3D Structure of the Nucleon: from JLab12 to JLab24

Aug 29 – 31, 2022
CERN

IWHSS-2022

International Workshop on Hadron Structure and Spectroscopy - 2022

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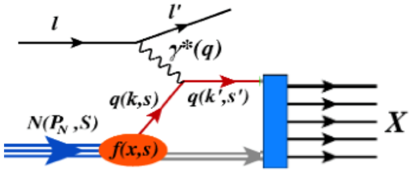
Understanding the QCD: from observables to QCD dynamics
- Projections as motivation for future studies
- Extending the phase space in P_T, Q^2 and x
- Studies of evolution properties
- Future studies of 3D

Summary

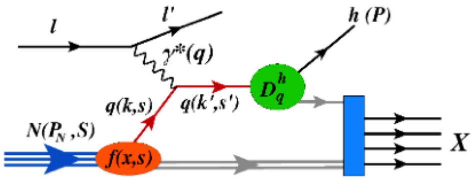
QCD: from testing to understanding

0h DIS

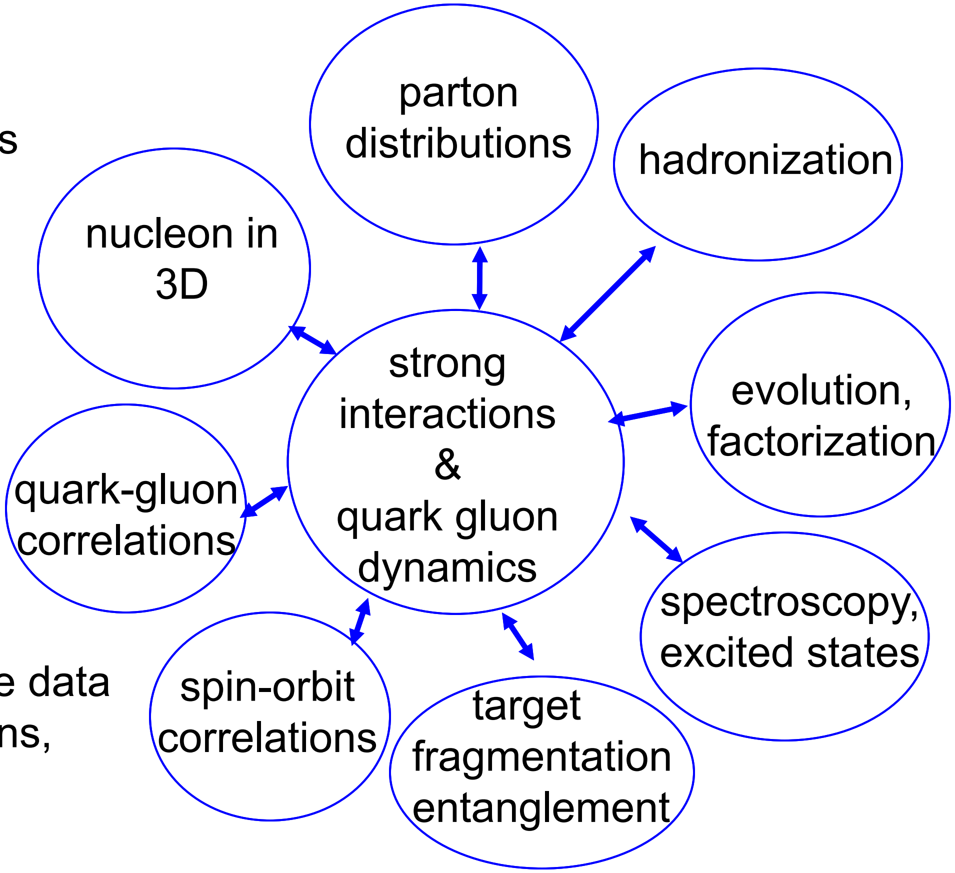


Testing stage:
pQCD predictions, observables in the kinematics where theory predictions are easier to get (higher energies, 1D picture, leading twist, IMF)

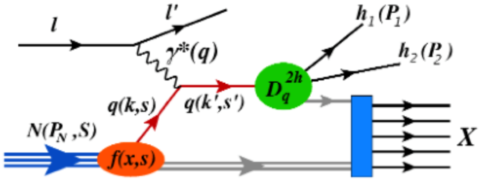
1h SIDIS/DVMP



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

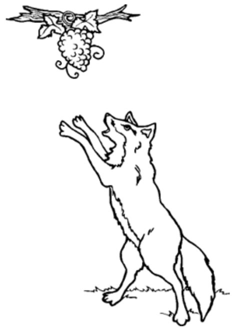


production in SIDIS provides access to correlations inaccessible in simple SIDIS (dihadron fragmentation, correlations of target and current regions, entanglement....)

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

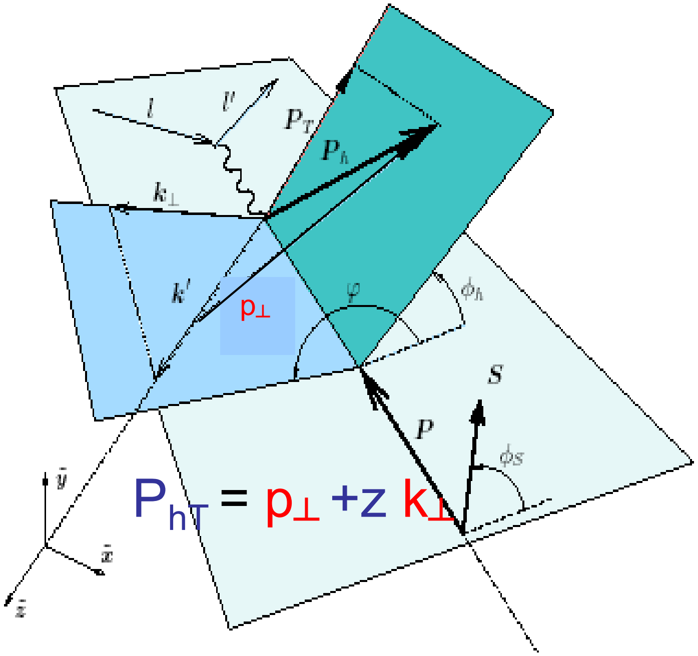
3)Identify the measurements with 22 GeV that can set the bridge between JLab12 and EIC (complementarity)

- Produce sets of event for relevant observables (SIDIS, DVCS, Large x,….) and process them using existing detector reconstructuion 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,

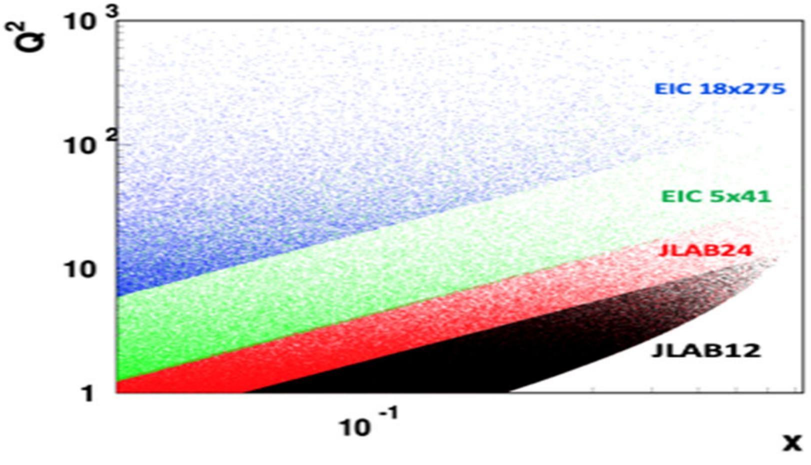
- Making the case it will be relevant in future

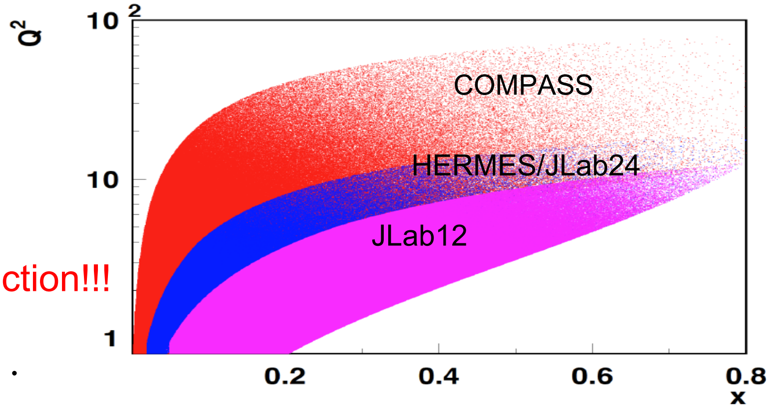
SIDIS kinematical coverage and observables



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

EIC

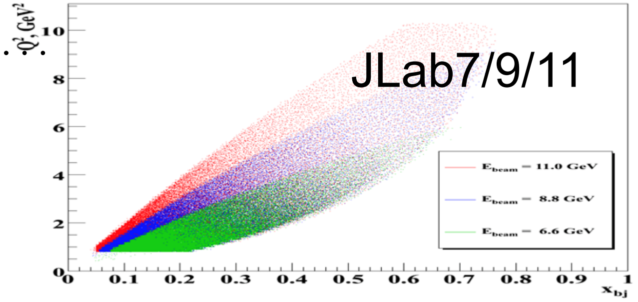




SIDIS experiments measure azimuthal dependence of the cross section!!!

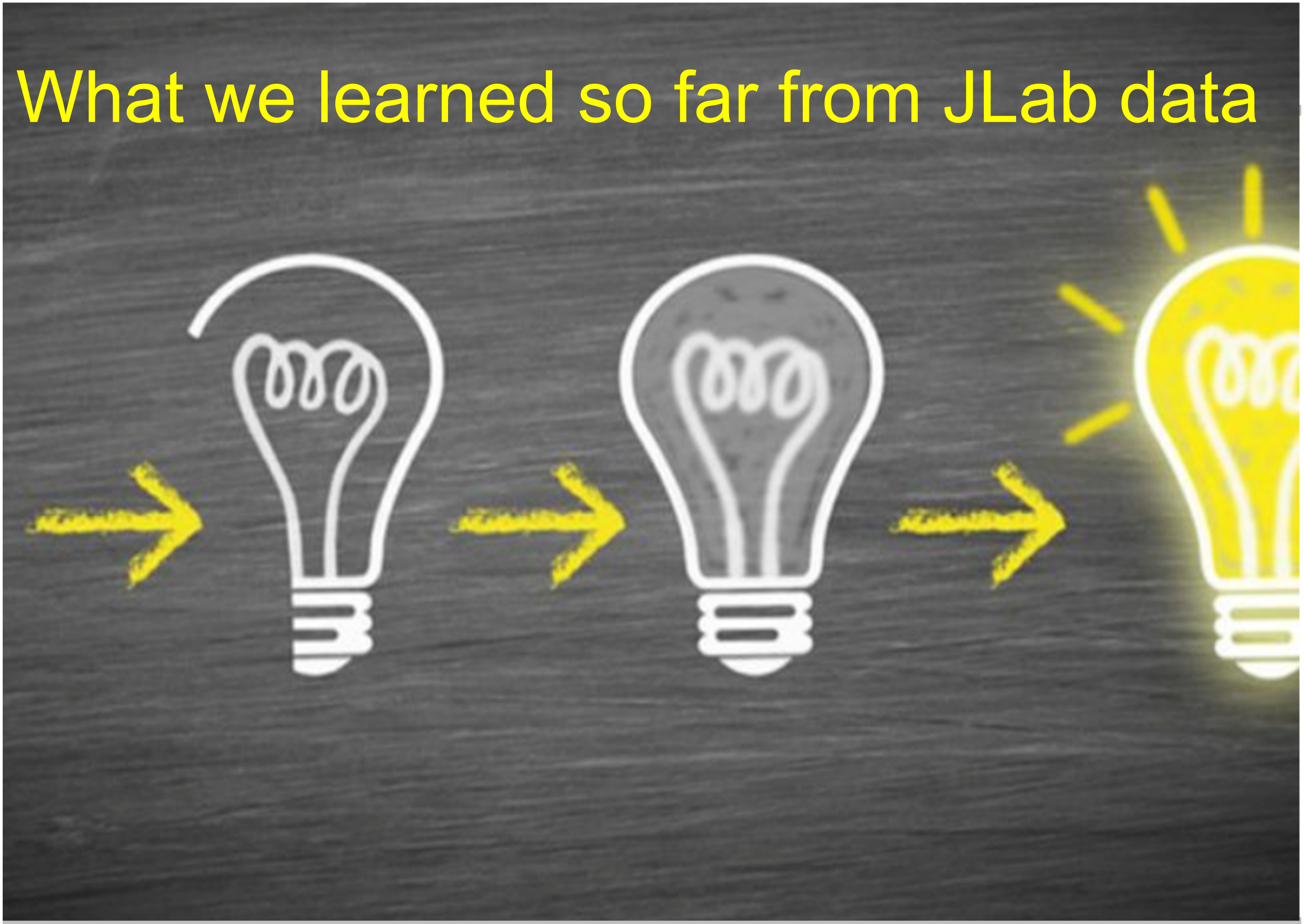
$$\sigma \propto F_{UU} + P_b\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi + P_t\epsilon F_{UL}^{\sin 2\phi}\sin 2\phi + \dots$$

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



- 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,ϕ)

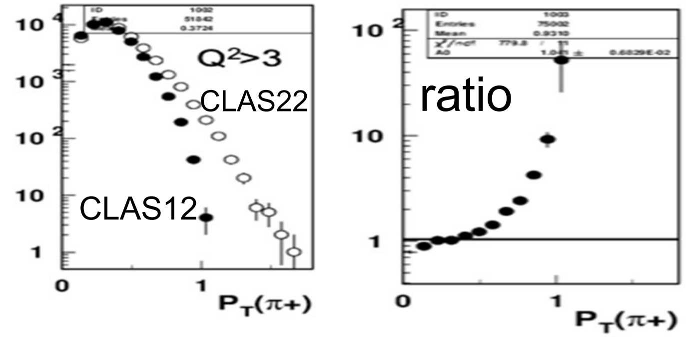
  Collinear SIDIS, is just the proper integration, over P_T,ϕ

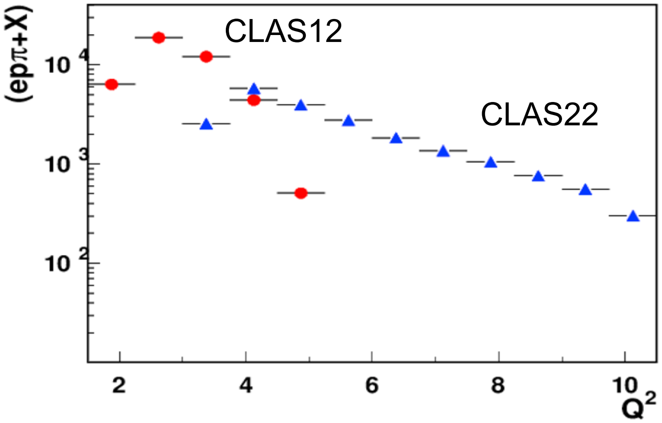
- SIDIS observations relevant for interpretations of experimental results:
  1. Understanding the kinematic domain where non-perturbative effects of interest are significant (ex. x,P_T-range)
  2. Understanding of P_T-dependences of observables in the full range of P_T dominated by non-perturbative physics 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

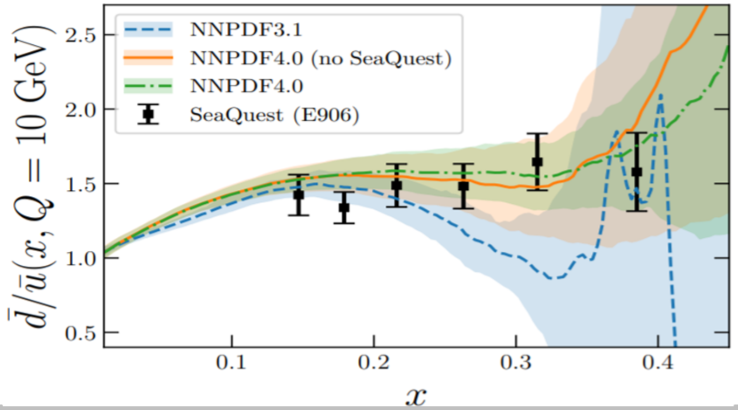
Opportunities with 20+ GeV

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

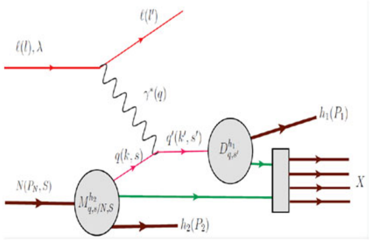




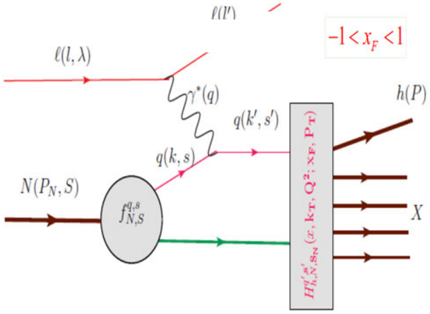


MC simulations: Why LUND works?

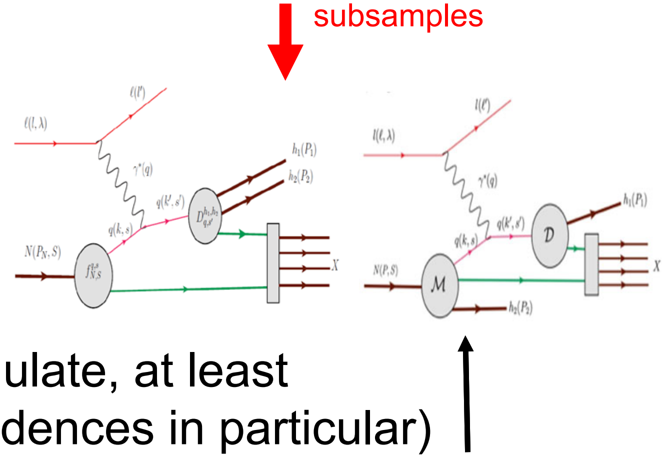
- A single-hadron MC with the SIDIS cross-section where widths of k_T-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.



