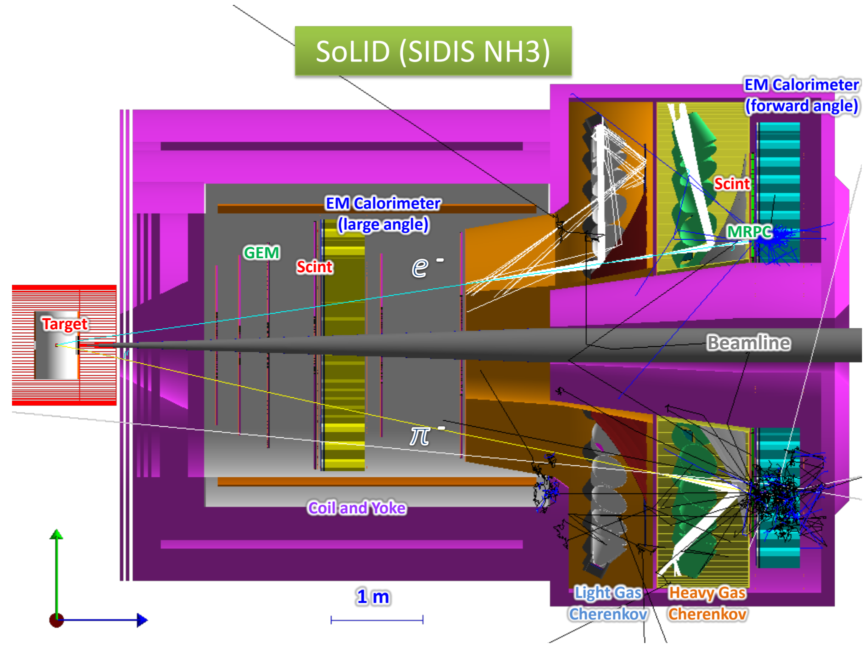




→ Constrain the QCD trace anomaly, Proton mass , LHCb charmed pentaquark

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**

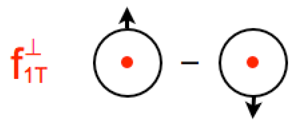
Several run group experiments approved: TMDs, GPDs, and much more

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

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.

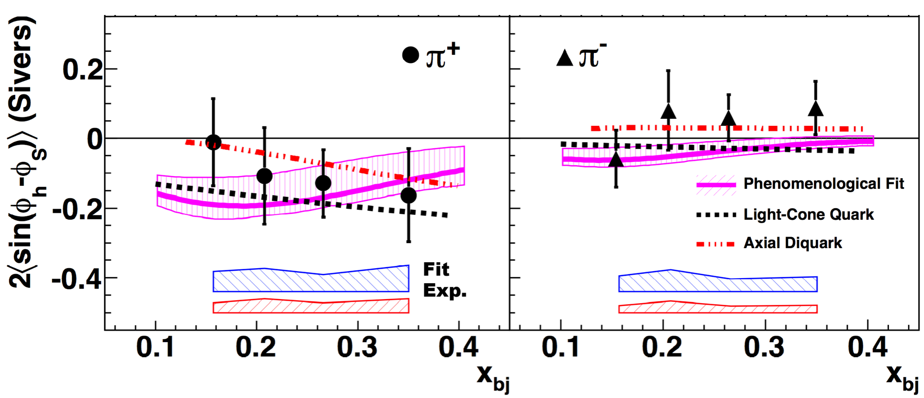
$$f_{1T}^{\perp q}(x, k_\perp)\Big|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x, k_\perp)\Big|_{\text{DY}}$$

Measurement in SIDIS

Single spin asymmetry

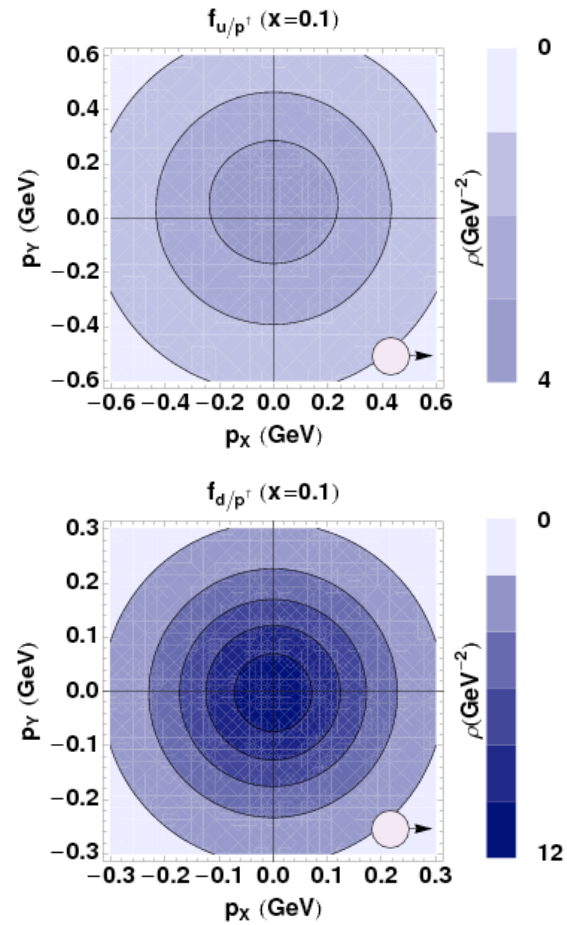
(Sivers asymmetry)

