Experimental Studies of Evolution Properties of Structure Functions in Polarized SIDIS

Harut Avakian (JLab)

Apr 12 – 14, 2023, Minneapolis, Minnesota

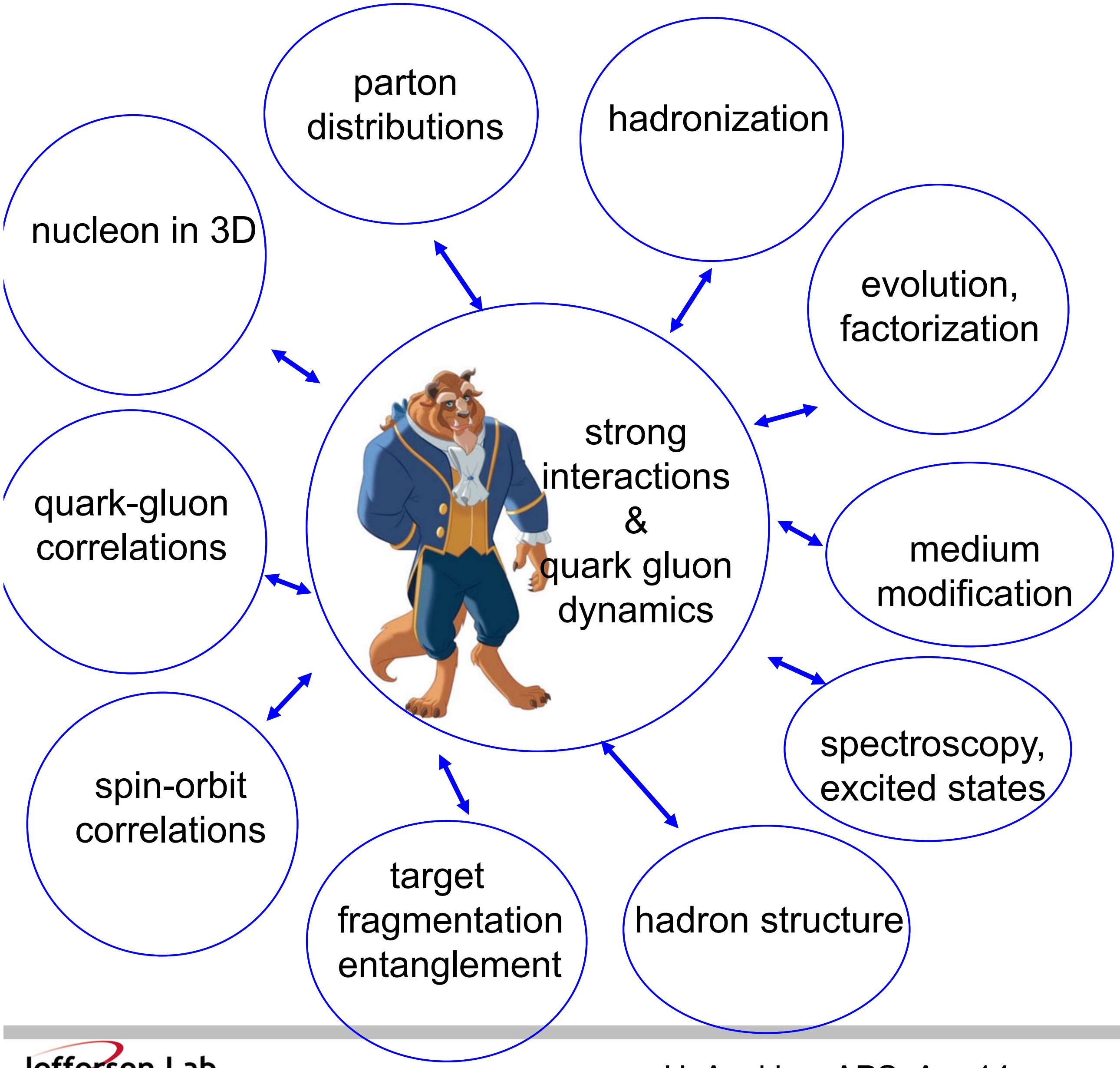
10th workshop of the APS Topical Group on Hadronic Physics

Understanding the QCD: from observables to QCD dynamics

- Testing the QCD based frameworks for finite energies in SIDIS with experiments with polarized beams and targets
- Studies of evolution properties of observables
- Impact of multihadron correlations

Summary

QCD: from testing to understanding



strong interactions & quark gluon dynamics

parton distributions

hadronization

evolution, factorization

medium modification

spectroscopy, excited states

hadron structure

target fragmentation entanglement

spin-orbit correlations

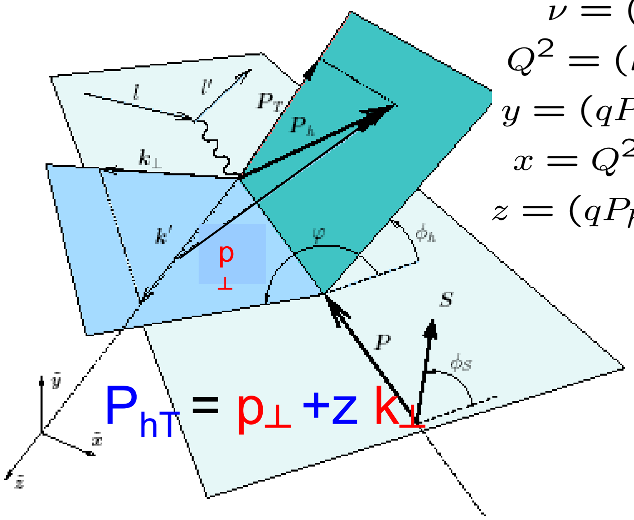
quark-gluon correlations

nucleon in 3D

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

Understanding stage:
non-perturbative QCD, observables in the real life kinematics where most of the data is available and interactions are strong (more complex observables revealing details of the dynamics,…)