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 a 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)

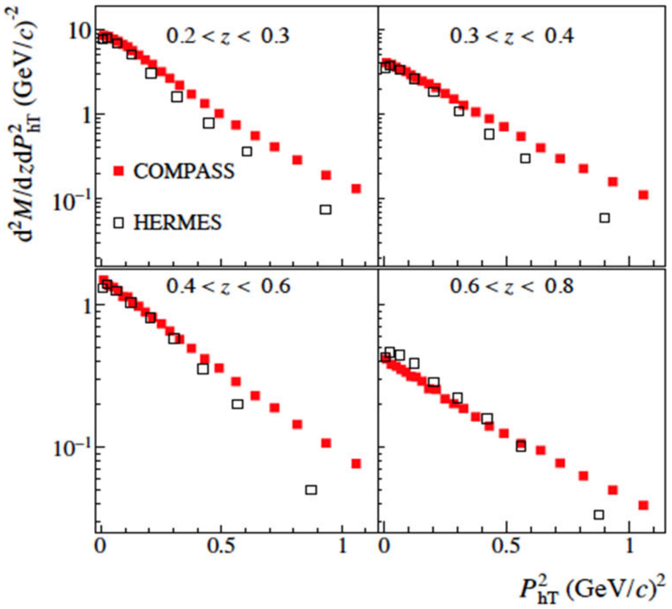
The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!

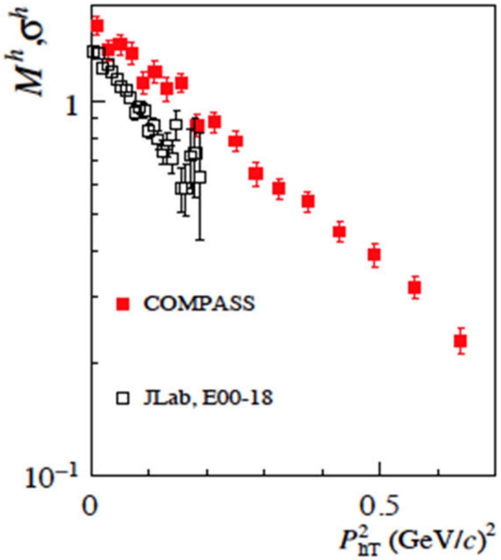
Multiplicities of hadrons in SIDIS

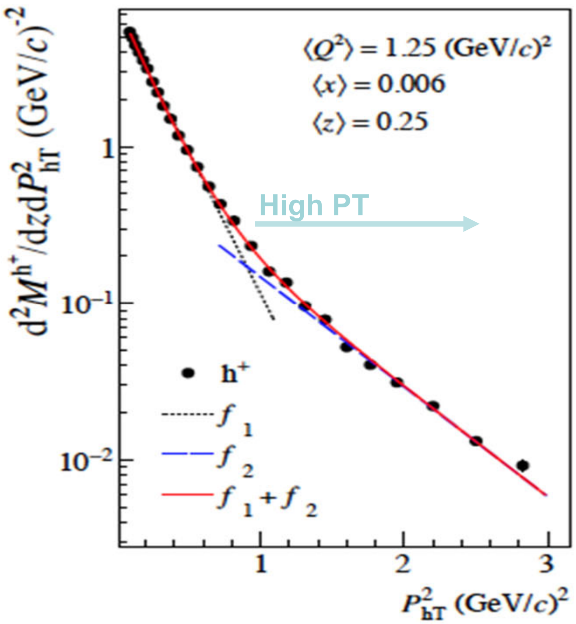
Gaussian Ansatz $\boxed{f_1^q} \otimes \boxed{D_1^{q\to h}} = x f_1^q(x)\, D_1^{q\to h}(z) \frac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$

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

COMPASS:1709.07374





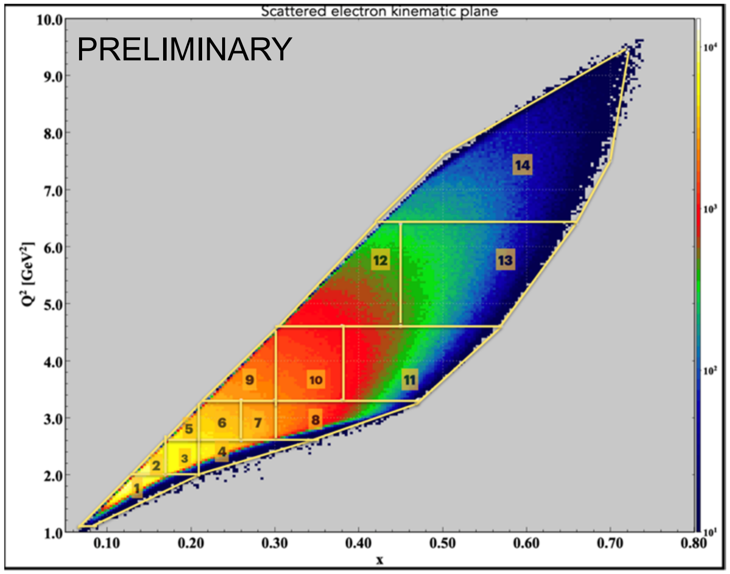


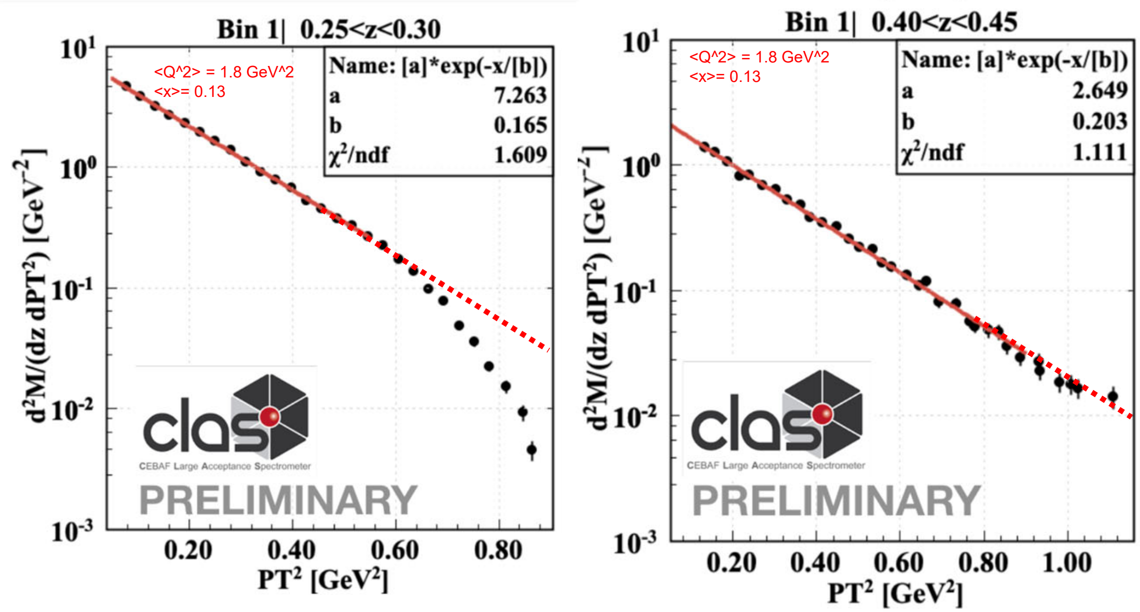
JLab: not enough energy to
produce large P_T
HERMES: not enough luminosity
to access large P_T

- What is the origin of the "high" P_T (0.8-1.8) tail?

1) Perturbative contributions?
2) Non perturbative contributions?

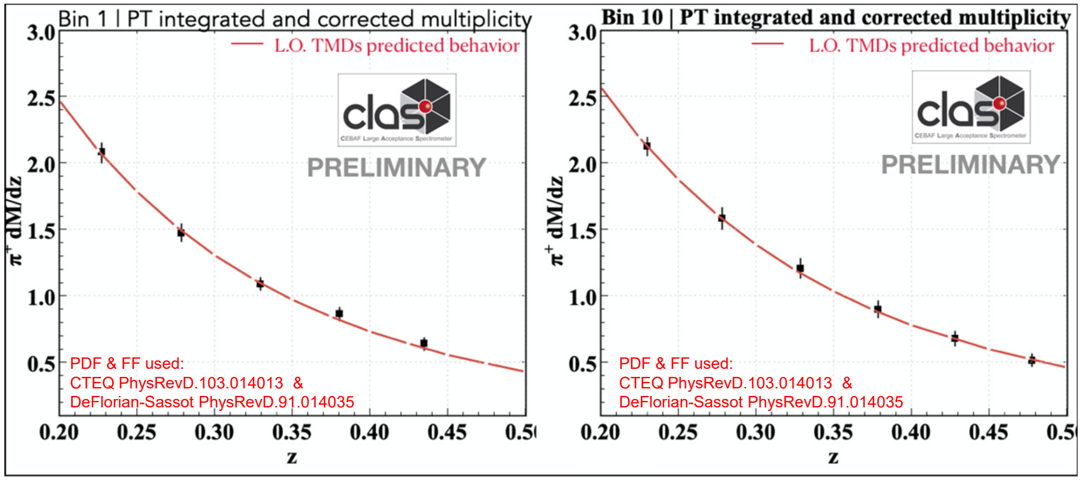
CLAS12 Multiplicities: high P_T & phase space



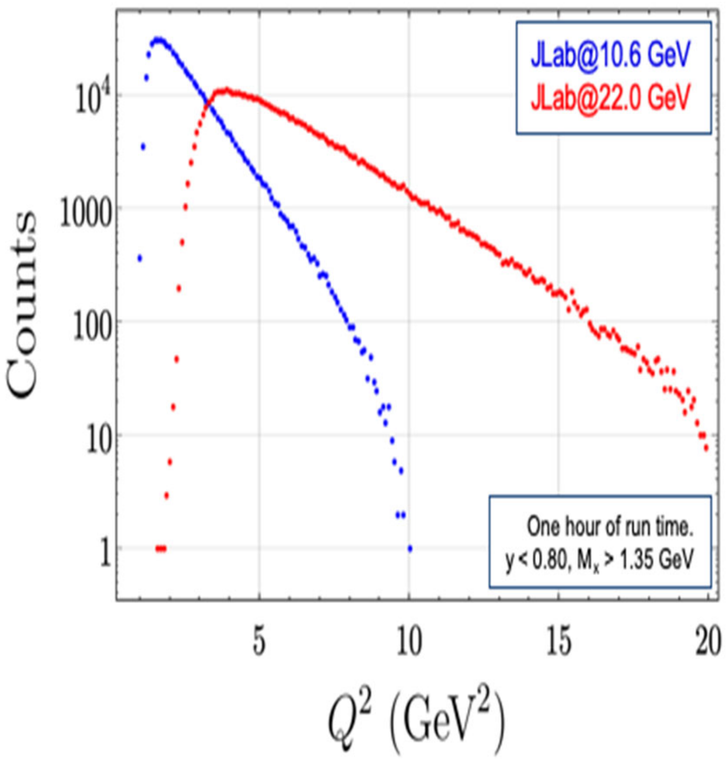


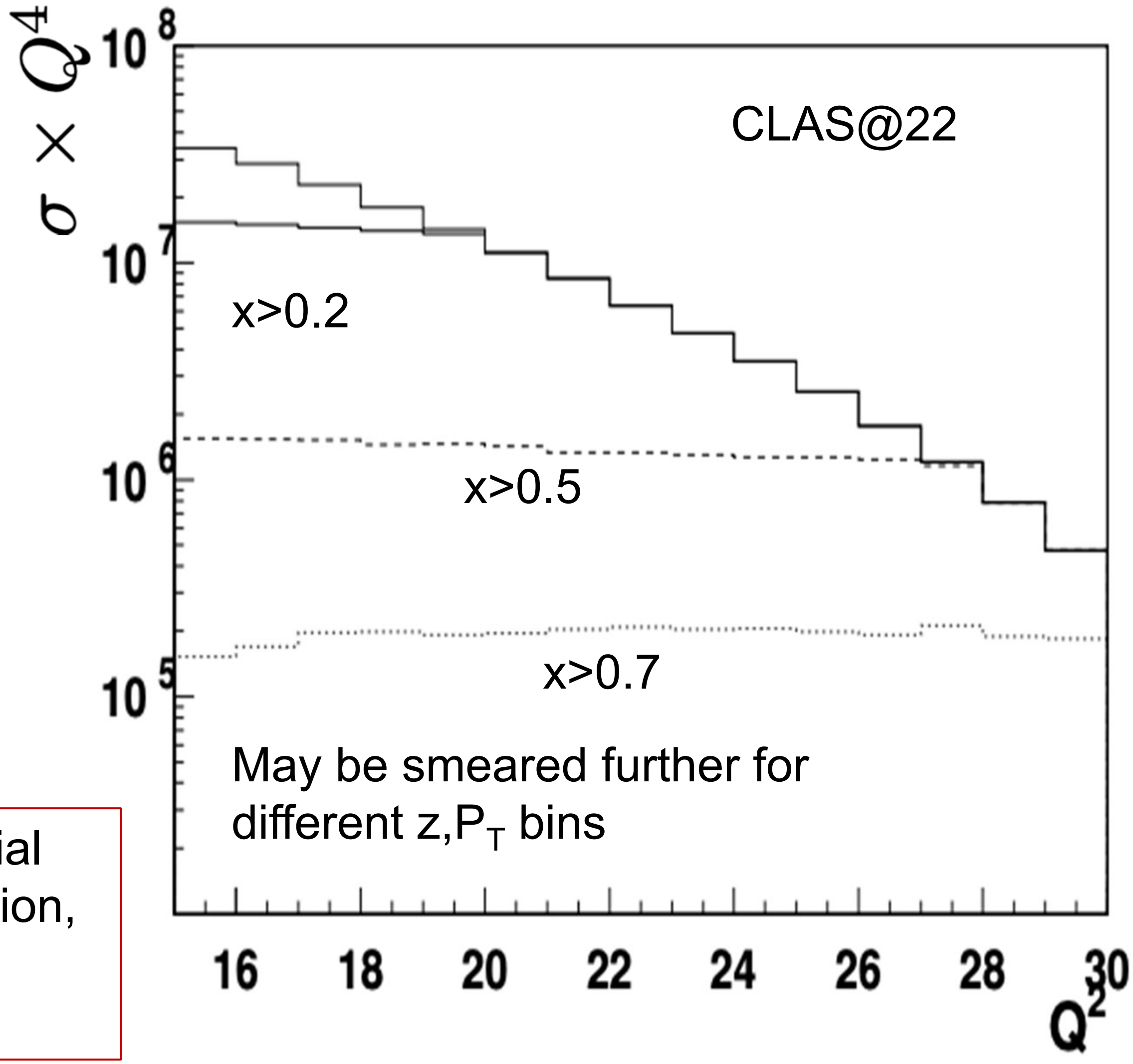
For some kinematic regions, at low z, the high P_T distribution appear suppressed: there is no enough energy in the system to produce hadron with high transverse momentum (phase space effect).

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



Finite energy: Kinematic limitations





May be smeared further for different z,P_T bins

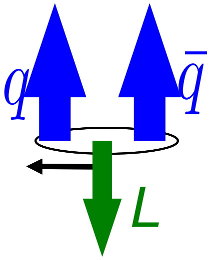
Kinematic correlations, due to trivial energy and momentum conservation, may mask the real dependences

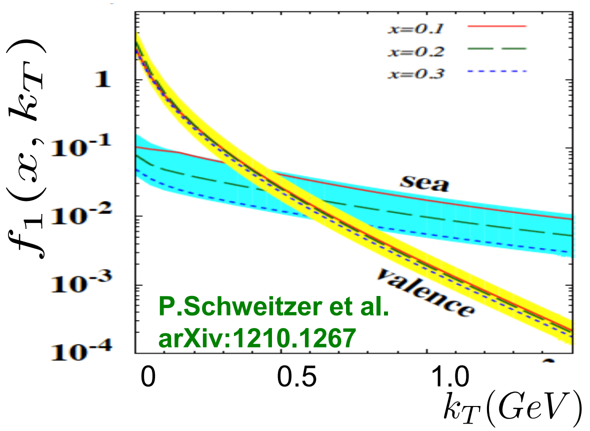
- Can be easily accounted

Most critical with JLab20+: access to large P_T

Possible sources of large P_T in SIDIS

Non perturbative sea



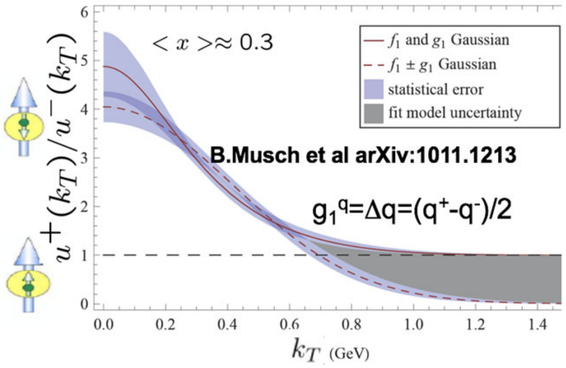


P.Schweitzer et al. arXiv:1210.1267

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

Wider in k_T d-quark distributions

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



B.Musch et al arXiv:1011.1213

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

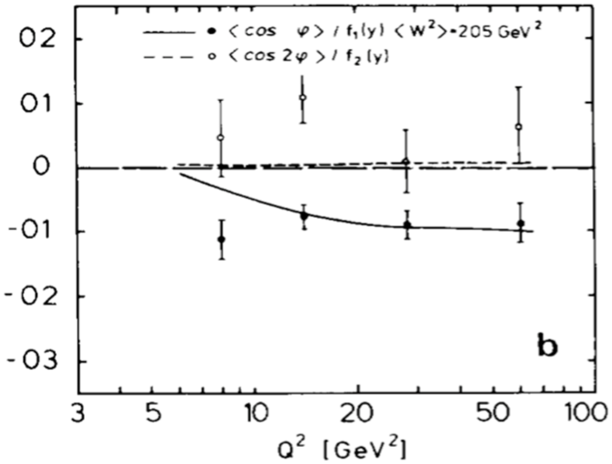
Large P_T-coverage critical for all those measurements!!!

