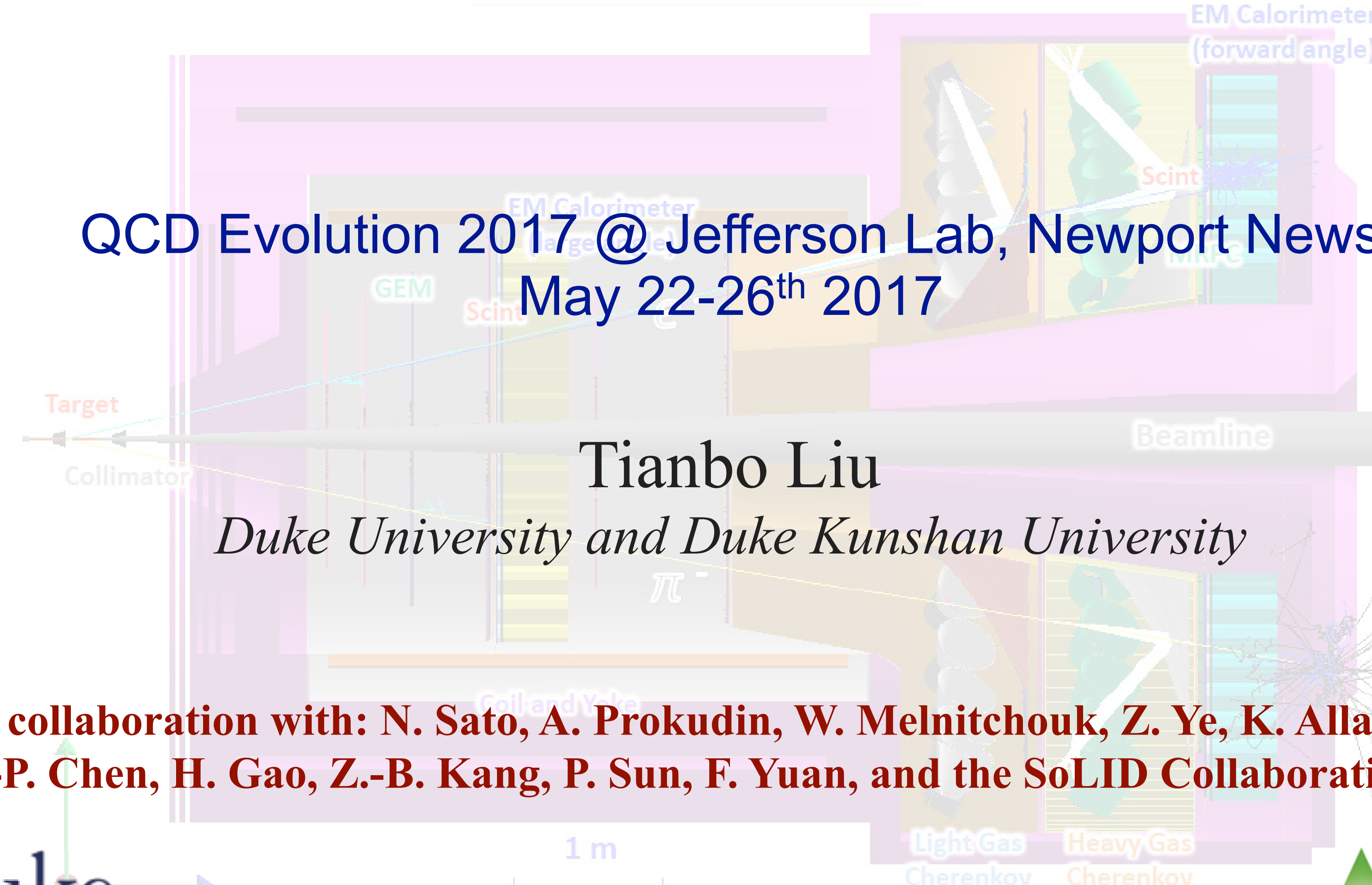
Impact of SoLID Experiment on TMDs



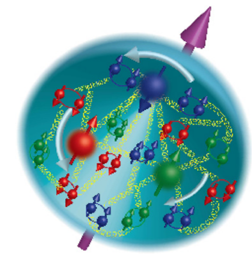
QCD Evolution 2017 @ Jefferson Lab, Newport News
May 22-26th 2017

Tianbo Liu

Duke University and Duke Kunshan University

In collaboration with: N. Sato, A. Prokudin, W. Melnitchouk, Z. Ye, K. Allada, J.-P. Chen, H. Gao, Z.-B. Kang, P. Sun, F. Yuan, and the SoLID Collaboration

Nucleon Spin Decomposition



Proton spin puzzle

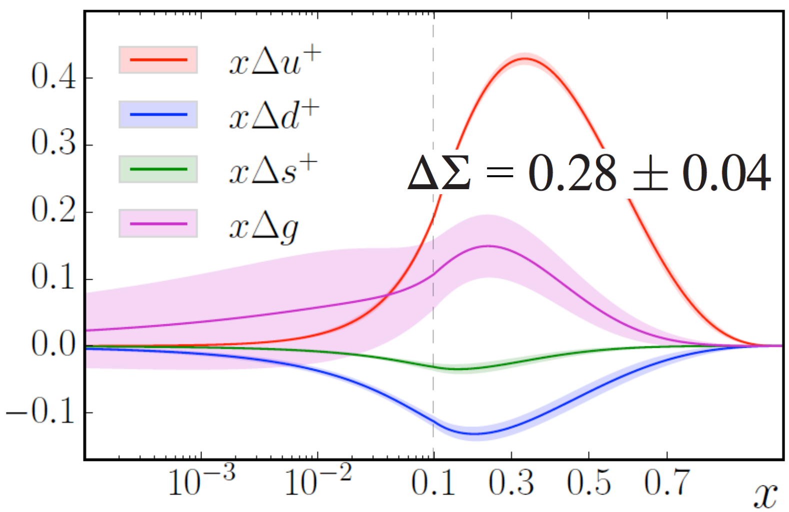
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

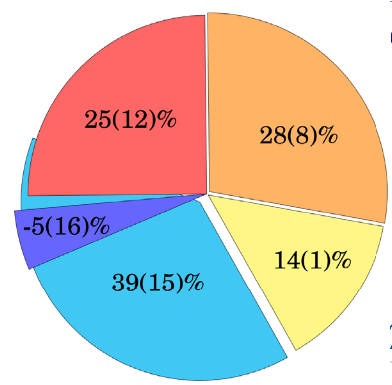
J. Ashman *et al.*, PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

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



JAM Collaboration, PR D 93, 074005 (2016).



χQCD Collaboration, PR D 91, 014505 (2015).

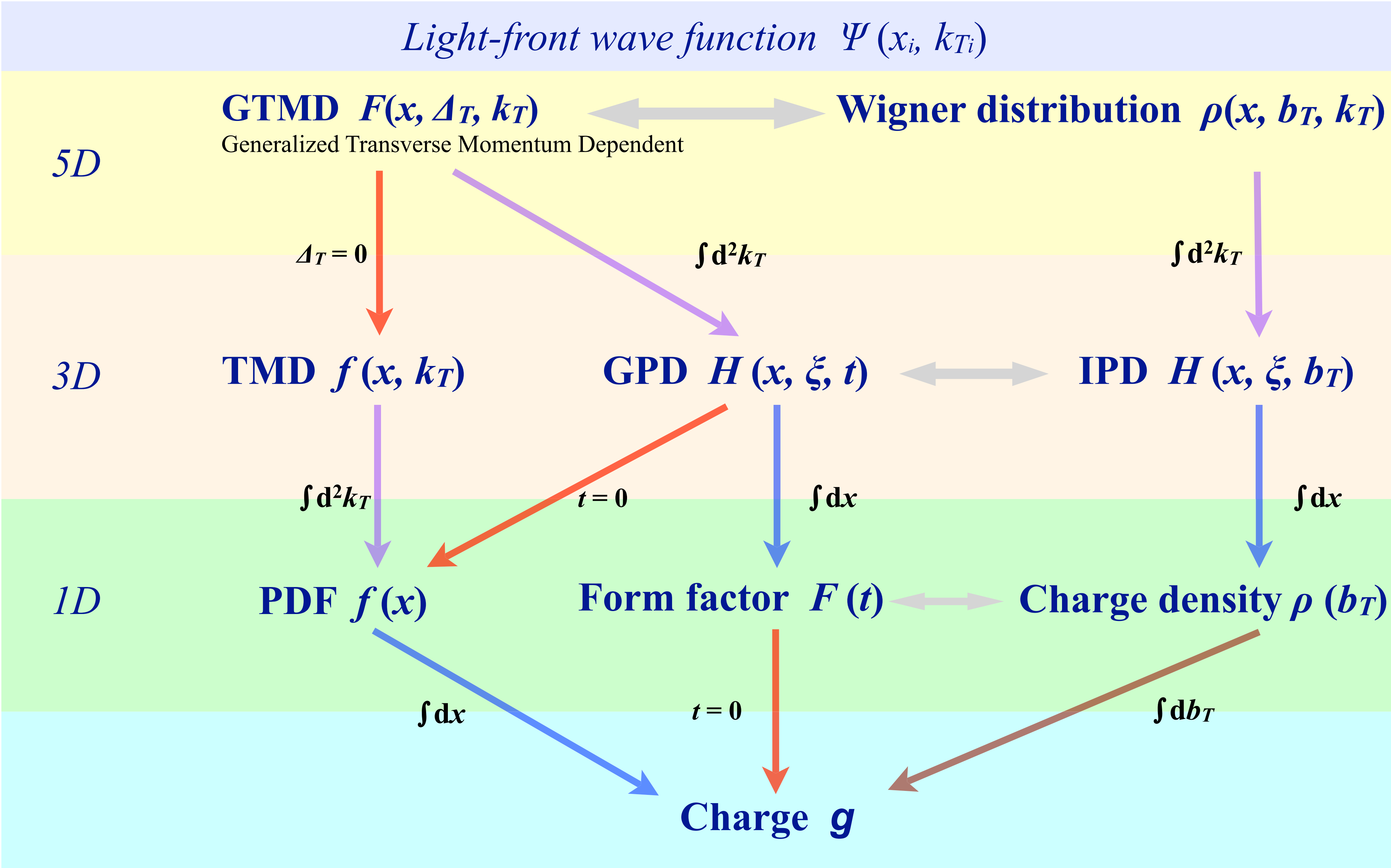
Access to $L_{q/g}$

It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3*D* imaging of the nucleon.

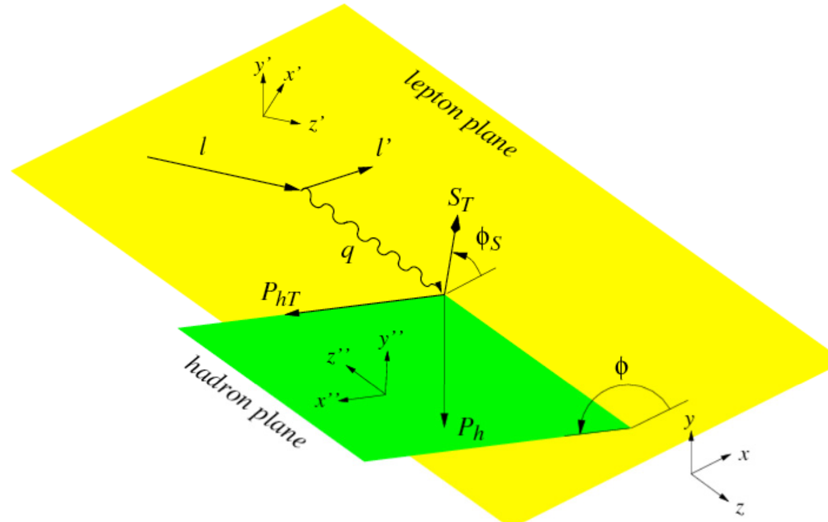
Unified View of Nucleon Structure



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]

$$\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\psi} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

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

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

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

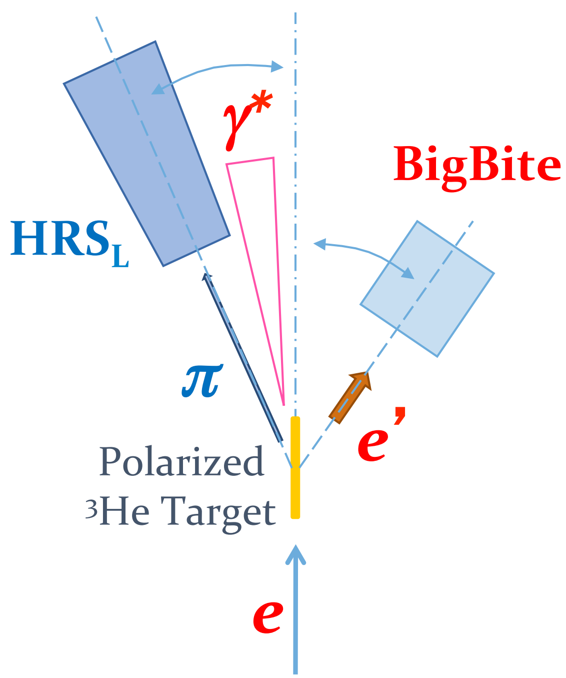
$$+ \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$

