TMD Program at Jefferson Lab

Chiral Dynamics 2018, Sep. 17-21, 2018

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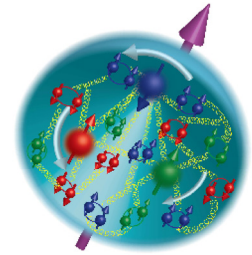
Duke University and Thomas Jefferson National Accelerator Facility

Duke UNIVERSITY

Jefferson Lab

Nucleon Spin Decomposition



Proton spin puzzle

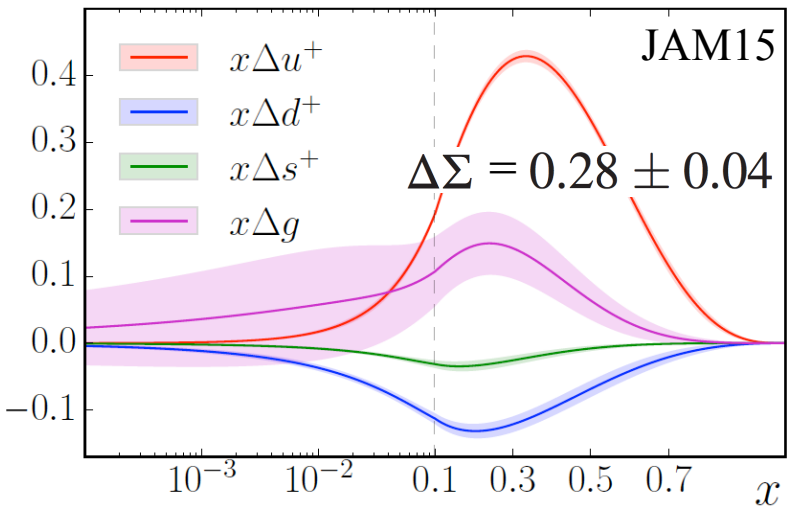
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

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

Spin decomposition

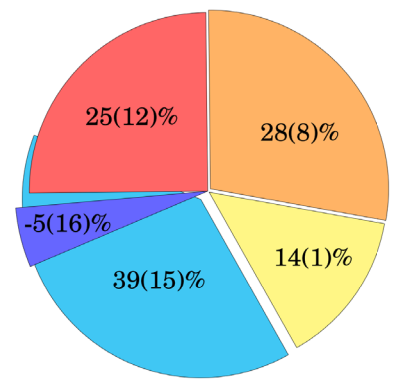
$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



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

JAM17: $\Delta\Sigma = 0.36 \pm 0.09$

JAM Collaboration, PRL 119, 132001 (2017).



Lattice QCD
(kinetic decomposition)

- L^u (CI + DI)
- L^d (CI + DI)
- L^s (DI)
- J^g
- $\frac{\Delta\Sigma}{2}\Big|^{u+d+s}$

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

Gluon spin from LQCD: $S_g = 0.251(47)(16)$

50% of total proton spin

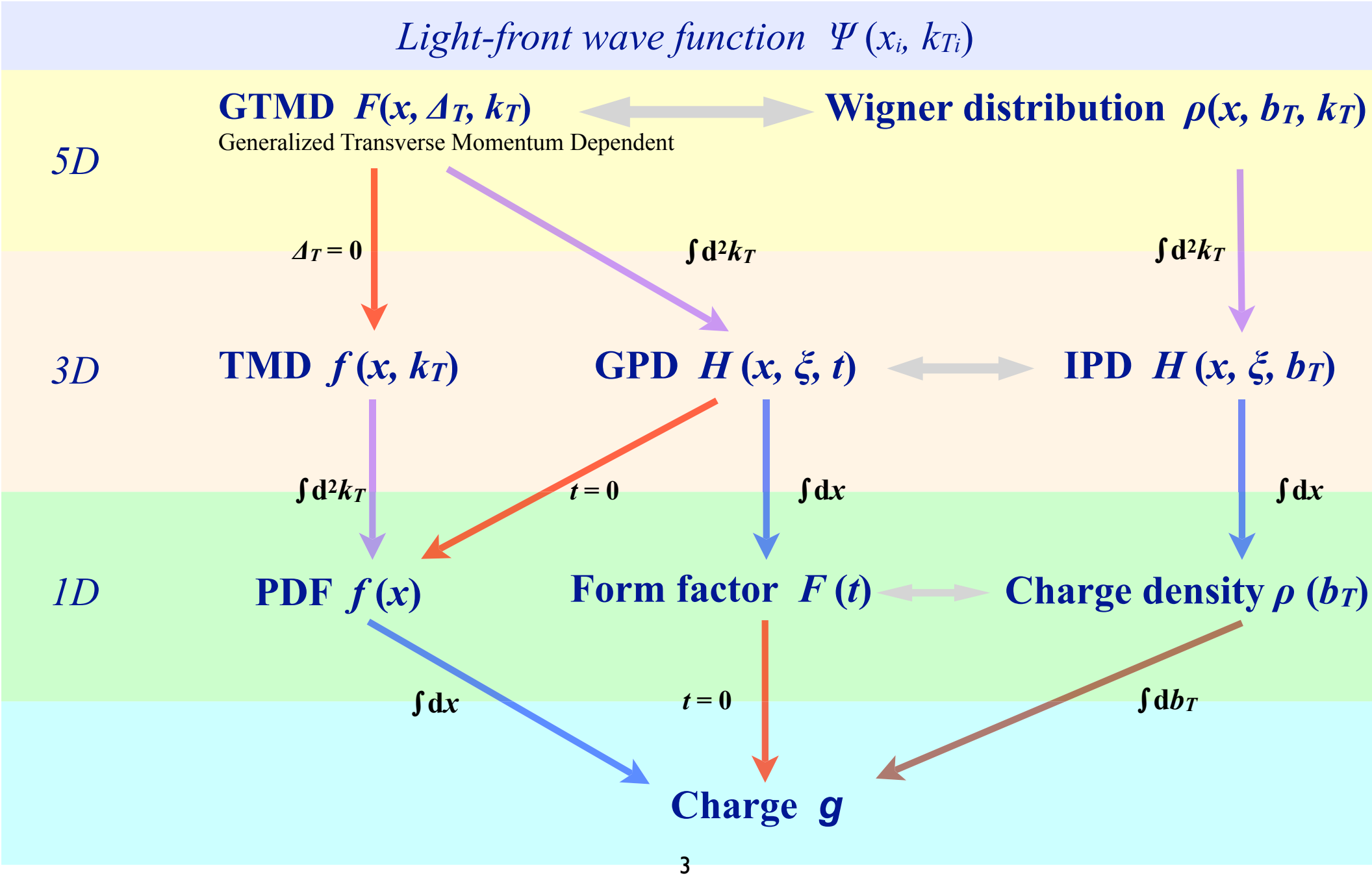
Y.-B. Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017).

Access to $L_{q/g}$

It is necessary to have transverse information.

3*D* imaging of the nucleon.