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



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

Model Calculation



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

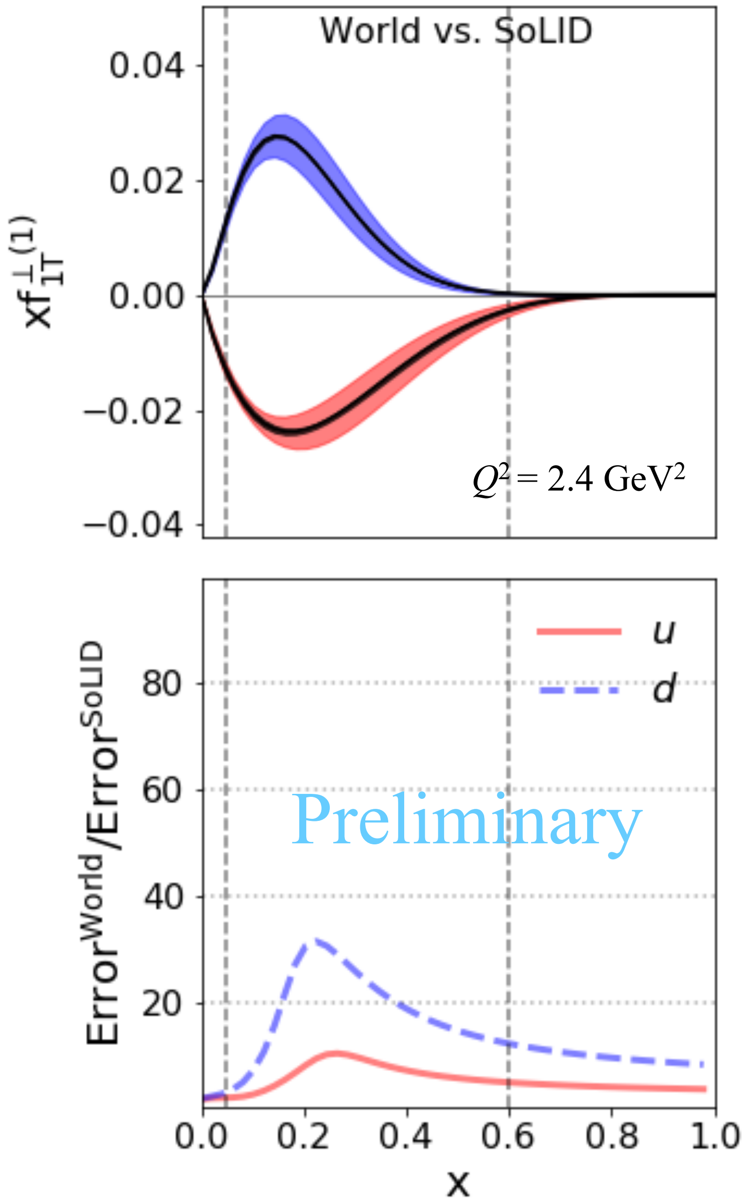
SoLID Impact on Sivers

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

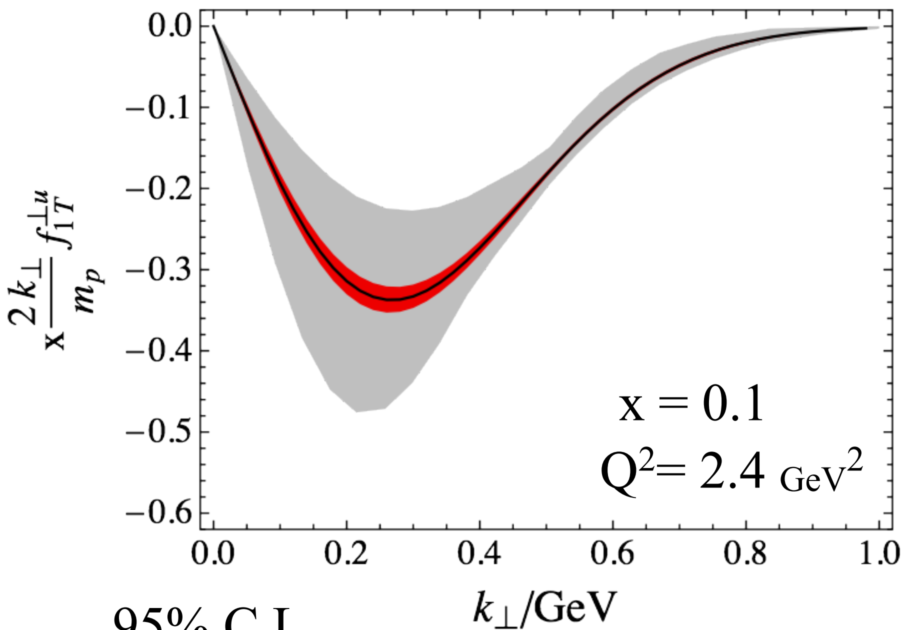
Monte Carlo method with nested sampling algorithm is applied

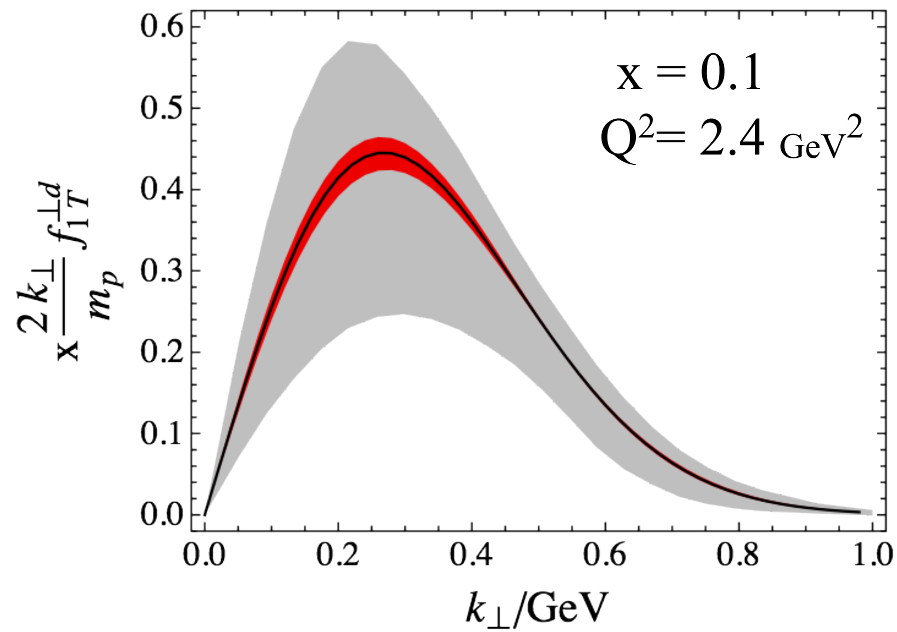
TMD evolution is not included

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).

