# *Experimental TMD Program at JLab*

Jian-ping Chen, Jefferson Lab, Virginia, USA

3-D Modeling Workshop @ JLab, March, 2017

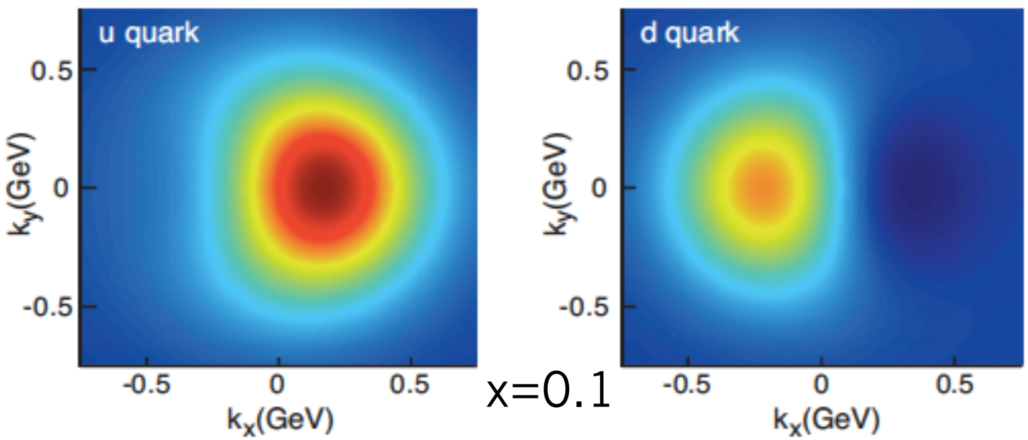
- Introduction
- TMDs: 3-D Structure of the Nucleon in Momentum Space
  - Spin-Flavor, Orbital Angular Momentum
  - Transeversity and Tensor Charge
  - Sivers, Worm-Gear, Pretzelosity
- JLab Multi-Hall Program
  - Hall C: Cross Sections, L/T separation, $P_T$ study
  - Hall B: Medium luminosity/large acceptance, general survey,
  - Hall A/SBS: pi and Kaon, large x/Q2
  - **Hall A/SoLID: High luminosity/large acceptance with polarized n/p**

    **Precision 4-d mapping of TMD asymmetries**
- Summary

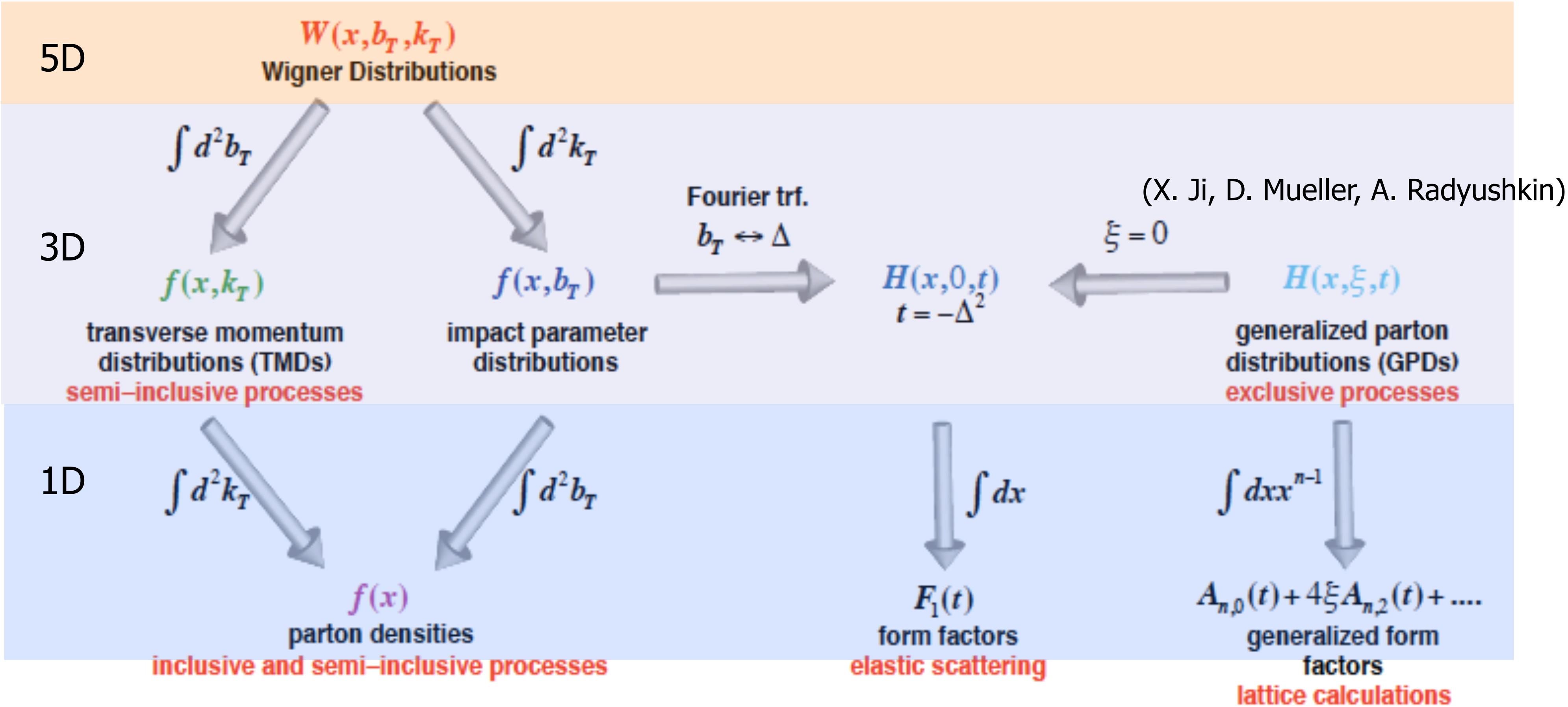
Thanks to my colleagues for help with slides: H. Avagyan, M. Cantalbrigo, E. Cisbani, R. Ent, H. Gao, D. Gaskell, T. Liu, A. Prokudin, A. Puckett, …

# Introduction

## TMDs: Transverse Structure of Nucleon in Momentum Space



## ❑ Wigner distributions (Belitsky, Ji, Yuan)



# *Leading-Twist TMD PDFs*

Nucleon Spin

Quark Spin

| Nucleon Polarization \ Quark polarization | Unpolarized (U) | Longitudinally Polarized (L) | Transversely Polarized (T) |
|---|---|---|---|
| U | $f_1$ | | $h_1^{\perp}$ Boer-Mulders |
| L | | $g_1$ Helicity | $h_{1L}^{\perp}$ Long-Transversity |
| T | $f_{1T}^{\perp}$ Sivers | $g_{1T}$ Trans-Helicity | $h_1$ Transversity<br>$h_{1T}^{\perp}$ Pretzelosity |

# TMDs

| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_1$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$ $h_{1T}^\perp$ |

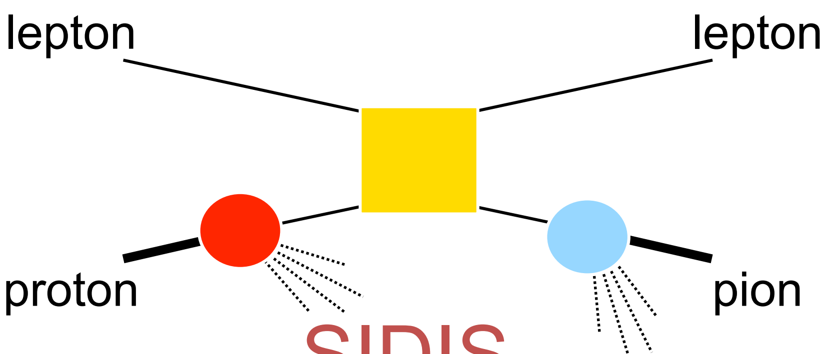
8 functions in total (at leading Twist)

Each represents different aspects of partonic structure

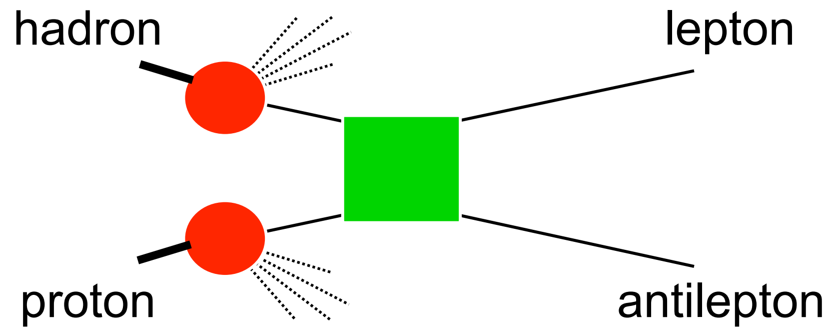
Each function is to be studied

Mulders, Tangerman (1995), Boer, Mulders (1998)

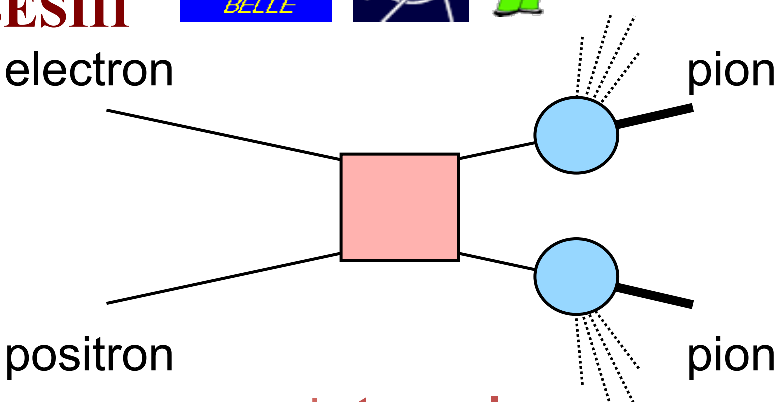
# *Access TMDs through Hard Processes*




SIDIS




Drell-Yan

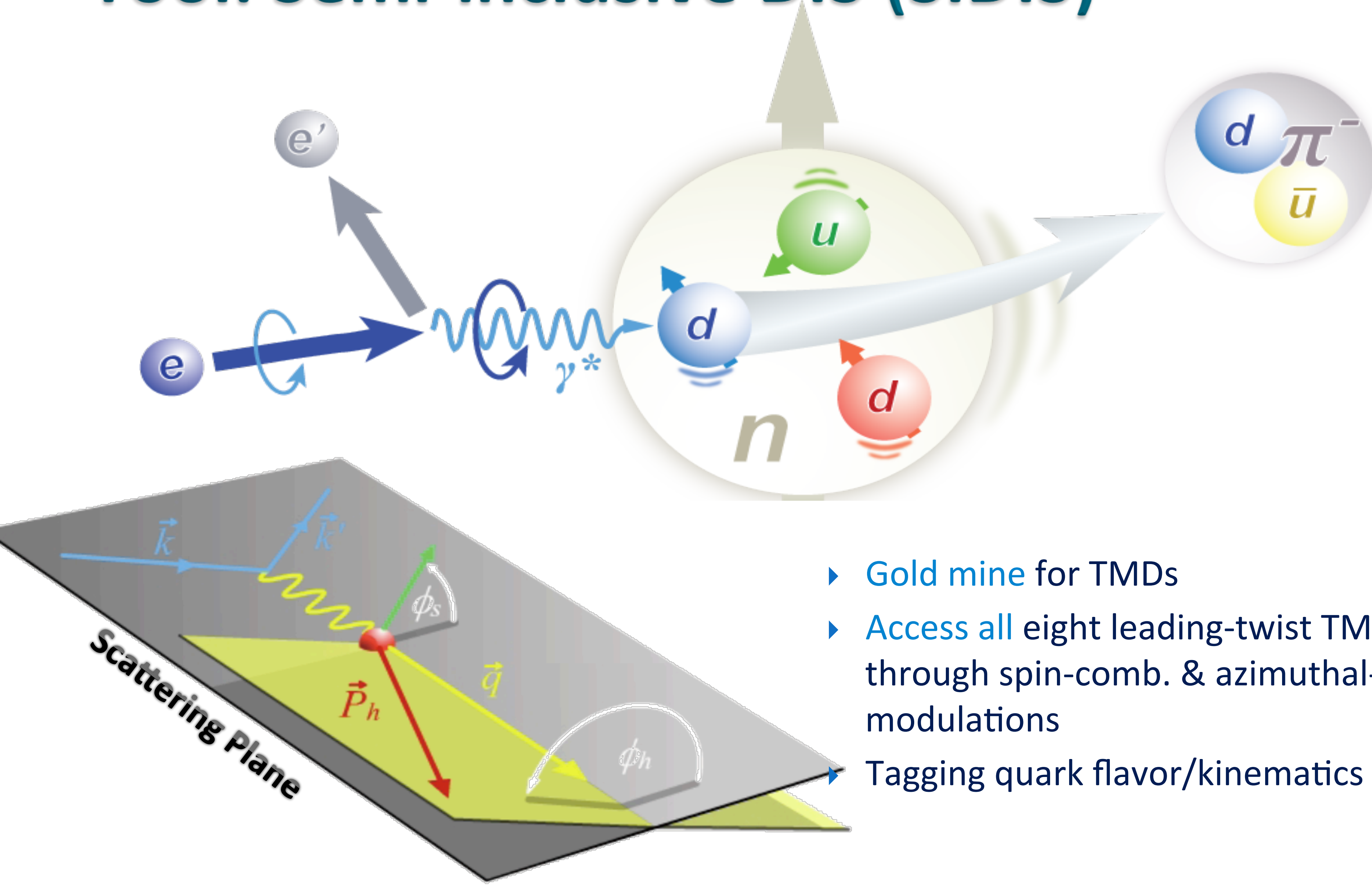



$e^{-}e^{+}$ to pions

- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

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

# Tool: Semi-inclusive DIS (SIDIS)




- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics

# Explore TMD with JLab 6 GeV

- Demonstrate Feasibility
- Initial study on $P_T$ spin-flavor dependence
- First measurements with transversely polarized $^3$He (neutron)

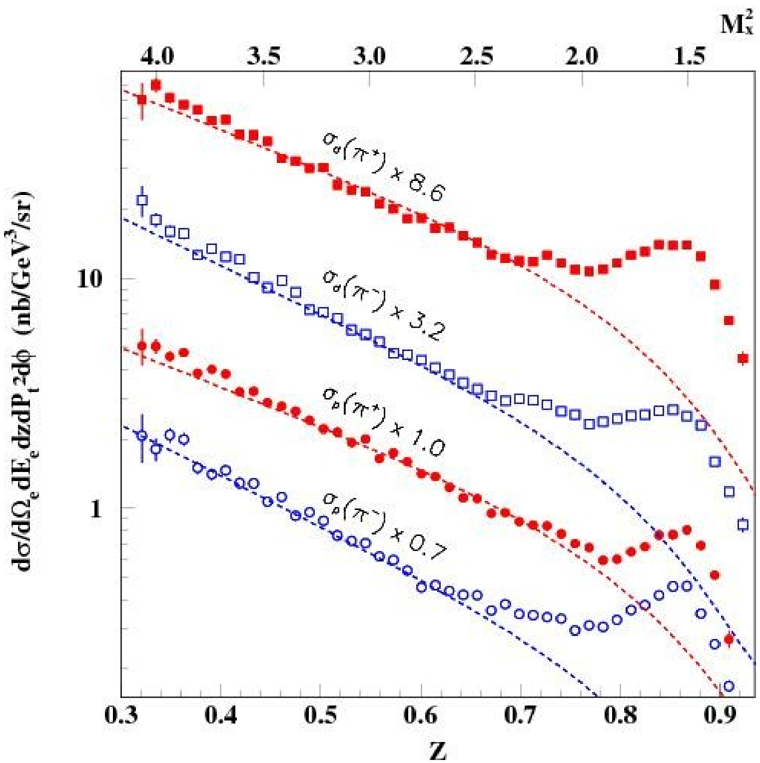
# Is JLab Energy High Enough?

- To extract TMDs from SIDIS, more demanding in energy than in DIS
- Is JLab 12 GeV and/or 6 GeV energy high enough?

