3D structure of the nucleon: challenges and prospects

QNP2022 - The 9th International Conference on Quarks and Nuclear Physics

Sep 5 –9, 2022

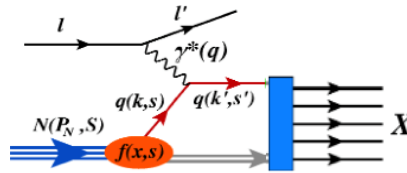**Harut Avakian (JLab)**

Sep 5, 2022

Understanding the QCD: from observables to QCD dynamics
– Testing the QCD based frameworks for finite energies of polarized target experiments
– Extending the phase space in P_T, Q^2 and x
– Studies of evolution properties
– Future studies of 3D
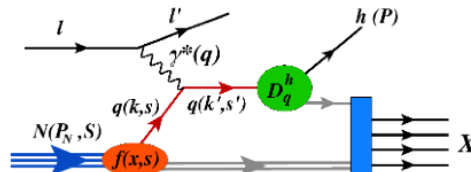Summary

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)
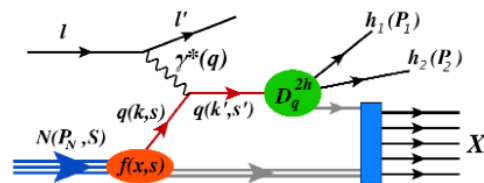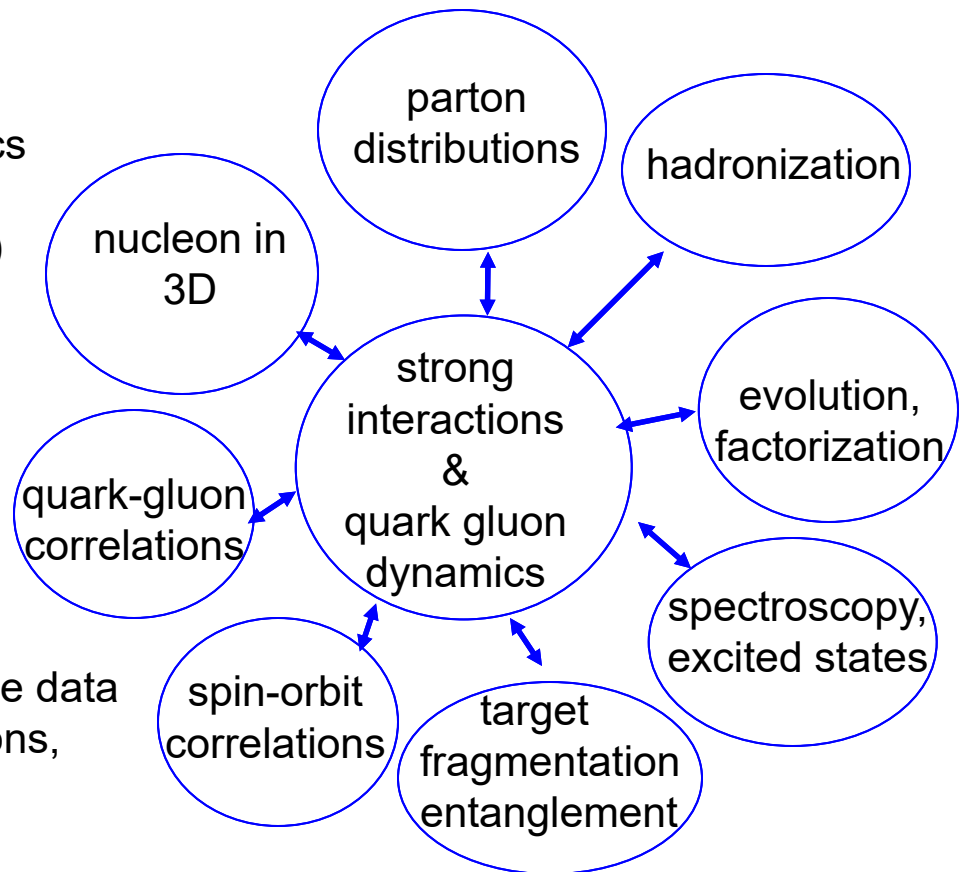
1h SIDIS/DVMP

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)
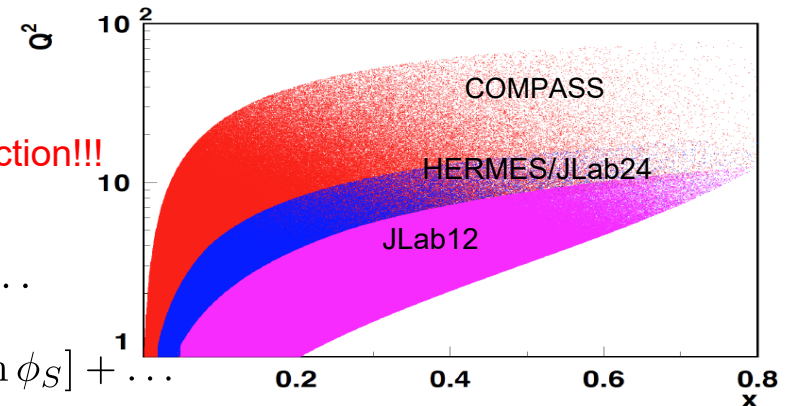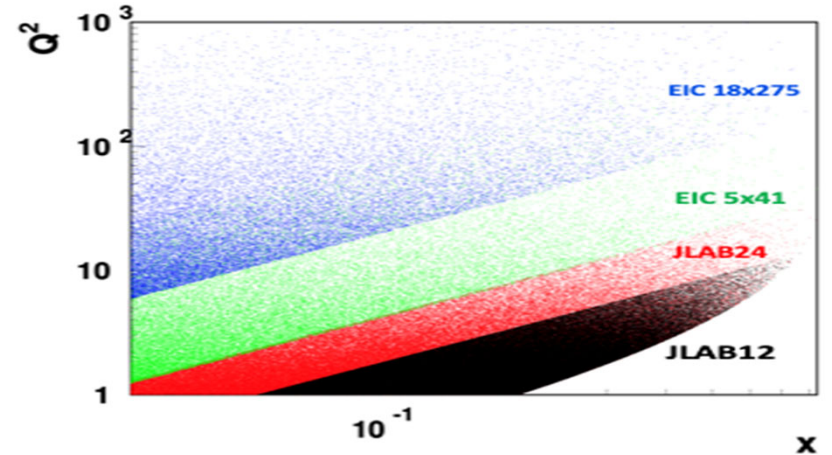
2h SIDIS/DVMP

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

parton distributions

hadronization

nucleon in 3D

strong interactions & quark gluon dynamics

evolution, factorization

quark-gluon correlations

spectroscopy, excited states

spin-orbit correlations

target fragmentation entanglement

H. Avakian, QNP-2022, Sep 5

SIDIS kinematical coverage and observables

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

$$P_{hT} = p_\perp + z\, k_\perp$$
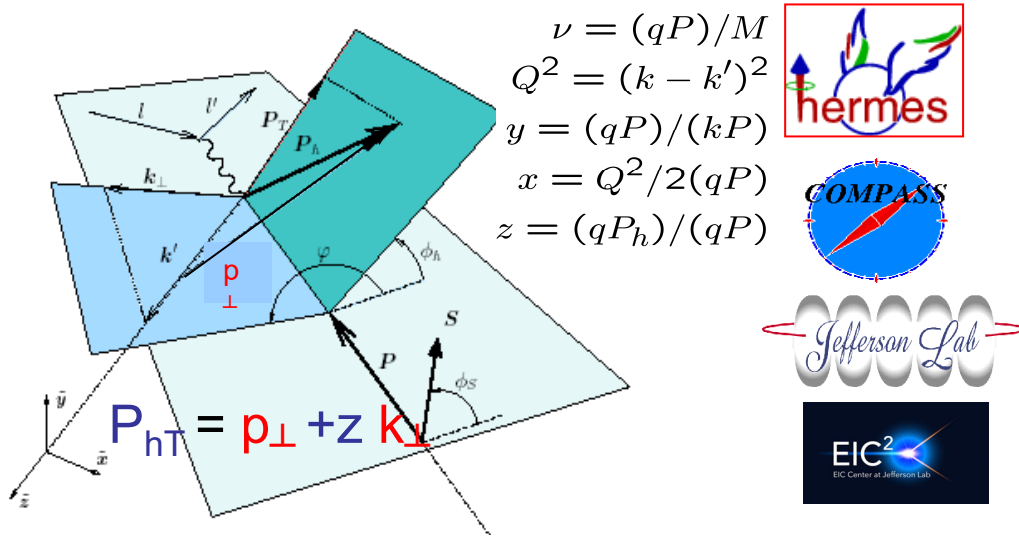
SIDIS experiments measure azimuthal dependence of the cross section!!!

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

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

- Studies of azimuthal modulations give access to underlying 3D partonic distributions
- All assumptions involved in description of SFs, should be tested!
- QCD predicts only the Q^2-dependence of 3D PDFs
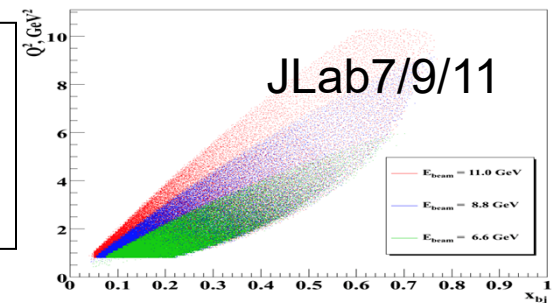
What we learned so far from JLab data
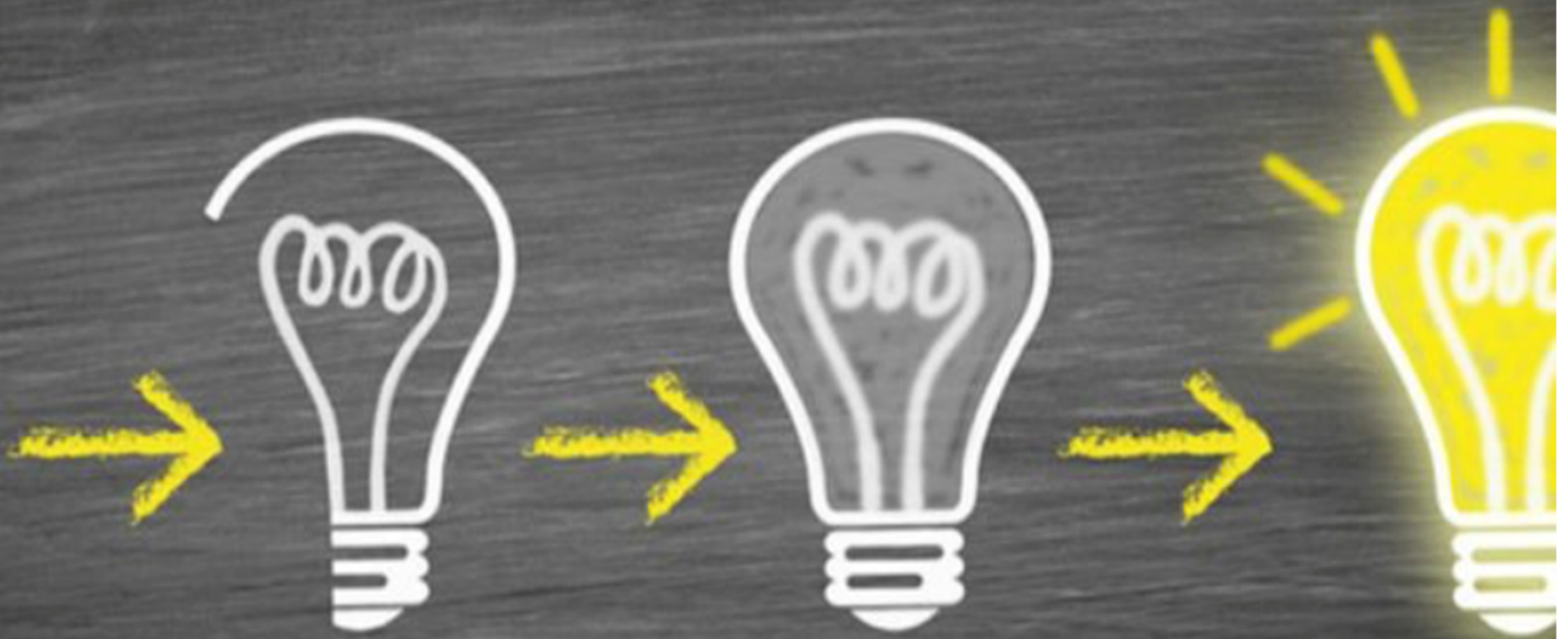
What we learned: missing parts of the mosaic

- 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,ϕ), 6D for transverse target, $+\phi_S$

    Collinear SIDIS, is just the proper integration, over P_T,ϕ,ϕ_S

- 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

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 a as target and current fragments accounted
- ….

subsamples
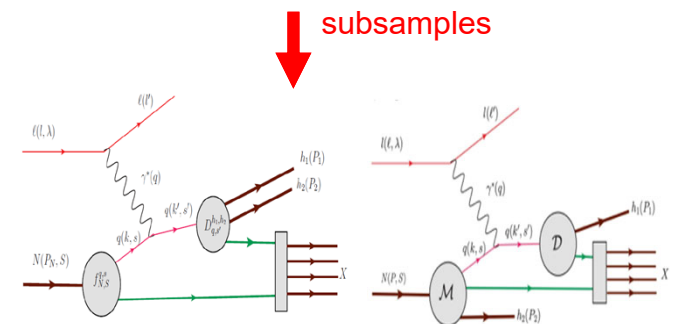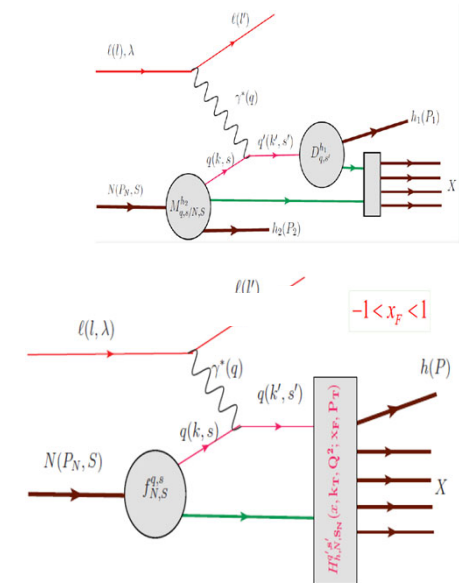
To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

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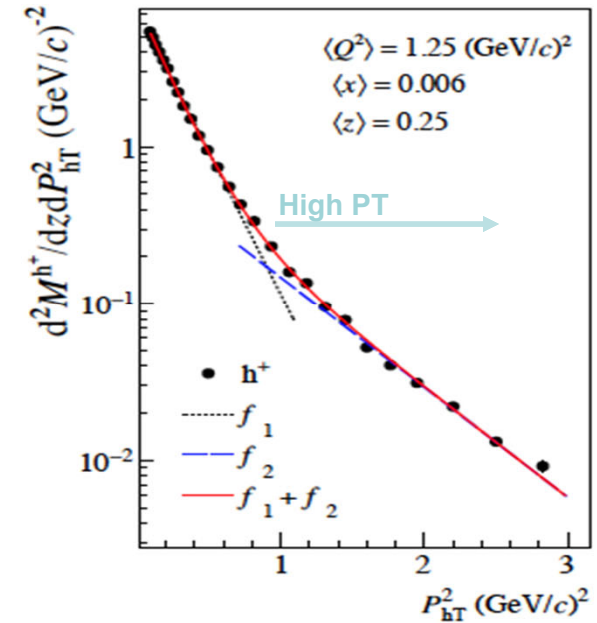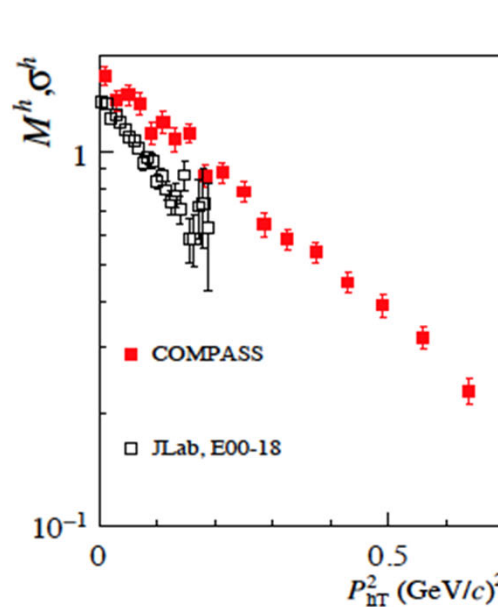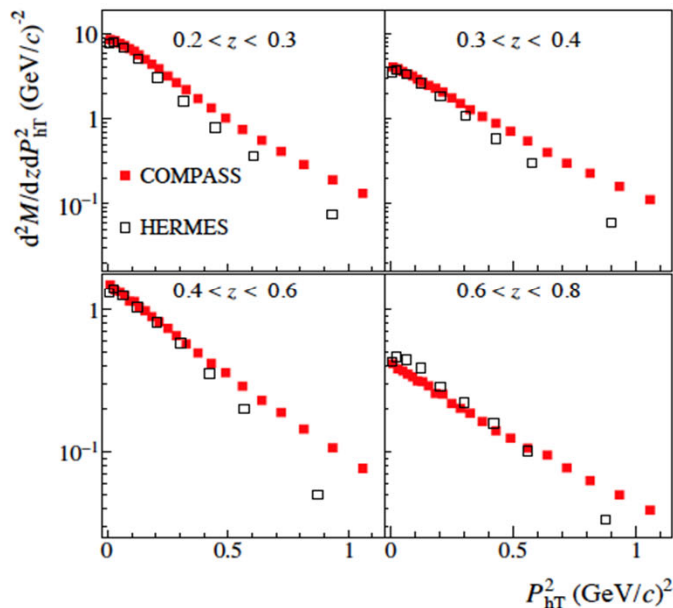
Multiplicities of hadrons in SIDIS