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

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

SIDIS Experiment @ JLab-6GeV

E06-010 @ Hall A

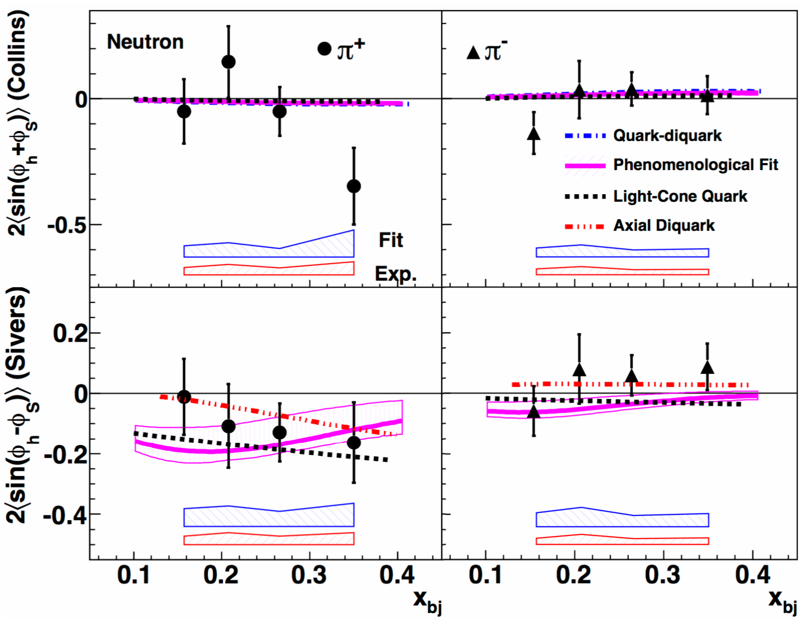


- First neutron data in SIDIS
- Electron beam energy: 5.9 GeV
  Average current: 12μA
- 40cm transversely polarized ^{3}He target
  Average polarization: $55.4 \pm 2.8\%$
- BigBite at 30˚ as **electron** arm
  scattered electron momentum 0.6~2.5 GeV/c
- HRS at 16˚ as **hadron** arm
  hadron momentum ~ 2.35 GeV/c

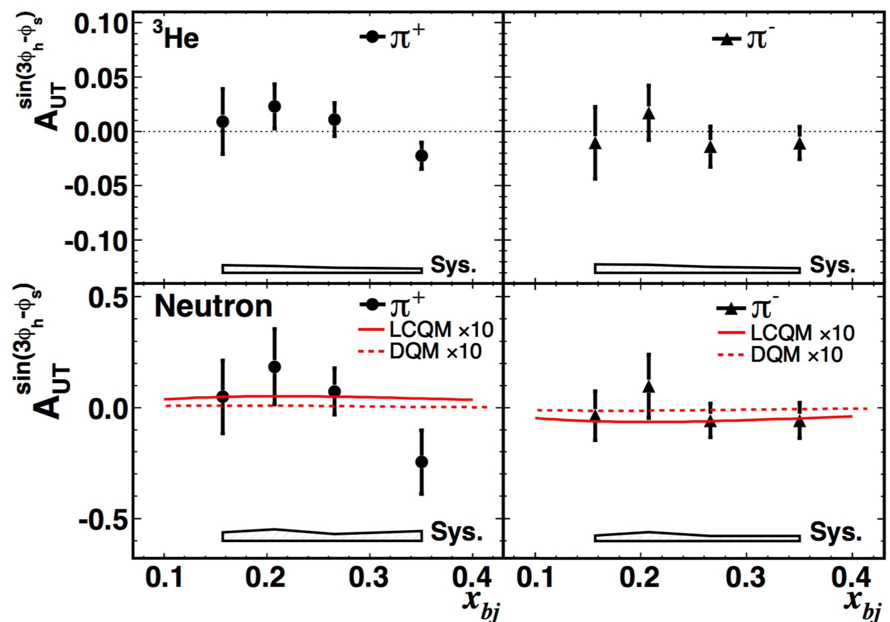
Published results from E06-010:

- X. Qian *et al.,* Sivers and Collins SSA of $\pi^\pm$ production in SIDIS, *Physical Review Letters* 107, 072003 (2011).
- Y. Zhang *et al.,* Pretzelosity SSA of $\pi^\pm$ production in SIDIS, *Physical Review* C 90, 055209 (2014).
- Y.X. Zhao *et al.,* Sivers and Collins SSA of $K^\pm$ production in SIDIS, *Physical Review* C 90, 055201 (2014).
- J. Huang *et al.,* Beam-target DSA of $\pi^\pm$ production in SIDIS, *Physical Review Letters* 108, 052001 (2012).
- K. Allada *et al.,* SSA of inclusive hadron, $\pi^\pm$, $K^\pm$, and proton, productions, *Physical Review* C 89, 042201(R) (2014).
- Y.X. Zhao *et al.,* DSA of inclusive hadron, $\pi^\pm$, $K^\pm$, and proton, productions, *Physical Review* C 92, 015207(R) (2015).
- X. Yan *et al.*, Unpolarized differential cross section of $\pi^\pm$ production in SIDIS, *Physical Review* C 95, 035209 (2017).

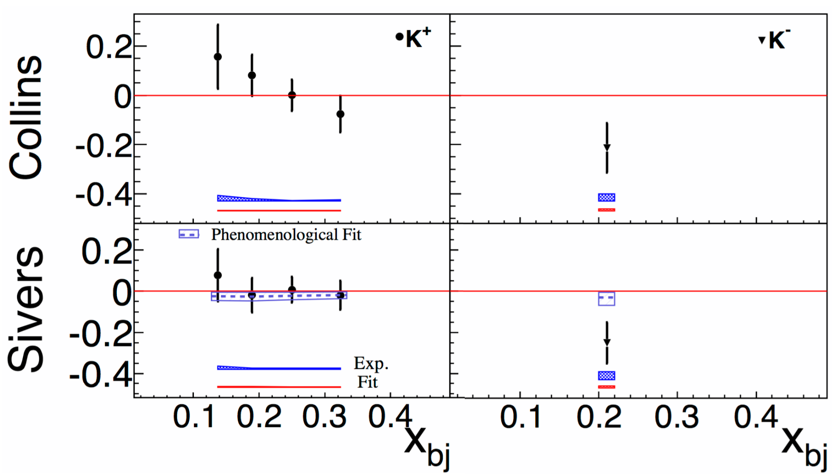
SIDIS SSA/DSA Results from E06-010



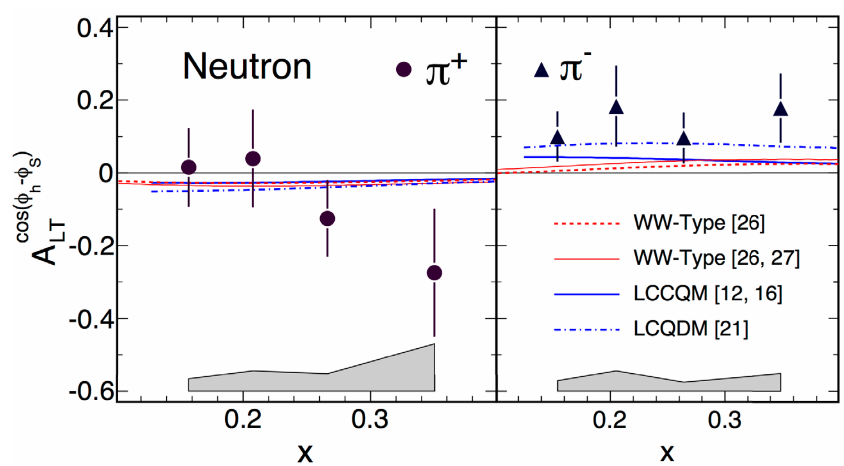
X. Qian *et al.*, PRL 107, 072003 (2011).



Y. Zhang *et al.*, PR C90, 055209 (2014).



Y.X. Zhao *et al.*, PR C90, 055201 (2014).



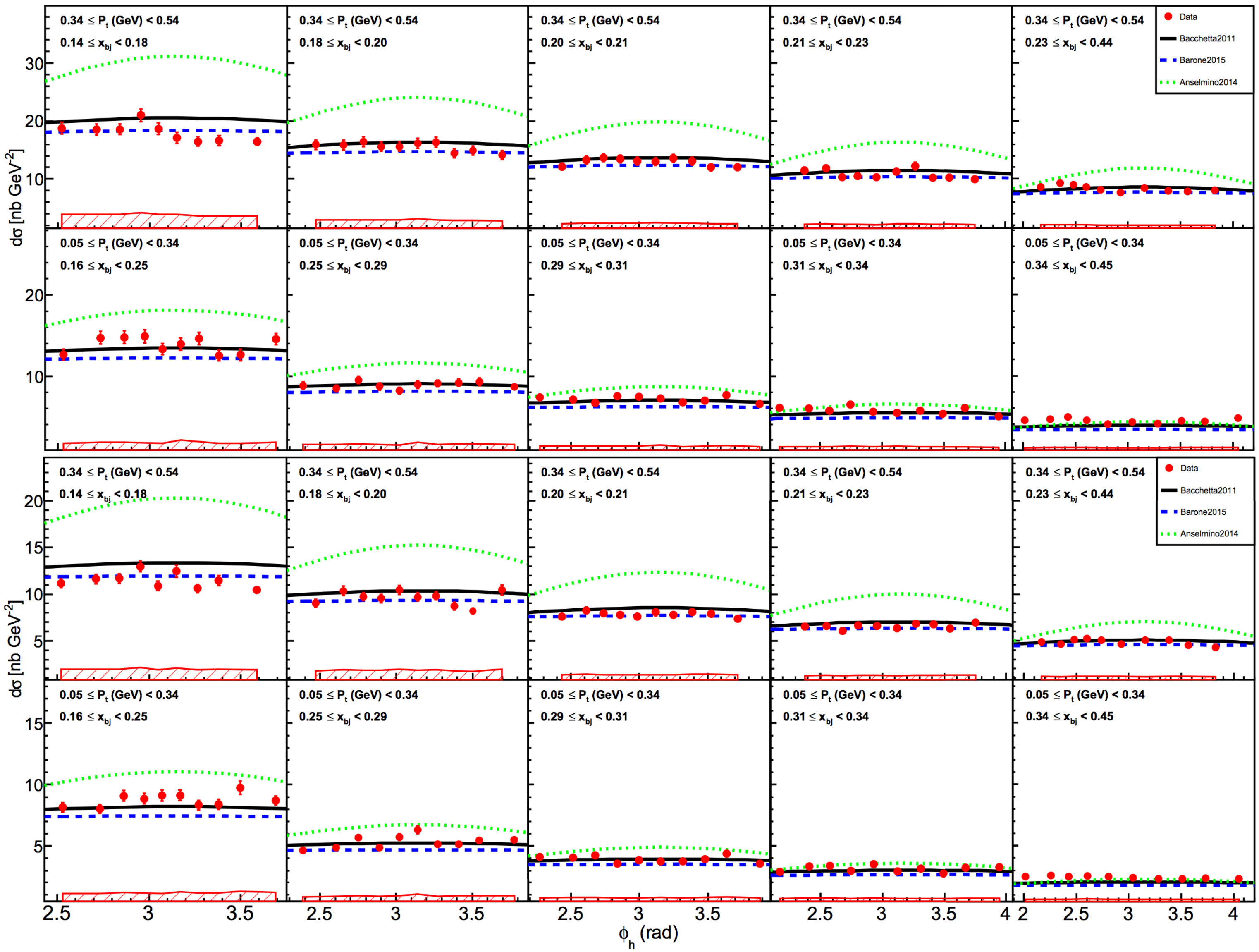
J. Huang *et al.*, PRL 108, 052001 (2012).

