

# **TMDs from precision spectrometer experiments in JLab Halls A and C: Existing results and outlook**

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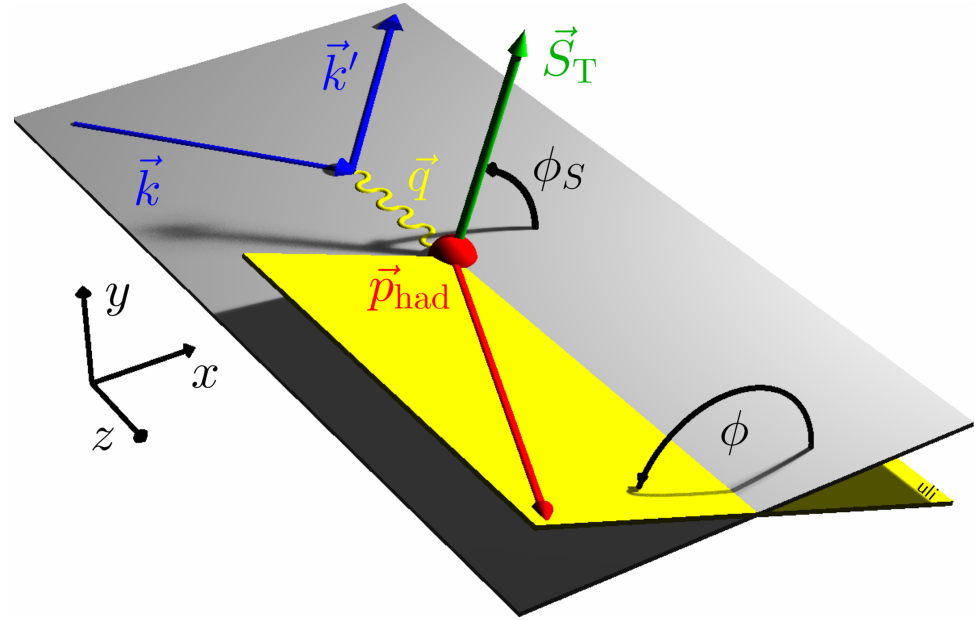
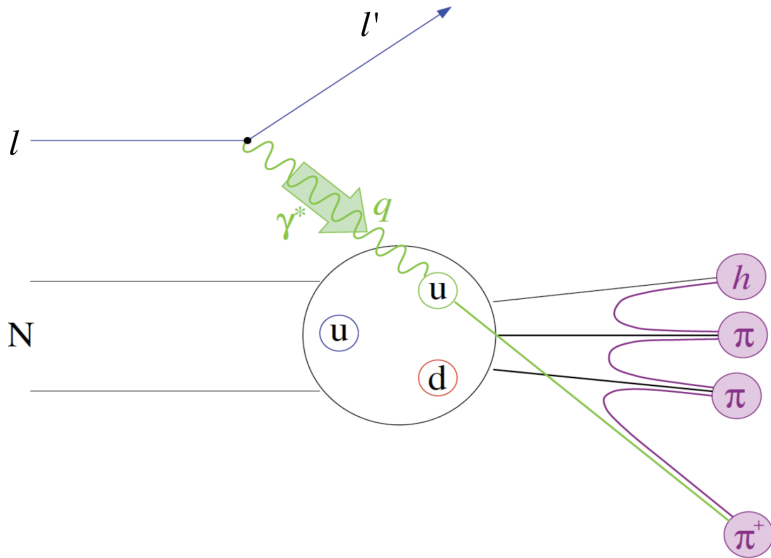
SPIN 2016

9/26/2016

# Outline

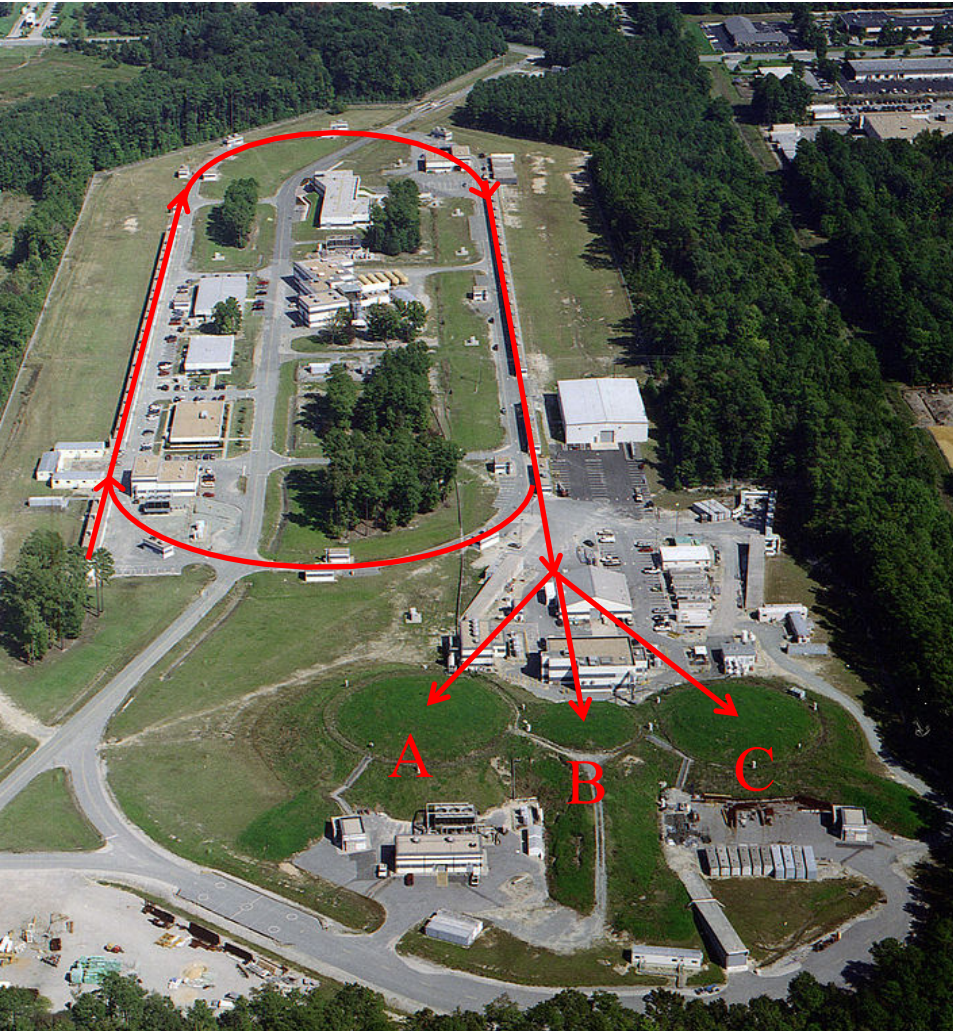
- Introduction: Semi-Inclusive DIS and TMDs
- The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab
  - Accelerator
  - Experimental Halls @6 GeV
- Published and forthcoming SIDIS results from Halls A/C during the JLab 6 GeV era
- Outlook for the 12 GeV era
- Summary, Conclusions

# Semi-Inclusive Deep Inelastic Scattering

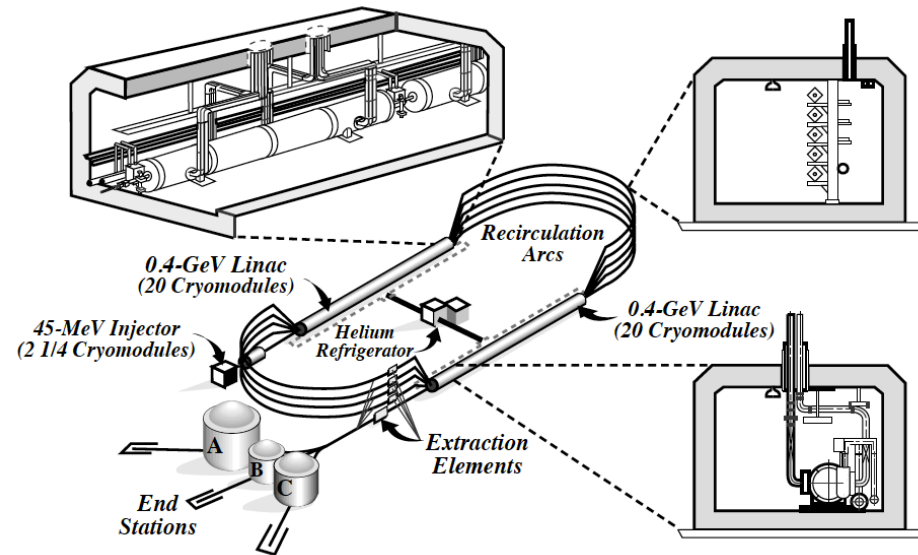


- Detecting leading (high-energy) hadrons in DIS, single inclusive hadron electroproduction  $N(e,e'h)X$  provides sensitivity to additional aspects of the nucleon's partonic structure not accessible in inclusive DIS:
  - quark flavor
  - quark transverse motion
  - quark transverse spin
- ***Goal of SIDIS studies is (spin-correlated) 3D imaging of nucleon's quark structure in momentum space.***
- Transverse Momentum Dependent (TMD) PDF formalism: *Bacchetta et al. JHEP 02 (2007) 093, Boer and Mulders, PRD 57, 5780 (1998), etc, etc...*

# CEBAF @ Jefferson Lab

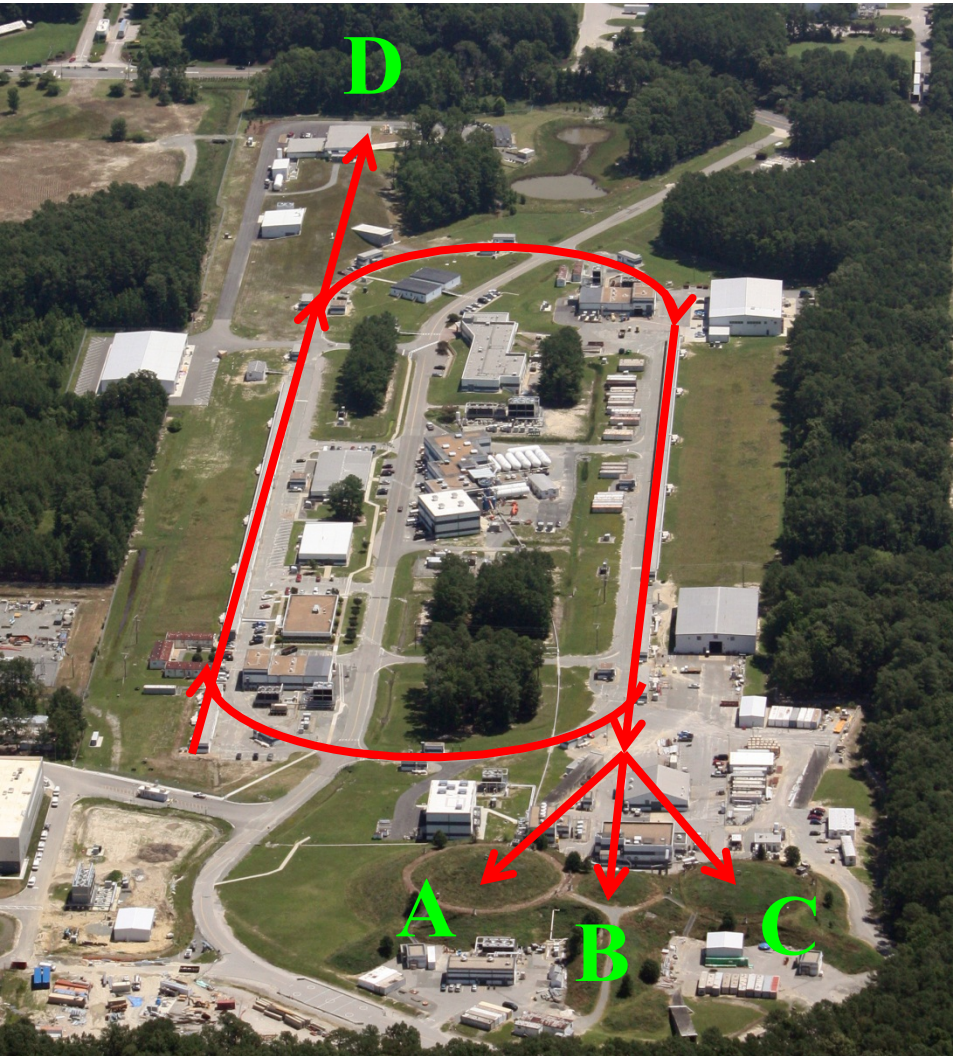


JLab Aerial View

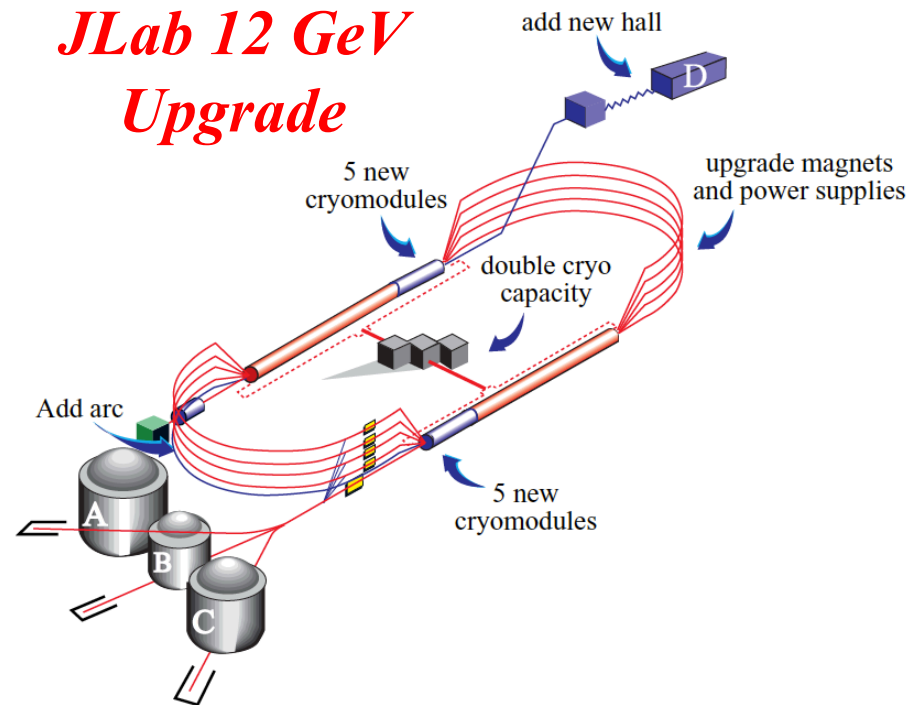


- Superconducting RF electron linacs with up to 5X recirculation
- CW (“100%” duty factor) operation (2 ns bunch period,  $\sim 0.3$  ps bunch length)
- Polarized source: up to 85-90% polarization
- Three experimental Halls
- Energy up to 6 GeV (upgrade increased to 11(12) GeV to Halls A/B/C (D))
- Current (up to 180  $\mu\text{A}$  CW)

# The 12 GeV Upgrade of CEBAF

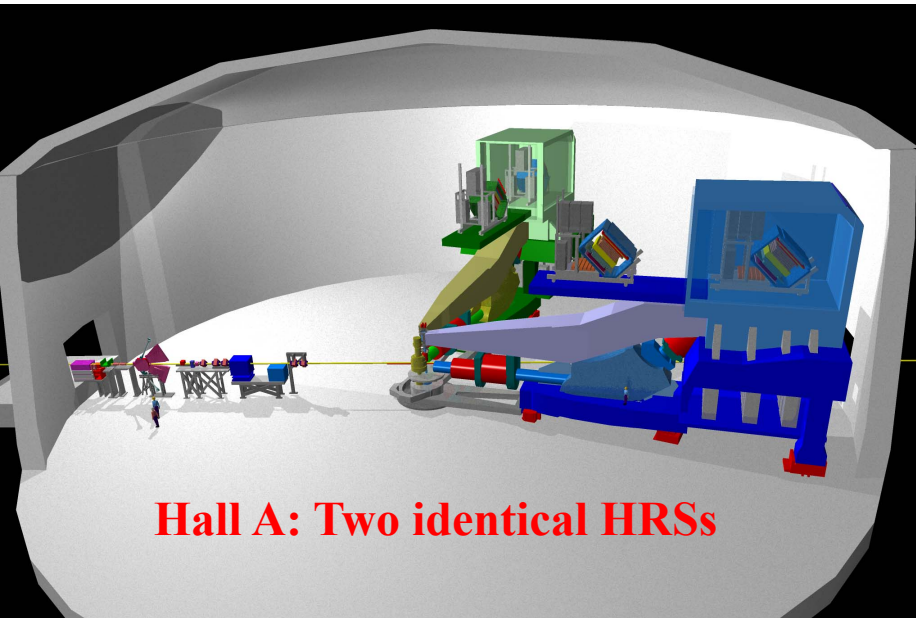


Site Aerial, June 2012

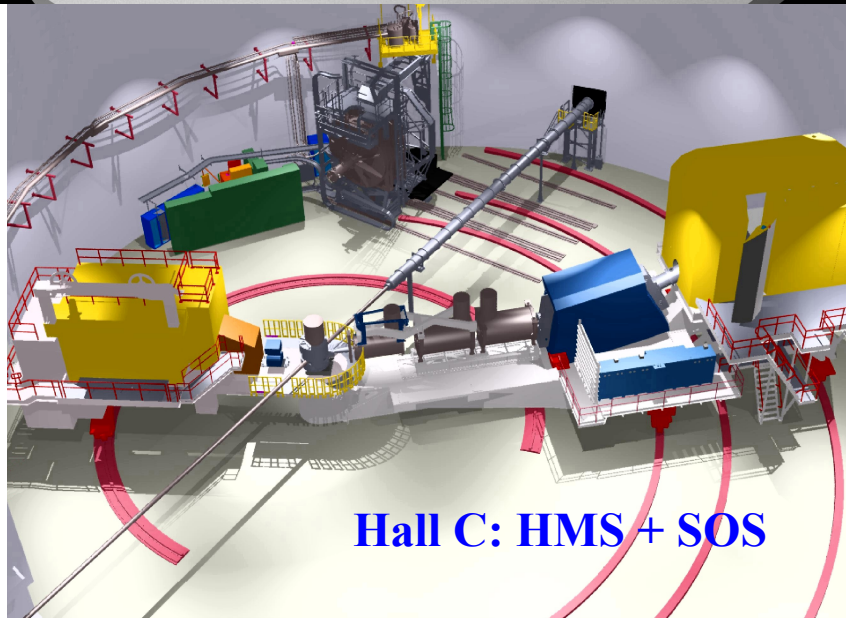


- Superconducting RF electron linacs with up to 5X recirculation
- CW (100% duty factor) operation
- Polarized source: up to 85% polarization
- Three experimental Halls
- Energy up to 11(12) GeV to Halls A/B/C (D)

# CEBAF Experimental Halls @6 GeV

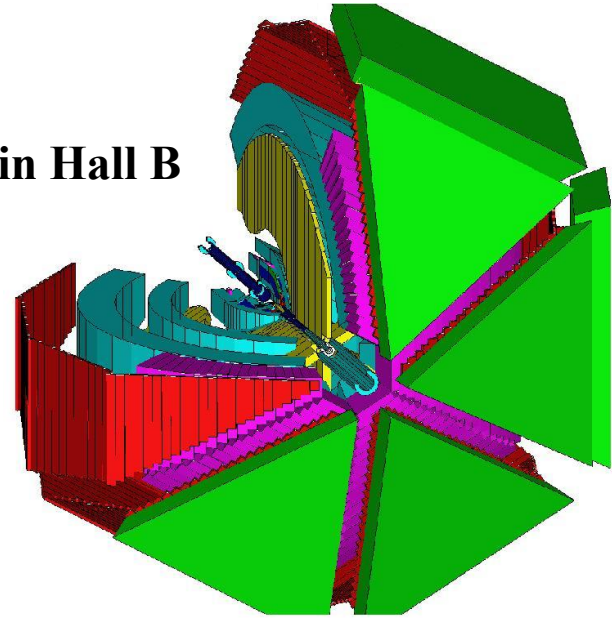


**Hall A: Two identical HRSs**



**Hall C: HMS + SOS**

**CLAS in Hall B**



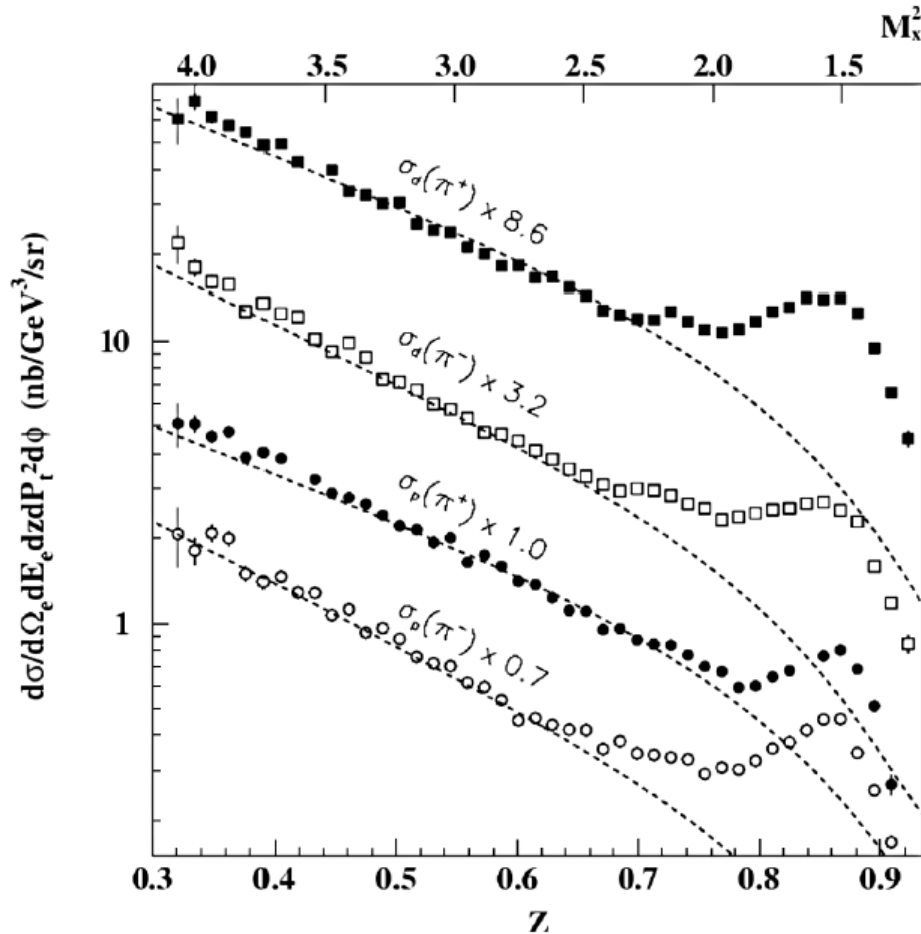
- **Hall A:** High resolution ( $dp/p \sim 10^{-4}$ ) spectrometers, small acceptance for targeted measurements w/ well-controlled systematics, well-defined kinematics at high luminosities. *NIM A 522, 294 (2004)*
- **Hall B:** Large acceptance, moderate resolution/luminosity for measurement of multi-particle final states with broad kinematic coverage: *NIM A 503, 513 (2003)*
- **Hall C:** High momentum spectrometer and Short Orbit Spectrometer—well-controlled acceptance for precise cross section measurements: *PRC 78, 045202 (2008)*

# The essential role of “two arm” coincidence experiments using precision spectrometers in lepton-nucleus physics

- The SIDIS process  $N(e, e' h)X$  is to hadron physics as elastic/quasi-elastic  $A(e, e' p)$  scattering is to nuclear physics;
  - Indeed, the appeal of DIS as a probe of the nucleon's quark structure rests on the *factorization* of the hard scattering (elastic electron-parton scattering) from the underlying distribution functions in coordinate and momentum space of the constituents of the target.
- The major difference is that in the SIDIS case, the ratio of binding energy/constituent mass is *large*, such that the bound states of partons that we call *hadrons* are always highly relativistic, as opposed to nucleons in nuclei, for which the ratio  $E/m$  is typically *small*, and a more-or-less non-relativistic treatment of the nuclear wave-function is often applicable.
- In both cases, two-arm coincidence experiments using independent magnetic spectrometers (“electron arm” and “hadron arm”) in fixed-target eN/eA scattering have historically been extremely productive:
  - Well-defined kinematics and acceptances
  - Tolerance for high luminosities
  - Simple, reliable data analysis (straight-line tracking in well-shielded detectors located in field-free regions)
- For SIDIS in the regime of applicability of TMD factorization, the “two arm” approach is completely natural—at large  $Q$ , high  $z$ , small  $p_T$ , the direction of the outgoing hadrons is basically fixed, once the electron kinematics are chosen.
  - With the advent of high-rate tracking technology, a next-generation capability for “two arm” experiments is realized by devices such as the BigBite and Super BigBite Spectrometer in JLab's Hall A

# Results from “two-arm” experiments during the 6 GeV era *@*CEBAF

# Hall C SIDIS Cross Section Data



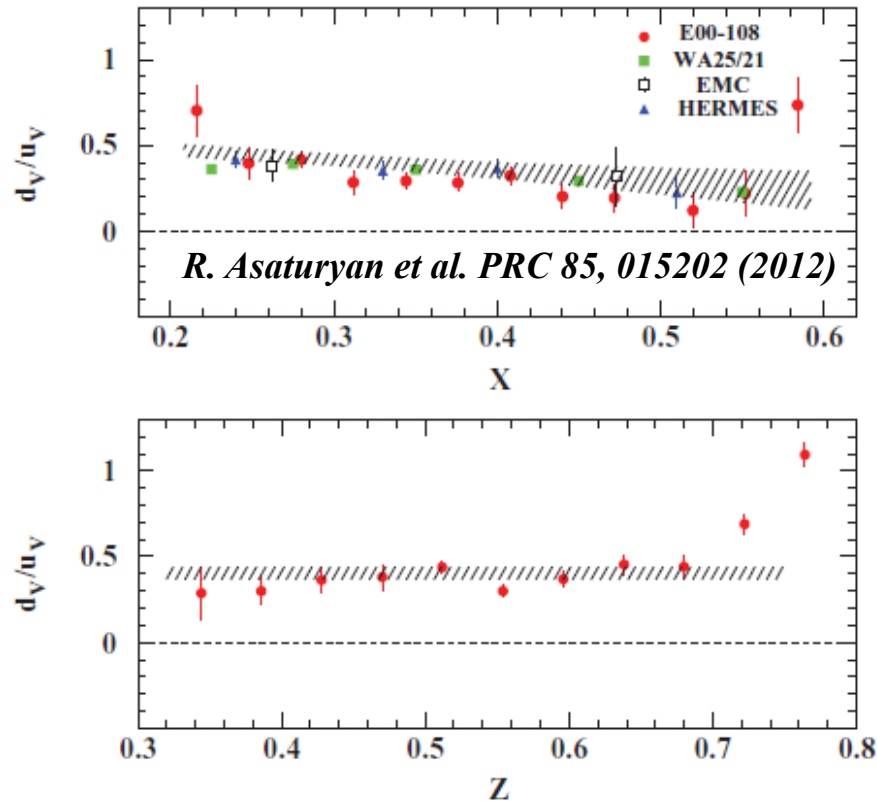
Hall C SIDIS cross section data are in reasonable agreement with simple, LO, naive partonic picture, provided  $M_X^2 > \sim 2.5 \text{ GeV}^2$

- First dedicated SIDIS experiment at JLab:
  - *T. Navasardyan et al. PRL 98, 022001 (2007)*
  - *R. Asaturyan et al. PRC 85, 015202 (2012)*
- $E \sim 5.5 \text{ GeV}$
- Differential cross section measurements with three sets of targeted kinematic variations:
  - z-scan ( $0.3 < z < 1$ ) at fixed  $(x, Q^2) = (0.32, 2.3 \text{ GeV}^2)$ ,  $p_T \sim 0$
  - x-scan ( $0.2 < x < 0.6$ ,  $1.5 < Q^2 < 4.6 \text{ GeV}^2$ ) at fixed  $z = 0.55$ ,  $p_T \sim 0$
  - $p_T$ -scan ( $0 < p_T < 0.4 \text{ GeV}$ ) at fixed  $(x, z, Q^2) = (0.32, 0.55, 2.3 \text{ GeV}^2)$
  - All measurements: fixed  $\nu = 3.8 \text{ GeV}$
- Measurements of  $\pi^+/\pi^-$  on liquid  $\text{H}_2$  and  $\text{D}_2$  targets

$$\frac{\frac{d\sigma}{d\Omega_e dE_{e'} dz dp_T^2 d\phi}}{\frac{d\sigma}{d\Omega_e dE_{e'}}} = \frac{dN}{dz} b e^{-b p_T^2} \frac{1 + A \cos(\phi) + B \cos(2\phi)}{2\pi}, \quad (1)$$

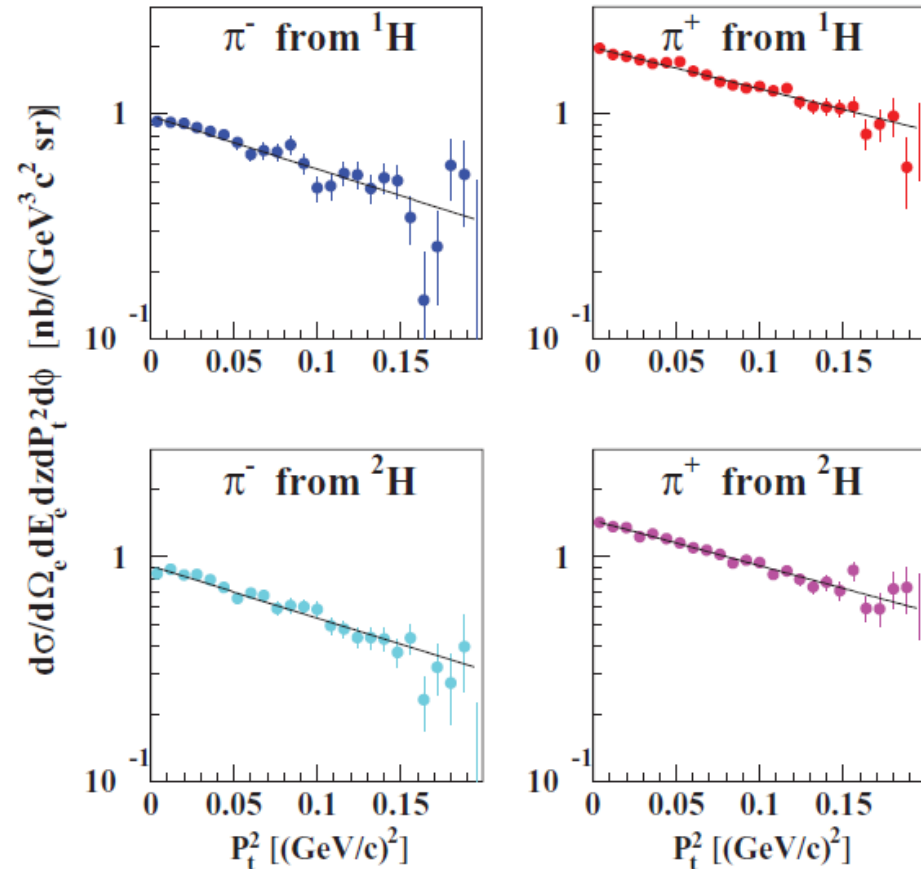
$$\frac{dN}{dz} \sim \sum_q e_q^2 q(x, Q^2) D_{q \rightarrow \pi}(z, Q^2), \quad (2)$$

