Overview of the SIDIS/TMD program at Jefferson Lab

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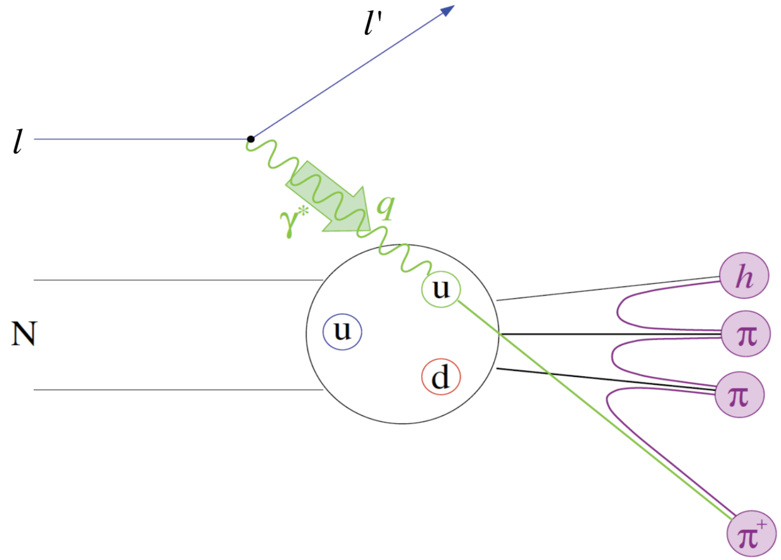
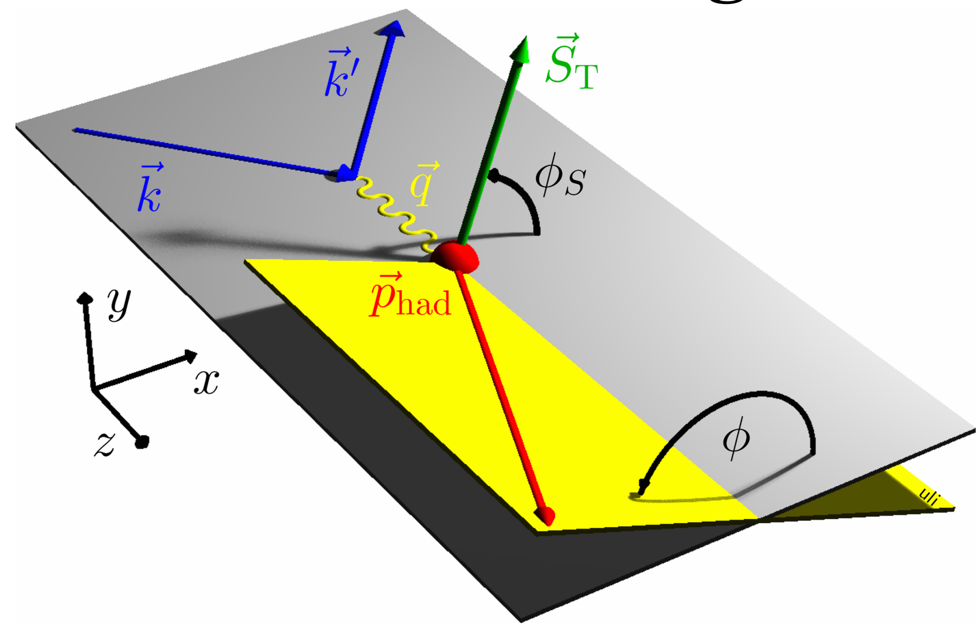
DIS 2017: 25th International Workshop on Deep Inelastic Scattering and Related Topics

Outline

- Introduction: Single-hadron SIDIS process and TMD formalism
- The Continuous Electron Beam Accelerator Facility at Jefferson Lab
  - Experimental Halls at 6 GeV
  - The 12 GeV Upgrade
- Selected highlights from the 6 GeV era
- Overview of 11 GeV SIDIS program in Halls A, B, and C
- Summary and Outlook

Semi-Inclusive Deep Inelastic Scattering





- Detecting the leading (high-energy) hadrons in DIS collisions; i.e., the single inclusive hadron electroproduction *N(e,e'h)X* process provides sensitivity to additional aspects of the nucleon's partonic structure not accessible in inclusive DIS, including:
    - quark flavor
    - quark transverse momentum
    - 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...***

SIDIS Kinematics—Notation and Definitions

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

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

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

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

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

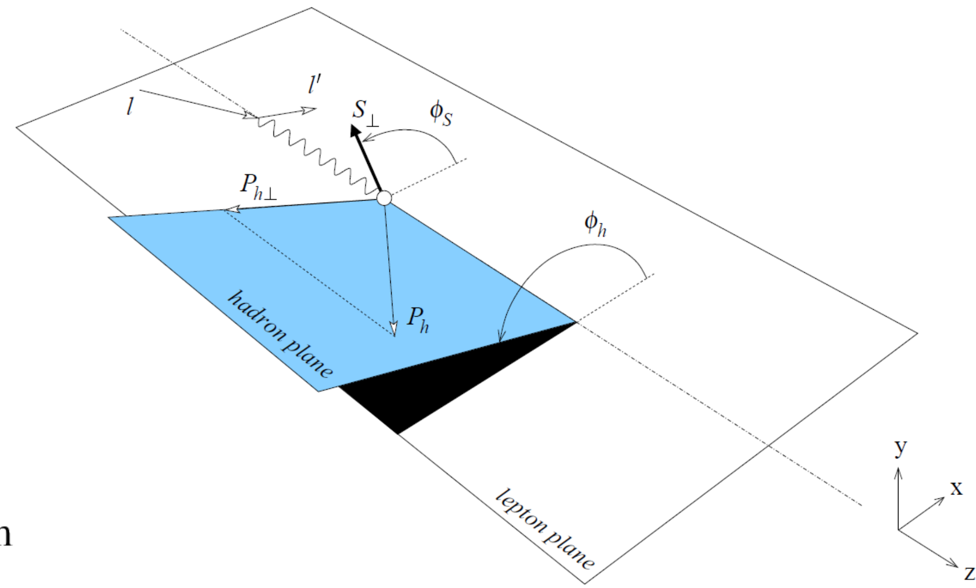
$$z = \frac{P\cdot P_h}{P\cdot q} = E_h/\nu, \text{ Hadron energy fraction}$$

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

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

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

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



General Expression for SIDIS Cross Section: *Bacchetta et al., JHEP 02, 093 (2007)*

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

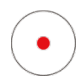
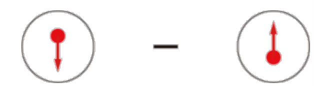
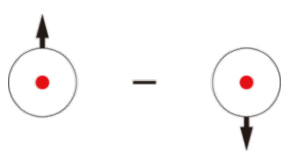
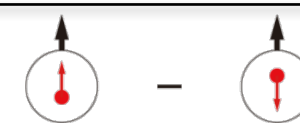
- Sivers
- Collins
- "Pretzelosity"

- 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
- λ = lepton helicity
- 18 structure functions up to twist-three
- **Eight terms survive at leading twist; the rest are twist-3 (M/Q suppressed)**

$$\gamma = \frac{2Mx}{Q}$$

$$\epsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

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

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$ 		$h_1^\perp =$ 
	L		$g_1 =$ 	$h_{1L}^\perp =$ 
	T	$f_{1T}^\perp =$ 	$g_{1T} =$ 	$h_1 =$  $h_{1T}^\perp =$ 

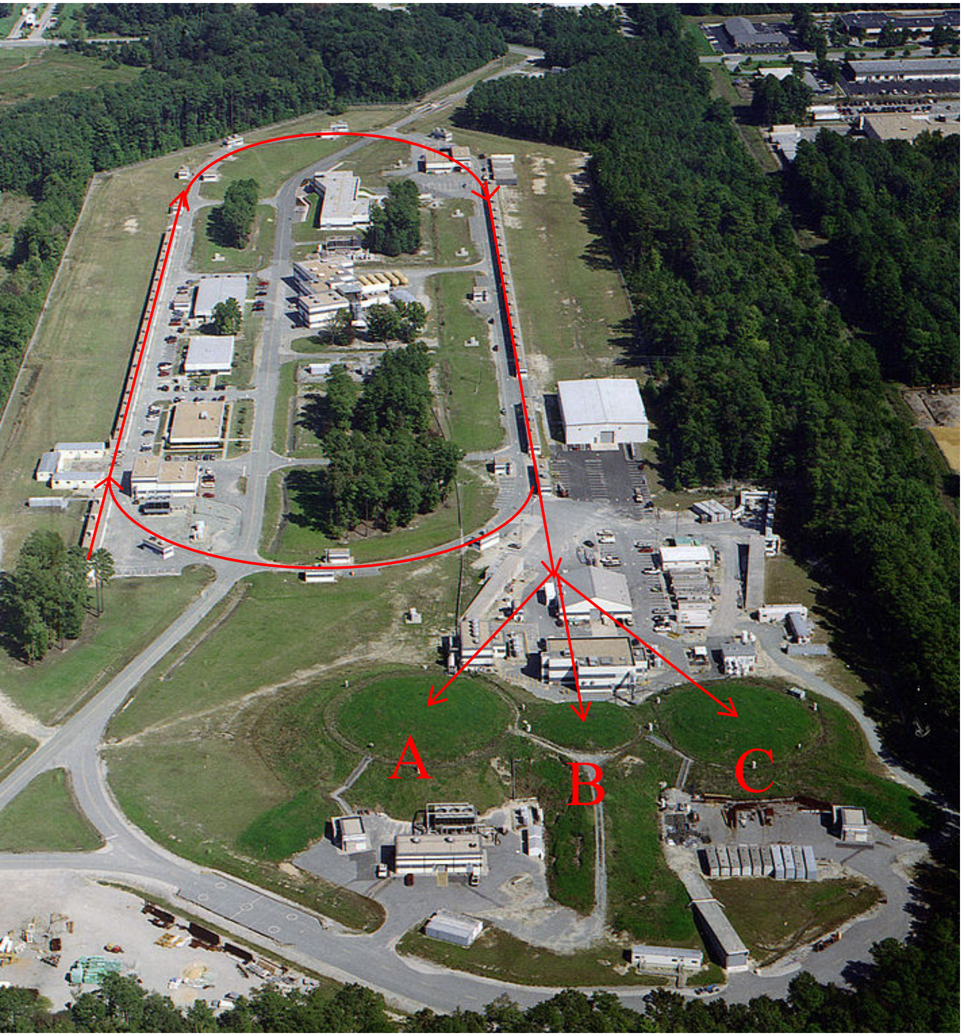
SIDIS Structure Functions in Terms of TMDs

$$
\begin{aligned}
F_{UU,T} &\sim f_1 \otimes D_1 \\
F_{UU}^{\cos 2\phi_h} &\sim h_1^{\perp} \otimes H_1^{\perp} \\
F_{UL}^{\sin 2\phi_h} &\sim h_{1L}^{\perp} \otimes H_1^{\perp} \\
F_{LL} &\sim g_1 \otimes D_1 \\
F_{UT}^{\sin(\phi_h - \phi_S)} &\sim f_{1T}^{\perp} \otimes D_1 \\
F_{UT}^{\sin(\phi_h + \phi_S)} &\sim h_1 \otimes H_1^{\perp} \\
F_{UT}^{\sin(3\phi_h - \phi_S)} &\sim h_{1T}^{\perp} \otimes H_1^{\perp} \\
F_{LT}^{\cos(\phi_h - \phi_S)} &\sim g_{1T} \otimes D_1
\end{aligned}
$$

