TMD Results and Future SIDIS Program at Jefferson Lab

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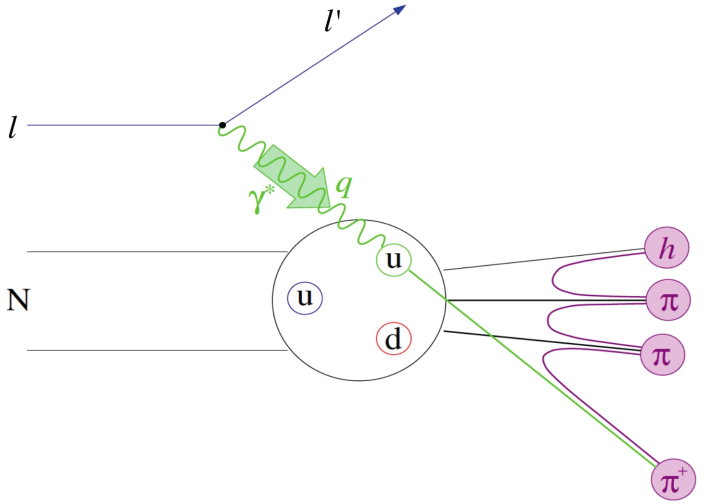
Outline

- Semi-inclusive DIS - Introduction
- Unpolarized SIDIS cross-sections results from Hall C
- Longitudinal target and beam spin asymmetries from CLAS (Hall B)
- Transverse single and double spin asymmetry results from Hall A
  - Inclusive hadron production ($lp^{\uparrow}$ -> hX)
- Plans for future 12 GeV measurements at JLab

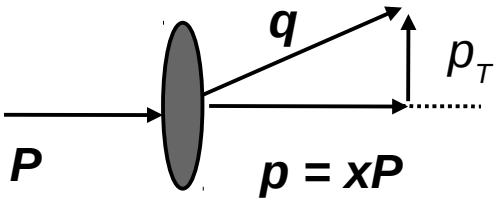
Semi-Inclusive DIS

$$ep^{\uparrow} \rightarrow e'\pi X$$

$\nu = E - E'$
$x = Q^2/2M\nu$
$y = \nu/E$
$z = E_h/\nu$



$$d\sigma^{\ell p \to \ell' h X} = \sum_q \hat{f}_{q/p}(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{\ell q \to \ell q} \otimes \hat{D}_{h/q}(z, \boldsymbol{p}_\perp; Q^2).$$

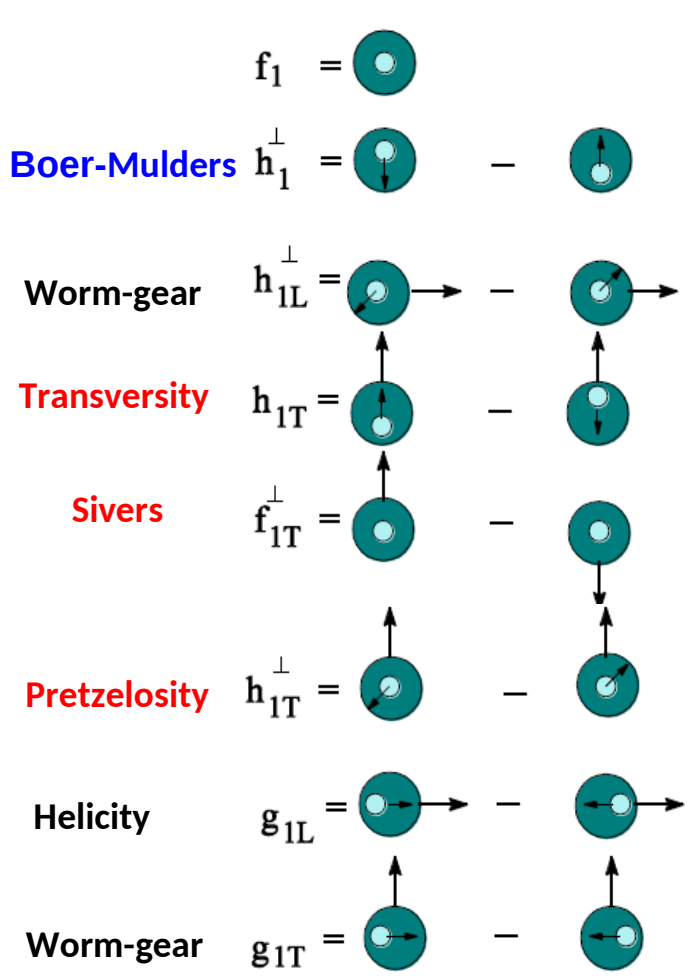


- Detect leading hadron, *z* at least > 0.2
- Quark flavor tagging via fragmentation function ($D_{q->h}$)
- At $P_T \sim \Lambda_{QCD} << Q$ - sensitive to intrinsic transverse momentum (k_T) of the struck quark
- Access to Transverse Momentum Dependent PDFs
  - Links intrinsic parton motion($\boldsymbol{k}^q_T$) and parton spin($\boldsymbol{s}^q_T$) to the nucleon spin ($\boldsymbol{S}^N_T$)
  - Provides access to quark OAM through spin-orbit correlations
  - Provides 3-D imaging of quarks in momentum space
  - Access to quark-gluon-quark correlations through higher-twist observables

Leading Twist TMDs Accessible in SIDIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

A. Bacchetta et al., JHEP 02, 093 (2007)



$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$
$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$
$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$
$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

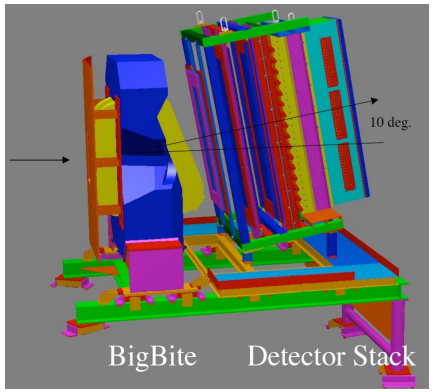
Polarized target

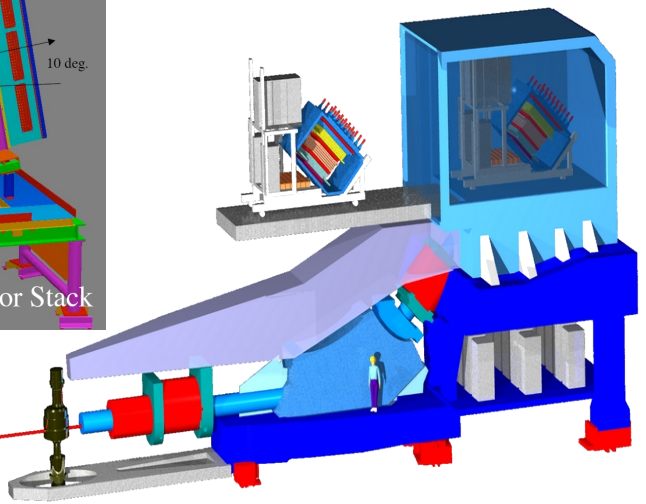
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$
$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

Polarized beam and target

S_T and S_L are target polarization and λ_e is beam polarization

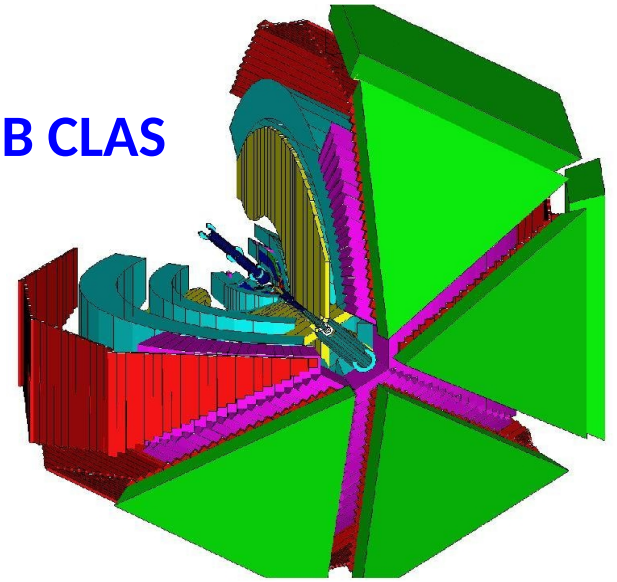
JLab@6 GeV for SIDIS Program

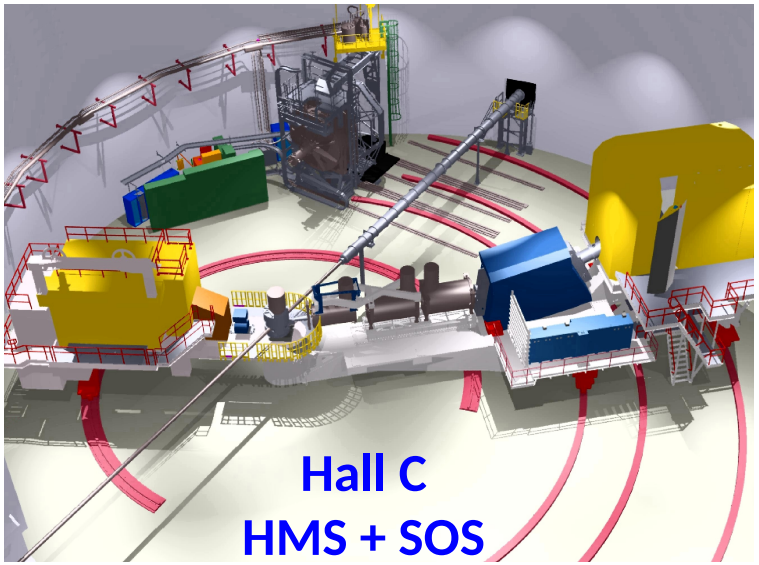




Hall A
HRS + BigBite

Hall B CLAS





Hall C
HMS + SOS

JLab 6 GeV TMD program explored different structure functions that appear in the SIDIS cross-section:

- Unpolarized contributions (Hall-B, Hall-C)
- Longitudinally polarized contributions (Hall-B)
- Transversely polarized contributions (Hall-A)

Hall C E00-108 Experiment: SIDIS Cross Section

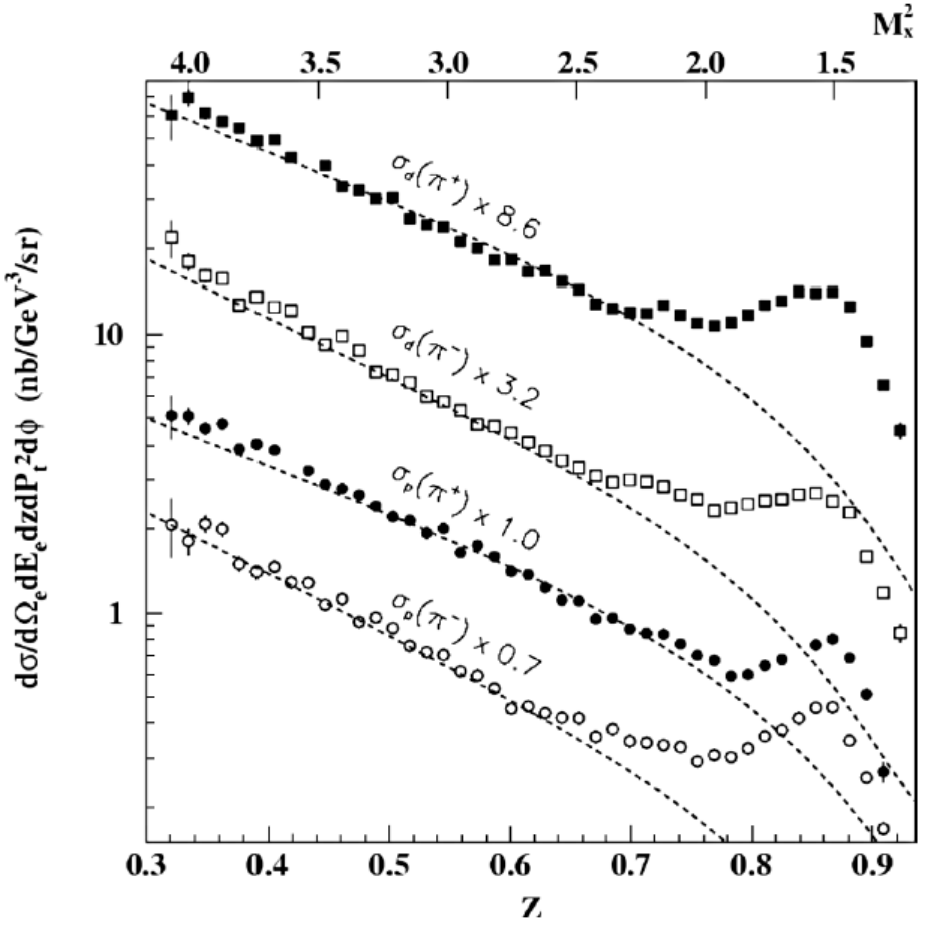
$$e + p/d \longrightarrow e' + \pi^{+/-} + X$$

