

# 3D Structure of the Nucleon: from JLab12 to JLab24



International Workshop on Hadron Structure and Spectroscopy - 2022

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(JLab)**

Aug 29, 2022, CERN

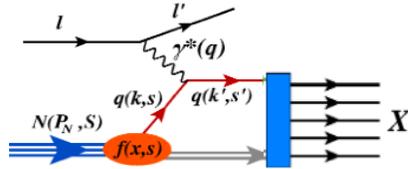
Understanding the QCD: from observables to QCD dynamics

- Projections as motivation for future studies
- Extending the phase space in  $P_T$ ,  $Q^2$  and  $x$
- Studies of evolution properties
- Future studies of 3D

Summary

# QCD: from testing to understanding

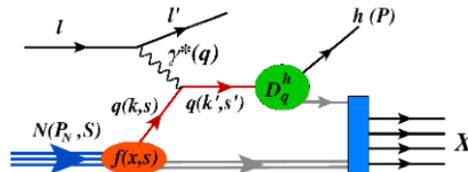
## 0h DIS



### Testing stage:

pQCD predictions, observables in the kinematics where theory predictions are easier to get (higher energies, 1D picture, leading twist, IMF)

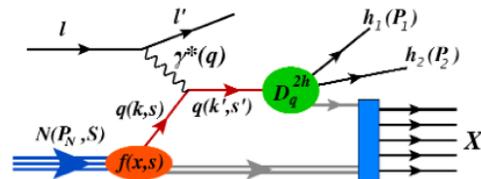
## 1h SIDIS/DVMP



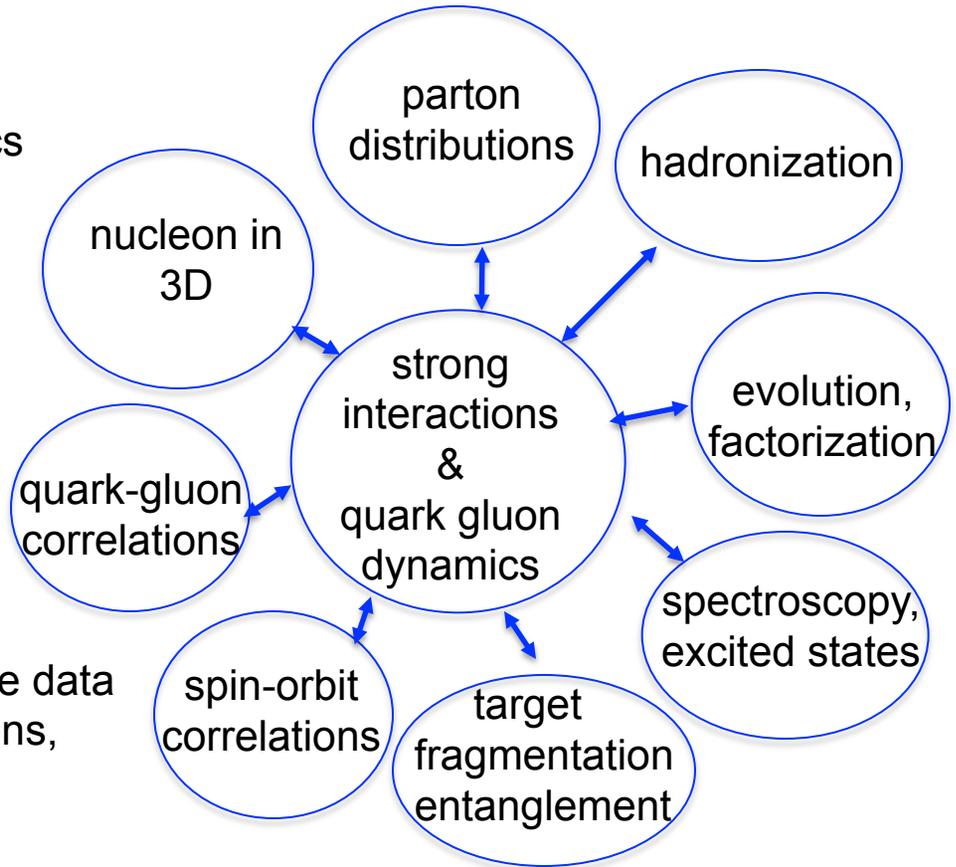
### Understanding stage:

non-perturbative QCD, strong interactions, observables in the kinematics where most of the data is available (all energies, quark-gluon correlations, orbital motion)

## 2h SIDIS/DVMP



production in SIDIS provides access to correlations inaccessible in simple SIDIS (dihadron fragmentation, correlations of target and current regions, entanglement....)



# Motivating the JLab 20+ upgrade

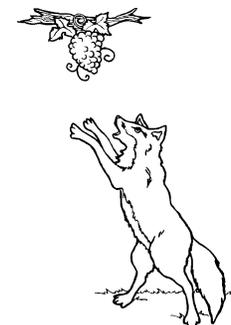
Need to classify observables, summarize the set of projection for key observables

1) Identify the flagship measurements that can be done only with 20+ GeV

2) Identify the flagship measurements with 22 GeV that can extend, improve the 11 GeV, helping interpretation, multidimensional bins in extended kinematics

3) Identify the measurements with 22 GeV that can set the bridge between JLab12 and EIC (complementarity)

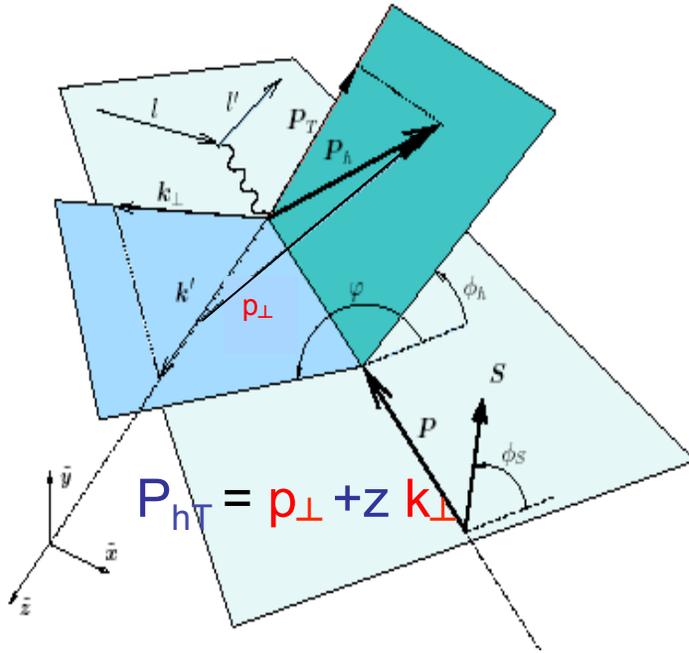
- Produce sets of event for relevant observables (SIDIS, DVCS, Large  $x$ ,....) and process them using existing detector reconstruction chains (ex. CLAS12, SoLID, Hall-A/C/D), **evaluate count rates, define kinematical coverage and resolutions**
  - Identify observables that can provide critical input without detector upgrades
  - Identify critical observables, that require certain detector upgrades



Projections summarize what we learned, teach us what we can do with our data, and where we need to combine it with higher energy data,

- Making the case it will be relevant in future

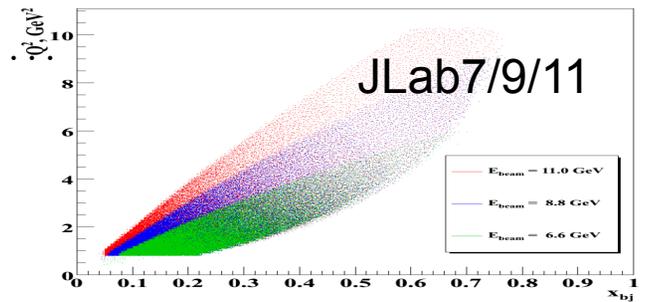
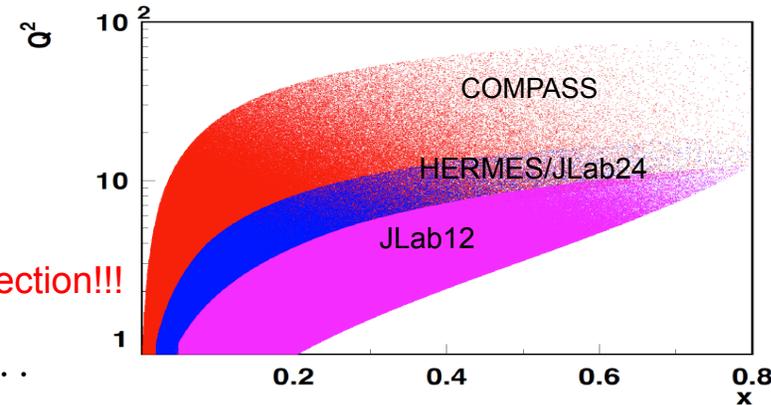
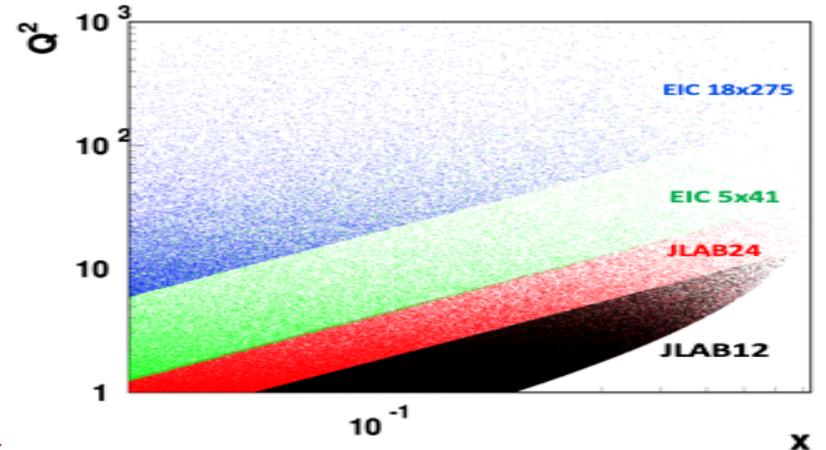
# SIDIS kinematical coverage and observables



$$P_{hT} = p_{\perp} + z k_{\perp}$$



EIC



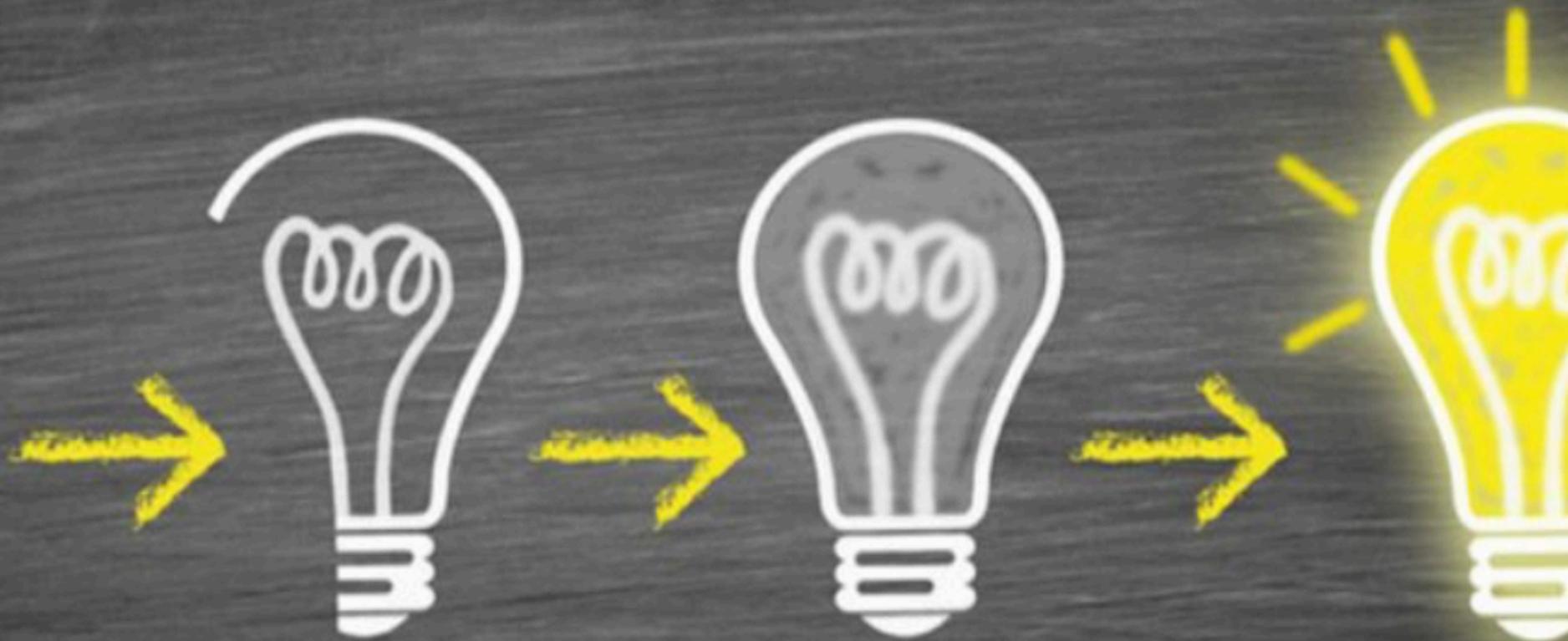
SIDIS experiments measure azimuthal dependence of the cross section!!!