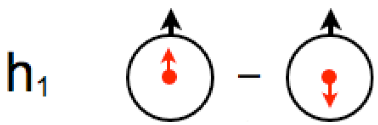
SoLID projection with transversely polarized neutron and proton data.

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

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

Transverse Spin Structure

Transversity



(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.

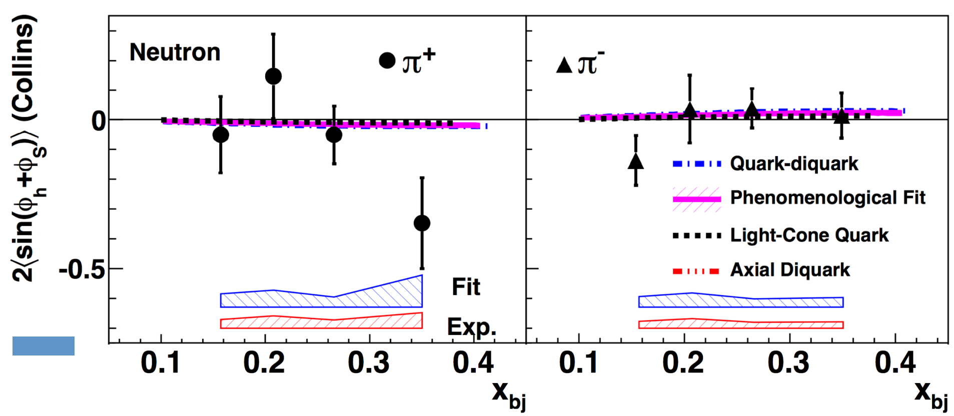
NOT accessible via inclusive DIS process.
Must couple to another chiral-odd function.
(*e.g.* Collins function $H_1^{\perp}$)
Measured via
SIDIS (E12-10-006, E12-11-008), Drell-Yan
Di-hadron (approved as run group with E12-10-006)

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

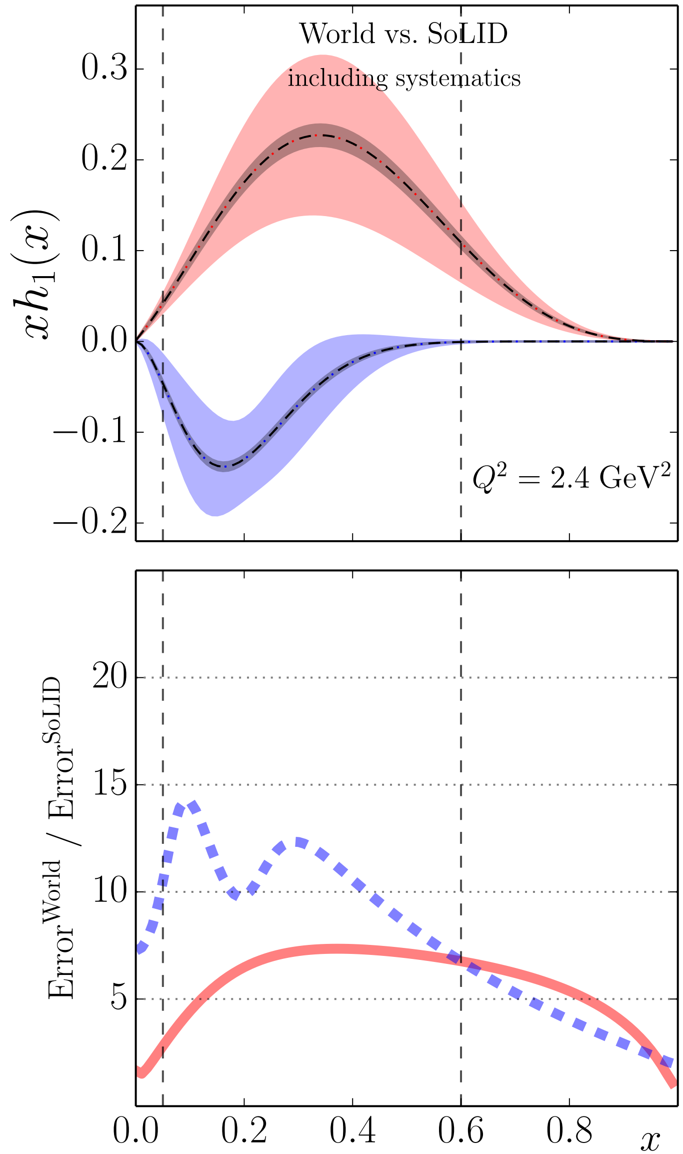
SIDIS data from HERMES, COMPASS and JLab-6 GeV

e^+e^- data from BELLE and BABAR

TMD evolution is included

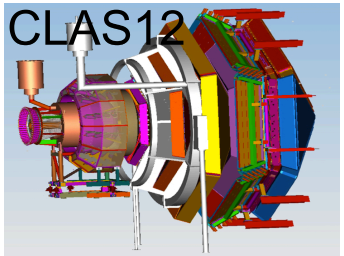
Both statistical and systematic uncertainties are included