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

TMDs universal, so what is the origin of the differences observed ?
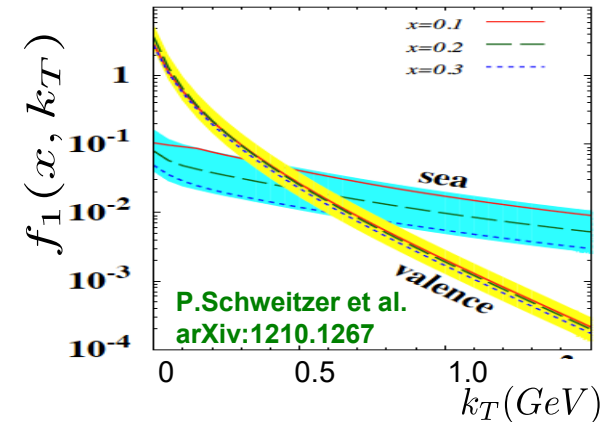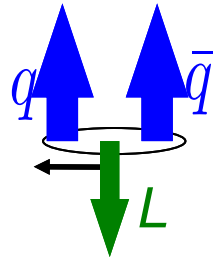
COMPASS:1709.07374

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?

Most critical in SIDIS: access to large P_T

Possible sources of large P_T in SIDIS (access to large k_T)

Non perturbative sea

q $\bar{q}$

L

$f_1(x, k_T)$

x=0.1
x=0.2
x=0.3

sea

valence

P.Schweitzer et al. arXiv:1210.1267

$k_T(GeV)$

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

$u^+(k_T)/u^-(k_T)$

$<x> \approx 0.3$

f_1 and g_1 Gaussian
$f_1 \pm g_1$ Gaussian
statistical error
fit model uncertainty

B.Musch et al arXiv:1011.1213

$g_1^q = \Delta q = (q^+ - q^-)/2$

k_T (GeV)
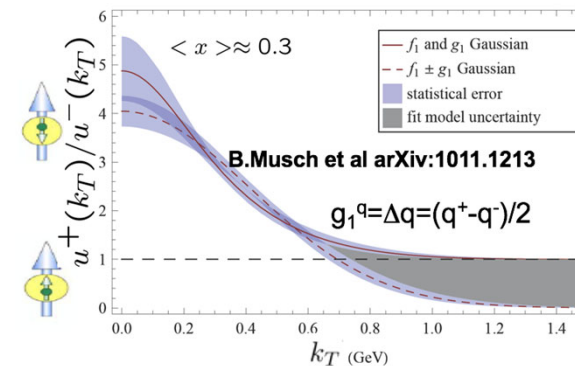
Wider in k_T d-quark distributions

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

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

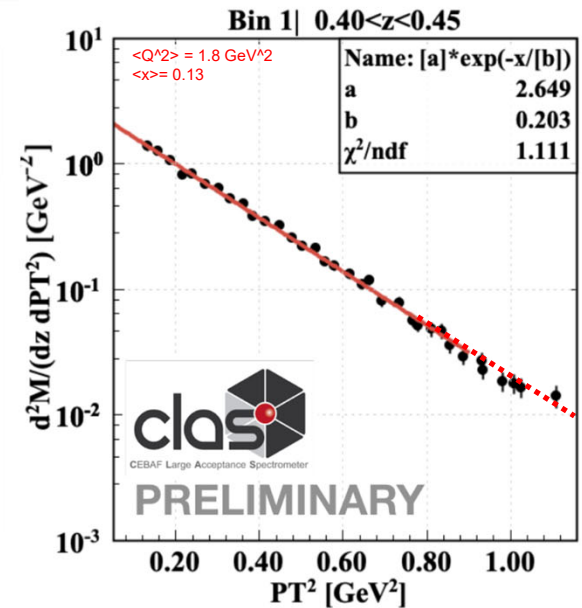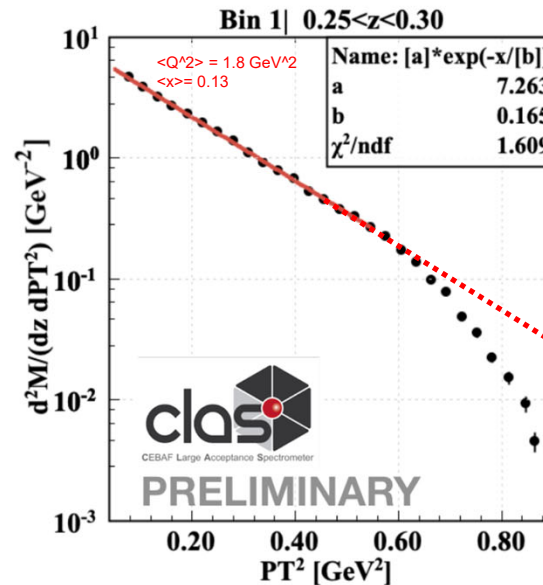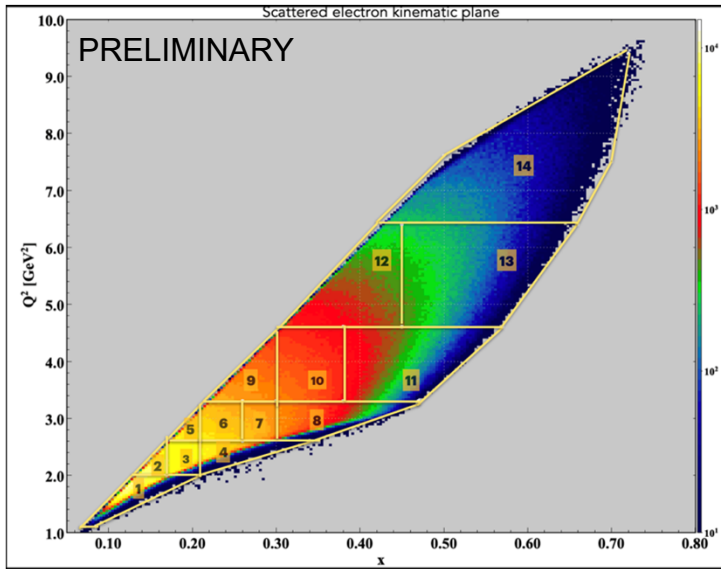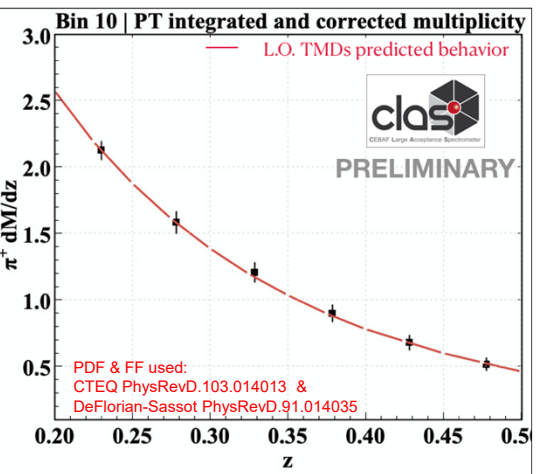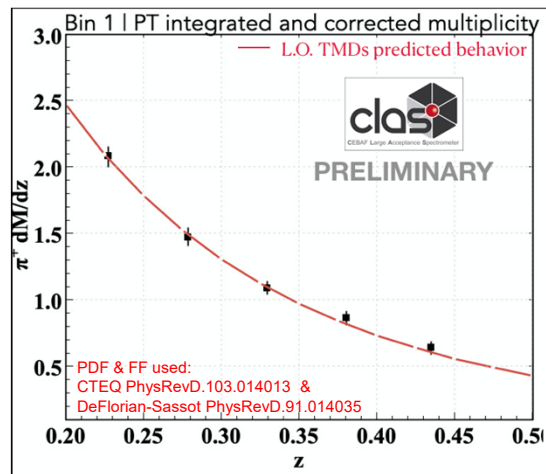# CLAS12 Multiplicities: high P_T & phase space

PRELIMINARY — Scattered electron kinematic plane

Bin 1 | 0.25<z<0.30
$<Q^2>$ = 1.8 GeV^2
$<x>$ = 0.13
Name: [a]*exp(-x/[b])
a   7.263
b   0.165
χ^2/ndf   1.609
PRELIMINARY

Bin 1 | 0.40<z<0.45
$<Q^2>$ = 1.8 GeV^2
$<x>$ = 0.13
Name: [a]*exp(-x/[b])
a   2.649
b   0.203
χ^2/ndf   1.111

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).
<u>If the effect is accounted, the CLAS
data follows global fits.</u>

Bin 1 | PT integrated and corrected multiplicity
— L.O. TMDs predicted behavior
PDF & FF used:
CTEQ PhysRevD.103.014013 &
DeFlorian-Sassot PhysRevD.91.014035
PRELIMINARY

Bin 10 | PT integrated and corrected multiplicity
— L.O. TMDs predicted behavior
PDF & FF used:
CTEQ PhysRevD.103.014013 &
DeFlorian-Sassot PhysRevD.91.014035
PRELIMINARY

Finite energy: Kinematic limitations
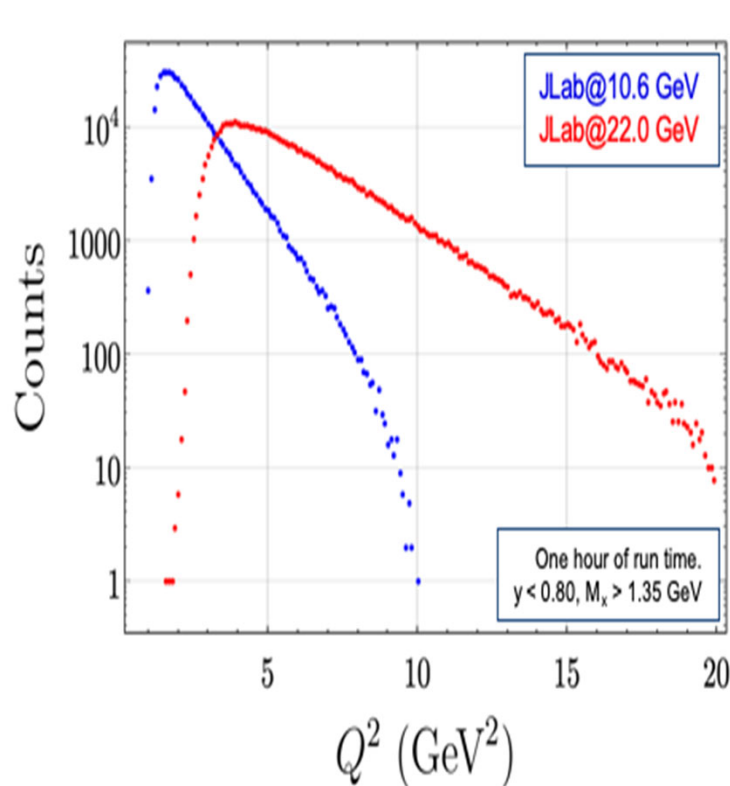
Kinematic correlations, (P_T and Q^2, in particular) due to trivial energy and momentum conservation, may mask the real dependences
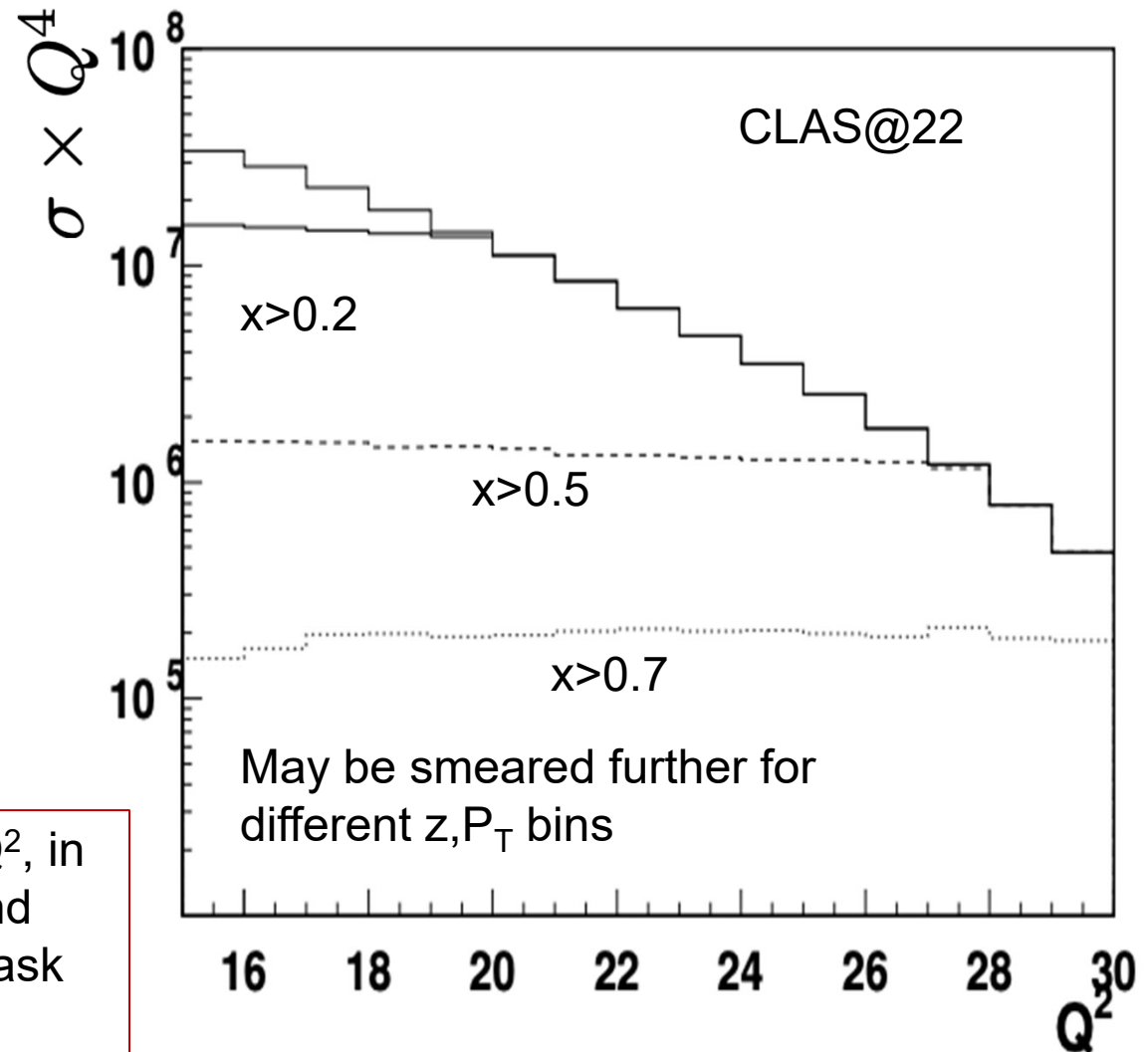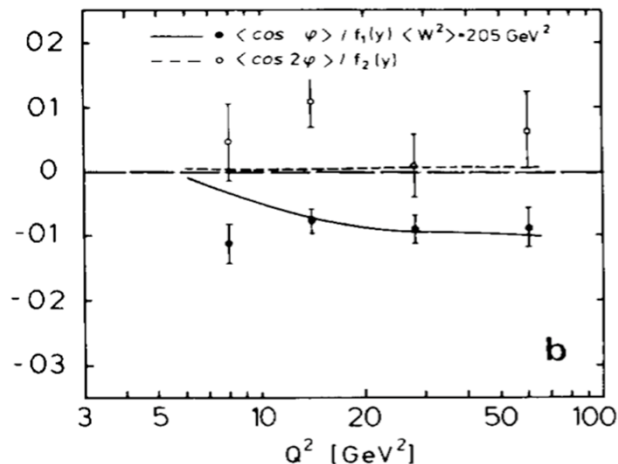- Can be easily accounted

Azimuthal distributions in SIDIS (unpolarized)

$$\frac{d\sigma}{dx_B \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} =$$

H.T.   H.T.

$$\frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h \, F_{UU}^{\cos\phi_h} \right.$$

H.T.

$$\left. + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h \, F_{LU}^{\sin\phi_h} \right\},$$
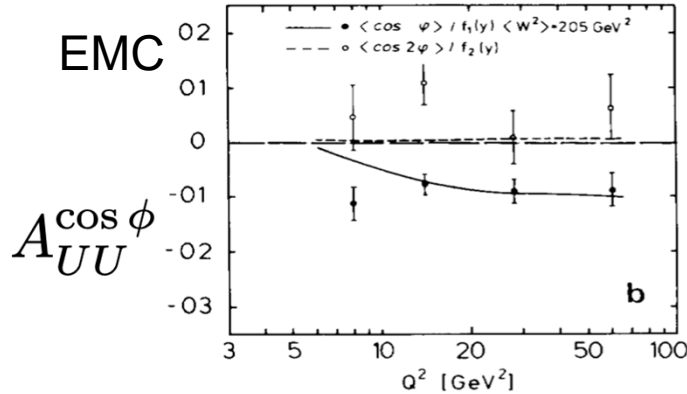
EMC-1983 (PL,v130,118)

Observables: - Azimuthal Moments   - Multiplicity

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

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

- 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)?

