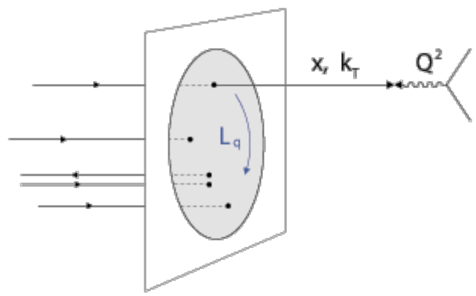
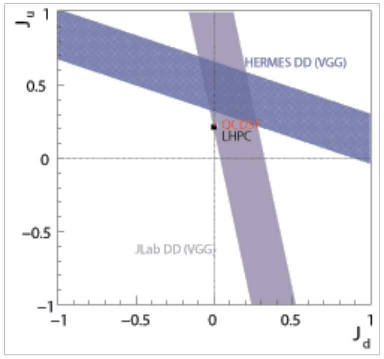
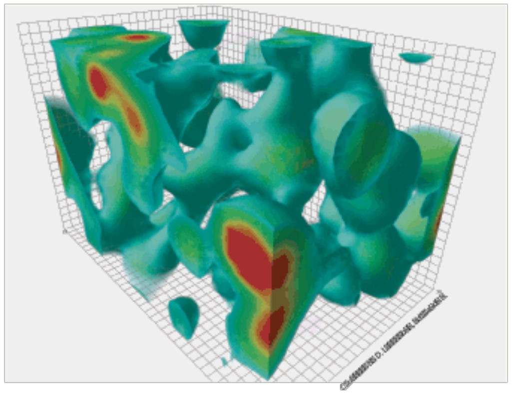
TMDs with JLab12 and EIC

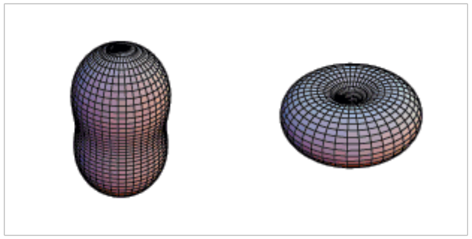
Harut Avakian (JLab)

INT Workshop on Orbital Angular Momentum in QCD
February 10 2012









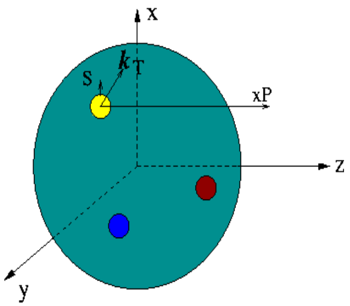
Outline

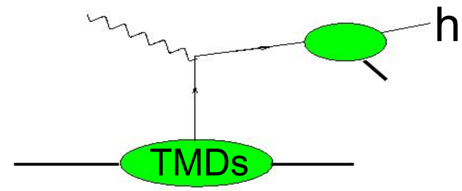
Transverse structure of the nucleon and partonic correlations

- k_T-effects with unpolarized and polarized target data
- Studies of 3D PDFs at JLab at 6 GeV
- Studies of 3D structure of the nucleon at JLab12
- Measuring spin and azimuthal asymmetries with EIC
- From asymmetries to TMDs
- Summary

3D structure of the nucleon

Semi-Inclusive processes and transverse momentum distributions

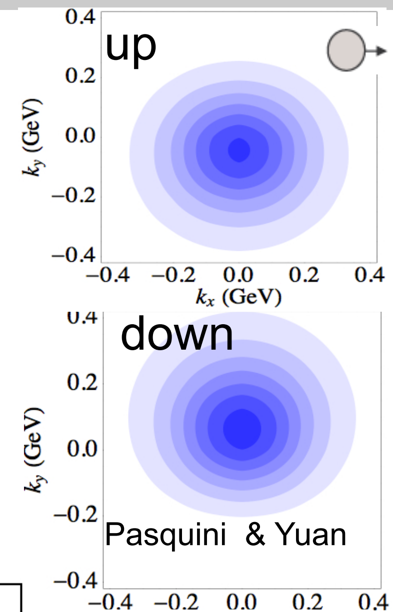




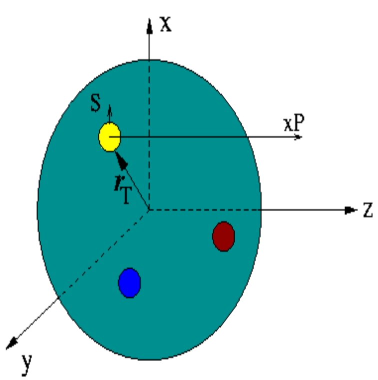
$f_1^q(x,\mathbf{k}_\perp)$ g_1^q $f_{1T}^{\perp q}$ g_{1T}^q

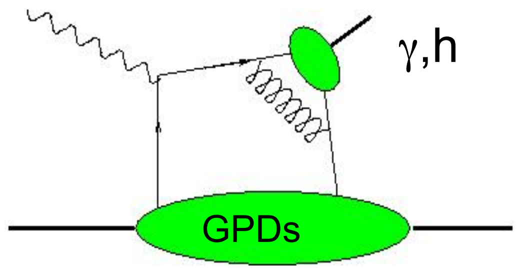
h_1^q $h_{1T}^{\perp q}$ $h_{1L}^{\perp q}$ $h_1^{\perp q}$

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



Hard exclusive processes and spatial distributions of partons

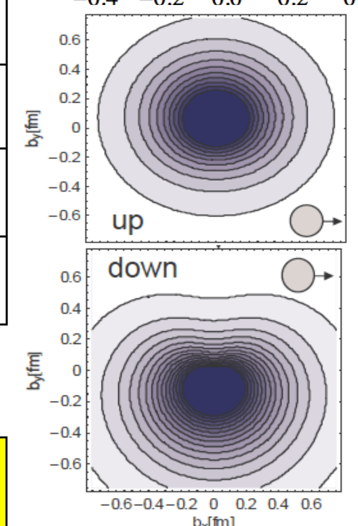




$H^q(x,\xi,t)$ $\tilde{H}^q$ E^q $\tilde{E}^q$

H_T^q $\tilde{H}_T^q$ E_T^q $\tilde{E}_T^q$

	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$



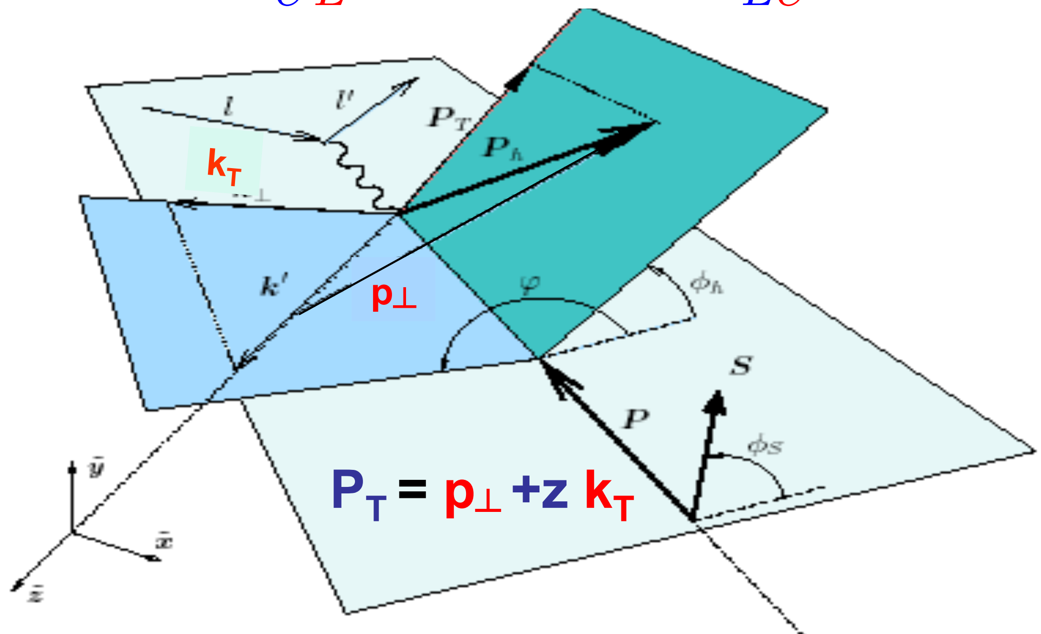
(QCDSF)

Wide kinematic coverage of large acceptance detectors allows studies of exclusive (GPDs) and semi-inclusive (TMDs) processes providing complementary information on transverse structure of nucleon

SIDIS: partonic cross sections

$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

$$\sigma = F_{UU} + P_t F_{UL}^{\sin\phi} \sin 2\phi + P_b F_{LU}^{\sin\phi} \sin\phi \ldots$$



Transverse momentum of hadrons in SIDIS provides access to orbital motion of quarks

Ji,Ma,Yuan Phys.Rev.D71:034005,2005

$$d\sigma^h \propto \sum e_q^2 \int d^2\vec{k}_T d^2\vec{p}_T d^2\vec{l}_T f^{H\to q}(x, k_T) D^{q\to h}(z, p_\perp) S(\vec{l_T}) H(Q) \delta(z\vec{k}_T + \vec{p}_T + \vec{l}_T - \vec{P}_T)$$

Azimuthal moments in SIDIS

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$
$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}$$
$$+\varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$
$$+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}\right]$$
$$+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$
$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+\varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$
$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$
$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

quark polarization

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

Higher Twist PDFs

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

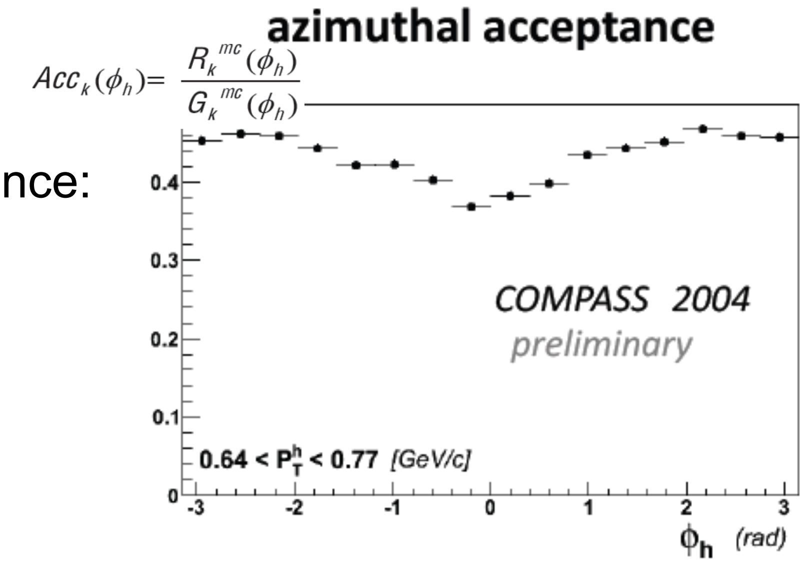
Experiment for a given target polarization measures all moments simultaneously

Extracting the moments

Moments mix in experimental azimuthal distributions

Simplest acceptance -> $1 + A\cos\phi$

Acceptance:



Correction to normalization

$$(1+\alpha\cos\phi)(1+A\cos\phi) \to 1 + A\alpha/2$$

$$(1+\beta\lambda\Lambda+\gamma\lambda\Lambda\cos\phi)(1+A\cos\phi)$$
$$\to 1 + (\beta+\gamma A/2)\lambda\Lambda$$

Correction to DSA

Moments/asymmetries:

$$(1+S_T\delta\sin\phi_S)(1+A\cos\phi)$$
$$\to 1 + S_T/2\delta A(\sin\phi-\phi_S) + \dots$$

Correction to SSA

$$\frac{1+\beta\lambda\Lambda}{1+a\cos\phi} \to 1 - a\beta\lambda\Lambda\cos\phi$$

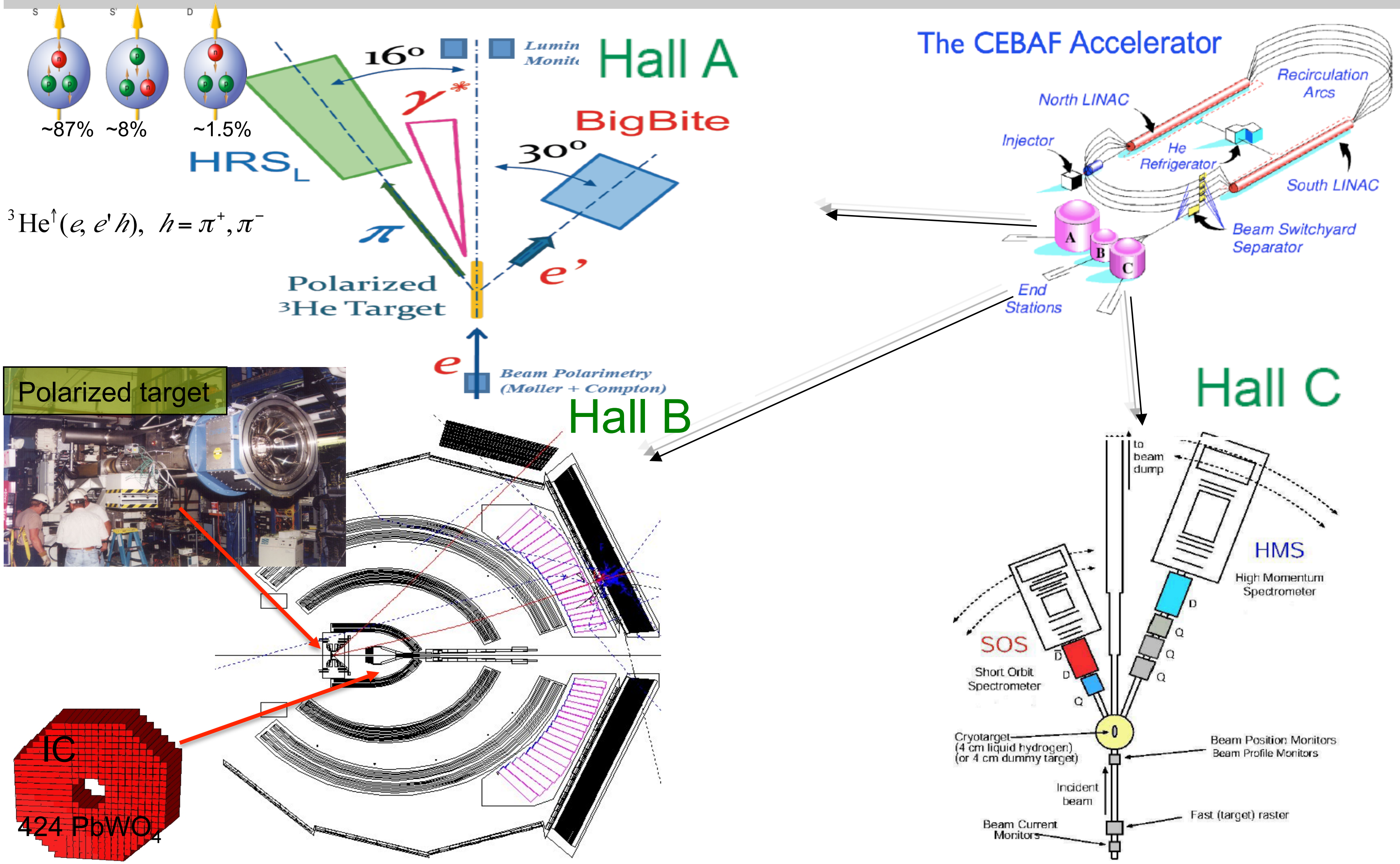
Fake DSA cos

Virtual photon angle:

$$\sin\theta_\gamma = \sqrt{\frac{4M^2x^2}{Q^2+4M^2x^2}\left(1-y-\frac{M^2x^2y^2}{Q^2}\right)}$$

Simultaneous extraction of moments is important also because of correlations!