About one order of magnitude improvement



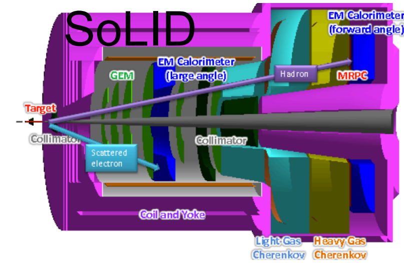
Accessing transversity in dihadron production at JLab

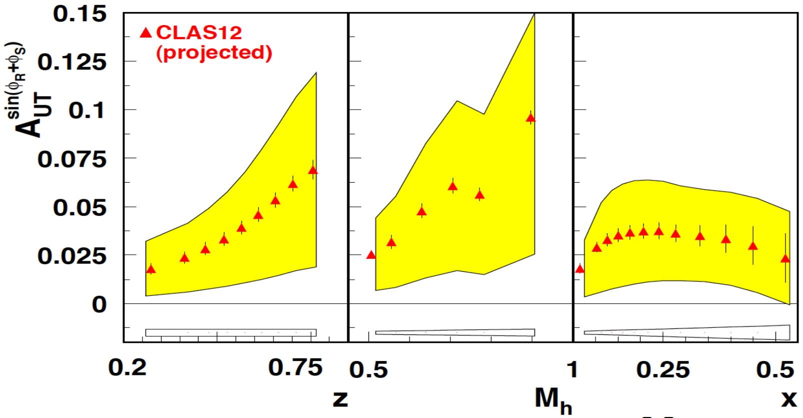
Measurements with polarized protons

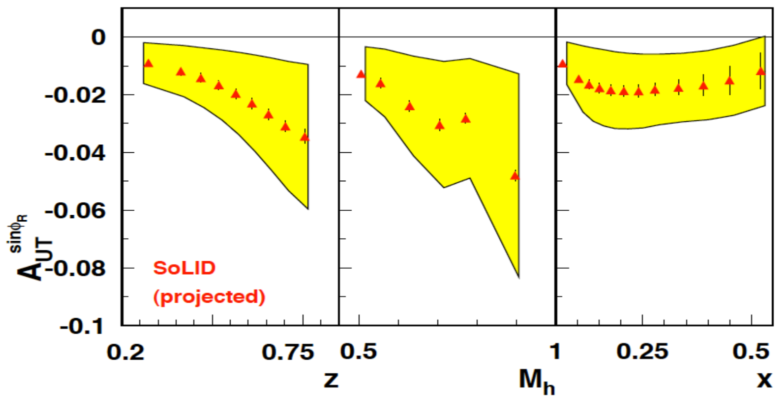


$$A_{UT}(\phi_R,\theta) = \frac{1}{fP_t}\frac{(N^+ - N^-)}{(N^+ + N^-)}$$

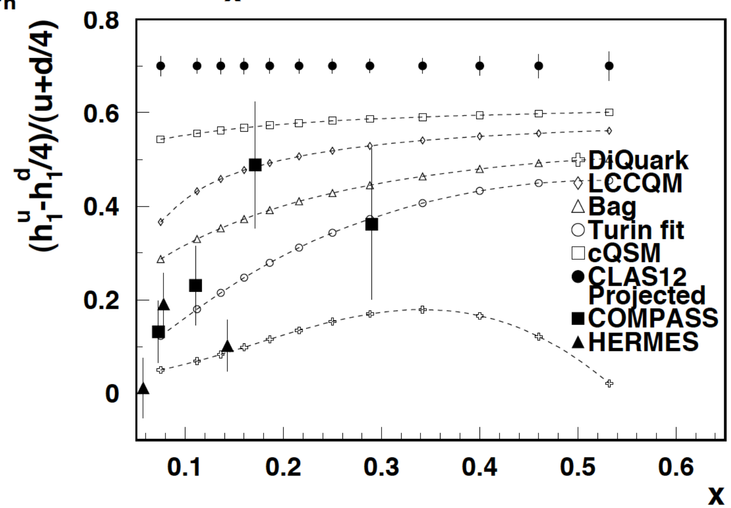
Measurements with polarized neutrons







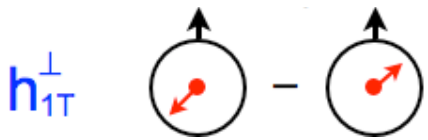
$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_h)[4h_1^u - h_1^d(x)]}{D_1^u(4f_1^u + f_1^d)}$$



$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_{\pi\pi})\,\left(4h_1^d(x) - h_1^u(x)\right)}{D_1^u(z,M_{\pi\pi})\,\left(4f_1^d(x) + f_1^u(x)\right)}$$

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)