- E = 5.5 GeV
- Measurement of π^+/π^- on liquid H_2 and D_2

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

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

Low energy semi-inclusive cross sections consistent with calculation using high energy parameters of frag. functions and CTEQ PDFs (for z<0.7 and M_x^2 >~ 2.5)



$$M_x^2 = W'^2 \approx M_p^2 + Q^2(1/x - 1)(1 - z)$$

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

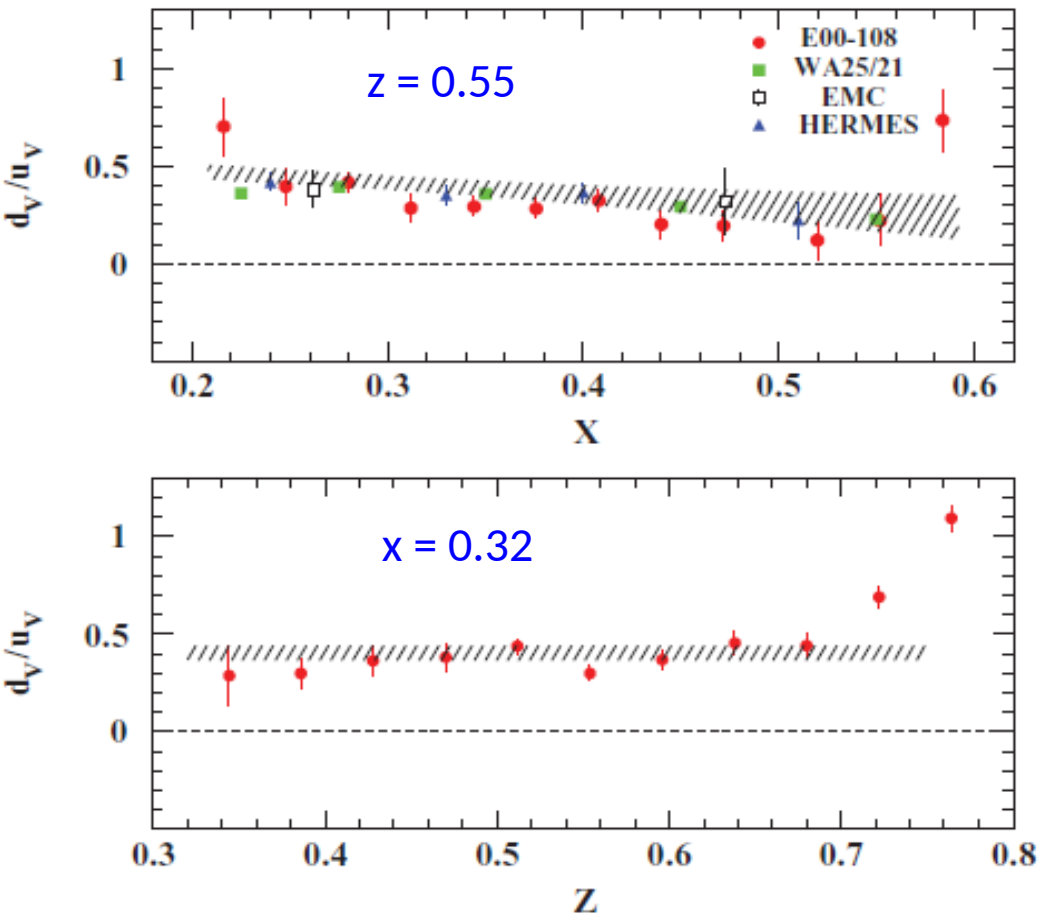
Hall C E00-108 Experiment: d/u valence quark

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

$$u_v = u - \bar{u}, \quad d_v = d - \bar{d}$$

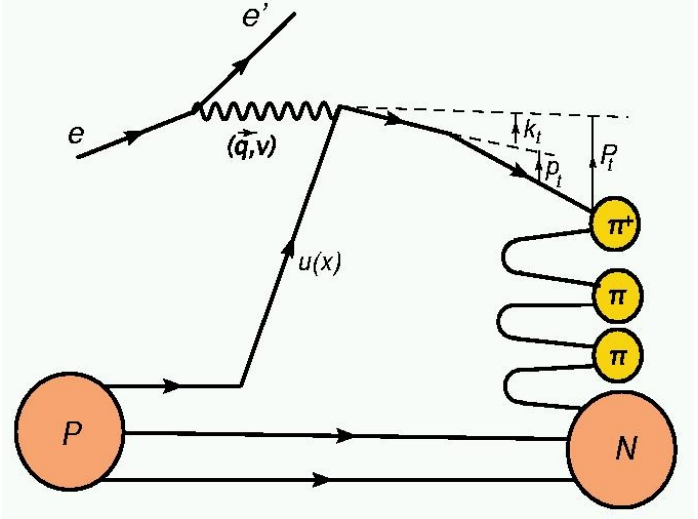
- p/d ratios of π^+/π^- cross section difference depends only on d_v/u_v at leading order
  - Small sea-quark contribution for x > 0.3
- Bands are ratio values along with uncertainties calculated using CTEQ PDFs
  - Good agreement with previous extractions
- Data for z < 0.7 in reasonable agreement with CTEQ6 LO PDFs

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



d_v/u_v extracted from differences and ratios of π^+ and π^- cross sections off H and D targets

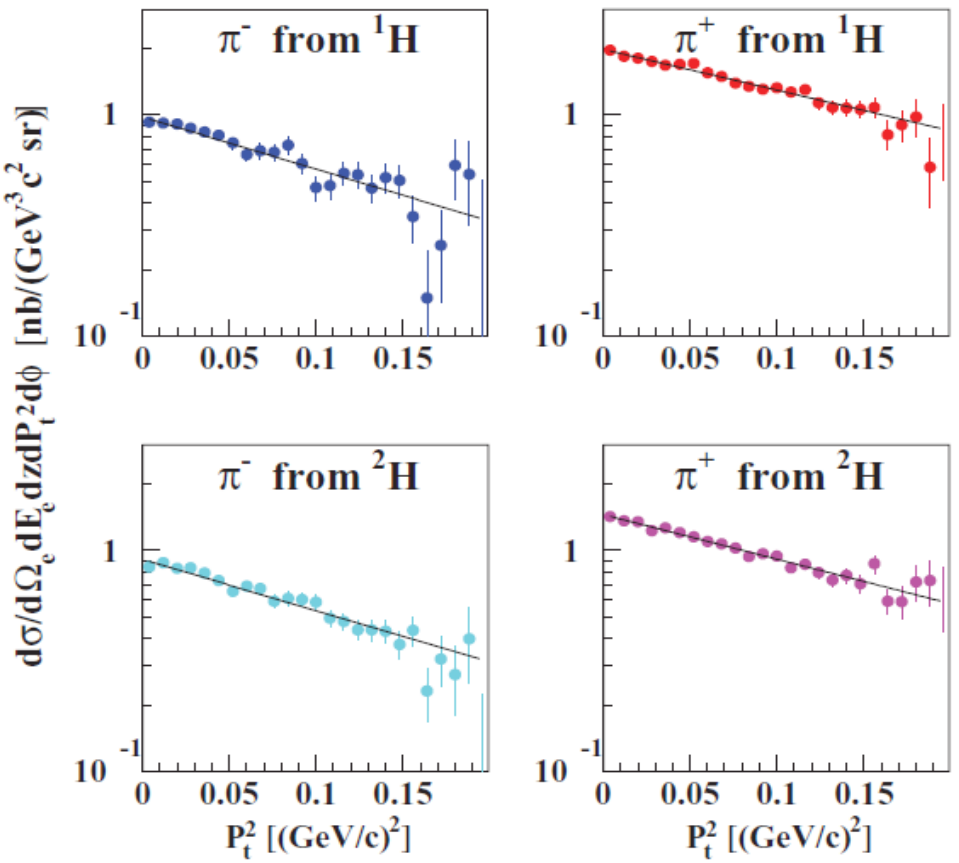
Hall C E00-108 Experiment : P_T dependence



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

- Measured P_T dependent cross sections in semi-inclusive pion production
- x = 0.32, z = 0.55, Q^2 = 2.3 $(GeV/c)^2$, P_T < 0.4 GeV
- P_T dependence very similar (not identical) for proton and deuterium targets

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



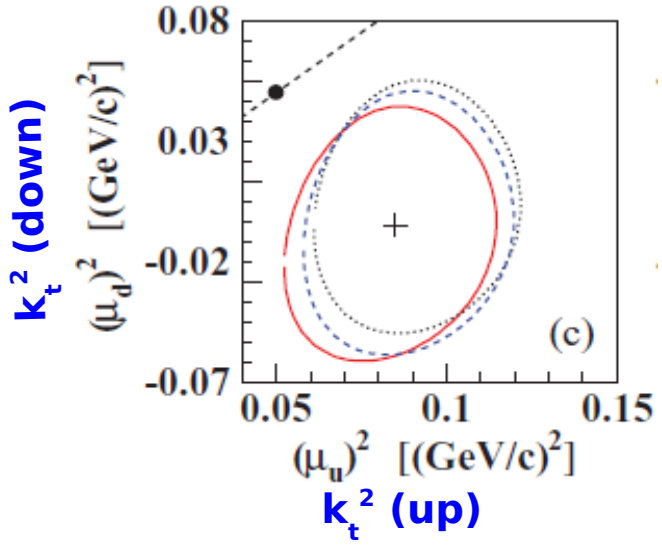
Hall C E00-108 Experiment : P_T dependence

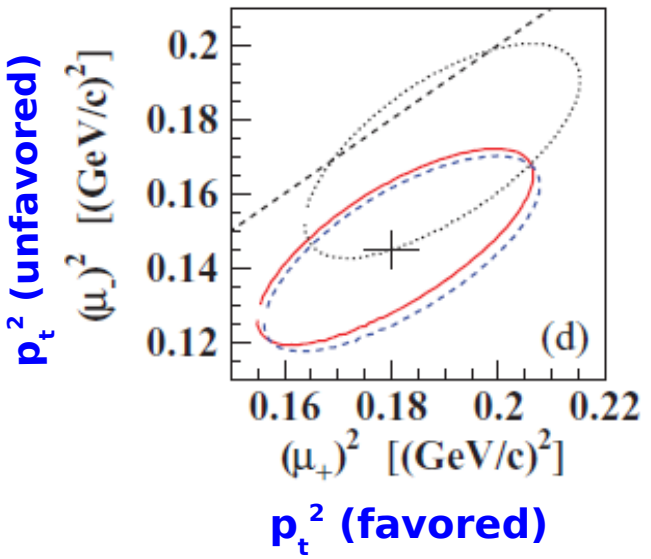
- Combination of π^+/π^- yields on proton and neutron (d) targets allows, in principle, separation of quark width from fragmentation width

- Possible flavor dependence of the transverse momentum dependence of quark distribution and FF

- Studied done in a simple model with several assumptions:
  - Factorization valid
  - No sea quark contribution
  - Fragmentation functions do not depend on quark flavor
  - Gaussian widths

- k_t width of u-quark larger than d-quark
- p_t widths of favored and unfavored FFs are similar and larger than quark widths





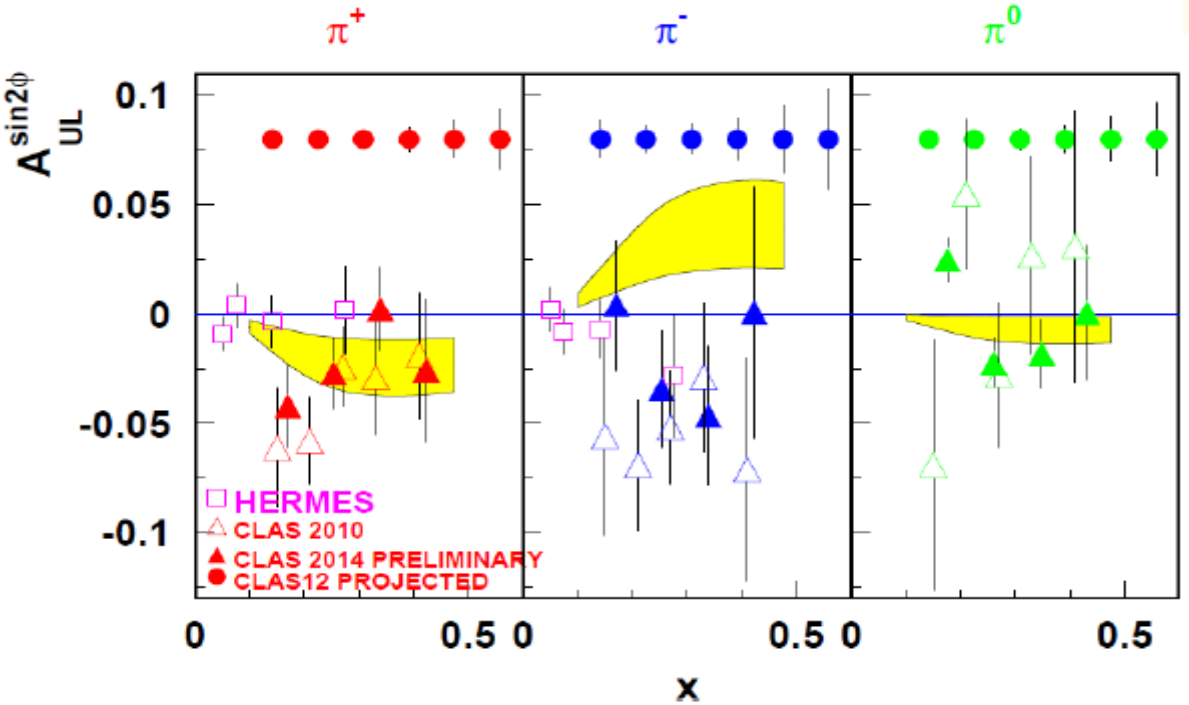
R. Asaturyan et al. PRC 85, 015202 (2012)

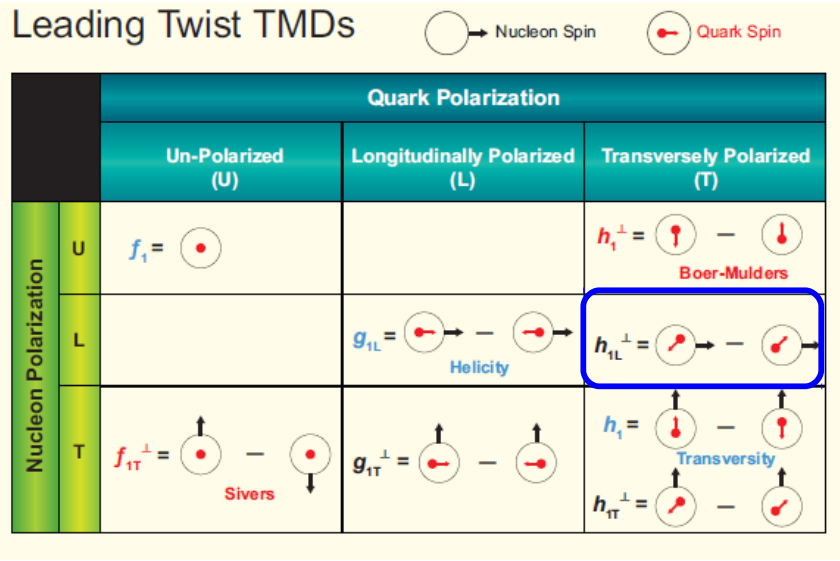
CLAS: Target Single Spin Asymmetries - $A_{UL}\sin 2\varphi$