SIDIS kinematical coverage and observables



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

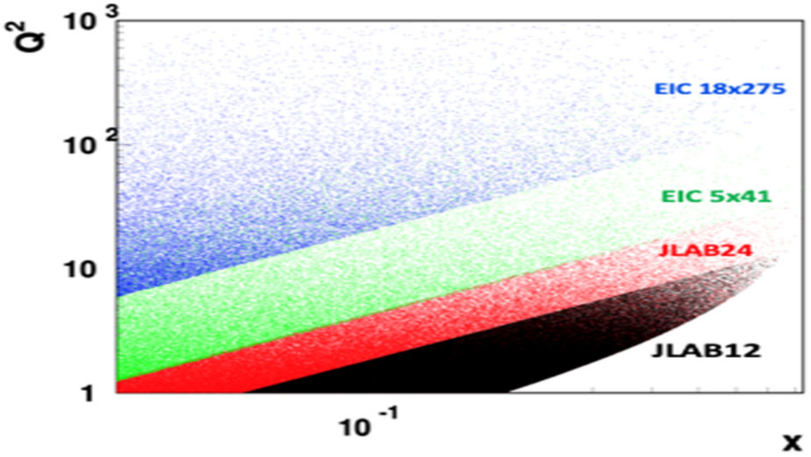
$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

hermes

COMPASS

Jefferson Lab

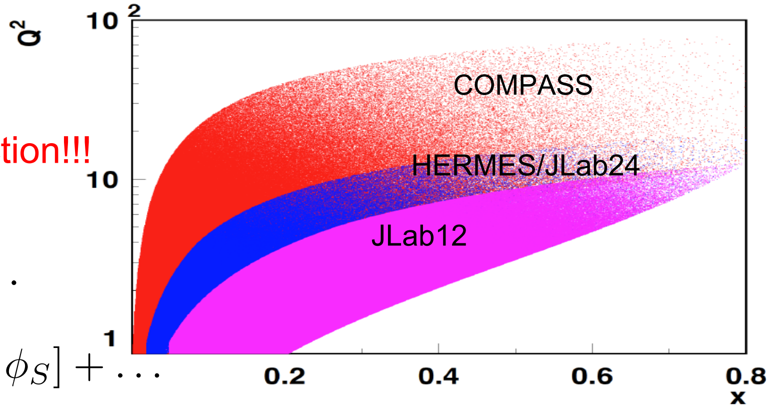
EIC² EIC Center at Jefferson Lab



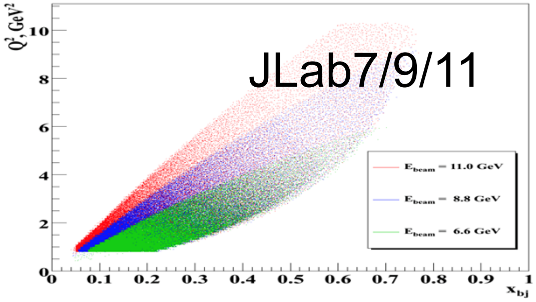
SIDIS experiments measure azimuthal dependence of the cross section!!!

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

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



- Studies of azimuthal modulations give access to underlying 3D partonic distributions
- All azimuthal modulations increase with P_T
- All assumptions involved in description of SFs, should be tested!
- QCD predicts only the Q^2-dependence of 3D PDFs

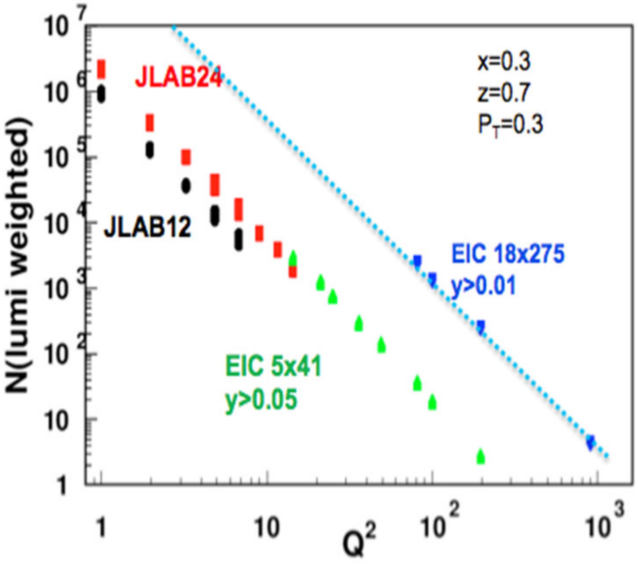


Structure functions and depolarization factors in SIDIS

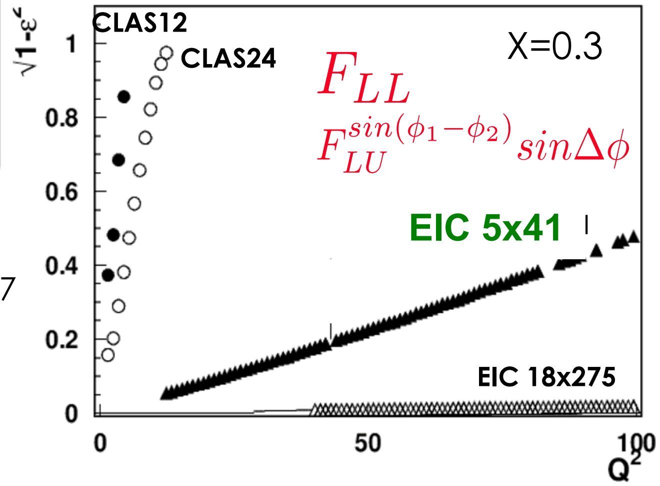
SIDIS at Large x : JLab domain!