Azimuthal distributions in SIDIS (unpolarized)

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Bigg\{F_{UU,T}+\varepsilon\,\overset{\substack{\text{H.T.}\\ \downarrow}}{F_{UU,L}}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,\overset{\substack{\text{H.T.}\\ \downarrow}}{F_{UU}^{\cos\phi_h}}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\Bigg\}\xleftarrow{\text{H.T.}},$$

EMC-1983 (PL,v130,118)



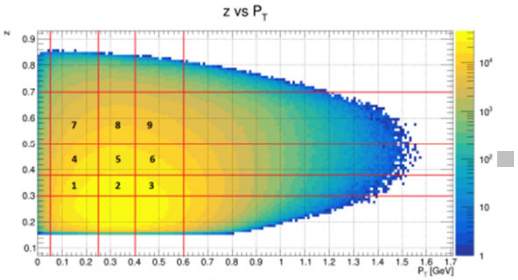
Observables: - Azimuthal Moments - Multiplicity

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

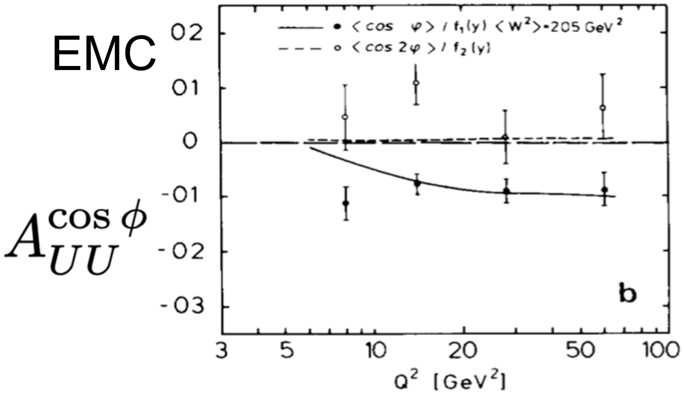
$$m^h(x,z,P_T^2,Q^2) = \frac{\pi F_{UU,T}(x,z,P_T^2,Q^2)+\pi\epsilon F_{UU,L}(x,z,P_T^2,Q^2)}{F_T(x,Q^2)+\epsilon F_L(x,Q^2)}$$

- Quark-gluon correlations are significant in electro production experiments (even at high energies).
- Large cosϕ 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)?

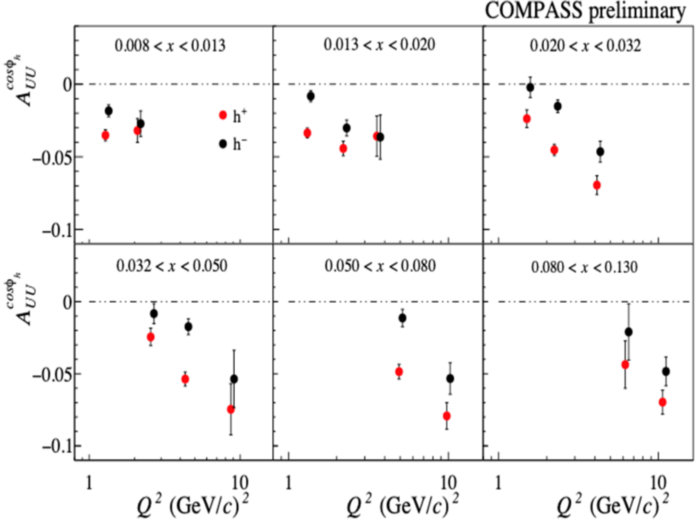
Attempts to understand Q^2-dependence of HT



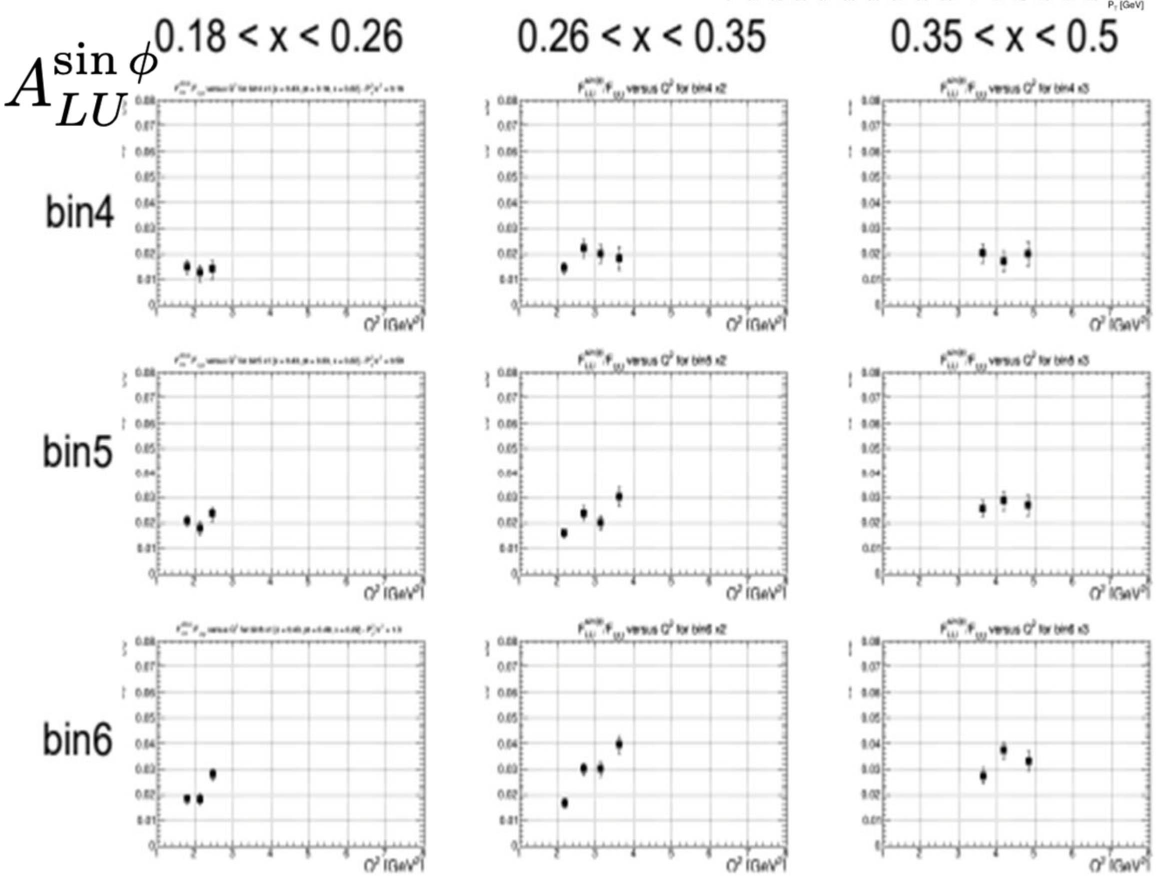
EMC



COMPASS



CLAS12(preliminary)

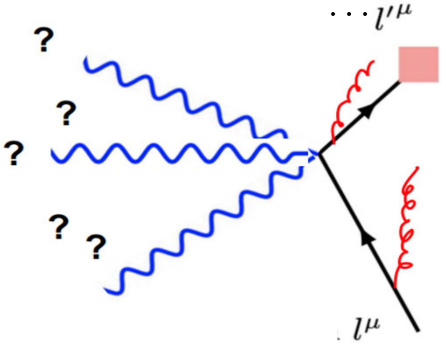


The ratios of SFs (to F_{UU}) are not decreasing with Q!!!
The HT observables, don't look much like HT observables, something missing in understanding
Understanding of these behavior can be a key to understanding of other inconsistencies

Relevance of RC in studies of complex azimuthal modulations

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

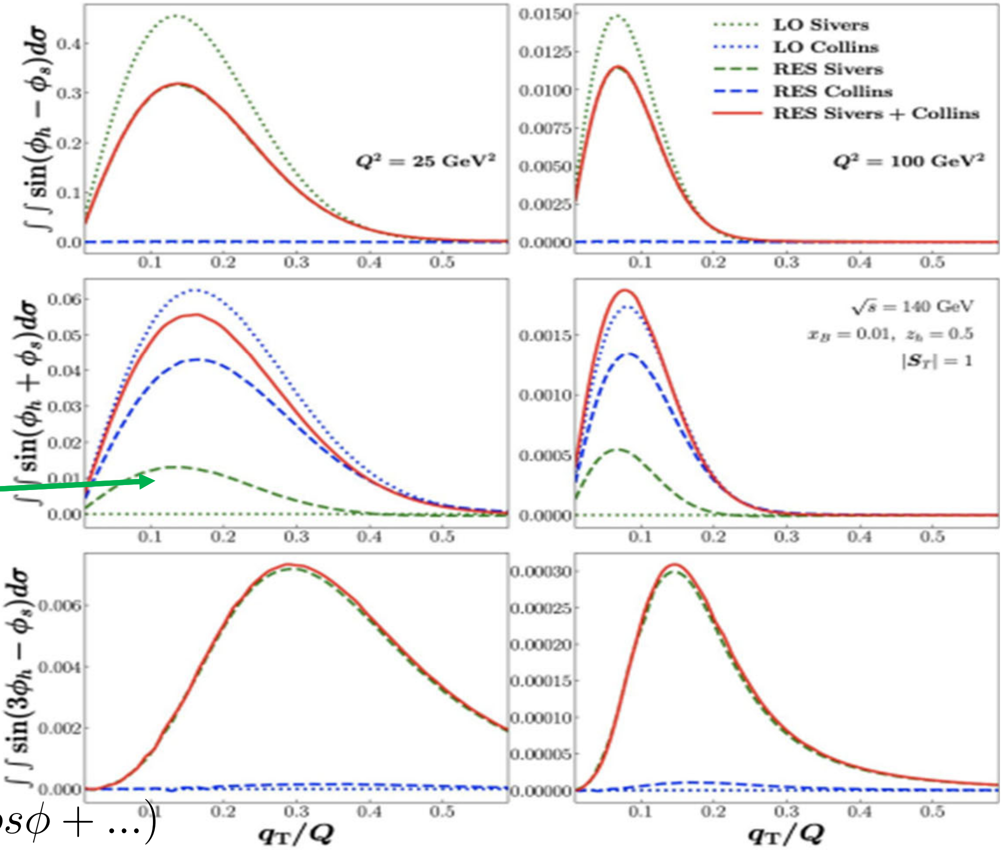
ignored



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

BUT with QED this does not hold!

$$\int \mathrm{d}\phi_h\,\mathrm{d}\phi_S\,\sin(\phi_h-\phi_S)\sin(\hat\phi_h+\hat\phi_S)\neq 0$$



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

Overlap of modulations from RC (Sivers→Collins)

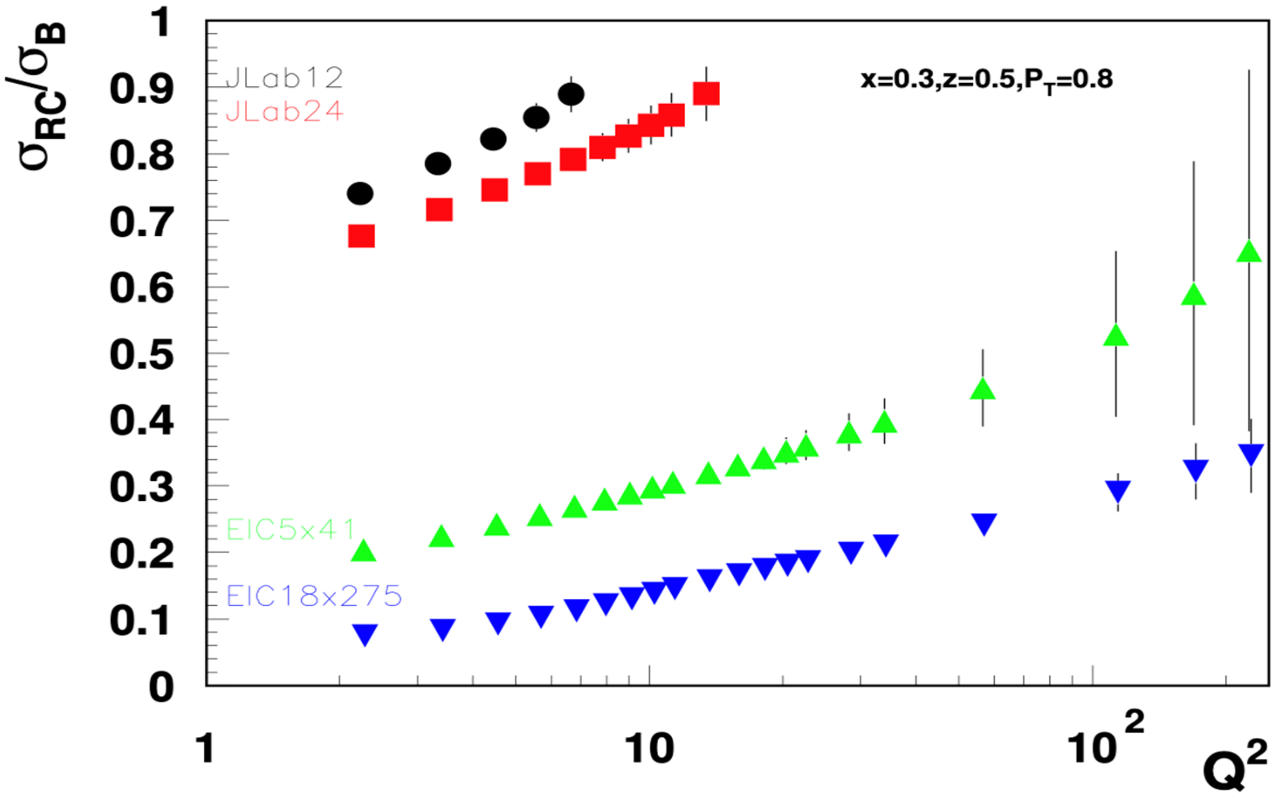
$$\sigma_{XY}^h(x,z,P_T)\to\sigma_{XY}^{B,h}(x,z,P_T)\times R(x,z,P_T,\phi_h)+\sigma_{XY}^{R,h}(\dots).$$

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

From JLab to EIC: complementarity

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

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

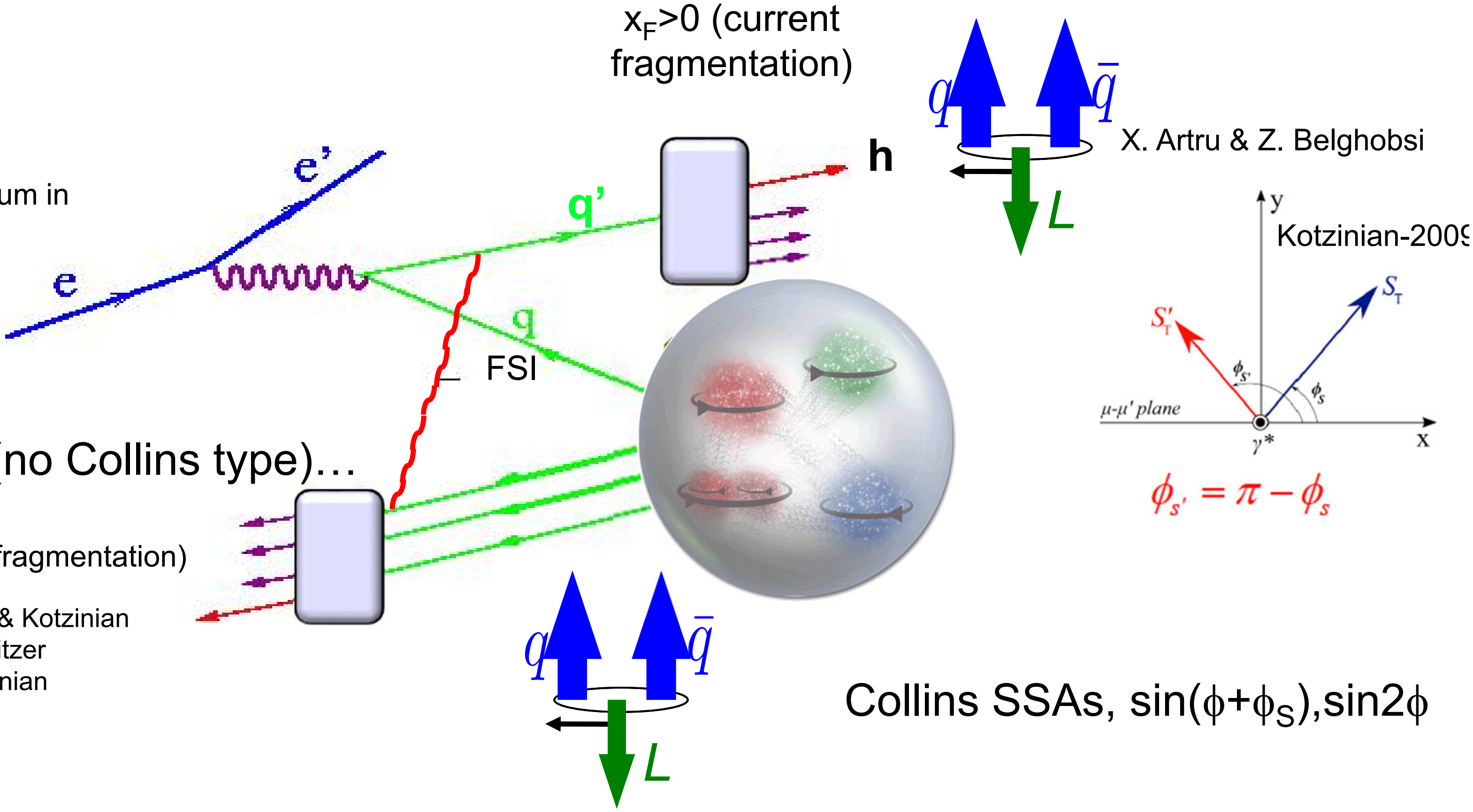


Cross section at low Q^2 suppressed at higher CM energies

- 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 – fractional momentum in the CM frame



Cahn, Sivers, (no Collins type)…

x_F<0 (target fragmentation)

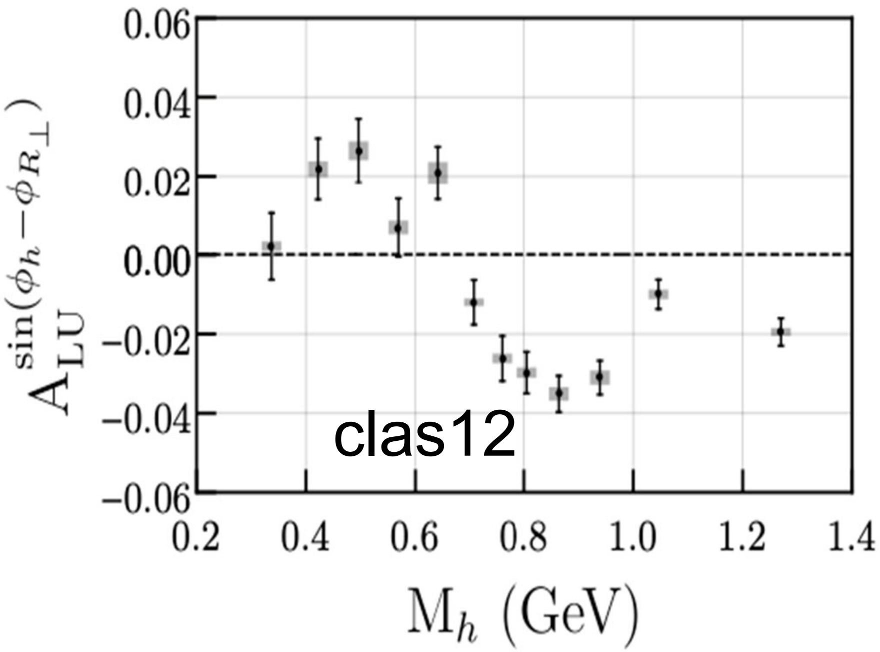
Karliner, Kharzeev , Ellis & Kotzinian
Strikman,Weiss & Schweitzer
Anselmino, Barone, Kotzinian

