Target fragmentation in eN at JLab12 and beyond

Harut Avakian (JLab)

CFNS Ad-hoc Workshop: Target fragmentation and diffraction physics with novel processes: Ultraperipheral, electron-ion, and hadron collisions

9 Feb 2022, 09:00 → 11 Feb 2022, 17:00 US/Eastern

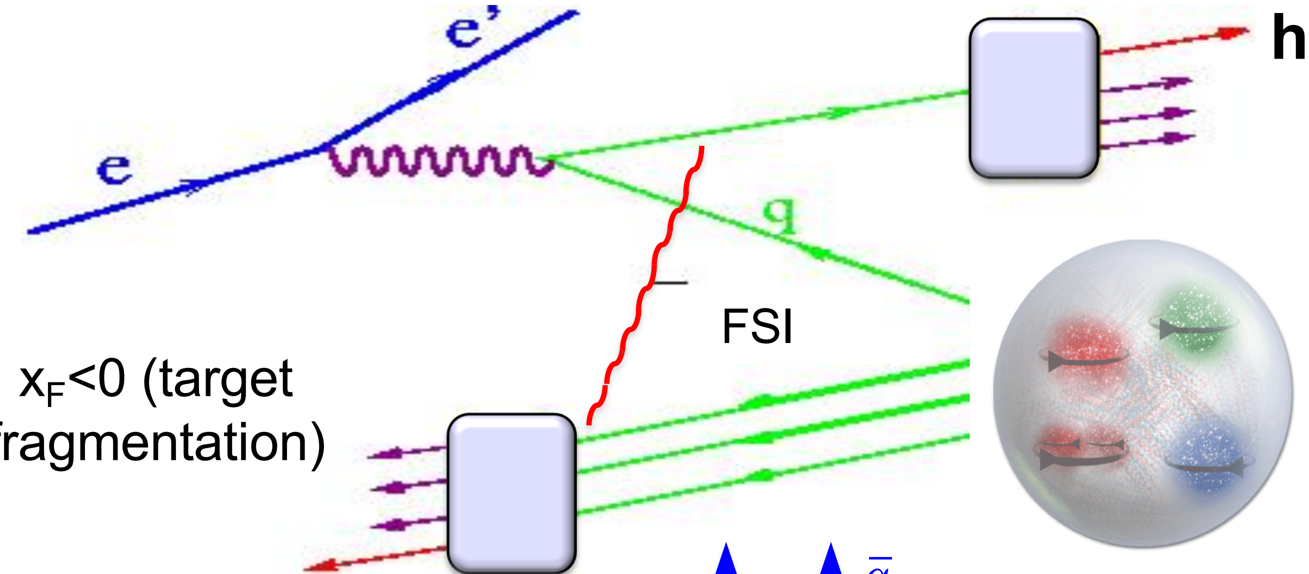
- Target fragmentation and Fracture Function Formalism
- Accessing spin-orbit correlations in di-hadron production
- Back to back production of hadrons in SIDIS
- Latest results and future measurements
- Summary

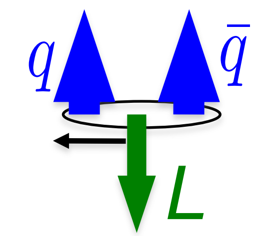
Hadron production in hard scattering

x_F – fractional momentum in the CM frame

x_F>0 (current fragmentation)

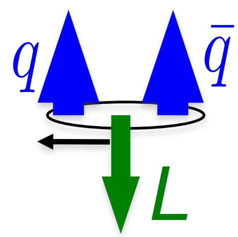
X. Artru & Z. Belghobsi





x_F<0 (target fragmentation)

Karliner, Kharzeev , Ellis & Kotzinian
Strikman,Weiss & Schweitzer
Anselmino, Barone, Kotzinian



x_F - momentum in the CM frame

2-hadron correlations in CFR studied in EMC(1986) and COMPASS(2015) CLAS12(2021)

Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles

Non-perturbative contributions

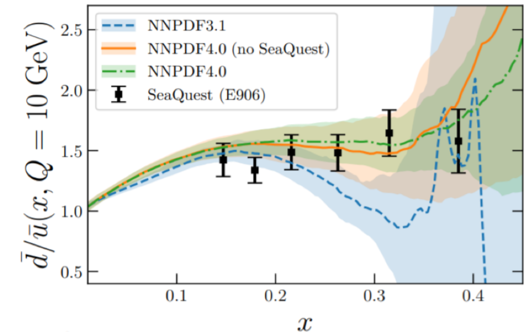
Non-perturbative sea ("tornado"/$^3P_0$) in nucleon is a key to understand the nucleon structure

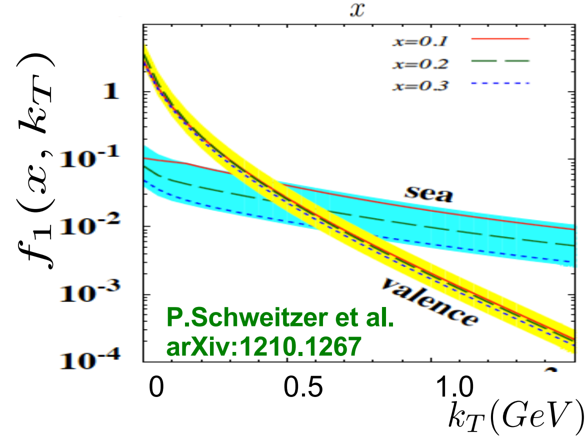
$$\bar{d} > \bar{u}$$

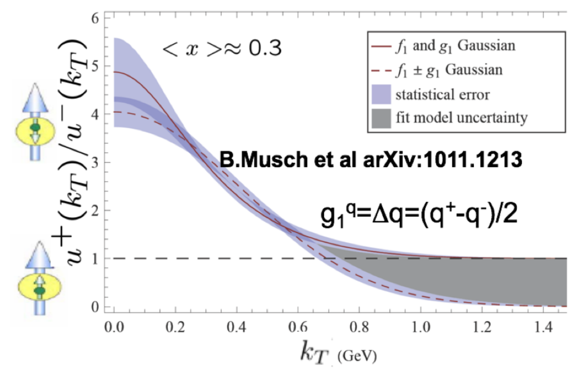
- Spin-Orbit correlations so far were shown (measurements and model calculations) to be significant in the region where non-perturbative effects dominate (x>0.02)
- Large transverse momenta of hadrons most relevant for understanding the non-perturbative QCD dynamics

- Predictions from dynamical model of chiral symmetry breaking [Schweitzer, Strikman, Weiss JHEP 1301 (2013) 163]

  -- k_T (sea) >> k_T (valence)
  -- short-range correlations between partons (small-size q-qbar pairs)
  -- may be directly observable in P_T-dependence of hadrons in SIDIS

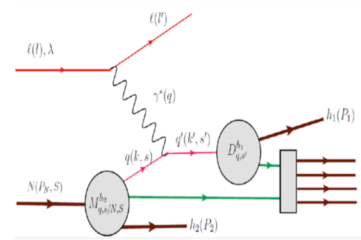


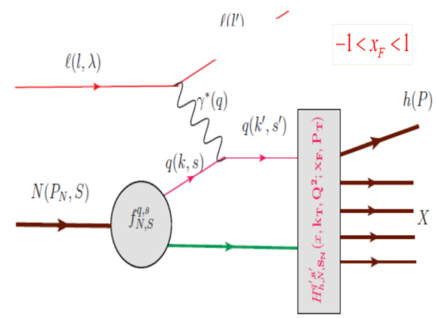




Hard scattering in e'hX and e'hhX

- A single-hadron MC with the SIDIS cross-section where widths of k_T-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.

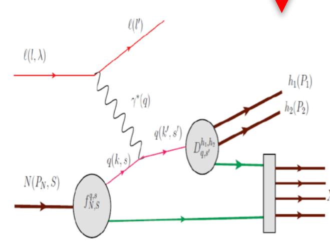


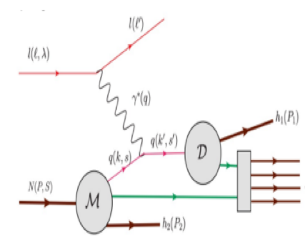


LUND-MCs are more successful in description of hard scattering processes, and SIDIS in the first place.

- The hadronization into different hadrons, in particular Vector Mesons is accounted (full kinematics)
- Accessible phase space properly accounted
- The correlations between hadrons, as well a as target and current fragments accounted
- ….

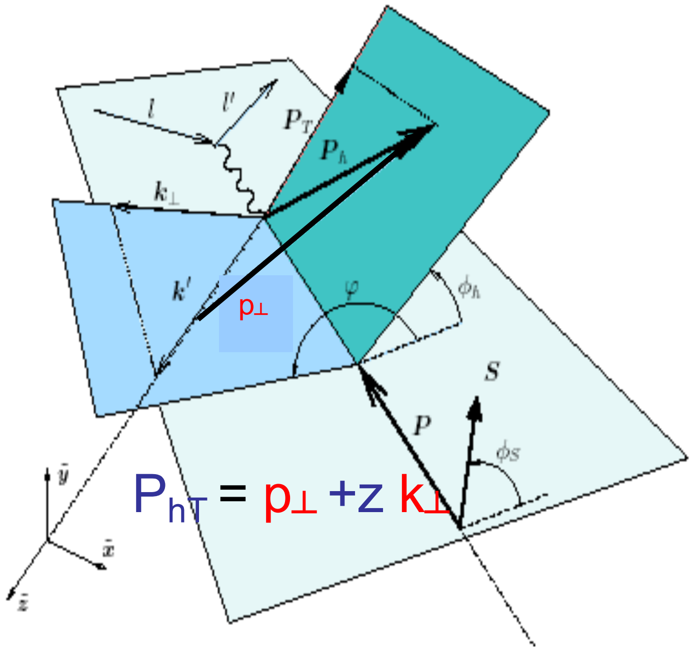
subsamples

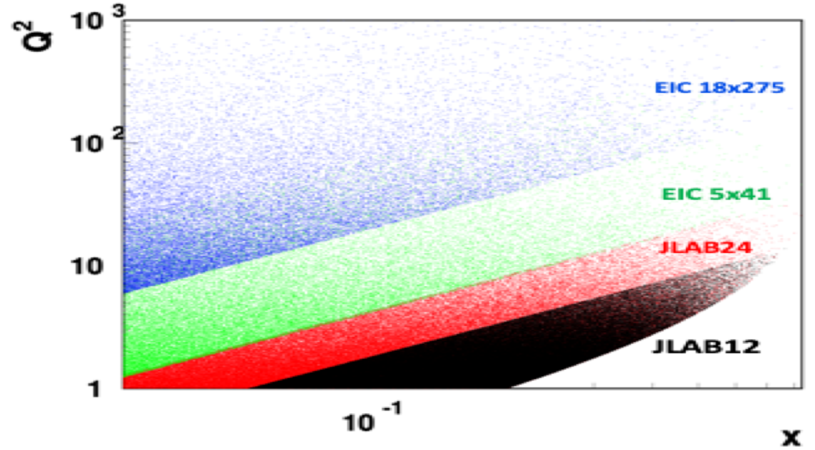


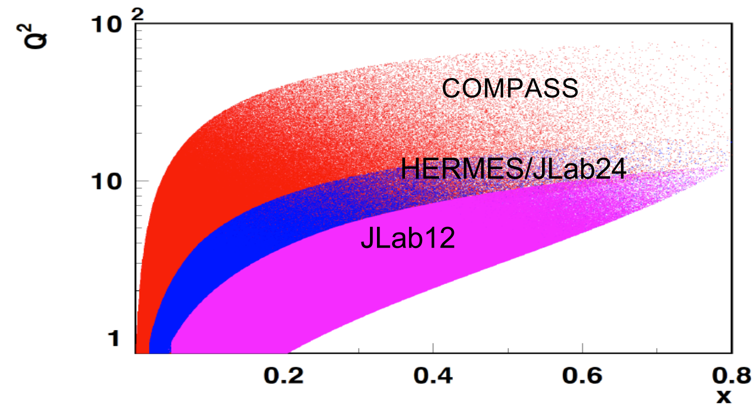


To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)
The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!