## Hall C E00-108 Exp.

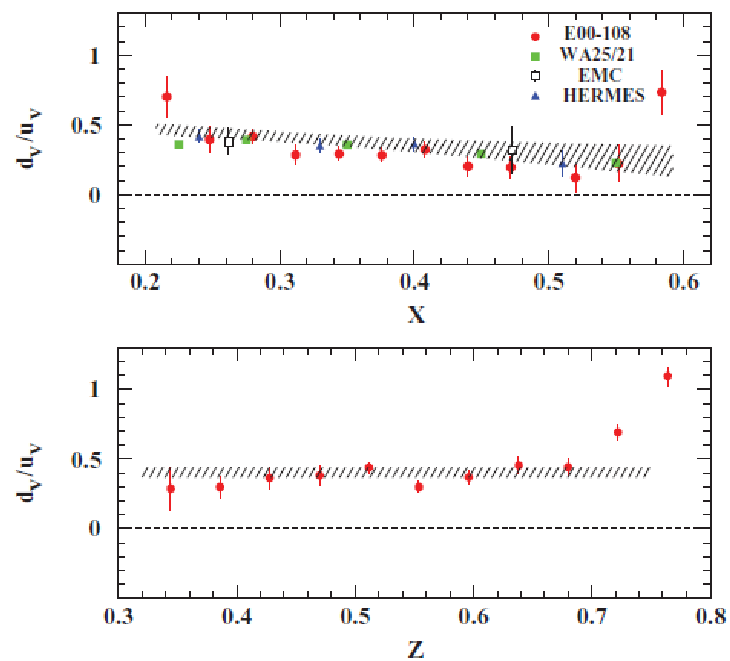
$e + LH_2/LD_2 \rightarrow e' + \pi+/\pi- + X$

**Ebeam=5.5 GeV**




T. Navasardyan et al. PRL 98, 022001 (2007)

bands evaluated using CTEQ PDFs

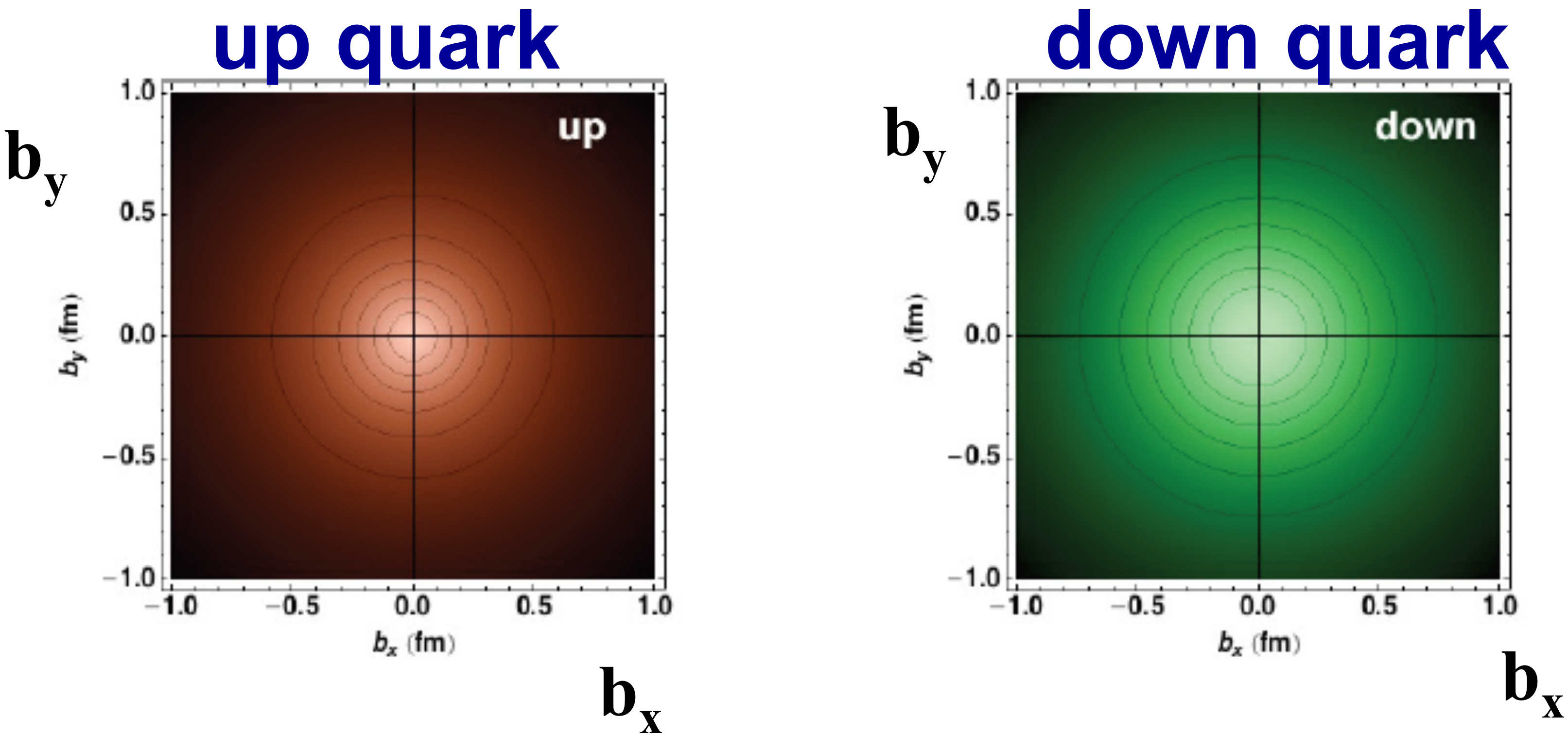



R. Asaturyan et al. PRL 85, 015202 (2012)

Low Energy SIDIS xsec reproduced by calculation using high energy parameters and PDF

# From Form Factors to Transverse Densities

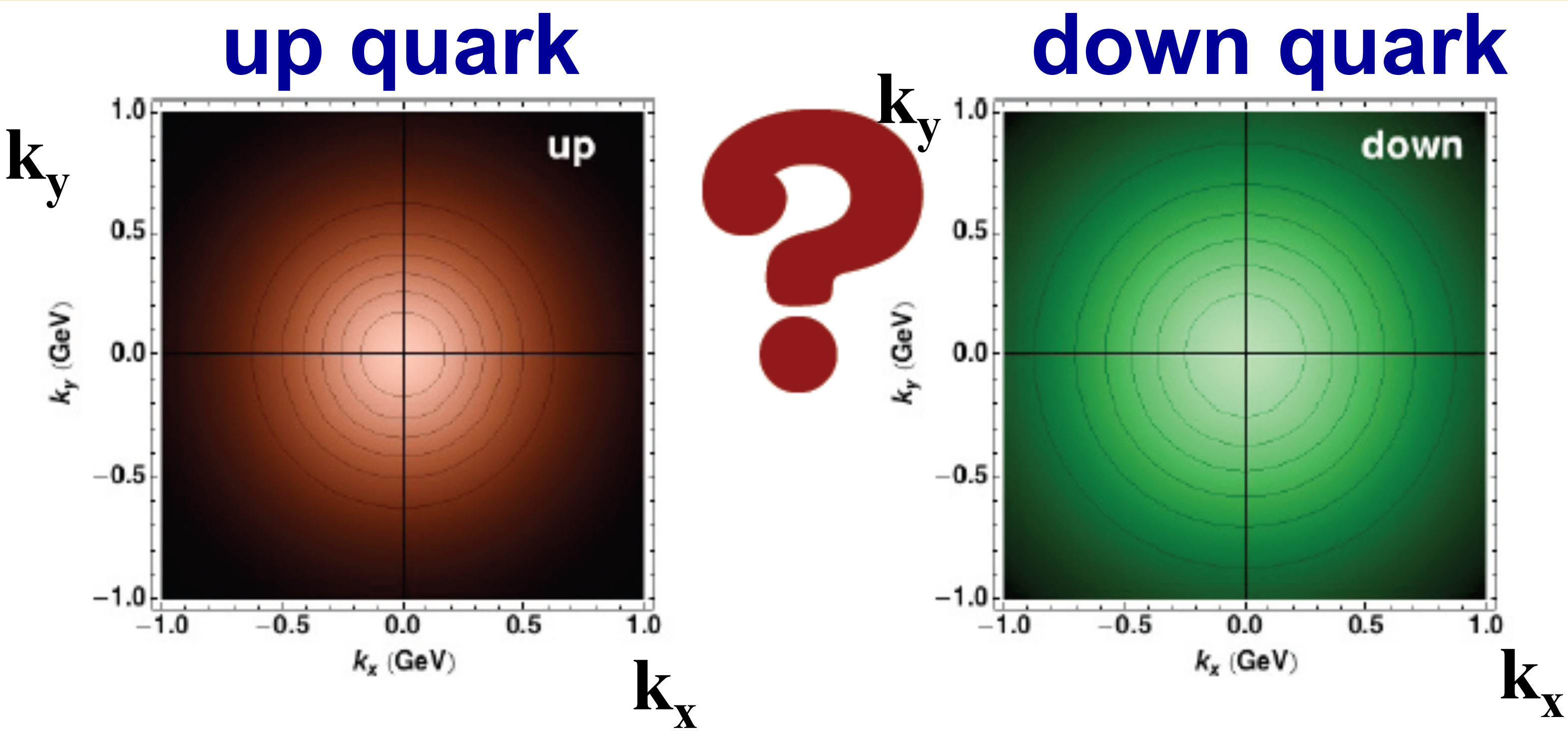
## Unpolarized Transverse Densities




Flavor-dependence in form factors can be translated into flavor-dependence of transverse densities

# Unpolarized TMD: Flavor $P_T$ Dependence?

## Flavor in transverse-momentum space




Is the up distribution wider or narrower than the down?

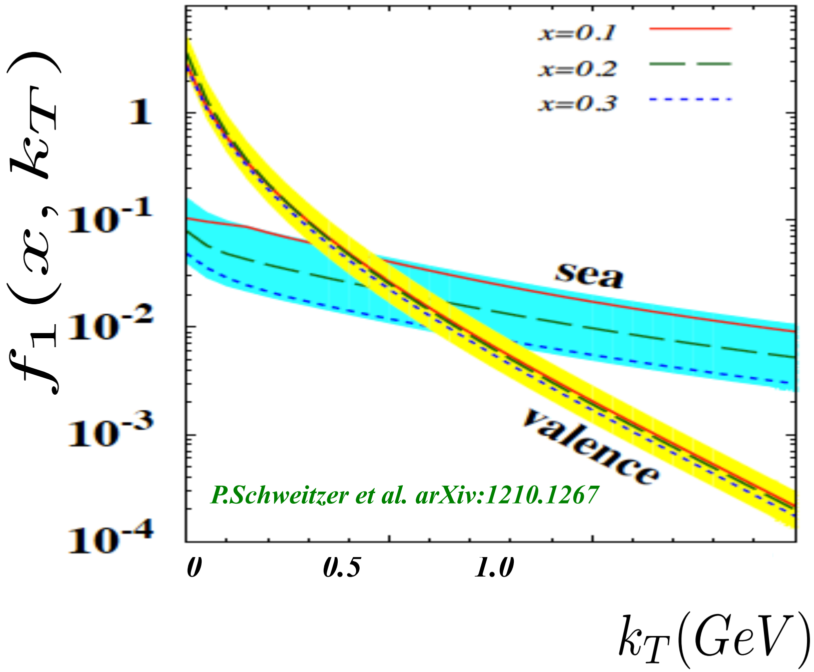
And the sea?

How wide are the distributions?

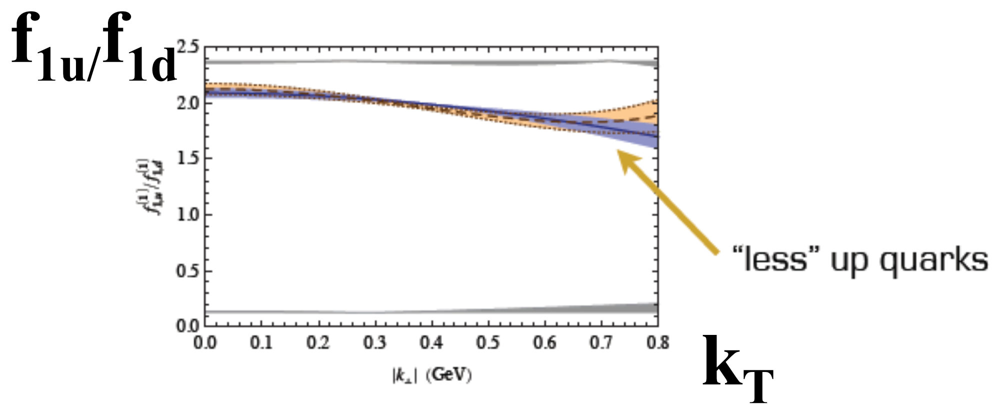
*A. Bacchetta, Seminar @ JLab, JHEP 1311 (2013) 194*

# Flavor $P_T$ Dependence from Theory

- Chiral quark-soliton model (Schweitzer, Strikman, Weiss, JHEP, 1301 (2013)) → sea wider tail than valanee




## Indications from lattice QCD



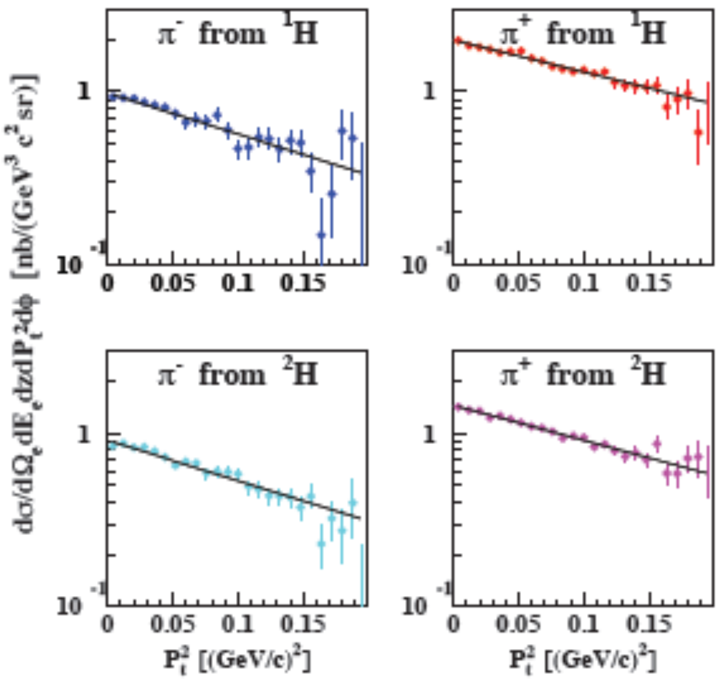

Musch, Hagler, Negele, Schafer, PRD 83 (11)

Pioneering lattice-QCD studies hint at a down distribution being wider than up

- Flagmentation model, Matevosyan, Bentz, Cloet, Thomas, PRD85 (2012) → unfavored pion and Kaon wider than favored pion

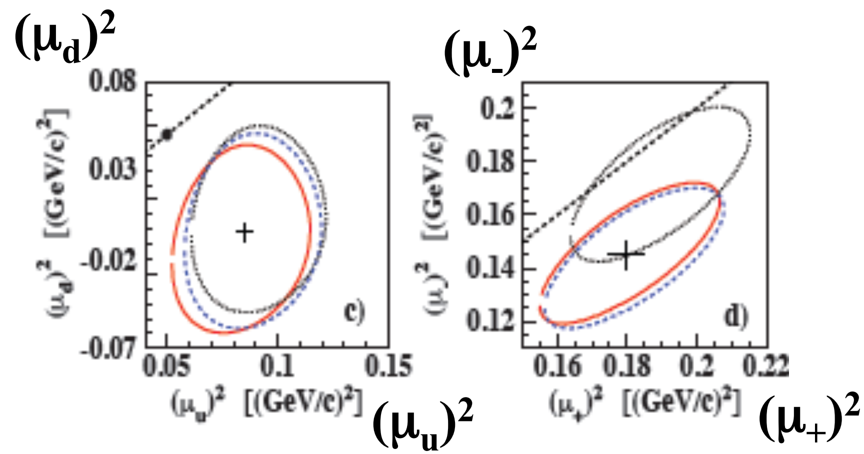
# Hall C Results: Flavor $P_T$ Dependence

## First indications from experiments




Asaturyan et al., E00-108, Hall C, PRC85 (2012)