Jefferson Lab   GW

Attempts to understand Q²-dependence of HT

z vs P_T

EMC

$A_{UU}^{\cos\phi}$

CLAS12(preliminary)

$A_{LU}^{\sin\phi}$

0.18 < x < 0.26   0.26 < x < 0.35   0.35 < x < 0.5

bin4

bin5

bin6

COMPASS

COMPASS preliminary

$A_{UU}^{\cos\phi_h}$

0.008 < x < 0.013   0.013 < x < 0.020   0.020 < x < 0.032

h+
h−

$A_{UU}^{\cos\phi_h}$

0.032 < x < 0.050   0.050 < x < 0.080   0.080 < x < 0.130

Q^2 (GeV/c)² Q^2 (GeV/c)² Q^2 (GeV/c)²
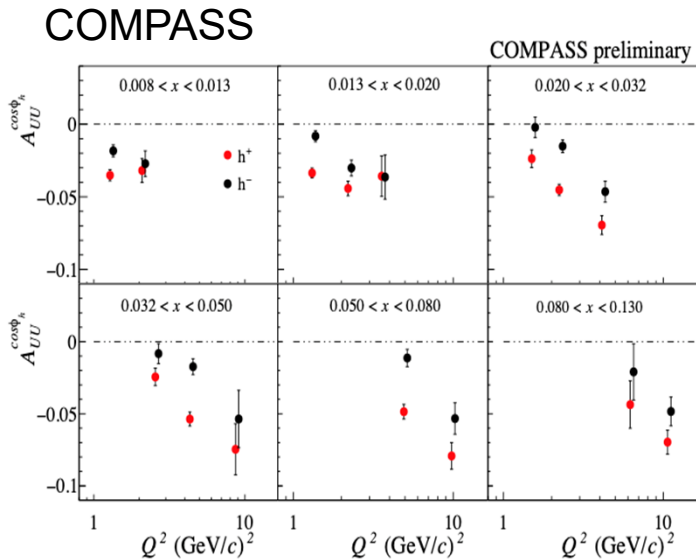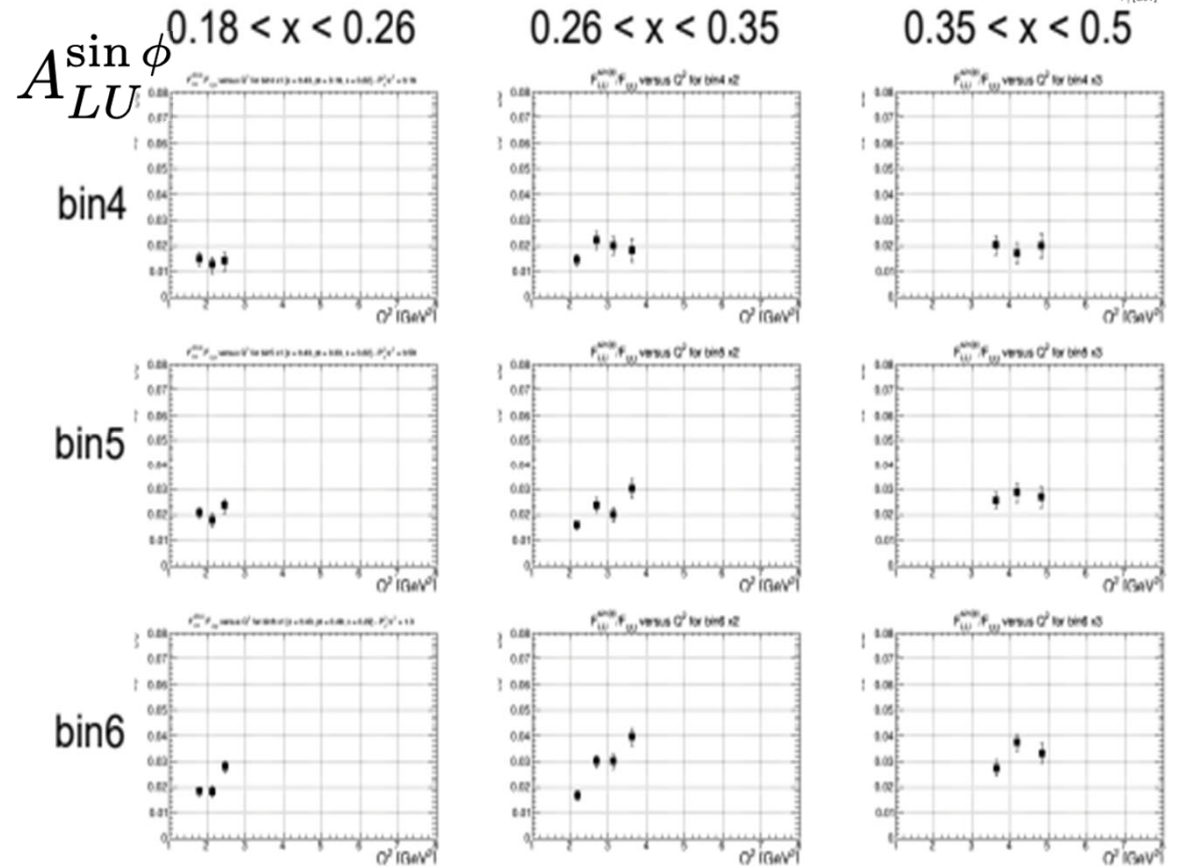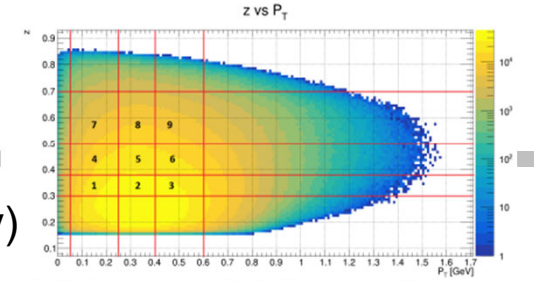
The ratios of SFs (to F_{UU}) are not decreasing with Q!!!
The HT observables, don't look much like HT observables, something missing in understanding
Understanding of these behavior can be a key to understanding of other inconsistencies

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

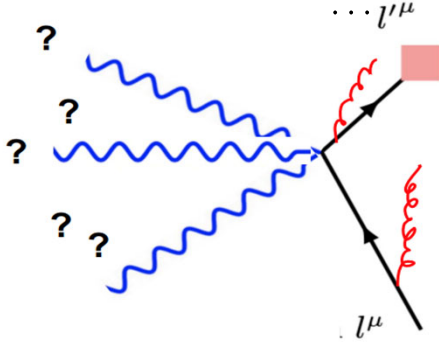 • Access the the full kinematical range (x>0.03) where the non-perturbative sea is expected to be significant
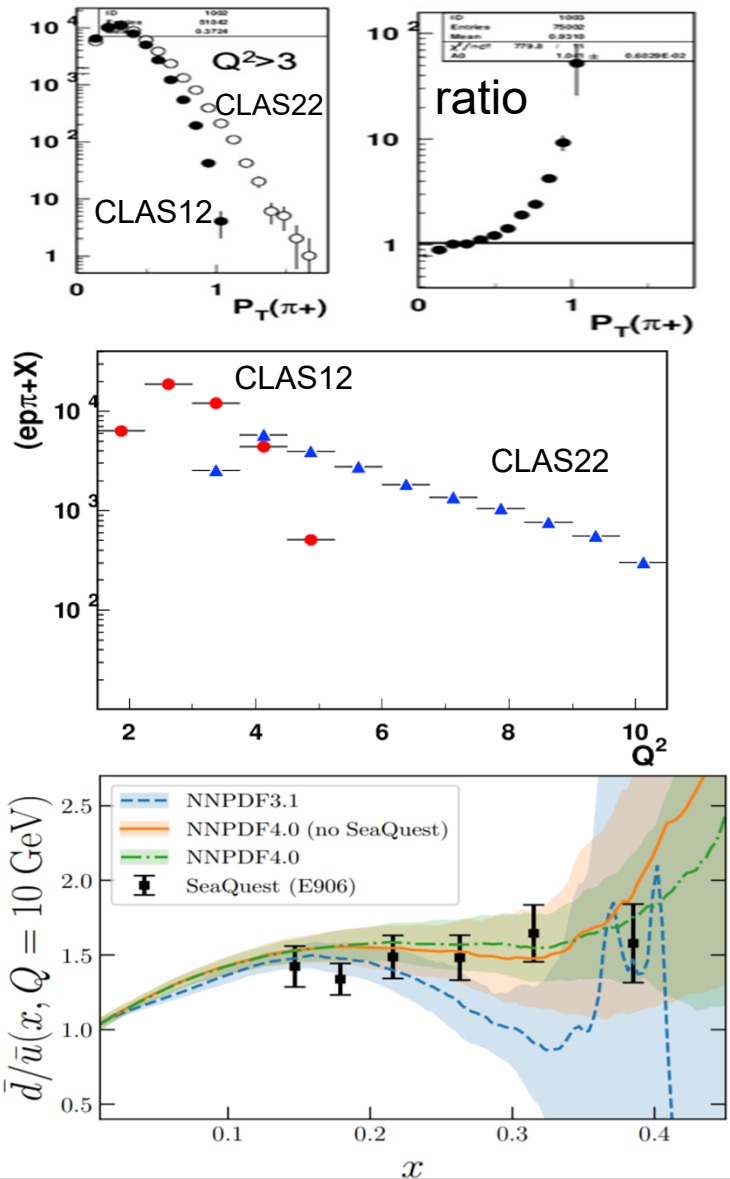
Relevance of RC in studies of complex azimuthal modulations

N.Sato (CPHI-2022)

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

$$\cdots l'^\mu$$

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!
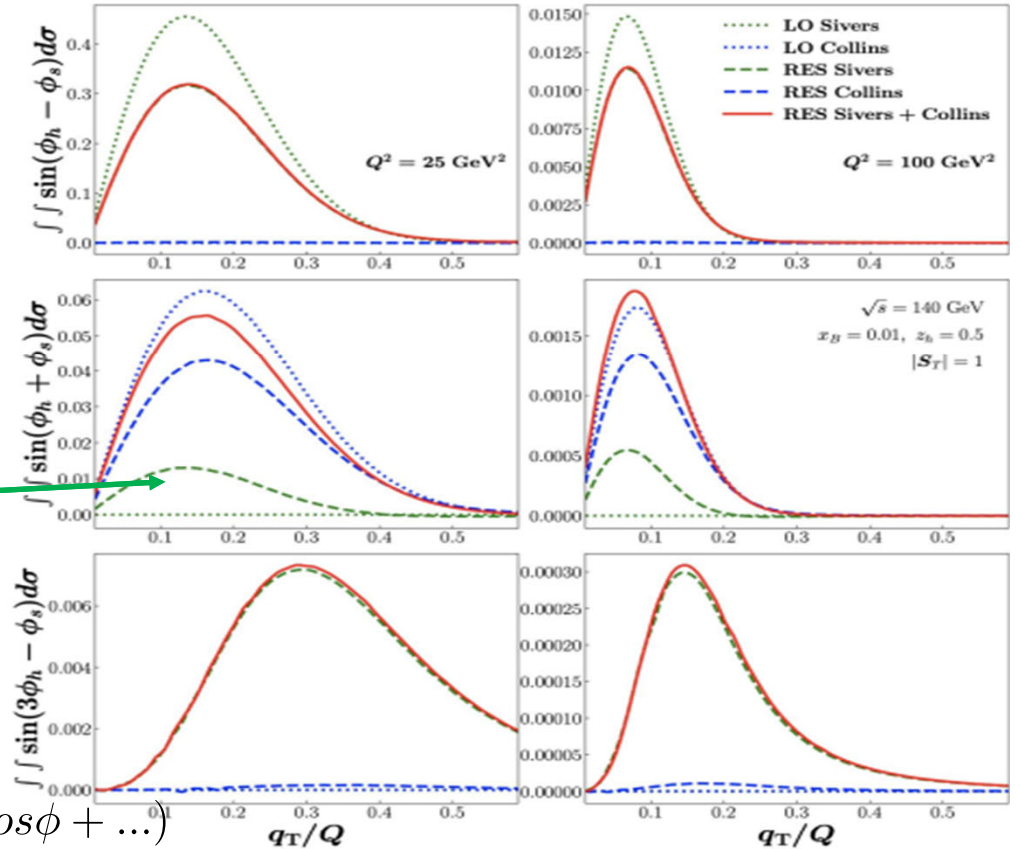
$$\int d\phi_h \, d\phi_S \, \sin(\phi_h-\phi_S)\sin(\hat\phi_h+\hat\phi_S)\neq 0$$

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

Overlap of modulations from RC (Sivers→Collins)

$$\sigma_{XY}^h(x,z,P_T)\to\sigma_{XY}^{B,h}(x,z,P_T)\times R(x,z,P_T,\phi_h)+\sigma_{XY}^{R,h}(\ldots).$$