# Hall C Cross Section Data (Continued)



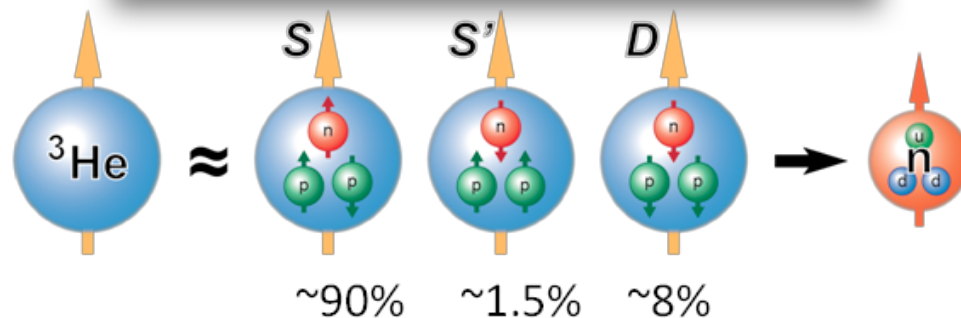
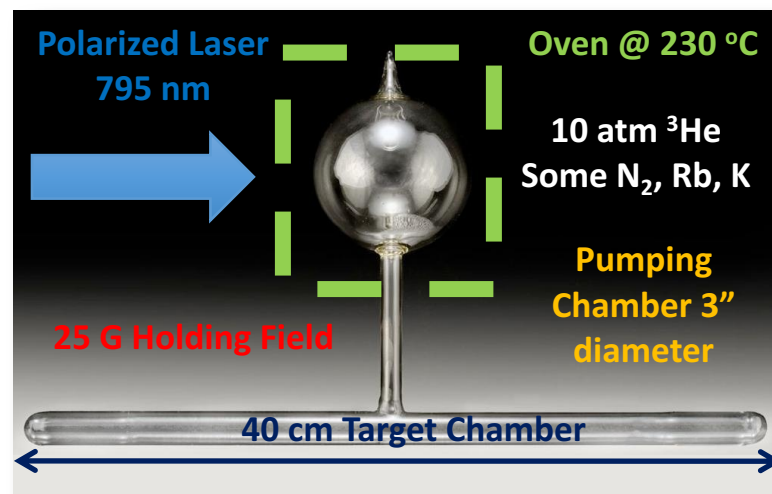
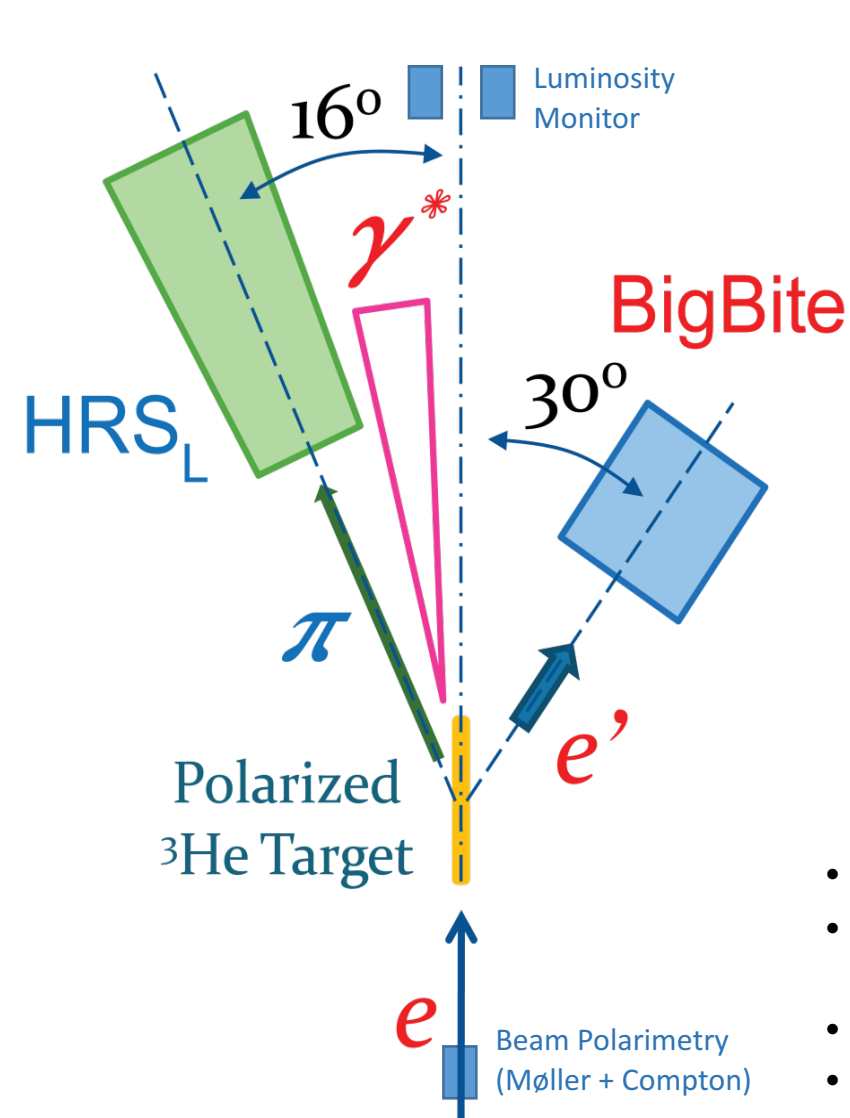
$$R_{pd}^-(x) = \frac{\sigma_p^{\pi^+}(x, z) - \sigma_p^{\pi^-}(x, z)}{\sigma_d^{\pi^+}(x, z) - \sigma_d^{\pi^-}(x, z)} = \frac{4u_v(x) - d_v(x)}{3[u_v(x) + d_v(x)]},$$

- p/d ratios of  $\pi^+$  -  $\pi^-$  cross section difference depends only on  $d_v/u_v$  at leading order
- Data for  $z < 0.7$  in reasonable agreement with CTEQ6 LO PDFs



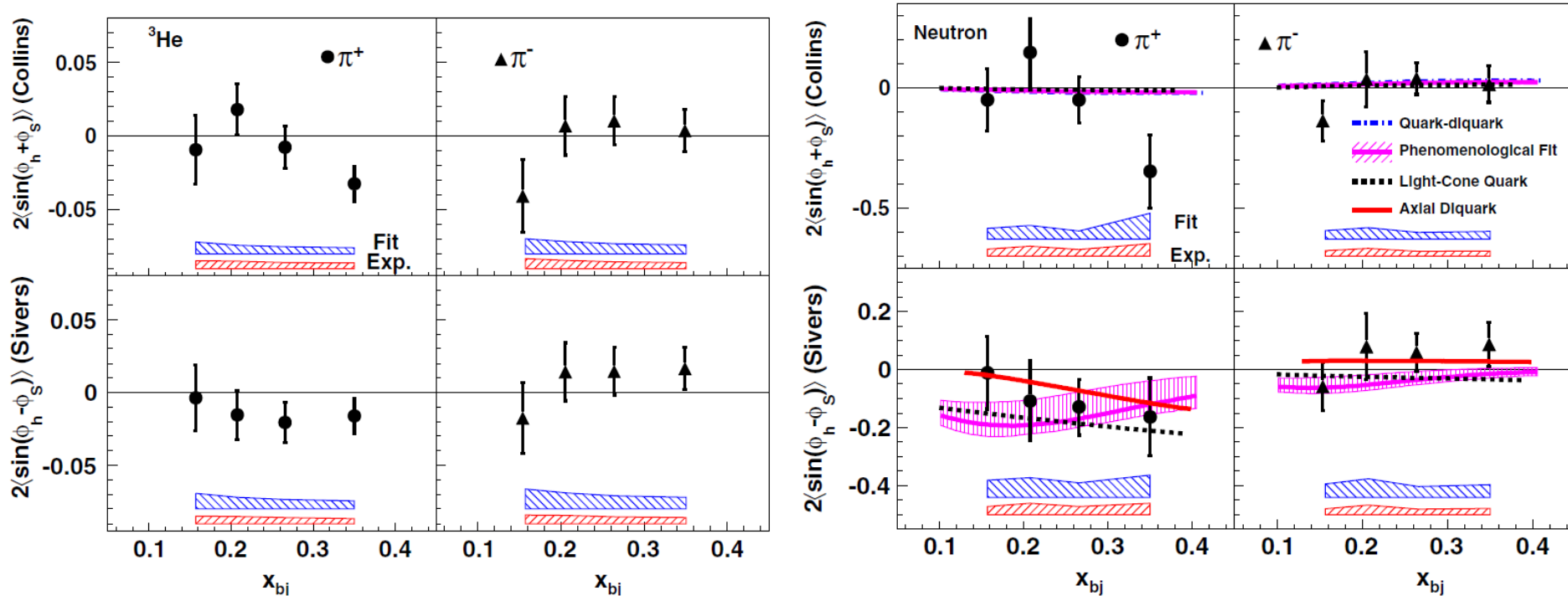
- $p_T$  dependence at  $(x, z, Q^2) = (0.32, 0.55, 2.30 \text{ GeV}^2)$  up to  $p_T < 0.4 \text{ GeV}$
- Data compatible with Gaussian  $p_T$  distribution, similar (but not identical) widths for p, d,  $\pi^+$ ,  $\pi^-$
- Small  $p_T$  range, strongly correlated with  $\phi$ —not venturing far from collinearity!

# Transverse Spin Asymmetries from Hall A: E06-010



- 5.9 GeV beam,  $\sim 85\%$  polarized
- Helium-3 target,  $\langle P_T \rangle = 55\%$  transverse (vertical and horizontal directions), flip every  $\sim 20$  minutes.
- Average beam current  $\sim 12 \mu\text{A}$
- Two-month run in Hall A in 2008/2009, expt. E06-010

# Collins and Sivers effects: *PRL 107, 072003 (2011)*

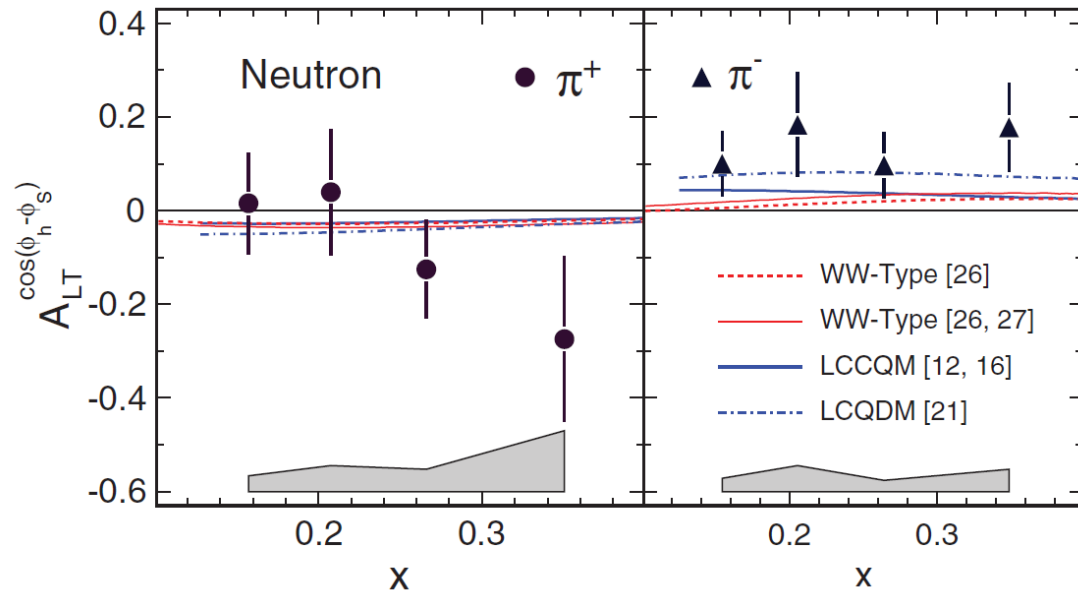
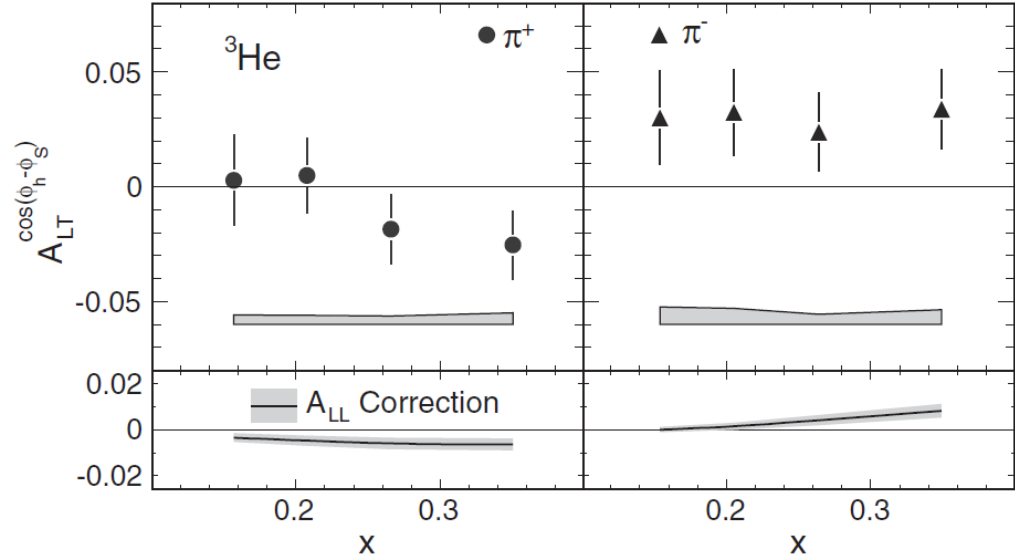


- Observed  $^3\text{He}$  Collins and Sivers asymmetries  $< 5\%$  in magnitude
- Extracted neutron C/S moments consistent w/model predictions available at time of publication
- In the valence region, despite relatively low statistics, E06-010 has best sensitivity to neutron Sivers moments, and comparable precision to COMPASS d-p for Collins moments, after correction for quark depolarization factor  $D_{NN} = (1-y)/(1-y + y^2/2)$
- *Impact of E06-010 data from a short-duration run with small-acceptance spectrometers demonstrates power of  $^3\text{He}$  target and lays foundation for high statistical FOM @11 GeV*

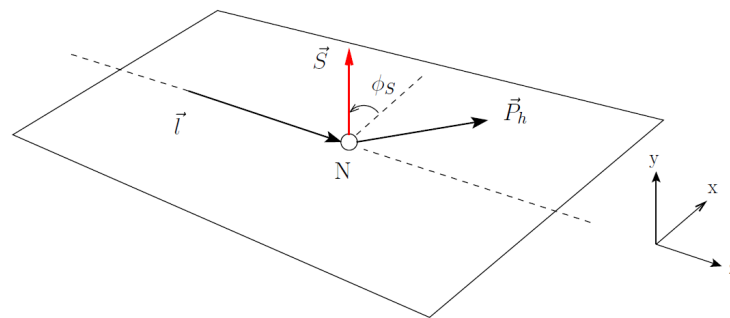
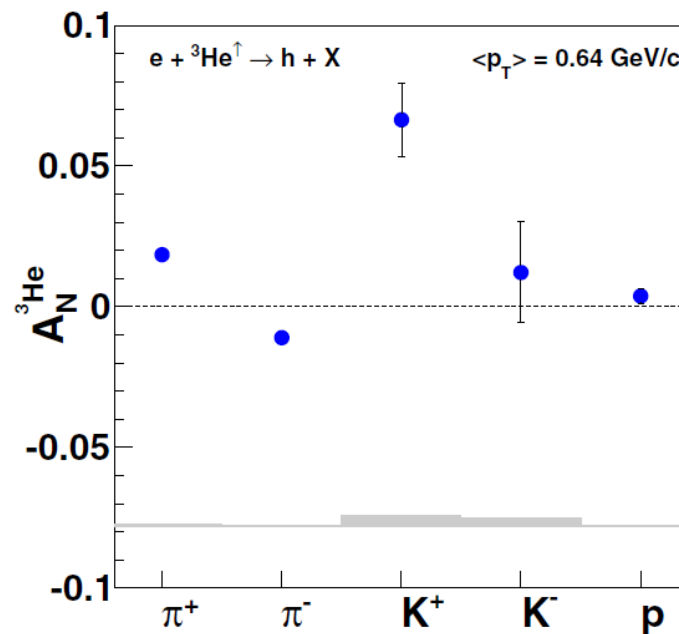
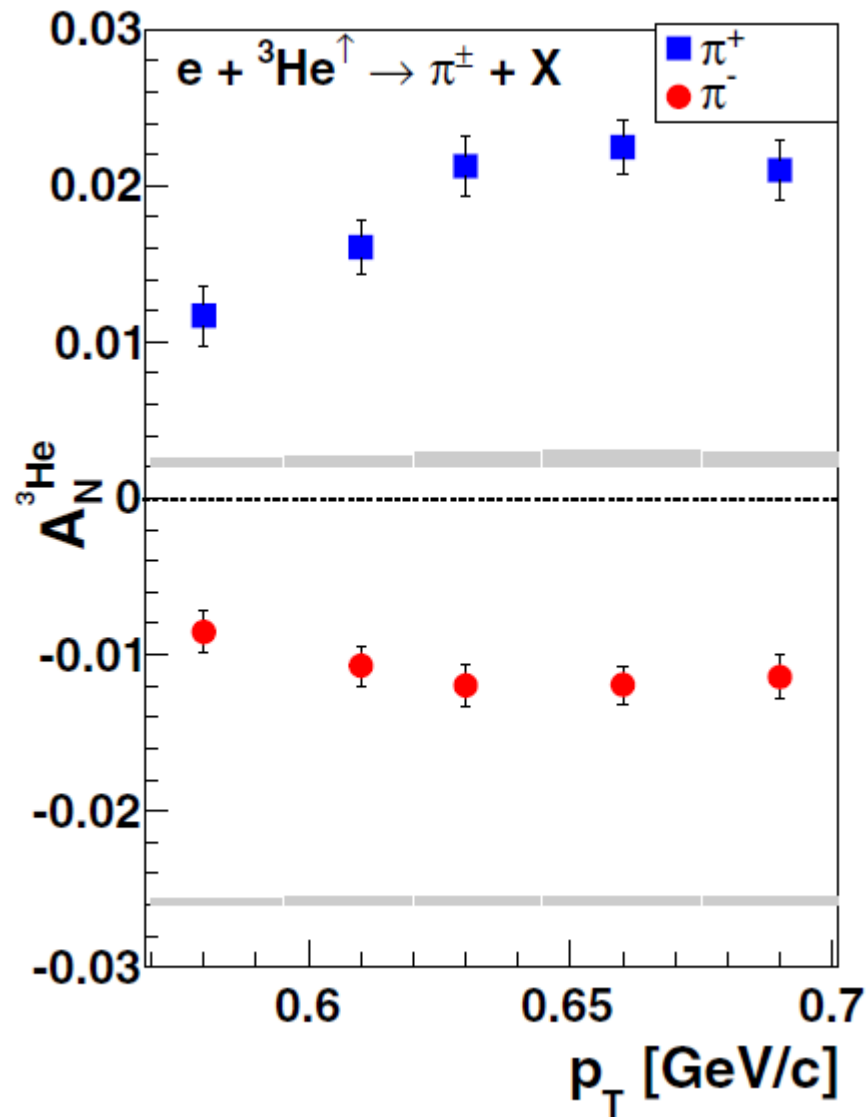
# “Trans-helicity” ( $A_{LT}^{\cos(\phi_h - \phi_S)}$ ): *PRL 108, 052001 (2012)*

- Above right: Helium-3 asymmetries:
  - $\pi^+$  asymmetries compatible with zero
  - $\pi^-$  asymmetries:  $2.8\sigma$  positive signal for 4 x bins combined
- First neutron data for  $A_{LT}$
- First clear non-zero  $A_{LT}$  observation
- Data suggest:
  - $g_{1T}^d$  is small at low x, favors negative values at larger x
  - $g_{1T}^u$  is positive, significantly non-zero  $\rightarrow$  *expect noticeable signal for proton target!*
- Related to real part of  $L=0$ ,  $L=1$  interference (Sivers  $\rightarrow$  imaginary part)

$$F_{LT}^{\cos(\phi_h - \phi_S)} \propto g_{1T} \otimes D_1$$

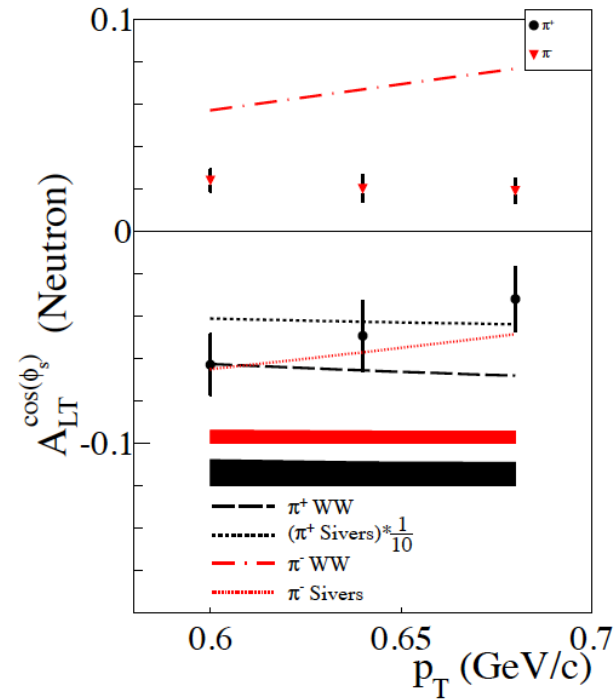
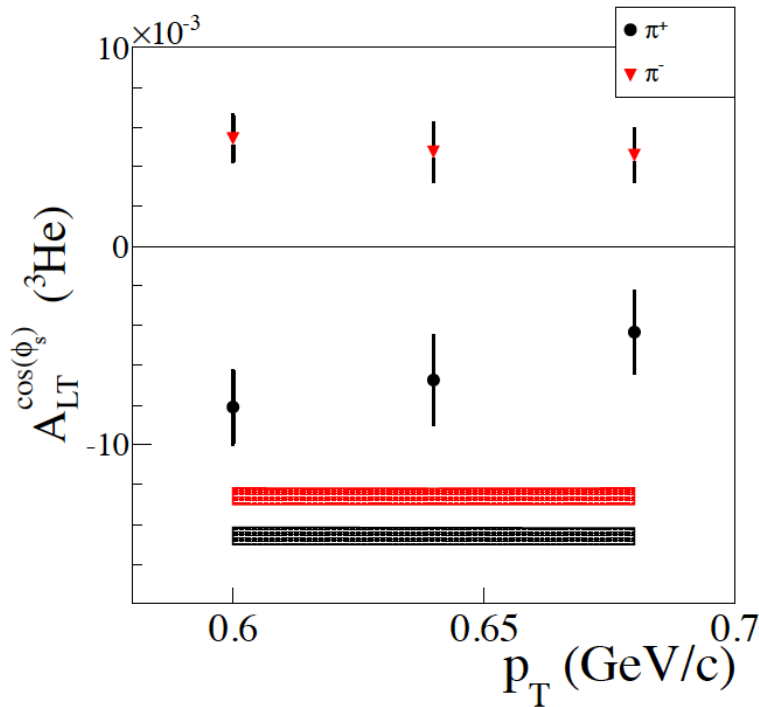


# Inclusive Hadron SSAs: *PRC 89, 042201(R) (2014)*



- No explicit prediction for JLab kinematics on a neutron available at time of publication, but:
- See Anselmino *et al.*, [arXiv:0911.1744](https://arxiv.org/abs/0911.1744)

# Inclusive Hadron DSAs—PRC 92 (2015), 015207



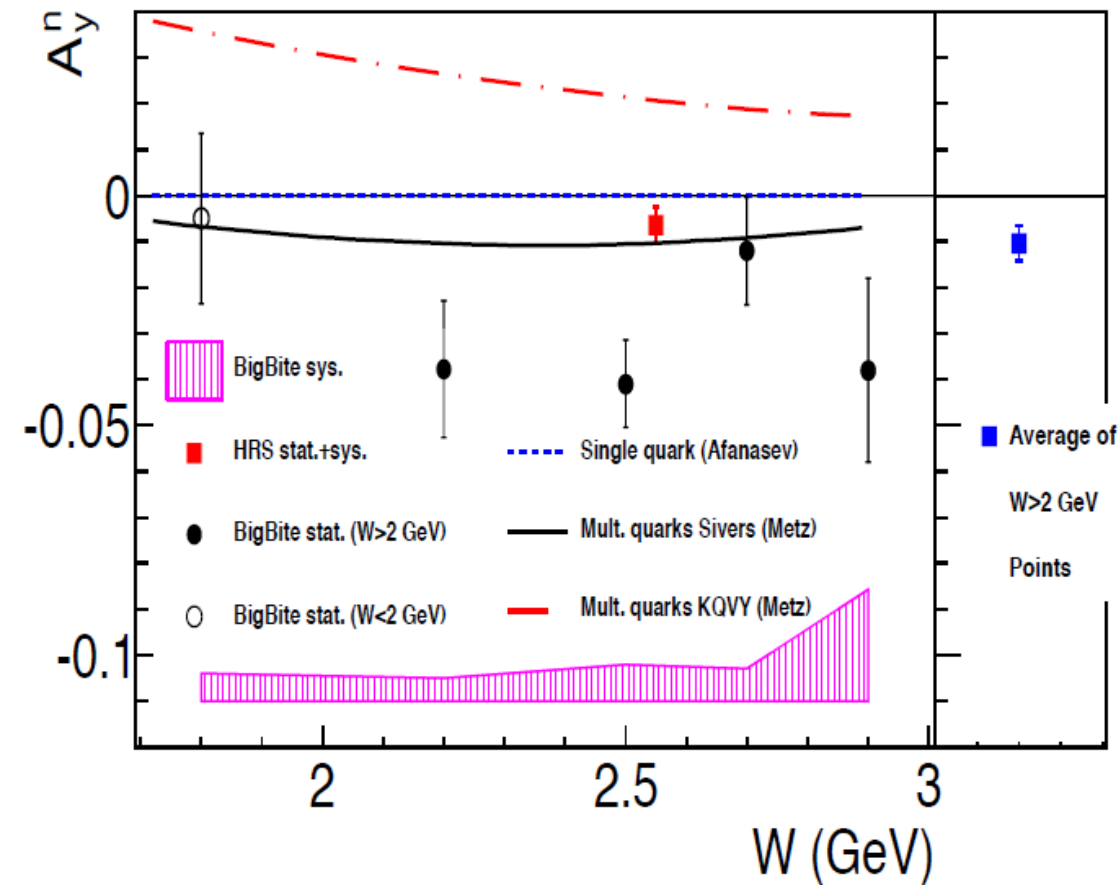
- Double-spin asymmetries for inclusive hadron production from a polarized nucleon:  

$$A_{LT} = A_{LT}^{\cos(\phi_s)} \cos(\phi_s)$$
- A twist-3 observable in Collinear factorization framework, provides insight into  $k_t^2$  moment of leading-twist TMD  $g_{1T}^\perp$  accessible in single-hadron SIDIS

- Predictions made using Wandzura-Wilczek approximation and “Sivers-like” approximation:  $\tilde{g}(x) \approx -f_{1T}^\perp(x)$   

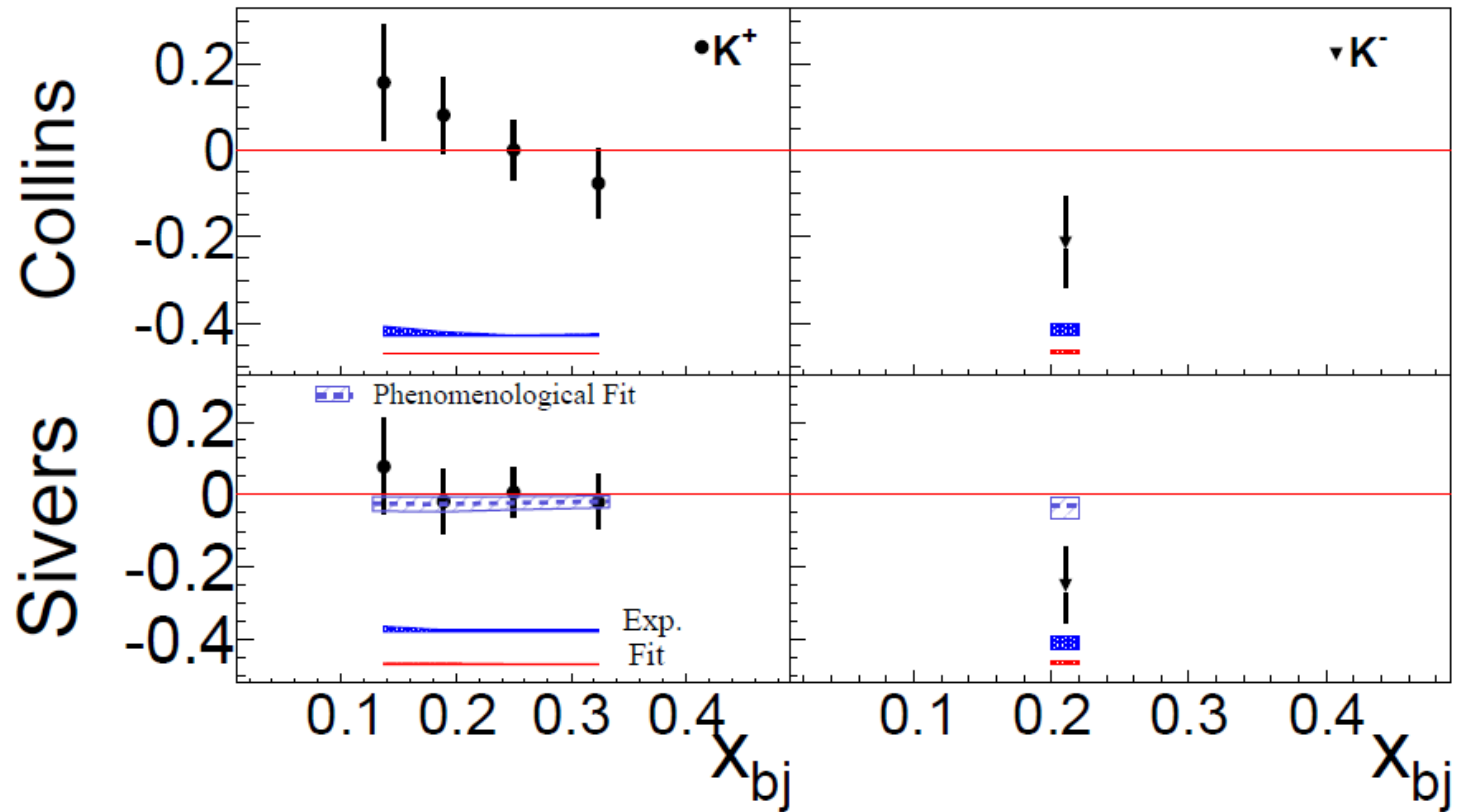
$$\tilde{g}(x) \approx x \int_x^1 \frac{dy}{y} g_1(y)$$
- Note:  $p_T$  range of Hall A data below regime of applicability of TMD framework

# Inclusive DIS $A_y$ : Phys. Rev. Lett. 113, 022502 (2014)



- Inclusive DIS  $A_y$  strictly zero in Born approximation; non-zero is a clear signal for multi-photon-exchange effects.
- Combined asymmetry for all  $W > 2$  GeV data is negative, non-zero by  $2.8\sigma$ .
- Consistent in sign w/model calculation based on twist-3 qqq correlators with input from Siverts function measured in SIDIS (**Metz *et al.*, PRD 86, 094039 (2012)**)

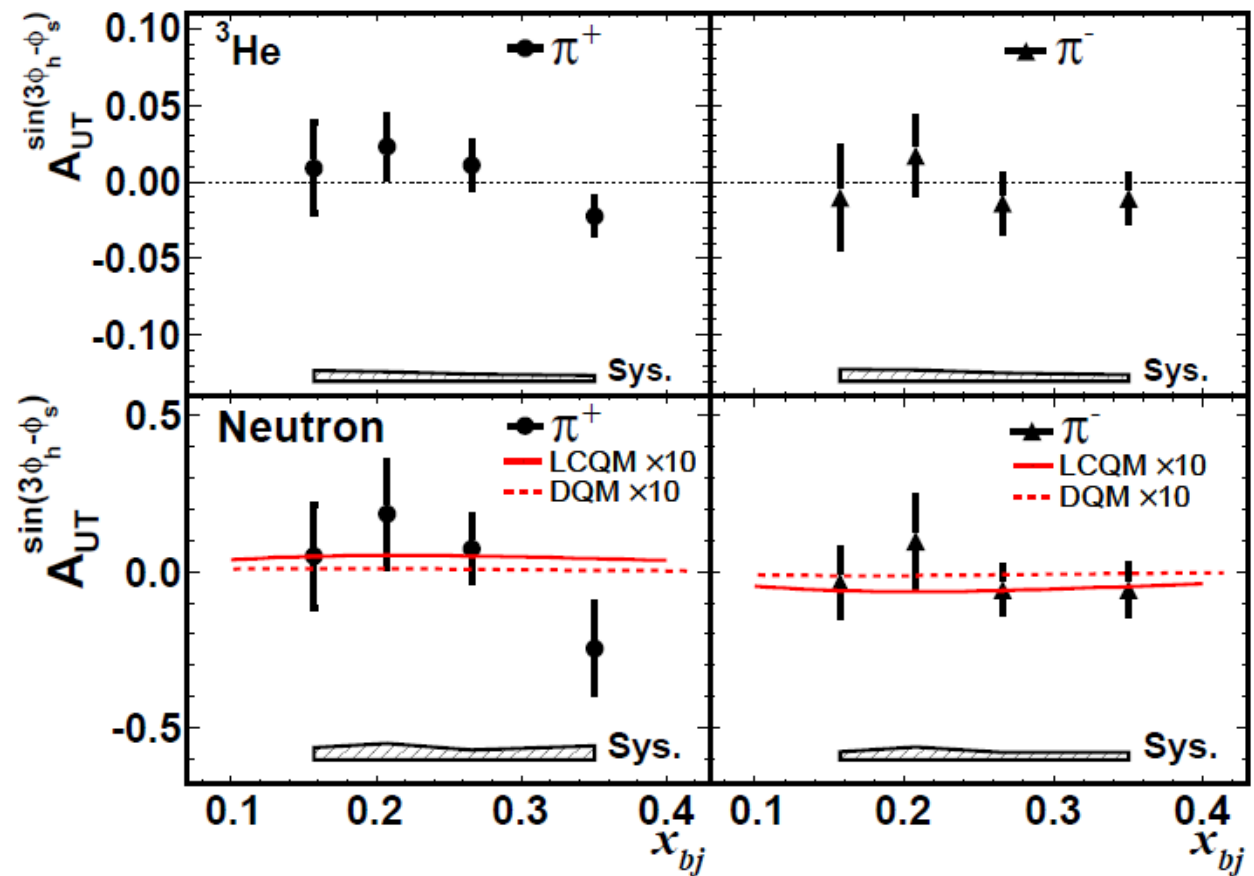
# $^3\text{He}(e,e'\text{K})\text{X}$ Collins/Sivers: PRC 90, 055201 (2014)