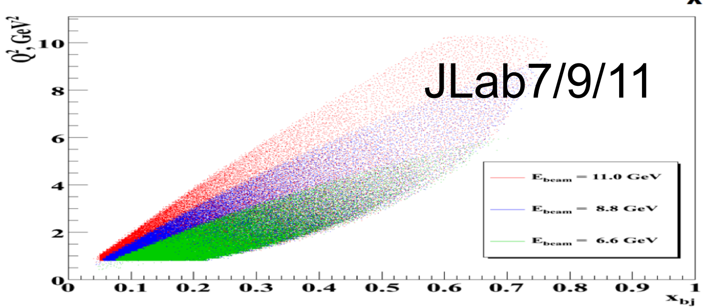
SIDIS kinematical coverage and observables







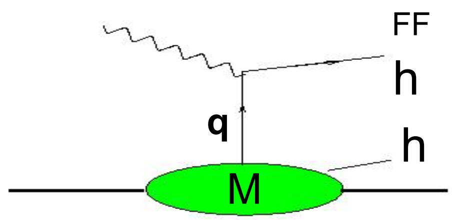
EIC

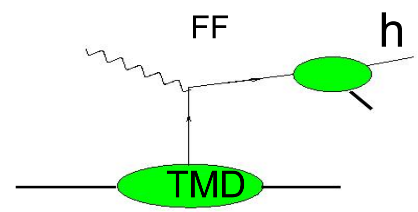


$$\sigma \propto F_{UU} + P_b\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi + P_t\epsilon F_{UL}^{\sin 2\phi}\sin 2\phi + \ldots$$

Studies of azimuthal modulations give access to underlying 3D partonic distributions

Electroproduction: extending 1D PDFs





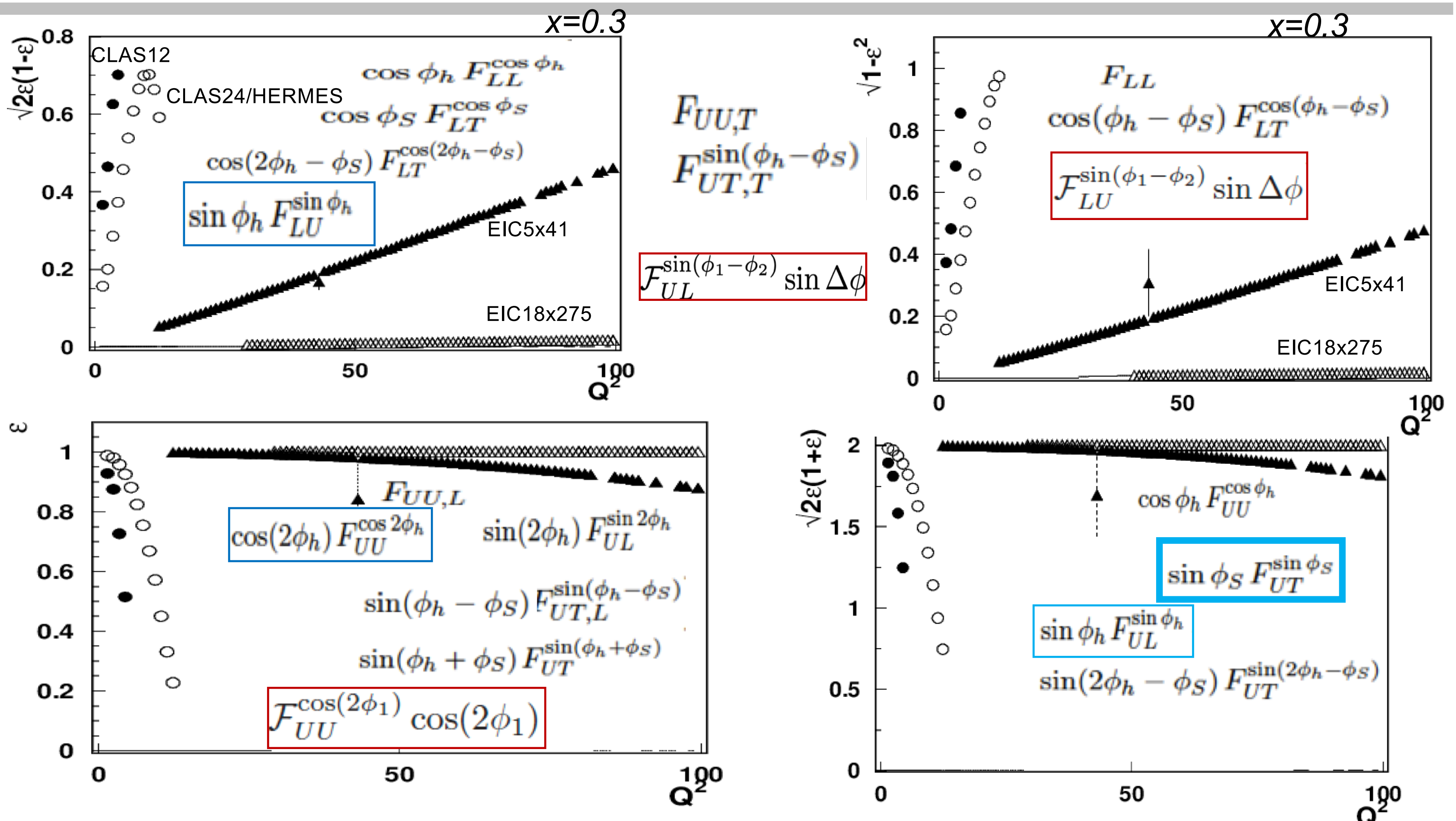
-1 Fracture Functions (target fragmentation xF<0) 0 TMDs (current fragmentation x_F>) x_F

N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

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

TFR studies provide a unique access to longitudinally polarized quarks in the unpolarized nucleons, and unpolarized quarks in the longitudinally polarized nucleons.

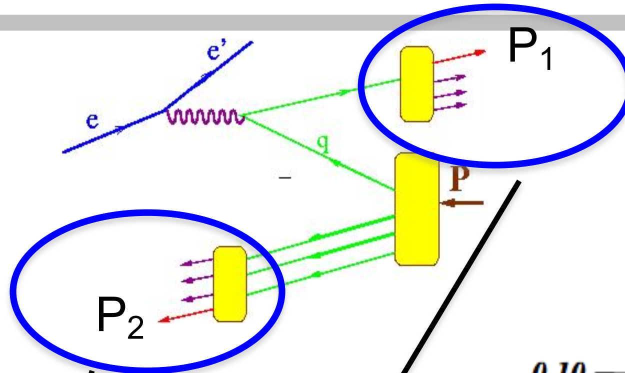
Kinematic factors at large x

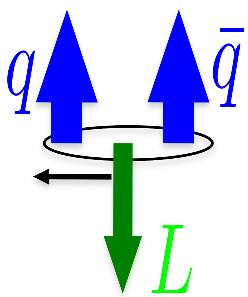


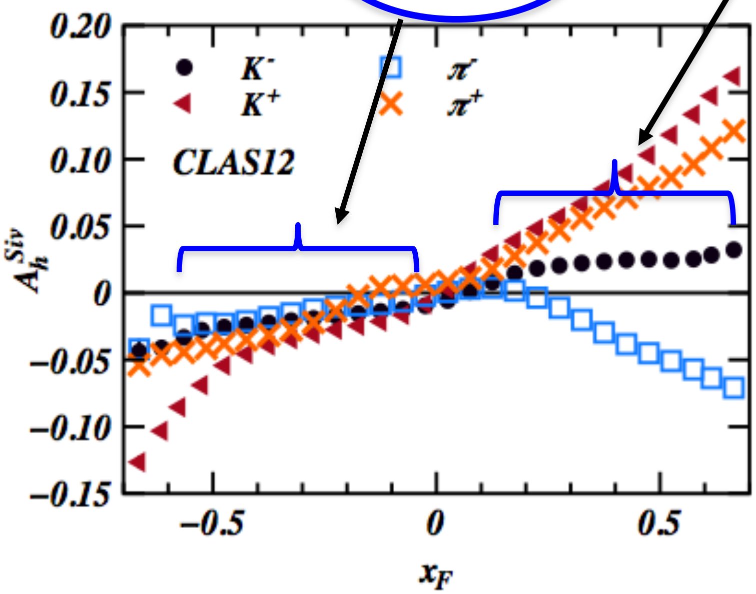
- Fixed target experiments are sensitive to all SSAs
- For EIC, observables surviving the $\varepsilon \to 1$ limit could be used

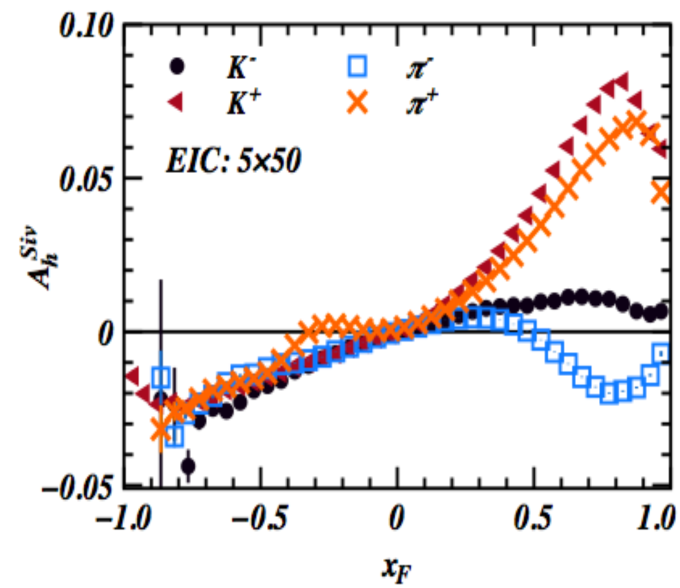
Target fragmentation: Sivers effect

H. Matevosyan et al.
arXiv:1502.02669







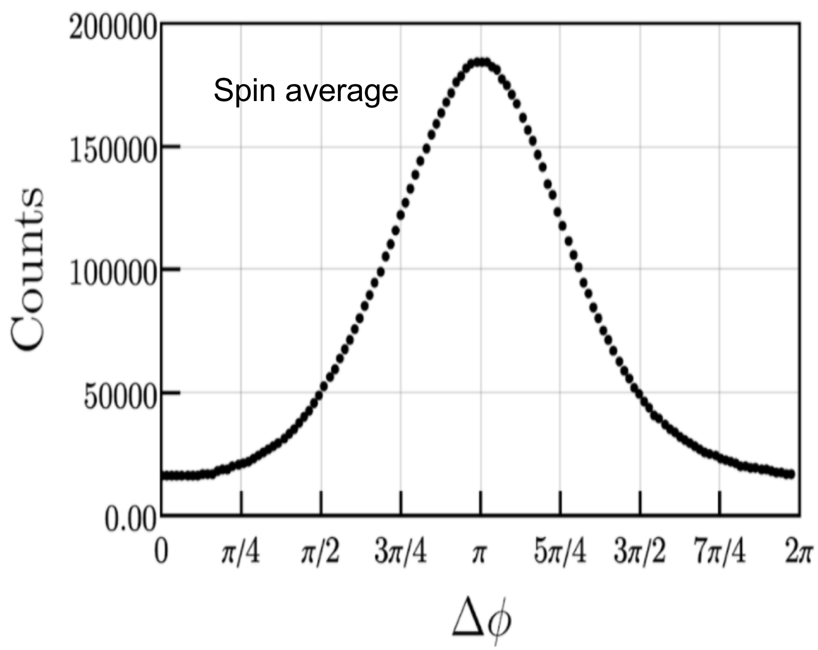


Wide coverage of CLAS12/24 and EIC will allow studies of kinematic dependences of the Sivers effect, both in current and target fragmentation regions

