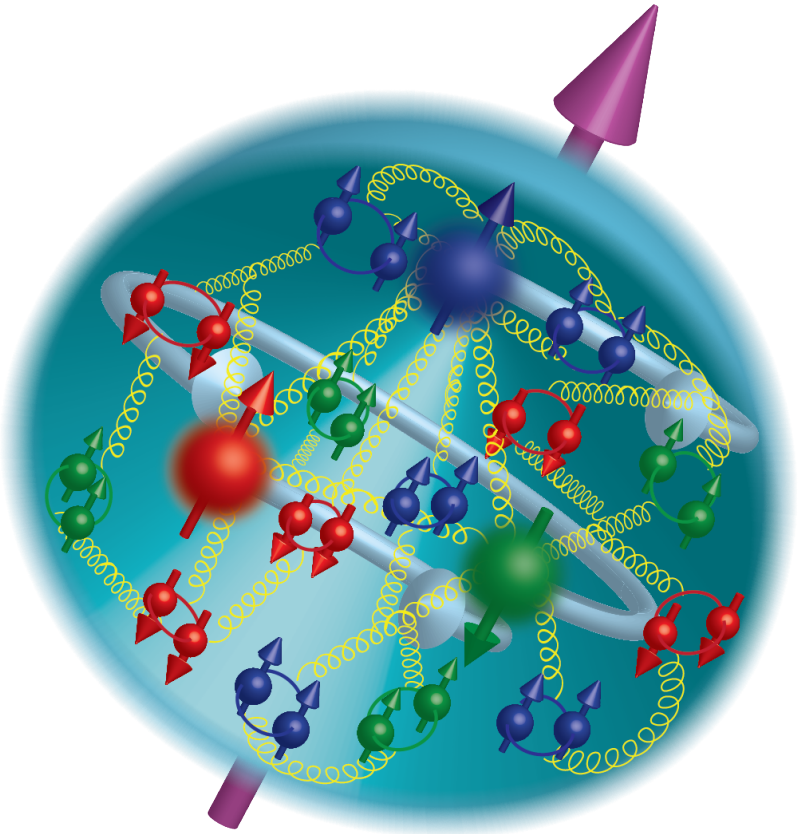
The SIDIS Program at Jefferson Lab

Zein-Eddine Meziani
Temple University



- Introduction
  - Science goals
  - Jlab 12GeV and its detectors facilities
- The SIDIS experimental program in Hall A, B and C
  - SBS & SoLID
  - CLAS12
  - HMS-SHMS
- Conclusion

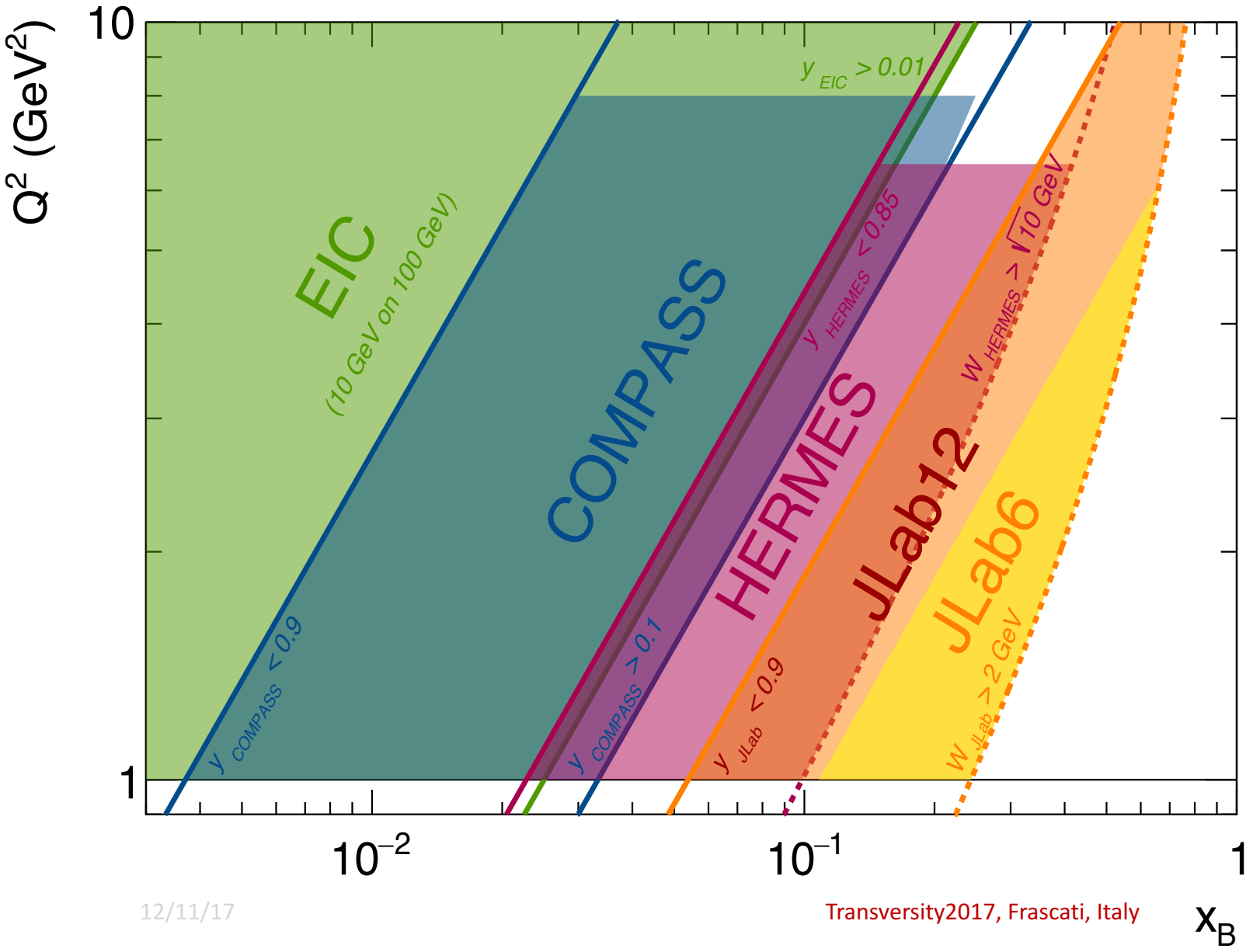
Credit: Thanks to the many people who developed the JLAB 12 SIDIS physics program
In particular, Harut Avakian, Jian-Ping Chen, Evaristo Cisbani, Marco Contabrigo & K. Hafidi

Disclaimer:
This talk is not a complete overview

Science Goals

- Exploring our understanding of QCD
  - Factorization
  - Evolution
- Dynamics of confined motion of partons-Orbital motion, spin-orbit correlations, phases
- 3D momentum information
- Hadronization or hadron formation
- Rest frame vs infinite momentum frame
- Models of the nucleon
- Lattice QCD

Kinematic Range Overview

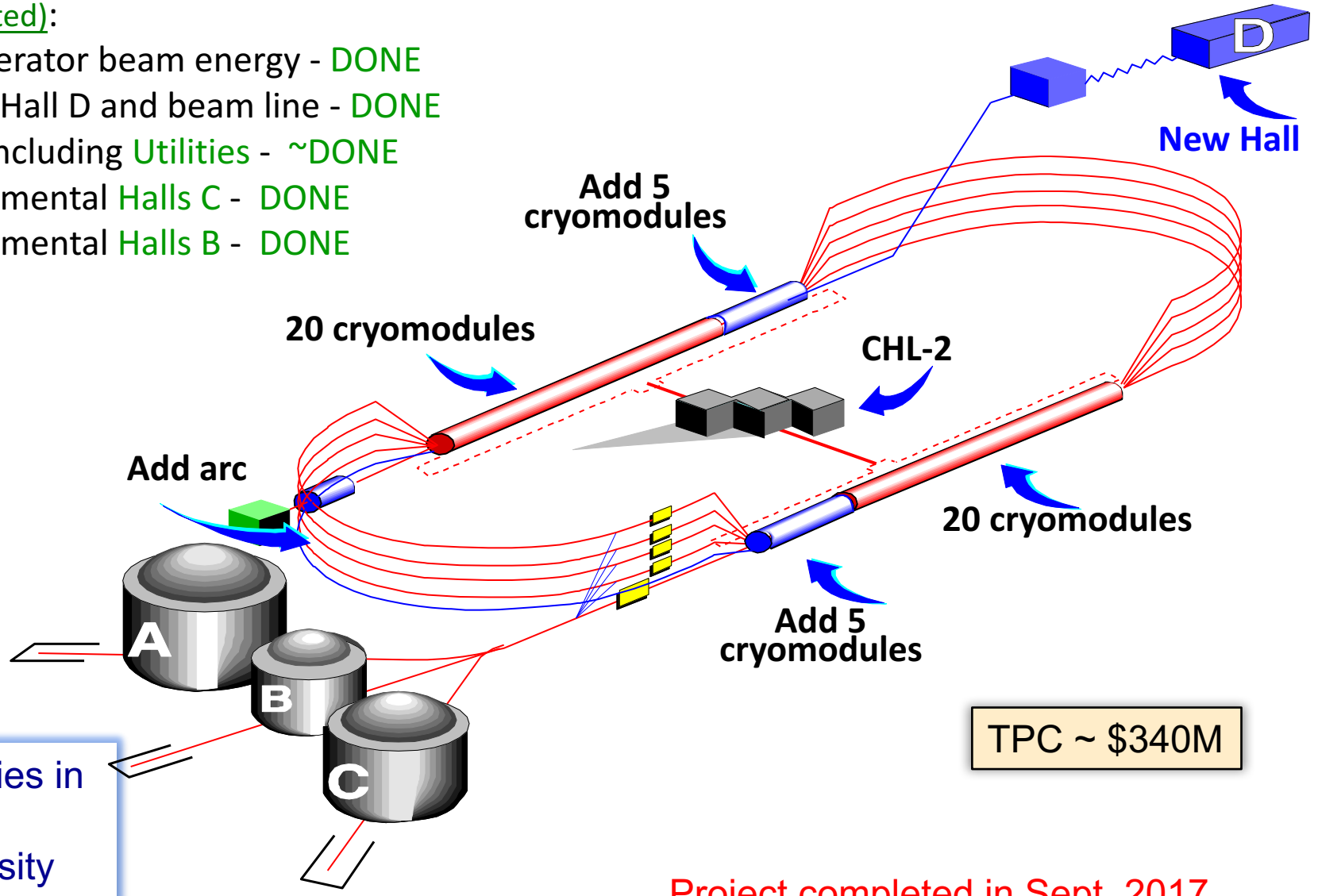


- JLab 12 will focus on the valence region with unprecedented polarized luminosities combined with large acceptances
- Use high resolution spectrometers to pin down transverse and longitudinal absolute cross sections

12 GeV Upgrade Project

Project Scope (completed):

- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including Utilities - ~DONE
- Upgrades to Experimental Halls C - DONE
- Upgrades to Experimental Halls B - DONE



TPC ~ $340M

- Enhanced capabilities in existing Halls
- Increase of Luminosity 10^{35} - ~10^{39} $cm^{-2}s^{-1}$

