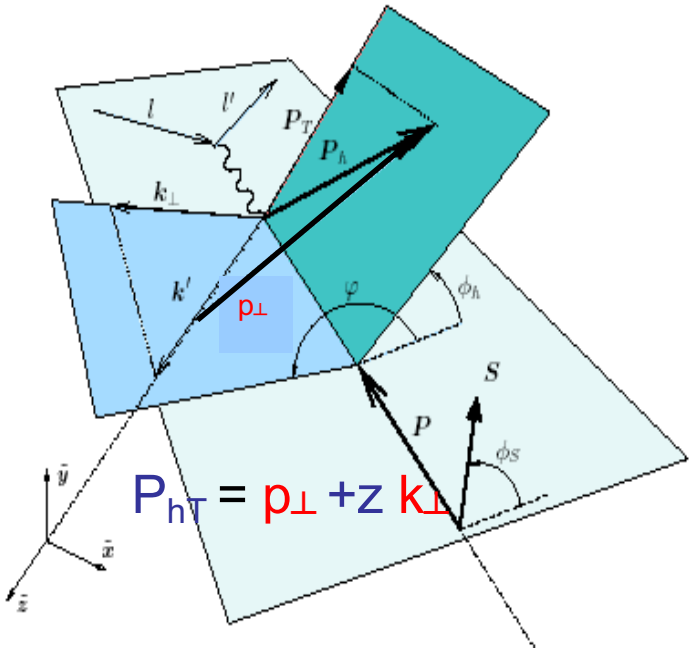
Opportunities for semi-inclusive studies at high-energy (experiment)

Harut Avakian (JLab)

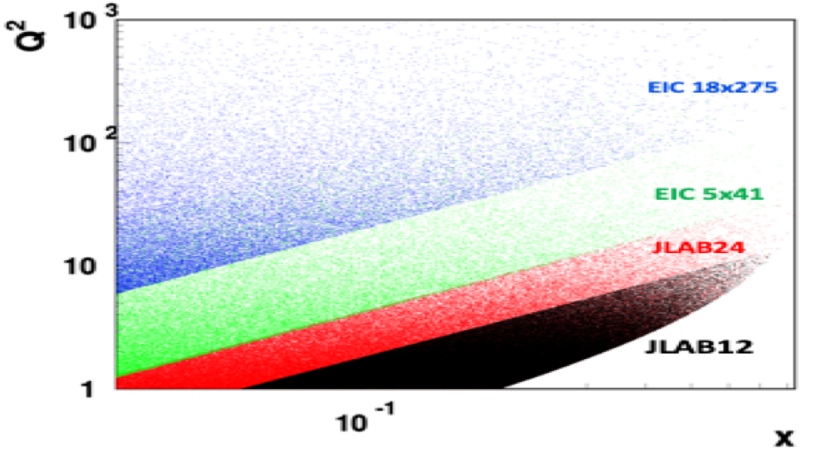
J-Future, March 28-30, 2022

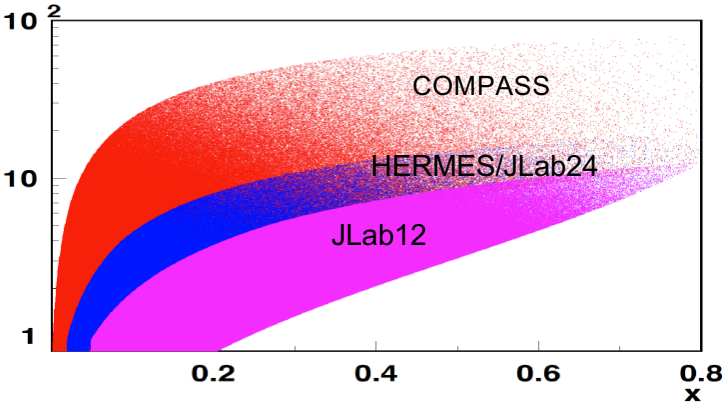
- Accessing spin-orbit correlations in SIDIS at JLab
- What we learned so far:
- Interpretation of P_T-dependences in SIDIS for medium P_T ($0.6< P_T <1.5$ GeV)
- Correlations between hadrons, both in TFR and CFR
- Understanding of Q^2-dependences crucial for validation of the theory
- Evolution and transverse momentum dependence of TMDs
- Measurements with polarized targets
- Complementarity of JLab12/24 and EIC
- Summary

SIDIS kinematical coverage and observables

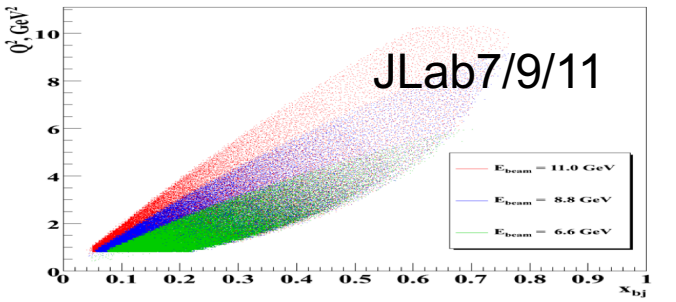


EIC





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

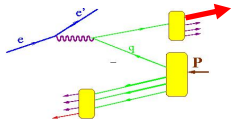


- Studies of azimuthal modulations give access to underlying 3D partonic distributions
- QCD predicts only the Q^2-dependence of 3D PDFs

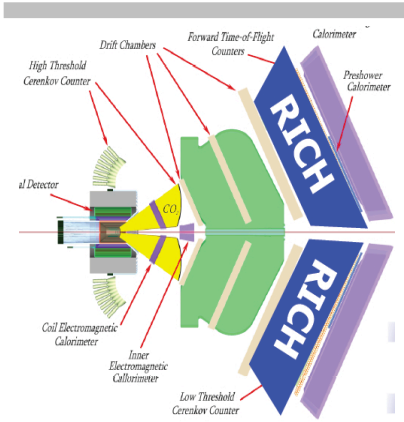
What we learned

- SIDIS, with hadrons detected in the final state, from experimental point of view, is a measurement of observables in 5D space (x,Q^2,z,P_T,ϕ)
- Collinear SIDIS, is just the proper integration, over P_T,ϕ

- SIDIS observations relevant for interpretations of experimental results:
  - Understanding of phase space effects is important
  - Understanding of P_T-dependences of observables in the full range of P_T dominated by non-perturbative physics is important
  - Understanding the role of vector mesons is important
  - Understanding of evolution properties of observables is important
  - Understanding of radiative effects may be important for interpretation
  - Multidimensional measurements with high statistics, critical for separation of different ingredients



SIDIS at JLab12



CLAS12

Proton

Quark spin polarization

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

E12-06-112: π^+,π^-,π^0
E12-09-008: K^+, K^-,K^0

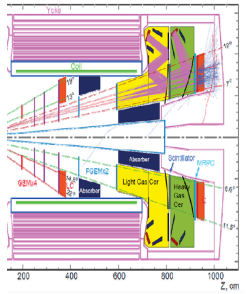
E12-07-107: π^+,π^-,π^0
E12-09-009: K^+,K^-,K^0

C12-11-111: π^+,π^-,π^0 K^+, K^-

H_2, NH_3, HD

Hall C | Hall A

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



C12-11-108: π^+,π^- Solid

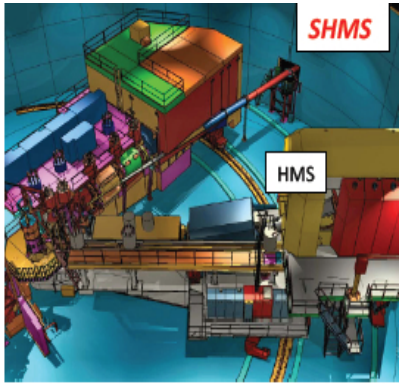
H_2 NH_3

Coverage of large Q^2 and large P_T

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

C12-20-002
$\pi^+,\pi^-.\pi^0$,K+

D_2

Quark spin polarization

Nucleon polarization \ 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

^{3}He

Quark spin polarization

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

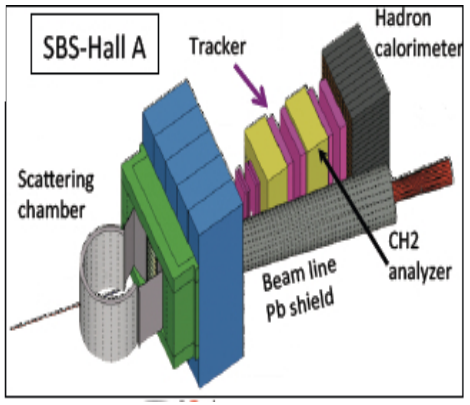
Hall A

E12-07-007: π^+,π^- Solid

E10-006: π^+,π^- Solid
E12-09-018: π^+,π^-, K^+,K^- SBS

^{3}He

Precision measurements of all SFs in a wide range



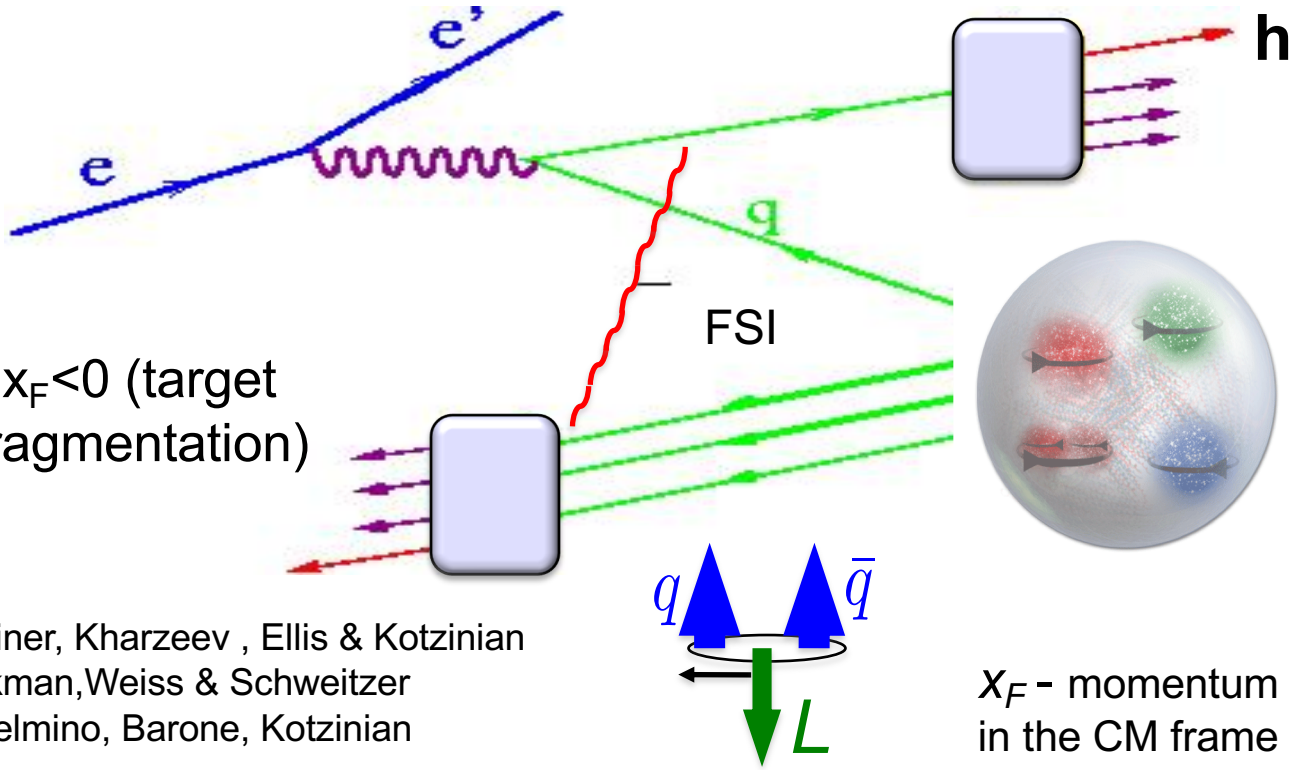
All proposals will benefit from energy upgrade

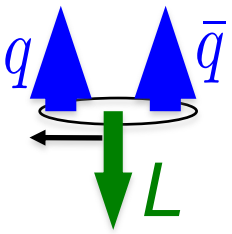
Hadron production in hard scattering

x_F – fractional momentum in the CM frame

x_F>0 (current fragmentation)

X. Artru & Z. Belghobsi





x_F<0 (target fragmentation)

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

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

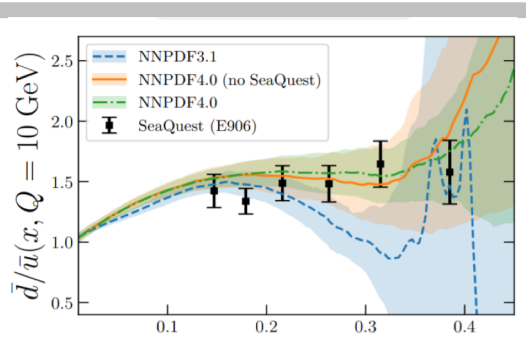
x_F - momentum in the CM frame

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

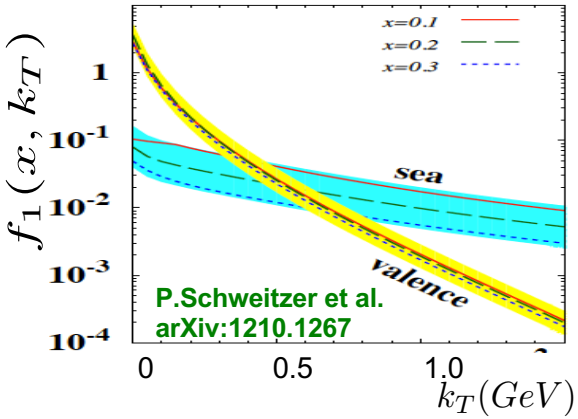
Non-perturbative contributions

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

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

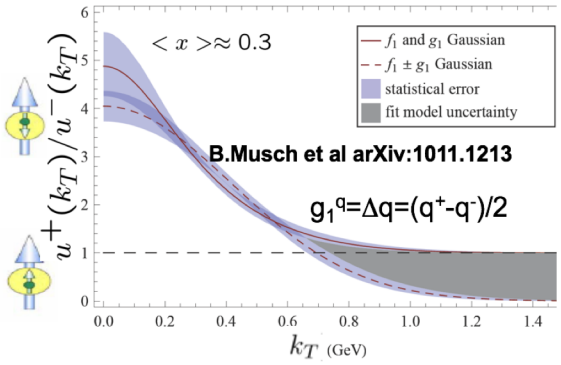


- Spin-Orbit correlations so far were shown (measurements and model calculations) to be significant in the region where non-perturbative effects dominate (x>0.02)
- Large transverse momenta of hadrons most relevant for understanding the non-perturbative QCD dynamics