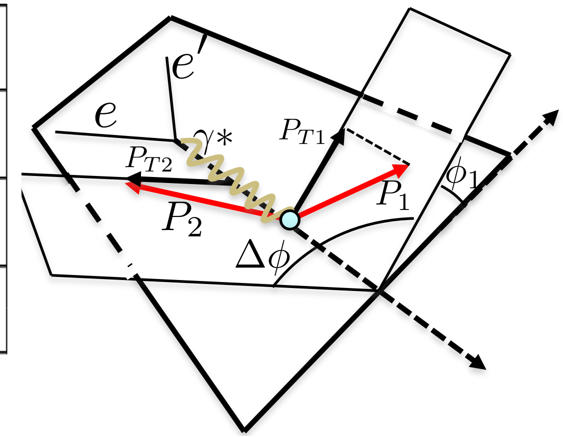
Correlations in 2 hadron production

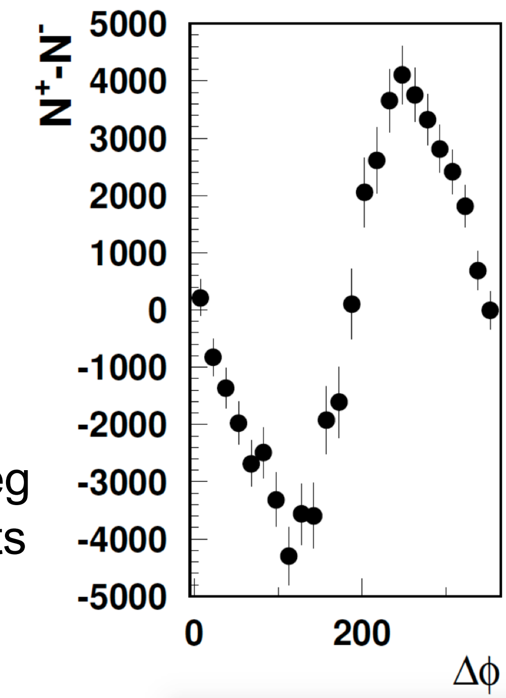
M. Anselmino, V. Barone and A. Kotzinian, Physics Letters B 713 (2012)

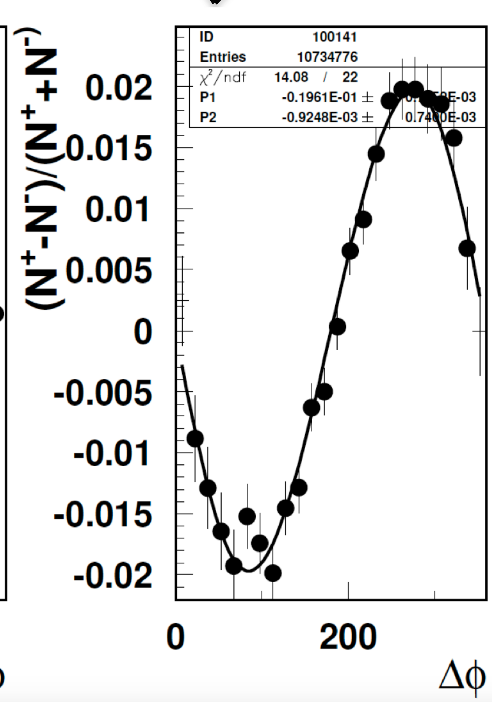
$$\mathcal{A}_{LU} = -\sqrt{1-\epsilon^2}\,\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$



N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$



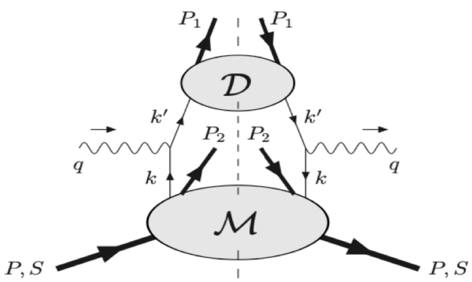


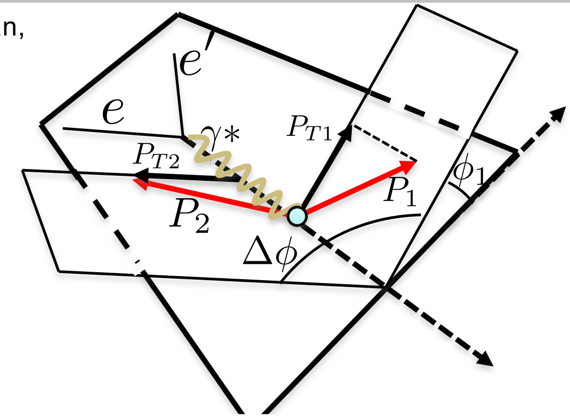


- Distributions in $\Delta\phi$ peak around 180 deg
- Strong $\sin\phi$ and a minor $\sin 2\phi$ moments the full range of accessible transverse momenta

Correlations in 2 hadron production

M. Anselmino, V. Barone and A. Kotzinian, Physics Letters B 713 (2012)

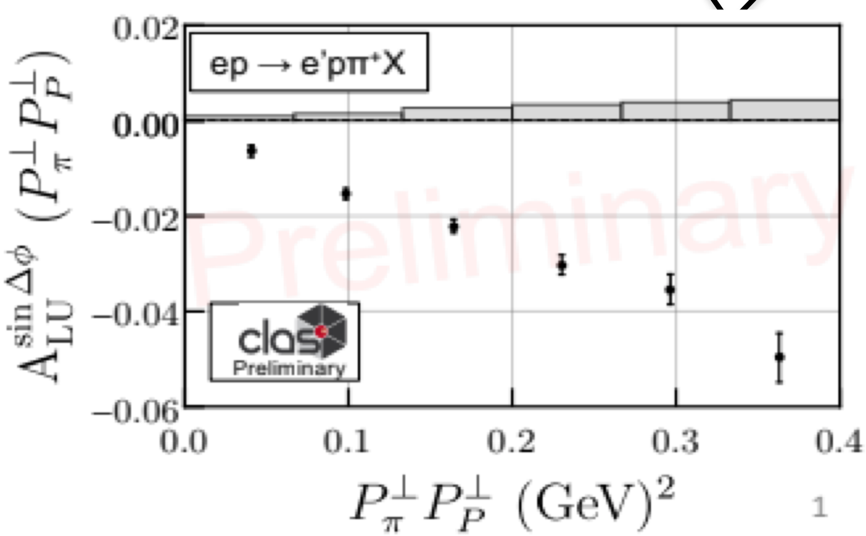


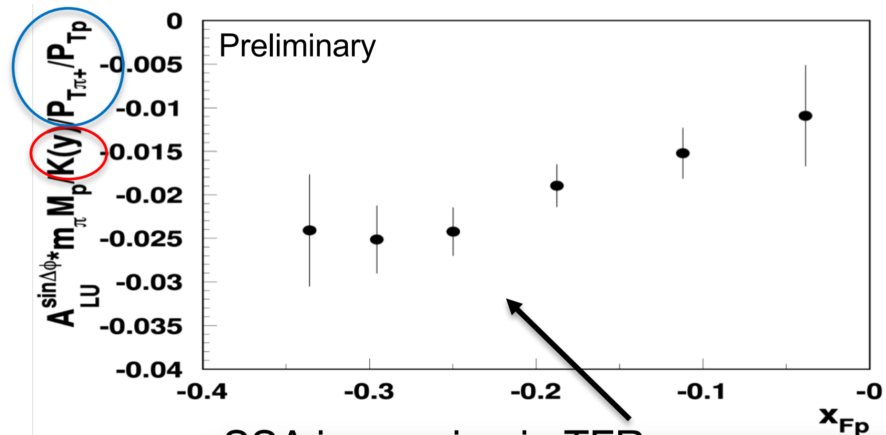


$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}} \sin\Delta\phi$$

$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2} \frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}$$

correlation $\times \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi,$ modulation