Collins SSAs, sin(ϕ+ϕ$_S$),sin2ϕ

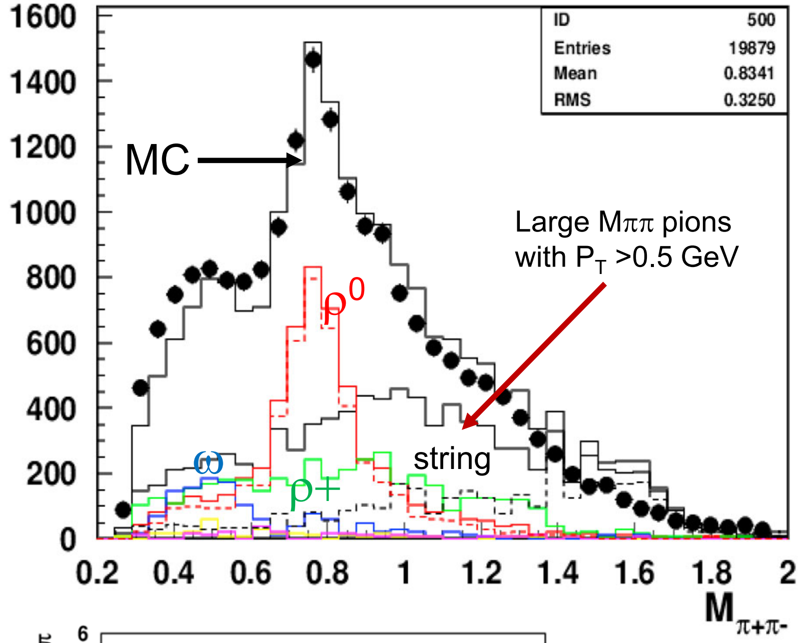
Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles (different in CFR and TFR)

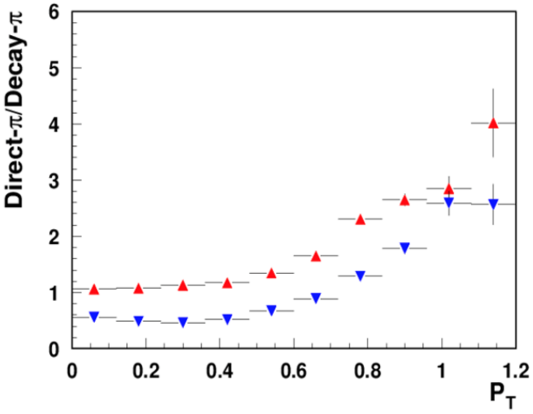
2 hadron correlations in CFR ep→e'$\pi^+\pi^-$X

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



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





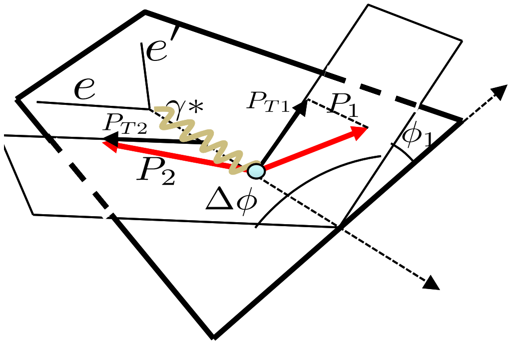

theory

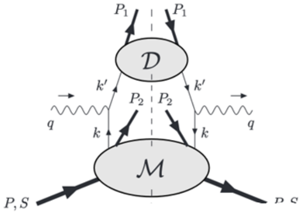
- Spin-azimuthal correlations in hadron pair production are very significant
- Hadron pairs in SIDIS (true from JLab to LHC) are dominated by VM decays (therefore single hadron channel too)
- Direct pions dominate only at relatively high P_T, (P_T >0.6-0.7 GeV)

CFR/TFR correlations in 2 hadron production

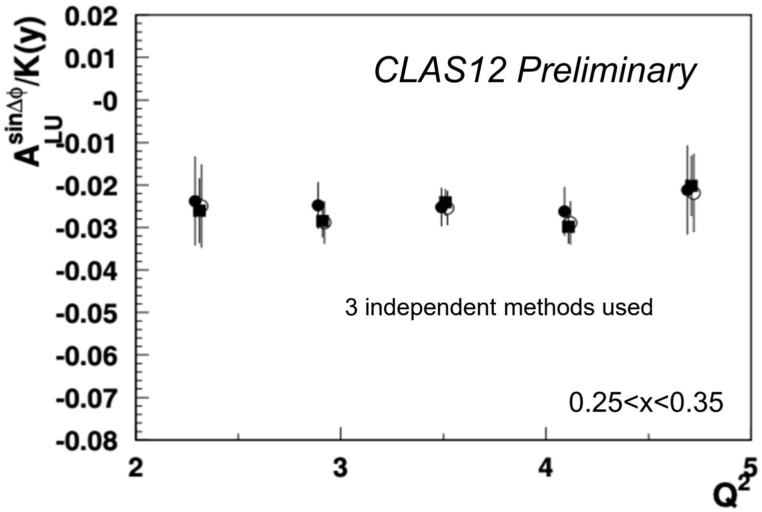
Submitted to PRL

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

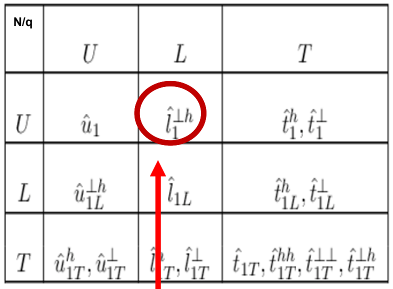




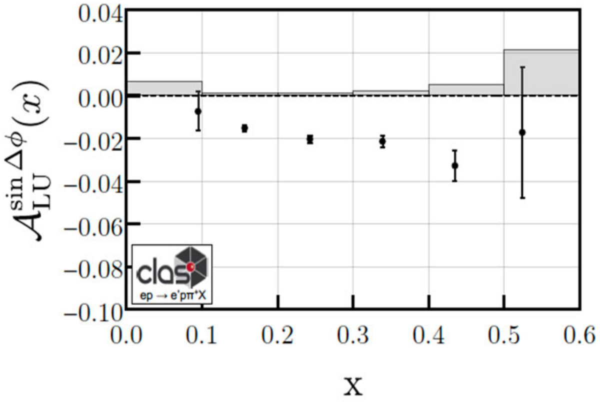
$$A_{LU} \propto \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin \Delta\phi$$



Twist-2 table



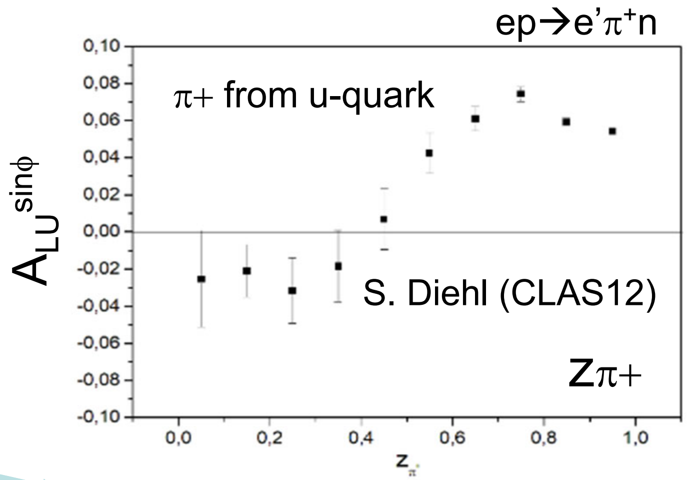
N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp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



- 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

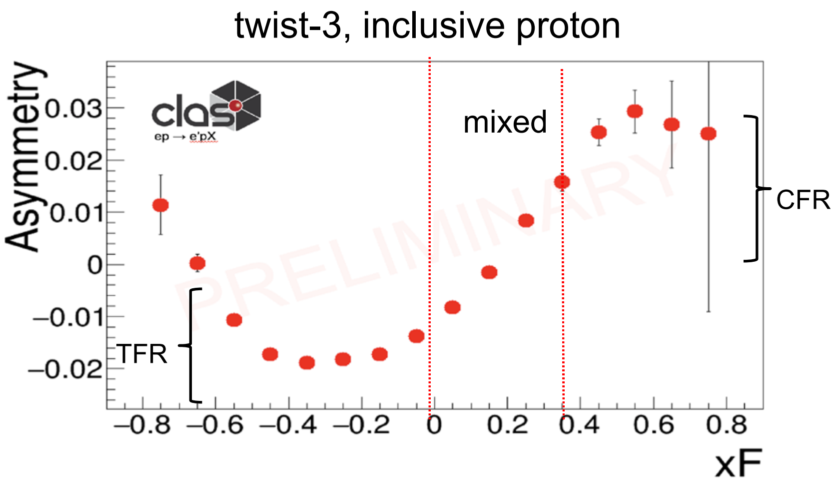
Beam SSA: Where is the struck quark?

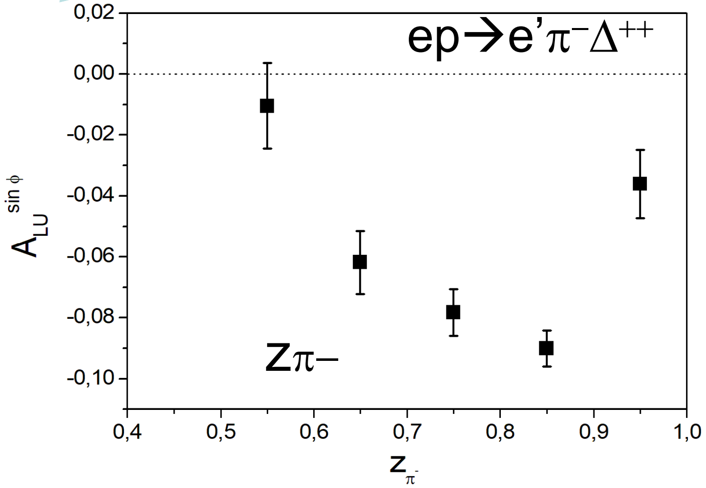
- CFR is defined by the kicked out quark, and in case the quark is polarized the SSA can define its signature
- Polarized d-quark, is hard to locate, and one obvious process where we can guarantee it was hit, is the production of Δ++



ep→e'π^+n

twist-3, inclusive proton

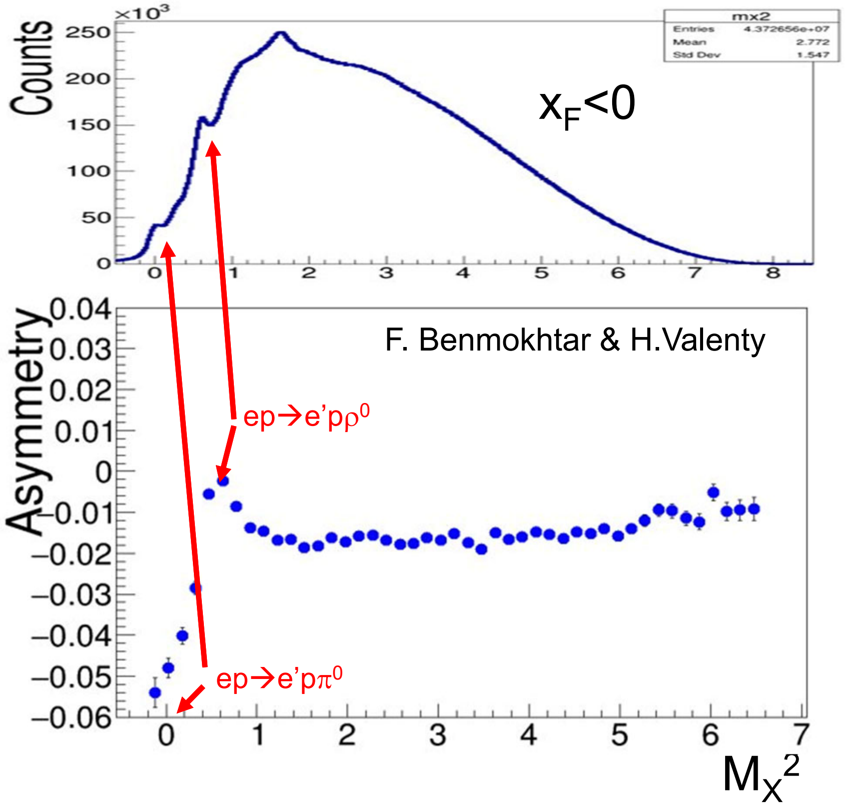




Negative sign of the SSA (plateau) defines the TFR dominance

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'pπ^0 or e'pρ^0)
- 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'pπ^0 (~8%) and ep→e'pρ^0 (~-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

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

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

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

Beam spin asymmetries in correlations of CFR and TFR

Twist-3

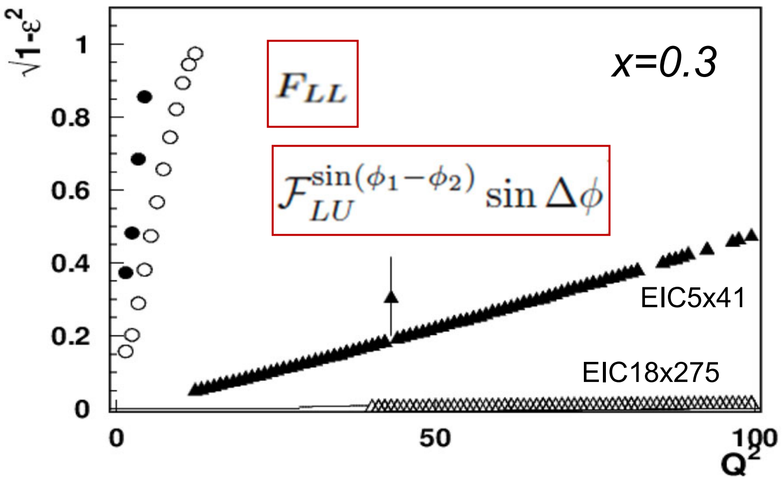
$\boxed{\sin\phi_h F_{LU}^{\sin\phi_h}}$

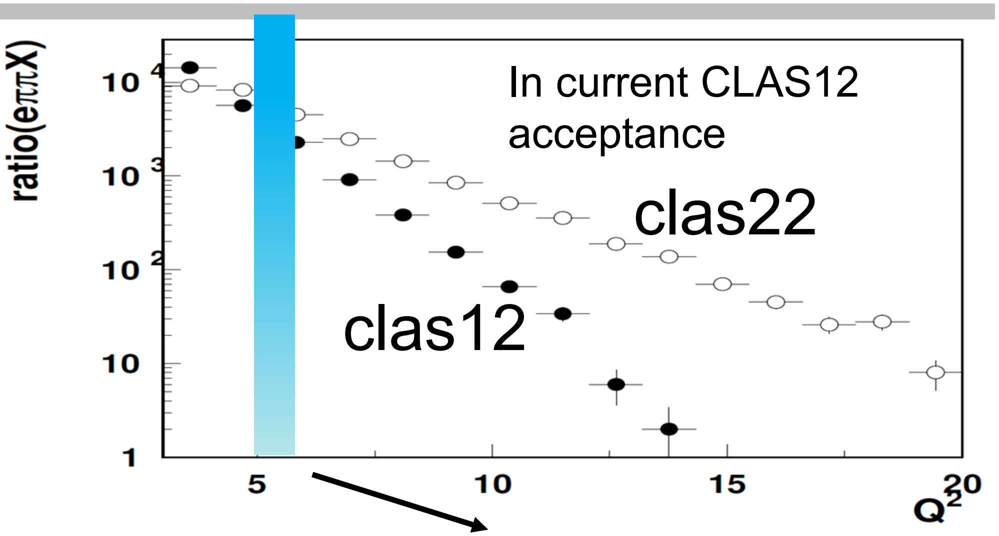
$\boxed{\mathrm{A}_{\mathrm{LU}}^{\sin\phi_{R_\perp}}}$

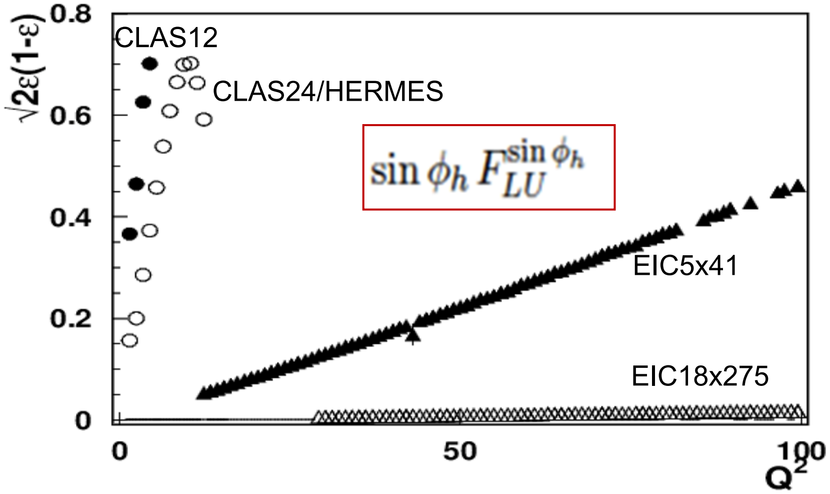
Beam spin asymmetries in CFR (single and dihadron)

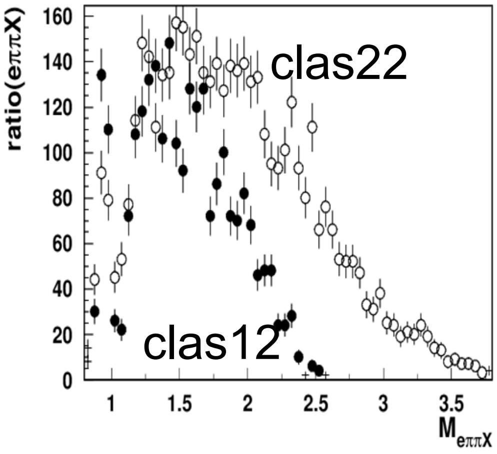
Exclusive processes in the x>0.1 domain, may most be in this category, due to resolutions and rapidly decreasing x-sections at higher energies
Much higher range in Q^2, compared to HERMES, may help with applicability of GPD formalism