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

$$+ \epsilon F_{UU,L} + |S_{\perp}| [F_{UT}^{\sin \phi - \phi_S} \sin(\phi - \phi_S) + \sqrt{2\epsilon(1+\epsilon)} F_{UT}^{\sin \phi_S} \sin \phi_S] + \dots$$

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

# What we learned so far from JLab data



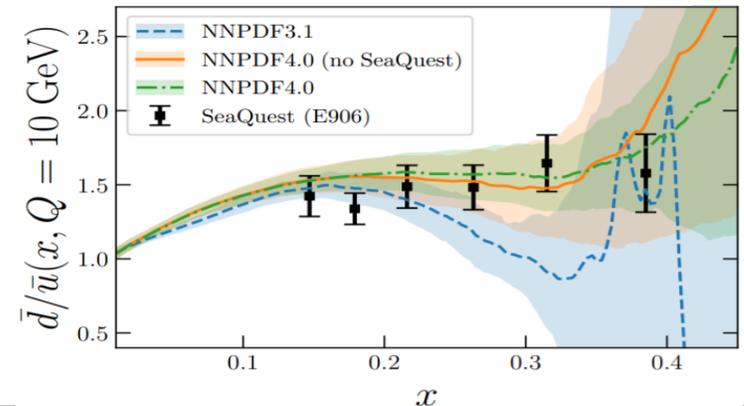
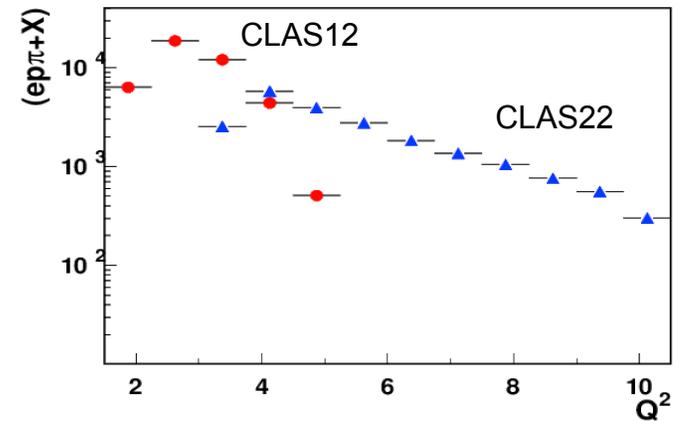
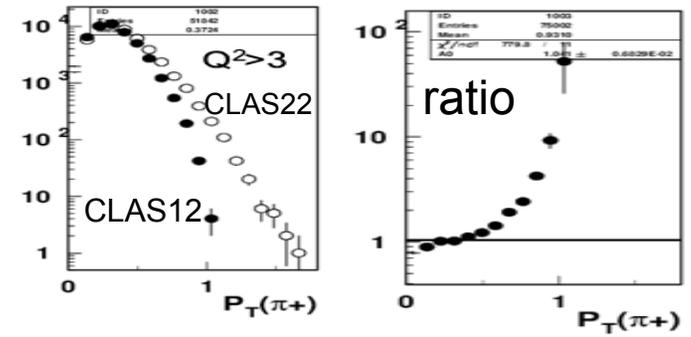
# What we learned: missing parts of the mosaic

- SIDIS, with hadrons detected in the final state, from experimental point of view, is a measurement of observables in 5D space  $(x, Q^2, z, P_T, \phi)$   
Collinear SIDIS, is just the proper integration, over  $P_T, \phi$
- **SIDIS observations relevant for interpretations of experimental results:**
  1. Understanding the kinematic domain where non-perturbative effects of interest are significant (ex.  $x, P_T$ -range)
  2. Understanding of  $P_T$ -dependences of observables in the full range of  $P_T$  dominated by non-perturbative physics is important
  3. Understanding of phase space effects is important (additional correlations)
  4. Understanding the role of vector mesons is important
  5. Understanding of evolution properties and longitudinal photon contributions
  6. Understanding of radiative effects may be important for interpretation
  7. Overlap of modulations (acceptance, RC,...) is important in separation of SFs
  8. **Multidimensional measurements with high statistics, critical for separation of different ingredients**
- **QCD calculations may be more applicable at lower energies when 1)-7) clarified**
- **Need a realistic chain for MC simulations of SIDIS to produce realistic projections with controlled systematics**

# Opportunities with 20+ GeV

Significantly wider phase space would allow

- Enhance the range in transverse momentum  $P_T$  of hadrons
  - Access to  $P_T$ -region where the dependence of the  $k_T$ -dependences of different flavors (valence and sea) and polarization states is most significant
- Enhance the  $Q^2$  range
  - Increase significant the range of high  $Q^2$ , where the theory is supposed to work better, and allow studies of evolution properties
- Enhance the  $x$ -range
  - Access the the full kinematical range ( $x > 0.03$ ) where the non-perturbative sea is expected to be significant

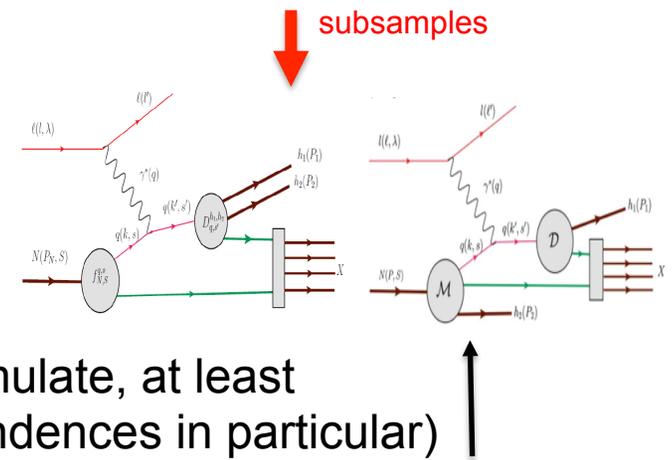
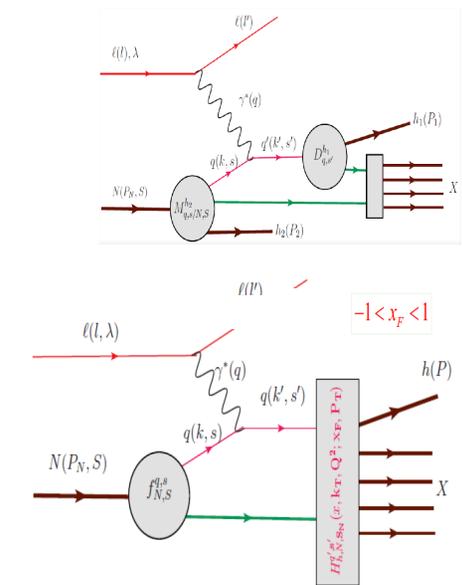


# MC simulations: Why LUND works?

- 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.

So why the LUND-MCs are so 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 as target and current fragments accounted
- .....



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)

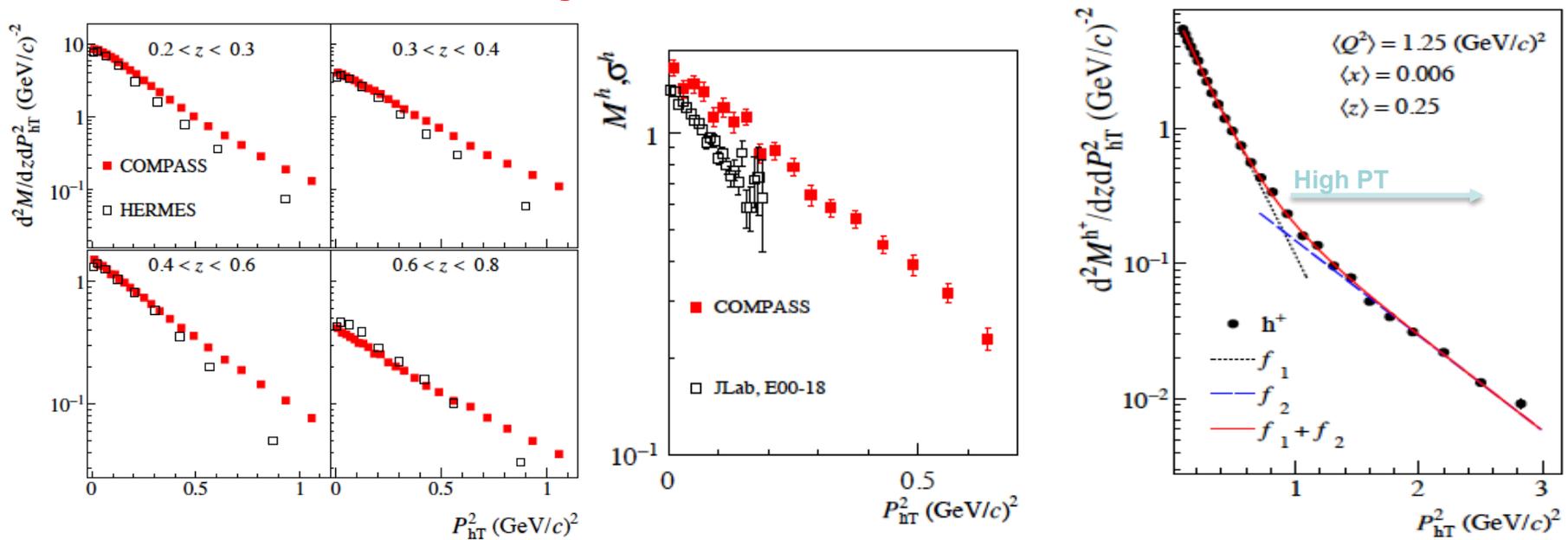
The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!

# Multiplicities of hadrons in SIDIS

Gaussian Ansatz  $f_1^q \otimes D_1^{q \rightarrow h} = x f_1^q(x) D_1^{q \rightarrow h}(z) \frac{e^{-P_{hT}^2 / \langle P_{hT}^2 \rangle}}{\pi \langle P_{hT}^2 \rangle}$

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

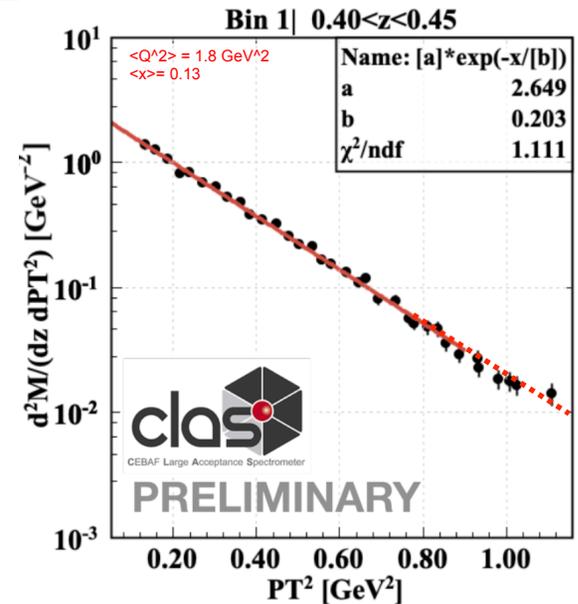
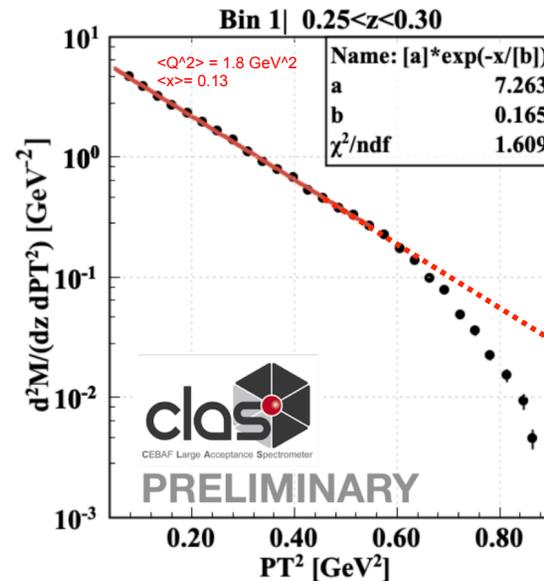
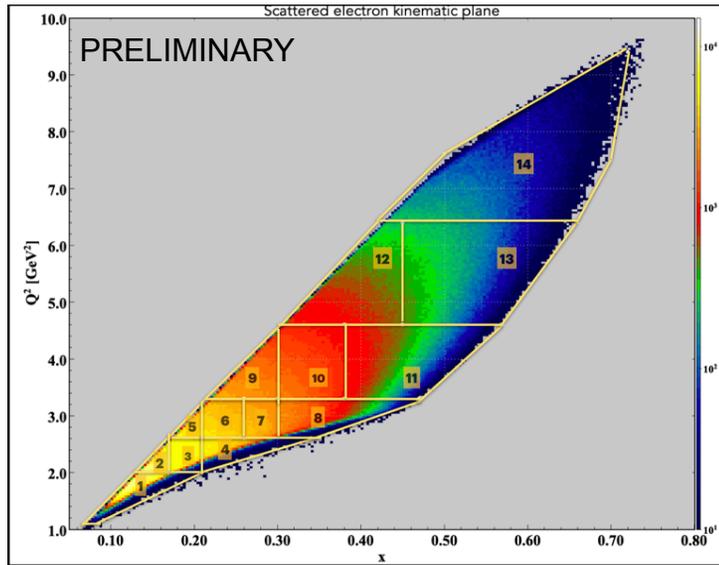
COMPASS:1709.07374