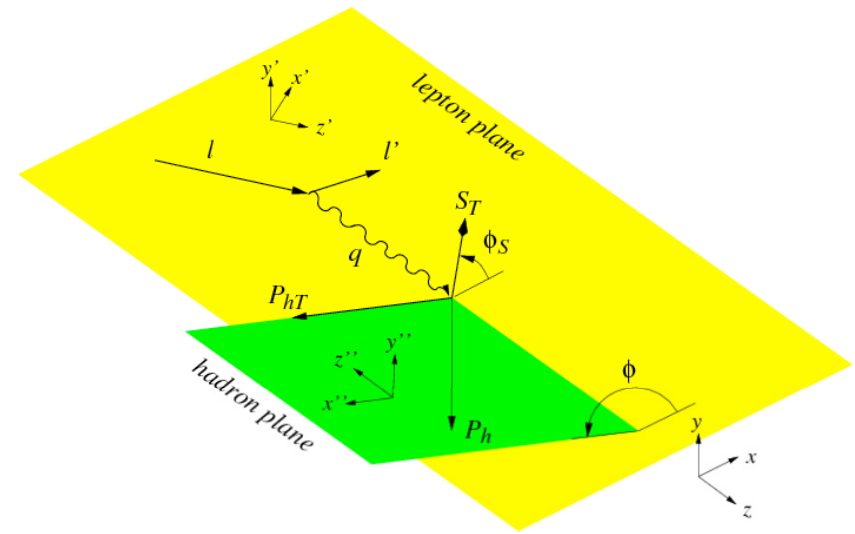
Unified View of Nucleon Structure



Structure Functions

SIDIS differential cross section

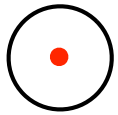
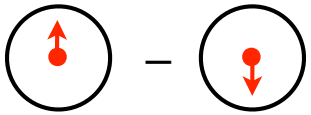
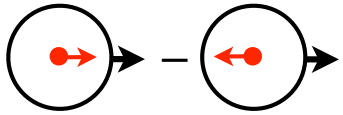
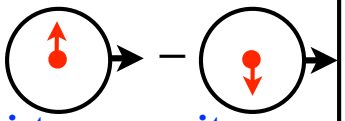
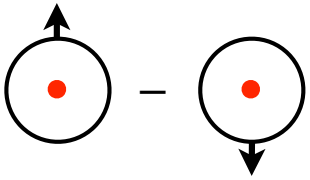
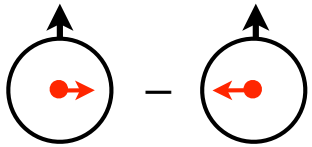
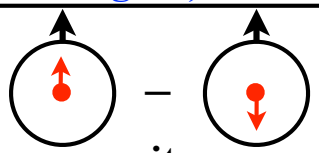
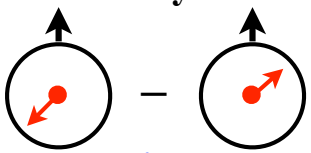
18 structure functions $F(x, z, Q^2, P_T)$,
model independent. (one photon exchange approximation)



[Diehl&Sapeta EPJC2005]

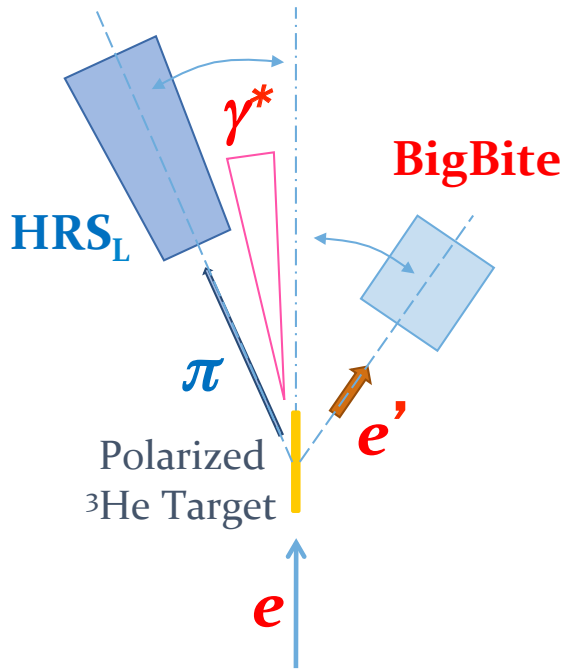
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\psi} \\
&= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
&\times \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos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

Leading Twist TMDs

Nucleon Polarization	Quark Polarization: U	Quark Polarization: L	Quark Polarization: T
U	f_1  **unpolarized**		$h_1^\perp$  **Boer-Mulders**
L		g_{1L}  **helicity**	$h_{1L}^\perp$  **longi-transversity (worm-gear)**
T	$f_{1T}^\perp$  **Sivers**	g_{1T}  **trans-helicity (worm-gear)**	h_1  **transversity** $h_{1T}^\perp$  **pretzelosity**

SIDIS Experiment @ JLab-6GeV

E06-010 @ Hall A

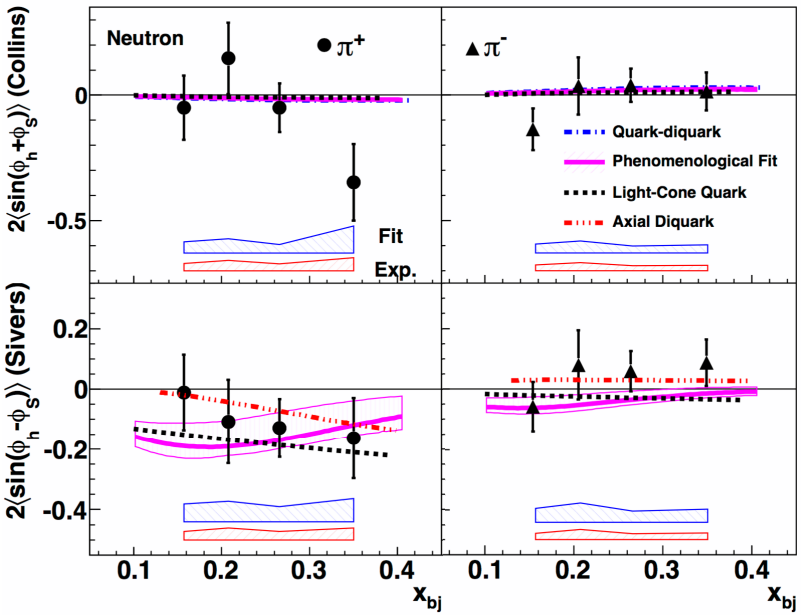


- First neutron data in SIDIS
- Electron beam energy: 5.9 GeV
  Average current: 12μA
- 40cm transversely polarized ^{3}He target
  Average polarization: 55.4 ± 2.8%
- BigBite at 30° as **electron** arm
  scattered electron momentum 0.6~2.5 GeV/c
- HRS at 16° as **hadron** arm
  hadron momentum ~ 2.35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

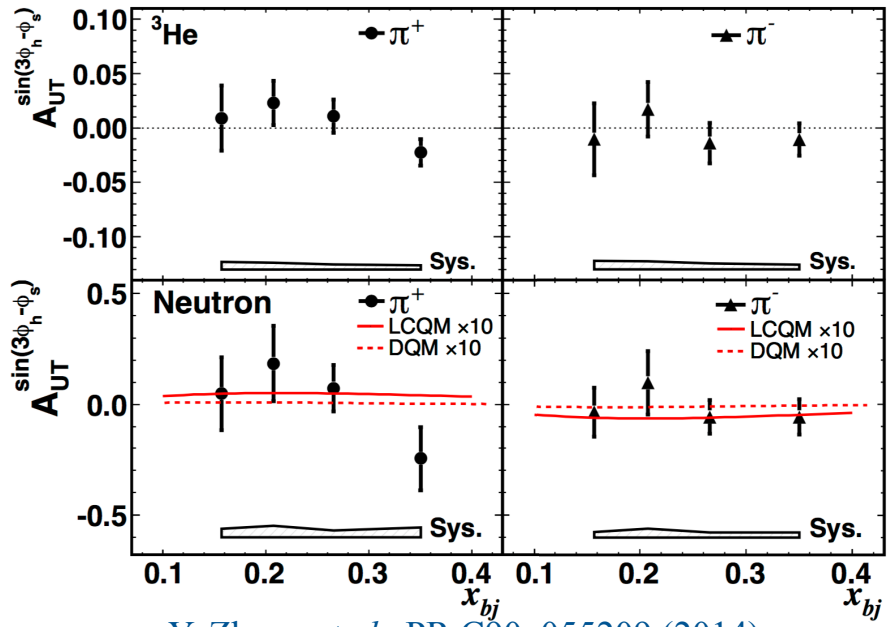
Published results from E06-010:

- 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).