- 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

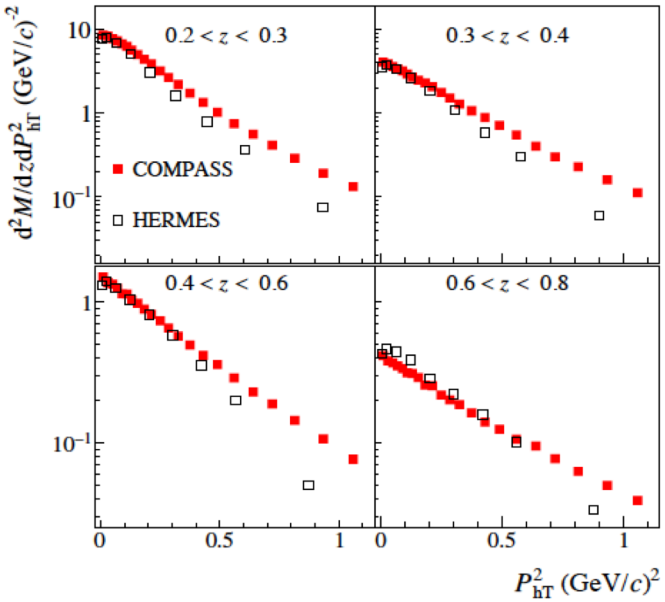


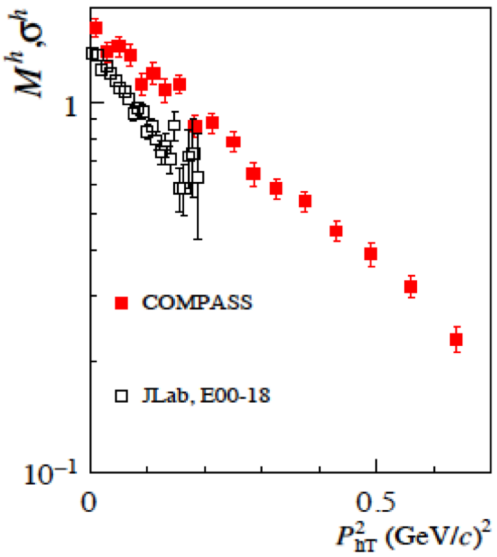
Understanding of the evolution of transverse momentum dependence most critical in validation of the theory

Multiplicities of hadrons in SIDIS

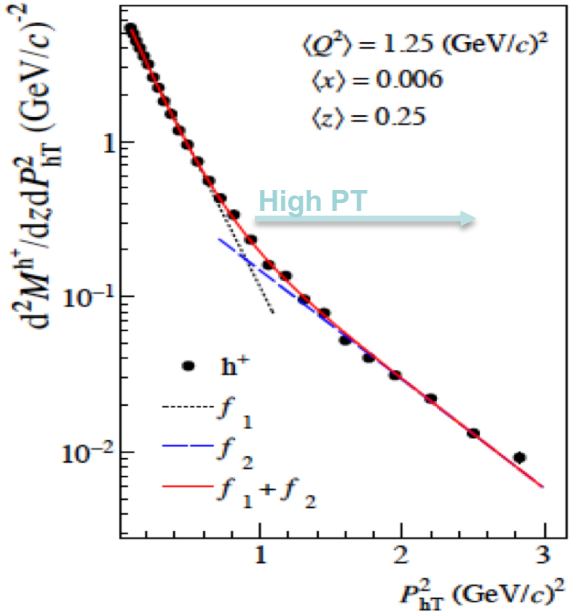
Gaussian Ansatz $f_1^q \otimes D_1^{q\to h} = x f_1^q(x)\, D_1^{q\to h}(z) \frac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$

TMDs universal, so what is the origin of the differences observed ?





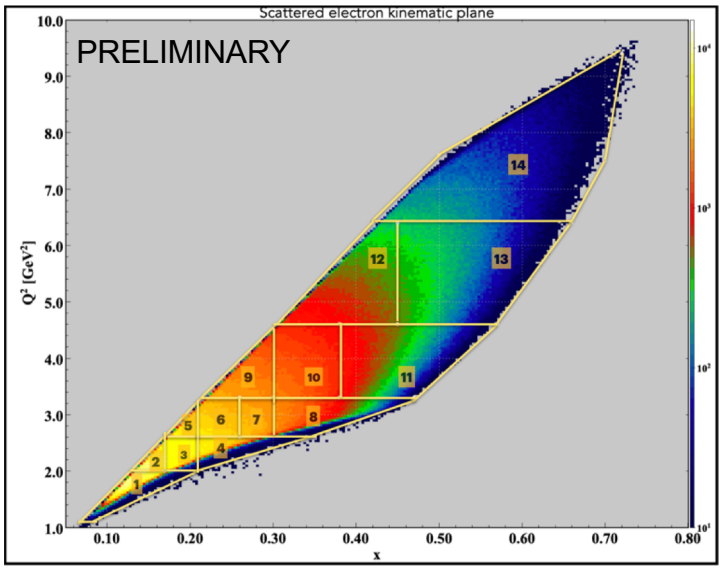
COMPASS:1709.07374

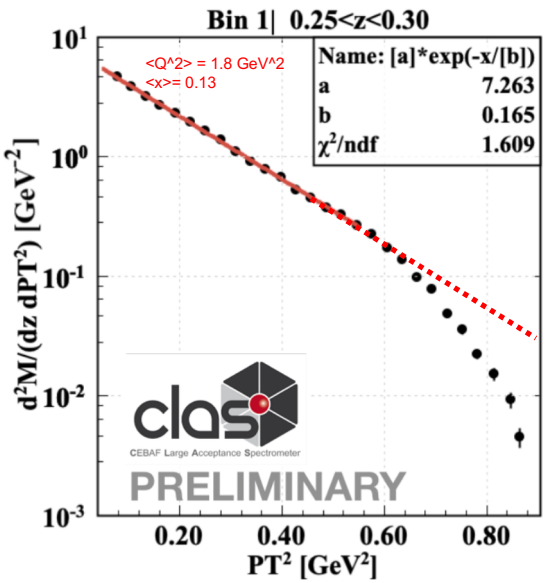


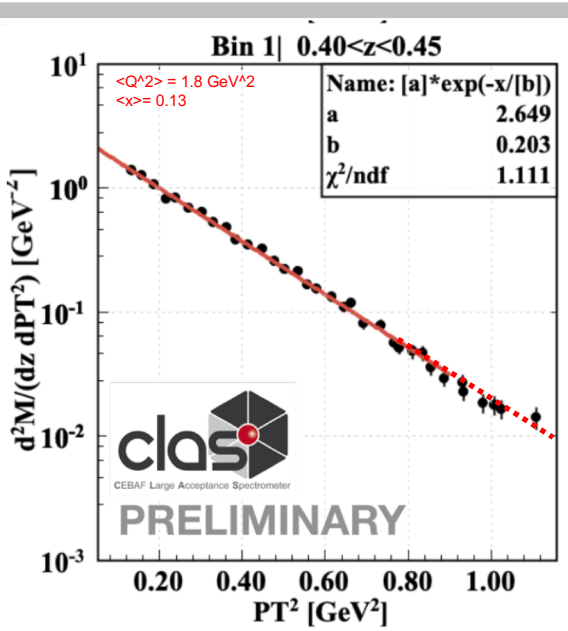
- TMDs evolution makes distribution wider
- Lower the beam energy, less phase space for high P_T

- What is the origin of the "high" P_T tail?
  1) Perturbative contributions?
  2) Non perturbative contributions? (TMDs dependence not 1 Gaussian)

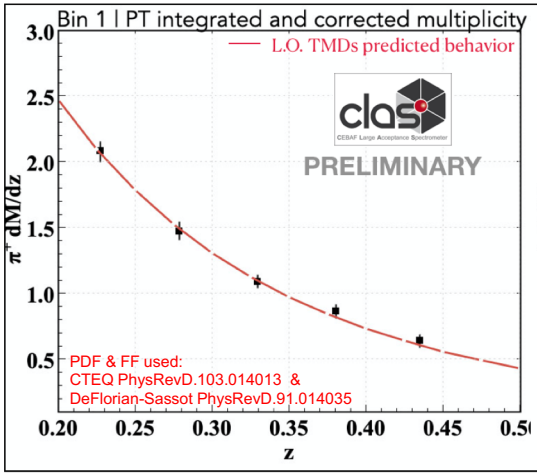
CLAS12 1h Multiplicities: high P_T & phase space

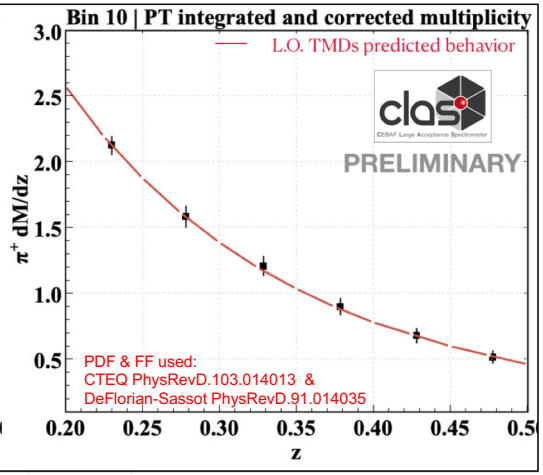






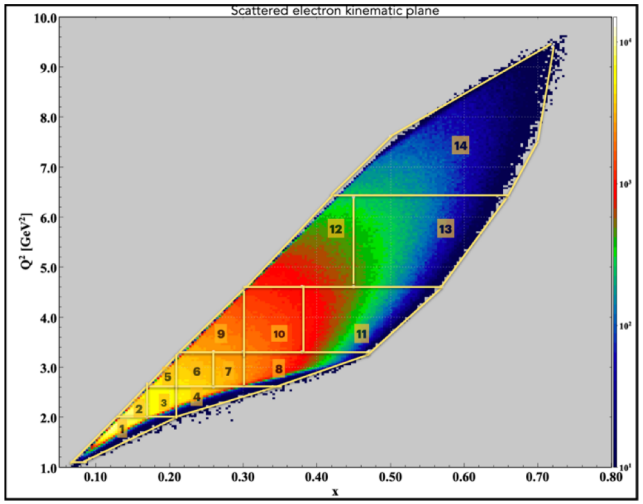
For some kinematic regions,
at low z, the high P_T distribution appear suppressed: there is no enough energy in the system to produce hadron with high transverse momentum (phase space effect).
If the effect is accounted, the CLAS data follows global fits.





CLAS12 1h Multiplicities: high P_T & phase space

G.Angelini (Sardinia 2021)



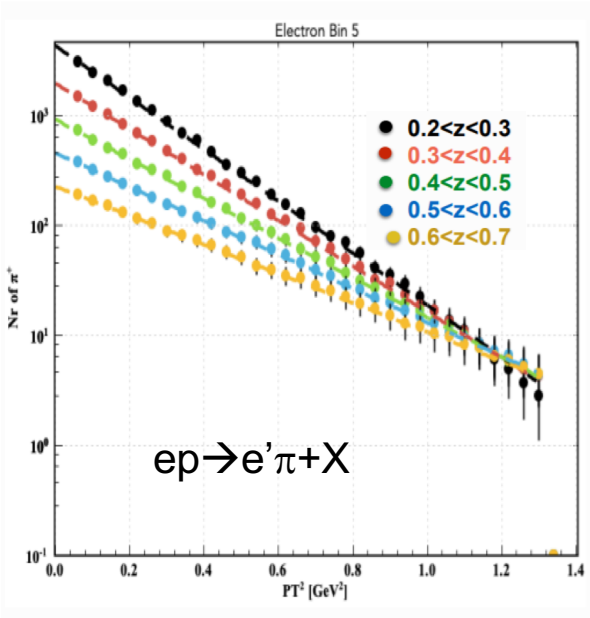
Coded PT distribution in generator (0.2<z<0.25)

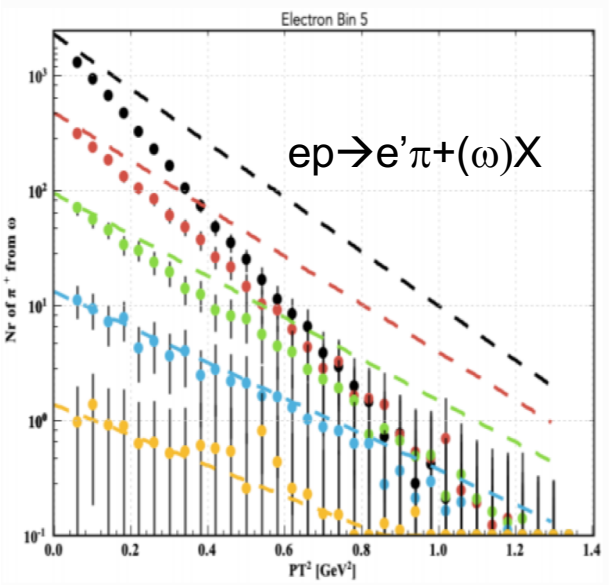
Directly Generated π+ (0.2 <z<0.25)

π+ decayed from ω (0.2 <z<0.25)

Gaussian Fit

The same Gaussian Ansatz for transverse momentum used for pions and VMs to see the impact on P_T distribution.

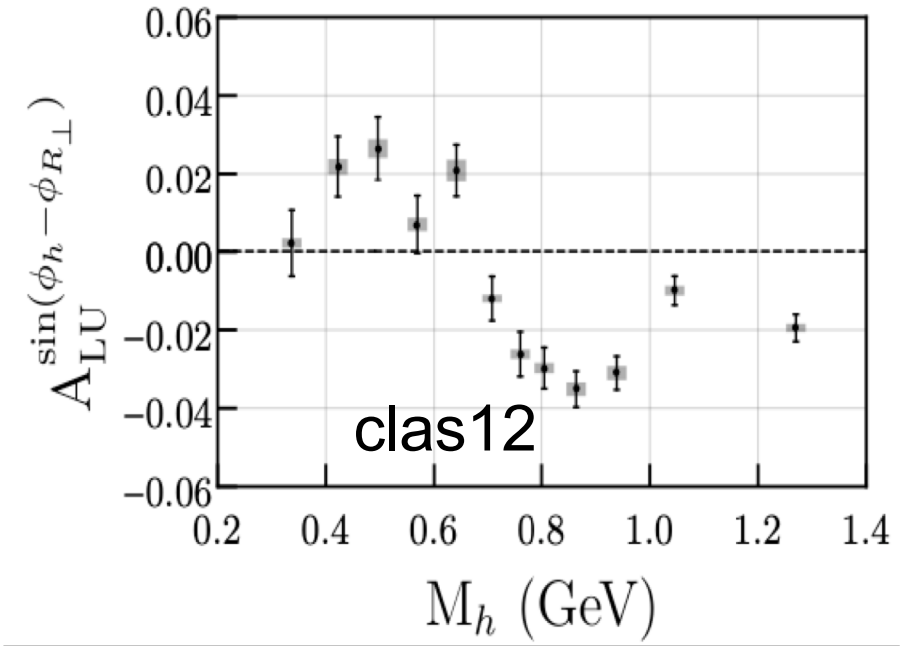




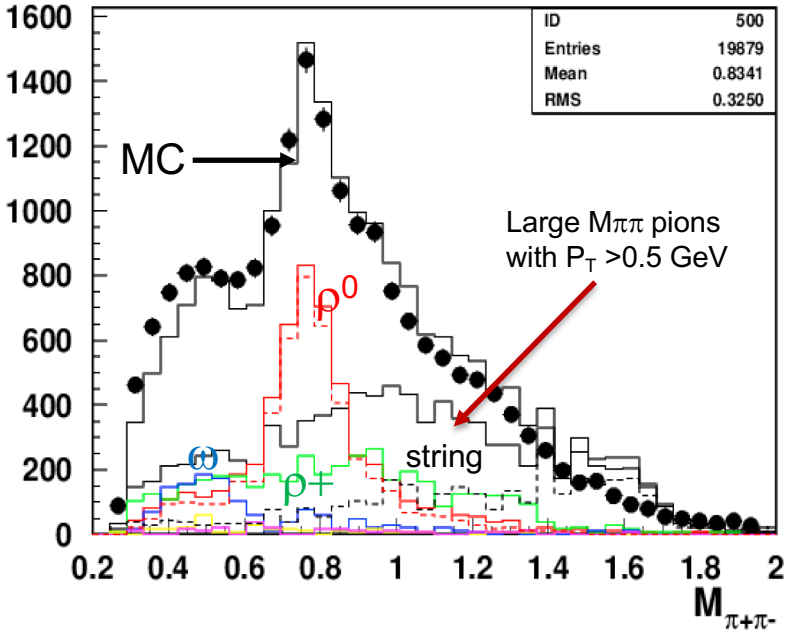
- Phase space limitations for direct pion production more significant at lower W, and lower z
- Decayed pions have a much steeper P_T distribution at the same z
- Proper studies of transverse momentum distributions, in particular for P_T-weighting, requires large number of bins in P_T and phi
- CLAS12 uses 20 bins in P_T and 6 in z for every x,Q^2 bin + 36 bins in ϕ (measure ϕ–dependence)