JLab: not enough energy to produce large  $P_T$   
 HERMES: not enough luminosity to access large  $P_T$

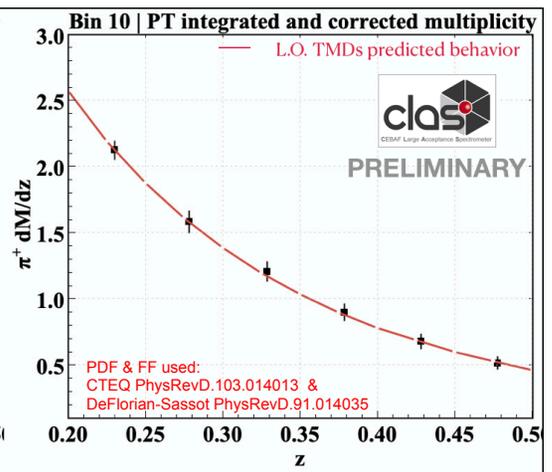
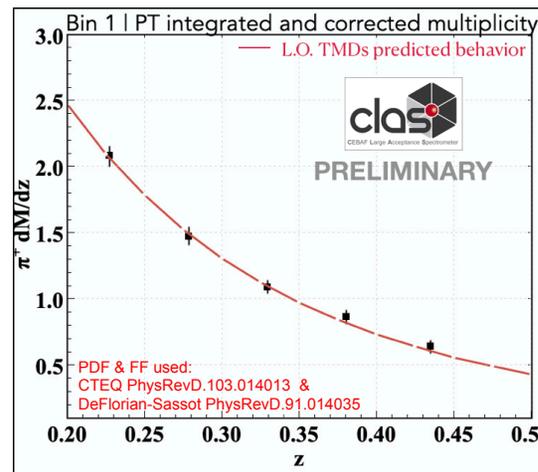
- What is the origin of the “high”  $P_T$  (0.8-1.8) tail?
  - 1) Perturbative contributions?
  - 2) Non perturbative contributions?

# CLAS12 Multiplicities: high $P_T$ & phase space

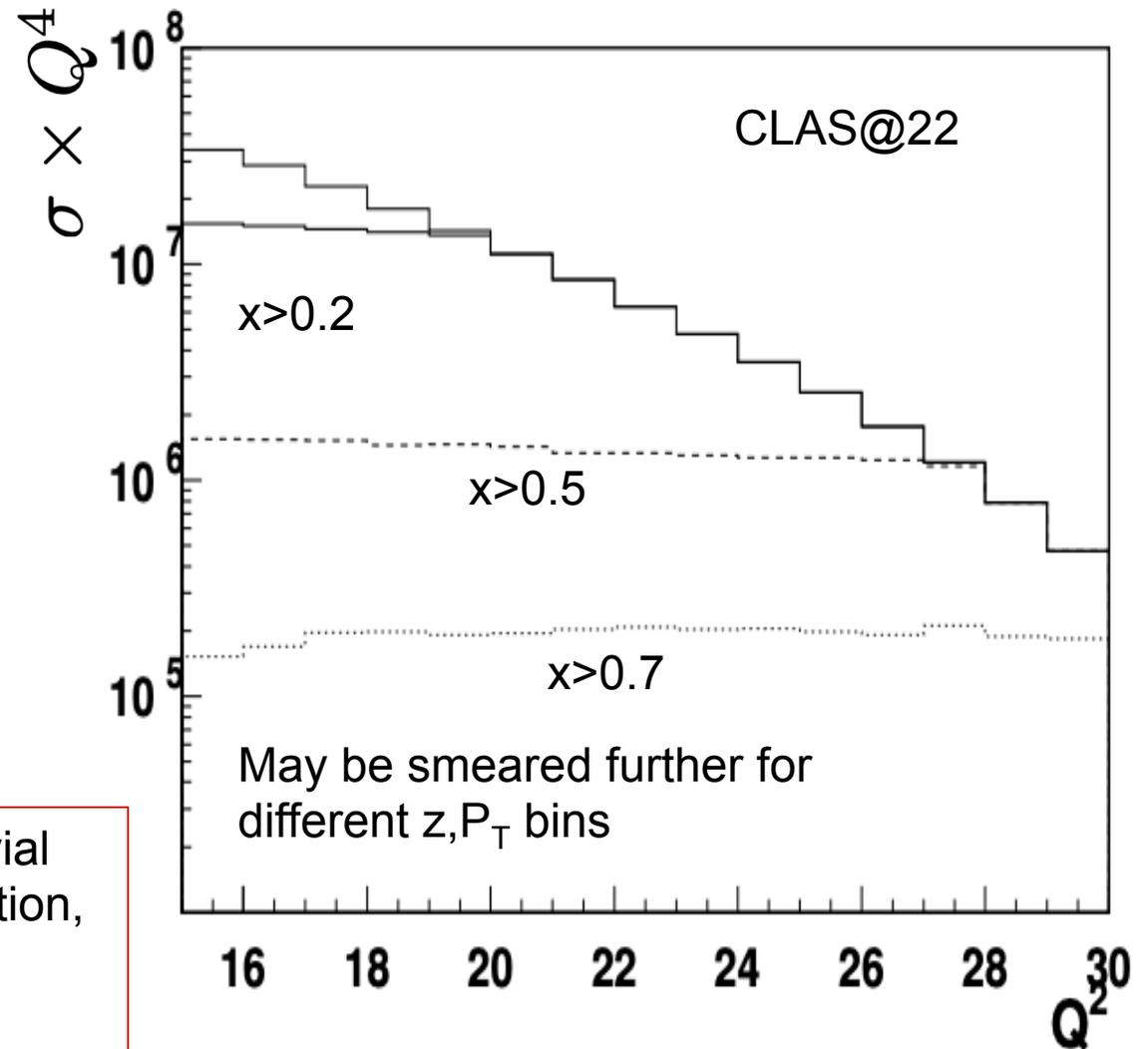
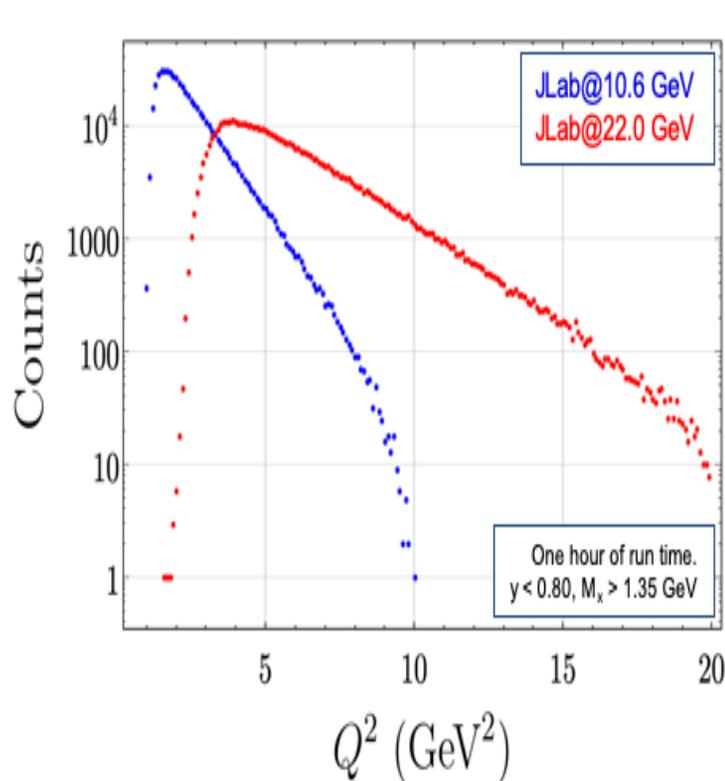


For some kinematic regions, at low  $z$ , the high  $P_T$  distribution appear suppressed: there is not enough energy in the system to produce hadron with high transverse momentum (phase space effect).

If the effect is accounted, the CLAS data follows global fits.



# Finite energy: Kinematic limitations



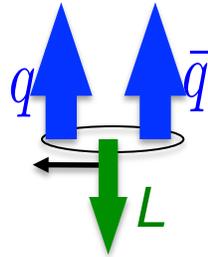
Kinematic correlations, due to trivial energy and momentum conservation, may mask the real dependences

- Can be easily accounted

# Most critical with JLab20+: access to large $P_T$

## Possible sources of large $P_T$ in SIDIS

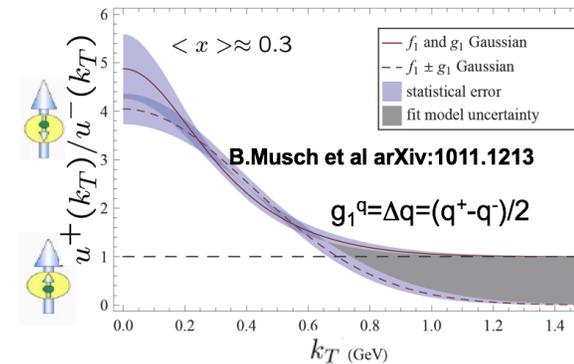
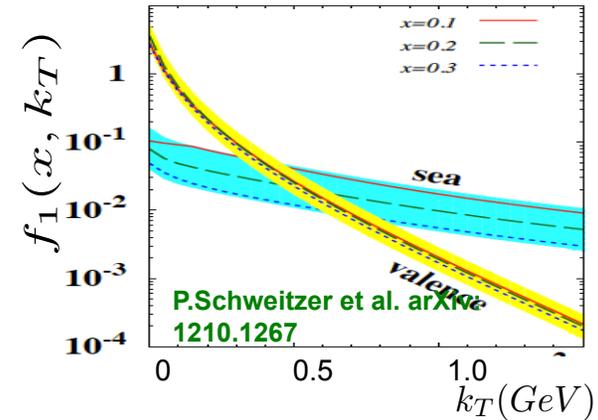
Non perturbative sea



Wider in  $k_T$  u- distributions (need long.pol.target)

Wider in  $k_T$  d-quark distributions

Wider in  $P_T$  longitudinal photon contributions ( $F_{UU,L}$ )

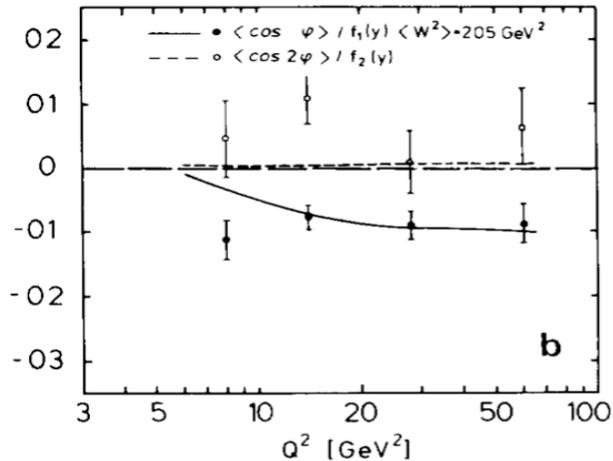


Large  $P_T$ -coverage  
critical for all those  
measurements!!!

