SIDIS Program at JLab Hall A and C

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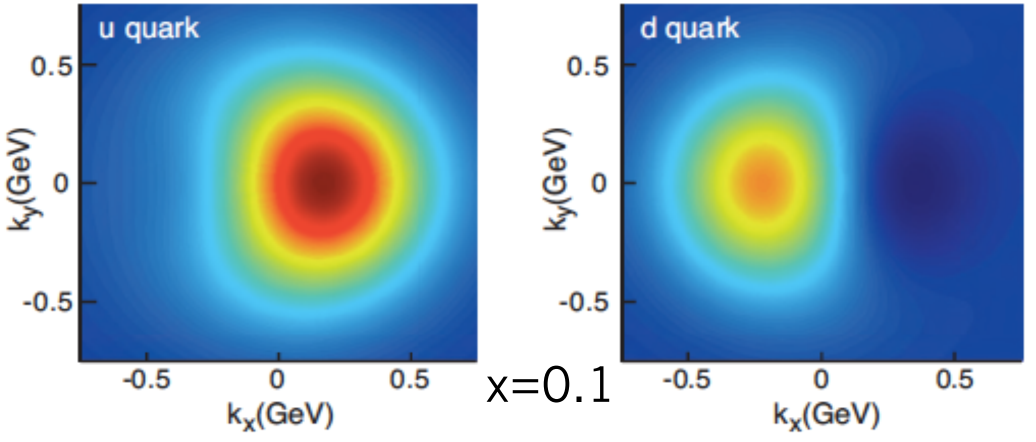
FF2019 Workshop @ Duke, March 14-16, 2019

- Introduction: SIDIS - Convolution of PDFs and Fragmentation Functions
- Results from JLab 6 GeV Experiments and 12 GeV Program
- Multi-Hall SIDIS Program
- ➢ Hall C: high luminosity/small acceptance
  cross sections, L/T separation, P_T study
- ➢ Hall B: medium luminosity/large acceptance, polarized p
- ➢ Hall A/SBS: high luminosity/medium acceptance, polarized n
- ➢ **Hall A/SoLID: high luminosity/large acceptance with polarized n/p**
  precision 4-d mapping of TMD asymmetries
- Summary

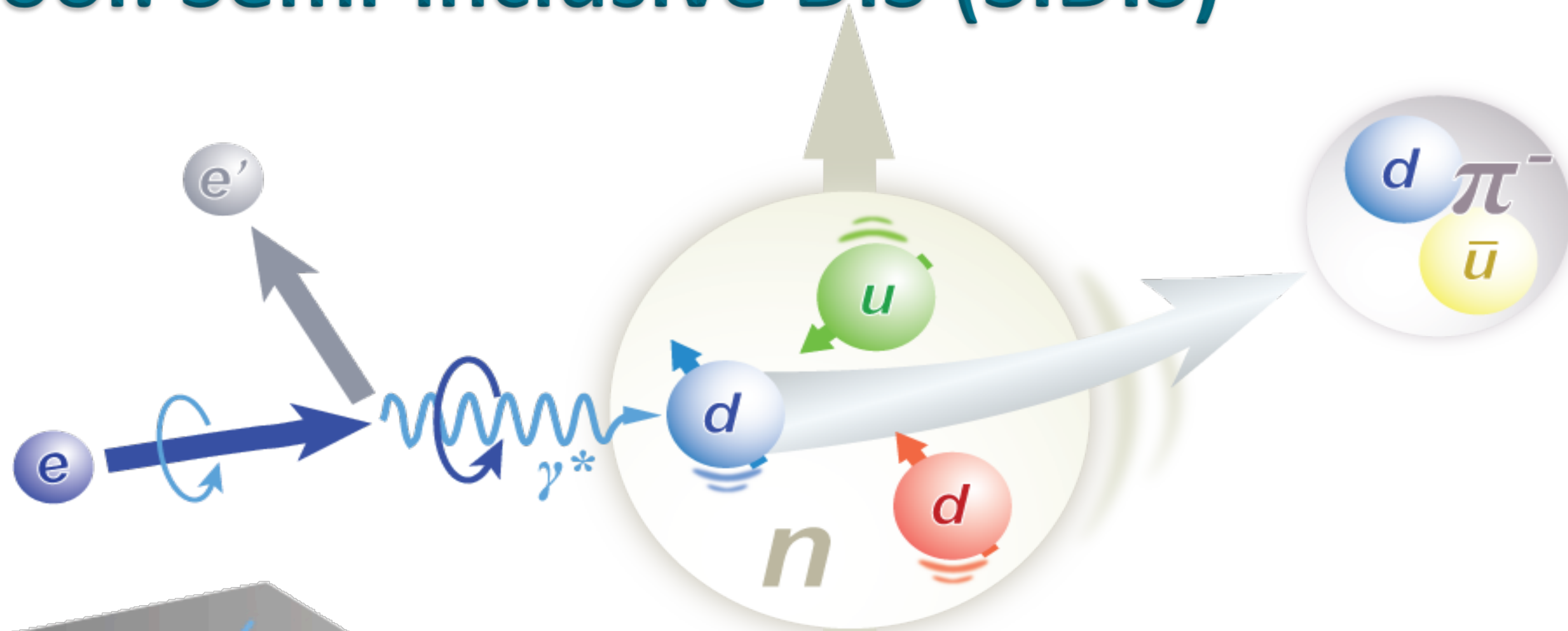
Thanks to my colleagues for help with slides: Transversity/Hall A and SoLID collaborators
and D. Gaskell, R. Ent for Hall C slides, A. Puckett … for SBS slide

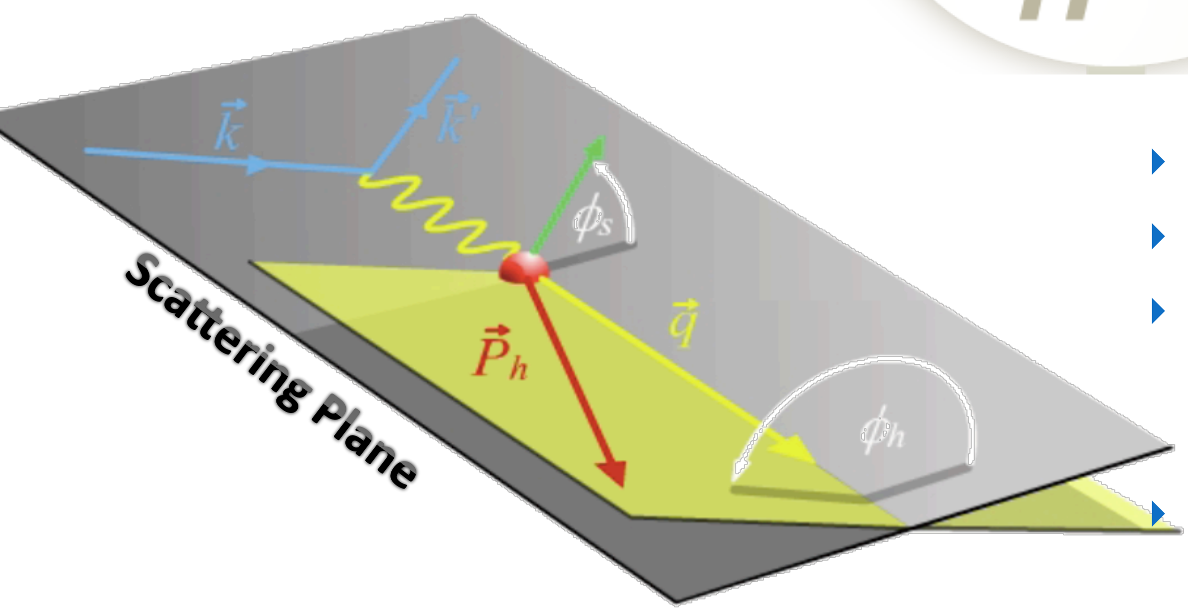
Introduction: SIDIS

1-d: Spin-Flavor Structure and Fragmentation Functions
3-d: TMDs: Transverse Momentum Dependent PDFs and Transverse Momentum Dependent Fragmentation Functions



Tool: Semi-inclusive DIS (SIDIS)





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

1-d: Spin Flavor Structure

- SIDIS for flavor tagging: (P_T integrated)

1. unpolarized: E00-108, E12-06-104, E12-09-002, E12-09-011, E12-09-017, E12-13-007 @ Hall C

   L/T separations for both pions and Kaons, study factorization

2. polarized lepton on longitudinally polarized nucleon

   HERMES/COMPASS/JLab6

   JLab12: e-p (E12-06-109 @ Hall B)

   e-n (^{3}He) (PR12-09-013, PR12-14-008, E12-11-007 @ Hall A)

   tagging pi+, pi-, K+, K-

   8 observables + 2 from inclusive channels

   LO: → 6 polarized light quark PDFs + 4 fragmentation functions

   NLO: some combinations might help to work at NLO level

   in general: global fits (combining with e+e- and pp, …)

- Issues:

1. experimentally only finite PT range covered
2. in current fragmentation region? more significant for Kaons: Kaon FF?

Leading-Twist TMD PDFs

Nucleon Spin

Quark Spin

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: 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 $h_{1T}^{\perp}$ Pretzelosity

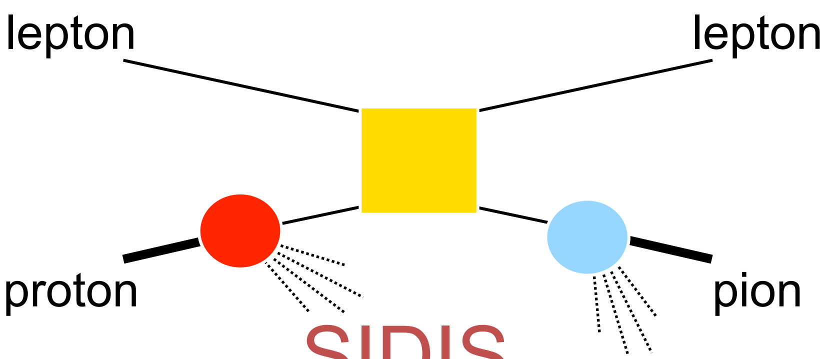
TMD Fragmentation Functions

quark pol.

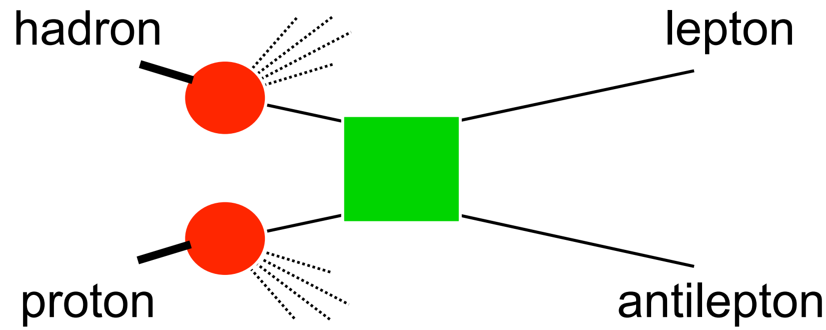
hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	$G_{1T}^\perp$	$H_1 \; H_{1T}^\perp$

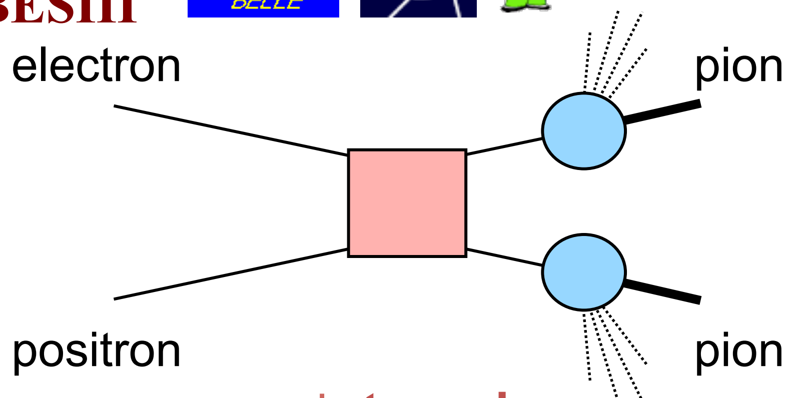
Access TMDs through Hard Processes



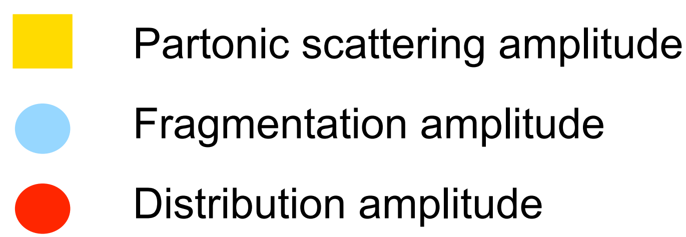
SIDIS



Drell-Yan



e^-e^+ to pions



JLab 6 GeV SIDIS Experiments

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

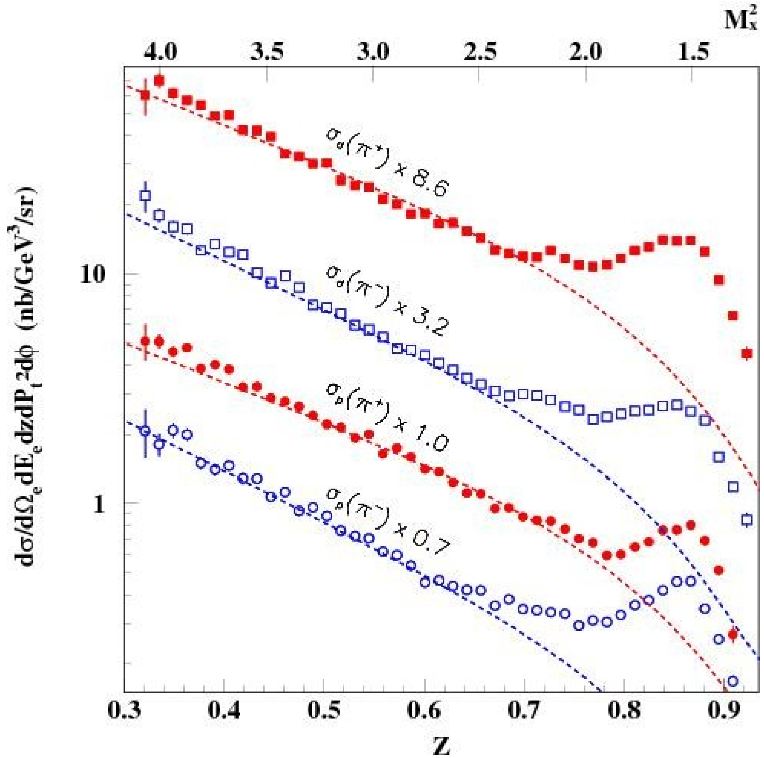
Is JLab Energy High Enough?

- **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.