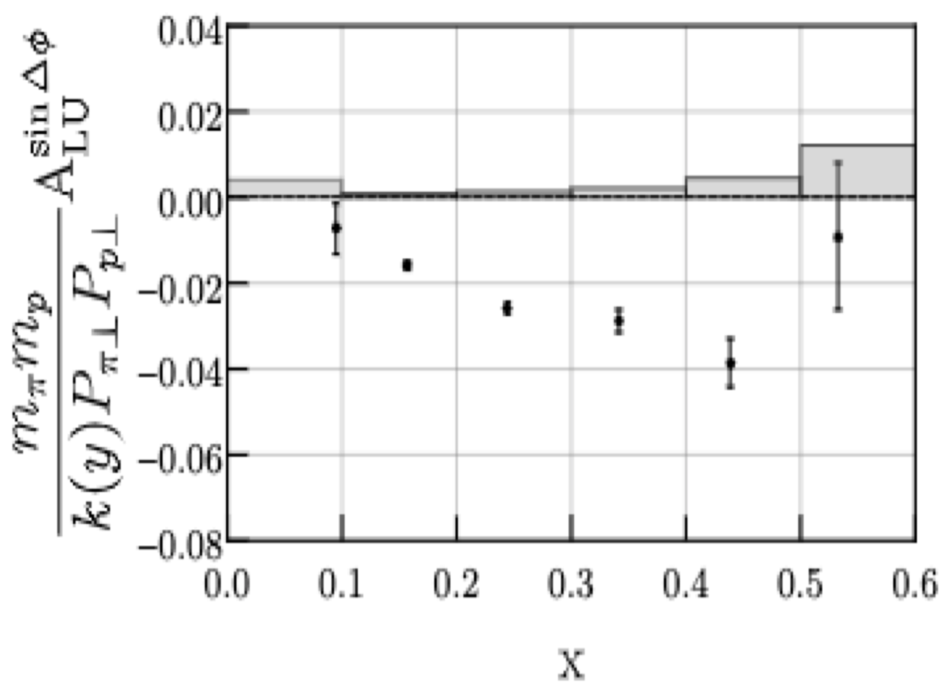
SSA increasing in TFR

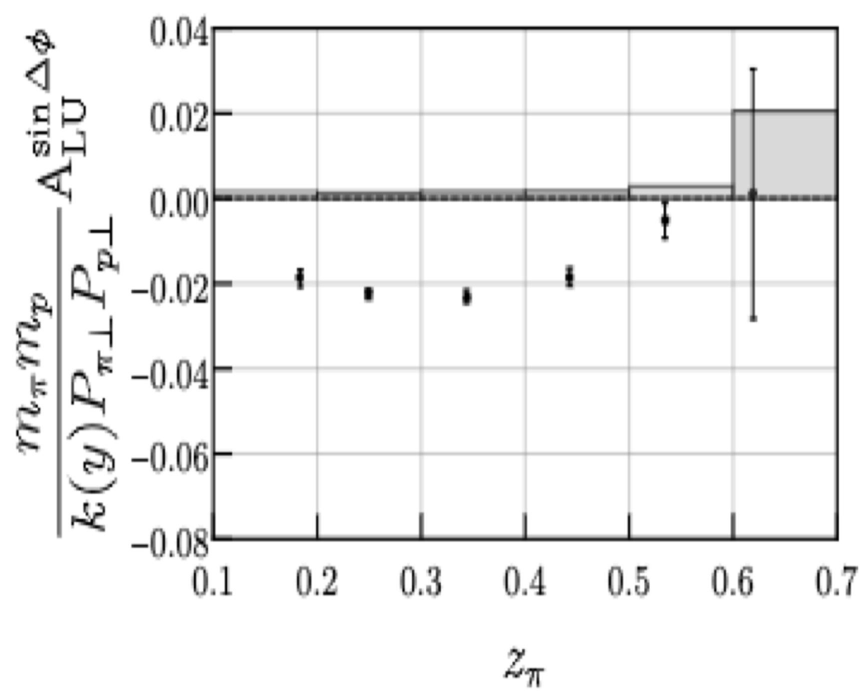
- Spin-azimuthal correlations in hadron pair production in CFR and TFR are very significant
- The beam SSA is suppressed at small y, and will be challenging in EIC kinematics
- Phase space accessible at JLab24 would allow the coverage in wider rapidity gaps

Correlations in 2 hadron production in CFR/TFR

M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)

$$\mathcal{A}_{LU}^{\sin(\phi_1-\phi_2)} \propto \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}$$





Increase of the Beam SSA at large x, consistent with valenc/non-perturbative nature of CFR/TFR correlations

Week dependence of the Beam SSA on the pion z consistent with u-quark dominance

CLAS12 Studies: Data vs MC

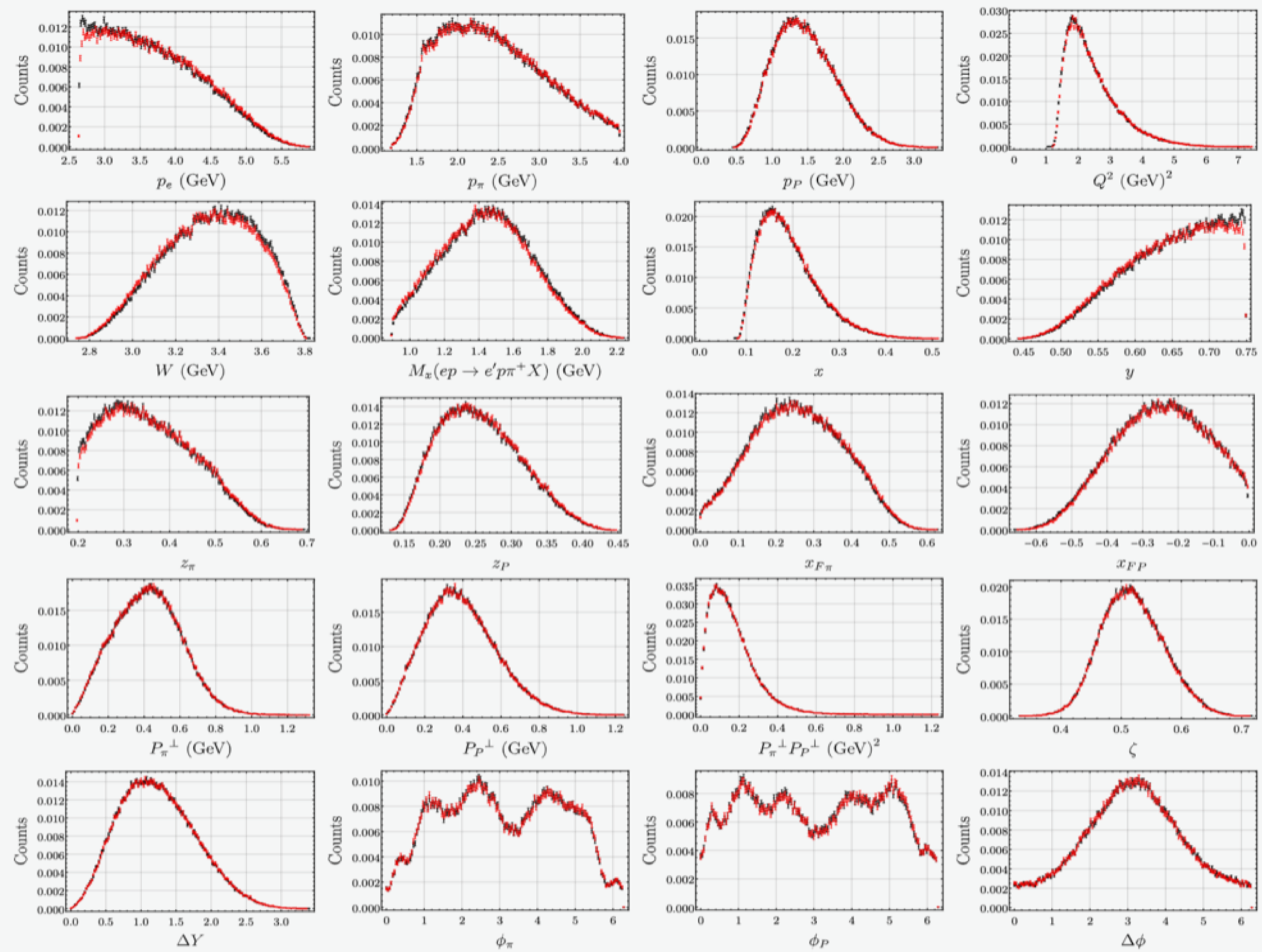


FIG. 41: Comparison between the Monte Carlo (red) and data (black). From left to right and top to bottom they are p_e, p_π, p_P, Q^2, W, M_x, x, y, z_π, z_P, $x_{F\pi}$, x_{FP}, $P_\pi^\perp$, $P_P^\perp$, $P_\pi^\perp P_P^\perp$, ζ, ΔY, ϕ_π, ϕ_P, $\Delta\phi$.

T.Hayward

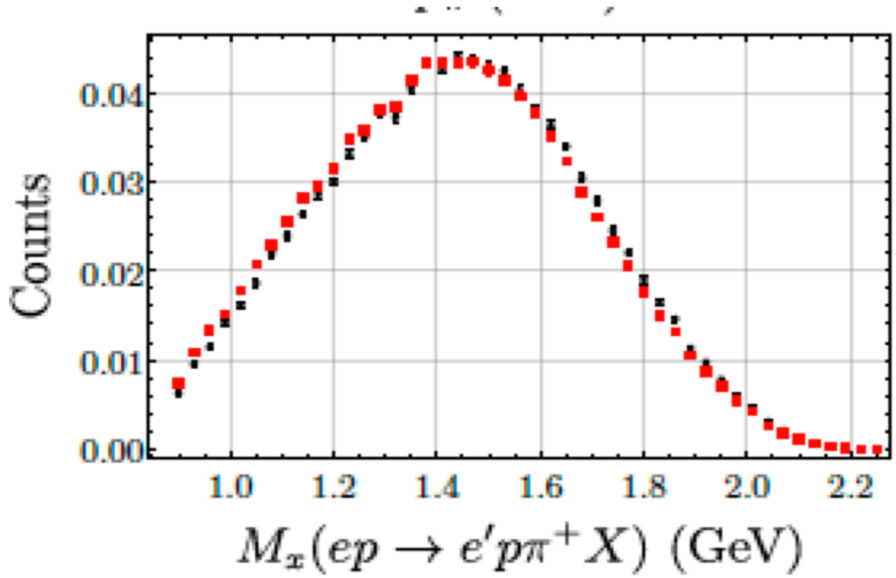
Good agreement for all relevant kinematical variables for