A_{UL}: Kotzinian-Mulder function → tranversely-polarized quark in a longitudinally-polarized proton

$$F_{UL}^{\sin 2\varphi} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

First measurement of non-zero $A_{UL}\sin 2\varphi$ for pions → potentially significant quark spin-orbit correlations





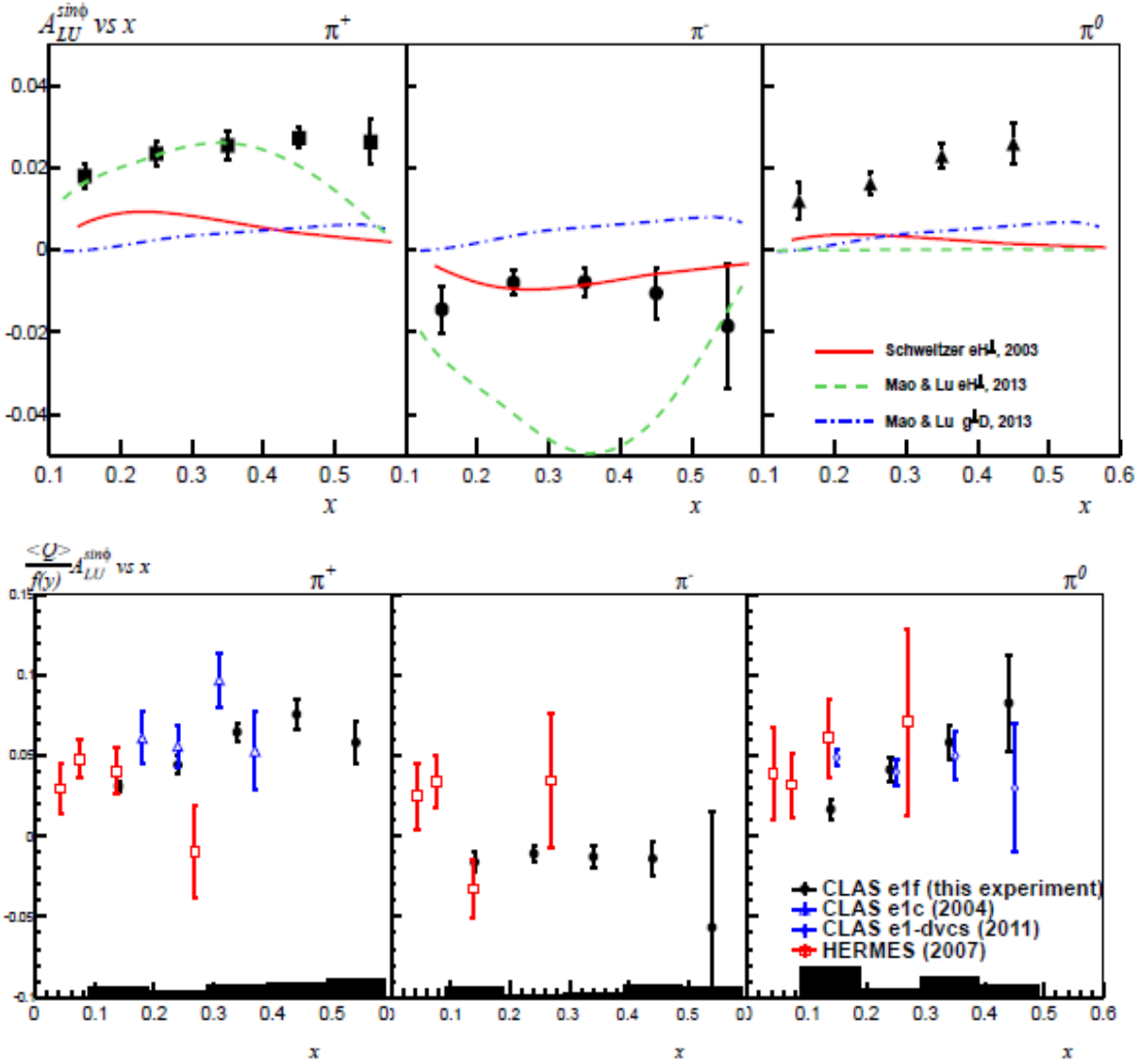
H. Avakian et al., PRL105: 262002 (2010)

Slide courtesy: Silvia Pisano, INFN

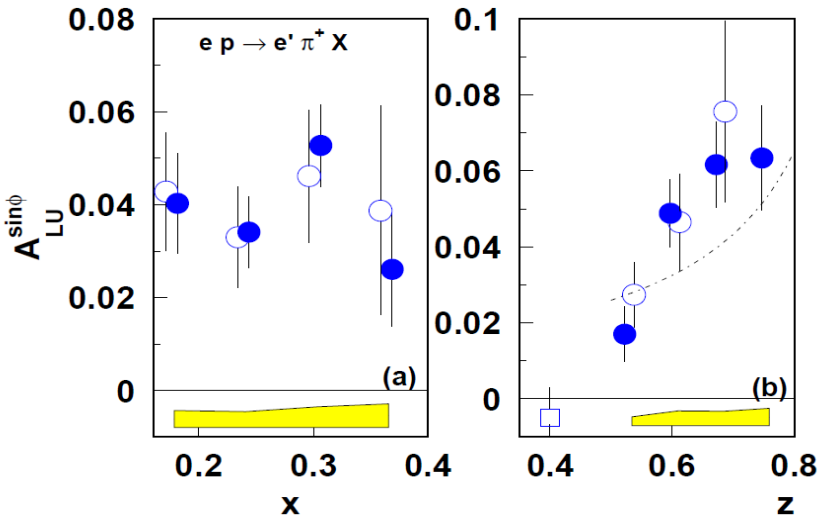
CLAS: Beam Spin Asymmetries in SIDIS - $A_{LU}\ sin(\phi)$

- A_{LU} on unpolarized H_2 target
- $A_{LU}\ sin(\phi) \propto e(x)$: twist-3 PDF sensitive to q-g-q correlations
- High statistics A_{LU} data (2014)

W. Gohn et al., PRD89, 072011 (2014)@5.5 GeV



H. Avakian et al., PRD69, 112004 (2004) @ 4.3 GeV



First clear evidence for non-zero BSA in SIDIS (2004)

Courtesy: Silvia Pisano, INFN

CLAS Di-hadron Beam Spin Asymmetry in DIS: A_{LU}

- *e(x)* : twist-3 collinear PDF sensitive to q-g-q correlations

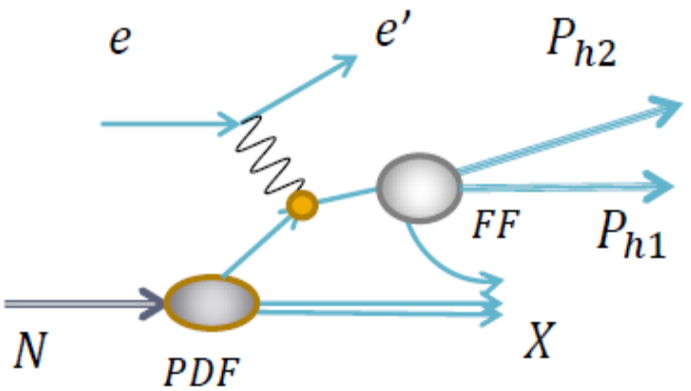
- e(x): Important information on the non-perturbative dynamics of the nucleon :
  - q-g-q correlations
  - nucleon scalar charge

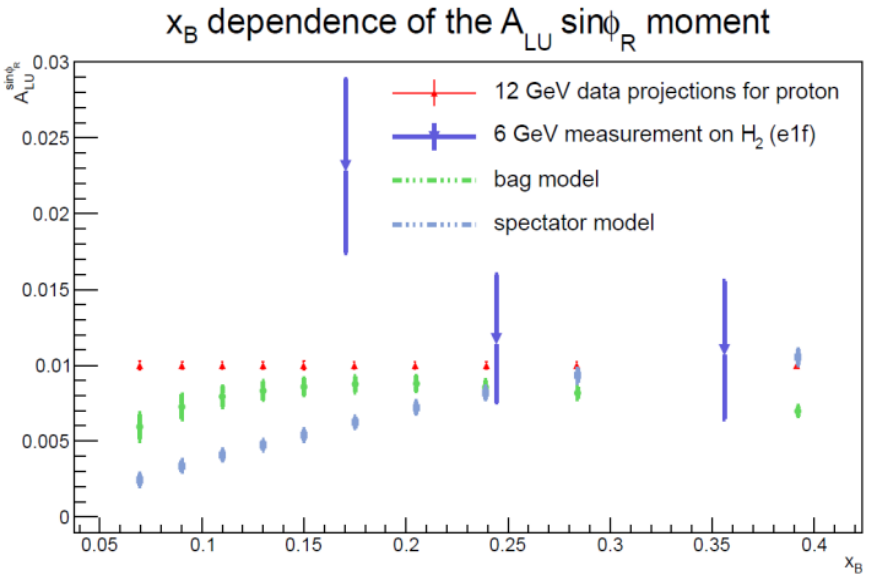
Appears in the di-hadron SIDIS beam-spin asymmetry:

Interference FF extracted from Belle data

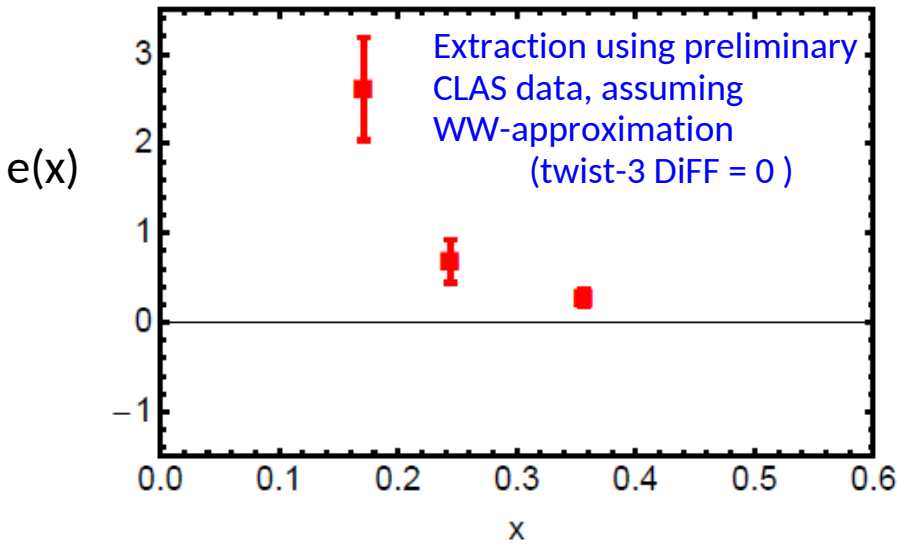
$$A_{LU} \propto F_{LU} = e(x)H_1^{\sphericalangle q} + f_1(x)\tilde{G}^{\sphericalangle q}$$