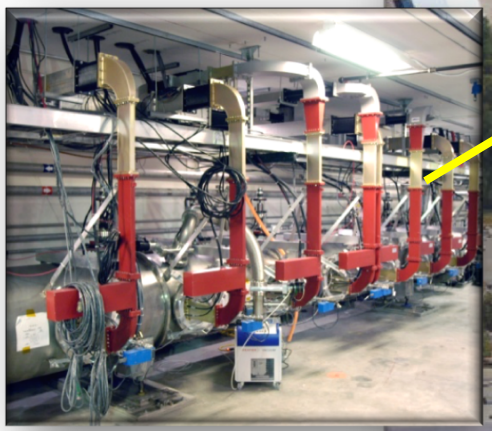
Project completed in Sept. 2017

Jefferson Lab Accelerator Complex

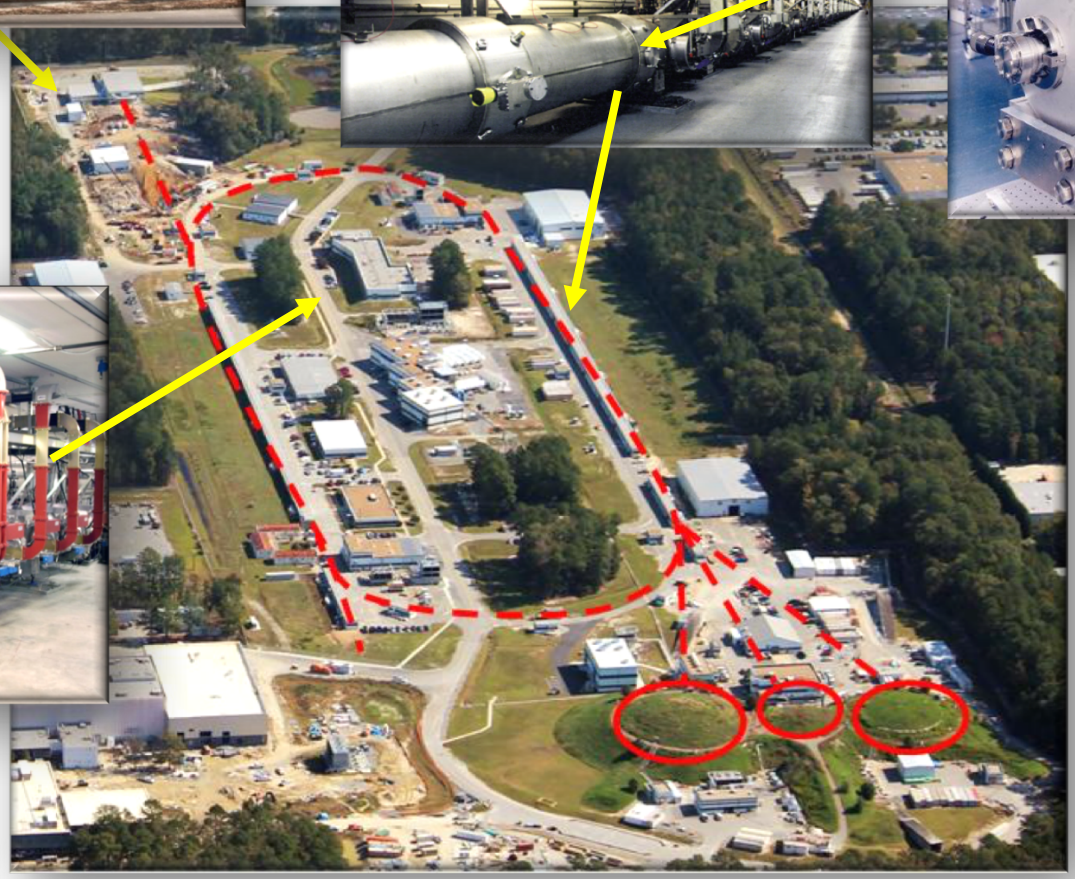
Hall D (new construction)

Cryomodules in the accelerator tunnel

Superconducting radiofrequency (SRF) cavities

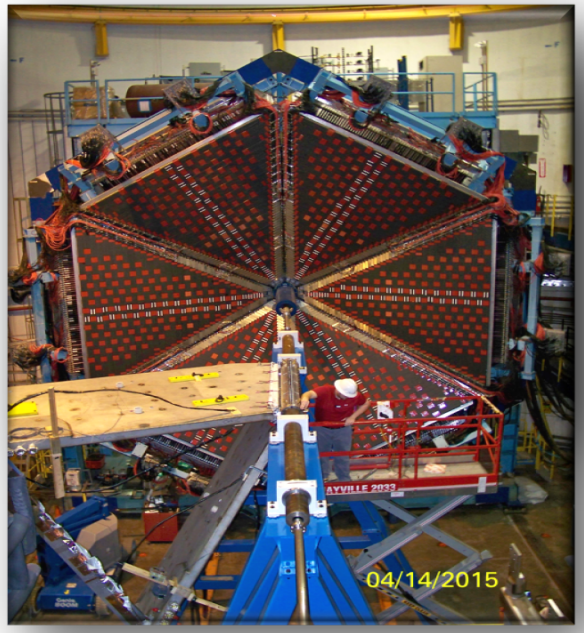


Free Electron Laser (FEL)

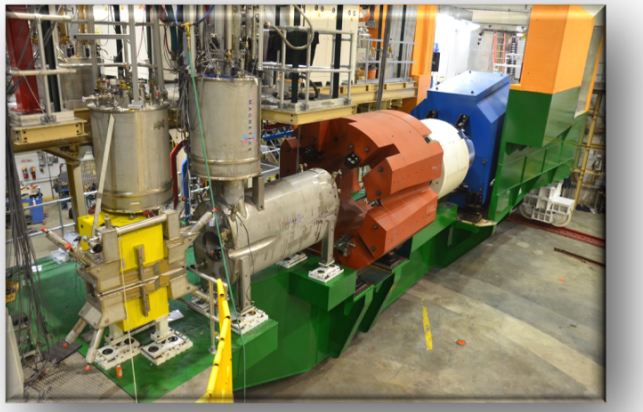


An aerial view of the recirculating linear accelerator and 4 experimental halls

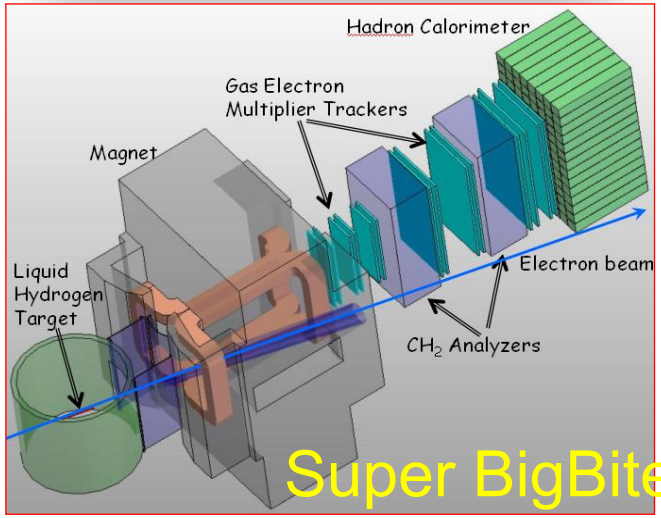
12 GeV Scientific Capabilities in SIDIS



Hall B** – understanding **nucleon structure** via **generalized parton distributions and transverse momentum distributions

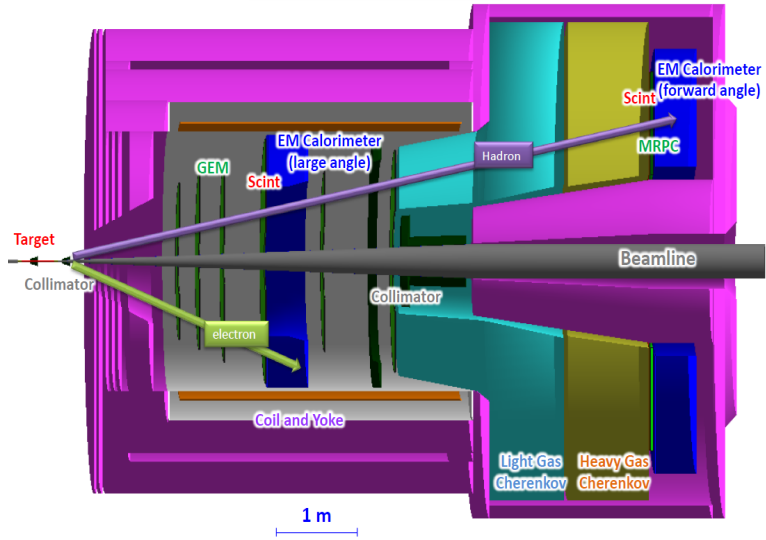


***Hall C** – precision determination of **valence quark** properties in nucleons and nuclei*



Hall A** – short range correlations, form factors, hyper-nuclear physics, **future new experiments (e.g., SoLID, Moller)

SoLID (SIDIS & J/ψ)



The Approved SIDIS Experiments in the 12 GeV Era

- **Hall A** (polarized ^{3}He and NH_3)
  - **Super Bigbite Spectrometer**
    - E12-09-018: SIDIS, 64d A-
  - **SoLID**
    - E12-11-108: *Target Single Spin Asymmetries in SIDIS (e,eπ±) Reaction on a Transversely Polarized Proton Target.* 120d A
    - E12-10-006: *Target Single Spin Asymmetries in SIDIS (e,eπ±) Reaction on a Transversely Polarized* ^{3}He target at 8.8 and 11 GeV 90d A
    - E12-11-007: *Asymmetries in SIDIS (e,eπ±) Reaction on a Londitudinally Polarized* ^{3}He target at 8.8 and 11 GeV ^{3}He, 35d A
- **Hall C** (unpolarized targets)
  - **SMS-SHMS**
    - E12-06-104: *Measurement of the ratio R= L/sigmaT in SIDIS,* 30d A
    - E12-13-007 *Measurement of Semi-Inclusive π⁰ Production as Validation of Factorization,* 40d A-
- **Hall B** (unpolarized and polarized NH3, ND3, HD)
  - CLAS12
    - C12-11-111 *SIDIS on Tranversely Polarized Target (HDICE)*
    - *C12-12-009 Measurement of transversity with di-hadrons production in SIDIS with transversely polarized target (HDICE)*
    - E12-06-112 *Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV,* 38d A
    - E12-09-008 *Studies of the Boer-Mulders Asymmetry in Kaon Electroproduction with Hydrogen and Deuterium Targets,* 38d A-
    - E12-07-107 *Studies of Spin-Orbit Correlations with Longitudinally Polarized Target* 38d A-
    - E12-09-009 *Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with polarized hydrogen and deuterium* targets, 38d B+
    - E12-06-112A/E12-09-008A *Semi-Inclusive \Lambda electroproduction in the Target Fragmentation Region*
    - E12-06-112B/E12-09-008B *Higher-twist collinear structure of the nucleon through di-hadron SIDIS on unpolarized hydrogen and deuterium.*

TMDs MultiHall exp. at JLab/12GeV

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

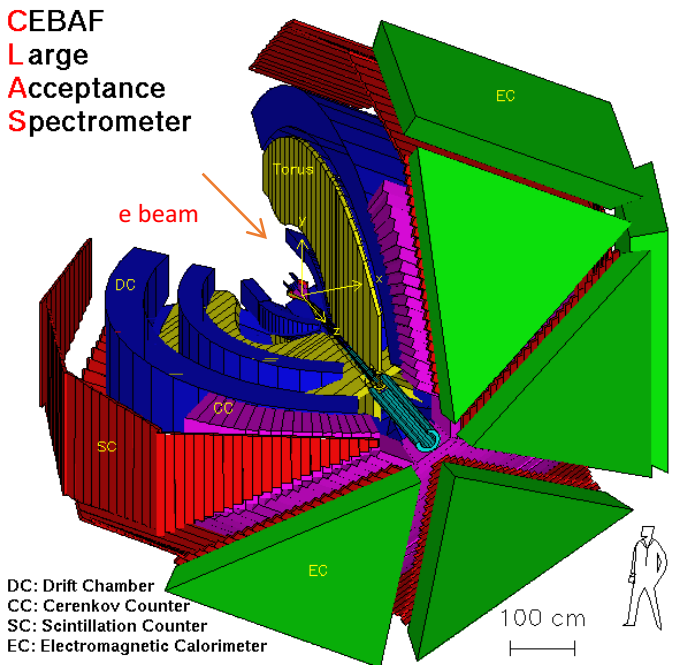
	Experiment							
	Test SIDIS		Complete TMDs investigation			Precise Measurements		
U	$\pi^\pm$ $K^\pm$	π^0	$\pi^{\pm,0}$ $K^{\pm,0}$					
L				$\pi^{\pm,0}$ $K^{\pm,0}$			$\pi^\pm$	
T					$\pi^{\pm,0}$ $K^\pm$	$\pi^{\pm,(0)}$ $K^\pm$	$\pi^\pm$	$\pi^\pm$
Target	LH2, LD2	LH2, LD2	LH_2 + LD_2	NH_3, ND_3 or ^{6}LiD or HD	HD	**^{3}He**	**^{3}He**	**NH_3**
Detector	HMS SHMS	HMS SHMS + π^0 detector	CLAS12	CLAS12 + RICH	CLAS12 + RICH	SBS + HERMES RICH	SoLID	SoLID
Lumi ($cm^{-2}s^{-1}$)	10^{36}	10^{36}	10^{35}	10^{35}	10^{34}	**$4\ 10^{36}$**	**$2\ 10^{36}$**	**10^{35}**
Experiment ID	E12-06-104 E12-09-017	E12-13-007 C12-11-102	E12-06-112, E12-09-008	E12-07-107, E12-09-009	C12-11-111	E12-09-018 (SIDIS)	E12-10-006 E12-11-007 (SoLID n)	C12-11-108 (SoLID p)