2 hadron correlations in CFR ep→e'$\pi^+\pi^-$X

T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)



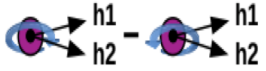
Contributions to π^+ in e'$\pi^+\pi^-$X sample from different channels



- Spin-azimuthal correlations in hadron pair production are very significant
- Hadron pairs in SIDIS (true from JLab to LHC) are dominated by VM decays (therefore single hadron channel too)
- Direct pions dominate only at relatively high P_T, (P_T >0.6-0.7 GeV)

Observation of SSAs in ep→e'$\pi^+\pi^-$X

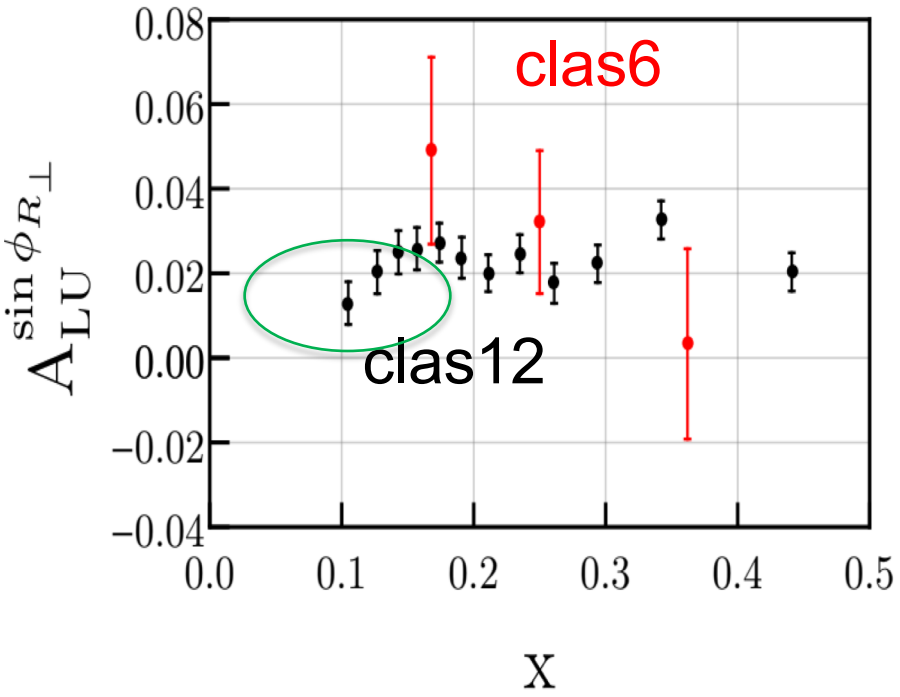
T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)

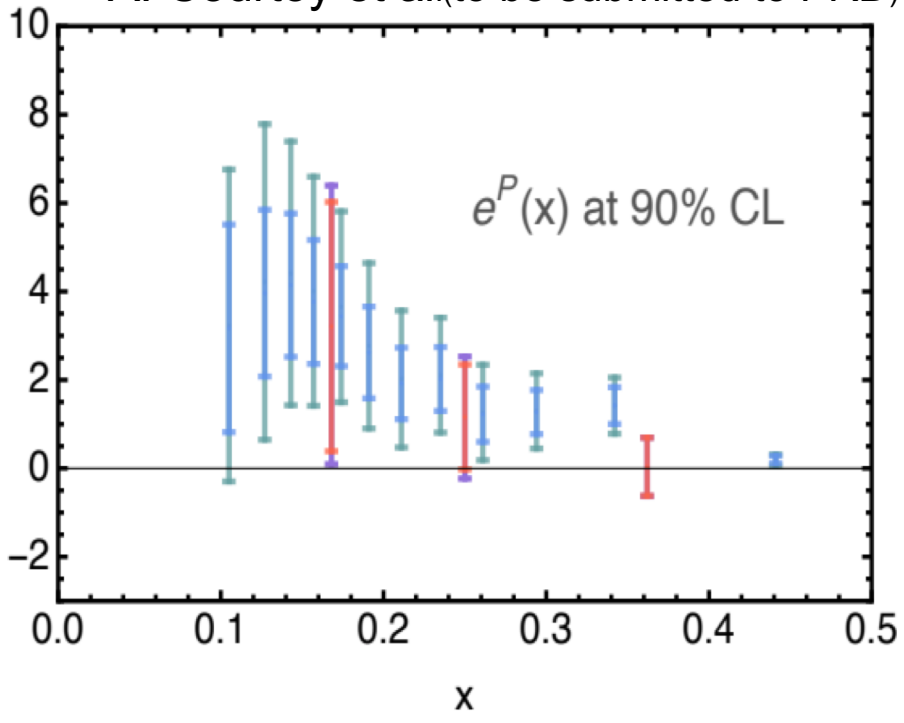
$H_1^{\sphericalangle}$ = 

$$d\sigma_{LU} \propto \lambda_e \sin(\phi_{R_\perp}) \left(xe(x)H_1^{\sphericalangle}(z, M_h) + \frac{1}{z} f_1(x)\tilde{G}^{\sphericalangle}(z, M_h) \right)$$

Bacchetta&Radici: arXiv:hep-ph/0311173

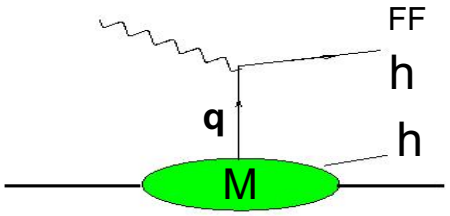
A. Courtoy et al.(to be submitted to PRD)

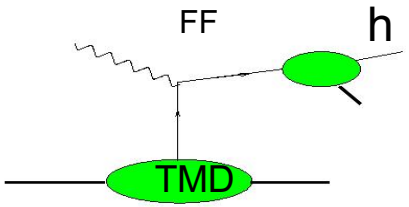


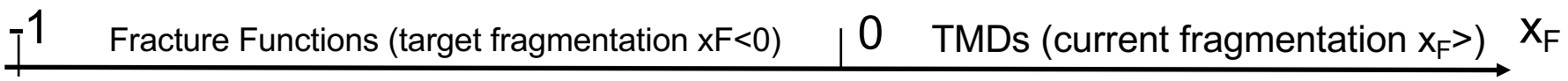


- Doubling the JLab beam energy, opens the phase space for SIDIS dihadrons (low x)
- First extractions support: quark gluon correlations may be very significant,
- PDF e describes the force on the transversely polarized quark after scattering, factorization and evolution studies by Vladimirov et al (in preparation)

Extending PDFs to TFR: Leading Twist







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}	$h_1, h_{1T}^\perp$

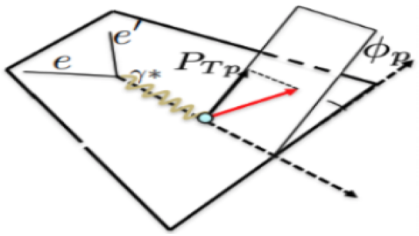
TFR studies provide a unique access to longitudinally polarized quarks in the unpolarized nucleons, and unpolarized quarks in the longitudinally polarized nucleons.

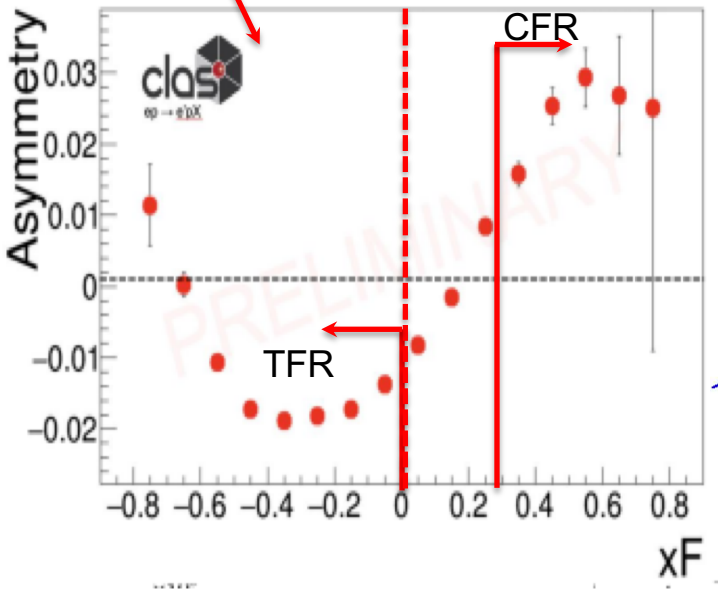
SSA in ep→e'pX production

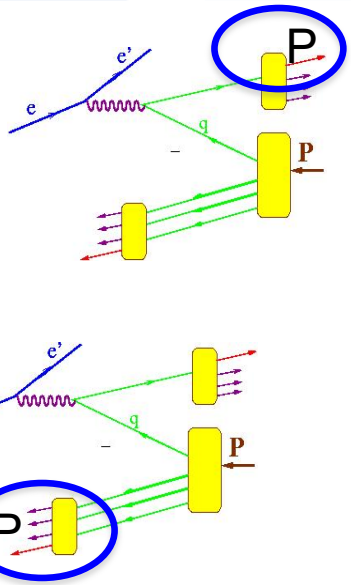
F. Benmokhtar (CPHI-2022)

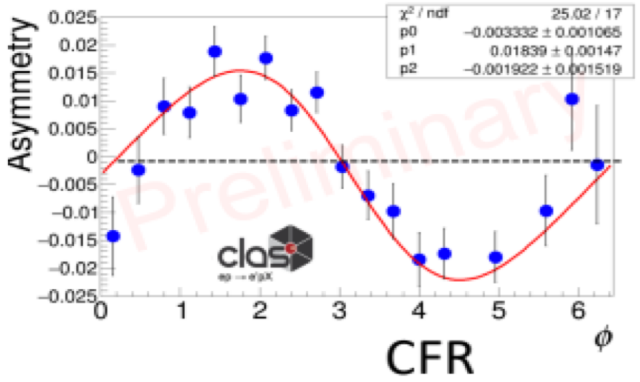
Nq	U	L	T
U	$\hat{u}_2^{\perp h}$	$\hat{l}_2^{\perp h}$	$\hat{t}_2, \hat{e}_2$
L	$\hat{u}_{2L}^{\perp h}$	$\hat{l}_{2L}^{\perp h}$	$\hat{t}_{2L}, \hat{e}_{2L}$
T	$\hat{u}_{2T}^{\perp h}, \hat{u}_{2T}^{\perp h}$	$\hat{l}_T, \hat{l}_{2T}^{\perp h}$	$\hat{t}_{2T}^{h}, \hat{e}_{2T}^{h}, \hat{t}_{2T}^{\perp h}, \hat{e}_{2T}^{\perp h}$

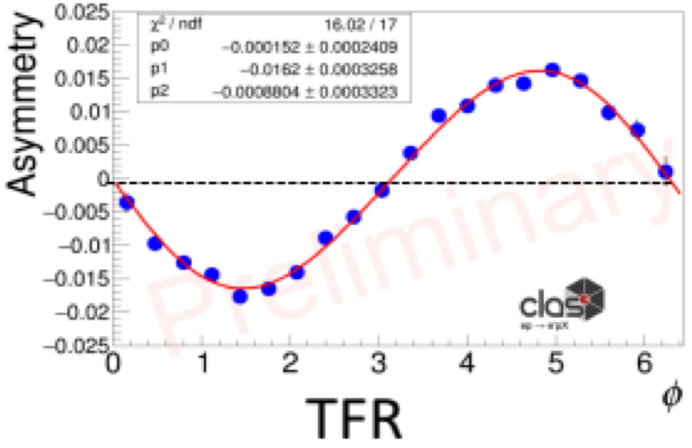
$$A(\phi)_{LU} = \frac{1}{p}\left(\frac{N^+ - N^-}{N^+ + N^-}\right) \rightarrow F_{LU}^{\sin\phi_h} = \frac{A(\phi)_{LU}}{\sqrt{2\varepsilon(1-\varepsilon)}}$$





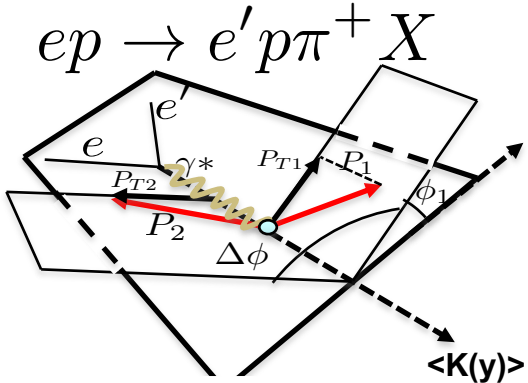






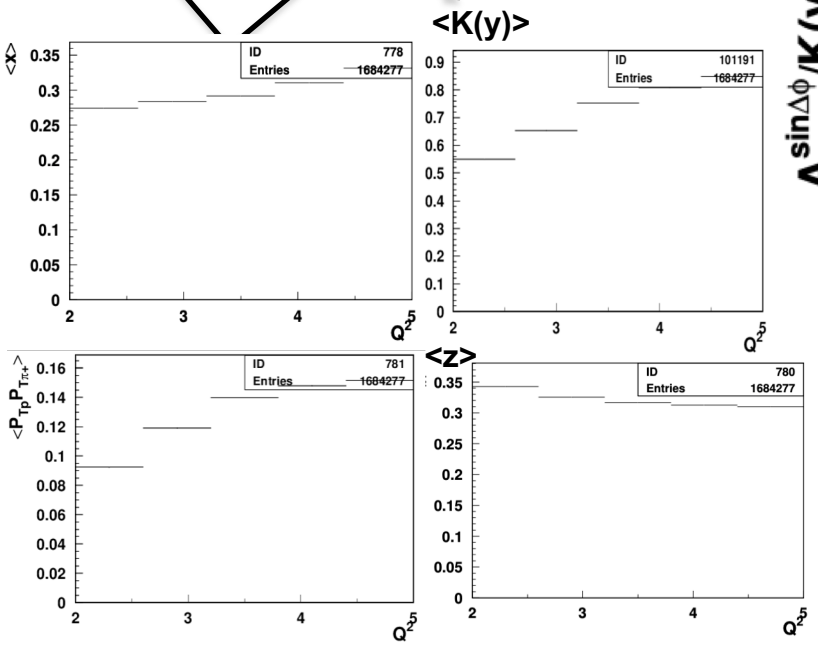
- The SSA, clearly changing the sign, may be used to define separation of TFR and CFR regions
- More baryons in the TFR, mesons in the CFR