- With rather low statistics,  $\text{K}^+$  Collins/Sivers consistent with zero,  $\text{K}^-$  Collins/Sivers both unexpectedly large, negative (but with large errors)

# Pretzelosity for $n(e,e'\pi^{+/-})X$ : Phys. Rev. C 90, 055209 (2014)

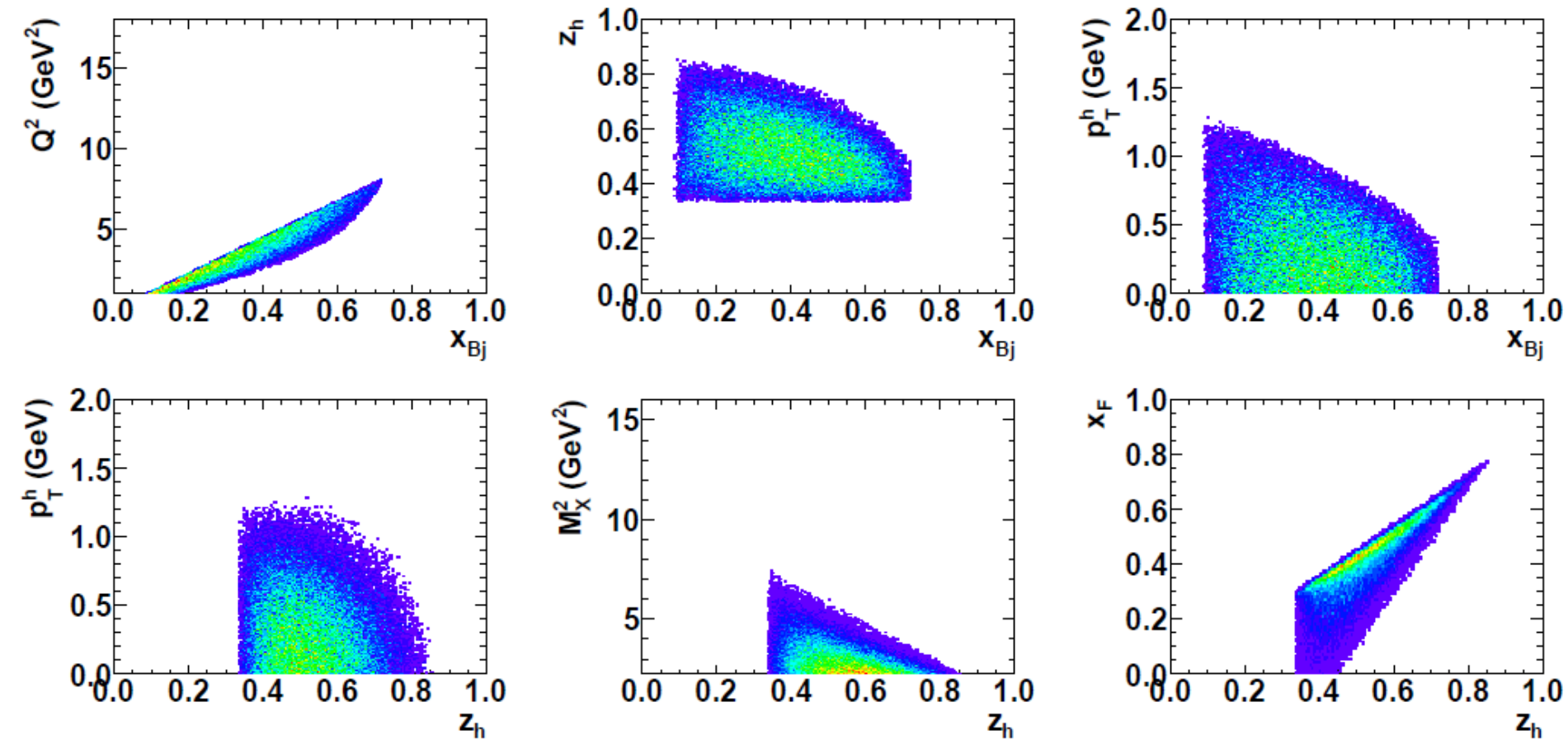
- Observed asymmetries consistent with zero and with model predictions.
- Much higher statistics are needed given small expected asymmetries



$$F_{UT}^{\sin(3\phi_h - \phi_s)} \propto h_{1T}^\perp \otimes H_1^\perp$$

# SIDIS/TMDs@JLab in the 12 GeV era

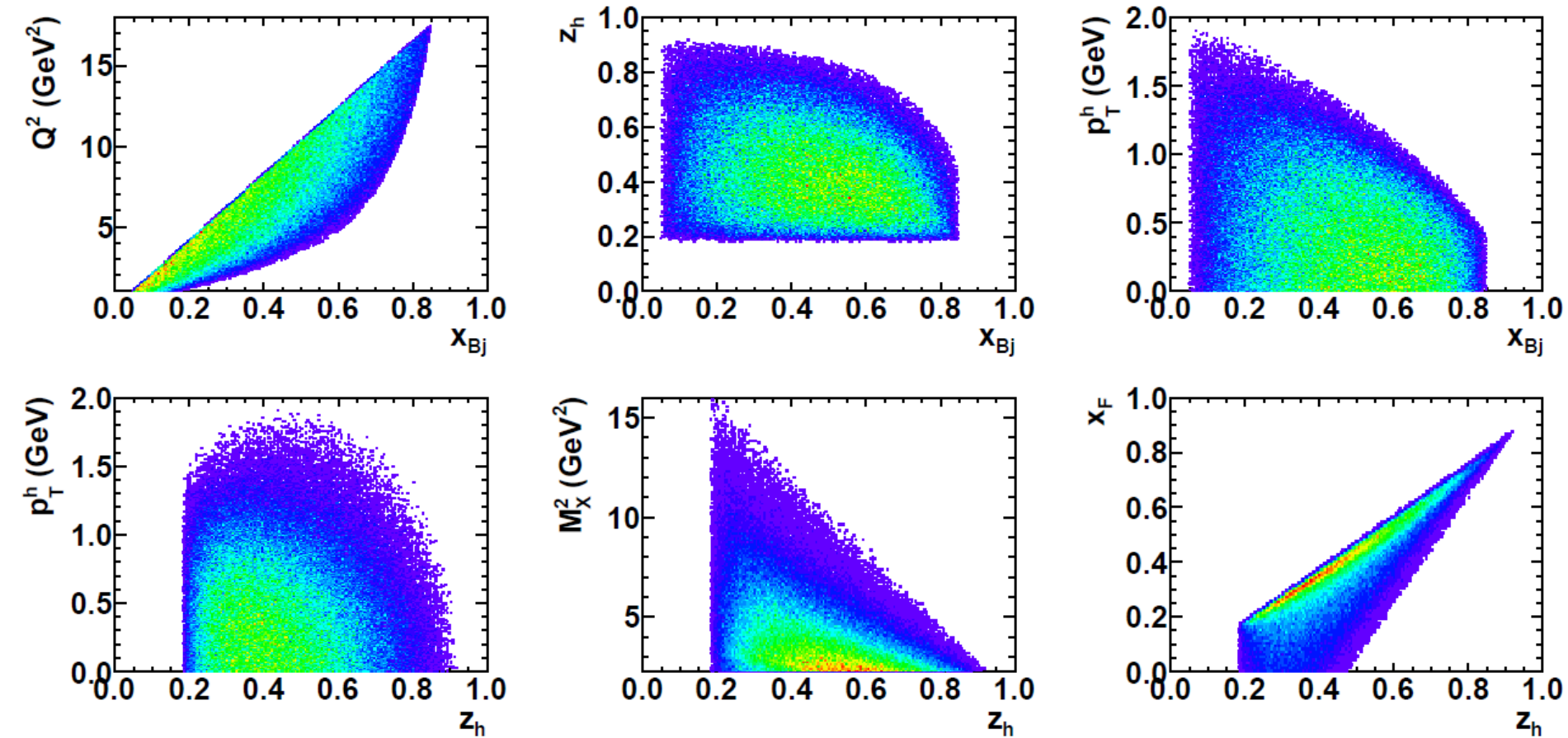
# Accessible phase space in fixed-target at 6 GeV



Above: phase space with SIDIS cuts (*before considering any detector acceptances*),  $E=6$  GeV

$$Q^2 \geq 1 \text{ GeV}^2, W > 2 \text{ GeV}, M_X > 1.5 \text{ GeV}, p_h \geq 2 \text{ GeV}$$

# Accessible phase space in fixed-target at 11 GeV



Above: phase space with SIDIS cuts (before considering any detector acceptances),  $E=11$  GeV

$$Q^2 \geq 1 \text{ GeV}^2, W > 2 \text{ GeV}, M_X > 1.5 \text{ GeV}, p_h \geq 2 \text{ GeV}$$

# Experiment Design Goals for TMD studies at 11 GeV CEBAF

- High luminosity
- Large acceptance
- High-performance polarized (and unpolarized) targets—proton and neutron for flavor separation
- Polarized beam
- Particle ID

# Unique Advantages/Complementarity of Halls A/B/C for SIDIS Experiments @ JLab:

## *Hall A*

- Polarized neutron measurements  $L > 10^{37} \text{ cm}^{-2} \text{ s}^{-1}$
- Transverse/longitudinally polarized  $^3\text{He}$  targets @ high luminosity
- Transversely polarized protons
- Large acceptance, open-geometry spectrometers; e.g., SBS, SOLID
- High-quality PID

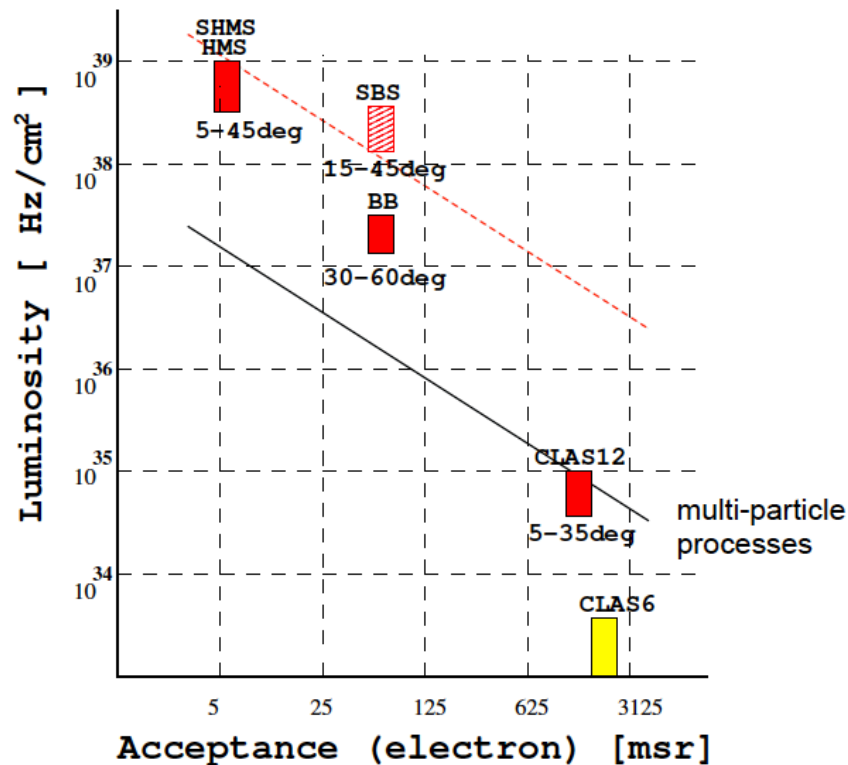
## *Hall B*

- Polarized and unpolarized proton/deuteron measurements;
- Longitudinally polarized p/d at max. luminosity of CLAS12  $\sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- Transverse target HDice—large acceptance, low dilution, but luminosity at best  $10^{34}$
- Very large acceptance
- Best 5D phase space coverage
- Provide information on closely related mechanisms, e.g. vector meson production

## *Hall C*

- Precision unpolarized cross section measurements w/ focusing magnetic spectrometers
- Require lower statistics compared to asymmetries
- proton/deuteron
- L/T separation
- Understand SIDIS reaction mechanism in precise detail with small systematic uncertainties—quantify deviations from leading-twist TMD picture.

# JLab detector landscape



A range of  $10^4$  in luminosity.

A big range in solid angle:  
from 5 msr (SHMS)  
to about 1000 msr (CLAS12).

=====

The SBS is in the middle:  
for solid angle (up to 70 msr)  
and high luminosity capability.

In several A-rated experiments  
SBS was found to be the best  
match to the physics.

GEM allows a spectrometer  
with open geometry (->large  
acceptance) at high L.

11/16/15

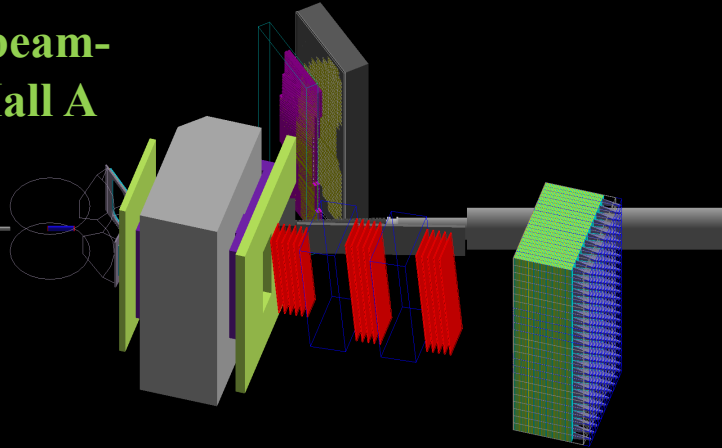
Super Bigbite Spectrometer Review

slide 9

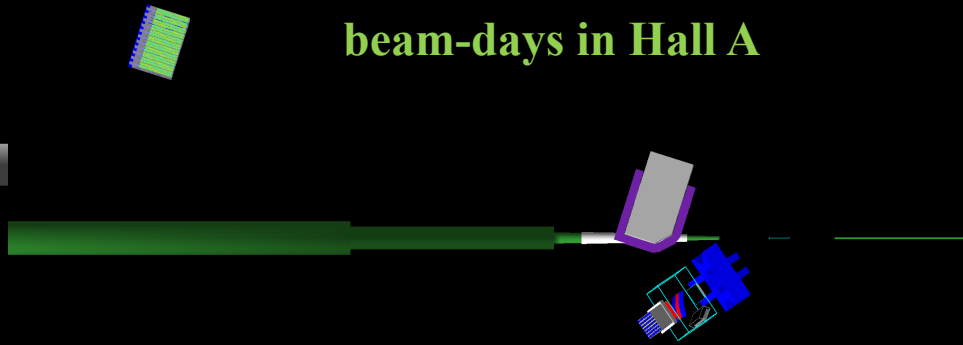
**Acknowledgements to B. Wojtsekhowski of JLab for this figure**

# The Super BigBite Spectrometer (SBS) in Hall A

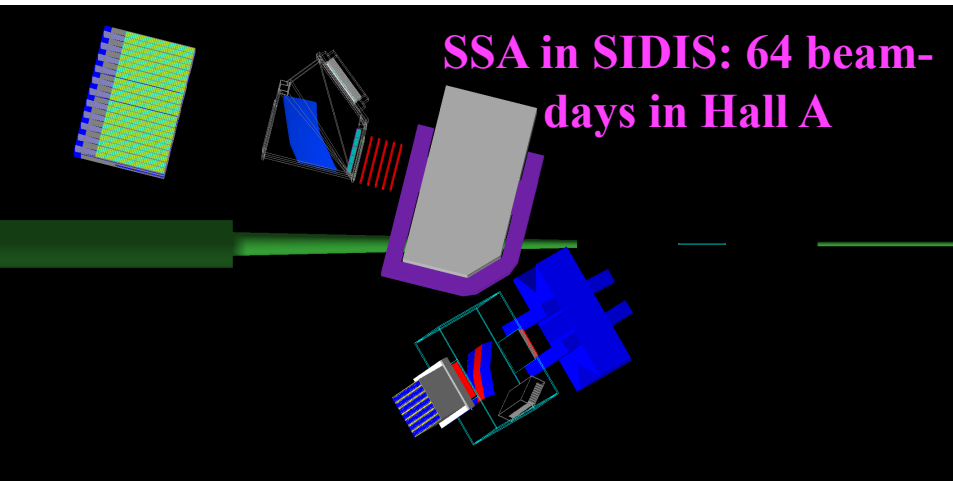
**GEP: 45 beam-days in Hall A**



**GEN + GMN: 50 + 25 beam-days in Hall A**



**E12-07-109: Proton form factor ratio  $G_{Ep}/G_{Mp}$  using polarization transfer**



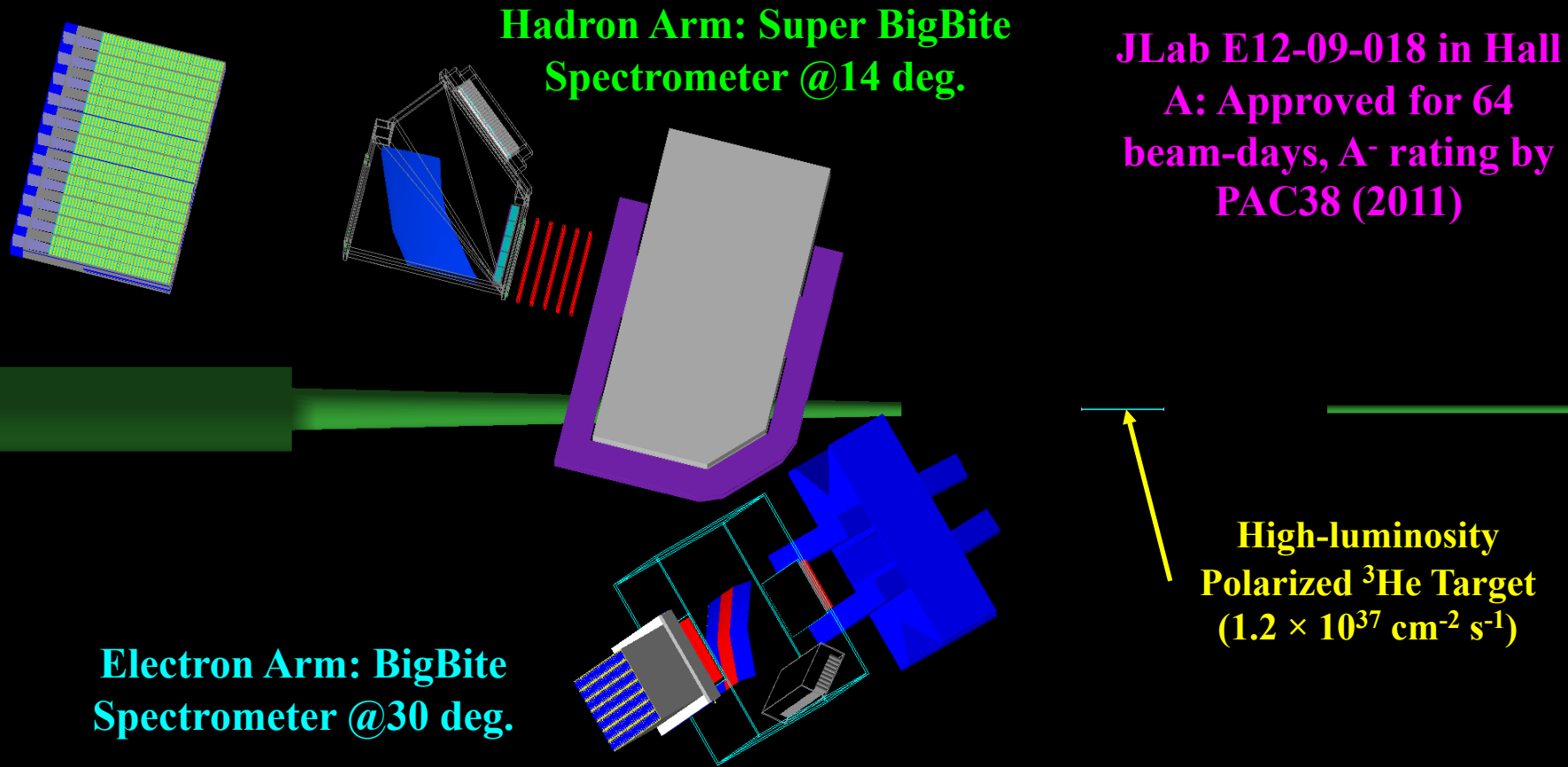
**SSA in SIDIS: 64 beam-days in Hall A**

**E12-09-018: Transverse target SSA in SIDIS**

**E12-09-016 and E12-09-019: Neutron magnetic form factor  $G_{Mn}$  and neutron form factor ratio  $G_{En}/G_{Mn}$**

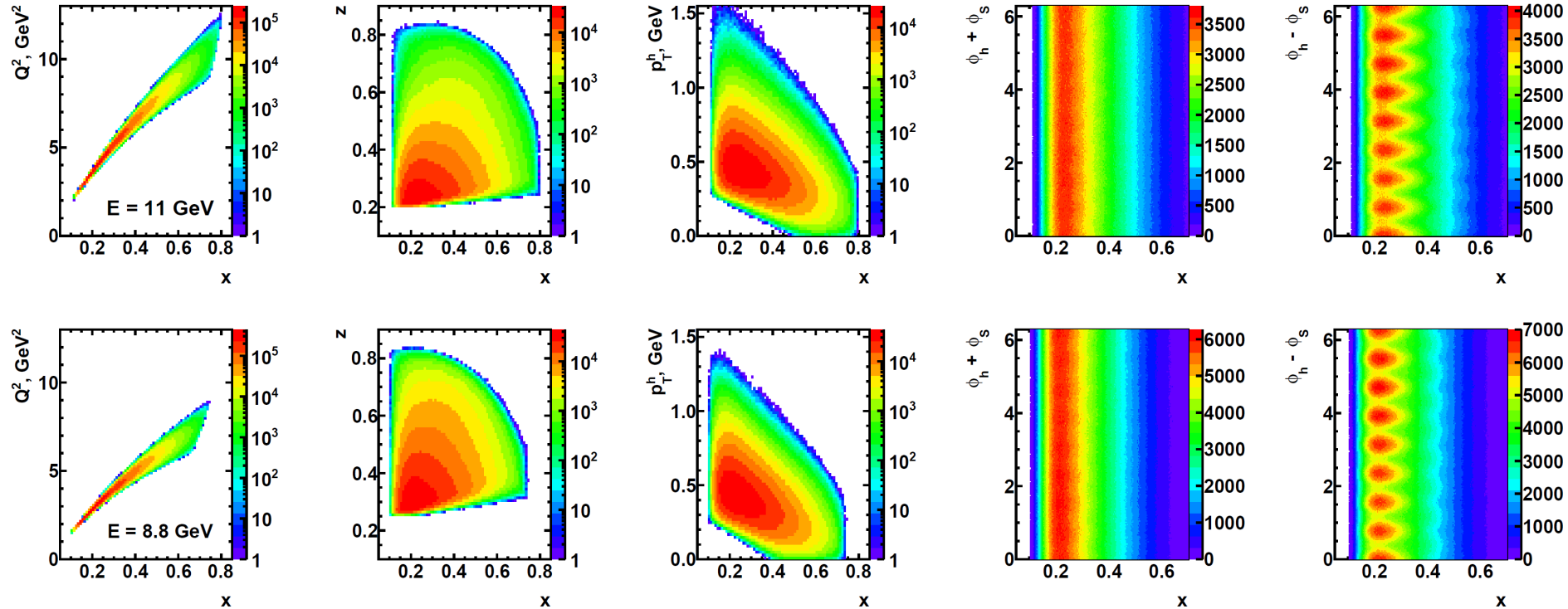
- SBS is a novel magnetic spectrometer based on time-tested “detectors behind a dipole magnet” approach
- Detects forward-going, high-energy particles with moderately large solid angle acceptance and large momentum bite at highest achievable luminosities of CEBAF
- **Physics program: nucleon EMFFs and SIDIS, 180 beam-days approved in Hall A**
- **Conditionally approved: Pion structure function via tagged DIS, 27 days Hall A**

# SBS E12-09-018: Transverse SSA in SIDIS



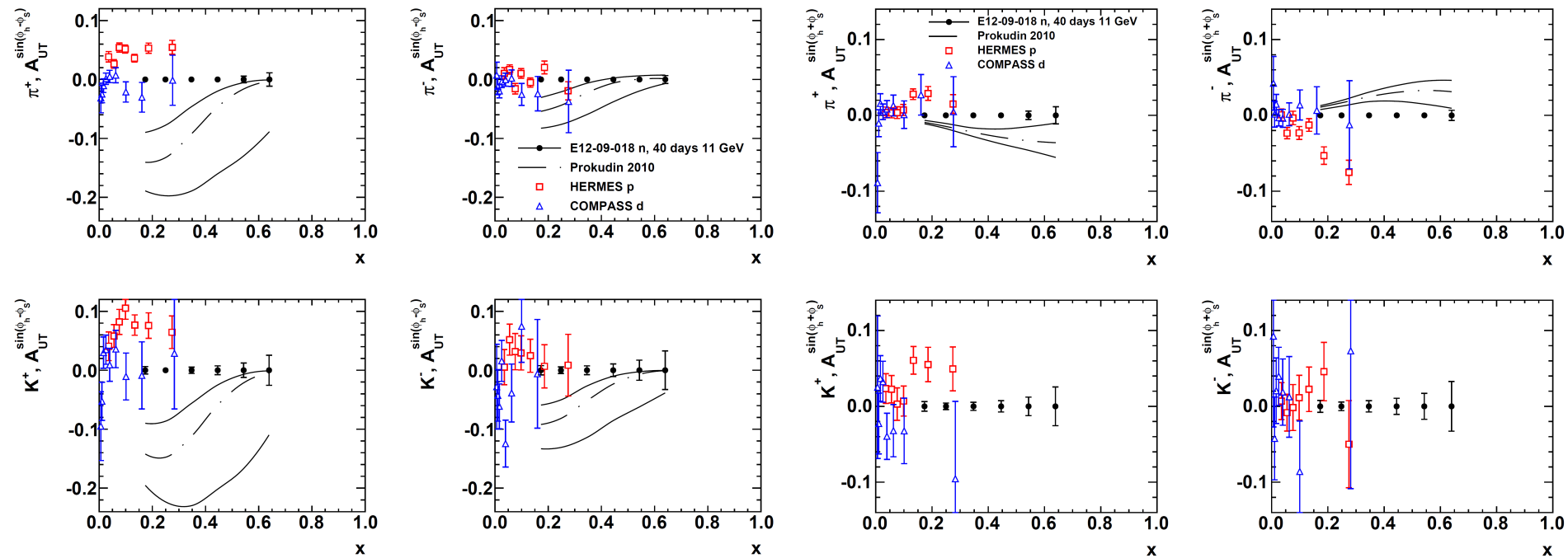
- **E12-09-018** is very similar to Hall A E06-010, but with  $\sim 1000\times$  greater statistical FOM, mainly by using SBS as hadron arm instead of HRS:
  - $\sim 6\times$  greater luminosity
  - $\sim 8\times$  greater hadron solid-angle acceptance
  - $>20\times$  greater hadron arm momentum bite

# SIDIS Kinematic Coverage of E12-09-018



- Wide, independent coverage of  $x$ ,  $z$ ,  $p_T$ ,  $\phi_h \pm \phi_S$ .
- $Q^2$ ,  $x$  strongly correlated due to dimensions of BigBite magnet gap.
- Data at  $E = 11, 8.8$  GeV provide data for significantly different  $Q^2$  at same  $x$
- Systematics control  $\rightarrow$  independent spectrometers, detectors in field-free regions, straight-line tracking, simple, well-defined (but adequately large) acceptance, etc.

# SBS+BB Projected Results: Collins and Sivers SSAs

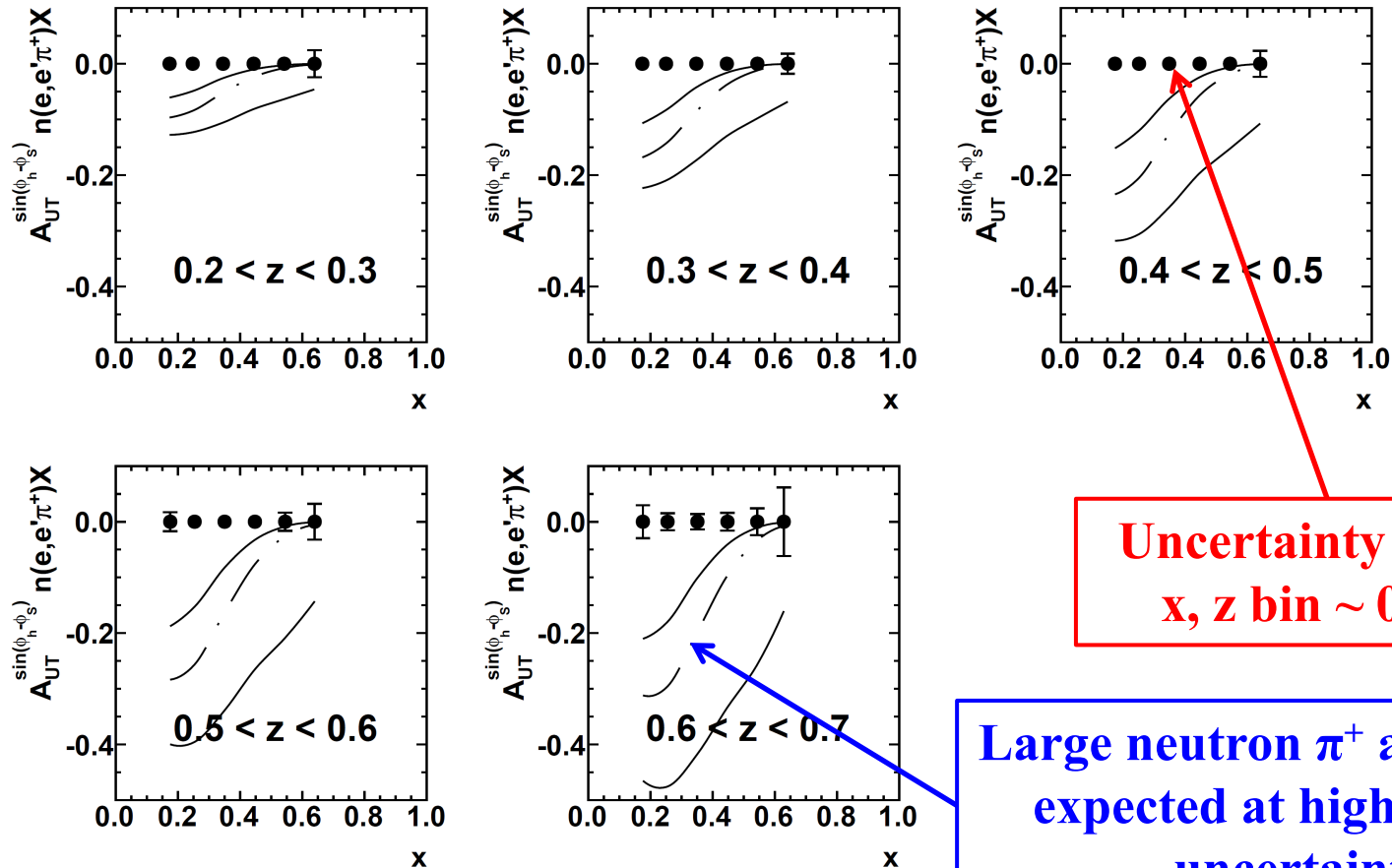


Projected  $A_{UT}^{\text{Sivers}}$  vs.  $x$

Projected  $A_{UT}^{\text{Collins}}$  vs.  $x$

- E12-09-018 will achieve statistical FOM for the neutron  $\sim 100X$  better than HERMES proton data and  $\sim 1000X$  better than E06-010 neutron data, and will reach  $(x, Q^2)$  up to  $(0.7, 10 \text{ GeV}^2)$ ; ( $x > \sim 0.3$  basically unexplored)
- Charged Kaon and (parasitically obtained) neutral pion data will aid flavor decomposition, and understanding of reaction-mechanism effects.