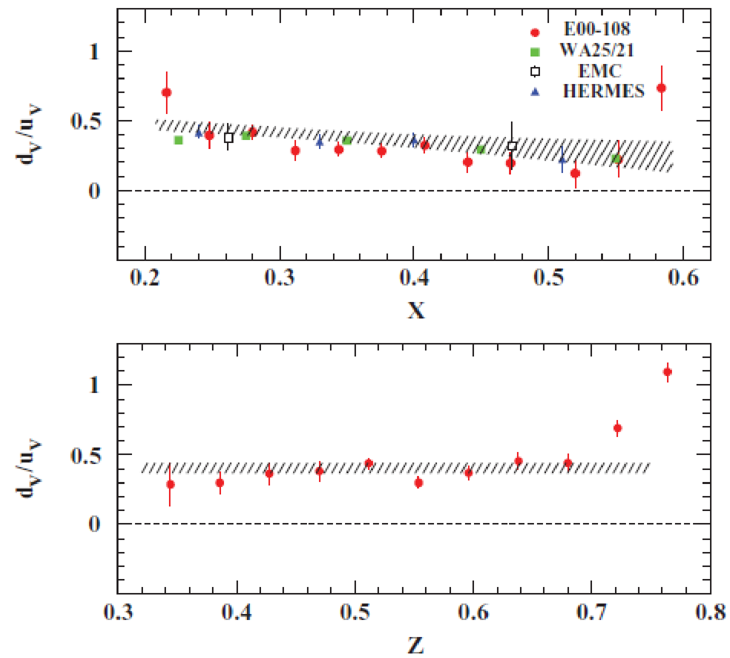
$e + LH_2/LD_2 \rightarrow e' + \pi+/\pi- + X$

Ebeam=5.5 GeV



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

bands evaluated using CTEQ PDFs

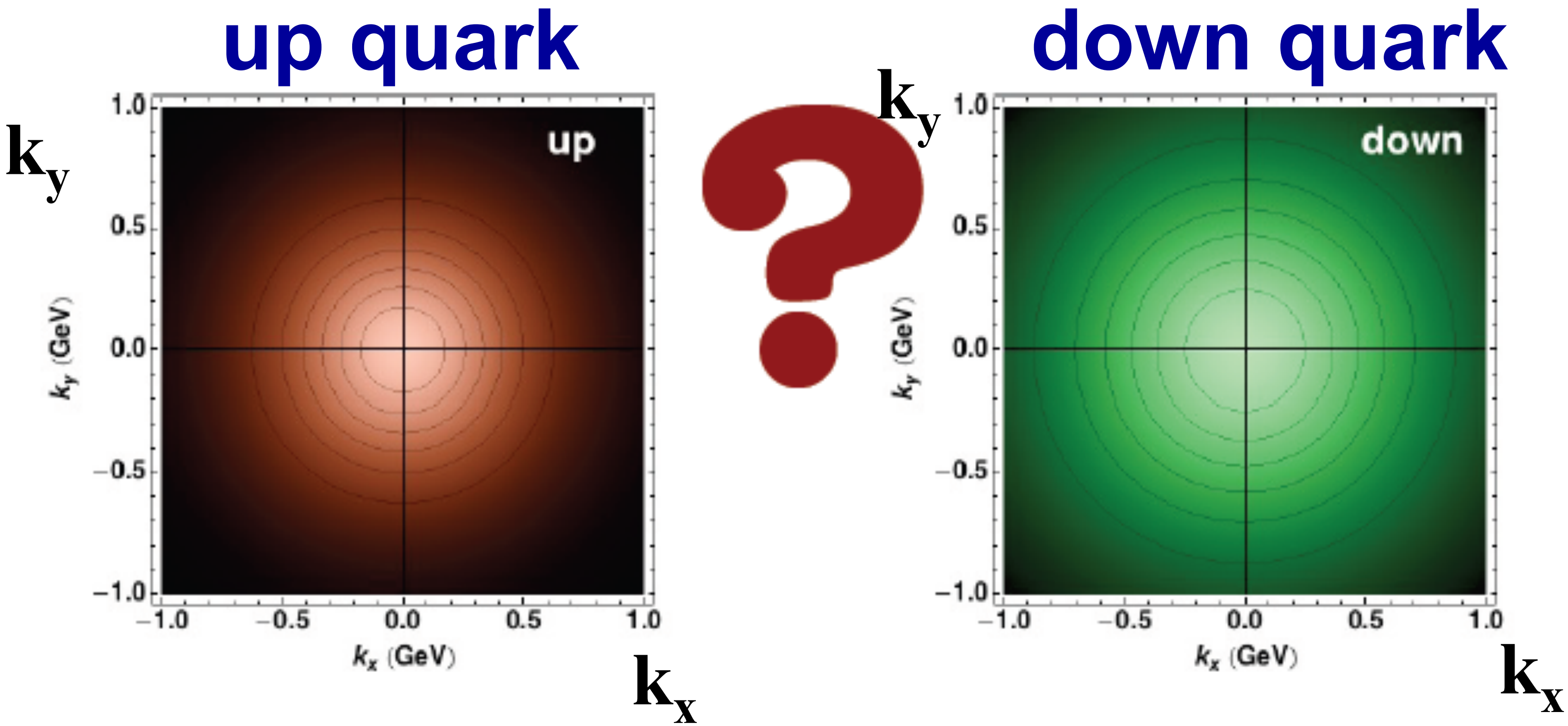


R. Asaturyan et al. PRL 85, 015202 (2012)

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

Unpolarized TMD: Flavor P_T Dependence?

Flavor in transverse-momentum space

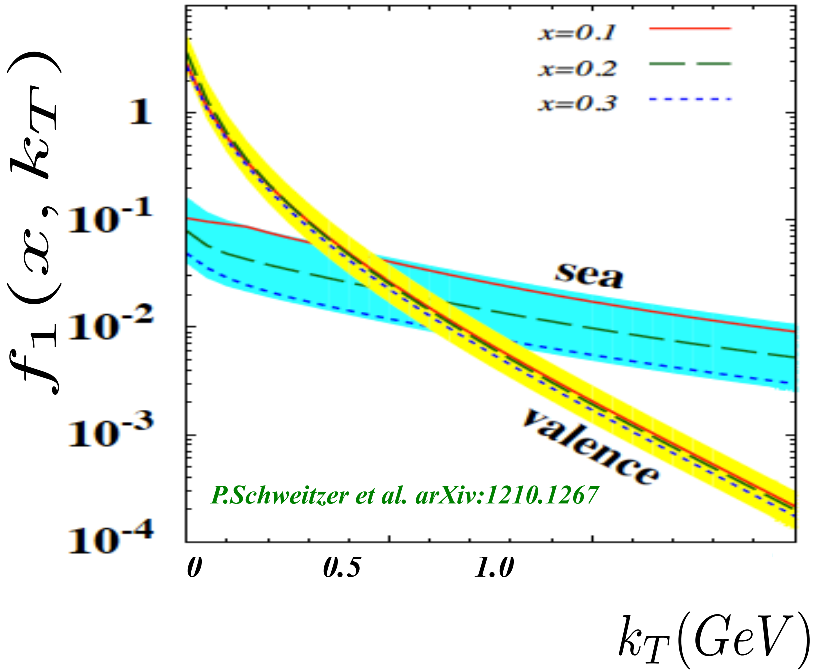


Is the up distribution wider or narrower than the down?
And the sea?
How wide are the distributions?

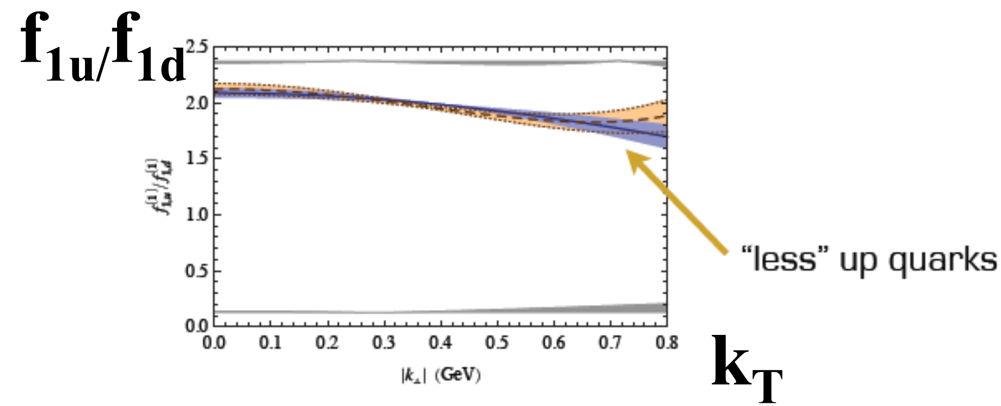
A. Bacchetta, Seminar @ JLab, JHEP 1311 (2013) 194

Flavor P_T Dependence from Theory

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



Indications from lattice QCD



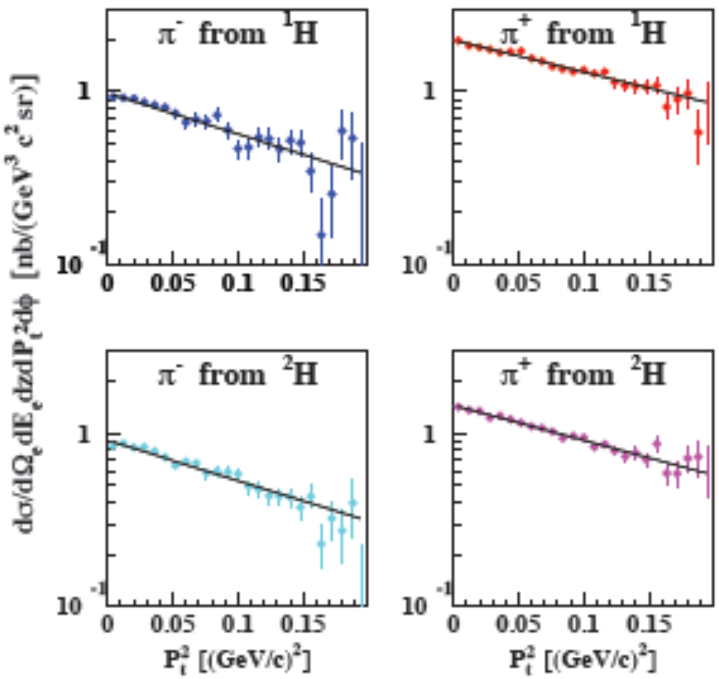
Musch, Hagler, Negele, Schafer, PRD 83 (11)

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

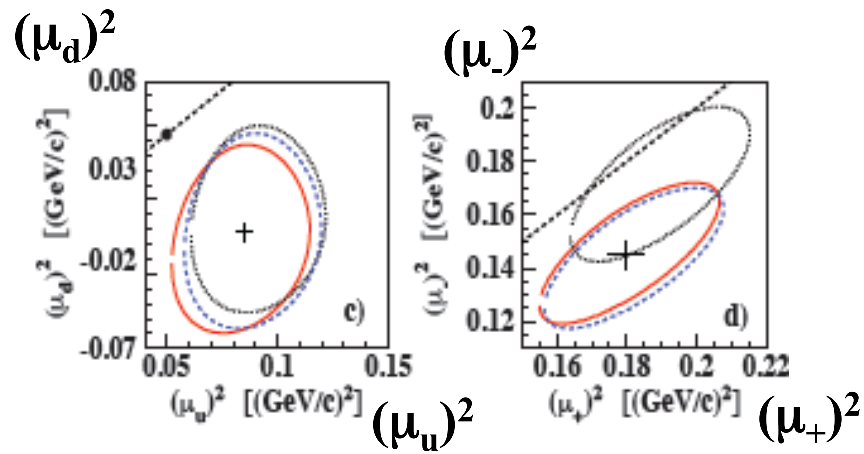
Hall C Results: Flavor P_T Dependence

First indications from experiments



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

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



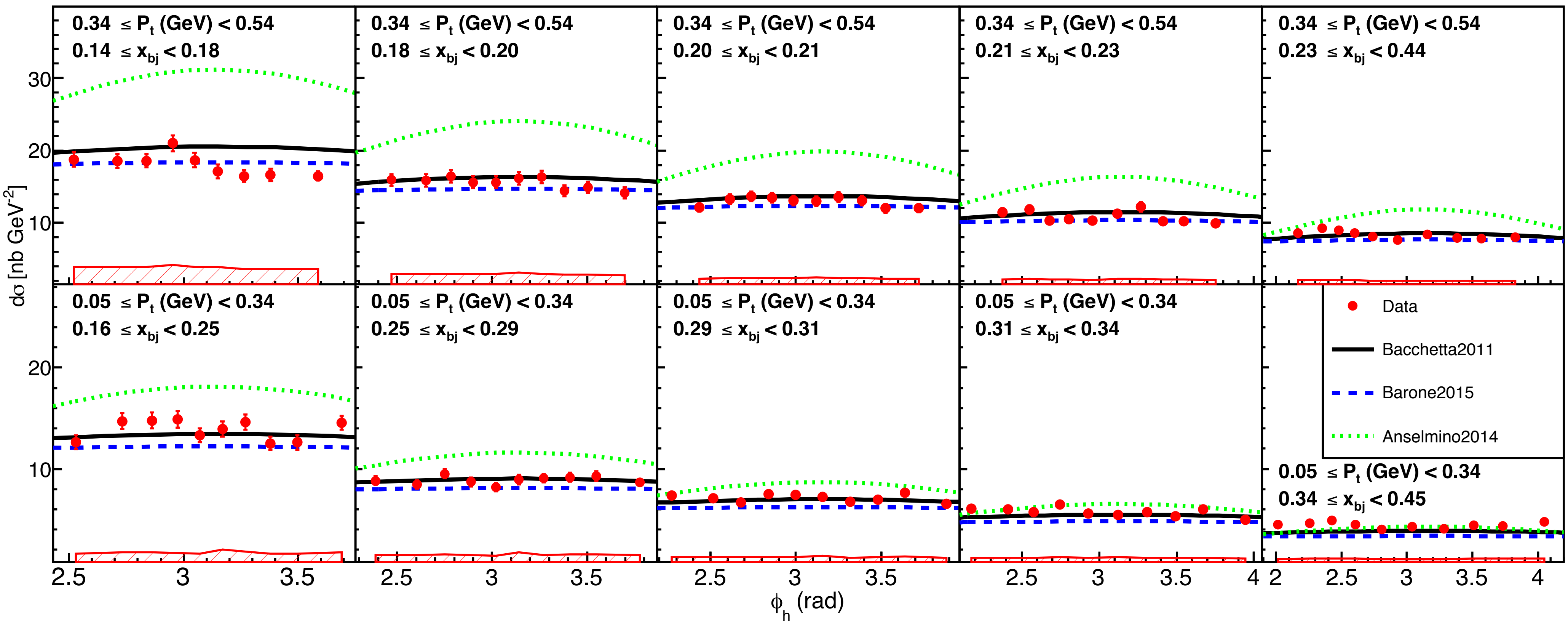
Conclusion: up is wider than down and favored wider than unfavored

Jefferson Lab

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

pi+ and pi- production on He3

X. Yan *et al.*, Hall A Collaboration, *PRC 95 (2017) 035209*

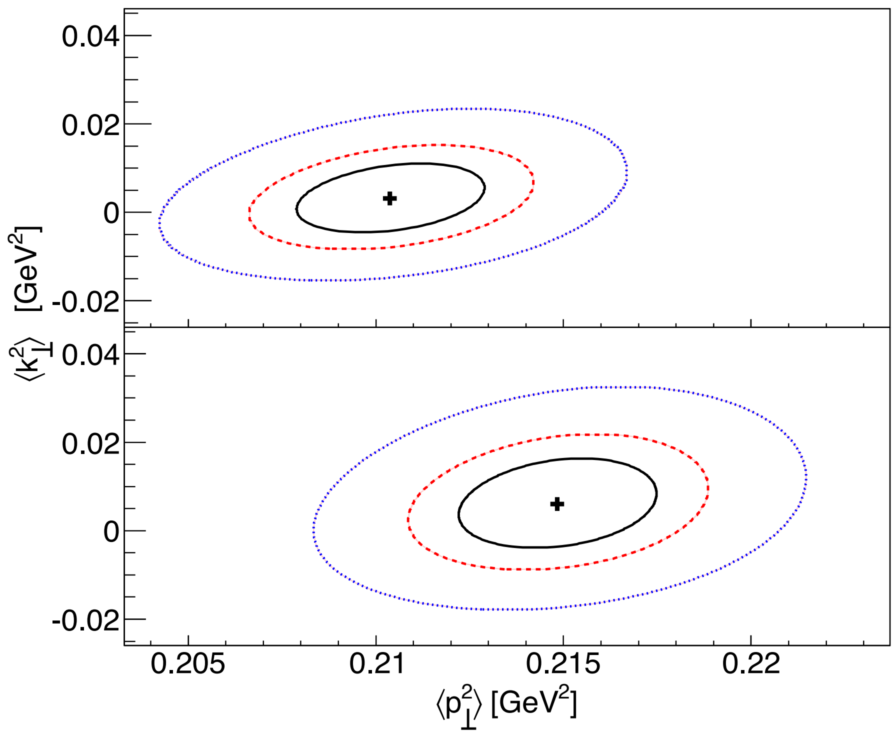


pi+ results **Φ_h (rad)**

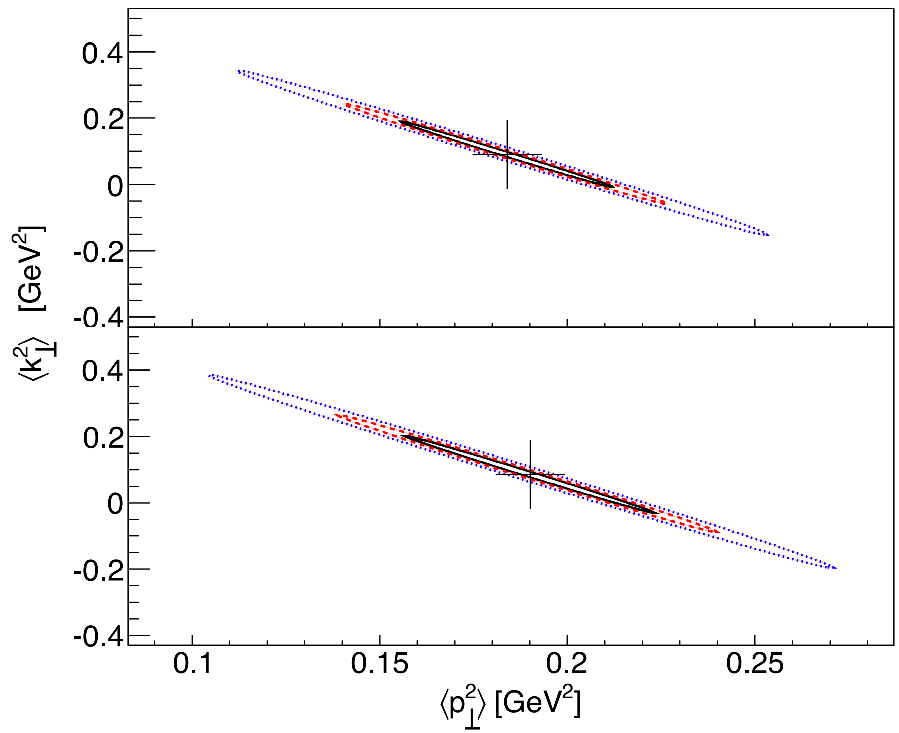
Hall A Results: Transverse Momentum dependence