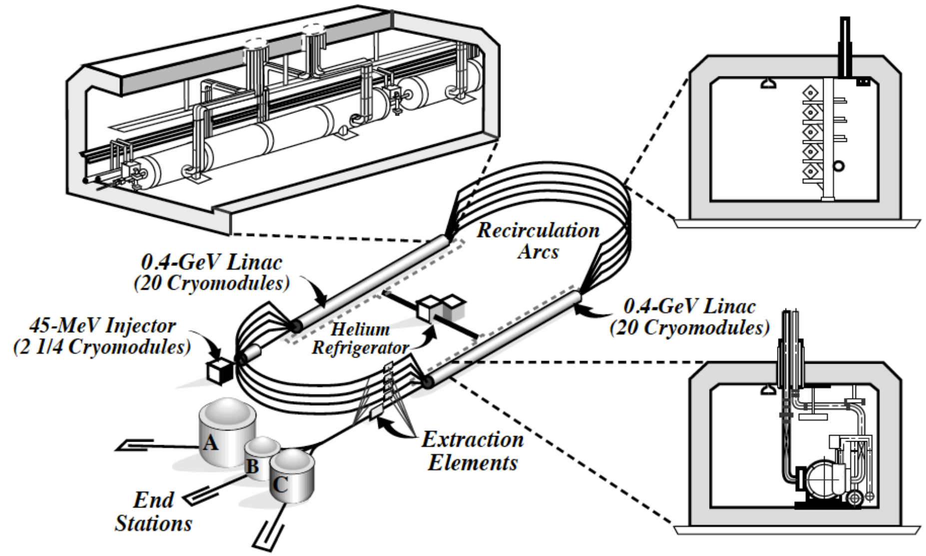
- Only f_1, g_1, h_1 survive integration over quark k_T
- All eight leading-twist TMDs are accessible in SIDIS with polarized beams/targets via azimuthal angular dependence of the SIDIS cross section
- Physical observables are convolutions over two (unobserved) transverse momenta:
  - Initial quark k_T
  - Hadron p_T relative to recoiling quark, generated during fragmentation

$$
\begin{aligned}
D_1(z, Q^2, p_\perp^2) &= \text{Unpolarized TMD FF} \\
H_1^{\perp}(z, Q^2, p_\perp^2) &= \text{Collins TMD FF}
\end{aligned}
$$

CEBAF @ Jefferson Lab

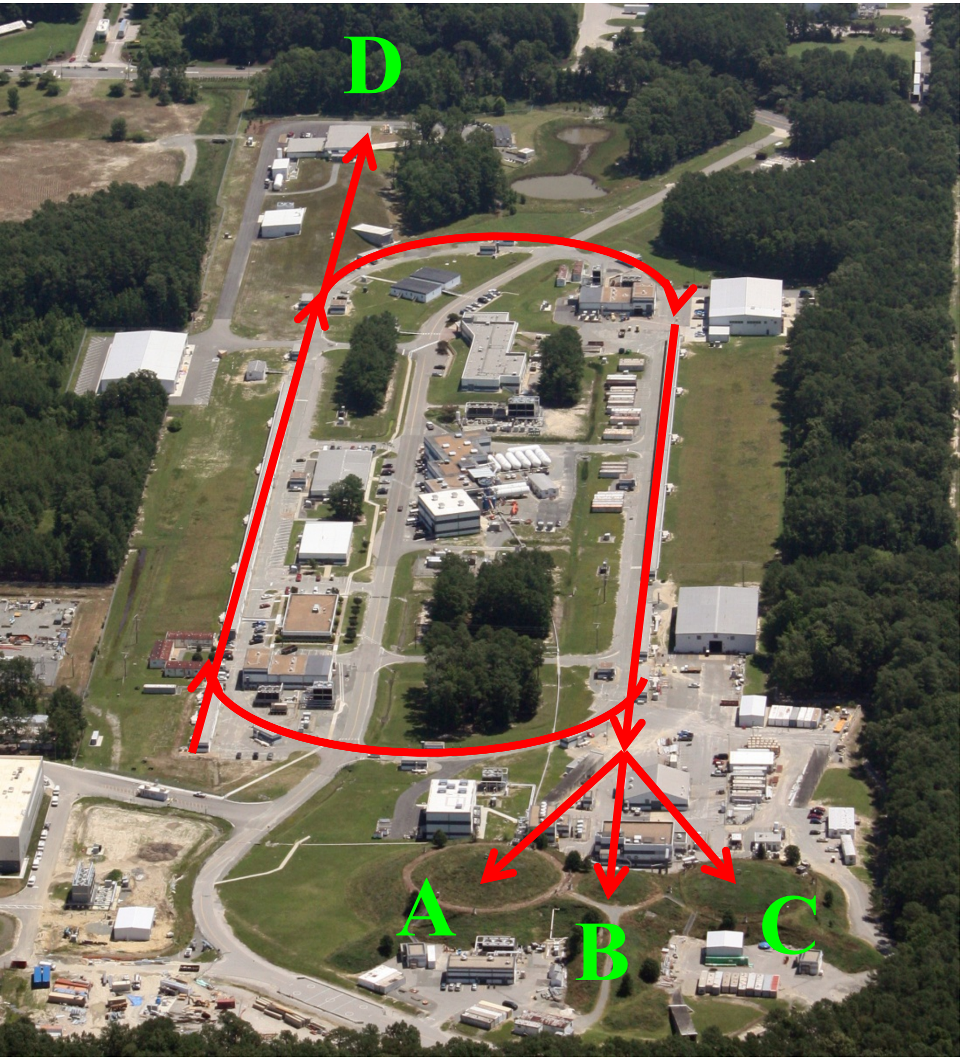


JLab Aerial View

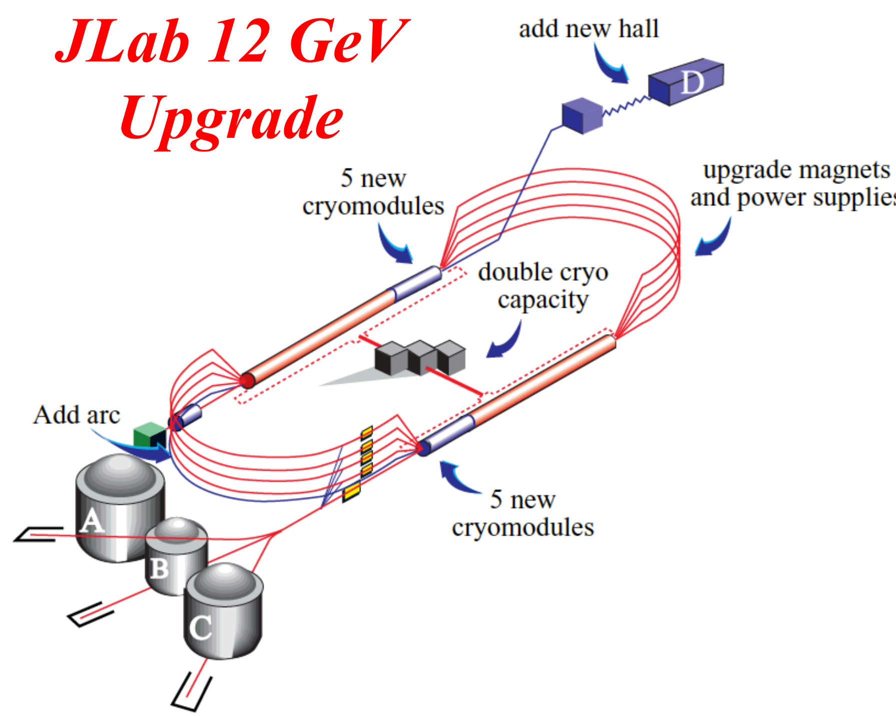


- Superconducting RF electron linacs with up to 5X recirculation
- CW ("100%" duty factor) operation (2 ns bunch period, ~0.3 ps bunch length)
- Polarized source: up to 85-90% polarization
- Three experimental Halls
- Energy up to 6 GeV (upgrade will increase to 11(12) GeV to Halls A/B/C (D))
- Current (up to 180 μA CW)

The 12 GeV Upgrade of CEBAF

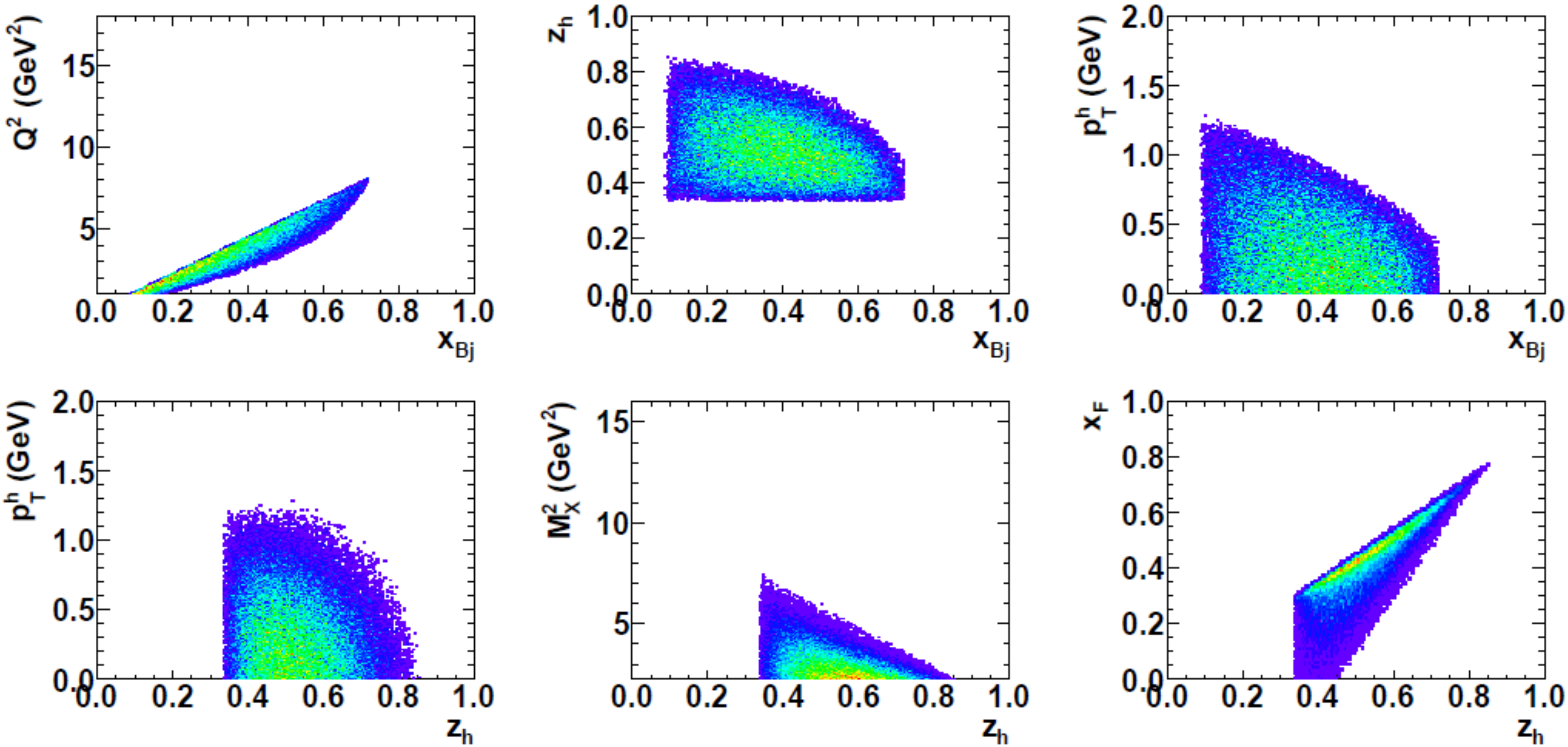


Site Aerial, June 2012



- 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 at 5 (5.5) passes to Halls A/B/C (D)