twist-3 DiFF





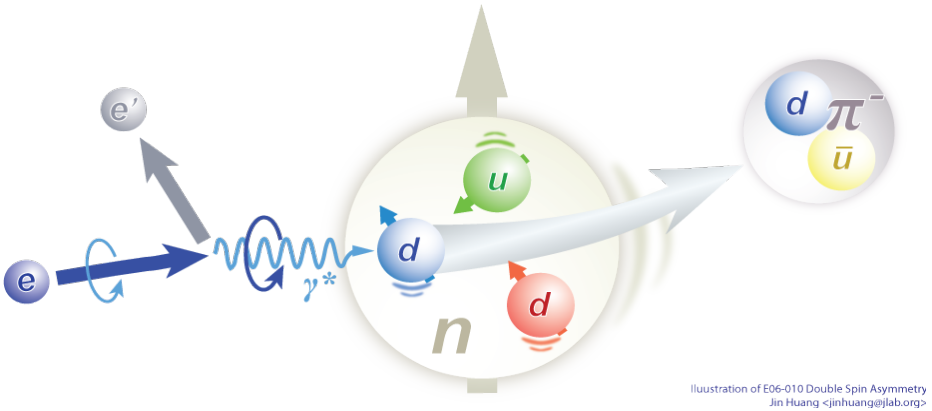
e(x) **A. Courtoy, arXiv:1405.7659**

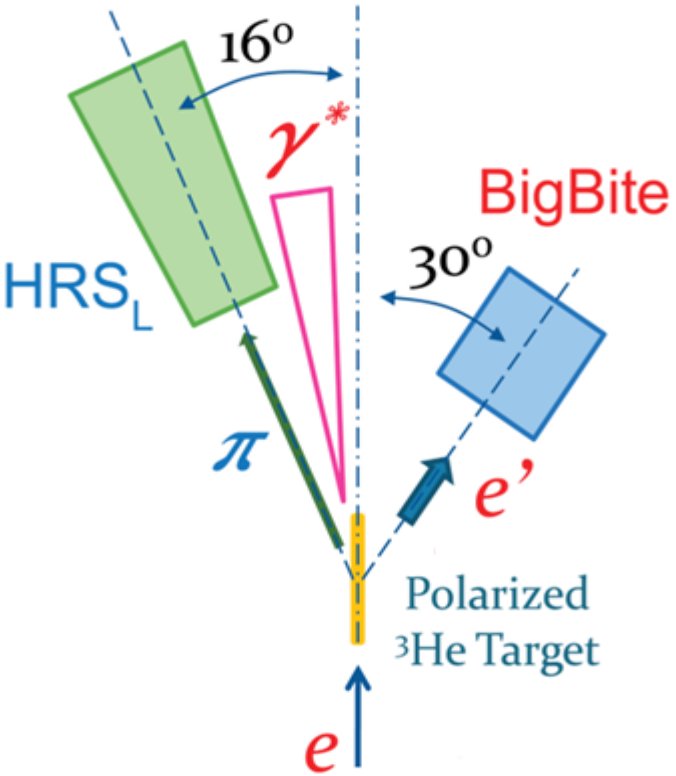


Courtesy: Silvia Pisano, INFN

Hall A Transversity Experiment

$$e + {}^3He^{\uparrow} \longrightarrow e' + h + X \qquad (h = \pi/K/p)$$





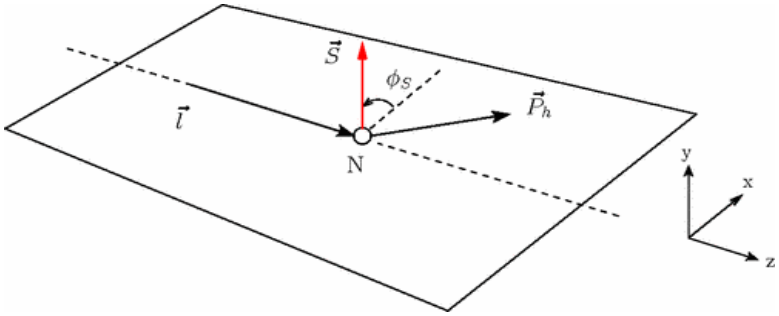
- Beam Energy: 5.9 GeV, polarized, 30Hz spin-flip
- Target:
  - ^{3}He : transversely and vertically polarized
  - In beam polarization: ~60%
  - Spin flips: 20 minutes
- Measured $\pi^{+/-}$, $K^{+/-}$ electroproduction
- Measured single and double spin asymmetries (A_{UT}, A_{LT})

x ~ 0.16 - 0.35, $\langle \mathbf{Q}^2 \rangle$ ~ 2.0 (GeV/c), $\langle \mathbf{z} \rangle$ ~ 0.5, $\langle \mathbf{P}_T \rangle$ ~ 0.3 GeV

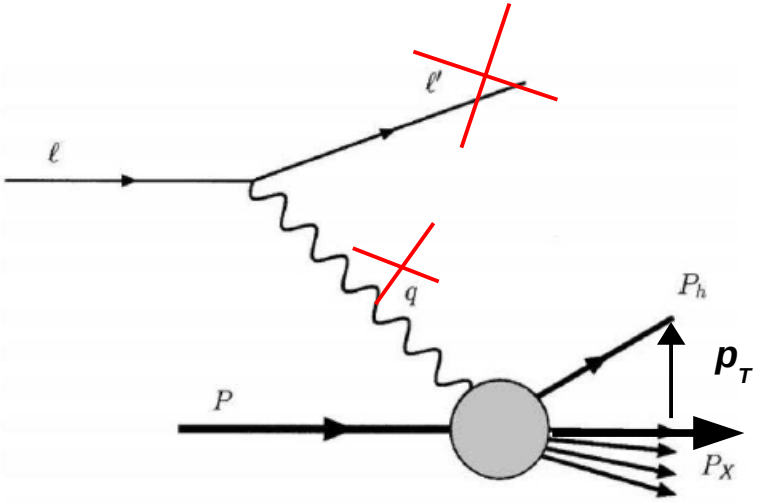
For SIDIS results refer to Xuefei Yan's talk next …

Transverse SSA in Inclusive Hadron Production

$$e + {}^3He^{\uparrow} \longrightarrow h + X \qquad (h = \pi/K/p)$$



$$A_{UT}(x_F, p_T) = \frac{1}{P}\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \sin\phi_S = A_N \sin\phi_S$$

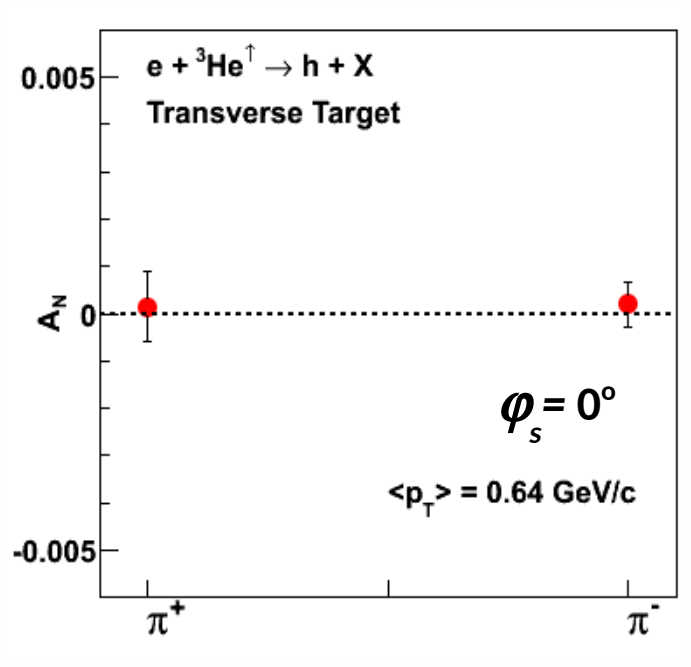


- Only one hard scale : P_T of the detected hadron
- Relevant kinematic variables:
  - p_T : Transverse momentum of hadron
  - $x_F \simeq 2p_L/\sqrt{s}$: p_L is the long. momentum of hadron
- Assuming TMD factorization valid in inclusive hadron production:
  - Sivers contribution dominates SSA (usually, for p_T > 1 GeV)
  - Collins contribution is negligible

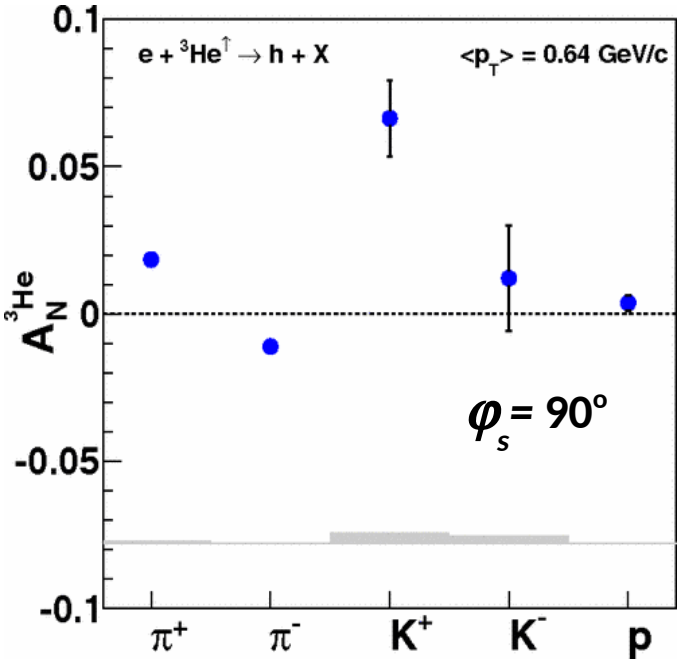
M. Anselmino et al.,
Phys. Rev. D81, 034007 (2010)

Transverse SSA in Inclusive Hadron Production

$$A_{UT}(x_F, p_T) = \frac{1}{P}\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}\sin\phi_S = A_N \sin\phi_S$$



^{3}He asymmetry

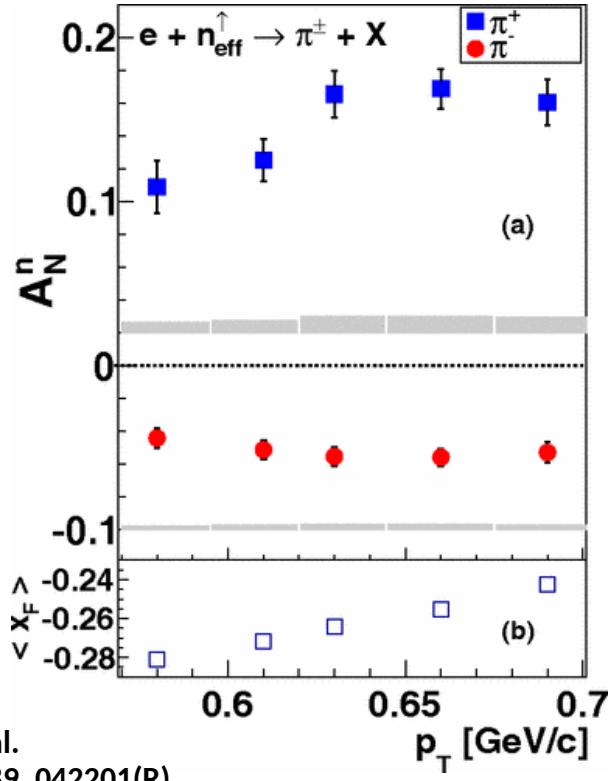


- A_N for φ_s= 0° indicate false asymmetry less than 0.1%
- Clear non-zero SSA observed for $\pi^{+/-}$, K^+ at φ_s= 90°
- π^+ and π^- have opposite sign

All the data is integrated into one bin for each particle

Transverse SSA in Inclusive Hadron Production

Neutron symmetry

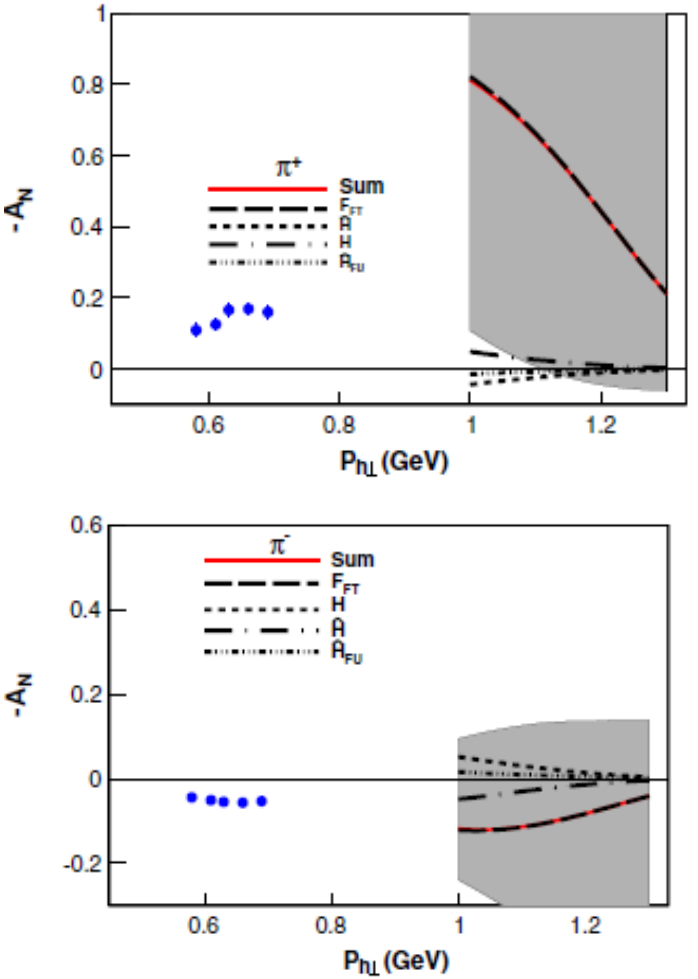


K. Allada, et al.
Phys. Rev. C 89, 042201(R)

- Clear non-zero SSA observed for $\pi^{+/-}$, K^+
- No theoretical prediction at low P_T
- Data agrees in sign with predictions from twist-3 collinear factorization (for P_T>1.0 GeV)
- Similar behavior to A_N in $pp^{\uparrow}$->hX

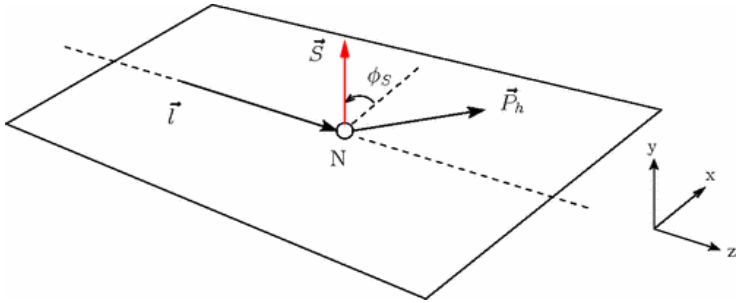
Theory Calculations (P_T > 1 GeV):

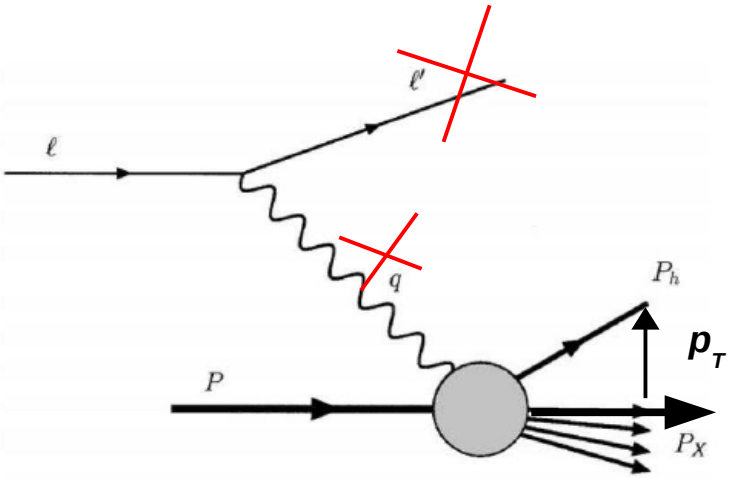
L. Gamberg et. al., PRD 90, 074012 (2014)