# SBS+BB Projected Precision in 2D (x,z) binning



**Uncertainty in this  
x, z bin  $\sim 0.6\%$**

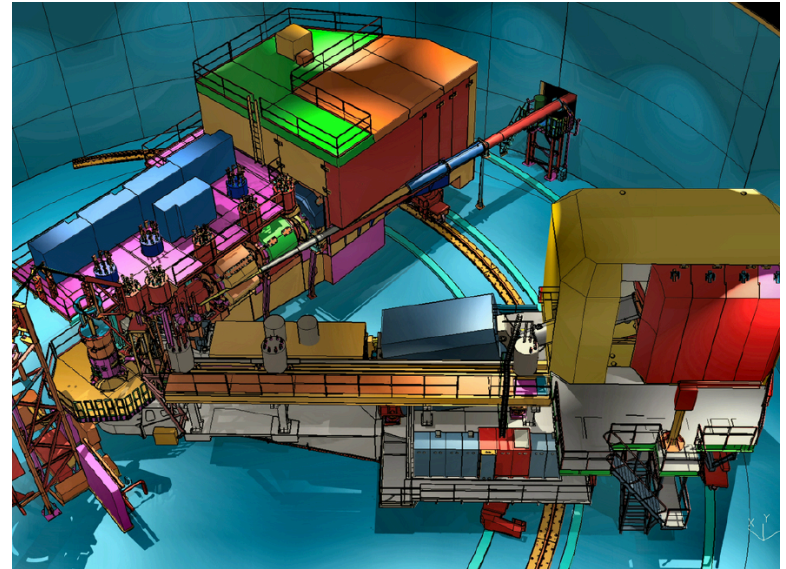
**Large neutron  $\pi^+$  asymmetry  
expected at high z, large  
uncertainty**

- 2D Extraction: Sivers  $A_{UT}$  in  $n(e, e' \pi^+) X$ , 6 x bins  $0.1 < x < 0.7$ , 5 z bins  $0.2 < z < 0.7$
- Curves are theory predictions (Anselmino et al.) with central value and error band

# Hall C SIDIS program

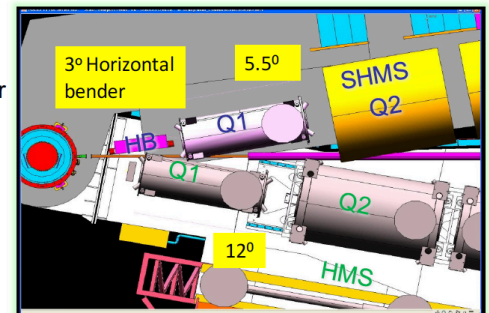
## Currently approved SIDIS experiments in Hall C:

- E12-06-104: L/T separation of SIDIS cross section
- E12-09-002: Precise measurement of  $\pi^+/\pi^-$  ratios in Semi-Inclusive DIS
- E12-09-017: Transverse momentum dependence of SIDIS cross section
- E12-13-007: Semi-inclusive  $\pi^0$  production as validation of factorization



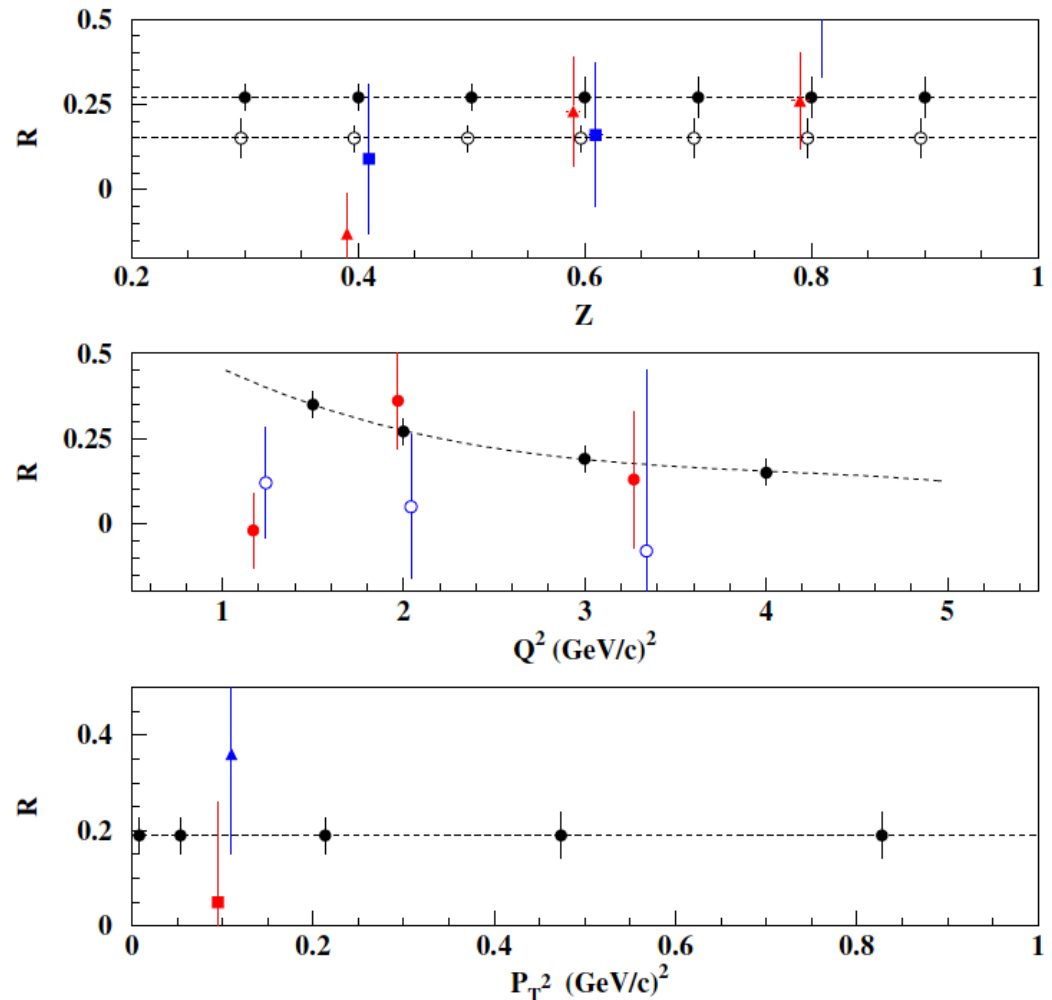
Hall C after 12 GeV Upgrade

- Beam Energy: 2 – 11 GeV/c
- Super High Momentum Spectrometer (SHMS)
  - Horizontal Bender, 3 Quads, Dipole
  - $P \rightarrow 11$  GeV/c
  - $dP/P$   $0.5 - 1.0 \times 10^{-3}$
  - Acceptance: 4msr, 30%
  - $5.5^\circ < \theta < 40^\circ$
  - Good  $e^-/\pi^-$   $e^+/\pi^+/K^+/p$  PID
- High Momentum Spectrometer (HMS)
  - $P \rightarrow 7.5$  GeV/c
  - $dP/P$   $0.5 - 1.0 \times 10^{-3}$
  - Acceptance: 6.5msr, 18%
  - $10.5^\circ < \theta < 90^\circ$
  - Good  $e^-/\pi^-$   $e^+/\pi^+/K^+/p$  PID
- Well shielded detector huts
- 2 beamline polarimeters
- Ideal facility for:
  - Rosenbluth (L/T) separations
  - Exclusive reactions
  - Low cross sections (neutrino level)
- Minimum opening angle:  $\sim 17^\circ$

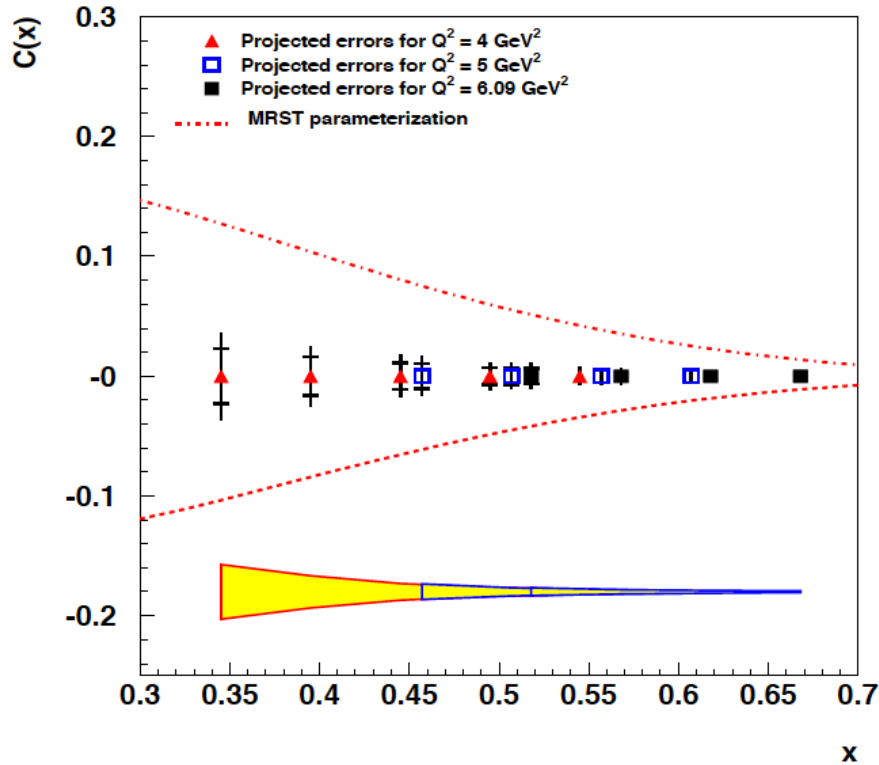


# E12-06-104: L/T Separation of SIDIS Cross Section

- Goal: precise measurement of  $R_{LT} = \sigma_L/\sigma_T$  in SIDIS (Rosenbluth separation) in targeted kinematics in the region of broad interest for the entire JLab 12 GeV program:
  - z-scan at  $(x, Q^2) = (0.2, 2.0 \text{ GeV}^2)$  and  $(0.4, 4.0 \text{ GeV}^2)$
  - $p_T$  scan at  $(x, Q^2) = (0.3, 3.0 \text{ GeV}^2)$  and fixed  $z = 0.5$
  - Two additional separations at  $Q^2 = 1.5, 5 \text{ GeV}^2$
- Basically no precise data exist for  $R_{LT}$  in SIDIS
- Important to understanding of reaction mechanism, broad interest to entire JLab SIDIS program



# E12-09-002: Precise measurement of $\pi^+/\pi^-$ ratios in Semi-Inclusive DIS



- Idea is to perform precise measurements of cross section ratios between  $\pi^+/\pi^-$  production in SIDIS kinematics on the simplest isoscalar target (deuterium)
- From these measurements, under certain assumptions on sea quark contributions, it is possible to constrain the degree of charge symmetry violation (CSV) in valence-quark PDFs; specifically the quantity:

$$\begin{aligned}
 C(x) &= \delta d(x) - \delta u(x) \\
 &= (d^p(x) - u^n(x)) - (u^p(x) - d^n(x))
 \end{aligned}$$

# Conclusions

- CEBAF at 6 GeV has already made significant contributions to our global knowledge of TMDs. More results from the accumulated 6 GeV data are forthcoming.
- JLab 12 GeV upgrade enables comprehensive 4D mapping of nucleon transverse spin structure at high  $x$ :
  - Dramatically expanded kinematic reach
  - Advances in targets and detectors to reach high statistical figure of merit
  - Coherent program exploiting complementary capabilities of Halls A/B/C
- "Two arm" experiments using "precision" magnetic spectrometers provide essential data in targeted kinematics with well-controlled systematic uncertainties, to validate the interpretation framework (L/T separations, etc)
- Super BigBite Spectrometer (SBS) is in the middle—can perform "two arm" experiments with moderately large acceptance and high luminosity capability, with (in principle) better control of systematics compared to "4 $\pi$ " detectors (in certain observables).
- CEBAF upgrade is essentially complete; accelerator commissioning and first physics beam underway in Halls A/B (and C starting in spring 2017)
  - **First SIDIS experiment in Hall C likely to run in 2017**
  - **SBS physics program expected to start ~2018**
    - **First experiment—neutron magnetic form factor  $G_{Mn}$  to ~13 GeV<sup>2</sup>**
  - **SBS SIDIS experiment E12-09-018 expected to run ~2019-2020**

# Backup Slides

# SIDIS Kinematics—Notation and Definitions

$$Q^2 = (k - k')^2 = 4E_e E'_e \sin^2 \left( \frac{\theta_e}{2} \right), \text{ Momentum transfer}$$

$$x = \frac{Q^2}{2M\nu}, \text{ quark momentum fraction}$$

$$\nu = \frac{P \cdot q}{M} = E_e - E'_e, \text{ N rest frame } E_{\text{loss}}$$

$$y = \frac{P \cdot q}{P \cdot k} = \frac{\nu}{E_e}$$

$$W^2 = (P + q)^2 = M^2 + Q^2 \frac{1-x}{x}, \gamma^* N \text{ invariant mass}$$

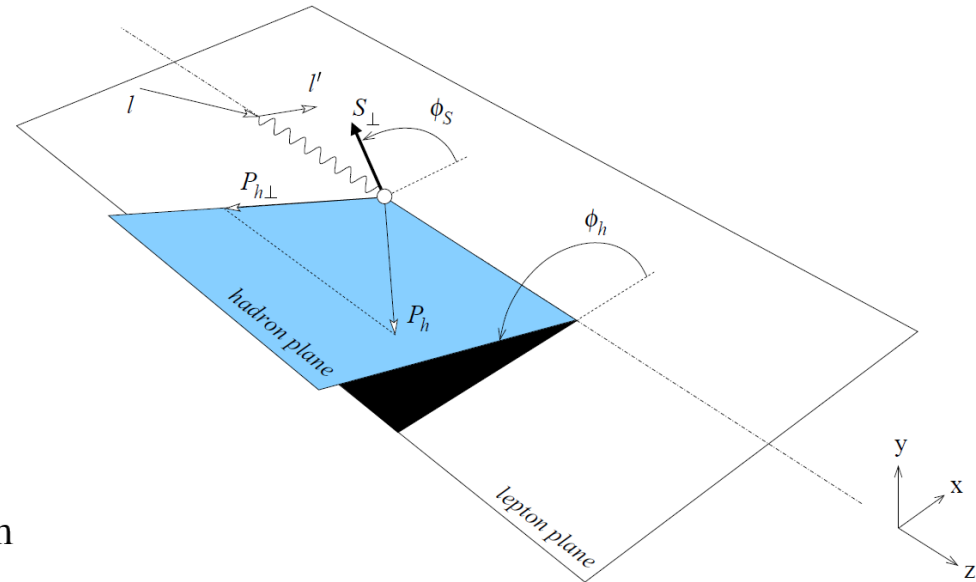
$$z = \frac{P \cdot P_h}{P \cdot q} = E_h / \nu, \text{ Hadron energy fraction}$$

$$p_T^h = \left| \mathbf{p}_h - \left( \frac{\mathbf{p}_h \cdot \mathbf{q}}{|\mathbf{q}|^2} \right) \mathbf{q} \right|, \text{ Hadron transverse momentum}$$

$$\phi_h = \text{Angle between lepton and hadron planes}$$

$$\phi_S = \text{Angle between lepton plane and nucleon spin}$$

$$W'^2 = M_X^2 = (P + q - P_h)^2, \text{ Missing mass}$$



# General Expression for SIDIS Cross Section:

## *Bacchetta et al., JHEP 02, 093 (2007)*

$$\begin{aligned}
 \frac{d\sigma}{dx dy dz d\phi_h d\phi_S dp_T^2} = & \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \epsilon F_{UU,L} + \right. \\
 & \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \\
 & \lambda_e \sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} + \\
 & S_{\parallel} \left[ \sqrt{2\epsilon(1+\epsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \epsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] + \\
 & S_{\parallel} \lambda_e \left[ \sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right] + \\
 & S_{\perp} \left[ \sin(\phi_h - \phi_S) F_{UT}^{\sin(\phi_h - \phi_S)} \right. \\
 & \quad \epsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} \\
 & \quad \left. \epsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \right. \\
 & \quad \left. \sqrt{2\epsilon(1+\epsilon)} \left( \sin \phi_S F_{UT}^{\sin \phi_S} + \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right) \right] + \\
 & S_{\perp} \lambda_e \left[ \sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \right. \\
 & \quad \left. \sqrt{2\epsilon(1-\epsilon)} \left( \cos \phi_S F_{LT}^{\cos \phi_S} + \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right) \right] \left. \right\}
 \end{aligned}$$

- Sivers
- Collins
- “Pretzelosity”

- SIDIS structure functions F depend on  $x, Q^2, z, p_T$
- U, L, T subscripts indicate unpolarized, longitudinally and transversely polarized beam, target, respectively
- S = nucleon spin
- $\lambda$  = lepton helicity
- **Eight terms survive at leading twist; the rest are twist-3 (M/Q suppressed)**

$$\begin{aligned}
 \gamma &= \frac{2Mx}{Q} \\
 \epsilon &= \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2}
 \end{aligned}$$

# Quark-parton Model Interpretation of SIDIS: Transverse Momentum Dependent PDFs (TMDs)

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \textcircled{\bullet}$		$h_1^\perp = \textcircled{\downarrow} - \textcircled{\uparrow}$
	L		$g_1 = \textcircled{\rightarrow} - \textcircled{\rightarrow}$	$h_{1L}^\perp = \textcircled{\nearrow} - \textcircled{\nearrow}$
	T	$f_{1T}^\perp = \textcircled{\uparrow} - \textcircled{\downarrow}$	$g_{1T} = \textcircled{\rightarrow} - \textcircled{\rightarrow}$	$h_1 = \textcircled{\uparrow} - \textcircled{\downarrow}$ $h_{1T}^\perp = \textcircled{\nearrow} - \textcircled{\nearrow}$

# SIDIS Structure Functions in Terms of TMDs

$F_{UU,T}$	$\sim$	$f_1 \otimes D_1$	<ul style="list-style-type: none"> <li>• Only <math>f_1, g_1, h_1</math> survive integration over quark <math>k_T</math></li> <li>• All eight leading-twist TMDs are accessible in SIDIS with polarized beams/targets via azimuthal angular dependence of the SIDIS cross section</li> <li>• Physical observables are convolutions over two (unobserved) transverse momenta: <ul style="list-style-type: none"> <li>• Initial quark <math>k_T</math></li> <li>• Hadron <math>p_T</math> relative to recoiling quark, generated during fragmentation</li> </ul> </li> </ul>
$F_{UU}^{\cos 2\phi_h}$	$\sim$	$h_1^\perp \otimes H_1^\perp$	
$F_{UL}^{\sin 2\phi_h}$	$\sim$	$h_{1L}^\perp \otimes H_1^\perp$	
$F_{LL}$	$\sim$	$g_1 \otimes D_1$	
$F_{UT}^{\sin(\phi_h - \phi_S)}$	$\sim$	$f_{1T}^\perp \otimes D_1$	
$F_{UT}^{\sin(\phi_h + \phi_S)}$	$\sim$	$h_1 \otimes H_1^\perp$	
$F_{UT}^{\sin(3\phi_h - \phi_S)}$	$\sim$	$h_{1T}^\perp \otimes H_1^\perp$	
$F_{LT}^{\cos(\phi_h - \phi_S)}$	$\sim$	$g_{1T} \otimes D_1$	

$$D_1(z, Q^2, p_\perp^2) = \text{Unpolarized TMD FF}$$

$$H_1^\perp(z, Q^2, p_\perp^2) = \text{Collins TMD FF}$$

# Transverse target spin effects in SIDIS

		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$ -
	L		$\Delta q$ -	$h_{1L}^\perp$ -
	T	$f_{1T}^\perp$ -	$g_{1T}^\perp$ -	$\delta q$ - $h_{1T}^\perp$ -

## Transverse target spin-dependent cross section for SIDIS

- Collins effect—chiral-odd quark transversity DF; chiral-odd Collins FF
- Sivers effect—access to quark OAM and QCD FSI mechanism
- “Transversal helicity”  $g_{1T}$ —real part of S wave-P wave interference (Sivers = imaginary part) (requires polarized beam)
- “Pretzelosity” or Mulders-Tangerman function—interference of wavefunction components differing by 2 units of OAM

$$\begin{aligned}
 A_{UT}(\phi, \phi_S) &= \frac{1}{P_T} \frac{d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi)}{d\sigma(\phi, \phi_S) + d\sigma(\phi, \phi_S + \pi)} \\
 &= A_{UT}^{Collins} \sin(\phi + \phi_S) + \\
 &\quad A_{UT}^{Sivers} \sin(\phi - \phi_S) + \\
 &\quad A_{UT}^{Pretz} \sin(3\phi - \phi_S)
 \end{aligned}$$

$$\begin{aligned}
 A_{UT}^{Collins} &\propto \delta q \otimes H_1^\perp \\
 A_{UT}^{Sivers} &\propto f_{1T}^\perp \otimes D_1 \\
 A_{UT}^{Pretz} &\propto h_{1T}^\perp \otimes H_1^\perp
 \end{aligned}$$

$D_1$  = unpolarized fragmentation function

$H_1^\perp$  = Collins

fragmentation function

$$\begin{aligned}
 A_{LT}(\phi, \phi_S) &= \frac{1}{P_e P_T} \frac{Y_+(\phi, \phi_S) - Y_-(\phi, \phi_S)}{Y_+(\phi, \phi_S) + Y_-(\phi, \phi_S)} \\
 &\sim A_{LT}^{\cos(\phi - \phi_S)} \cos(\phi - \phi_S) \\
 &\sim g_{1T} \otimes D_1
 \end{aligned}$$

# 3D and “4D” extraction of SIDIS SSAs with SBS

Example result for 3D binning

$(x, z, p_T)$

*Increasing  $z \rightarrow$*

- $E = 11$  GeV, 40 days

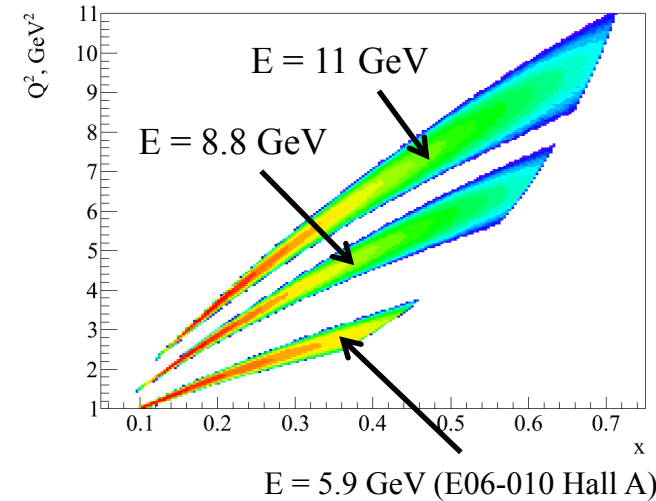
$A_{UT}^{\sin(\phi_h - \phi_S)}$  for  $n(e, e' \pi^+)X$  :

$0.1 \leq x \leq 0.7, \Delta x = 0.1$

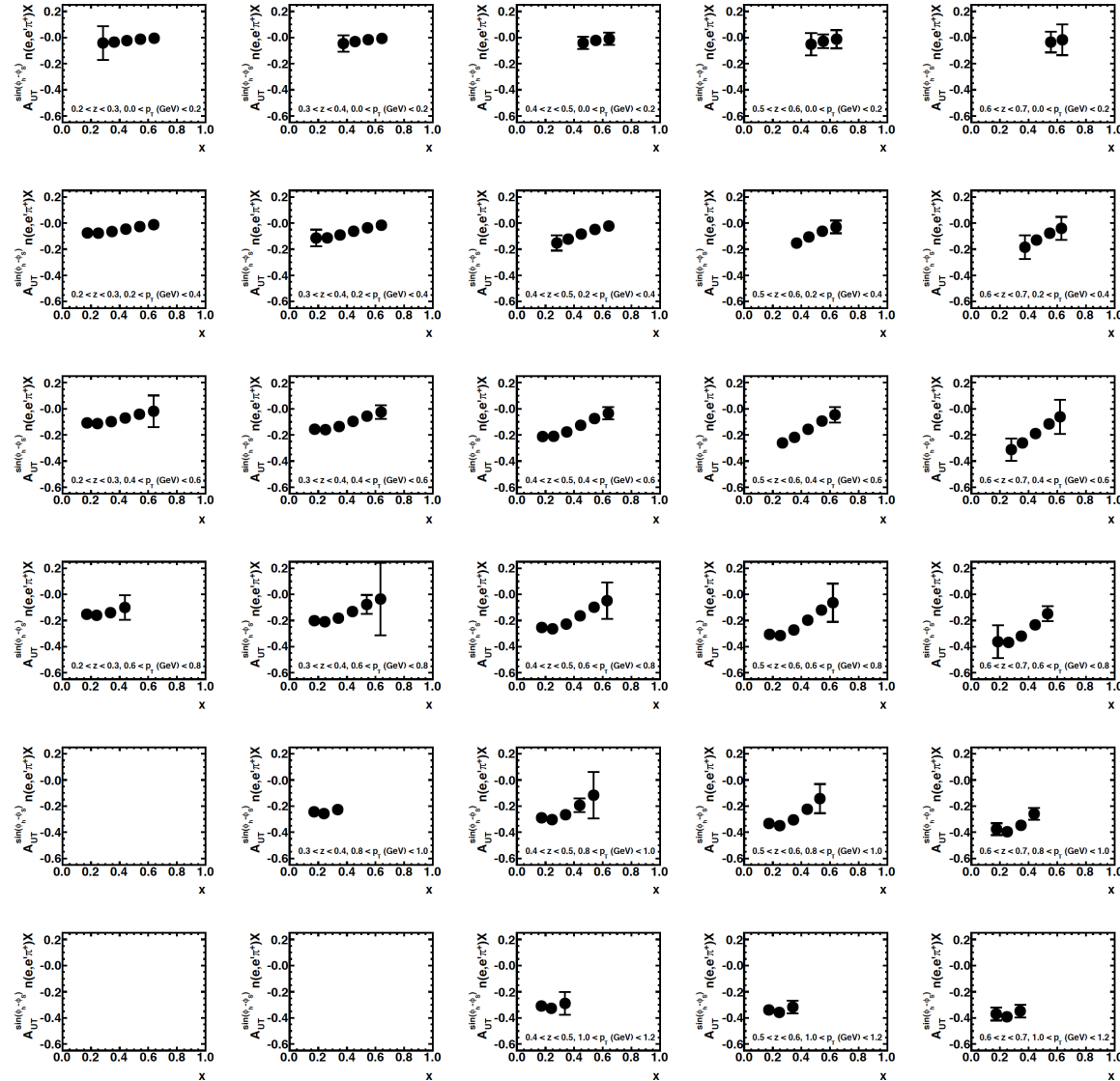
$0.2 \leq z \leq 0.7, \Delta z = 0.1$

$0 \leq p_T (\text{GeV}) \leq 1.2, \Delta p_T = 0.2 \text{ GeV}$

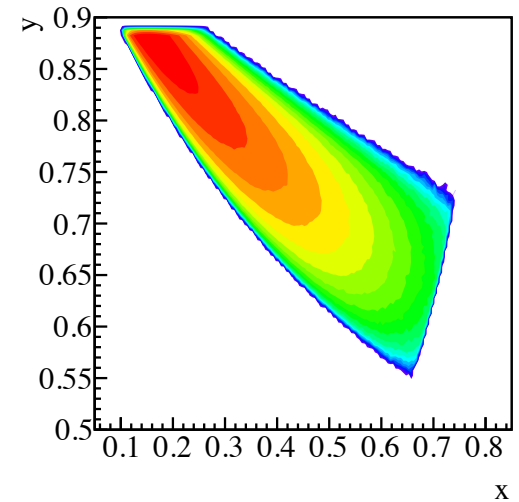
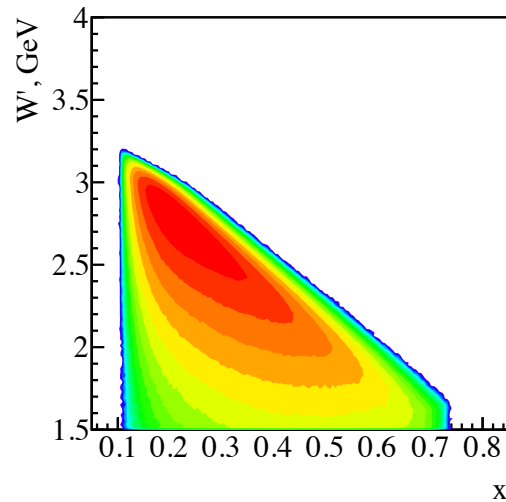
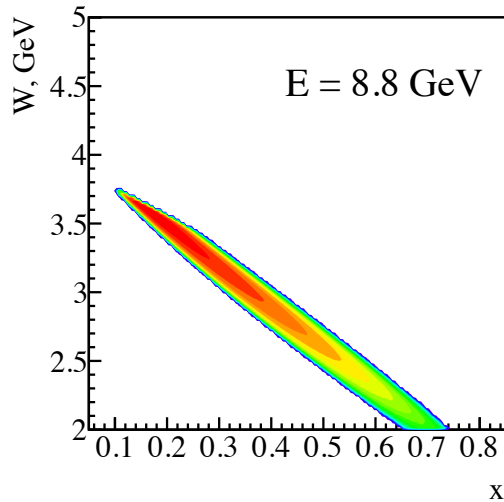
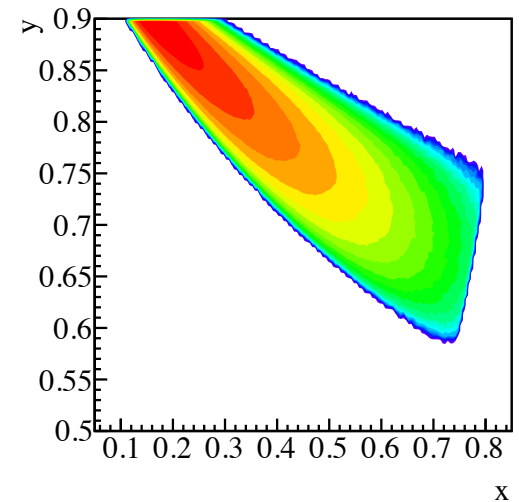
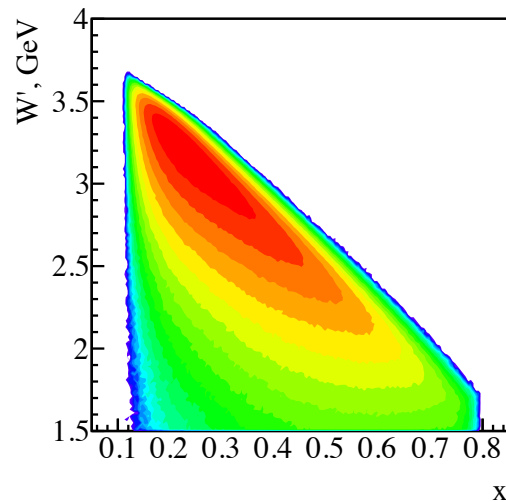
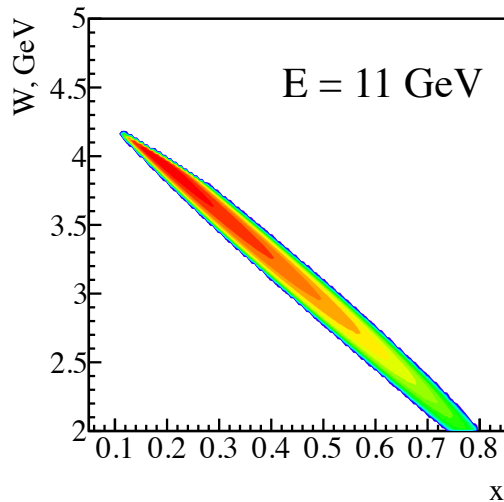
- “4D” with  $Q^2$  dependence from 20 days at 8.8 GeV:



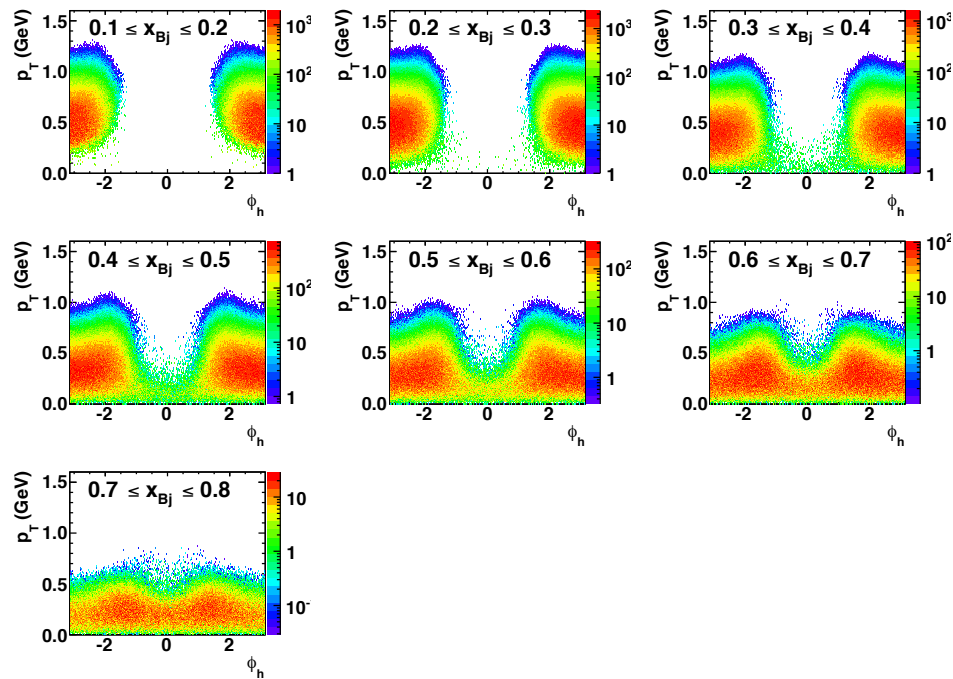
*Increasing  $p_T \leftarrow$*



# $W$ , $W'$ and $y$ vs. $x$ : $W > 2$ GeV, $W' > 1.5$ GeV, $y < 0.9$



# Comparison of SIDIS azimuthal coverage, SBS vs. SOLID



**SBS-BB  $p_T$  vs.  $\phi$  for different  $x$  bins,  
 $0.4 < z < 0.5$**

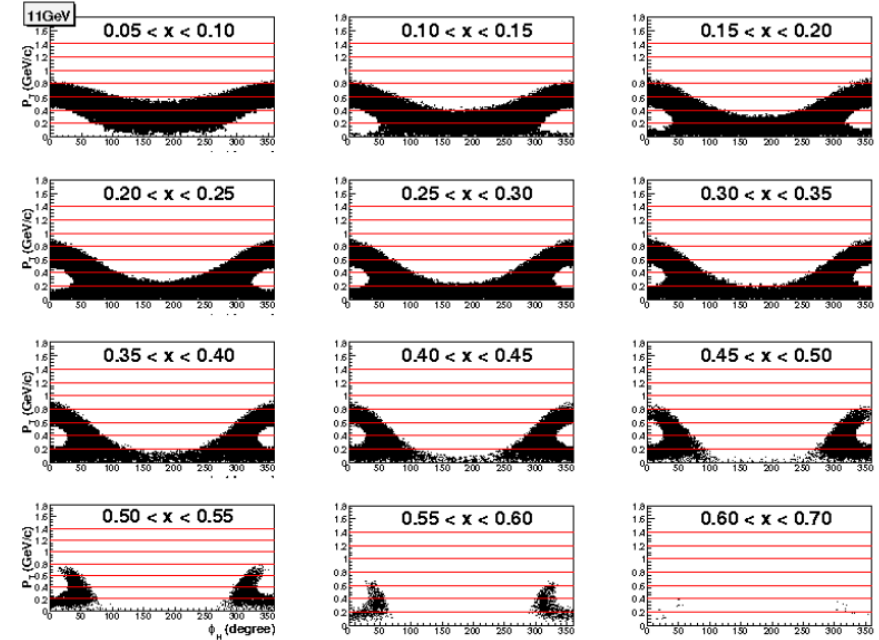
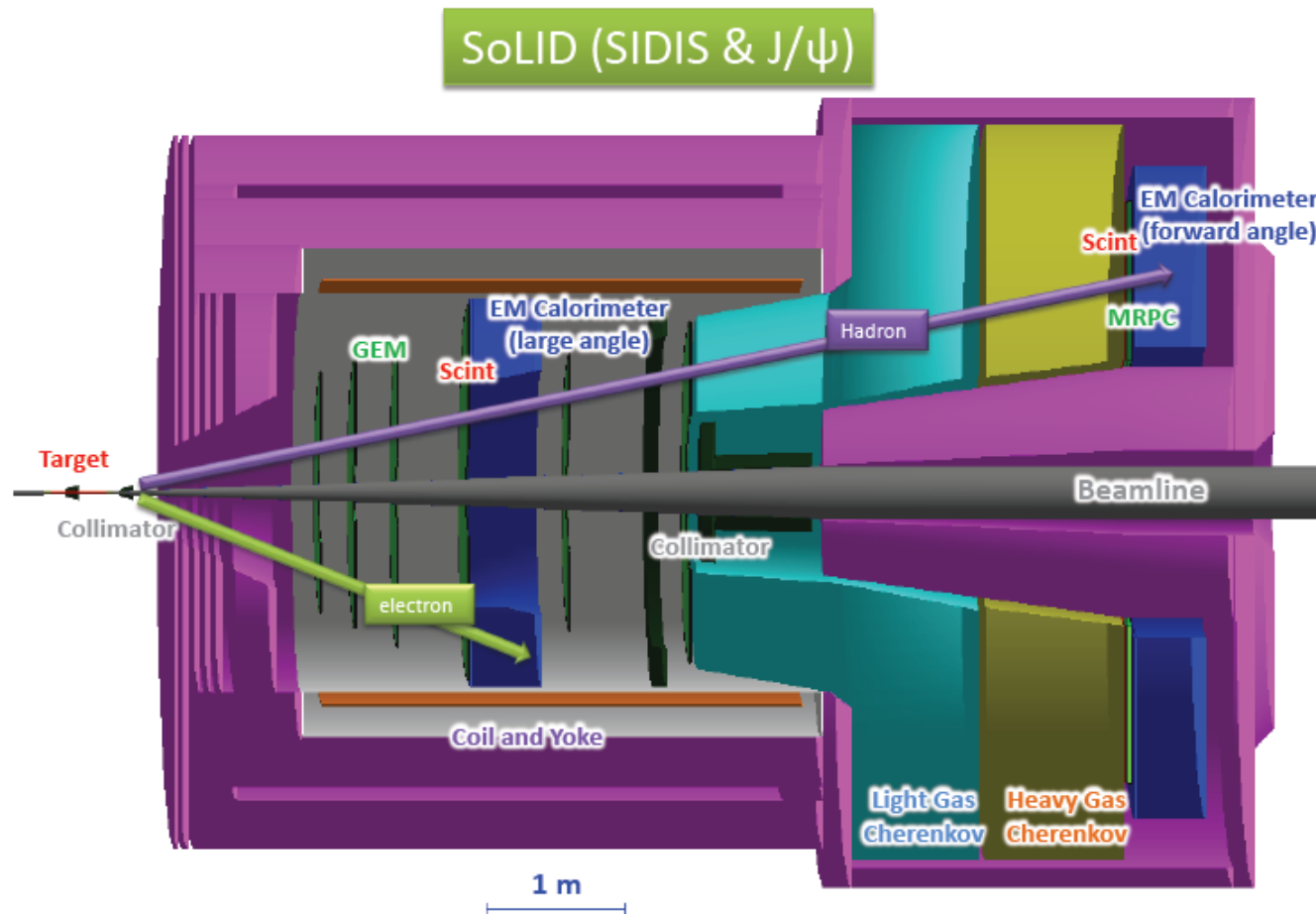


Figure 41: The  $p_T$  vs  $\phi_h$  coverage for  $(0.3, 0.35)$  of  $z$  bin for 11 GeV beam.

**SOLID  $p_T$  vs.  $\phi$  for different  $x$  bins,  
 $0.3 < z < 0.35$**

# SOLID



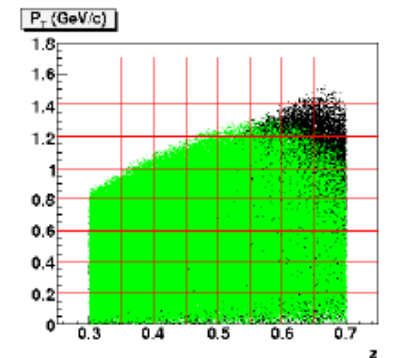
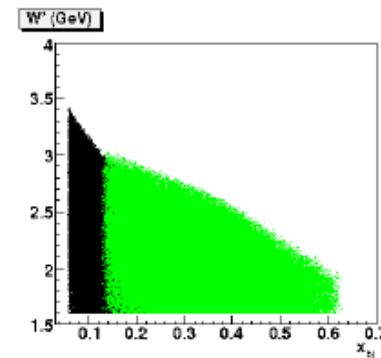
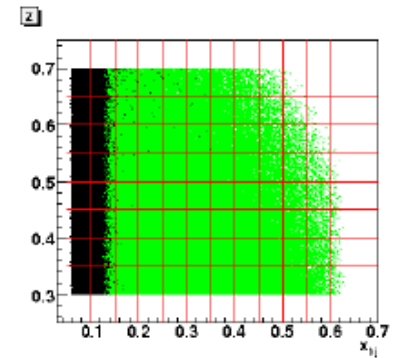
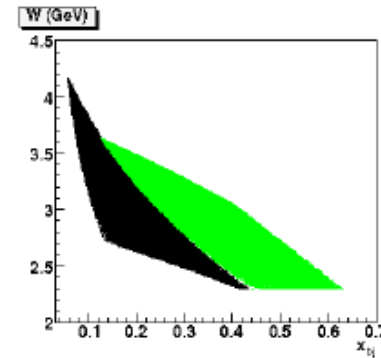
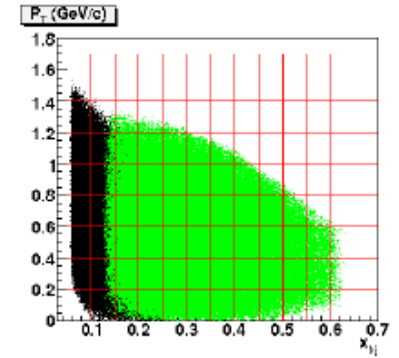
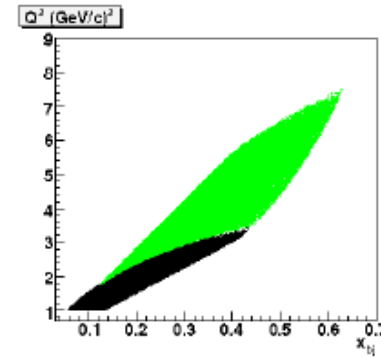
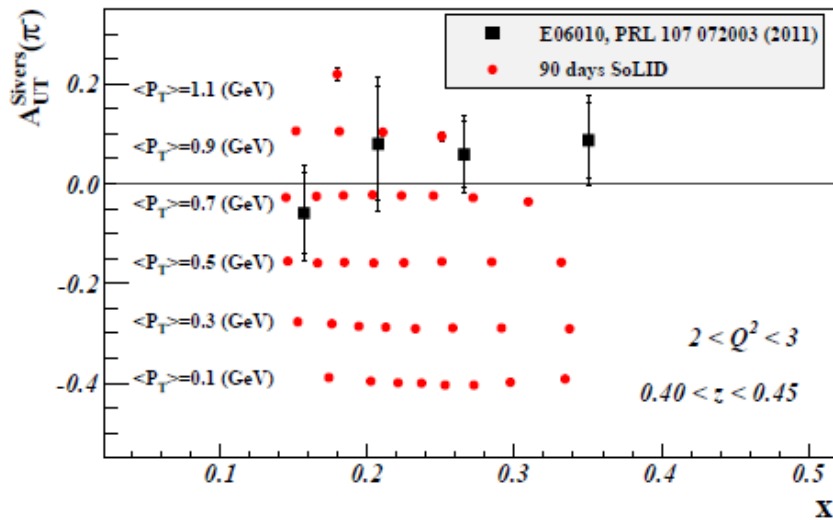
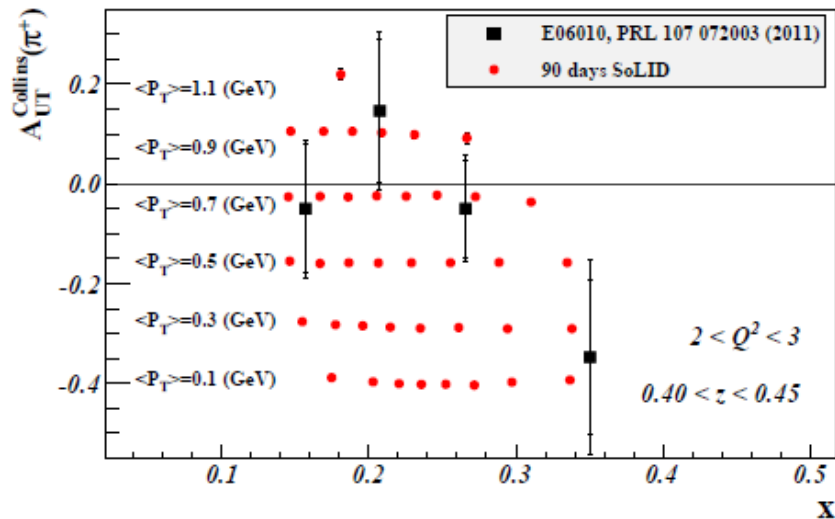
**Solenoidal Large Intensity Device (SOLID): large acceptance and high luminosity spectrometer using GEM technology**

**Physics program: SIDIS, J/ψ measurements, PVDIS**

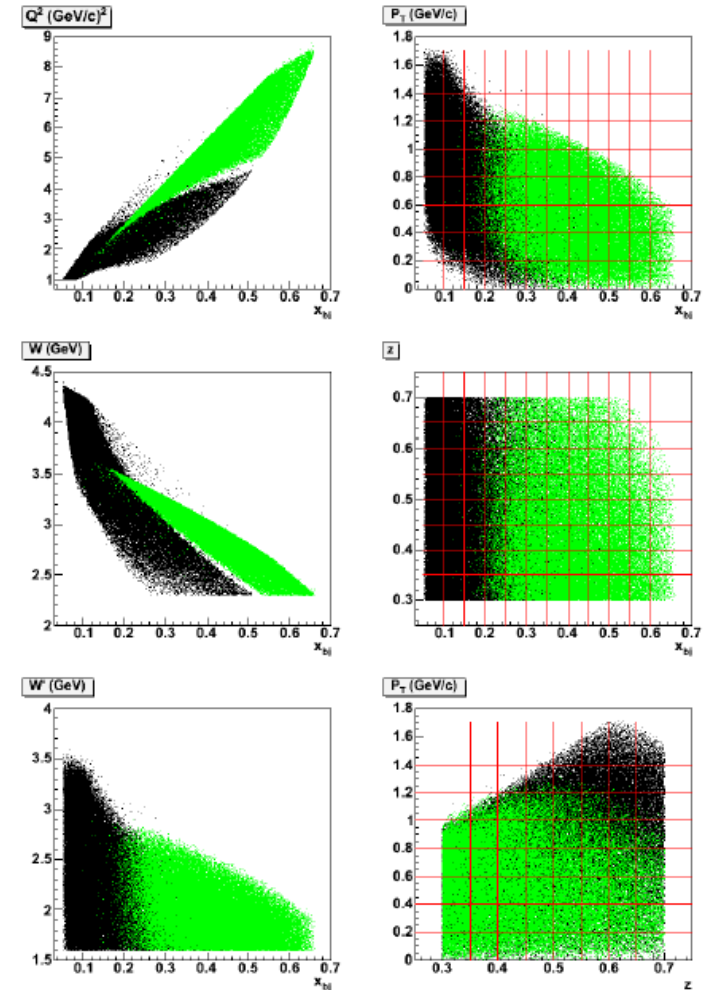
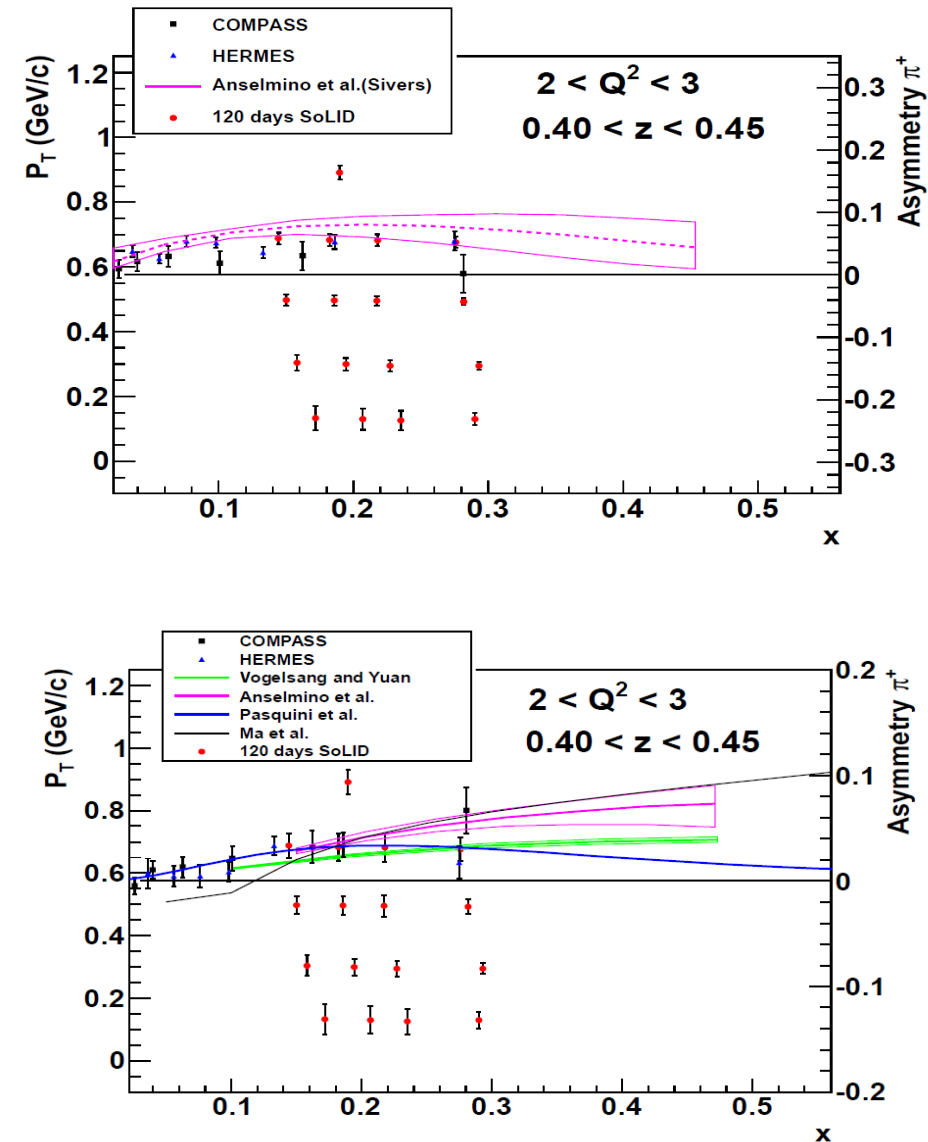
# SOLID SIDIS program

- Transversely polarized  $^3\text{He}$  (“neutron”) target:
  - E12-10-006: 90 beam-days approved, A rating
- Longitudinally polarized  $^3\text{He}$  (“neutron”) target:
  - E12-11-007: 35 beam-days approved, A rating
- Transversely polarized proton ( $\text{NH}_3$ ) target:
  - E12-11-108: 120 beam-days approved, A rating
- Collins/Sivers/Pretzelosity measurements for charged pions
- Precise measurement of flavor-separated nucleon tensor charge
- “Ultimate” precision 4D mapping of SIDIS polarized target observables  $A_{\text{UT}}/A_{\text{LT}}/A_{\text{UL}}/A_{\text{LL}}$ 
  - Combine large acceptance of Hall B with high luminosity of Hall A

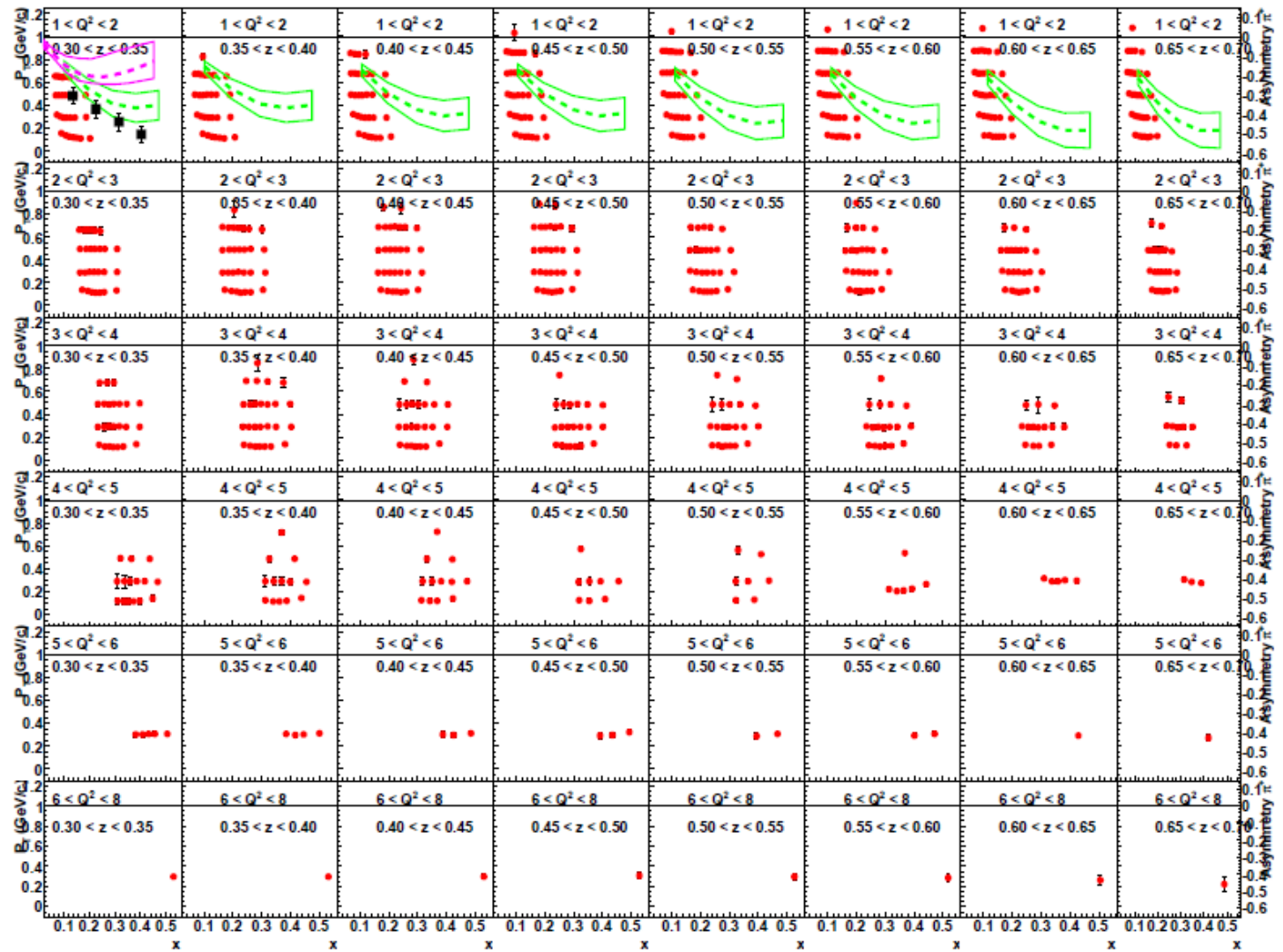
# SOLID $A_{UT}$ projections—neutron (from $^3\text{He}$ )



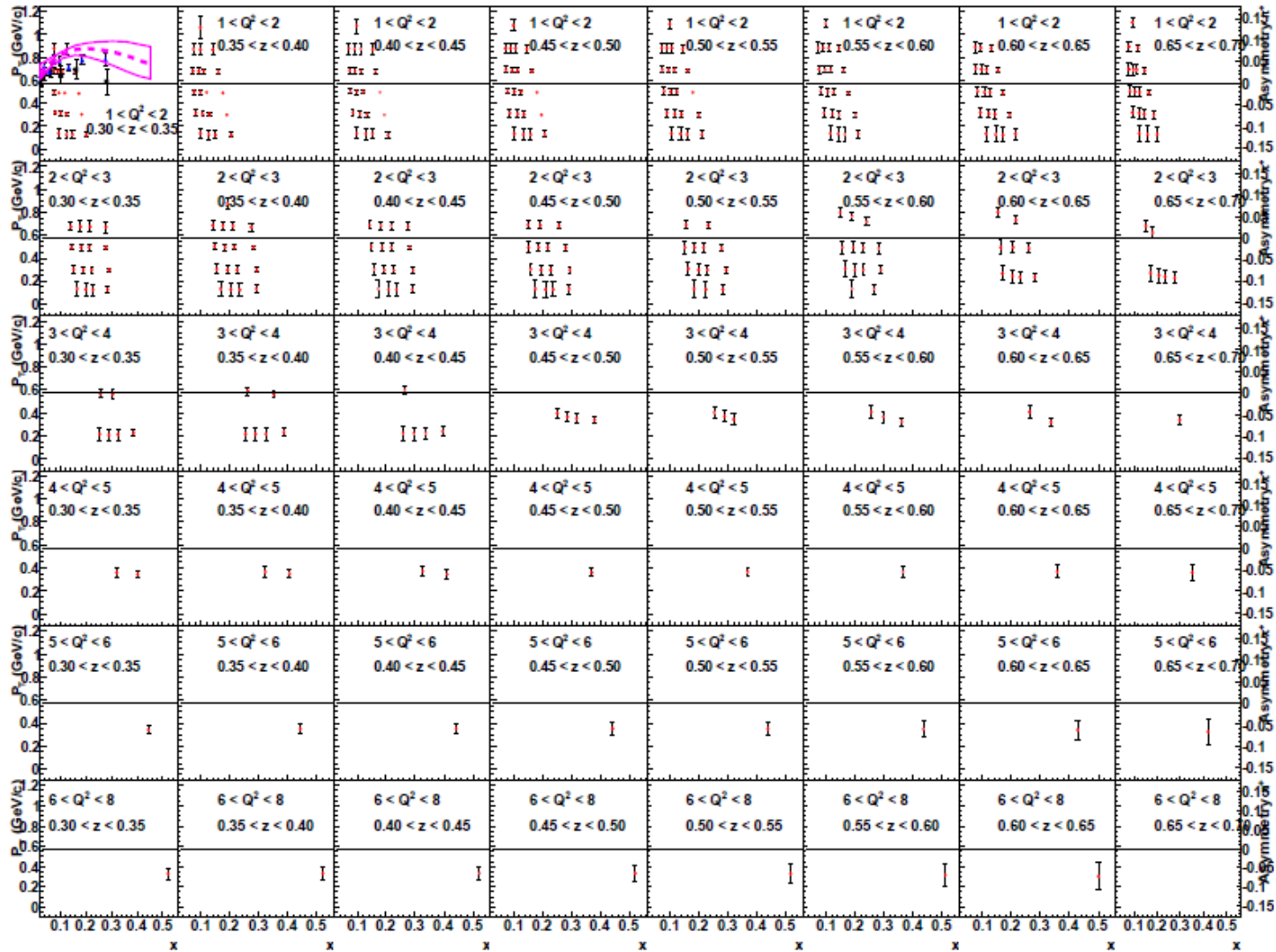
# SOLID $A_{UT}$ projections—proton ( $NH_3$ ) target

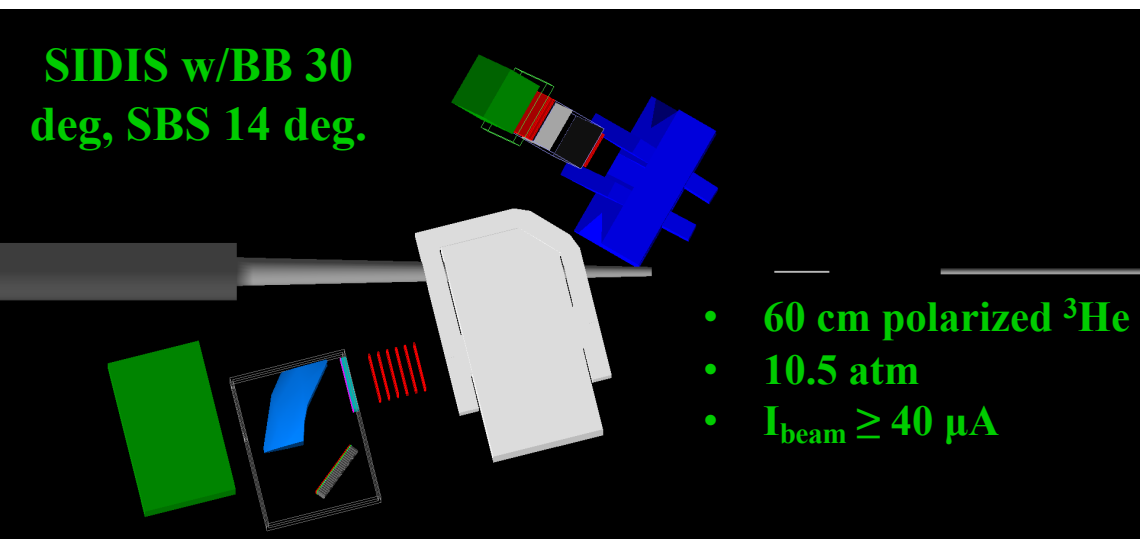
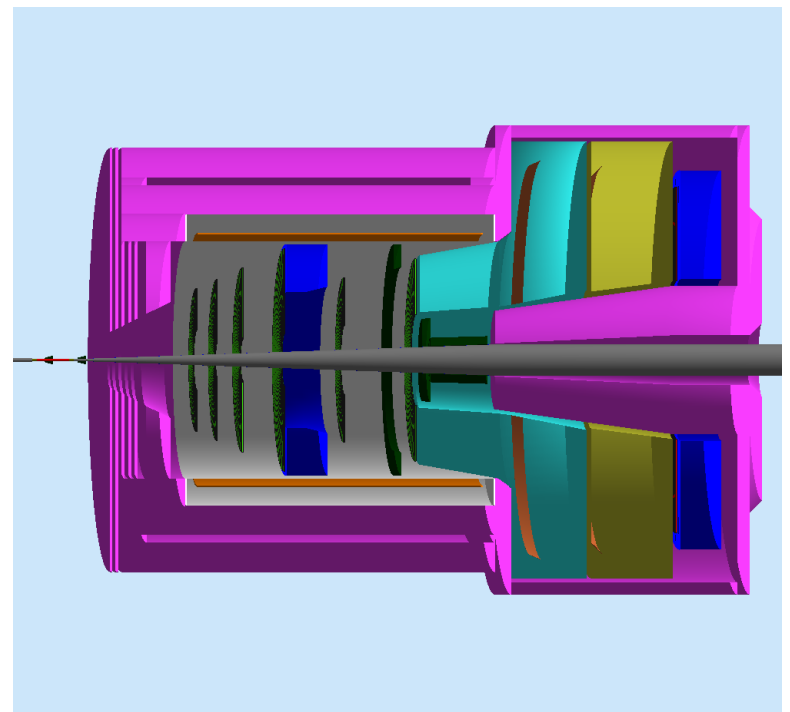
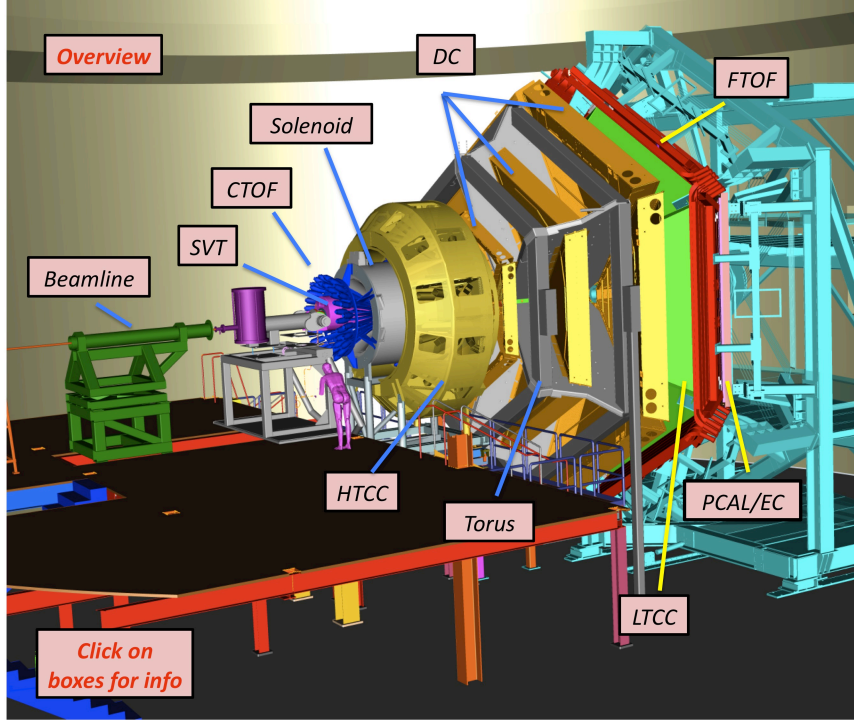


# SOLID Projected neutron $\pi^+$ Sivers Precision in 4D



# SOLID projected $\pi^+$ Sivers precision in 4D, proton target

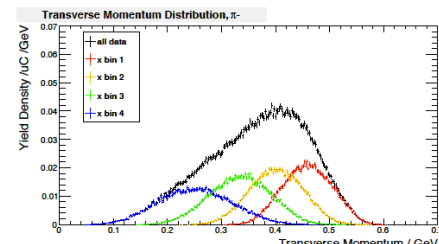
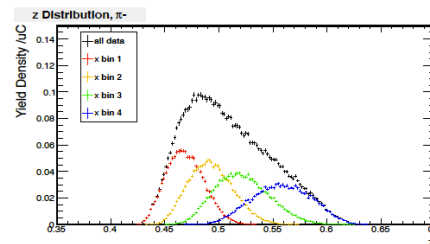
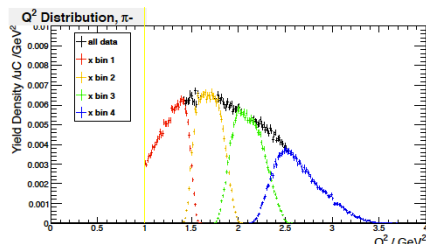
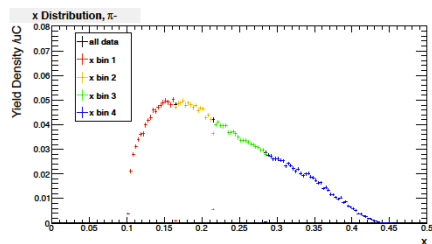
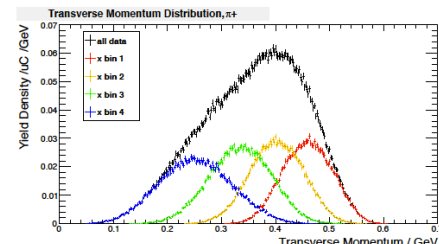
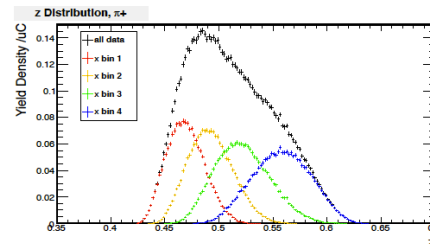
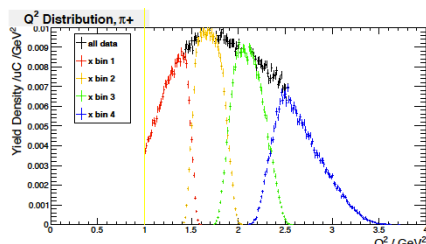
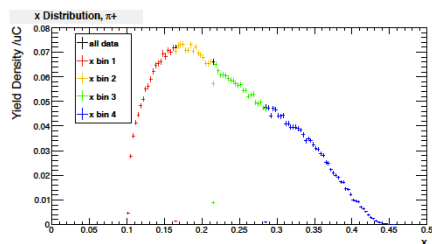




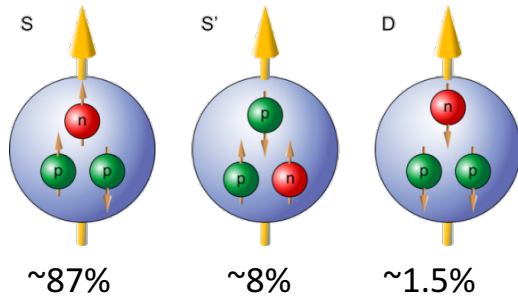
# E06-010 Phase Space

TABLE I. Central kinematics for the four  $x$  bins. The fractional  $e^-$  energy loss  $y$ , the hadron energy fraction  $z$  with respect of electron energy transfer and the transverse momentum  $P_{h\perp}$  are all defined following the notation of Ref. [10]. The pair production background  $f_{\text{pair}}^{\pi^\pm}$  and the proton dilution  $1 - f_p^{\pi^\pm}$  are shown with their total experimental systematic uncertainties. The numbers in parentheses represent the model uncertainties corresponding to unpolarized FSI effects.