Accessible phase space in fixed-target at 6 GeV

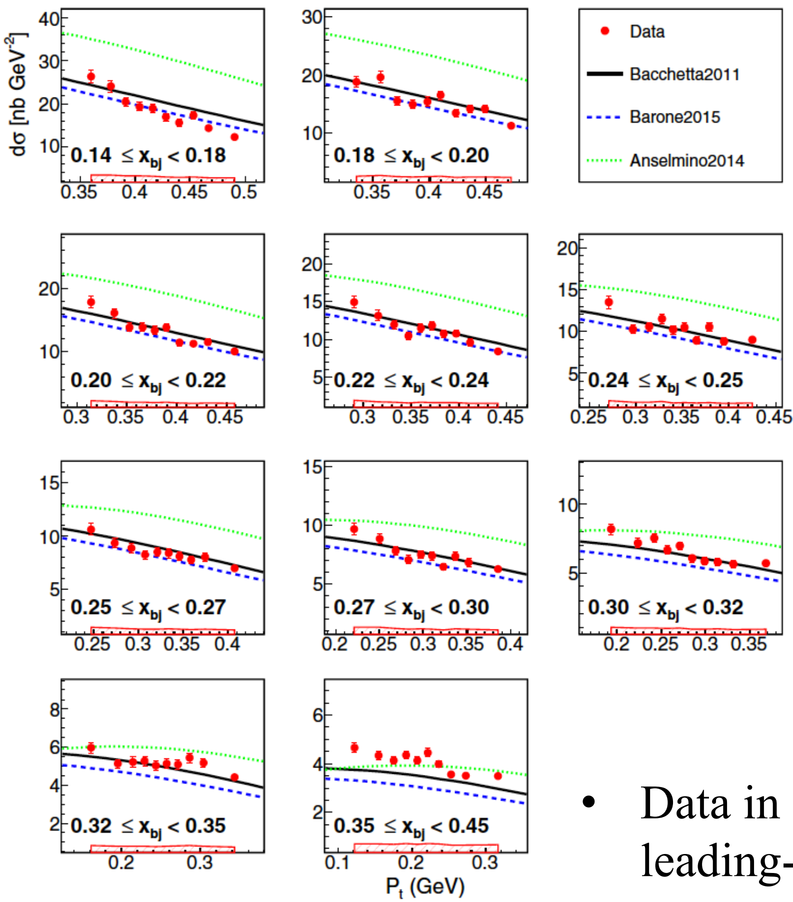


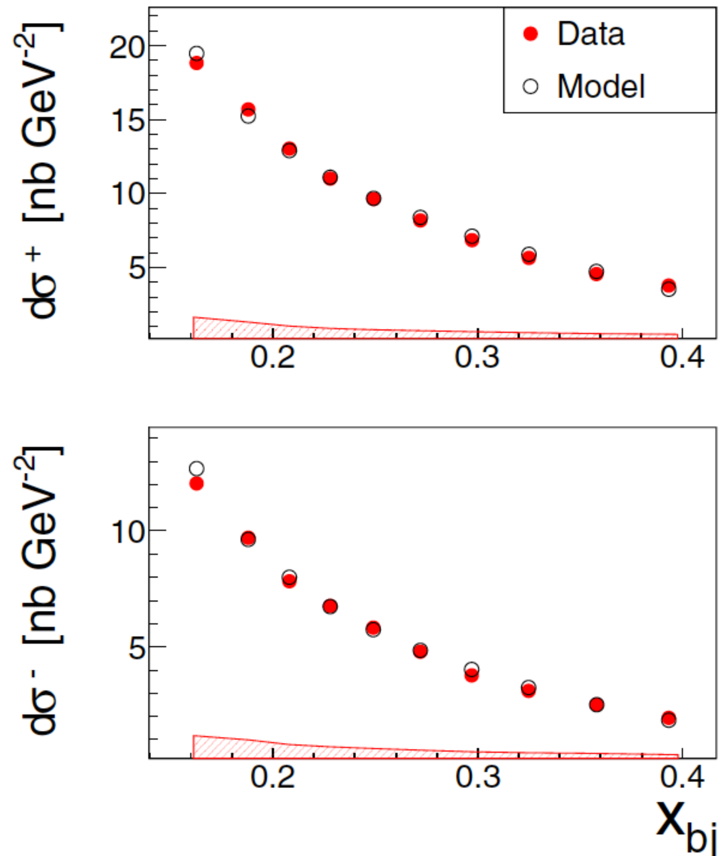
Above: phase space with SIDIS cuts (***before considering any detector acceptances***), E=6 GeV

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

Brand new! Hall A SIDIS cross sections: $^3He(e,e'\pi^{+/-})X$

$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,d\phi_S\,dP_t^2\,d\phi_h} = \frac{\alpha^2}{2Q^2 x_{bj}\,y}\left[A F_{UU} + B F_{UU}^{\cos\phi_h}\cos\phi_h + C F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right],$$

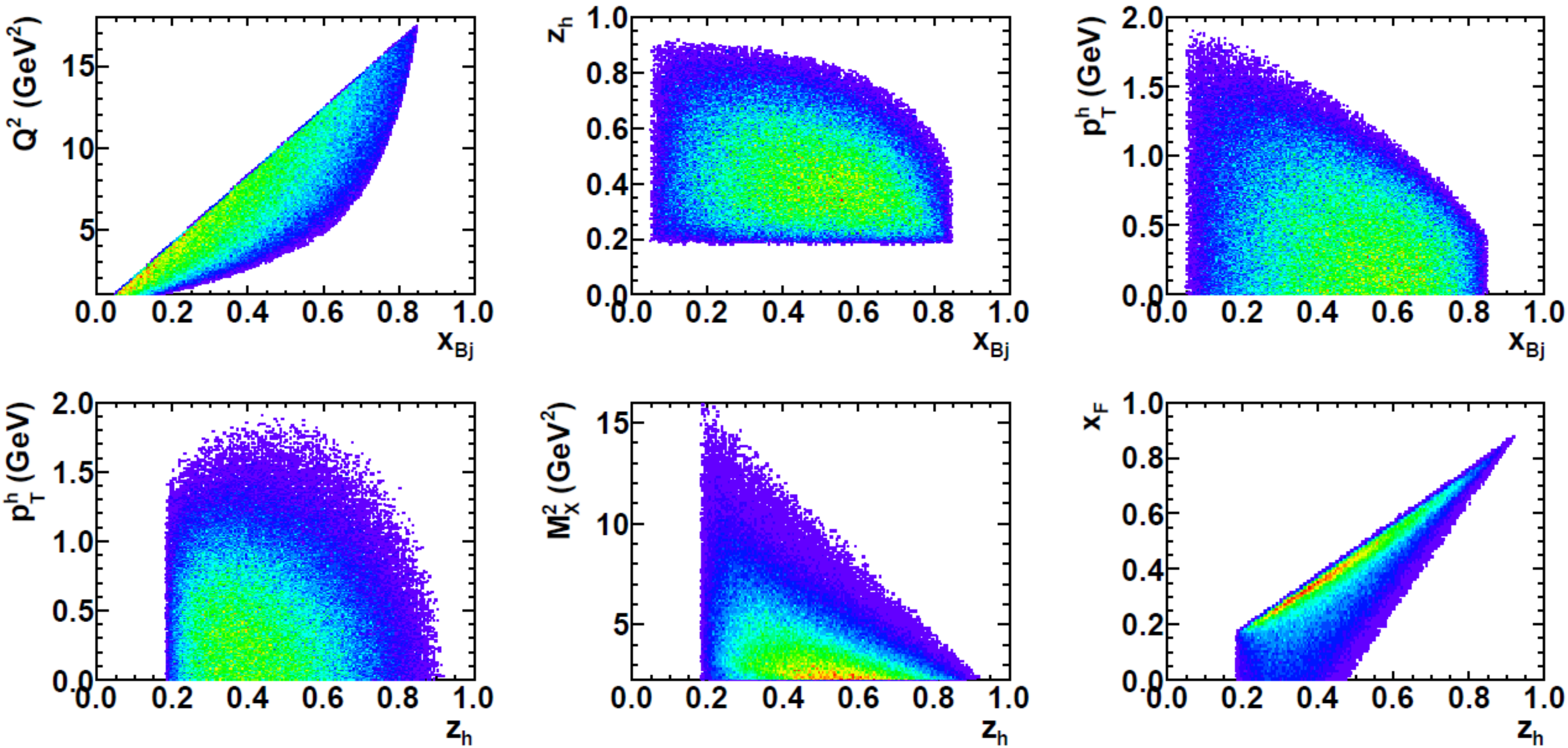




- Data in qualitatively good agreement with a factorized, LO, leading-twist parton-model picture.

- X. Yan *et al.*, published March 24, 2017: Phys. Rev. C **95**, 035209 (2017): E = 5.9 GeV, 0.12 < x < 0.45, 0.45 < z < 0.65, 0.05 < p_T < 0.55 GeV/c, 1 < Q^2 < 4 GeV^2

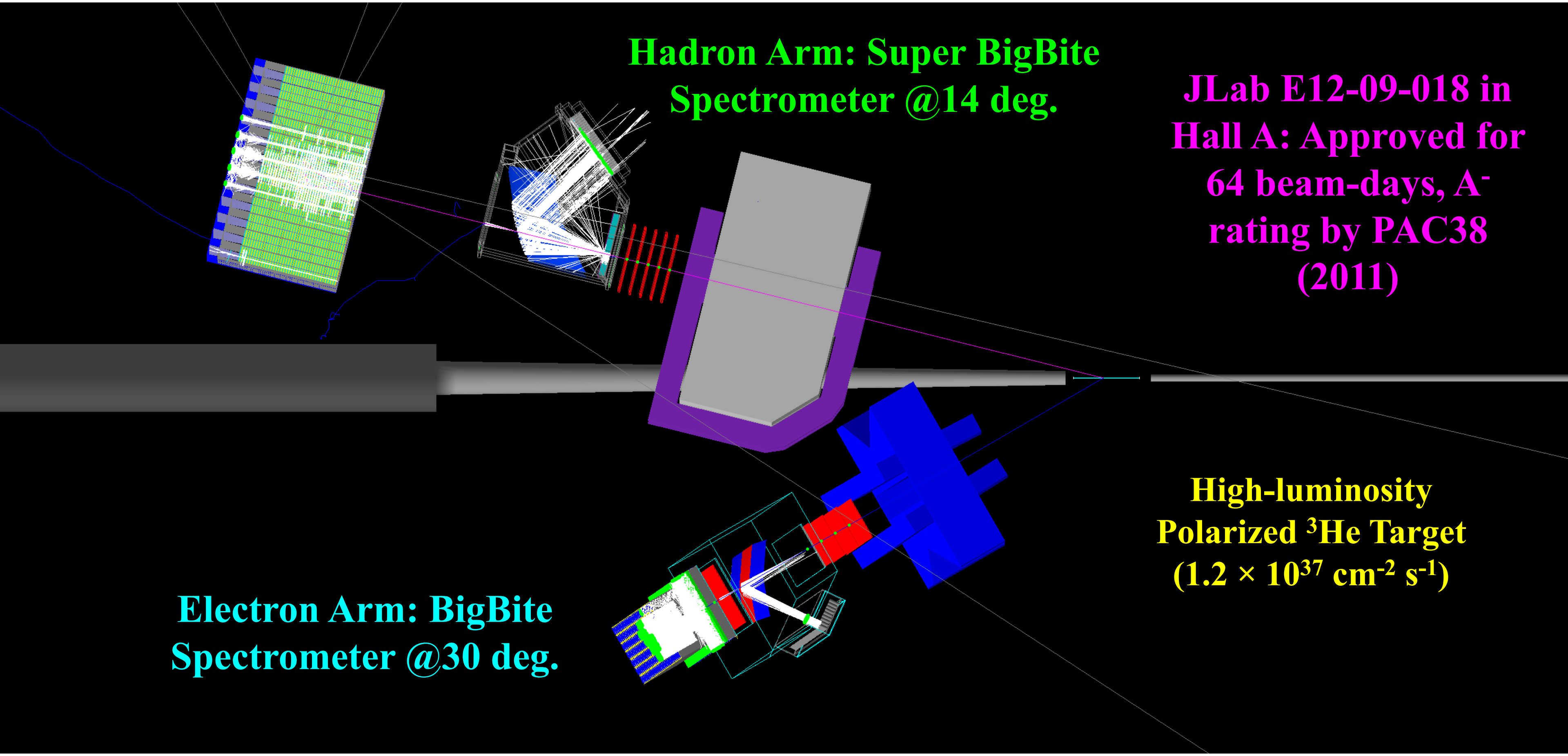
Accessible phase space in fixed-target at 11 GeV