# Azimuthal distributions in SIDIS (unpolarized)

$$\frac{d\sigma}{dx_B dy d\psi dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right) \left\{ \begin{array}{l} \overset{\text{H.T.}}{\downarrow} F_{UU,T} + \epsilon \overset{\text{H.T.}}{\downarrow} F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h \overset{\text{H.T.}}{\downarrow} F_{UU}^{\cos\phi_h} \\ + \epsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h \overset{\text{H.T.}}{\leftarrow} F_{LU}^{\sin\phi_h} \end{array} \right\},$$

EMC-1983 (PL,v130,118)



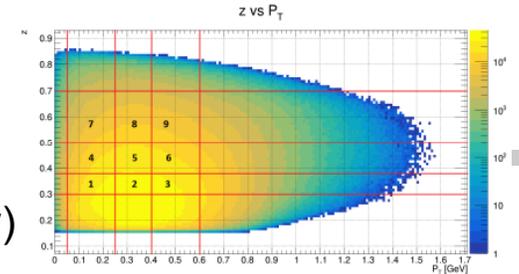
**Observables: - Azimuthal Moments - Multiplicity**

$$\frac{d^4 M^{\pi^\pm}(x, Q^2, z, P_T^2)}{dx dQ^2 dz dP_T^2} = \left( \frac{d^4 \sigma^{\pi^\pm}}{dx dQ^2 dz dP_T^2} \right) / \left( \frac{d^2 \sigma^{DIS}}{dx dQ^2} \right)$$

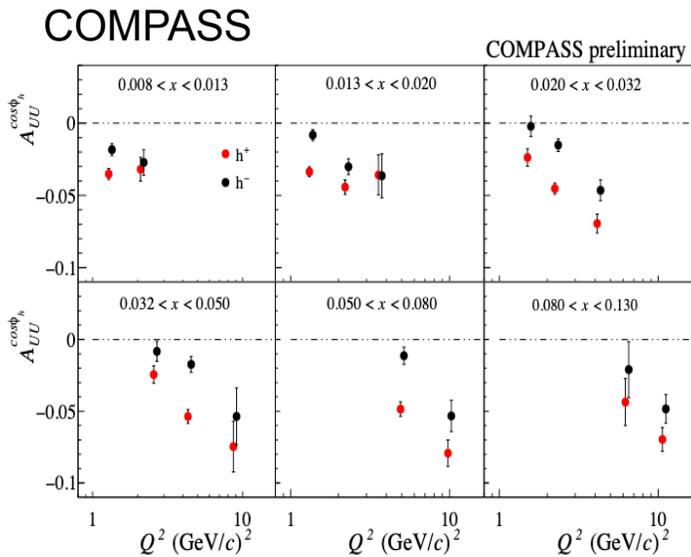
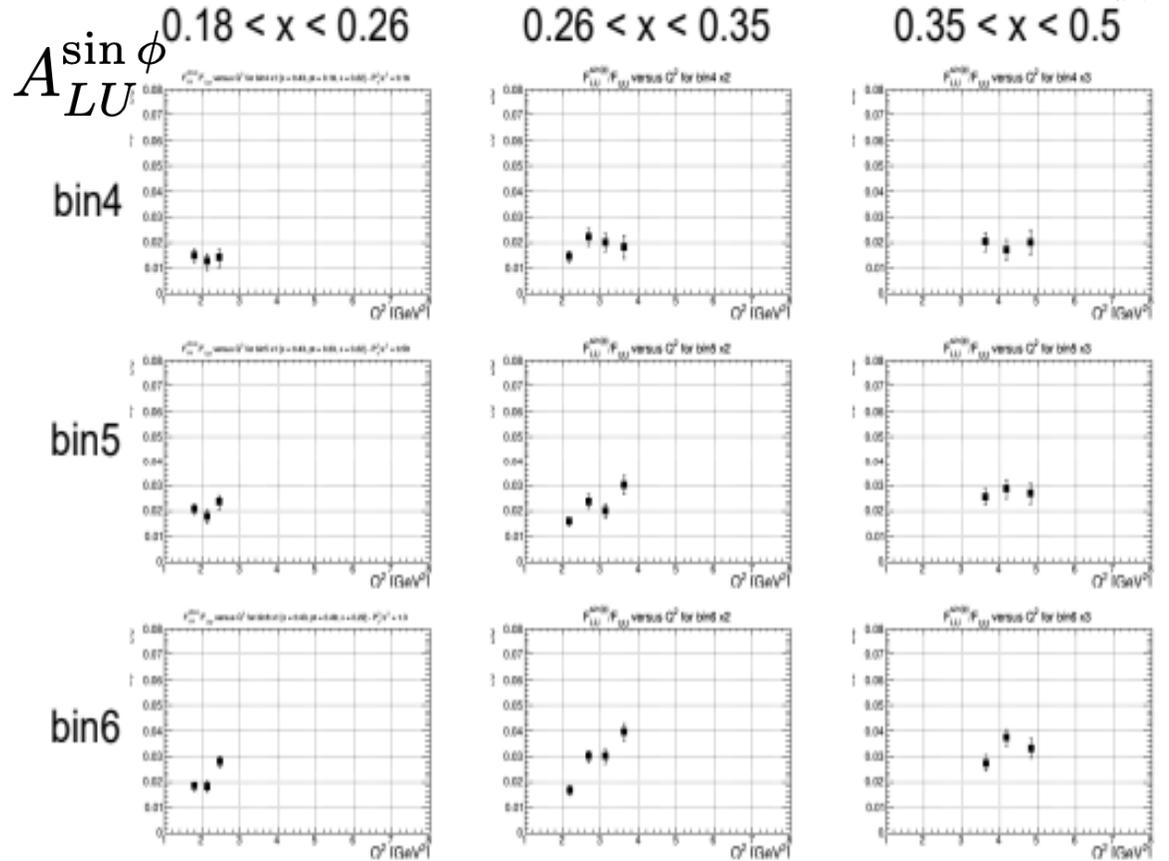
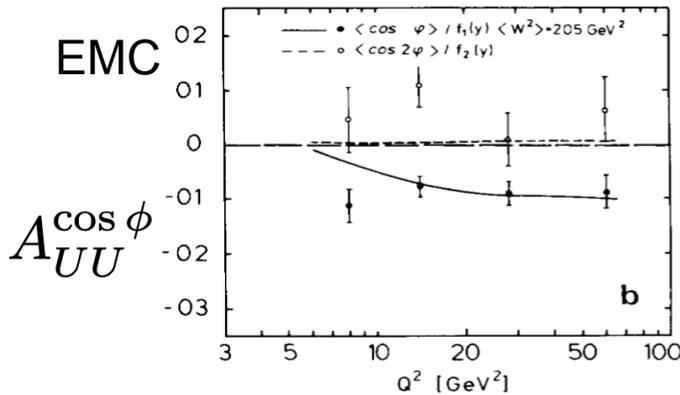
$$m^h(x, z, P_T^2, Q^2) = \frac{\pi F_{UU,T}(x, z, P_T^2, Q^2) + \pi \epsilon F_{UU,L}(x, z, P_T^2, Q^2)}{F_T(x, Q^2) + \epsilon F_L(x, Q^2)}$$

- Quark-gluon correlations are significant in electro production experiments (even at high energies).
- Large  $\cos\phi$  modulations observed in electroproduction (EMC, COMPASS, HERMES) may be a key in understanding of the QCD dynamics.
- What we know about the  $P_T$ -dependence of the  $F_{UU,L}$  (most likely increasing fast with  $P_T$ )?

# Attempts to understand $Q^2$ -dependence of HT



CLAS12(preliminary)

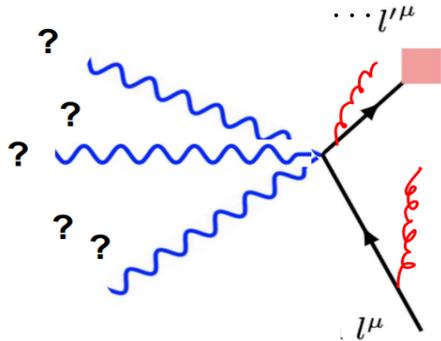


The ratios of SFs (to  $F_{UU}$ ) are not decreasing with  $Q$ !!!

The HT observables, don't look much like HT observables, something missing in understanding  
Understanding of these behavior can be a key to understanding of other inconsistencies

# Relevance of RC in studies of complex azimuthal modulations

N.Sato(CPHI-2022)  $F_{UU,T} + \epsilon F_{UU,L} + |S_{\perp}| [F_{UT}^{\sin \phi - \phi_S} \sin(\phi - \phi_S) + \epsilon F_{UT}^{\sin \phi + \phi_S} \sin(\phi + \phi_S) + \sqrt{2\epsilon(1 + \epsilon)} F_{UT}^{\sin \phi_S} \sin \phi_S] +$  ↓ ignored



$$\int d\phi_h d\phi_S \sin(\phi_h - \phi_S) \sin(\phi_h + \phi_S) = 0$$

➔ BUT with QED this does not hold!

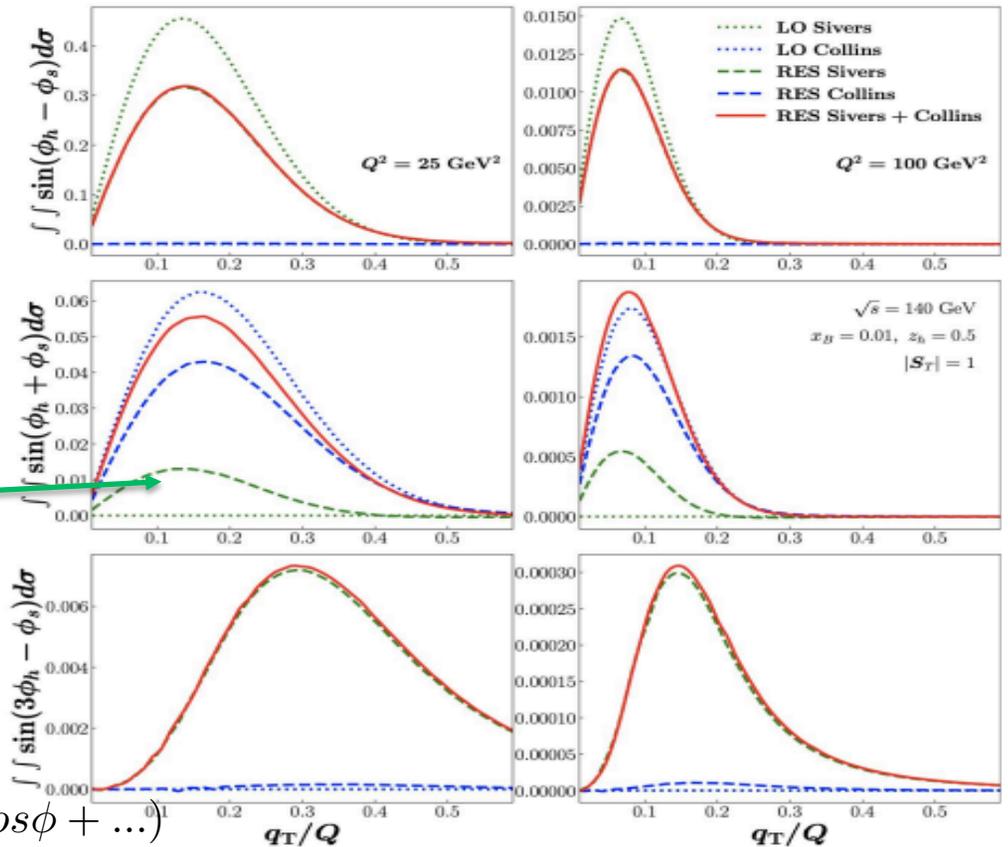
$$\int d\phi_h d\phi_S \sin(\phi_h - \phi_S) \sin(\hat{\phi}_h + \hat{\phi}_S) \neq 0$$

In the presence of QED radiation, the q direction is not fixed

Overlap of modulations from RC (Sivers → Collins)

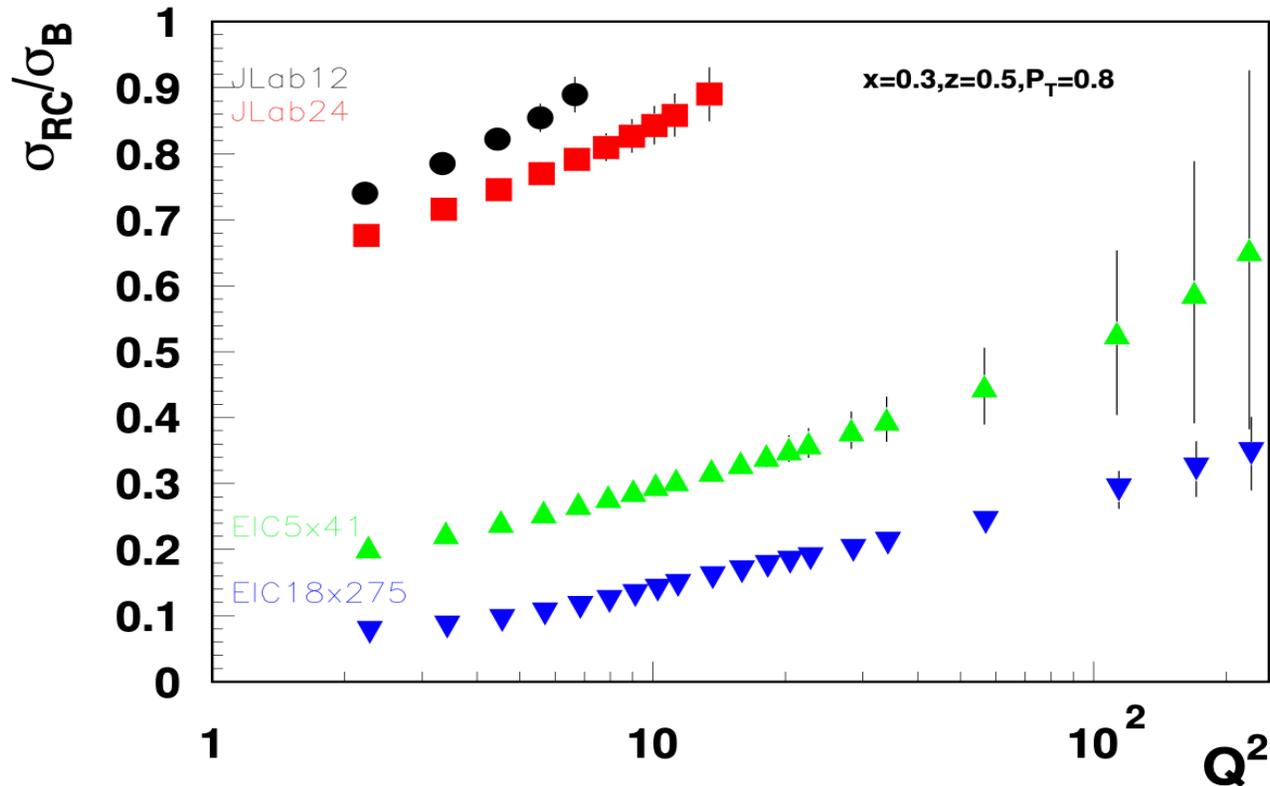
$$\sigma_{XY}^h(x, z, P_T) \rightarrow \sigma_{XY}^{B,h}(x, z, P_T) \times R(x, z, P_T, \phi_h) + \sigma_{XY}^{R,h}(\dots)$$

$$R(x, z, P_T, \phi) = f_{XY}(x, z, P_T) * (1 + a_{XY} * \cos \phi + \dots)$$



# From JLab to EIC: complementarity

The ratio of radiative cross ( $\sigma_{RC}$ ) section to Born ( $\sigma_B$ ) in SIDIS