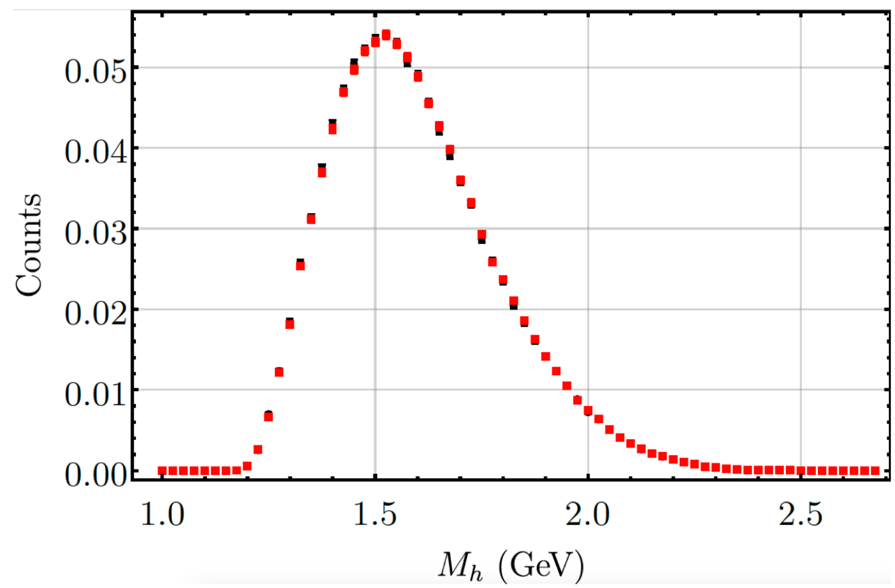
ep→e'pπX

Protion-pion distributions from data

Missing mass of e'pπ+X

Invariant mass of pπ+system

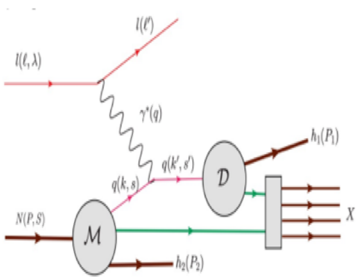


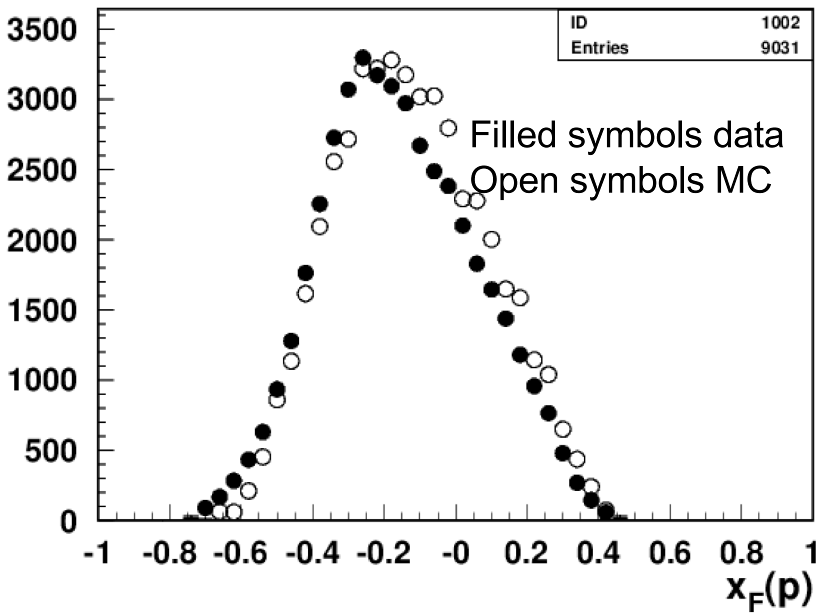


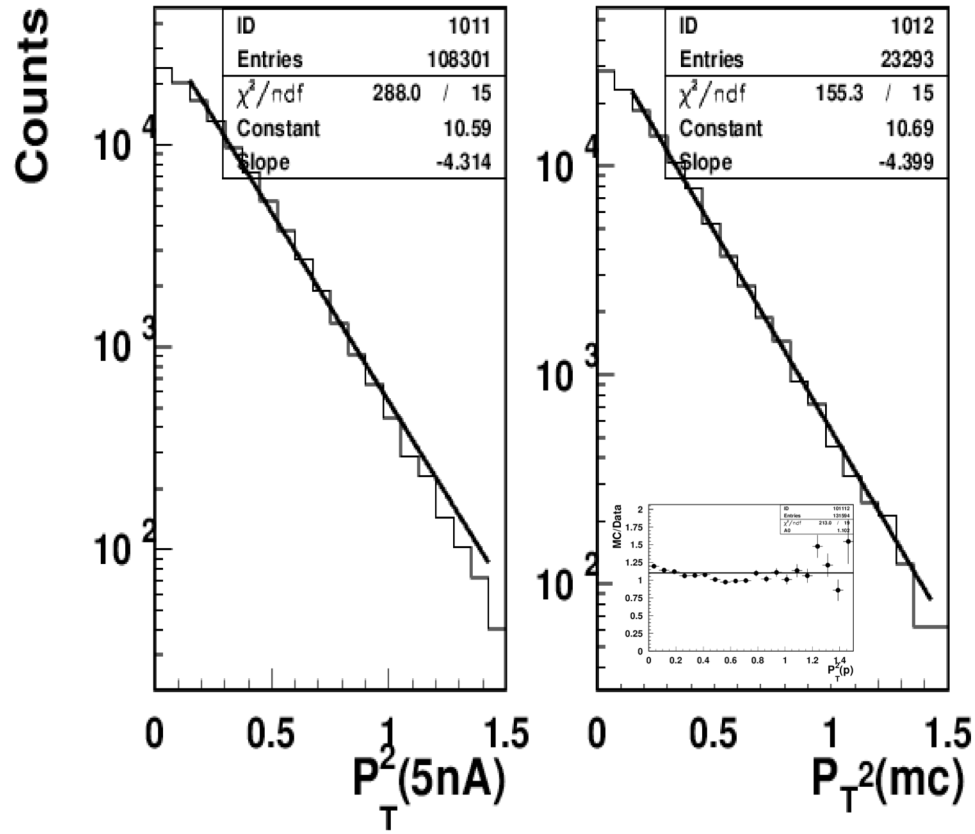
- Asymmetries were extracted in the full range of available missing masses, and invariant masses, and no significant variations were observed
- No indication of any specific channels (ex. Delta++) in the sample

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator

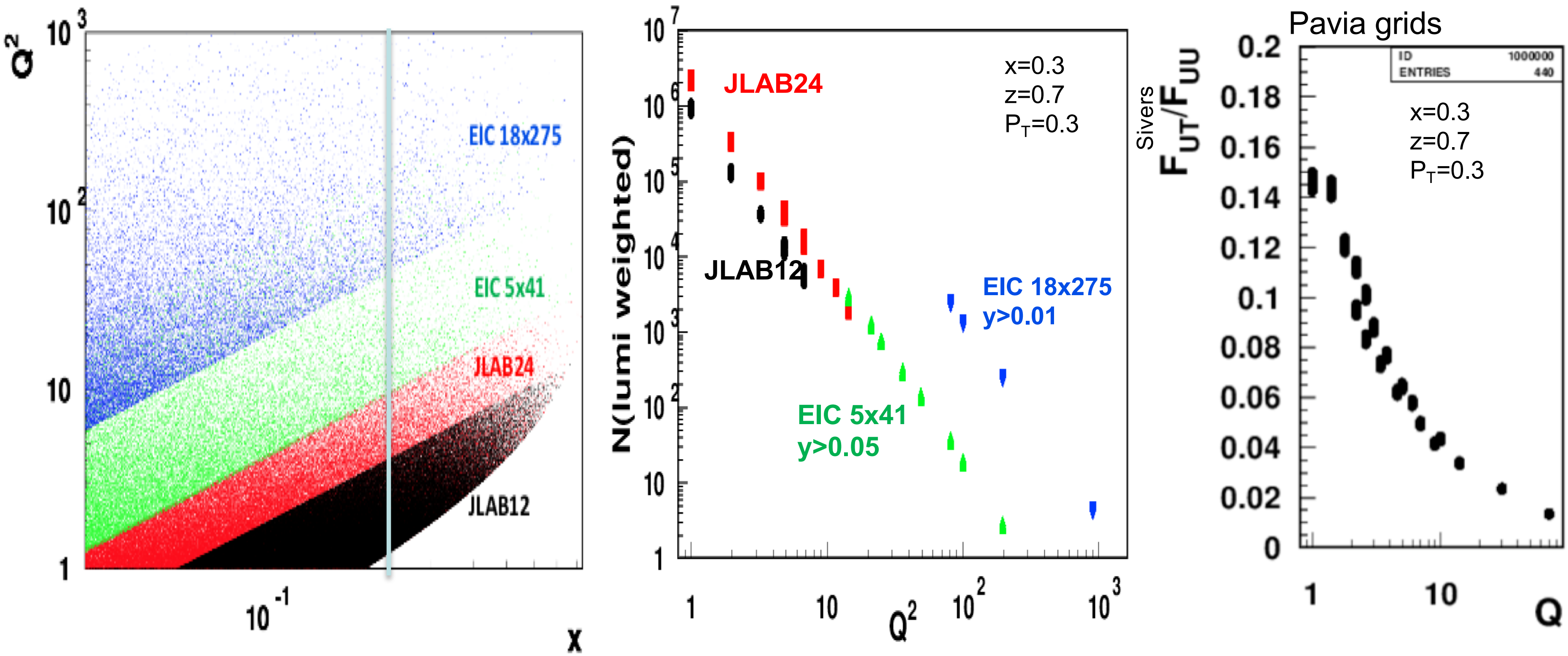






- Kinematic distributions, z,x_F,P_T-distributions of protons, and widths are in good agreement with LEPTO
- TFR may be a valuable source for studies of widths in hadronization
- Expect significantly better separation of TFR and CFR at JLab24

From JLab to EIC: complementarity

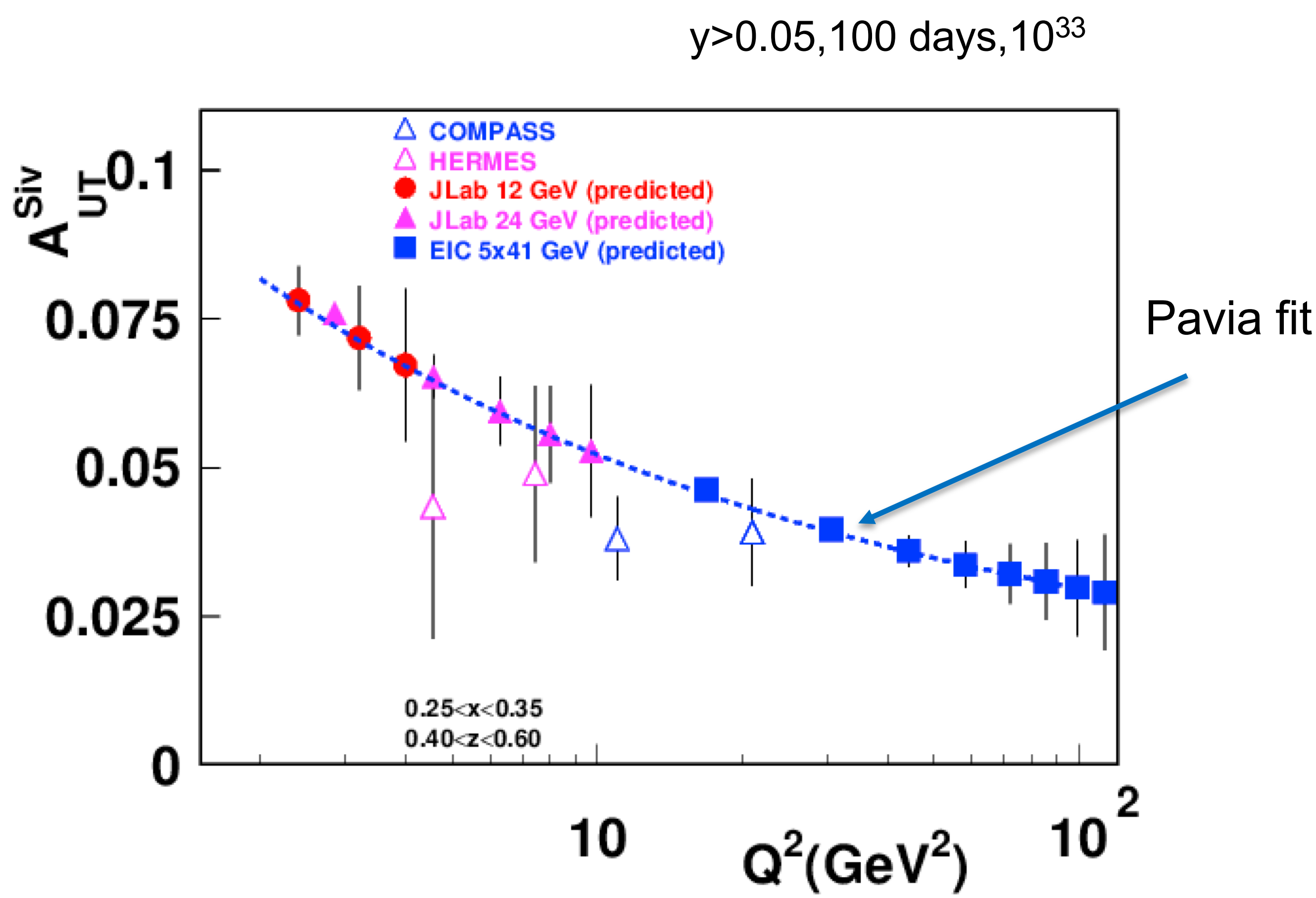


- The counts in a given bin, and the size of the effect will define the expected sensitivity.
- Proper evaluation of systematics, will require definition of fiducial kinematics, and the impact of the multidimensionality
- JLab at 24 GeV will provide critical input in evolution studies of TMDs
- Higher Q^2-coverage of “Low s” EIC running will provide validation of evolution studies at JLab at large x (will require high luminosity)

Contributions for 3D structure studies: Sivers

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

Sivers SSA has no ε-factor (depolarization)



- Measurements of Q^2-dependence of SSAs will be crucial in validation of the theory
- JLab24 will be crucial to bridge the TMD studies between JLab12 and EIC in the valence region