Transverse DSA in Inclusive Hadron Production

$e + {}^3He^{\uparrow} \longrightarrow h + X \qquad (h = \pi/K/p)$





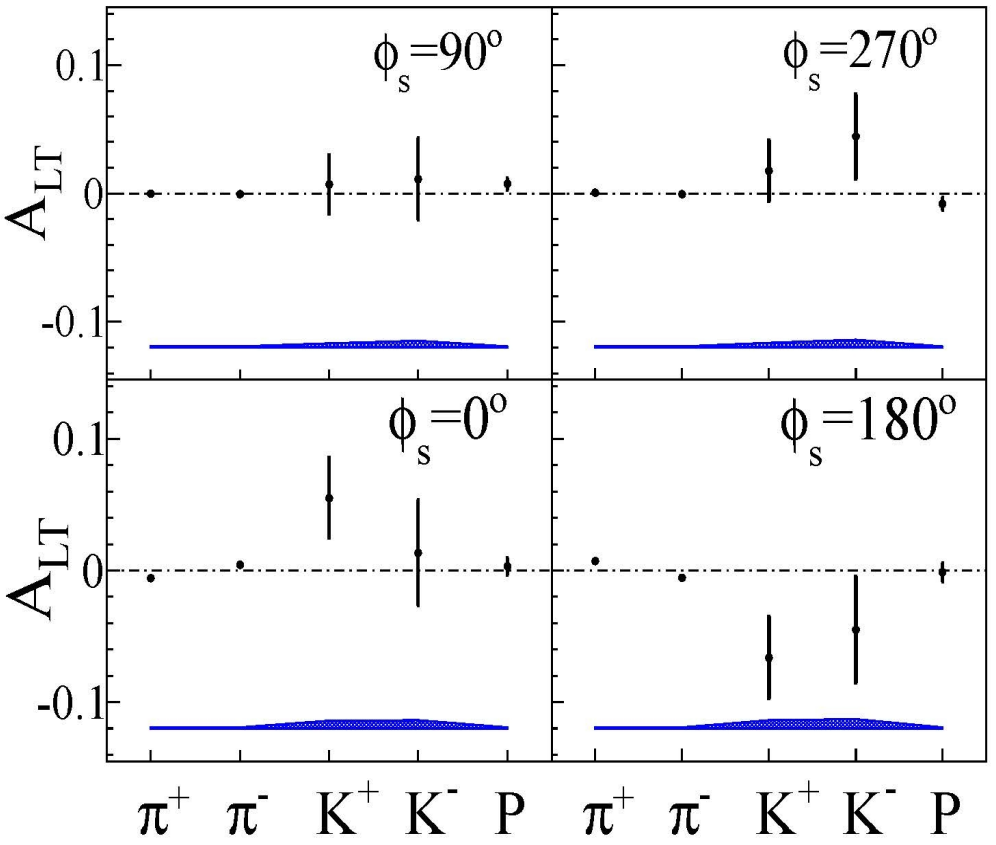
$$A_{\mathrm{LT}} = \frac{1}{|P_B P_{target}|} \frac{d\sigma^{\uparrow\rightarrow} - d\sigma^{\downarrow\rightarrow}}{d\sigma^{\uparrow\rightarrow} + d\sigma^{\downarrow\rightarrow}}$$
$$= A_{\mathrm{LT}}^{\cos(\phi_s)} \cos(\phi_s)$$

- A_{LT} in inclusive hadron is a sub-leading twist observable in collinear factorization
- Collinear twist-3 contributions from both distribution and fragmentation side
- Related to collinear twist-3 "Worm-Gear" type function $\tilde{g}(x)$
  - learn about q-g-q correlations in the nucleon
  - Twist-3 effects in fragmenting hadron

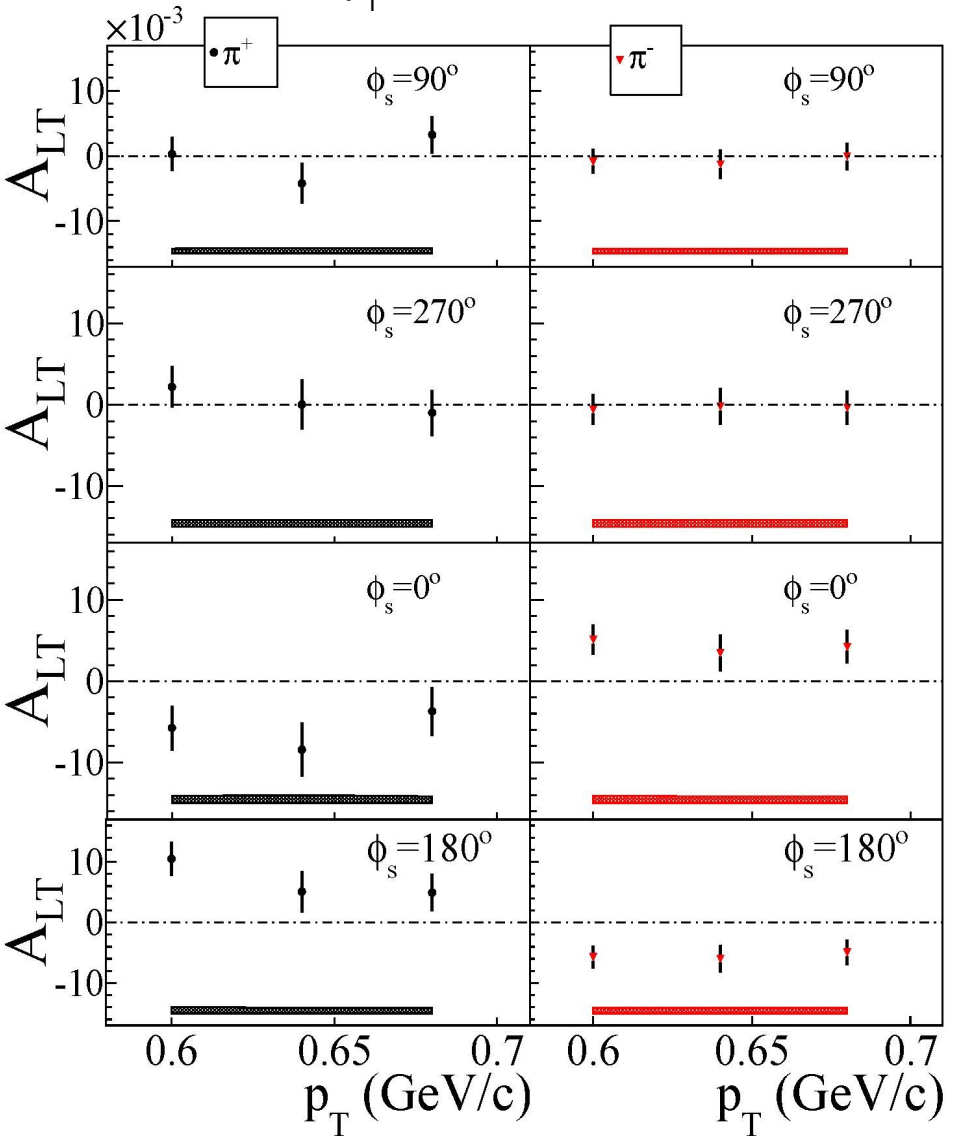
Transverse DSA in Inclusive Hadron Production

$A_{LT}^{\cos(\phi_s)} \cos(\phi_s)$

^{3}He Asymmetry for charged hadrons

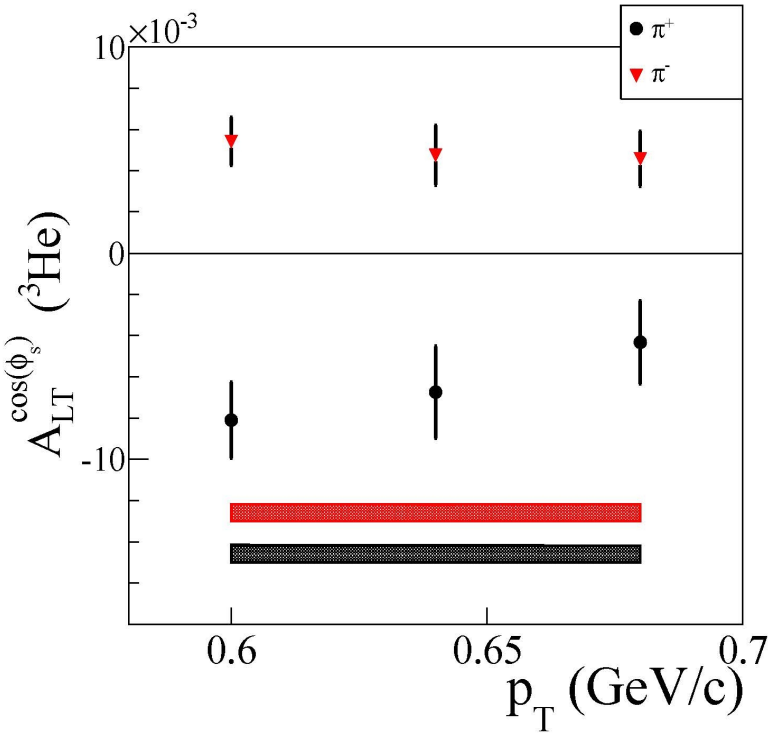


^{3}He asymmetry for charged pions
(p_T distribution)

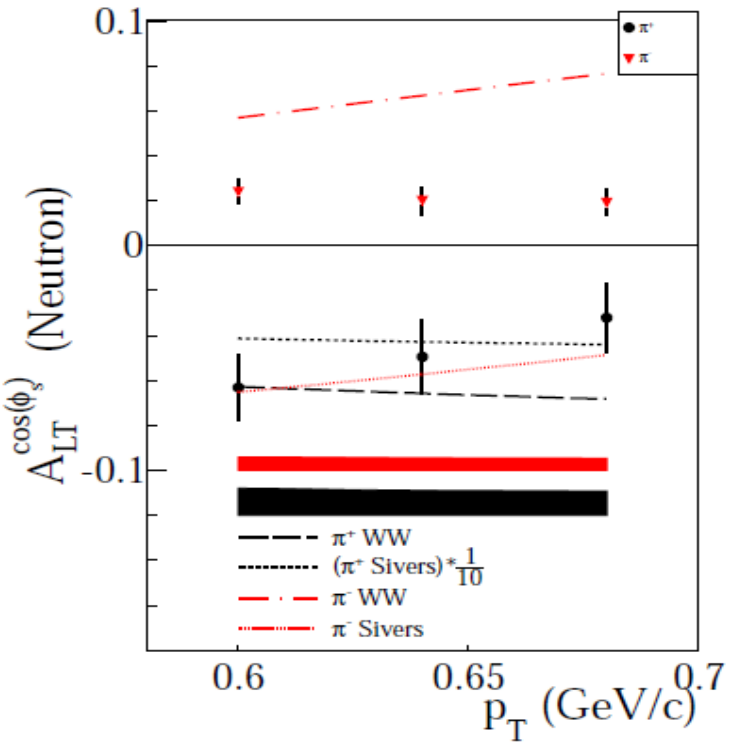


Transverse DSA in Inclusive Hadron Production

^{3}He asymmetry



Neutron asymmetry



- Clear non-zero SSA observed for $\pi^{+/-}$
- π^+ and π^- SSA have opposite sign
- Model predictions:
  - using WW-type approx agrees in sign
  - using Sivers-type approx do not agree

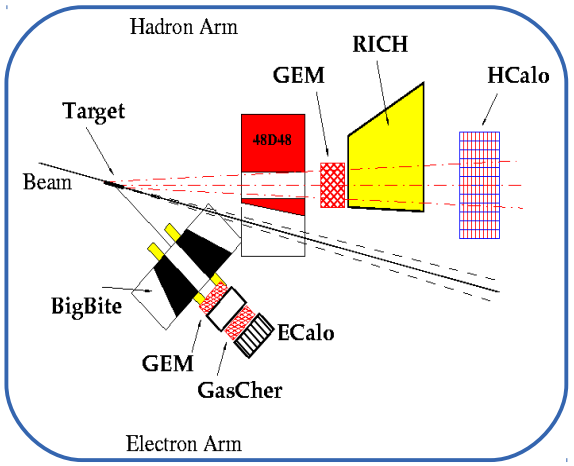
Y.X.Zhao et al.
PRC 92 , 015207 (2015)

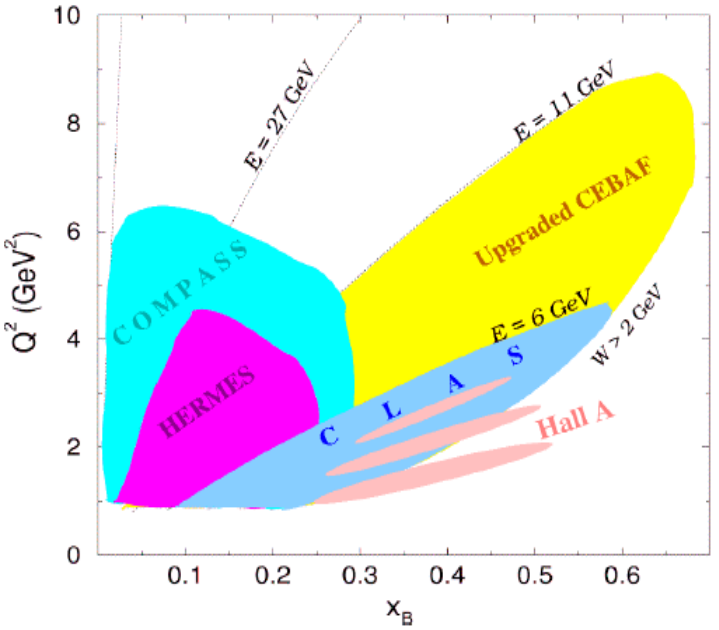
Predictions from K. Kanazawa et al.,
arXiv:1411.6459 (2014)