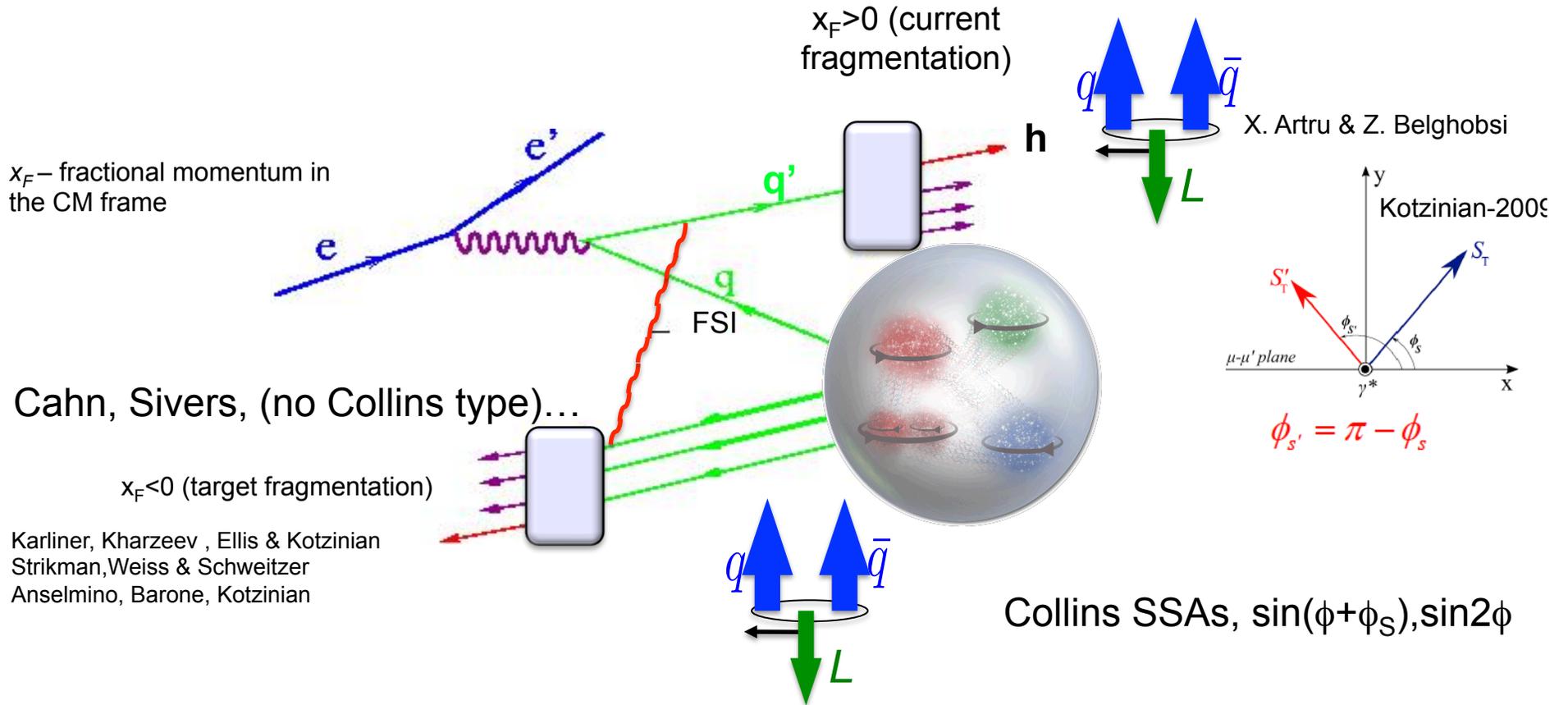


*T. Liu et al*  
*JHEP* 11 (2021) 15  
7  
Gaussian  $F_{UU}$   
( $\phi_h=0$ )

Cross section at low  $Q^2$   
suppressed at higher  
CM energies

- 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

# Hadron production in hard scattering

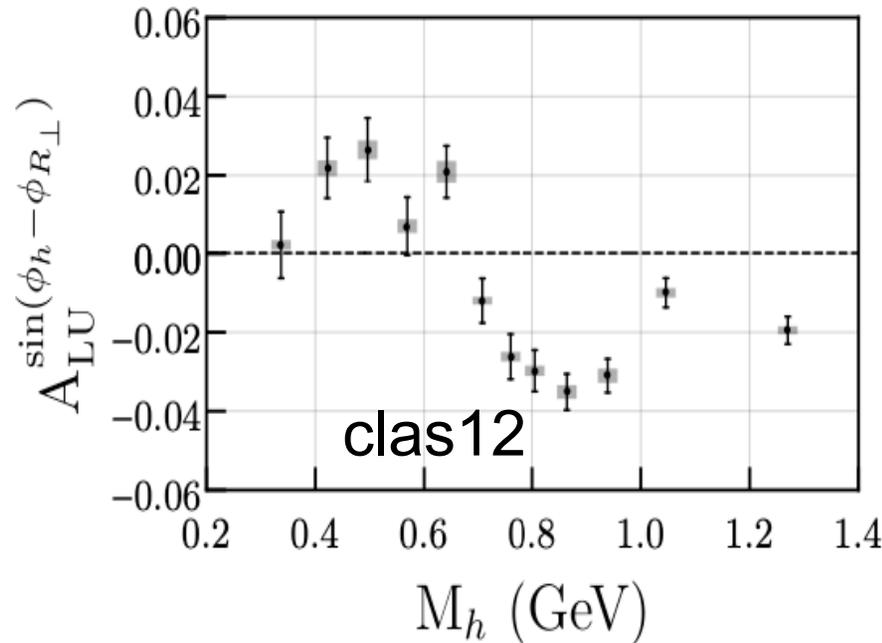


Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles (different in CFR and TFR)

H. Avakian, IWHSS-2022, Aug 29

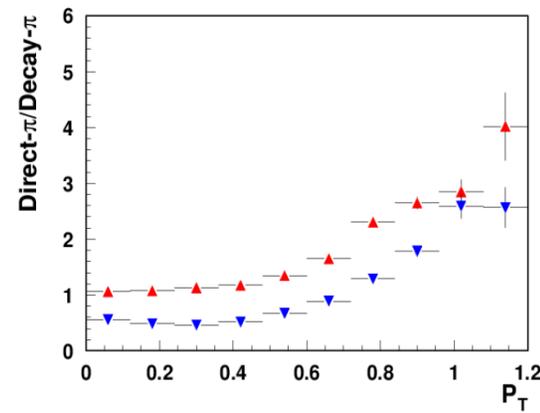
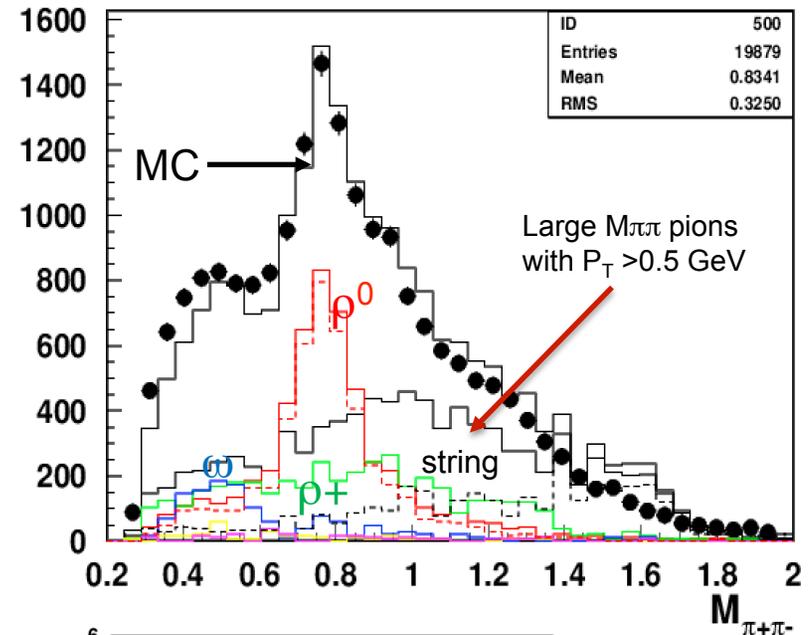
# 2 hadron correlations in CFR $ep \rightarrow e' \pi^+ \pi^- X$

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



- 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)

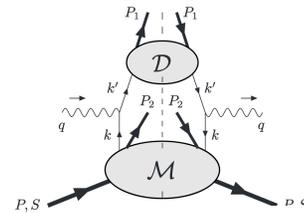
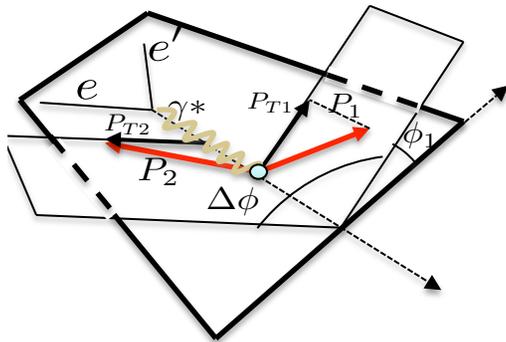
Contributions to  $\pi^+$  in  $e' \pi^+ \pi^- X$  sample from different channels



# CFR/TFR correlations in 2 hadron production

Submitted to PRL

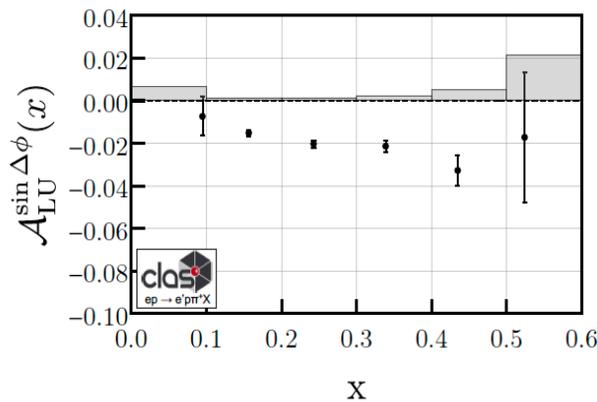
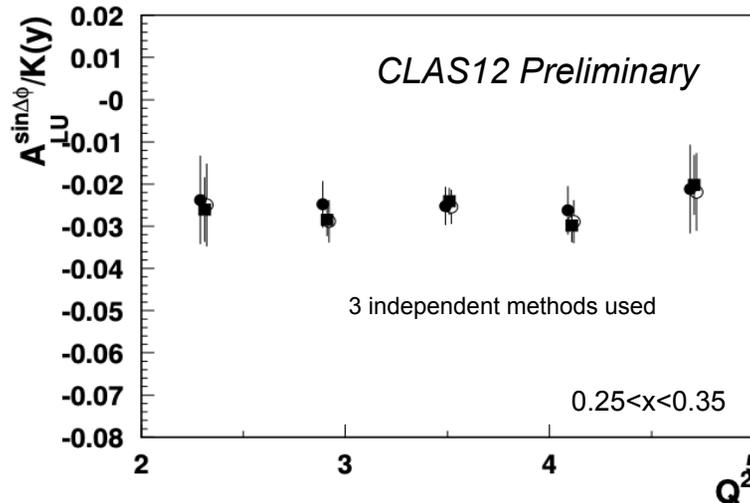
M. Anselmino, V. Barone and A. Kotzinian,  
Physics Letters B 713 (2012)



$$A_{LU} \propto \frac{C[w_5 \hat{l}_1^{\perp h} D_1]}{C[\hat{u}_1 D_1]} \sin \Delta\phi$$