Hall B SIDIS Program

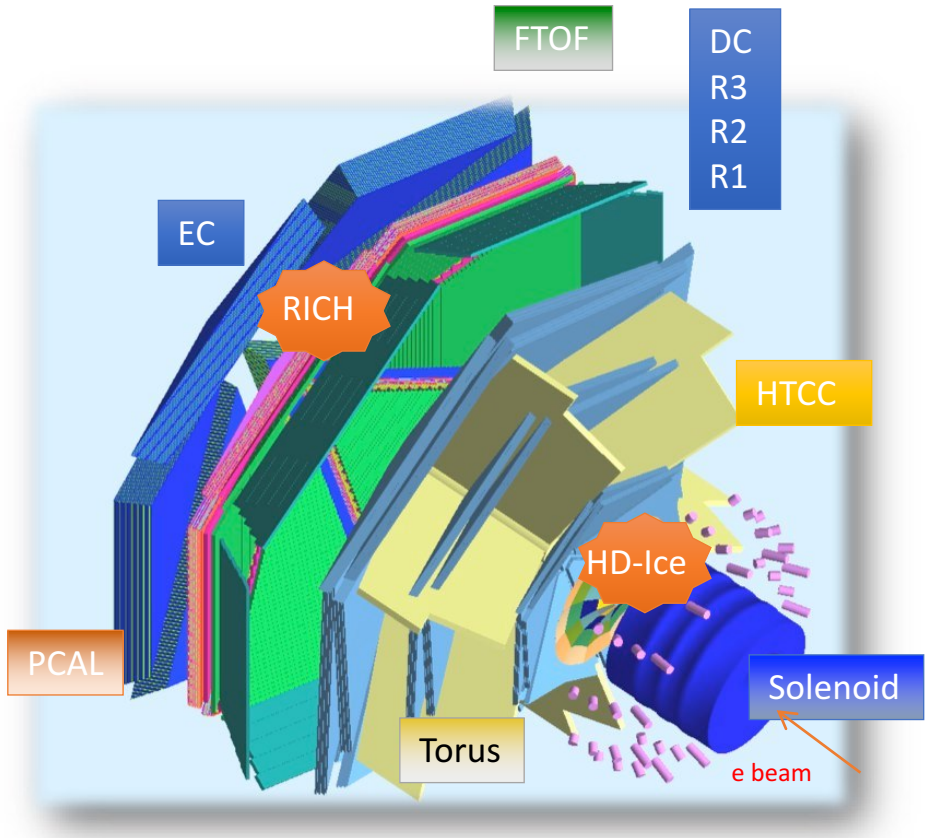
Luminosity up to 10^{35} cm^{-2} s^{-1}
Large acceptance (current & target fragmentation)
Polarized beam and targets (NH_3, ND_3, HD)
Multi-particle final state measurements

6 GeV

NIM A503, 513 (2003)

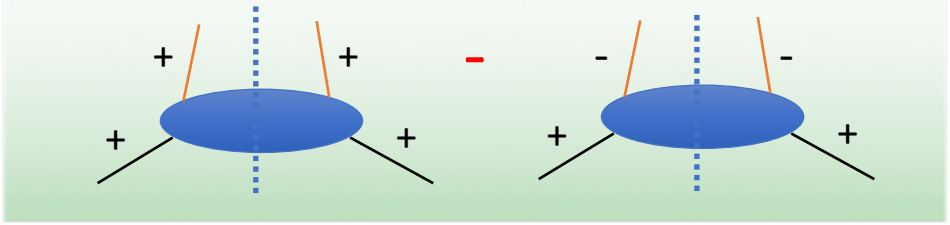


12 GeV



Quark Helicity @ CLAS12

$\Phi[\gamma^+\gamma^5]$ $\quad g_1(x) = q^+(x) - q^-(x)$



quark polarisation

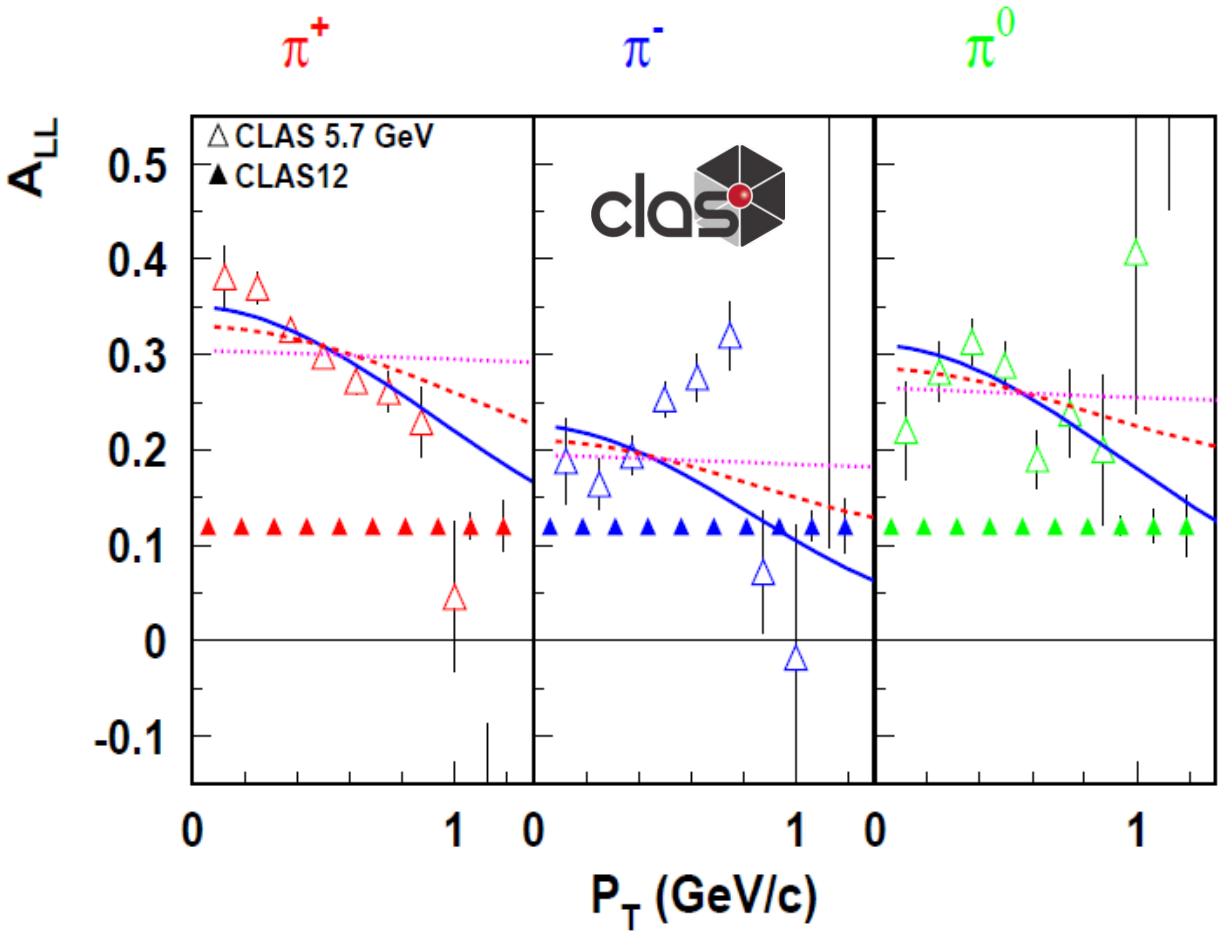
nucleon polarisation

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

quark polarisation

hadron polarisation

N/q	U	L	T
U	D_1		$H_1^\perp$

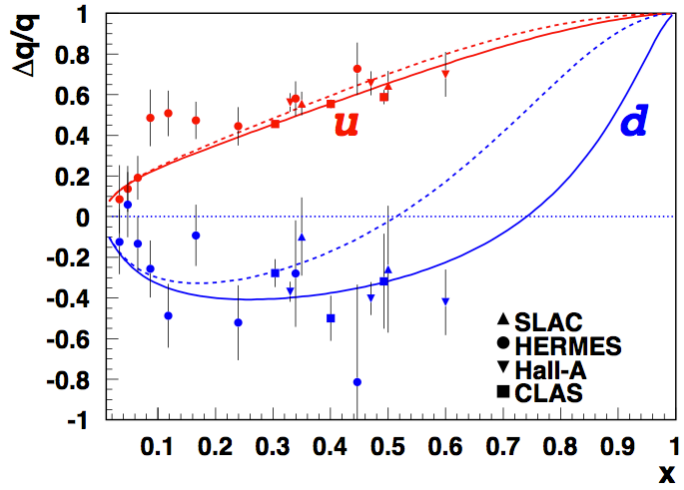


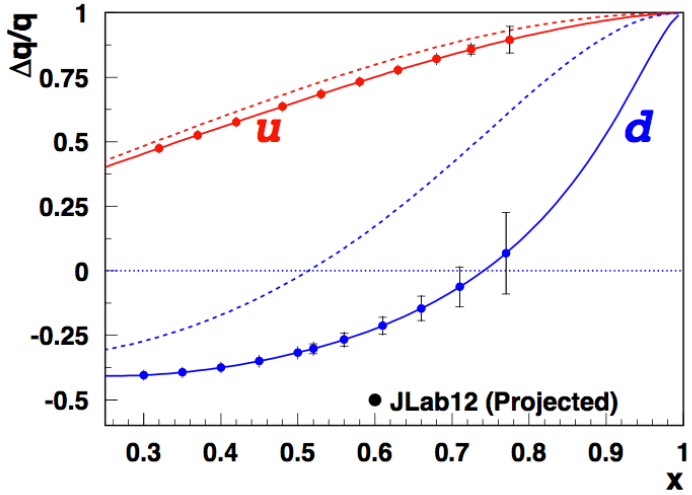
H. Avakian et al. PRL 105: 262002 (2010) [arXiv 1003.4549]