B2B correlations with long. Pol. Target

N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^{\perp}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^{\perp}$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^h, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

Kotzinian, PINAN 2011

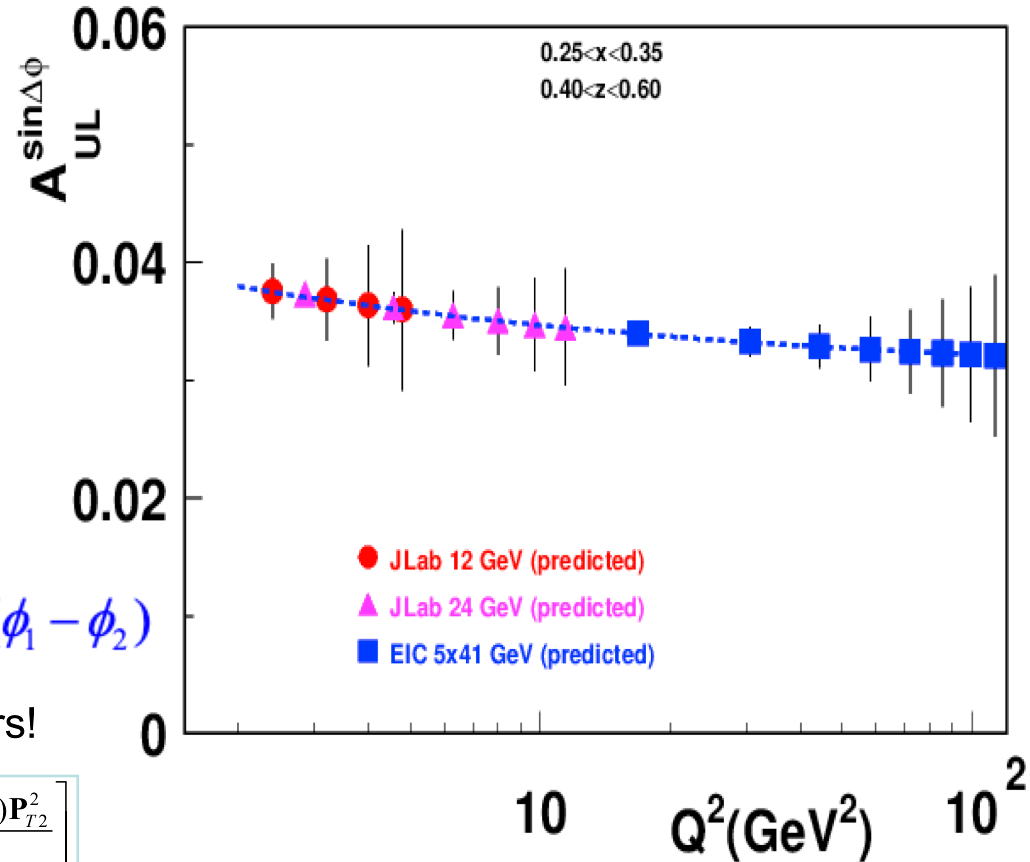
$$\sigma_{UU} = F_0^{\hat{u}\cdot D_1}$$

$$\sigma_{UL} = -\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\hat{u}_{1L}^{\perp h}\cdot D_1} \sin(\phi_1 - \phi_2)$$

No depolarization, like Sivers!

$$F_{k1}^{\hat{M}\cdot D} = C\left[\hat{M}\cdot D \frac{(\mathbf{P}_{T1}\cdot\mathbf{P}_{T2})(\mathbf{P}_{T2}\cdot\mathbf{k}) - (\mathbf{P}_{T1}\cdot\mathbf{k})\mathbf{P}_{T2}^2}{(\mathbf{P}_{T1}\cdot\mathbf{P}_{T2})^2 - \mathbf{P}_{T1}^2\mathbf{P}_{T2}^2}\right]$$

y>0.05,100 days,10^{33}



CLAS12 proposals

NH3/ND3

E12-09-009

E12-07-107

E12-09-007A

^3He

C12-20-002

^7LiD

E12-14-001

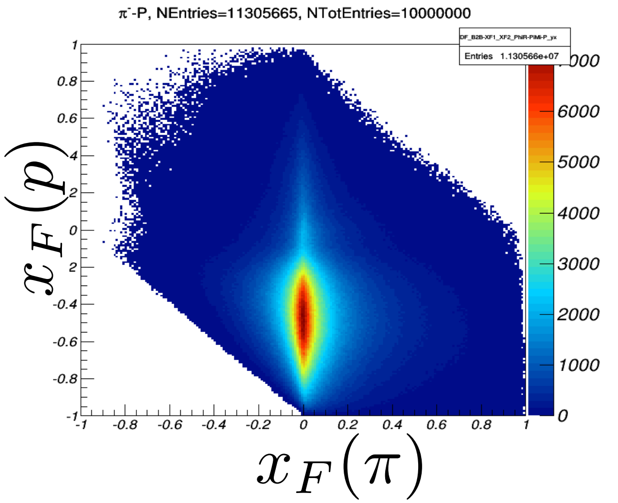
- Target SSA can be measured in the full Q^2 range, combining different facilities
- JLab24 will be crucial to bridge the studies of FFs between JLab12 and EIC in the valence region

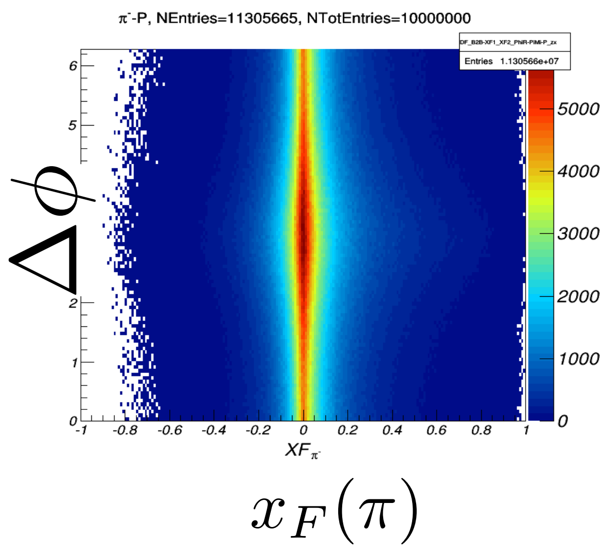
b2b distributions at EIC: (proton-pion)

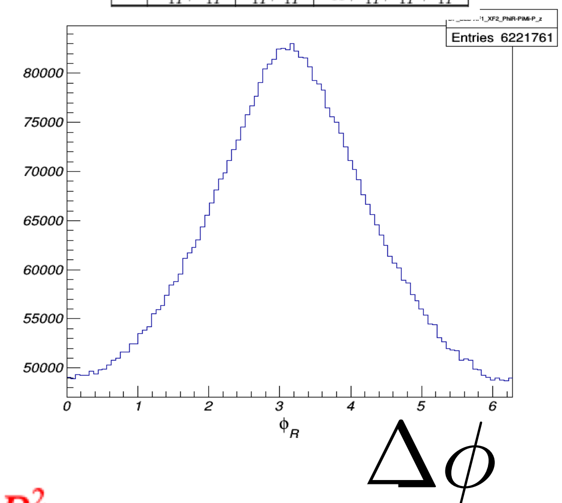
N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

$$ep \longrightarrow e'p\pi^+X$$

EIC 5x41







$$\sigma_{UL} = -\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\hat{u}_{1L}^{\perp h}\cdot D_1} \sin(\phi_1 - \phi_2)$$

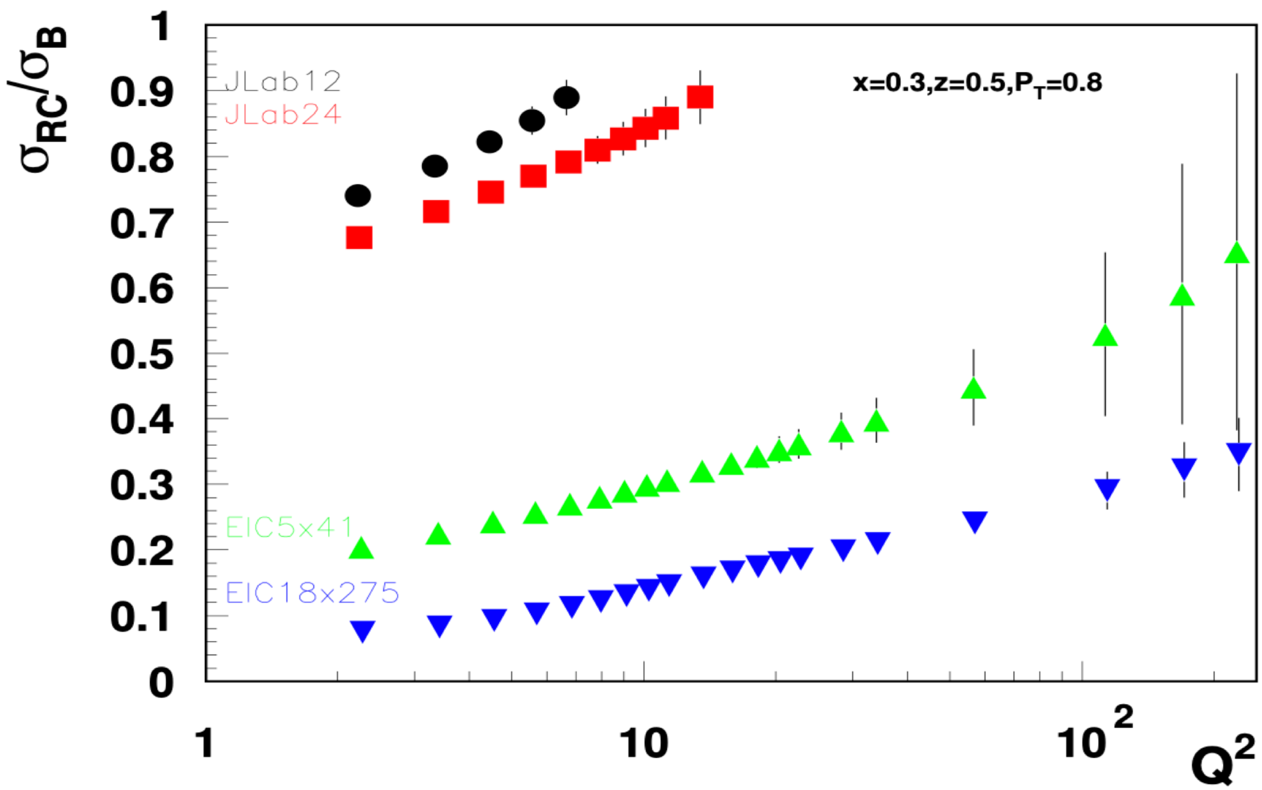
$$\frac{P_{T1}^2}{m_1 m_N} F_{kp1}^{\hat{t}_{1L}^{\perp}\cdot H_1} \sin(2\phi_1)$$

Target SSAs in ep→e'NhX are unique observables, accessible in EIC studies of TFR/CFR correlations, with clear separation of target and current fragmentation regions

From JLab to EIC: complementarity

The ratio of radiative cross (σ_{RC}) section to Born (σ_B) in SIDIS

T. Liu et al
JHEP 11 (2021) 157
Gaussian F_{UU} (ϕ_h=0)



- The radiative effects in SIDIS may be very significant and measurements in multidimensional space at different facilities will be crucial for understanding the systematics in evolution studies.
- Most sensitive to RC will be all kind of azimuthal modulations sensitive to cosines