Twist-2 table

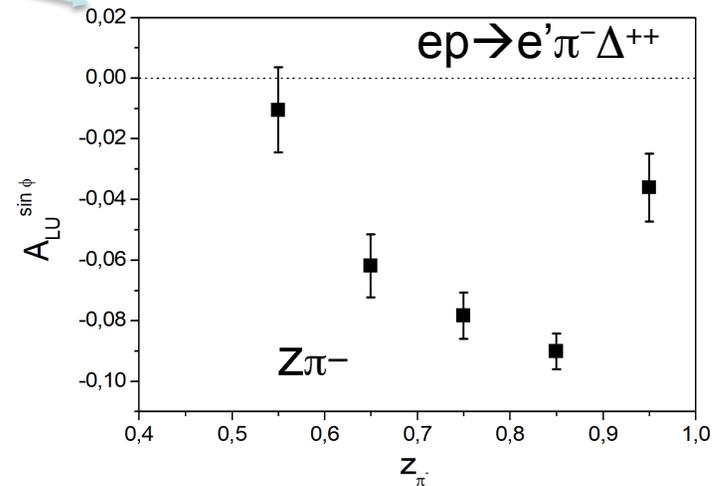
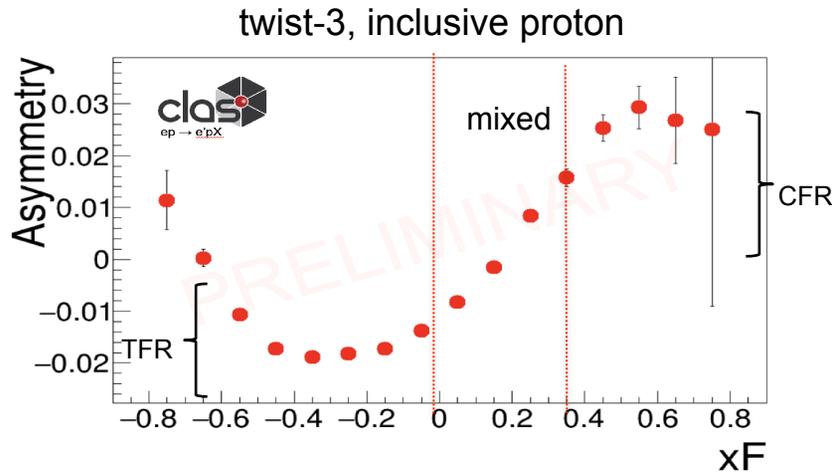
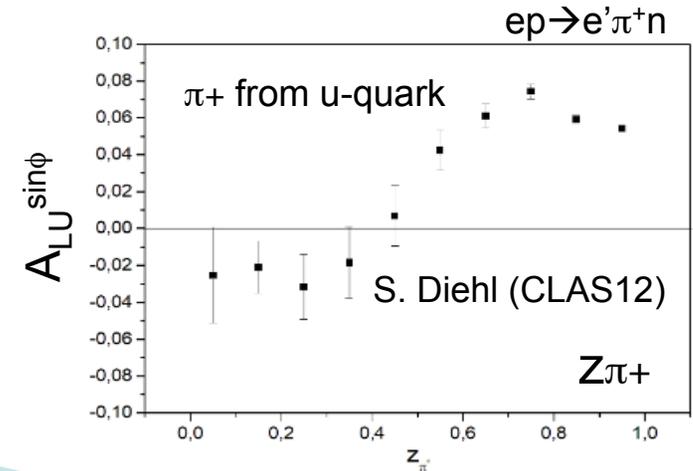
N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^{\perp}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^{\perp}$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^h, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}^h, \hat{t}_{1T}^{\perp}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp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



- Correlation asymmetry is linked to Leading Twist(LT) distributions of **longitudinally polarized quarks**
- SSA significant at large x where the valence quarks (non-perturbative sea)?
- First indication in large x SIDIS of a LT observable
- Multidimensional measurements crucial for evolution studies

# Beam SSA: Where is the struck quark?

- CFR is defined by the kicked out quark, and in case the quark is polarized the SSA can define its signature
- Polarized d-quark, is hard to locate, and one obvious process where we can guarantee it was hit, is the production of  $\Delta^{++}$

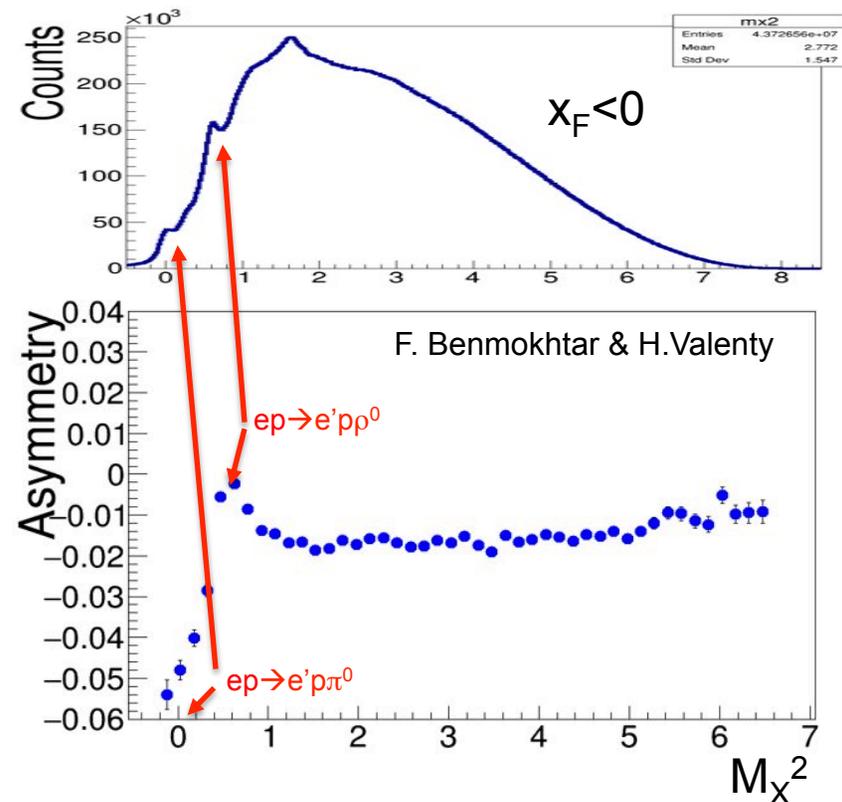


Negative sign of the SSA (plateau) defines the TFR dominance

# Dissecting the beam SSA ( $A_{LU}$ ) in $ep \rightarrow e'pX$

- SIDIS is a sum over multiple exclusive states, but has to keep an eye to make sure it is not dominated by some dominant channel (extraction of  $Q^2$ -dependence critical)
- The cut on the missing mass of the proton eliminates obvious exclusive channels, which tend to have higher positive or negative SSAs (ex.  $ep \rightarrow e'p\pi^0$  or  $e'p\rho^0$ )
- $M_X > 1.5$  no structures and SSA goes to plateau (no single channel dominates it) decreasing as the correlations get suppressed with multiple hadron production

Significant beam spin SSAs observed for exclusive  $ep \rightarrow e'p\pi^0$  ( $\sim 8\%$ ) and  $ep \rightarrow e'p\rho^0$  ( $\sim -20\%$ )



# “Only JLab20+” measurements

Measurements at relatively large  $x$ , where non-perturbative effects are expected to be significant, at lower energies will not cover kinematics, at higher energies will not have significance in multidimensional bins

Twist-2

$$A_{LL} = F_{LL}/F_{UU}$$

Double spin asymmetries in hadron production CFR and TFR at large  $x$

$$\mathcal{F}_{LU}^{\sin(\phi_1 - \phi_2)} \sin \Delta\phi$$

Beam spin asymmetries in correlations of CFR and TFR

$$\sin \phi_h F_{LU}^{\sin \phi_h}$$

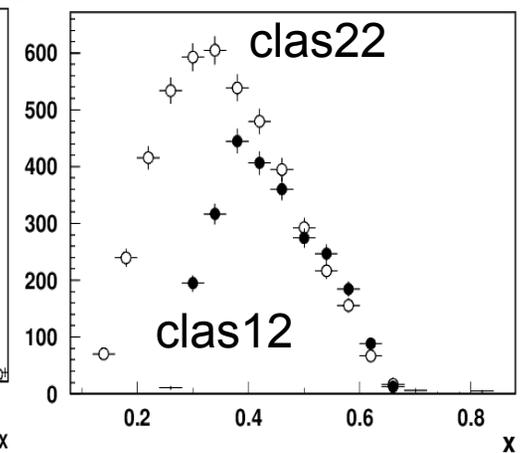
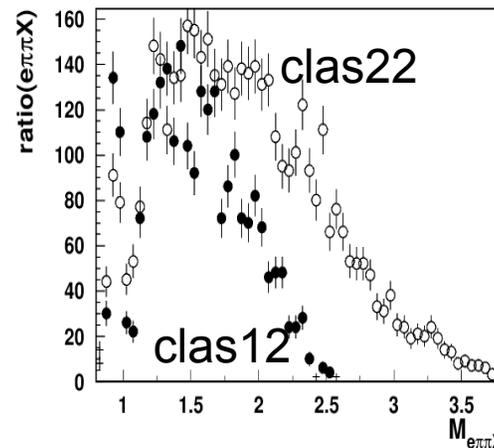
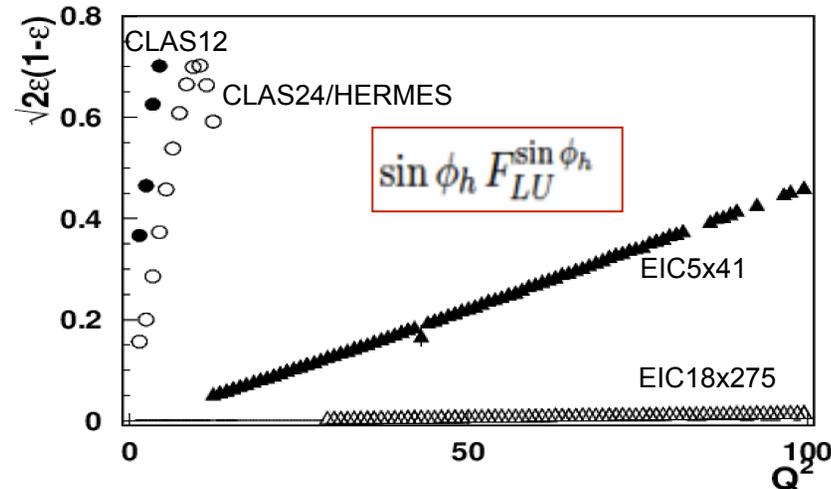
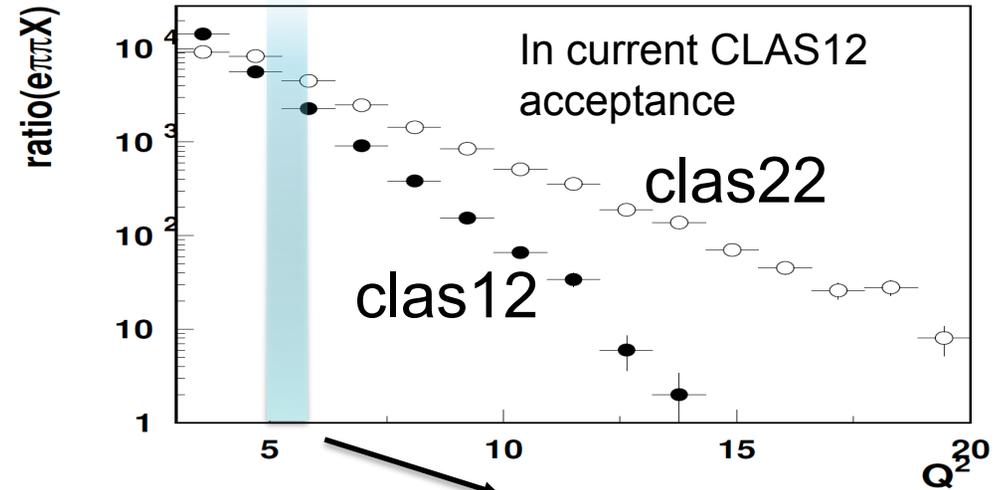
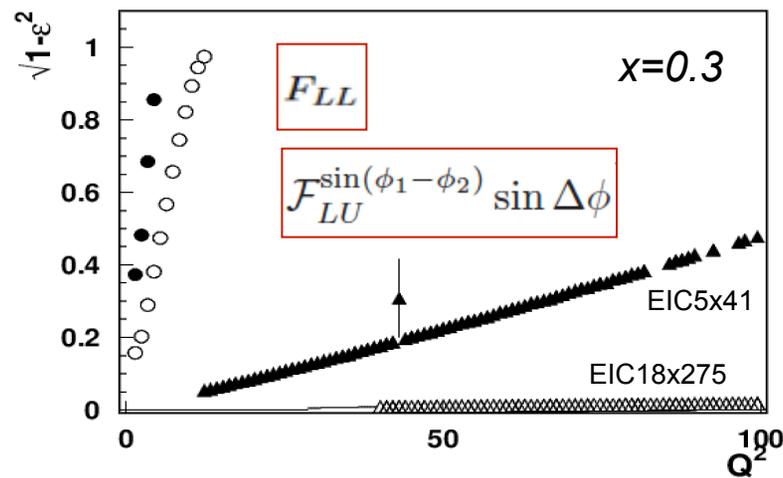
Twist-3

$$A_{LU}^{\sin \phi_{R\perp}}$$

Beam spin asymmetries in CFR (single and dihadron)

Exclusive processes in the  $x > 0.1$  domain, may most be in this category, due to resolutions and rapidly decreasing  $x$ -sections at higher energies  
Much higher range in  $Q^2$ , compared to HERMES, may help with applicability of GPD formalism