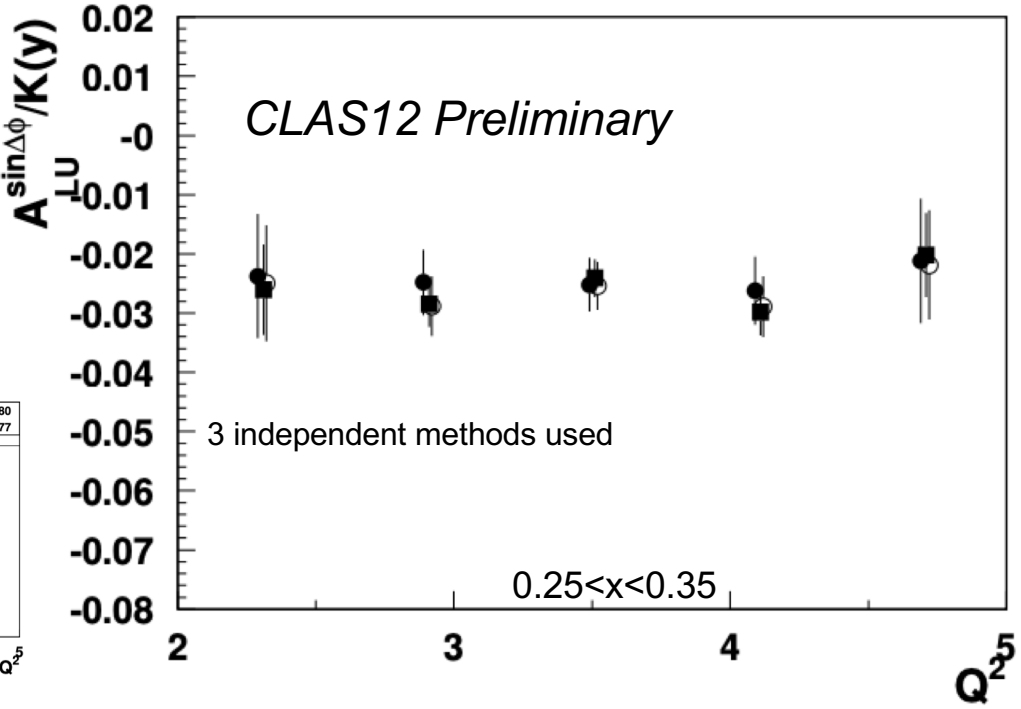
Back to back SSAs in ep→e'pπ+X



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

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	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

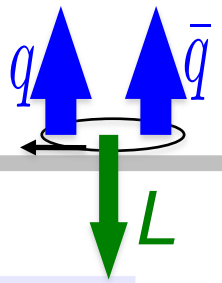




No significant Q^2-dependence observed for B2B A_{LU}

- First indication in large x SIDIS of a LT observable
- Multidimensional measurements crucial for evolution studies

3D PDFs: Common features



A. Vladimirov (CPHI-2022)

CS kernel discribes the interaction of out-going parton with the confining potential
Provides nonperturbative part of evolution for TMDs

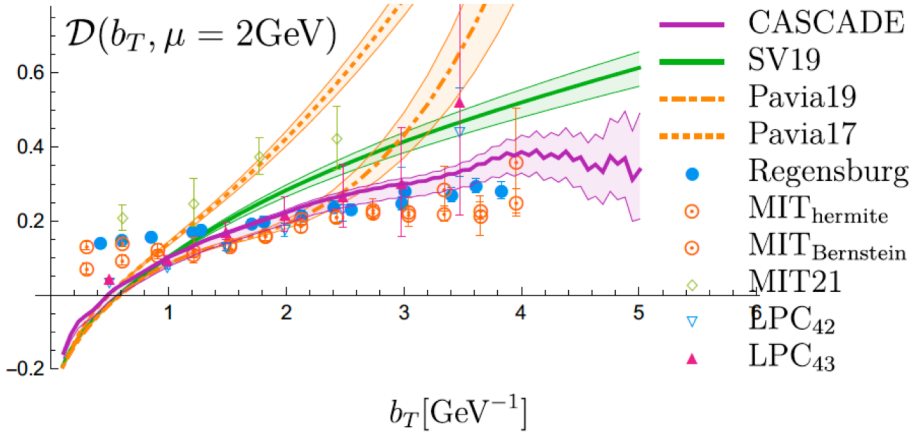
$$Q^2\frac{dF(x,b;Q)}{dQ^2} = -\left(\frac{\gamma_V(Q)}{2} + \mathcal{D}(b,Q)\right)F(x,b;Q)$$

quark AD perturbative known at N^3LO	CS kernel **nonperturbative**	TMD distribution **any tw2** many **tw3**

nonperturbative Q and x can be factorized

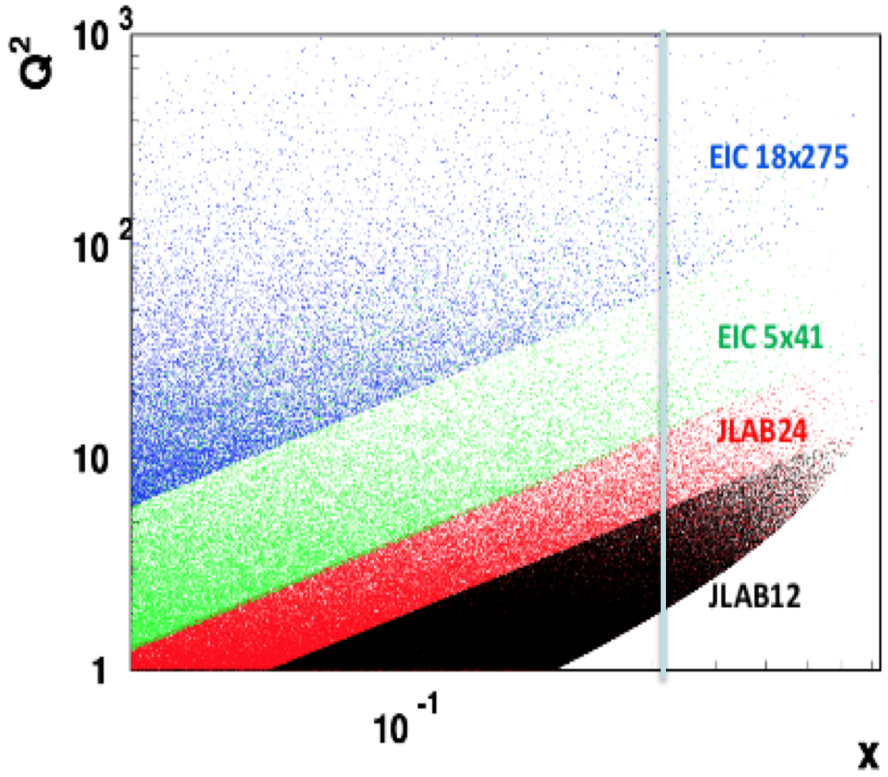
$$F(x,b;Q) = R[\mathcal{D},Q]F(x,b)$$

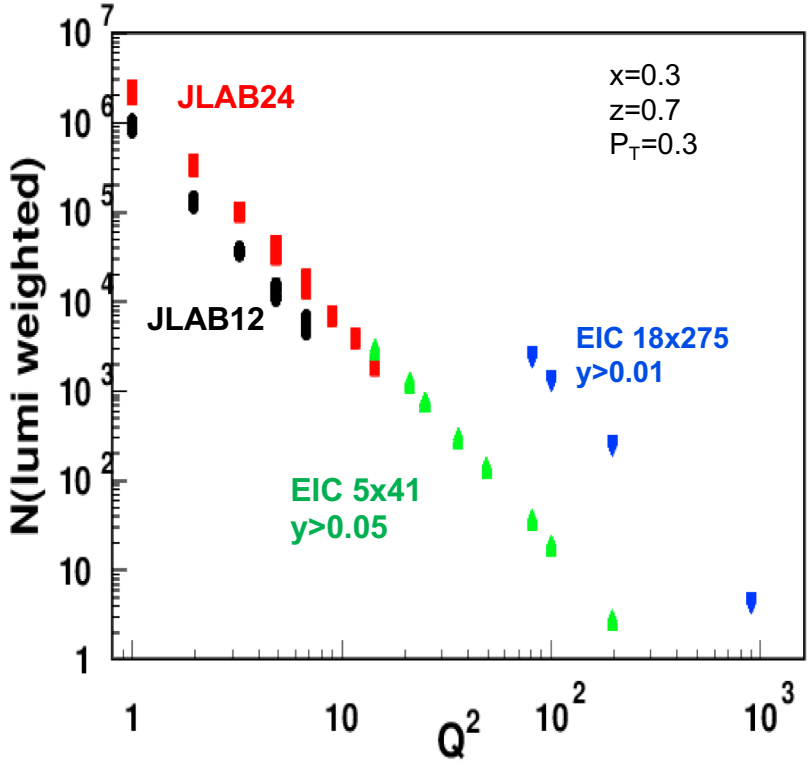
- R is known function
- $\mathcal{D}$ can de determined directly from data
  - requires dense coverage in p_T
  - requires proper adjustments of (x,z,Q)



The Collins Soper kernel, defining the evolution properties of TMDs related to non-perturbative q-q
Detailed studies of evolution properties of observables in different x-range will be needed

From JLab to EIC: complementarity

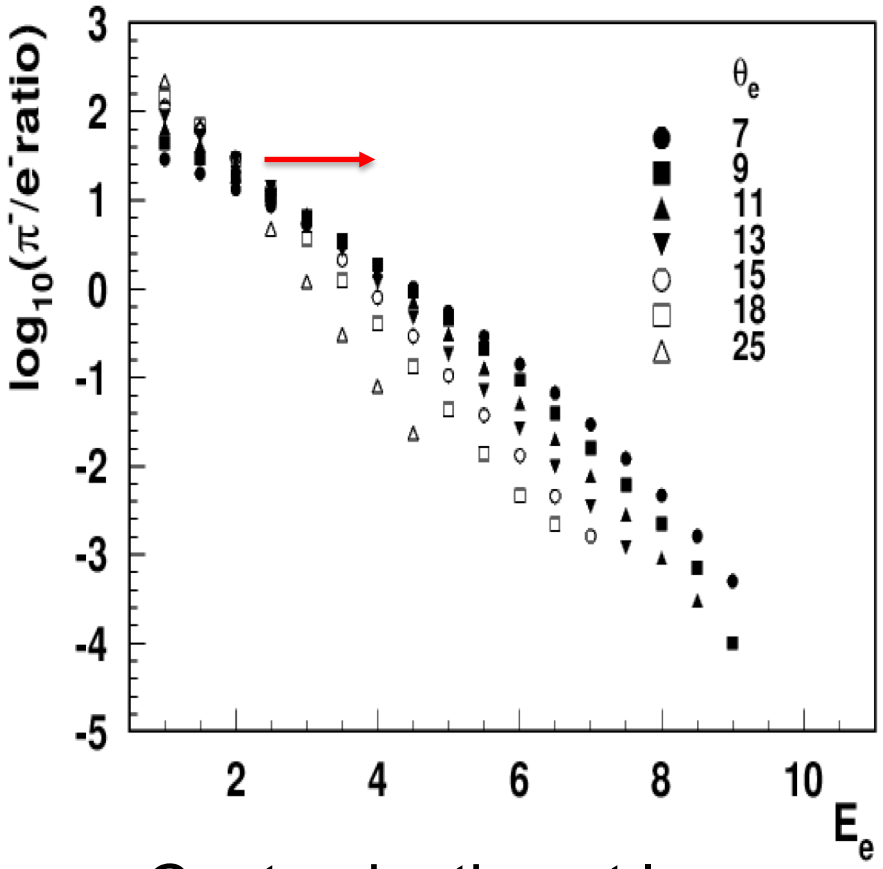




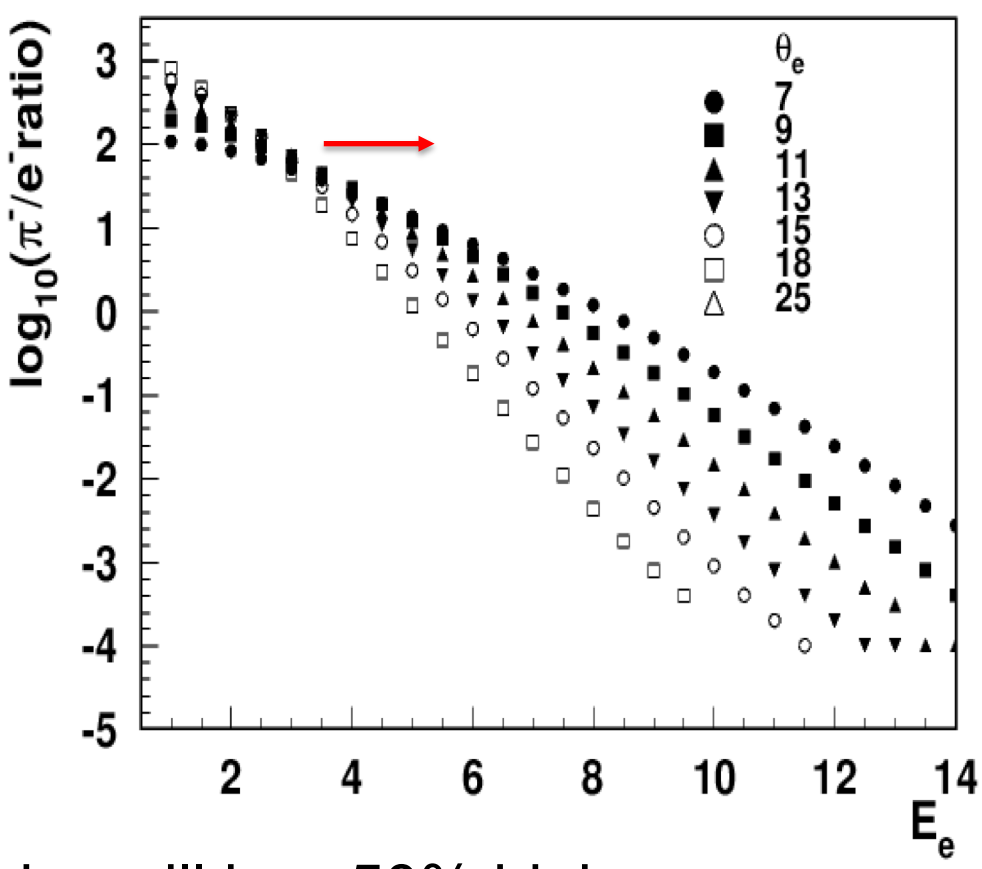
- The counts in a given bin, and the size of the effect will define the expected sensitivity.
- Proper evaluation of systematics, will require definition of fiducial kinematics, and the impact of the multidimensionality
- JLab at 24 GeV will provide critical input in evolution studies of TMDs, increase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