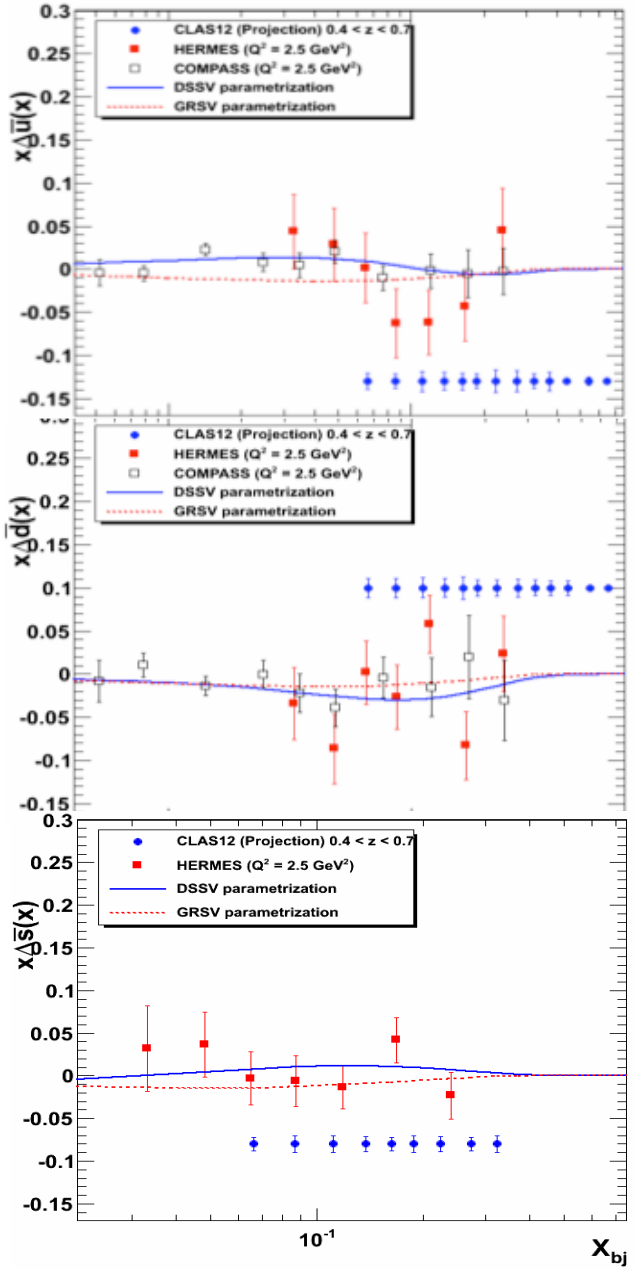
H. Avakian et al. E12-07-107 @ 12 GeV

Quark Helicity @ CLAS12

$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$





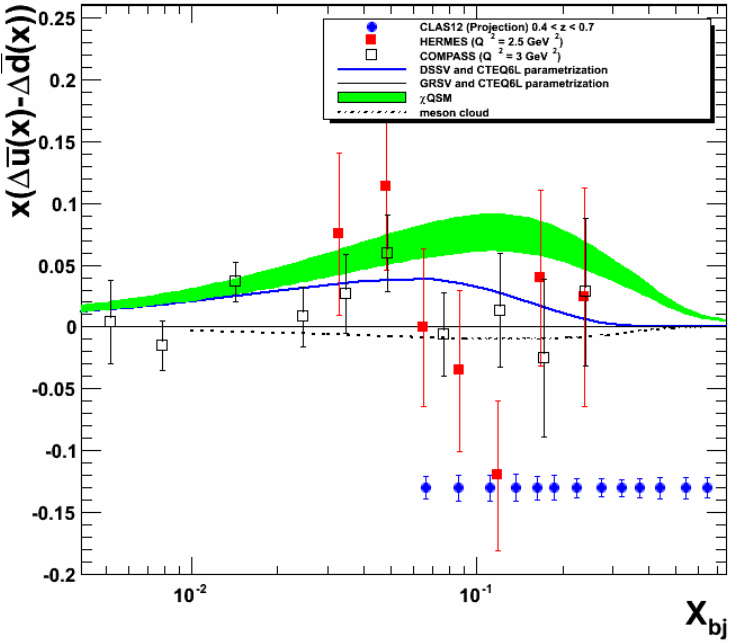


Δū

Δd̄

Δs

E12-09-007

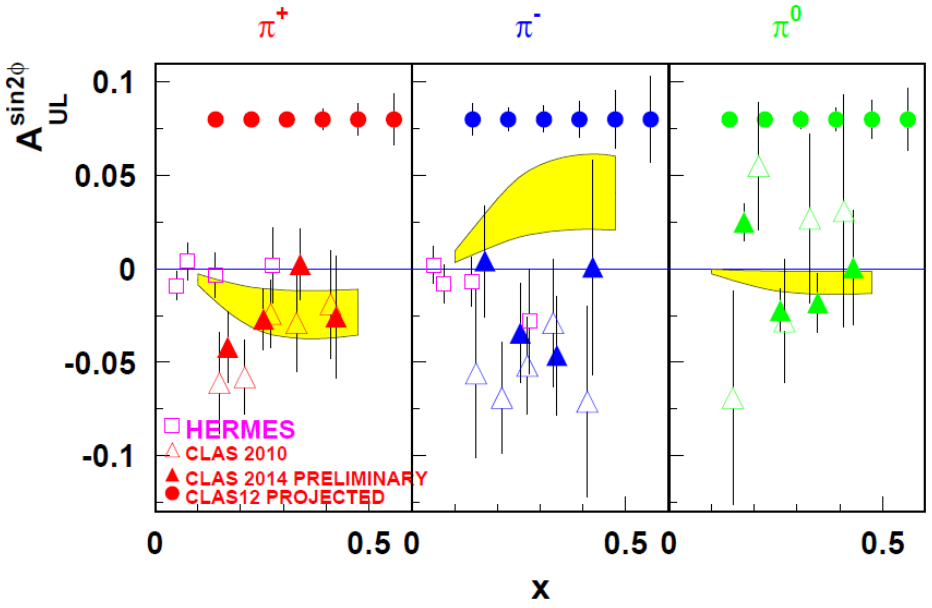


Extraction of
to test whether or not the light sea is symmetrically polarized

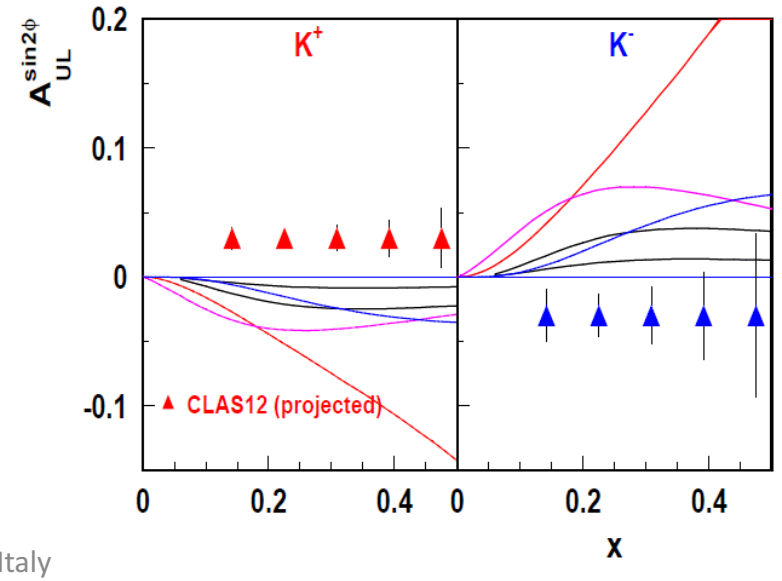
Spin-Orbit Correlations @ CLAS

$$\sigma_{UL}^{\sin 2\phi} \propto h_{1L} \otimes H_1^{\perp}$$

First indication of non-zero $A_{UL}^{\sin\varphi}$ for pions
Potentially significant quark spin-orbit correlations



H. Avakian et al., PRL105: 262002 (2010)
E12-07-107 (pions), E12-009-009 (kaons) @12 GeV



quark polarisation

nucleon polarisation: N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	$h_1, h_{1T}^{\perp}$

quark polarisation

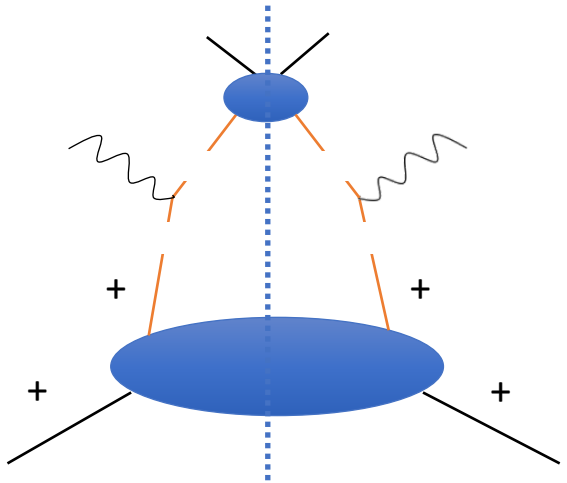
hadron polarisation: N/q	U	L	T
U	D_1		$H_1^{\perp}$

DIS Cross-Section

Wide kinematic coverage is needed to resolve the convolution

$$F_{UU} = f \otimes D = x \sum_q e_q^2 \int d^2 p_T d^2 k_T \;\; \delta^{(2)}(\mathbf{P}_{h\perp} - z\mathbf{k}_T - \mathbf{p}_T) \;\; w(\mathbf{k}_T, \mathbf{p}_T) \;\; f^q(x, k_T^2) \;\; D^q(z, p_T^2)$$

TMD Factorization holds for $p_T \ll Q$



Quark fragmentation

Hard scattering

Quark-quark correlator

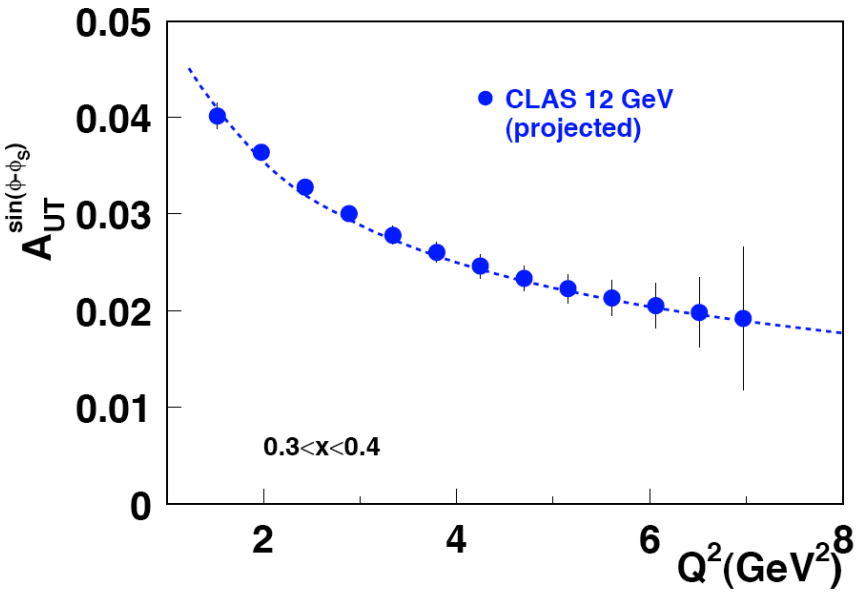
$$\frac{d^6\sigma}{dx dQ^2 dz dP_h d\phi d\phi_S} \overset{LT}{\propto} \left[F_{UU} + \varepsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \right] + S_L \left[\varepsilon \sin(2\phi) F_{UL}^{\sin(2\phi)} \right]$$

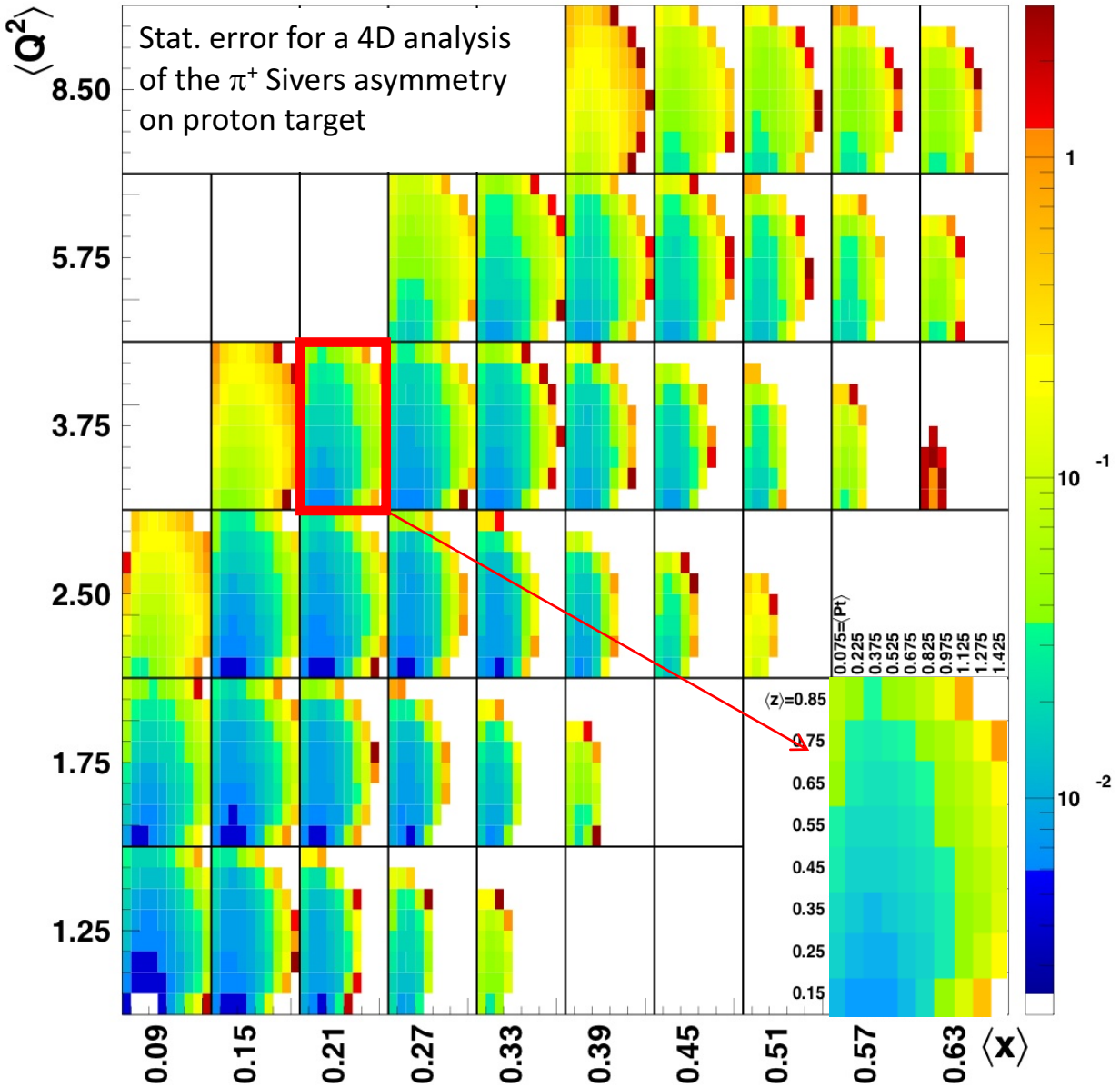
$$+ S_T \left[\sin(\phi - \phi_S) F_{UT}^{\sin(\phi-\phi_S)} + \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \right]$$

$$+ S_L \lambda_e \left[\sqrt{1-\varepsilon^2} F_{LL} \right] + S_T \lambda_e \left[\sqrt{1-\varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)} \right] + O\left(\frac{1}{Q}\right)$$