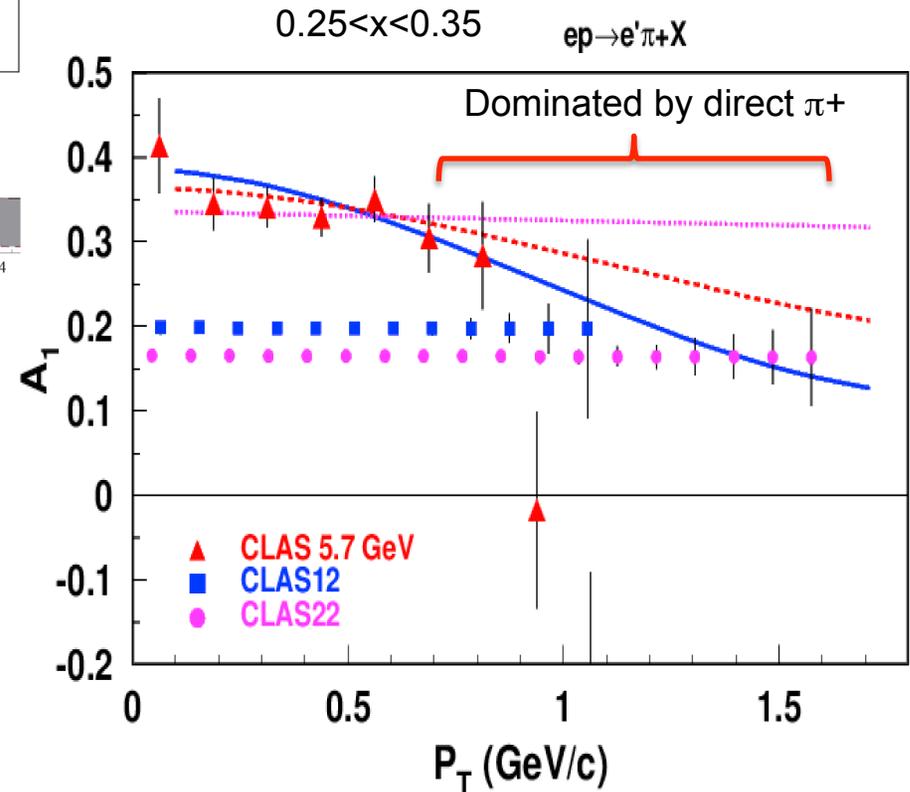
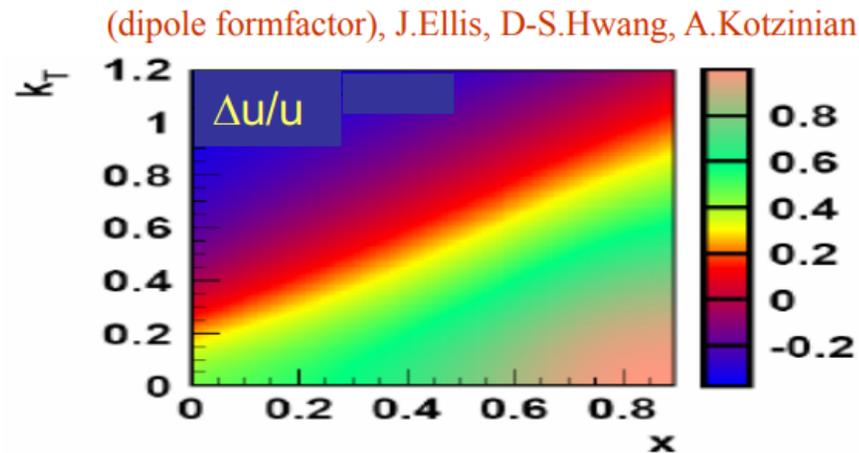
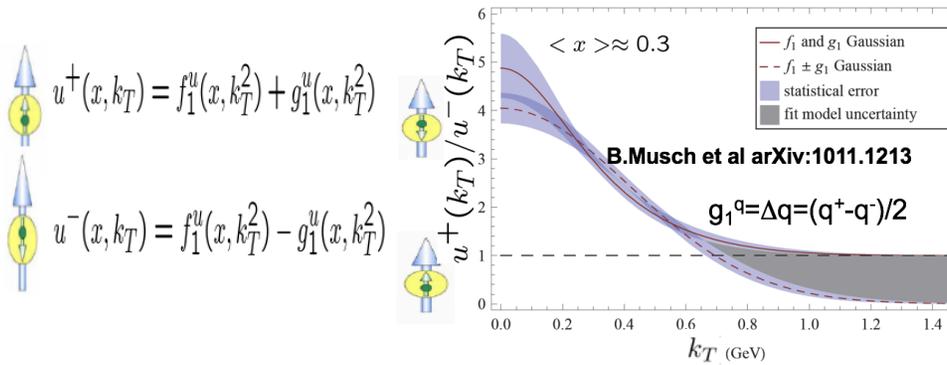
# Beam SSAs & Kinematic suppression at large x



- 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

# Unknown “known” $f_1, g_1$ TMDs

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

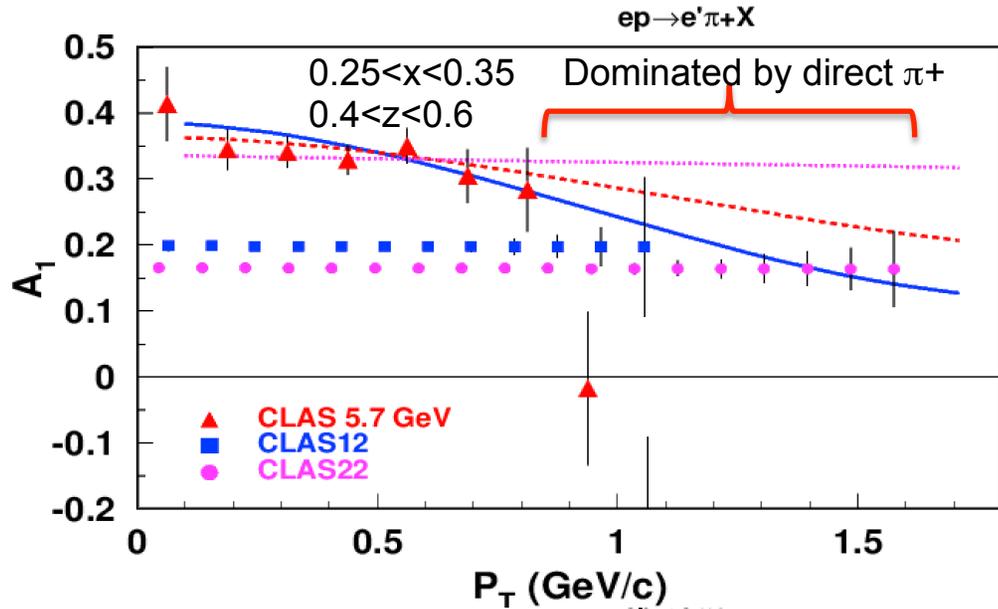


- Models and lattice predict very significant spin and flavor dependence for TMDs
- Large transverse momenta are crucial to access the large  $k_T$  of quarks
- Several CLAS12 proposals dedicated to  $g_1(x, k_T)$ -studies CLAS12
- Understanding of  $k_T$ -dependence of  $g_1$  will help in modeling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

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

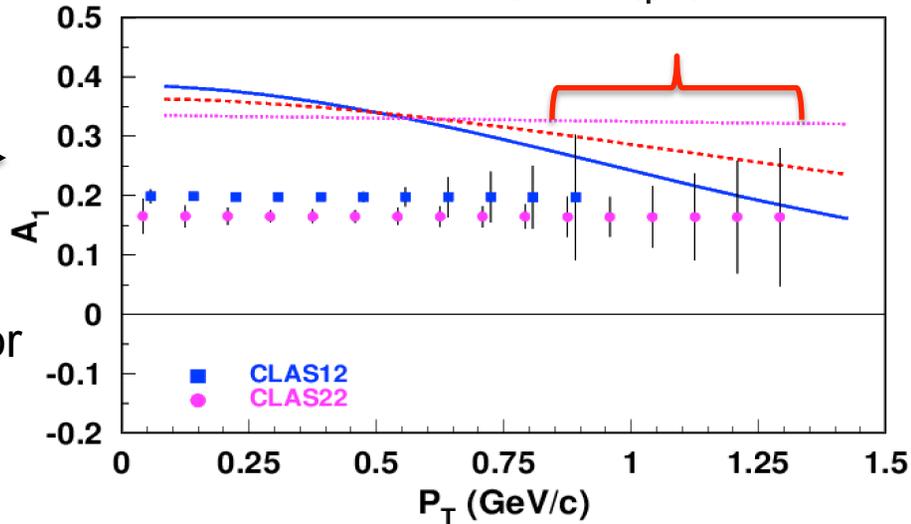
# Impact of limitations from theory

- Gain with 22 GeV will be more critical with additional kinematical cuts imposed by theory



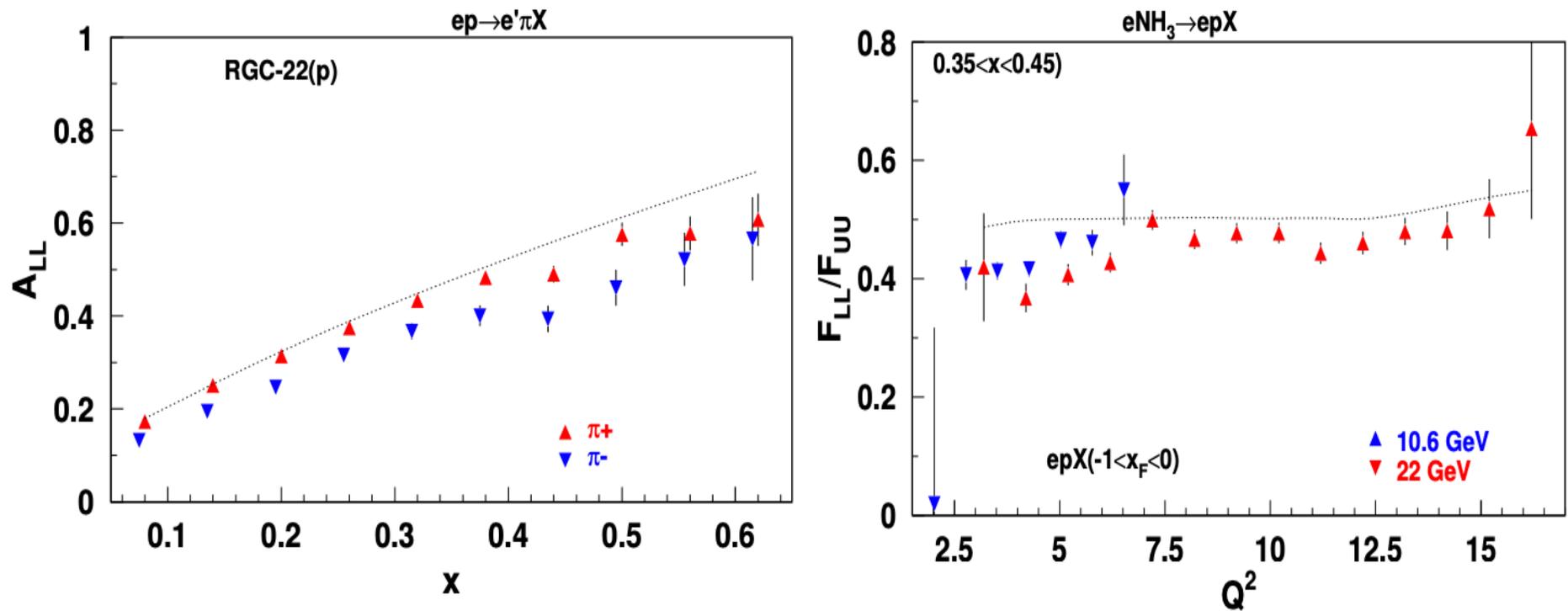
$P_T/z/Q < 0.5$  →

More theory limitation, may convert the observable from major improvement (type 2) to only possible with 20+ GeV (type 1)



# CLAS12 at 22 GeV with longitudinally polarized target

Full simulations using LUND-based generator and full CLAS12



- Studies of evolution of observed double spin asymmetries will be a critical task in validating the QCD predictions  $g_1(x, k_T)$ -studies CLAS12
- Asymmetries measured with input polarized and unpolarized PDFs, can be used to test the flavor decomposition capabilities
- Kinematical correlations, even for small bins relevant (multidimensional bins critical)

# Measurements of Collins-Soper kernel

## Validation of the TMD factorization based framework: Collins-Soper kernel

TMD factorization predicts a very specific pattern for cross-section

A. Vladimirov

$$d\sigma \sim \sigma_0(Q) \int d^2b e^{-i(qb)} R(Q, b) \sum_f F_f(x, b) D_f(z, b)$$

- ▶  $R$  is evolution factor (nonperturbative),
- ▶  $F$  and  $D$  are TMD distributions.

Making ratios of Fourier transforms of cross-section we can determine  $R$  directly from the data.