Differential Cross Section

First measurement of unpolarized SIDIS differential cross section on ^{3}He target

π^+

π^-

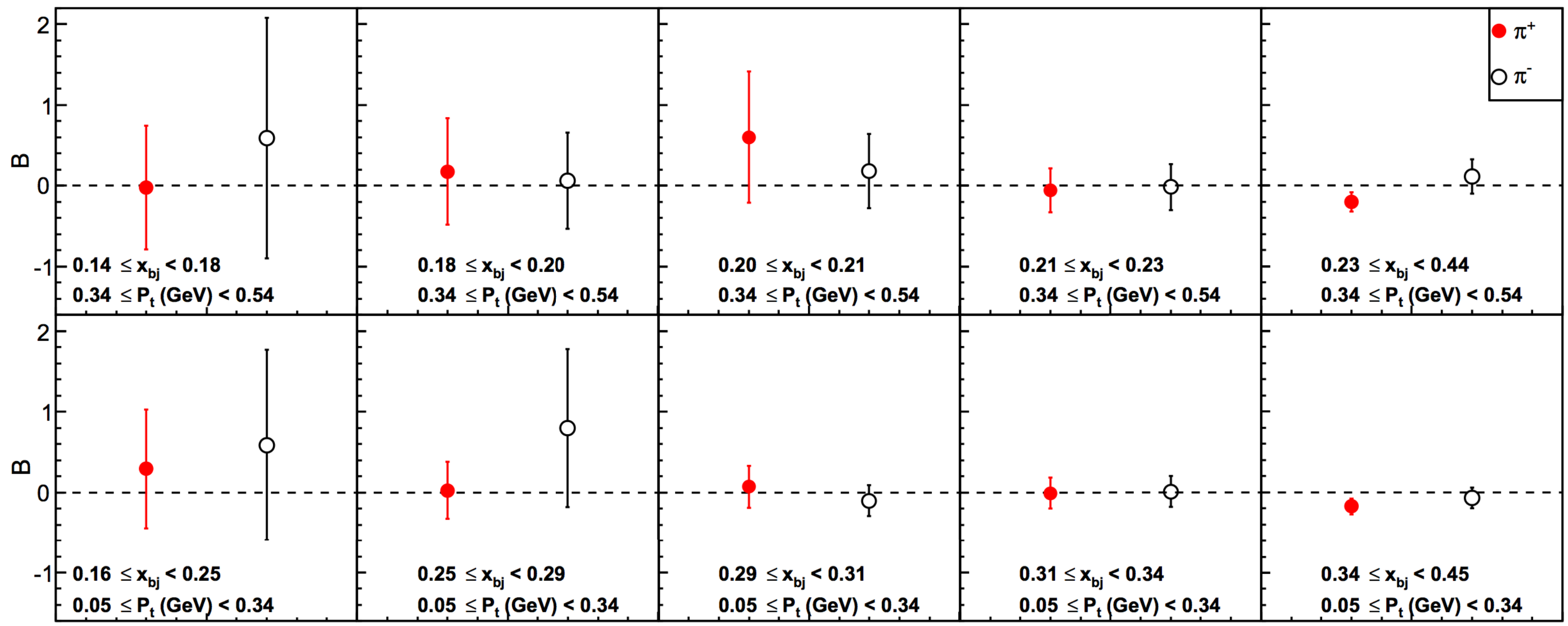


X. Yan *et al.*, Phys. Rev. C 95, 035209 (2017).

5 [x bins] × 2 [P_T bins] × 10 [ϕ_h bins]

Azimuthal Modulation

cos ϕ_h azimuthal modulations in unpolarized SIDIS cross section on ^{3}He target

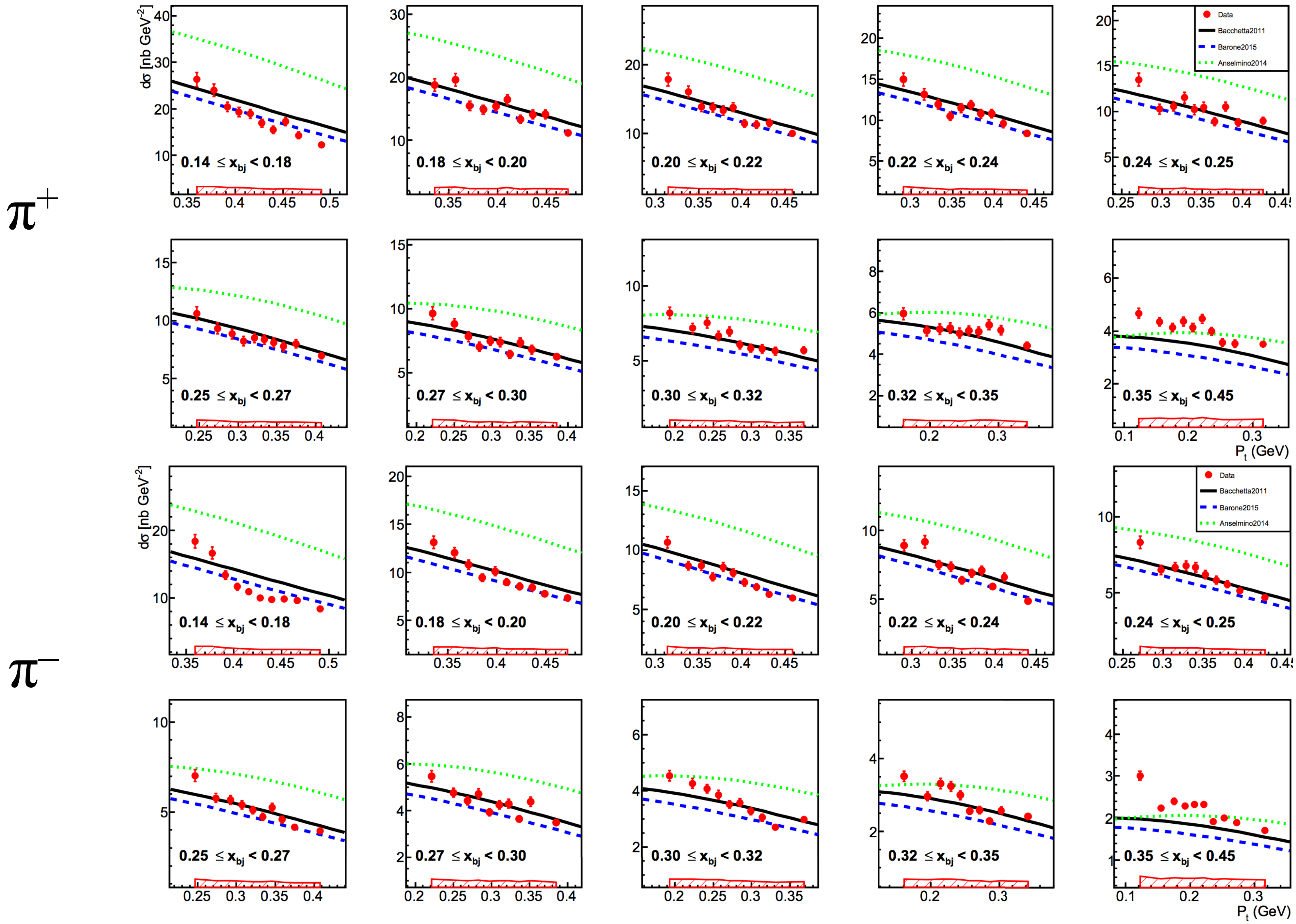


- Fit with $A\,(1 - B\cos\phi_h)$ to 10 ϕ_h bins in each x, P_T bin

X. Yan *et al.*, Phys. Rev. C 95, 035209 (2017).

Differential Cross Section

First measurement of unpolarized SIDIS differential cross section on ^{3}He target



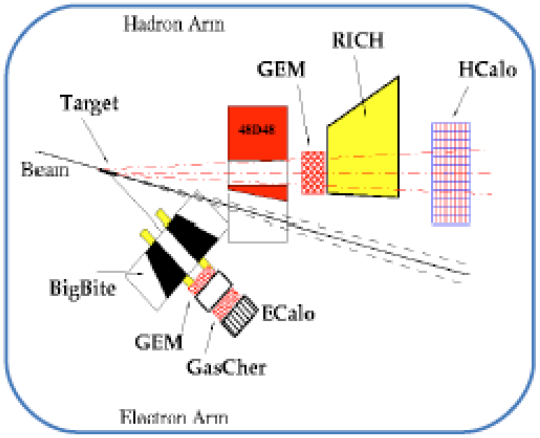
X. Yan *et al.*, Phys. Rev. C 95, 035209 (2017).

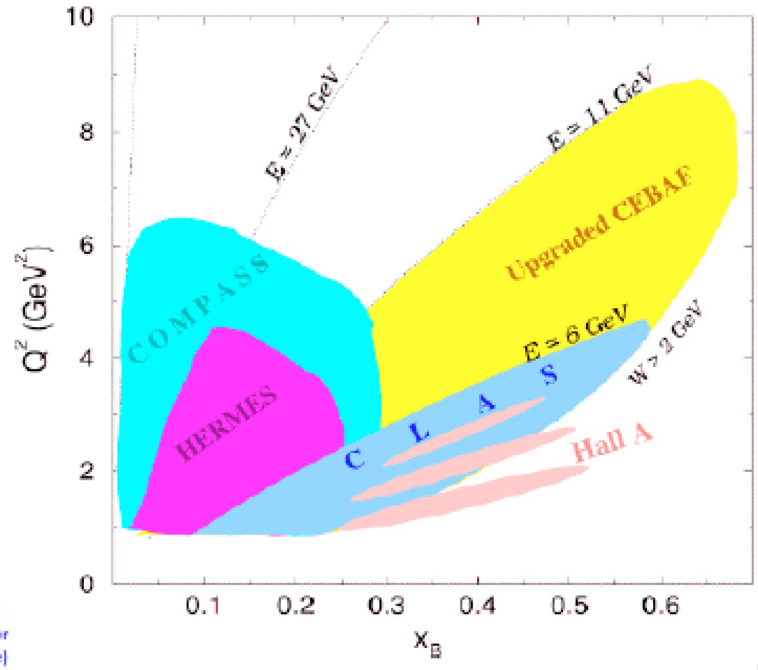
10 [x bins] × 10 [P_T bins]

Multi-Hall SIDIS Program @ JLab

Hall A: Super BigBite

SIDIS with ^{3}He, high x, Q^2

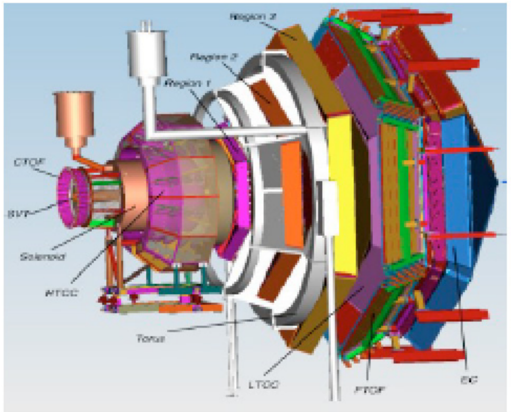




Hall B: CLAS12

SIDIS with polarized H/D

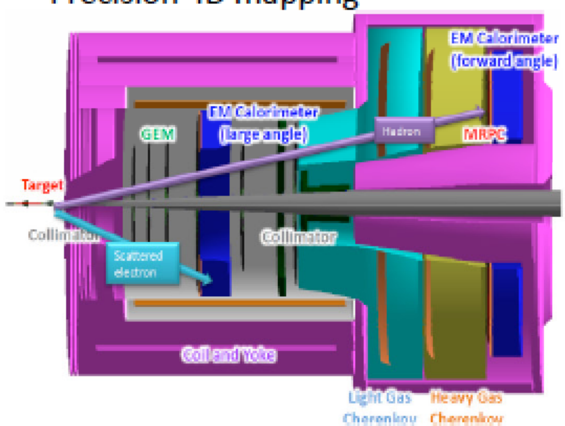
Comprehensive SIDIS program



Hall A: SoLID

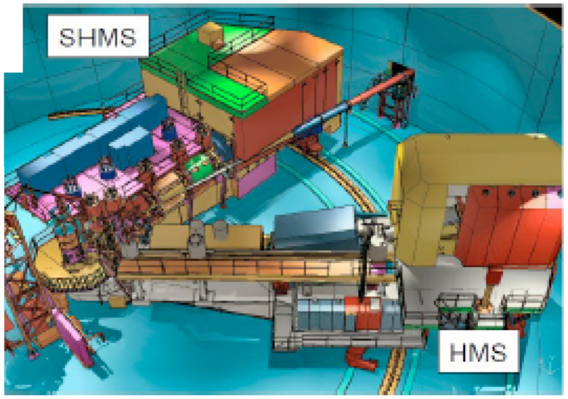
SIDIS with polarized ^{3}He/NH_3

Precision 4D mapping



Hall C: SHMS

SIDIS with unpolarized H/D



Overview of SoLID

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

Full exploitation of JLab 12 GeV upgrade with broad physics

- Luminosity ~ 10^{37} cm^{-2} s^{-1} (open geometry)
- 3D nucleon structure
  - TMD (Semi-inclusive DIS)
  - GPD (TCS, DVMP, DVCS, DDVCS)
- Conformal anomaly
  - J/ψ production near threshold

- Luminosity ~ 10^{39} cm^{-2} s^{-1} (baffled geometry)
- Standard model test, new physics in 10~20 TeV region
  - Parity-violating DIS