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

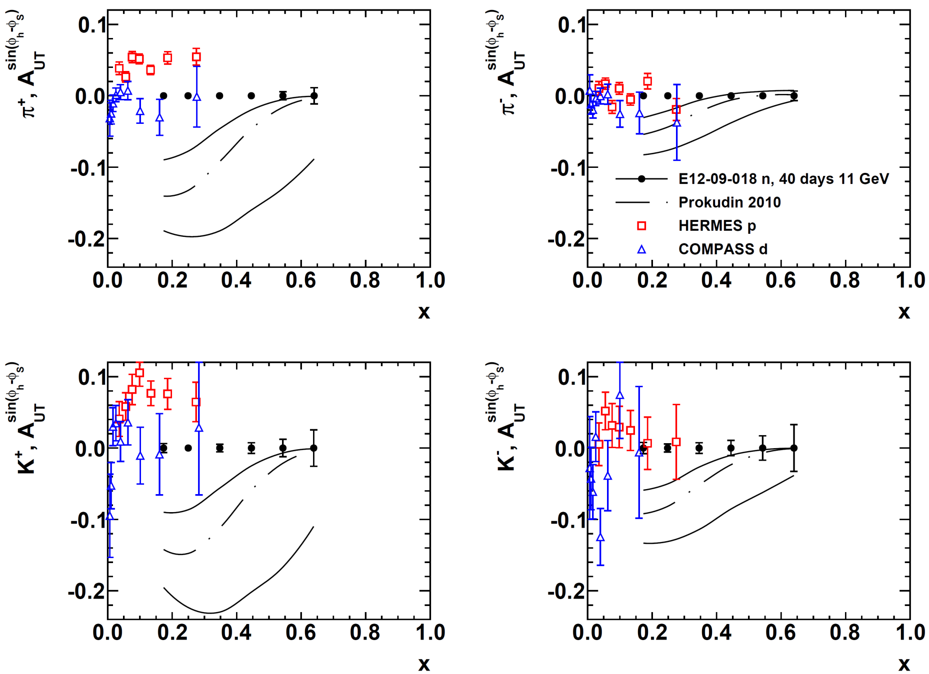
$$Q^2 \geq 1\ \text{GeV}^2, W > 2\ \text{GeV}, M_X > 1.5\ \text{GeV}, p_h \geq 2\ \text{GeV}$$

E12-09-018: Transverse Target SSA in ^{3}He(e,e'h)X

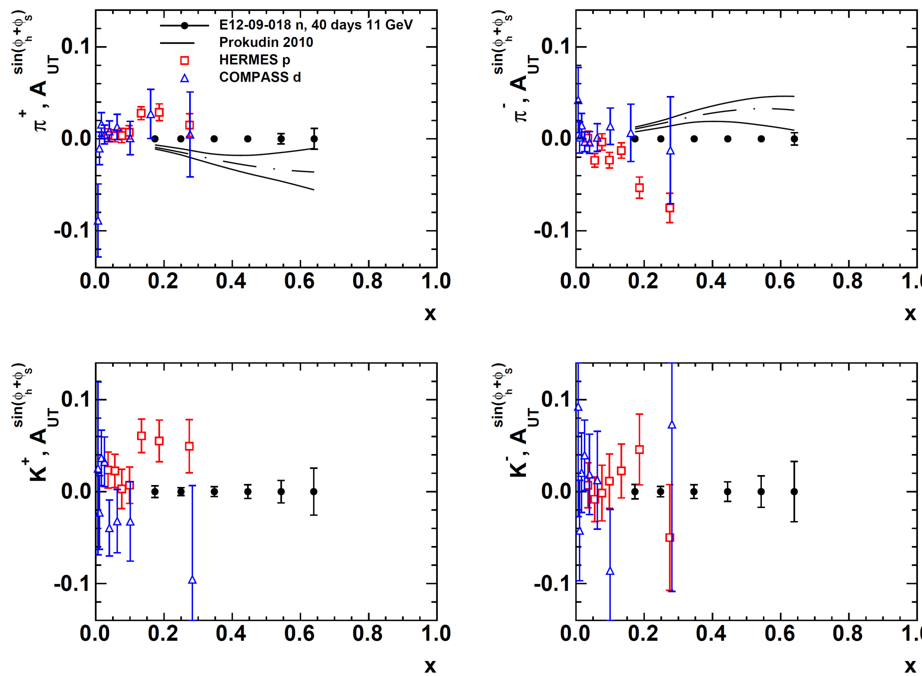


- **E12-09-018** in Hall A: transverse spin physics with high-luminosity polarized ^{3}He.
- 40 (20) days production at E = 11 (8.8) GeV—significant Q^2 range at fixed x
- Collins, Sivers, Pretzelosity, A_{LT} for n(e,e'h)X, h = $\pi^+/\pi^-/\pi^0/K^+/K^-$
- Re-use HERMES RICH detector for charged hadron PID
- Reach high x (up to ~0.7) and high statistical FOM (~1,000X Hall A E06-010 @6 GeV)

SBS+BB Projected Results: Collins and Sivers SSAs



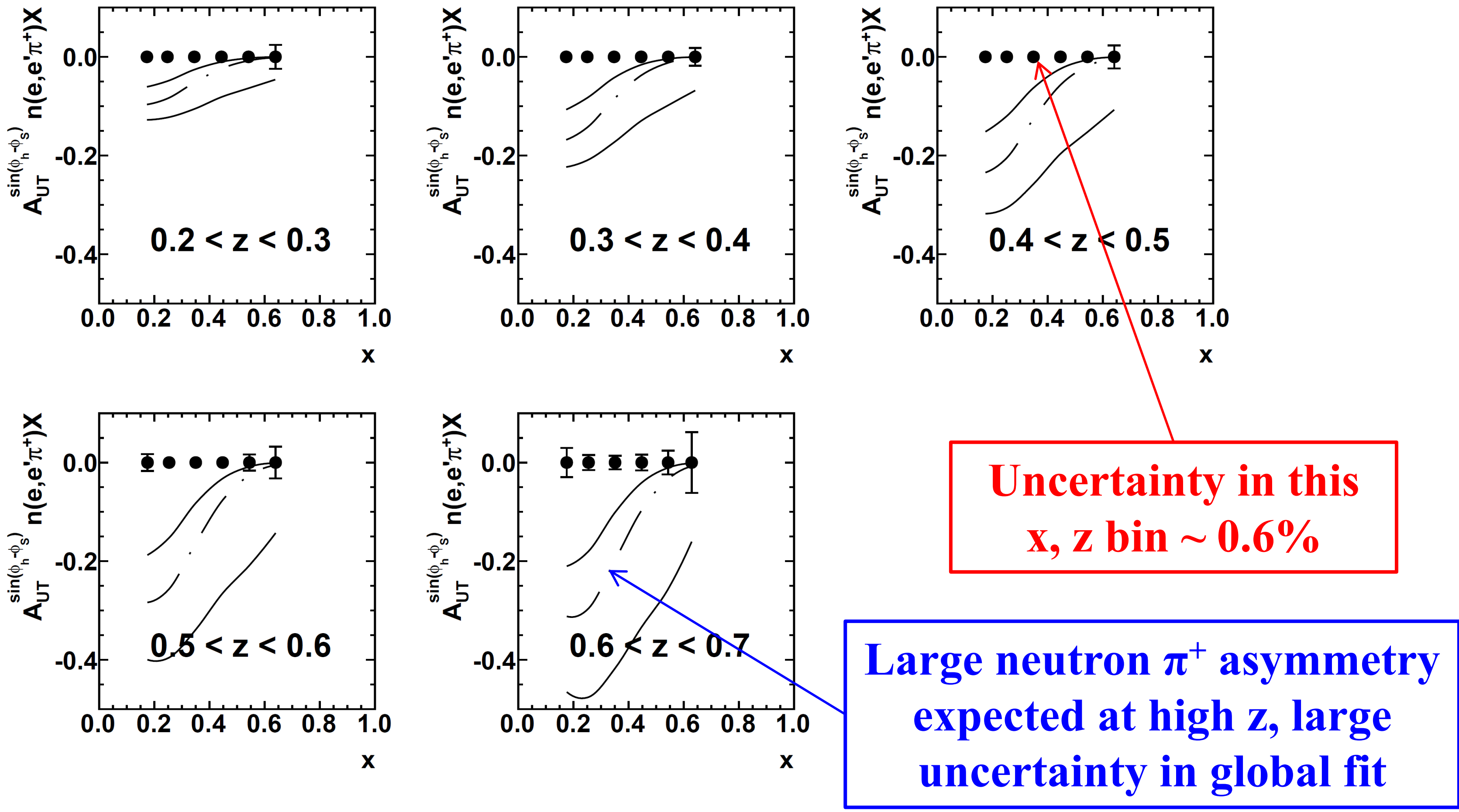
Projected A_{UT}^{Sivers} vs. x (11 GeV data only)



Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)