no kaons, no sea,
no *x-z* dependence

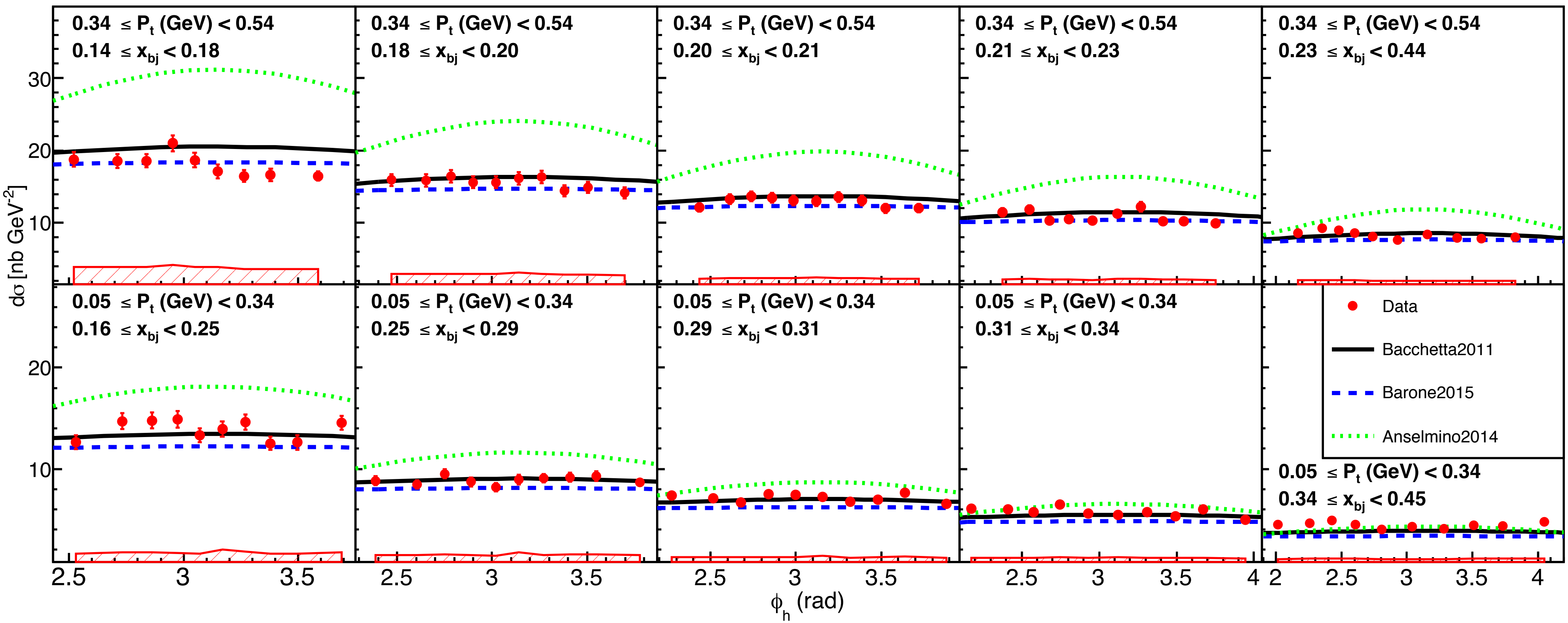



Conclusion: up is wider than down and favored wider than unfavored

# Hall A SIDIS Cross Section Results From E06-010 (Transversity):

**pi+ and pi- production on He3**

**X. Yan *et al.*, Hall A Collaboration, arXiv:1610.02350, Accepted by PRC**

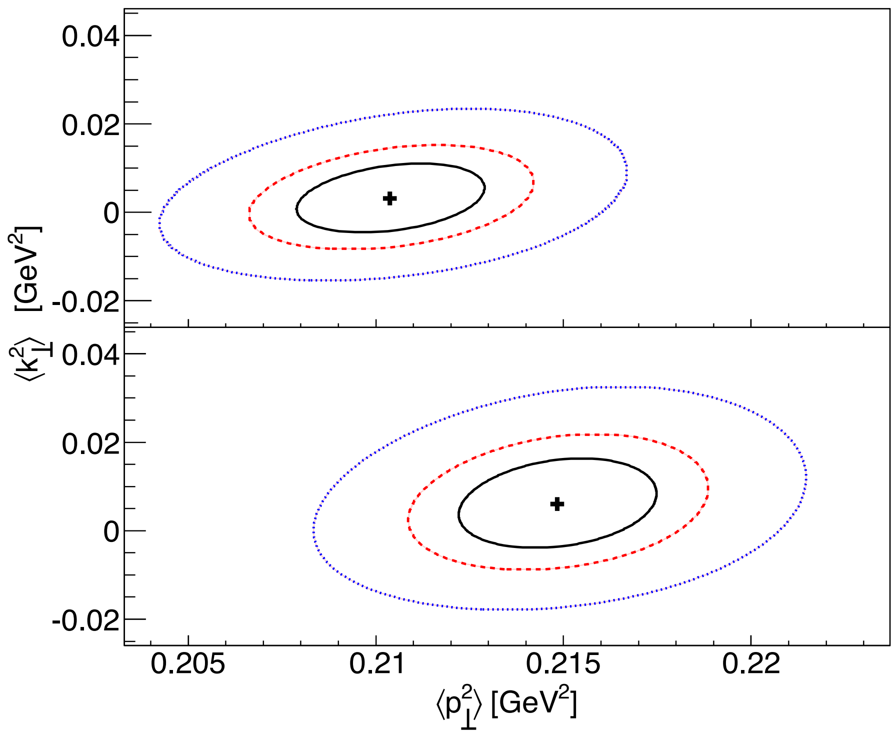



**pi+ results** $\Phi_h$ **(rad)**

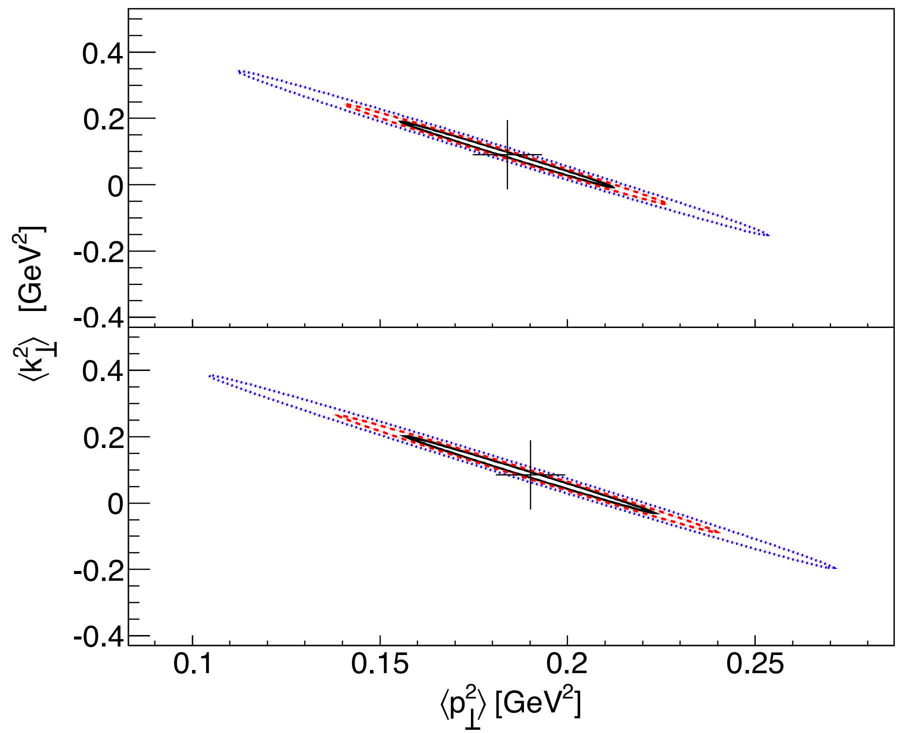
# Hall A Results: Transverse Momentum dependence

**average quark transverse momentum distribution squared**
**vs. average quark transverse momentum in fragmentation squared**

**with modulation**




**no modulation**



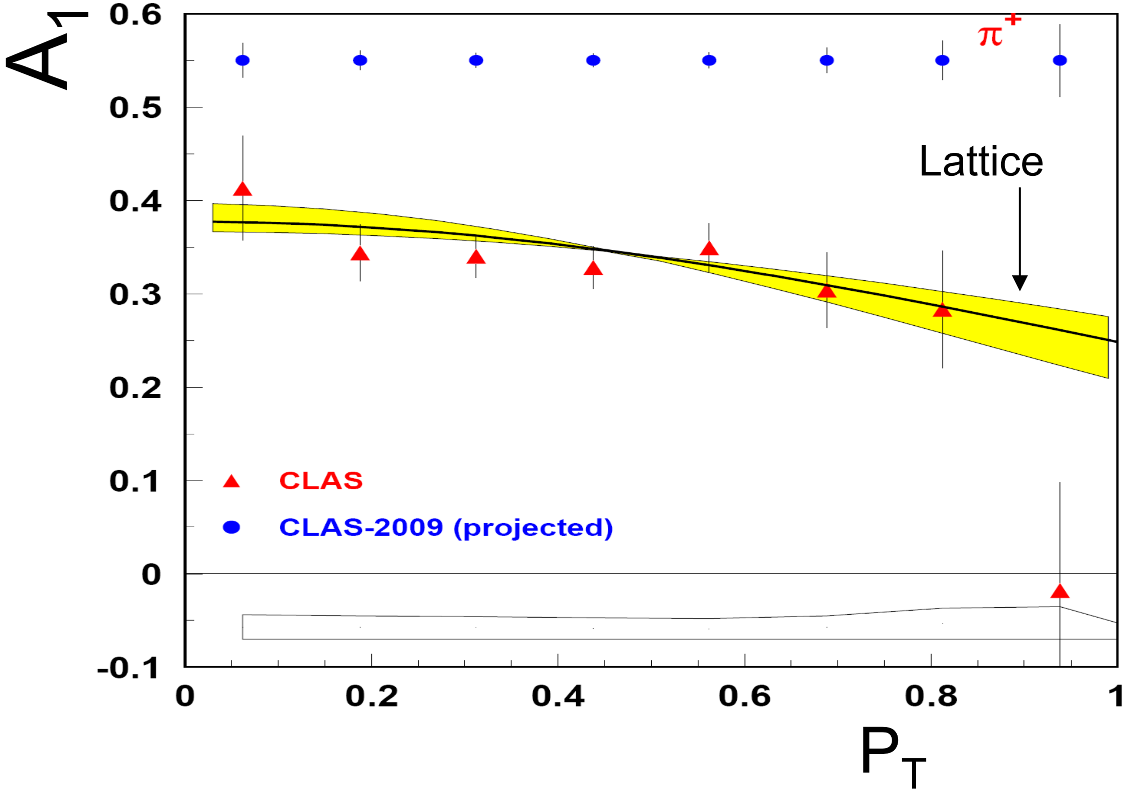
| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_1$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$ $h_{1T}^\perp$ |

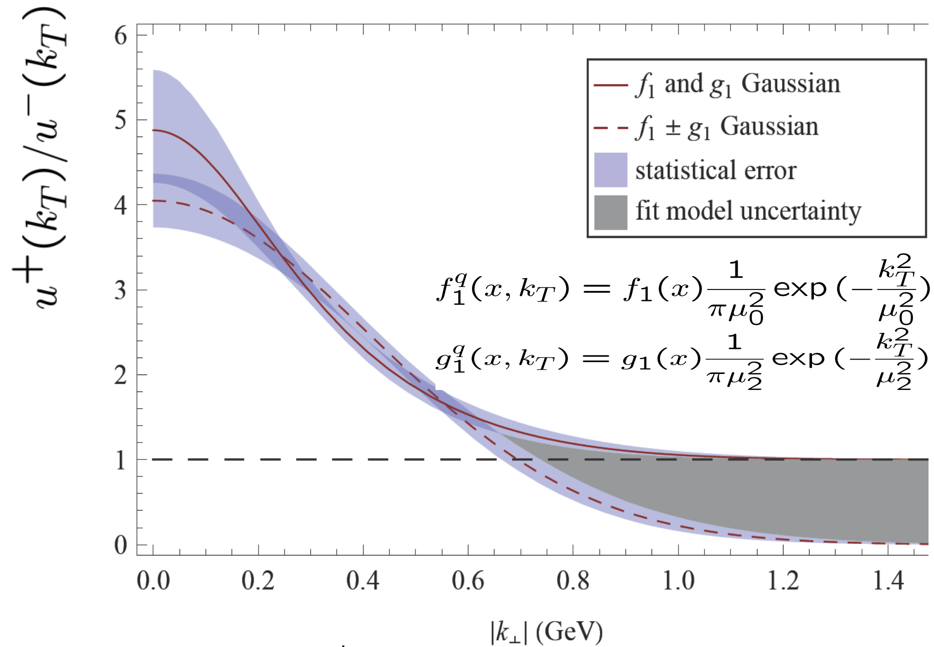
# $A_1$ $P_T$-dependence

**arXiv:1003.4549**

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

$$A_1(x,z,P_T) = A_1(x,z)\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)$$




**B.Musch et al arXiv:1011.1213**

$$\mu_2^2/\mu_0^2 = 0.692 \pm 0.039 \pm 0.045$$

CLAS data suggests that width of $g_1$ is less than the width of $f_1$

# Planned Precision TMD Studies with JLab 12

## Multi-Hall Program, SoLID

## *Precision Study of TMDs: JLab 12 GeV*

- Explorations: HERMES, COMPASS, RHIC-spin, JLab6,…
- From exploration to precision study

  JLab12: valence region

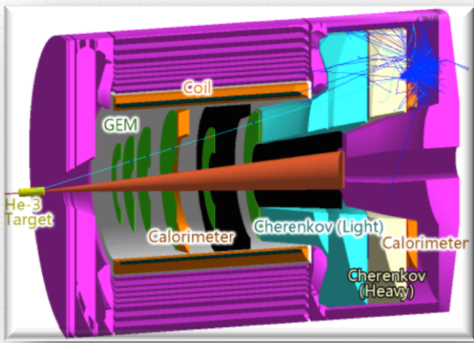
  Transversity: fundamental *PDF*s, tensor charge
- *TMD*s: 3-d momentum structure of the nucleon

  → information on quark orbital angular momentum

  → information on QCD dynamics
- Multi-dimensional mapping of *TMD*s
- Precision → high statistics
  - high luminosity and/or large acceptance

# JLab 12: Multi-Halls TMD Program

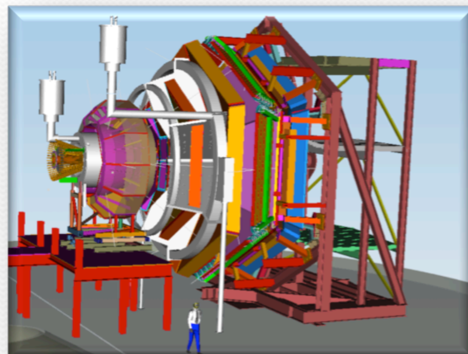
**Hall A/SOLID**
**High Lumi and acceptance – 4D**




$^{3}He$, $NH_3$

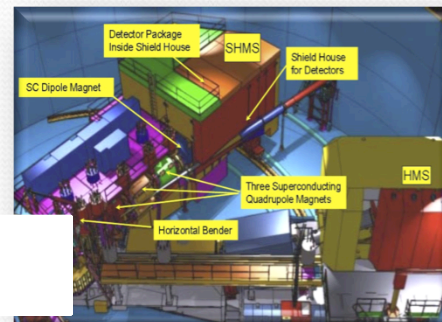
**Hall A/SBS**
**High x - $Q^2$, 2-3D**

**Hall B/CLAS12**
**General survey, medium luminosity**



$H_2/D_2$, $NH_3/ND_3$, HD

**Hall C/SHMS**
**L-T studies, precise $\pi^+/\pi^-$ ratios**




$H_2$ $D_2$

# The Multi-Hall SIDIS Program at 12 GeV

*M. Aghasyan, K. Allada, H. Avakian, F. Benmokhtar, E. Cisbani, J-P. Chen, M. Contalbrigo, D. Dutta, R. Ent, D. Gaskell, H. Gao, K. Griffioen, K. Hafidi, J. Huang, X. Jiang, K. Joo, N. Kalantarians, Z-E. Meziani, M. Mirazita, H. Mkrtchyan, L.L. Pappalardo, A. Prokudin, A. Puckett, P. Rossi, X. Qian, Y. Qiang, B. Wojtsekhowski*

JLab SIDIS working group

The complete mapping of the multi-dimensional SIDIS phase space will allow a comprehensive study of the TMDs and the transition to the perturbative regime.

Flavor separation will be possible by the use of different target nucleons and the detection of final state hadrons.

Measurements with pions and kaons in the final state will also provide important information on the hadronization mechanism in general and on the role of spin-orbit correlations in the fragmentation in particular.

Higher-twist effects will be present in both TMDs and fragmentation processes due to the still relatively low $Q^2$ range accessible at JLab, and can apart from contributing to leading-twist observables also lead to observable asymmetries vanishing at leading twist. These are worth studying in themselves and provide important information on quark-gluon correlations.

# Hall C – Cross Sections in SIDIS

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

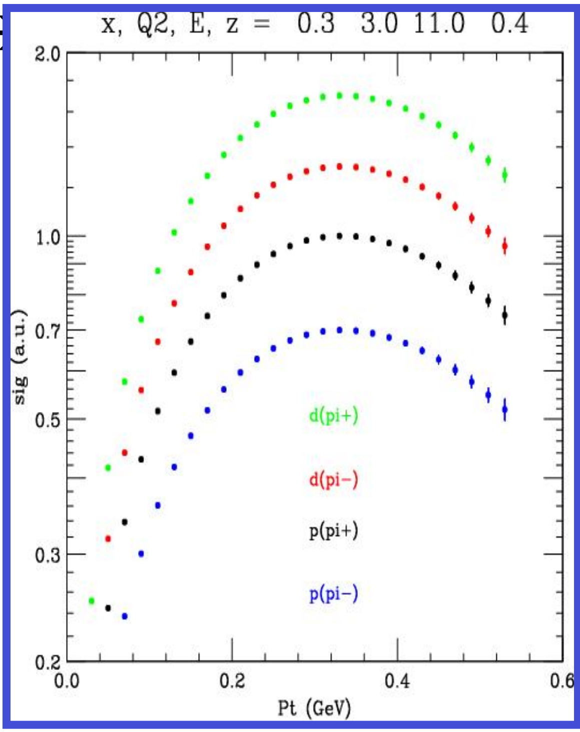
Cross section measurements with magnetic focusing spectrometers (HMS/SHMS) will play important role in JLab SIDIS program

→ Demonstrate understanding of reaction mechanism, test factorization

→ Able to carry out precise comparisons of charge states, $\pi+/\pi-$

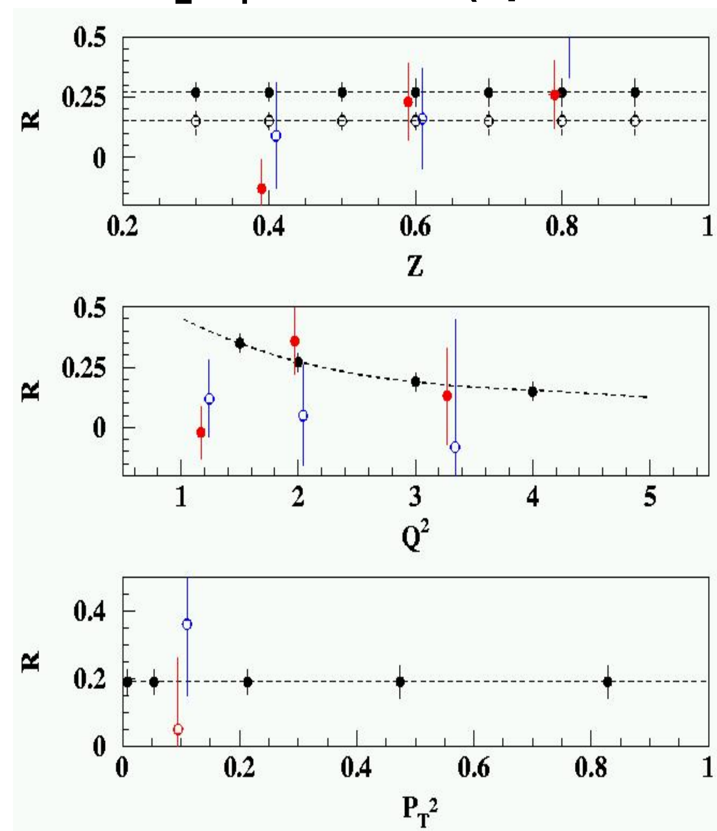
→ … at small $P_T$, access to large … SHMS/HMS will allow precise L-T separations

→ Does $R_{DIS} = R_{SIDIS}$?