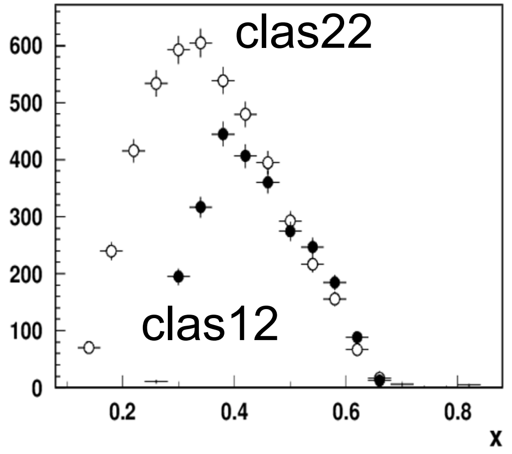
Beam SSAs & Kinematic suppression at large x







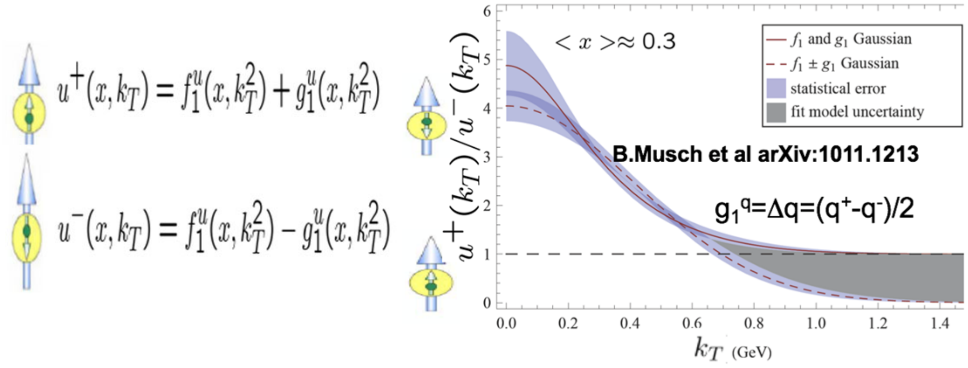




- Fixed target experiments are sensitive to all SSAs
- Higher energy opens up the phase space allowing access to, sea and large Q^2
- Measurements of beam SSAs (+some others) at large x, will be challenging at EIC

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



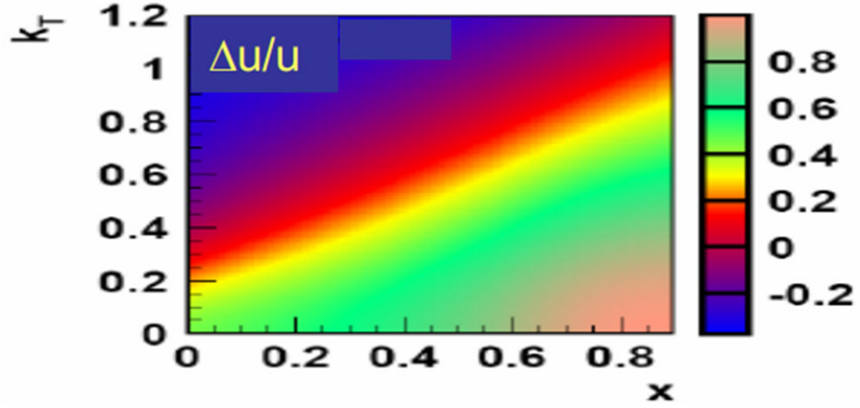
$$u^+(x,k_T) = f_1^u(x,k_T^2) + g_1^u(x,k_T^2)$$

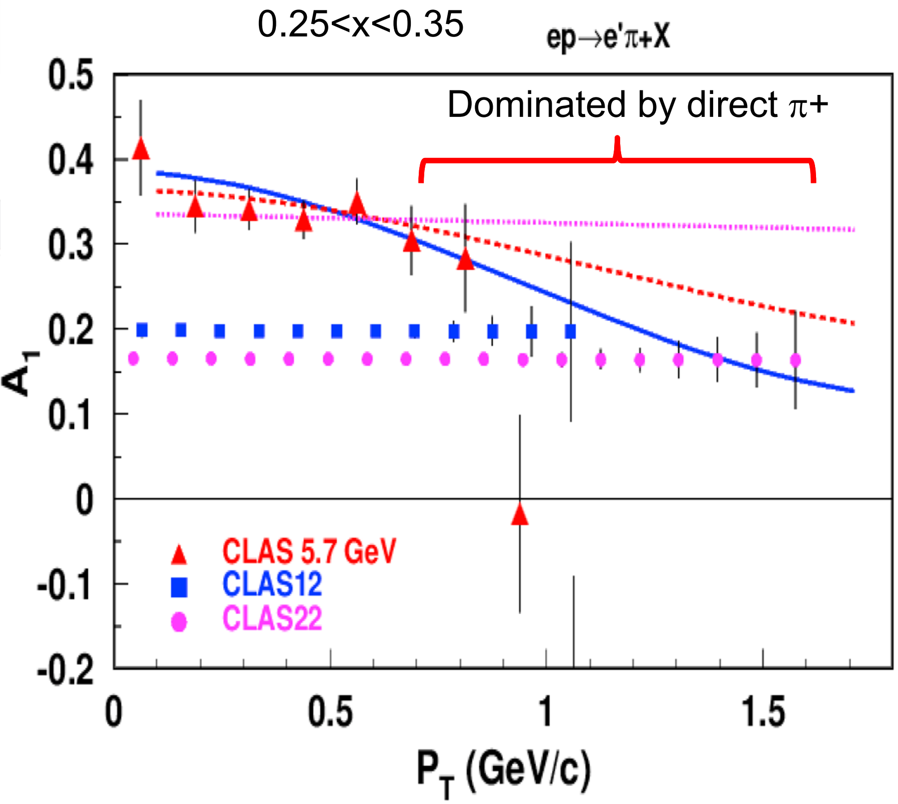
$$u^-(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$$

B.Musch et al arXiv:1011.1213

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

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

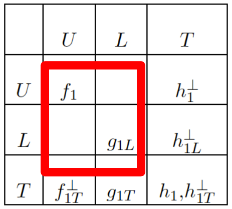




Dominated by direct π+

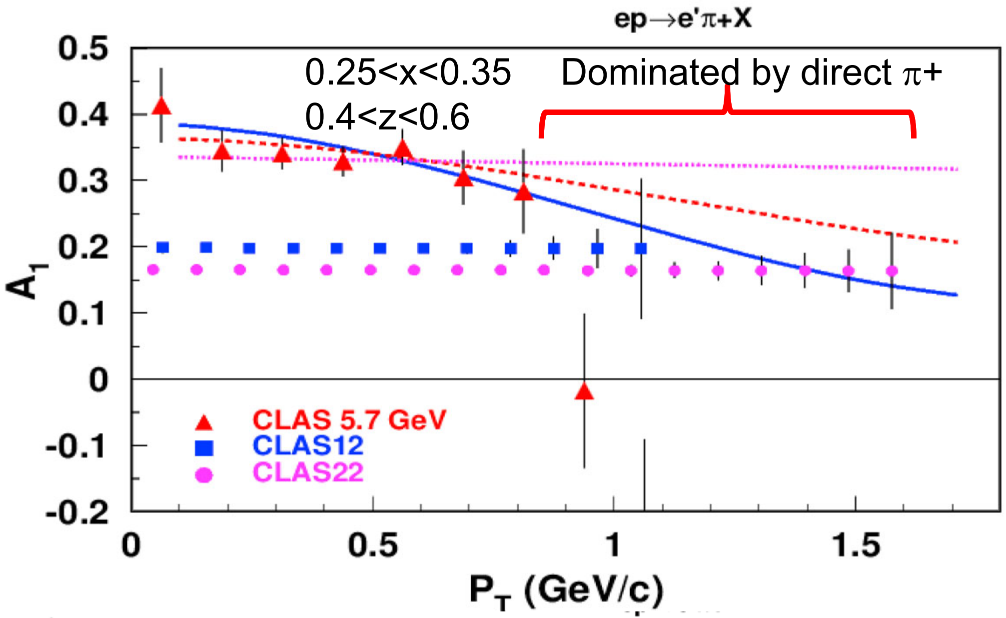
- Models and lattice predict very significant spin and flavor dependence for TMDs
- Large transverse momenta are crucial to access the large k_T of quarks
- Several CLAS12 proposals dedicated to $g_1(x,k_T)$-studies CLAS12
- Understanding of k_T-dependence of g_1 will help in modeling of f_1

Impact of limitations from theory

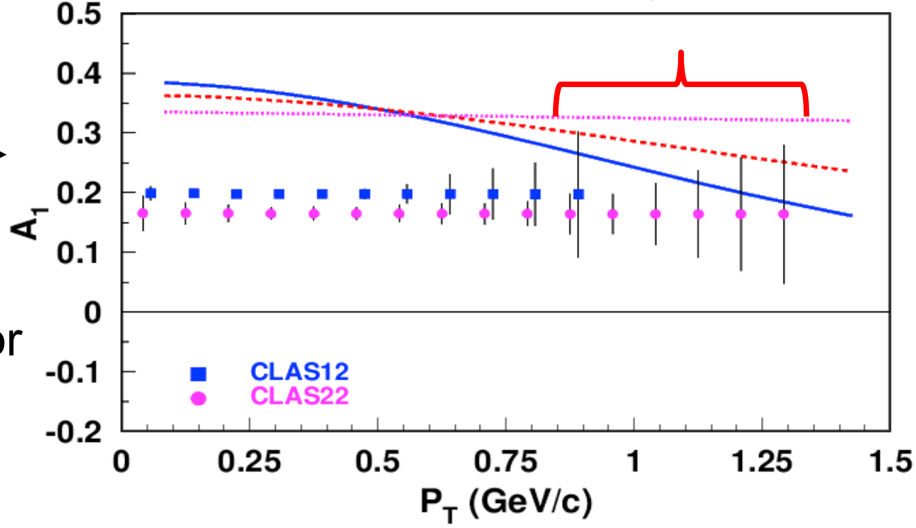


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

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



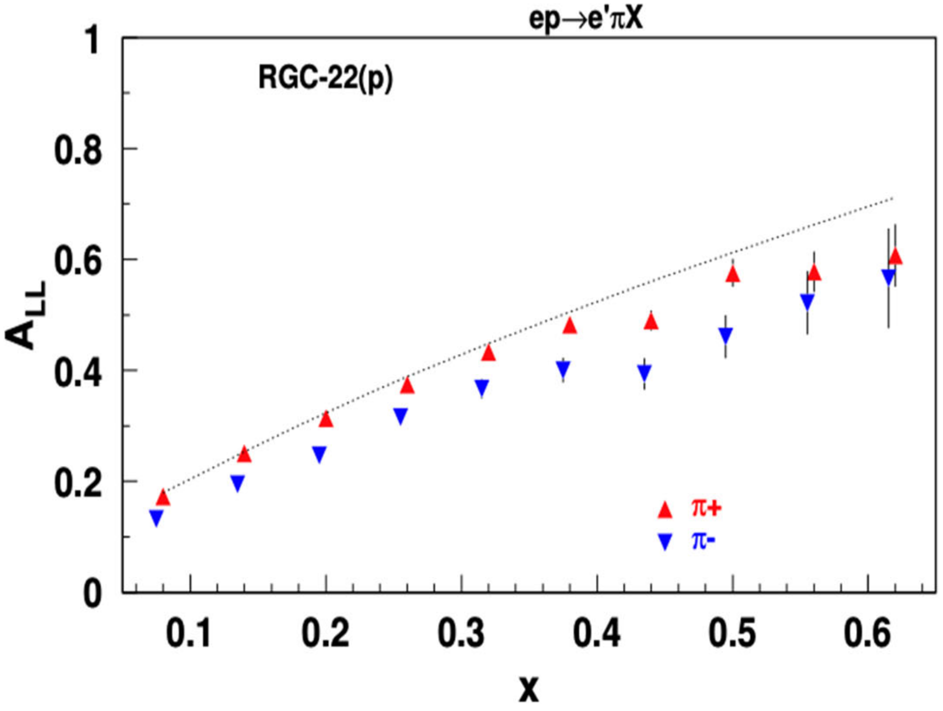
$P_T/z/Q<0.5$ →

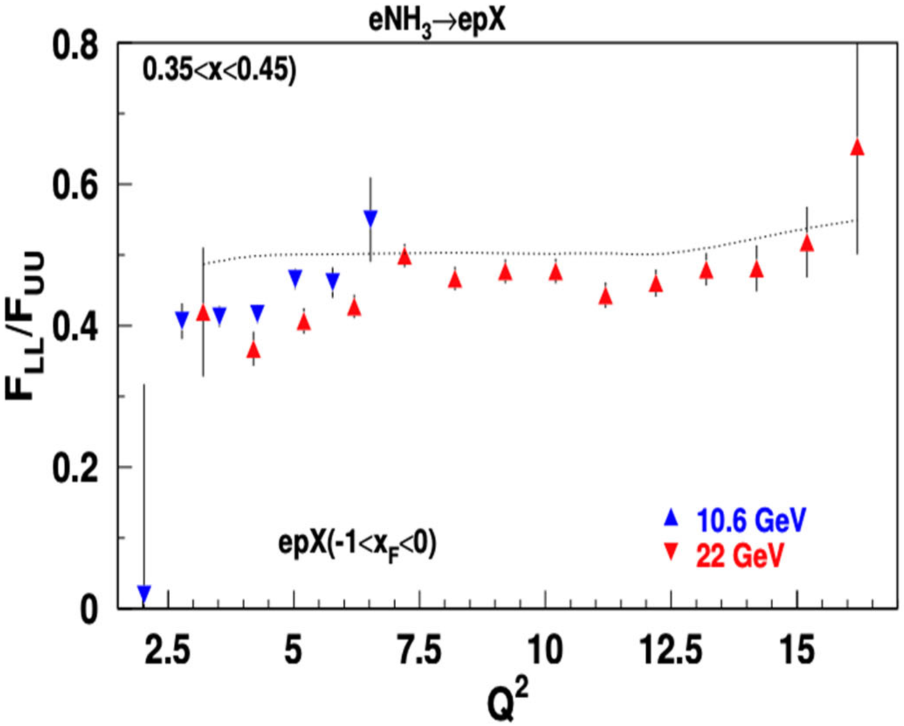


More theory limitation, may convert the observable from major improvement (type 2) to only possible with 20+ GeV (type 1)

CLAS12 at 22 GeV with longitudinally polarized target

Full simulations using LUND-based generator and full CLAS12 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

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

- 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]

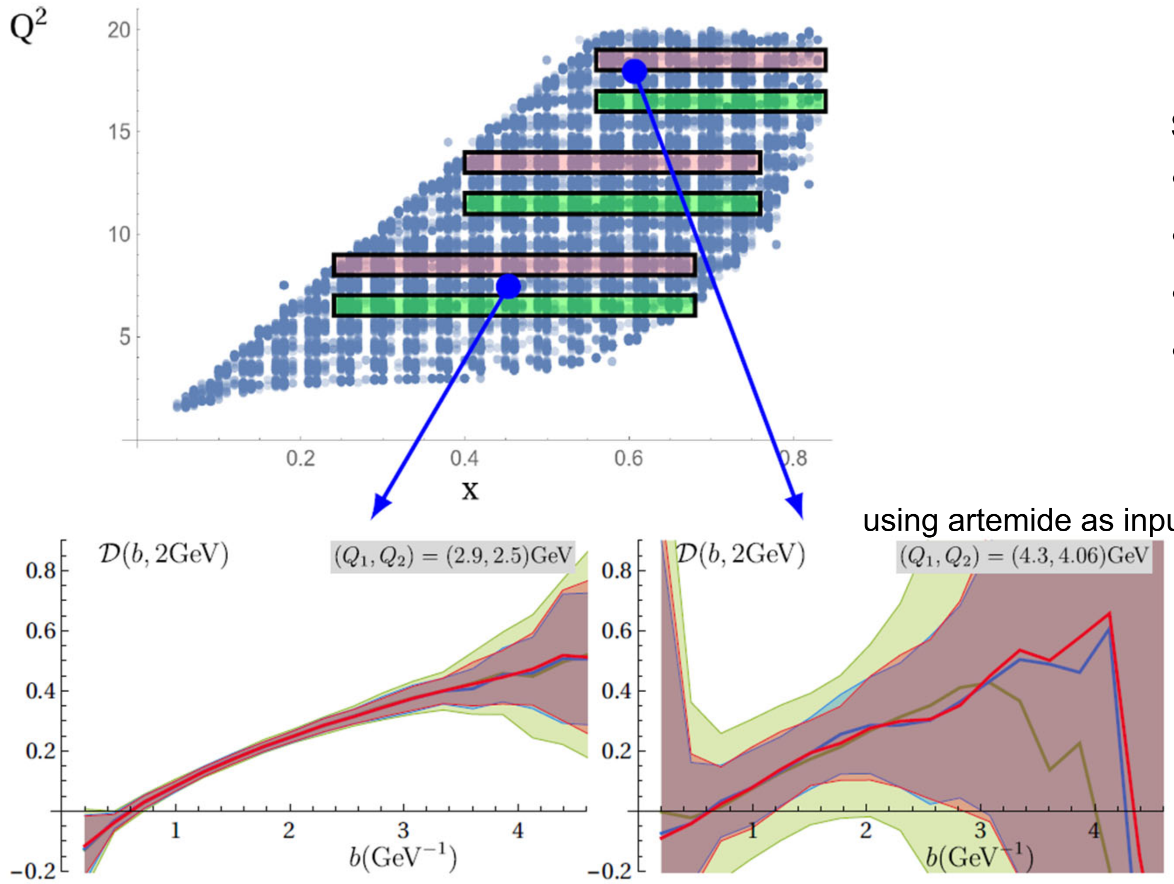
Extracting the CS-kernel from data

A. Vladimirov

Is such study possible?

YES!