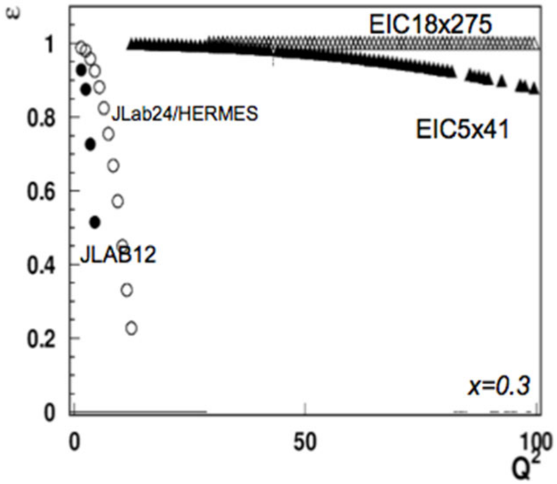
- **At large x fixed target experiments are sensitive to ALL Structure Functions**
- **For proper measurement of $F_{UU,T}$, need $F_{UU,L}$ measured and subtracted, not trivial at higher energies ($\varepsilon \rightarrow 1$)**

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$
$$+ S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$
$$+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}$$
$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Bigg\}$$



x-section from Bacchetta et al, 1703.10157





Combination of statistics and depolarization factors defines measurable SFs

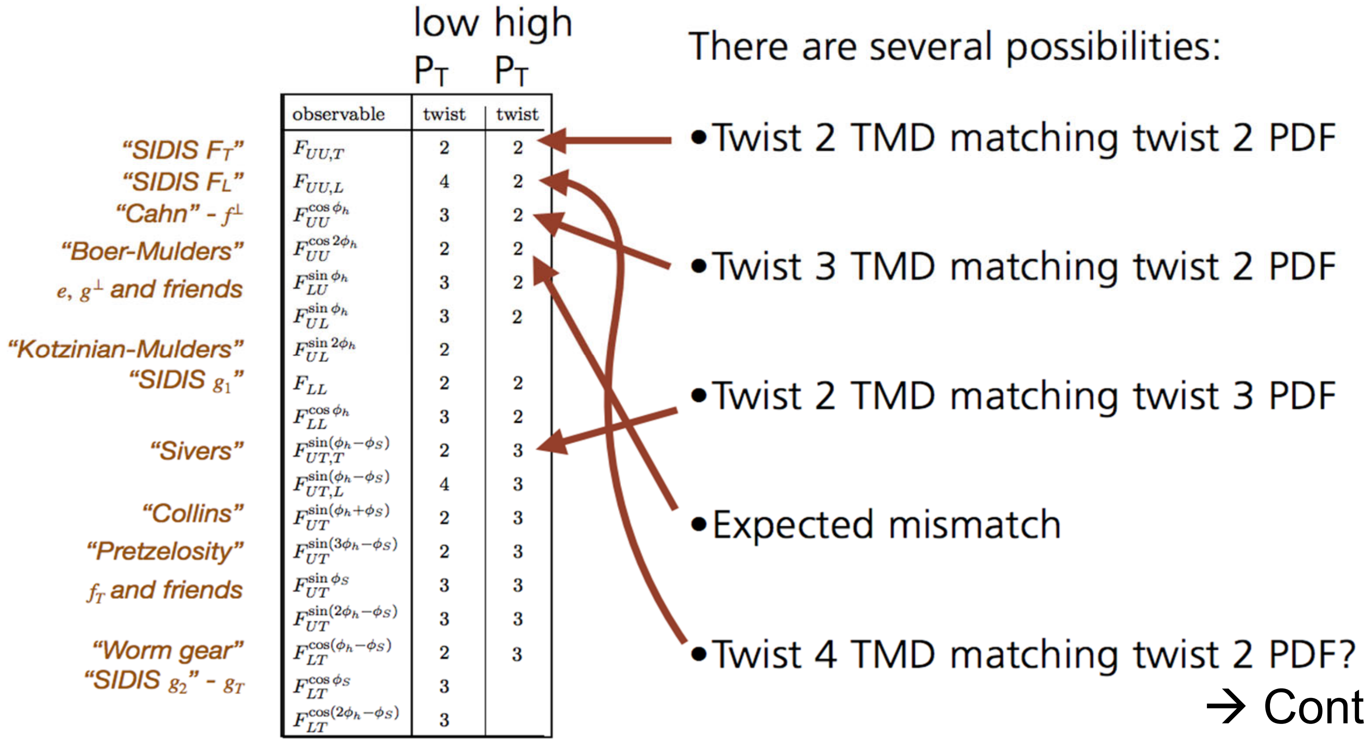
Steps to control the systematics in interpretation

- 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 of P_T-dependences of observables in the full range of P_T dominated by non-perturbative physics
  2. Understanding of phase space effects is important (additional correlations)
  3. Understanding the role of vector mesons in independent fragmentation
  4. Understanding of evolution properties and longitudinal photon contributions
  5. Understanding of correlations in hadron production in hard scattering
  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

Longitudinal photon contributions in SIDIS

A. Bacchetta



	observable	low P_T twist	high P_T twist
"SIDIS F_T"	$F_{UU,T}$	2	2
"SIDIS F_L"	$F_{UU,L}$	4	2
"Cahn" - $f^\perp$	$F_{UU}^{\cos\phi_h}$	3	2
"Boer-Mulders"	$F_{UU}^{\cos 2\phi_h}$	2	2
e, $g^\perp$ and friends	$F_{LU}^{\sin\phi_h}$	3	2
	$F_{UL}^{\sin\phi_h}$	3	2
"Kotzinian-Mulders"	$F_{UL}^{\sin 2\phi_h}$	2	
"SIDIS g_1"	F_{LL}	2	2
	$F_{LL}^{\cos\phi_h}$	3	2
"Sivers"	$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	2	3
	$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	4	3
"Collins"	$F_{UT}^{\sin(\phi_h+\phi_S)}$	2	3
"Pretzelosity"	$F_{UT}^{\sin(3\phi_h-\phi_S)}$	2	3
f_T and friends	$F_{UT}^{\sin\phi_S}$	3	3
	$F_{UT}^{\sin(2\phi_h-\phi_S)}$	3	3
"Worm gear"	$F_{LT}^{\cos(\phi_h-\phi_S)}$	2	3
"SIDIS g_2" - g_T	$F_{LT}^{\cos\phi_S}$	3	
	$F_{LT}^{\cos(2\phi_h-\phi_S)}$	3	

There are several possibilities:

- Twist 2 TMD matching twist 2 PDF
- Twist 3 TMD matching twist 2 PDF
- Twist 2 TMD matching twist 3 PDF
- Expected mismatch
- Twist 4 TMD matching twist 2 PDF?