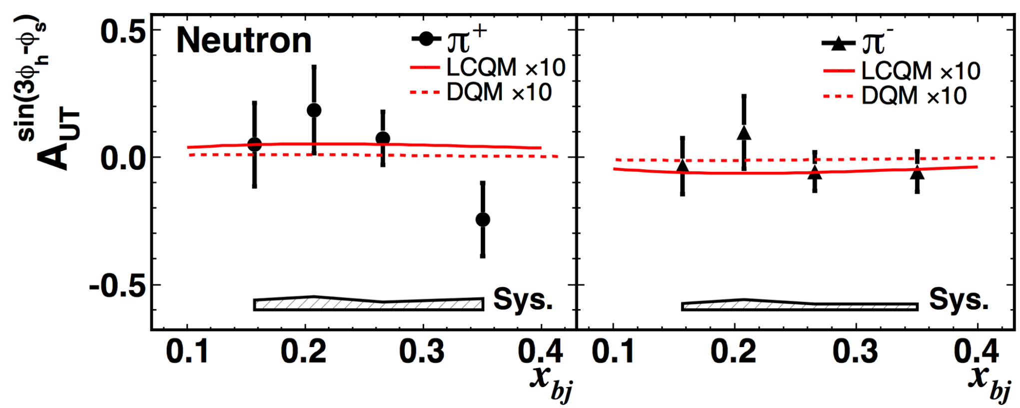
Measurement in SIDIS

Single spin asymmetry

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

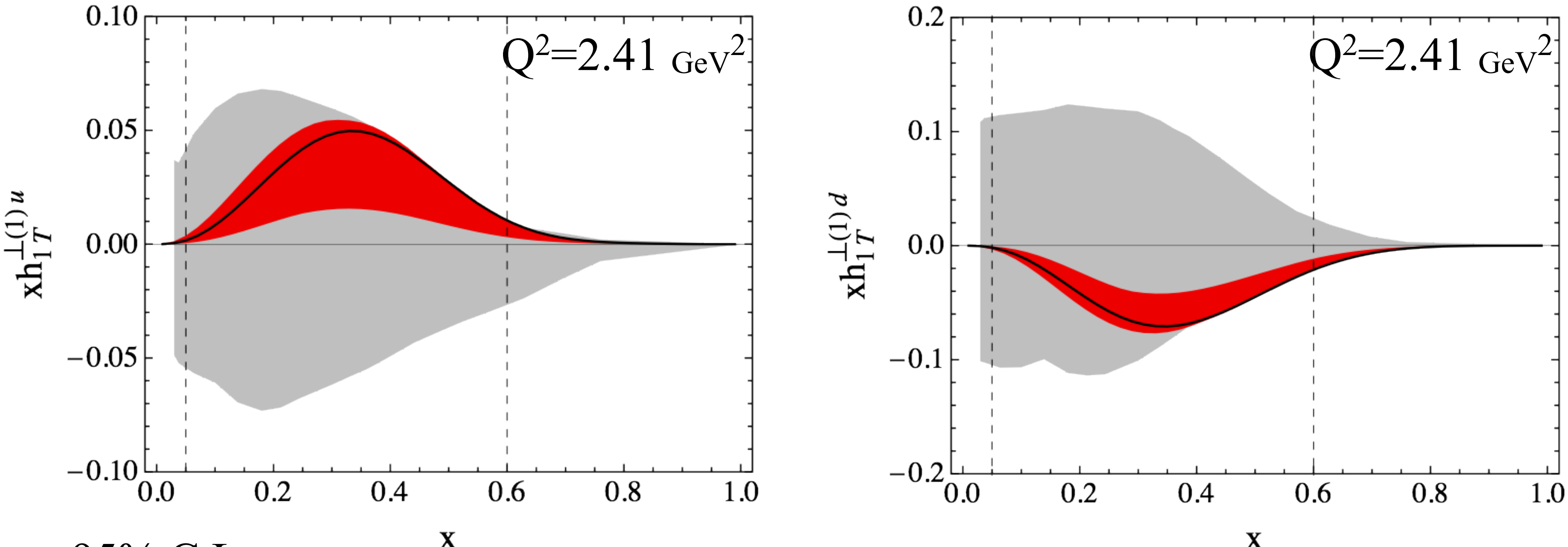
A global fit to 175 data from COMPASS, HERMES, and JLab found comparable with null signal hypothesis at 72% C.L..

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



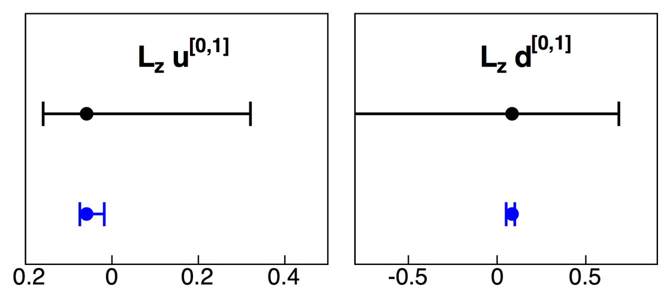
95% C.L.

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

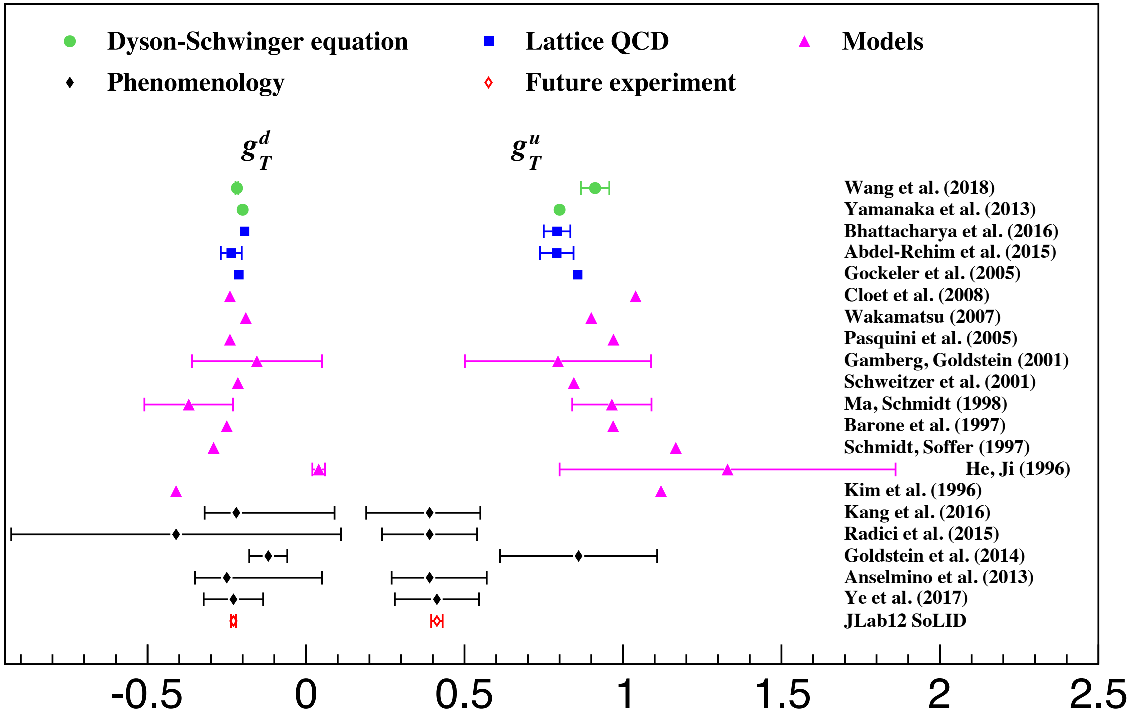
$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = g_T^q\,\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S) \qquad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