JLab Experimental Halls



P_T-dependence studies at Hall-C

H. Mkrtchyan(DIS2011)

Experiment E00-108

Beam energy 5.5 GeV

4 cm LH2 and LD2 targets

$$P_t = p_t + zk_t$$

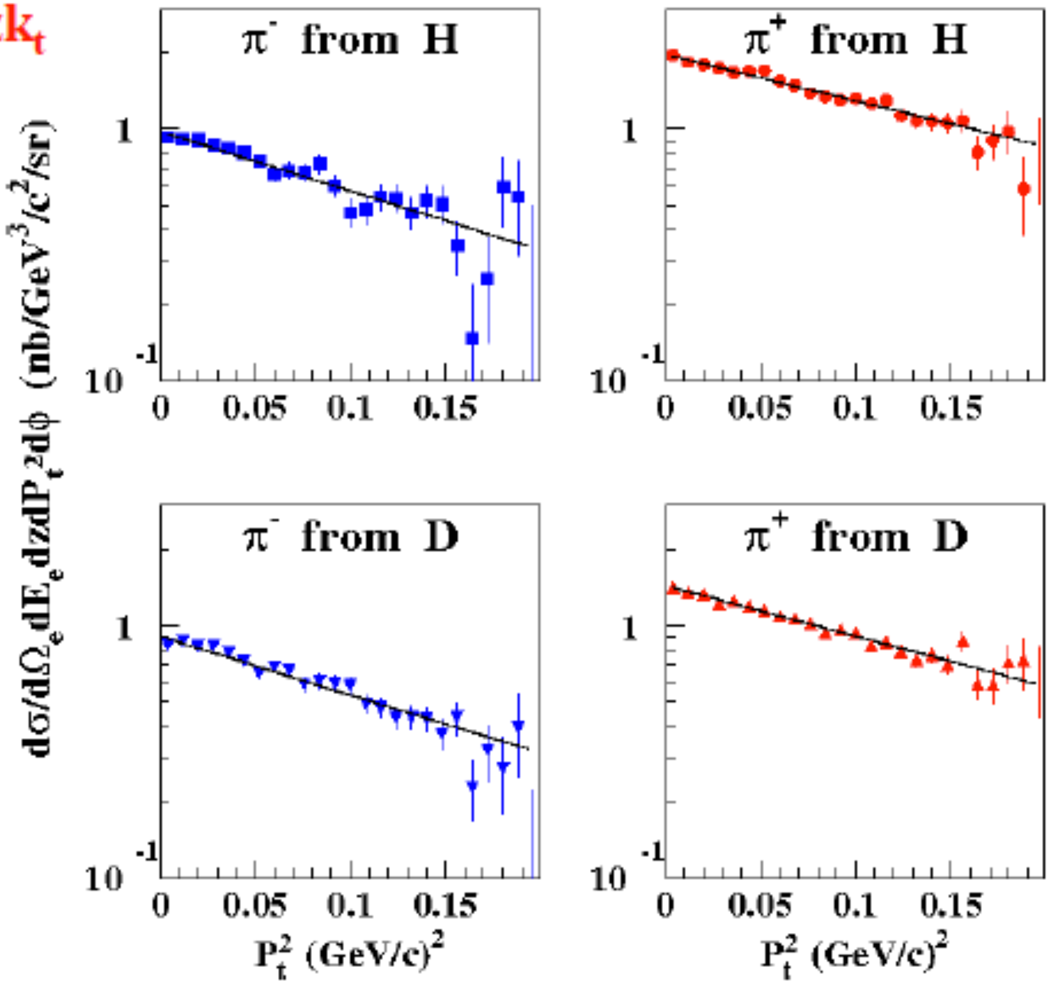
$$\sigma_{SIDIS} \sim \sigma_{DIS}\,(dN/dz)\; b\, \exp(-bP_t^2)$$

$b_H^- = 5.44 \pm 0.36$

$b_D^- = 5.35 \pm 0.26$

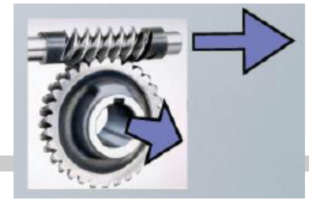
$b_H^+ = 4.24 \pm 0.17$

$b_D^+ = 4.64 \pm 0.17$



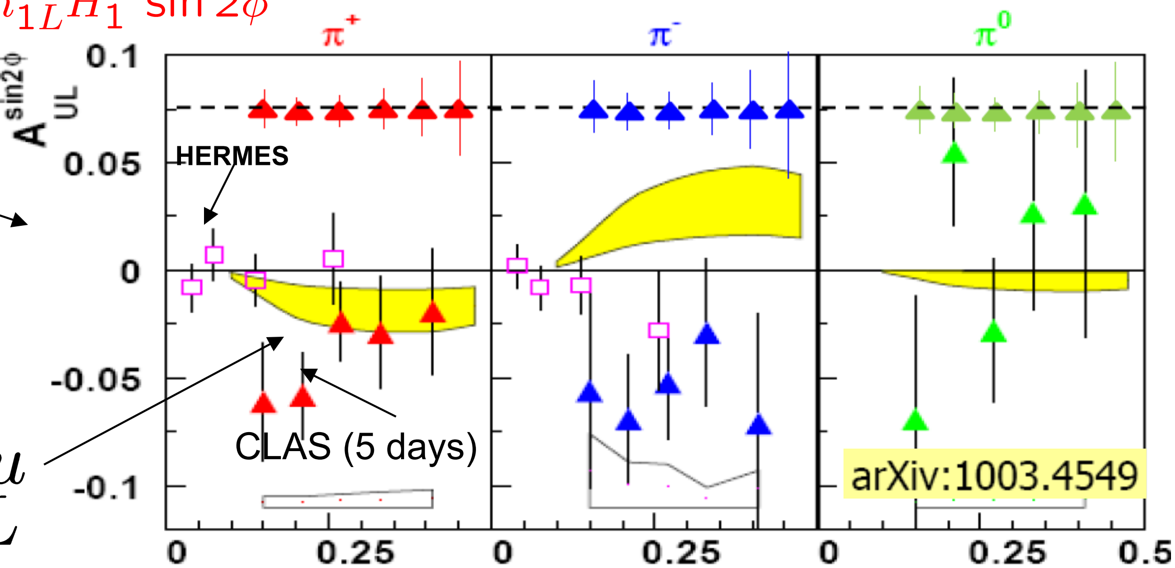
Data (assuming only valence quarks and only two fragmentation functions contribute) indicate that k_T-width of u-quarks is larger than for d-quarks

Kotzinian-Mulders Asymmetries



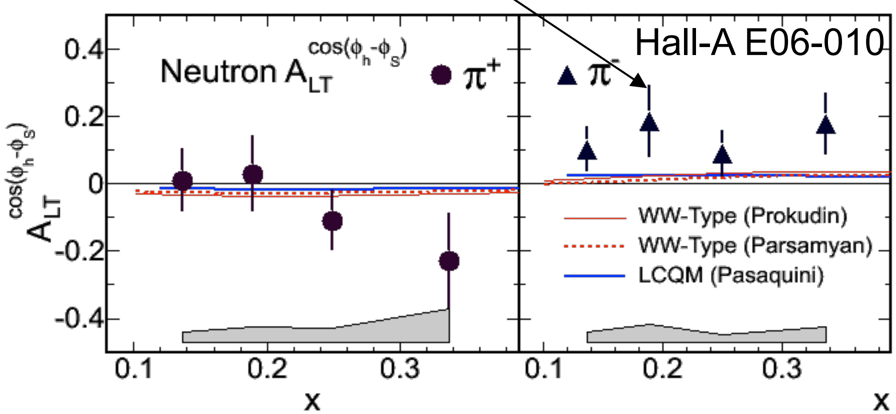
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

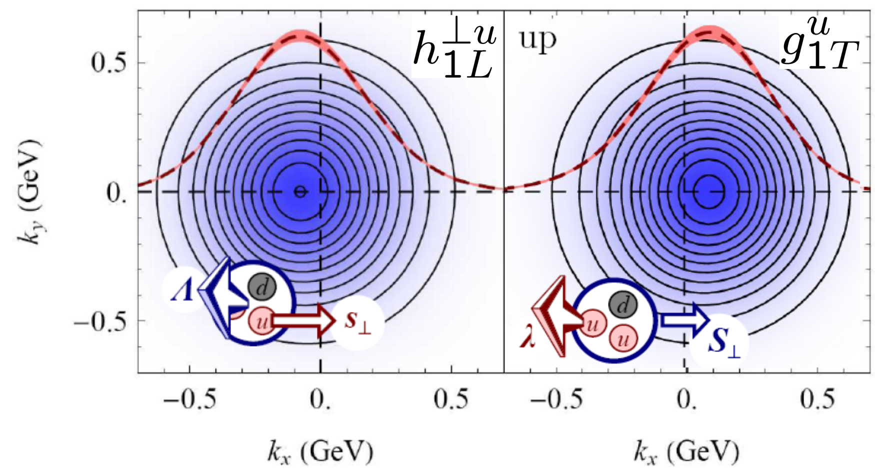
$$A_{UL}^{\sin 2\phi} \sim h_{1L}^\perp H_1^\perp \sin 2\phi$$



$$g_{1T}^u \approx -h_{1L}^{\perp u}$$

J. Huang (DIS2011)



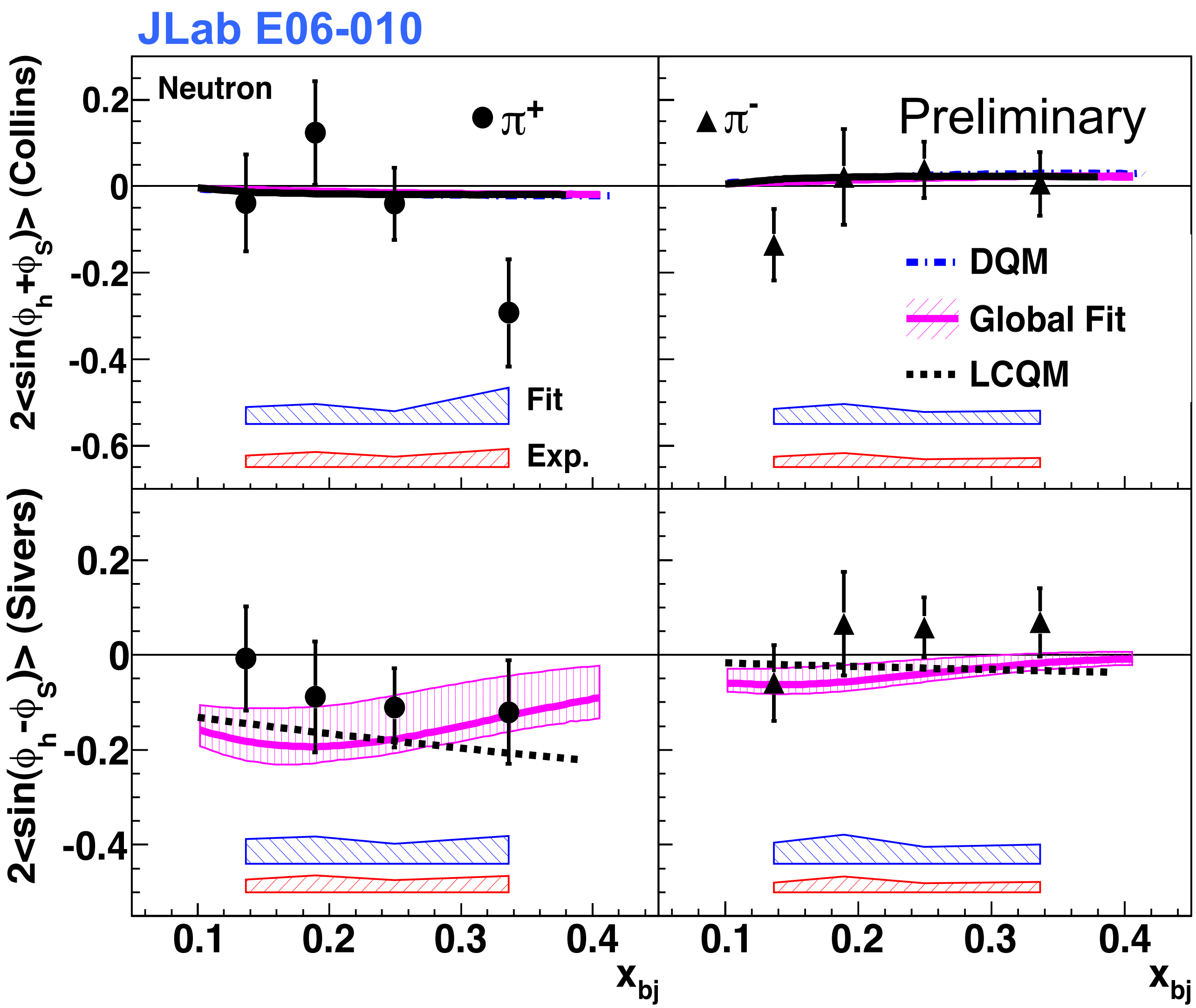


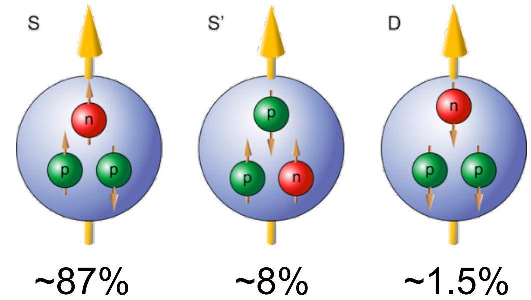
B.Musch arXiv:0907.2381
B.Pasquini et al, arXiv:0910.1677