→ Contributes everywhere,
→ we know nothing!!!

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2} = \frac{2\pi\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left\{2\pi F_{UU,T}(x,z,P_{h\perp}^2,Q^2) + \varepsilon\,2\pi F_{UU,L}(x,z,P_{h\perp}^2,Q^2)\right\}$$

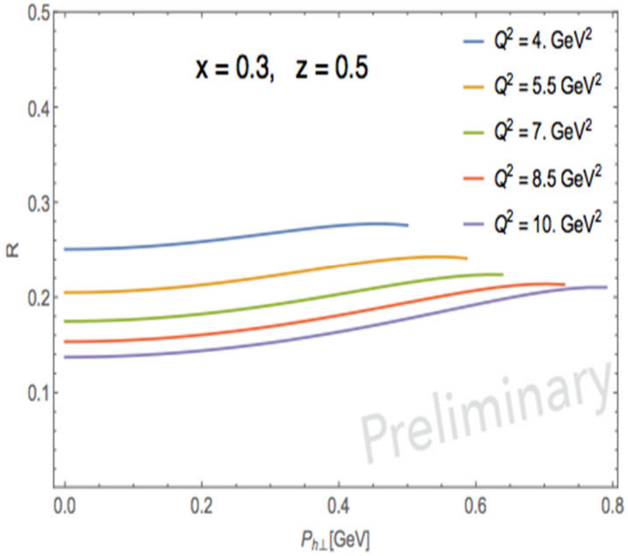
$$\frac{d\sigma}{dx\,dy\,dz} = \frac{4\pi\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left\{F_{UU,T}(x,z,Q^2) + \varepsilon\,F_{UU,L}(x,z,Q^2)\right\}$$

$$R = \frac{F_{UU,L}}{F_{UU,T}}$$

$F_{UU,L}$ possible behavior

A. Bacchetta

Low transverse momentum		High transverse momentum	Integrated
$F_{UU,T} = \mathcal{C}\Big[f_1 D_1\Big]$	Twist 2	$F_{UU,T} = \frac{\alpha_s}{P_{h\perp}^2}\Big[f_1 \otimes D_1\Big]_A$	$F_{UU,T} = x f_1 D_1 + \alpha_s \Big[f_1 \otimes D_1\Big]_C$
$F_{UU,L} = \mathcal{O}\left(\frac{M^2}{Q^2}, \frac{P_{h\perp}^2}{Q^2}\right)$	Twist 4	$F_{UU,L} = \frac{\alpha_s}{P_{h\perp}^2}\frac{P_{h\perp}^2}{Q^2}\Big[f_1 \otimes D_1\Big]_B$ $= 2\,F_{UU}^{\cos 2\phi_h}$	$F_{UU,L} = \alpha_s \Big[f_1 \otimes D_1\Big]_D$



$$F_{UU,L} = \frac{M^2}{Q^2}\mathcal{C}\left[\frac{4k_T^2}{M^2}f_1 D_1 + \frac{m^2}{M^2}f_1 D_1 + \tilde{f}_2 D_1 + f_1 \tilde{D}_2 + \ldots\right]$$

kinematic twist 4
(à la Wandzura-Wilczek)

mass corrections

dynamic twist 4

sometimes denoted with

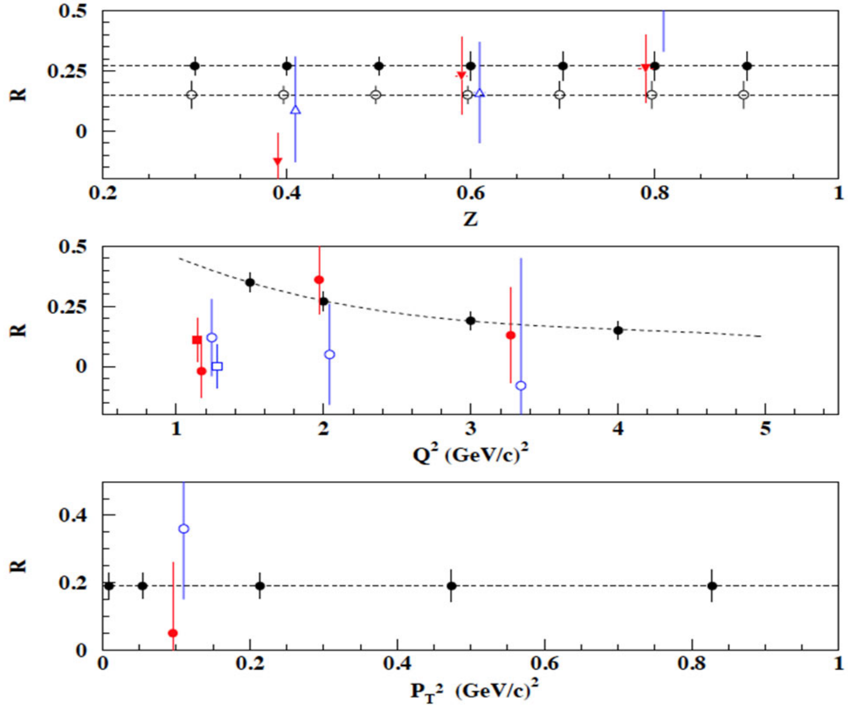
f_3

factorization breaking terms?