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 2016 parameterization.



Tensor Charge

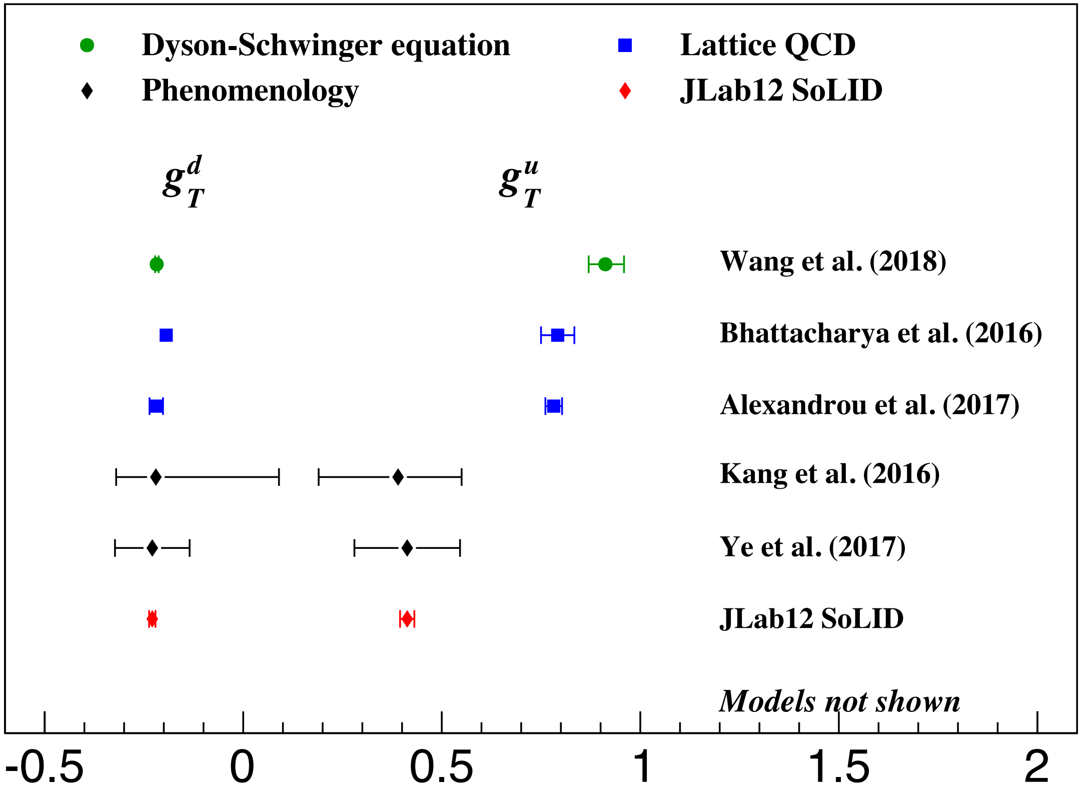
Definition

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

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 2016 parameterization.

Constraint on Quark EDMs

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

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

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

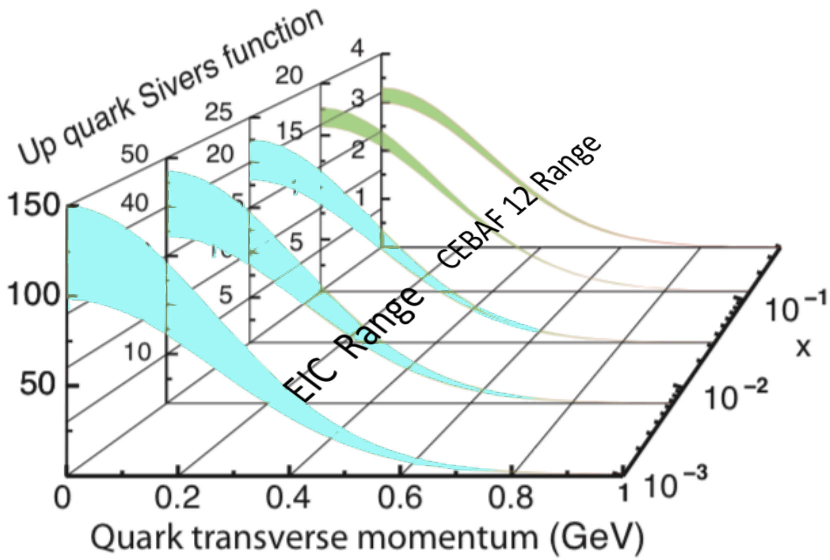
Three orders of magnitude improvement on quark EDM limit → Probe to 30 ~ 40 times higher scale