Measure $P_T$ dependence to access $k_T$ depedence of parton distributions

**R = $\sigma_L/\sigma_T$ in SIDIS (ep → e'$\pi^{+/-}$X)**

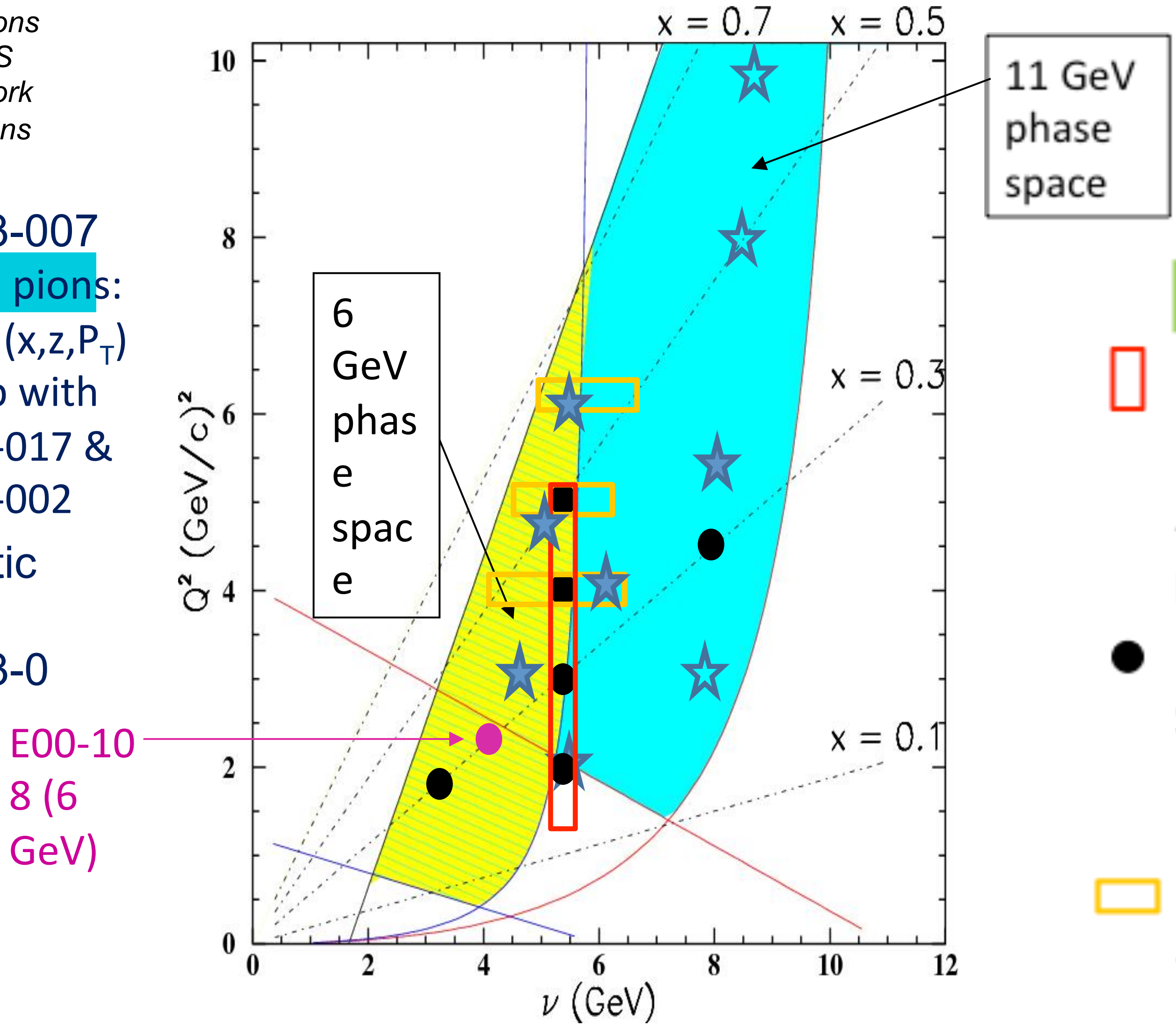


# Hall C SIDIS Program – HMS+SHMS+NPS

*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:

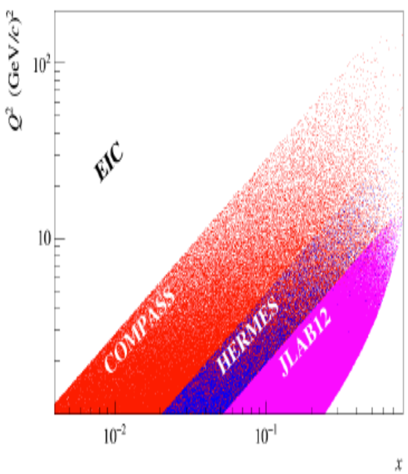
E12-06-104
L/T scan in (z,$P_T$)
No scan in $Q^2$ at fixed x: $R_{DIS}(Q^2)$ known

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

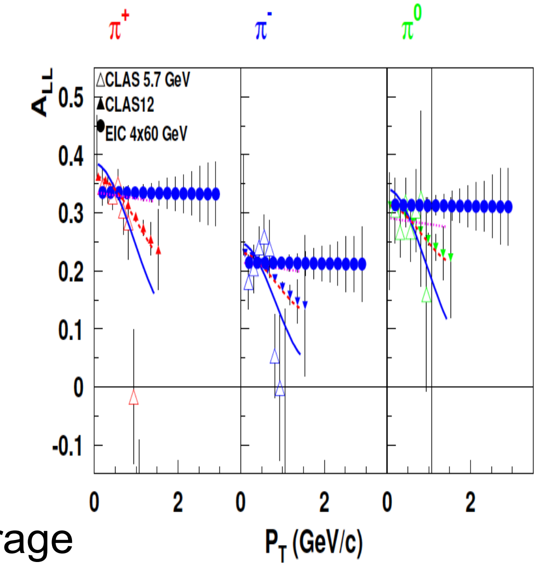
E12-09-002
+ scans in z

*Courtesy R. Ent*

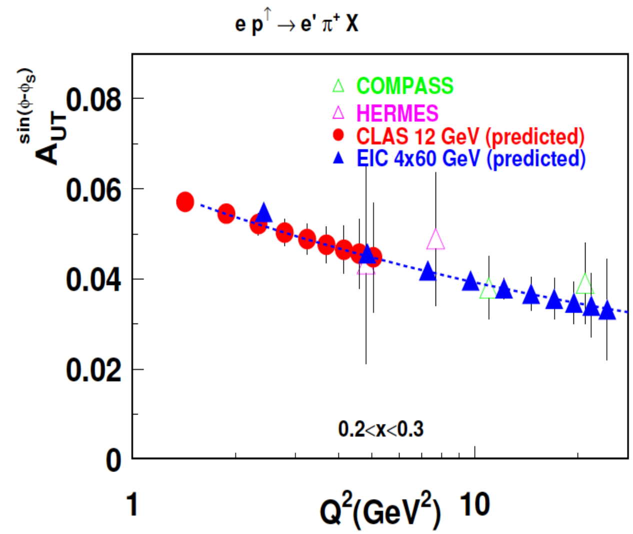
# CLAS12: Evolution and $k_T$-dependence of TMDs



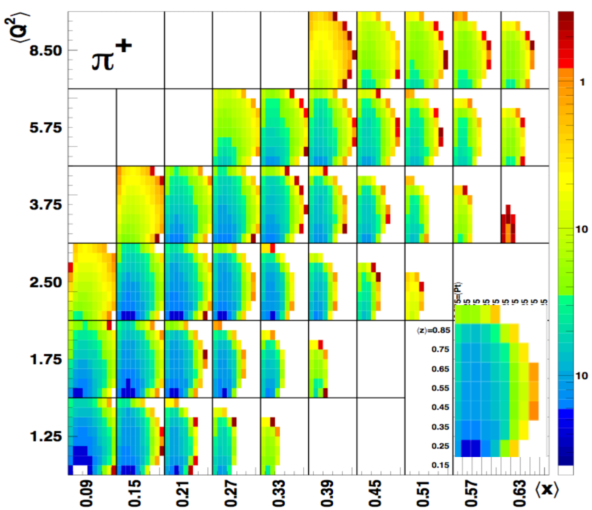

CLAS12 kinematical coverage




$k_T$-dependence of $g_1(x, k_T)$




$Q^2$-dependence of Sivers $f_{1T}^{\perp}(x, k_T)$




- 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.

# Overview of SoLID

**So**lenoidal **L**arge **I**ntensity **D**evice

- **Full exploitation of JLab 12 GeV Upgrade**

  → A **Large Acceptance** Detector **AND** Can Handle **High Luminosity** ($10^{37}$-$10^{39}$)

  Take advantage of latest development in detectors , data acquisitions and simulations

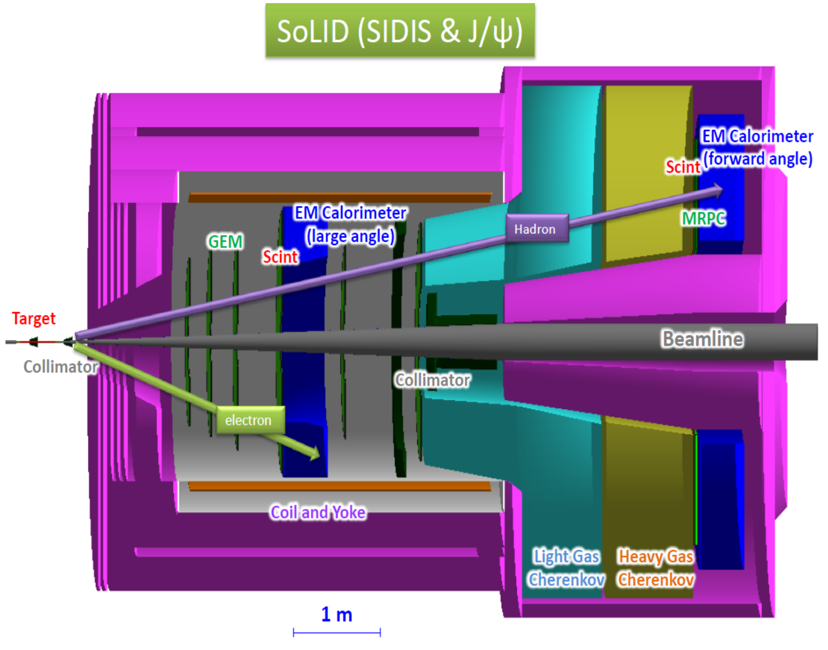
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-*x* region and threshold J/ψ

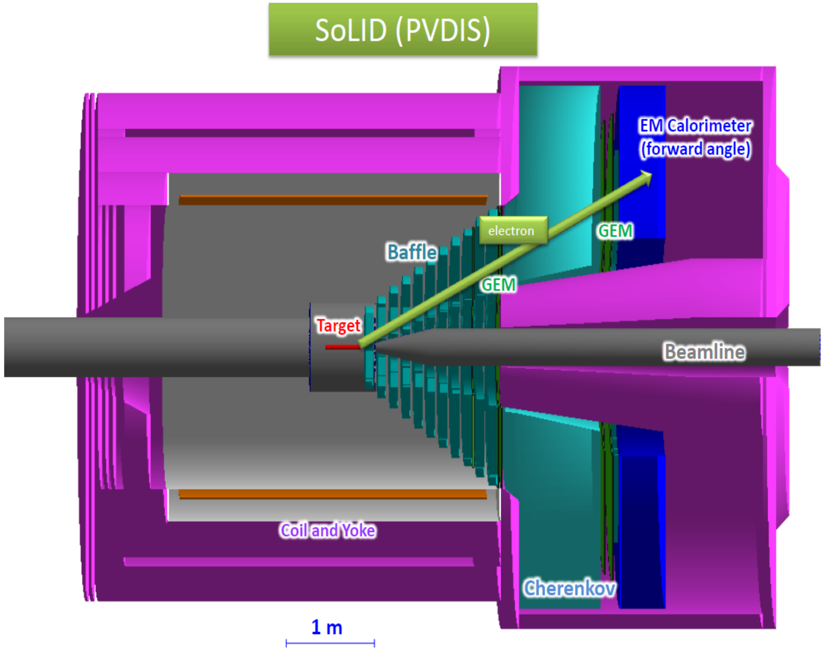
- **5 highly rated experiments approved**

  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 3 run group experiments)

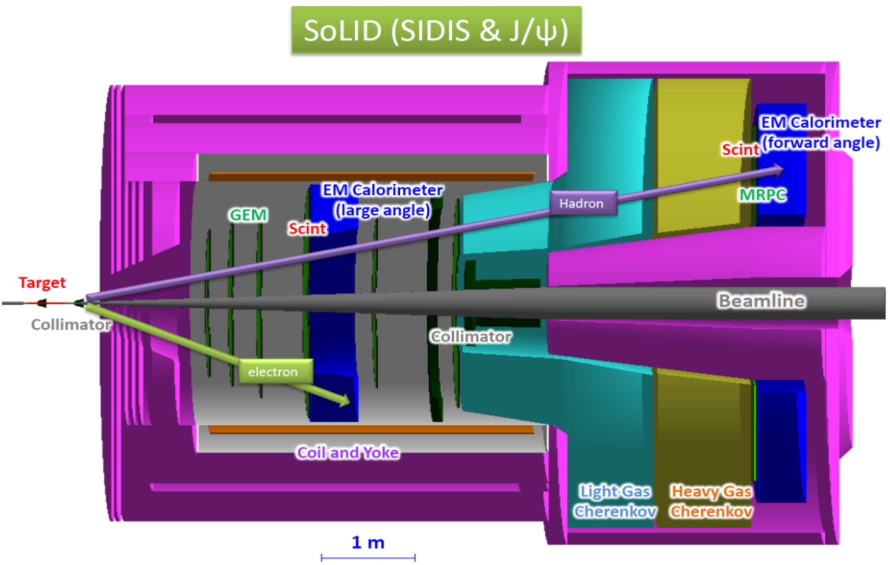
- **Strong collaboration** (250+ collaborators from 70+ institutes, 13 countries)

  Significant international contributions (Chinese collaboration)



# *SoLID-Spin: SIDIS on $^3$He/Proton @ 11 GeV*



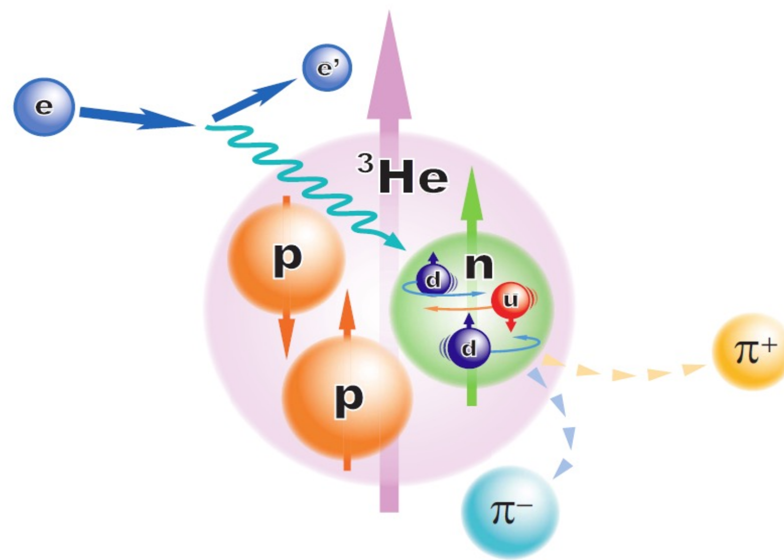

**E12-10-006:** Single Spin Asymmetry on Transverse $^3$He, **rating A**

**E12-11-007:** Single and Double Spin Asymmetries on $^3$He, **rating A**

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

**Two run group experiments: DiHadron and Ay**

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



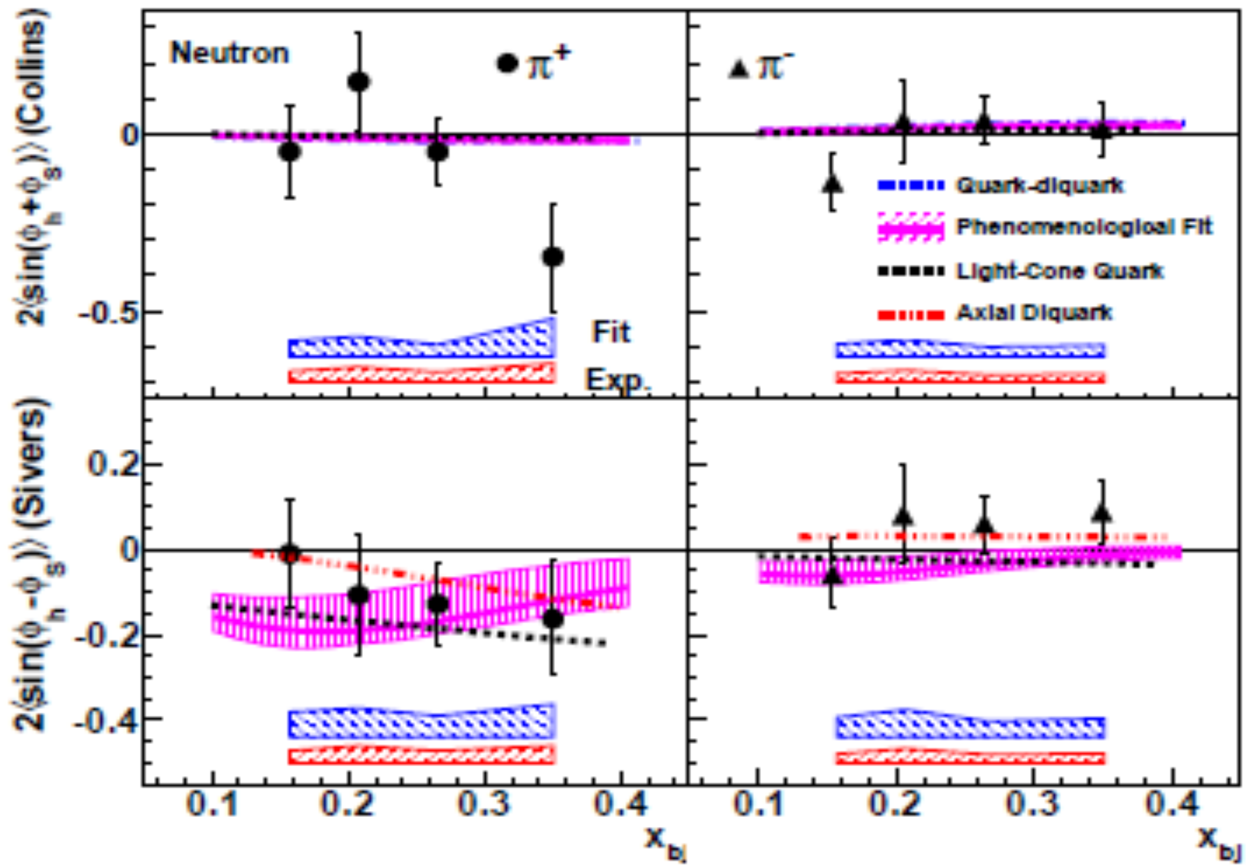
# Collins Asymmetry: Transversity

Transverse Spin, Tensor Charge

# JLab6: $^3$He (n) Target Single-Spin Asymmetry in SIDIS

**JLab E06-010 collaboration**, X. Qian at al., **PRL 107:072003(2011)**

$$n^{\uparrow}(e,e'h), h = \pi^{+}, \pi^{-}$$




**neutron Collins SSA small**
**Non-zero at highest x for π+**

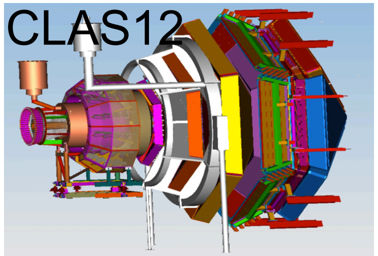
| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^{\perp}$ |
| L | | $g_1$ | $h_{1L}^{\perp}$ |
| T | $f_{1T}^{\perp}$ | $g_{1T}$ | $h_1$ $h_{1T}^{\perp}$ |