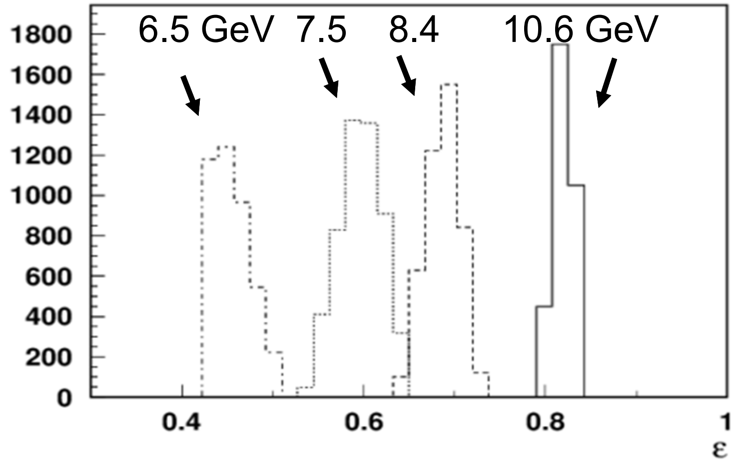
$F_{UU,L}$ tends to stay large even at Q^2>100GeV^2 !!!
20% in average, may mean dominant at large P_T!!!

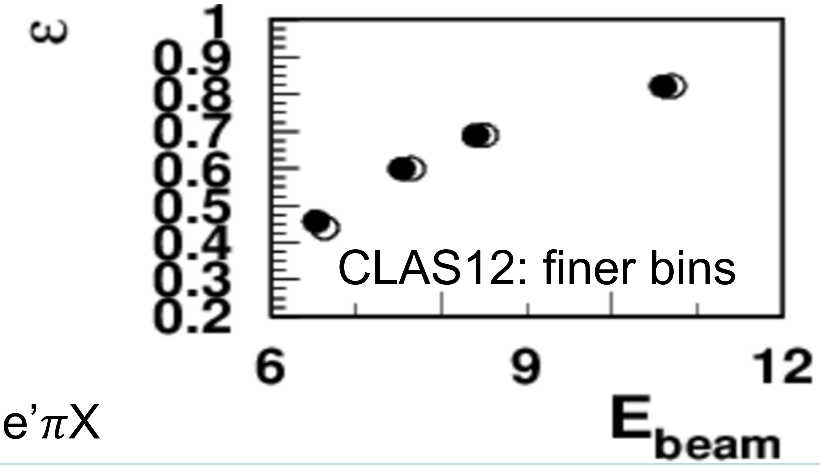
Measuring $F_{UU,L}$ at JLab

Hall-C: E12-06-104



$0.32<x<0.34,2.9<x<Q^2<3.1$





CLAS12: finer bins

- Projections vs existing Cornell Data (projections assume RSIDIS = RDIS)
- Projections: Solid Black H, Open Black D e'πX

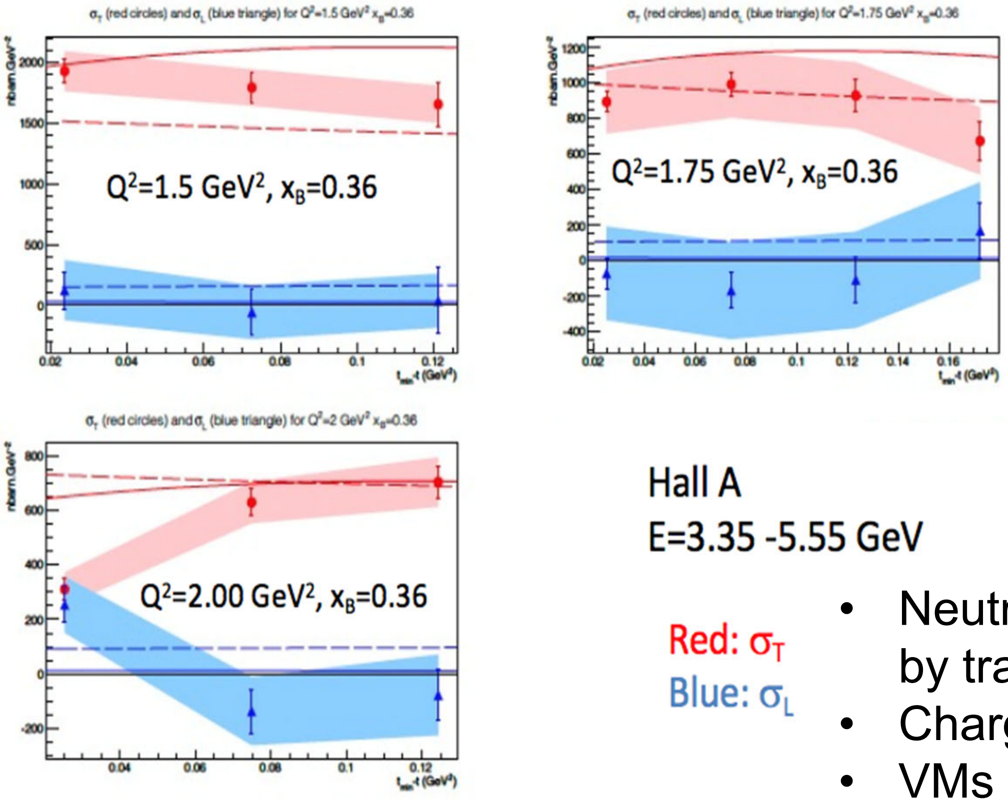
Complementarity of JLab Halls:
Precision measurements (Hall-C) combined with wide acceptance (Hall-B)