$x$	$Q^2$ GeV <sup>2</sup>	$y$	$z$	$P_{h\perp}$ GeV	$W$ GeV	$W'$ GeV	$f_{\text{pair}}^{\pi^+}$	$f_{\text{pair}}^{\pi^-}$	$1 - f_p^{\pi^+}$	$1 - f_p^{\pi^-}$
0.156	1.38	0.81	0.50	0.435	2.91	2.07	$22.0 \pm 4.4\%$	$24.0 \pm 4.8\%$	$0.212 \pm 0.032(0.027)$	$0.348 \pm 0.032(0.022)$
0.206	1.76	0.78	0.52	0.38	2.77	1.97	$8.0 \pm 2.0\%$	$14.0 \pm 2.0\%$	$0.144 \pm 0.031(0.029)$	$0.205 \pm 0.037(0.027)$
0.265	2.16	0.75	0.54	0.32	2.63	1.84	$2.5 \pm 0.9\%$	$5.0 \pm 1.8\%$	$0.171 \pm 0.029(0.028)$	$0.287 \pm 0.036(0.024)$
0.349	2.68	0.70	0.58	0.24	2.43	1.68	$1.0 \pm 0.5\%$	$2.0 \pm 1.0\%$	$0.107 \pm 0.026(0.030)$	$0.220 \pm 0.032(0.026)$



# Polarized $^3\text{He}$ Target



Polarized  $^3\text{He}$  as effective polarized neutron target

$$A_{^3\text{He}} = P_n(1 - f_p)A_n + P_p f_p A_p$$

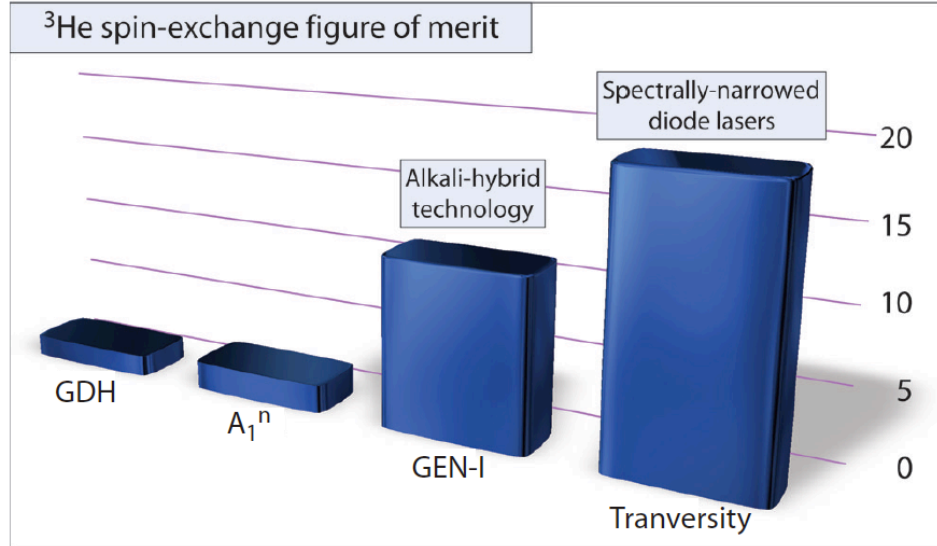
$$P_n = 0.86^{+0.036}_{-0.02}$$

$$P_p = -0.028^{+0.009}_{-0.004}$$

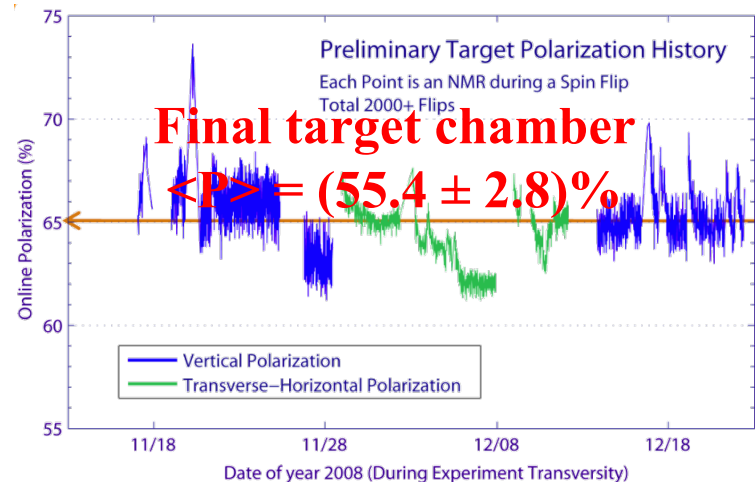
$$f_p = \frac{2\sigma_p}{\sigma_{^3\text{He}}}$$

Effective nucleon polarization approach:

Scopetta, PRD 75, 054005 (2007)

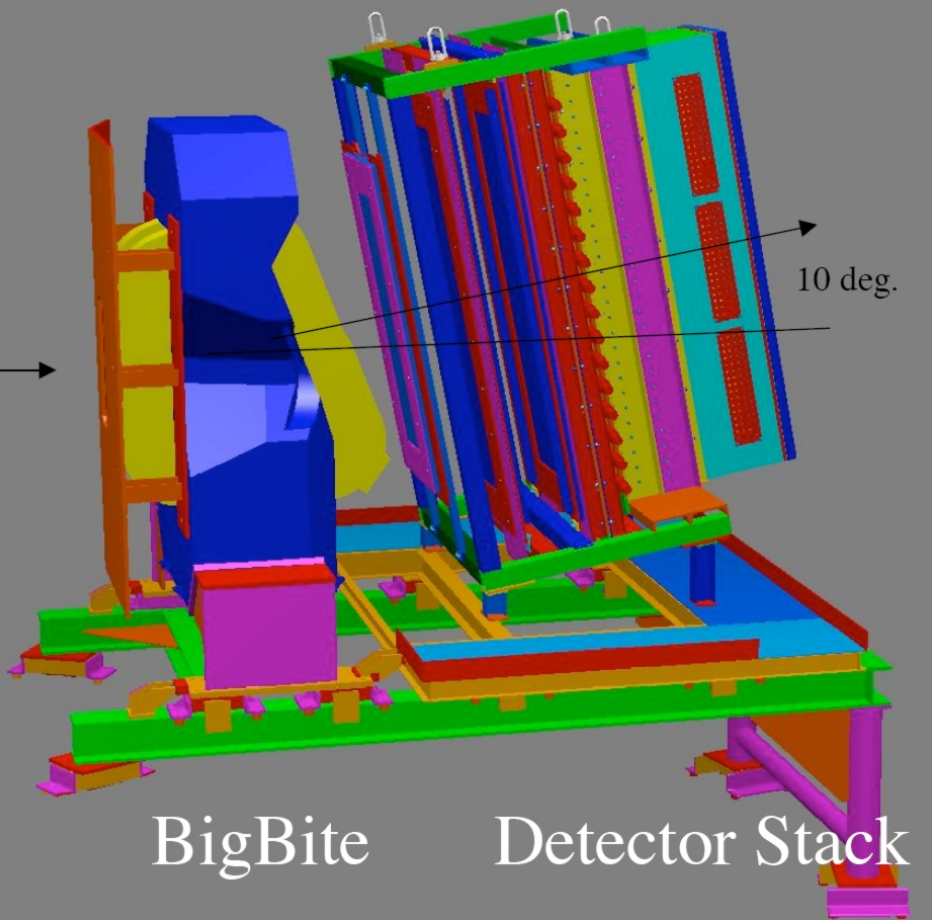


$\sim 10 \text{ atm } ^3\text{He} = \sim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$  en luminosity

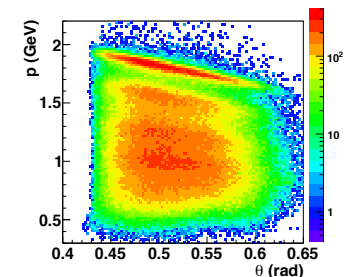
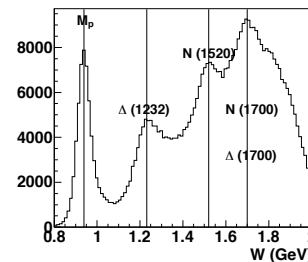
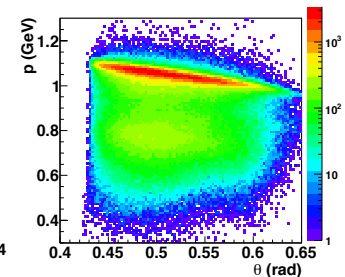
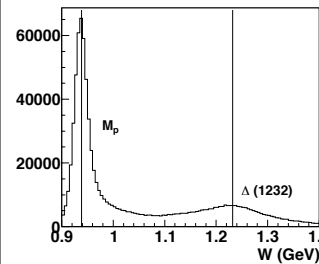


# BigBite Spectrometer

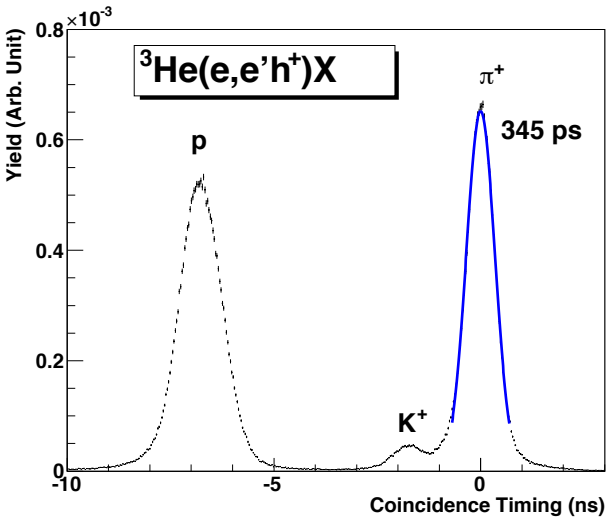
- 1.2 Tesla dipole magnet in front of detector stack
- Positioned to subtend  $\sim 64$  msr solid angle
- Large out-of-plane angle acceptance ( $\sim \pm 240$  mrad), essential to maximize  $\phi$  coverage, separate Collins/Sivers effects
- Three drift chambers for tracking
- Shower+Preshower for electron PID
- Scintillator for timing



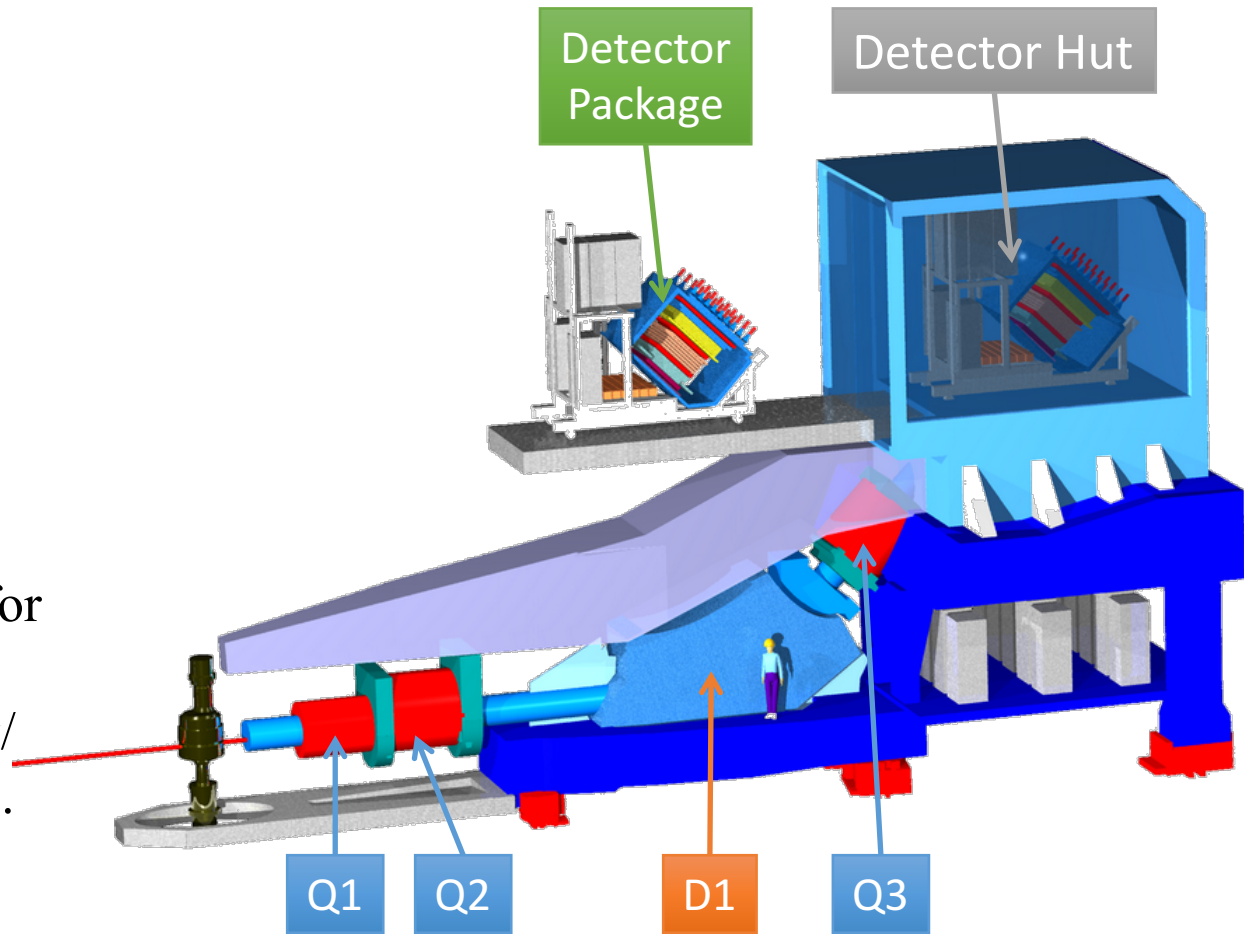
BigBite Spectrometer



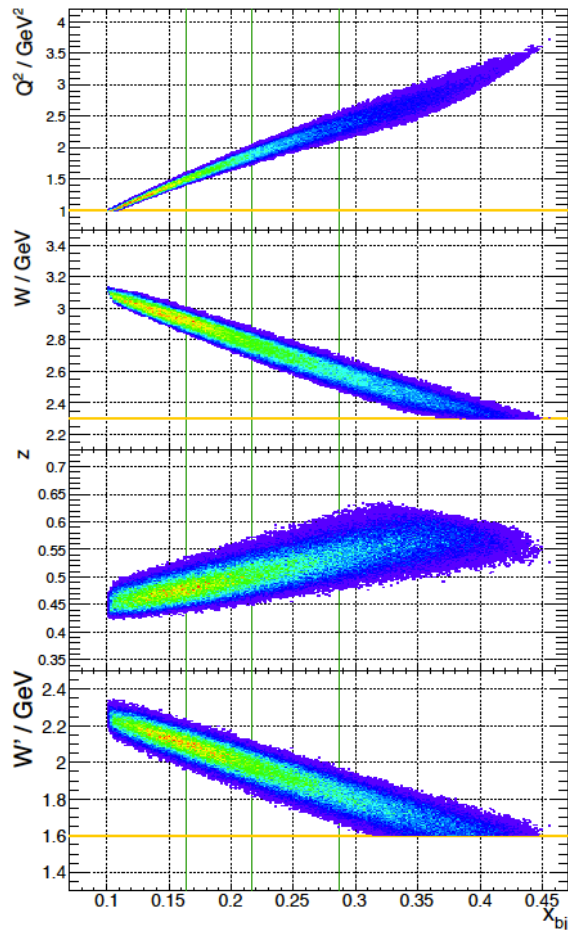
# High Resolution Spectrometer



- Gas Cherenkov+Lead-glass for  $e/\pi$  separation
- Coincidence Vertex + TOF w/ Bigbite suppress random coinc.
- Aerogel+RICH+TOF:  $\pi/K$  separation  $>10:1$  K rejection factor

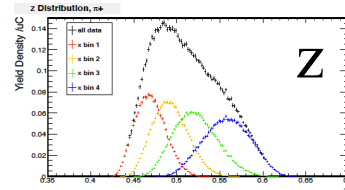


# Kinematic and Azimuthal Coverage

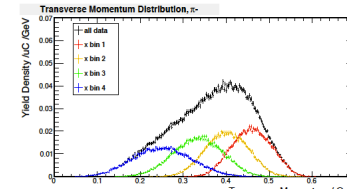
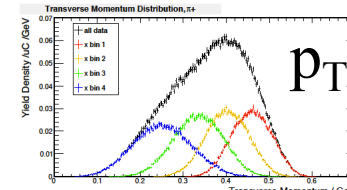
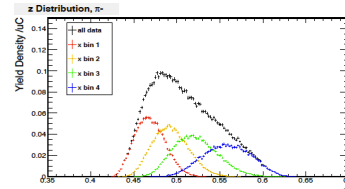


$Q^2, W, z, W'$  vs.  $x$

$\pi^+$

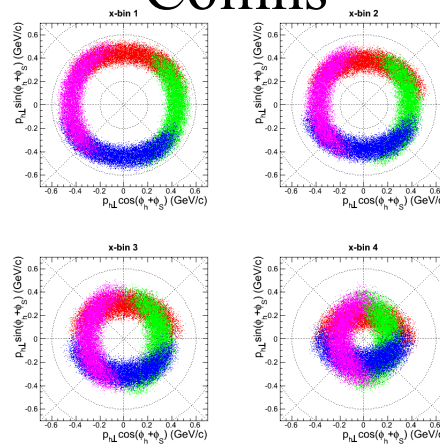


$\pi^-$

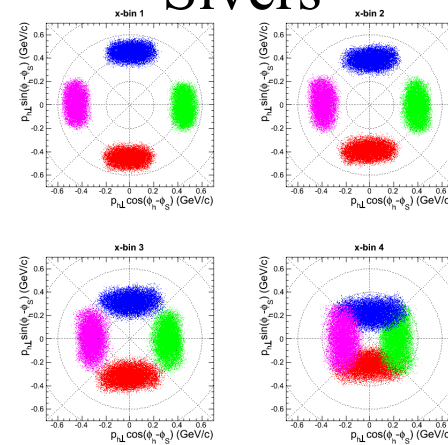


$z, p_T$  for different  $x$  bins,  $\pi^\pm$

Collins



Sivers



Collins/Sivers angle coverage,  $x$  bins 1-4,  
different target spin states

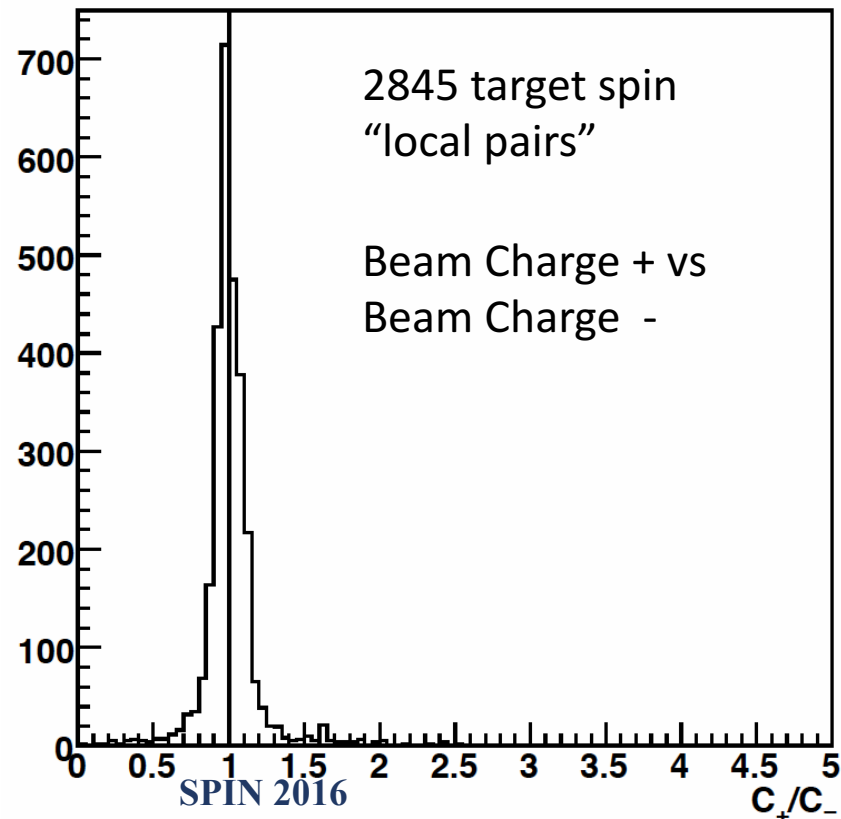
# Analysis: Target Single-Spin Asymmetry

Target single-spin asymmetry from normalized yields, need to consider :  
beam charge, target density, DAQ life time, detector efficiency etc.

$$A(\phi_h, \phi_S) = \frac{1}{|S_T|} \frac{Y_{\phi_h, \phi_S} - Y_{\phi_h, \phi_S + \pi}}{Y_{\phi_h, \phi_S} + Y_{\phi_h, \phi_S + \pi}}$$

**Automatic target spin flip  
once every 20 minutes.**

Beam charges are well-balanced  
between the pairs

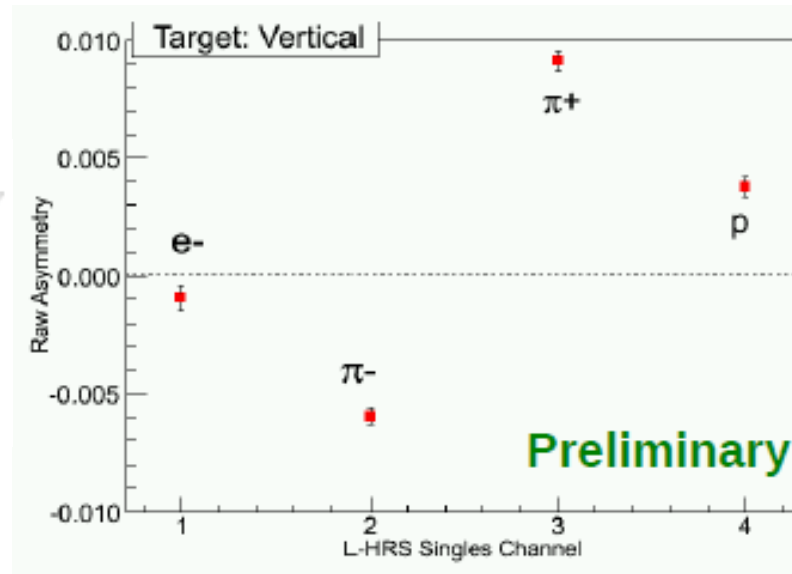
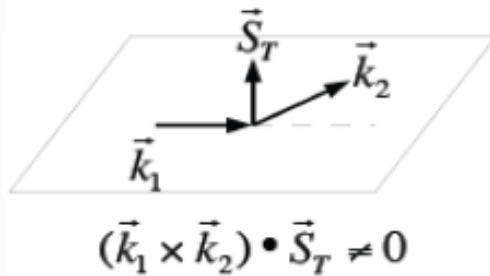
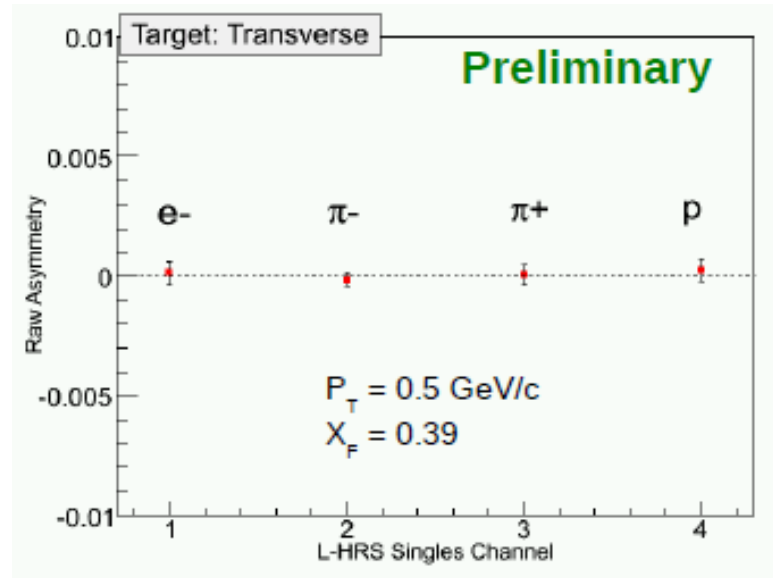
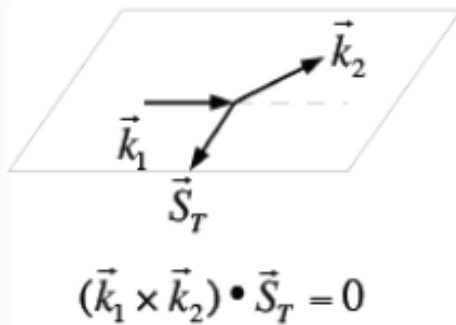


# SSA check: HRS single-arm $^3\text{He}$ SSA

(Witness channels on  $^3\text{He}$ , not corrected for target polarization and dilution)

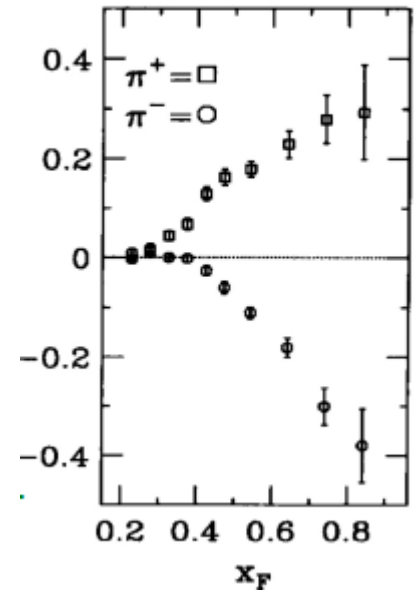
$$e + {}^3\text{He} \rightarrow A + X$$

$$A = e', \pi^{+/-} \text{ or } p$$


















K. Allada  
Univ. of Kentucky  
2010.

FNAL-E704:  $\sqrt{s} = 20 \text{ GeV}$ .  
PLB 264 (1991) 462.