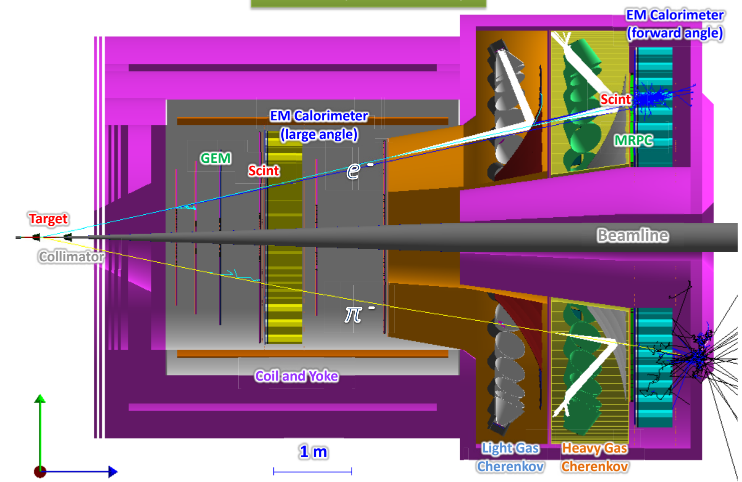
Five highly rated approved experiments

- Three SIDIS, one PVDIS, one J/ψ production
- Run group: di-hadron, TCS, inclusive SSA …

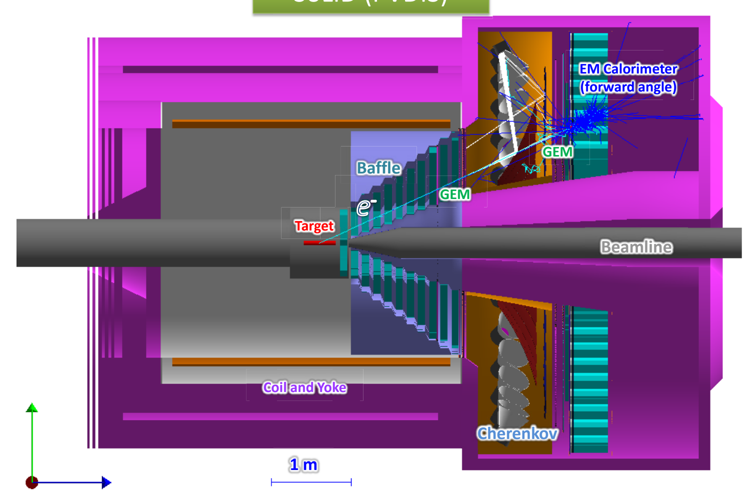
Strong collaboration

- 250+ collaborators from 70+ institutes, 13 countries
- Significant international collaborations and strong theoretical support

SoLID (SIDIS He3)

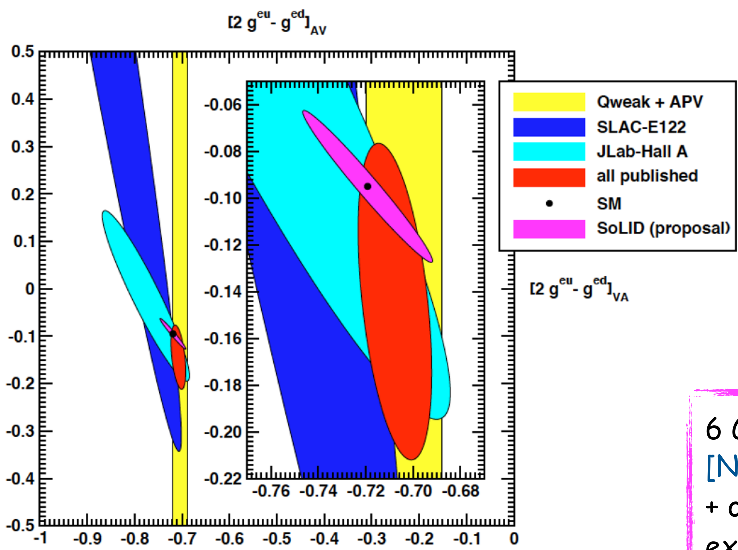


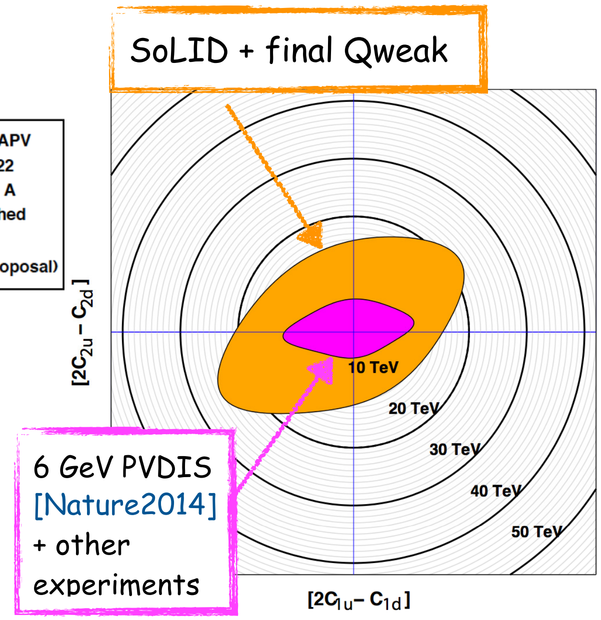
SoLID (PVDIS)



PVDIS @ SoLID

Test new physics beyond SM

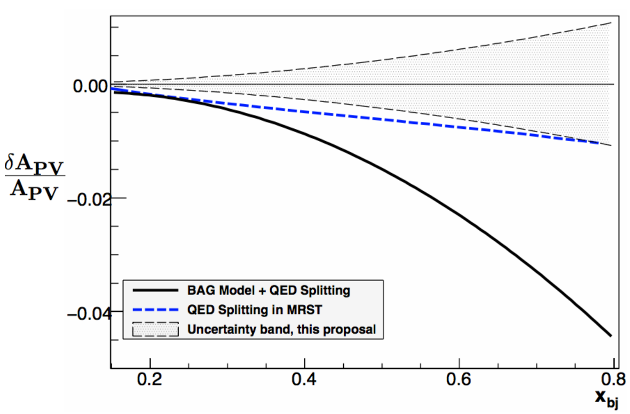




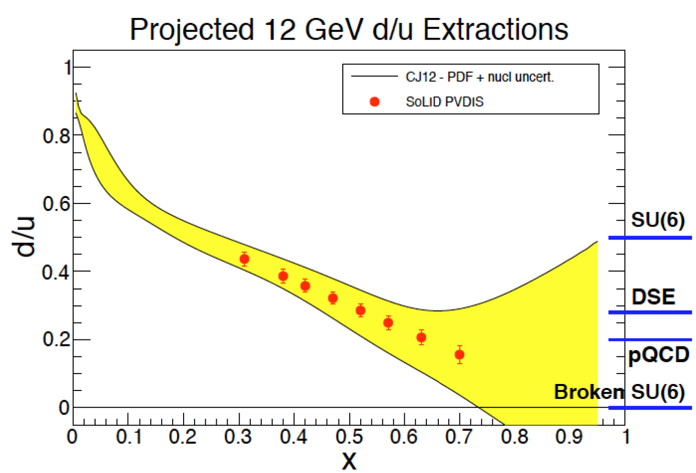
E12-10-007:
Parity violating asymmetry in DIS with LH_2 and LD_2 targets.

- Sub 1% precision over broad kinematic range
- High luminosity ~ 10^{39} cm^{-2} s^{-1}
- Large scattering angle — large x and y

Charge symmetry violation



d/u ratio free of nuclear effect

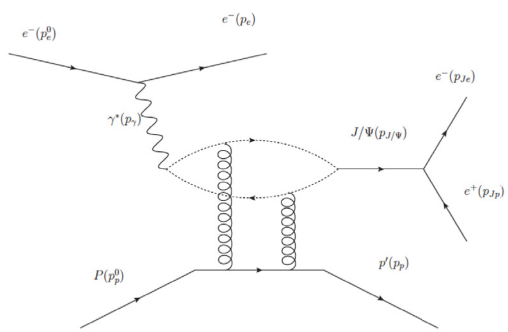


- Precision test of SM with sensitivity to new PV physics in 10~20 TeV
- Search for charge symmetry violation at partonic level
- Test QCD higher twist corrections
- Measure *d/u* ratio for proton free of nuclear effect

J/ψ @ SoLID

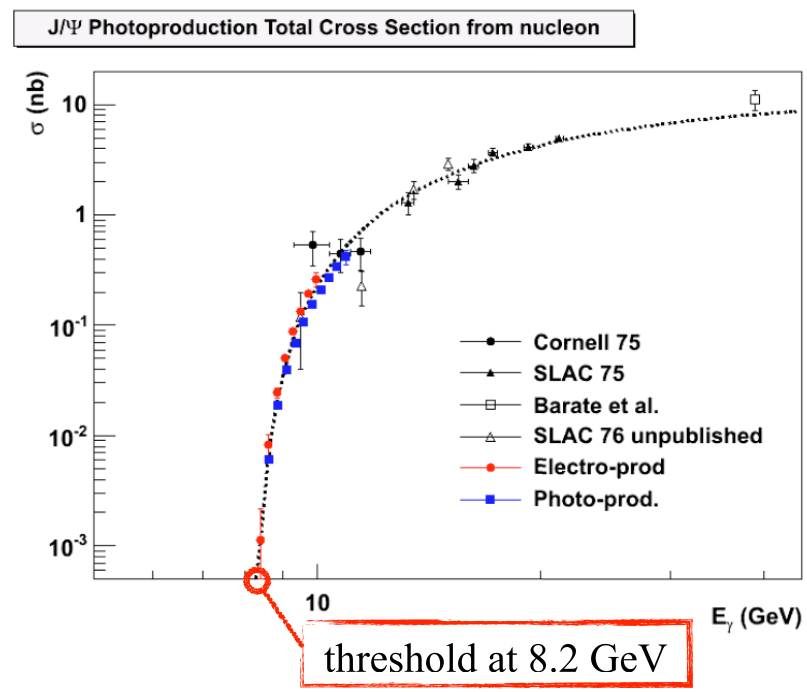
Approved J/ψ near threshold production

E12-12-006: measure J/ψ near threshold production cross section on proton (LH_2).



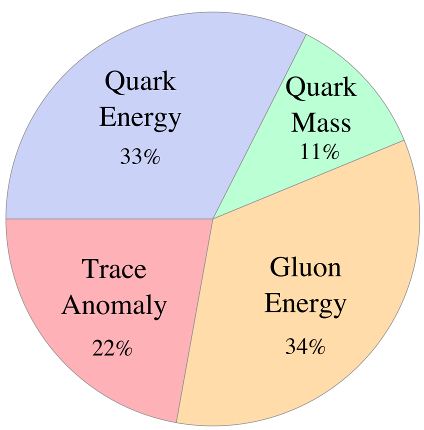
Imaginary part: total cross section through the optical theorem.
Real part: contains the conformal anomaly.

Run group:
E12-12-006A Timelike Compton Scattering (TCS).



Proton mass:

$\overline{MS}$ and $\mu = 2$ GeV



H. Gao *et al.*, The Universe 3, no.2, 18 (2015).

- electro- and photo- production with unprecedented precision in unexplored region
- Probe color force inside the nucleon
- Conformal anomaly (proton mass budget)
- A window for future J/ψ-N interaction studies

SIDIS @ SoLID

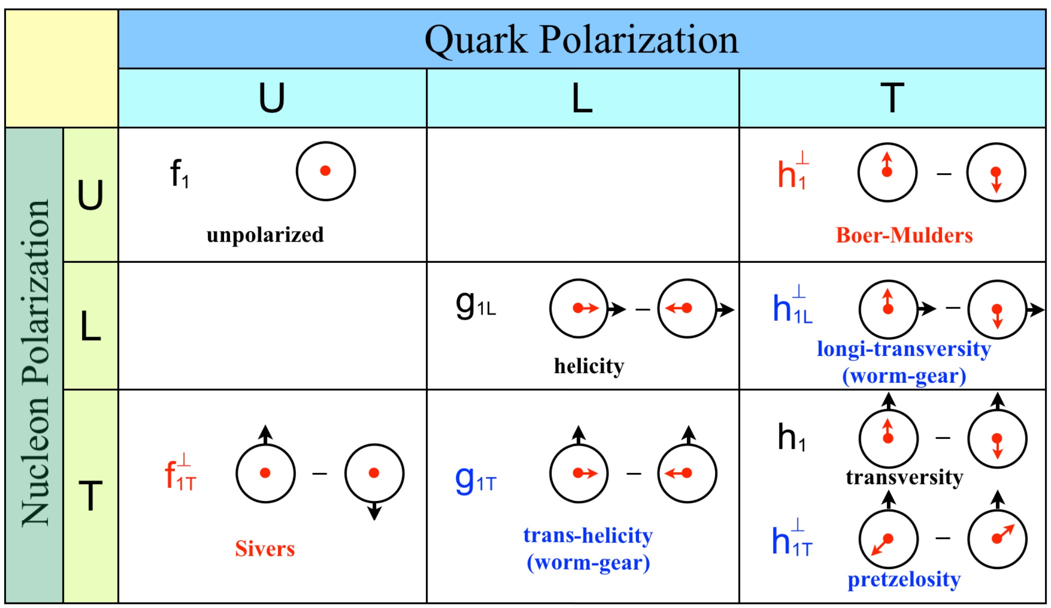
Approved SIDIS experiments 11/8.8 GeV

E12-10-006: Single Spin Asymmetry on Transversely polarized ^3He, 90 days.