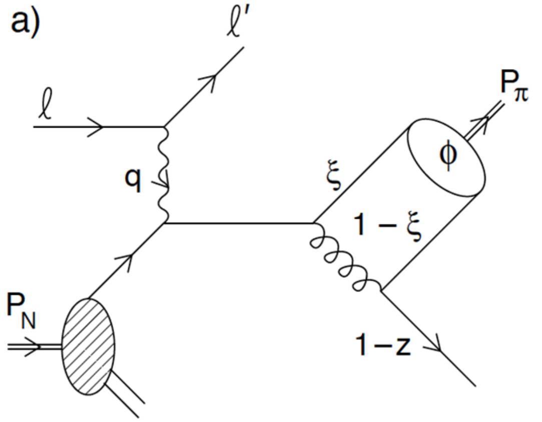
Longitudinal contributions in exclusive limit

Measured in exclusive limit for π0

predicted in semi-exclusive limit

DVMP (π^0) L/T Separation





Hall A

E=3.35 -5.55 GeV

Red: σ_T

Blue: σ_L

- Neutral pions seem to be dominated by transverse photons
- Charged pions may be more affected
- VMs known to have large longitudinal photon contributions

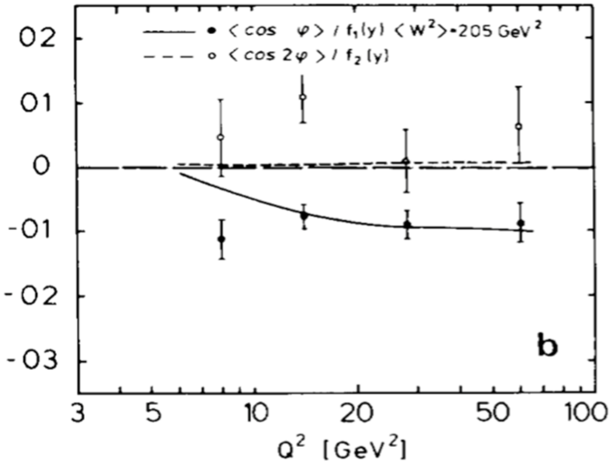
M. Defurne Phys. Rev. Lett. 117 (2016) 26, 262001

Azimuthal distributions in SIDIS (unpolarized)

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

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

EMC-1983 (PL,v130,118)



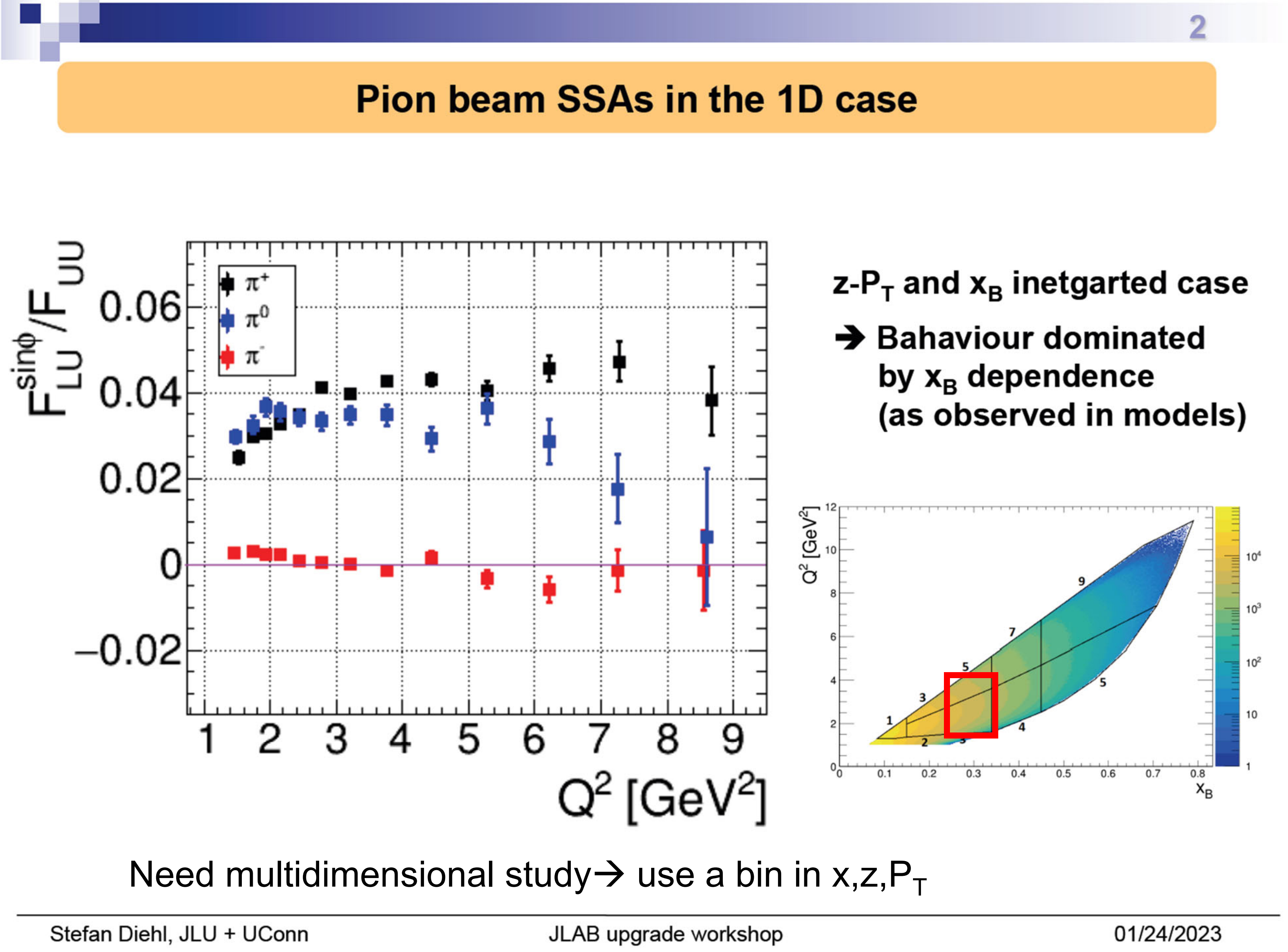
Observables: - Azimuthal Moments - Multiplicity

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

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

- Quark-gluon correlations are significant in electro production experiments (even if at high energy).
- Large cosϕ modulations observed in electroproduction (EMC, COMPASS, HERMES) may be a key in understanding of the QCD dynamics.