False asymmetry < 0.1%

# Transverse target spin asymmetries in SIDIS

		quark		
		U	L	T
nucleon	U	q 		$h_1^\perp$  - 
	L		$\Delta q$  - 	$h_{1L}^\perp$  - 
	T	$f_{1T}^\perp$  - 	$g_{1T}^\perp$  - 	$\delta q$  -  $h_{1T}^\perp$  - 

## Transverse target spin-dependent cross section for SIDIS

- Collins effect—chiral-odd quark transversity DF; chiral-odd Collins FF
- Sivers effect—access to quark OAM and QCD FSI effects
- “Transversal helicity”  $g_{1T}$ —real part of S wave-P wave interference (Sivers = imaginary part)
- “Pretzelosity” or Mulders-Tangeman function—access to wavefunction components differing by 2 units of OAM

$$\begin{aligned}
 A_{UT}(\phi, \phi_S) &= \frac{1}{P_T} \frac{d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi)}{d\sigma(\phi, \phi_S) + d\sigma(\phi, \phi_S + \pi)} \\
 &= A_{UT}^{Collins} \sin(\phi + \phi_S) + \\
 &\quad A_{UT}^{Sivers} \sin(\phi - \phi_S) + \\
 &\quad A_{UT}^{Pretz} \sin(3\phi - \phi_S)
 \end{aligned}$$

$$\begin{aligned}
 A_{UT}^{Collins} &\propto \delta q \otimes H_1^\perp \\
 A_{UT}^{Sivers} &\propto f_{1T}^\perp \otimes D_1 \\
 A_{UT}^{Pretz} &\propto h_{1T}^\perp \otimes H_1^\perp
 \end{aligned}$$

$D_1$  = unpolarized fragmentation function

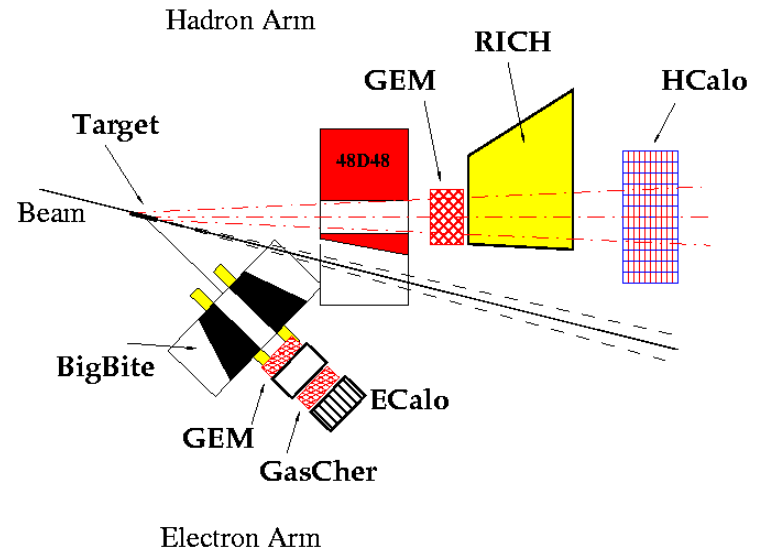
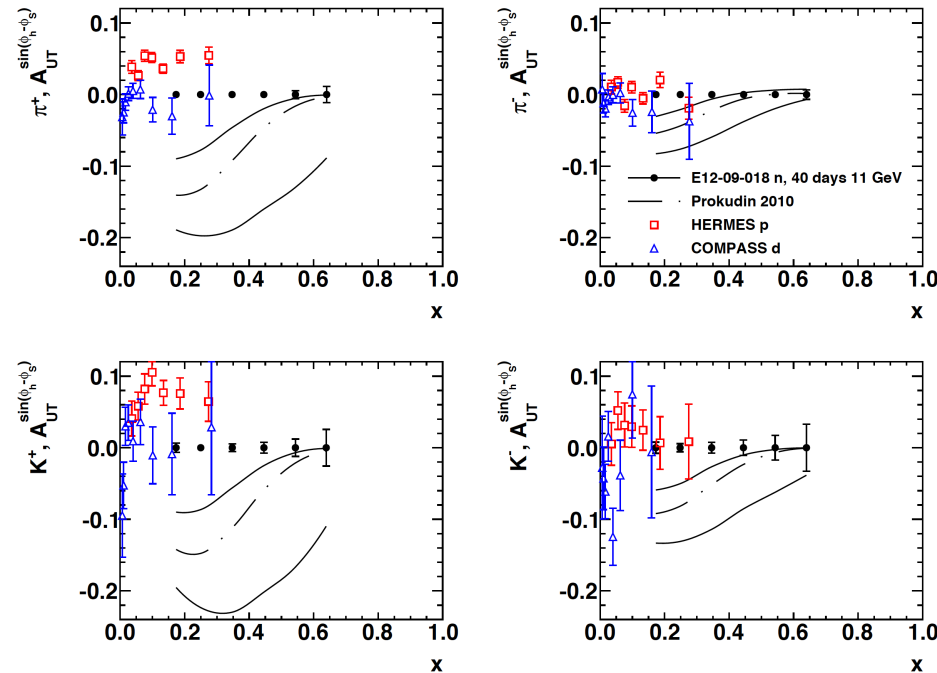
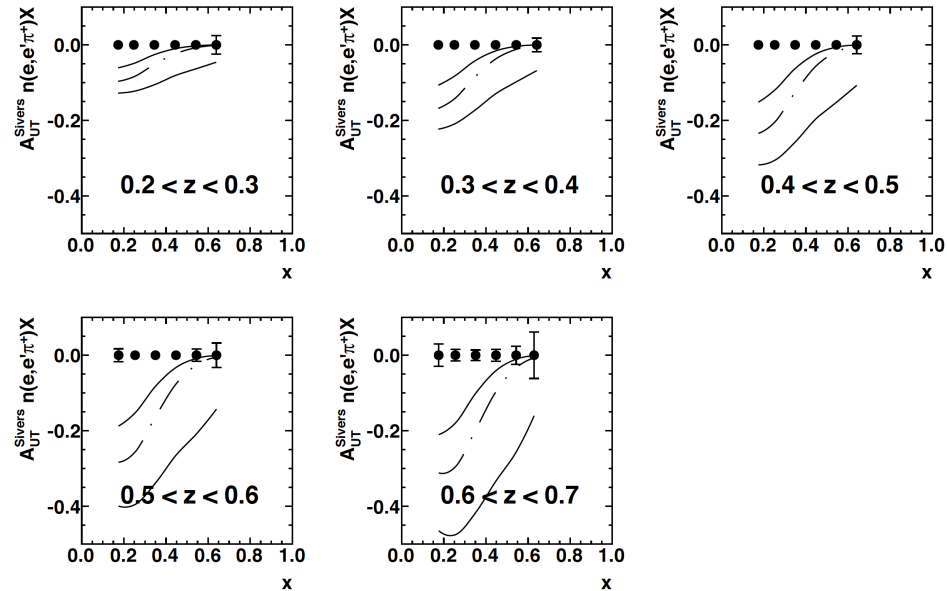
$H_1^\perp$  = Collins

fragmentation function

$$\begin{aligned}
 A_{LT}(\phi, \phi_S) &= \frac{1}{P_e P_T} \frac{Y_+(\phi, \phi_S) - Y_-(\phi, \phi_S)}{Y_+(\phi, \phi_S) + Y_-(\phi, \phi_S)} \\
 &\sim A_{LT}^{\cos(\phi - \phi_S)} \cos(\phi - \phi_S) \\
 &\sim g_{1T} \otimes D_1
 \end{aligned}$$

# SIDIS/Neutron Transversity—E12-09-018

- BigBite as electron arm: DIS electrons at  $\sim 30^\circ$ ,  $1 < p_e < 4$  GeV
- SBS as hadron arm @  $14^\circ$ ,  $p_h > 2$  GeV
- High-luminosity  $^3\text{He}$  target (same as GEN, but more target spin directions)
- **High-impact SSA/TMD physics (Collins/Sivers effects): 100X higher FOM for neutron than HERMES proton**
- **Approved by PAC38, A<sup>-</sup> rating, 40 (20) days production at 11 (8.8) GeV**
- **Charged kaon and  $\pi^0$  SSAs in addition to charged pions**



# 3D and “4D” extraction of SIDIS SSAs with SBS

Example result for 3D binning

$(x, z, p_T)$

*Increasing  $z \rightarrow$*

- $E = 11$  GeV, 40 days

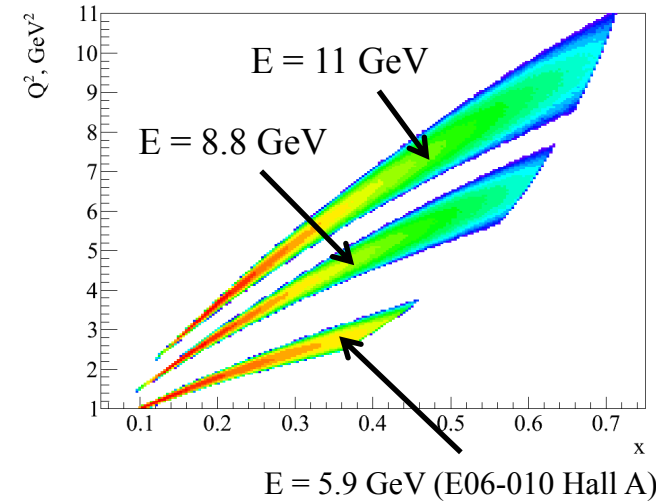
$A_{UT}^{\sin(\phi_h - \phi_S)}$  for  $\mathbf{n}(e, e' \pi^+)X$  :

$0.1 \leq x \leq 0.7, \Delta x = 0.1$

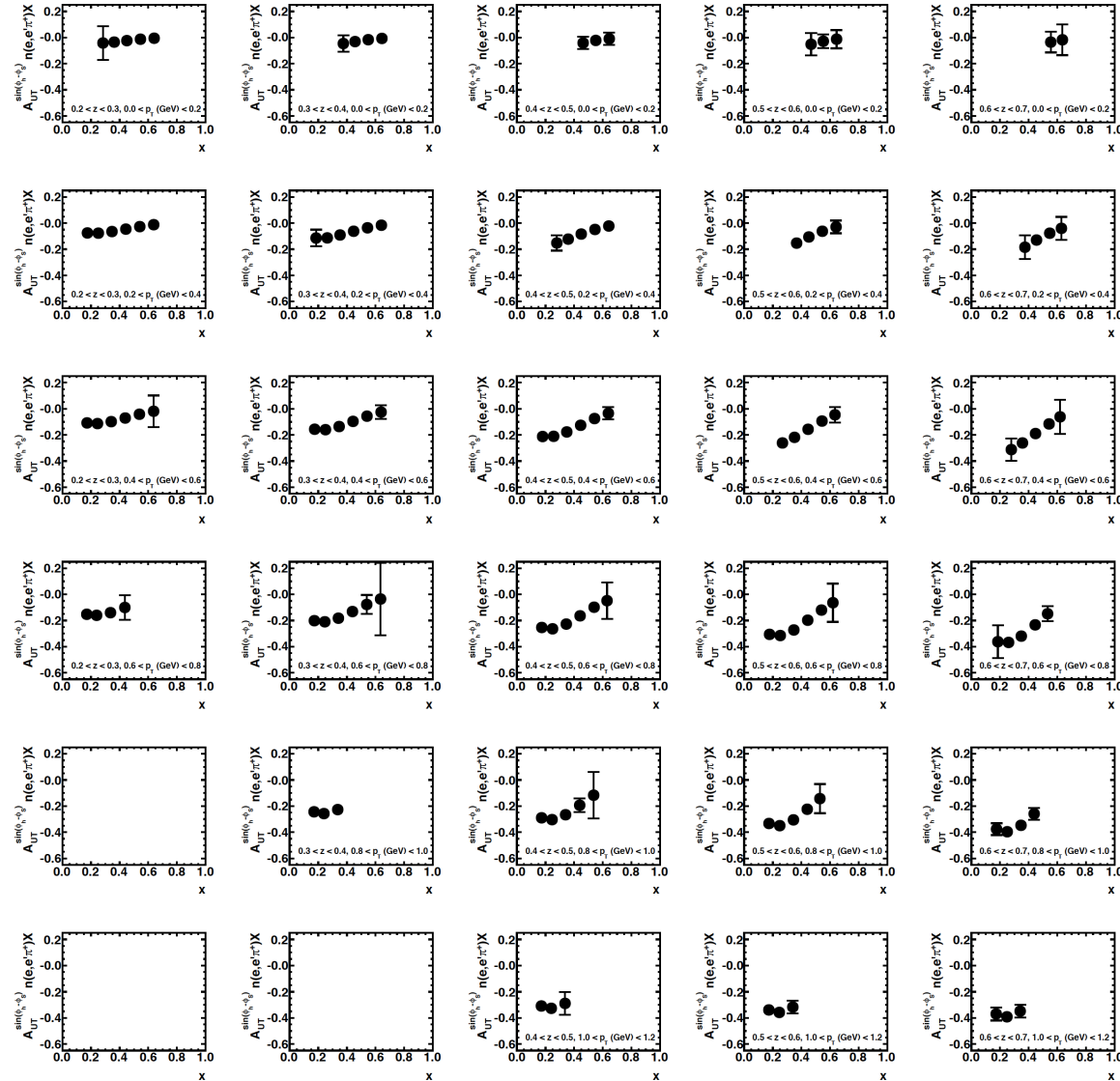
$0.2 \leq z \leq 0.7, \Delta z = 0.1$

$0 \leq p_T (\text{GeV}) \leq 1.2, \Delta p_T = 0.2 \text{ GeV}$

- “4D” with  $Q^2$  dependence from 20 days at 8.8 GeV:



*Increasing  $p_T \leftarrow$*



# COMPASS 2012 proton data

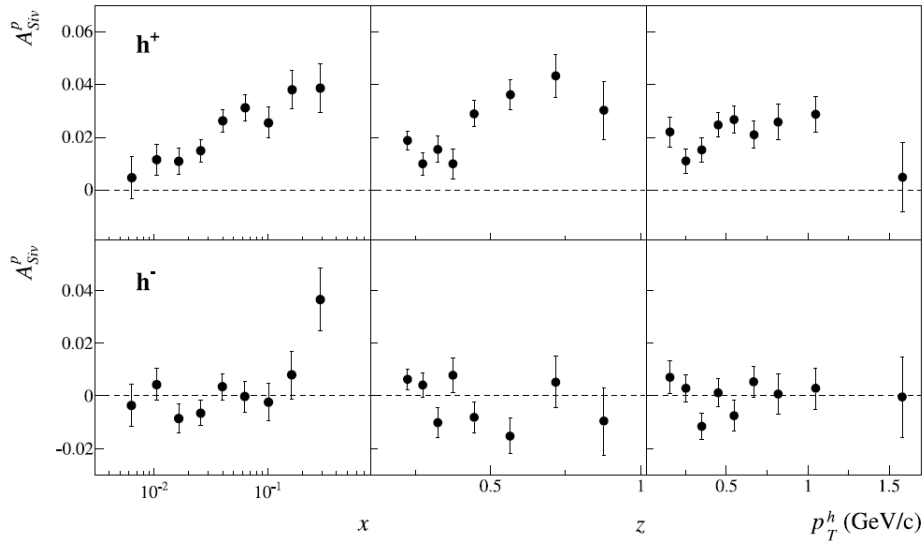


Fig. 1. Sivers asymmetry as a function of  $x$ ,  $z$  and  $p_T^h$  for positive (top) and negative (bottom) hadrons.

**Sivers asymmetries: Phys. Lett. B 717 (2012) 383**

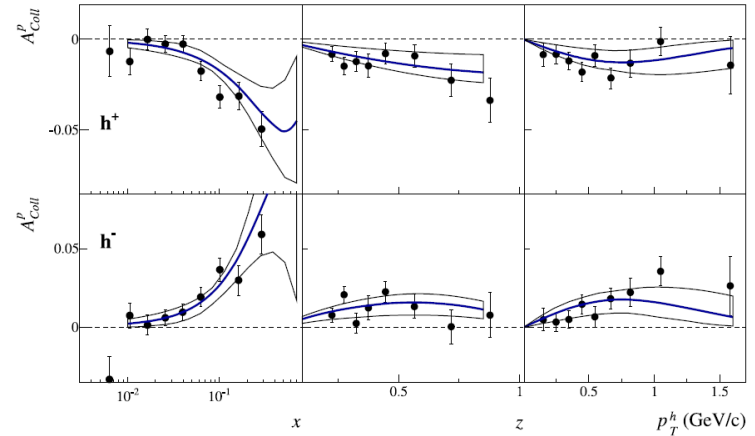
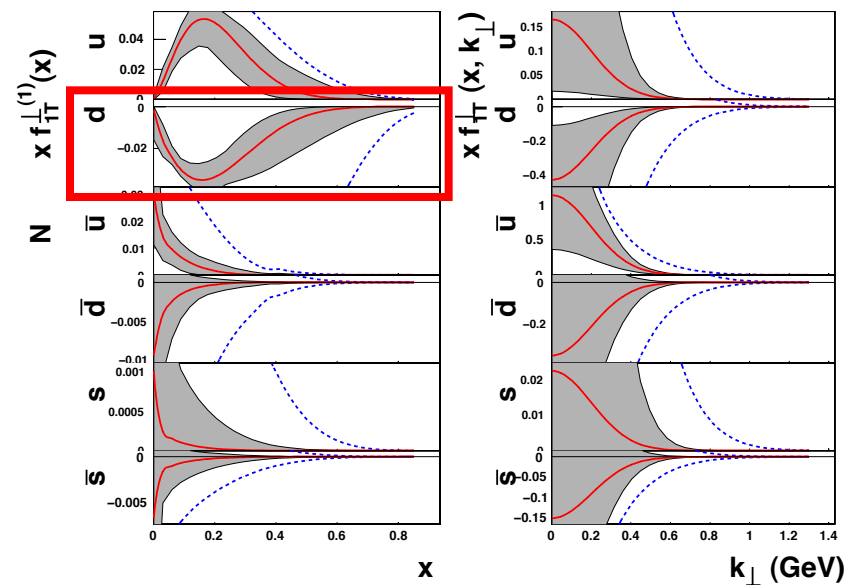
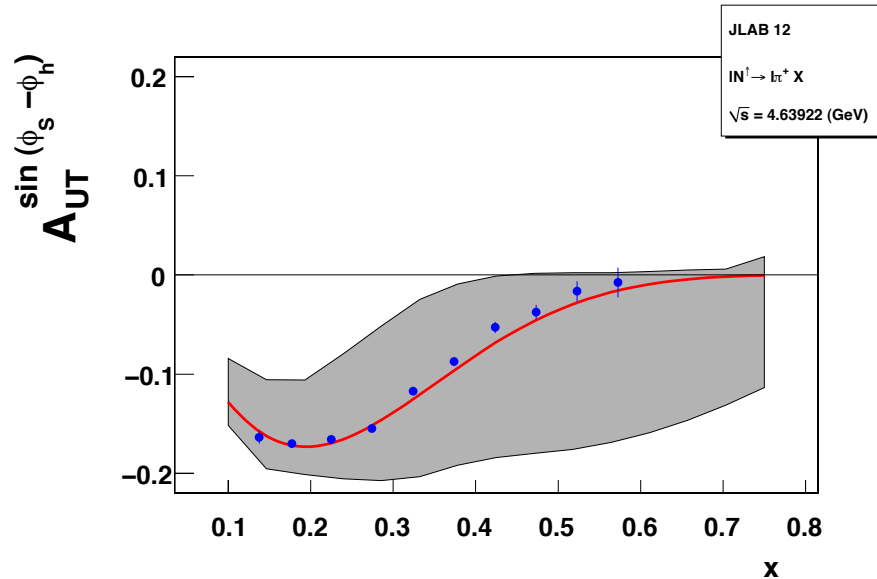


Fig. 3. Collins asymmetry as function of  $x$ ,  $z$  and  $p_T^h$  for positive (top) and negative (bottom) hadrons. The curves are from Ref. [30].

**Collins asymmetries: Phys. Lett. B 717 (2012) 376**

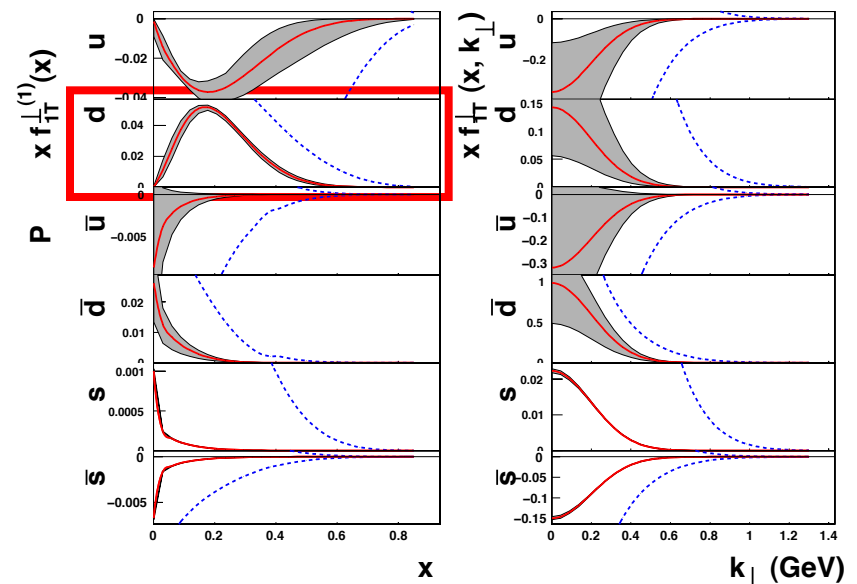
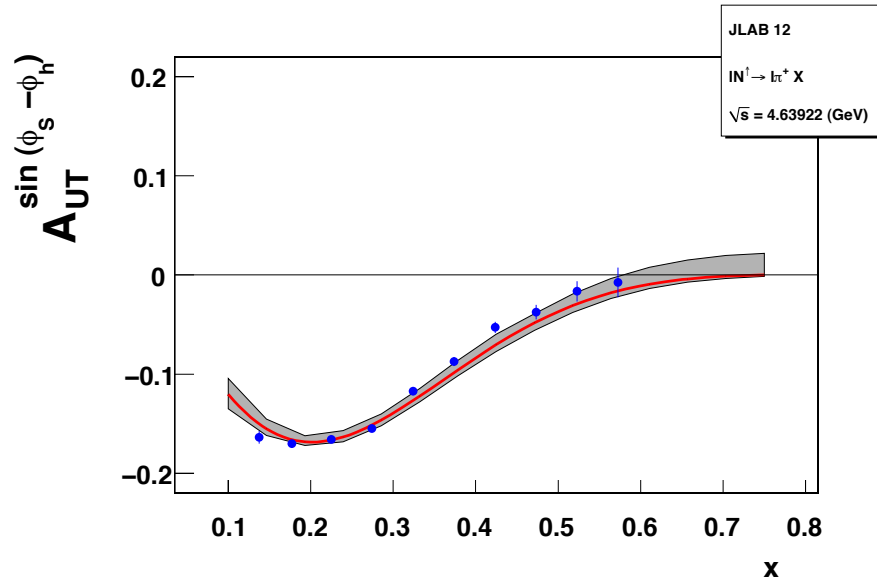
- Collins results largely consistent with HERMES proton data
- Sivers results qualitatively in agreement with HERMES data, but smaller in magnitude (for positive hadrons)
  - Suggest significant  $Q^2$  dependence

# Example Impacts of SBS SIDIS Experiment



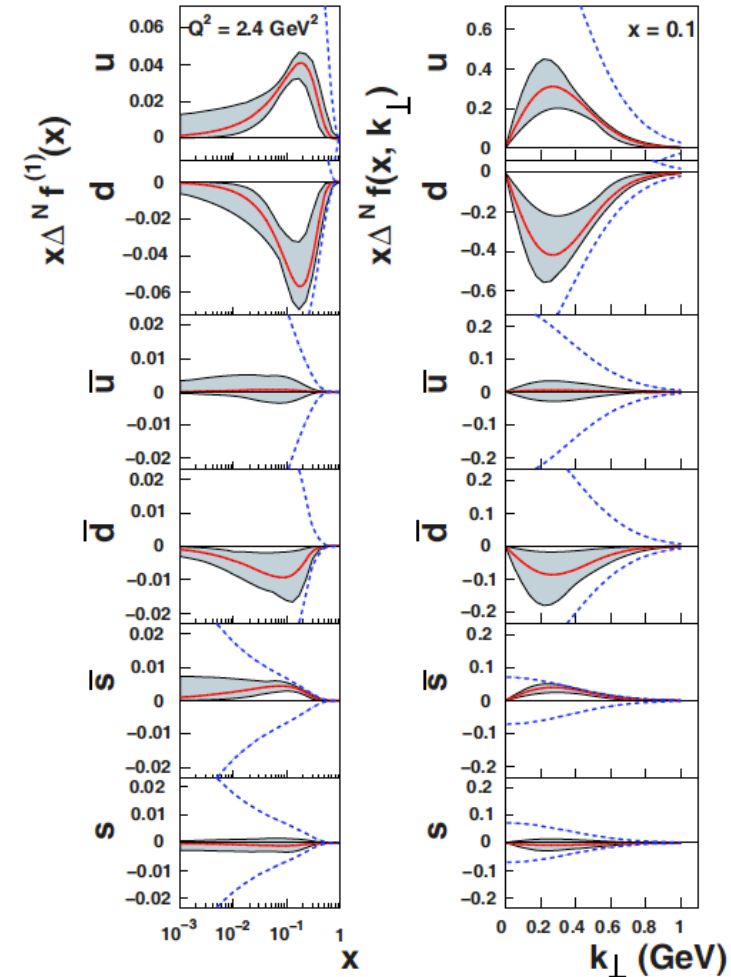
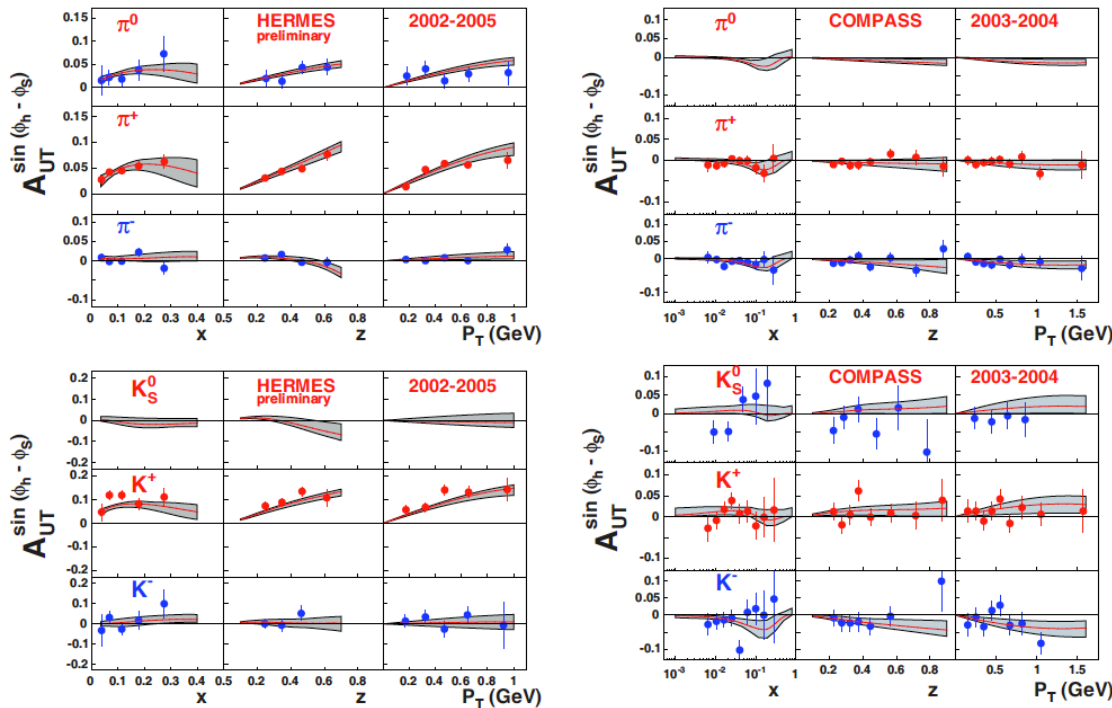
- 2011 impact study by A. Prokudin, global fit with E12-09-018 projected results,  $\pi^+$  Sivers moments at  $E = 11$  GeV,  $\frac{1}{2}$  of projected statistics.
- Left:  $>5X$  shrinking of  $n(e, e' \pi^+)X$  Sivers  $A_{UT}$  band
- Right: reducing the uncertainty in  $d$  quark Sivers in six-flavor extraction
- **E12-09-018 will provide  $\pi^\pm/\pi^0/K^\pm$  at similar precision (Kaon errors 2-3X pion errors) for both  $E = 8.8$  GeV and  $E = 11$  GeV Collins/Sivers (and Pretzelosity)**

# Example Impacts of SBS SIDIS Experiment



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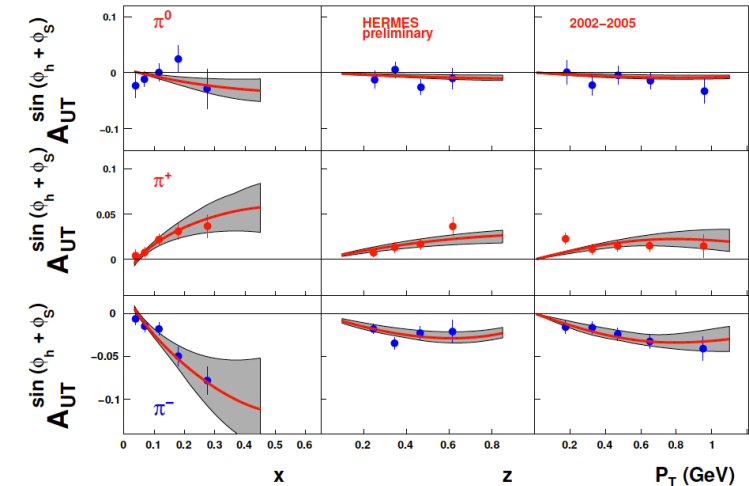
# Existing Data: the Sivers function



*Anselmino et al., EPJ A 39, 89 (2009)*

- Fit to  $A_{UT}^{\text{Sivers}}$  data from SIDIS experiments:
  - HERMES proton: PRL 103, 152002 (2009)
  - COMPASS deuteron: PLB 673, 127 (2010)
- Clear signal seen in  $\pi^+/K^+$  production on the proton

# Existing Data: the Collins effect

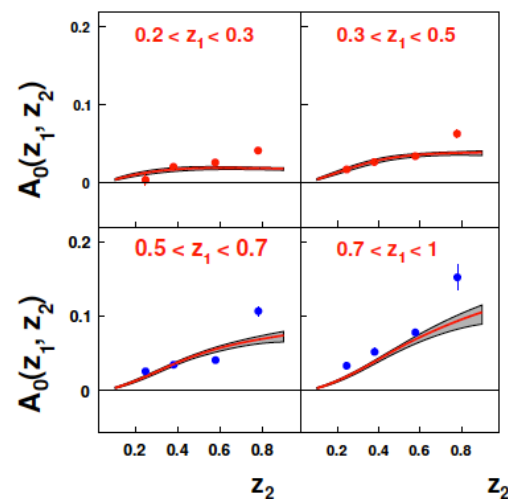
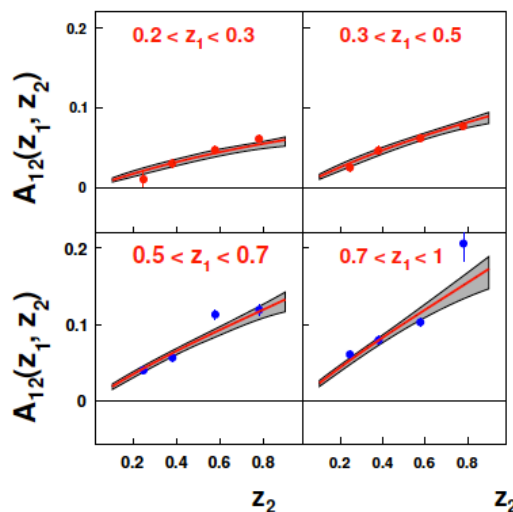
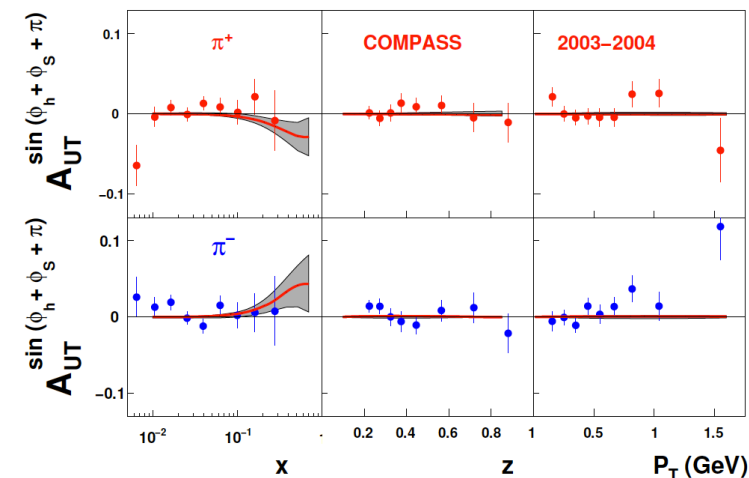


- SIDIS data:

- HERMES, PLB 693, 11 (2010):  $e^\pm$  SIDIS on transversely polarized protons
- COMPASS, PLB 673, 127 (2009): muon SIDIS on transversely polarized deuterons

- $e^+e^-$  annihilation data:

- BELLE, PRD 78, 032011 (2008)
- Directly access the Collins Fragmentation Function



# Hall B Unpolarized Data, Continued

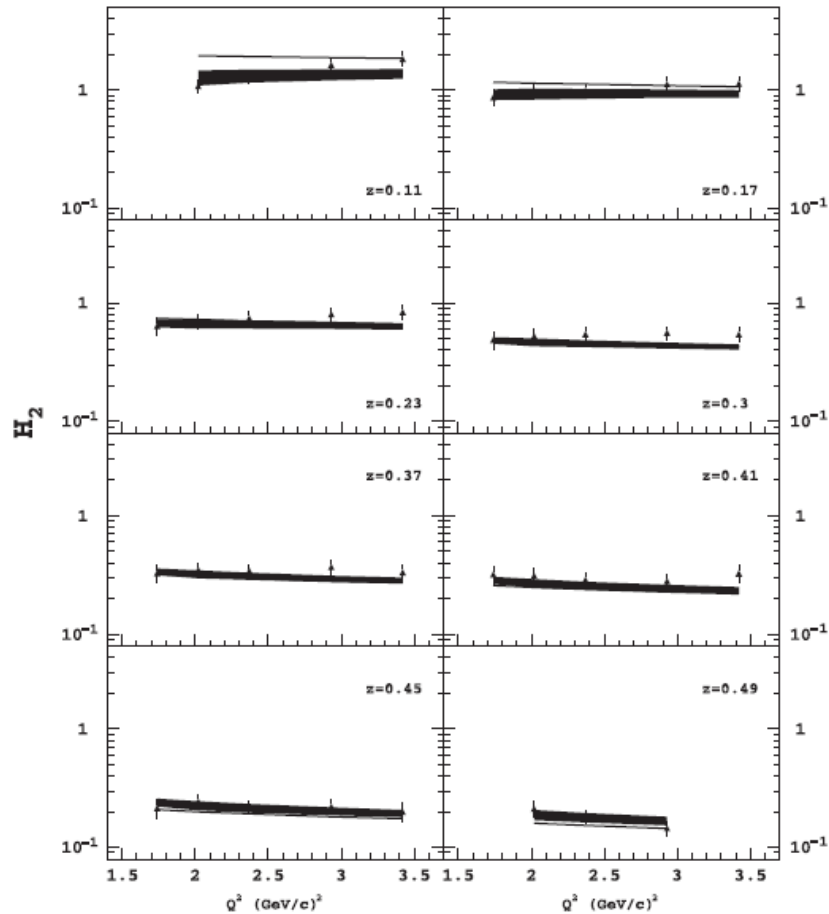


FIG. 19. Same as Fig. 17 except with  $H_2$  plotted as a function of  $Q^2$  rather than  $z$  at  $x = 0.33$ .