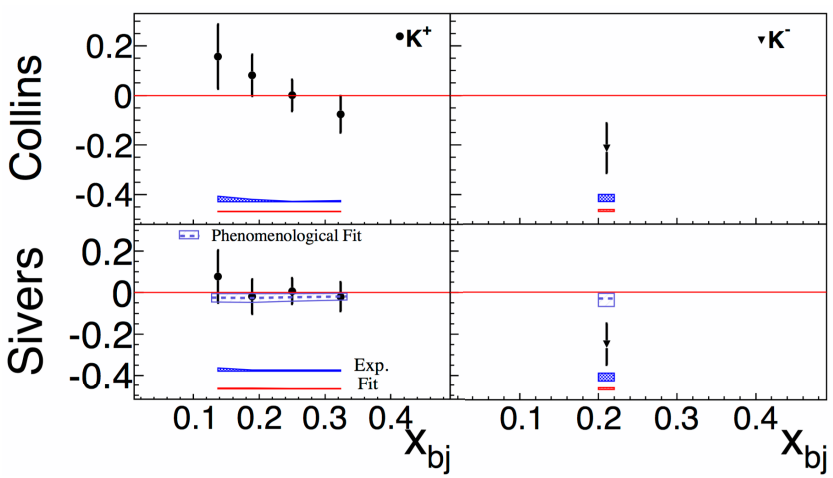
SIDIS SSA/DSA Results from E06-010



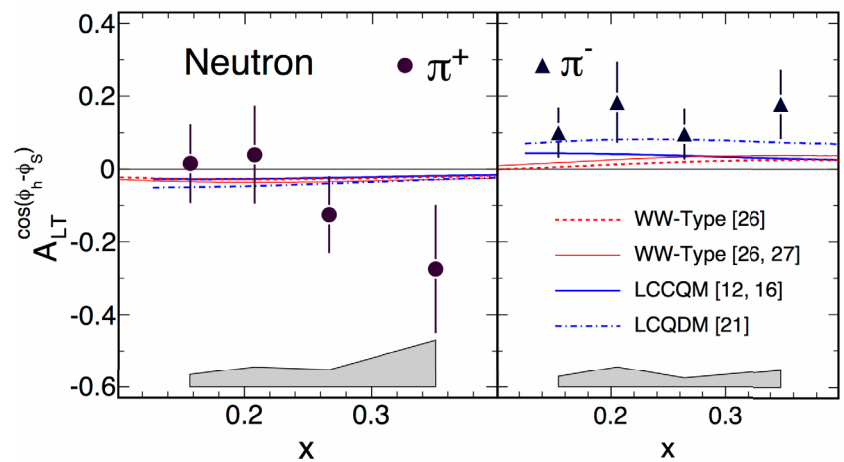
X. Qian *et al.*, PRL 107, 072003 (2011).



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



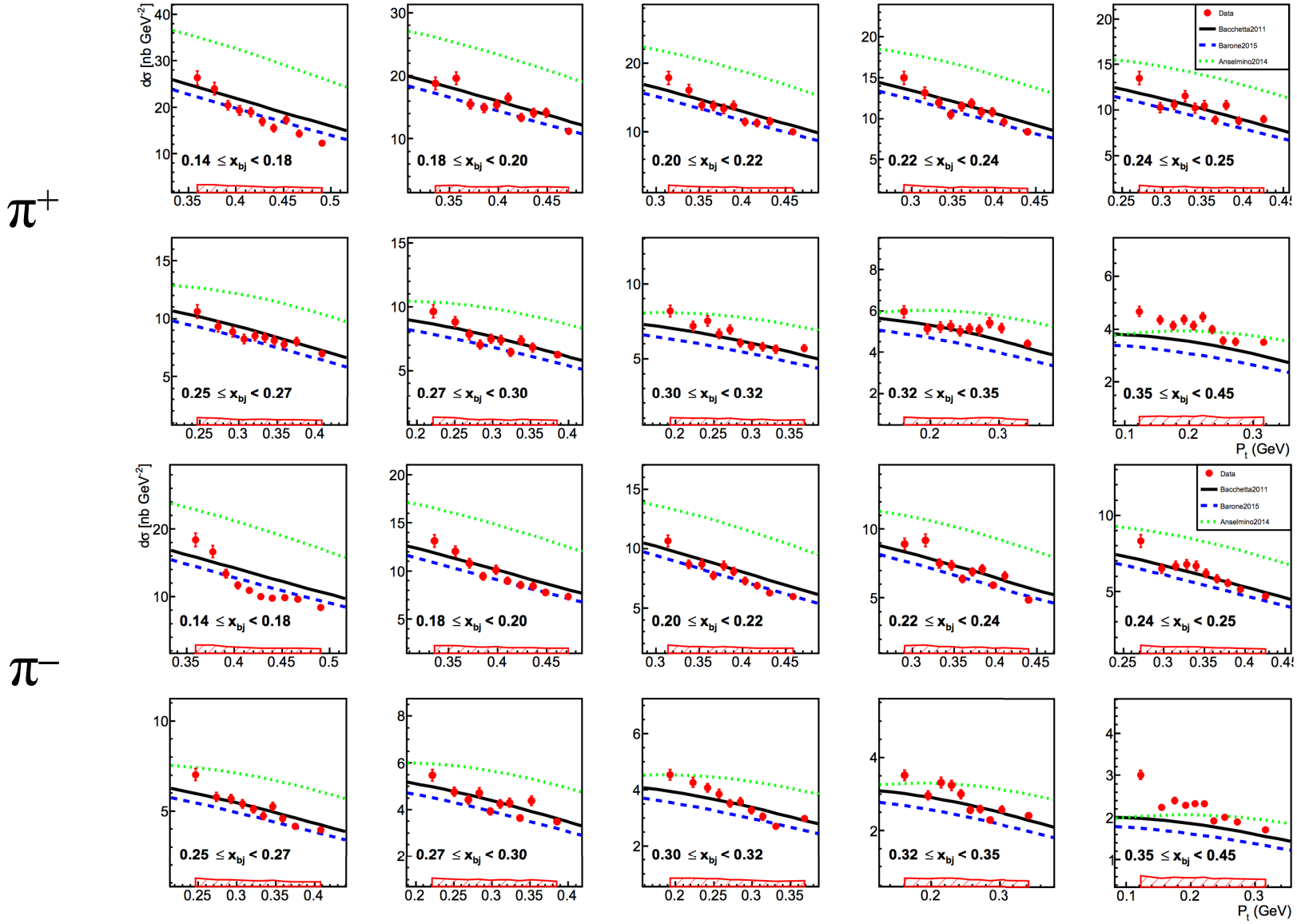
Y.X. Zhao *et al.*, PR C90, 055201 (2014).



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

SIDIS Cross Section from E06-010

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

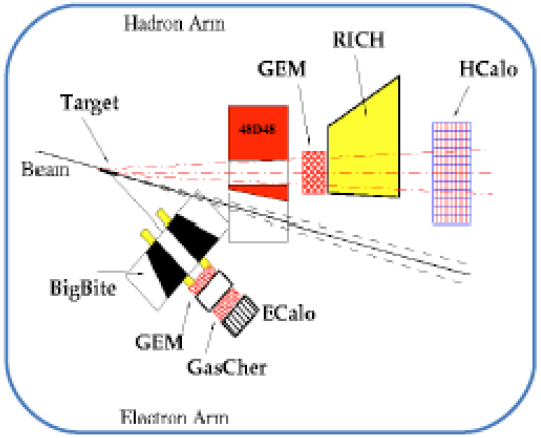


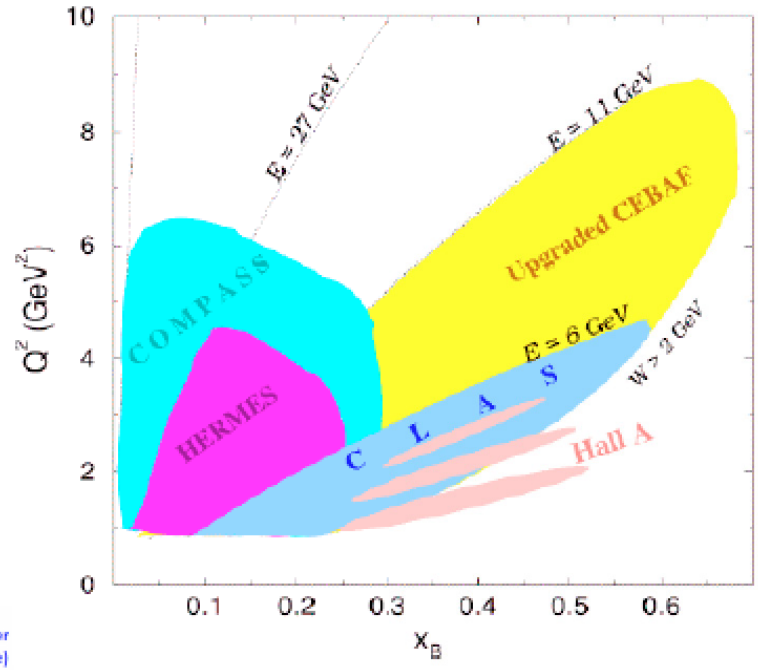
X. Yan *et al.*, Phys. Rev. C 95, 035209 (2017).