Summary

• Measurements of dihadron multiplicities and asymmetries at large transverse momenta provide qualitatively new possibilities for understanding the structure of the nucleon, and the process of hadronization, including understanding of correlations leading to spin-azimuthal asymmetries in SIDIS

•Large Single Spin Asymmetries have been observed by CLAS12 experiment in proton pion production, indicating correlations between hadrons in CFR and TFR can be very significant

•Extending JLab measurements to a wider range in Q^2 and P_T with energy upgrade, will be crucial in studies of evolution properties of underlying PDFs, and separation of higher twist contributions, critical for understanding the QCD dynamics

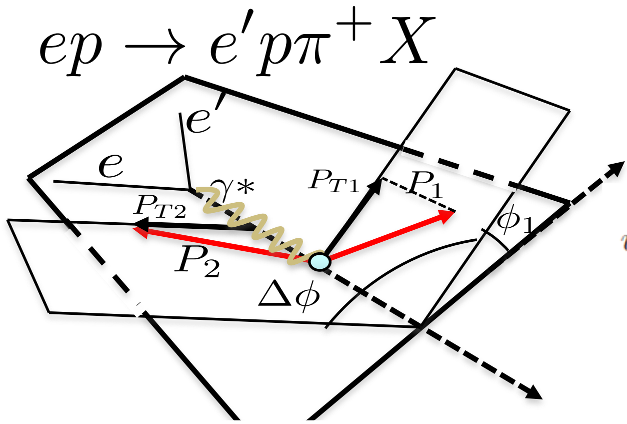
•New single spin asymmetries have been proposed for studies at JLab12/24, as well as using the medium energy EIC at large x, sensitive to quark distributions in the longitudinally polarized nucleons

•Large acceptance of the EIC combined with clear separation of target and current fragmentation regions provide a unique possibility to study the nucleon structure in target fragmentation region and correlations of target and current fragmentation regions

Support slides

b2b SSAs

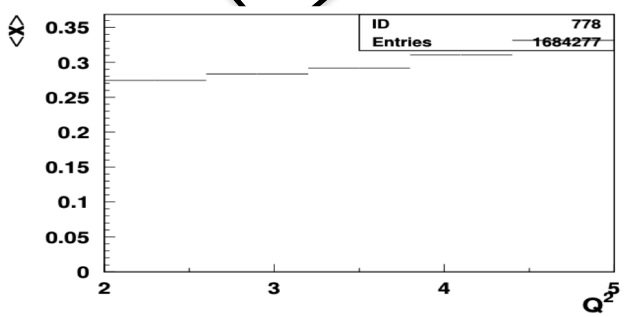
$$ep \rightarrow e'p\pi^+X$$

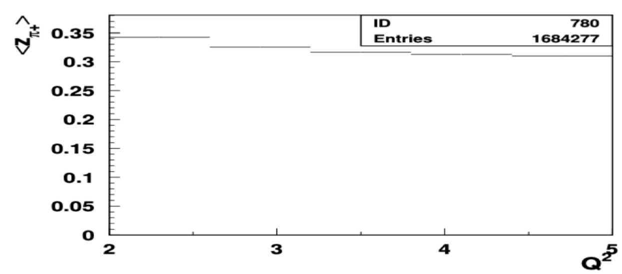


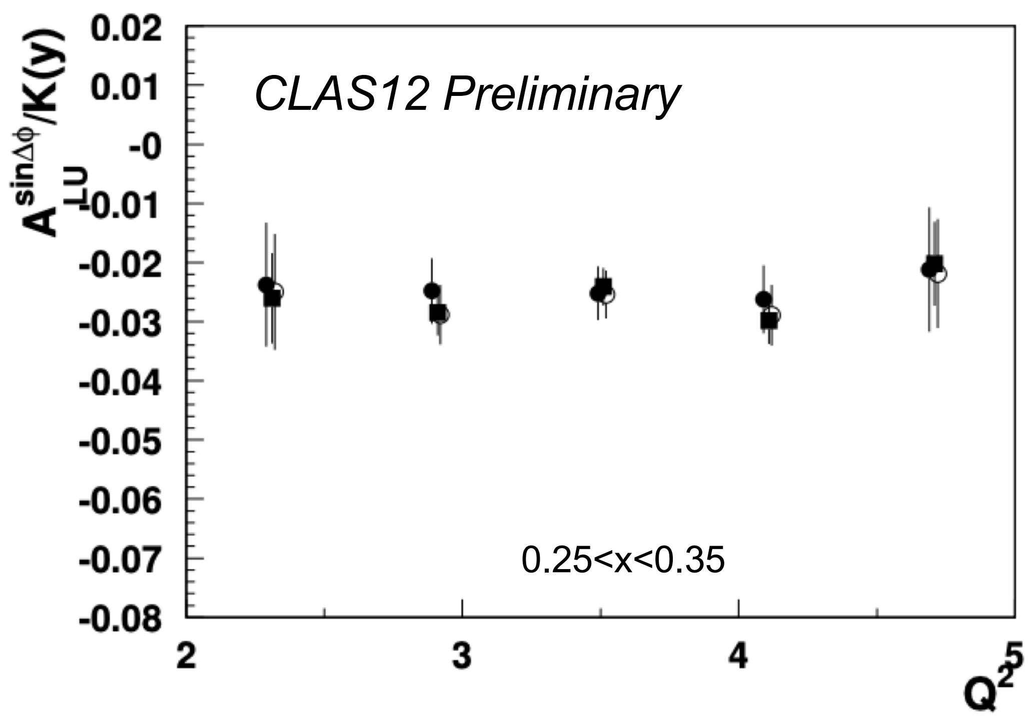
$$\mathcal{A}_{LU}^{\sin(\phi_1-\phi_2)} \propto \frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}$$

$$w_5 = \frac{(\mathbf{k}_\perp \cdot \mathbf{P}_{2\perp})(\mathbf{P}_{1\perp} \cdot \mathbf{P}_{2\perp}) - (\mathbf{k}_\perp \cdot \mathbf{P}_{1\perp})\mathbf{P}_{2\perp}^2}{(\mathbf{P}_{1\perp} \cdot \mathbf{P}_{2\perp})^2 - \mathbf{P}_{1\perp}^2 \mathbf{P}_{2\perp}^2}$$