Worm gear TMDs are unique (no analog in GPDs)

^{3}He Target Single-Spin Asymmetry in SIDIS

$$^3He^{\uparrow}(e, e'h), \quad h = \pi^+, \pi^-$$





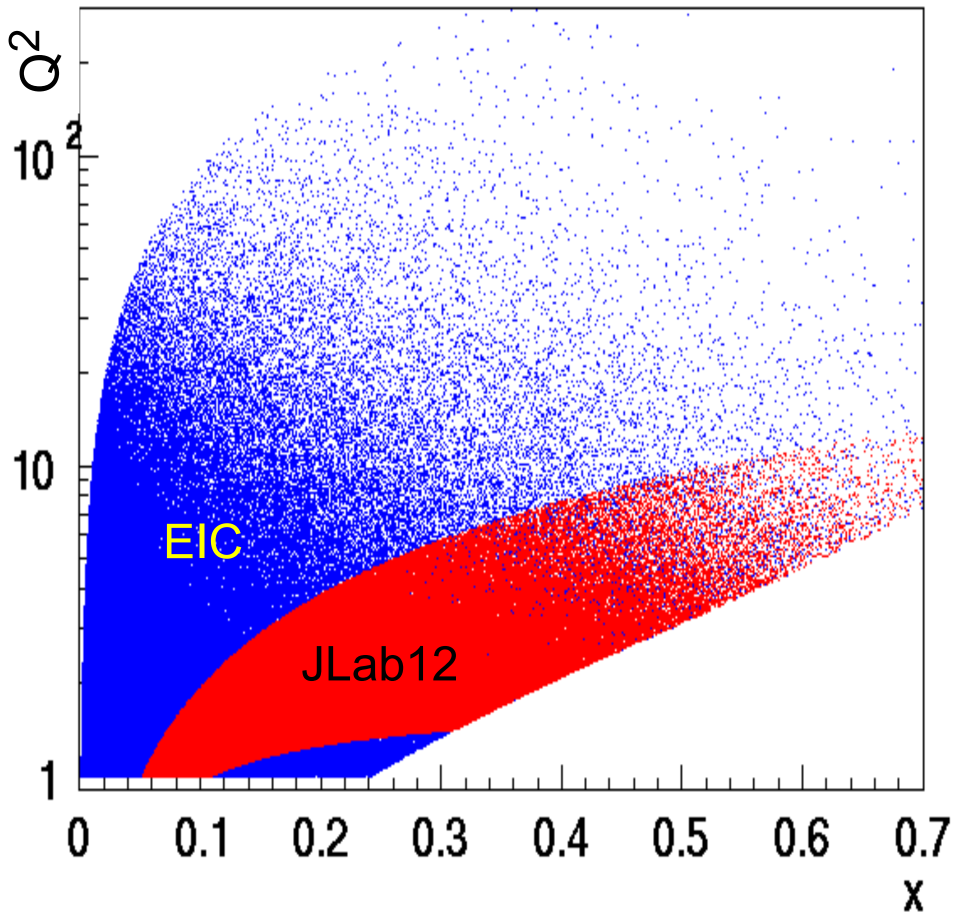
To extract information on neutron, one would assume:

$$^3He^{\uparrow} = 0.865 \cdot n^{\uparrow} - 2 \times 0.028 \cdot p^{\uparrow}$$

Collins asymmetries for neutron are not large, except at x=0.34

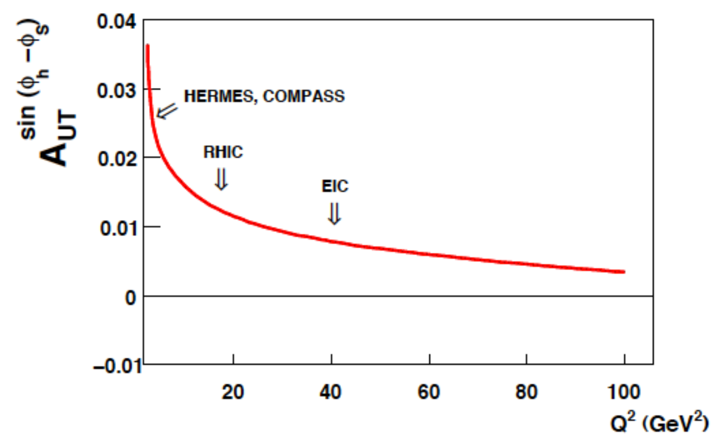
Sivers agree with global fit, and light-cone quark model.

Hard Scattering Processes: Kinematics Coverage

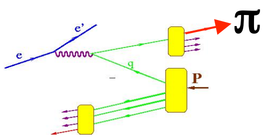


JLab@12GeV (25)
→ $0.1<x_B<0.7$: valence quarks
EIC $\sqrt{s}$ = 140, 50, 15 GeV
→ $10^{-4}<x_B<0.3$: gluons and quarks, higher P_T and Q^2.

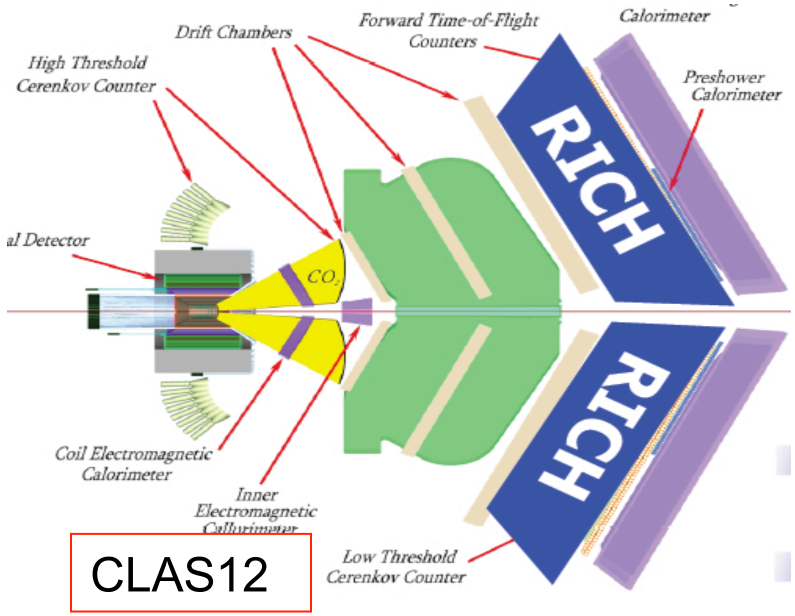
Aybat,Prokudin&Rogers arXiv:1112.4423

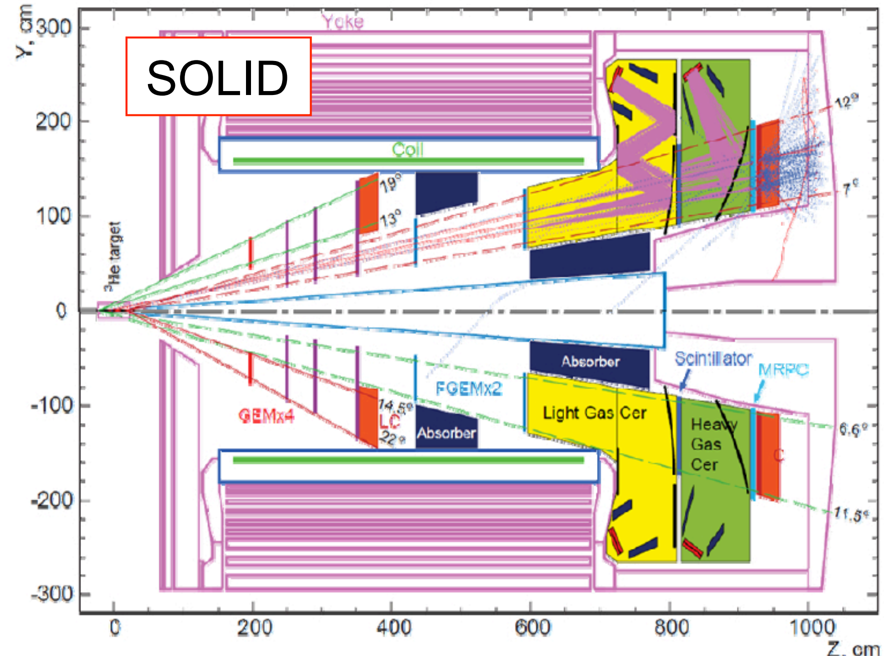


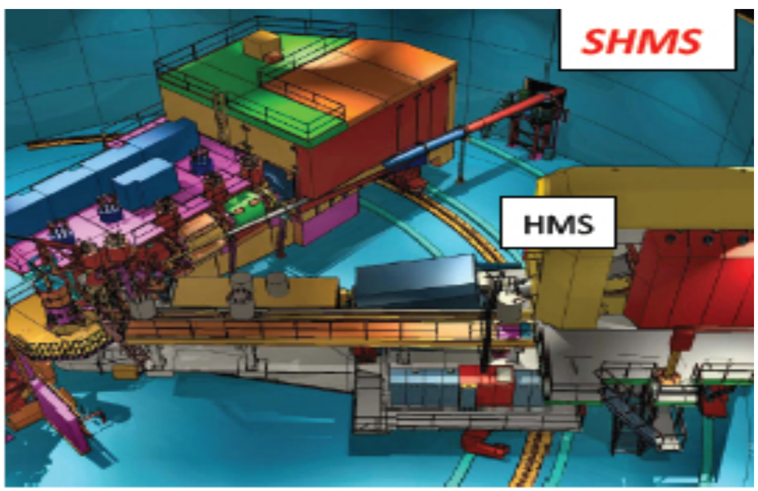
- Study of high **x** domain requires high luminosity, low **x** higher energies
- Wide range in Q^2 is crucial to study the evolution
- Overlap of EIC and JLab12 in the valence region will be crucial for the TMD program

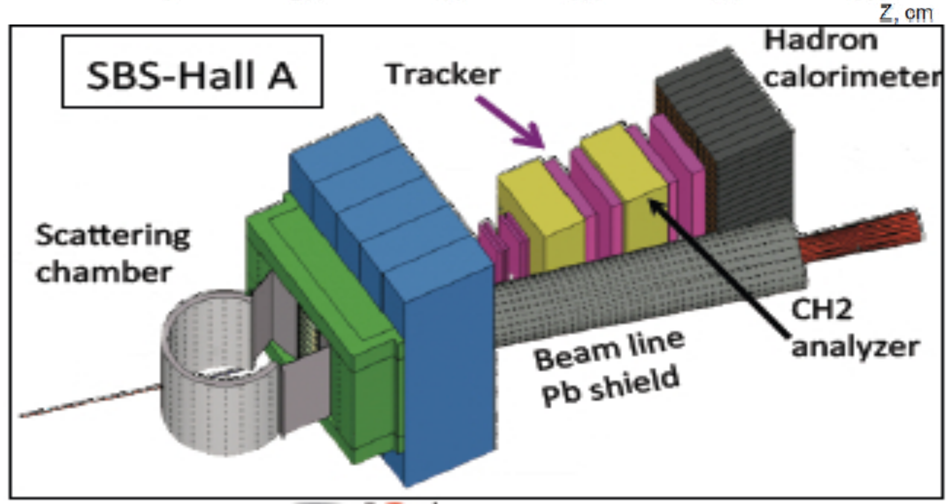


SIDIS at JLab12









The Multi-Hall SIDIS Program at 12 GeV

M. Aghasyan, K. Allada, H. Avakian, F. Benmokhtar, E. Cisbani, J-P. Chen, M. Contalbrigo, D. Dutta, R. Ent, D. Gaskell, H. Gao, K. Griffioen, K. Hafidi, J. Huang, X. Jiang, K. Joo, N. Kalantarians, Z-E. Meziani, M. Mirazita, H. Mkrtchyan, L.L. Pappalardo, A. Prokudin, A. Puckett, P. Rossi, X. Qian, Y. Qiang, B. Wojtsekhowski

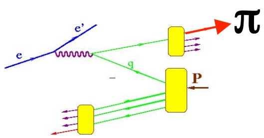
for the Jlab SIDIS working group

The complete mapping of the multi-dimensional SIDIS phase space will allow a comprehensive study of the TMDs and the transition to the perturbative regime.

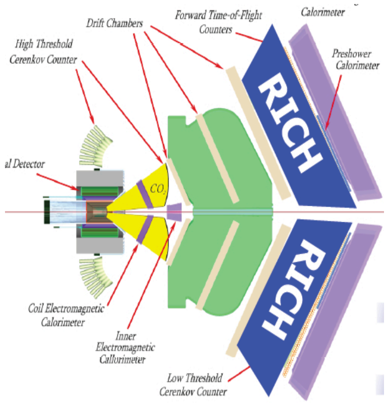
Flavor separation will be possible by the use of different target nucleons and the detection of final state hadrons.

Measurements with pions and kaons in the final state will also provide important information on the hadronization mechanism in general and on the role of spin-orbit correlations in the fragmentation in particular.