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

with modulation



no modulation



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

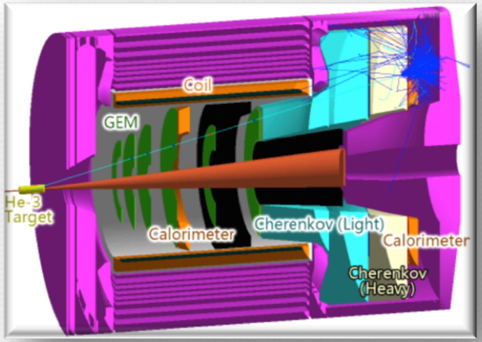
  Transversity: fundamental *PDF*s, tensor charge
- *TMD*s: 3-d momentum structure of the nucleon

  → 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

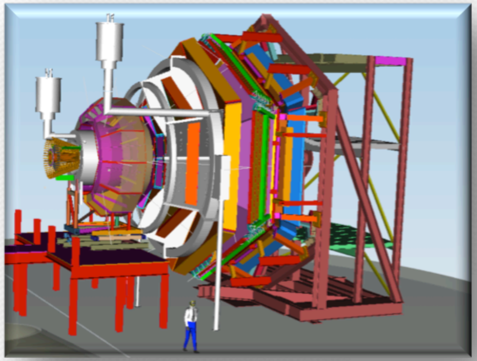
JLab 12: Multi-Halls TMD Program

Hall A/SOLID
High Lumi and acceptance – 4D



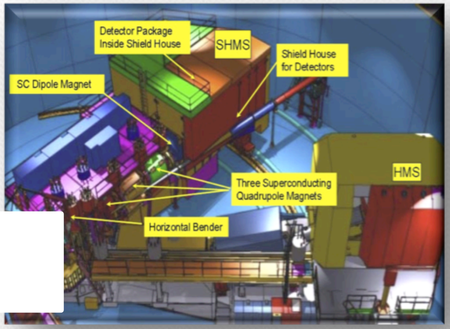
^3He, NH_3

Hall B/CLAS12
General survey, medium luminosity



H_2/D_2,
NH_3/ND_3, HD

Hall C/SHMS
L-T studies, precise π^+/π^- ratios



H_2 D_2

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

Hall C – Cross Sections in SIDIS

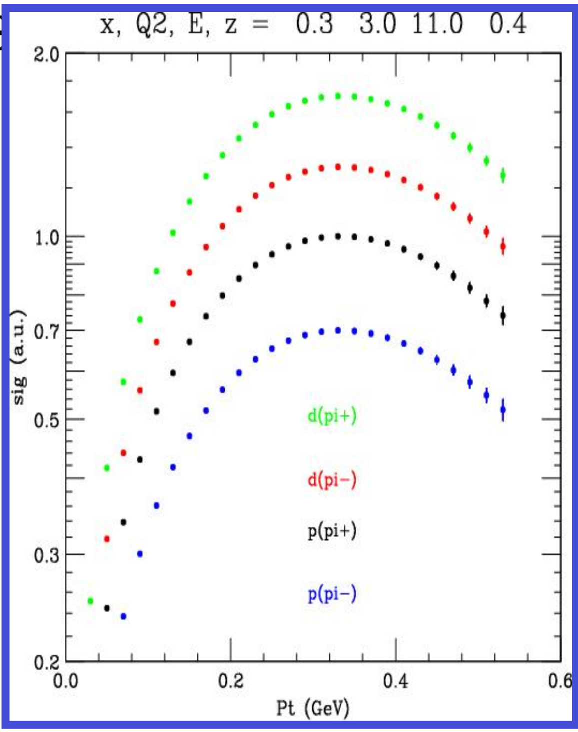
$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

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

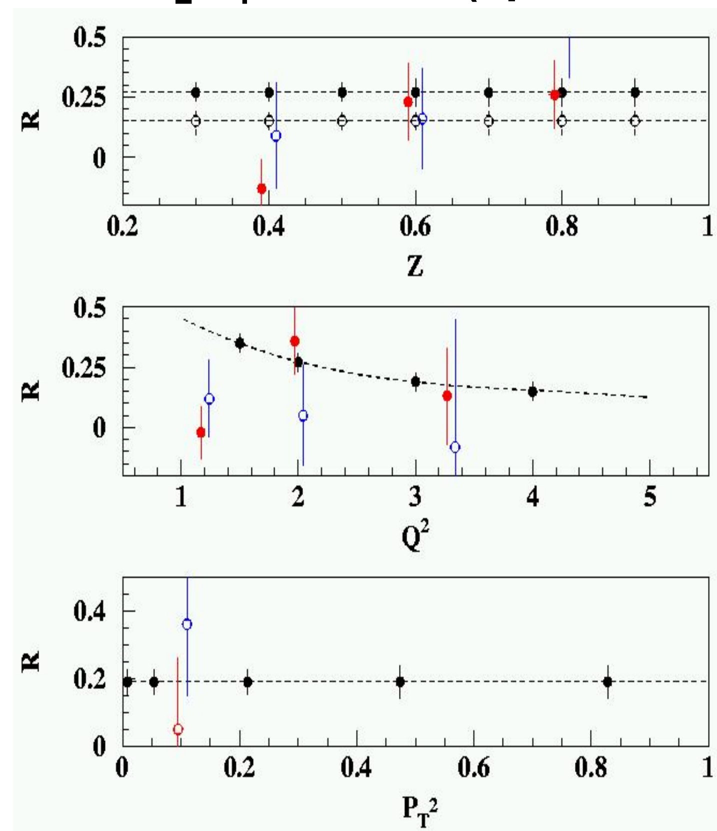


SHMS/HMS will allow precise L-T separations

→ Does $R_{DIS} = R_{SIDIS}$?

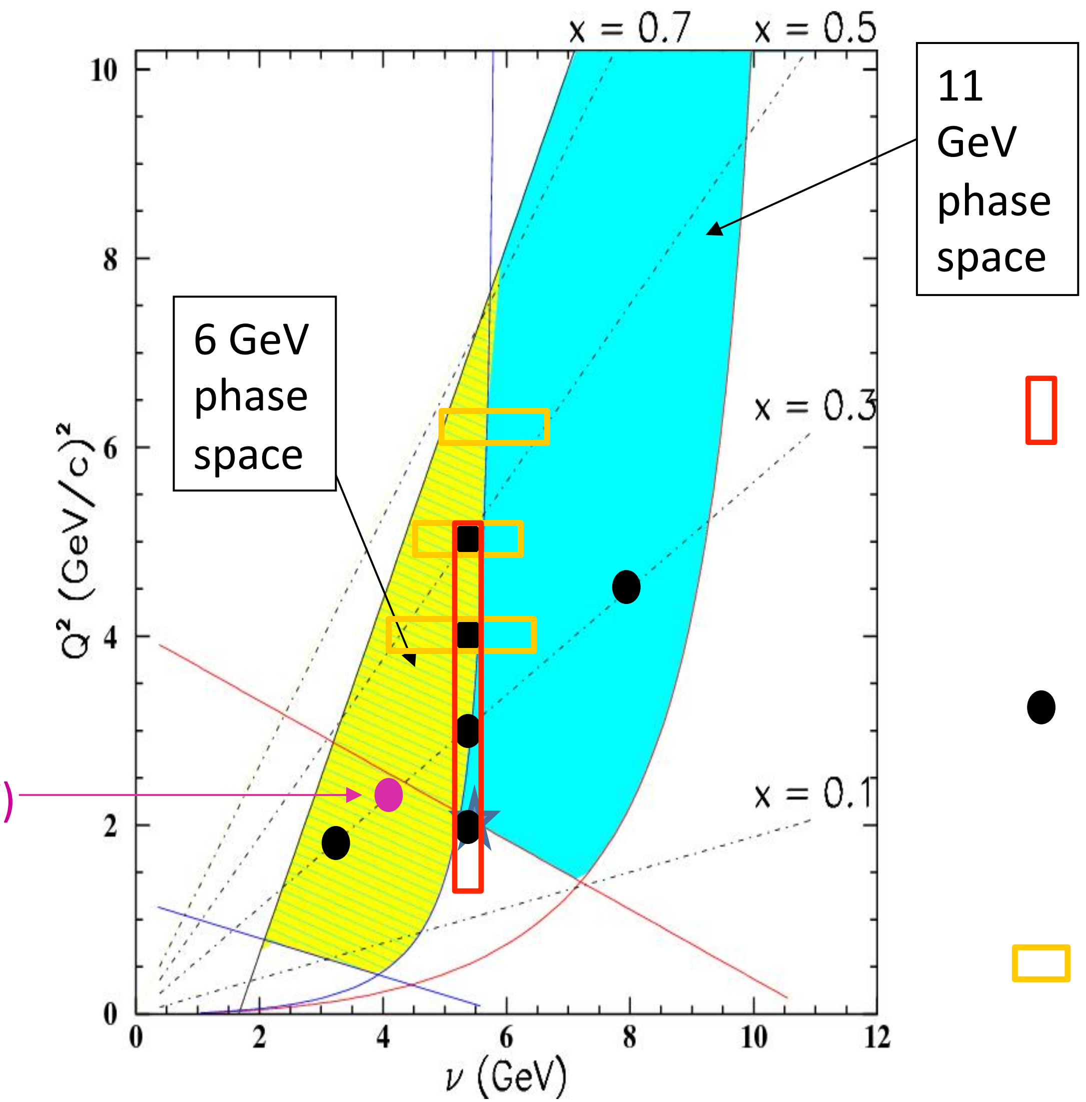
Measure P_T dependence to access k_T depedence of parton distributions

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



Hall C SIDIS Program – HMS+SHMS

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



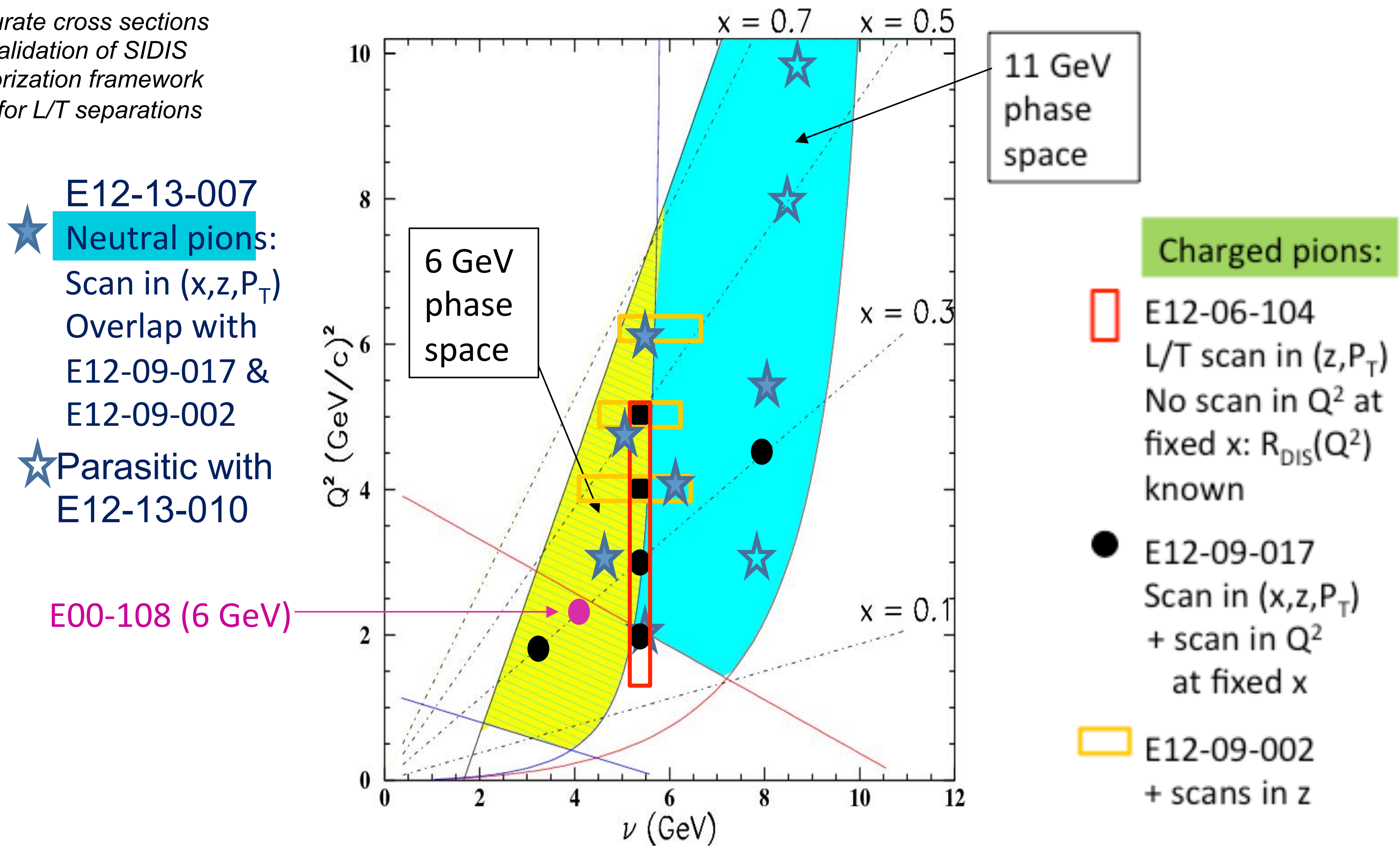
Charged pions:

- 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

Hall C SIDIS Program – HMS+SHMS+NPS

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

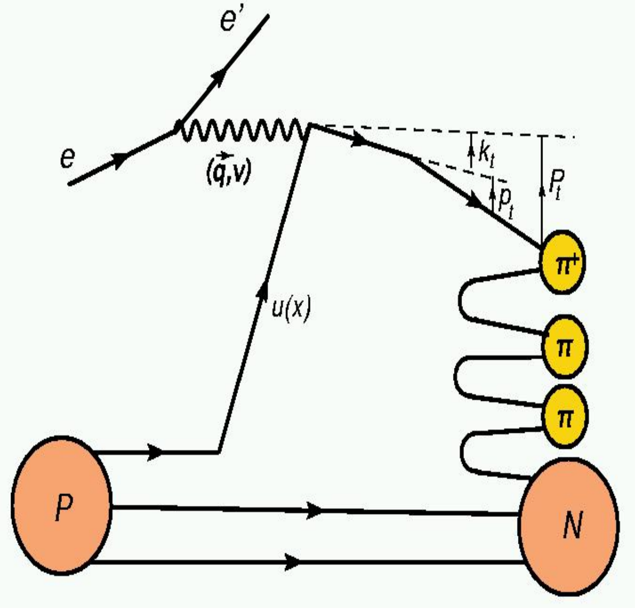


Courtesy R. Ent

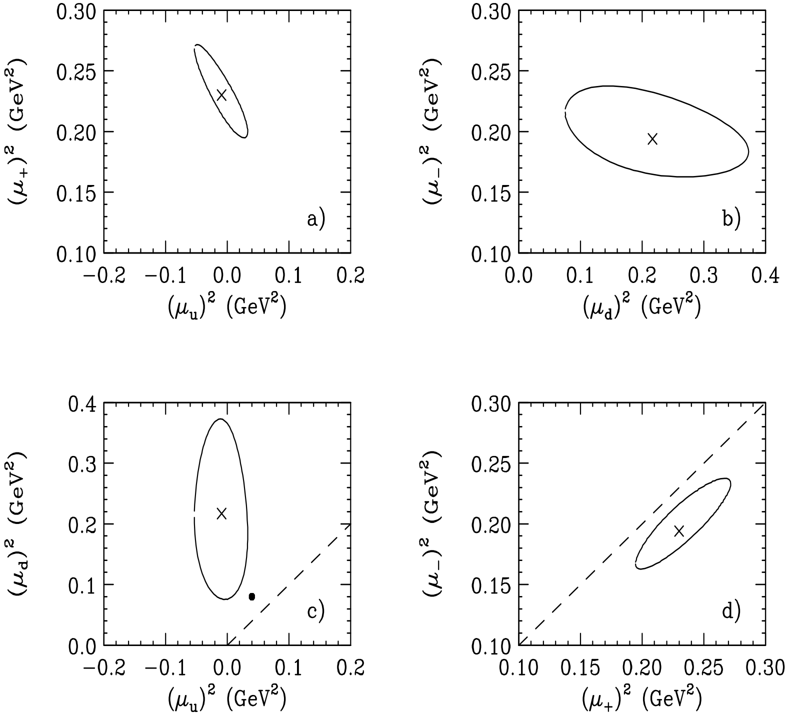
E12-09-017: Transverse Momentum Dependence of Semi-Inclusive Pion Production

Spokespersons: P. Bosted, R. Ent, E. Kinney, H. Mkrtchyan

Transverse momentum of pion = convolution of k_t of quark and p_t generated during fragmentation



$P_t = p_t + z\, k_t + O(k_t^2/Q^2)$



Results from Hall C 6 GeV data

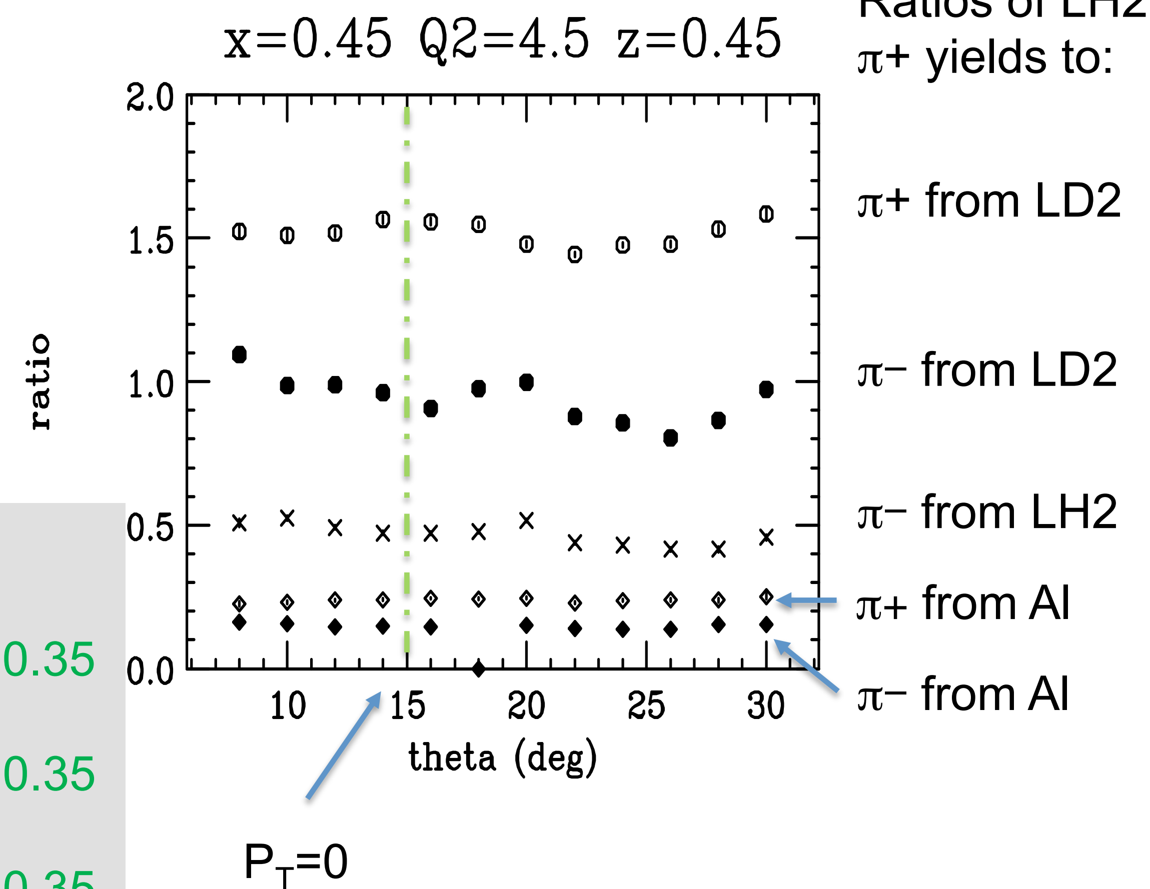
Experiment goal: Extract information about transverse distribution of up and down quarks by measuring P_T dependence of π^+/π^- cross sections and ratios from LH2 and LD2

E12-09-017 Status

- Ran for about 28 days in Spring 2018
- Ran for another 2 weeks in Fall 2018 to complete experiment

→ Initial raw yield ratios look reasonable
→ High precision ratios will require more detailed analysis – understanding tracking at

Kinematics:
1. x=0.31, Q^2=3.1 GeV^2
   → z=0.9-0.45 at P_T=0, P_T=0-0.6 at z=0.35
2. x=0.3, Q^2=4.1 GeV^2
   → z=0.9-0.45 at P_T=0, P_T=0-0.6 at z=0.35
3. x=0.45, Q^2=4.5 GeV^2
   → z=0.9-0.45 at P_T=0, P_T=0-0.6 at z=0.35



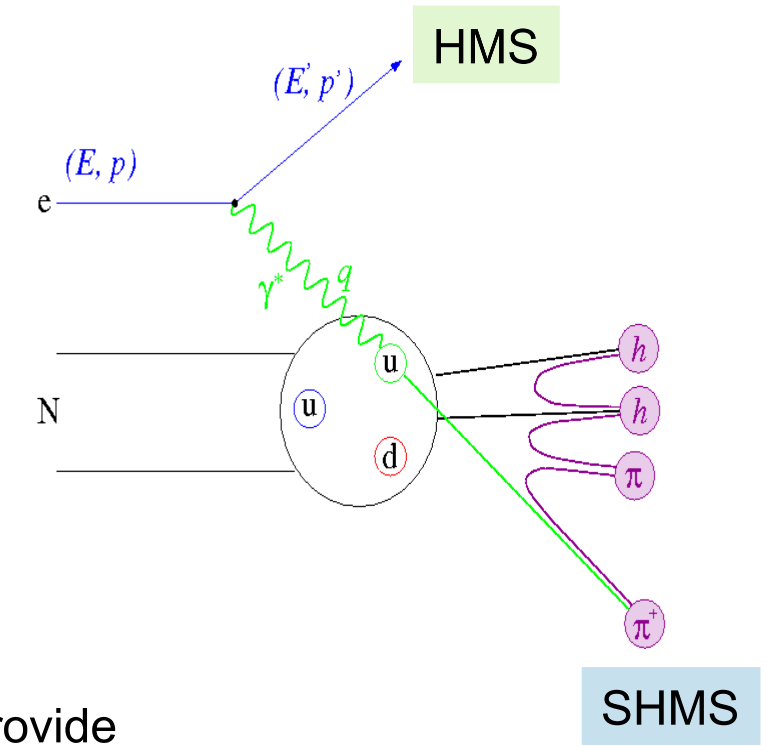
E12-09-002: Charge Symmetry Violating Quark Distributions via π^+/π^- in SIDIS

Experiment: Measure Charged pion electroproduction in semi-inclusive DIS off deuterium

Ratio of π^+/π^- cross sections sensitive to CSV quark distributions

$$R_Y(x,z) = \frac{Y^{D\pi^-}(x,z)}{Y^{D\pi^+}(x,z)} \longrightarrow$$

δd-δu where
$\delta d=d^p-u^n$ and $\delta u=u^p-d^n$



→ $\bar{u}(x) \neq \bar{d}(x)$ extraction relies on the implicit assumption of charge symmetry

→ Viable explanation for NuTeV anomaly → $\sin^2\theta_W$

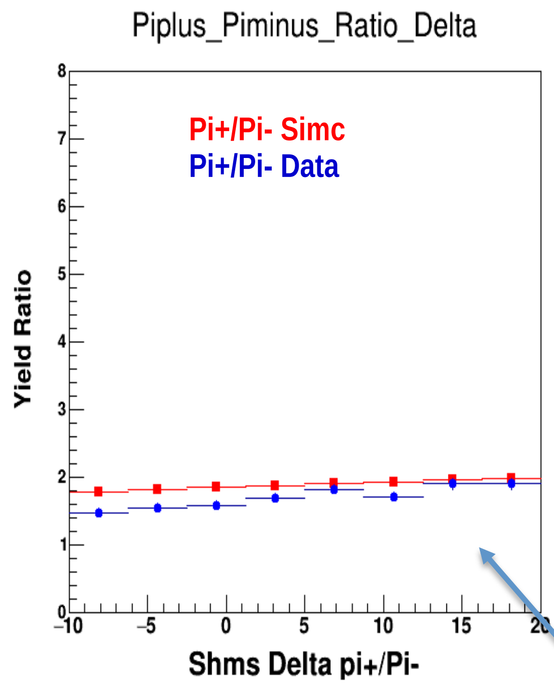
→ CS is a necessary condition for many relations between structure functions

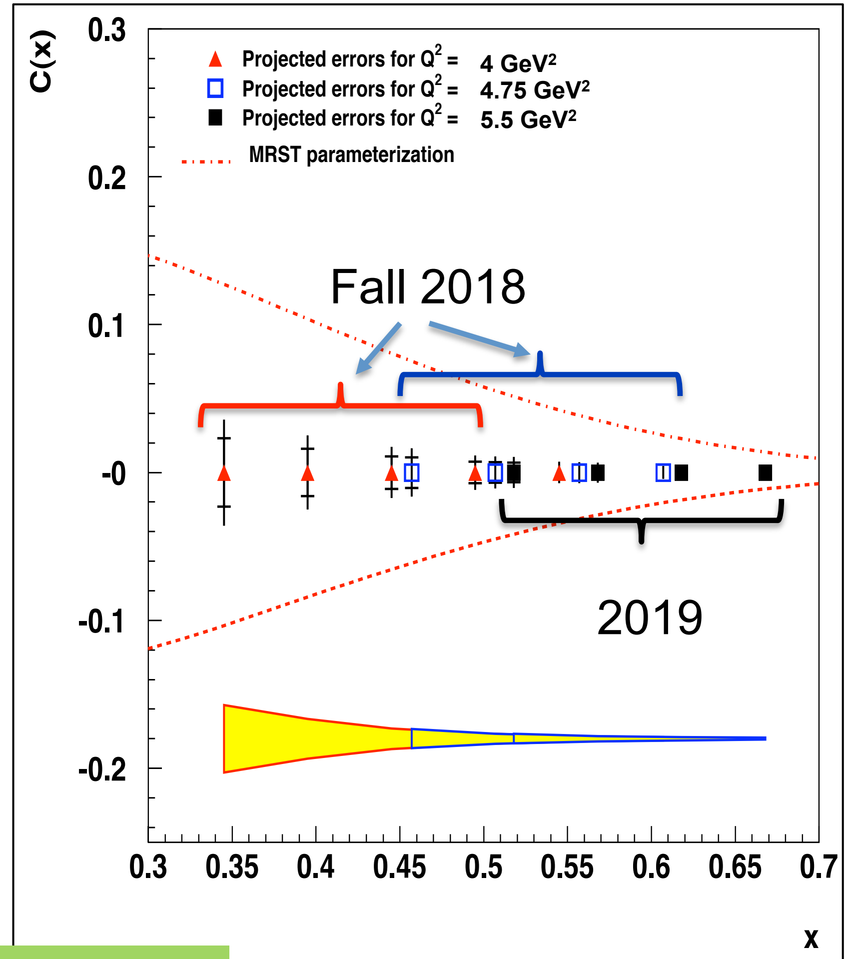
IN addition, precise cross sections and π^+/π^- ratios will provide information on SIDIS reaction mechanism at JLab energies

Spokespersons: W. Armstrong, D. Dutta, D. Gaskell, K. Hafidi

E12-09-002 Status

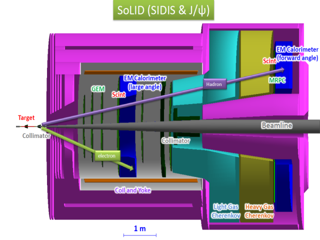
E12-09-002 took data at lower Q^2 values in Fall 2018
→ Data taking for largest x, Q^2 in progress now!
→ In addition to data on deuterium for CSV extraction, took data on hydrogen for cross sections, factorization checks





Barely offline results
→ Ratios roughly consistent with MC expectation
→ One setting out of 8 taken in Fall 2018

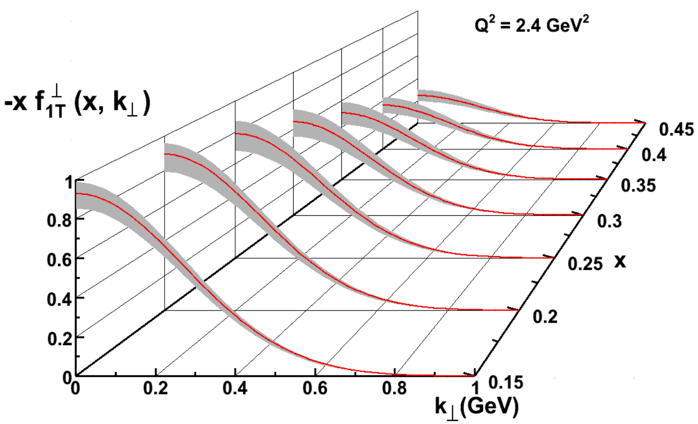
Solenoidal Large Intensity Device (SoLID)

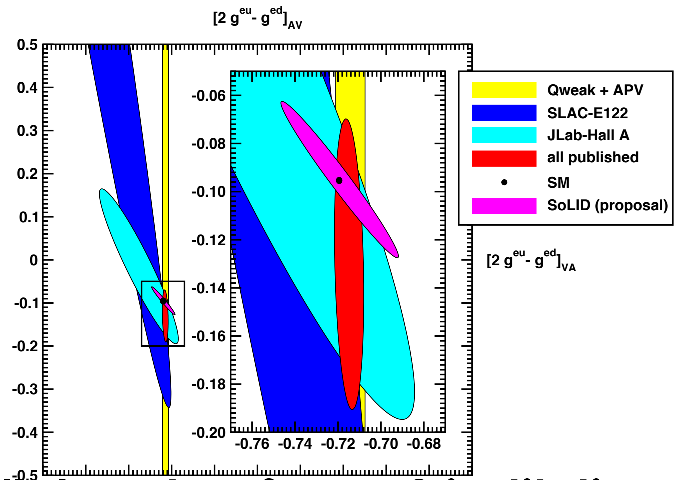


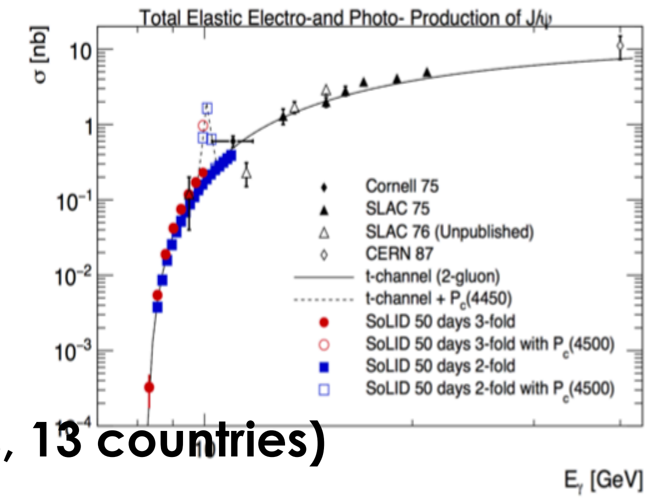
- **Full exploitation of JLab 12 GeV Upgrade to maximize scientific return**