Attempts to understand Q^2-dependence of HT



Pion beam SSAs in the 1D case

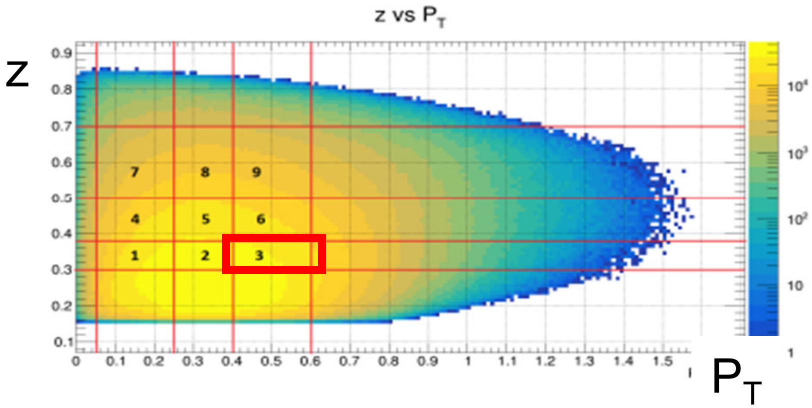
z-P_T and x_B inetgarted case

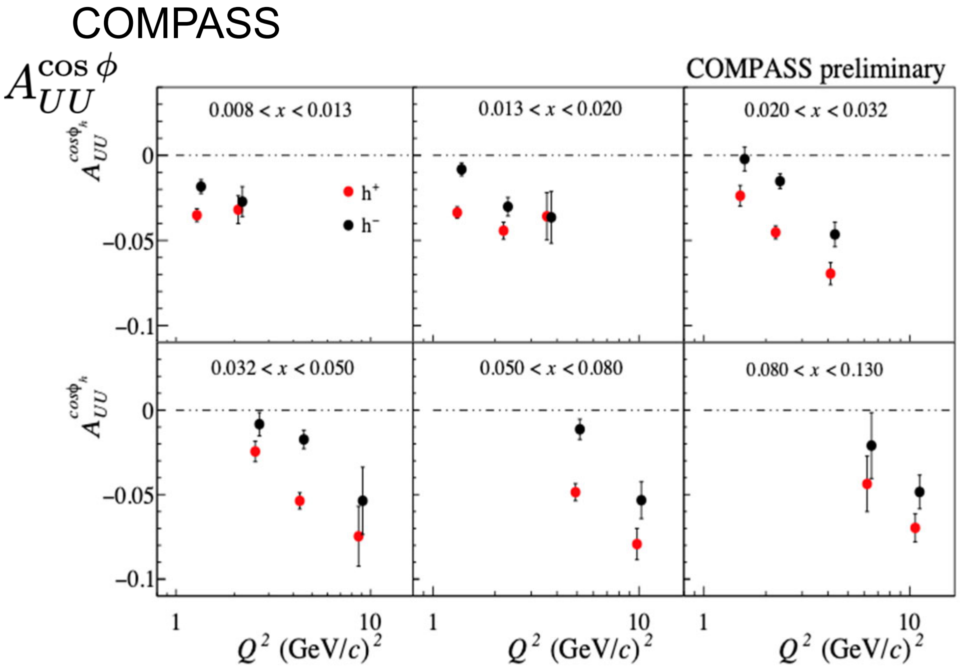
➔ Bahaviour dominated by x_B dependence (as observed in models)

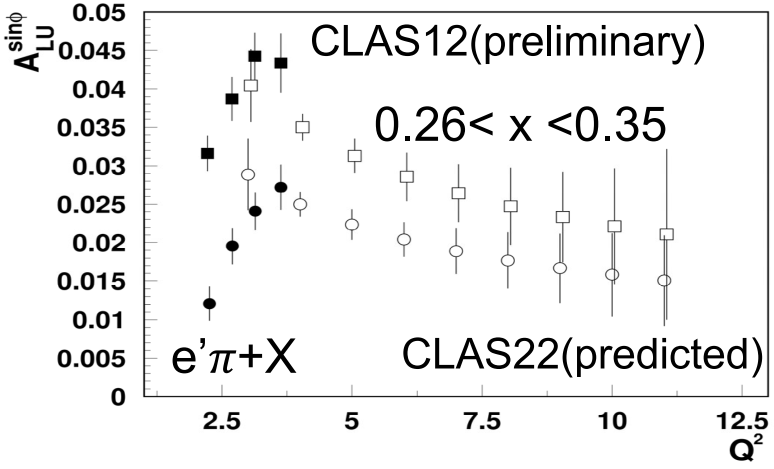
Need multidimensional study→ use a bin in x,z,P_T

Stefan Diehl, JLU + UConn JLAB upgrade workshop 01/24/2023

Attempts to understand Q^2-dependence of HT





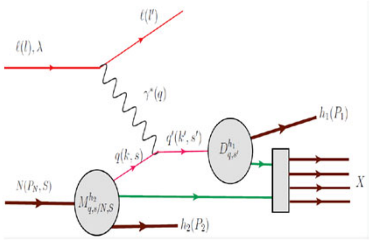


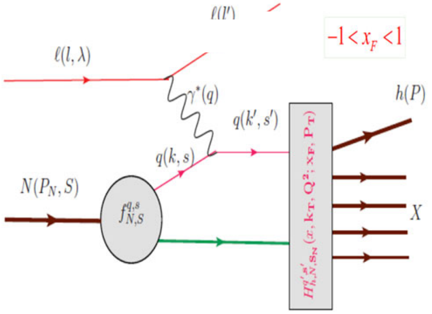
- We always measure ratio to $F_{UU,T} + \varepsilon F_{UU,L}$
- Separation of $F_{UU,T}$ critical

- The moments defined as a ratio to ϕ-independent x-section(to $F_{UU,T}$), 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**
- Checking the Q^2 and P_T-dependences of the $F_{UU,L}$ may provide crucial input for validation

MC simulations: Why LUND works?