Relative fluxes: e- vs π-

CLAS12



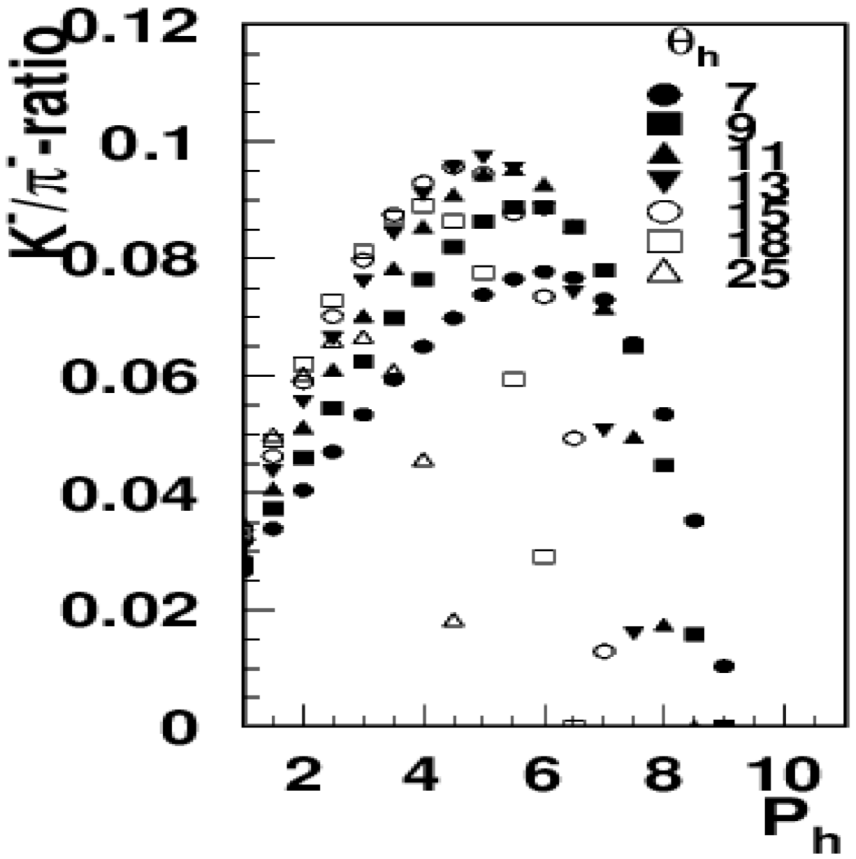
CLAS22



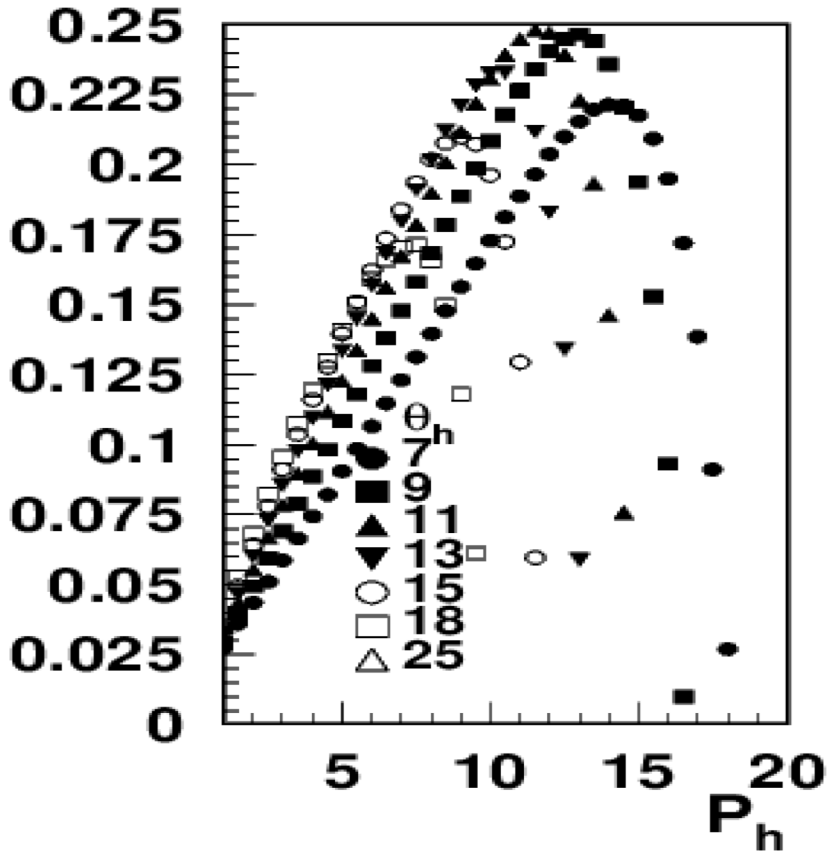
Contamination at low energies will be ~50% higher
(electrons <2 GeV may not be much useful anyway)

Relative fluxes: kaon vs pion

CLAS12



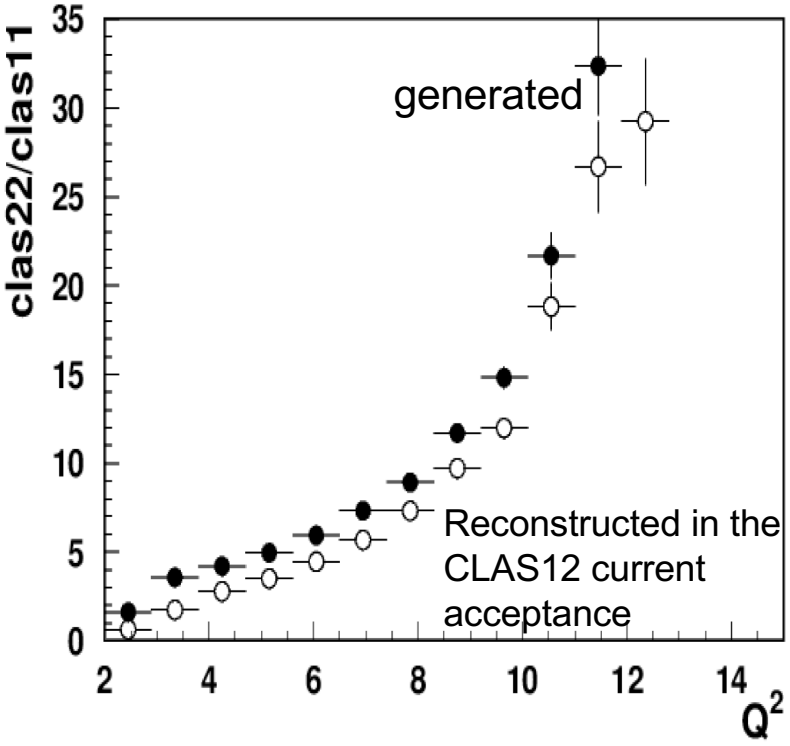
CLAS22



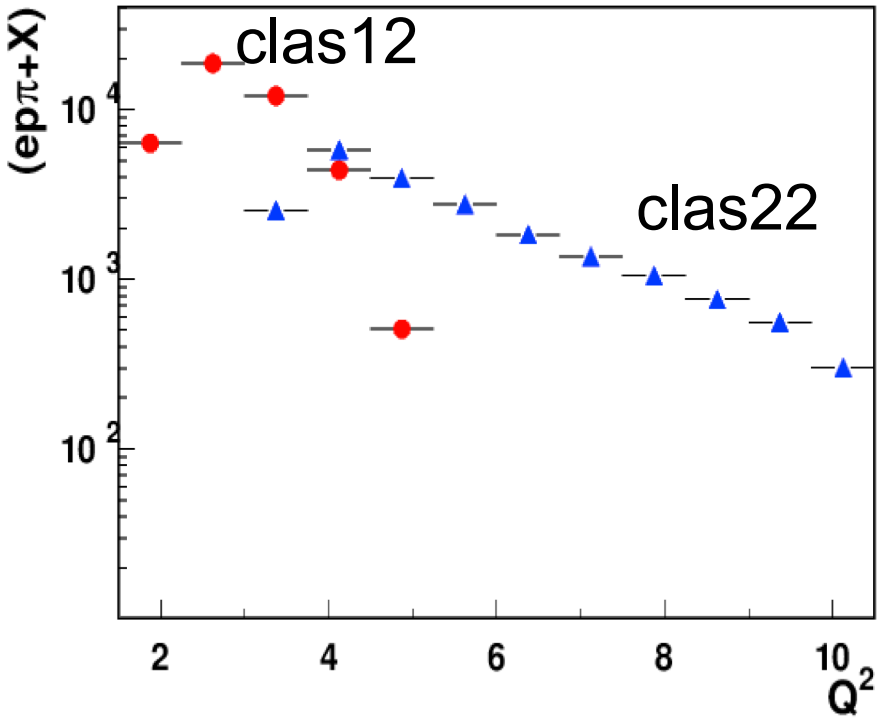
Significant (x2) increase of ratios of Kaon to pion, K- in particular
(more RICH will be helpful)

Q^2-dependence of the counts: CLAS12 vs CLAS22

Inclusive electrons



Events reconstructed using the current CLAS12 gemc-coatjava chain

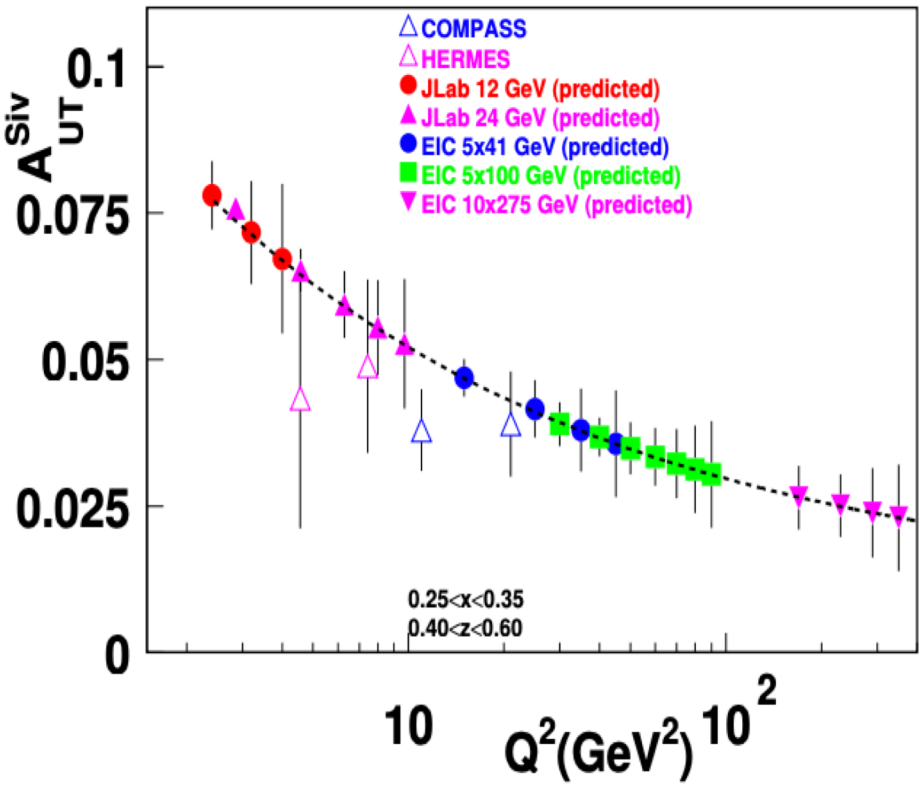


- Measurements of Q^2-dependence of SSAs will be crucial in validation of the theory
- JLab24 will be crucial to provide evolution studies in a wide range

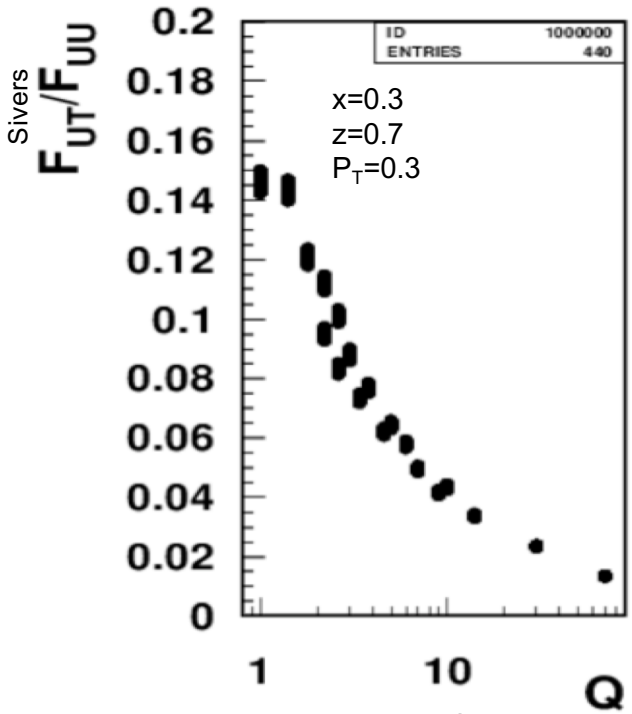
Contributions for 3D structure studies: Sivers

y>0.05,100 days (corrected for EIC official lumi)

H.A./C.Pecar/A.Vossen



Pavia grids



At large z drops faster

- 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	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

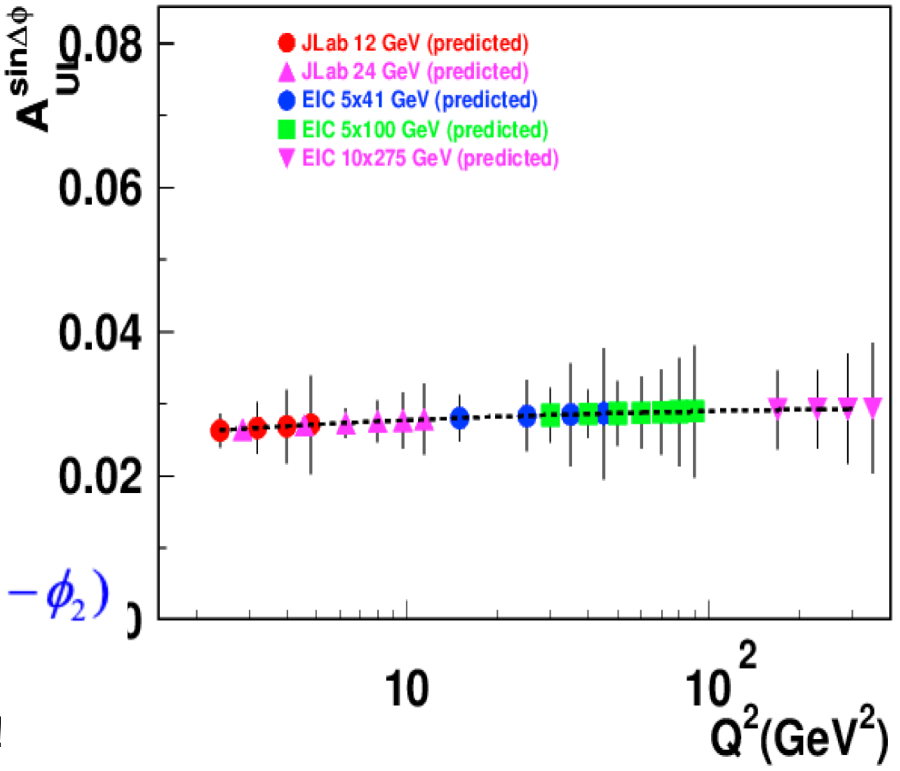
A. Kotzinian, arXiv:1107.2292

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

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

No depolarization, like Sivers!