Estimation for the JLab22



using artemide as input

Different experiments most sensitive to different ranges in b

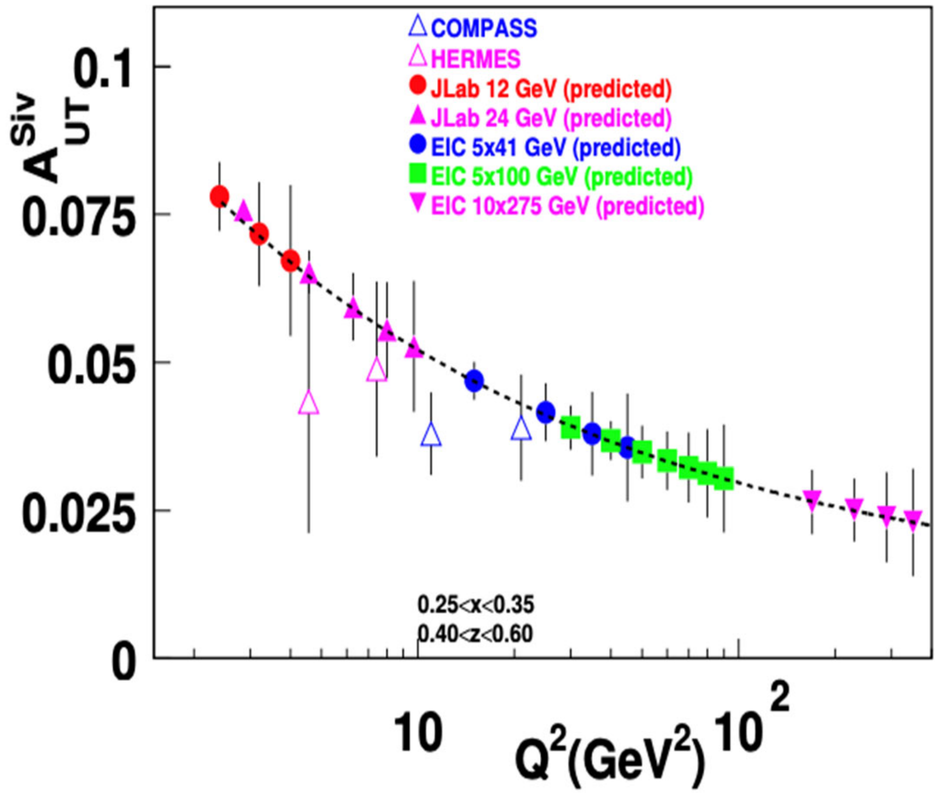
- JLab ~1<b<4
- EIC ~0.5<b<1.5
- LHC b<0.5
- COMPASS overlaps

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

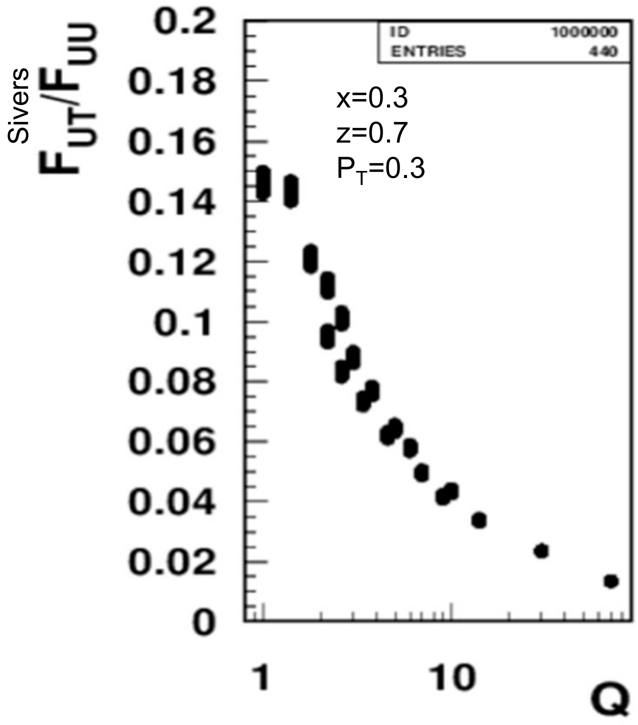
Contributions for 3D structure studies: Sivers

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

A. Kotzinian et al, arXiv:1107.2292

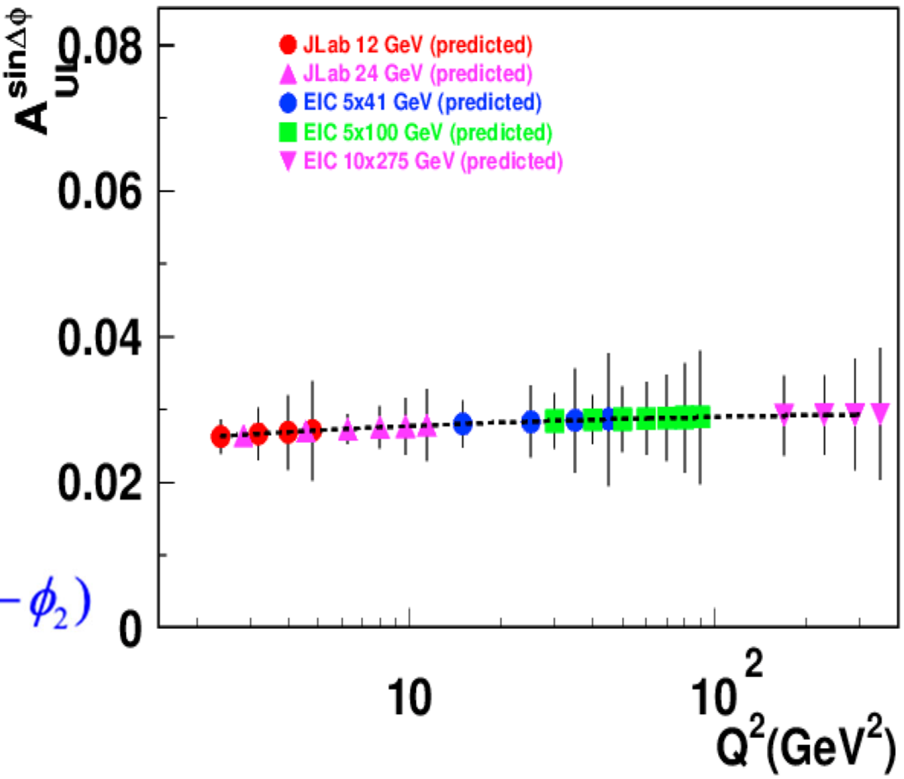
$$\sigma_{UU} = F_0^{\hat{u}\cdot D_1}$$

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

No depolarization, like Sivers!

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

y>0.05,100 days



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

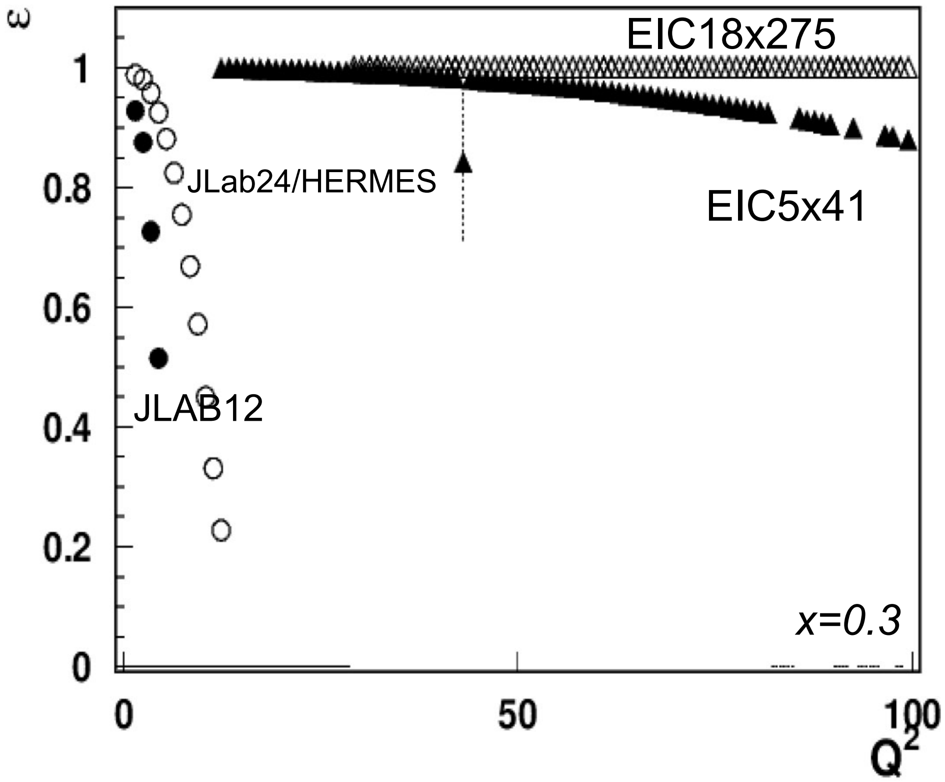
- Significant single spin asymmetries have been observed in CFR and TFR, indicating large correlations between hadrons
- Measurements of SFs from the azimuthal distributions of final state hadrons in electroproduction, requires high statistics in multidimensional bins, also to address kinematical limitations 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 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

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



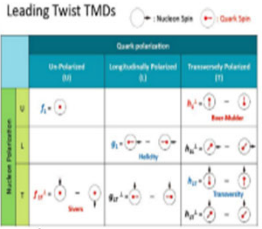
$F_{UU,L}$ kinematically enhanced, but requires a reasonable range and resolutions to be separated from the $F_{UU,T}$

Understanding the TMD phenomenology

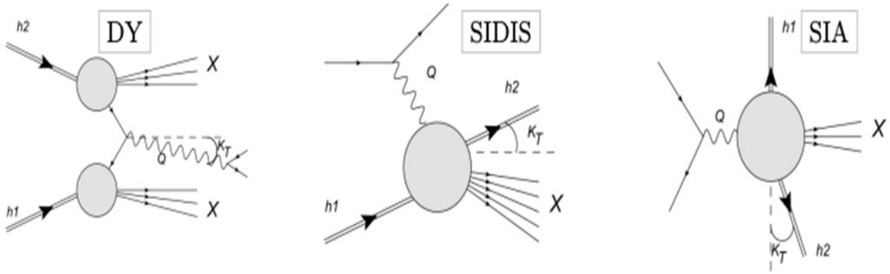
Link to the zoom video of A. Vladimirovs presentation (scroll to 01:45:06)

https://us06web.zoom.us/rec/share/QB62hDI-l4oI6D0yvVBVEgocvg7ZAYd7KVvXI9fESE9raCDf6ZEBCKgXWPqb6IgF.-TYPr1-88YdtfyoO

Passcode:4E8Z.@#Q



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



Main scales:

The invariant mass of photon: $|q^2| = Q^2$

Transverse component of photon momentum: q_T

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

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

Evol.factor
our goal!

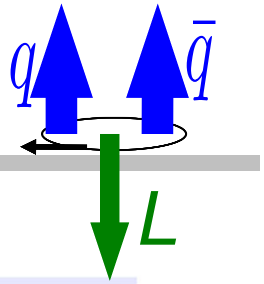
TMDs
trash

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

Building the new observable

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

3D PDFs: Common features



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 N^{3}LO

CS kernel
nonperturbative

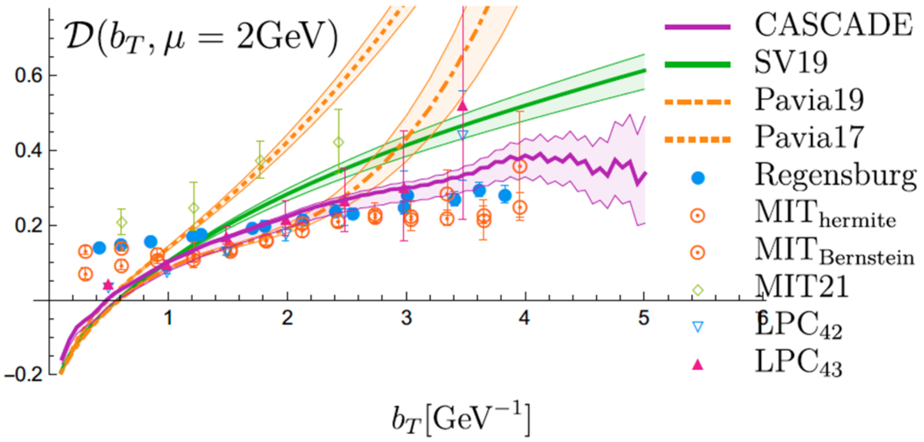
TMD distribution
any tw2
many **tw3**

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)



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-l4oI6D0yvVBVEgocvg7ZAYd7KVvXI9fESE9raCDf6ZEBCKgXWPqb6IgF.-TYPr1-88YdtfyoO

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

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

Calculable with perturbation theory

Evol.factor
our goal!

TMDs
trash

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

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

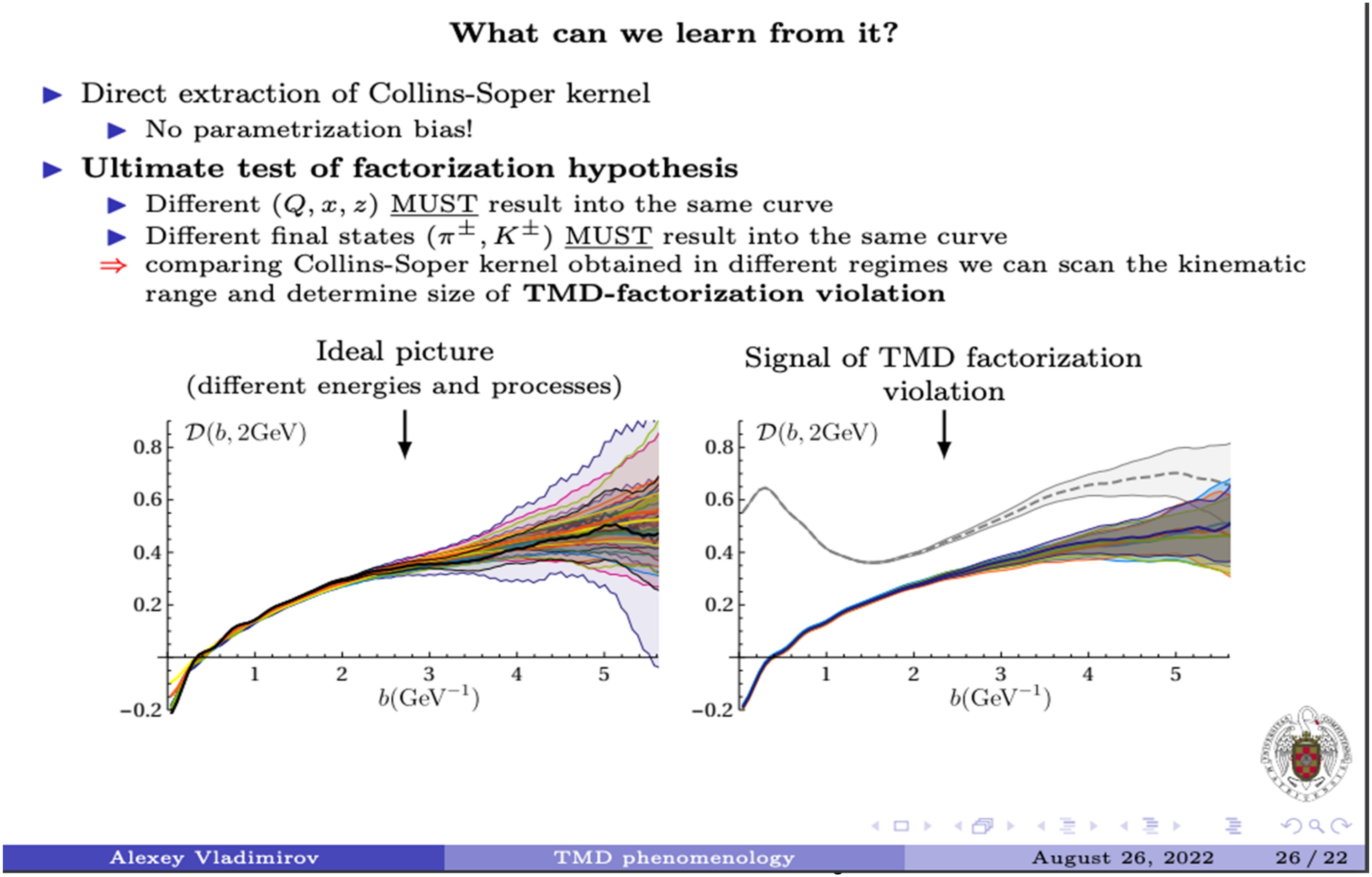
$$\Sigma(Q,x,z,b) = \int dq_T q_T J_0(q_T b)\frac{d\sigma}{dQ^2dxdzdk_\perp^2}$$

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

$$R[b,Q_1\to\mu] = \exp\left(2\int_{P(Q_1\to\mu)}\left(\boxed{\gamma_F(\mu,\zeta)\frac{d\mu}{\mu}} - \mathcal{D}(b,\mu)\frac{d\zeta}{\zeta}\right)\right)$$

$$\mathcal{D}(b,\mu) = \frac{\ln\left(\frac{\Sigma(Q_1)}{\Sigma(Q_2)}\right) - \ln Z(Q_1,Q_2) - 2\Delta_R(Q_1,Q_2,\mu)}{4\ln(Q_2/Q_1)} - 1$$

Validation of TMD formalism



What can we learn from it?

- Direct extraction of Collins-Soper kernel
  - No parametrization bias!
- **Ultimate test of factorization hypothesis**
  - Different (Q, x, z) MUST result into the same curve
  - Different final states $(\pi^{\pm}, K^{\pm})$ MUST result into the same curve
  - ⇒ comparing Collins-Soper kernel obtained in different regimes we can scan the kinematic range and determine size of **TMD-factorization violation**

Ideal picture
(different energies and processes)

Signal of TMD factorization
violation

Alexey Vladimirov TMD phenomenology August 26, 2022 26 / 22

Projections for Sivers

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

$\sin(\phi - \phi_S)$

arXiv:1208.1244

arXiv:1212.1701

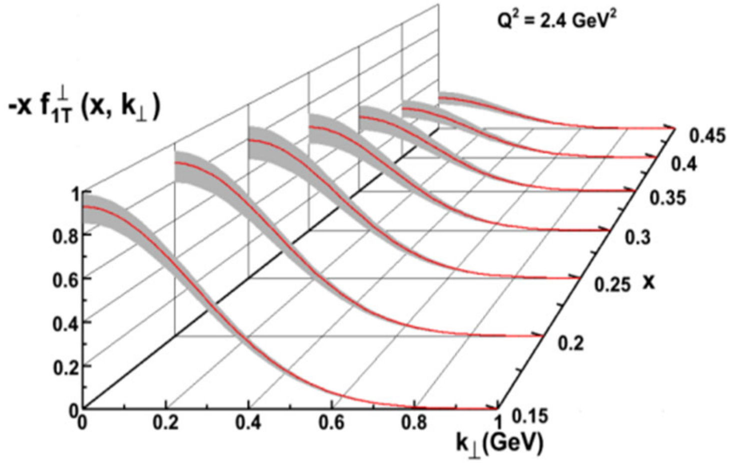


Figure 3.4 The Sivers function for the up quark as a function of $k_\perp$ at different values of x as determined by analysis of JLab 12 pseudo data generated for ^{3}He target. The central line is the model profile of [3-35]; real Jefferson Lab 12 GeV data will eventually reveal the actual shape of the distribution. The error bands have been projected about the model profile.