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

From JLab to EIC: complementarity
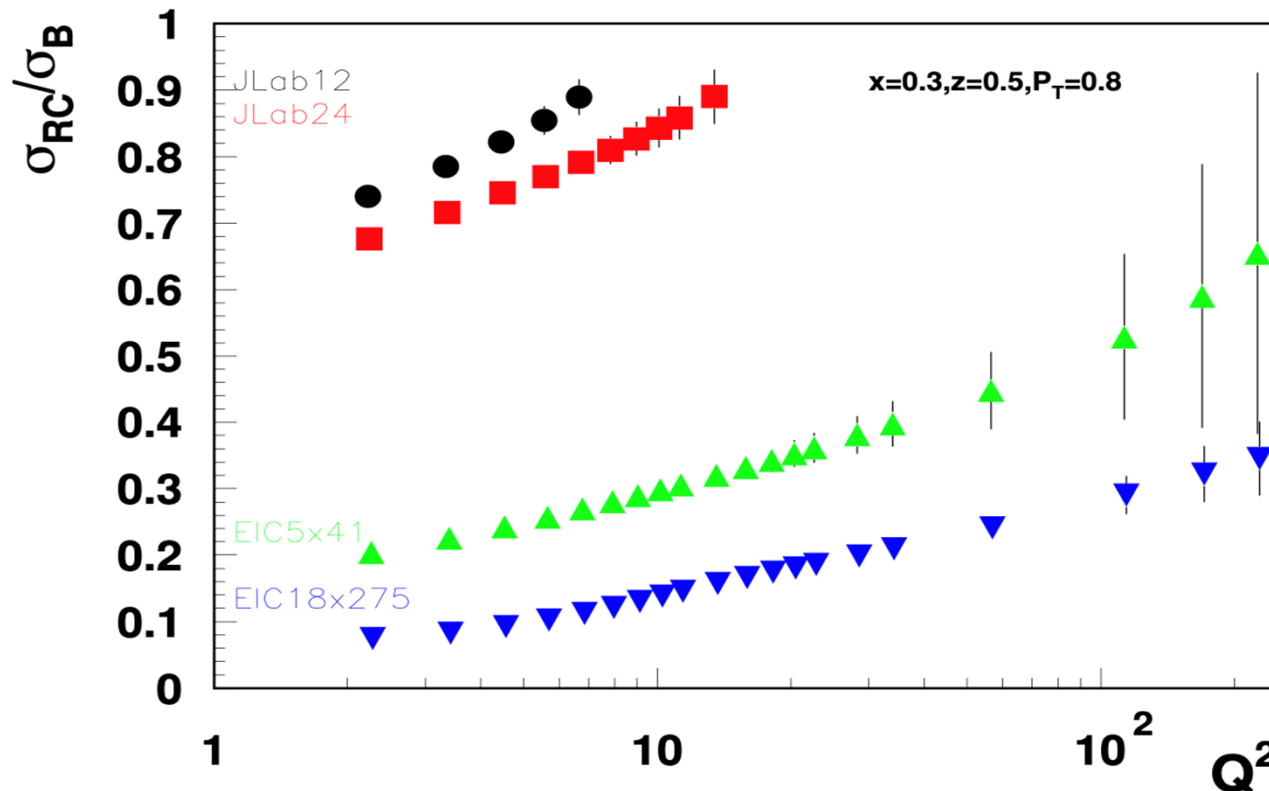
The ratio of radiative cross (σ_{RC}) section to Born (σ_B) in SIDIS

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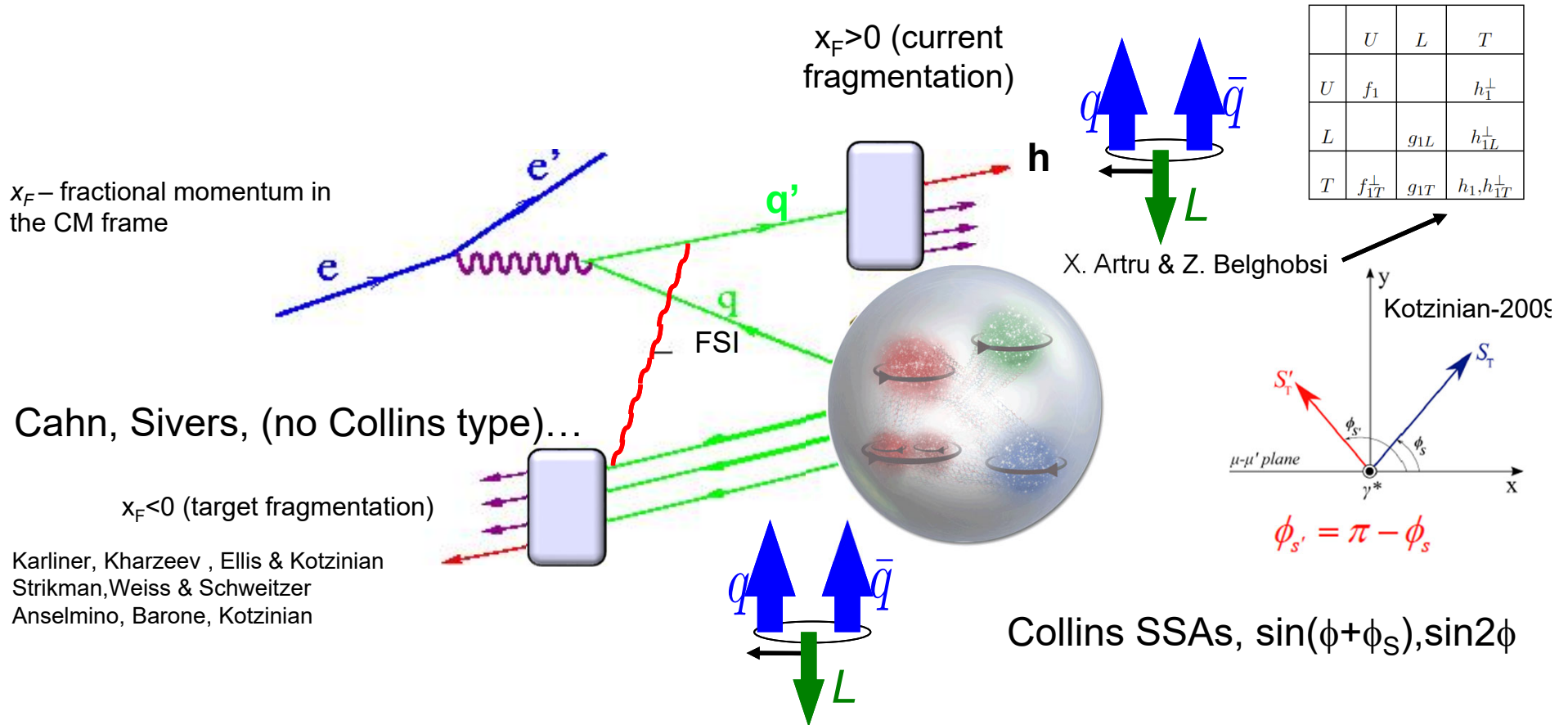*JHEP* 11 (2021) 157
Gaussian F_{UU} (ϕ_h=0)

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

x_F>0 (current fragmentation)

x_F – fractional momentum in the CM frame

h

X. Artru & Z. Belghobsi

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

Kotzinian-2009

$\phi_{s'} = \pi - \phi_s$

Cahn, Sivers, (no Collins type)…

$x_F<0$ (target fragmentation)

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

FSI

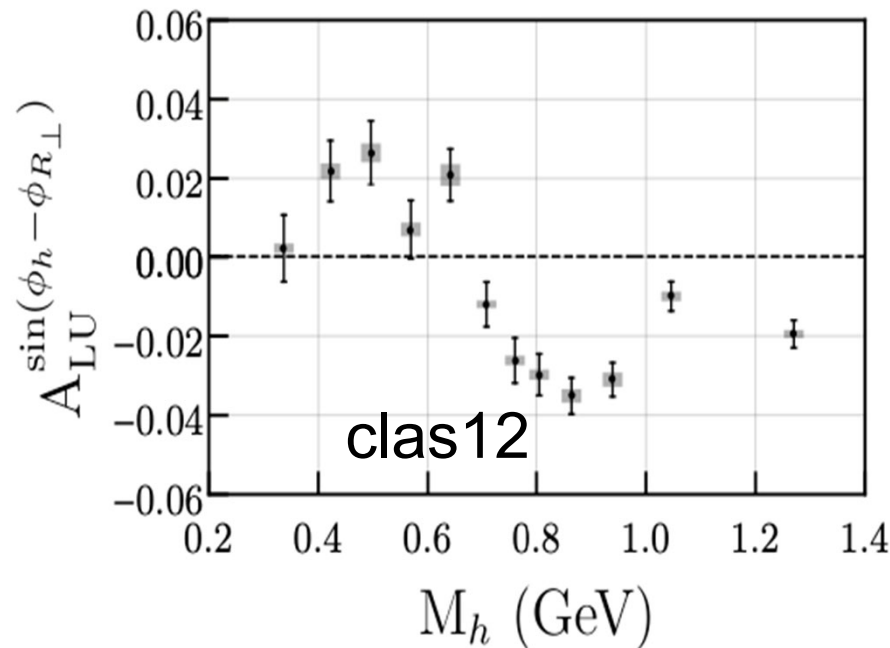Collins SSAs, $\sin(\phi+\phi_S)$, $\sin 2\phi$

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, QNP-2022, Sep 5

2 hadron correlations in CFR ep$\rightarrow$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

clas12

MC

ρ^0

Large M$\pi\pi$ pions
with P_T >0.5 GeV

ω

$\rho+$

string

- 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)
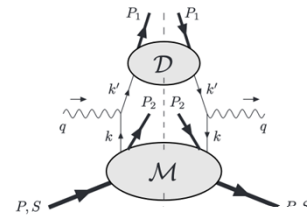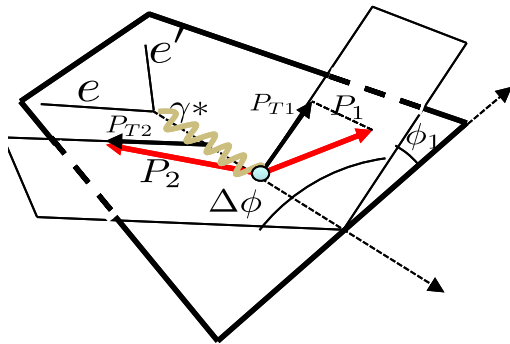- Direct pions dominate only at relatively high
  P_T, (P_T >0.6-0.7 GeV)

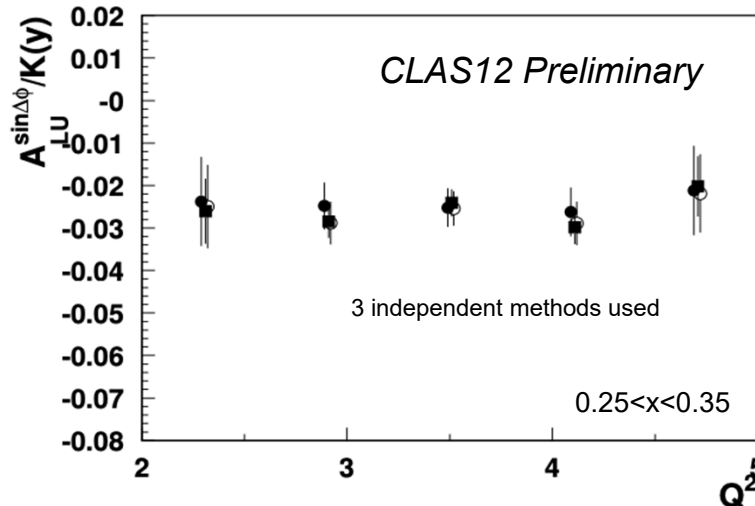
theory
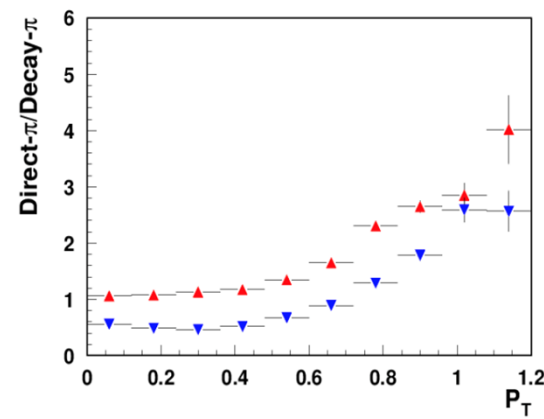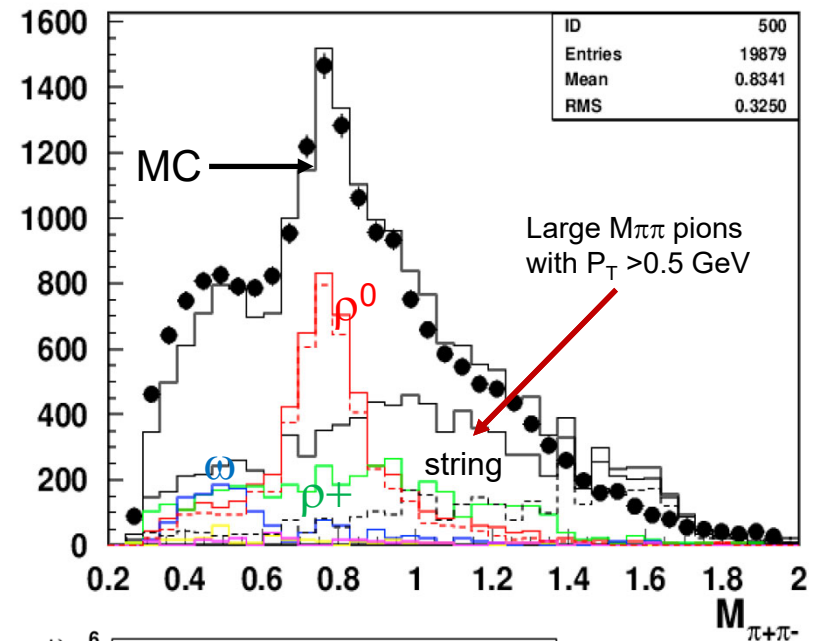
CFR/TFR correlations in 2 hadron production

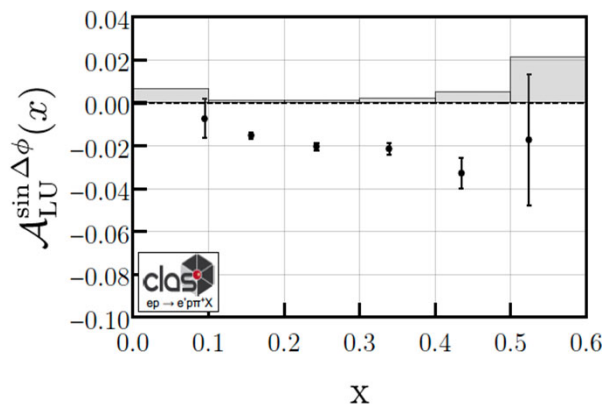M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)

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

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

CLAS12 Preliminary

3 independent methods used

$0.25 < x < 0.35$
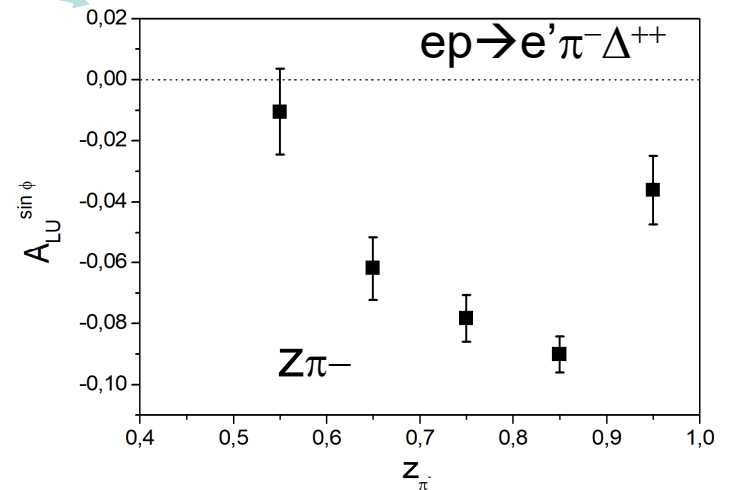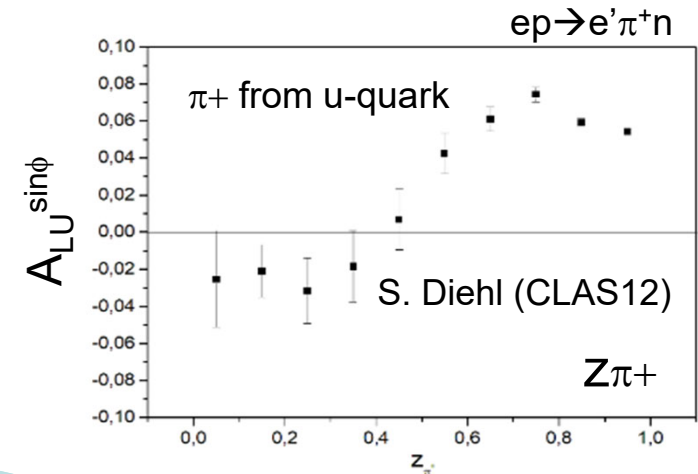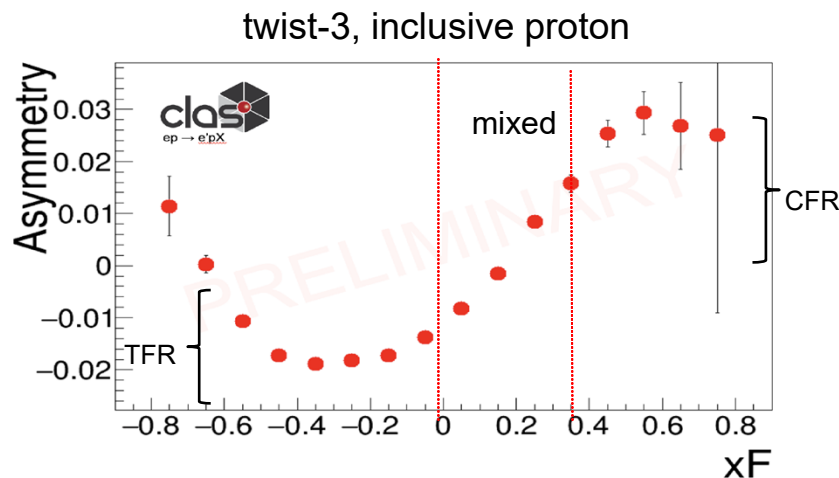
arXiv:2208.05086