Lumi: JLab 10^{35}, EIC4x51/5x100/10x275 0.044,0.6,1x10^{34})
y>0.05,100 days



CL AS12 proposals

NH3/ND3
E12-09-009

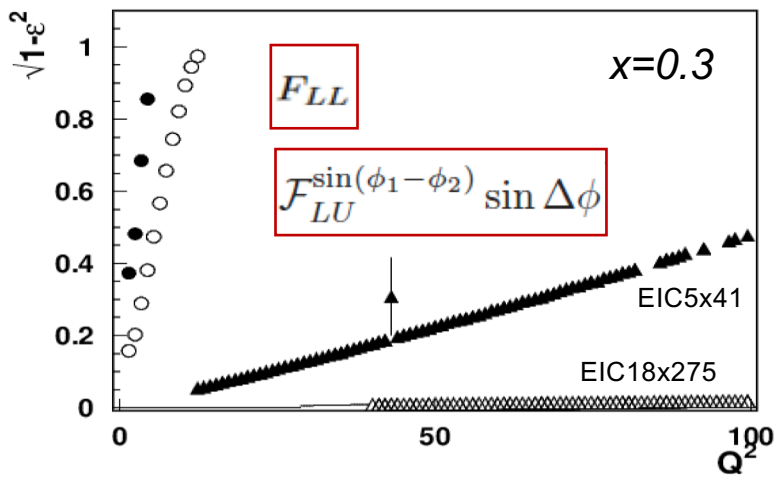
E12-07-107
E12-09-007A

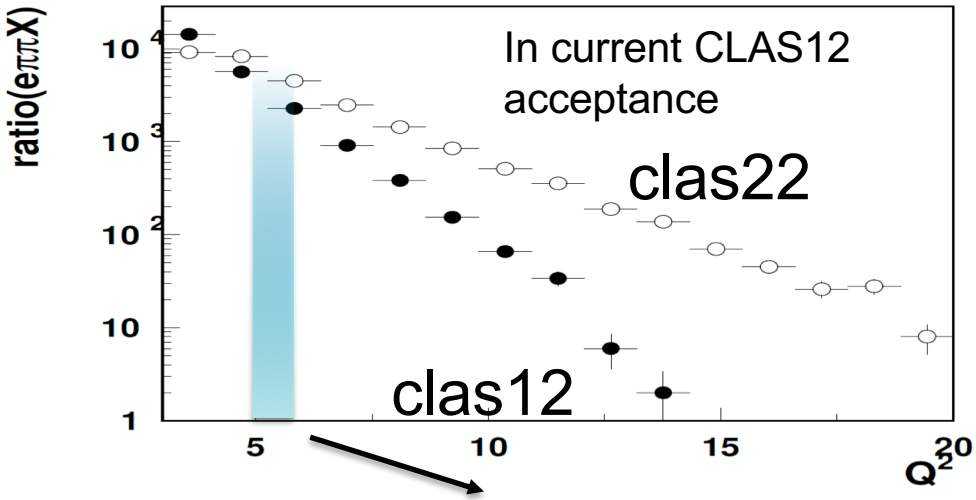
^{3}He
C12-20-002

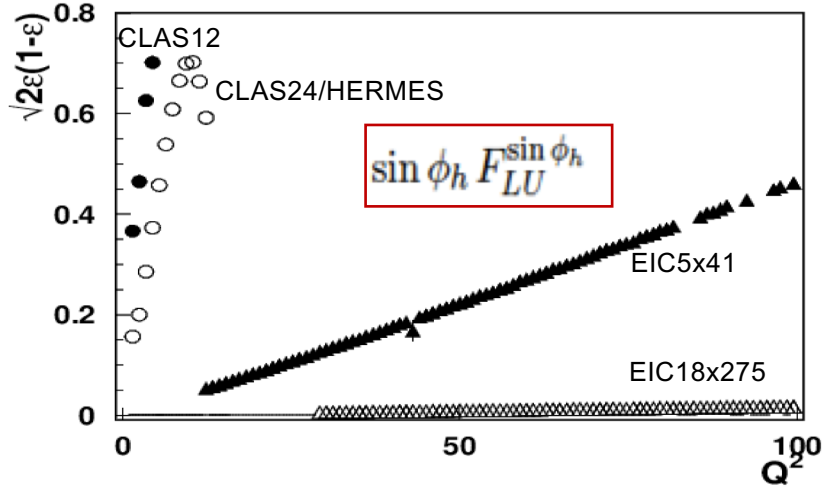
^{7}LiD
E12-14-001

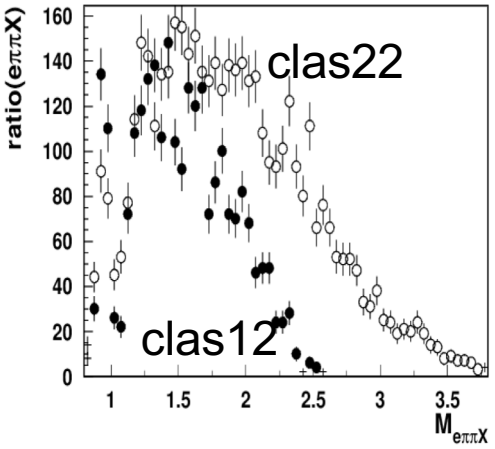
- Target SSA can be measured in the full Q^2 range, combining different facilities
- Advantages: Higher Lumi for JLab, less suppression at high Q^2 for EIC
- JLab24 will be crucial to bridge the studies of FFs between JLab12 and EIC in the valence region

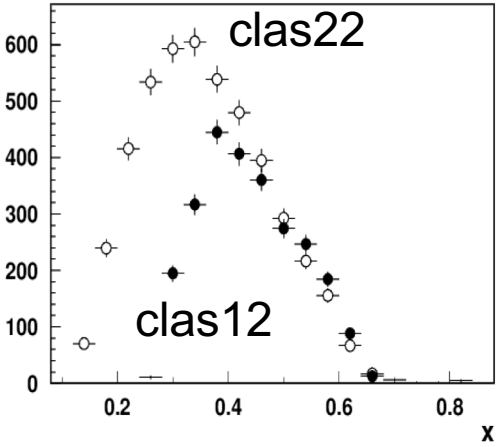
Beam SSAs & Kinematic suppression at large x





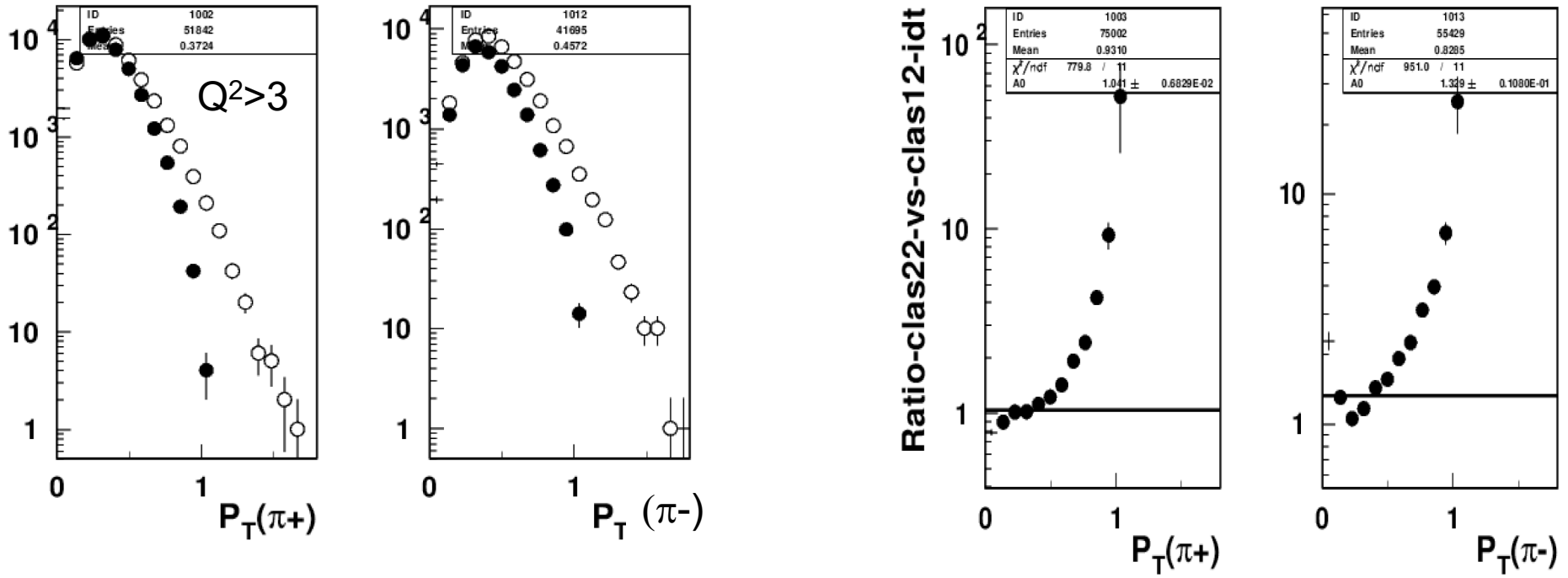






- Fixed target experiments are sensitive to all SSAs
- Higher energy opens up the phase space allowing access to, sea and large Q^2
- Measurements of beam SSAs (+some others) at large x, will be challenging at EIC

P_T-dependences: JLab11 vs JLab22



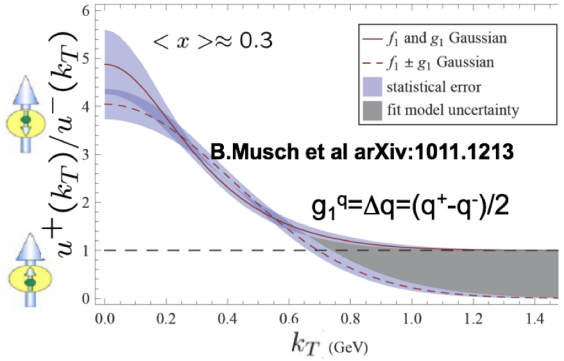
- Large transverse momentum coverage (P_T>0.8)critical for TMD studies
- The same lumi, with e- π+ and π- reconstructed and properly identified in the current CLAS12 detector
- Higher energy provides significant improvements in P_T-coverage

Unknown "known" f_1,g_1 TMDs

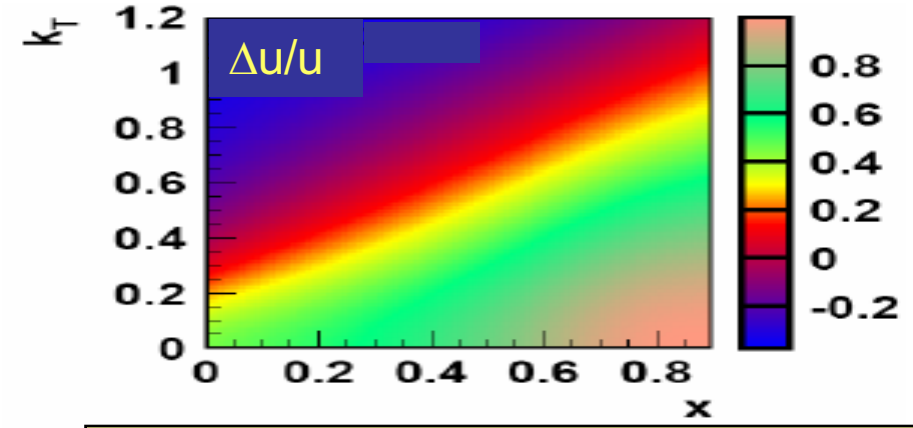
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

$$u^{\uparrow}(x,k_T) = f_1^u(x,k_T^2) + g_1^u(x,k_T^2)$$

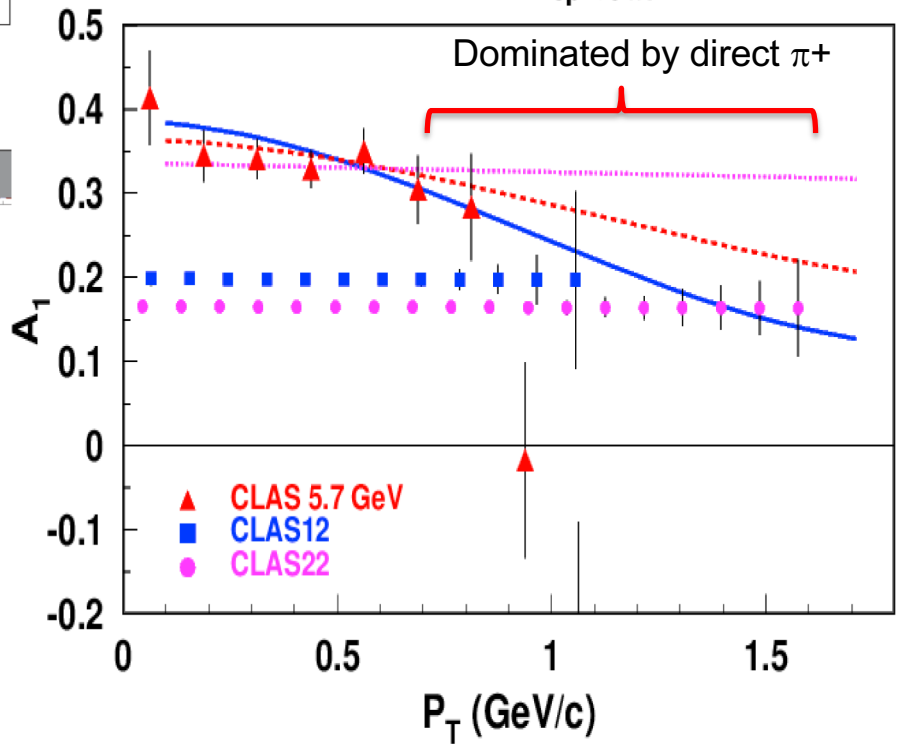
$$u^{\downarrow}(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$$



(dipole formfactor), J.Ellis, D-S.Hwang, A.Kotzinian



0.25<x<0.35 ep→e'π+X



- Models and lattice predict very significant spin and flavor dependence for TMDs
- Large transverse momenta are crucial to access the large k_T of quarks
- Several CLAS12 proposals dedicated to $g_1(x,k_T)$-studies CLAS12
- Understanding of k_T-dependence of g_1 will help in modeling of f_1

Summary

•Multidimensional measurements of spin-azimuthal modulations in single and di-hadron production in SIDIS, are critical for interpretation of observed significant correlations between hadrons, both in CFR and TFR

•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

•Realistic projections have been performed using the existing CLAS12 software, with the existing CLAS12 acceptance, showing complementarity with CLAS12 and EIC

•Proposed measurements with upgraded JLab, will be the part of SIDIS studies in motivating the upgrade (suggested for the flagship list).