**neutron Sivers SSA:**
**negative for $\pi^+$,**
**Agree with Torino Fit**

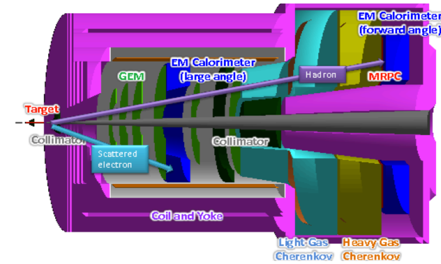
**Blue band**: model (fitting) uncertainties
**Red band**: other systematic uncertainties

# Accessing transversity in dihadron production at JLab

Measurements with polarized protons

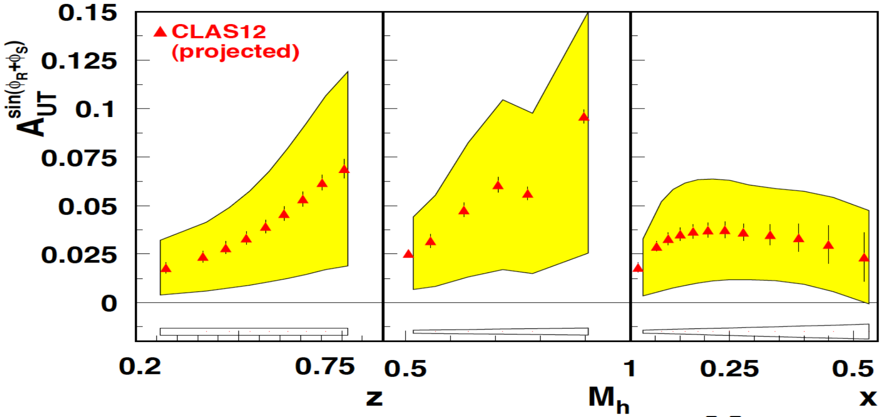


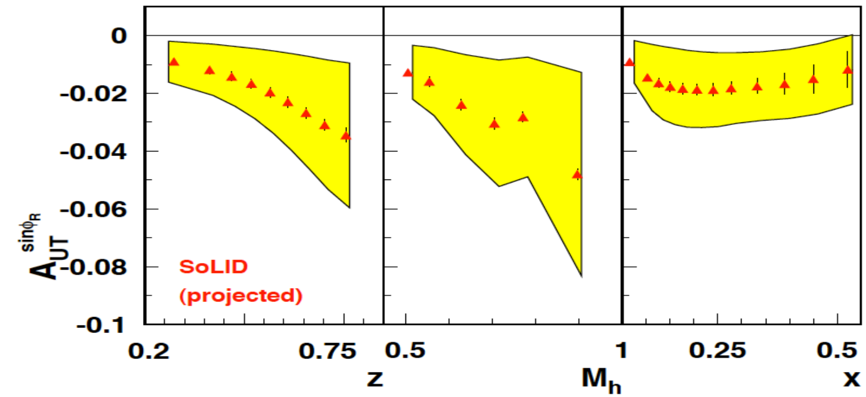

Measurements with polarized neutrons



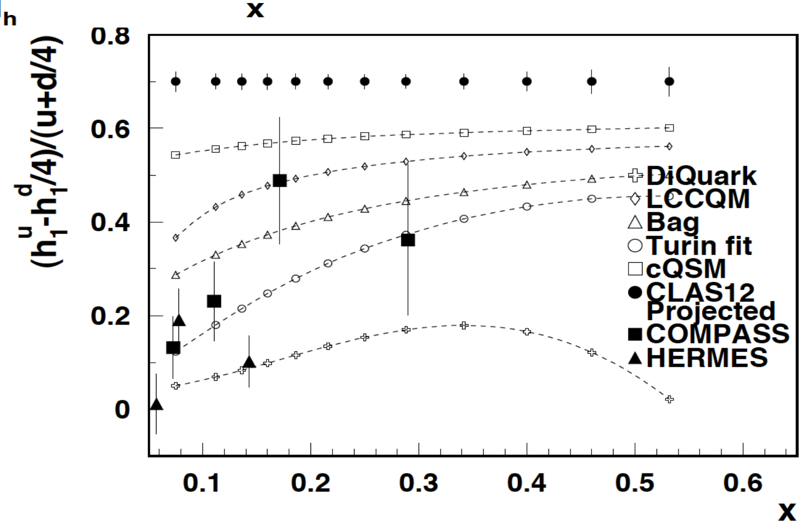

SoLID

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




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

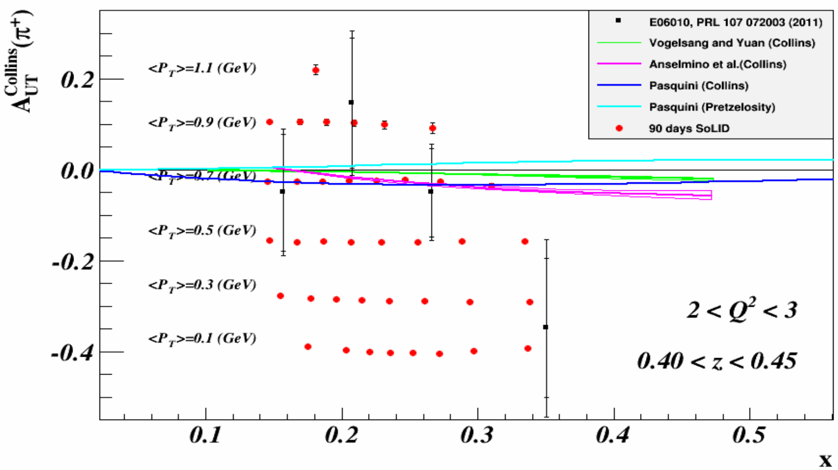



$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_{\pi\pi})\ (4h_1^d(x) - h_1^u(x))}{D_1^u(z,M_{\pi\pi})\ (4f_1^d(x) + f_1^u(x))}$$

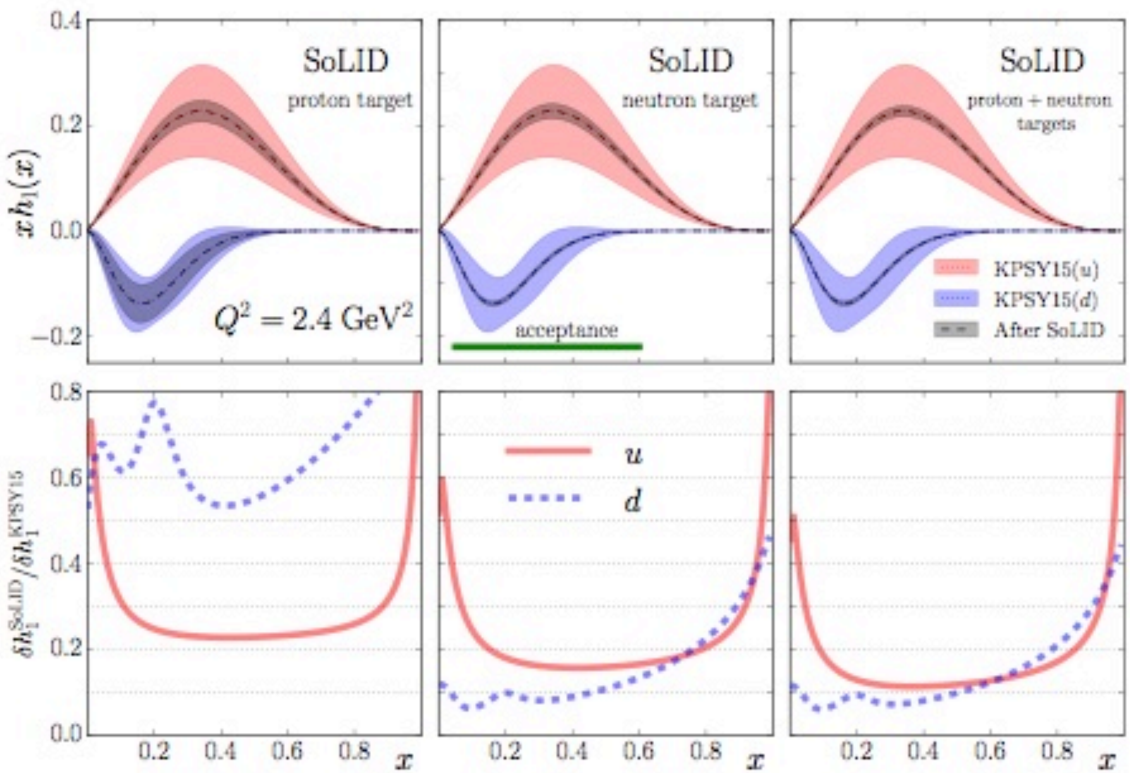
# Transversity from SoLID

- Collins Asymmetries ~ Transversity (x) Collin Function
- **Transversity**: chiral-odd, not couple to gluons, **valence behavior**, largely unknown
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with **trans polarized n & p** → Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, …) on impact study

***Collins Asymmetries***



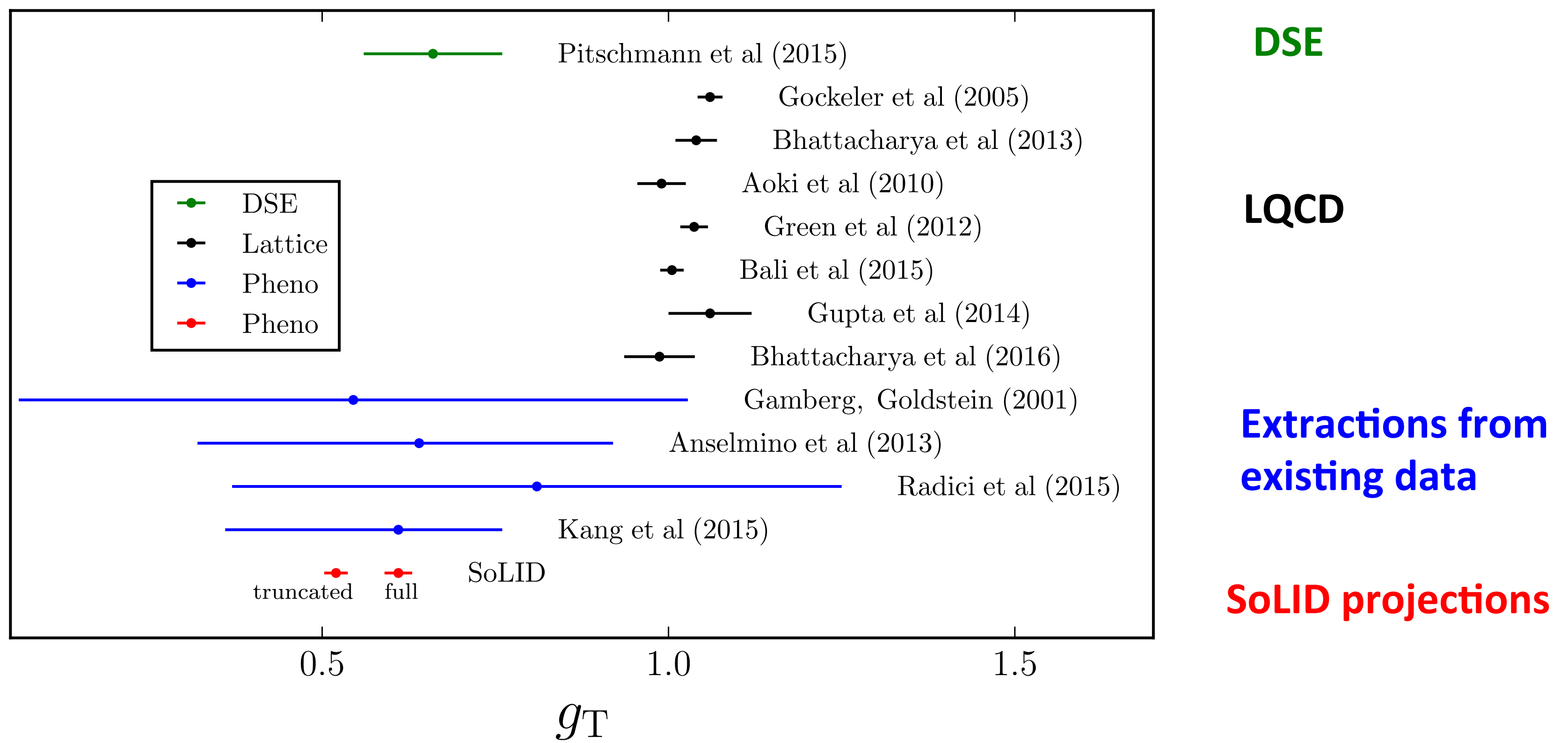

***$P_T$ vs. x for one ($Q^2$, z) bin***
***Total > 1400 data points***




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

# Tensor Charge from SoLID

- **Tensor charge (0th moment of transversity): fundamental property**
  **Lattice QCD,** Bound-State QCD (Dyson-Schwinger) , …
- **SoLID** with **trans polarized n & p** → determination of tensor charge




*Tensor Charges*

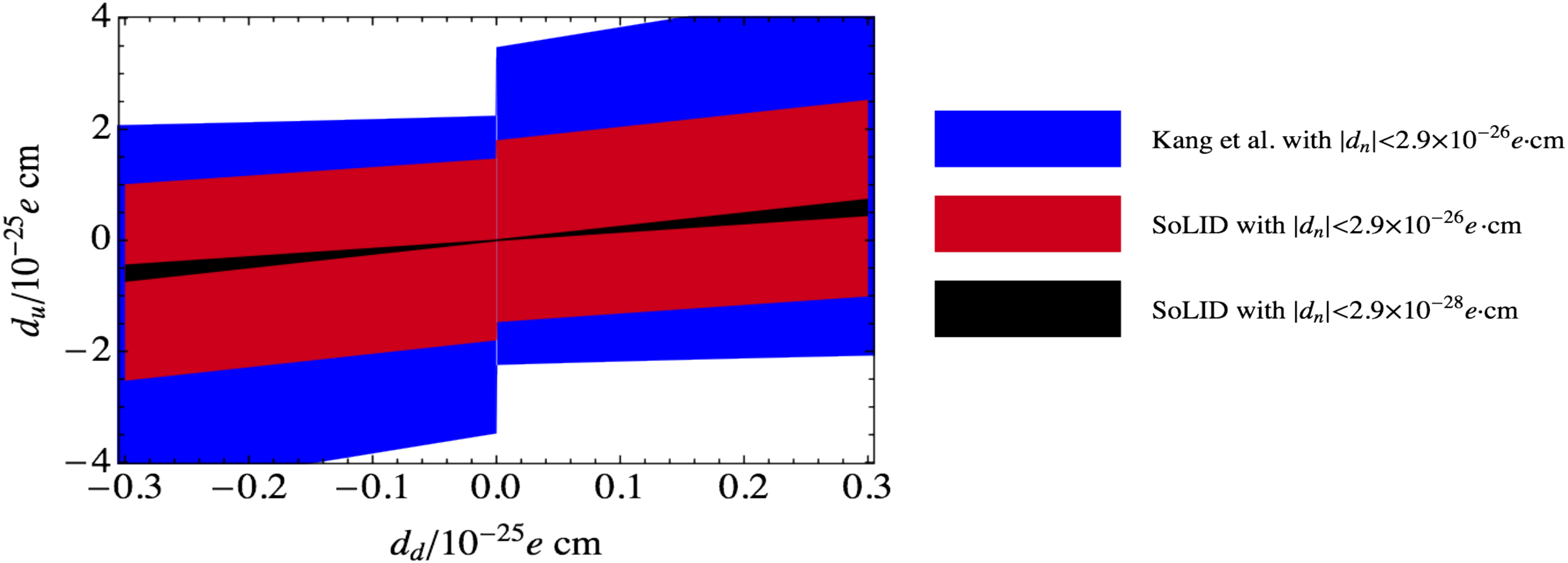
***Projections with a model QCD evolutions included***