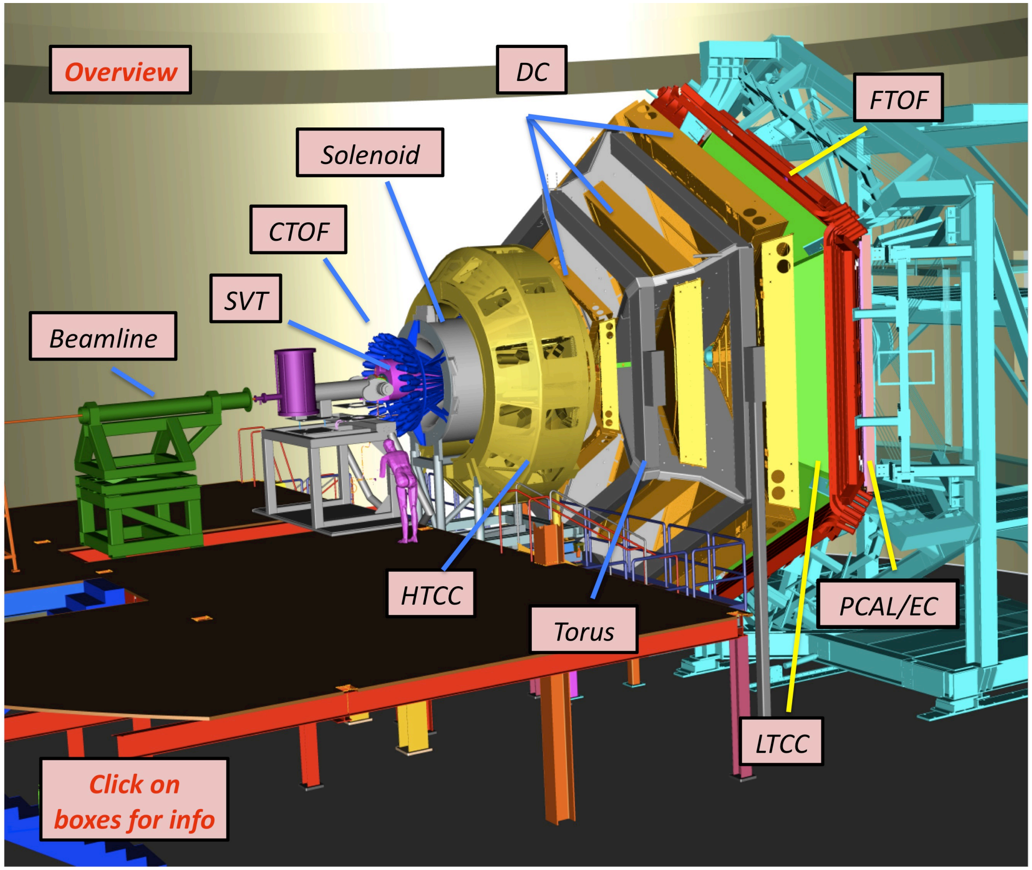
- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than E06-010 neutron data.
- Kaon and neutral pion data will aid flavor decomposition, and understanding of reaction-mechanism effects.

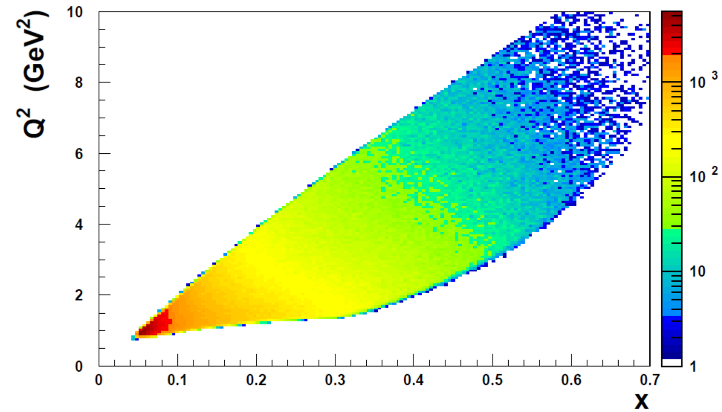
SBS+BB Projected Precision in 2D (x,z) binning