Higher-twist effects will be present in both TMDs and fragmentation processes due to the still relatively low Q^2 range accessible at JLab, and can apart from contributing to leading-twist observables also lead to observable asymmetries vanishing at leading twist. These are worth studying in themselves and provide important information on quark-gluon correlations.



SIDIS at JLab12



Proton

CLAS12

- E12-06-112: π^+,π^-,π^0; E12-09-008: K^+, K^-, K^0
- E12-07-107: π^+,π^-,π^0; E12-09-009: K^+,K^-,K^0
- C12-11-111: π^+,π^-,π^0, K^+, K^-

H_2, NH_3, HD

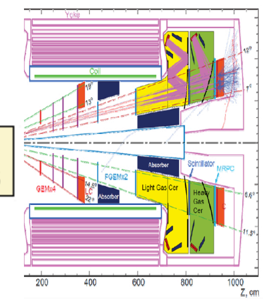
Quark spin polarization (columns) / Nucleon polarization (rows)

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

Hall C | Hall A

- E12-09-017: π^+,π^-, K^+,K^-; C12-11-102: π^0 — HMS SHMS
- C12-11-108: π^+,π^- — Solid

H_2 | NH_3



D_2

CLAS12

- E09-008: π^+,π^-,π^0, K^+, K^-,K^0
- E07-107: π^+,π^-,π^0; E09-009: K^+,K^-,K^0

D_2, ND_3

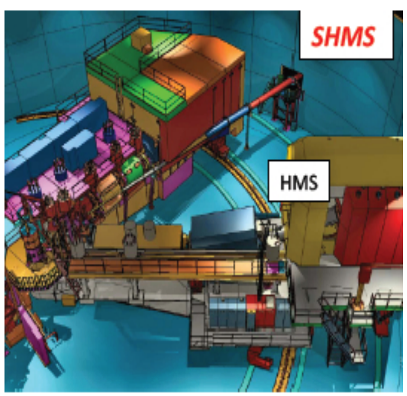
Quark spin polarization (columns) / Nucleon polarization (rows)

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

Hall C

- E12-09-017: π^+,π^-, K^+,K^-; C12-11-102: π^0 — HMS SHMS

D_2



^3He

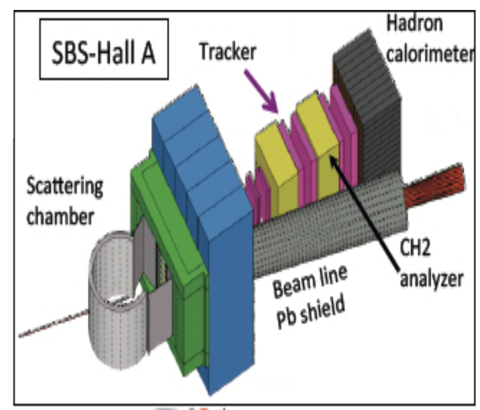
Quark spin polarization (columns) / Nucleon polarization (rows)

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

Hall A

- E12-07-007: π^+,π^- — Solid
- E10-006: π^+,π^- — Solid; E12-09-018: π^+,π^-, K^+,K^- — SBS

^3He

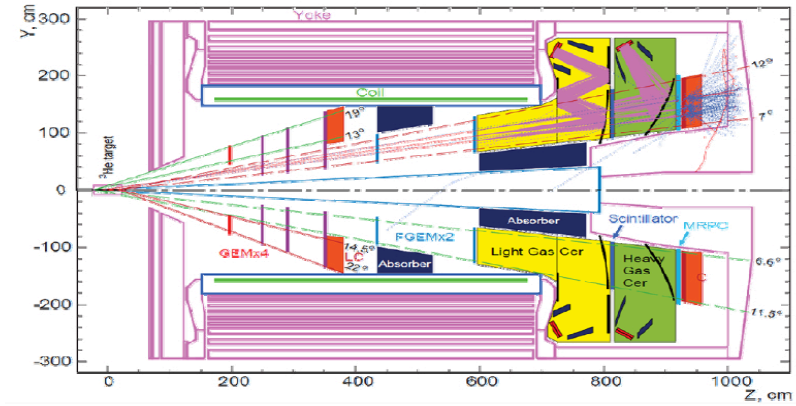


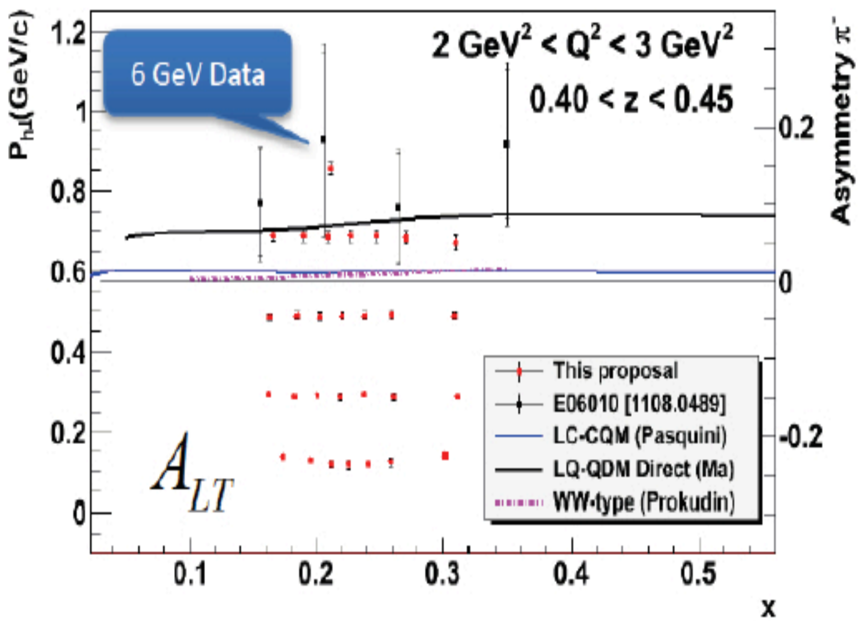
SOLID A_{UL} on ^{3}He

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

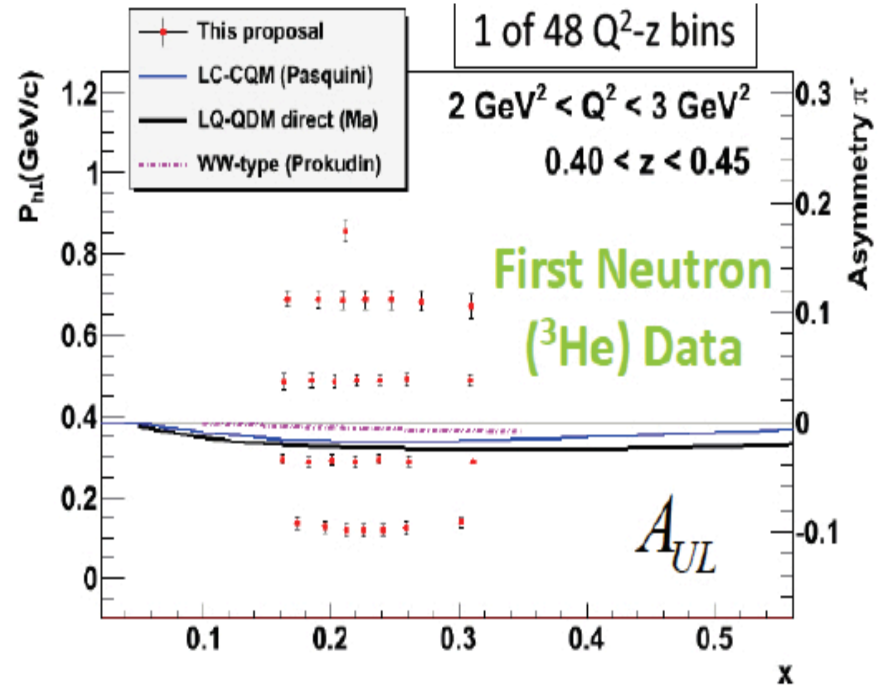
E12-11-007

$e^3He \to e\pi^- X$



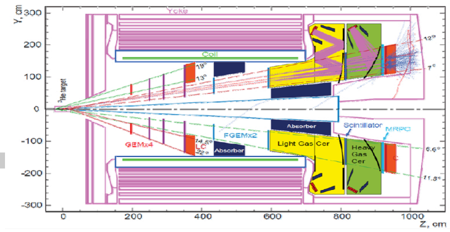


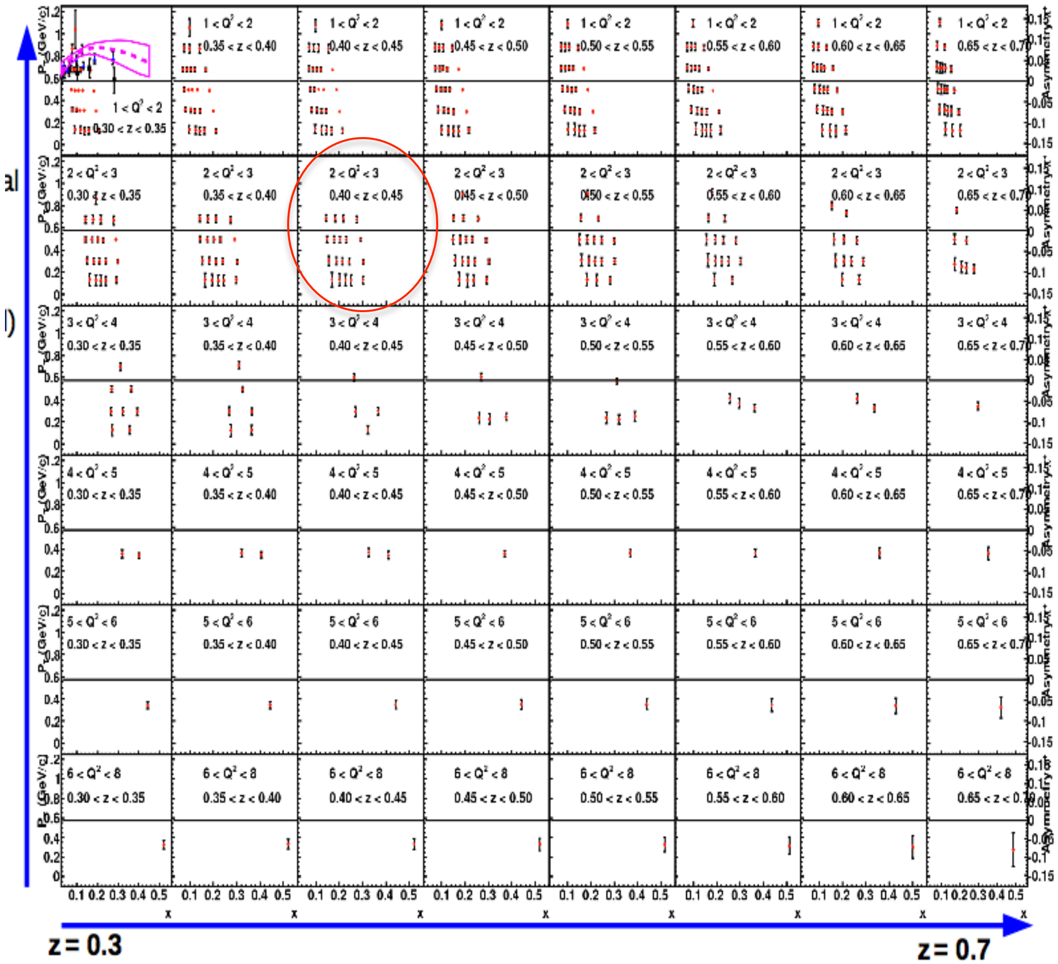
1 of 48 Q^2-z bins

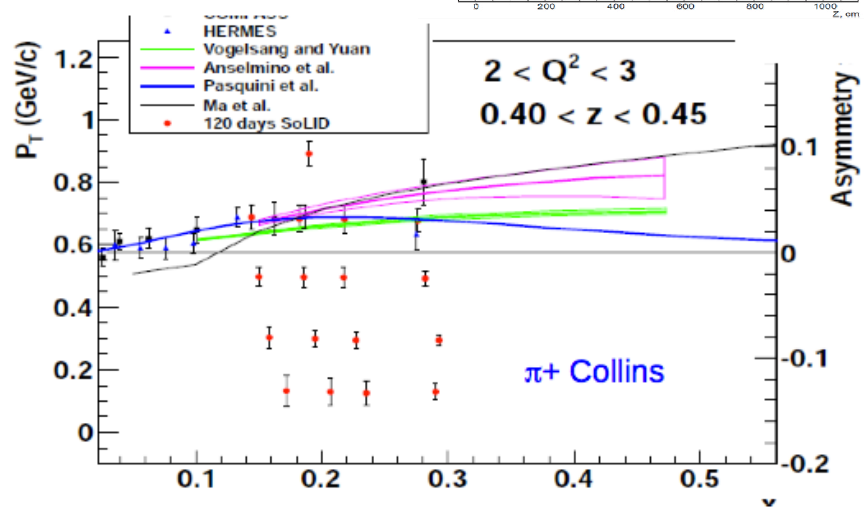


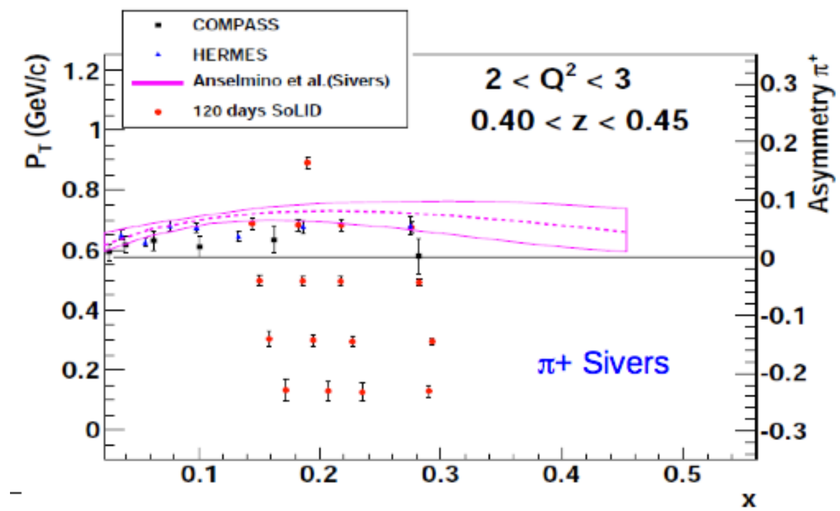
E12-11-108

A_{UT} studies using SOLID









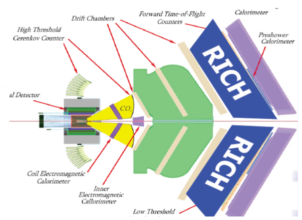
Precision 4-d mapping of target SSA using SoLID and polarized NH3(p) target