Multi-Hall SIDIS Program at JLab

Hall A: Super BigBite

SIDIS with ^{3}He, high x, Q^2

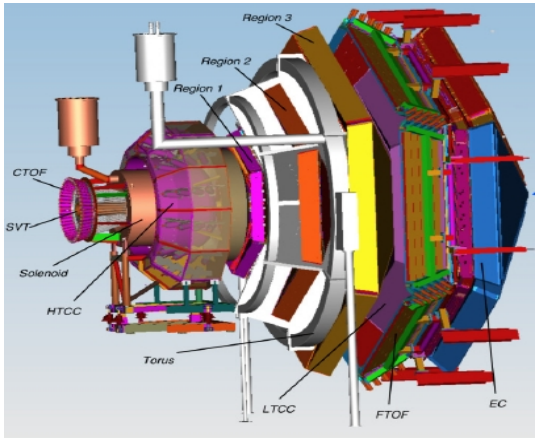




Hall B: CLAS12

SIDIS with polarized H/D

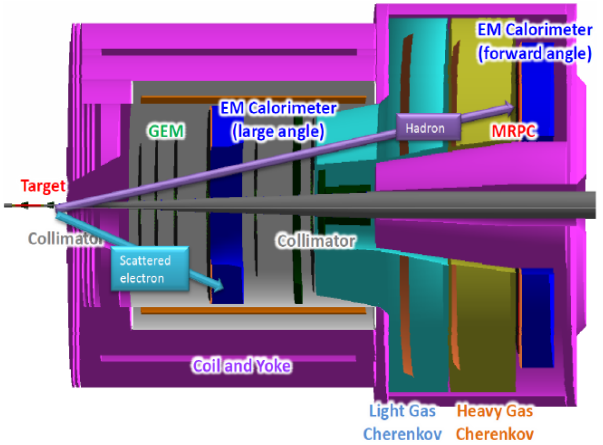
Comprehensive SIDIS program



Hall A: SoLID

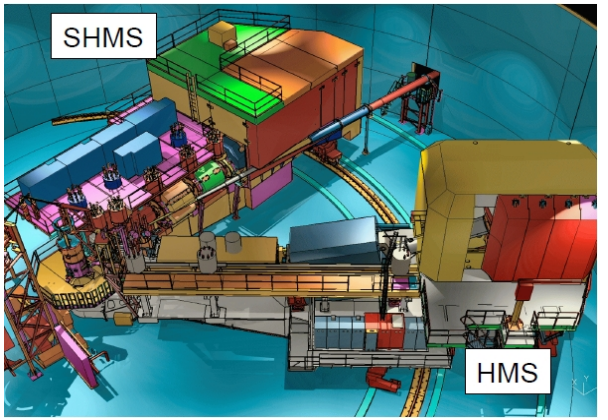
SIDIS with polarized ^{3}He/NH_3

Precision 4D mapping



Hall C: SHMS

SIDIS with unpolarized H/D

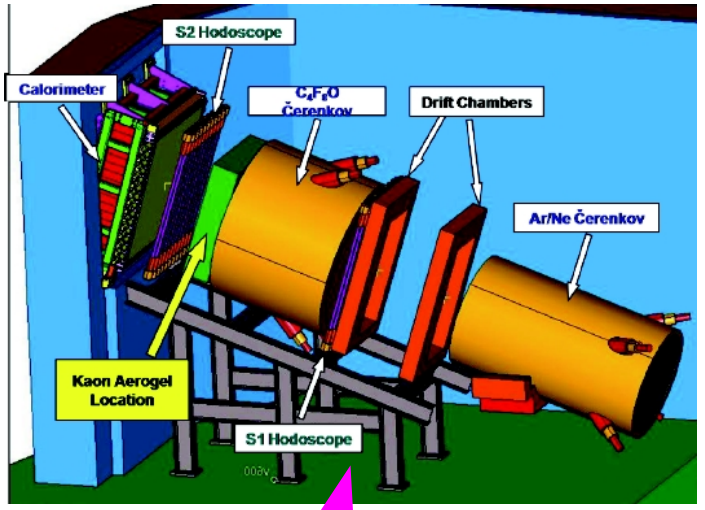


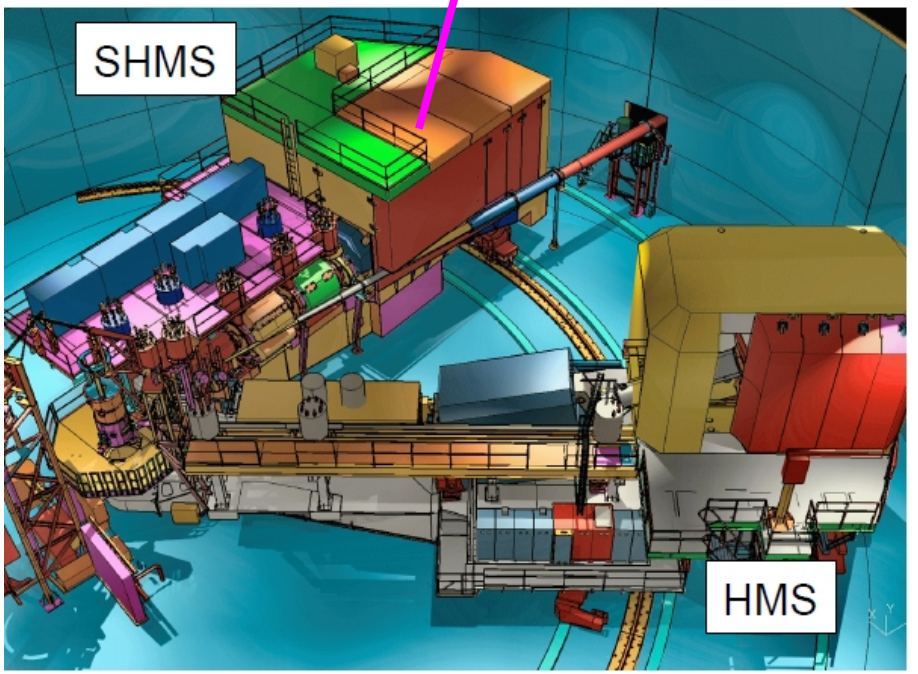
SIDIS with Super HMS in Hall-C

High Momentum Spectrometer (HMS)
dΩ ~ 6 msr, P_0 = 0.5 – 7 GeV/c
θ_0=10.5 - 80 deg.

Super-HMS:
dΩ ~ 5 msr, P_0 = 1 – 11 GeV/c
θ_0=5.5 - 40 deg.

Spectrometers provide very good control of systematics





- Main goal of SIDIS program:
  - Precise measurements of absolute cross-sections
- Approved SIDIS proposals:
  - E12-09-002: π^+/π^- ratios on H/D targets
  - E12-06-104: $R_{SIDIS} = \sigma_L/\sigma_T$ on H/D targets
  - E12-09-017: p_T dependence studies in SIDIS
  - E12-13-007: π^0 production

E12-09-017: P_T Dependence of Semi-Inclusive Pion Production

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

In a simple framework, Gaussian width is assumed for the k_T and p_T behavior of TMD PDFs and FFs, respectively

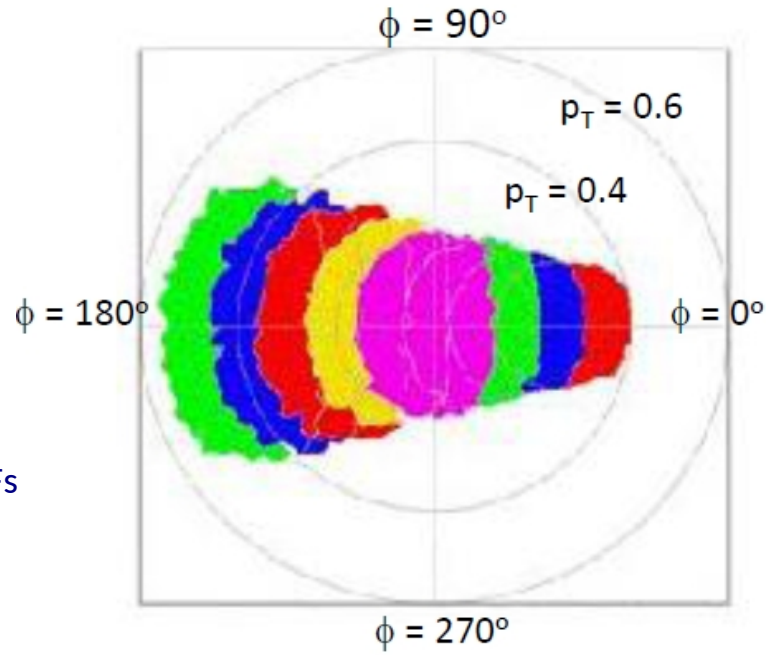
Anselmino et al., PRD 74, 074015 (2006)

$$f_1^q(x, k_\perp) = f_1^q(x) \frac{1}{\pi \mu_0^2} \exp\left(-\frac{k_\perp^2}{\mu_0^2}\right)$$

describes k_T of quarks

$$D_q^h(z, p_\perp) = D_q^h(z) \frac{1}{\pi \mu_D^2} \exp\left(-\frac{p_\perp^2}{\mu_D^2}\right)$$

describes p_T dependence of FFs



Hall C: E12-09-017

- Precise measurements of $\pi^{+/-}$ and $K^{+/-}$ cross sections and ratios
- Can cover low p_T (up to 0.05 GeV) with very good angle and momentum resolution
- Constrain k_T dependence of u and d-quarks separately by combining π^+ and π^- yields, proton and deuteron targets

For P_T ~ 0.5 GeV, use ϕ dependencies measured in CLAS12 experiments

E12-09-017: P_T Dependence of Semi-Inclusive Pion Production

Expected statistical precision for pion and kaon production

Kinematic coverage:

x = 0.2 – 0.5

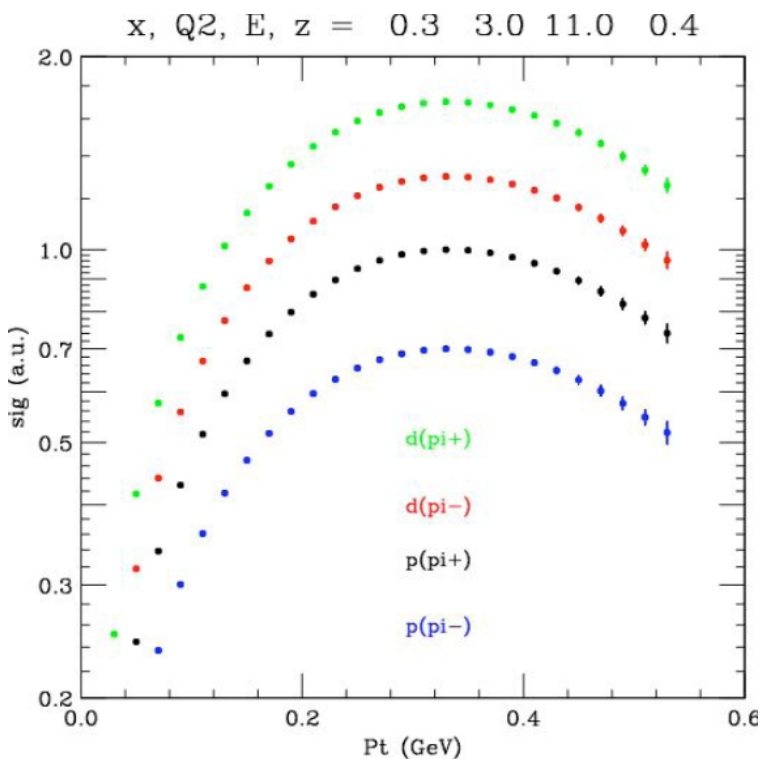
Q^2 = 2 – 5 GeV^2

z = 0.3 – 0.5

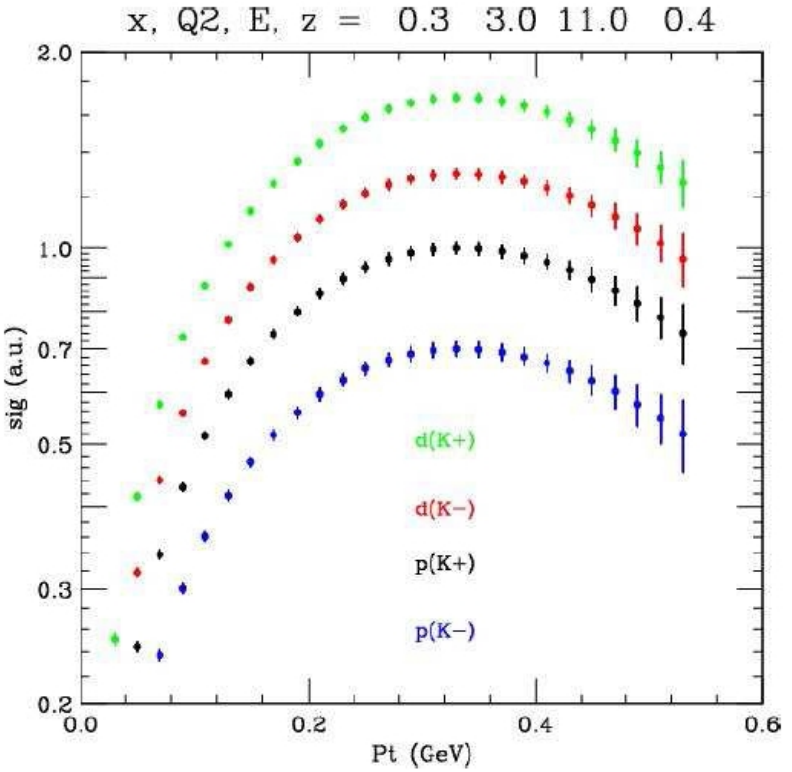
$P_{h\perp}$ < 0.5 GeV

Projections in one (x,Q^2,z) bin

pions

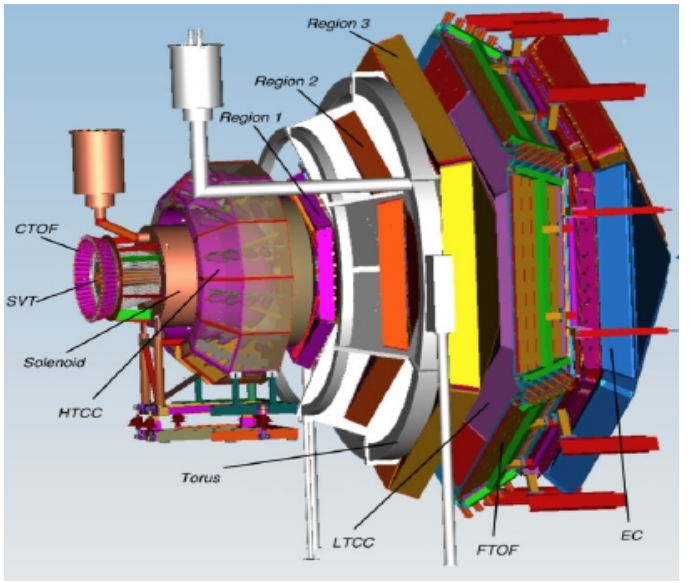


Kaons



CLAS 12 TMD Program

- Luminosity up to 10^{35} $cm^{-2}s^{-1}$
- H and D polarized targets:
  - Solid NH_3, ND_3
  - HD-Ice target
    - Pros: very low field ($\int Bdl \sim 0.005\text{-}0.05 Tm$), small dilution
    - Less radiation length, better FOM
    - Cons: highly complex
    - Need to demonstrate 1-2 nA electron beam can sustain polarization for long periods of time
- Broad kinematic range