# Tensor Charge and Neutron EDM

Electric Dipole Moment

## Tensor charge and EDM

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



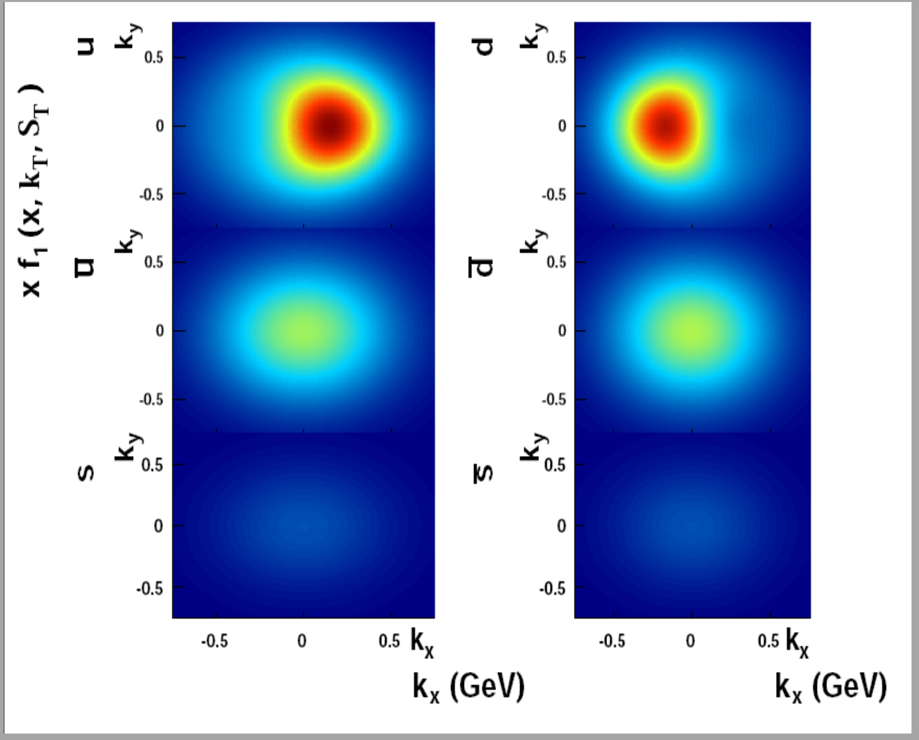

current neutron EDM limit $|d_n| < 2.9 \times 10^{-26}\, e \cdot \mathrm{cm}$

# Sivers Function

3-D Imaging, QCD dynamics

# Access to 3D imaging

$$f(x,\mathbf{k}_T,S) = f_1(x,\mathbf{k}_T^2) - \frac{[\mathbf{k}_T \times \hat{P}] \cdot S_T}{M} f_{1T}^{\perp}(x,\mathbf{k}_T^2)$$




Sivers function from experimental data HERMES and COMPASS

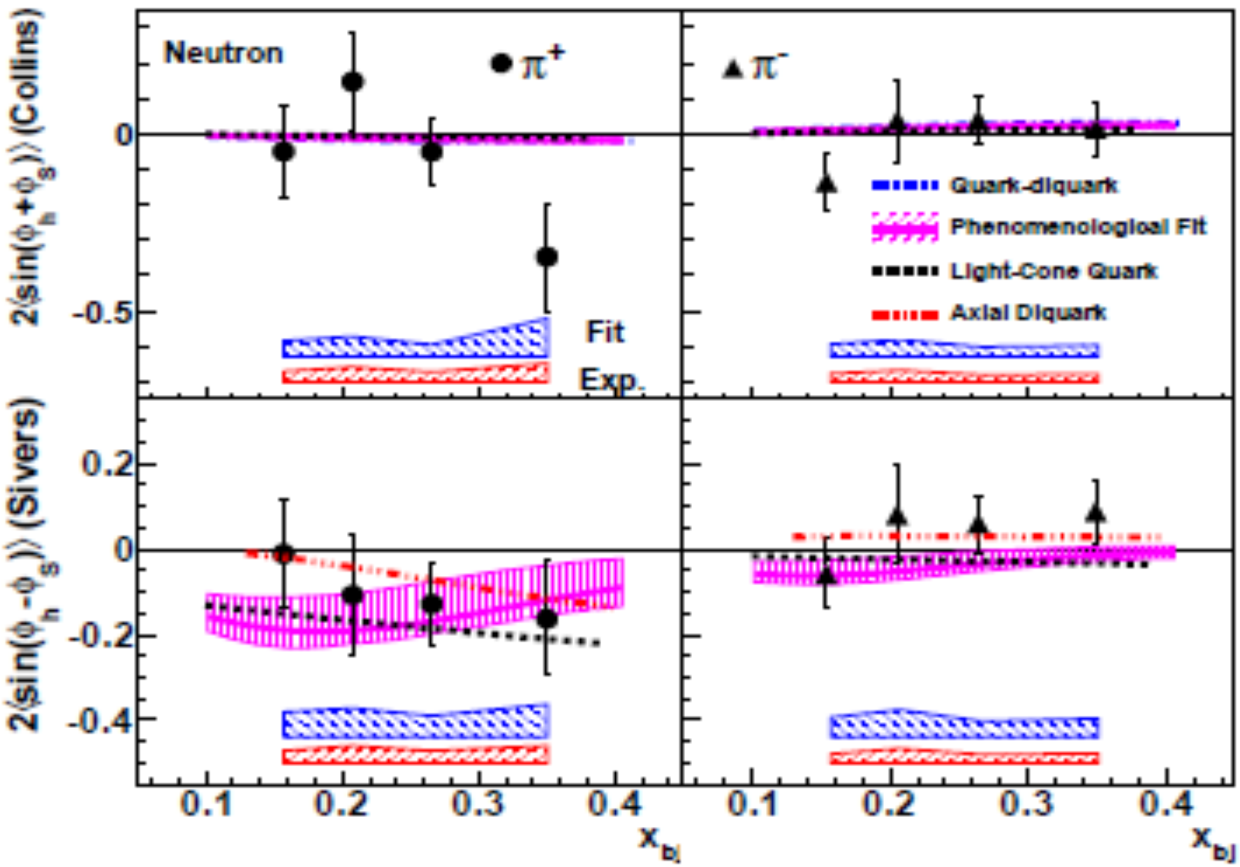
Anselmino et al 2005

**Dipole deformation**

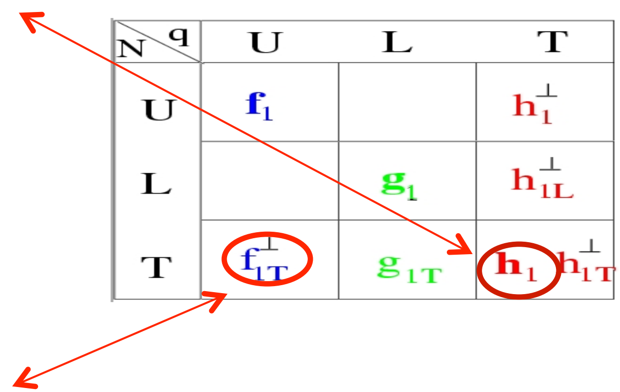
# JLab6: $^3$He (n) Target Single-Spin Asymmetry in SIDIS

**E06-010 collaboration**, X. Qian at al., **PRL 107:072003(2011)**

$$n^{\uparrow}(e,e'h), h=\pi^{+},\pi^{-}$$




**neutron Collins SSA small**
**Non-zero at highest x for π+**



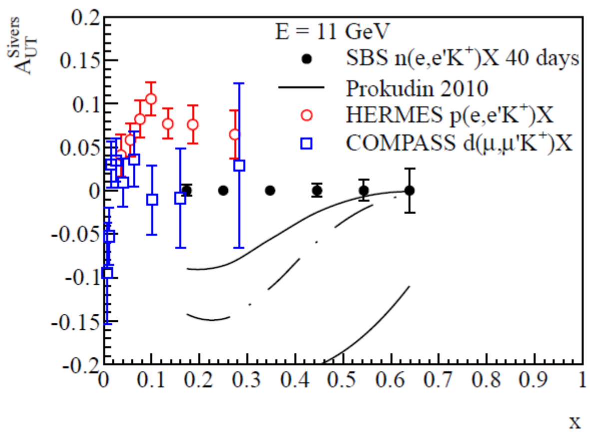

**neutron Sivers SSA:**
**negative for $\pi^+$,**
**Agree with Torino Fit**

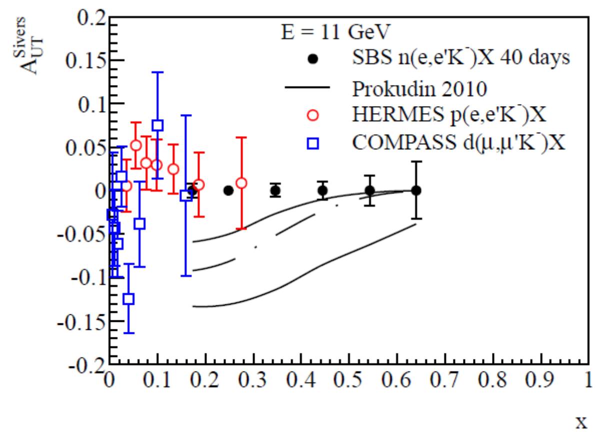
**Blue band**: model (fitting) uncertainties
**Red band**: other systematic uncertainties

# Hall A SBS Projection: pi/K Sivers

## 11 GeV SIDIS: Expected Effects

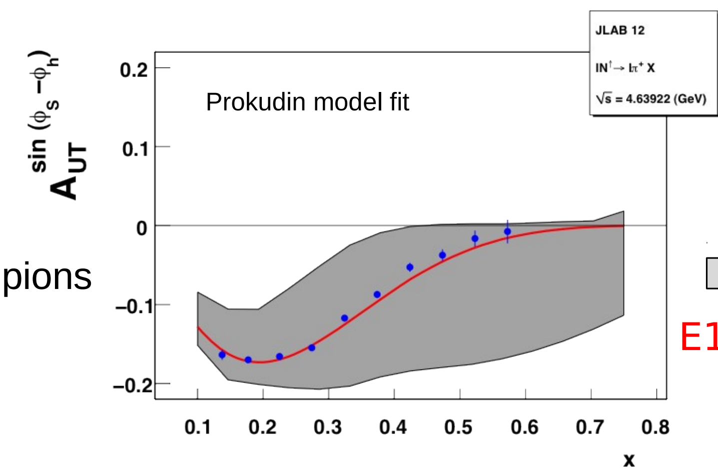
kaons



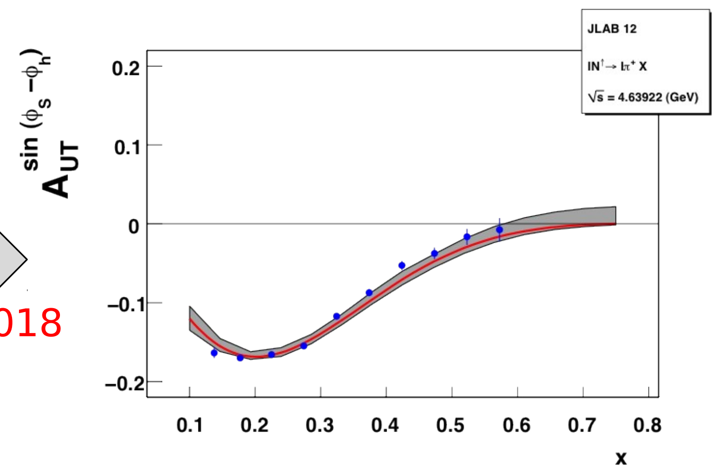




*Squeeze* model uncertainty corridor

pions

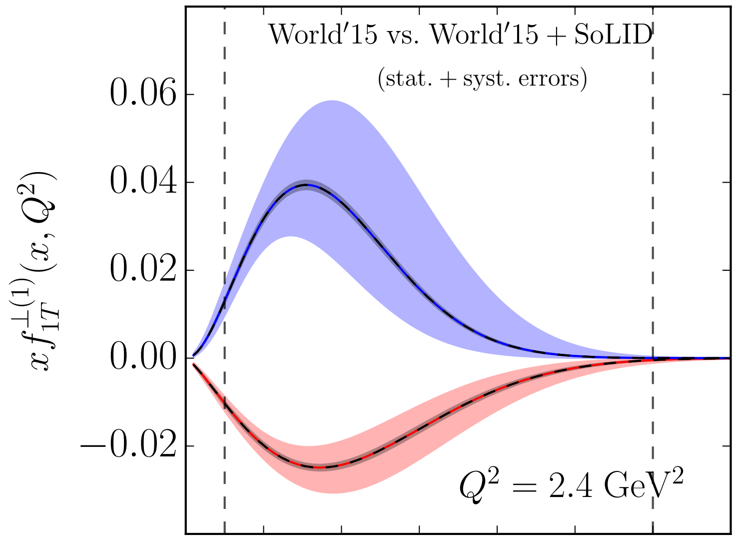



E12-09-018



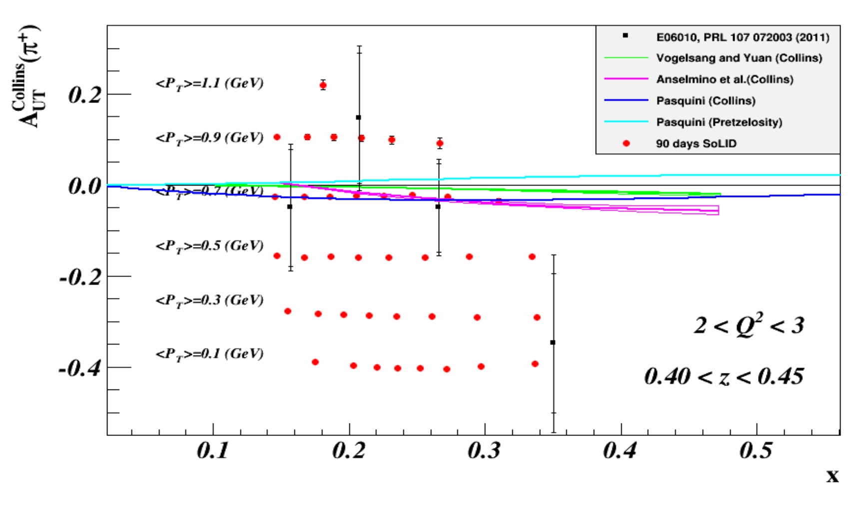
# Mapping Sivers Asymmetries with SoLID

- Sivers Asymmetries ~ Sivers Function $(x, k_T, Q^2)$ (x) Fragmentation Function $(z, p_T, Q^2)$
- Leading-twist/not Q power suppressed: Gauge Link/ QCD Final State Interaction
- Transverse Imaging
- QCD evolutions
- **SoLID**: precision multi-d mapping
- Collaborating with theory group: impact study

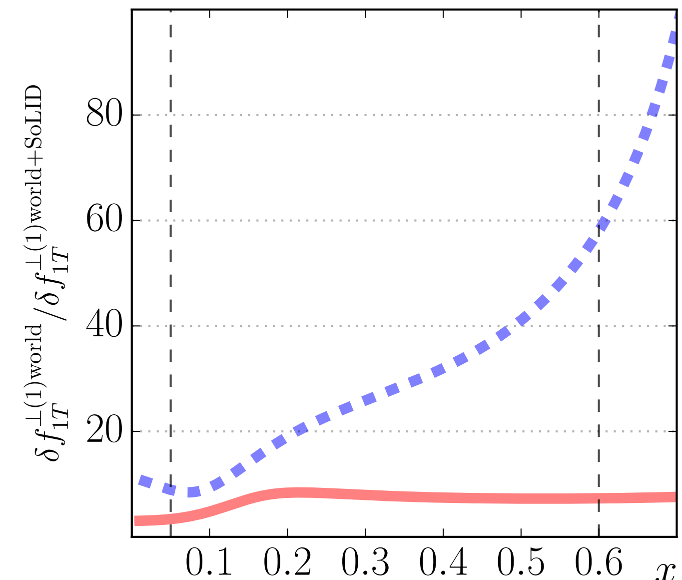



Liu, Sato, Prokudin,…

### *Sivers Asymmetries*

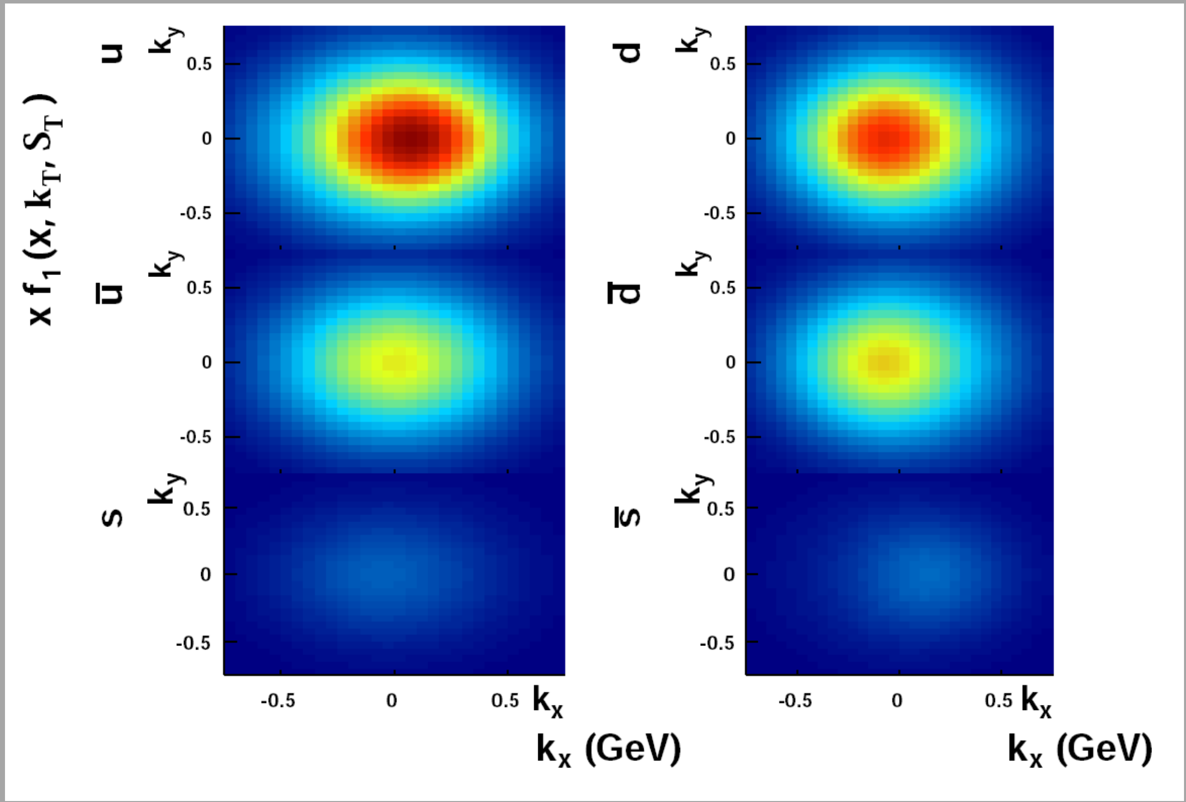



***$P_T$ vs. x for one $(Q^2, z)$ bin***
***Total > 1400 data points***



# What do we learn from 3D distributions?

$$f(x,\mathbf{k_T},\mathbf{S_T}) = f_1(x,\mathbf{k_T^2}) - f_{1T}^{\perp}(x,\mathbf{k_T^2})\frac{\mathbf{k_{T1}}}{M}$$