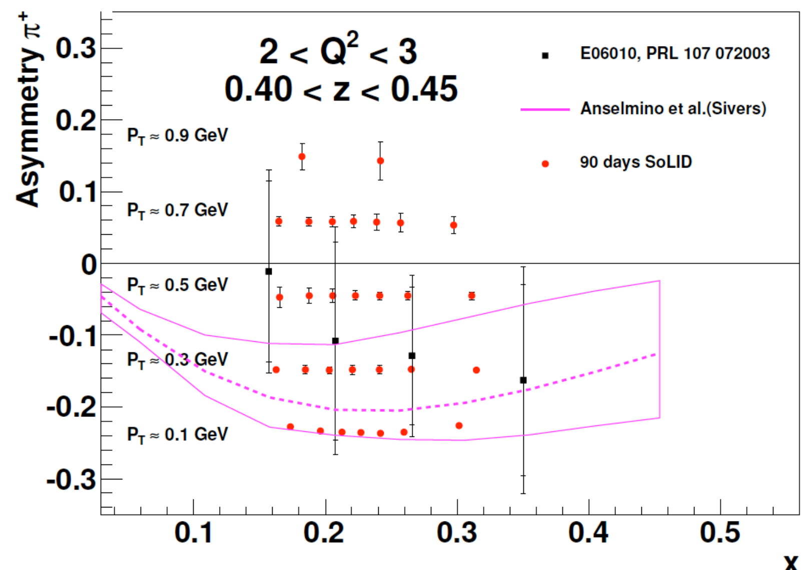
E12-11-007: Single and Double Spin Asymmetry on Longitudinally polarized ^3He, 35 days.

E12-10-008: Single Spin Asymmetry on Transversely polarized proton (NH_3), 120 days.

Two run groups:
E12-10-006A, E12-11-108A
Dihadron process
Target single spin asymmetry A_y



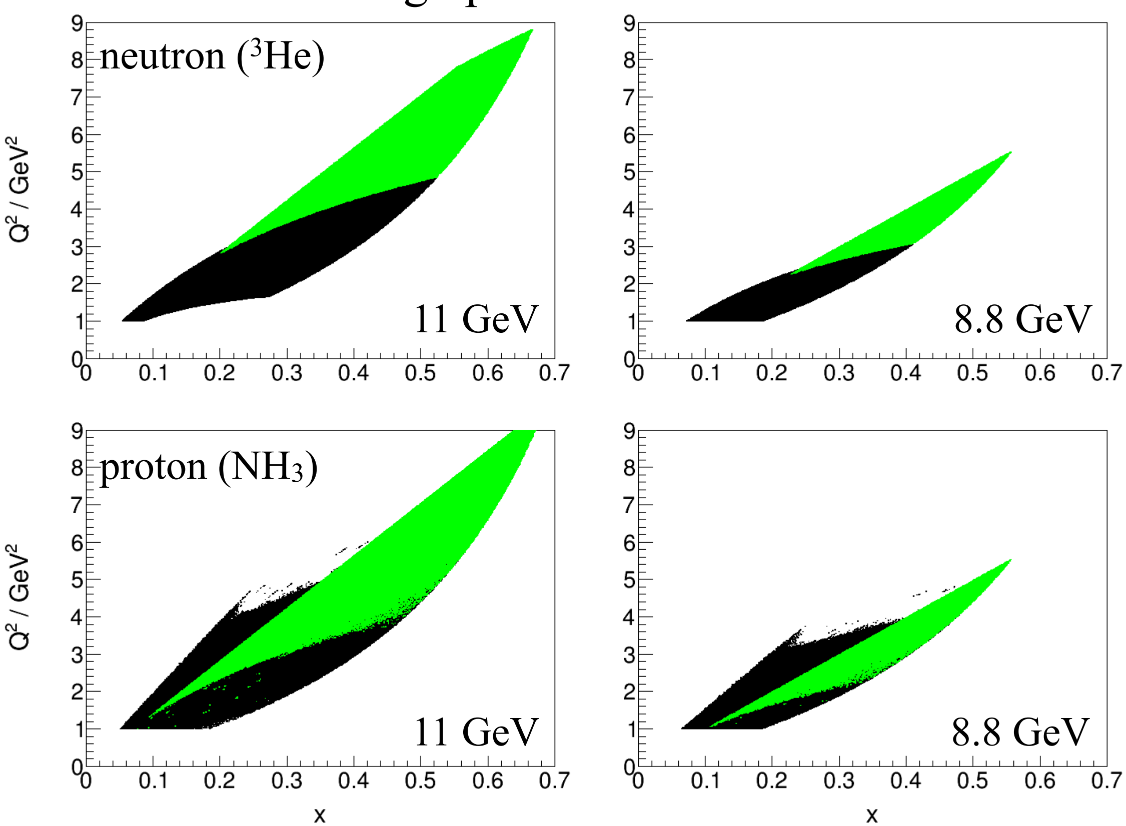
High statistics (example)

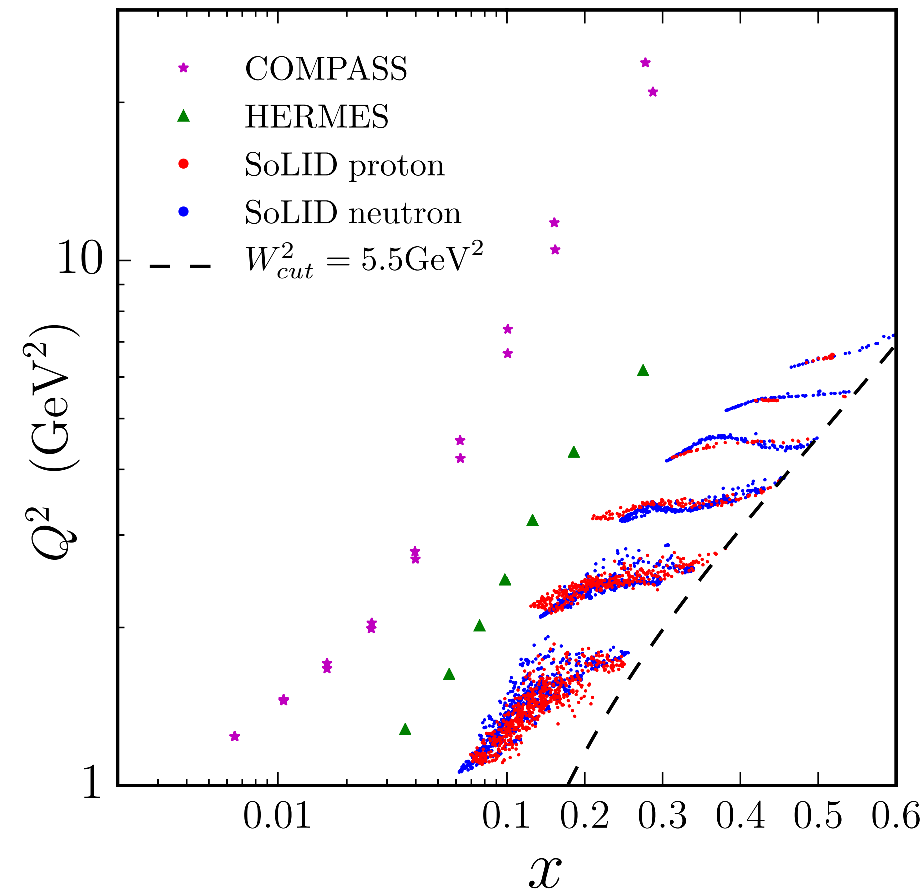


Projected data of E12-10-006

SIDIS @ SoLID

- Electron beam: 11GeV and 8.8 GeV
- Targets: neutron (^{3}He) and proton (NH_3)
- Luminosity: ~ 10^{36} n cm^{-2} s^{-1}, 10^{35} p cm^{-2} s^{-1}
- Polar angle: 8° ~ 24°
- Azimuthal angle: full 2π coverage
- In beam polarization: ~60% (^{3}He), ~70% (NH_3)
- 4D bins with high precision

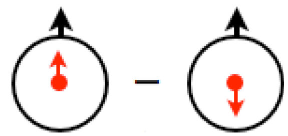




$0.3 < z < 0.7$
$W' > 1.6$ GeV
$Q^2 > 1.0$ GeV^2

Impact of SoLID: Transversity

Transversity distribution

h_1  (Collinear & TMD)

A transverse counter part to the longitudinal spin structure: helicity g_{1L}, but NOT the same.

- Chiral-odd:

Unique for the quarks, no mixing with gluons, and simpler evolution effect.

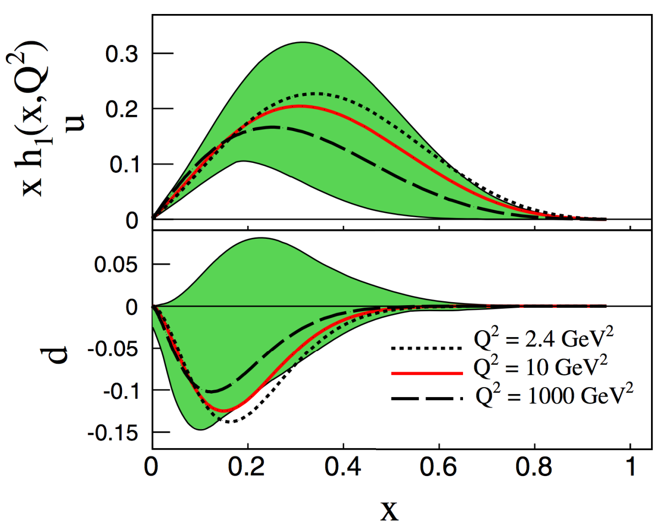
Couple to another chiral-odd function. (*e.g.* Collins function $H_1^{\perp}$)

SIDIS (E12-10-006, E12-11-008), Drell-Yan

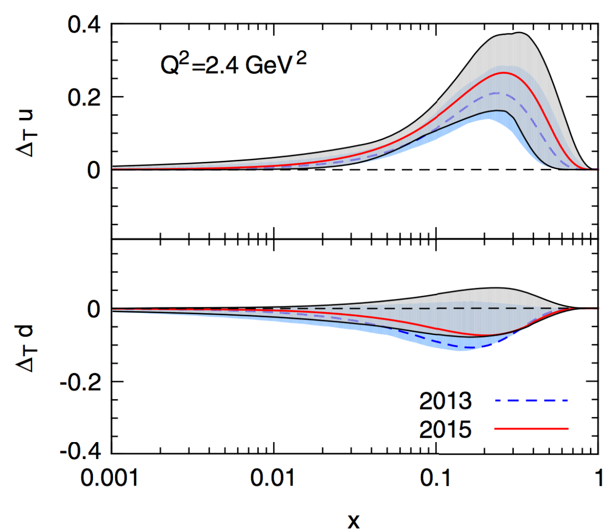
Di-hadron (approved as run group with E12-10-006)

- Collins asymmetry

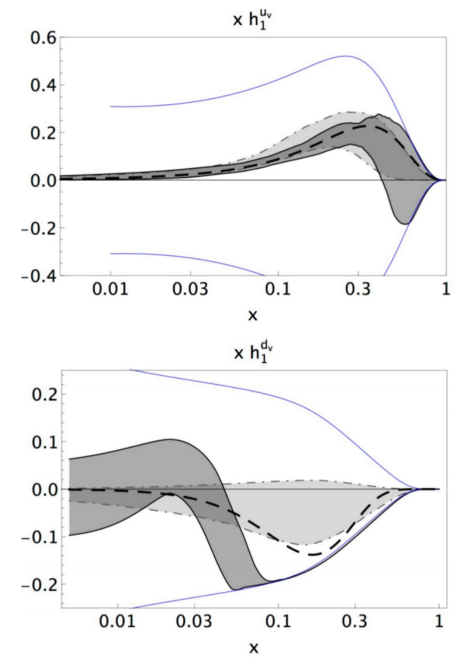
$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1(x, k_\perp) \bigotimes H_1^\perp(z, p_\perp)$$