- 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 $\Delta++$
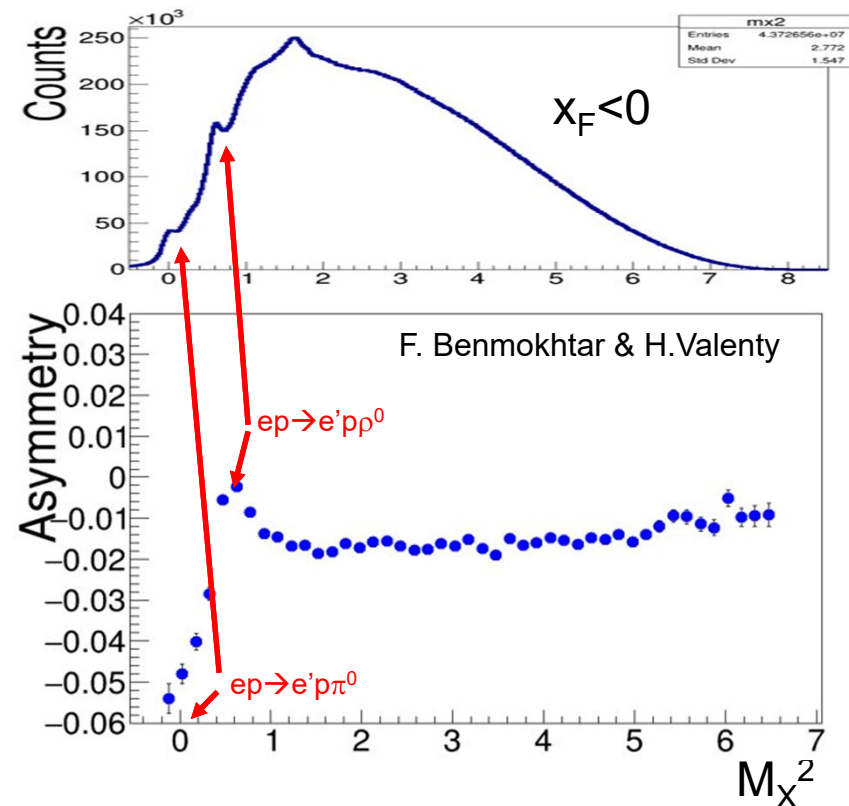

$ep \rightarrow e'\pi^+n$

$\pi+$ from u-quark

S. Diehl (CLAS12)

$Z\pi+$

twist-3, inclusive proton

mixed

CFR

TFR

$ep \rightarrow e'\pi^- \Delta^{++}$

$Z\pi-$

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

Dissecting the beam SSA (A_{LU}) in ep→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 Q2-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→e'pπ⁰ or e'pρ⁰)

- $M_X > 1.5$ no structures and SSA goes to plato (no single channel dominates it) decreasing as the correlations get suppressed with multiple hadron production
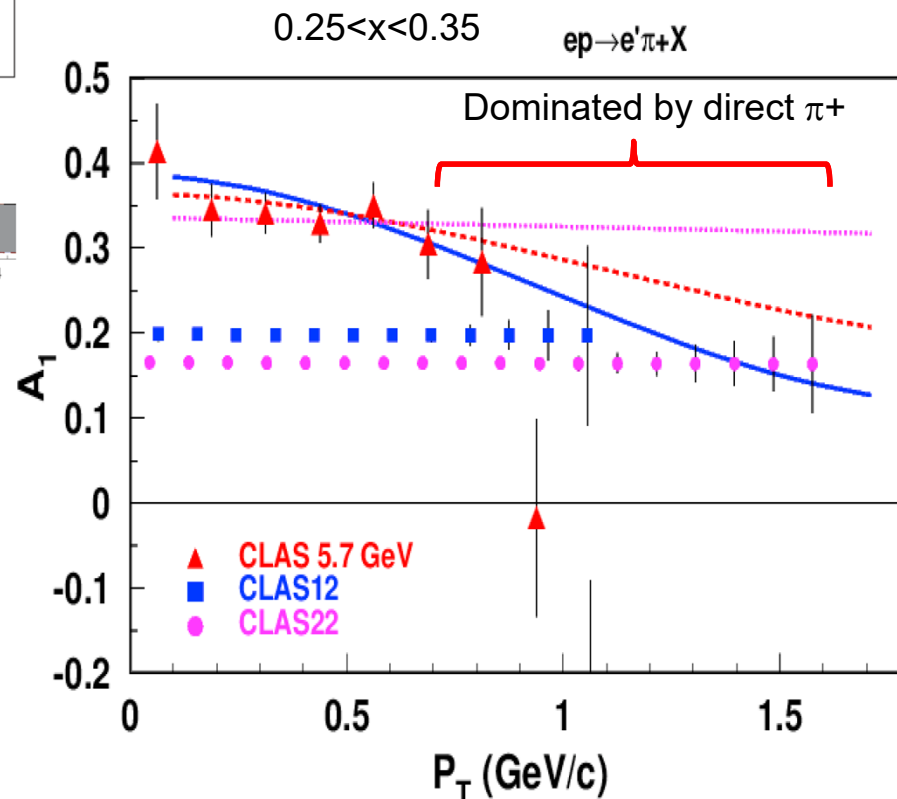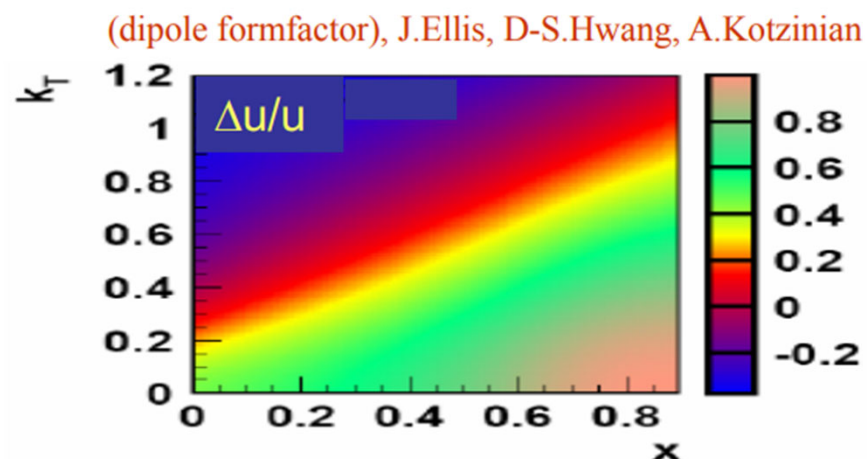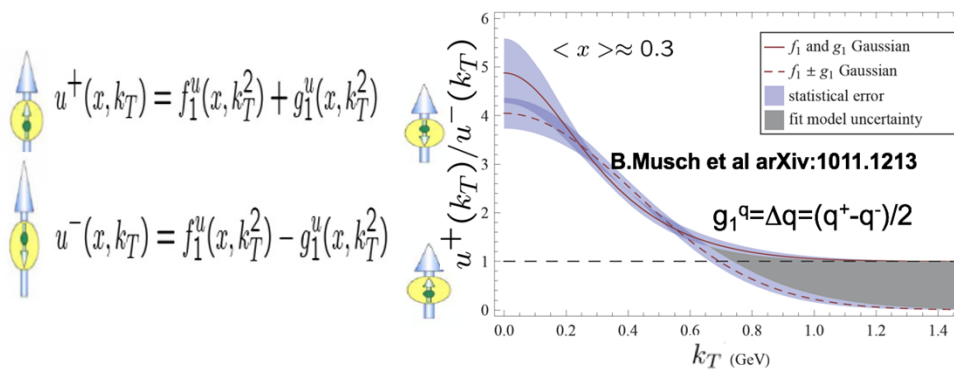
Significant beam spin SSAs observed for exclusive ep→e'pπ⁰ (~8%) and ep→e'pρ⁰ (~-20%)

What is SIDIS?

F. Benmokhtar & H.Valenty

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

$$u^+(x, k_T) = f_1^u(x, k_T^2) + g_1^u(x, k_T^2)$$

$$u^-(x, k_T) = f_1^u(x, k_T^2) - g_1^u(x, k_T^2)$$

$< x > \approx 0.3$

- f_1 and g_1 Gaussian
- $f_1 \pm g_1$ Gaussian
- statistical error
- fit model uncertainty

B.Musch et al arXiv:1011.1213

$g_1^q = \Delta q = (q^+ - q^-)/2$

$u^+(k_T)/u^-(k_T)$

k_T (GeV)

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

$\Delta u/u$

$0.25 < x < 0.35$ $ep \rightarrow e'\pi^+ X$

Dominated by direct π+

A_1

▲ CLAS 5.7 GeV
■ CLAS12
● CLAS22

P_T (GeV/c)

- 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

CLAS12 at 22 GeV with longitudinally polarized target

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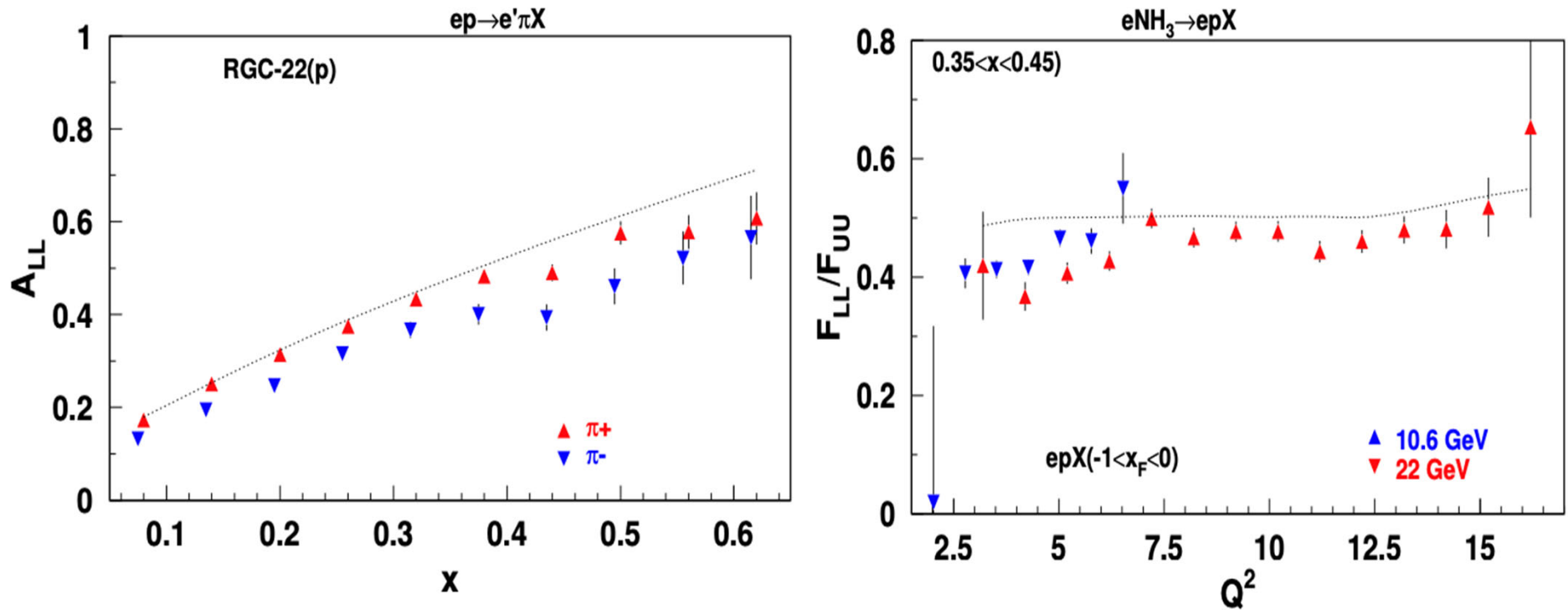
- Studies of evolution of observed double spin asymmetries will be a critical task in validating the QCD predictions $g_1(x,k_T)$-studies CLAS12
- Asymmetries measured with input polarized and unpolarized PDFs, can be used to test the flavor decomposition capabilities
- Kinematical correlations, even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

Measurements of Collins-Soper kernel

Validation of the TMD factorization based framework:Collins-Soper kenel

TMD factorization predicts a very specific pattern for cross-section

A. Vladimirov

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

CS-kernel most fundamental property

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

Making ratios of <u>Fourier transforms</u> 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

Extracting CS-kernel from 2 slices in Q (Q_1 and Q_2)

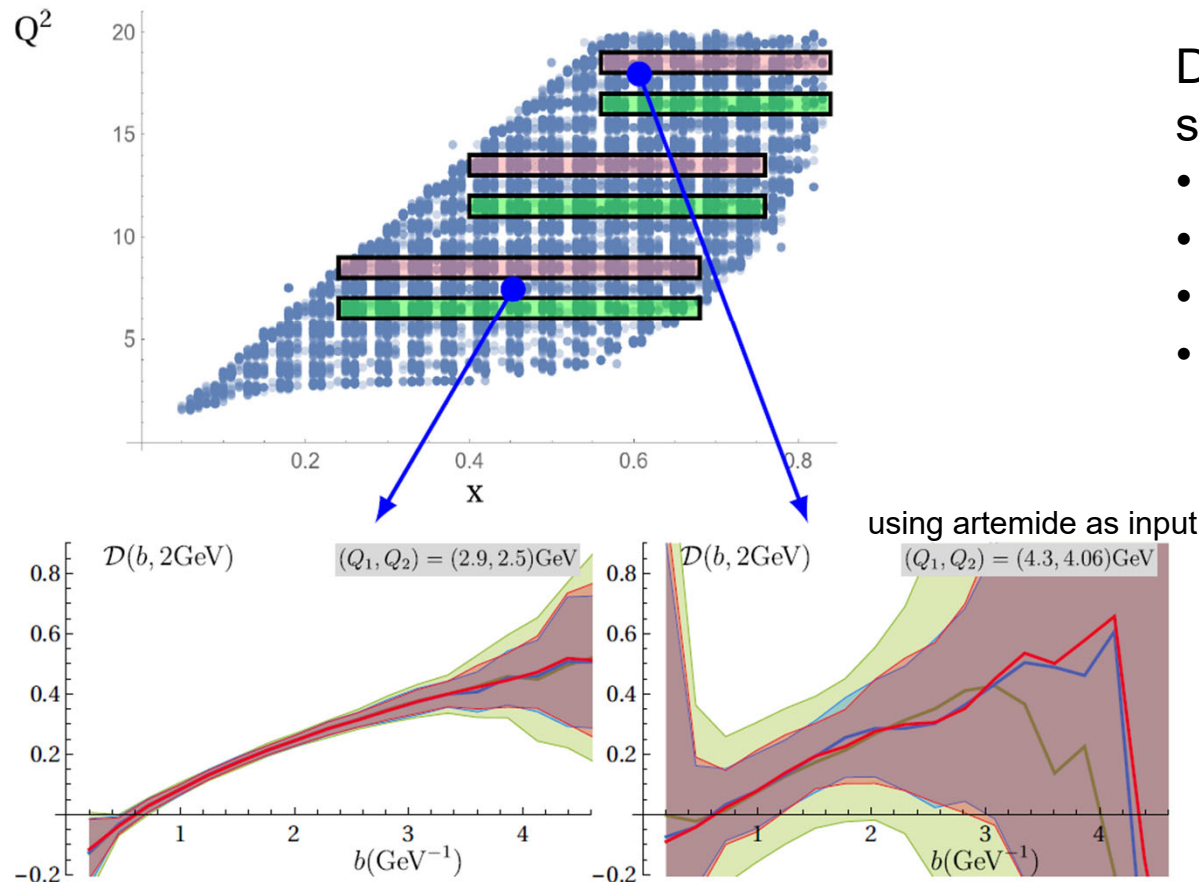[A.B.Martinez, A.Vladimirov, 2206.01105]

Extracting the CS-kernel from data

Is such study possible?
YES!