Leading Twist TMDs

: Nucleon Spin : Quark Spin

Nucleon Polarization	Quark polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 =		$h_1^\perp$ = − (Boer-Mulder)
L		g_1 = − (Helicity)	$h_{1L}^\perp$ = −
T	$f_{1T}^\perp$ = − (Sivers)	$g_{1T}^\perp$ = −	h_{1T} = − (Transversity); $h_{1T}^\perp$ = −

E12-06-112: Pion SIDIS
E12-09-008: Kaon SIDIS

E12-07-107: Pion SIDIS
E12-09-009: Kaon SIDIS

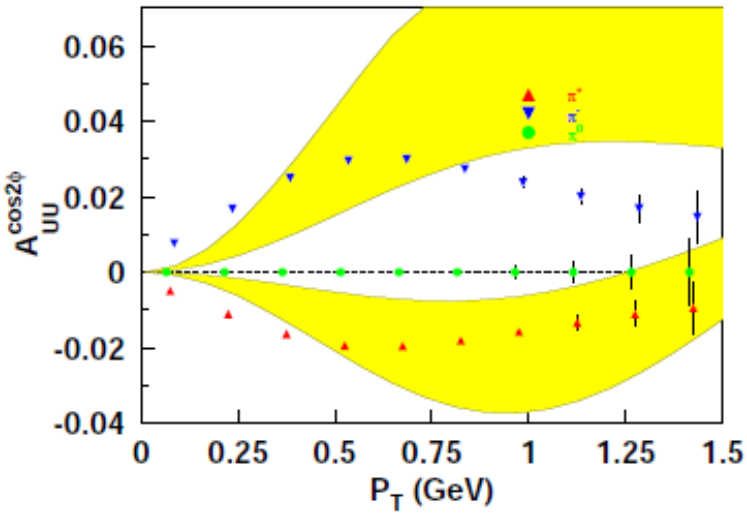
PR12-11-111: Pion/Kaon SIDIS
PR12-12-009: Pion/Kaon SIDIS

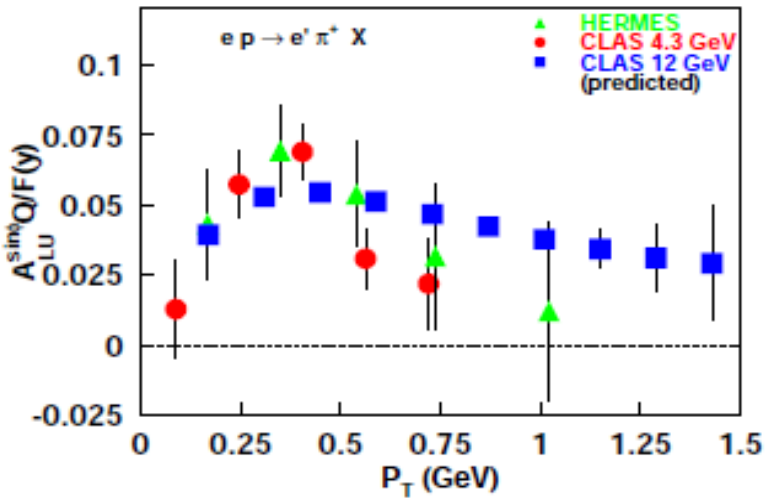
CLAS 12: P_T and Q^2 Dependence in SIDIS

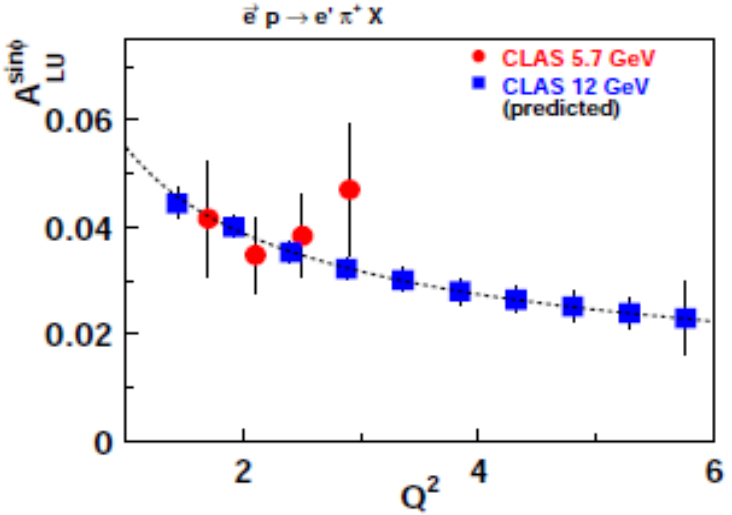
- **E12-06-112** will measure A_{UU} and A_{LU} (beam-spin asymmetry)
- Cos (2φ) azimuthal moment:
  - Boer-Mulder's TMD, related to L=0 and L=1 light-cone wave function
- Cos (φ) and Sin (φ) azimuthal moments:
  - Higher-twist contributions, related q-g-q interactions
- P_T dependence study – perturbative to non-perturbative regime

$$\frac{d\sigma}{dx_B\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\, F_{LU}^{\sin\phi_h}\right\},$$

Expected statistical precision





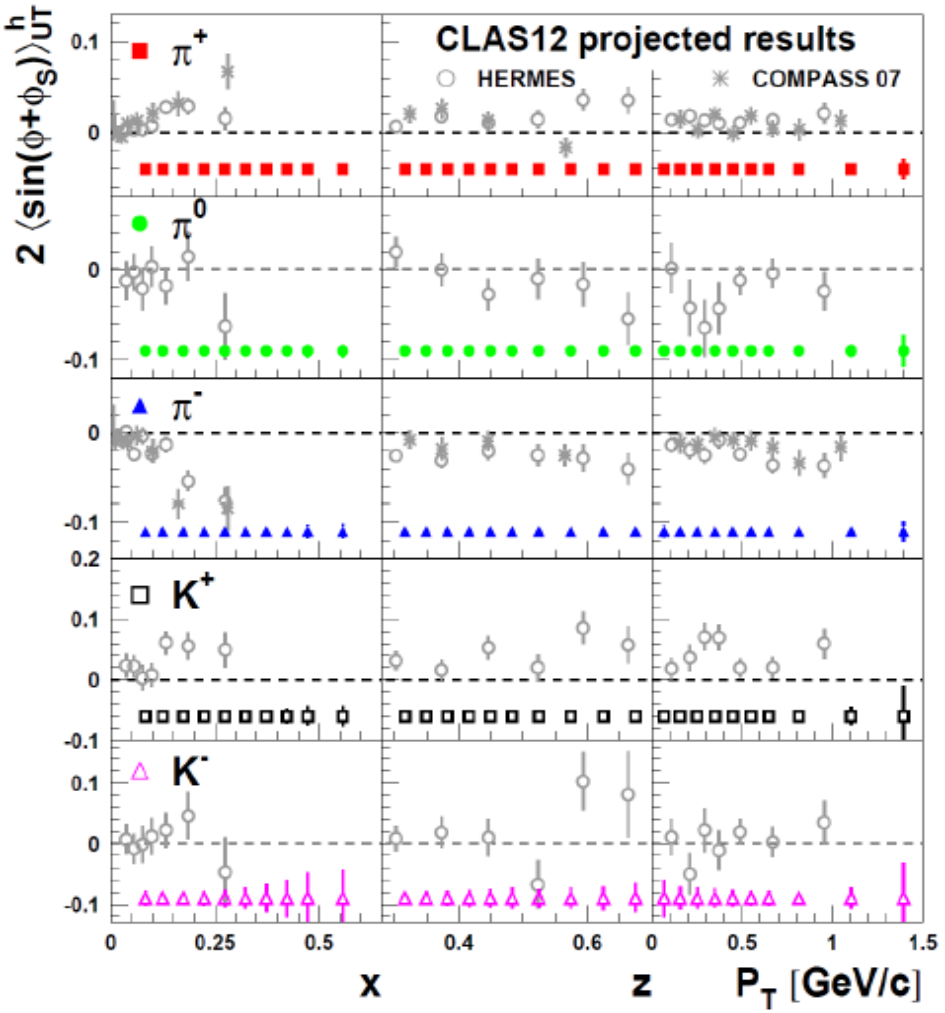


Courtesy: H. Avakian

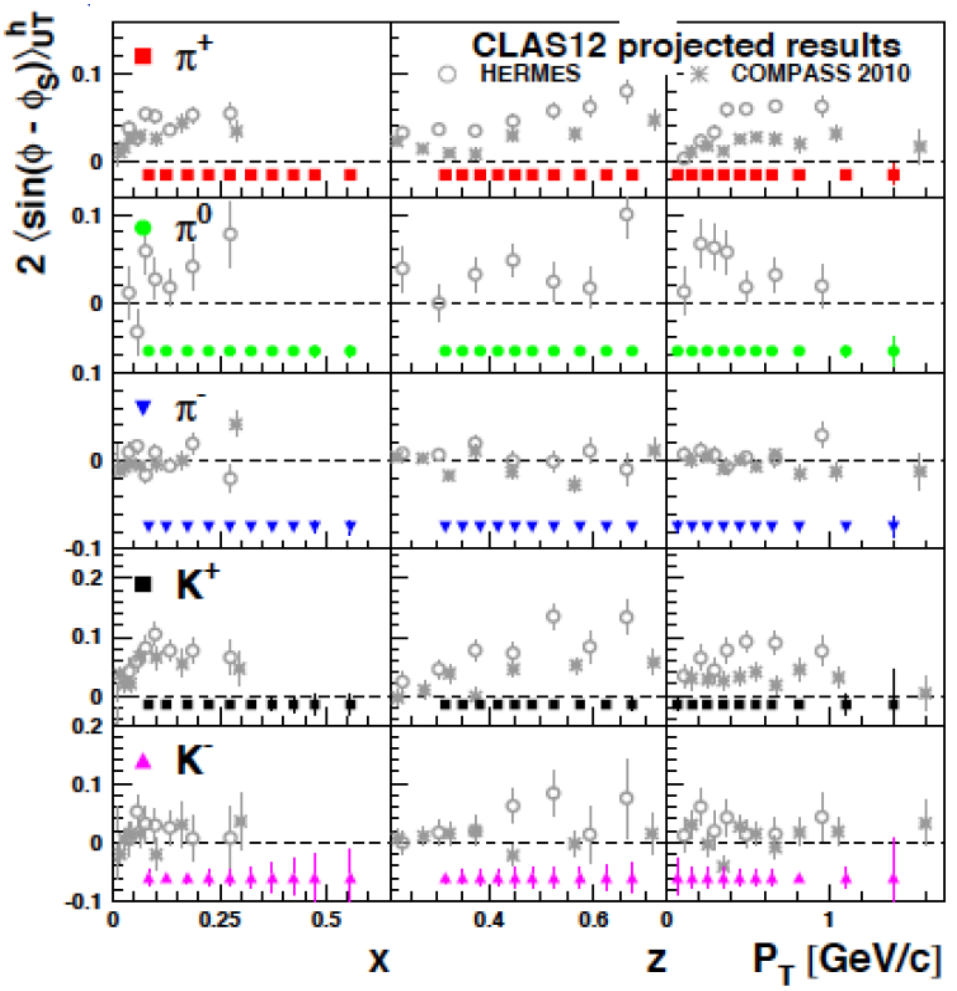
CLAS 12 Projections: Collins and Sivers Moments

100 days @ L = 5×10^{33} $cm^{-2}s^{-1}$, HD-Ice target (60% H pol, f = 1⁄3), RICH detector