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

- Reach ultimate precision for tomography of the nucleon
- PVDIS in high-x region - providing sensitivity to new physics at 10-20 TeV
- Threshold J/Psi - probing strong color fields in the nucleon and the origin of its mass (trace anomaly)



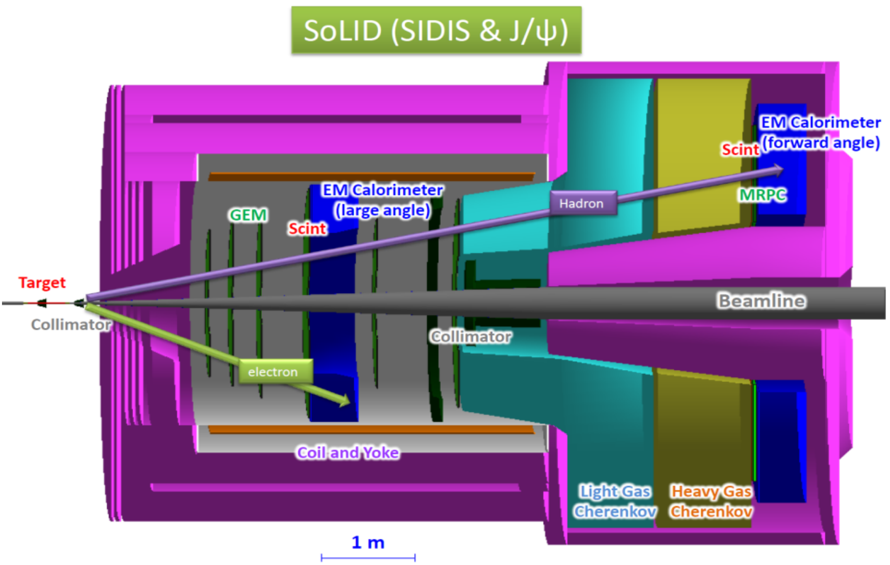




- **Strong collaboration (300 collaborators from 72 institutions, 13 countries)**
  - Significant international contributions
  - Strong theoretical support

- **2015 LRP recommendation IV**
  - We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories – **SoLID – mid-scale project**

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV



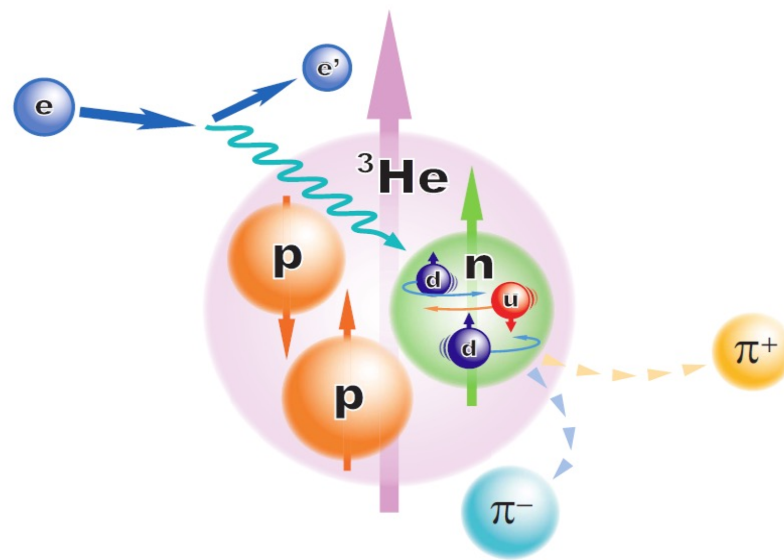
E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

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**

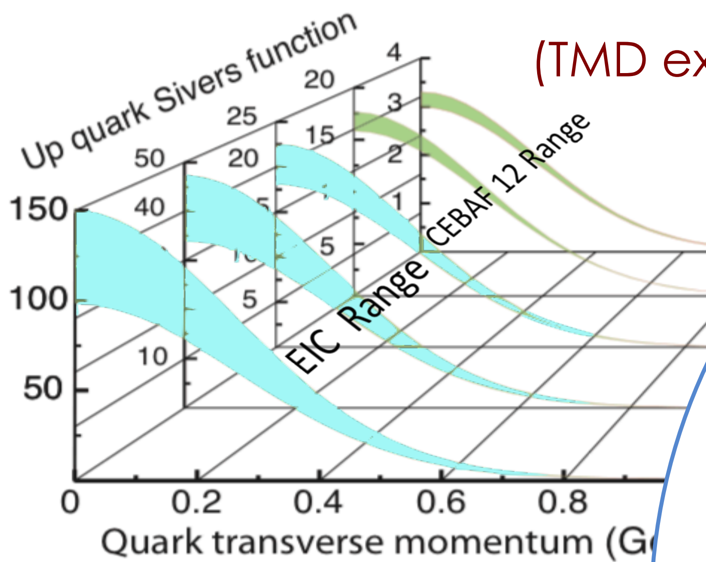
Three run group experiments: DiHadron, Ay and SIDIS-Kaon

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

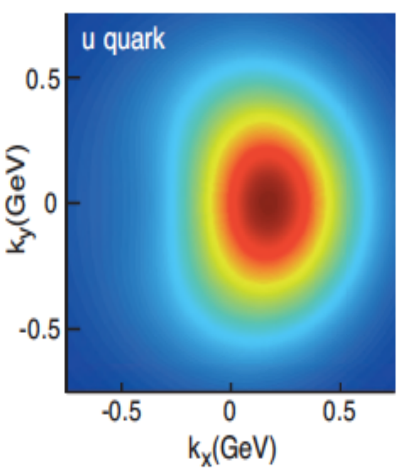


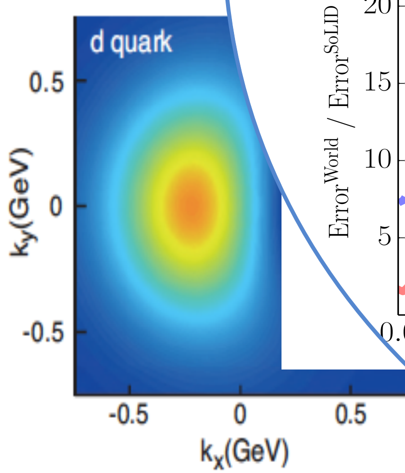
SoLID: a Bridge to EIC Science on full imaging of nucleons

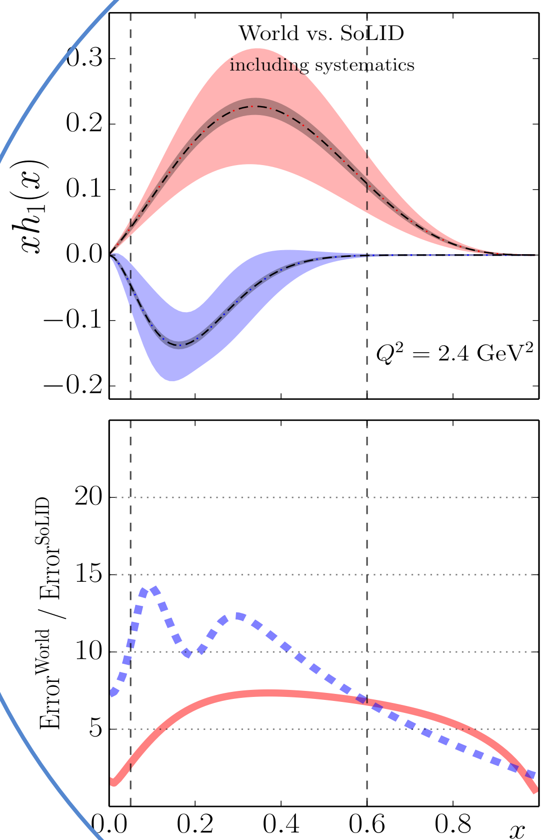
(TMD examples)

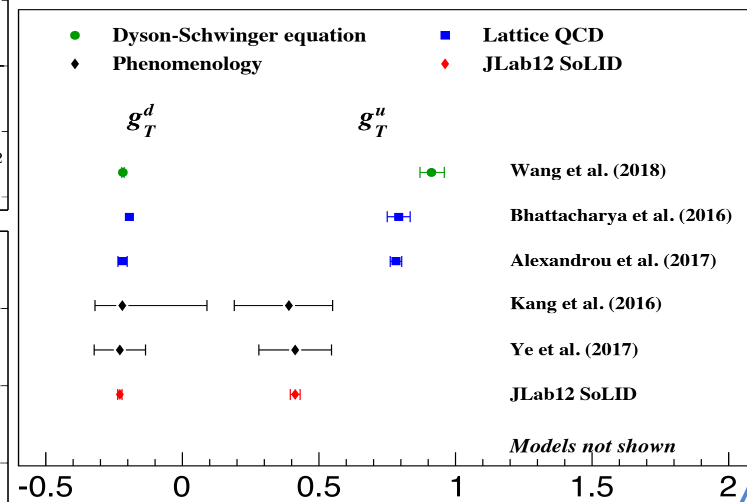


Polarized Quark 3D Momentum distri









Transversity: valence quark effect

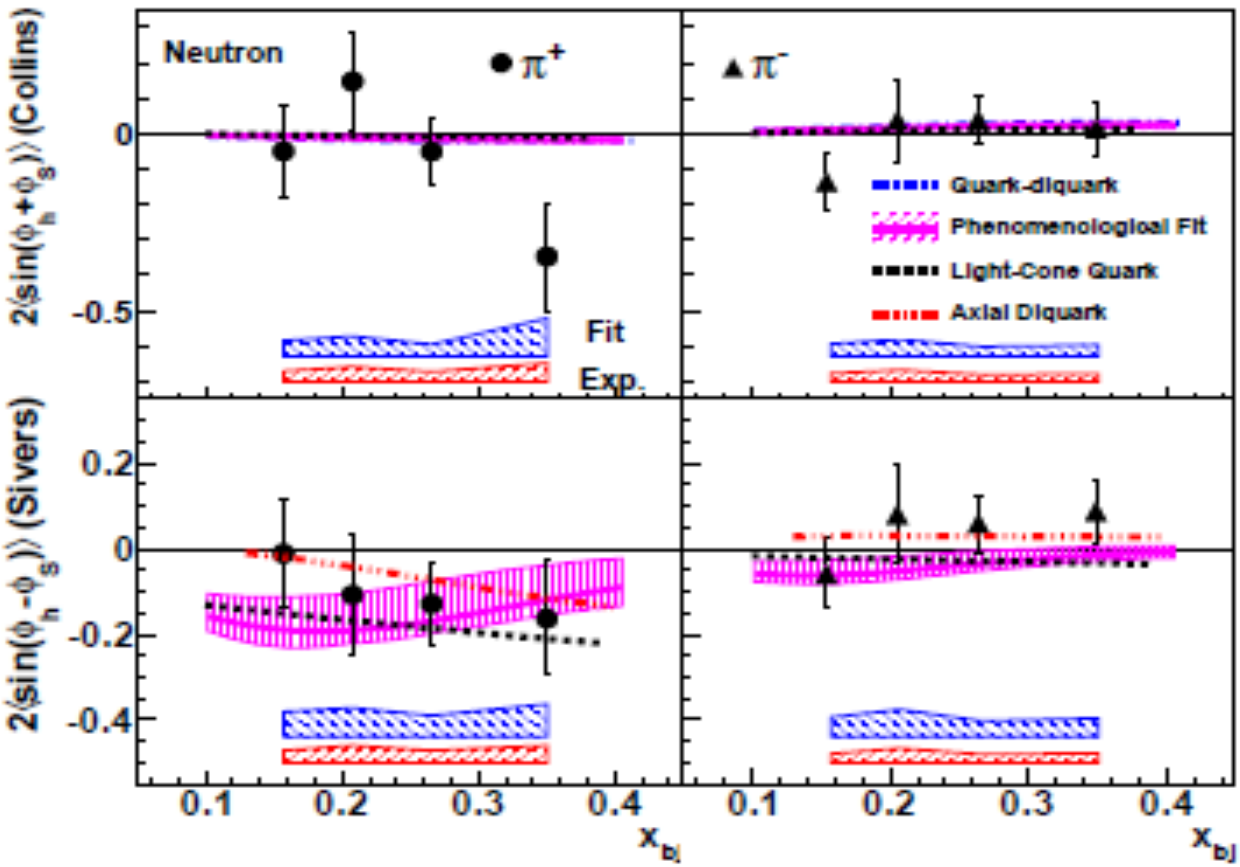
Collins Asymmetry: Transversity and Collins FF

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 $h_{1T}^{\perp}$

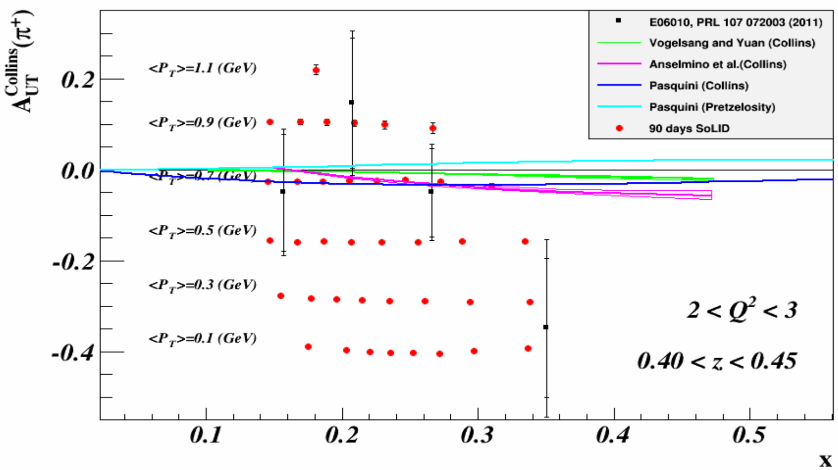
neutron Sivers SSA:
negative for π^+,
Agree with Torino Fit