Estimation for the JLab22

A. Vladimirov (Pohang-2022)

Different experiments most sensitive to different ranges in b

- JLab ~1<b<4
- EIC ~0.5<b<1.2
- LHC b<0.5
- COMPASS overlaps

using artemide as input

Better control over systematics requires thin slices in Q^2, and good resolutions
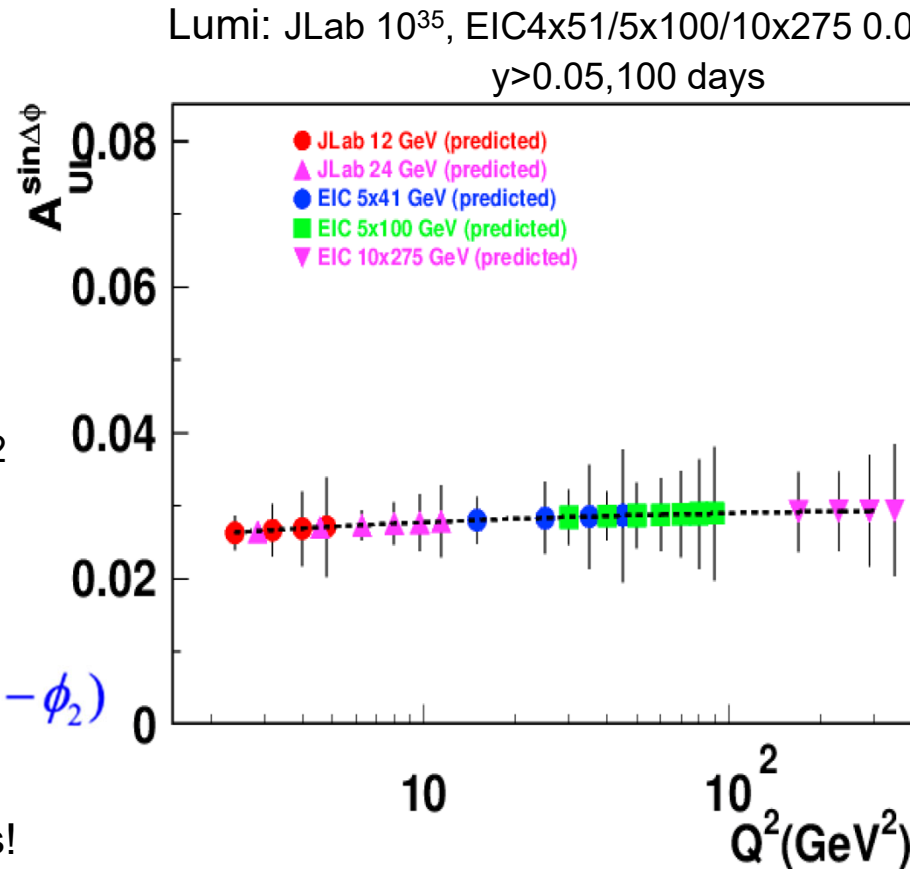
B2B correlations with longitudinally polarized target

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

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^{34})
y>0.05,100 days

- JLab 12 GeV (predicted)
- JLab 24 GeV (predicted)
- EIC 5x41 GeV (predicted)
- EIC 5x100 GeV (predicted)
- EIC 10x275 GeV (predicted)

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

Summary

- 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 <u>evolution properties and transverse momentum dependences</u> 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

Support slides…

Jefferson Lab

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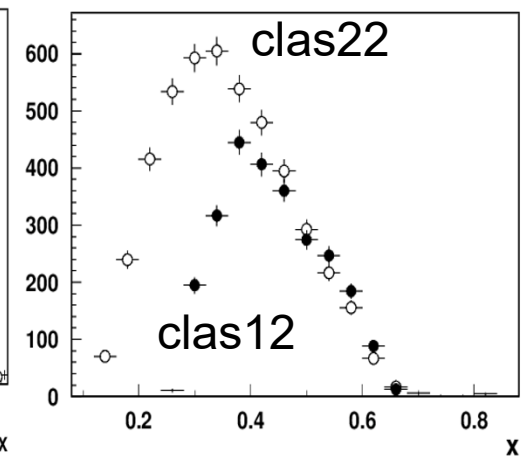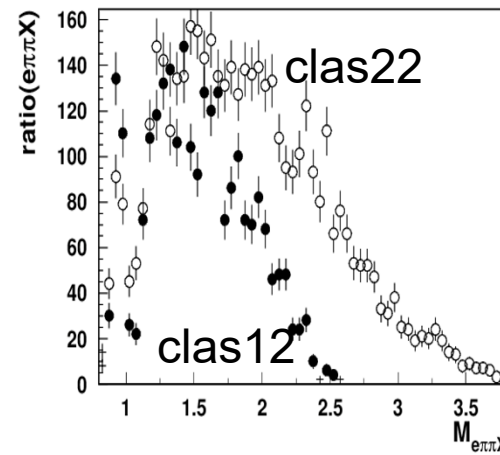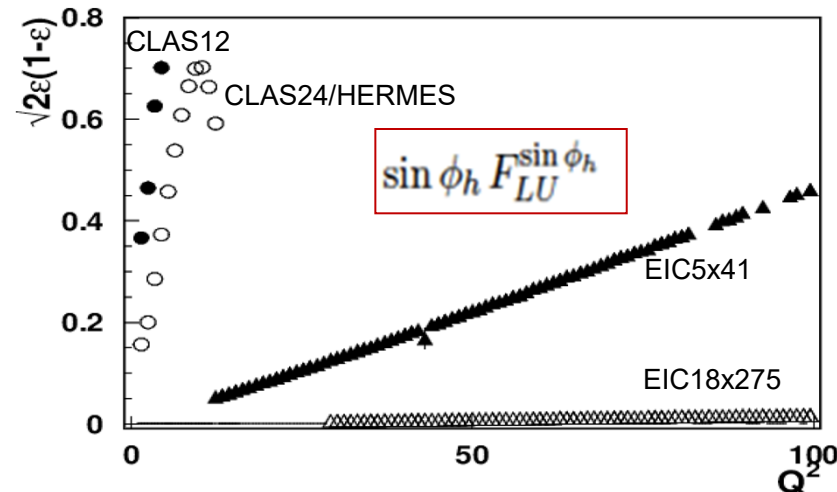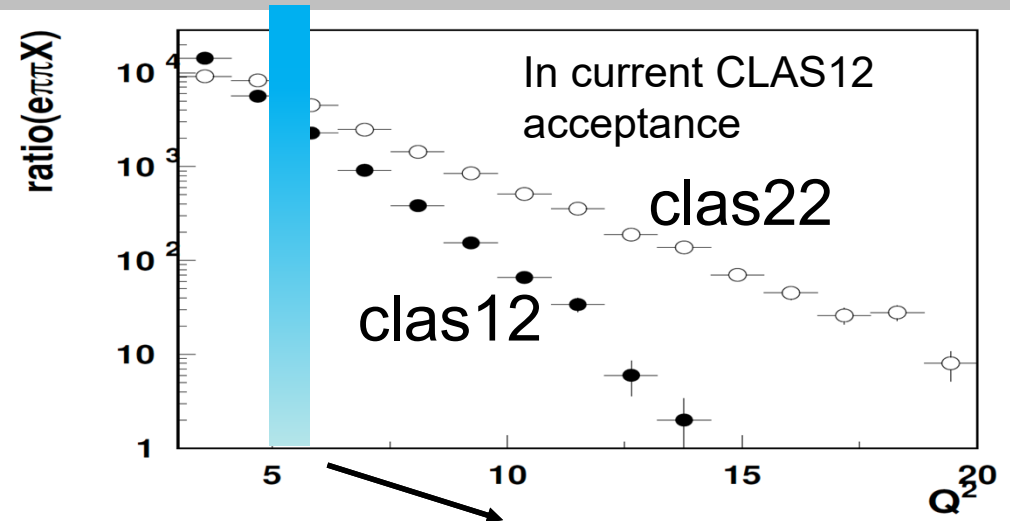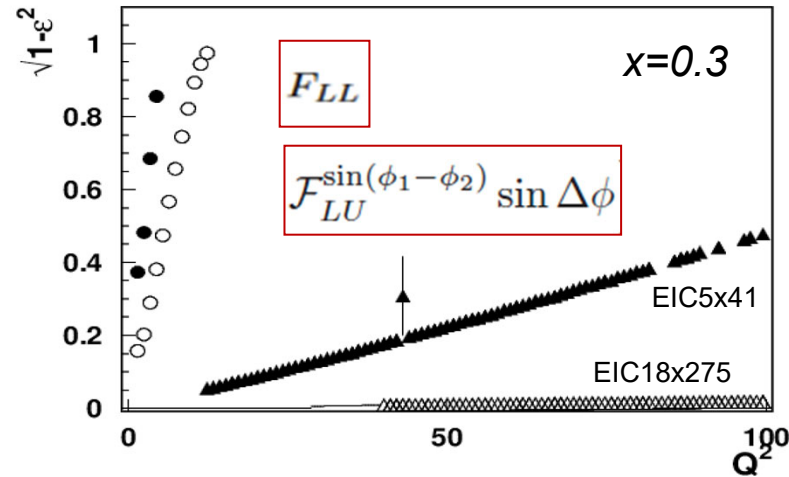
- Fixed target experiments are sensitive to all SSAs
- Higher energy opens up the phase space allowing access to, sea and large Q^2
- Measurements of beam SSAs (+some others) at large x, will be challenging at EIC

$F_{UU,L}$ 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
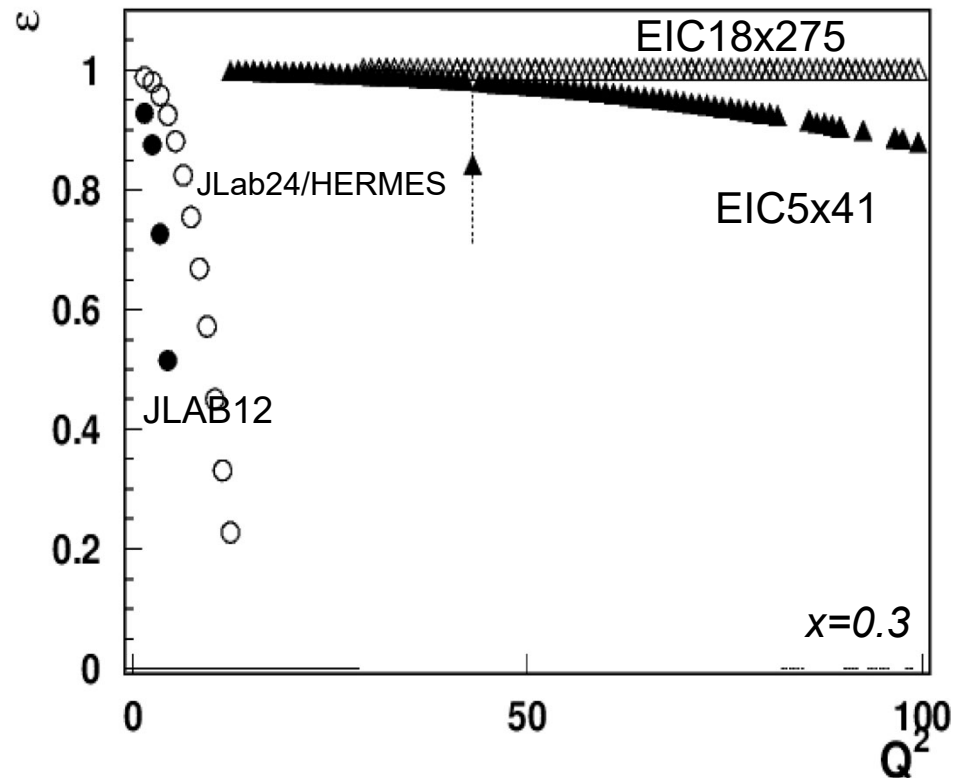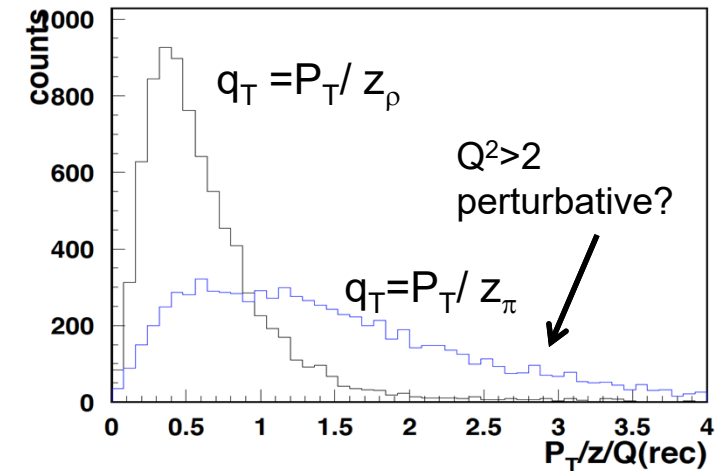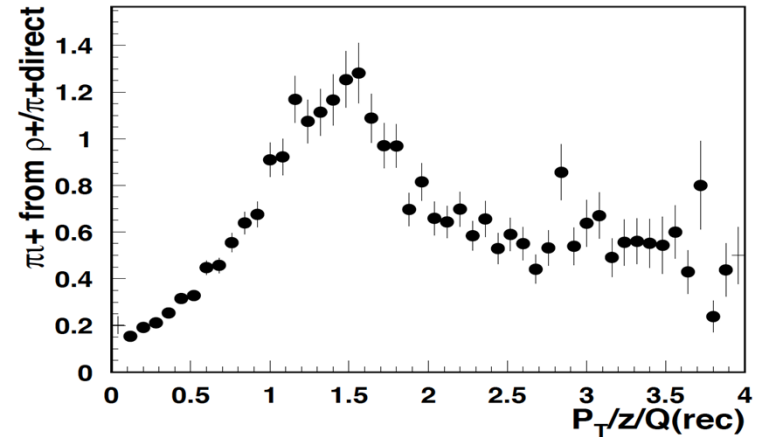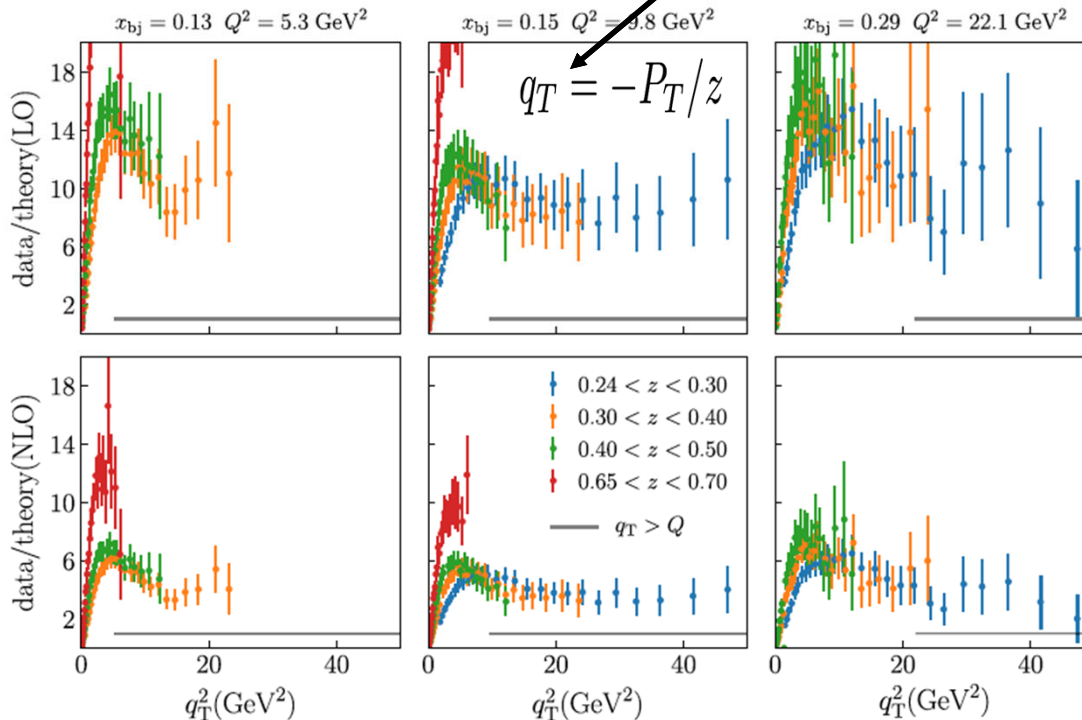

$F_{UU,L}$ kinematically enhanced, but requires a reasonable range and resolutions to be separated from the $F_{UU,T}$

Does it matter if the pion comes from correlated pairs?

$$F_{XY}^h(x, z, P_T, Q^2) \propto \sum H^q \times f^q(x, k_T, ..) \otimes D^{q \to h}(z, p_T, ..) + Y(Q^2, P_T) + \mathcal{O}(M/Q)$$

$$\int d^2 \vec{k}_T d^2 \vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

quark transverse momentum

$$q_T = -P_T/z$$

$q_T = P_T/z_\rho$

$Q^2 > 2$ perturbative?