10 [x bins] × 10 [P_T bins]

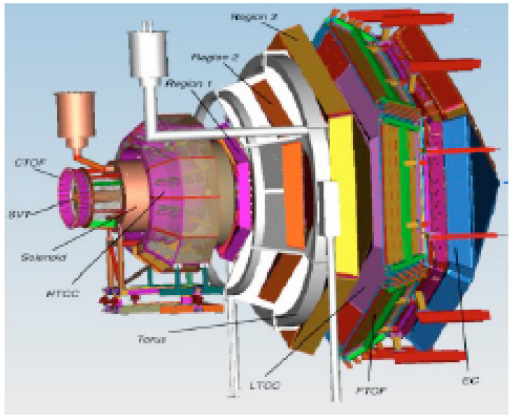
Multi-Hall SIDIS Program @ JLab-12

Hall A: Super BigBite
SIDIS with ^{3}He, high x, Q^2

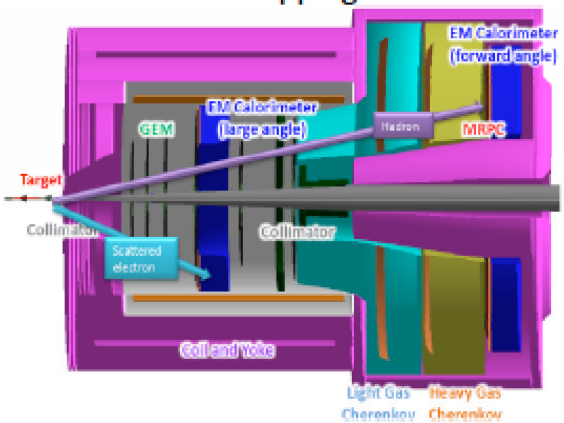




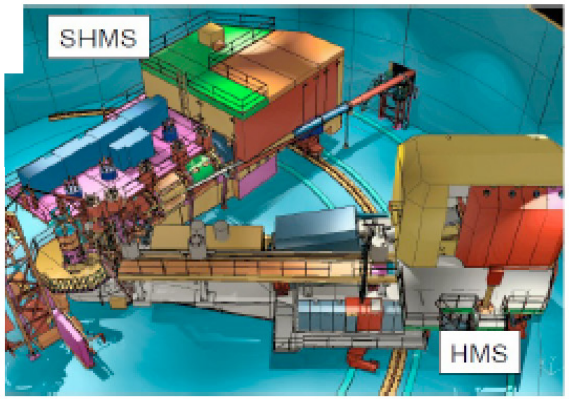
Hall B: CLAS12
SIDIS with polarized H/D
Comprehensive SIDIS program