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

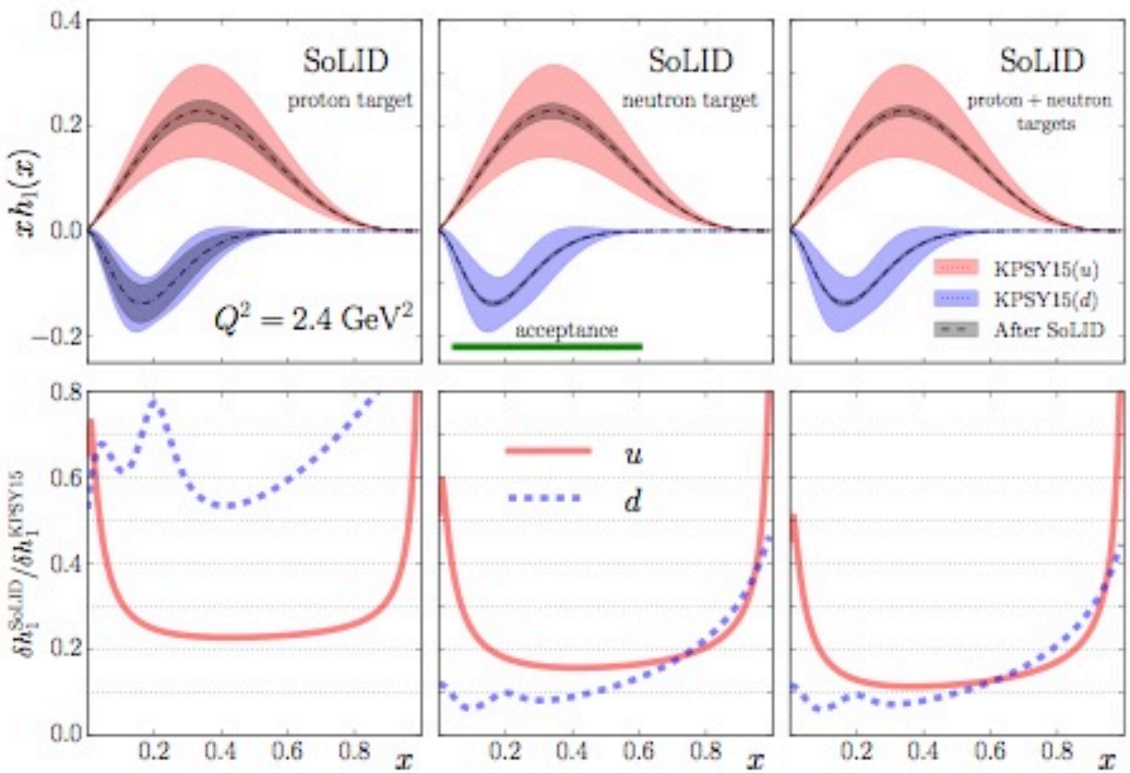
Transversity from SoLID

- 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



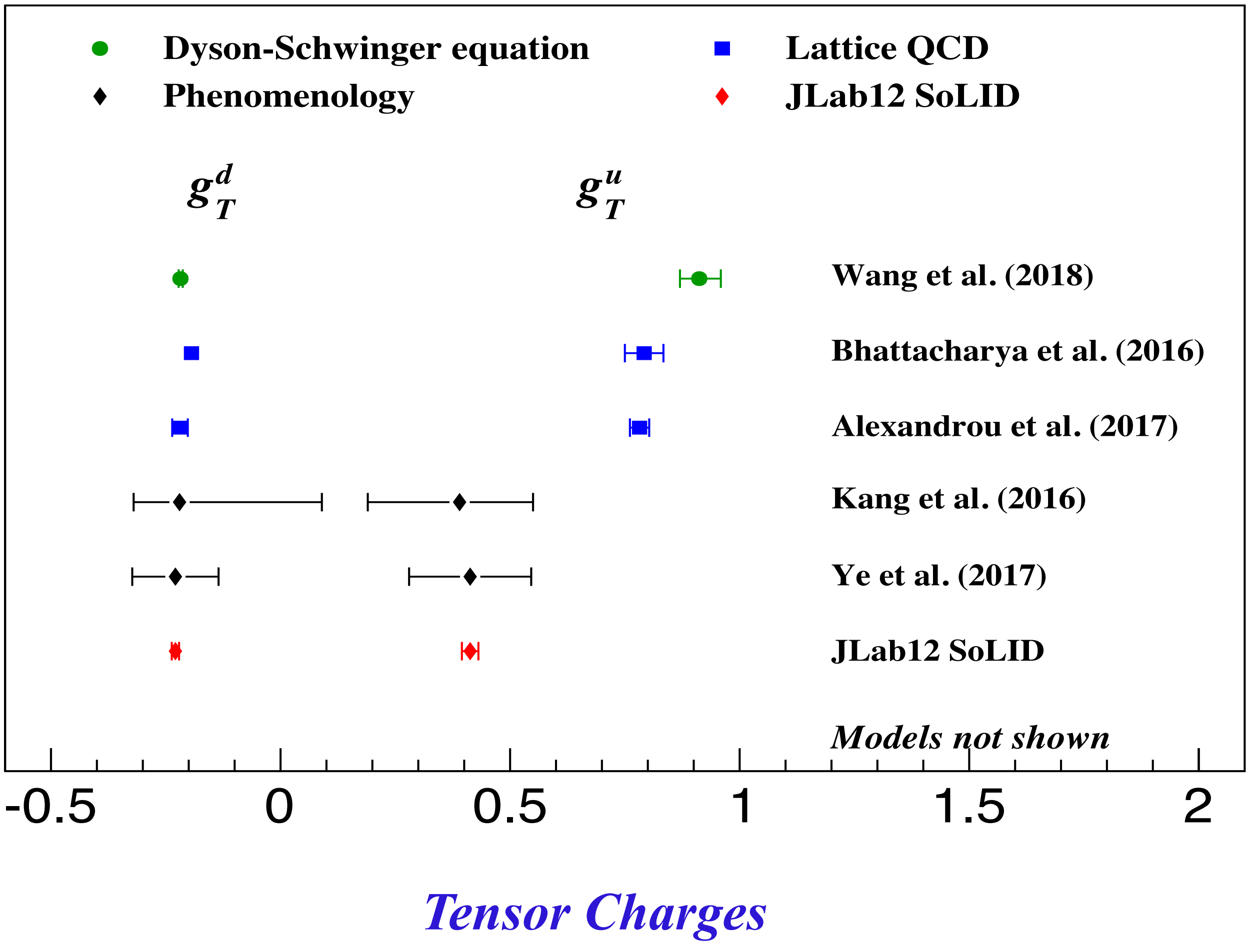
P_T vs. x for one (Q^2, z) bin
Total > 1400 data points



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



DSE

LQCD

Extractions from existing data

SoLID projections

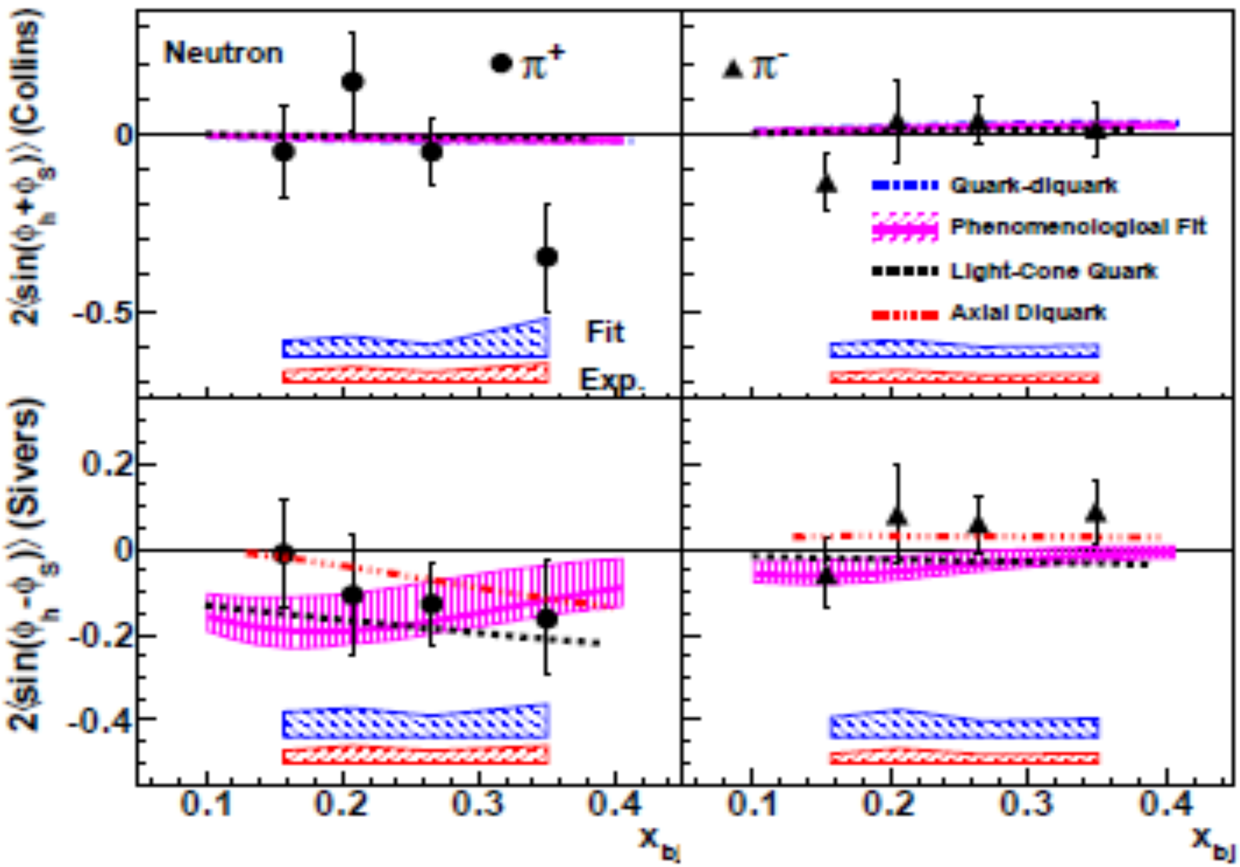
Sivers Function

3-D Imaging, QCD Dynamics

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+

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 $h_{1T}^{\perp}$

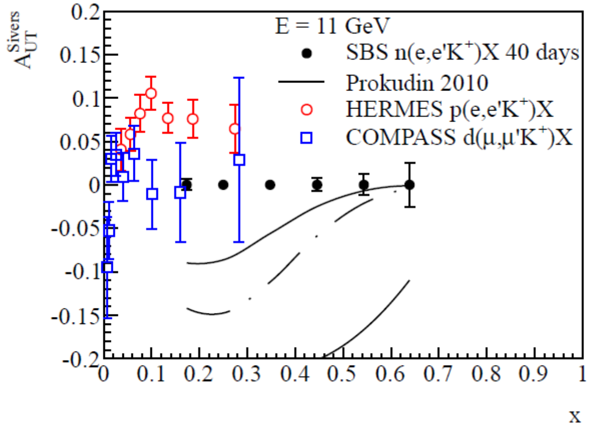
neutron Sivers SSA:
negative for π^+,
Agree with Torino Fit

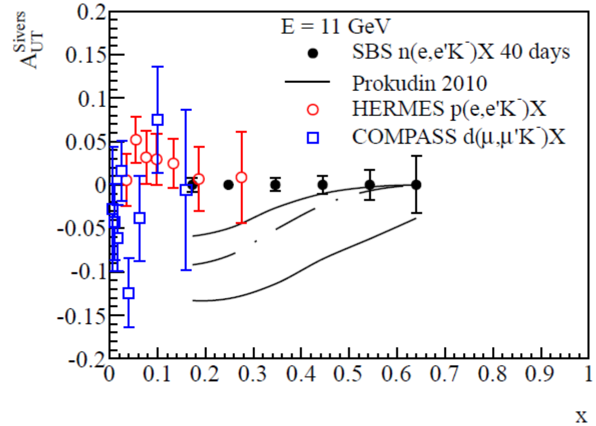
Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

Hall A SBS Projection: pi/K Sivers

11 GeV SIDIS: Expected Effects

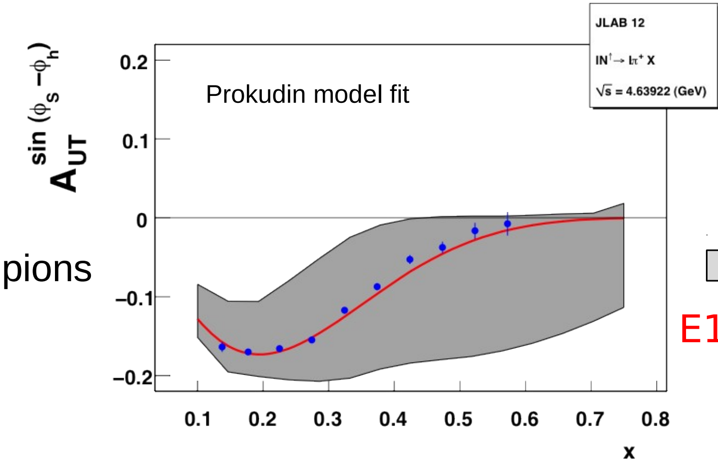
kaons



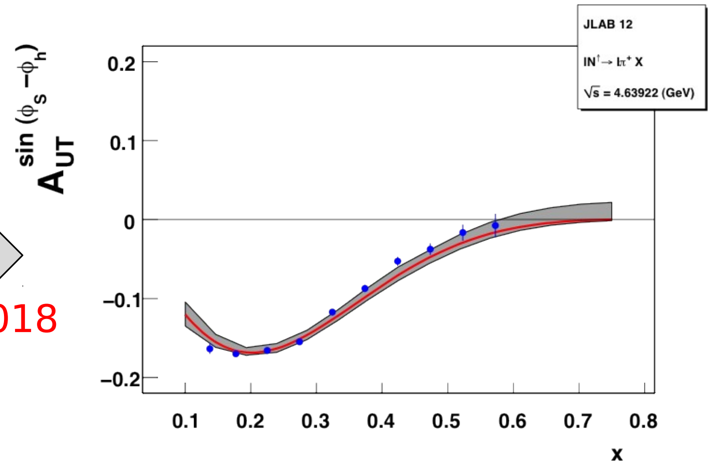


Squeeze model uncertainty corridor

pions

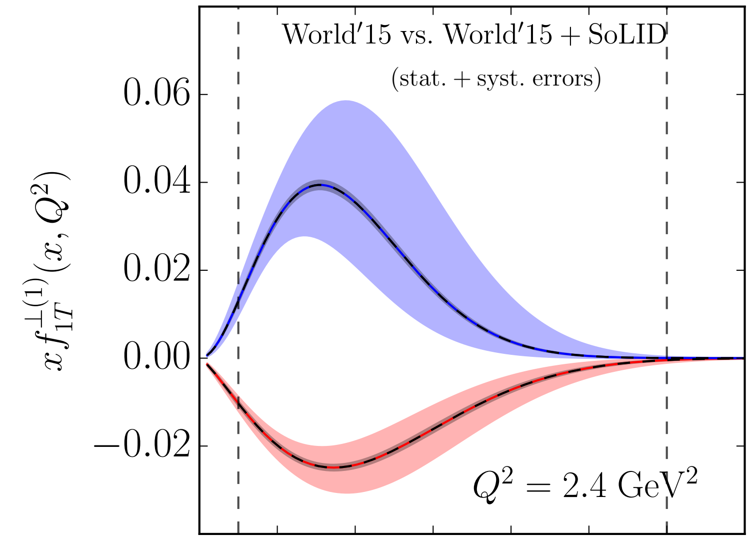


E12-09-018



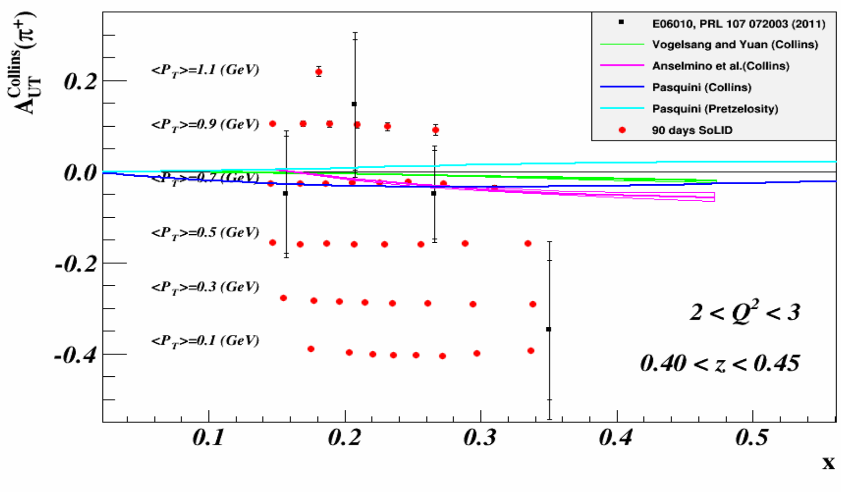
Mapping Sivers Asymmetries with SoLID

- 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

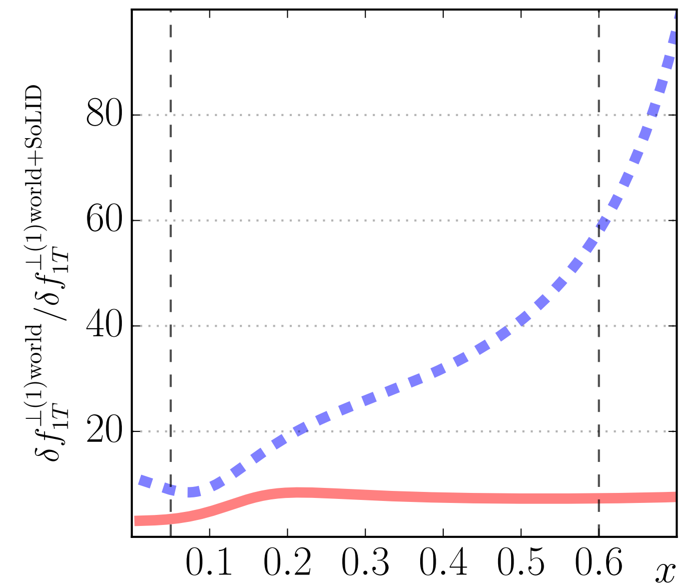


Liu, Sato, Prokudin,…

Sivers Asymmetries



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



Summary

- TMDs:
  both TMD pdfs and TMD FFs
  transverse spin, tensor charge
  QCD dynamics, quark orbital angular momentum
  angular correlations in fragmentation process
- **JLab-SIDIS** Program
  Multi-Hall to study TMDs from all directions
  Precision multi-dimensional mapping in the valence region