N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

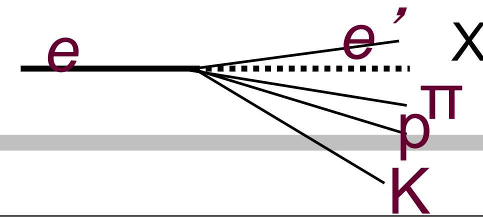


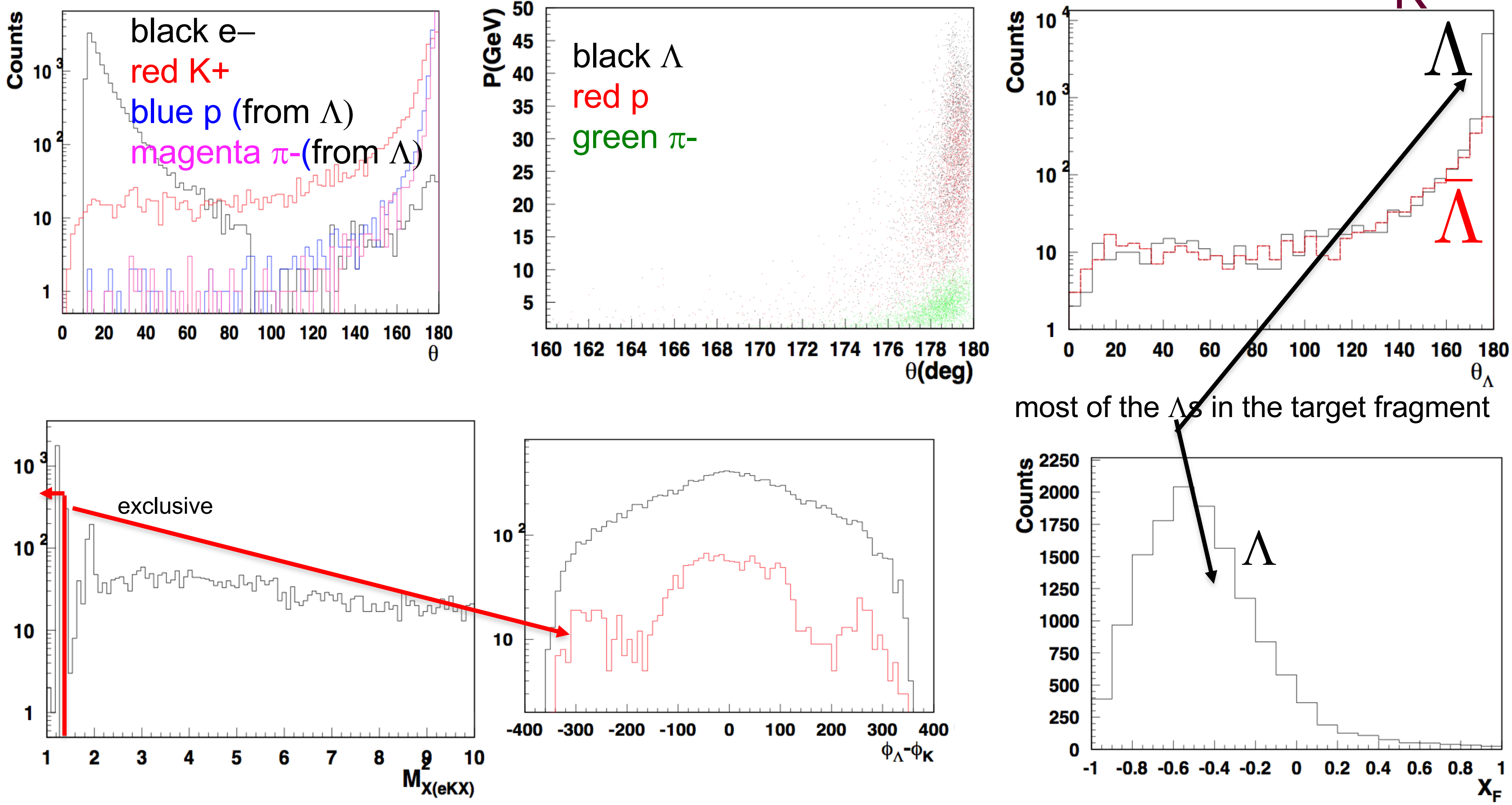




No significant Q^2-dependence observed for b2b A_{LU}

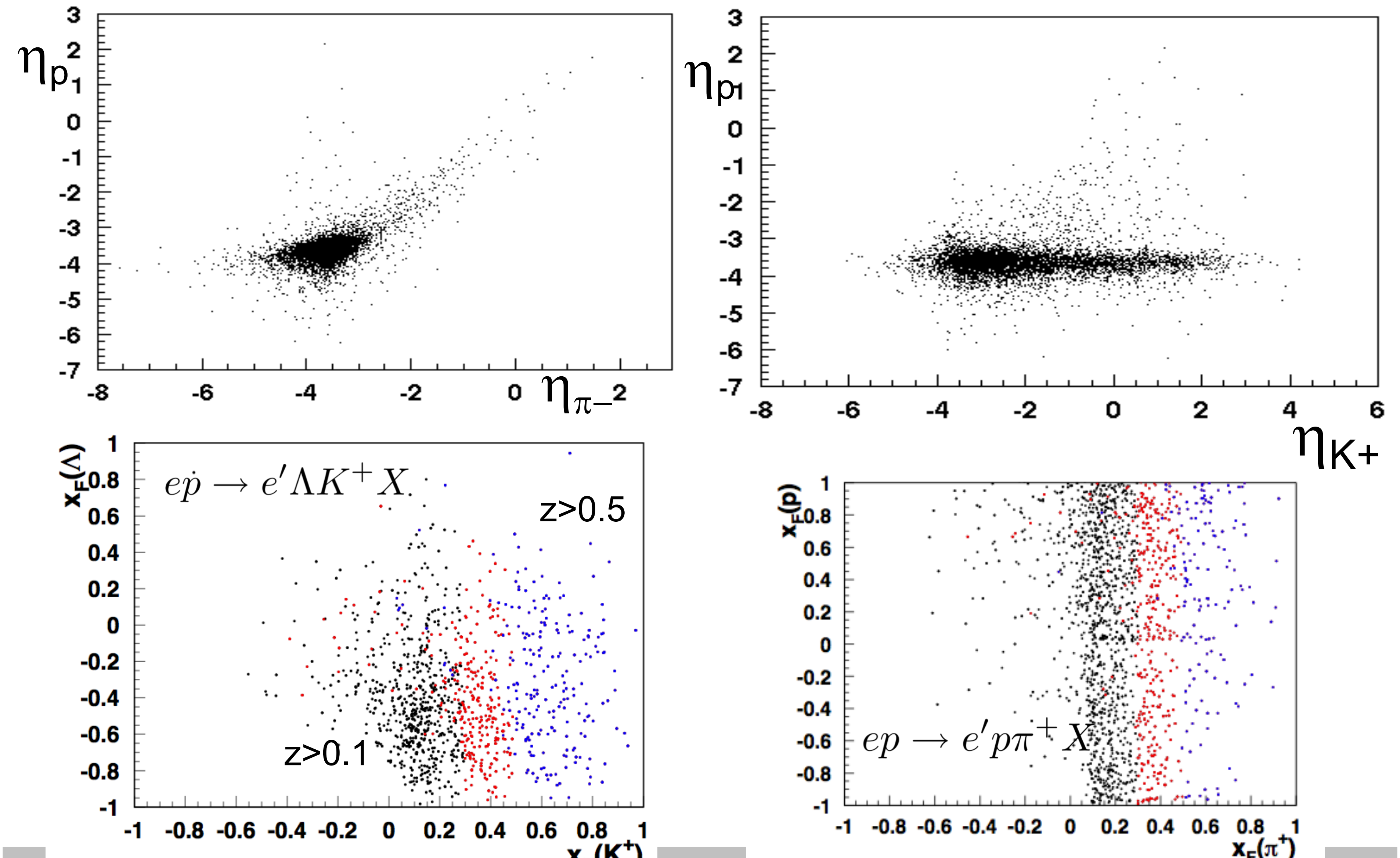
Lambda production in EIC (5x50 GeV)



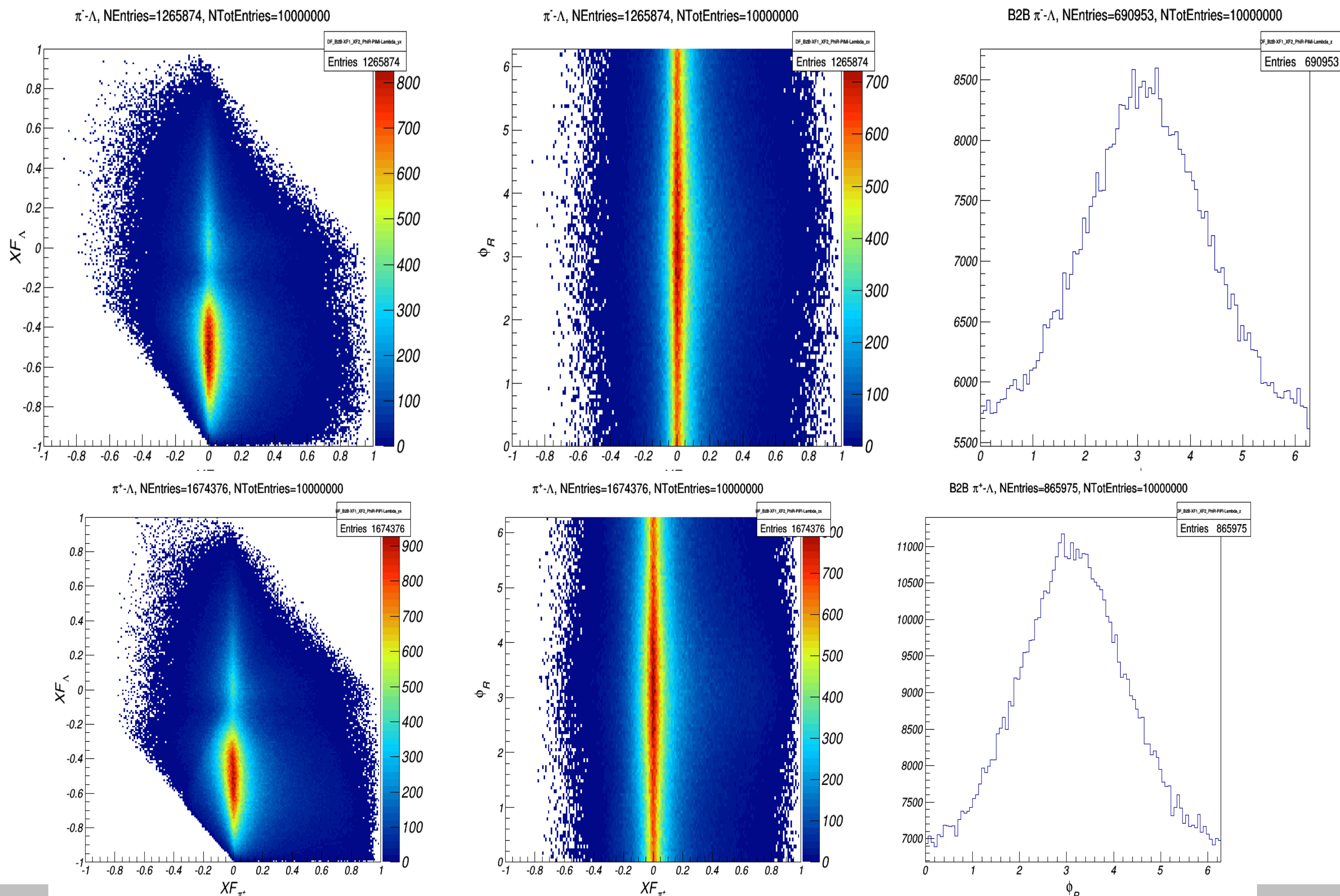


At forward angles Lambdas are mainly from target fragments

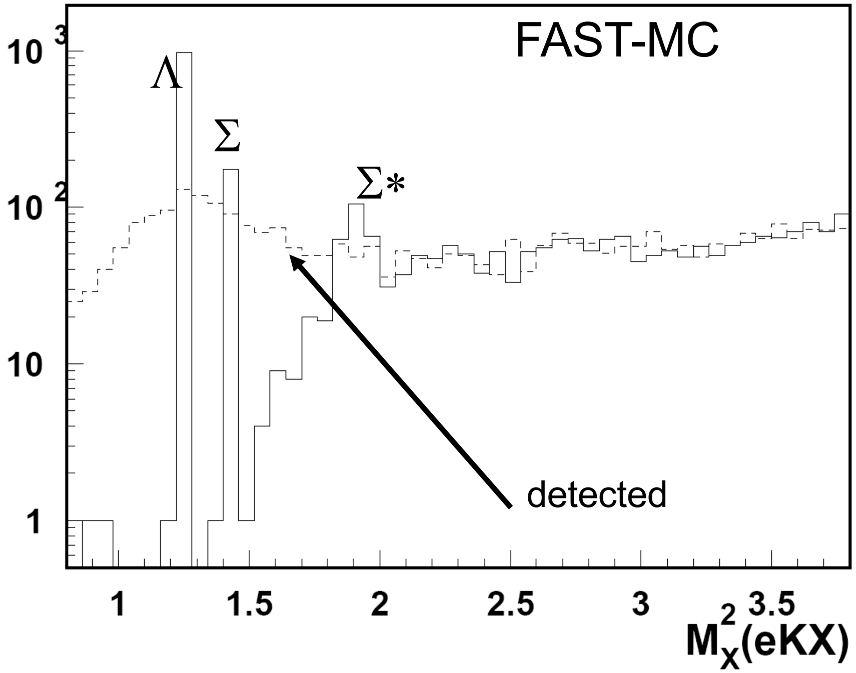
EIC 5x50 GeV: Kinematic distributions of Lambdas and Kaons

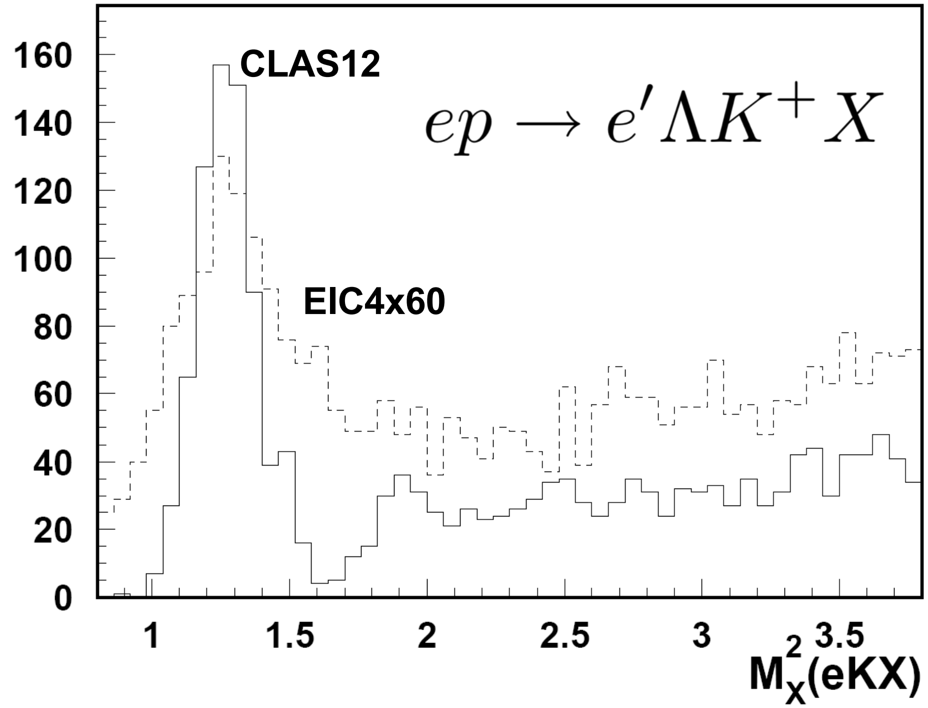


b2b distributions: EIC 5x50 (Lambda-pi)



Kaon production in SIDIS





$\sigma(p) = 0.05 + 0.06*p$ [GeV] %

Identification using the missing mass may be possible

b2b distributions: CLAS12 (proton-pion)