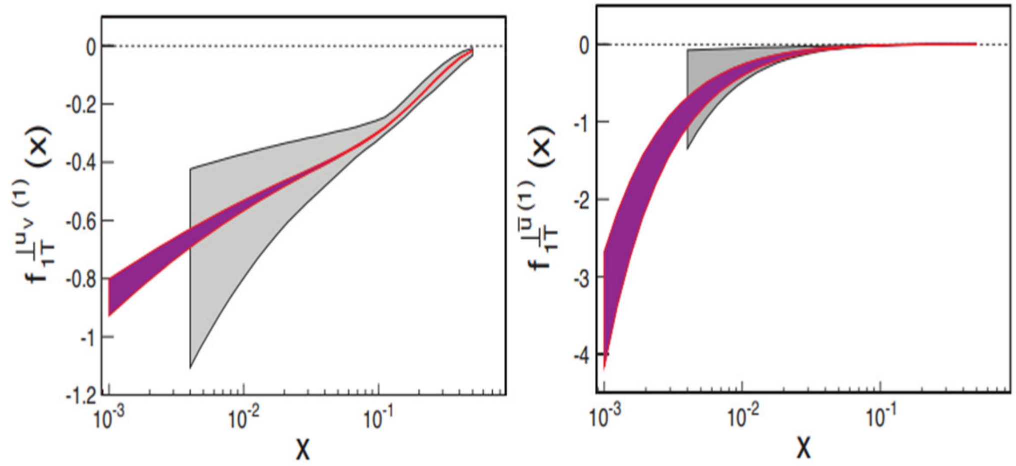
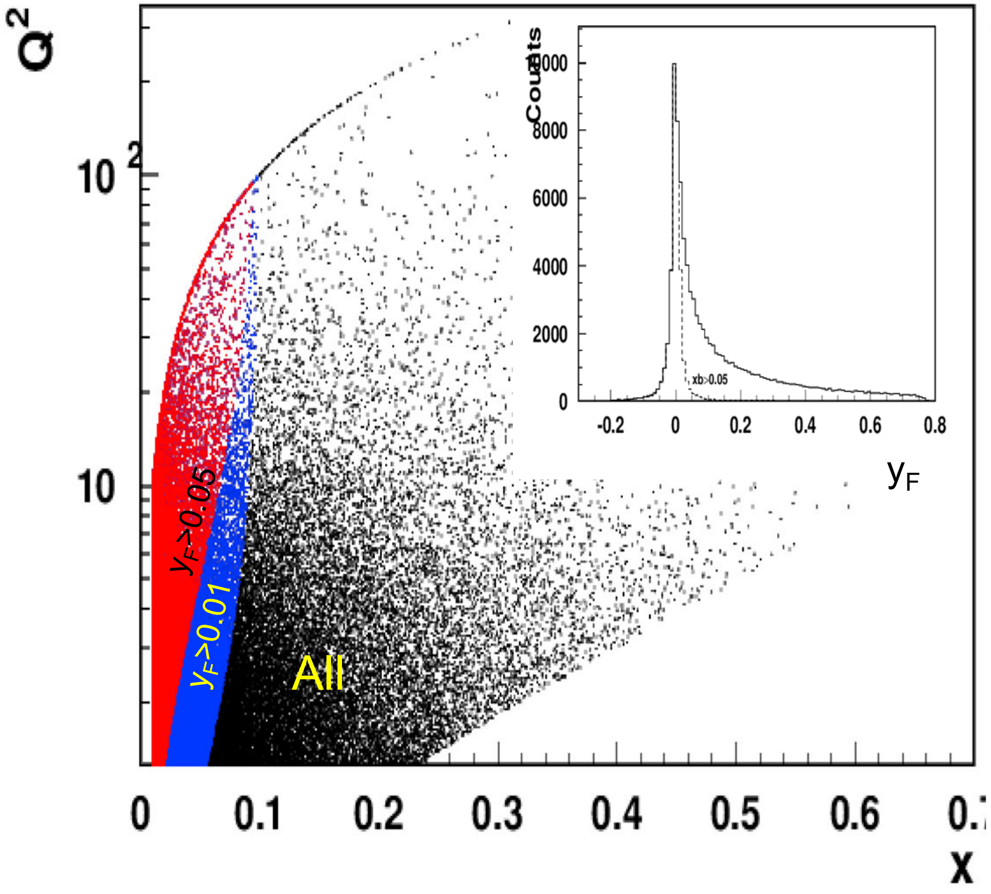


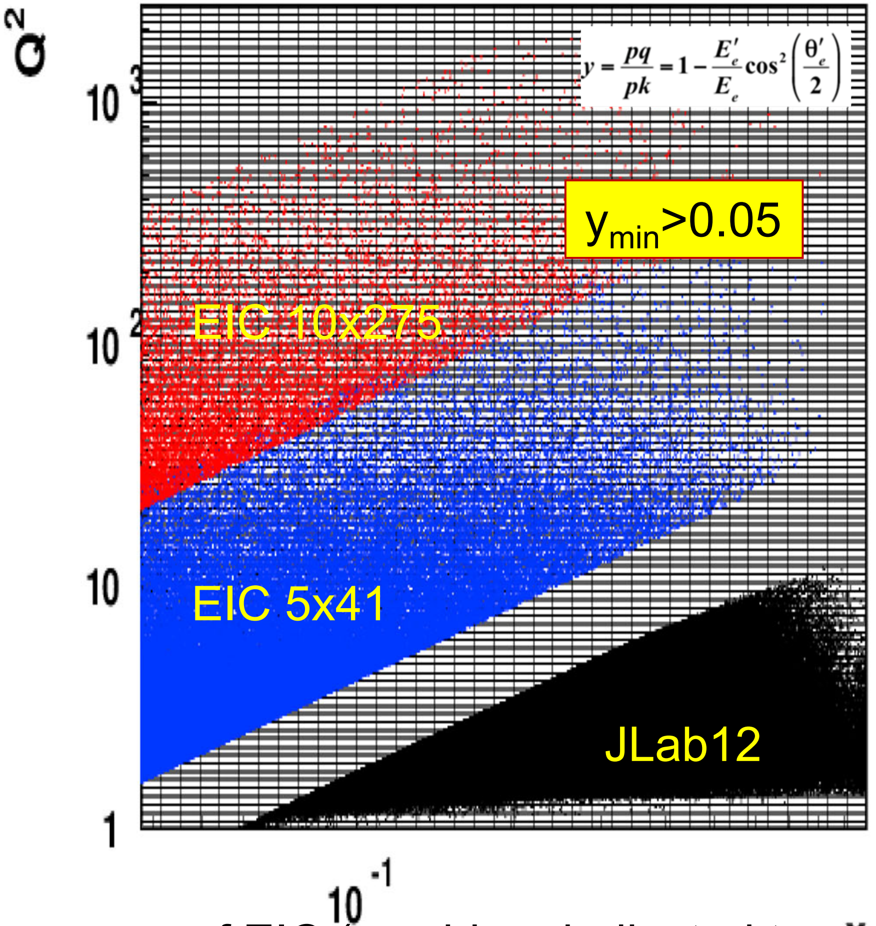
Figure 2.16: Comparison of the precision (2-σ uncertainty) of extractions of the Sivers function for the valence (left) $u_v = u - \bar{u}$ and sea (right) $\bar{u}$ quarks from currently available data [77] (grey band) and from pseudo-data generated for the EIC with energy setting of $\sqrt{s} = 45$ GeV and an integrated luminosity of 10 fb^{-1} (purple band with a red contour). The uncertainty estimates are for the specifically chosen underlying functional form.

Without clear understanding of systematics from separation of different modulations, and impact of model assumptions/approximations used in their production, this projections suppressed development of proper extraction frameworks with controlled systematics for years.

X vs Q^2 from JLab to EIC



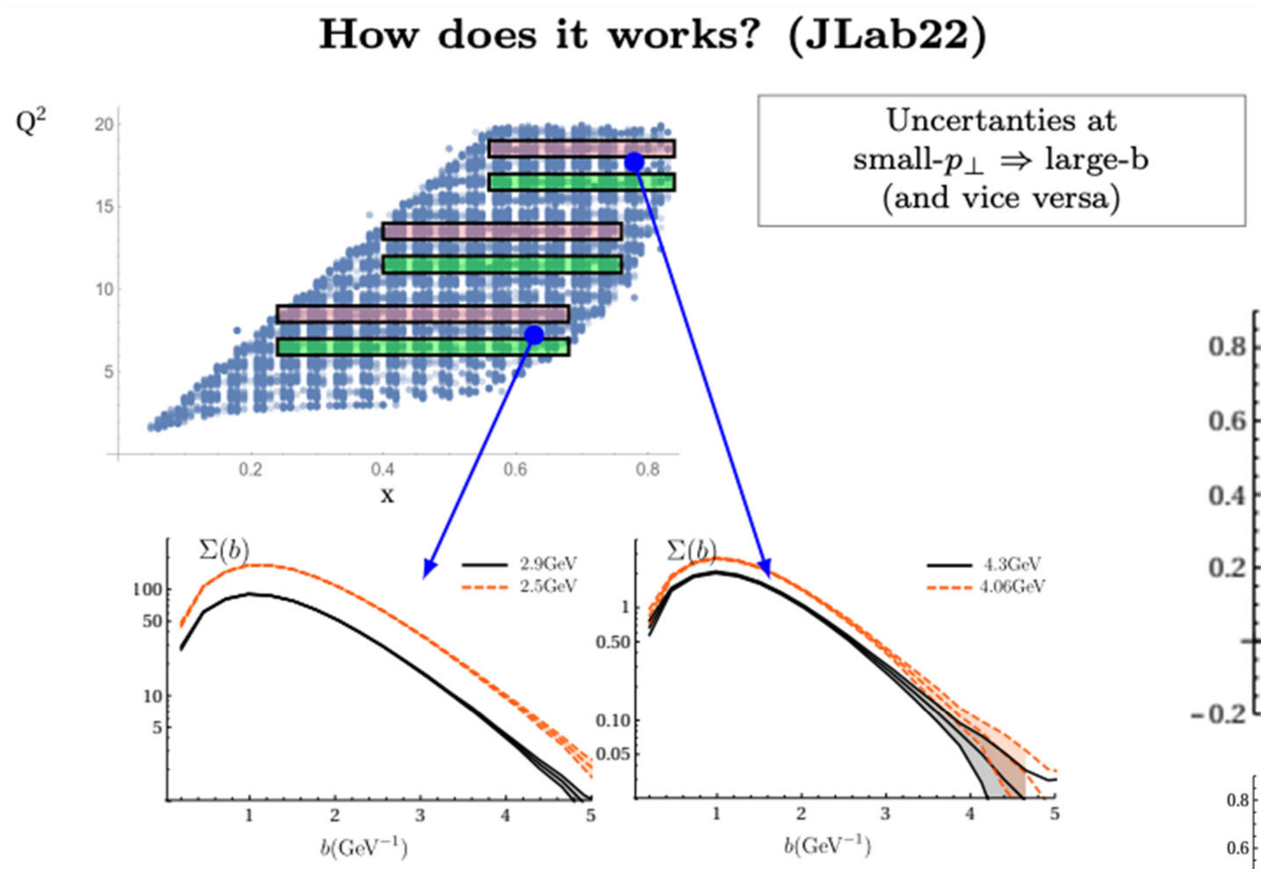
Large x events all in region of small y_F=1.0-E'/Ebeam



$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

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

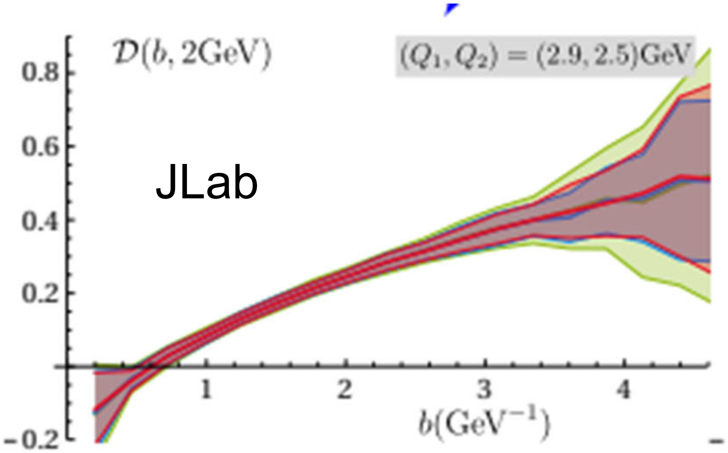
Extracting the CS kernel

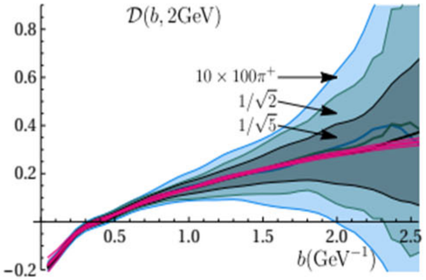


How does it works? (JLab22)

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

Complementarity:
JLab access large b





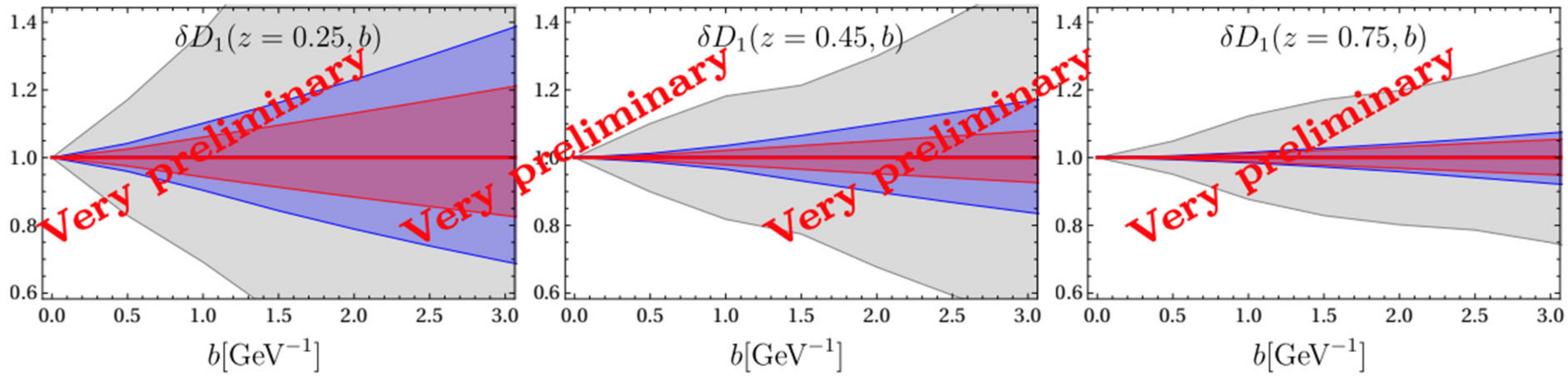
EIC

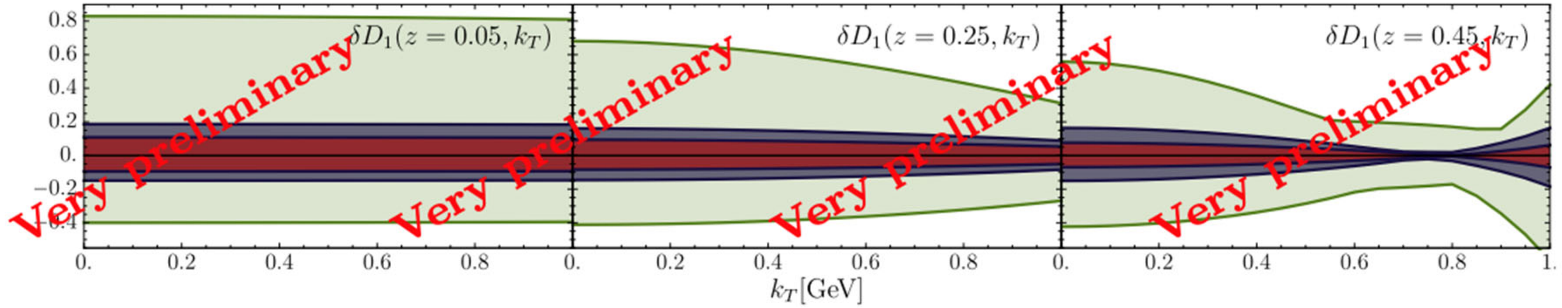
Understanding the TMD phenomenology

Link to the zoom video of A. Vladimirovs 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

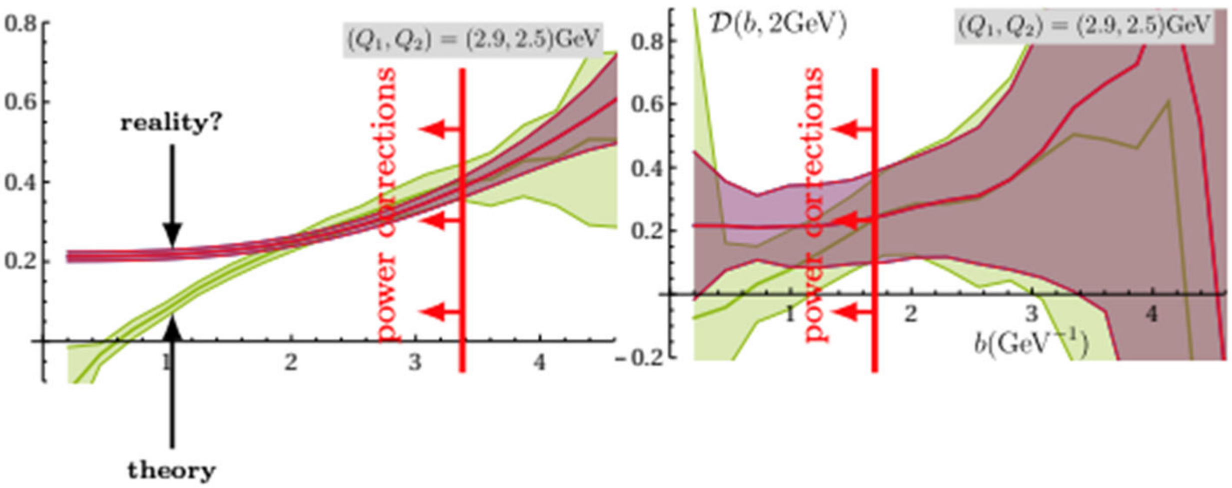
Impact on fragmentation function studies, preliminary, biased (JLab22-red, EIC-blue)