The slice is at:

$x = 0.1$

Low-x and high-x region is uncertain

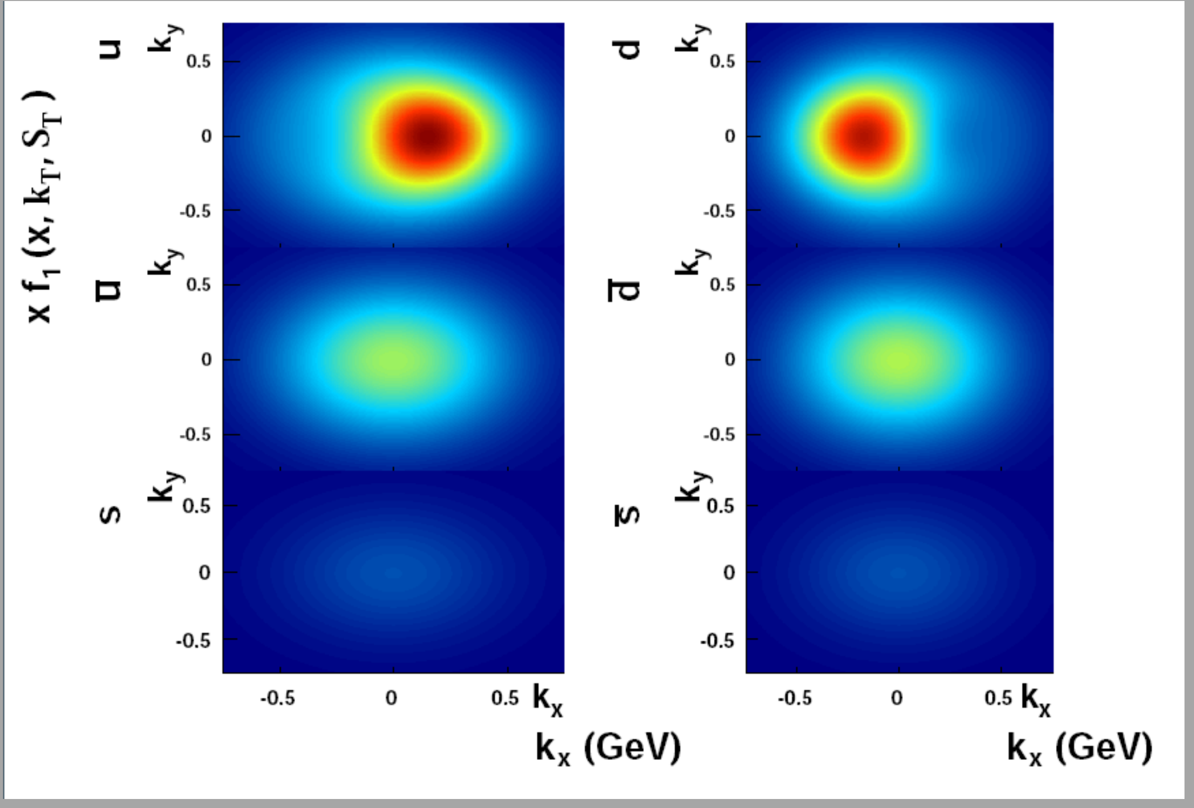
JLab 12 and EIC will contribute

No information on sea quarks

Picture is still quite uncertain

# What do we learn from 3D distributions?

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_{T1}}}{M}$$




The slice is at:

$x = 0.1$

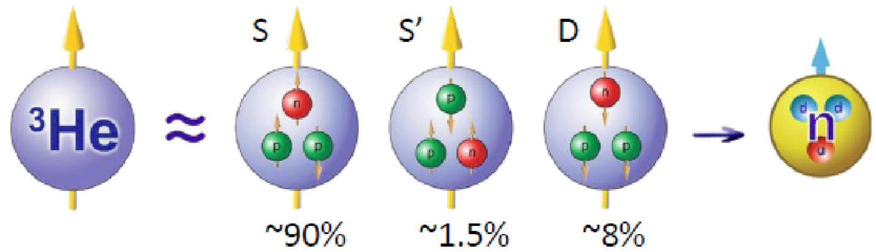
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

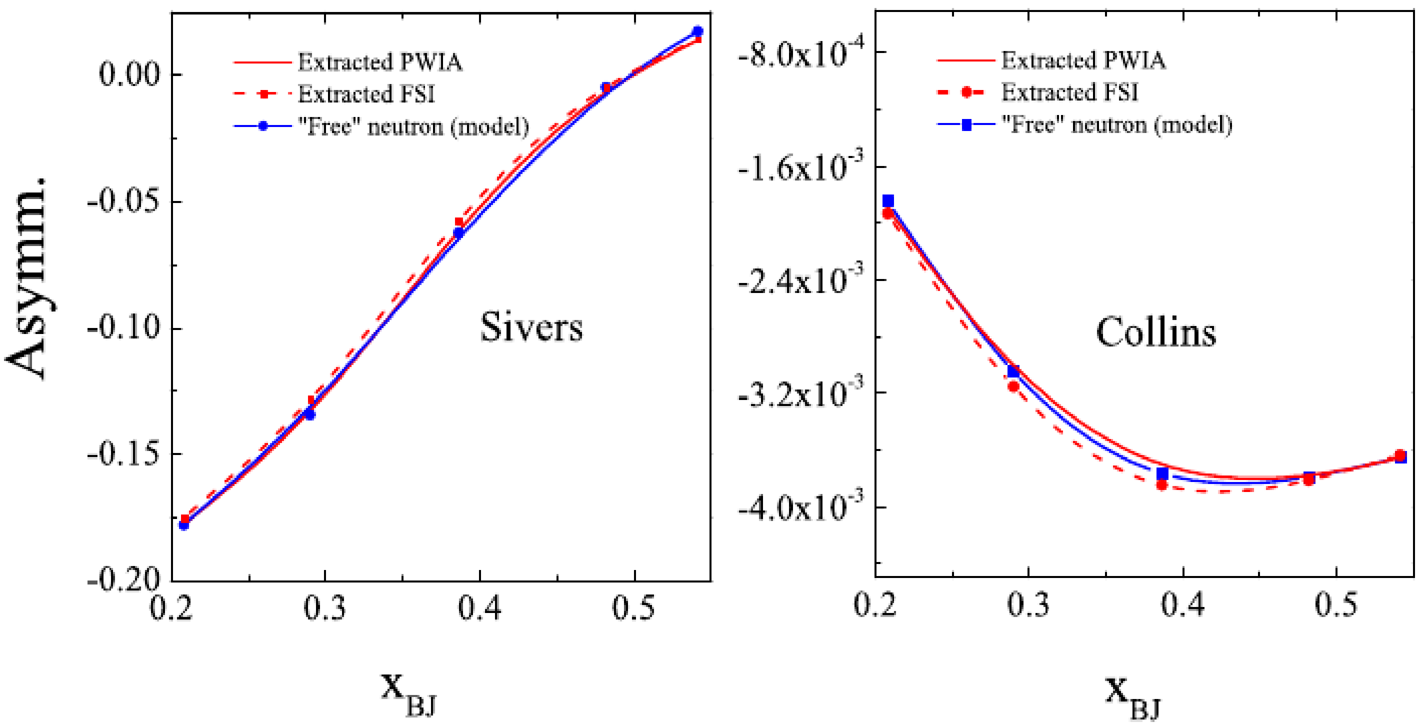
No information on sea quarks

In future we will obtain much clearer picture

# Nuclear Effect in 3He for neutron TMD Study

- Effective polarization
- PWIA
- FSI through distorted spectral function




Alessio Del Dotto et al., Few Body Syst. 56 (2015) 425-430 ; arXiv1602.06521 ; EPJ Web Conf. 113 (2016) 05010.

# TMDs and Orbital Angular Momentum

Pretzelosity ($\Delta L=2$), Worm-Gear ($\Delta L=1$),
Sivers: Related to GPD E through Lensing Function

# Quark Orbital Angular Momentum

Nucleon spin ½ = ½ ΔΣ + $L_q$ + $J_g$ Ji (gauge invariant)

= ½ ΔΣ + $\mathcal{L}_q + \Delta G + \mathcal{L}_g$ Jeffe-Manohar (light-cone)

- Spin Puzzle: missing piece, orbital angular momentum (OAM)
- Indirect evidence → OAM is significant
- Lattice Calculation: u and d cancellation?

  disconnected diagrams
- Ji's sum rule:

$$J_{q,g} = \frac{1}{2}\int dx x\left(H_{q,g}(x,0,0) + E_{q,g}(x,0,0)\right) \; ,$$

measure GPDs to access the total angular momentum

needs GPD E (and H) be measured in all x at fixed ξ

DVCS only access GPDs @ x=ξ ridge

experimentally difficult to measure GDPs at all x with fixed ξ, if not impossible

DDVCS?

# OAM and Parton Distributions

- How best to access/measure quark orbital angular momentum?

  Extensively discussed in the last decade or so

  X. Ji, et al., arXiv:1202.2843; 1207.5221

  " Thus a partonic picture of the orbital contribution to the nucleon helicity necessarily involves parton's transverse momentum. In other words, TMD parton distributions are the right objects for physical measurements and interpretation. "

- Transversely polarized nucleon: $$J_q = \frac{1}{2} \sum_i \int dx x \left[ q_i(x) + E_i(x, 0, 0) \right] ,$$

- Longitudinally polarized nucleon: related to Twist-3 GPDs (more difficult?)

- Intuitive definition: L= r x p → can be defined in Wigner Distributions

$$L(x) = \int (\vec{b}_\perp \times \vec{k}_\perp) W(x, \vec{b}_\perp, \vec{k}_\perp) d^2\vec{b}_\perp d^2\vec{k}_\perp ,$$

  access through both TMDs and GPDs

  possible direct measurement of Wigner distributions? J. Qiu, S. Liuti

- Parton spin-orbital correlations → transverse momentum

  TMDs provide direct information

- TMD information related to $\mathbf{L_q}$ and /or $\mathcal{L}_q$ ?

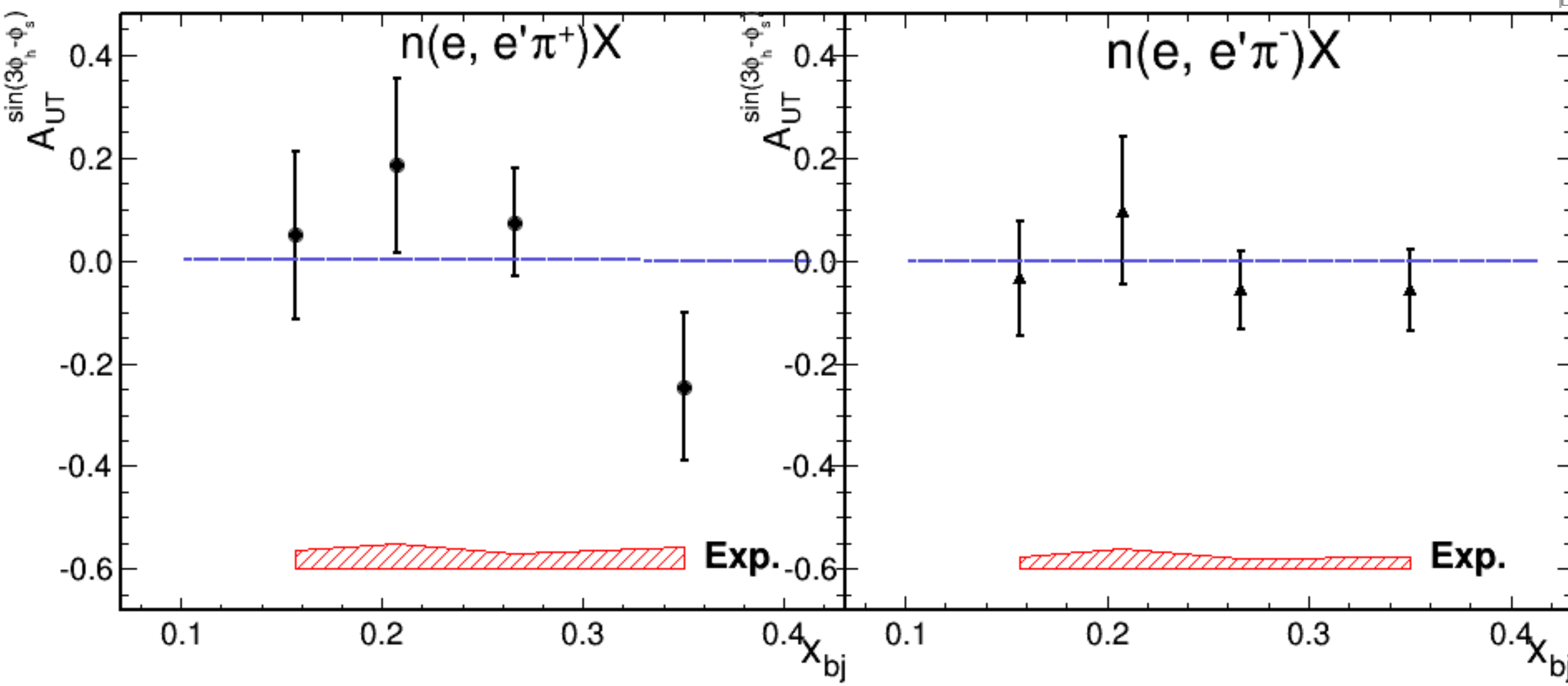
# Pretzelosity Results on Neutron

## (from E06-010)

Y. Zhang, et al., PRC 90 5, 055209(2014)

| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_1$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$ $h_{1T}^\perp$ |