$q_T = P_T/z_\pi$

The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.
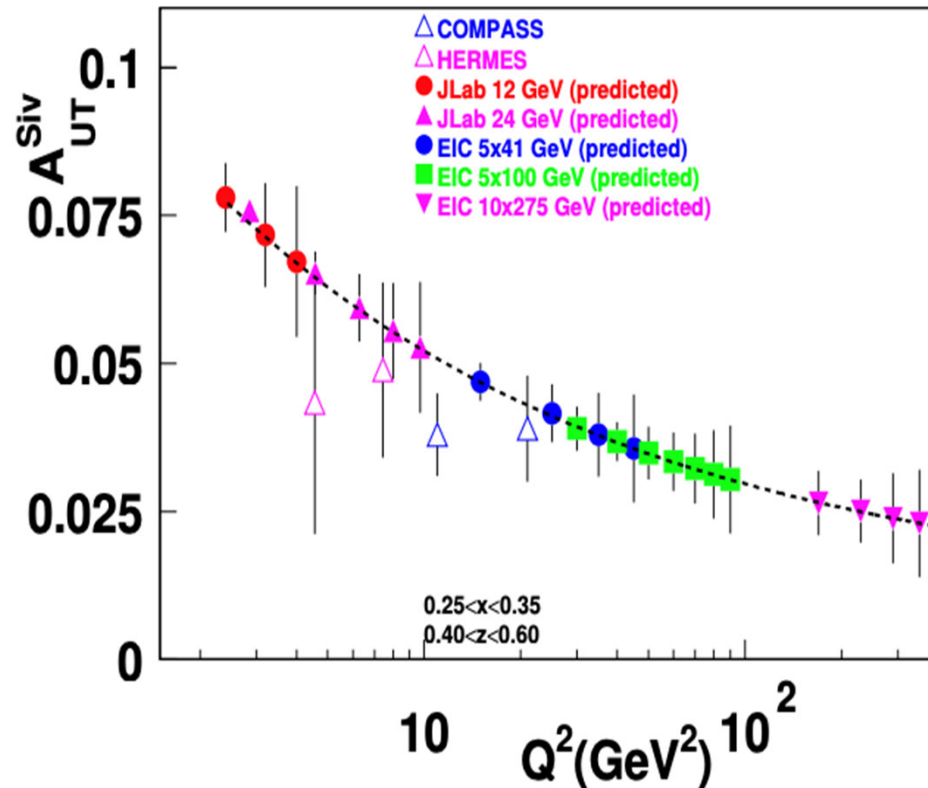
Gonzalez-Hernandez et al, PRD 98, 114005 (2018)

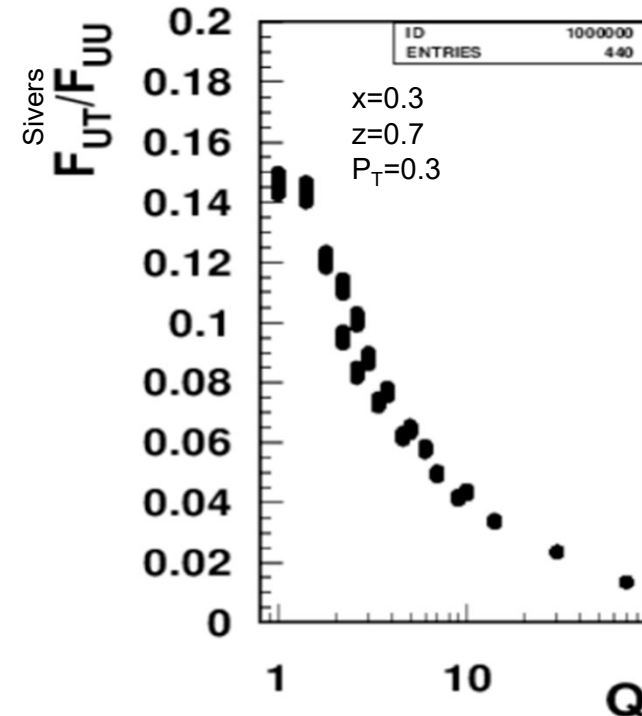understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of q_T distributions

Contributions for 3D structure studies: Sivers

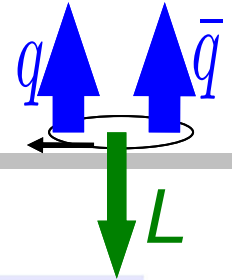y>0.05,100 days (corrected for EIC official lumi)

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

3D PDFs: Common features

q $\bar{q}$

L

Rodini & Vladimirov, arXiv:2204.03856, J. O. Gonzalez-Hernandez, T. Rogers, N. Sato, arXiv:2205.0575,…

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
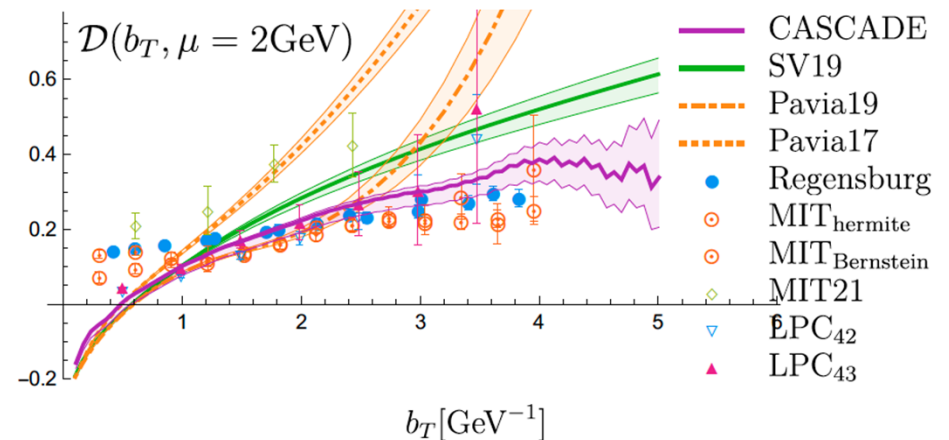perturbative
known at N³LO

CS kernel
nonperturbative

TMD distribution
any tw2
many **tw3**

Includes "e"

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)

$\mathcal{D}(b_T, \mu = 2\text{GeV})$

- CASCADE
- SV19
- Pavia19
- Pavia17
- Regensburg
- MIT_hermite
- MIT_Bernstein
- MIT21
- LPC₄₂
- LPC₄₃

$b_T[\text{GeV}^{-1}]$

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

Direct extraction of Collins-Soper kernel and direct tests of TMD factorization

Link to the zoom video of A. Vladimirovs presentation (scroll to 02:10:35)

https://us06web.zoom.us/rec/share/QB62hDl-l4ol6D0yvVBVEgocvg7ZAYd7KVvXl9fESE9raCDf6ZEBCKgXWPqb6lgF.-TYPr1-88YdtfyoO

Calculable with perturbation theory

$$q_T = \frac{k_\perp}{z}$$

$$\frac{d\sigma}{dQ^2 dx dz dk_\perp^2} = \frac{\pi \alpha_{\rm em}^2(Q)}{Q^4} \frac{y^2}{1-\varepsilon} W(Q, x, z, k_\perp)$$

$$\int_0^\infty \frac{b\,db}{(2\pi)^2} J_0\left(\frac{k_\perp b}{z}\right) R[b, Q \to \mu] |C_V(Q)|^2 \sum_f e_f^2 f_1(x, b; \mu) d_1(z, b; \mu)$$

Evol.factor
our goal!

TMDs
trash

Building the new observable (need thin slice Q-bins and fine binning in q_T)

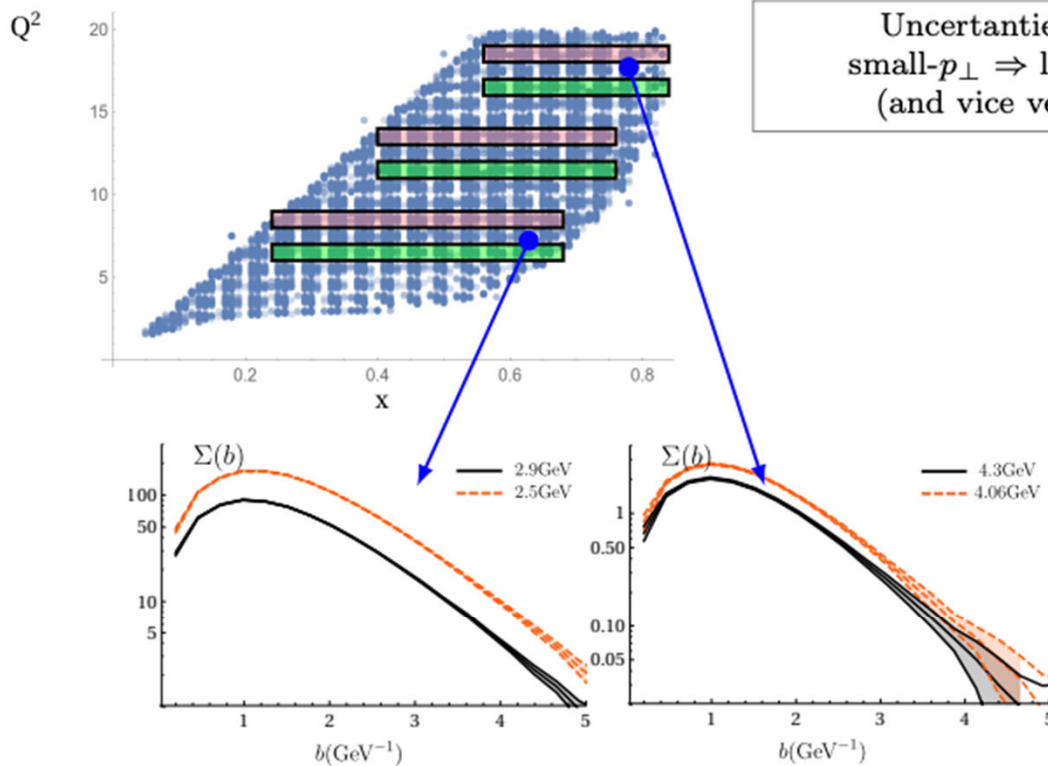$$\Sigma(Q, x, z, b) = \int dq_T \, q_T \, J_0(q_T b) \frac{d\sigma}{dQ^2 dx dz dk_\perp^2}$$

$$\frac{\Sigma(Q_1, x, z, b)}{\Sigma(Q_2, x, z, b)} = \left(\frac{Q_2}{Q_1}\right)^4 \frac{\alpha_{\rm em}^2 |C_V(Q_1)|^2}{\alpha_{\rm em}^2 |C_V(Q_2)|^2} \frac{R[b, Q_1 \to \mu] \sum_f f_1(x, b, \mu) d_1(x, b, \mu)}{R[b, Q_2 \to \mu] \sum_f f_1(x, b, \mu) d_1(x, b, \mu)}$$

$$R[b, Q_1 \to \mu] = \exp\left(2 \int_{P(Q_1 \to \mu)} \left(\gamma_F(\mu, \zeta) \frac{d\mu}{\mu} - \mathcal{D}(b, \mu) \frac{d\zeta}{\zeta}\right)\right)$$
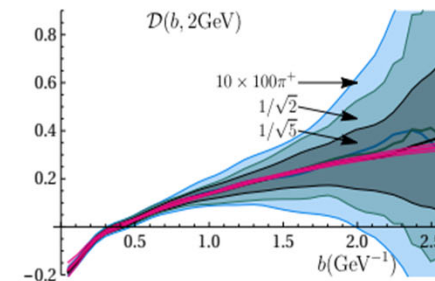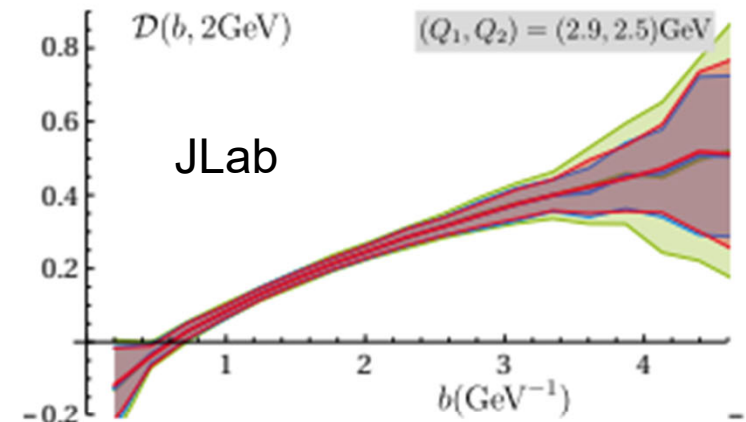
$$\mathcal{D}(b, \mu) = \frac{\ln\left(\frac{\Sigma(Q_1)}{\Sigma(Q_2)}\right) - \ln Z(Q_1, Q_2) - 2\Delta_R(Q_1, Q_2, \mu)}{4 \ln(Q_2/Q_1)} - 1$$

Understanding the TMD phenomenology

Link to the zoom video of A. Vladimirovs presentation (scroll to 01:45:06)

$$\frac{d\sigma}{dQ^2 dx dz dk_\perp^2} = \frac{\pi \alpha_{em}^2(Q)}{Q^4} \frac{y^2}{1-\varepsilon} W(Q, x, z, k_\perp)$$

$$\int_0^\infty \frac{b db}{(2\pi)^2} J_0\left(\frac{k_\perp b}{z}\right) R[b, Q \to \mu] |C_V(Q)|^2 \sum_f e_f^2 f_1(x, b; \mu) d_1(z, b; \mu)$$

Evol.factor
our goal!