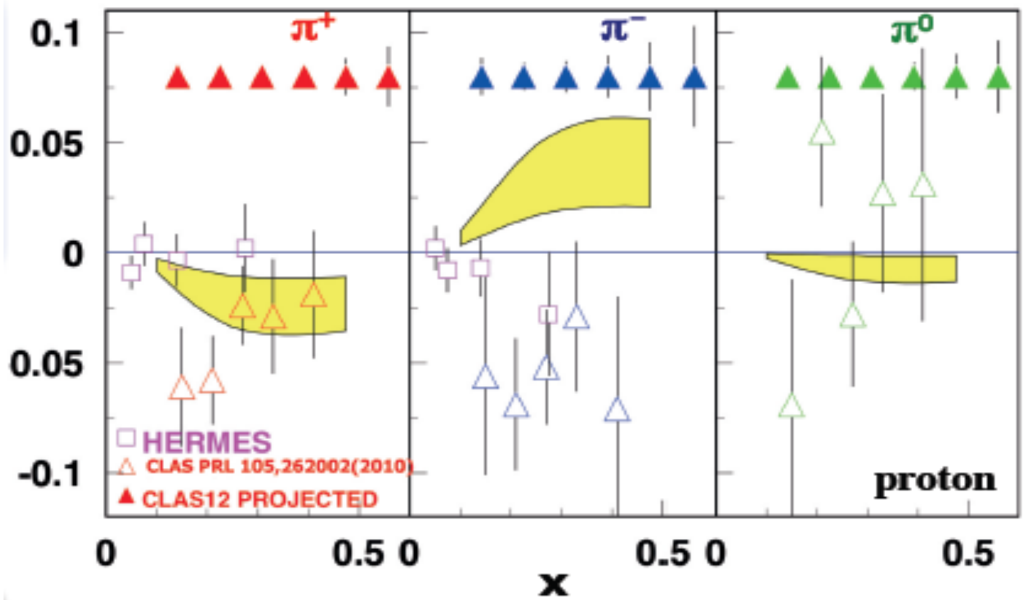
E12-07-107: Studies of Spin-Orbit Correlations with Longitudinally Polarized Target

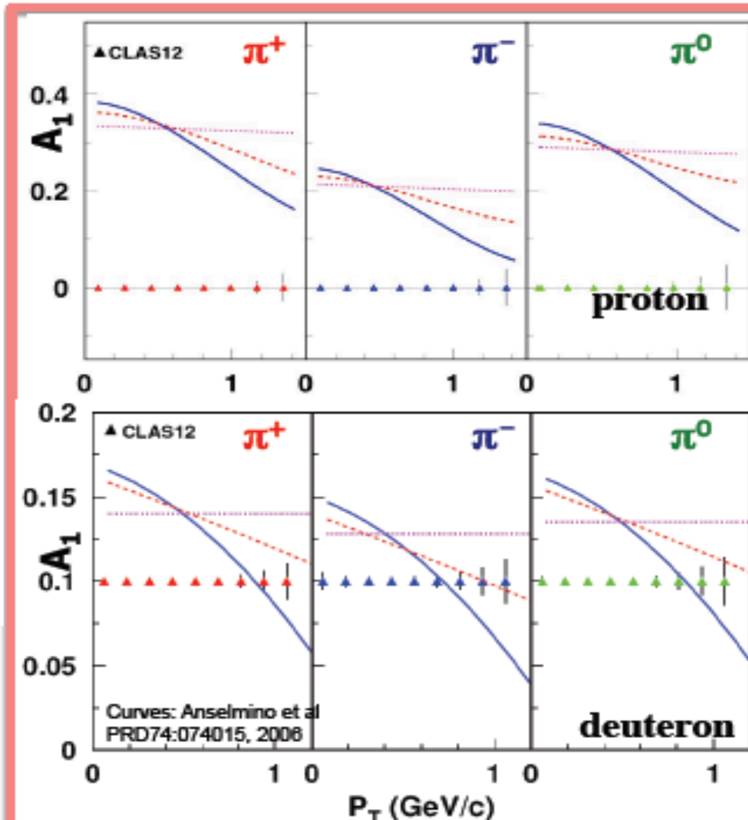
N \ q	U	L	T
L		g_{1L}	$h_{1L}^{\perp}$

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} \propto S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \epsilon\sin(2\phi_h)F_{UL}^{\sin(2\phi_h)}\right]$$
$$+S_L\lambda_e\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_h)F_{LL}^{\cos(\phi_h)}\right]$$

h.t. ($F_{UL}^{\sin\phi_h}$); $h_{1L}^{\perp}\otimes H_1^{\perp}$ ($F_{UL}^{\sin(2\phi_h)}$); $g_{1L}\otimes D_1$ (F_{LL}); h.t. ($F_{LL}^{\cos(\phi_h)}$)

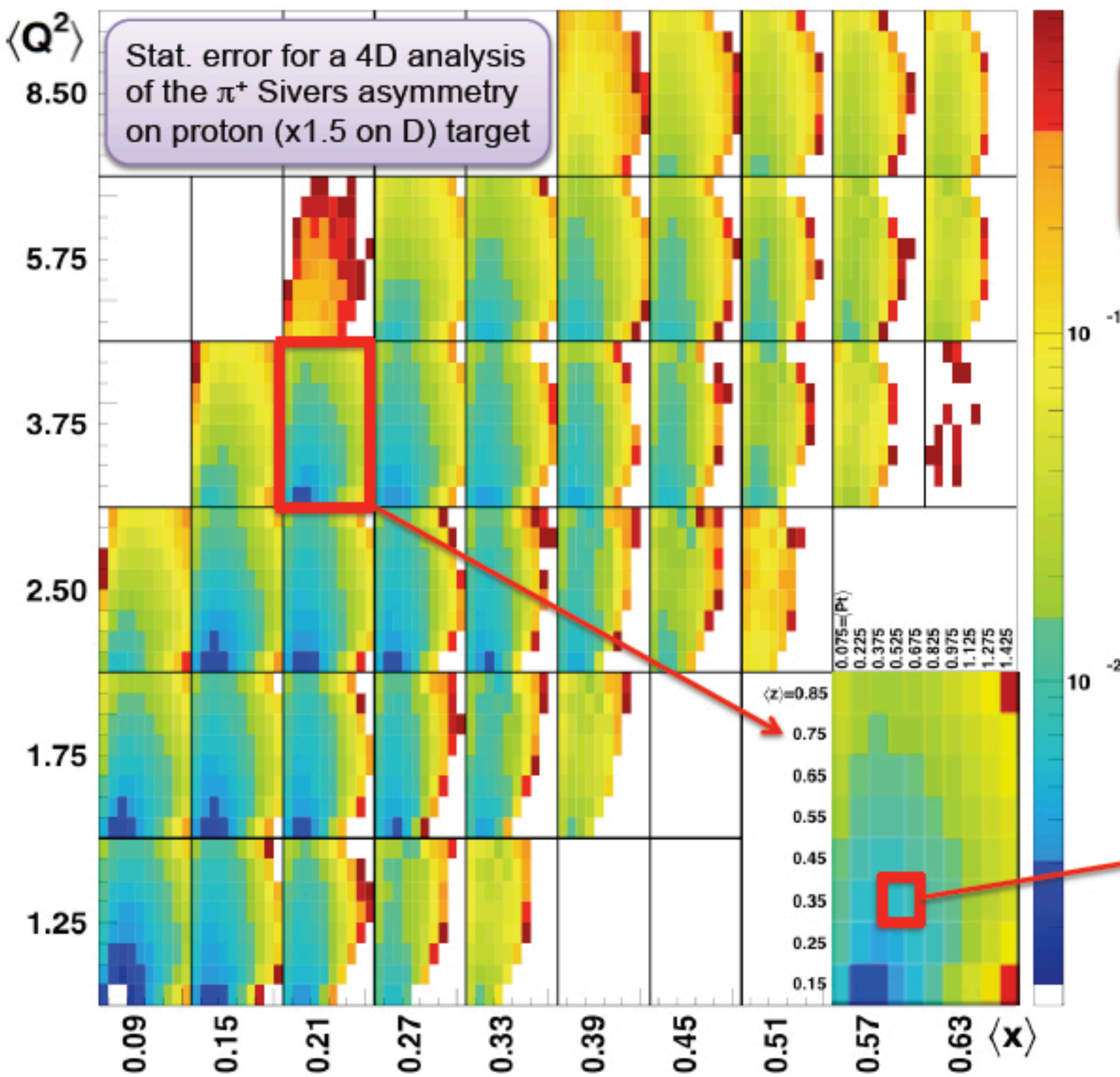


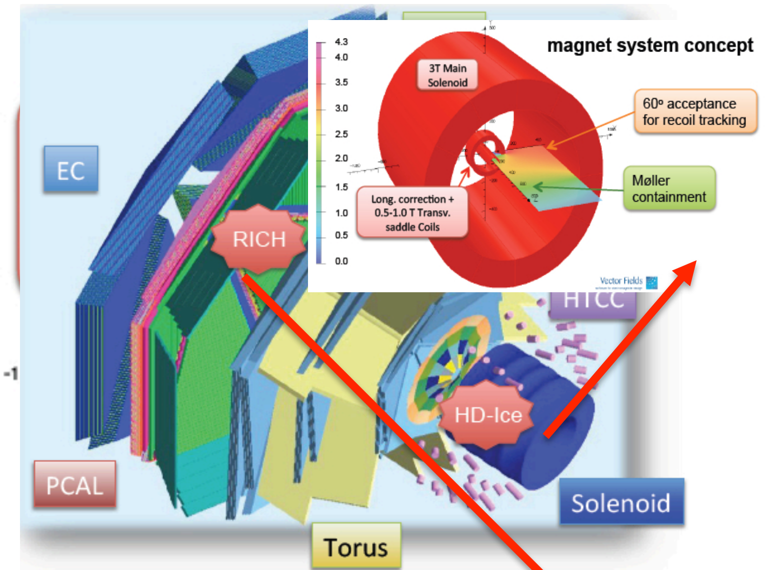


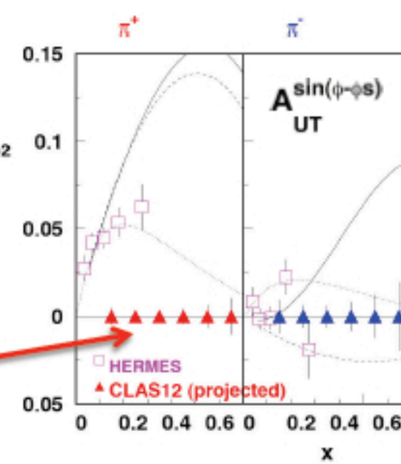


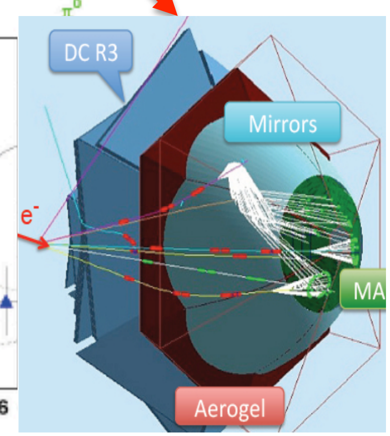
- A_1 P_T-dependence provides access to helicity dependence of k_T-distributions of quarks
- p & d data required for P_T-dependence flavor decomposition

CLAS12 A_{UT} with transverse proton target



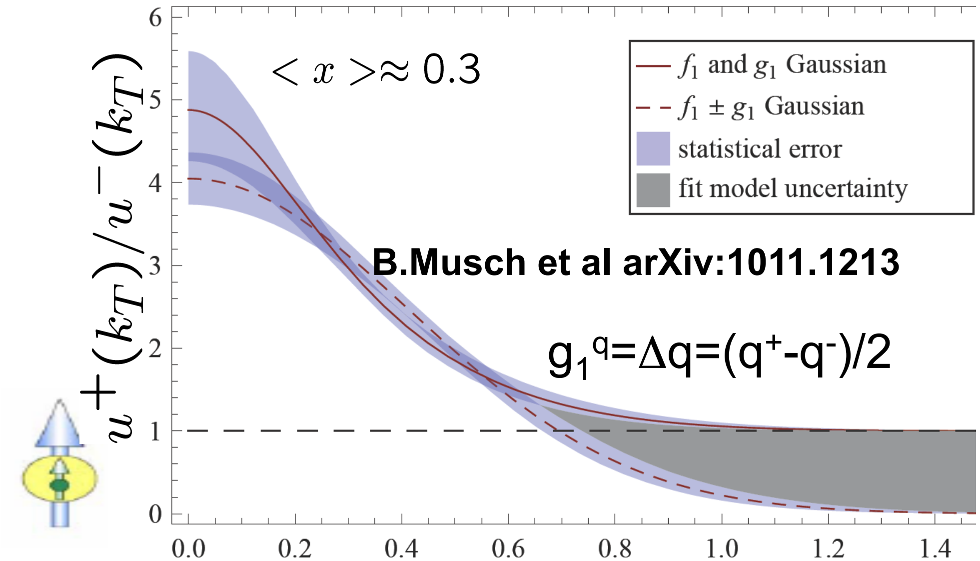






Curves from hep-ph/0507266 and hep-ph/0507181

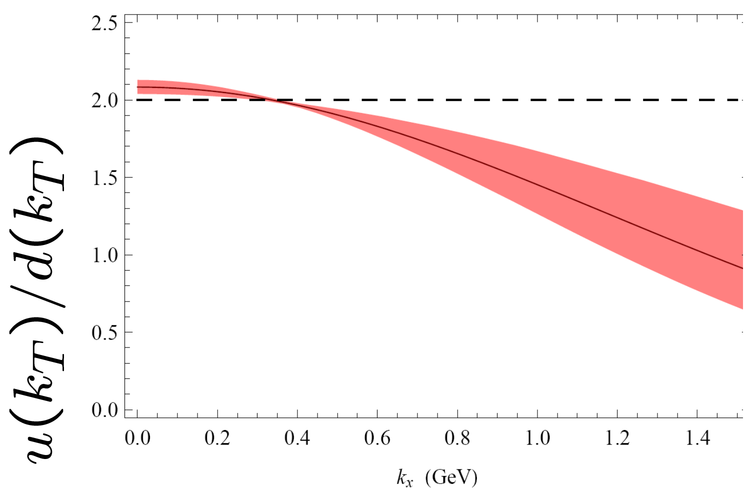
Quark distributions at large k_T: lattice