EIC will expand the study to sea quarks and gluons

Related News from China

- BESIII
  - Collins FF (pion) Extraction: PRL 116 (2016) 042001
  - Kaon data under analysis
  - P_T dependence under analysis

- **EIC @ China (EicC) is under intense discussions**
  - polarized e, polarized p: 3.5 x 20 GeV, luminosity ~ (2- 4) x 10^{33}
  - COM energy range: (3-5) x (15-25) GeV → sqrt(s) ~ 10-20 GeV
  - also polarized d, ^{3}He, unpolarized ions up to Uranium
  - Kinematics region complementary to JLab12/US-EIC

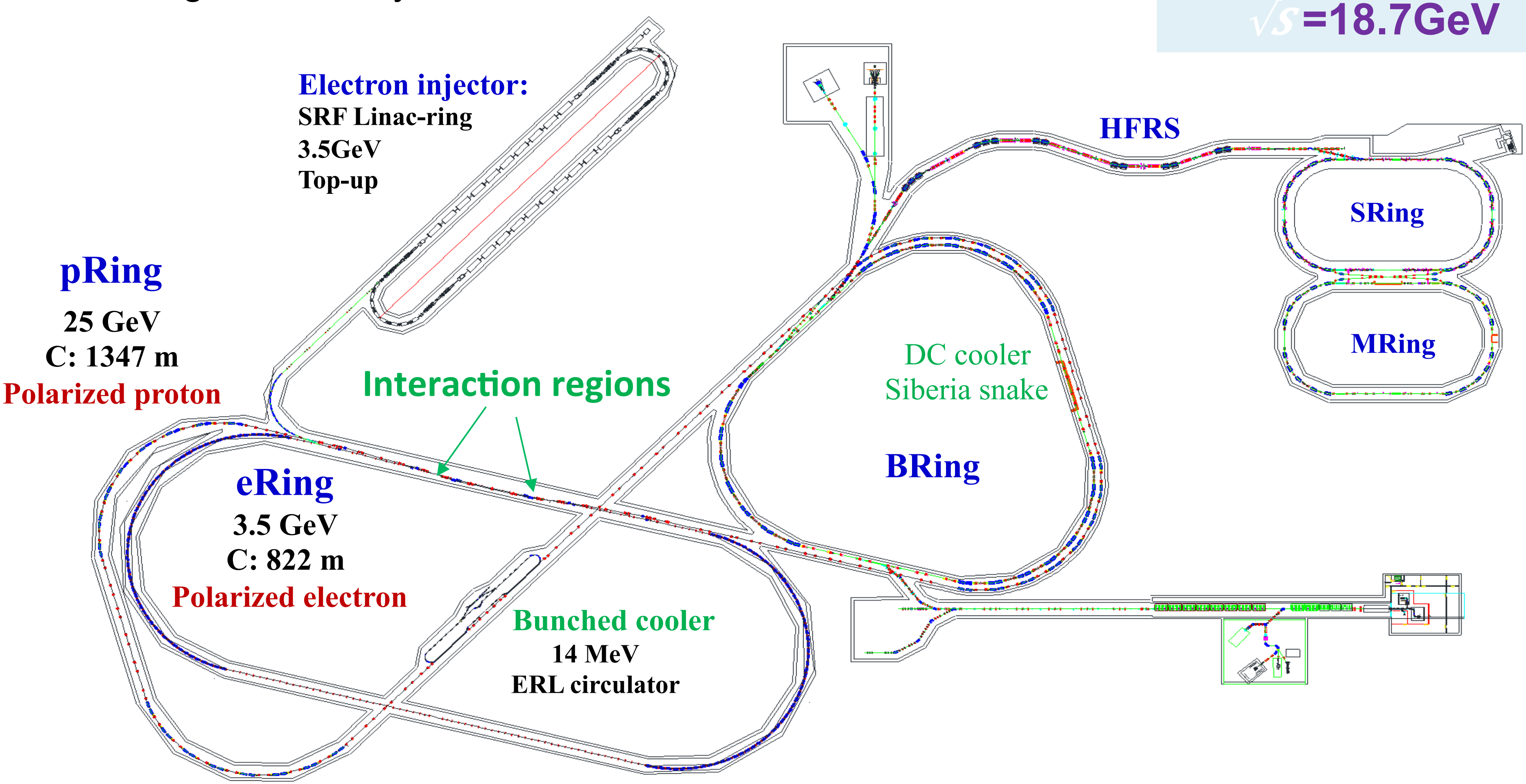
- hadron-China2019: 8/22-28/2019 at Nankai University, Tianjin, China
  - https://indico.ihep.ac.cn/event/8987/

The whole layout of EicC-1- New design

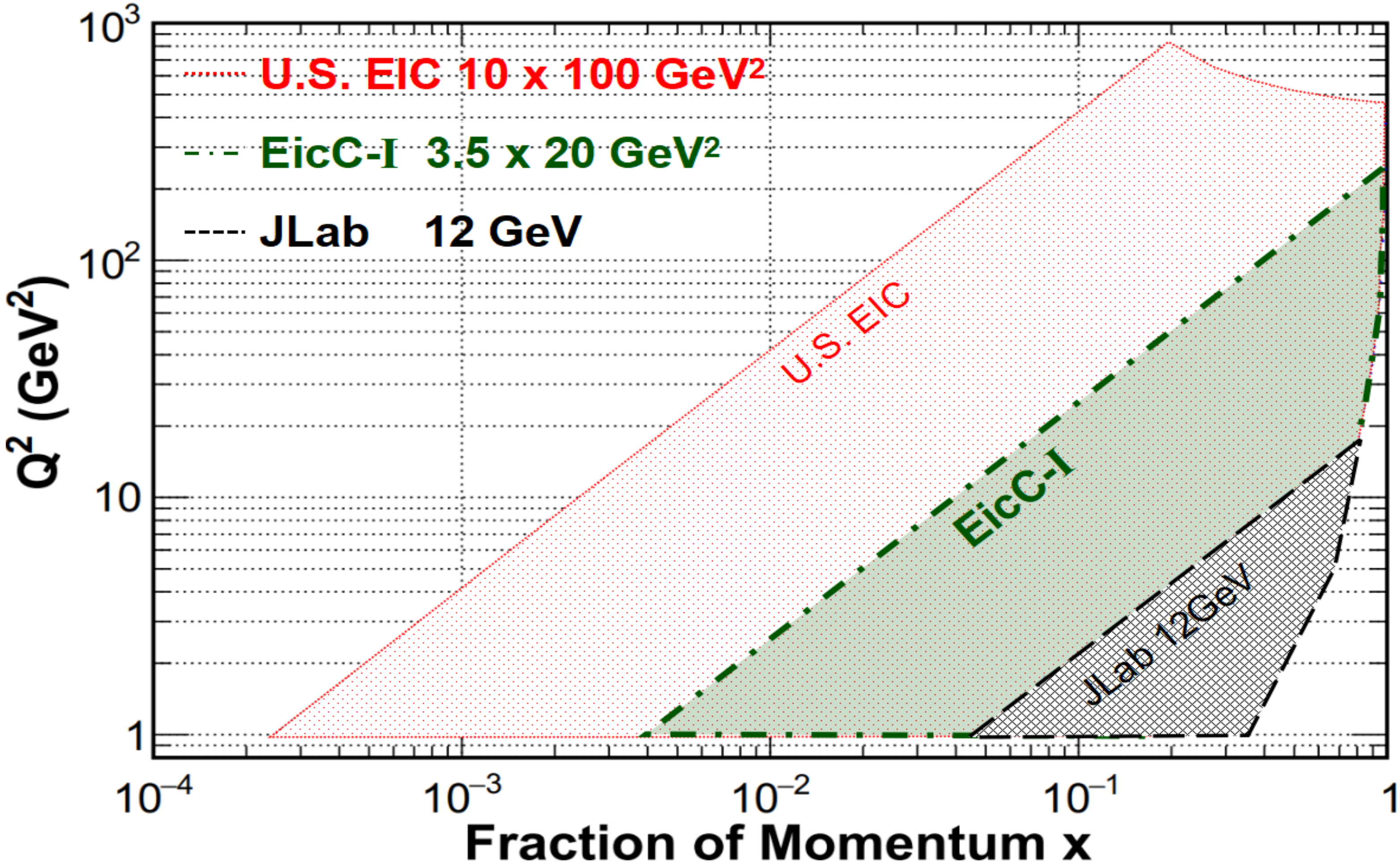
Main changes

- Figure-8 shape ion collider with four long straight sections – detector and cooler
- Two interaction points for detectors
- The high luminosity 2 x10^{33} cm^{-2}s^{-1}, **4 x10^{33} cm^{-2}s^{-1}**

25GeV p + 3.5GeV e
$\sqrt{s}$=18.7GeV



Machine Kinematics



EicC-I: **$4x10^{-3}$ < x < ~ 1** region

1) Valance- and sea-quark

Extras/ Backups

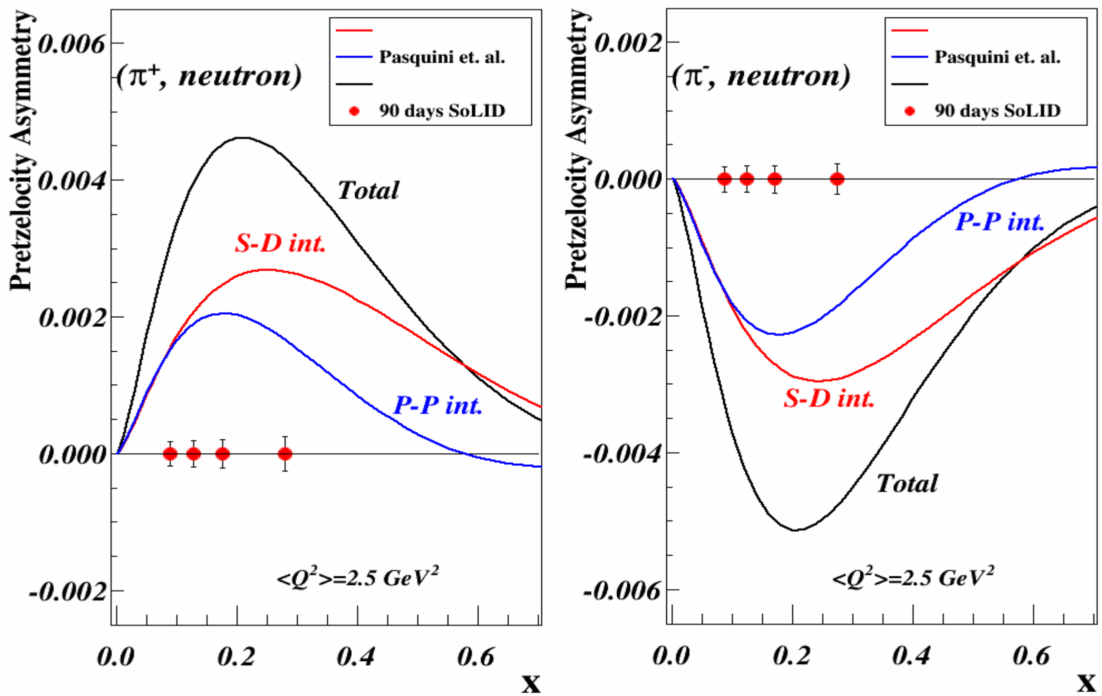
TMDs and Orbital Angular Momentum

Pretzelosity ($\Delta L=2$), Worm-Gear ($\Delta L=1$),

Sivers: Related to GPD E through Lensing Function

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

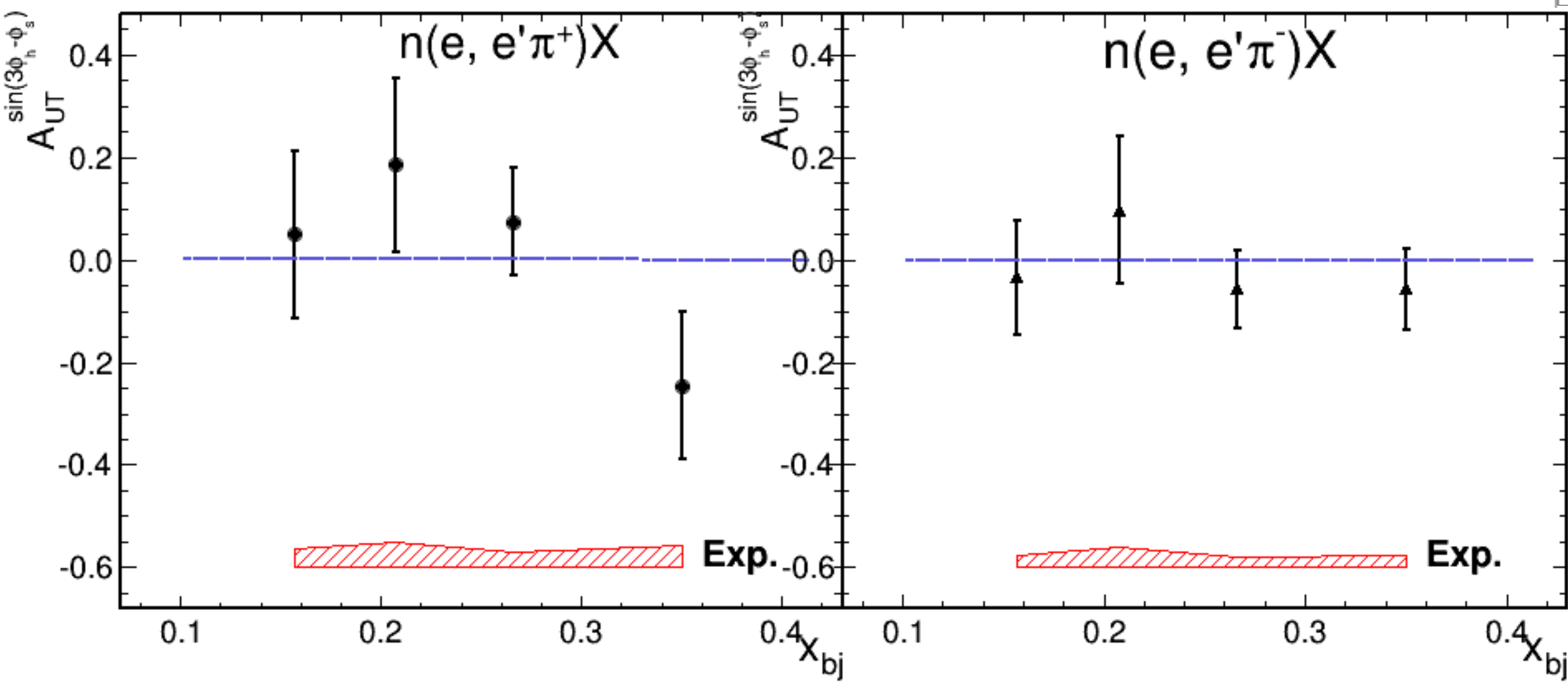
Pretzelosity Results on Neutron

(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

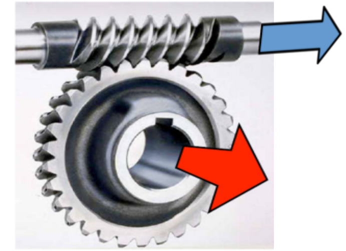
6 GeV Exploration: Asymmetry A_{LT} Results

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

To leading twist:

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

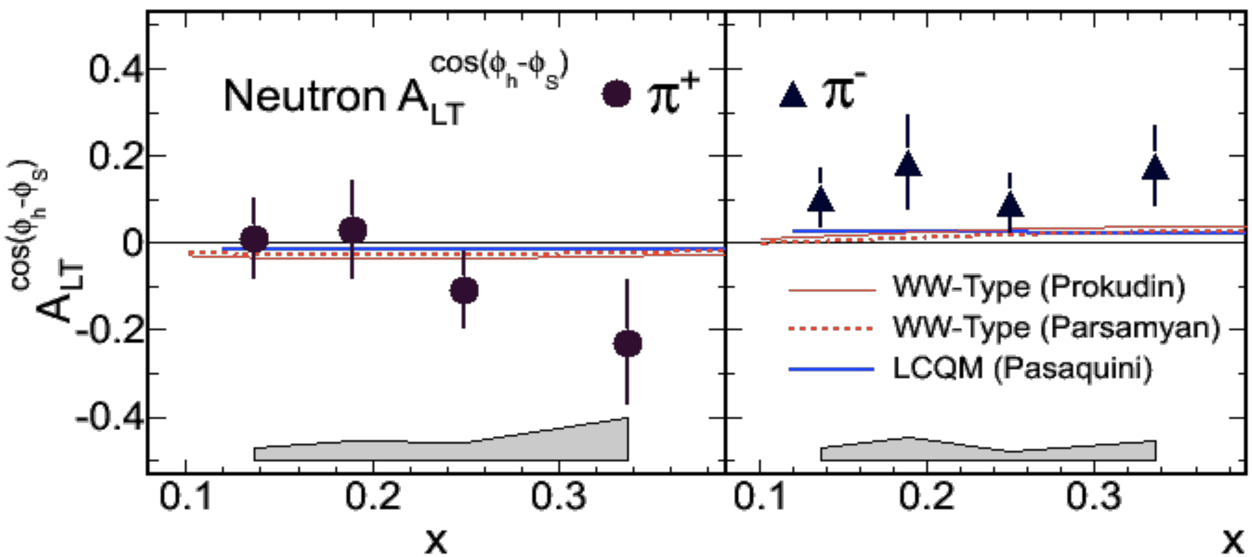
Dominated by L=0 (S) and L=1 (P) interference



Worm-Gear
Trans helicity

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 $h_{1T}^{\perp}$

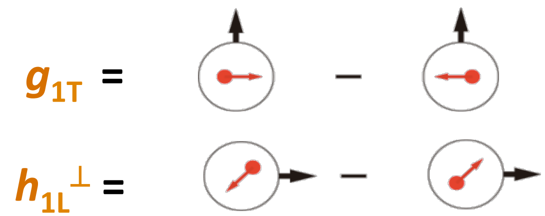
- **neutron A_{LT}: Positive for π-**
- **Consist w/ model in signs, suggest larger asymmetry**

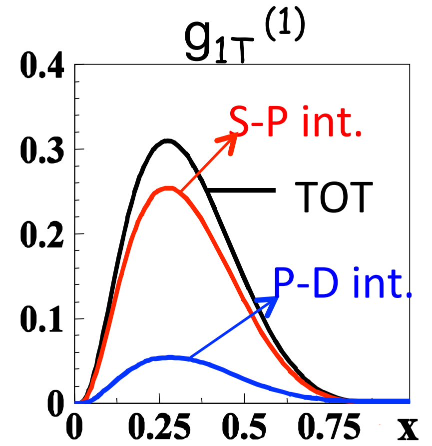


Worm-gear Functions

SoLID Projections

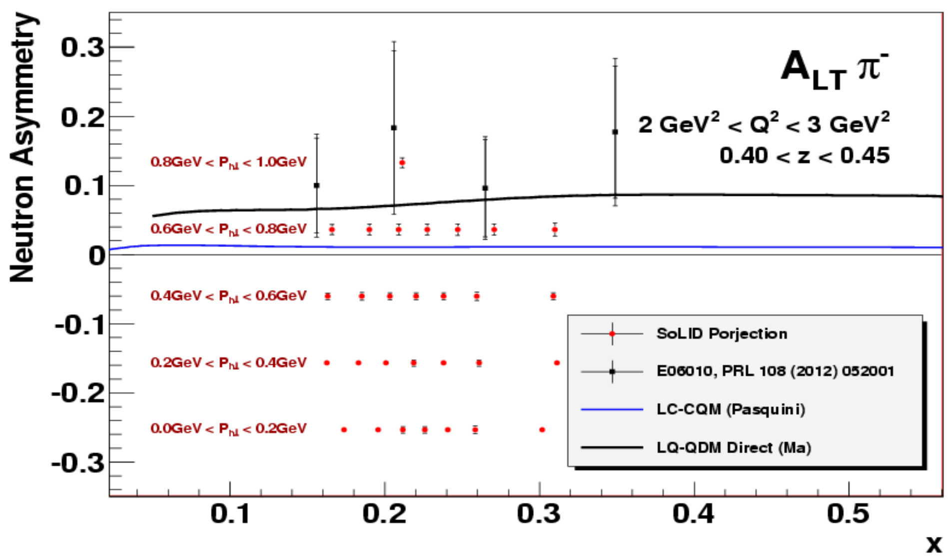
- Dominated by real part of interference between **L=0 (S) and L=1 (P) states**
- No GPD correspondence
- Exploratory lattice QCD calculation:
  Ph. Hägler et al, EPL 88, 61001 (2009)

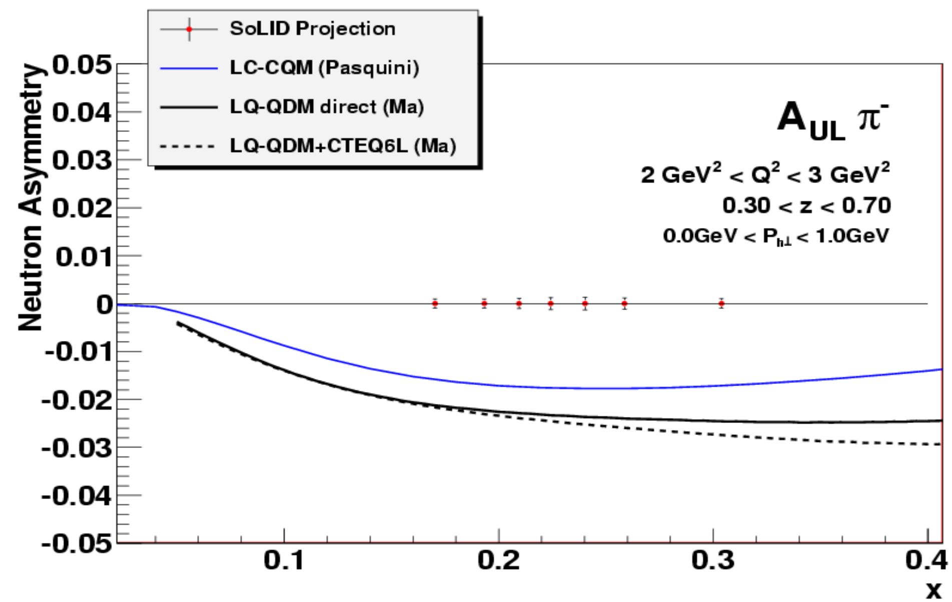




Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

SoLID Neutron Projections,



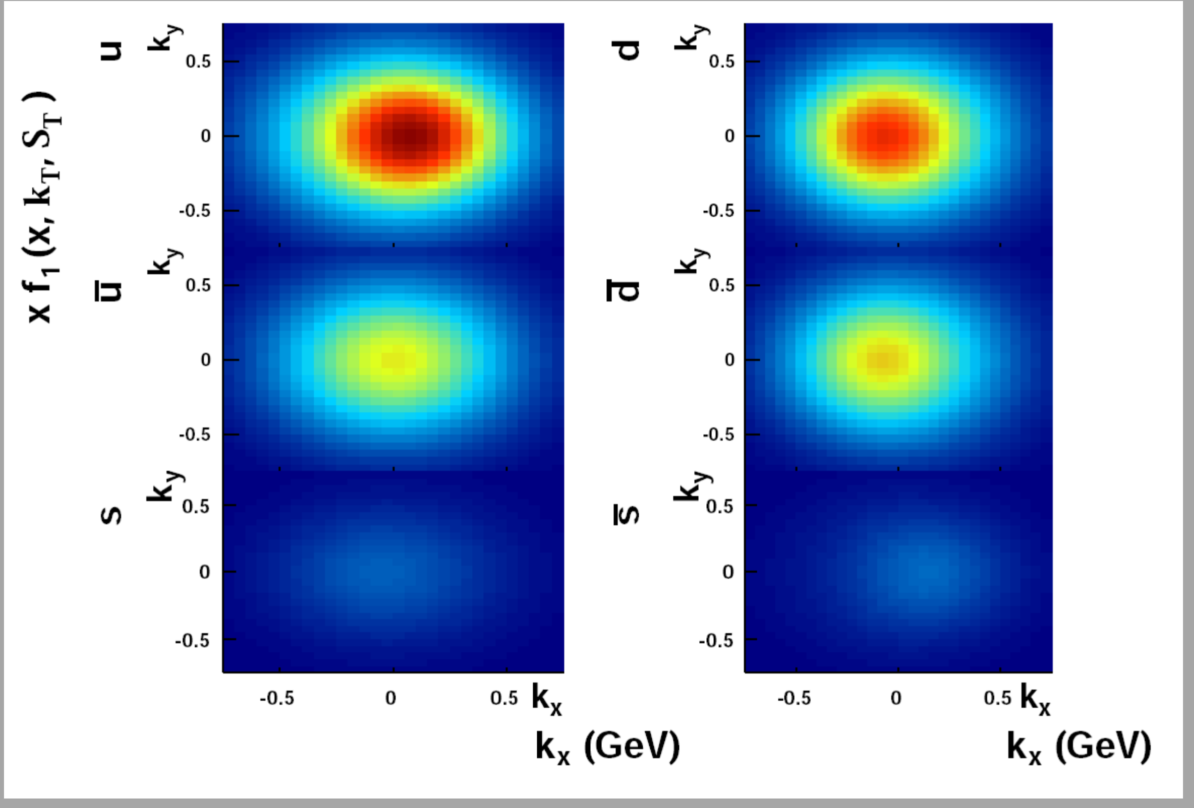


$$A_{LT} \sim g_{1T}(x) D_1(z)$$

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

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:

$x = 0.1$

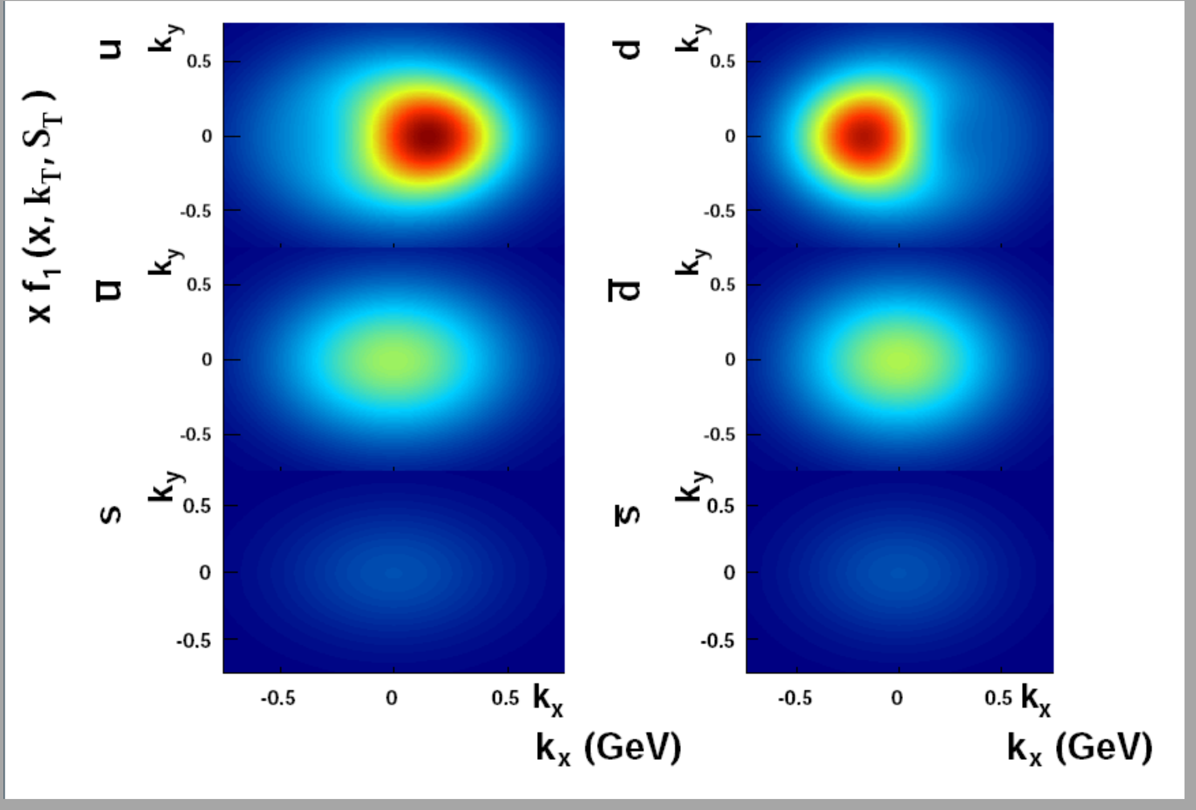
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

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:

$x = 0.1$

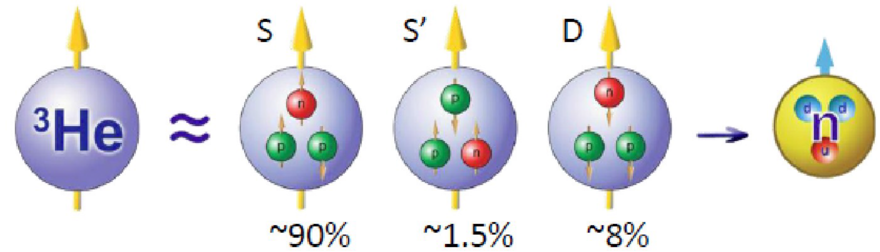
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

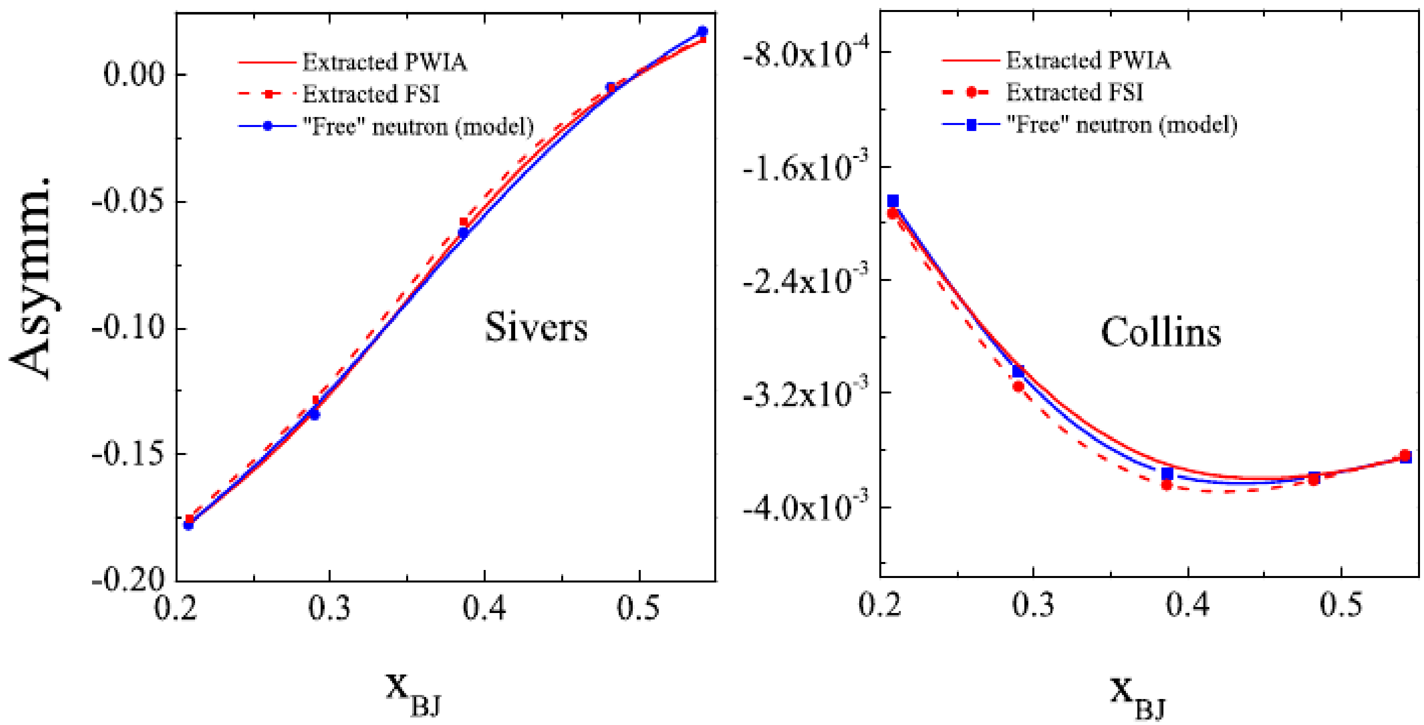
No information on sea quarks

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.

Kinematic domain (Q^2, x_B) and DVCS world data