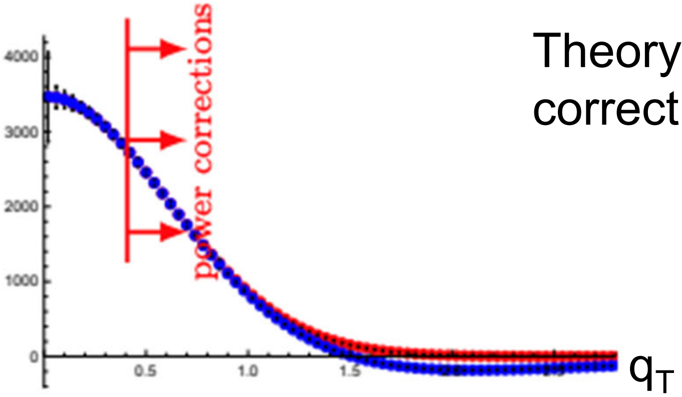


Extracting the CS kernel

More realistic picture

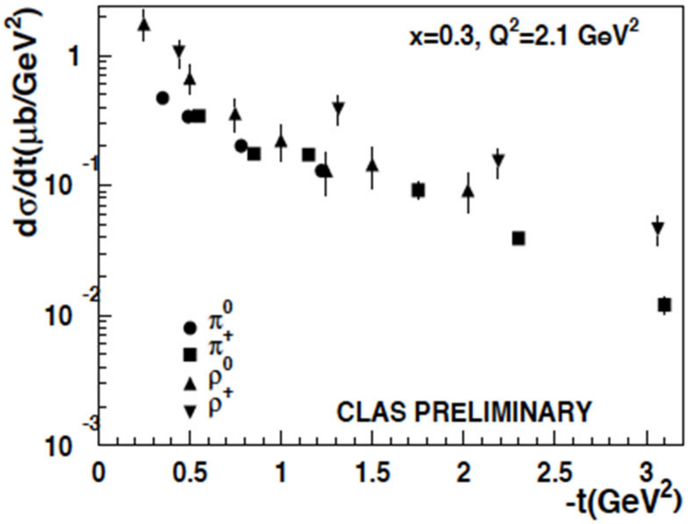


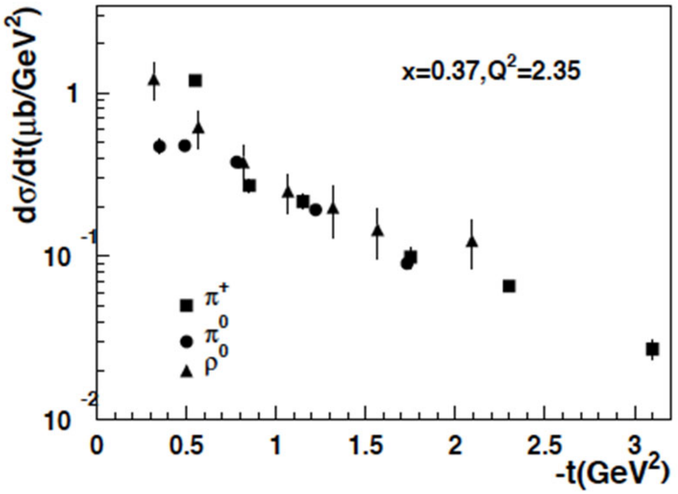
x-section goes negative (blue line)

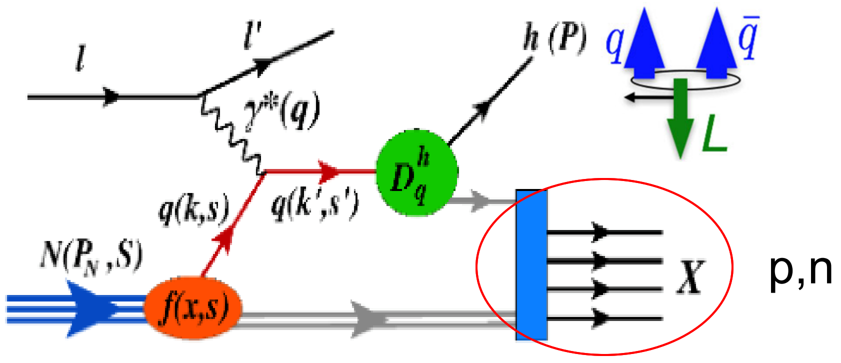


Theory gets large power corrections, have to sort out that

Exclusive π/ρ production at large t





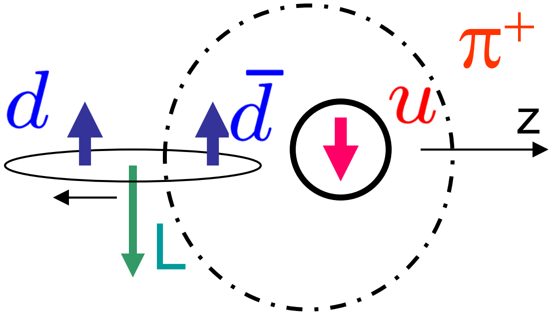


Implications

- 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
- ………

SSA for pions from ρ (Collins effect,…)

Simple string fragmentation for pions (Artru model)



leading pion out of page

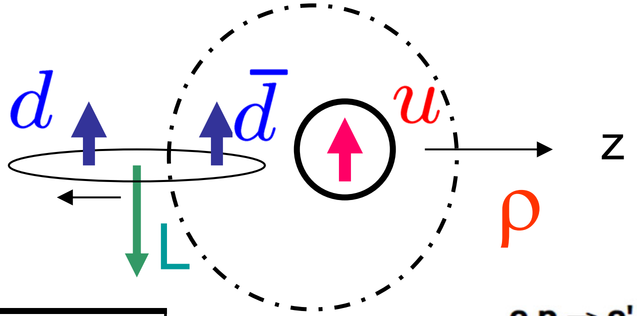
$$h_1 H_1^{\perp u\to\pi}$$

Leading ρ opposite to leading π(into page)

$$H_1^{\perp u\to\rho} \sim -\frac{1}{3} H_1^{\perp u\to\pi}$$

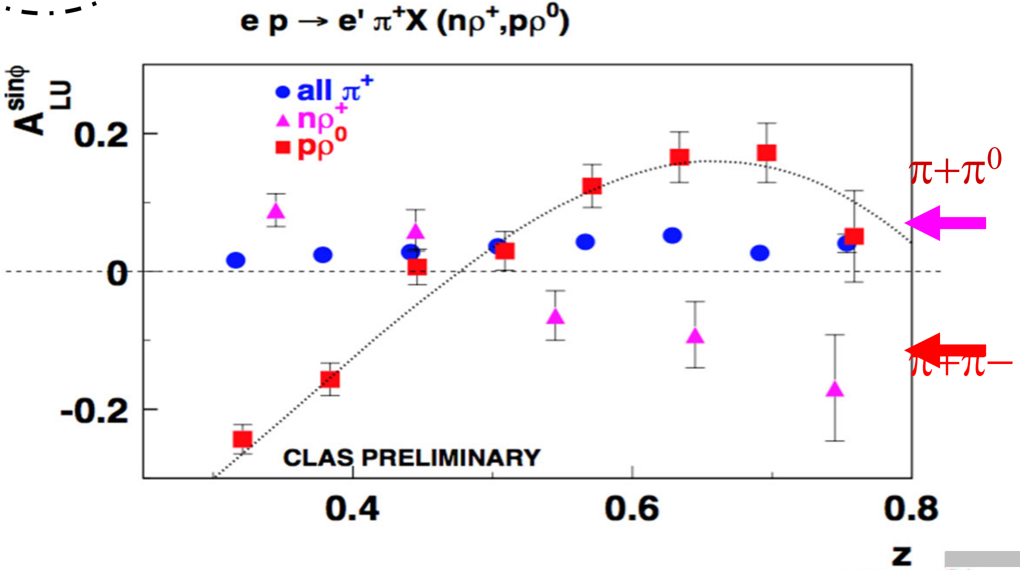
hep-ph/9606390

ρ production may produce an opposite sign A_{UT}



Fraction of ρ in eπX	% left from eπX asm
20% 40%	~75% ~50%

Pions from rho decays may require special treatment for understanding of certain observables

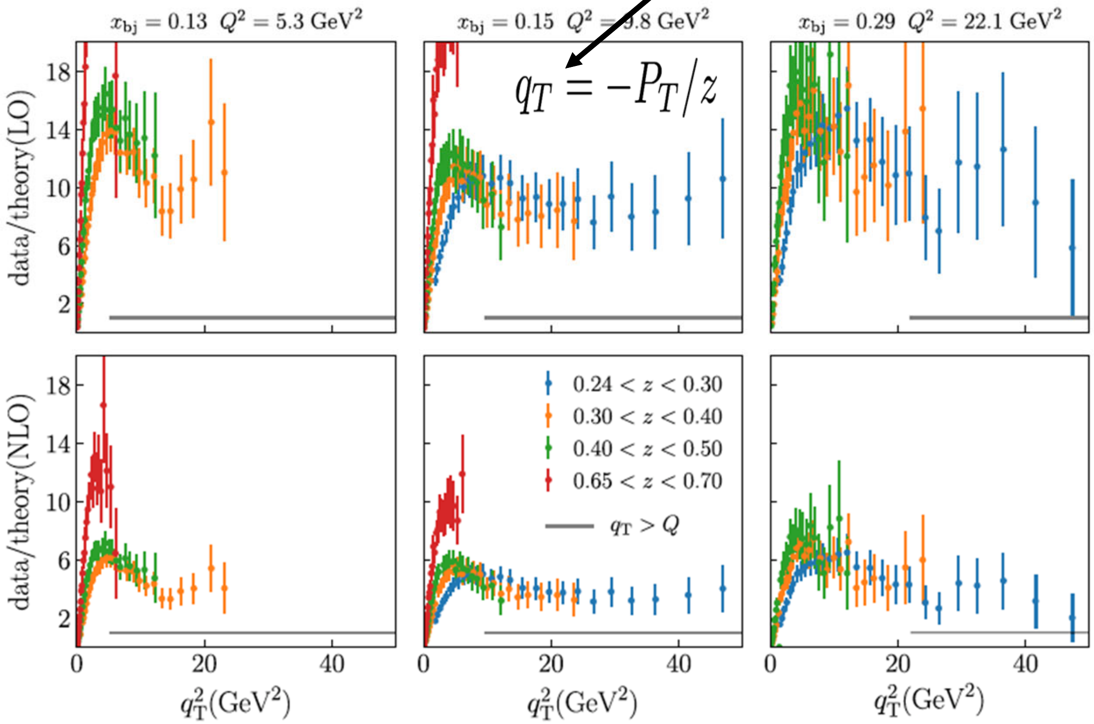


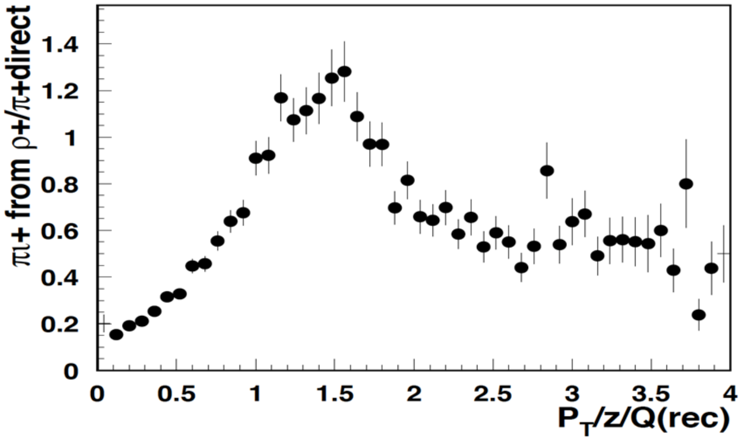
Does it matter if the pion comes from correlated pairs?

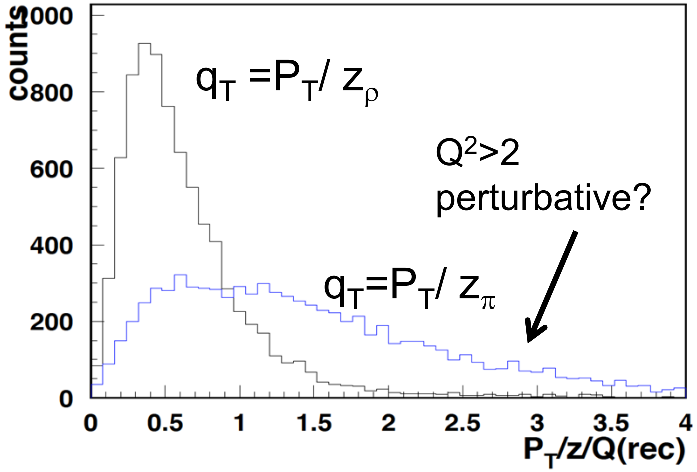
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

quark transverse momentum







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)

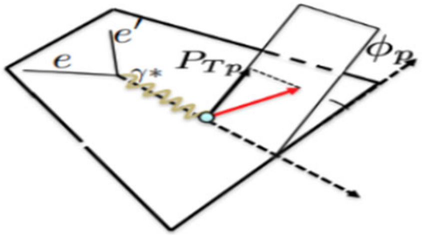
understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of q_T distributions

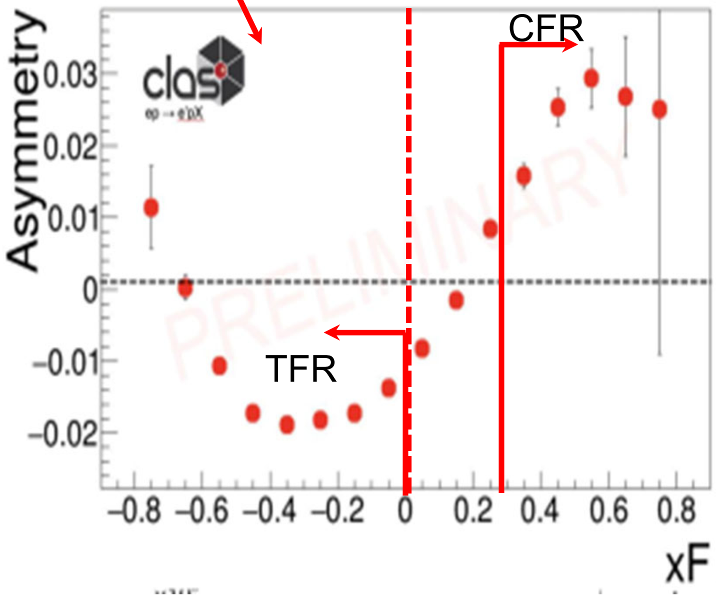
SSA in ep→e'pX production

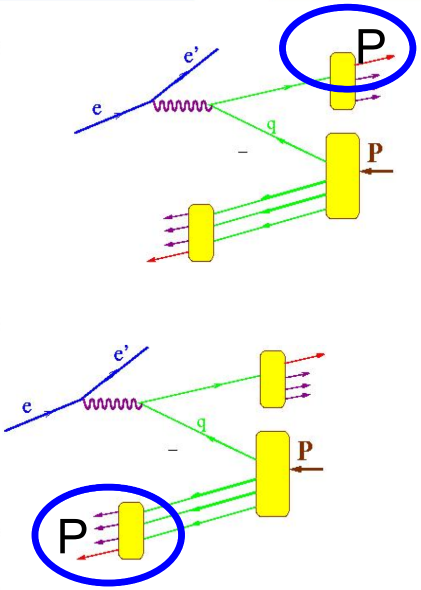
F. Benmokhtar (CPHI-2022)

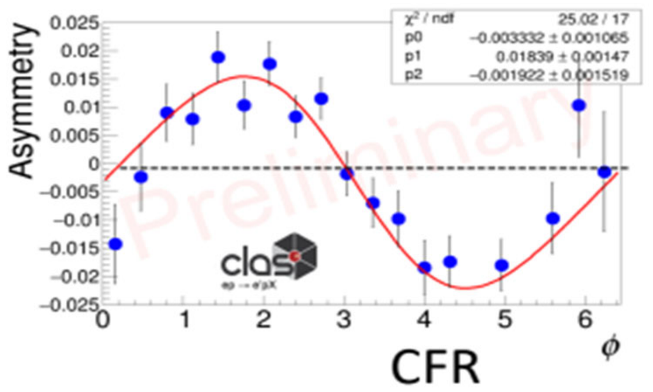
Nq	U	L	T
U	$\hat{u}_2^{\perp h}$	$\hat{l}_2^{\perp h}$	$\hat{t}_2, \hat{e}_2$
L	$\hat{u}_{2L}^{\perp h}$	$\hat{l}_{2L}^{\perp h}$	$\hat{t}_{2L}, \hat{e}_{2L}$
T	$\hat{u}_{2T}^{\perp\prime h}, \hat{u}_{2T}^{\perp h}$	$\hat{l}_T, \hat{l}_{2T}^{\perp h}$	$\hat{t}_{2T}^{h}, \hat{e}_{2T}^{h}, \hat{t}_{2T}^{\perp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

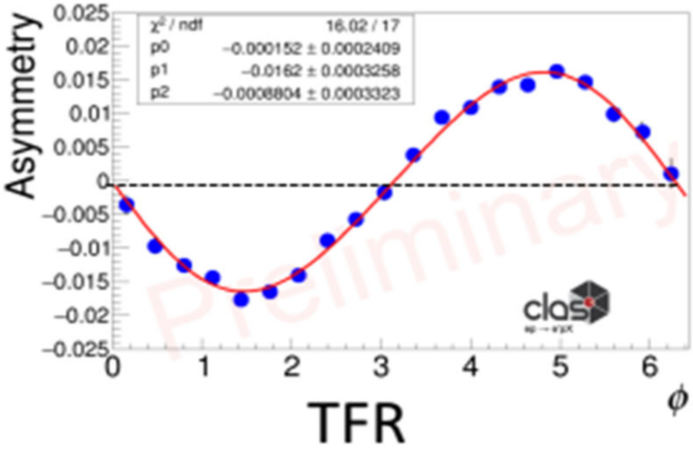
$$A(\phi)_{LU} = \frac{1}{p}\left(\frac{N^+ - N^-}{N^+ + N^-}\right) \rightarrow F_{LU}^{\sin\phi_h} = \frac{A(\phi)_{LU}}{\sqrt{2\varepsilon(1-\varepsilon)}}$$











- 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