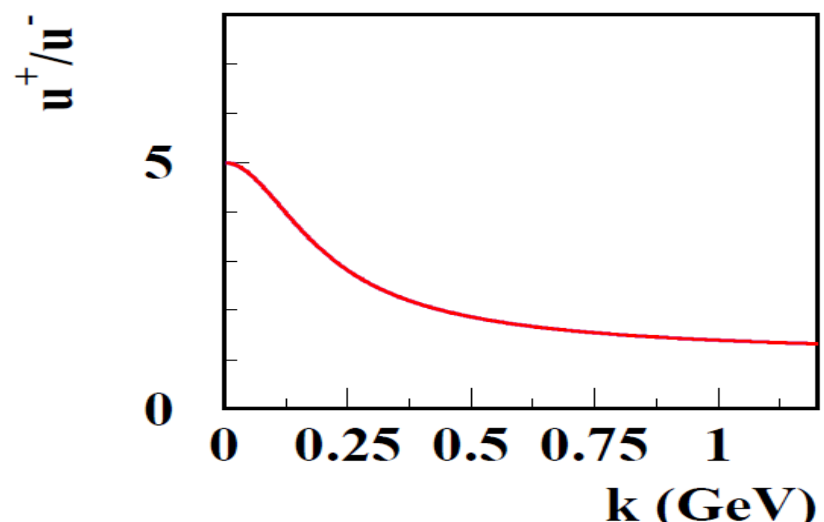
$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

Higher probability to find a quark anti-aligned with proton spin at large k_T and b_T



B.Pasquini et al

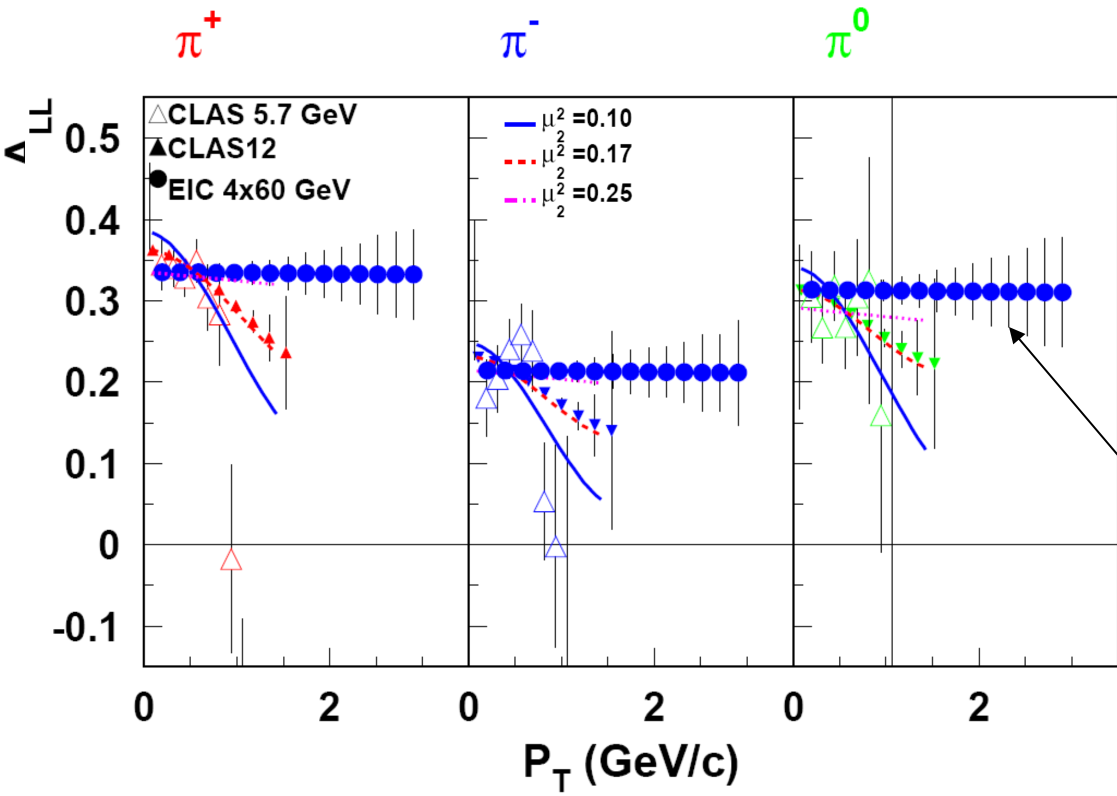


Significant correlations of spin and transverse degrees of freedom predicted

A_1 P_T-dependence in SIDIS

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \; e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

M.Anselmino et al
hep-ph/0608048



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

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

Perturbative limit calculations available for $g_1^q(x,k_T), f_1(x,k_T)$:

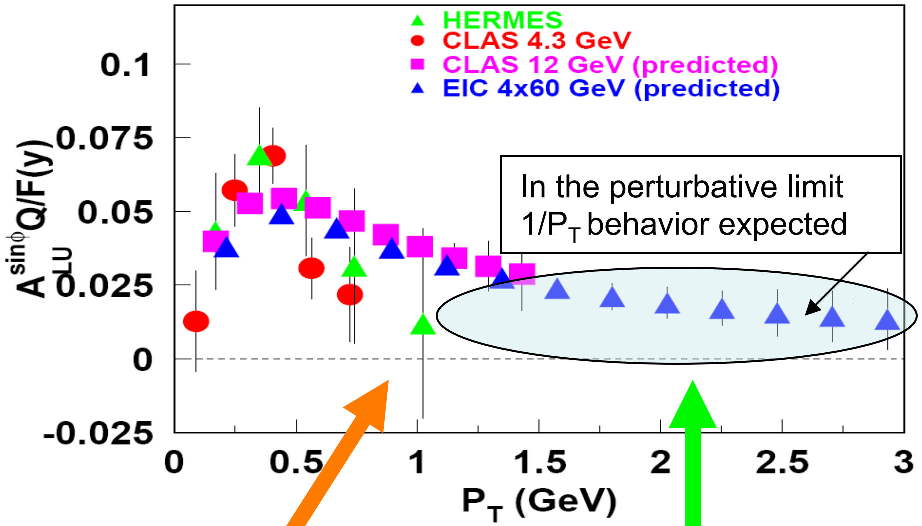
J.Zhou, F.Yuan, Z Liang: arXiv:0909.2238

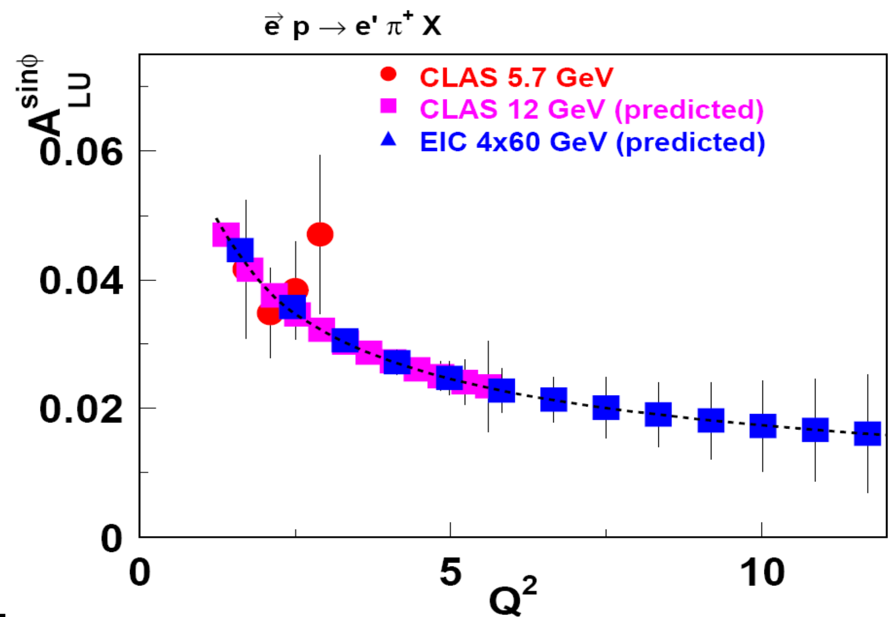
- A_{LL} (π) **sensitive to difference in k_T distributions for f_1 and g_1**
- **Wide range in P_T allows studies of transition from TMD to perturbative approach**

P_T and Q^2-dependence of beam SSA

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

$$A_{LU} \propto g^{\perp}(x) D_1(z)$$



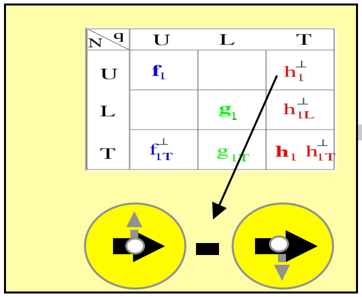


Nonperturbative TMD

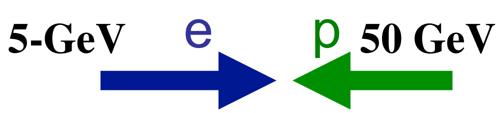
Perturbative region

1/Q behavior expected (fixed x bin)

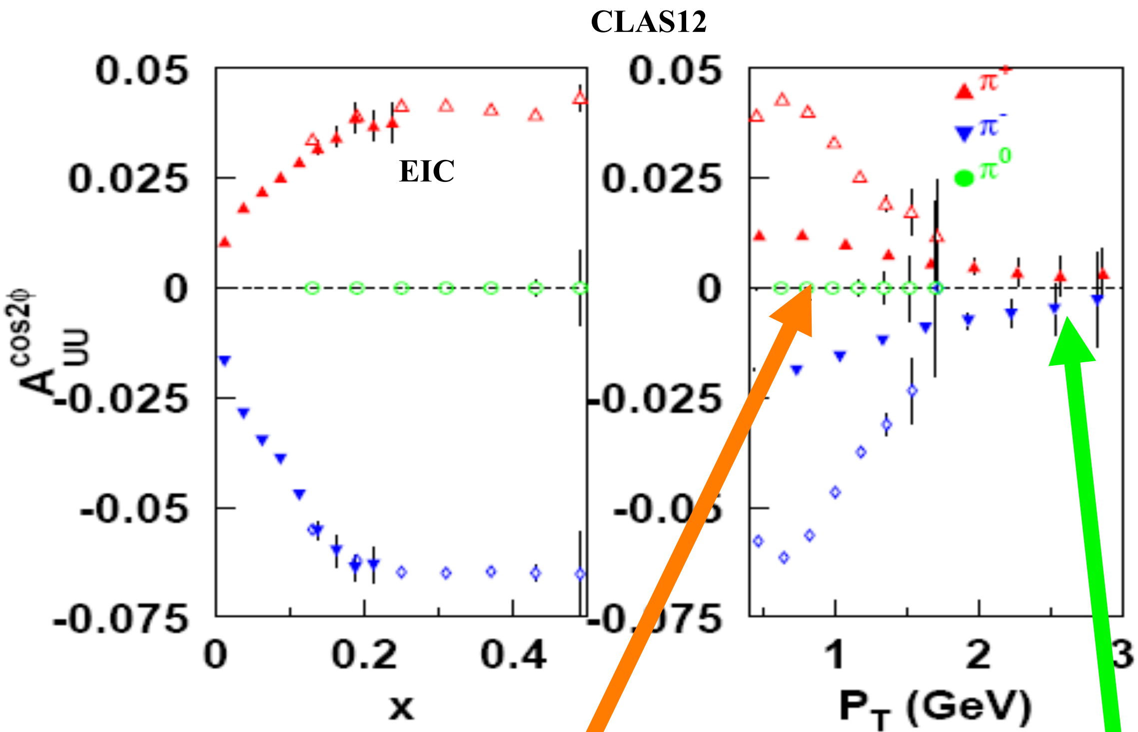
- Study for SSA transition from non-perturbative to perturbative regime.
- EIC will significantly increase the P_T range.
- Study for Q^2 dependence of beam SSA allows to check the higher twist nature and access quark-gluon correlations.