**$H_2$  vs.  $Q^2$  at fixed  $x = 0.33$  in different  $z$  bins**

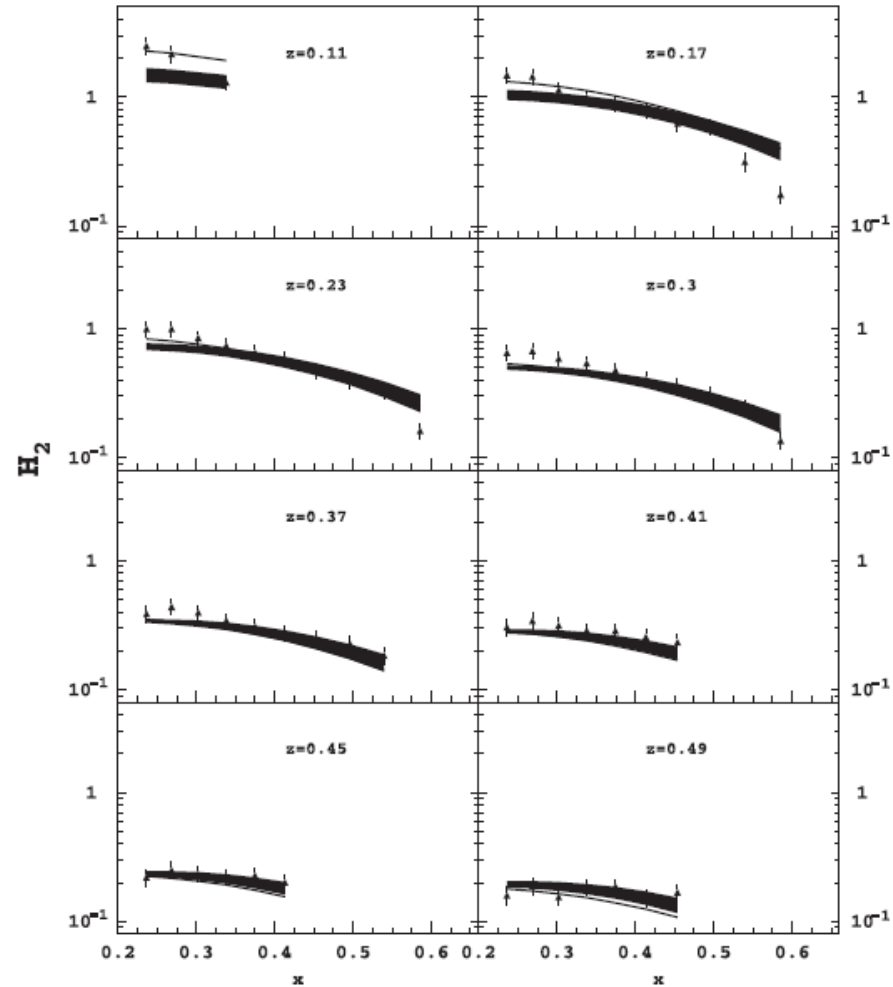
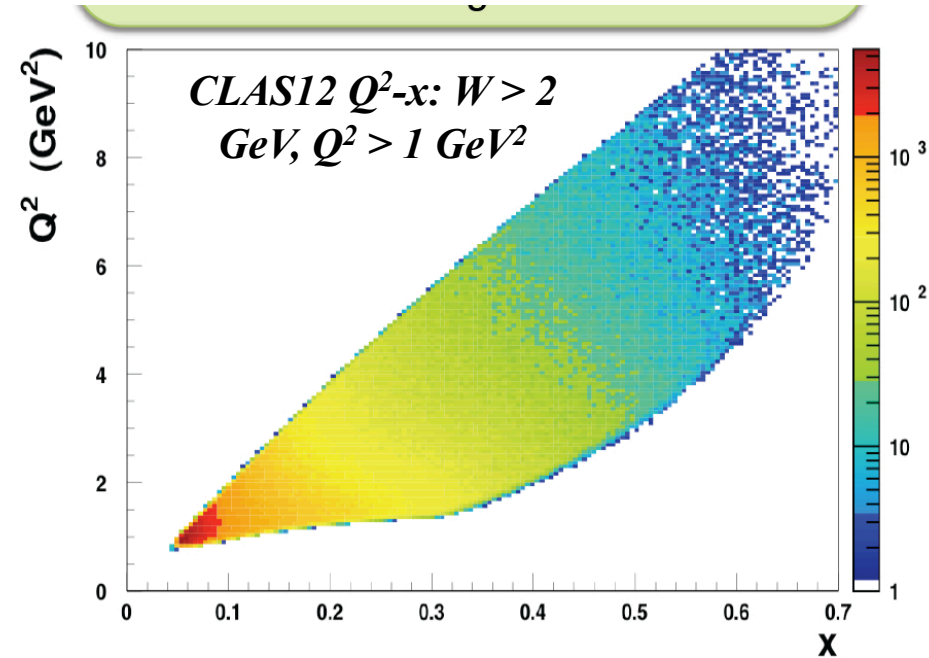
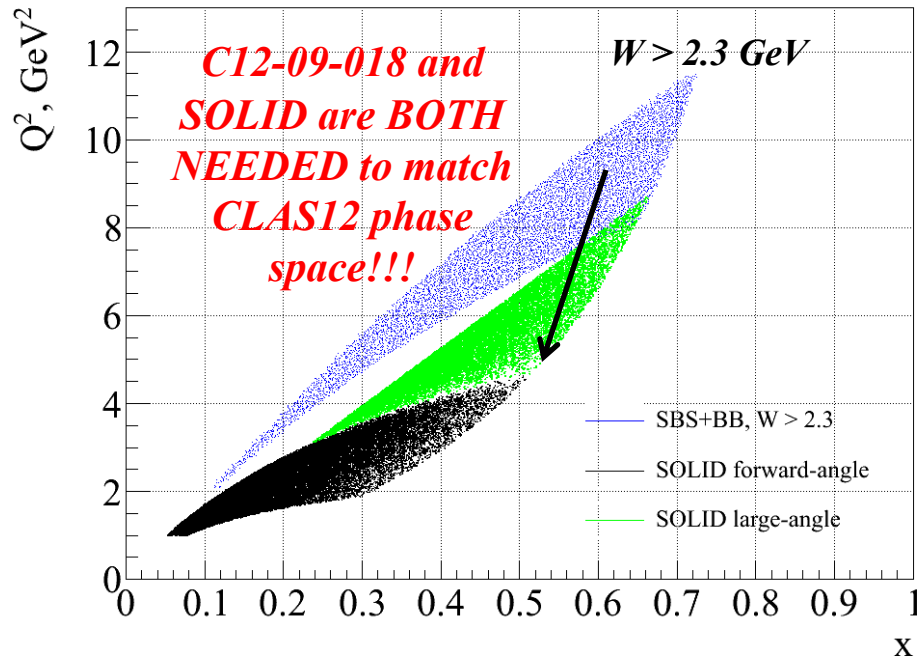


FIG. 18. Same as Fig. 17 except with  $H_2$  plotted as a function of  $x$  rather than  $z$ .

**$H_2$  vs.  $x$  in different  $z$  bins**

# Phase Space: SBS+BB, SOLID and CLAS12

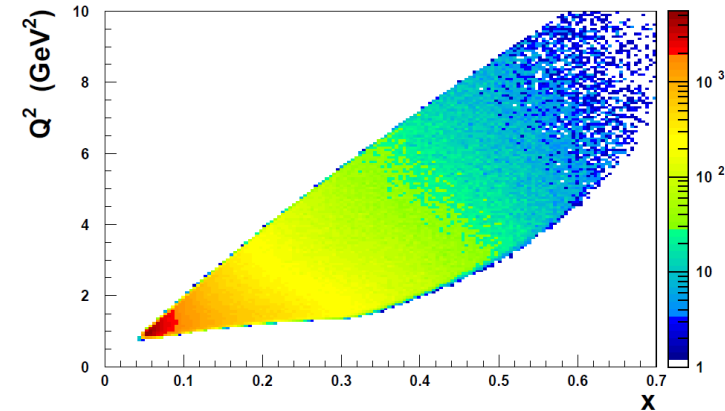
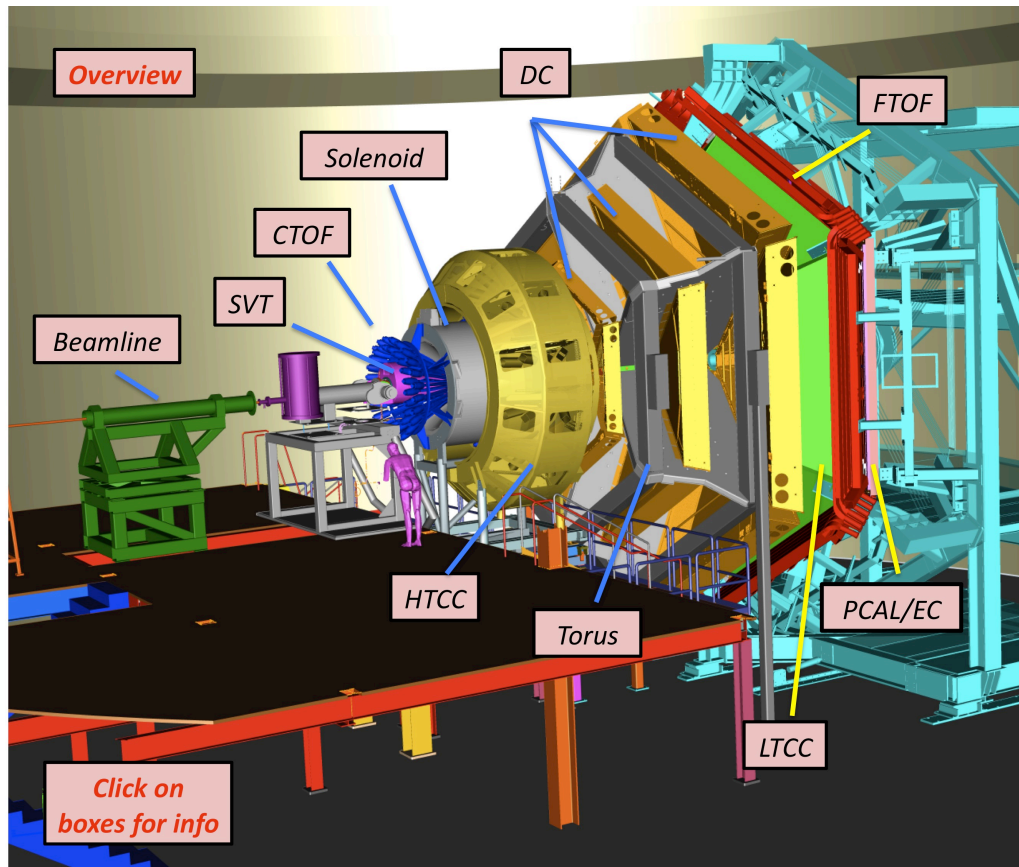


- *E12-09-018 and SOLID kinematics are almost entirely complementary at a given beam energy, with E12-09-018 covering higher  $Q^2$  at a given  $x$*
- *Coverage of other dimensions ( $z$ ,  $p_T$ ) is very similar (see backup slide 39)*
- *Both experiments are needed to cover the same/similar  $x$ - $Q^2$  phase space for the neutron that CLAS12 could provide for the proton/deuteron with HD target.*
- *Both SOLID and SBS+BB have significantly higher FOM for neutron measurements than CLAS12*

# Other forthcoming results from JLab 6 GeV

- The long shutdown of CEBAF for the upgrade to 12 GeV has halted the flow of new data for the last  $\sim 2$  years.
- Substantial volume of additional SIDIS data “in the can” with analysis ongoing, mainly from CLAS:
  - SIDIS multiplicity ratios  $A/D$  for C, Fe, Pb targets from CLAS eg2 data (Ph. D. thesis of T. Mineeva, U.Conn, advisor K. Joo)
  - SIDIS unpolarized cross sections and azimuthal moments  $\cos(\phi)$ ,  $\cos(2\phi)$  from CLAS e1f data (Ph. D. thesis of N. Harrison, U.Conn, advisor K. Joo).
  - Higher-statistics  $A_{LL}$  and  $A_{UL}$  SIDIS asymmetries from recent CLAS eg1-dvcs data,  $NH_3$  and  $ND_3$  targets (Ph.D. thesis of S. Jawalkar, W&M, advisor K. Griffioen)
- Potential for SIDIS “data-mining” from CLAS experiments not primarily dedicated to SIDIS
- Probably other results and/or ongoing analyses I’ve left out...

# SIDIS Studies with CLAS12 in Hall B



CLAS12  $Q^2$  vs  $x$  coverage

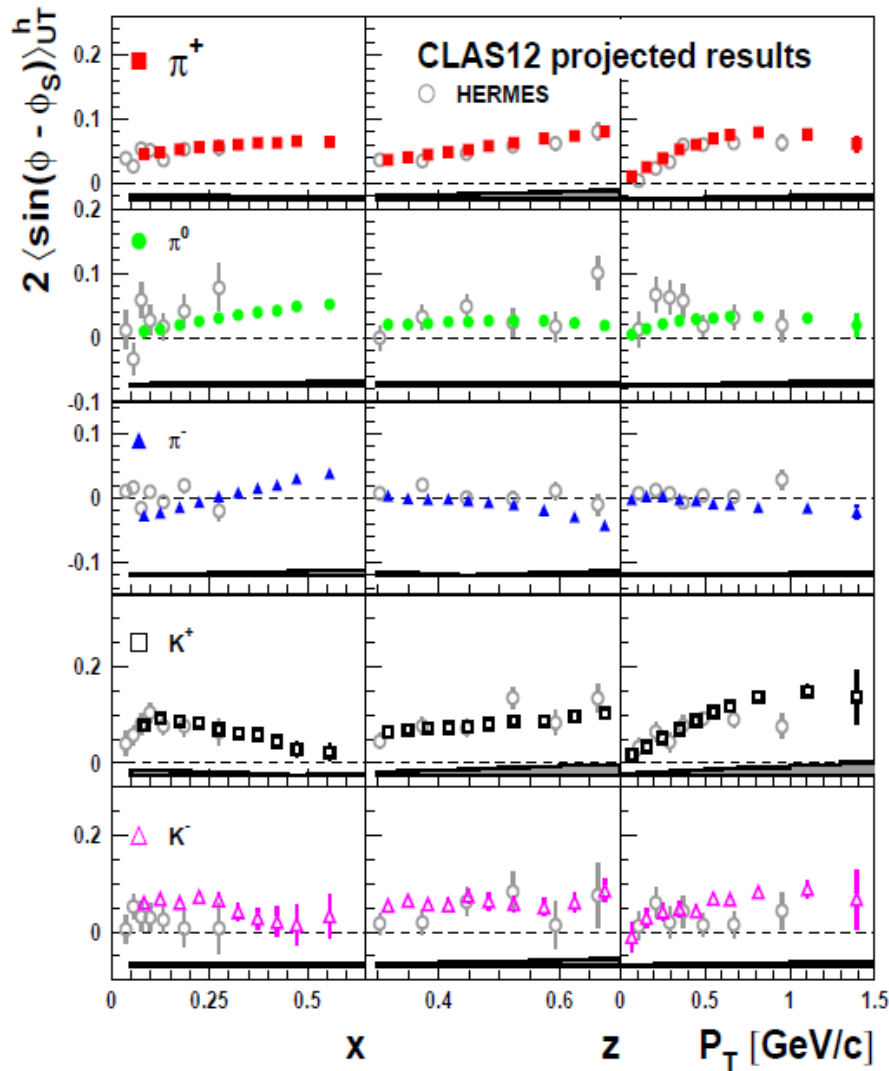
- CLAS12 is a large-acceptance, general purpose detector for charged and neutral particles,  $p > \sim 1 \text{ GeV}$ , scattering angles from 5-135 deg, near  $2\pi$  azimuthal angle acceptance, luminosity up to  $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- Large acceptance for broad-based surveys of total accessible phase space with 11 GeV beam

# CLAS12 SIDIS Program

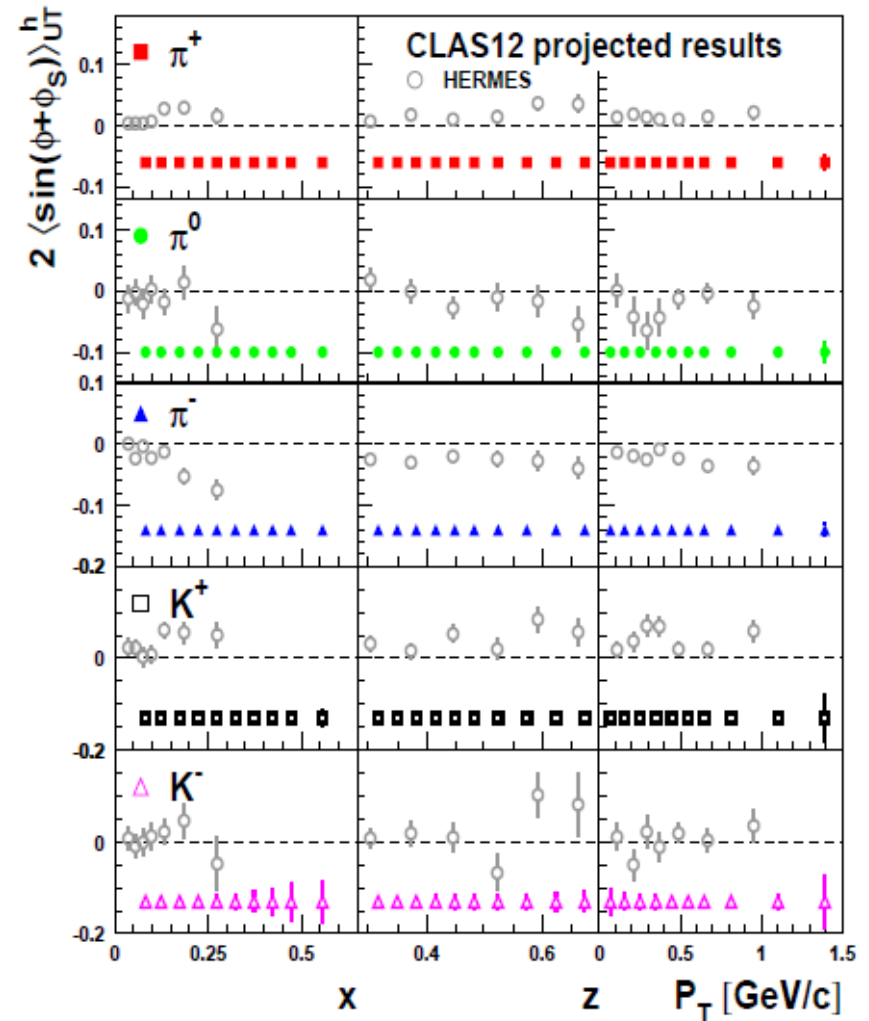
- SIDIS unpolarized cross section ( $F_{UU}$ ,  $A_{UU}^{\cos(2\phi)}$ ,  $A_{UU}^{\cos(\phi)}$ , etc.) and beam spin asymmetry  $A_{LU}^{\sin(\phi)}$  measurements w/broad kinematic acceptance on unpolarized H, D targets:
  - CLAS12 Run-group A (139 d, unpolarized  $H_2$ ): E12-06-112 (A)
  - CLAS12 Run-group B (90 d, unpolarized  $D_2$ ): E12-11-109a, E12-09-007a (A-), E12-09-008 (A-)
- $A_{LL}$ ,  $A_{UL}$  for SIDIS on longitudinally polarized proton ( $NH_3$ ) and deuteron ( $ND_3$ ) targets:
  - CLAS12 Run-group C (170 d): E12-07-107 (A-), E12-11-109b, E12-09-007b, E12-09-009 (B+)
- SIDIS on transversely polarized proton (HDice) target:
  - CLAS12 Run-group G (110 d): C12-11-111, C12-12-009.

**Expected HDice luminosity  $\sim 10^{34}$**

# CLAS12 $A_{UT}$ projections—1D

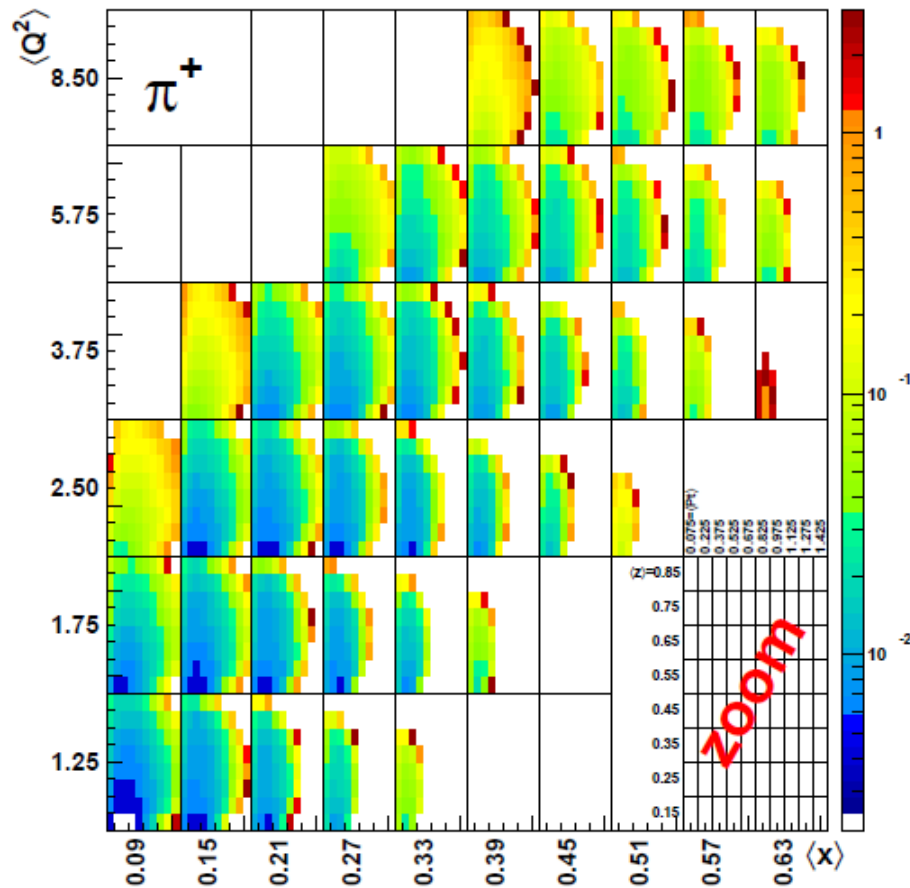


Sivers Asymmetries

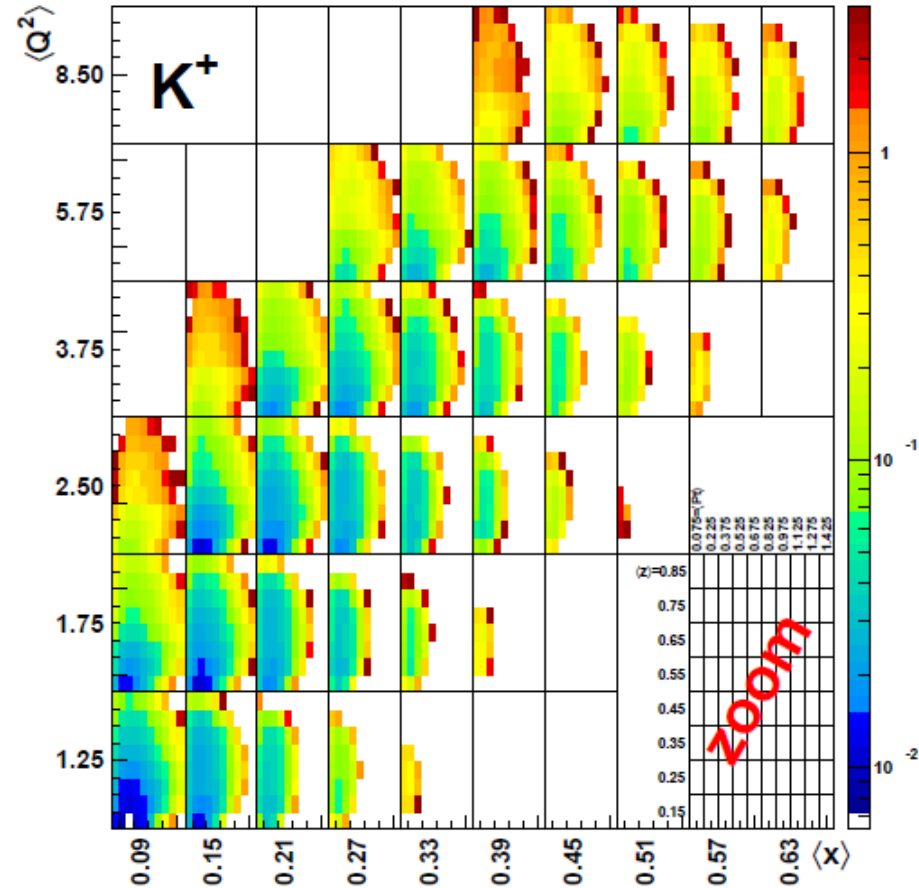


Collins Asymmetries

# CLAS12 $A_{UT}$ projections—4D analysis



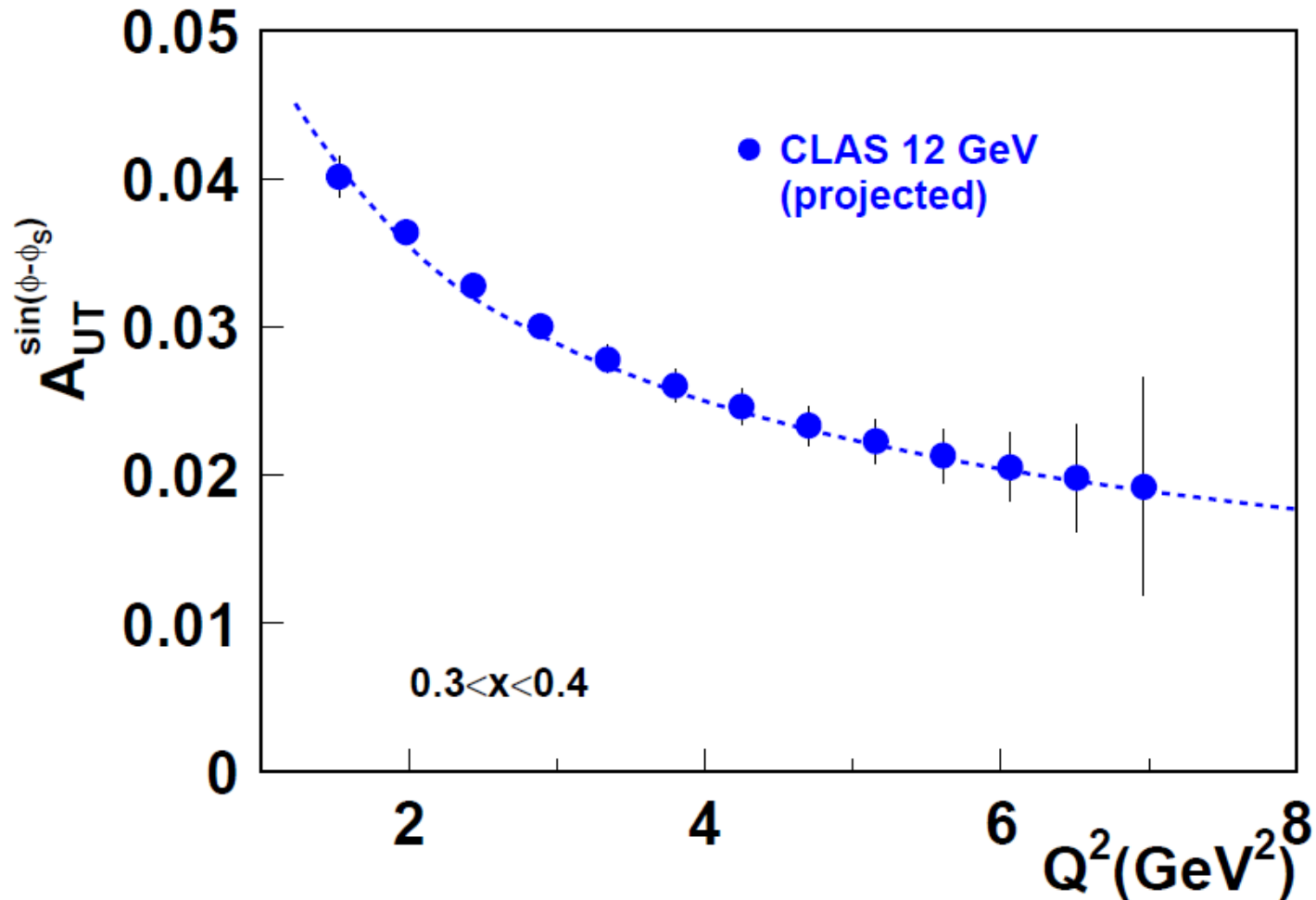
CLAS12 4D analysis for  $\pi^+$



CLAS12 4D analysis for  $K^+$

- Each subpanel shows the 2D ( $z, p_T$ ) dependence of  $A_{UT}$  absolute statistical uncertainty for a given ( $x, Q^2$ ) bin

# CLAS12 Projections—Sivers $Q^2$ evolution



Projected Sivers  $A_{UT}$  precision from CLAS12 w/predicted  $Q^2$  evolution in a single  $x$  bin

# CLAS12 SIDIS asymmetries w/longitudinally polarized $\text{NH}_3$ , $\text{ND}_3$

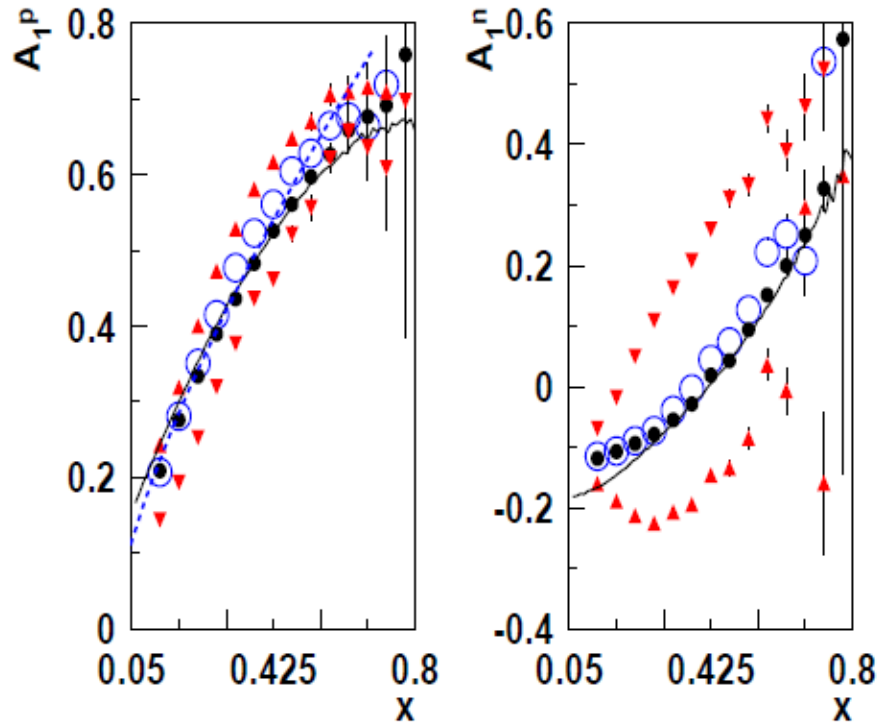


Figure 8: The double spin asymmetries on proton (left) and neutron(right) targets, for  $\pi^+$  (triangles up),  $\pi^-$  (triangles down)  $\pi^0$  (empty circles), inclusive electrons (filled circles). The solid line is

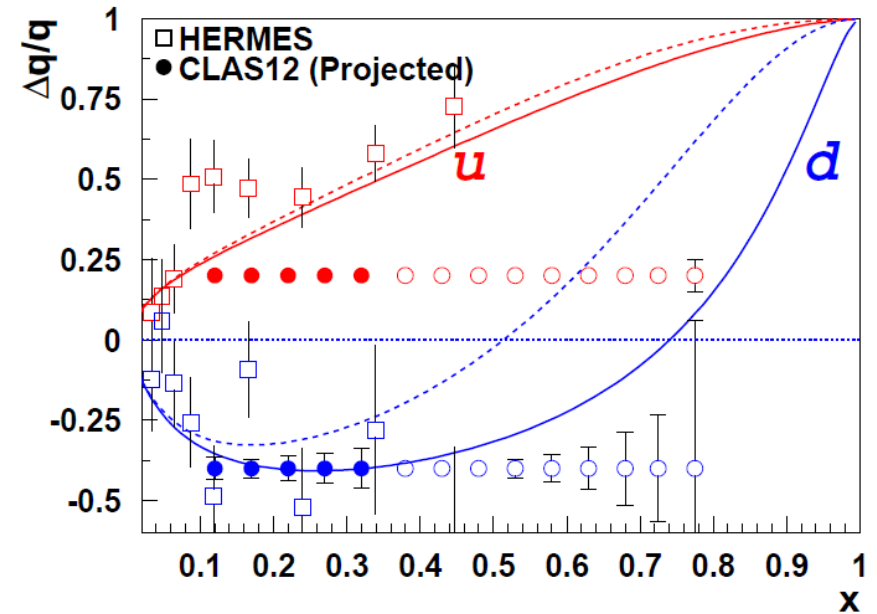


Figure 12: The polarization of valence quarks ( $\frac{\Delta q}{q}$ ) in the nucleon. The filled symbols are for the SIDIS data only and open symbols are for DIS data neglecting sea contributions. The curves are pQCD based predictions with (solid) and without (dashed) OAM contributions [29].

Experiment E12-07-107: Flavor decomposition and transverse momentum dependence of the nucleon's longitudinal spin structure via double-spin asymmetry  $A_{LL}$  measurements  $p(e,e'h)X$  and  $d(e,e'h)X$