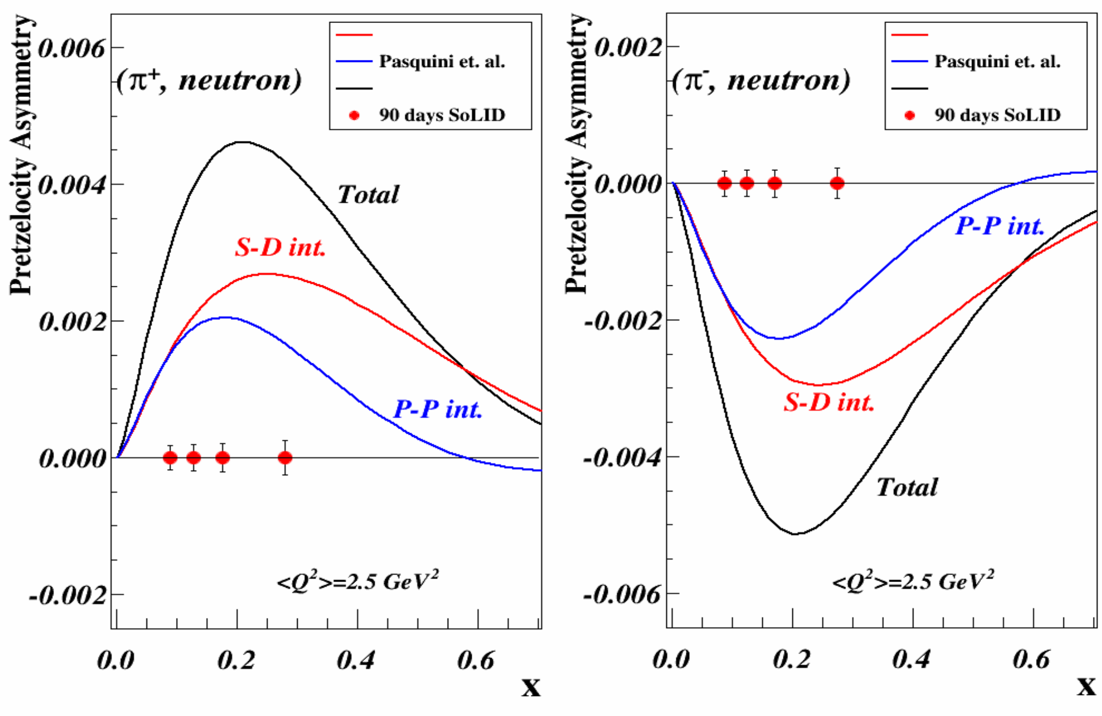
## Extracted Pretzelosity Asymmetries




In models, directly related to OAM, L=0 and L=2 interference

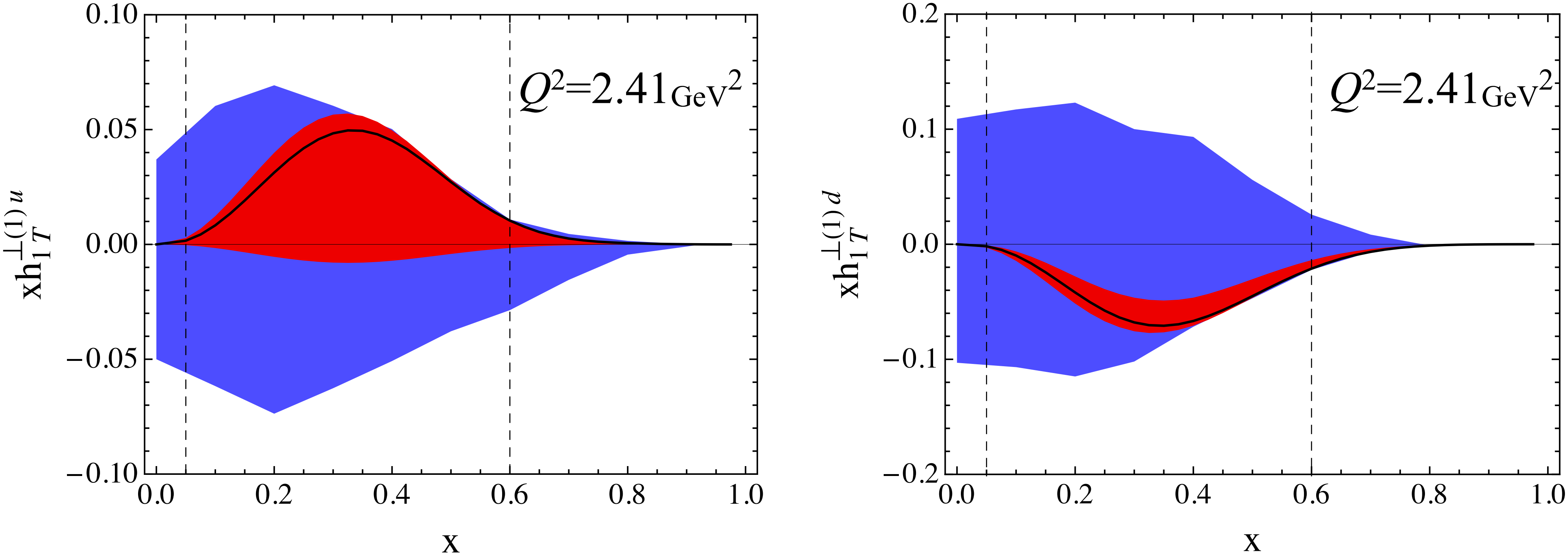
# TMDs: Access Quark Orbital Angular Momentum

- TMDs : Correlations of transverse motion with quark spin and orbital motion
- **Without OAM, off-diagonal TMDs=0**,
  no direct model-independent relation to the OAM in spin sum rule yet
- Sivers Function: QCD lensing effects
- In a large class of models, such as light-cone quark models
  **Pretzelosity: ΔL=2 (L=0 and L=2 interference , L=1 and -1 interference)**
  **Worm-Gear: ΔL=1 (L=0 and L=1 interference)**
- **SoLID with trans polarized n/p → quantitative knowledge of OAM**




**SoLID Projections Pretzelosity**

# *SoLID Impact on Pretzelosity*




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

SoLID transversely polarized $^3$He, E12-10-006.

95% C.L.

Duke UNIVERSITY

*by Tianbo Liu (Duke & DKU)*

昆山杜克大学 DUKE KUNSHAN UNIVERSITY

# Angular Momentum (1)

**T. Liu**

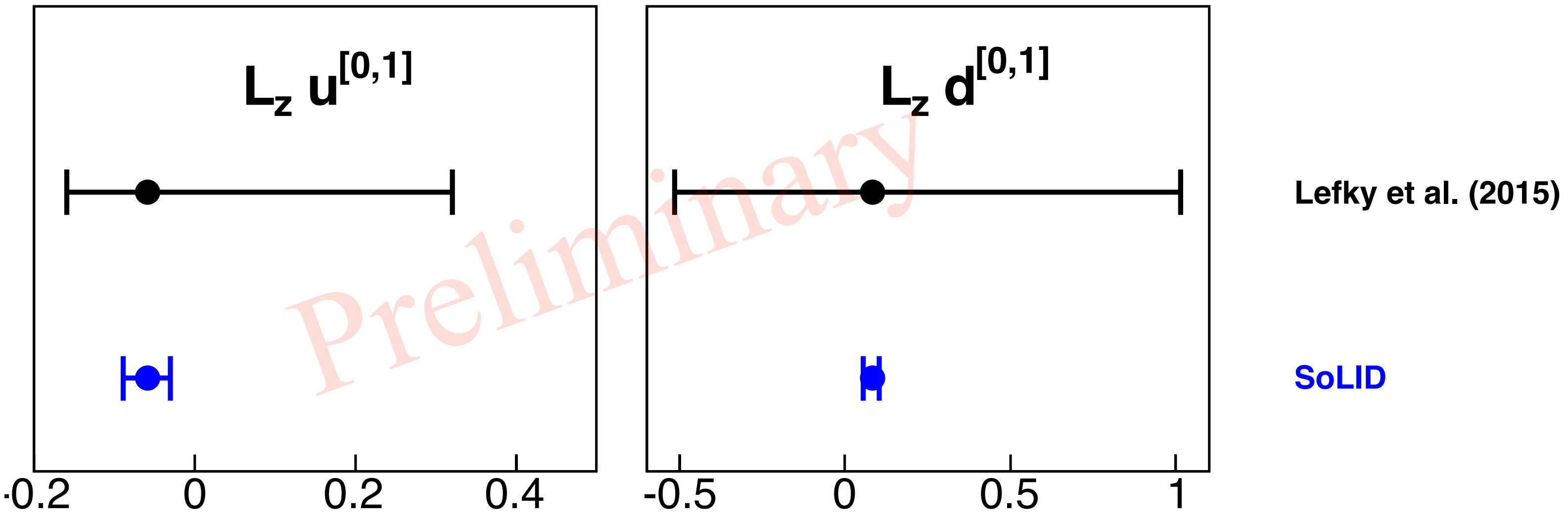
## OAM and pretzelosity:

model dependent

$$L_z = -\int d\,x\,d^2\,k_\perp\,\frac{k_\perp{}^2}{2\,M_p^2}\,h_{1T}^\perp\left(x,k_\perp{}^2\right)$$

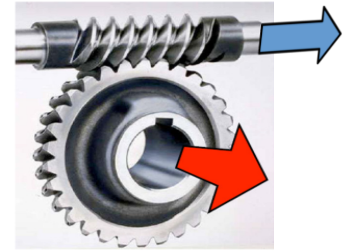
J. She *et al.*, PR D 79, 058008 (2009).

## SoLID impact:



# 6 GeV Exploration: Asymmetry $A_{LT}$ Results

E06-010, J. Huang et al., **PRL. 108, 052001 (2012).**



Worm-Gear
Trans helicity

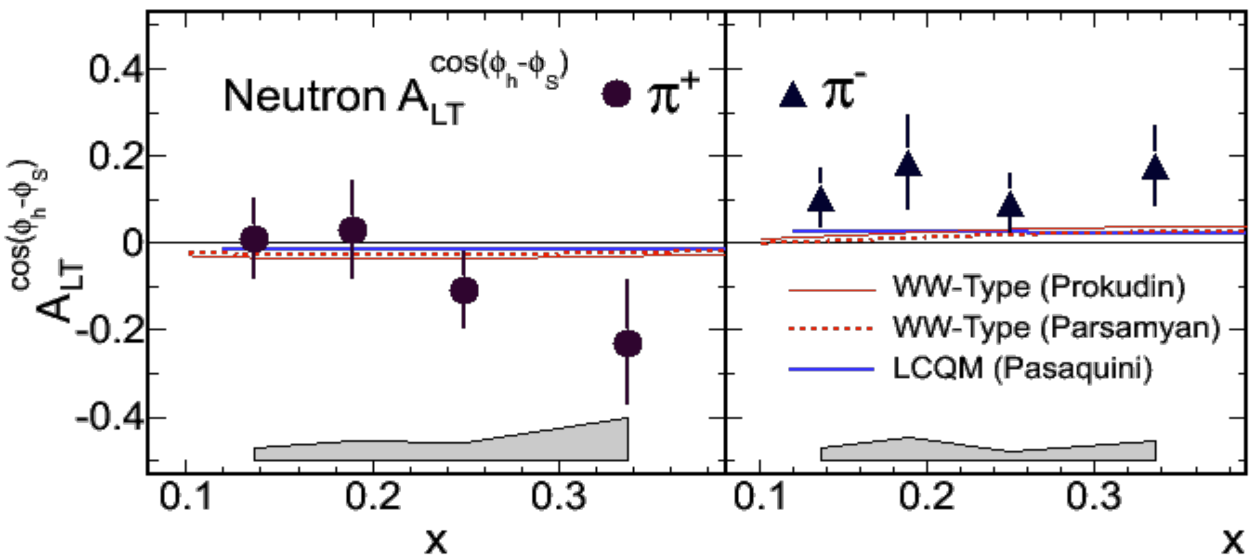
*To leading twist:*

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

***Dominated by L=0 (S) and L=1 (P) interference***

| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_1$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$ $h_{1T}^\perp$ |

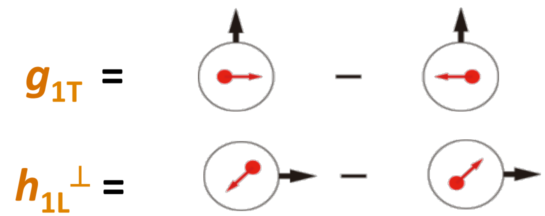
- **neutron $A_{LT}$: Positive for π-**
- **Consist w/ model in signs, suggest larger asymmetry**

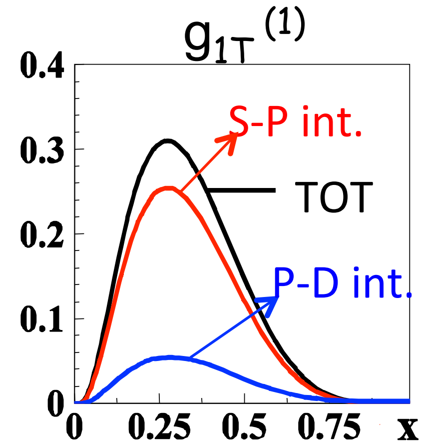


# Worm-gear Functions

## SoLID Projections

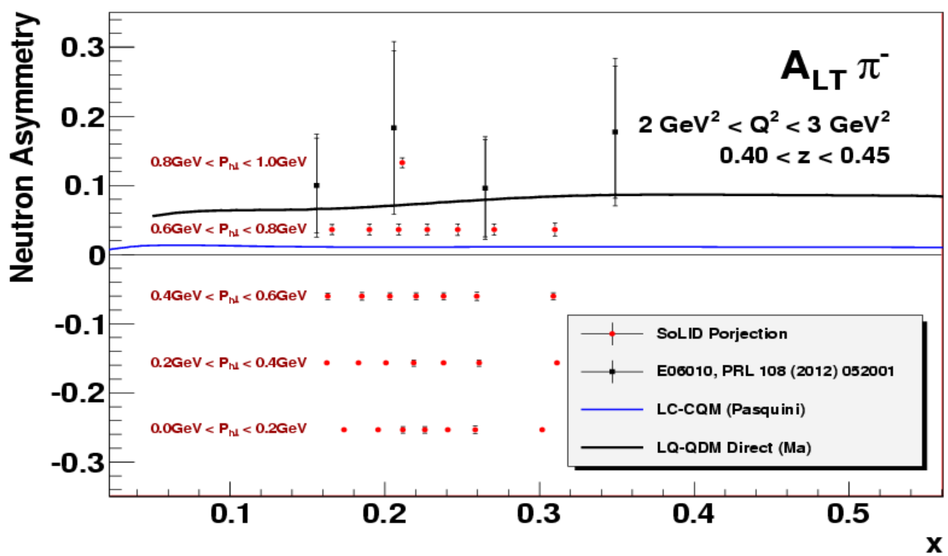
- Dominated by real part of interference between **L=0 (S) and L=1 (P) states**
- No GPD correspondence
- Exploratory lattice QCD calculation:
  Ph. Hägler et al, EPL 88, 61001 (2009)

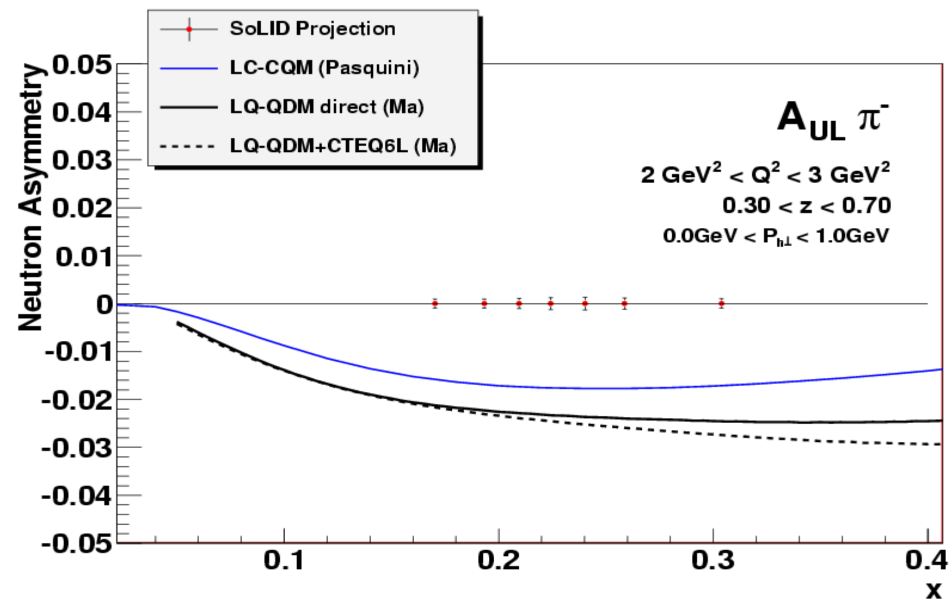



Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

SoLID Neutron Projections,




$$A_{LT} \sim g_{1T}(x) D_1(z)$$

$$A_{UL} \sim h_{1L}^{\perp}(x) \otimes H^{\perp}{}_1(z)$$

# Angular Momentum (2)

Sivers and GPD *E*:

model dependent

$$f_{1T}^{\perp(0)}(x, Q_0^2) = -L(\mathrm{x})\, E\left(x, 0, 0, Q_0^2\right)$$

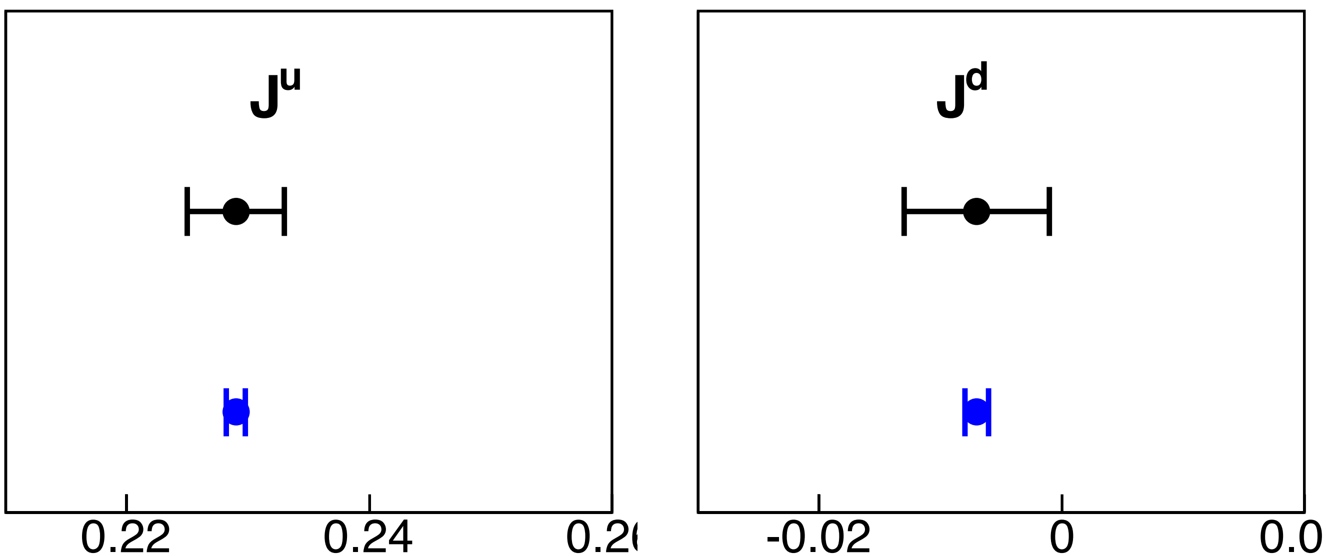
$$L(\mathrm{x}) = \frac{\mathrm{K}}{(1-x)^{\eta}}$$ lensing function

A. Bacchetta *et al.*, PR L 107, 212001 (2011).

K and η are fixed by anomalous magnetic moments $\kappa^p$ and $\kappa^n$.

$$J = \frac{1}{2}\int dx\, x\,[\,H(x,0,0) + E(x,0,0)\,]$$

SoLID:



# *Summary*

- TMDs:
  - transverse imaging
  - transverse spin, tensor charge
  - QCD dynamics
  - access quark orbital angular momentum
- **JLab-**TMD Program
  - Multi-Hall to study TMDs from all directions
  - Precision multi-dimensional mapping in the valence region

EIC will continue the study for sea quarks and gluons

**→Understanding nucleon 3-d structure, study QCD dynamics, quark orbital angular momentum and more**