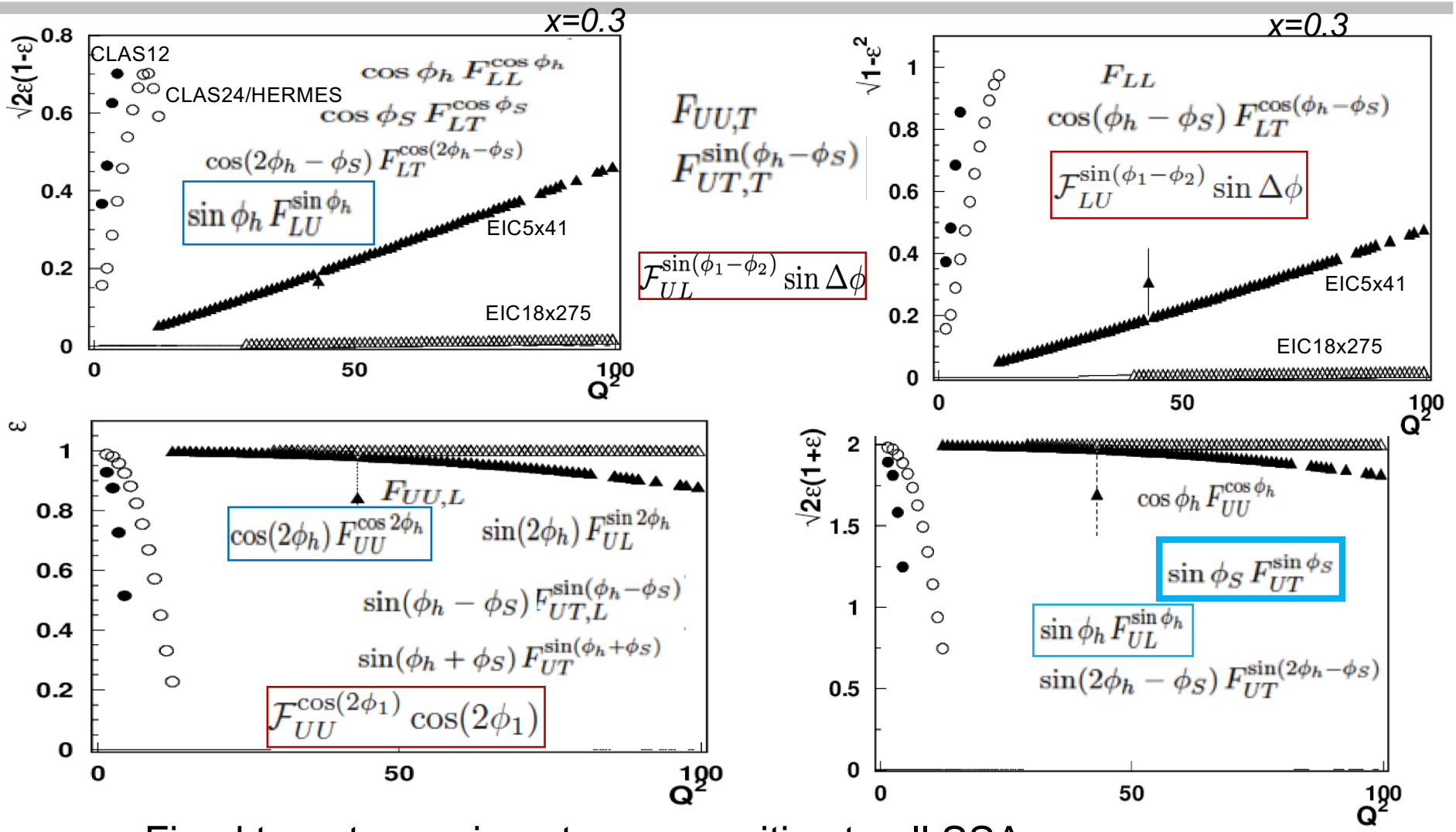
Meetings in 2022 dedicated to JLab20+ upgrade in general, and the 3D, in particular

•Town meeting on upgrade (3D), June 2022 (H. Avakian, J-P.Chen, X. Ji)
•APCTP, Pohang,Korea, Luly 18-23 (H.Avakian, K. Joo, Y. Oh) →https://indico.knu.ac.kr/event/566/
•ECT*, Trento, Italia , Sep 26-30 (J. Arrington, H.Avakian, A. Bacchetta, O. Hen, X. Ji, K. Joo, S.Niccolai,X. Zheng)
→https://www.ectstar.eu/workshops/opportunities-with-jlab-energy-and-luminosity-upgrade/

Final output → a clear physics program accessible with upgrade (white paper)

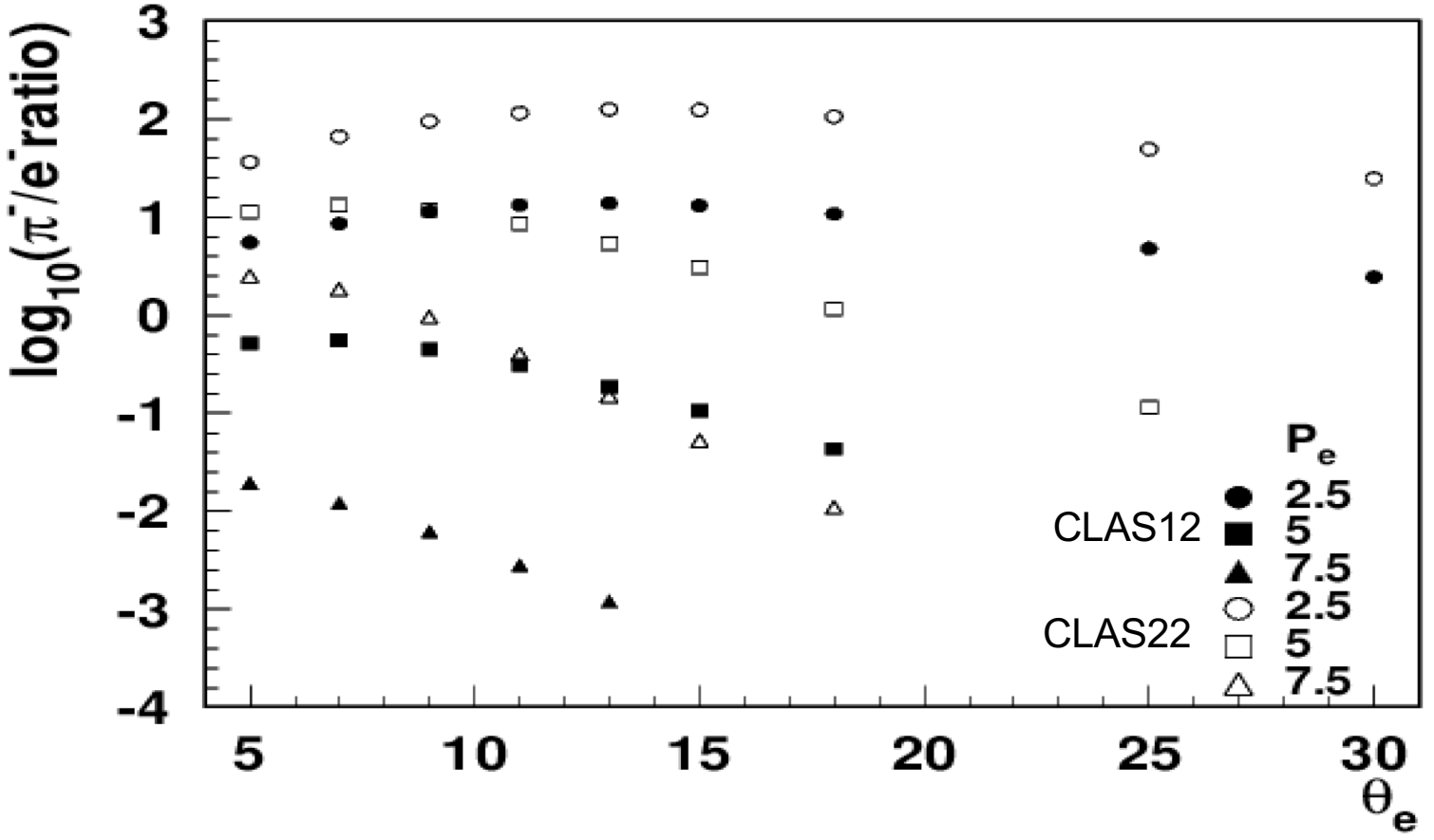
Support slides

Kinematic factors at large x



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

Relative fluxes: e- vs pi-



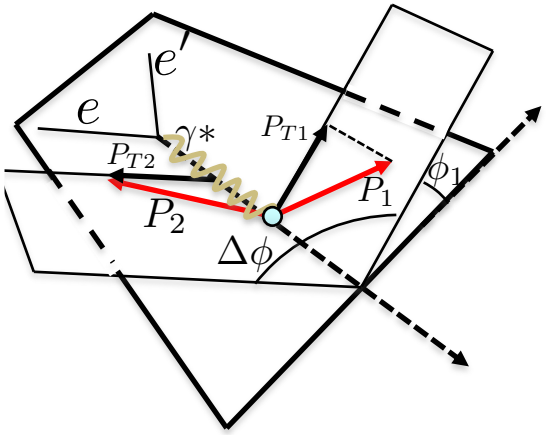
Relative fraction of pi- increases for a fixed energy
For a constant y (y<0.75 used) they are consistent

Correlations in 2 hadron production

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

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

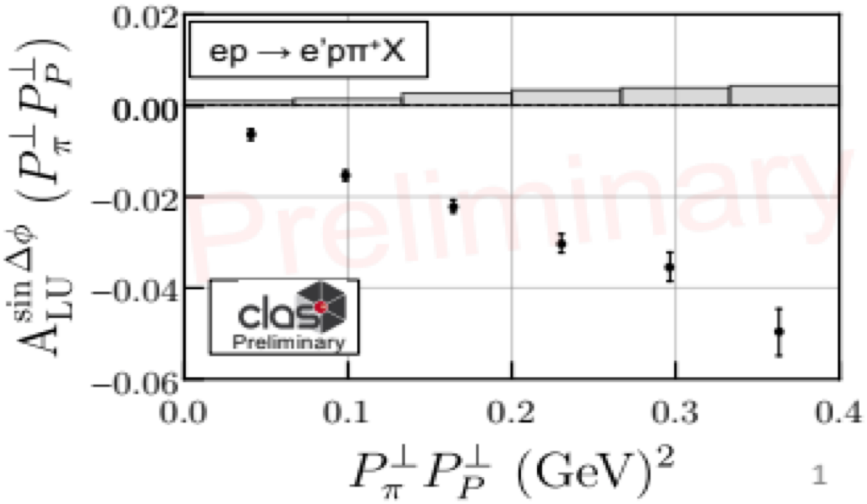
N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^{h}, \hat{t}_1^{\perp}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^{h}, \hat{t}_{1L}^{\perp}$
T	$\hat{u}_{1T}^{h}, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^{h}, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp},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



- Depolarization goes to 0 at high energies of EIC

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

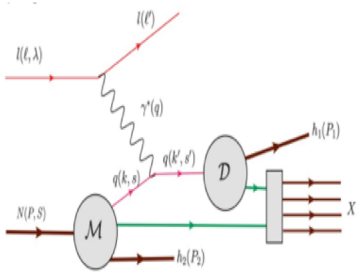
$$= \underbrace{-\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2}}_{\text{correlation}}\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \times \frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\underbrace{\sin\Delta\phi}_{\text{modulation}}$$

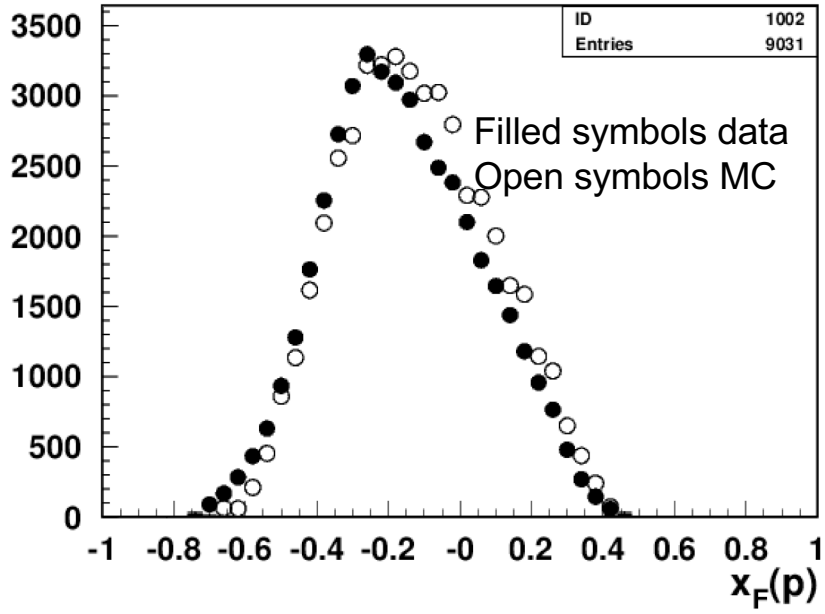


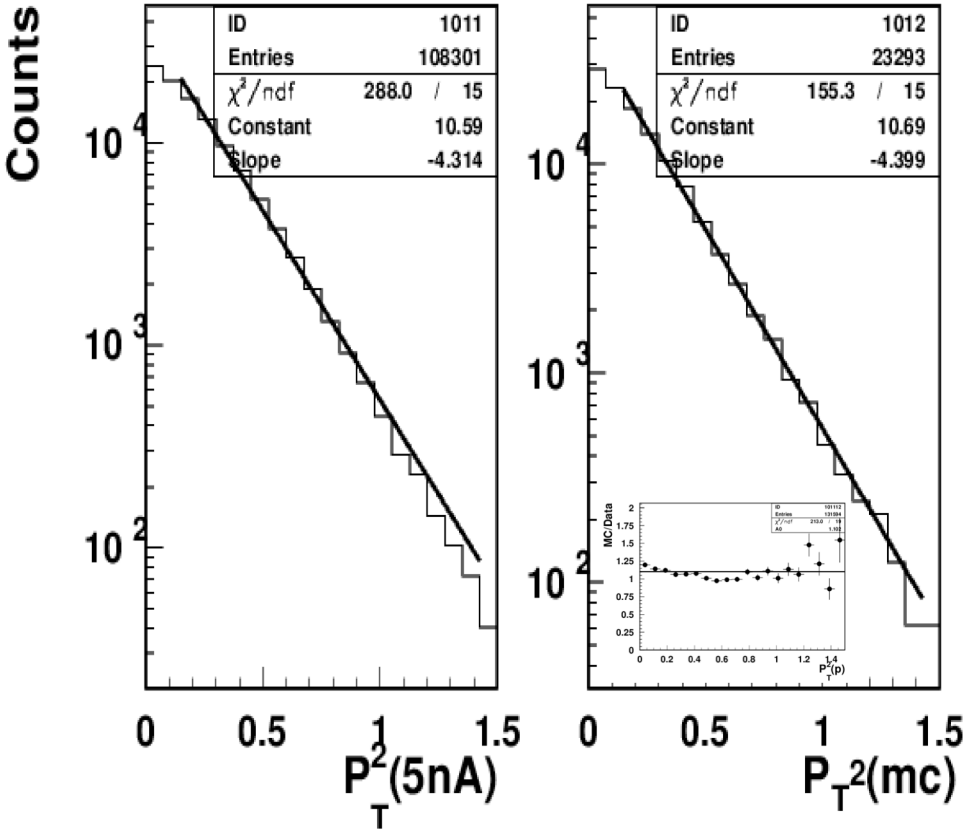
The correlation is most significant at large x, where the valence quarks most significant, and at large P_T