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



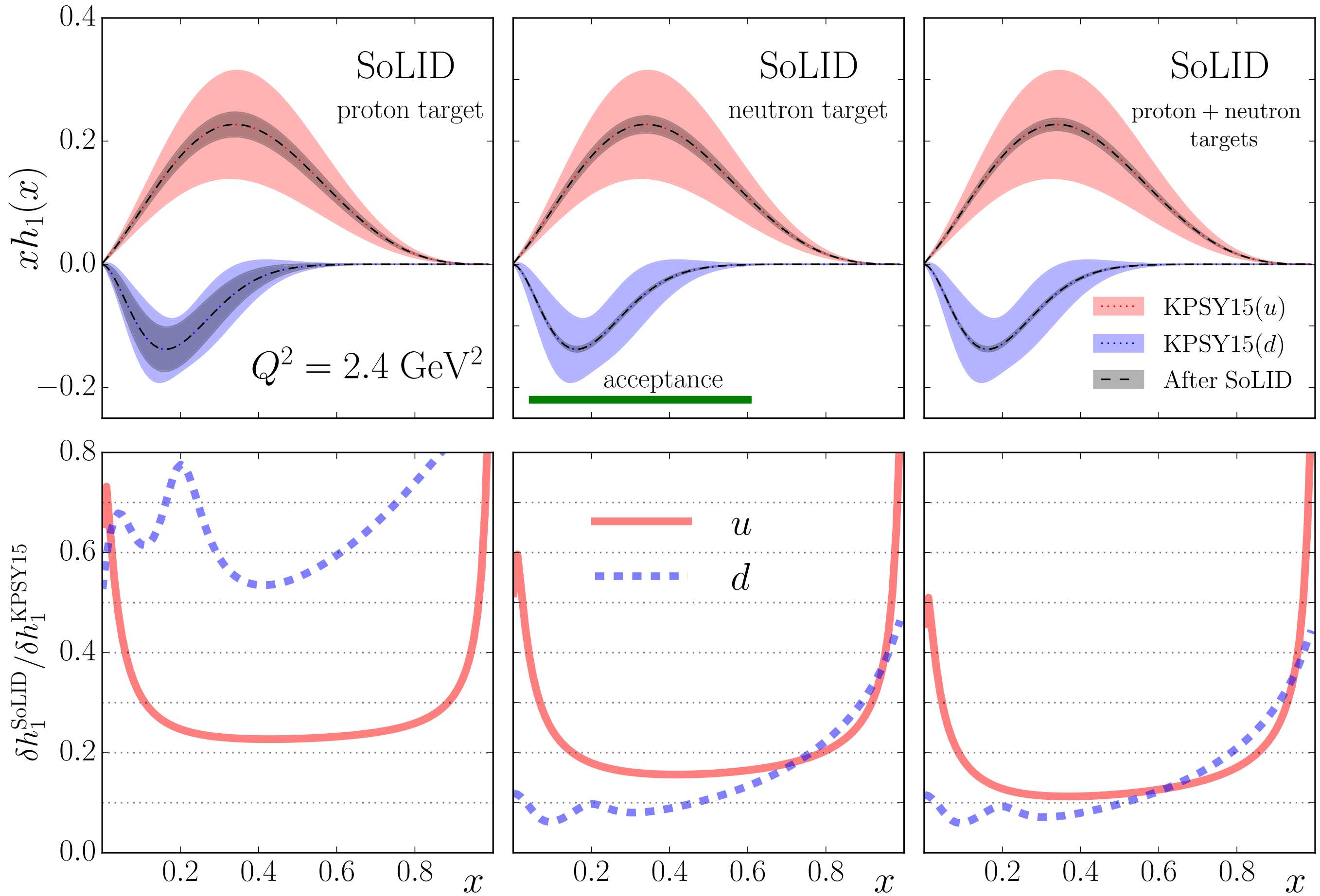
M. Anselmino et al., Phys. Rev. D 92, 114023 (2015).



M. Radici et al., JHEP 05 (2015) 123.

Impact of SoLID: Transversity

The improvement on transversity distributions



- With both statistical and systematic errors
- 1 order of magnitude improvement

Ye, Sato, Allada, TL, Chen, Gao, Kang, Prokudin, Sun, Yuan, Phys. Lett. B 767, 91 (2017).

Impact of SoLID Data: Tensor Charge

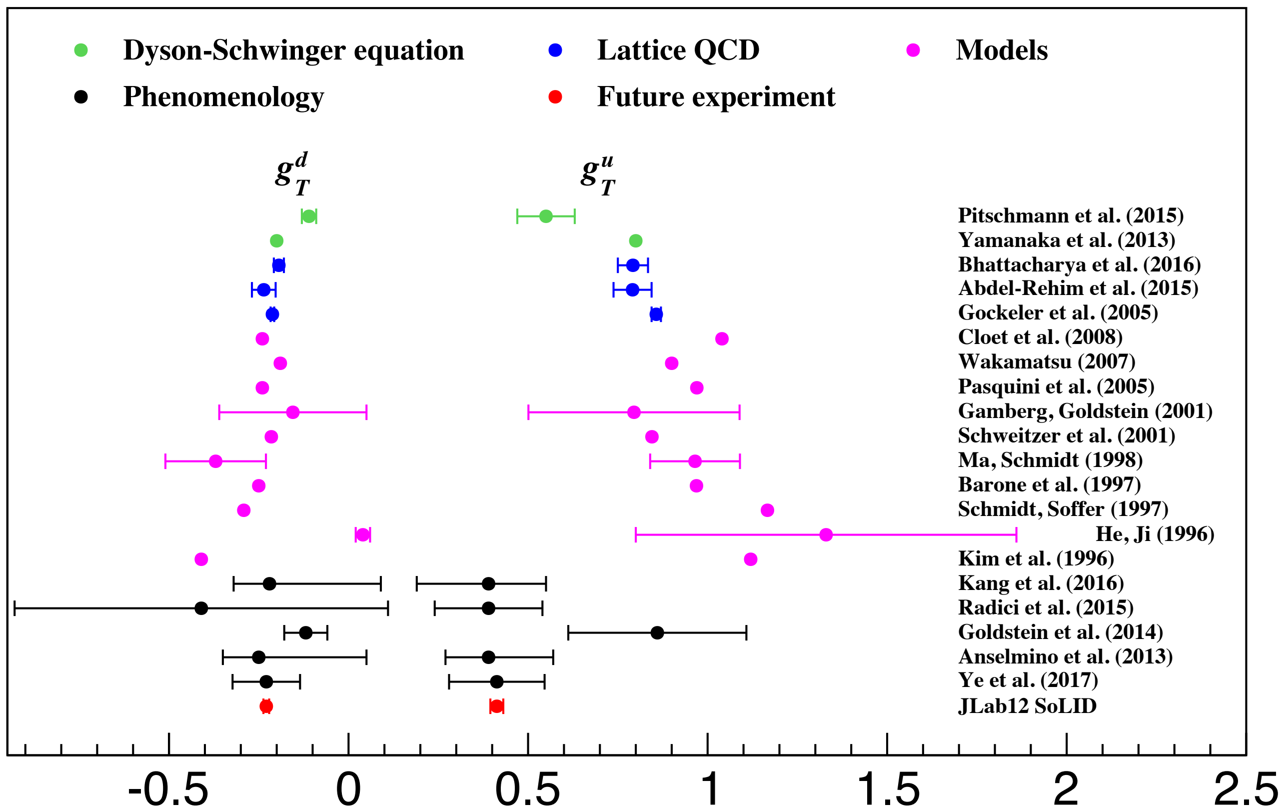
Tensor charge

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

- A fundamental QCD quantity: matrix element of local operators.
- Moment of the transversity distribution: valence quark dominant.
- Calculable in lattice QCD.

SoLID impact

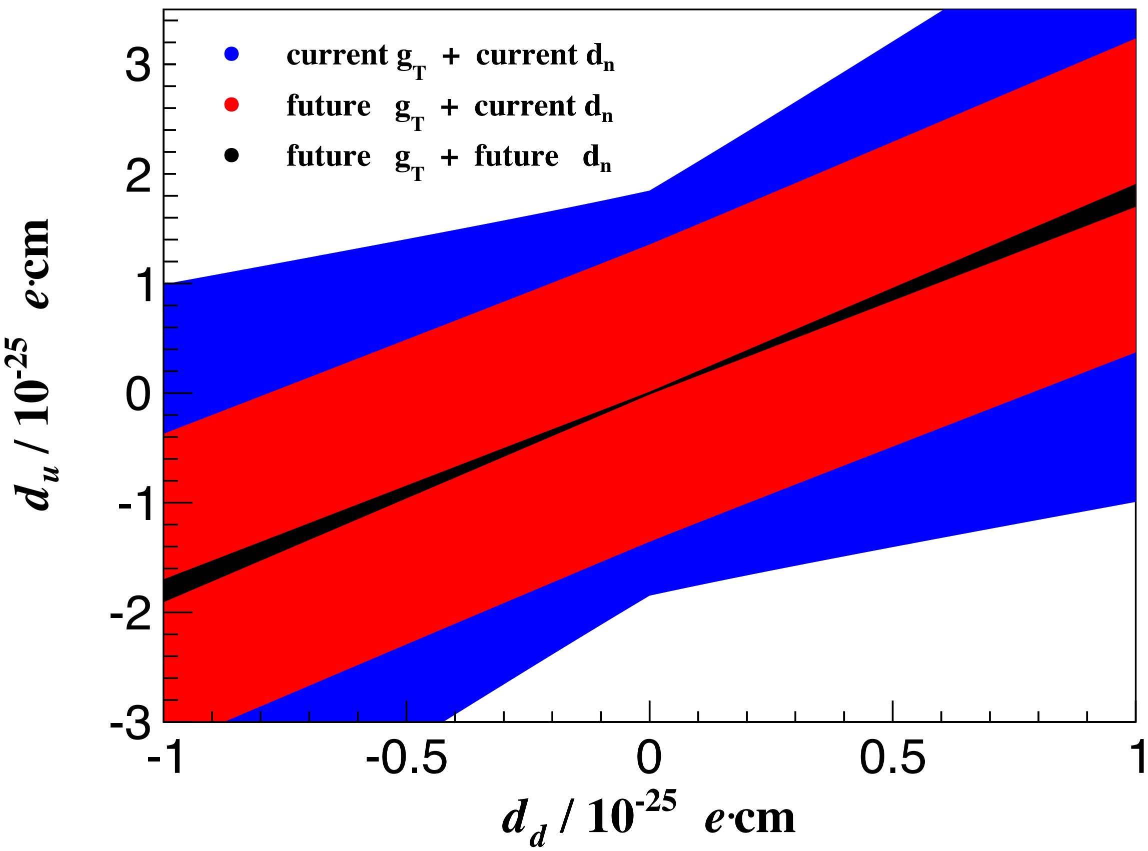
- With both statistical and systematic errors
- 1 order of magnitude improvement



Tensor Charge and Neutron EDM

Electric **D**ipole **M**oment

Tensor charge and nEDM

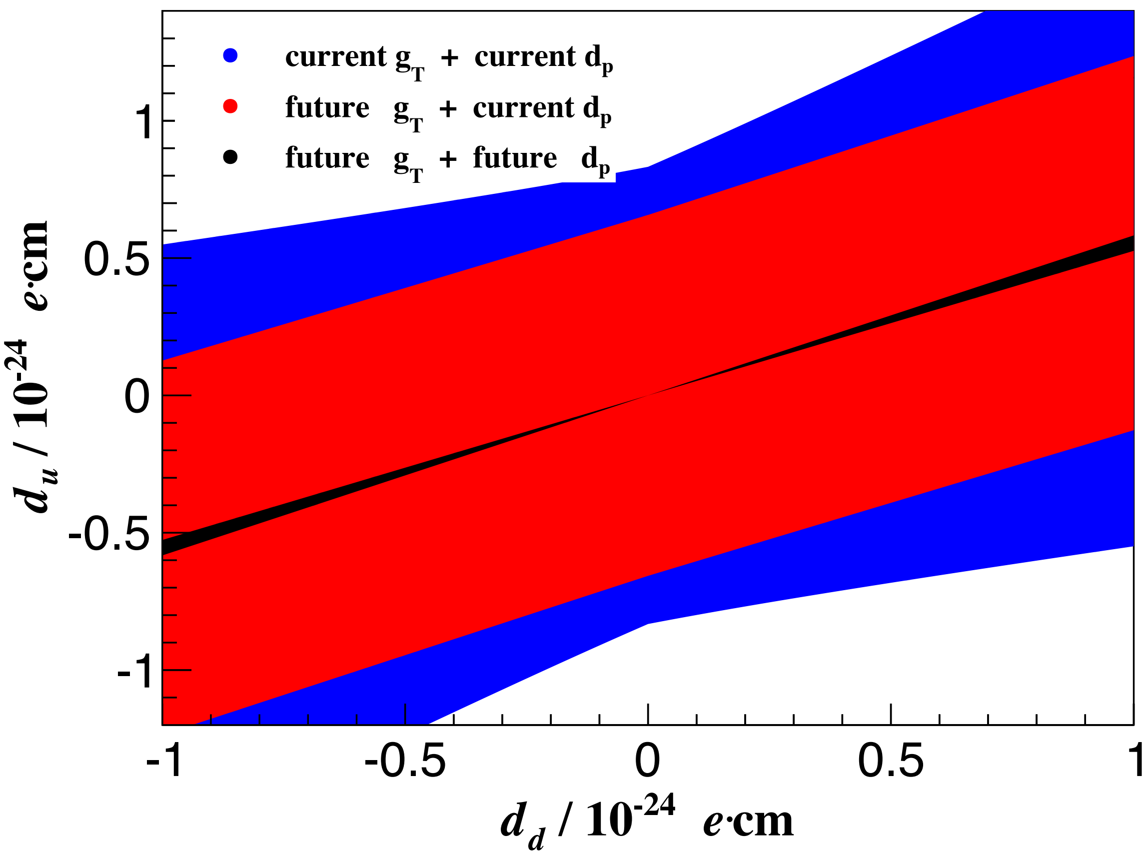


- Current neutron EDM limit: 3.0×10^{-26} e cm, J.M.Pendlebury *et al.*, Phys. Rev. D 92, 092003 (2015).
- Future neutron EDM experiments are expected to have the sensitivity of 10^{-28} e cm.