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

SIDIS Studies with CLAS12 in Hall B





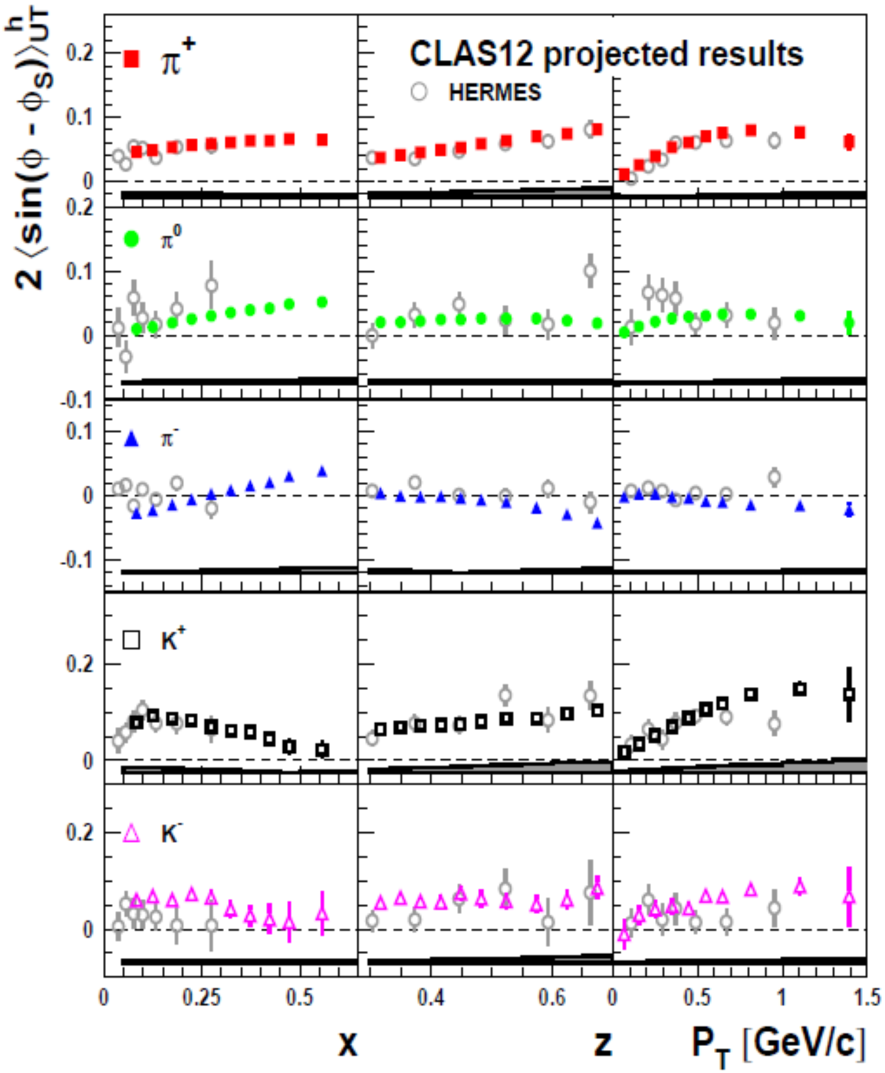
CLAS12 Q^2 vs x coverage

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

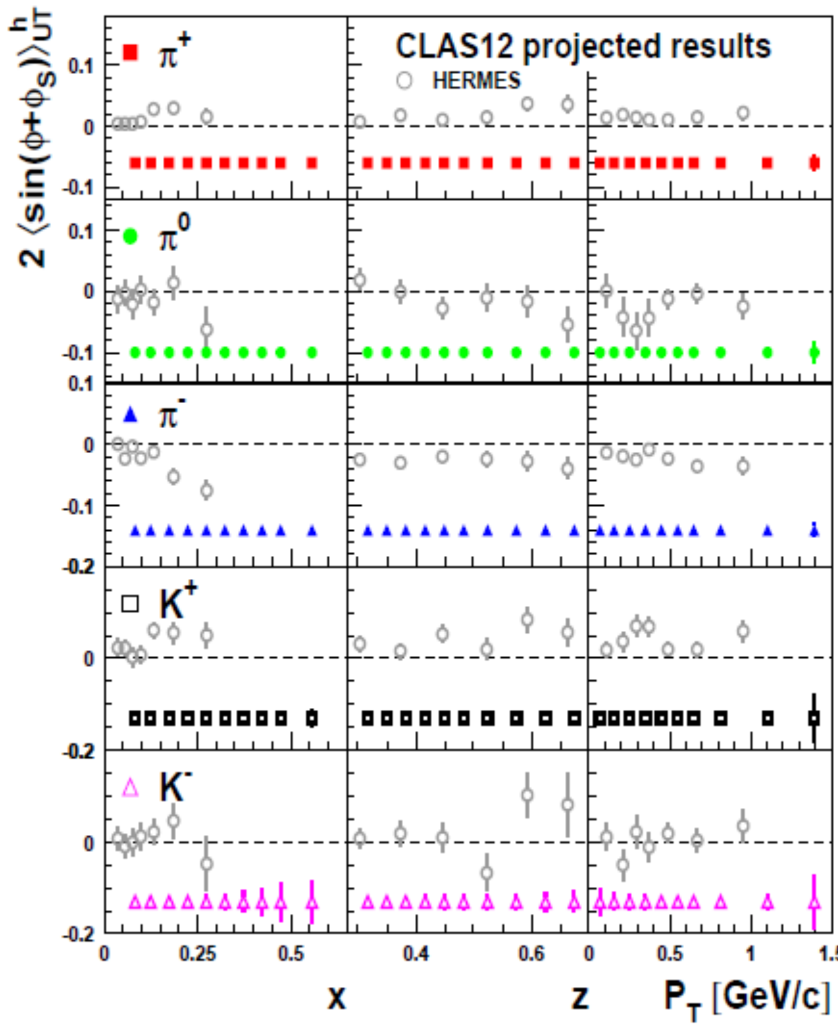
CLAS12 SIDIS Program

- 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 ~10^{34}**

CLAS12 A_{UT} projections—1D

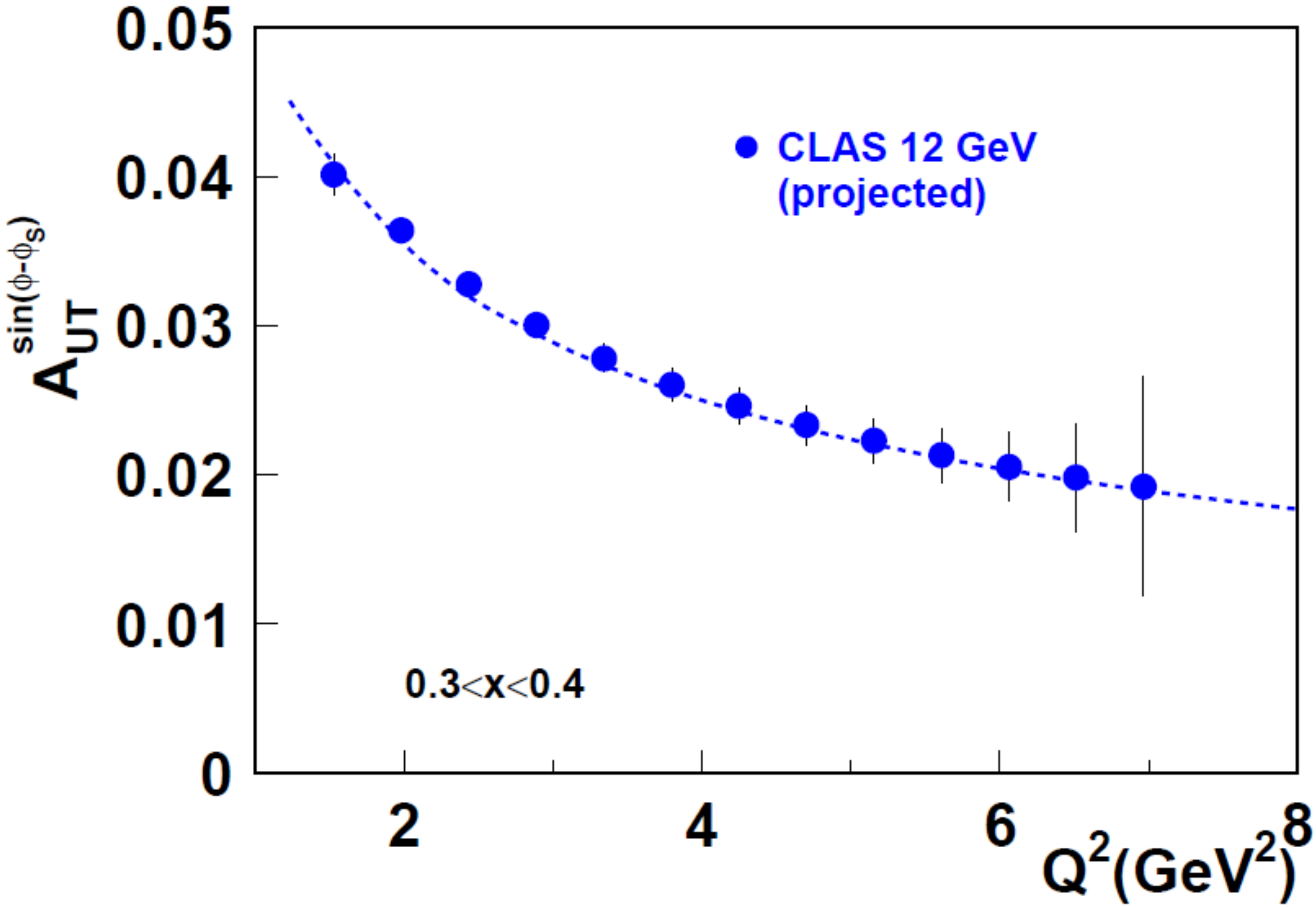


Sivers Asymmetries



Collins Asymmetries

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 NH_3, ND_3

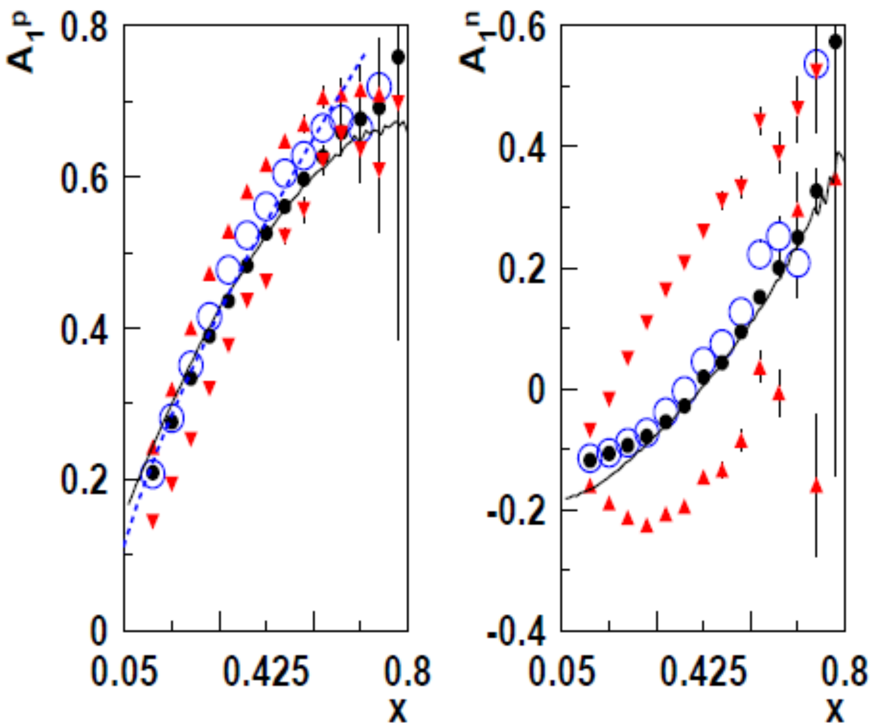


Figure 8: The double spin asymmetries on proton (left) and neutron(right) targets, for π^+ (triangles up), π^- (triangles down) π^0 (empty circles), inclusive electrons (filled circles). The solid line is

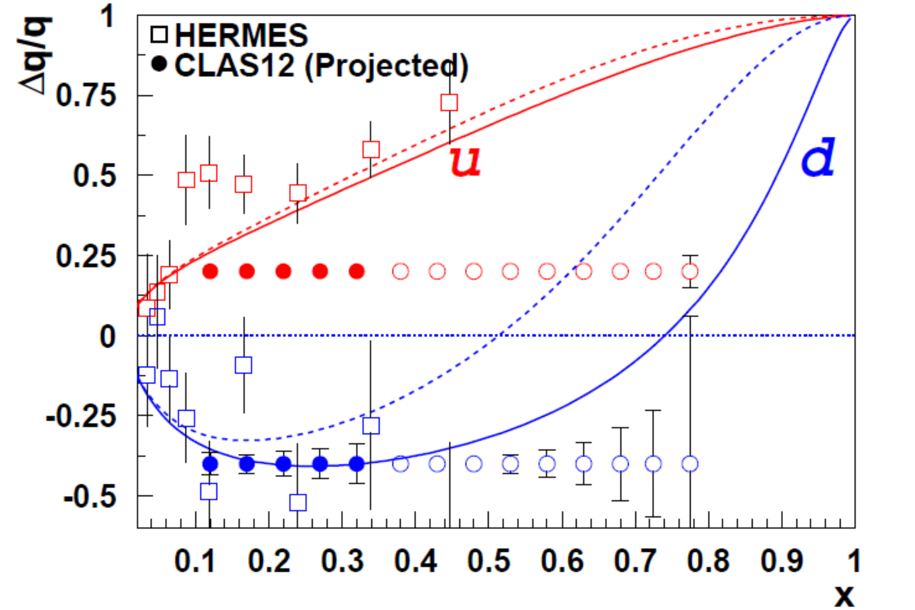
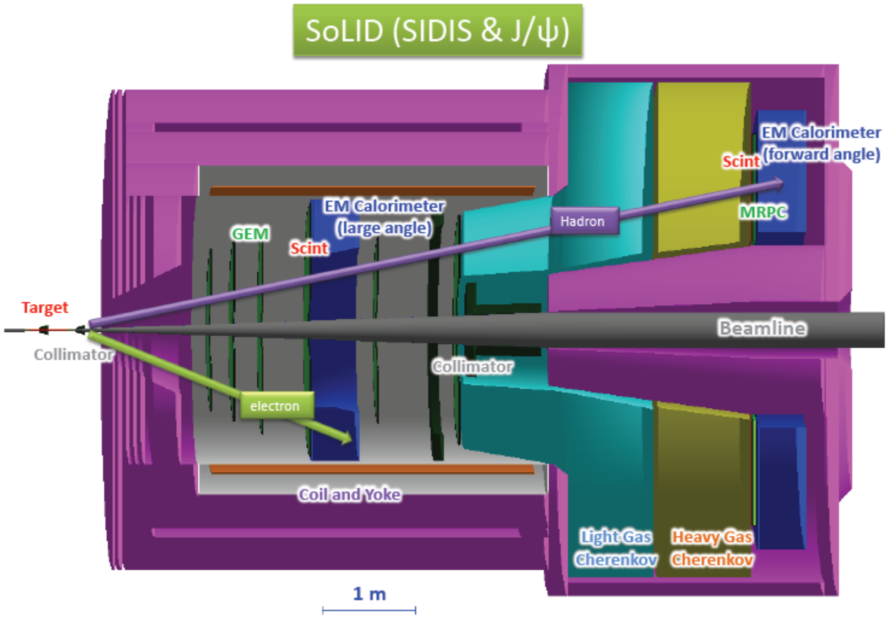
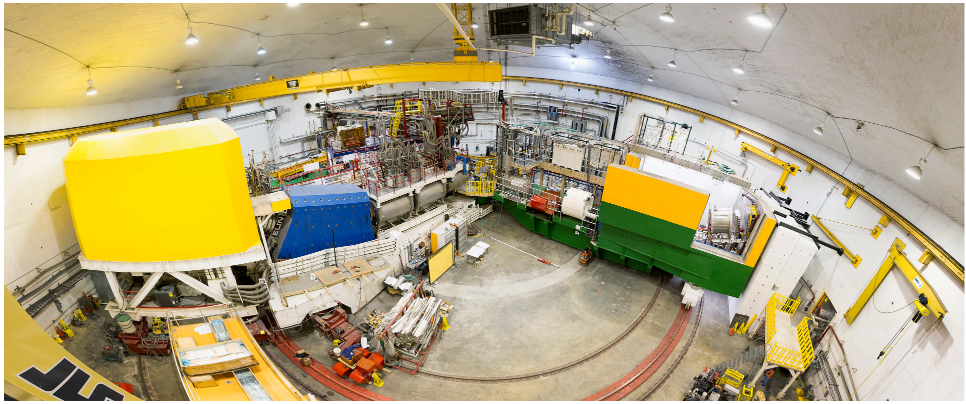


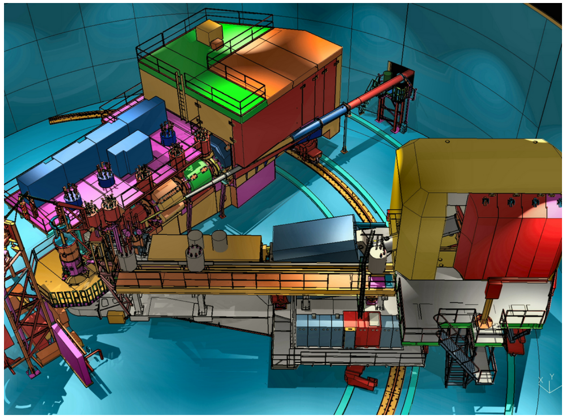
Figure 12: The polarization of valence quarks $(\frac{\Delta d_V}{d_V})$ in the nucleon. The filled symbols are for the SIDIS data only and open symbols are for DIS data neglecting sea contributions. The curves are pQCD based predictions with (solid) and without (dashed) OAM contributions [29].

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

SOLID in Hall A and Hall C SIDIS program







Solenoidal Large Intensity Device (SOLID): large acceptance and high luminosity spectrometer using GEM technology and reusing existing solenoid magnet

Physics program: SIDIS, J/ψ measurements, PVDIS

See next talk by Kalyan Allada (MIT)!

Hall C: High Momentum Spectrometer (HMS), and Super-HMS. SIDIS program including precise cross sections measurements, L/T separations, etc.

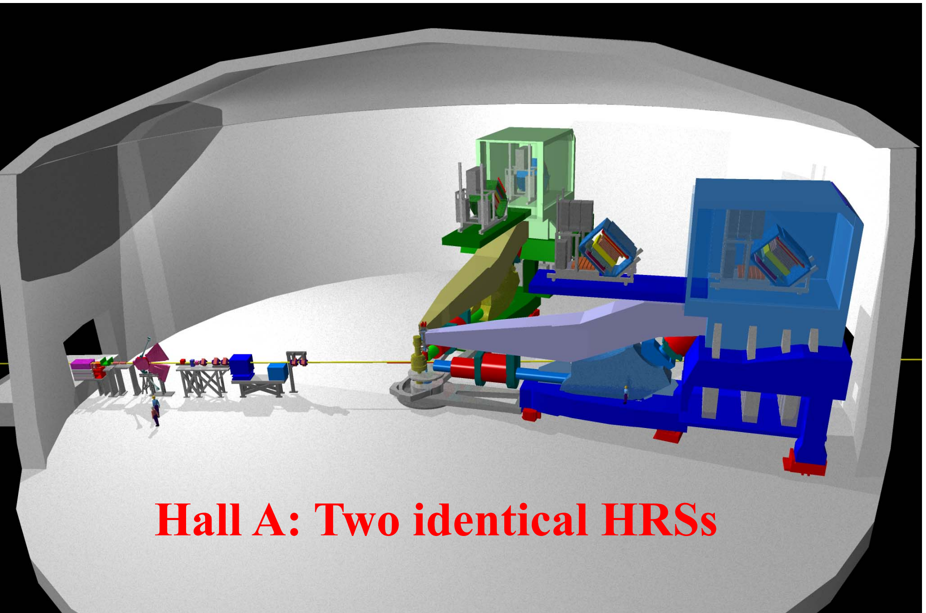
See Ed Kinney (U. Colorado) talk later this session!