Hall A: SoLID
SIDIS with polarized ^{3}He/NH_3
Precision 4D mapping

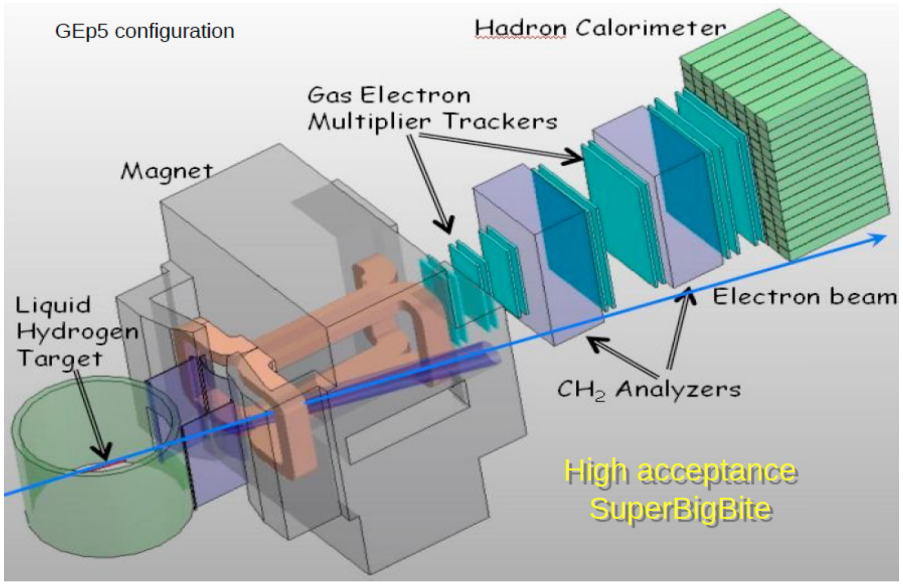


Hall C: SHMS
SIDIS with unpolarized H/D



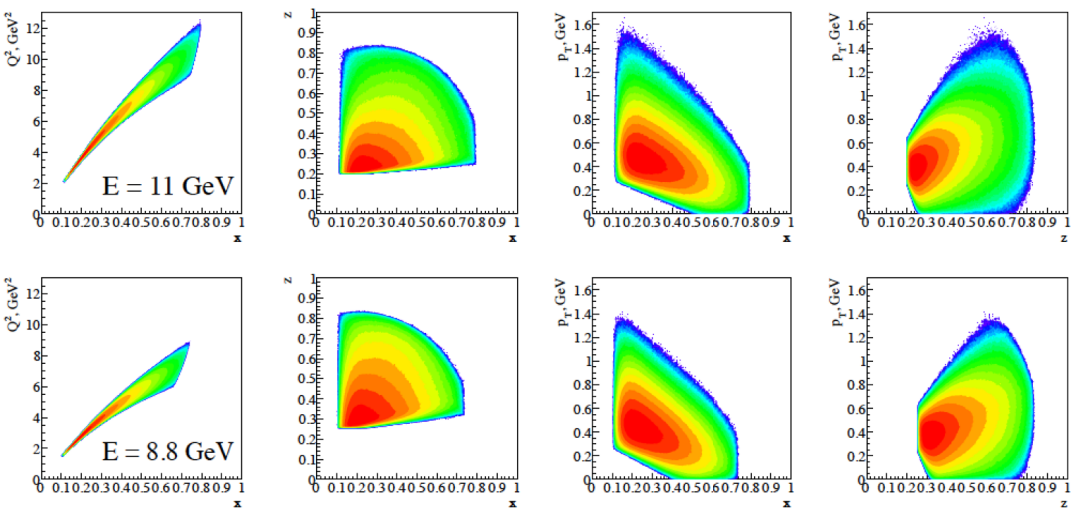
SBS SIDIS Program

SuperBigbite Spectrometer

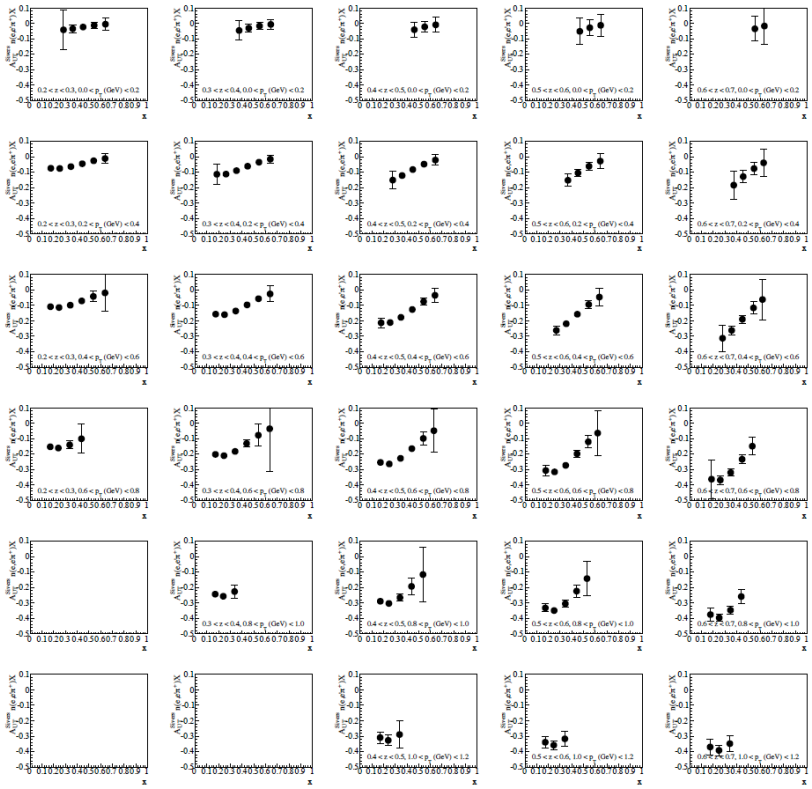


E12-09-018: 64 days

neutron (^{3}He) target

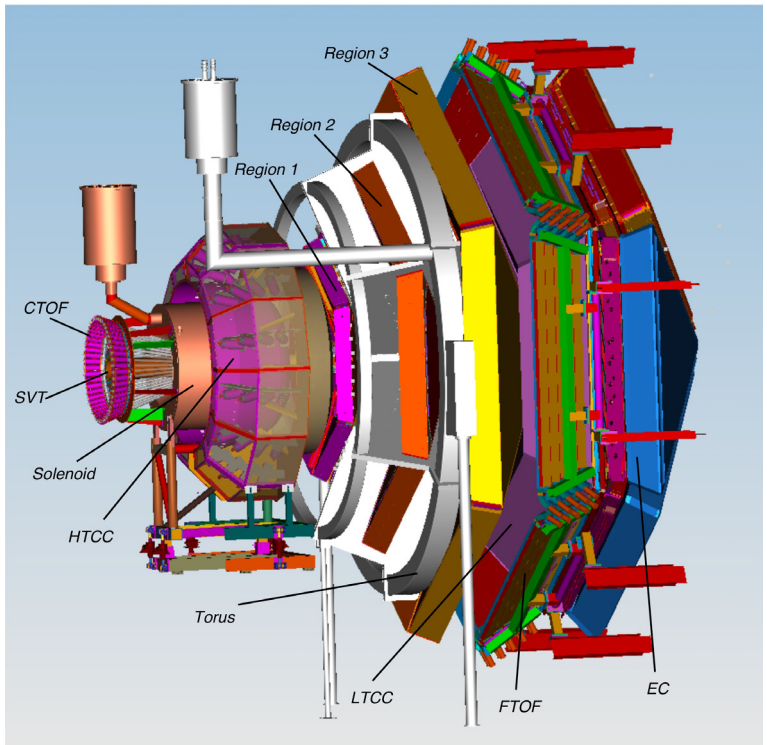


3D mapping example



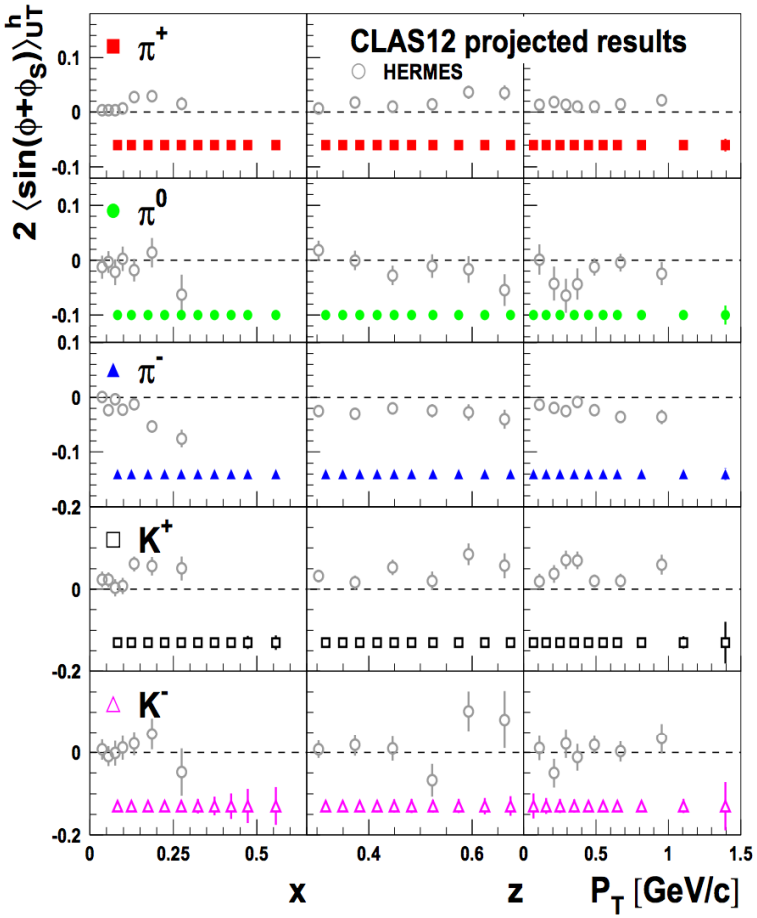
Projected data of E12-09-018

CLAS12 SIDIS Program

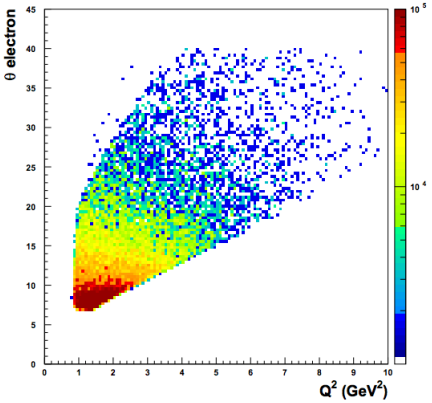


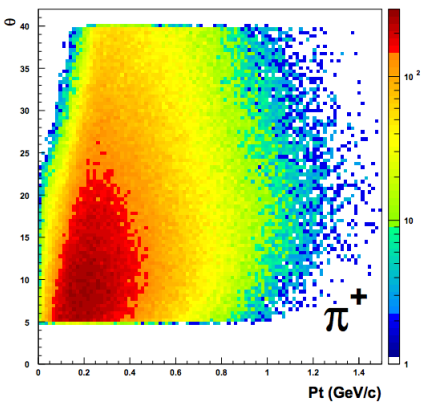
E12-09-007, E12-09-008
E12-09-009, E12-07-107
NH_3 and ND_3 targets

C12-11-111, HDice target



Projected data of C12-11-111





Hall C SIDIS Program (typ. $x/Q^2 \sim$ constant)

[R. Ent, DIS2016]

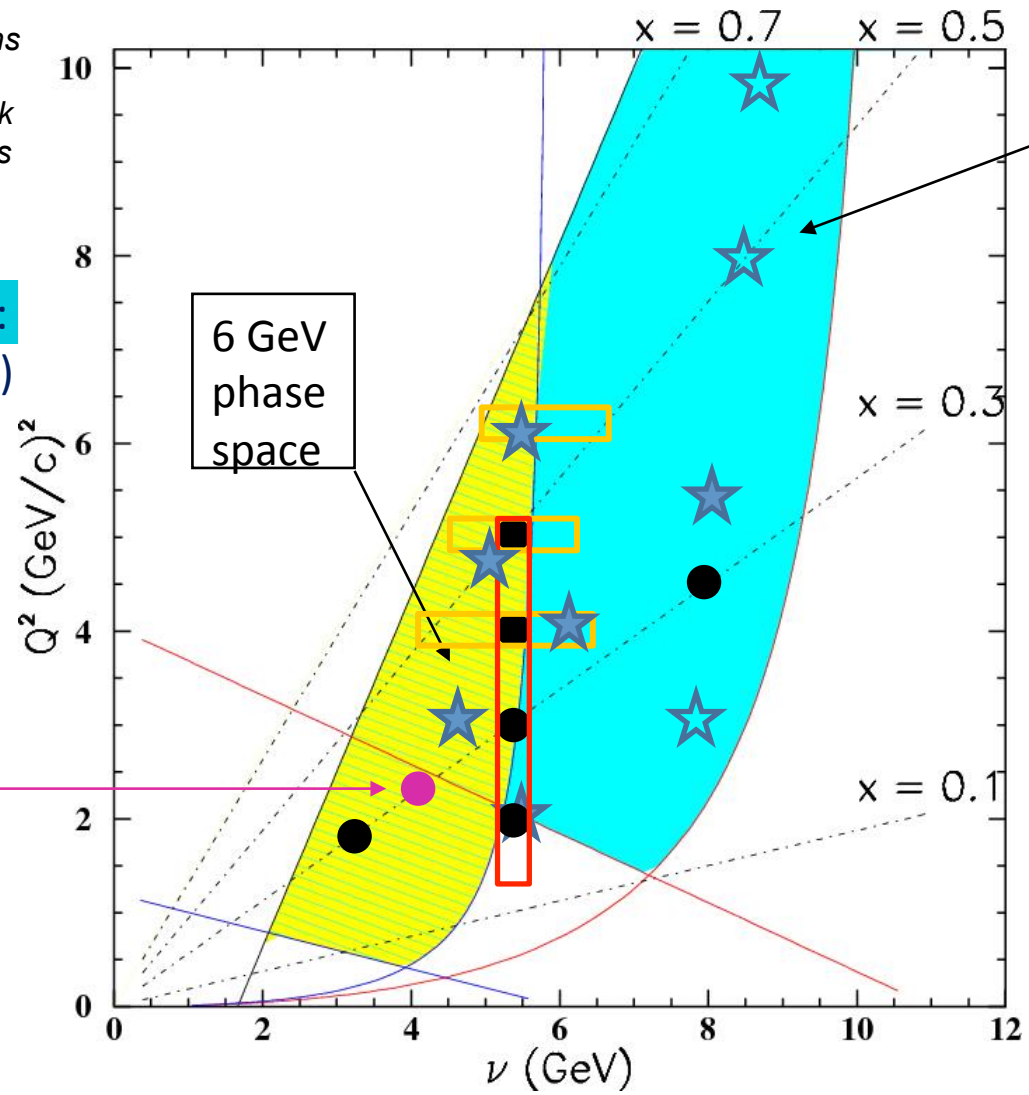
HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