Collins



Sivers

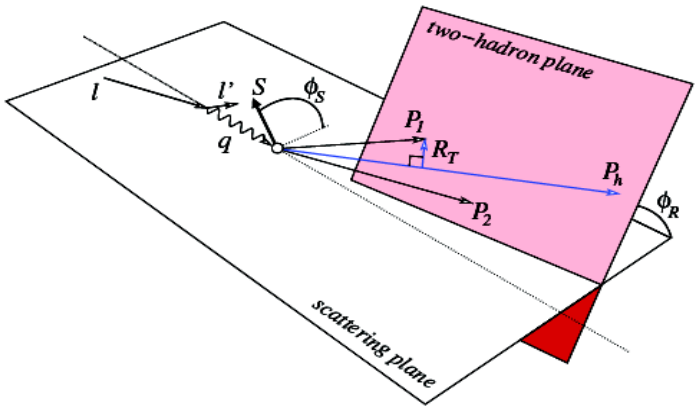


Courtesy, Silvia Pisanos

Transversity From Di-hadron Production in DIS

$$e + p^{\uparrow} \longrightarrow e' + (\pi^{+}\pi^{-}) + X$$

Access transversity through di-hadron production in SIDIS



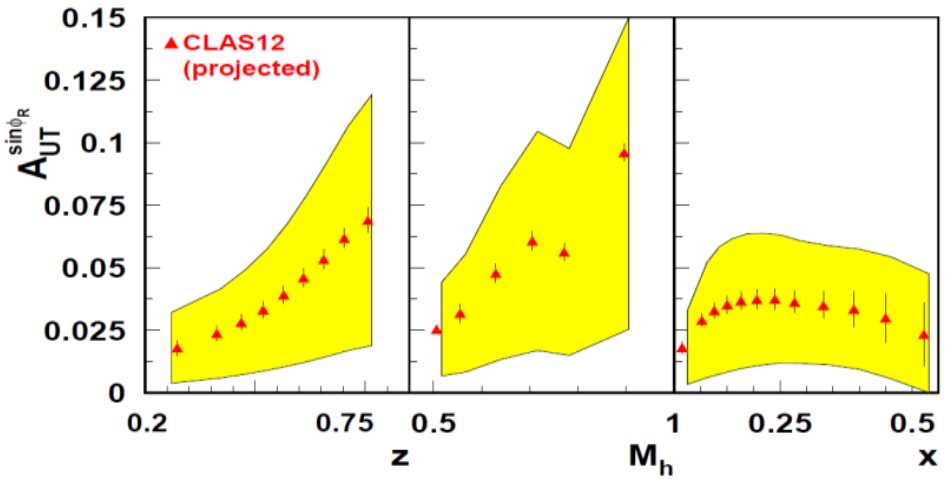
Extracted from Belle data

$$A_{\rm DIS}(x,z,M_h^2,Q^2) = -C_y \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\, \frac{|\vec{R}|}{M_h}\, H_{1,sp}^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2)\quad D_1^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}$$

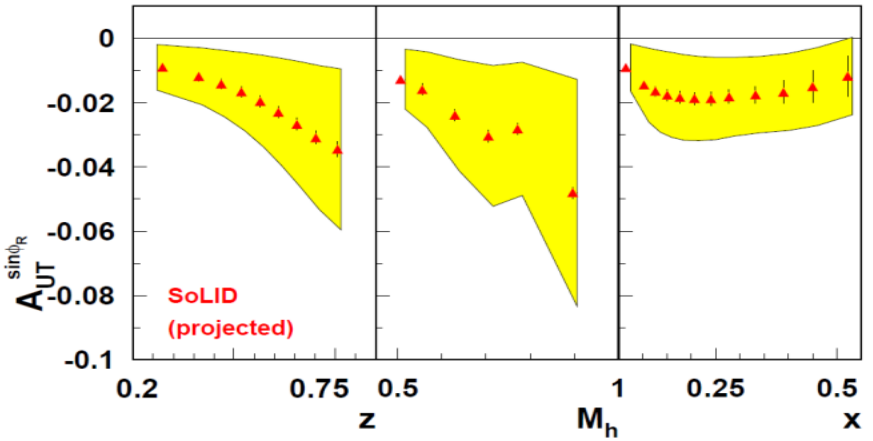
Complementary measurements on proton and neutron:
Hall-A (by SoLID, E12-10-006A) and Hall-B (CLAS12, C12-12-009)

Image courtesy: A. Courtoy

Proton



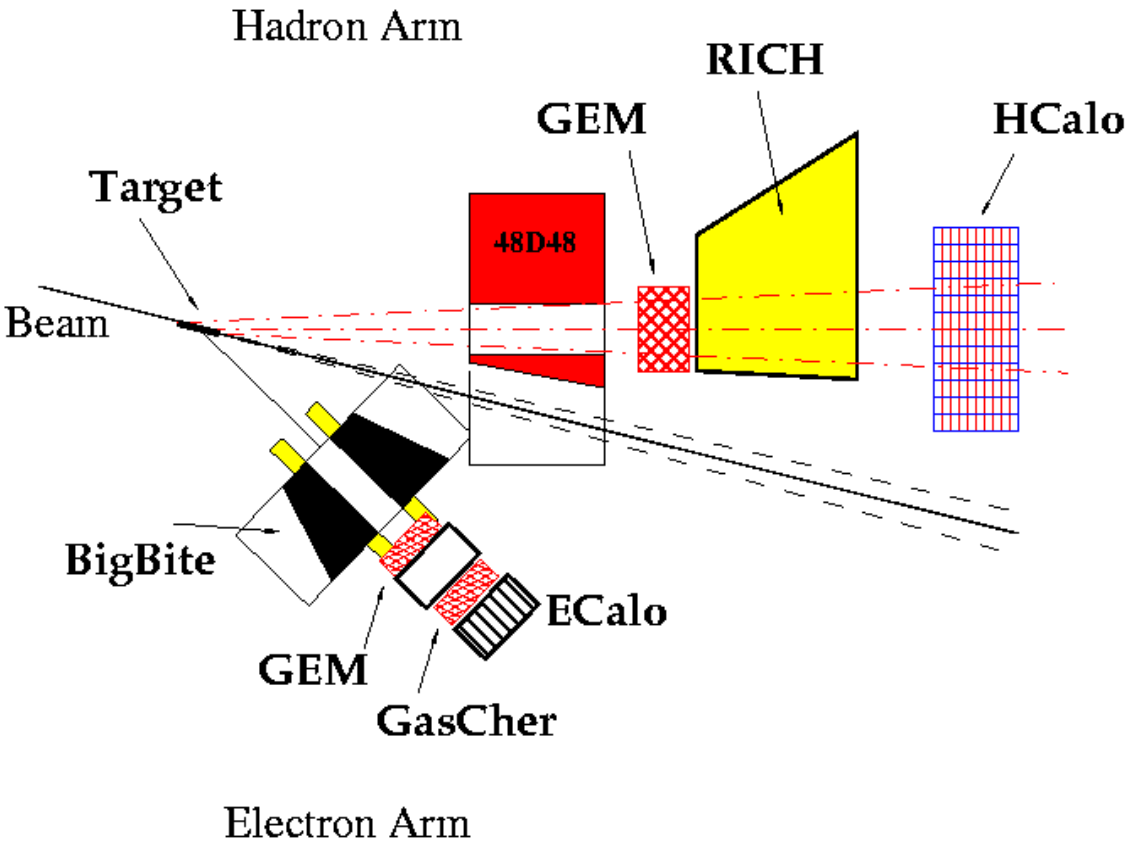
Neutron (^{3}He)



Courtesy, Silvia Pisanos

SIDIS with Super BigBite in Hall A

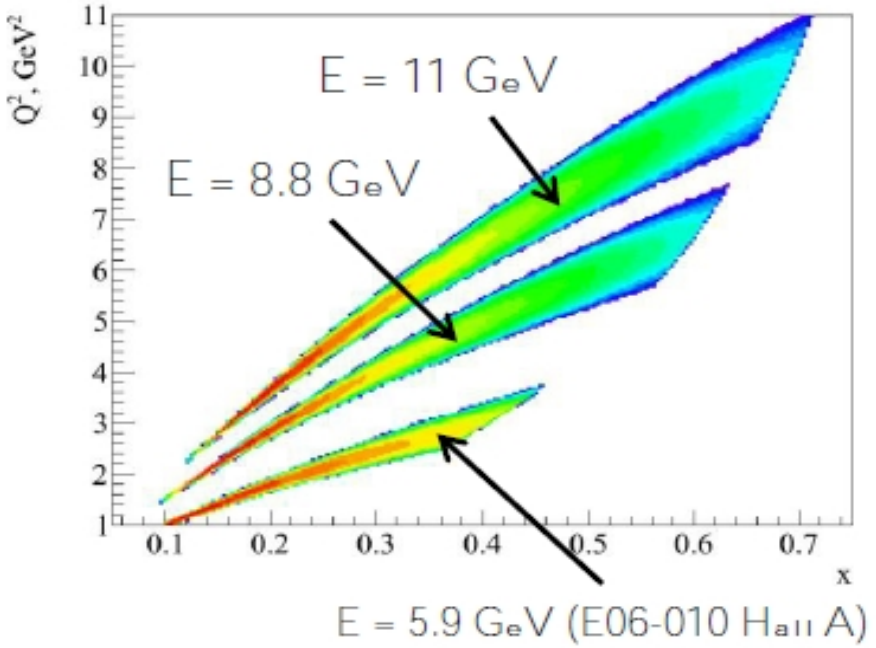
- Approved experiment E12-09-018
- BigBite as electron arm: DIS electrons at ~30 deg., 1 < p < 4 GeV
- SBS as hadron arm @ 14 deg.
- High-luminosity (10^{36} $cm^{-2}s^{-1}$) polarized ^{3}He target (with spin-flip)
- Reuse HERMES RICH detector for Kaon PID
- Will extract Collins/Sivers/pretzelosity for pion and kaons
- Expected to run ~2018 or after



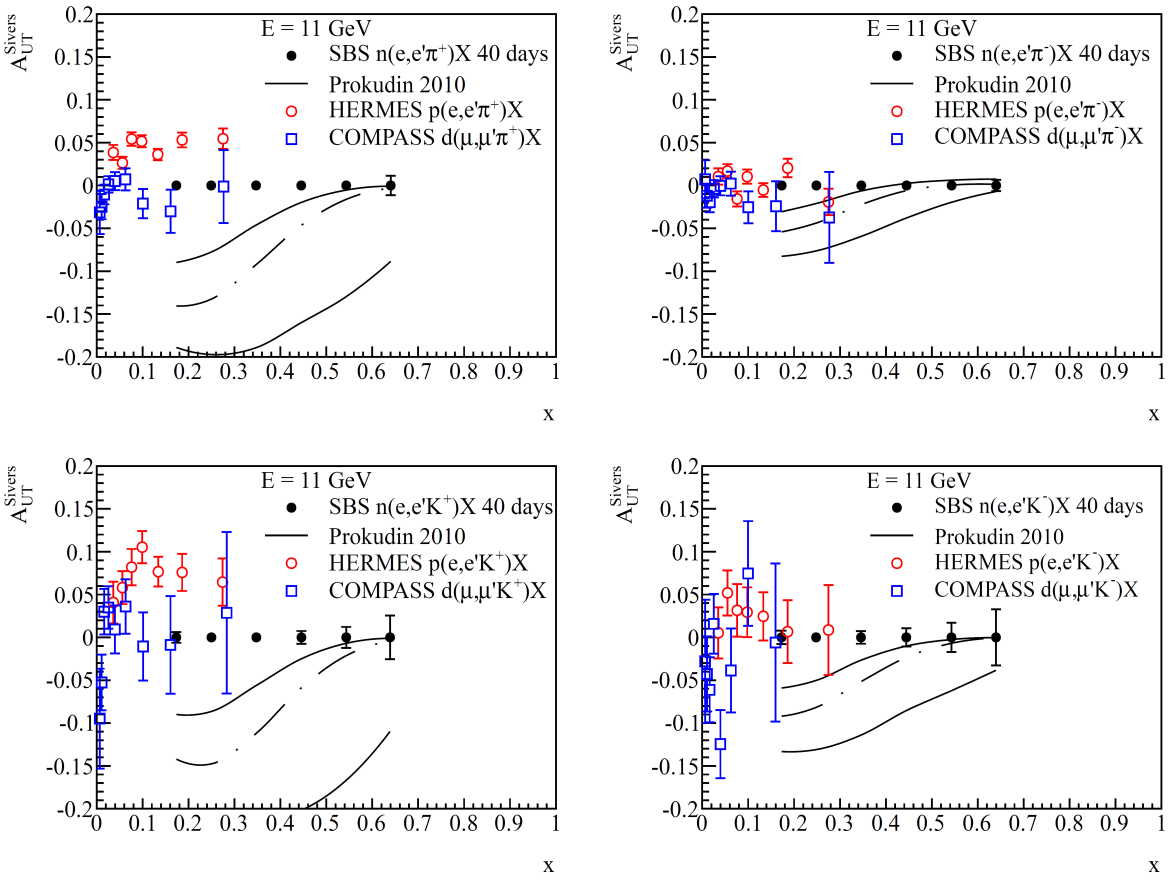
Courtesy, A. Puckett

SIDIS with Super BigBite in Hall A

SBS-SIDIS: Q^2 vs x coverage



Expected precision on Sivers Asymmetry



- 40 days @ 11 GeV
- 20 days @ 8.8 GeV
- ~100X higher statistical FOM than HERMES proton data

Courtesy, A. Puckett

Summary

- Many important results from JLab 6 GeV SIDIS program:
  - Unpolarized cross-section results suggest that partonic interpretation of SIDIS data is reasonable at low energy of JLab
  - P_T dependence studies reveal possible flavor dependence of k_t widths for u and d-quarks
  - Non-zero beam SSA (A_{LU}) from CLAS suggest the importance of sub-leading twist PDFs in TMD studies
  - Non-zero target SSA (A_{UL}) from CLAS point to spin-orbit correlations - related to quark OAM
  - Large SSA in inclusive hadron production – challenge in interpreting low P_T data
  - Non-zero DSA in inclusive hadron production – provide insights into twist-3 q-g-q correlations, albeit at low P_T

- The 6 GeV SIDIS program has laid a strong foundation for precision studies at JLab 12 GeV

- A comprehensive SIDIS program at 12 GeV:
  - Wide kinematic coverage and large acceptance
  - Precise un-polarized cross-sections and their kinematic dependence
  - Study leading and sub-leading twist TMDs

Spare Slides