Summary and Outlook

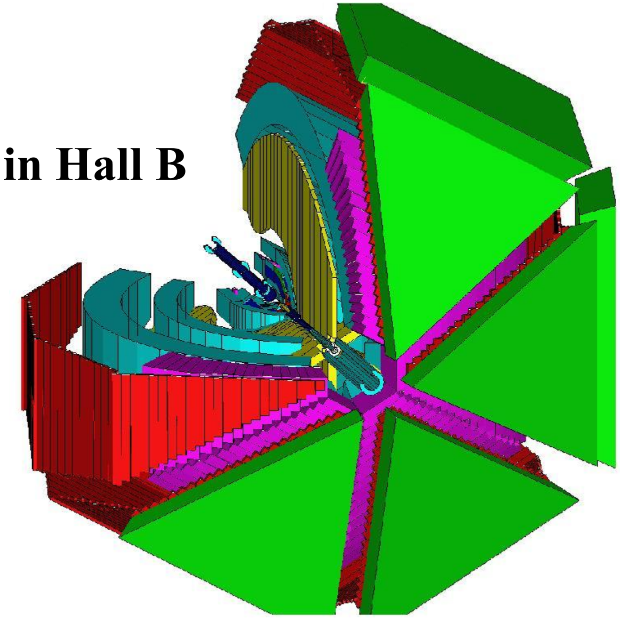
- The 6 GeV era demonstrated that a ”factorized”, partonic interpretation of the SIDIS process is feasible even at the relatively modest energies of JLab.
- The recent 11 GeV upgrade significantly expands the accessible kinematic regime for which ”factorization” is expected to be applicable @JLab.
- The unparalleled duty factor, luminosity and polarization capability of CEBAF makes the precision “fully differential” 4D mapping of novel spin-azimuthal asymmetries in the SIDIS process possible, particularly in the valence region.
  - Unique worldwide capability of JLab!
- A coherent, comprehensive and exciting program of experiments is planned in Halls A, B and C!

Backup Slides

CEBAF Experimental Halls @6 GeV

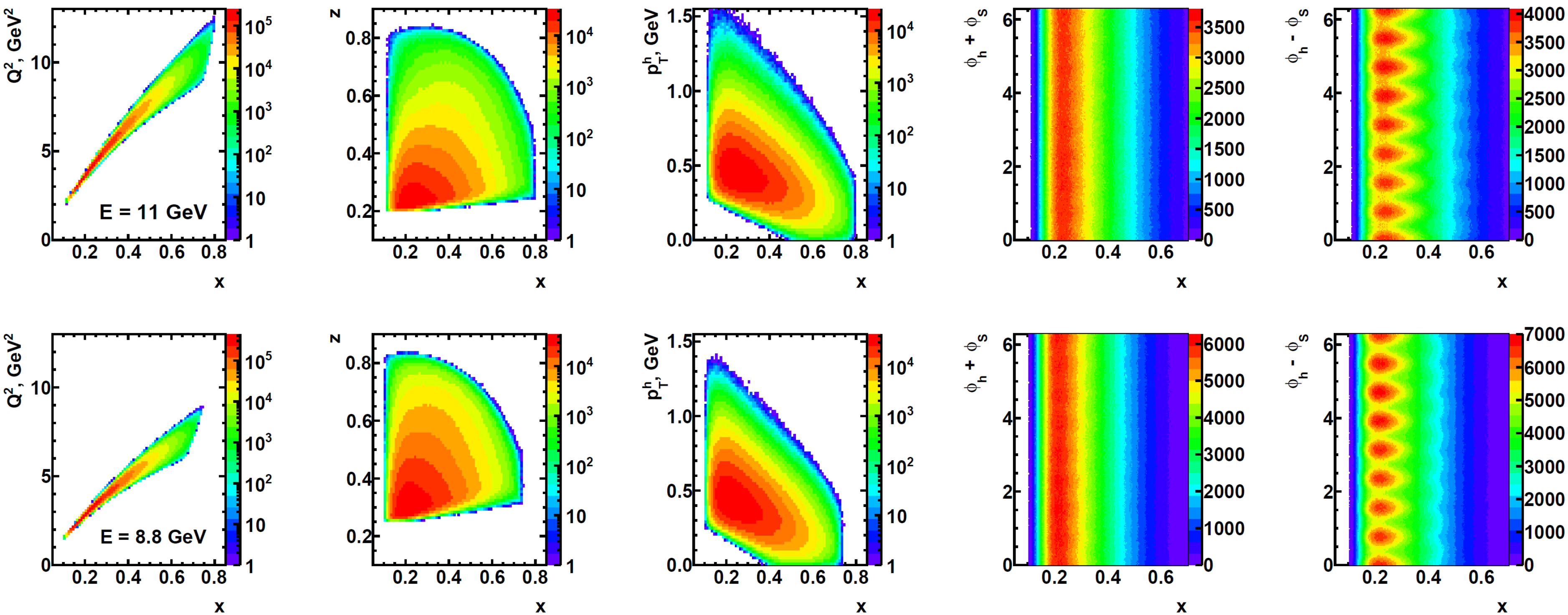


CLAS in Hall B



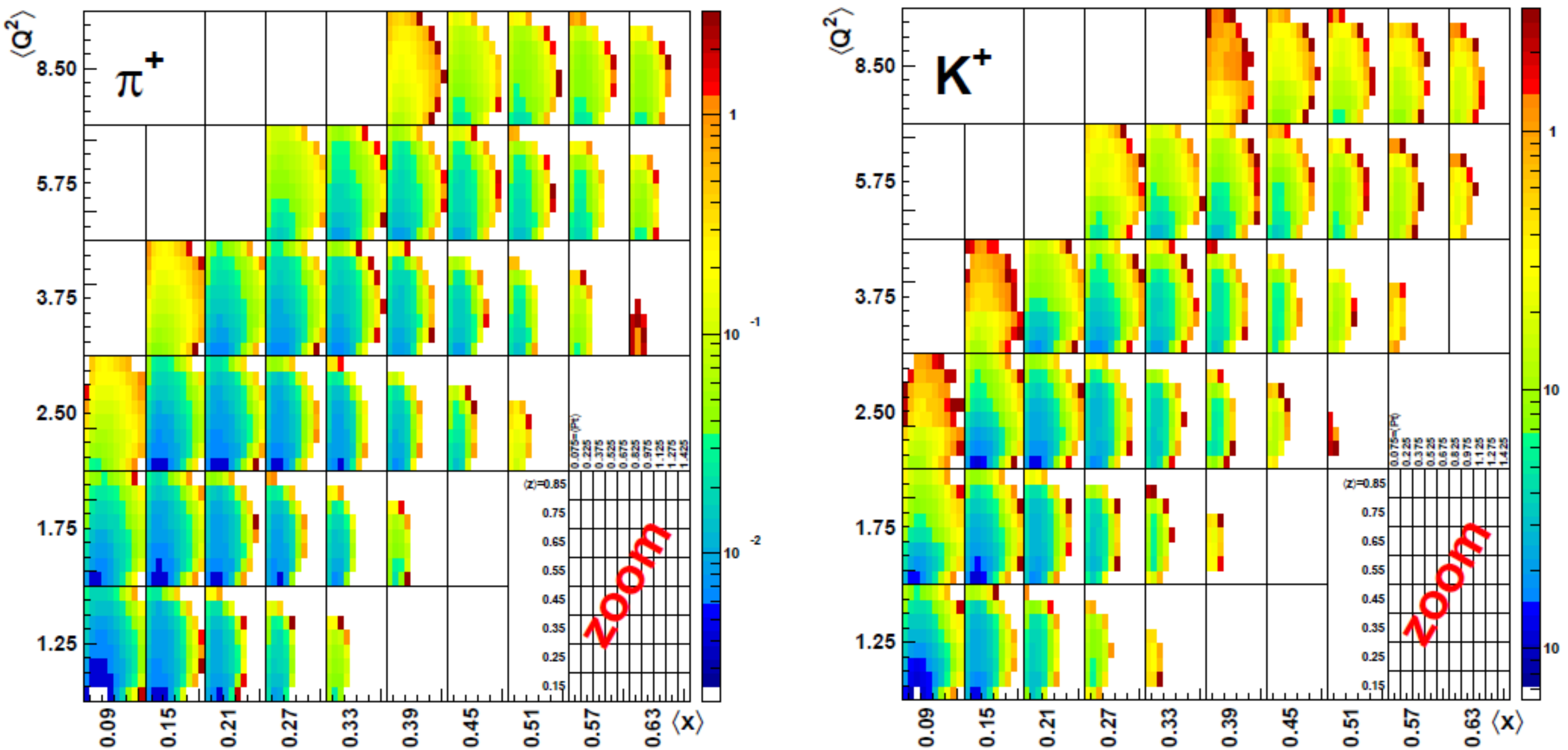
- **Hall A**: High resolution (dp/p ~ 10^{-4}) spectrometers, small acceptance for targeted measurements w/ well-controlled systematics, well-defined kinematics at high luminosities. ***NIM A 522, 294 (2004)***
- **Hall B**: Large acceptance, moderate resolution/luminosity for measurement of multi-particle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