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:

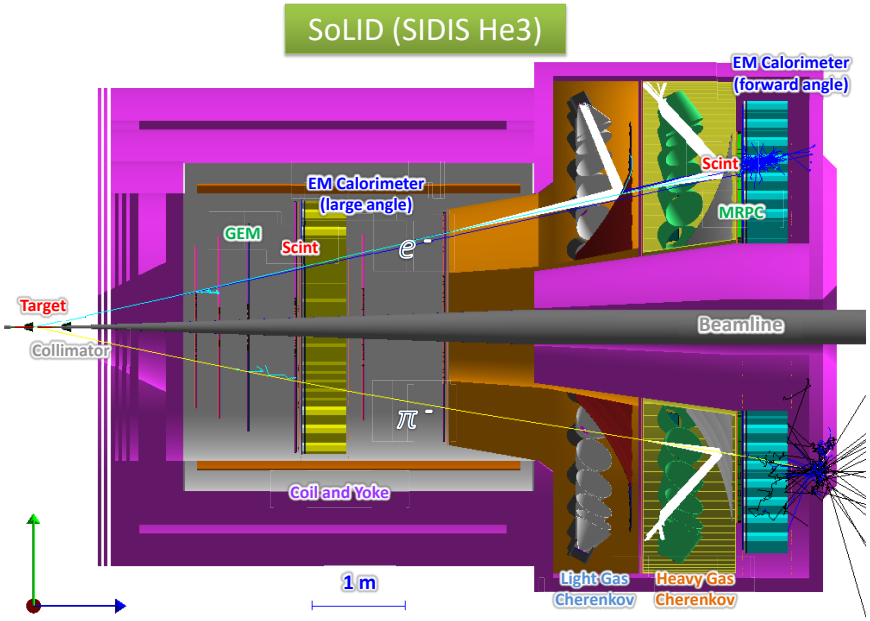
E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

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

E12-09-002
+ scans in z

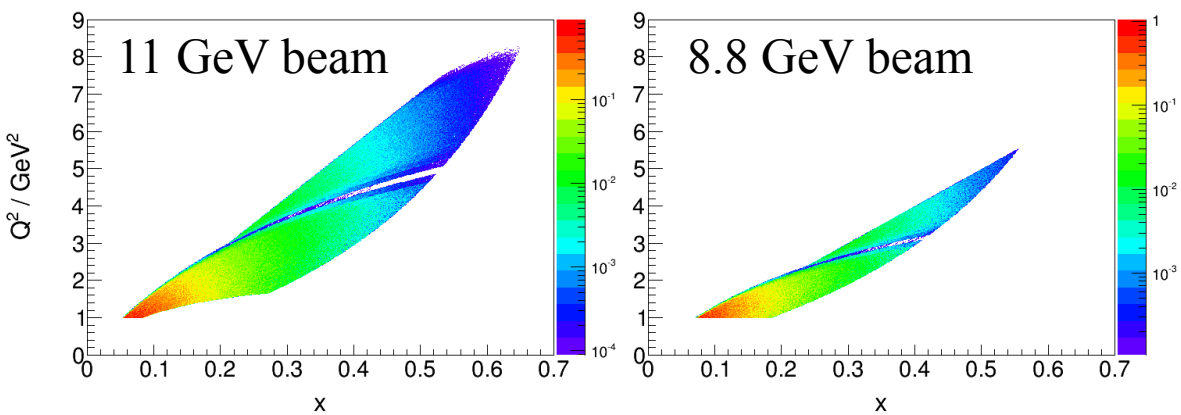
SoLID SIDIS Program

Solenoidal Large Intensity Device

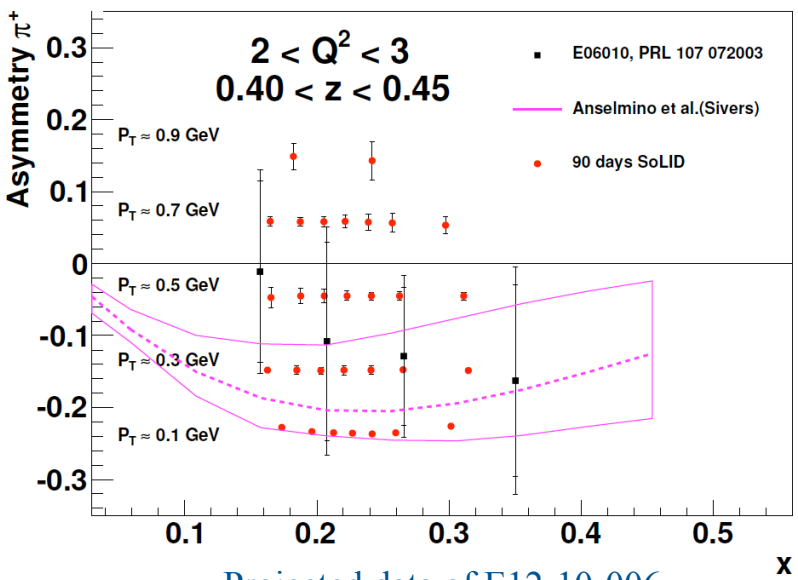


- High luminosity ~ 10^{37} cm^{-2} s^{-1}
- Large acceptance, full azimuthal coverage
- In beam polarization: ~60% (^{3}He), ~70% (NH_3)
- 4D bins with high precision

E12-10-006: Transversely polarized ^{3}He, 90 days.
E12-11-007: Longitudinally polarized ^{3}He, 35 days.
E12-10-008: Transversely polarized NH_3, 120 days.



High statistics (example)

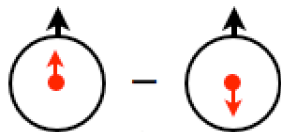


Projected data of E12-10-006

What is the impact of JLab SIDIS program?