Boer-Mulders Asymmetry with CLAS12 & EIC



Transversely polarized quarks in the unpolarized nucleon



$\sin(\phi_C) = \cos(2\phi_h)$

$$A_{UU}^{\cos 2\phi} \propto h_1^{\perp(1)} H_1^{\perp}$$

$$\langle \cos 2\phi \rangle |_{P_{h\perp} \gg \Lambda_{QCD}} \propto \frac{1}{P_{h\perp}^2}$$

Perturbative limit calculations available for $f_1(x, k_T), h_1^{\perp}(x, k_T)$

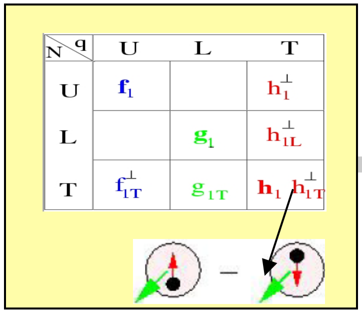
J.Zhou, F.Yuan, Z Liang: arXiv: 0909.2238

Nonperturbative TMD

Perturbative region

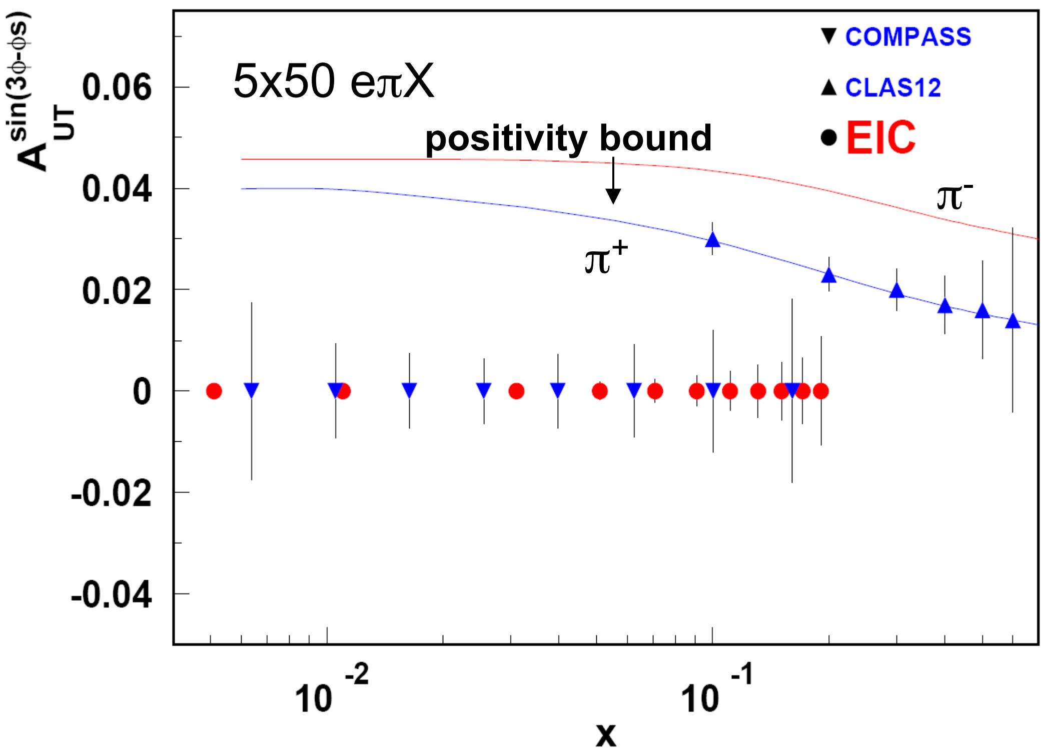
CLAS12 and EIC **studies of transition from non-perturbative to perturbative regime will provide complementary info on spin-orbit correlations and test unified theory (Ji et al)**

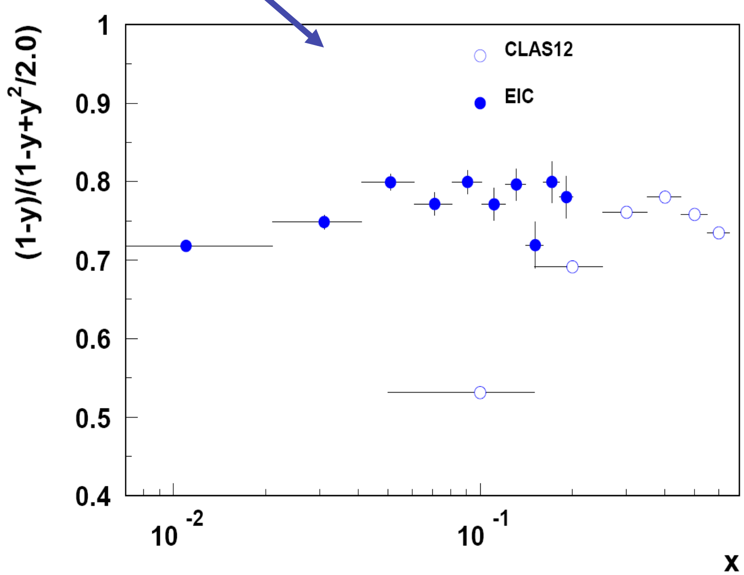
Pretzelosity @ EIC



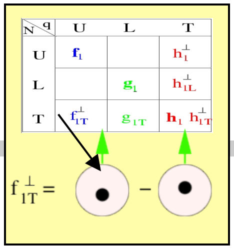
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

$$A_{UT}^{\sin(3\phi-\phi_S)} \propto \frac{1-y}{1-y+y^2/2} \frac{\sum_q e_q^2 h_{1T}^{\perp(1)q} H_1^{\perp q}}{\sum_q e_q^2 f_1^q D_1^q}$$





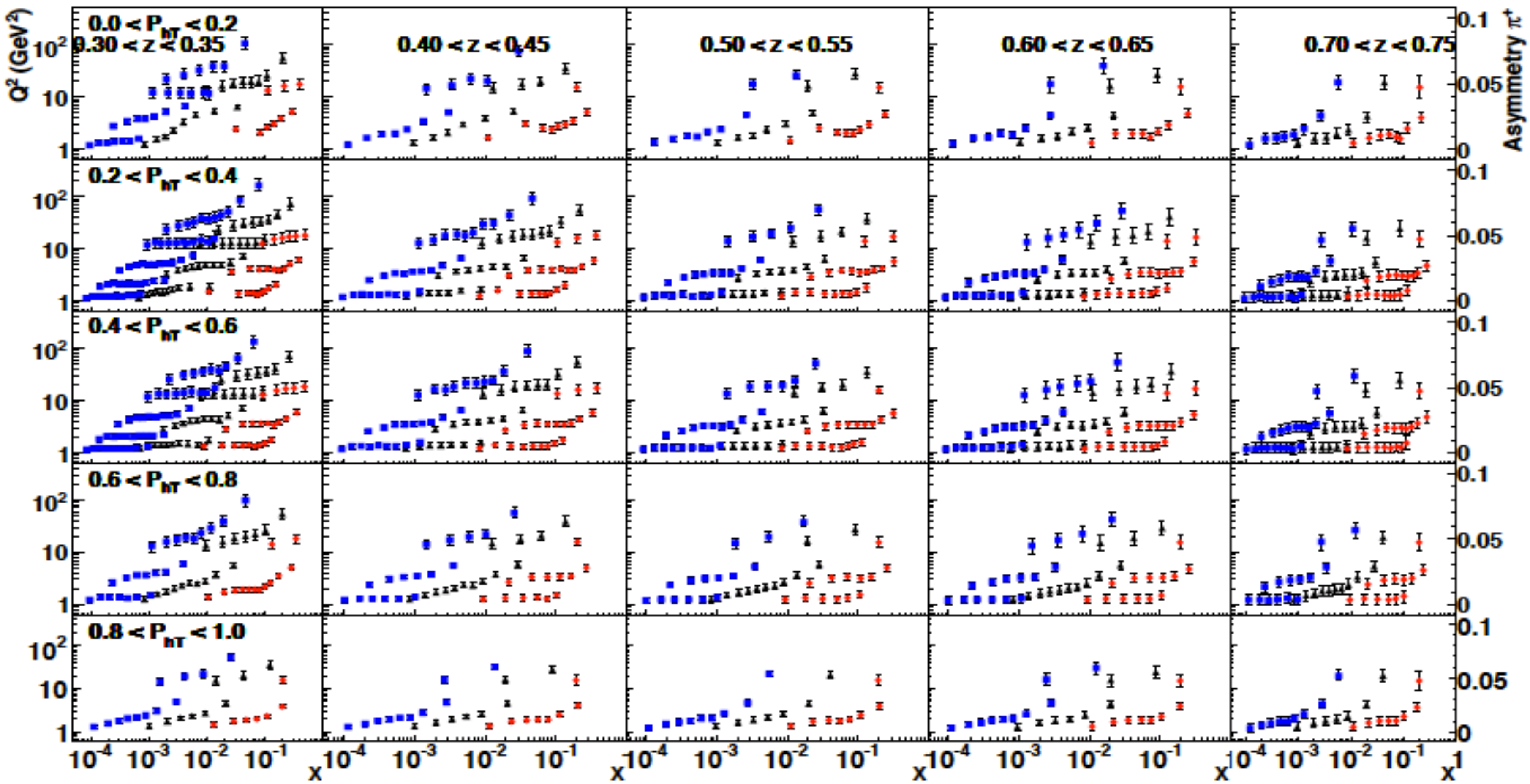
•EIC measurement combined with CLAS12 will provide a complete kinematic range for pretzelosity measurements



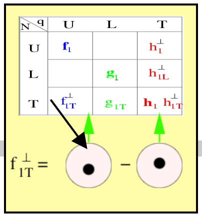
Sivers effect: π+ from EIC

$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

√s = 140 GeV, √s = 50 GeV and √s = 15 GeV EIC configurations, respectively.
Event counts correspond to an integrated luminosity of 30 fb−1 **arXiv:1108.1713**

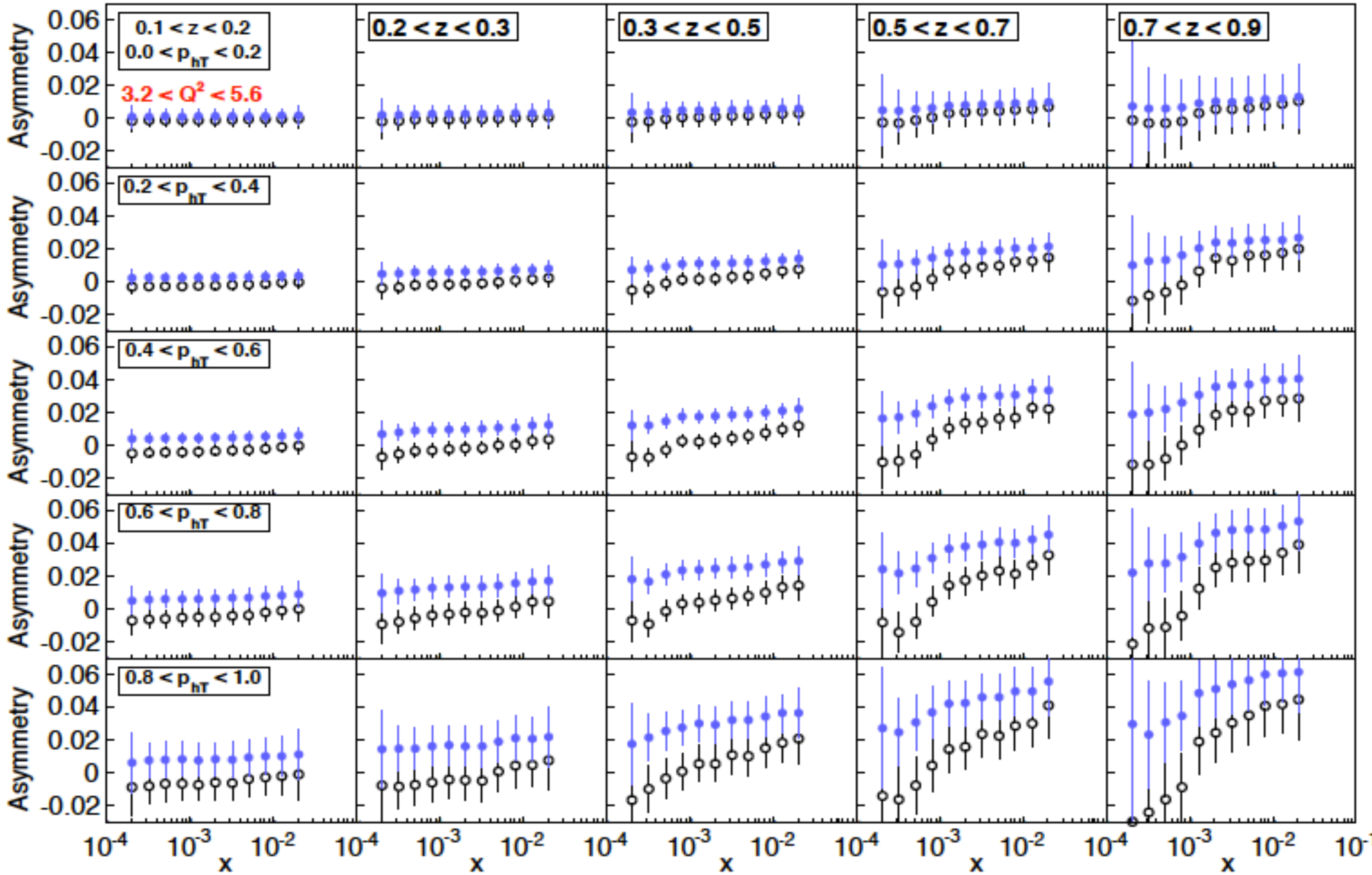


•Large acceptance and energy range of EIC makes it ideal place to study the contributions of sea quarks to Sivers asymmetry



Sivers effect: K+ from EIC

arXiv:1108.1713

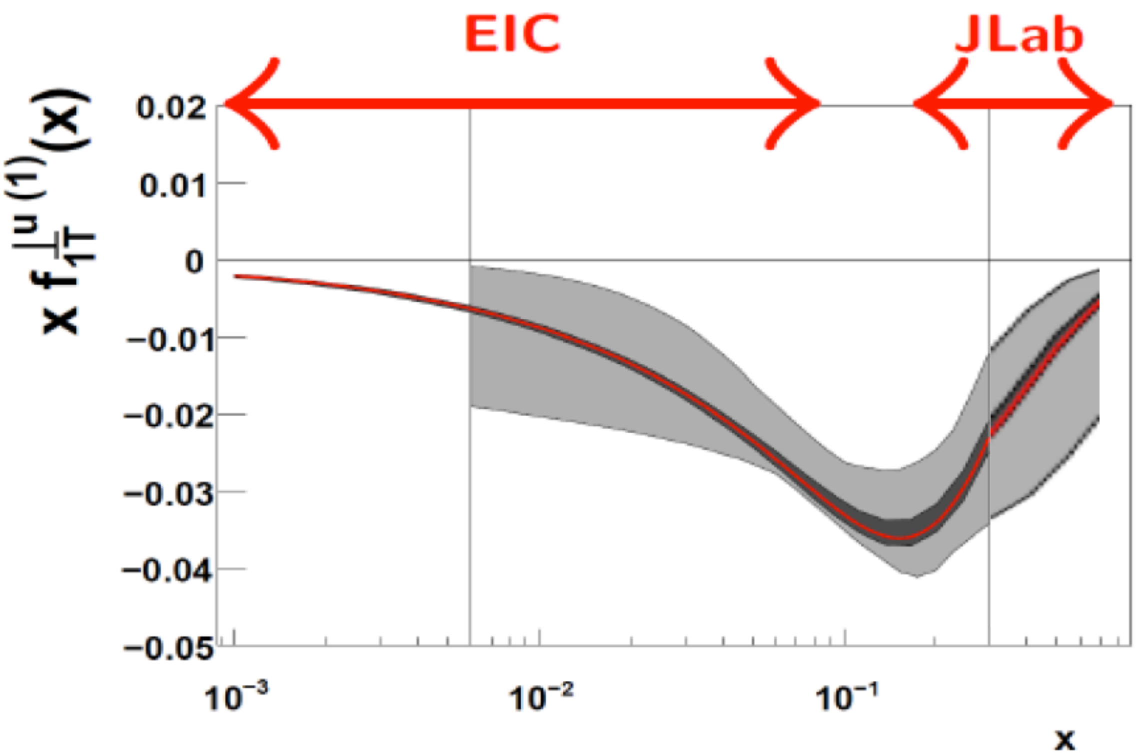


- EIC Kaon are more sensitive to contribtions from sea Sivers.