Sivers Coverage @ CLAS12

$$\sigma_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

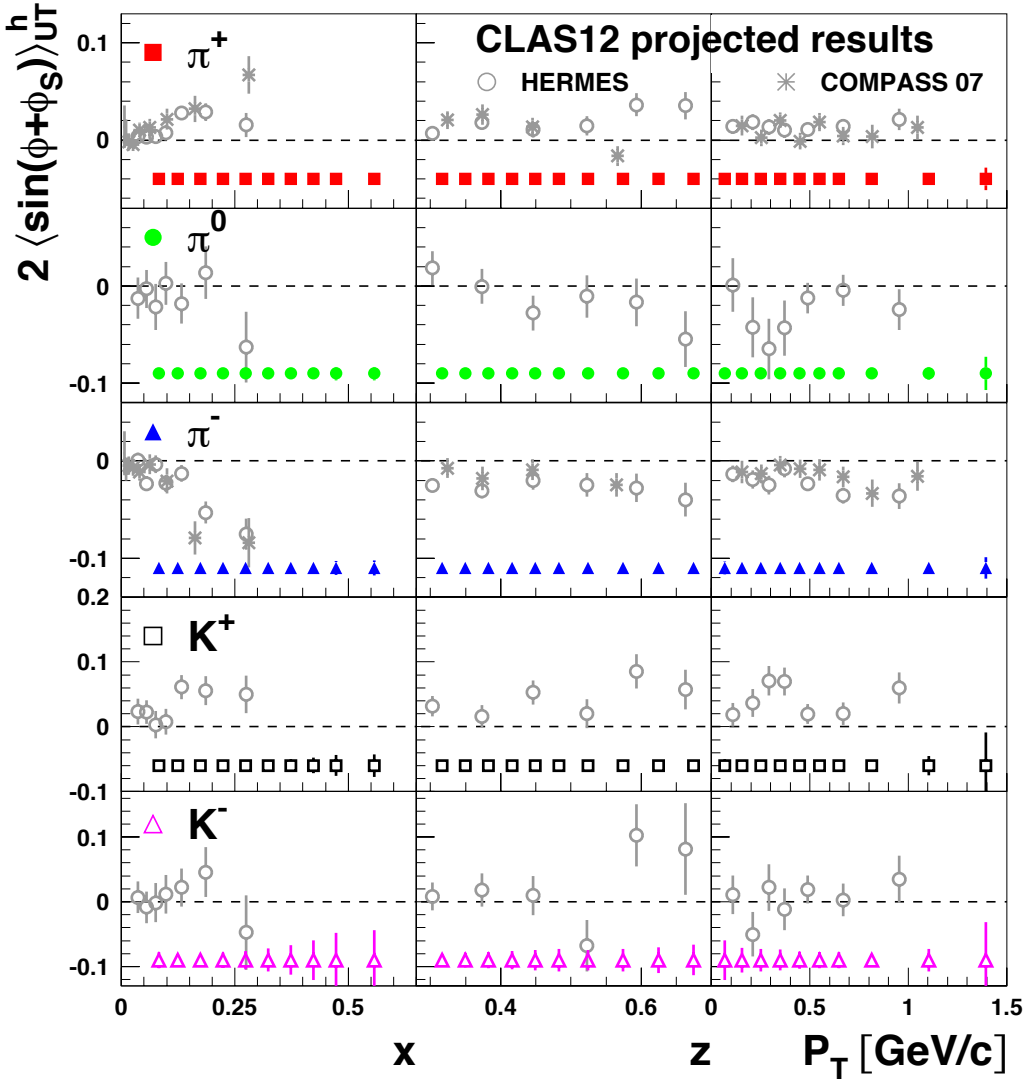




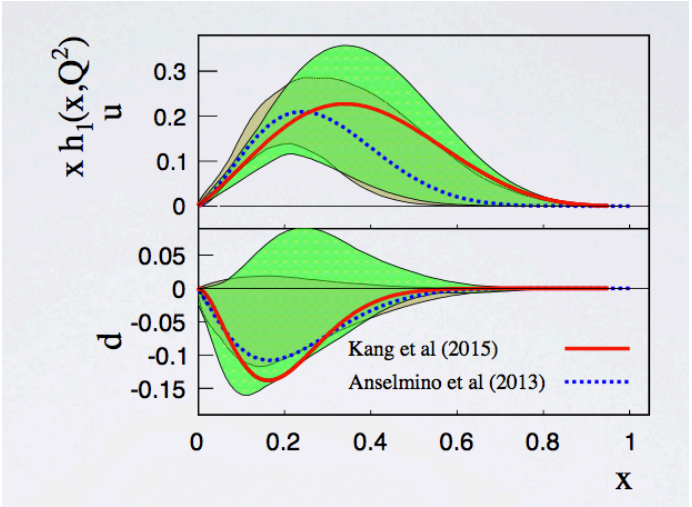
Transversity @ CLAS12

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

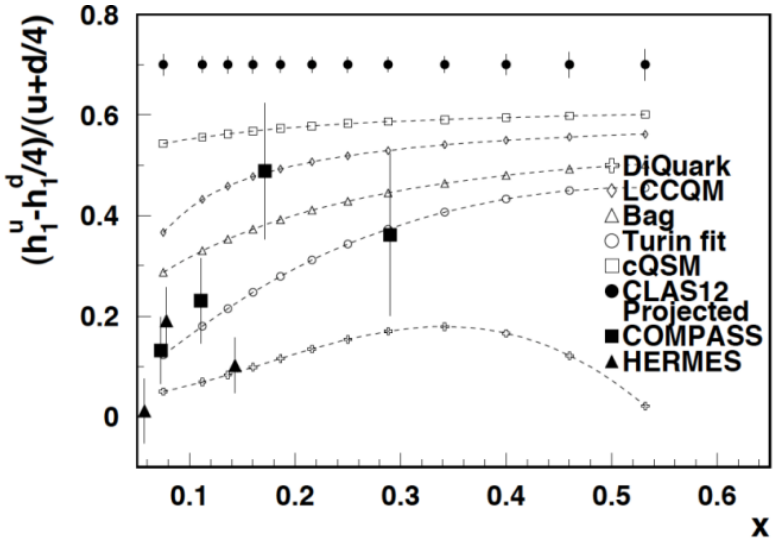
Single hadron channel: C12-11-111 Hall-B



Distributions:



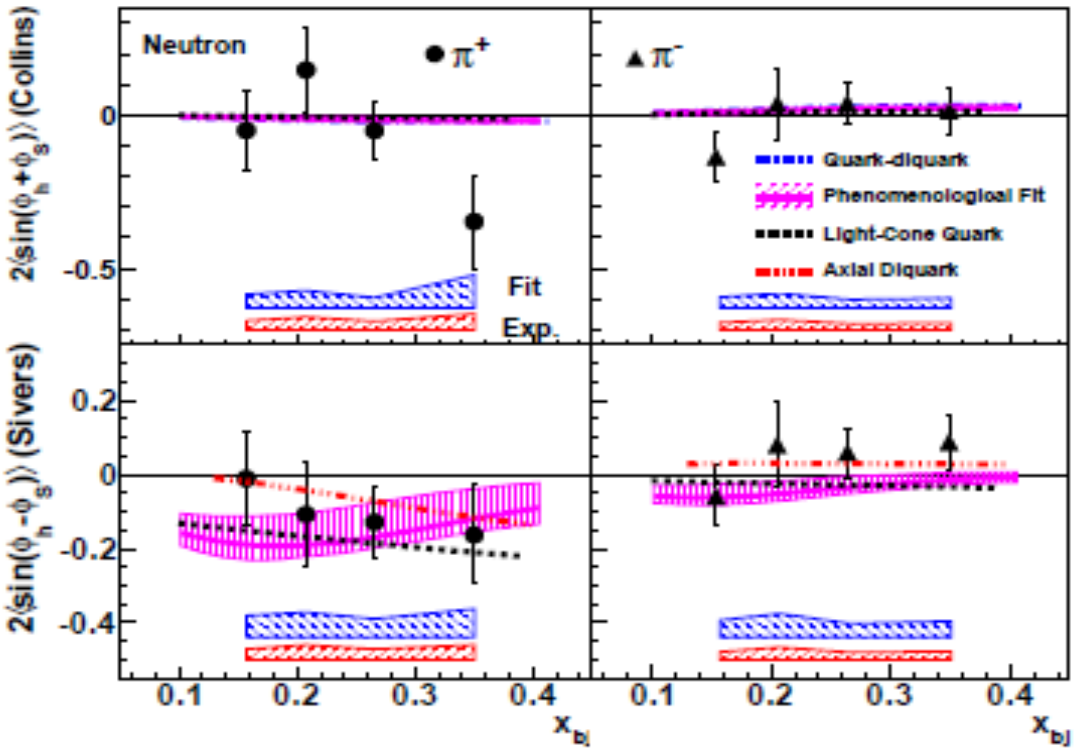
Di-hadron channel:



^{3}He (n) Target Single-Spin Asymmetry in SIDIS Hall A

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^+,
Agrees with Torino's Fit

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

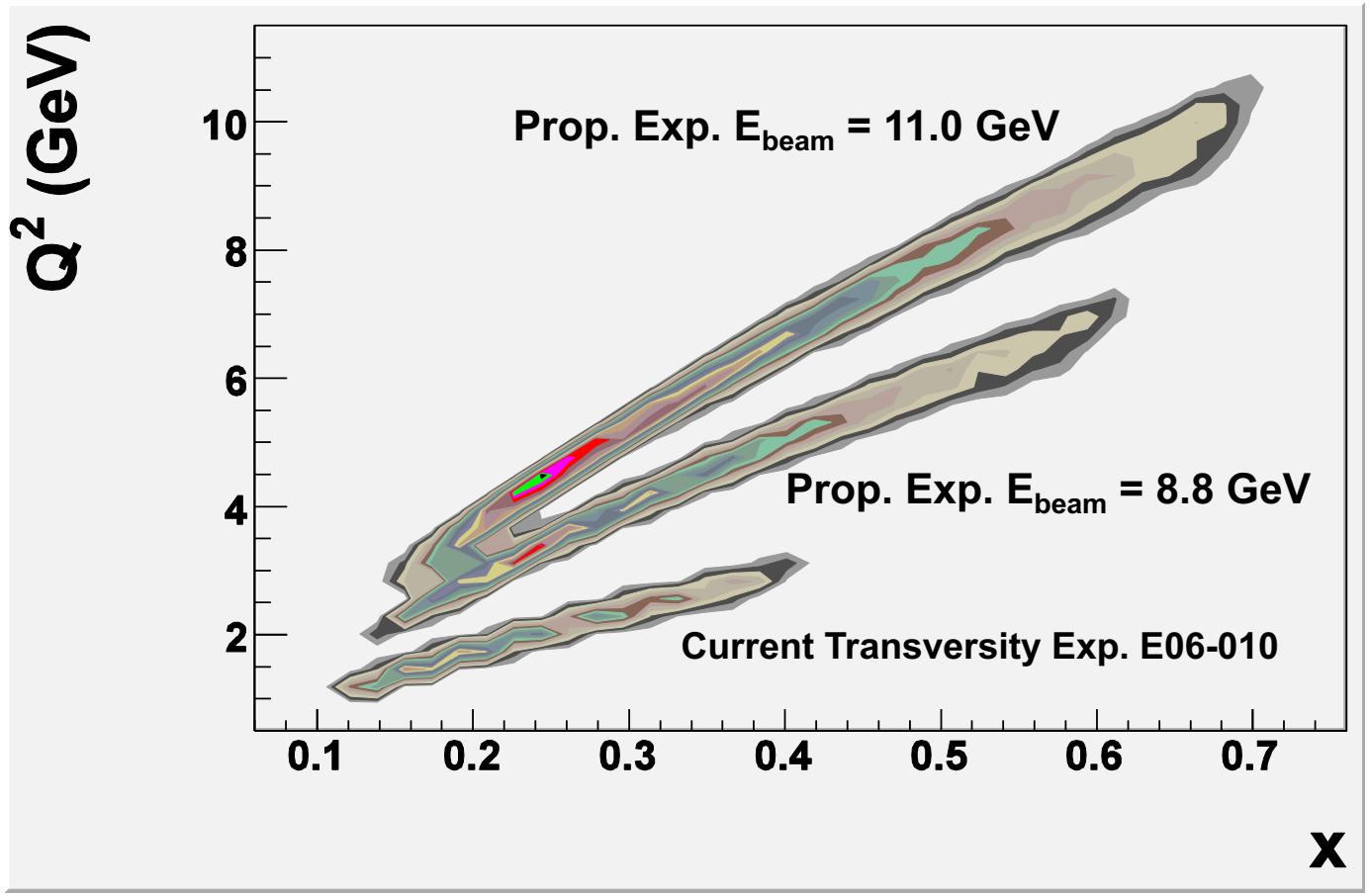
SBS 12 GeV SIDIS in Hall A: Q^2 coverage