H. Gao, TL, Z. Zhao, arXiv:1704.00113.

Tensor Charge and Proton EDM

Tensor charge and pEDM

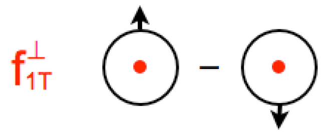


- Current proton EDM limit: 2.6×10^{-25} e cm derived from mercury EDM.
- Future storage ring proton EDM experiment is expected to have the sensitivity of 10^{-29} e cm.

H. Gao, TL, Z. Zhao, arXiv:1704.00113.

Sivers Distribution

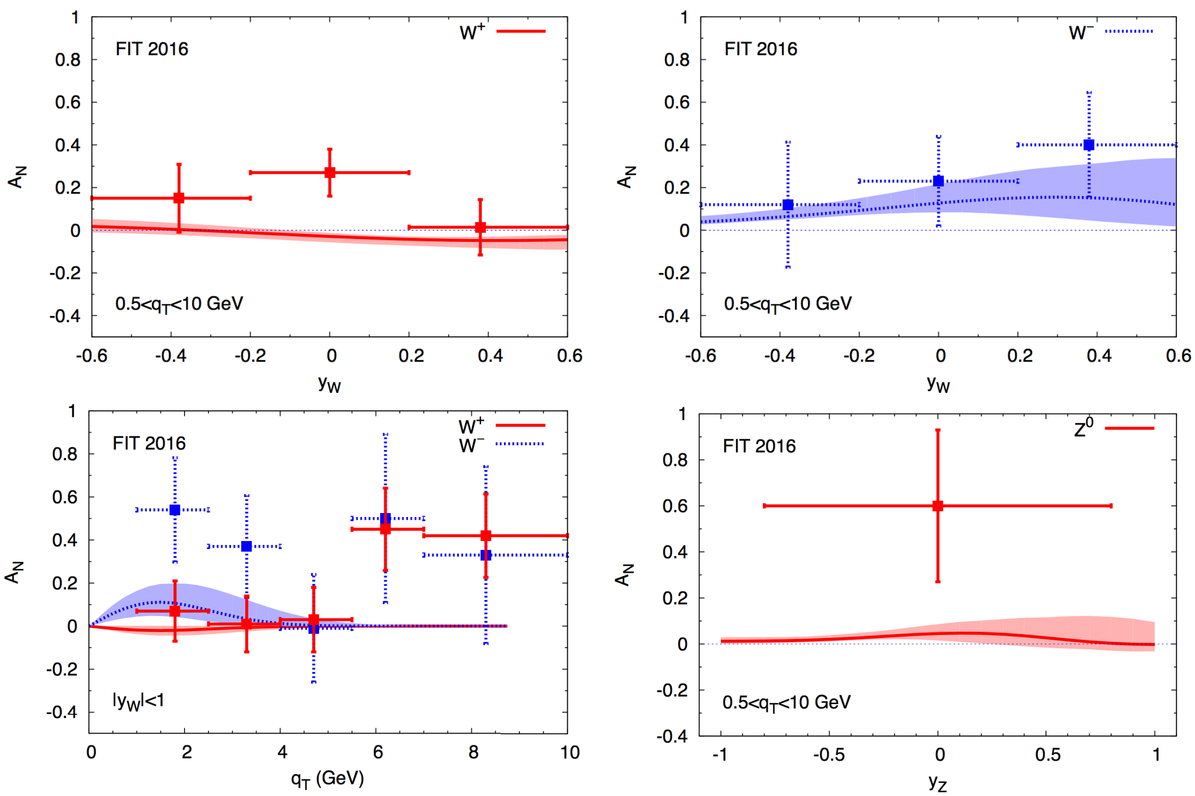
Sivers distribution

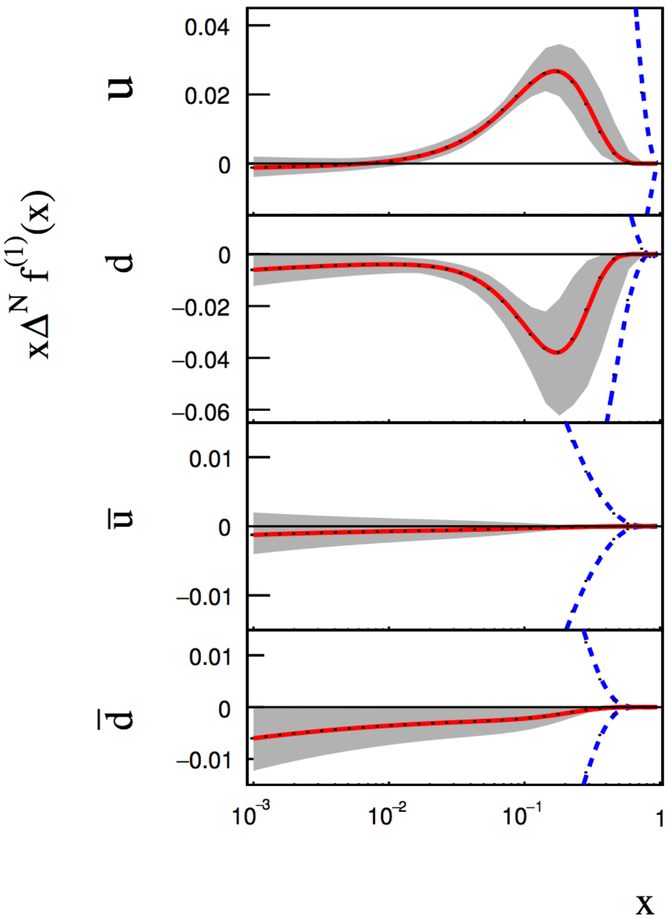


naively time-reversal odd.

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

Test the sigh change

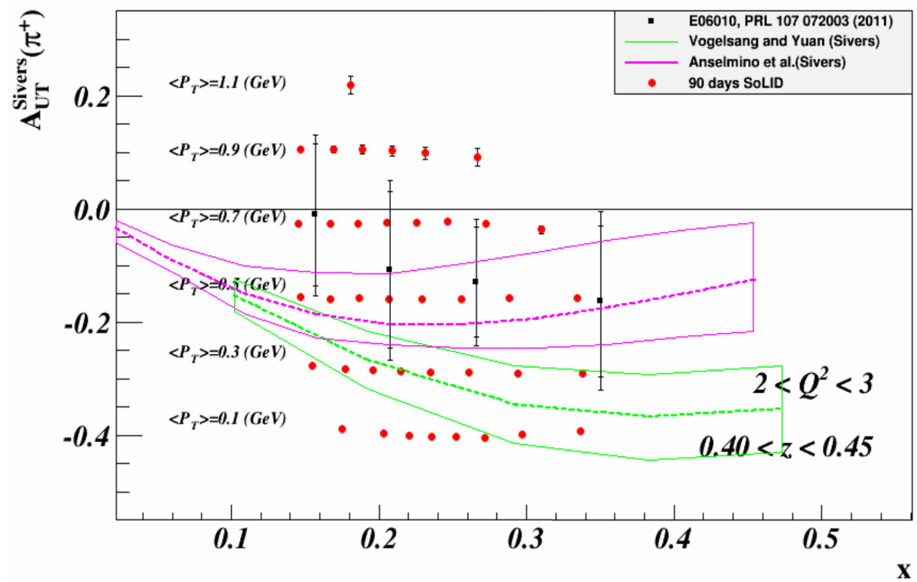




M. Anselmino, M. Boglione, U. D'Alesio, F. Murgia, A. Prokudin, JHEP 04 (2017) 046.

Impact of SoLID: Sivers

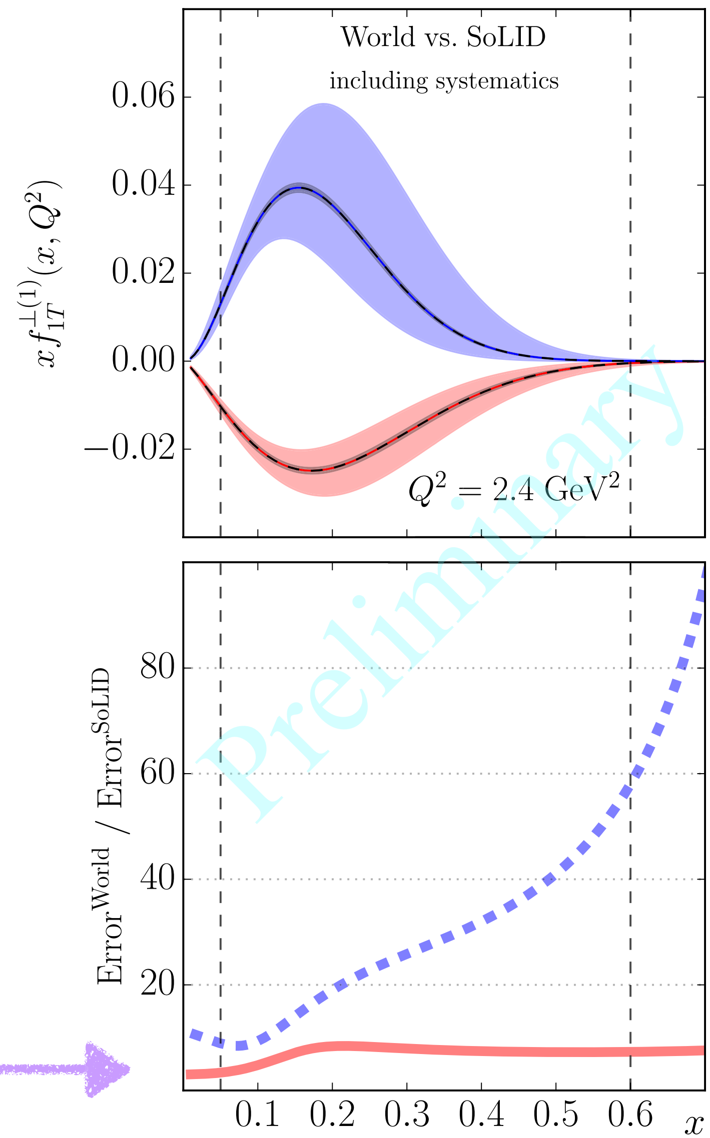
Projected data (example)