Extracting Sivers function from asymmetries

$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

EIC with energy setting of √s = 45 GeV and an integrated lumi of 4 fb−1



Extraction based on Gaussian Sivers, generated and then extracted with assumption of the same shape as used in generation (unclear systematics)

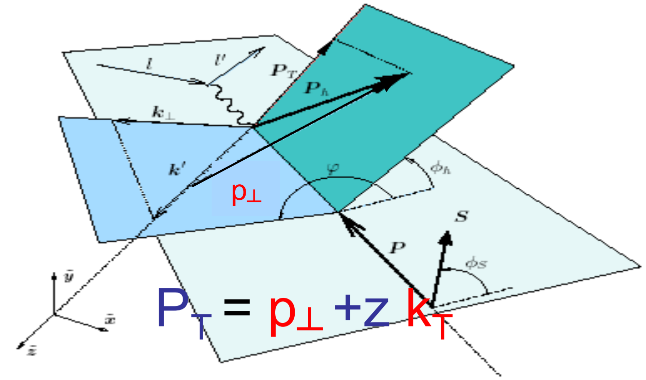
- At small x of EIC Kaon relative rates higher, combined with pions may provide precision measurements of Sivers asymmetries (in particular K-).
- Combination with CLAS12 data will provide almost complete x-range.

FAST-MC for CLAS12

SIDIS MC in 8D $(x,y,z,\phi,\phi_S,p_T,\lambda,\pi)$

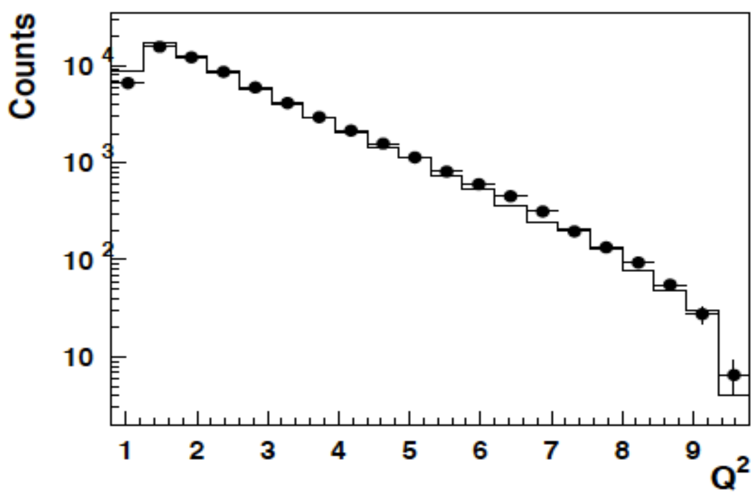
Simple model with 10% difference between f1 (0.2GeV^2) and g1 widths with a fixed width for D1 (0.14GeV^2)

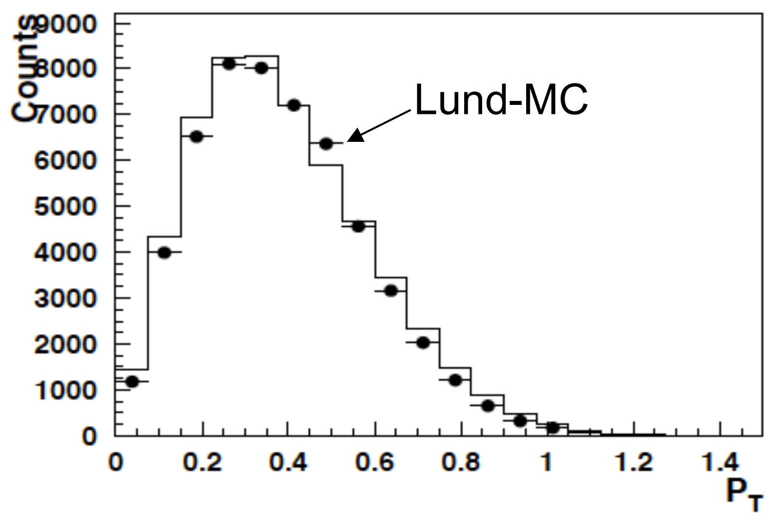
$$f_q(x,k_\perp) = f_q(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$



CLAS12 acceptance & resolutions

Events in CLAS12





Reasonable agreement of kinematic distributions with realistic LUND simulation

BGMP: extraction of k_T-dependent PDFs

Need: project x-section onto Fourier mods in b_T-space to avoid convolution

Boer, Gamberg, Musch &Prokudin arXiv:1107.5294

$$\int_0^\infty d|P_{h\perp}|\,|P_{h\perp}|\,J_0(|P_{h\perp}||b_T|)\left[\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz_h\,d\phi_h\,|P_{h\perp}|d|P_{h\perp}|}\right]$$

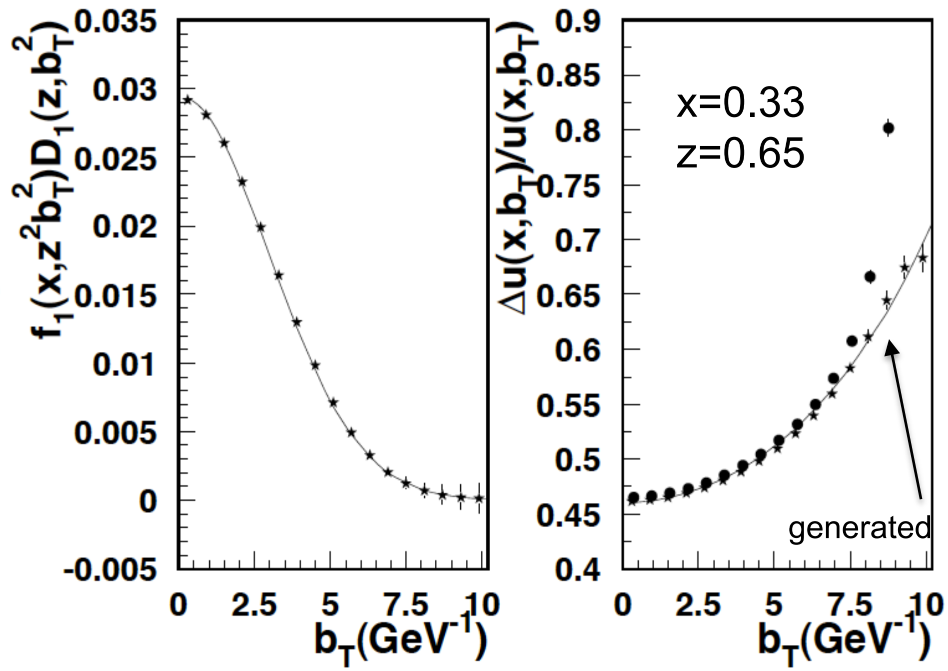
$$S_\pi^{unp\pm}(x_i, z_i, b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/\eta_i/A(x_i, y_i)$$

acceptance

$$A(x,y) = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

$$\tilde{f}_1^q(x, z^2 b_T^2)\,\tilde{D}_1^{q\to\pi}(z, b_T^2)$$

$$\Delta u(x, b_T)/u(x, b_T) = \frac{S_\pi^{pol+} - S_\pi^{pol-}}{S_\pi^{unp+} + S_\pi^{unp-}}$$



•the formalism in **b_T-space** avoids convolutions → easier to **perform a model independent analysis**

•provides a model independent way to study kinematical dependences of TMD

BGMP: extraction of k_T-dependent PDFs

Need: project x-section onto Fourier mods in b_T-space to avoid convolution

Boer, Gamberg, Musch &Prokudin arXiv:1107.5294

$$\int_0^{2\pi} d\phi_h \sin\phi_h \int_0^{\infty} d|\mathbf{P_{h\perp}}||\mathbf{P_{h\perp}}| \frac{2J_1(|\mathbf{P_{h\perp}}||\mathbf{b_T}|)}{zM_h|\mathbf{b_T}|} \left[\frac{d\sigma}{dxdydzd\phi_h|\mathbf{P_{h\perp}}|d|\mathbf{P_{h\perp}}|}\right]$$

$$\sum_a e_a^2 \tilde{e}^a(x, z^2 b_T^2) \tilde{H}_1^{\perp(1)a}(z, b_T^2) + \dots$$

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = -x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T|^2 J_1(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\, Mz\, \tilde{f}_{1T}^{\perp(1)}(x, z^2\boldsymbol{b}_T^2)\, \tilde{D}_1(z, \boldsymbol{b}_T^2),$$

$$F_{LL} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T| J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\, \tilde{g}_{1L}(x, z^2\boldsymbol{b}_T^2)\, \tilde{D}_1(z, \boldsymbol{b}_T^2),$$

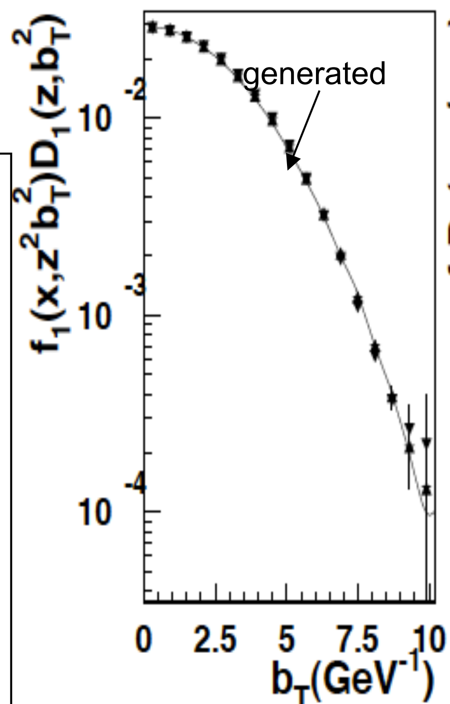
$$F_{LT}^{\cos(\phi_h-\phi_s)} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T|^2 J_1(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\, Mz\, \tilde{g}_{1T}^{\perp(1)}(x, z^2\boldsymbol{b}_T^2)\, \tilde{D}_1(z, \boldsymbol{b}_T^2),$$

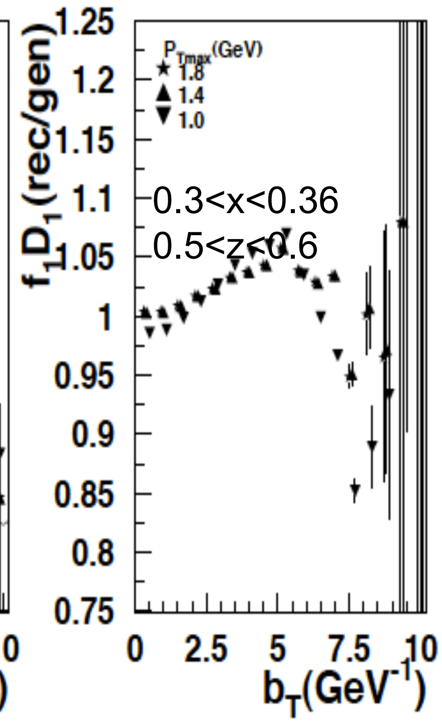
$$F_{UT}^{\sin(\phi_h+\phi_S)} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T|^2 J_1(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\, M_h z\, \tilde{h}_1(x, z^2\boldsymbol{b}_T^2)\, \tilde{H}_1^{\perp(1)}(z, \boldsymbol{b}_T^2),$$

$$F_{UU}^{\cos(2\phi_h)} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T|^3 J_2(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|) M M_h z^2\, \tilde{h}_1^{\perp(1)}(x, z^2\boldsymbol{b}_T^2)\, \tilde{H}_1^{\perp(1)}(z, \boldsymbol{b}_T^2),$$

$$F_{UL}^{\sin(2\phi_h)} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T|^3 J_2(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|) M M_h z^2\, \tilde{h}_{1L}^{\perp(1)}(x, z^2\boldsymbol{b}_T^2)\, \tilde{H}_1^{\perp(1)}(z, \boldsymbol{b}_T^2),$$

$$F_{UT}^{\sin(3\phi_h-\phi_S)} = x_B \sum_a e_a^2 \int \frac{d|\boldsymbol{b}_T|}{(2\pi)} |\boldsymbol{b}_T|^4 J_3(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|) \frac{M^2 M_h z^3}{4} \tilde{h}_{1T}^{\perp(2)}(x, z^2\boldsymbol{b}_T^2)\, \tilde{H}_1^{\perp(1)}(z, \boldsymbol{b}_T^2).$$





- With different Bessel weights BGMP provides a model independent way to extract k_T-dependences for all TMDs
- requires wide range in hadron P_T

Summary

- **Measurements of azimuthal dependences of double and single spin asymmetries in SIDIS indicate that there are significant correlations between spin and transverse distribution of quarks.**
- **Studies of quark-gluon correlations and hadronization are important in studies of TMD PDFs.**
- **Precision data from JLab12 and EIC will provide a complete set of azimuthal moments in a wide range in x required for extraction of TMD PDFs in valence and sea regions, respectively**
- **k_T-dependent flavor decomposition procedure is required to extract the PDFs in multidimensional space in a model independent way (Bessel weighting?)**