Example: Transversity Distribution

Transversity distribution

h_1  (Collinear & TMD)

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

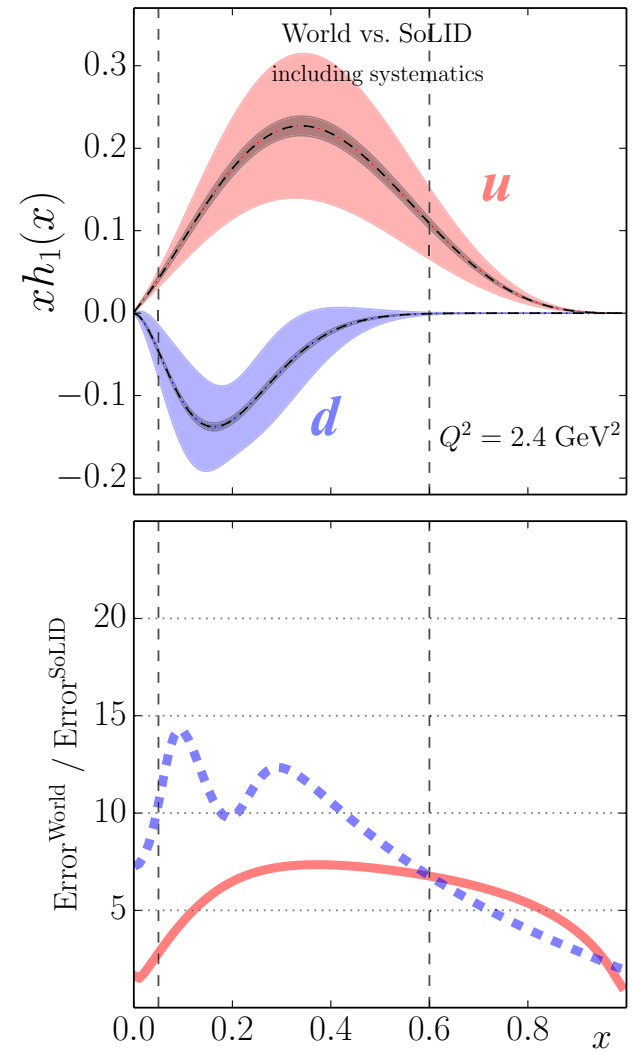
- Chiral-odd:
  No mixing with gluons
  Couple to another chiral-odd function.
  (*e.g.* Collins function $H_1^{\perp}$)

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

- Collins asymmetry

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

A study of the SoLID case



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

Tensor Charge

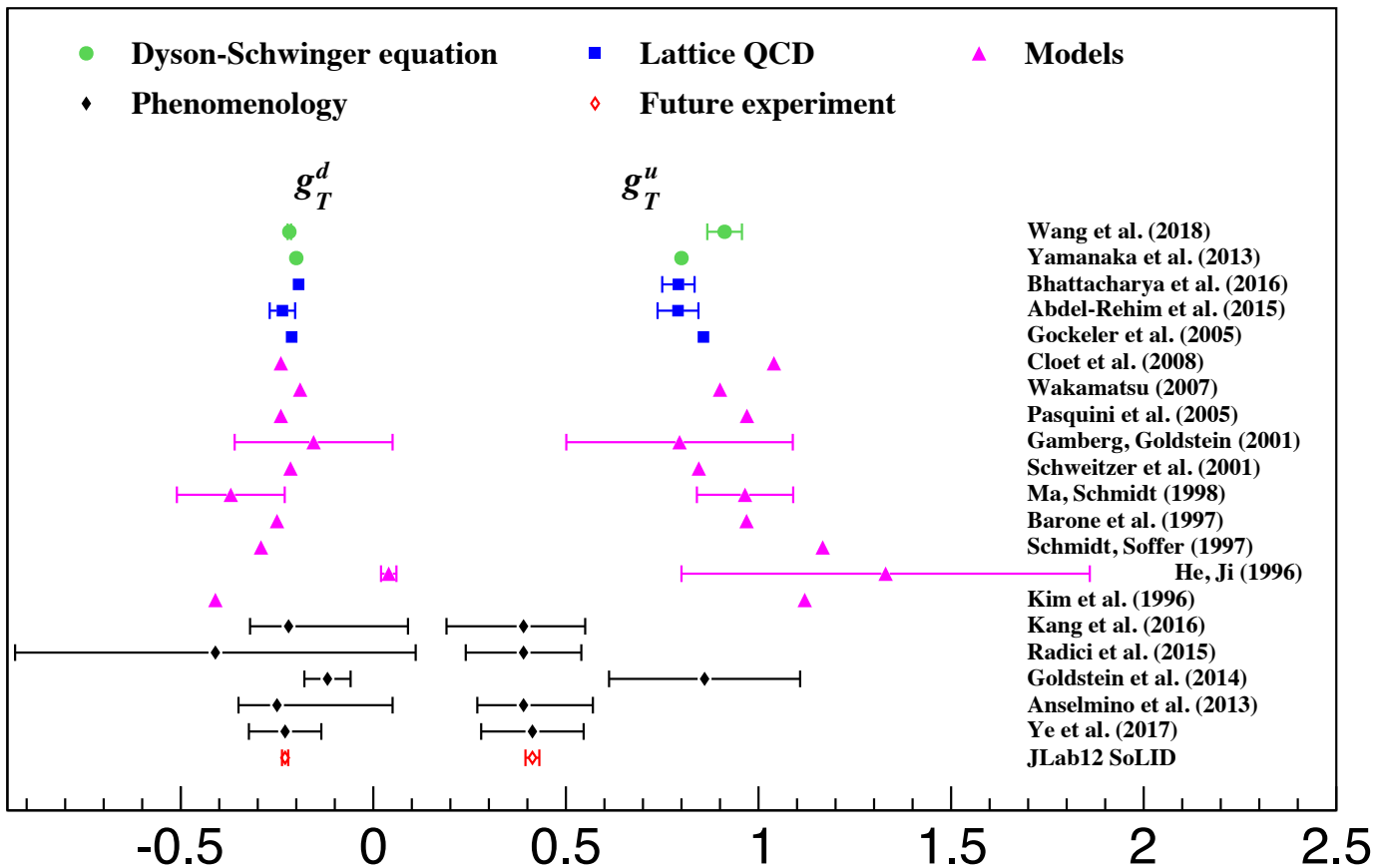
Tensor charge

$$\langle P,S|\bar{\psi}^q i\sigma^{\mu\nu}\gamma_5\psi^q|P,S\rangle = g_T^q\,\bar{u}(P,S)i\sigma^{\mu\nu}\gamma_5 u(P,S) \qquad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]\,dx$$

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

SoLID impact

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



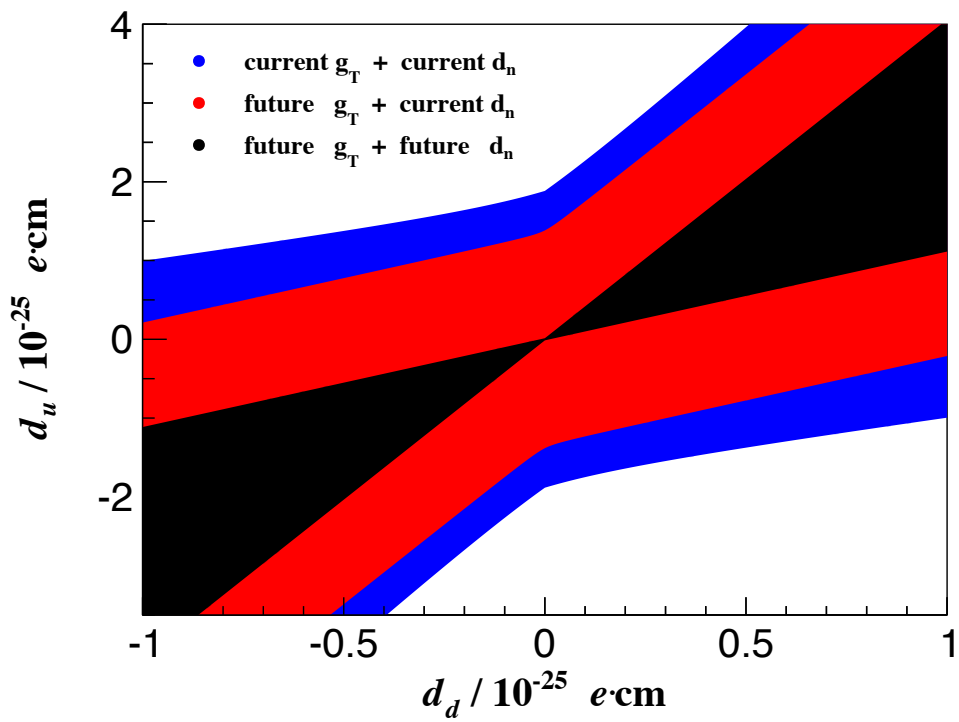
Constraint on Quark EDMs (I)

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

TL, Z. Zhao, H. Gao, Phys. Rev. D 97, 074018 (2018).