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

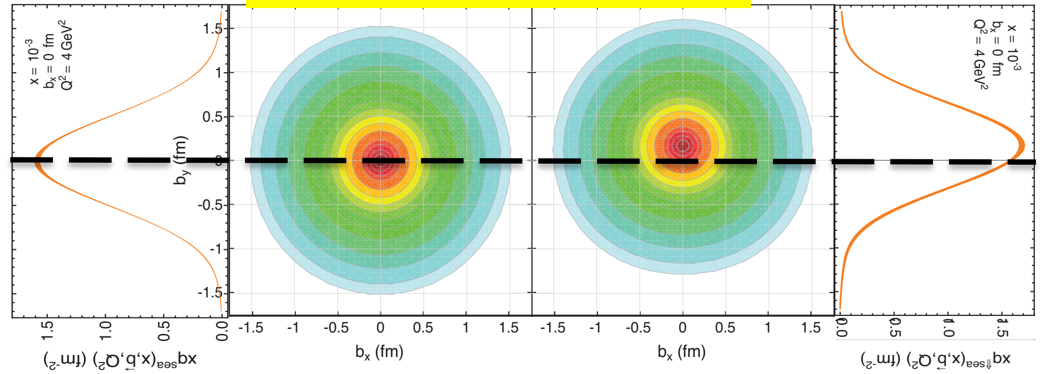
Future quark EDM limit: $10^{-27} e$ cm → 30 ~ 40 TeV

H. Gao, T. Liu, Z. Zhao, PRD 97, 074018 (2018)

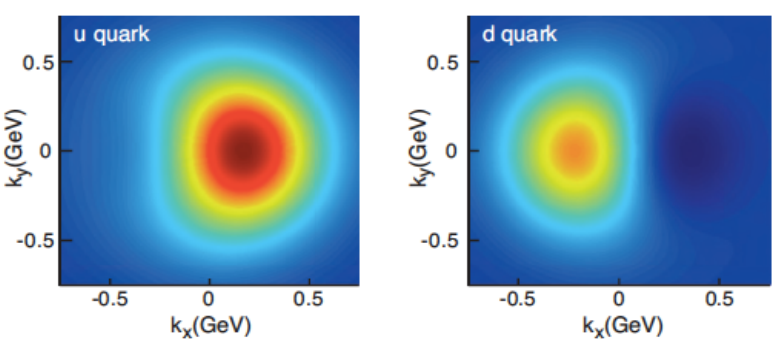
EIC Science: Imaging quarks and gluons in nucleons



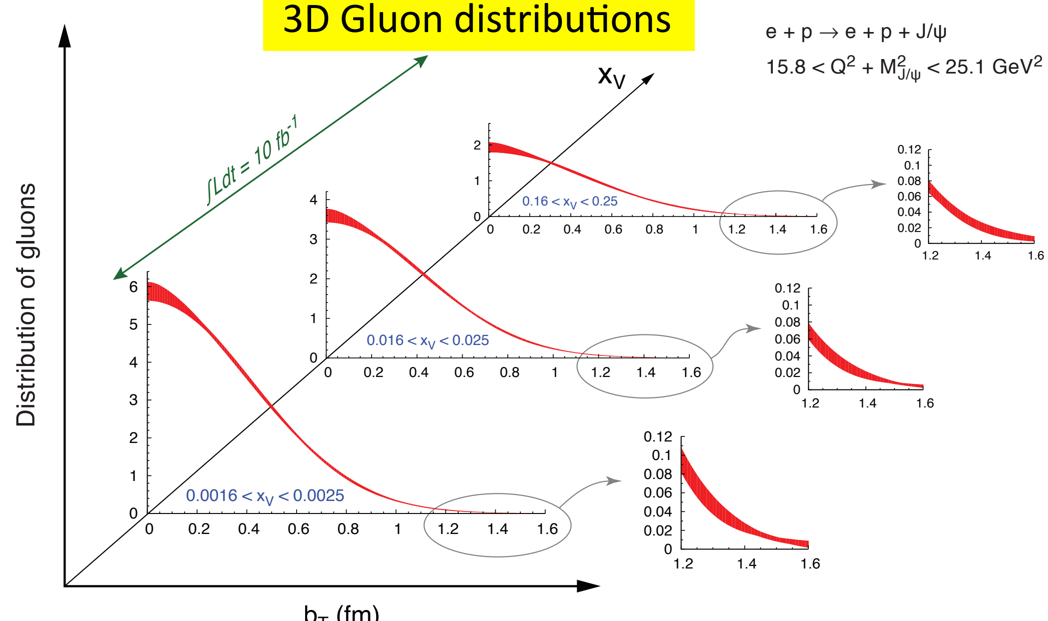
3D Sea Quark distributions unpolarized and polarized