SIDIS Kinematic Coverage in E12-09-018



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

CLAS12 A_{UT} projections—4D analysis

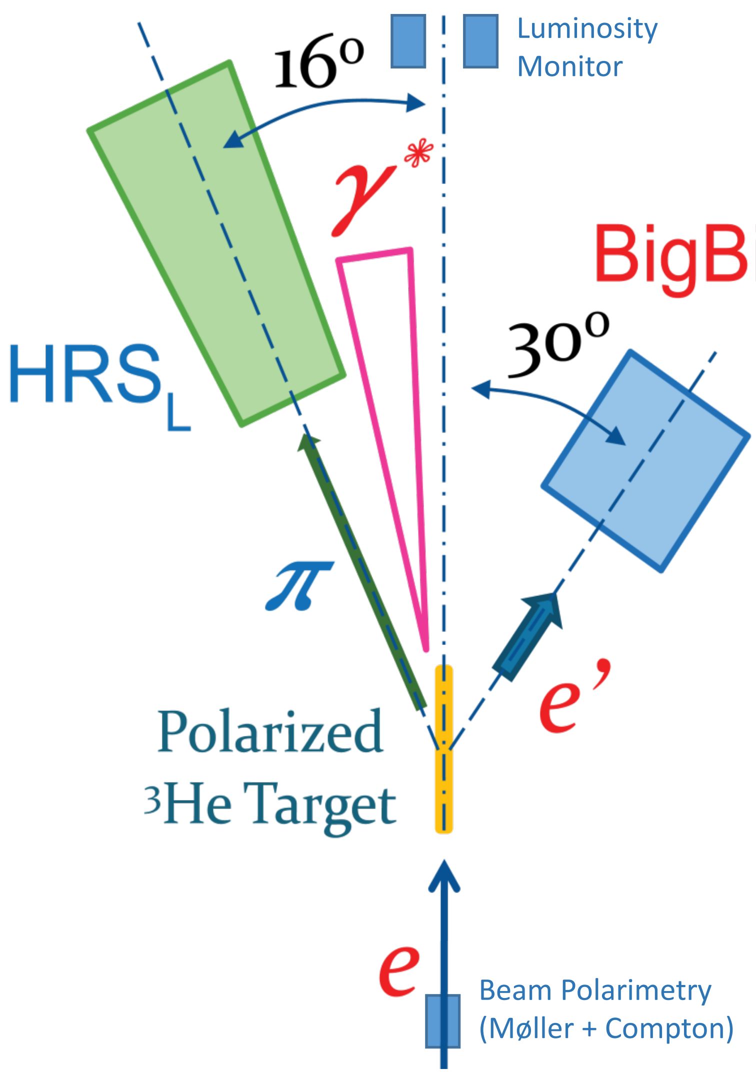


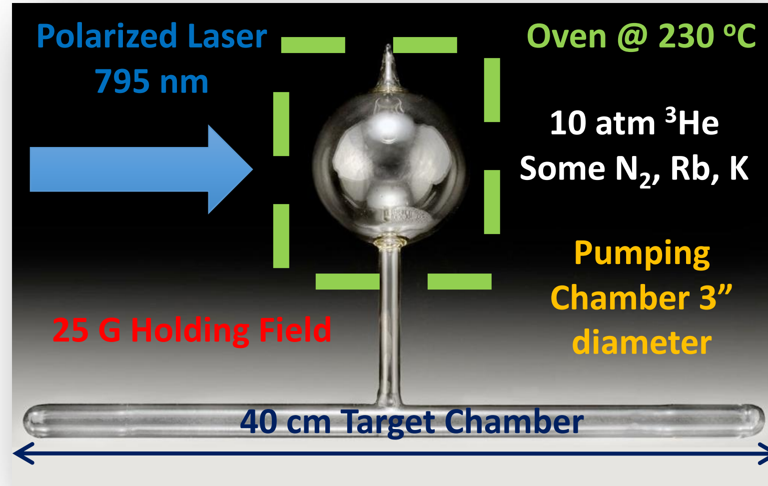
CLAS12 4D analysis for π^+

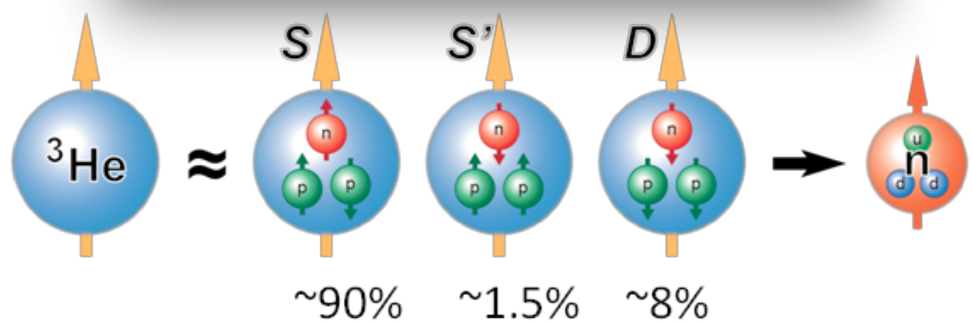
CLAS12 4D analysis for K^+

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

Hall A "Transversity" Experiment: E06-010

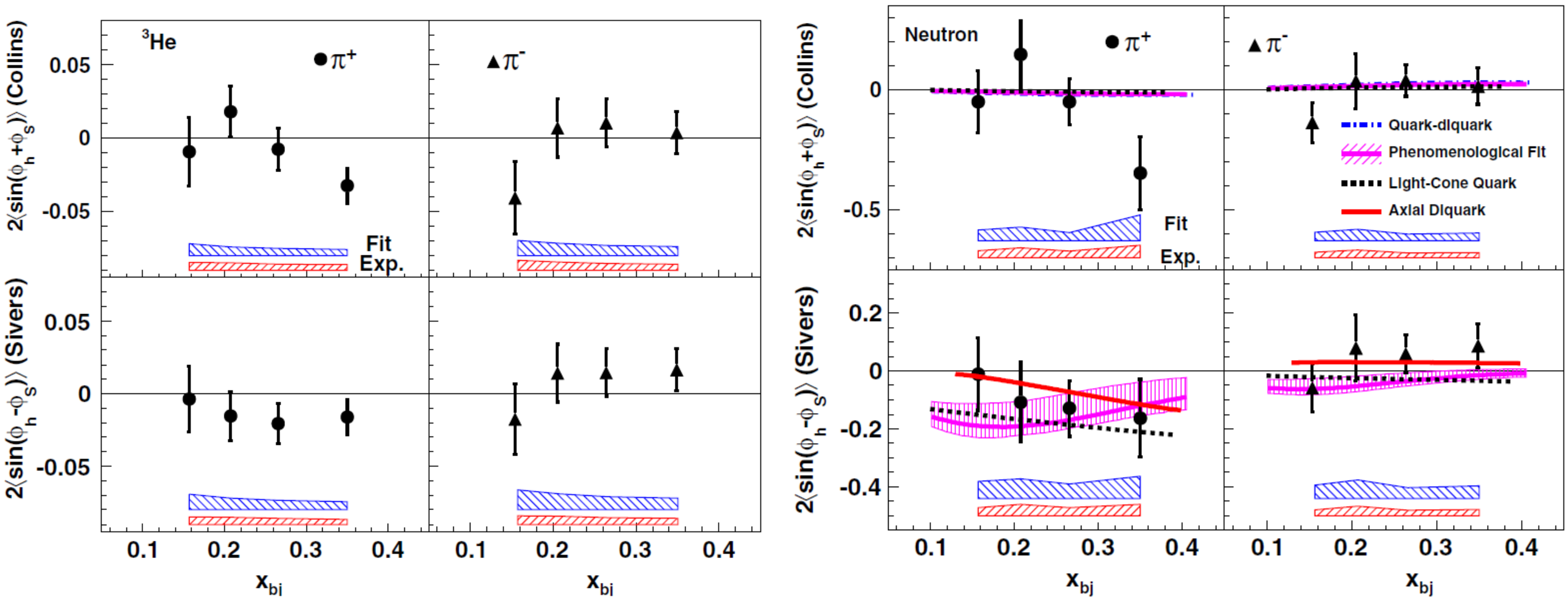






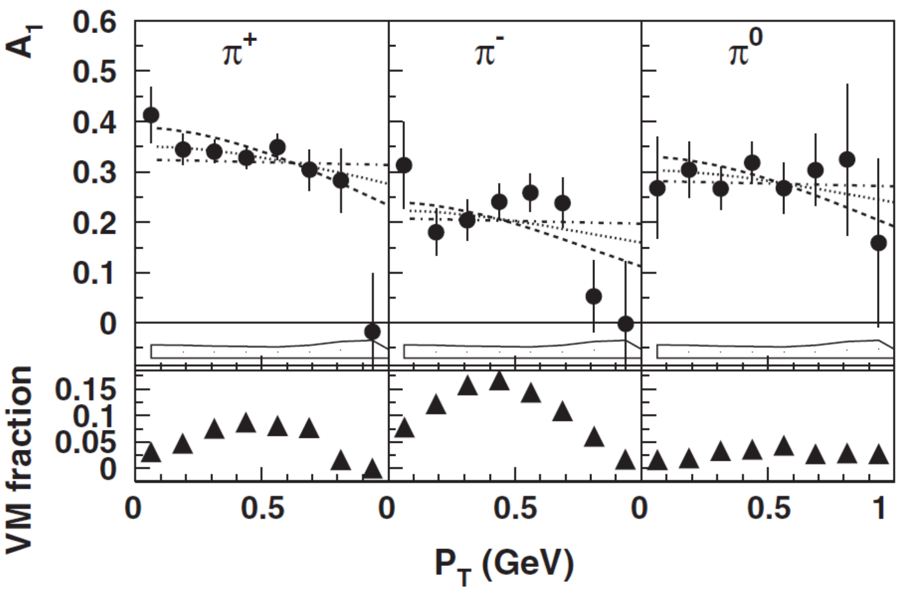
- 5.9 GeV beam, ~85% polarized
- Helium-3 target, <P_T> = 55% transverse (vertical and horizontal directions), flip every ~20 minutes.
- Average beam current ~12 μA
- Two-month run in Hall A in 2008/2009, expt. E06-010

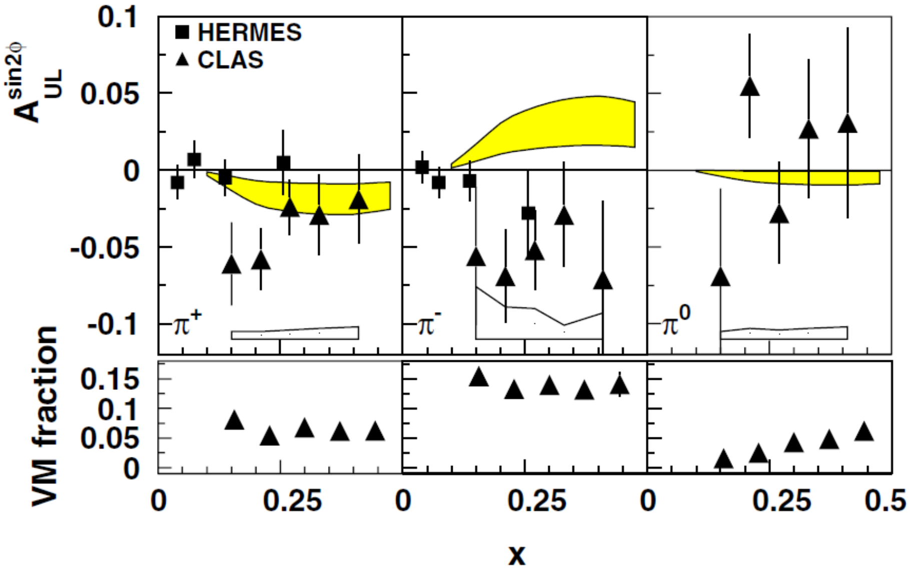
Collins and Sivers effects: *PRL 107, 072003 (2011)*



- Observed ³He 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 $D_{NN} = (1\text{-}y)/(1\text{-}y + y^2/2)$
- ***Impact of E06-010 data from a short-duration run with small-acceptance spectrometers demonstrates power of ³He target and lays foundation for high statistical FOM @11 GeV***

CLAS SIDIS A_1, A_{UL}





$$A_1 \propto g_1(x, k_T^2, Q^2) \otimes D_1(z, p_T^2, Q^2)$$

$$A_{UL}^{\sin(2\phi)} \propto h_{1L}^{\perp}(x, k_T^2, Q^2) \otimes H_1^{\perp}(z, p_T^2, Q^2)$$

- ***PRL 105, 262002 (2010)***
- E = 5.7 GeV, I_{beam} = 5 nA, $P_B \sim 0.7$
- NH_3 polarized target (DNP method), $P_T \sim 0.75$.
- Average dilution from unpolarized N, $f_D \sim 0.14$
- ***Also: Higher-precision data from CLAS eg1-dvcs run (2009) still forthcoming!***

- First measurement of transverse momentum dependence of A_1 asymmetry in SIDIS
  - Hints at possible helicity-dependence of quark k_T distributions.
- First measurement of non-zero $A_{UL}^{\sin(2\phi)}$, indicating potentially significant quark spin-orbit correlations