2.4<W<4 GeV *

0.1<P⊥<1.2 GeV

0.2<z<0.7

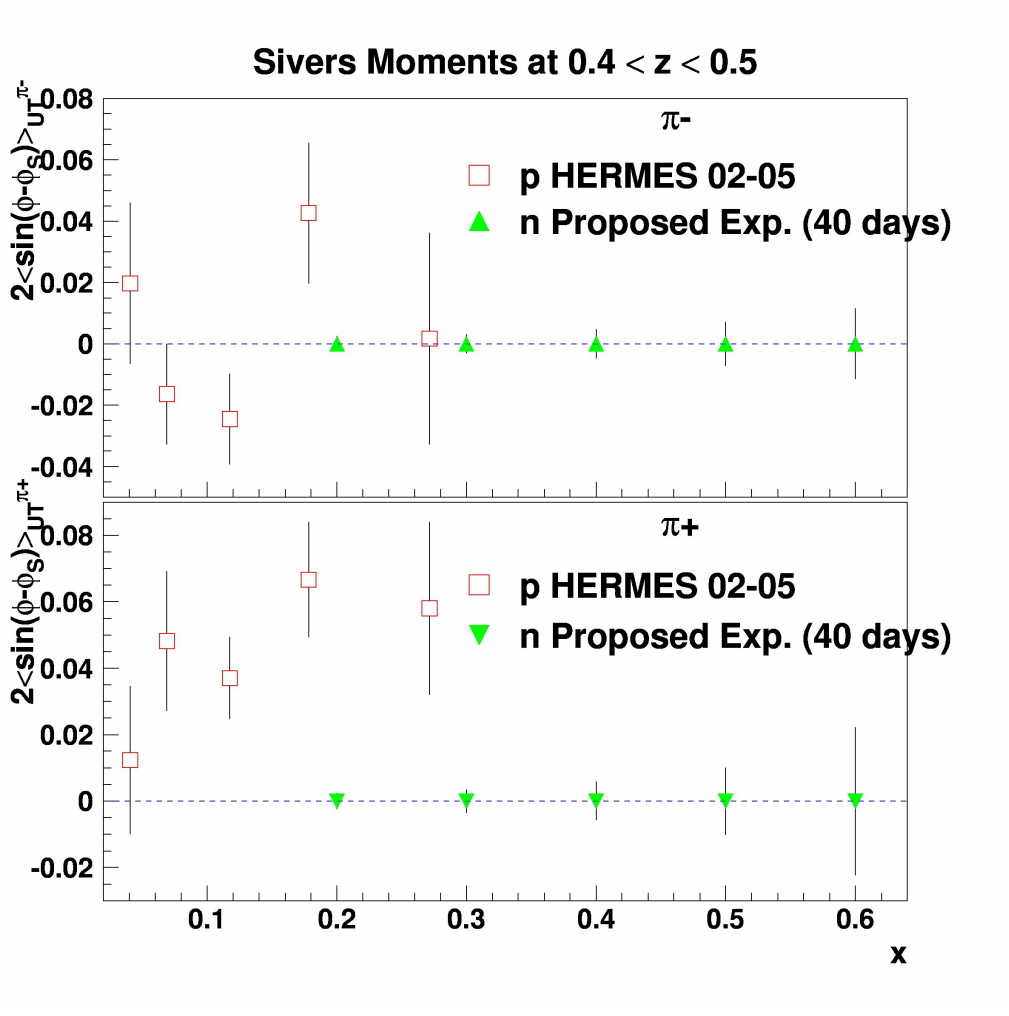
0.7<y<0.9 *

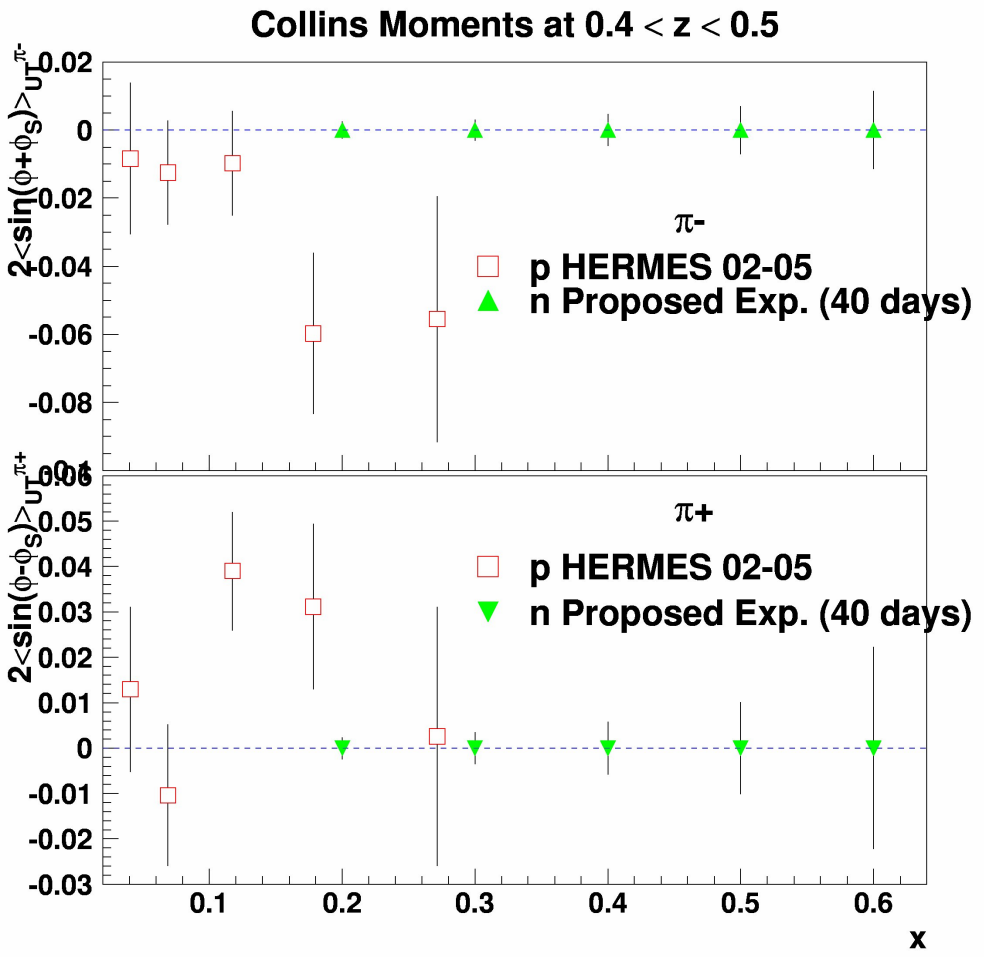


Investigate the Q^2 dependence of the Sivers and Collins functions, with overlap in the region of HERMES; reveal higher twist effects?

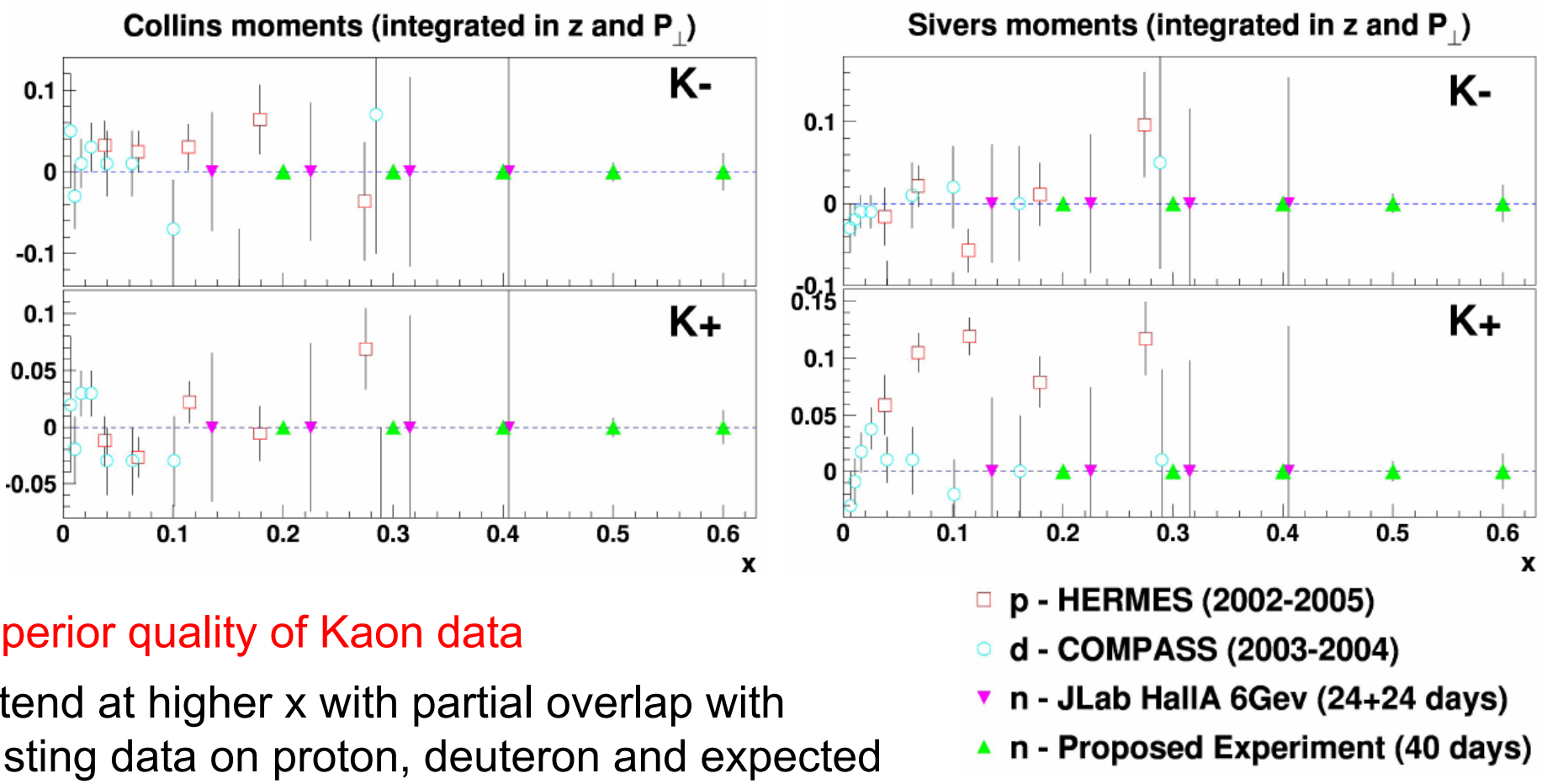
Analysis of the Q^2 effect will use also the results of 6 GeV E06-010 Transversity experiment

SBS projections for Sivers and Collins Moments





12 GeV SIDIS: Expected Accuracy on **Ks**



- Superior quality of Kaon data
- Extend at higher x with partial overlap with existing data on proton, deuteron and expected results of Hall A Transversity 6 GeV

DF from CTEQ5M
FF from DSS
Rate normalized to HERMES/p+d K production

SoLID, Why?