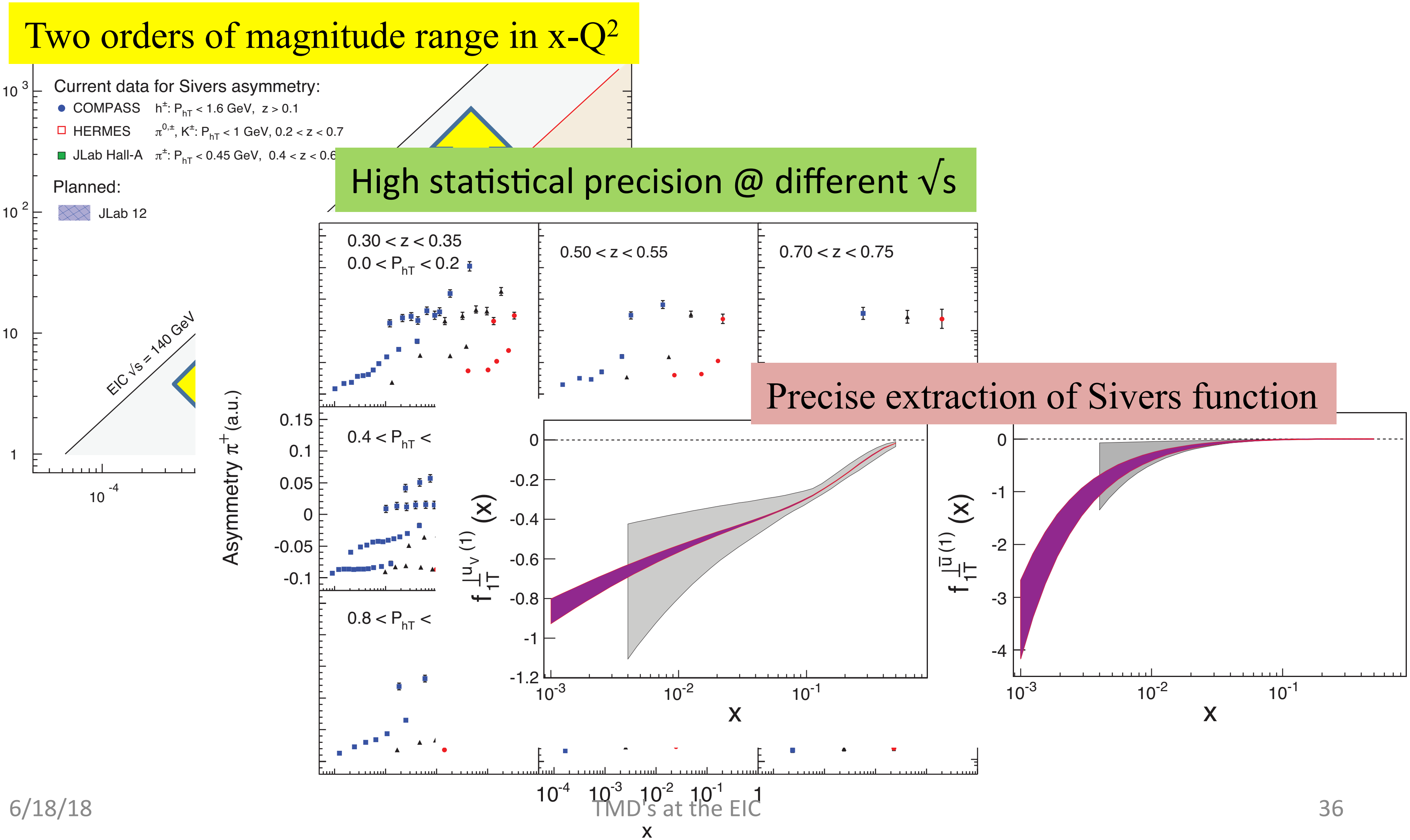
Polarized Quark 3D Momentum distributions



3D Gluon distributions



Scope & possible impact of EIC on Sivers' Function measurements - Quark TMDs



Gluon TMDs just as important, but no measurements yet!

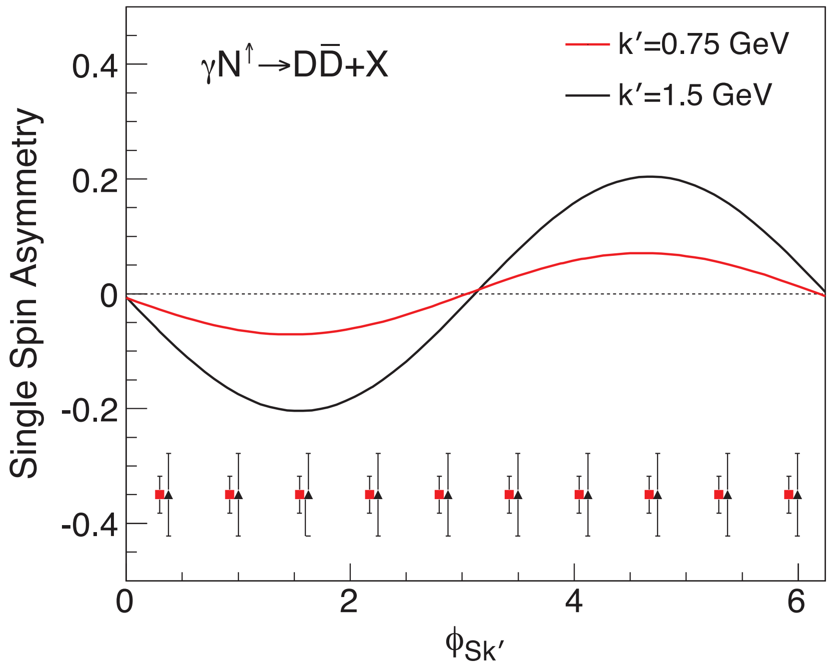
Possible to measure them at the EIC with the following possible measurement campaigns:

❖ Di-Jet or Di-hadron product fusion process

❖ Heavy quark production

❖ Quarkonium production

--- All with *transversely polari*



These measurements were thought of l time simulations studies (other than di EIC-White Paper. Now these studies are timely.

Summary

- Three-dimensional imaging of nucleon helps solve the remaining puzzle to the proton spin, and uncovers the rich dynamics of QCD, TMDs also uncover the confined motion of quarks and gluons inside the nucleon
- 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, EDM experiments, ….
- TMDs at EIC: Sea quark region and the gluons, together with 12-GeV, provide full tomography of nucleons in momentum space

Thanks to H. Avakian, J.-P Chen, A. Deshpande, R. Ent, C. Keppel, T.-B. Liu, Z.-E. Meziani, A. Prokudin, A. Puckett, 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