CS-kernel

Perturbative

$$\mathcal{D}(b, m_0) = \frac{\ln\left(\frac{\Sigma_1}{\Sigma_2}\right) - \ln Z(Q_1, Q_2) - 2\Delta_R(Q_1, Q_2; m_0)}{4 \ln(Q_2/Q_1)} - 1.$$

Ratio of cross-sections

[A.B.Martinez, A.Vladimirov, 2206.01105]



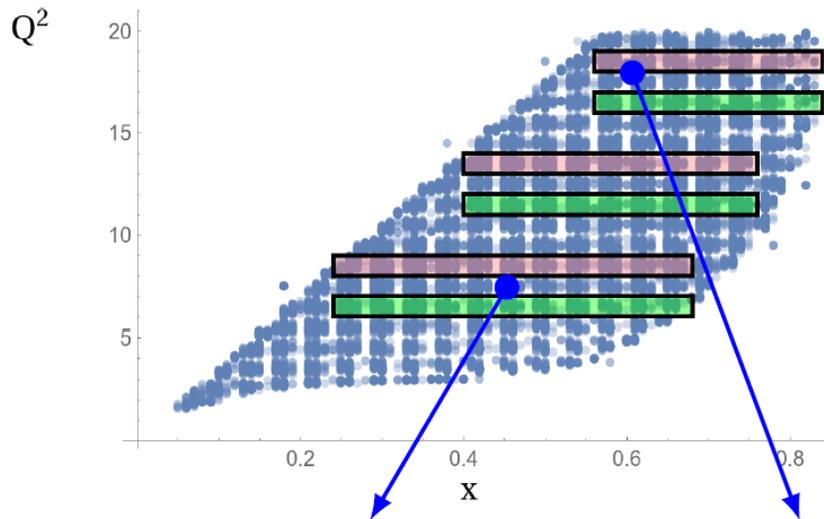
# Extracting the CS-kernel from data

Is such study possible?

YES!

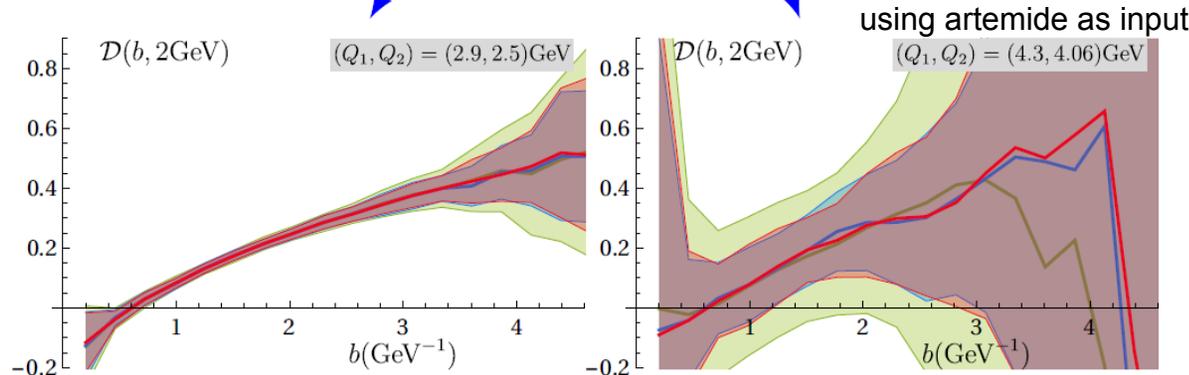
A. Vladimirov

## Estimation for the JLab22



Different experiments most sensitive to different ranges in  $b$

- JLab  $\sim 1 < b < 4$
- EIC  $\sim 0.5 < b < 1.5$
- LHC  $b < 0.5$
- COMPASS overlaps

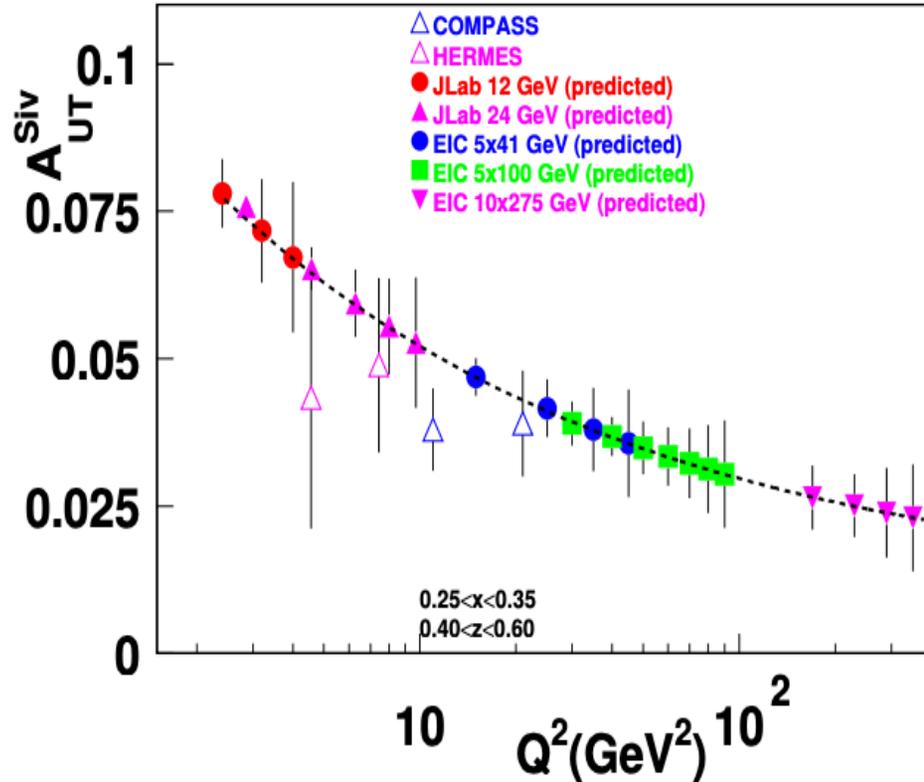


Better control over systematics requires thin slices in  $Q^2$ , and good resolutions

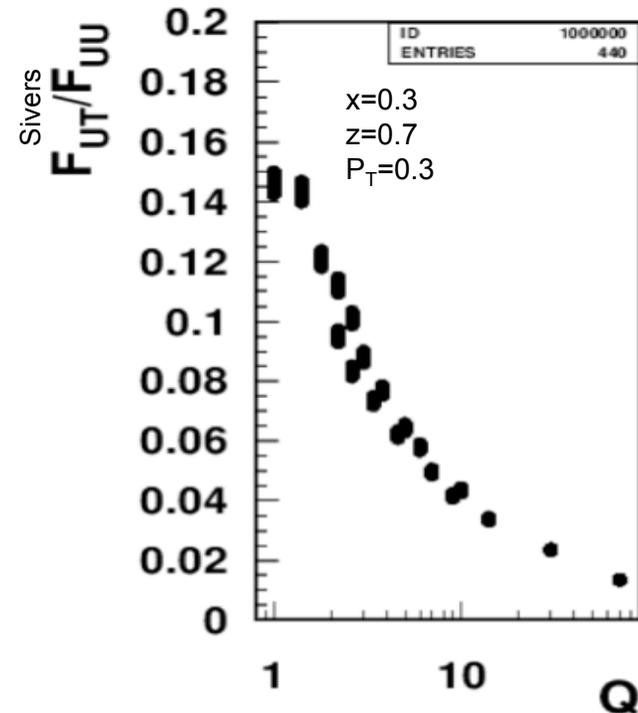
# Contributions for 3D structure studies: Sivers

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

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



Pavia grids



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

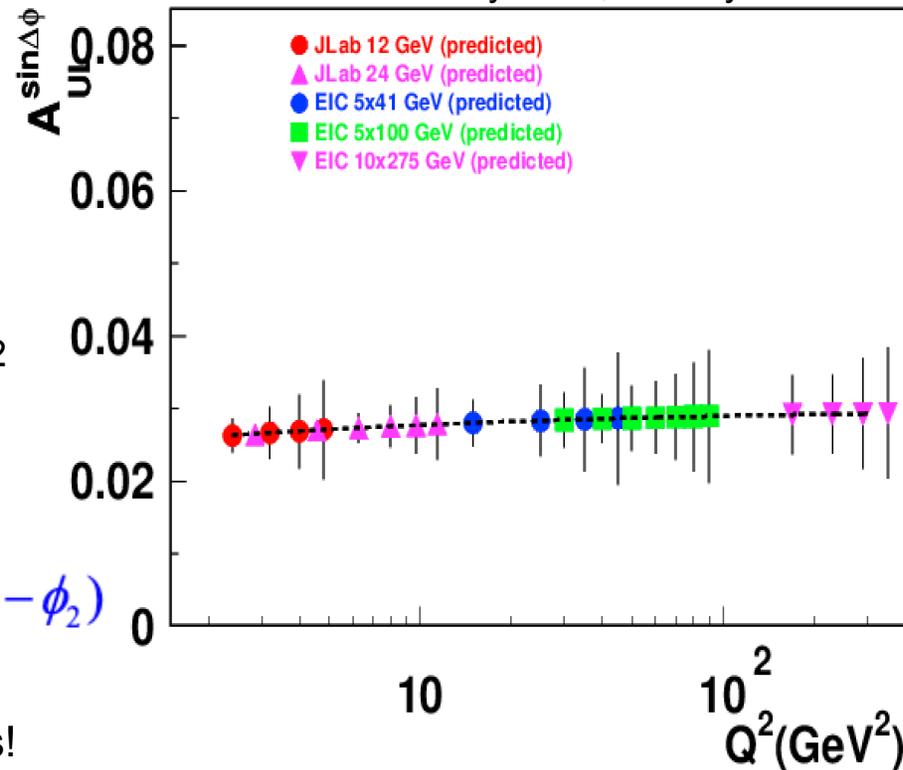
A. Kotzinian et al, arXiv:1107.2292

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

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

No depolarization, like Sivers!

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



CLAS12 proposals

NH3/ND3

[E12-09-009](#)

[E12-07-107](#)

[E12-09-007A](#)

<sup>3</sup>He

[C12-20-002](#)

<sup>7</sup>LiD

[E12-14-001](#)

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

# Summary

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- Significant single spin asymmetries have been observed in CFR and TFR, indicating large correlations between hadrons
- Measurements of SFs from the azimuthal distributions of final state hadrons in electroproduction, requires high statistics in multidimensional bins, also to address kinematical limitations due to finite energies
- Better understanding of the systematics in the process of extraction of final physics quantities (development of validation mechanism) can help to control the systematics, optimize the output format of the data (ex, multidimensional binning, providing events...)
- Extending JLab measurements to a wider range in  $Q^2$  and  $P_T$  with energy upgrade, will be crucial in studies of evolution properties and transverse momentum dependences of underlying PDFs.
- The 3D physics with SIDIS and hard exclusive production processes can provide a set of flagship measurements, superior at JLab20+, critical for understanding of QCD dynamics, and required for validation of different QCD based formalisms

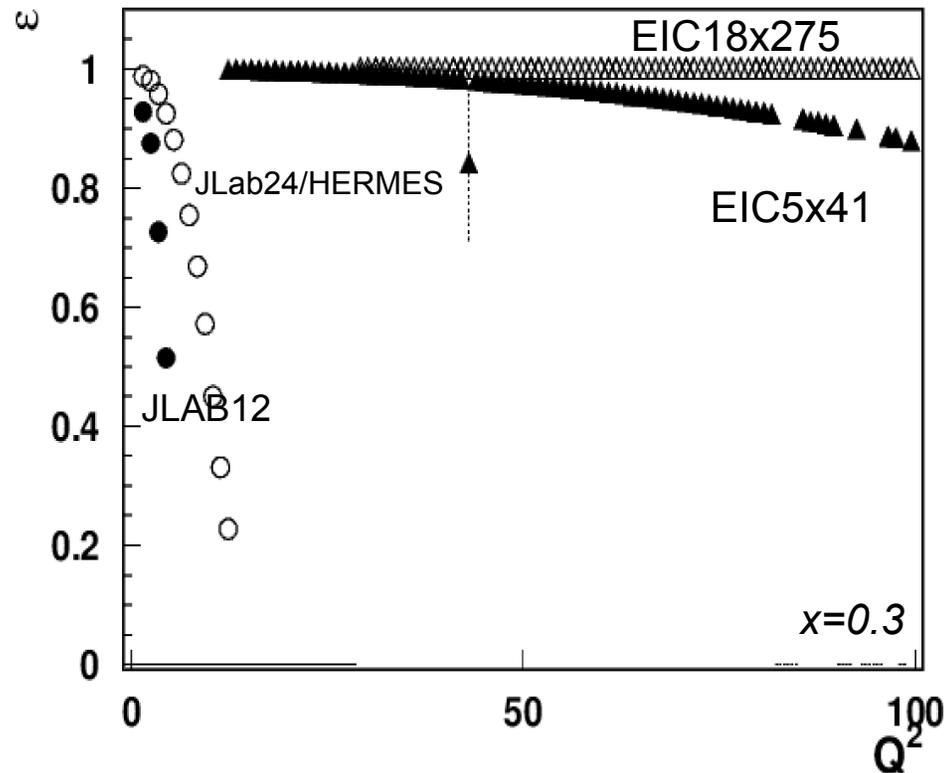
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# Support slides...

# $F_{UU,L}$ from JLab and EIC

$$\sigma \sim F_{UU,T} + \varepsilon F_{UU,L}$$

$F_{UU,L}$  (longitudinal photon contribution), typically neglected in phenomenology, may be important part of systematics in certain kinematics, in particular at large  $P_T$



$F_{UU,L}$  kinematically enhanced, but requires a reasonable range and resolutions to be separated from the  $F_{UU,T}$