- JLab 6 GeV: precision measurements
  - ➥ high luminosity (10^{39} cm^{-2} s^{-1}) but small acceptance (HRS/HMS: < 10 msr)
  - ➥ or large acceptance but low luminosity (CLAS6: 10^{34} cm^{-2} s^{-1})
- JLab 12 GeV upgrade opens up a window of opportunities (DIS, SIDIS, Deep Exclusive Processes) to study valence quark (3-D) structure of the nucleon and other high impact physics (PVDIS, J/ψ, …)
- High precision in multi-dimension or rare processes requires very high statistics → large acceptance and high luminosity
- CLAS12: luminosity upgrade (one order of magnitude) to 10^{35} cm^{-2} s^{-1}
- To fully exploit the potential of 12 GeV, taking advantage of the latest technical (detectors, DAQ, simulations, …) development

→ SoLID: large acceptance detector can handle 10^{37} cm^{-2} s^{-1} luminosity (no baffles)

10^{39} cm^{-2} s^{-1} with baffles

Overview of SoLID

Solenoidal Large Intensity Device

- 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

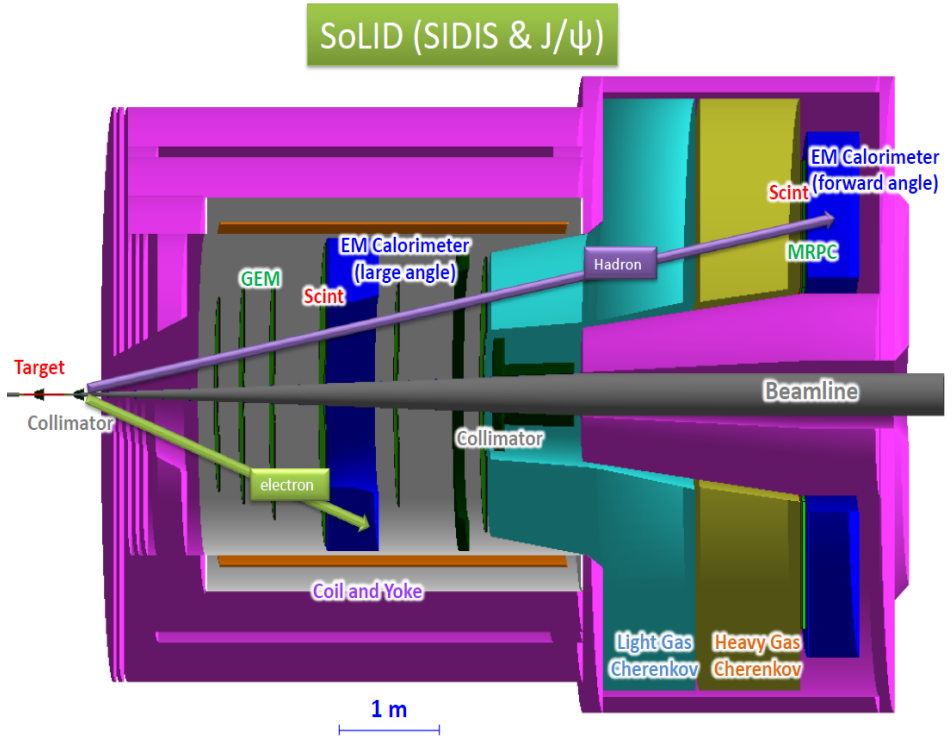
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-x region and threshold J/ψ

- 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)

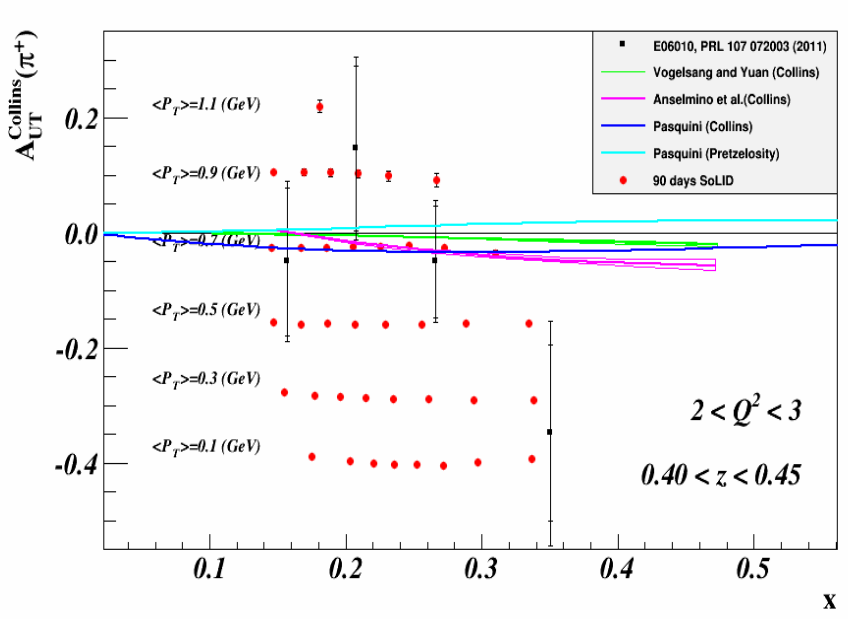
  Significant international contributions (Chinese collaboration)



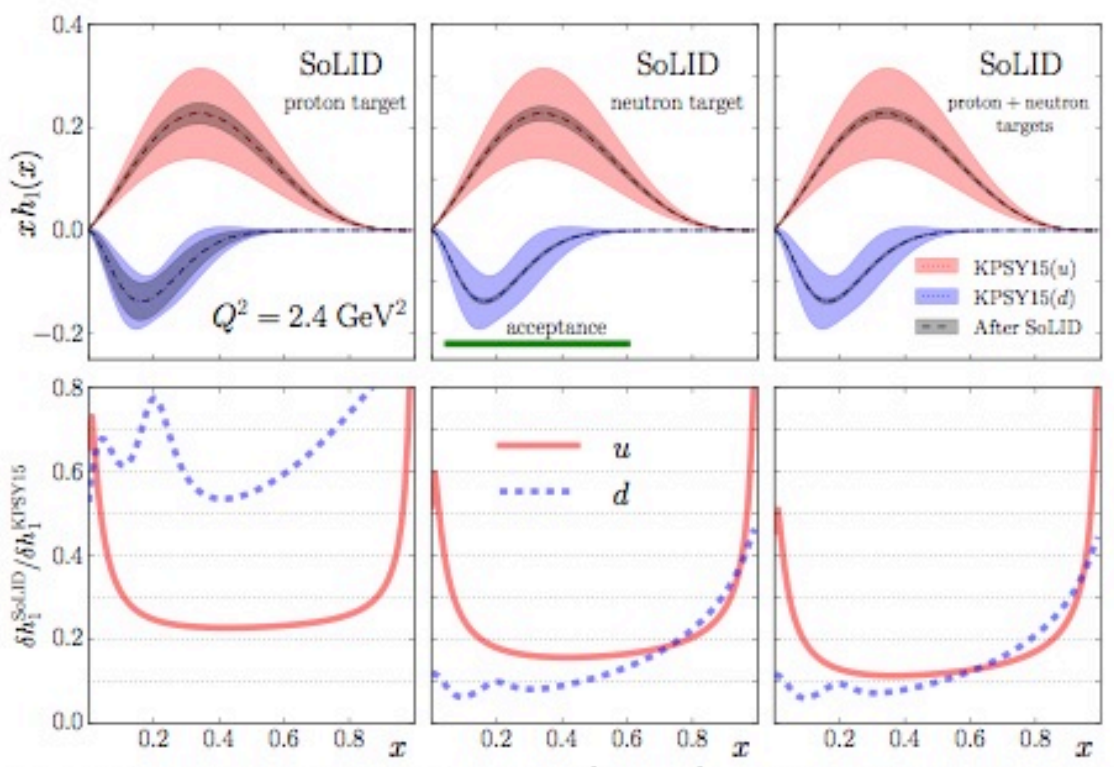
Transversity using SoLID

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

Collins Asymmetries



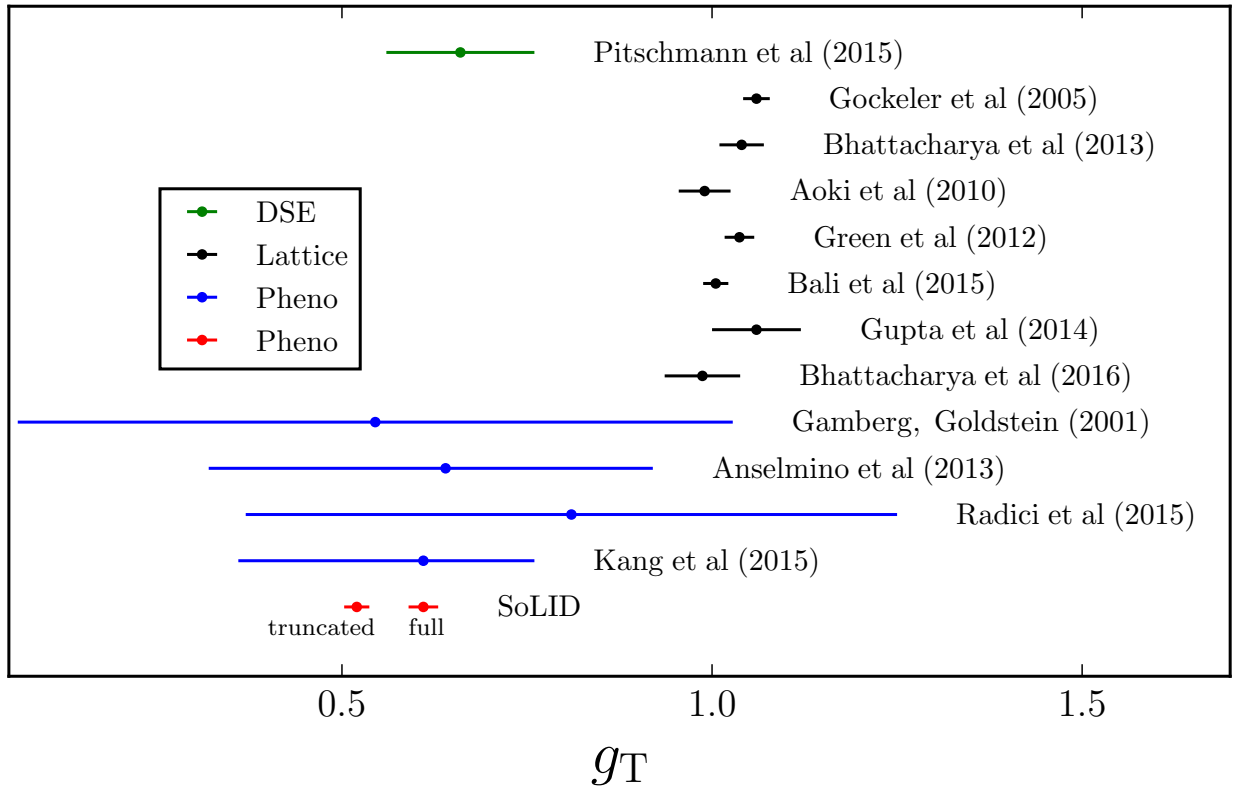
P_T vs. x for one (Q^2, z) bin
Total > 1400 data points