TMDs
trash

$$\frac{d\sigma}{dp_T} = \sigma_0 \int \frac{d^2 b}{(2\pi)^2} e^{i(bp_T)} C\left(\frac{Q}{\mu}\right) F_1(x_1, b; \mu, \zeta) F_2(x_2, b; \mu, \zeta)$$

DY   SIDIS   SIA

$$q_T = \frac{k_\perp}{z}$$

Building the new observable

Main scales:
The invariant mass of photon: $|q^2| = Q^2$
Transverse component of photon momentum: q_T

$$\Sigma(Q, x, z, b) = \int dq_T q_T J_0(q_T b) \frac{d\sigma}{dQ^2 dx dz dk_\perp^2}$$

Extracting the CS kernel

How does it works? (JLab22)

Uncertanties at
small-$p_\perp$ $\Rightarrow$ large-b
(and vice versa)

Complementarity:
JLab access large b

JLab

EIC

Understanding the TMD phenomenology

Link to the zoom video of A. Vladimirov's presentation (scroll to 02:07:14)

https://us06web.zoom.us/rec/play/NEmkShSthea_M82Hhu3YjpQ1j-y7nRlEIpZ_L99SSohbKF3or67hnlMoyhz2gPSP69O1RKzB6IeZDBwl.Ezt5kHCV-nf4we6X?continueMode=true&_x_zm_rtaid=_GMibhnmSYmV4ZFDIoy9Jw.1658829231891.34bdec5186ba83efa29ff34c88de2e63&_x_zm_rhtaid=545
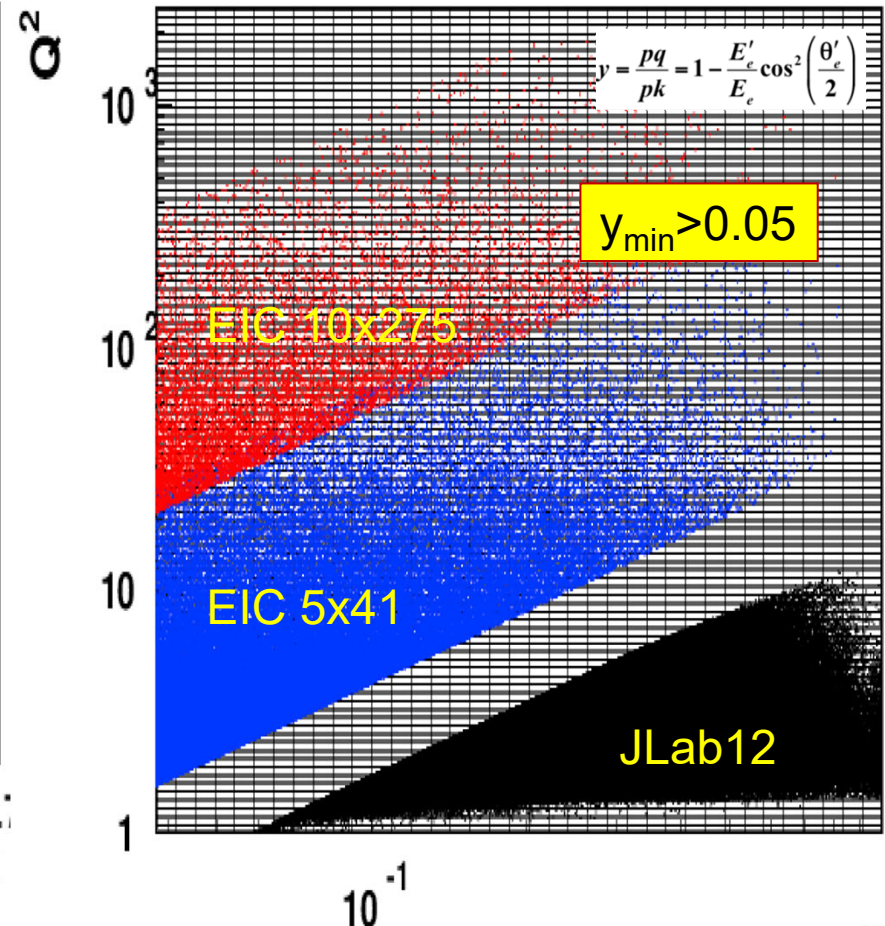
Impact on fragmentation function studies, preliminary, biased (JLab22-red, EIC-blue)

Jefferson Lab
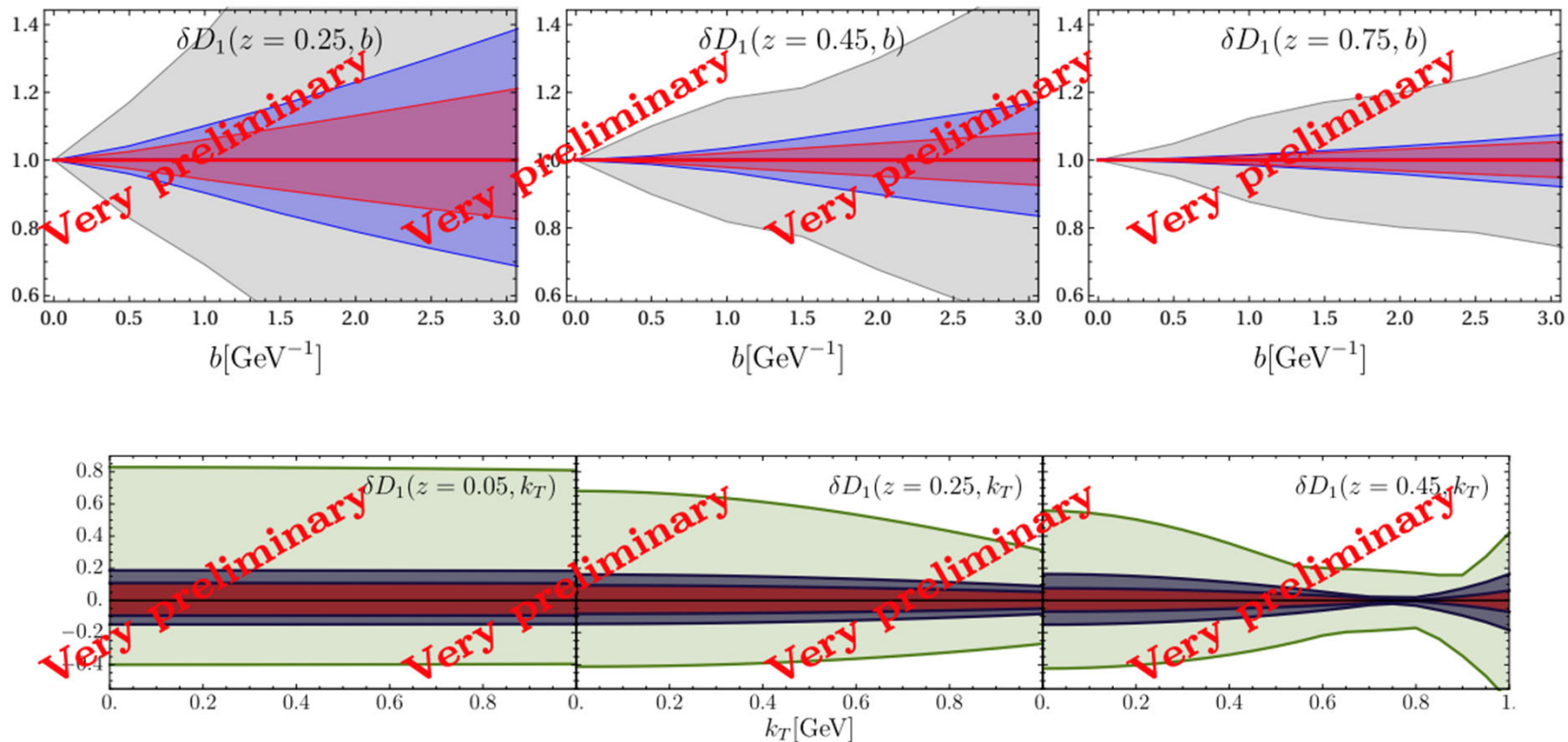
X vs Q² from JLab to EIC
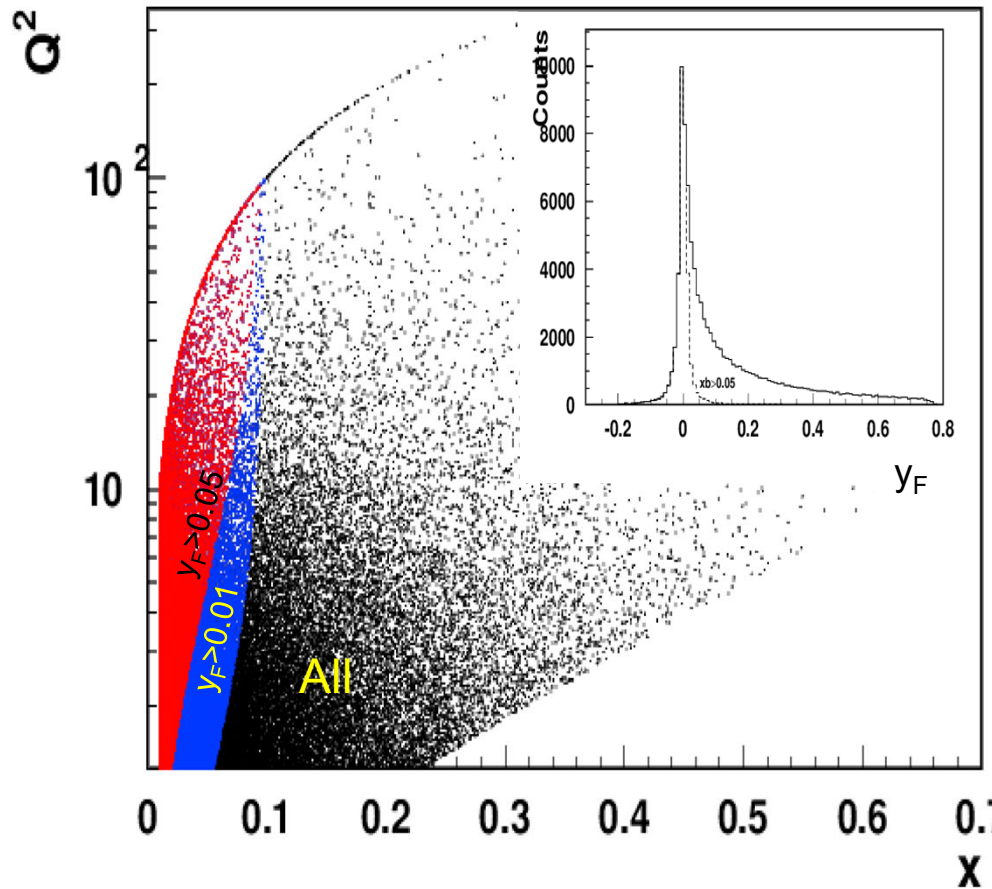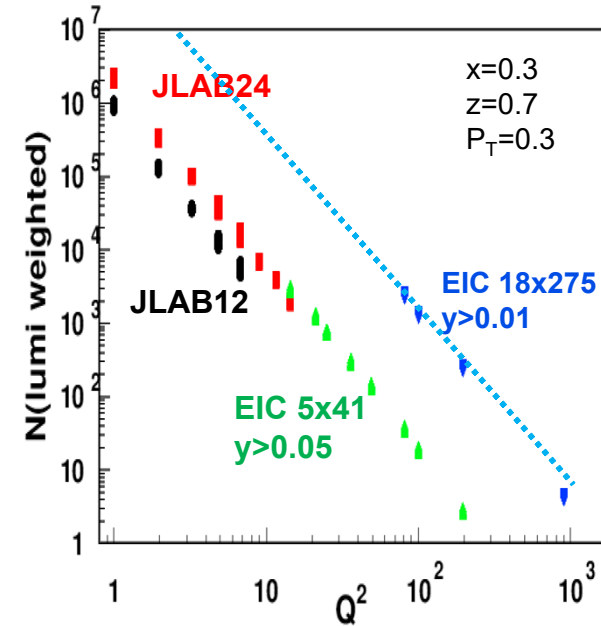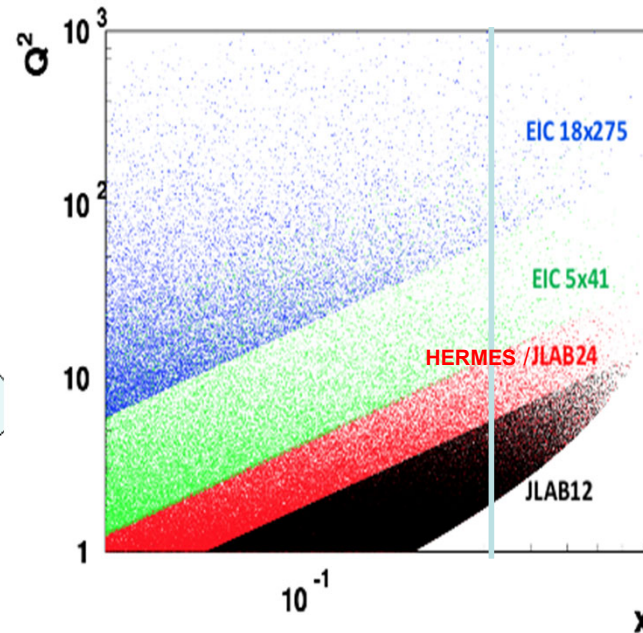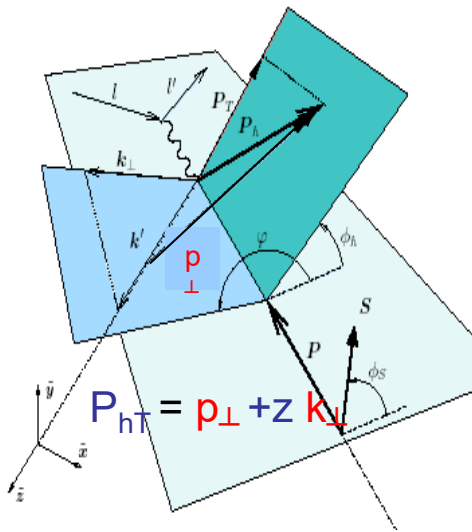

Large x events all in region of small $y_F = 1.0 - E'/E_{beam}$

Non overlapping ranges of EIC (machine dedicated to gluon studies) and JLab may be a problem for evolution studies, which are most critical for the 3D structure
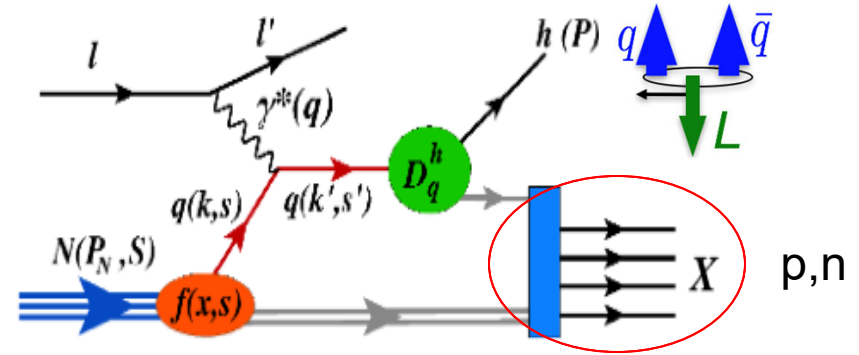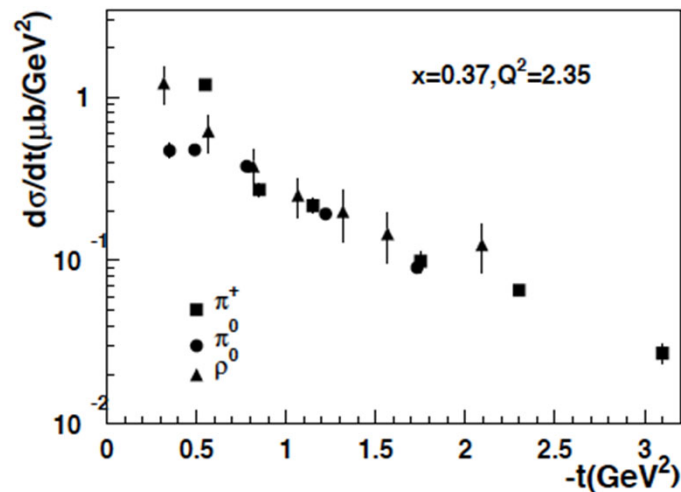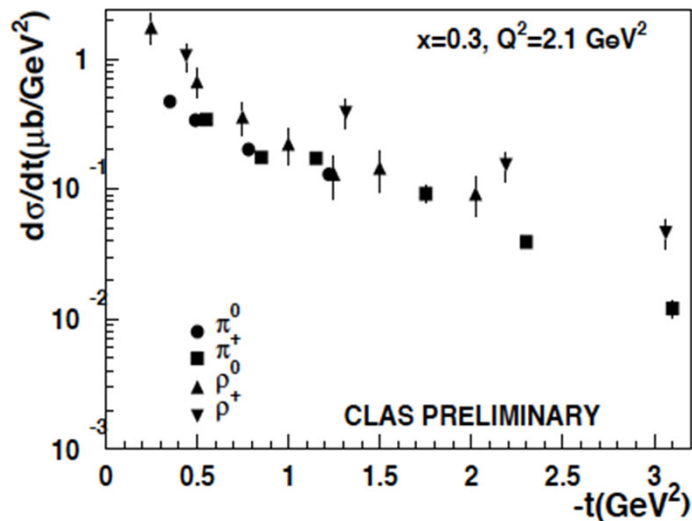
SIDIS kinematical coverage and observables

Crucial to evaluate counts in the fiducial region (resolutions, acceptance, RC,…)

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

- Higher energies open the phase space for large transverse momenta and Q^2, and lower x, but move events to lower y
- Wider range in Q^2- allows evolution studies of 3D PDFs
  - Higher statistics, better resolutions vs wider range in EIC (complementary)

Exclusive π/ρ production at large t

x=0.3, Q^2=2.1 GeV^2

$d\sigma/dt(\mu b/GeV^2)$

-t(GeV^2)

- π^0
- π^+
- ρ^0
- ρ^+

CLAS PRELIMINARY

x=0.37,Q^2=2.35

$d\sigma/dt(\mu b/GeV^2)$

-t(GeV^2)

- π^+
- π^0
- ρ^0

l l' h (P) q $\bar{q}$

$\gamma^*(q)$

D_q^h L

$q(k,s)$ $q(k',s')$

$N(P_N,S)$

$f(x,s)$ X p,n

Implications

- x-section of measured exclusive process at large t exhibit similar pattern
- $\rho+>\rho^0$ →Diffractive production suppressed
- at large t production mechanism most likely is similar to SIDIS
- Slightly higher rho x-sections indicate the fraction of SIDIS pions from VM > 60%
- consistent with LUND-MC in fraction of pions from rho
- ……...