Simultaneously fit to unpolarized and polarized data

- HERMES multiplicity data
- COMPASS, HERMES, JLab single spin asymmetry data

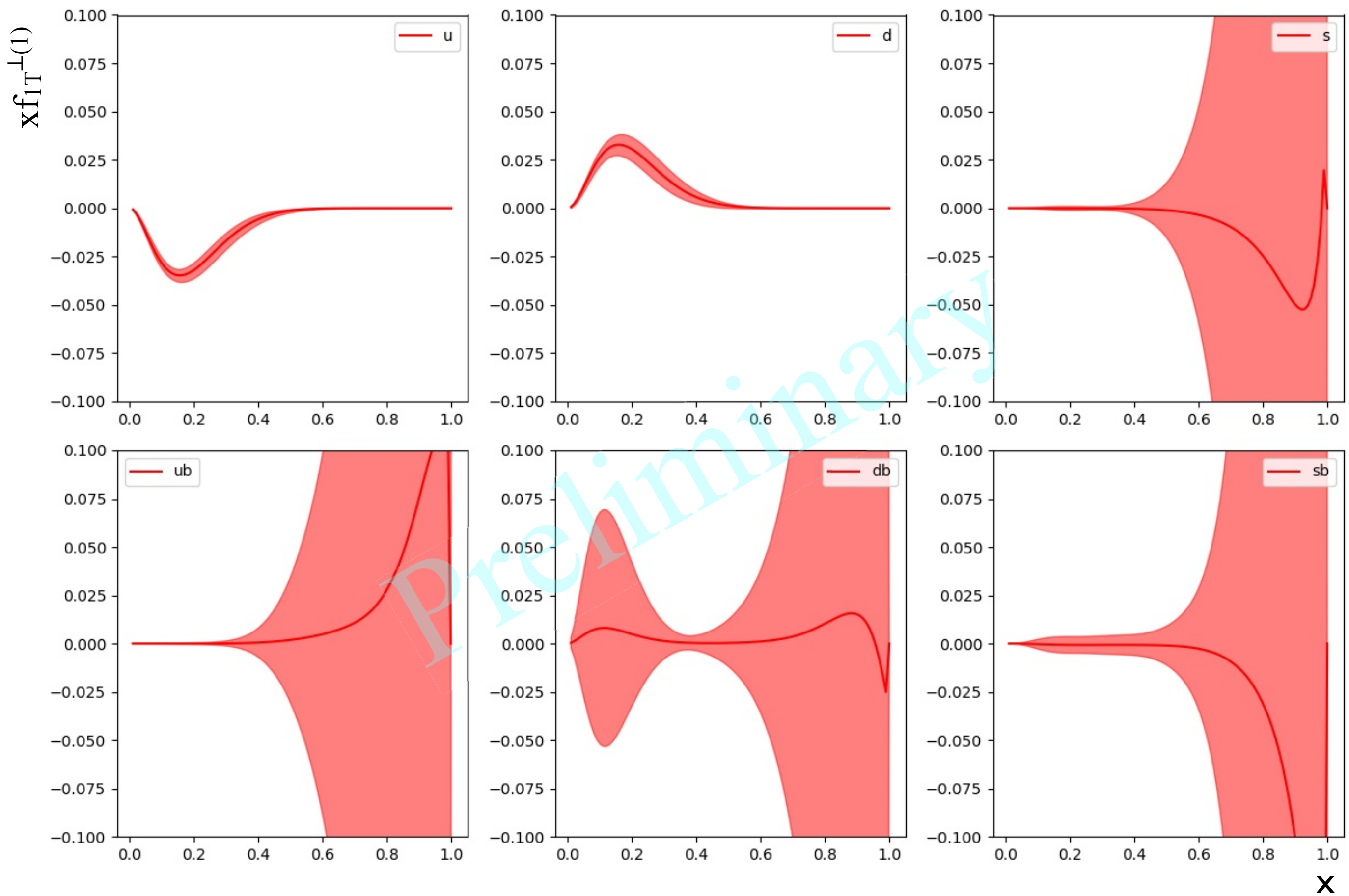
preliminary result with a single fit



On-going with N.Sato, A. Prokudin, W. Melnitchouk, Z. Ye, K. Allada, H. Gao, J.-P. Chen.

Monte Carlo Sampling

Preliminary result with the nested sampling. http://kylebarbary.com/nestle/



On-going with N.Sato, A. Prokudin, W. Melnitchouk, Z. Ye, K. Allada, H. Gao, J.-P. Chen.

Summary

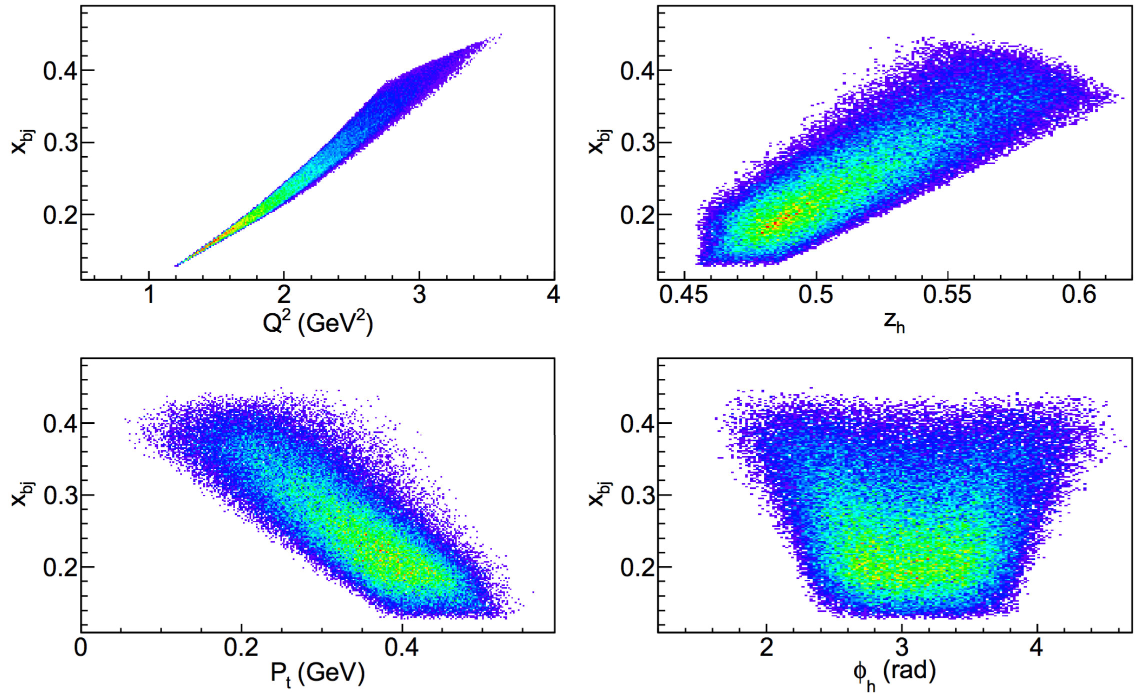
- Lepton scattering is a powerful tool to probe the internal structure of the nucleon.
- Many efforts have been made in JLab 6-GeV SIDIS experiments.
- SIDIS experiments in JLab 12-GeV era, *e.g.* SoLID: high luminosity and large acceptance, multidimensional mapping with high precision.
- Transversity as an example: SoLID experiment will improve the precision by one order of magnitude.
- New physics: tensor charge together with next generation EDM experiments.
- Sivers as an example (ongoing): simultaneously fit to unpolarized and polarized data.

Thank you!

Backup

Differential Cross Section Analysis

Kinematics

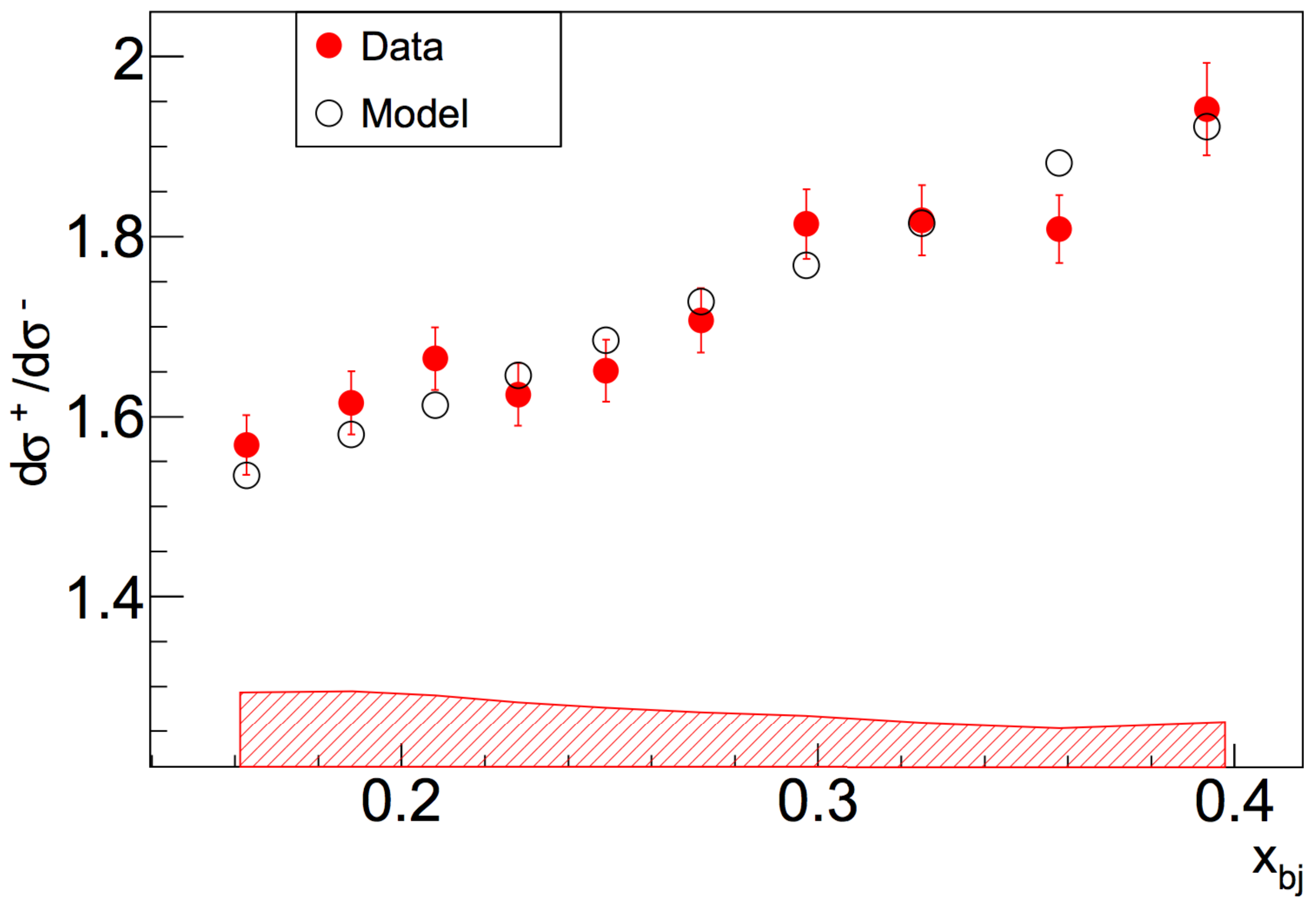


Systematic uncertainties:

Source	Range (%)
e^- identification in BigBite	2.0-8.0
e^- tracking efficiency in BigBite	<3.0
$\pi^\pm$ identification in the HRS	<2.0
Experimental acceptance corrections	5.0-10.0
Radiative corrections	1.0-3.5
Exclusive tail subtractions	1.0-3.0
Bin-centering corrections	<3.0

X. Yan *et al.*, Phys. Rev. C 95, 035209 (2017).

Differential Cross Section Ratio



X. Yan *et al.*, Phys. Rev. C 95, 035209 (2017).

Tensor Charge Improvement by SoLID

observable	$Q^2(\mathrm{GeV}^2)$	KPSY15	δ_{KPSY15}	δ_{SoLID}	$\delta_{\mathrm{SoLID}}/\delta_{\mathrm{KPSY15}}(\%)$
$\delta u^{[0,0.05]}$	2.4	0.046	0.010	0.005	49
$\delta u^{[0.05,0.6]}$	2.4	0.349	0.122	0.015	12
$\delta u^{[0.6,1]}$	2.4	0.018	0.007	0.001	14
$\delta u^{[0,1]}$	2.4	0.413	0.133	0.018	14
$\delta u^{[0,0.05]}$	10	0.051	0.011	0.005	46
$\delta u^{[0.05,0.6]}$	10	0.332	0.117	0.014	12
$\delta u^{[0.6,1]}$	10	0.0126	0.0048	0.0007	14
$\delta u^{[0,1]}$	10	0.395	0.128	0.018	14
$\delta d^{[0,0.05]}$	2.4	-0.029	0.028	0.003	10
$\delta d^{[0.05,0.6]}$	2.4	-0.200	0.073	0.006	9
$\delta d^{[0.6,1]}$	2.4	-0.00004	0.00009	0.00001	13
$\delta d^{[0,1]}$	2.4	-0.229	0.094	0.008	9
$\delta d^{[0,0.05]}$	10	-0.035	0.030	0.003	10
$\delta d^{[0.05,0.6]}$	10	-0.184	0.067	0.006	9
$\delta d^{[0.6,1]}$	10	-0.00002	0.00006	0.00001	14
$\delta d^{[0,1]}$	10	-0.219	0.090	0.008	9
$g_T^{(\mathrm{truncated})}$	2.4	0.55	0.14	0.018	13
$g_T^{(\mathrm{full})}$	2.4	0.64	0.15	0.021	14
$g_T^{(\mathrm{truncated})}$	10	0.51	0.13	0.017	13
$g_T^{(\mathrm{full})}$	10	0.61	0.14	0.020	14

Z. Ye, N. Sato, K. Allada, T.L., J.-P. Chen, H. Gao, Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, Phys. Lett. B 767, 91 (2017).

Systematic Uncertainties

Statistical (abs.)	Systematic (abs.)		Systematic (rel.)	
	Raw asymmetry	0.0014	Target polarization	3%
	Detector resolution	< 0.0001	Nuclear effect	$4 \sim 5\%$
			Random coincidence	0.2%
			Radiative correction	$2 \sim 3\%$
			Diffractive meson	3%
0.0067	Total	0.0014	Total	$6 \sim 7\%$

Z. Ye, N. Sato, K. Allada, T.L., J.-P. Chen, H. Gao, Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, Phys. Lett. B 767, 91 (2017).