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

DSE

LQCD

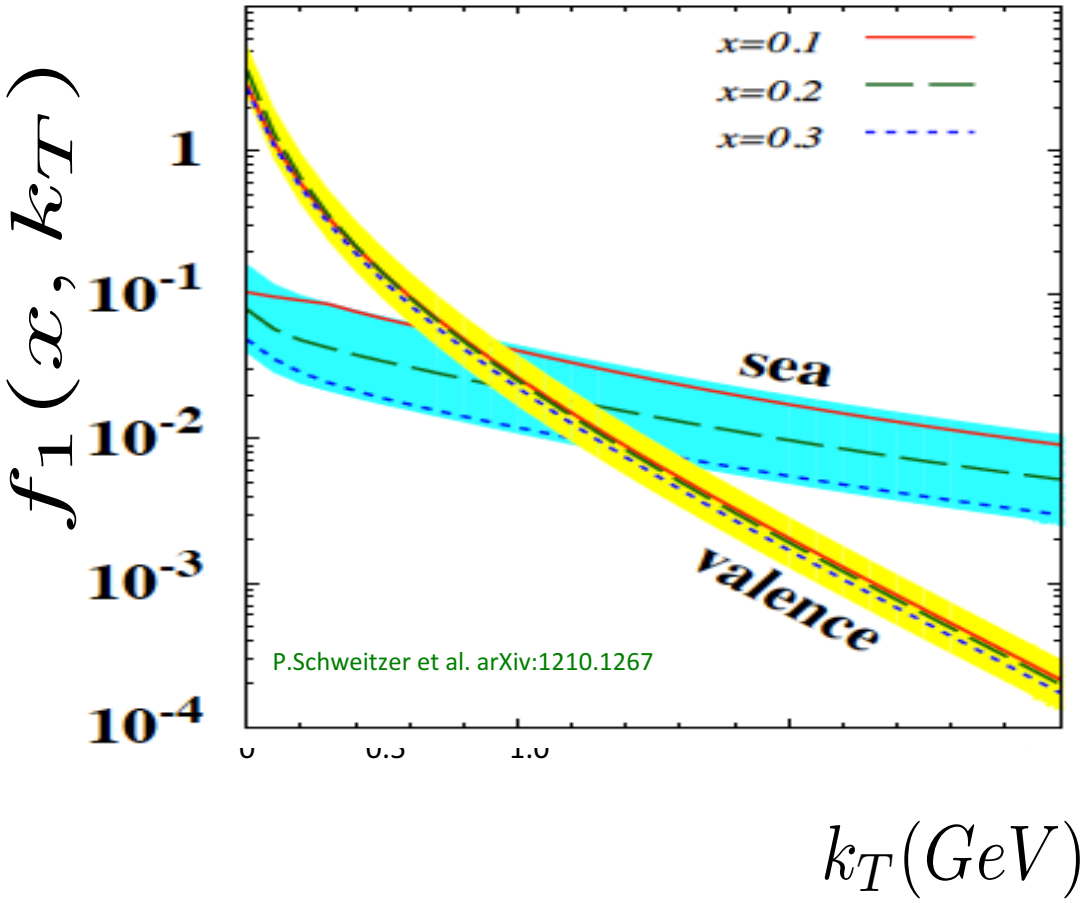
Extractions from existing data

SoLID projections

rojections with a model
QCD evolutions included

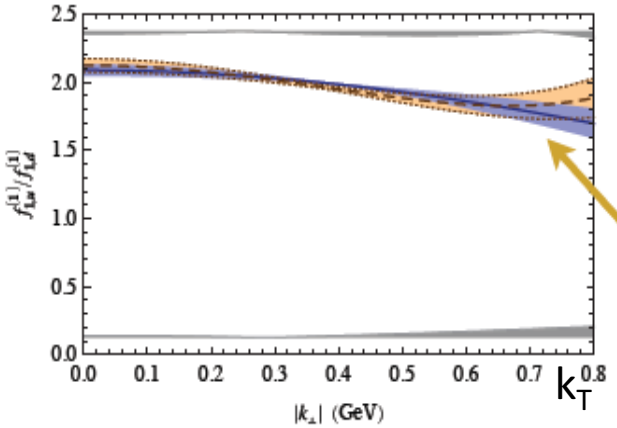
Flavor P_T Dependence from Theory

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



Indications from lattice QCD

f_{1u}/f_{1d}



"less" up quarks

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

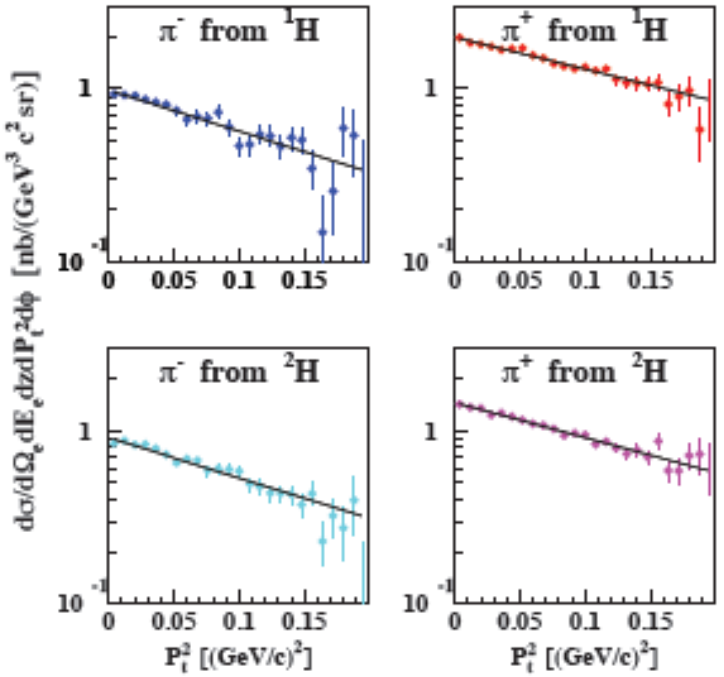
Pioneering lattice-QCD studies hint at a down distribution being wider than up

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

Hall C Results: Flavor P_T Dependence

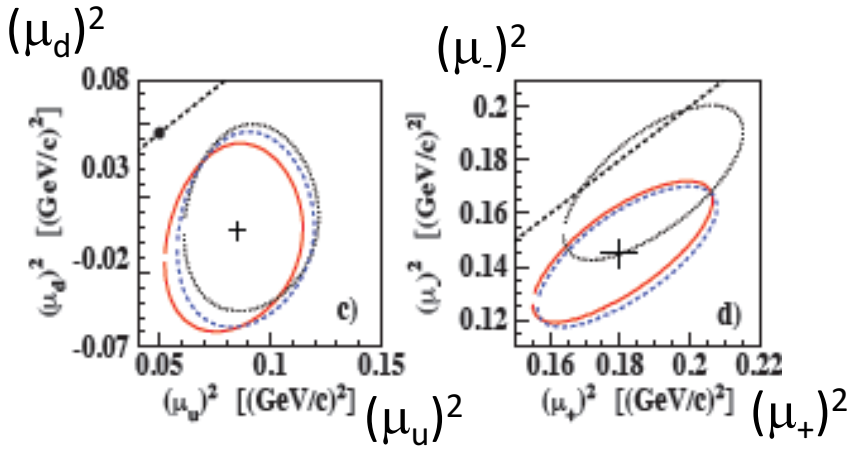
First indications from experiments

<z>=0.55, <x>=0.32



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

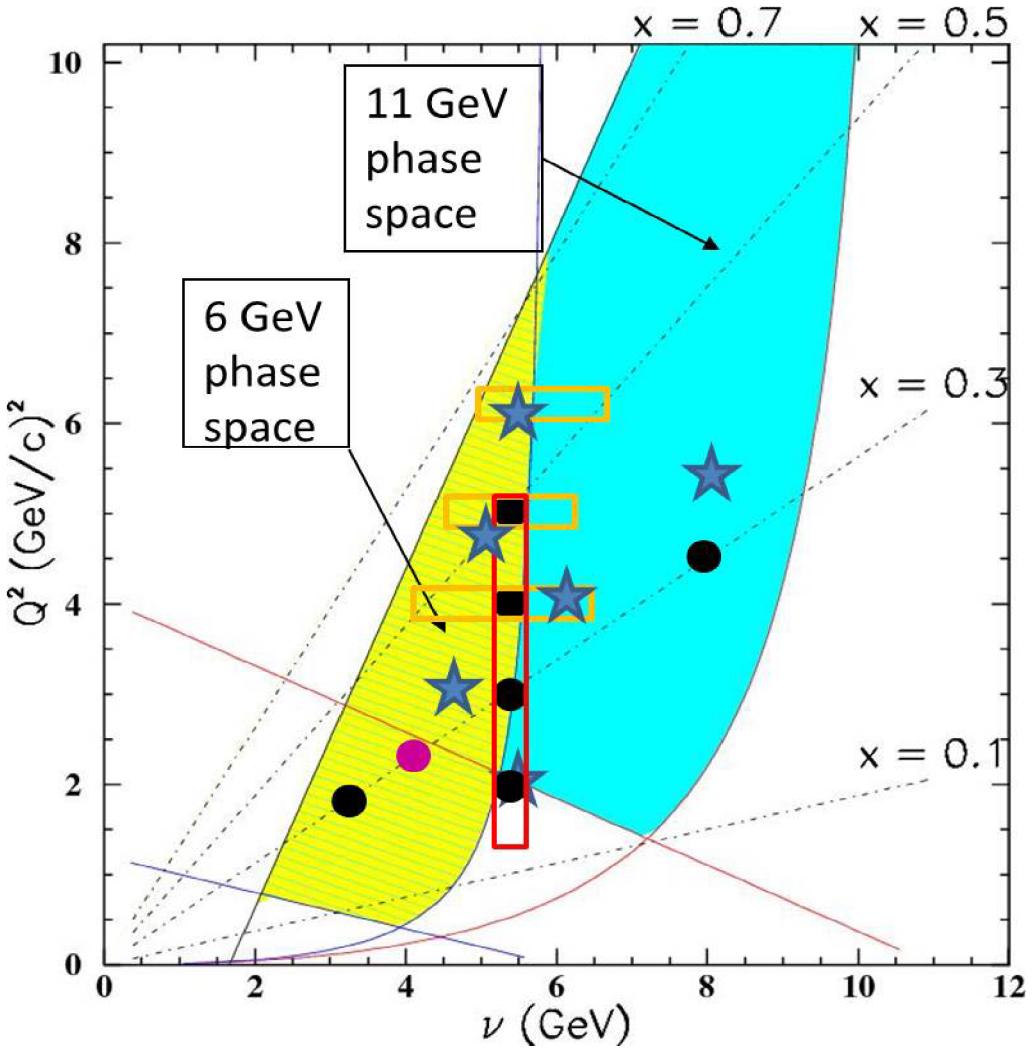
no kaons, no sea,
no *x*-*z* dependence

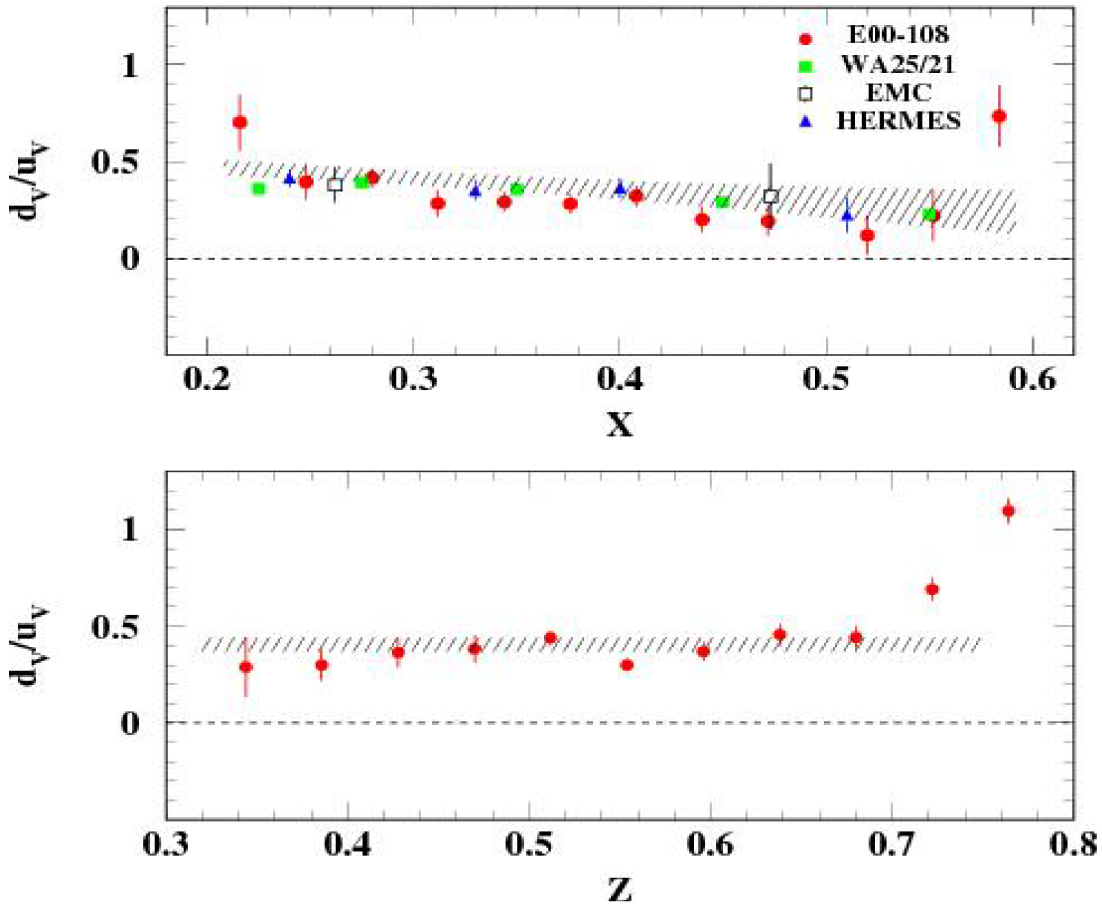


Conclusion: up is wider than down and favored wider than unfavored

Jefferson Lab

Hall C Precision Cross Section Measurements





Experimental Issues

- Extracting TMDs from experimental data
  - Theory/experiment combined (global) analysis
  - Evolutions
  - Y-term, uncertainty from perturbative part at low-intermediate Pt
  - Bessel weighting
  - Fragmentation @ low Q^2
  - Corrections (radiative, nuclear,…)

- Consideration for tensor charge measurements
  - SoLID/JLab 12 cover the main part of x range, constraint on high-x tail
  - Low x tail: valence behavior, much better than spin (Bjorken) sum rule

    how large? ~(5-10)% +- (5-10)% ?

- Orbital Angular Momentum
  - Model-dependent measurements of OAM

    Sivers (related to GDP(E) through lensing function)

    Pretzelosity and Worm-gear functions
  - Direct through GTMD/Wigner?

- Are there the most important/exciting measurements ?

Conclusion

SIDIS Program at Jefferson Lab 12 GeV: a unique combination of wide-acceptance, high-luminosity high-polarization experiments leads to

Comprehensive study of the partonic transverse degrees of freedom in the quark valence region of the nucleon

- Constrain models in the valence region
- Test factorization
- Study higher twist effects
- Investigate non-perturbative to perturbative transition (along P_T)
- Flavor separation via proton and deuteron, ^{3}He targets and hadron ID
- Test of Lattice QCD calculations: tensor charge and other observables
- Access to OAM