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator



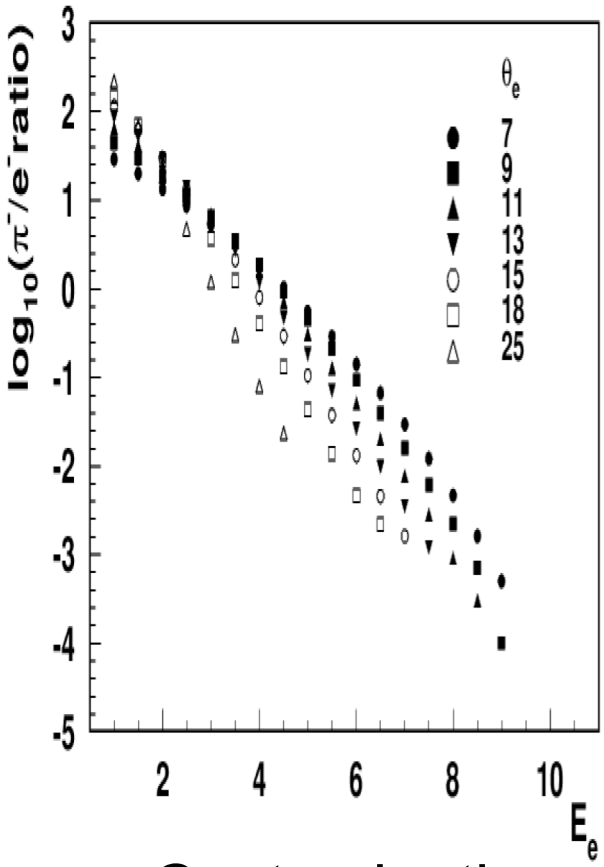




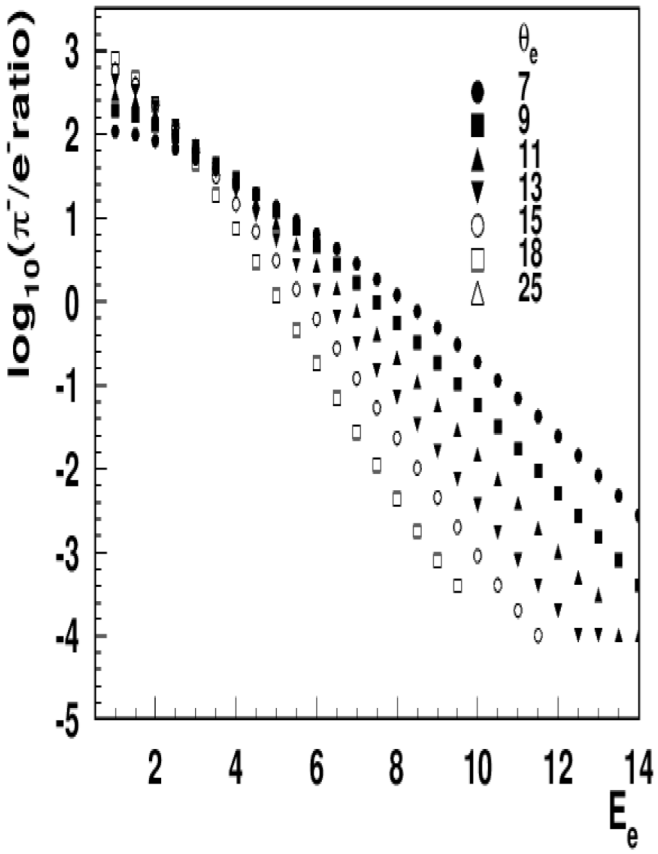
- Kinematic distributions, z,x_F,P_T-distributions of protons, and widths are in good agreement with LEPTO
- TFR may be a valuable source for studies of widths in hadronization
- Expect significantly better separation of TFR and CFR at JLab24

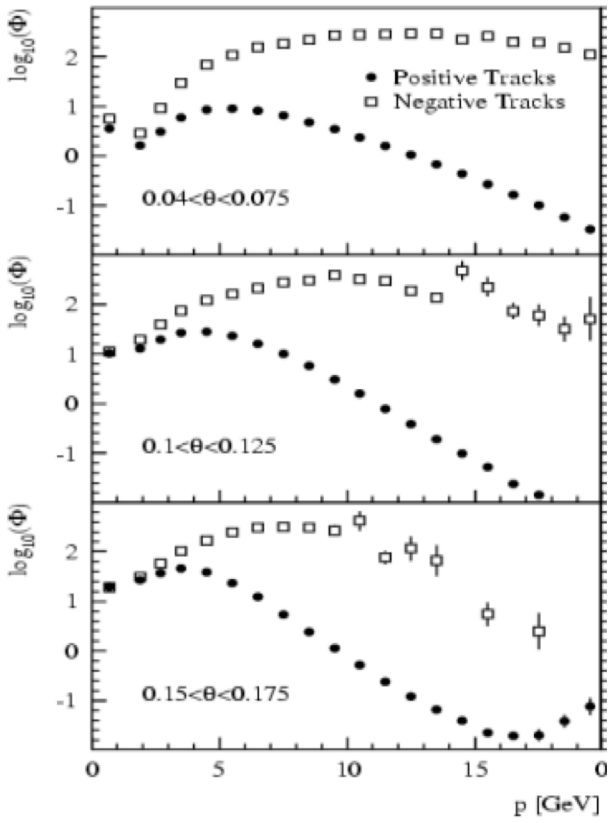
Relative fluxes: e- vs pi-

CLAS12



CLAS22

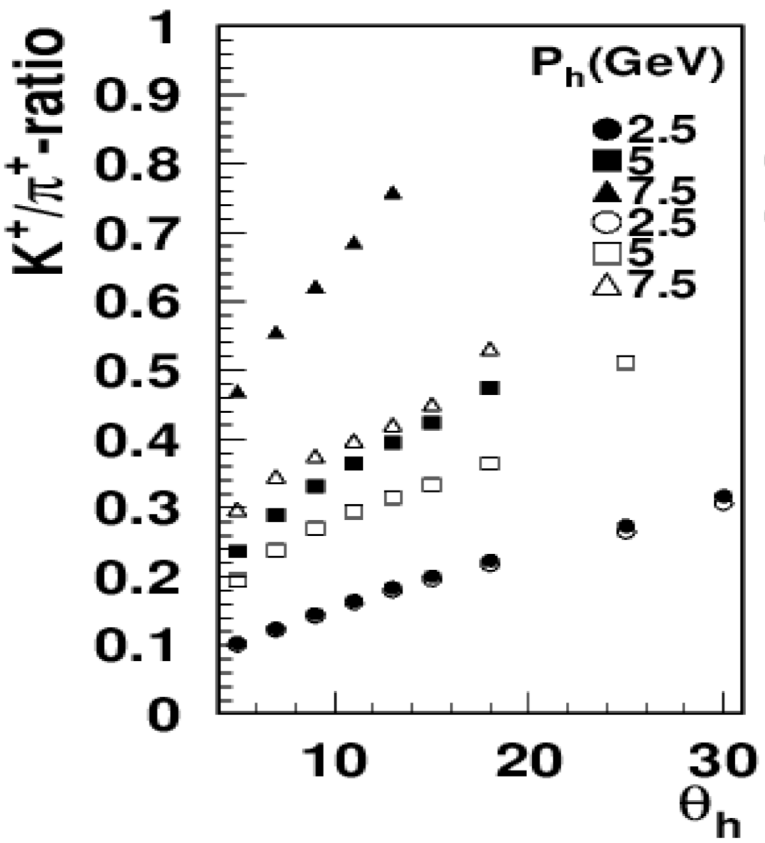




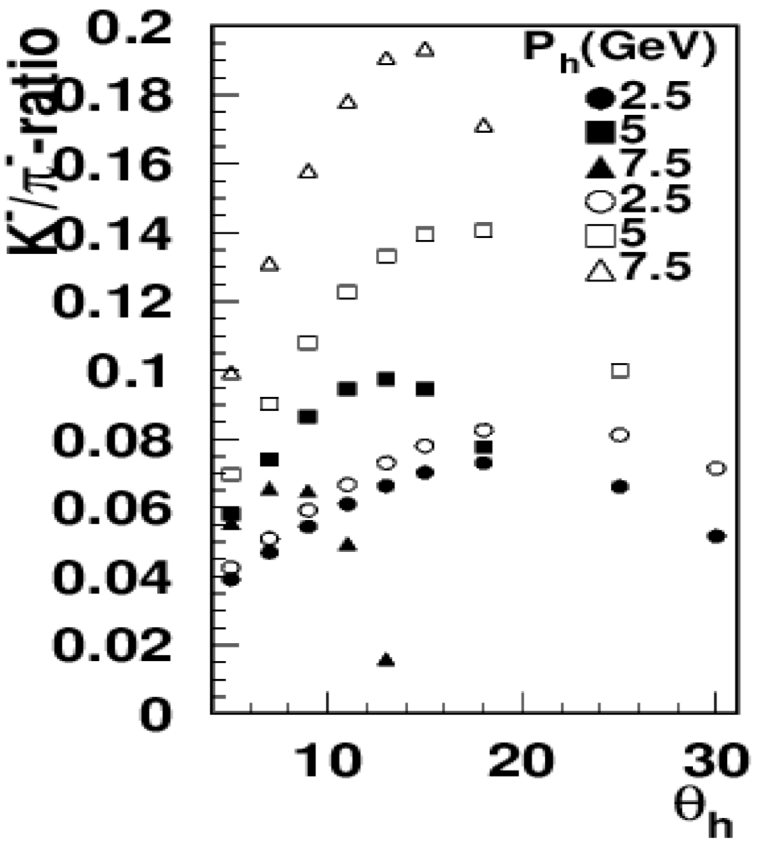
Contamination at low energies will be ~50% higher
(electrons <2 GeV may not be much useful anyway)

Relative fluxes: kaon vs pion

CLAS12



CLAS22

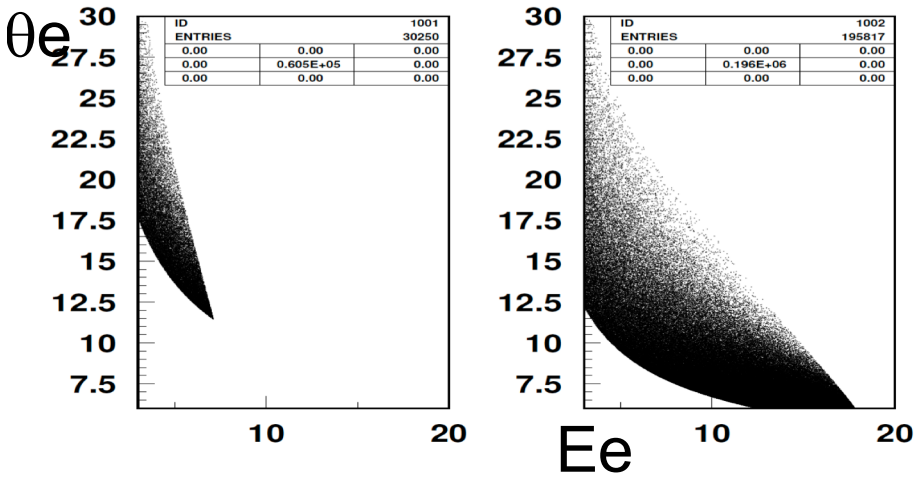


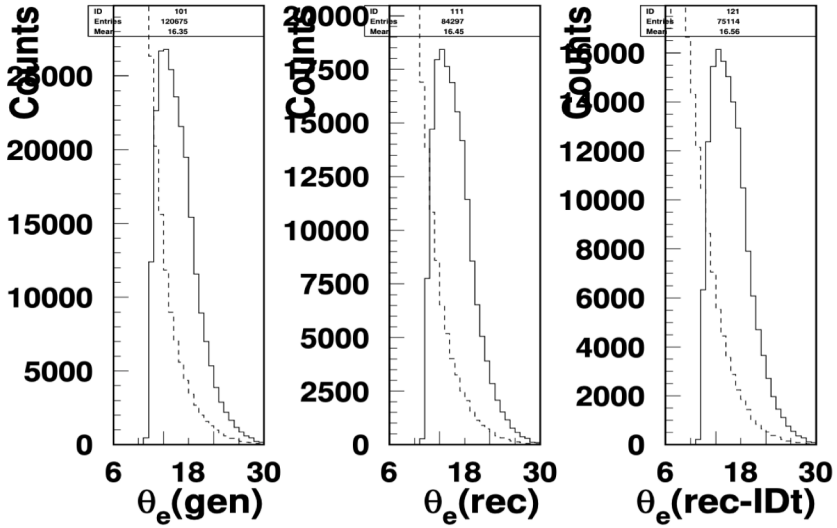
Relative ratios of Kaon to pion increases ~30% (more RICH will be helpful)

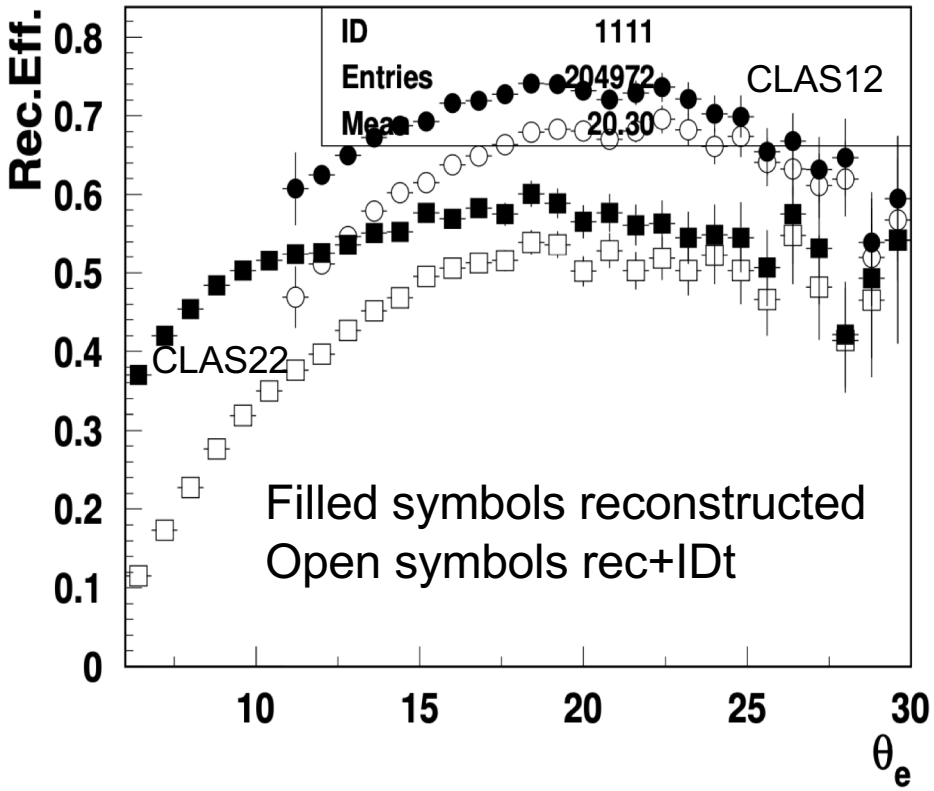
CLAS12 chain: CLAS12 vs CLAS22

gemc+coatjava

Electrons for $Q^2>3$







Most events at smaller angles,
Still rates much higher
Need to improve ID