Constraint on Quark EDMs (II)

Current upper limit on the proton EDM

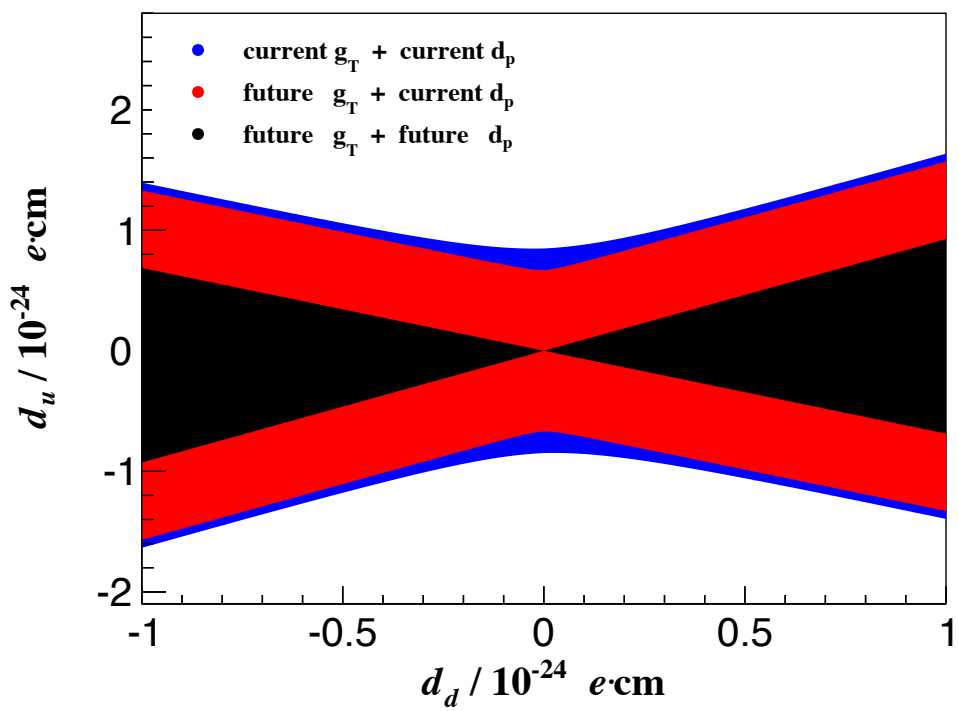
- Mercury atom EDM limit: $7.4 \times 10^{-30}\, e\,\mathrm{cm}$ (95% CL)

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

- Derived proton EDM limit: $2.6 \times 10^{-25}\, e\,\mathrm{cm}$

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

TL, Z. Zhao, H. Gao, Phys. Rev. D 97, 074018 (2018).

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	1.27×10^{-24} e cm	1.17×10^{-24} e cm
SoLID g_T + current EDMs	6.72×10^{-25} e cm	1.07×10^{-24} e cm
SoLID g_T + future EDMs	1.20×10^{-27} e cm	7.18×10^{-28} e cm

including 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 EDMs → Probe 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

TL, Z. Zhao, H. Gao, Phys. Rev. D 97, 074018 (2018).

A Toolkit to Extract TMDs: JAM3D

JAM3D codes — A framework to study TMDs

- It provides the tools to extract TMDs from experimental reactions: electron-proton, electron-positron or proton-proton scattering.
- It provides a single fitter and a MC analysis using the nested sampling algorithm.

Available on Github: https://github.com/JeffersonLab/jam3d

Documentation: https://jeffersonlab.github.io/jam3d

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- Wally Melnitchouk
- Alexei Prokudin
- Daniel Pitonyak
- Mason Albright

Jefferson Lab Angular Momentum Collaboration

Jefferson Lab EXPLORING THE NATURE OF MATTER

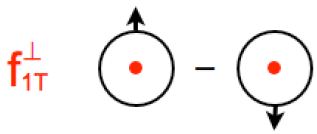
UCONN

PennState Berks

Lebanon Valley College

Example: Sivers Distribution

Sivers distribution



naively time-reversal odd.

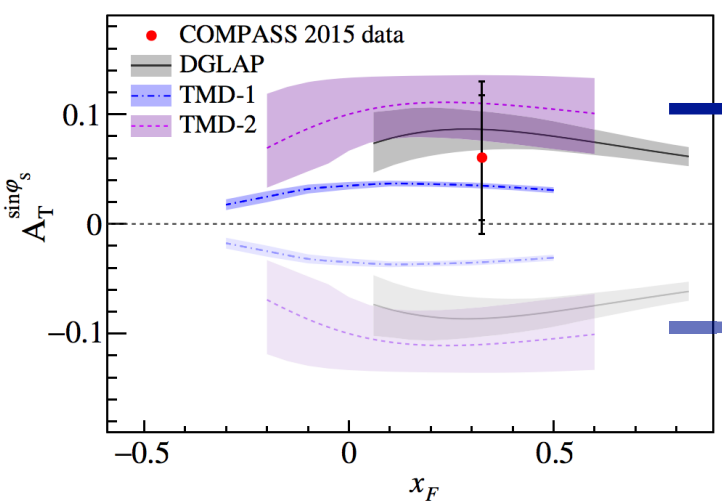
$$f_{1T}^{\perp q}(x,k_\perp)\Big|_{\rm SIDIS} = -f_{1T}^{\perp q}(x,k_\perp)\Big|_{\rm DY}$$

Measurement in SIDIS

Single spin asymmetry: Sivers asymmetry

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

Test of the sign change

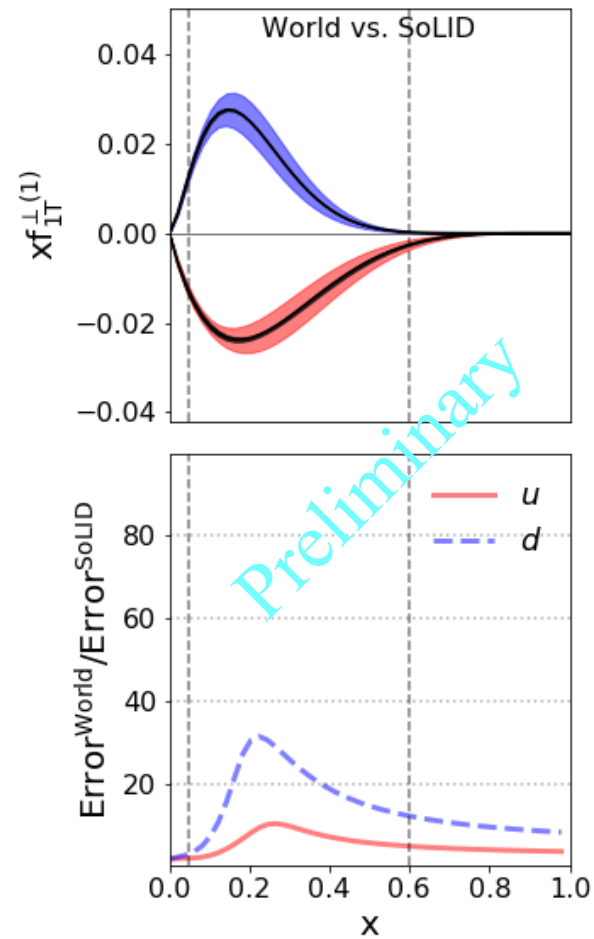


with sign change

without sign change

M. Aghashyan *et al.* (COMPASS Collaboration), PRL 119, 112002 (2017).

A Monte Carlo fit and SoLID impact



on-going analysis with N. Sato, A. Prokudin, W. Melnitchouk, Z. Ye, H. Gao, J.-P. Chen

Summary

- Three dimensional imaging of the nucleon can help understand the remaining puzzle to the proton spin and uncover rich dynamics of strong interaction.
- Lepton scattering is a powerful tool to probe nucleon internal structures.
- Many efforts have been made in JLab 6-GeV SIDIS experiments.
- Rich TMD program at 12 GeV JLab: SBS, CLAS12, Hall-C, SoLID
- Physics impact:
  - unprecedented precision on TMDs, *e.g.* Sivers, transversity, …
  - tensor charge, lattice calculations, EDMs, …
- Analysis tools in development for upcoming data, JAM3D, …

Thank you!