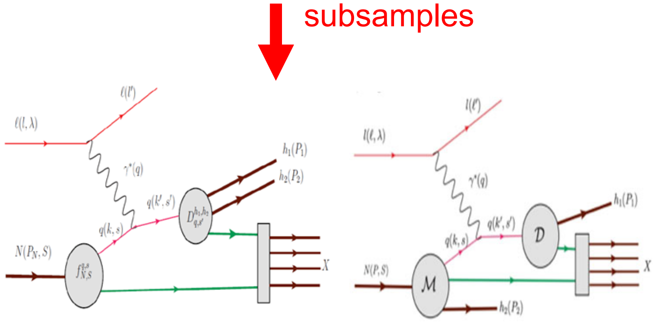
- A single-hadron MC with the SIDIS cross-section where widths of k_T-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.





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
- ….

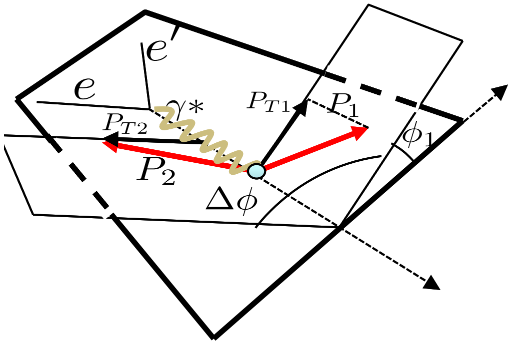


To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

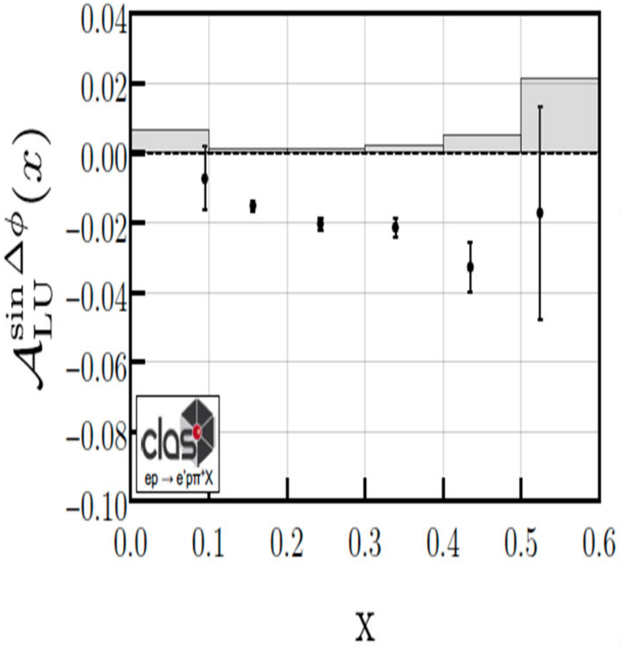
The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!

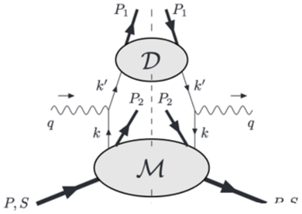
Correlations of hadrons in current and target fragmentation

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

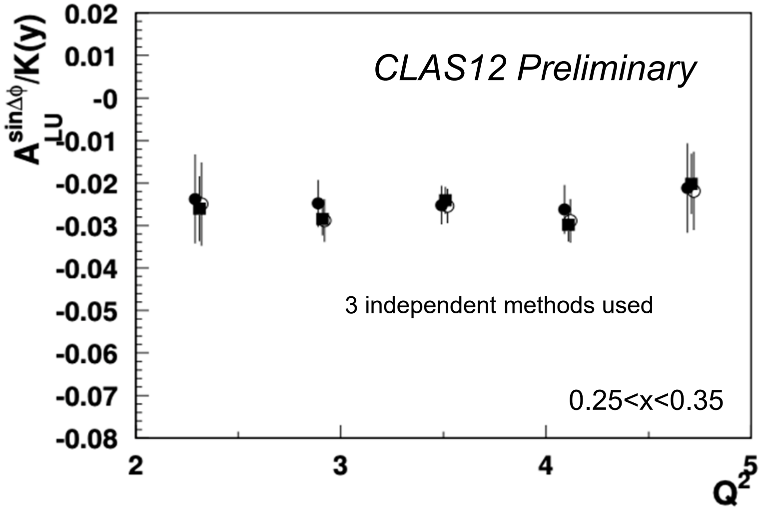


ep→e'pπ+X



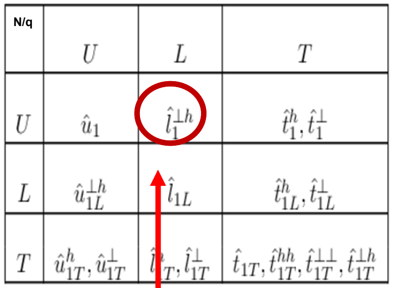


$$A_{LU} \propto \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi$$



arXiv: 2208.05086 (PRL-2023)

Twist-2 table
(Fracture Functions)



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

- SSA significant at large x, where the valence quarks (non-perturbative sea) dominate?
- Correlation asymmetry is linked to Leading Twist(LT) distributions of longitudinally polarized quarks
- First indication in large x SIDIS of a LT observable
- Correlation between the struck quark and the remnant produces correlation between hadrons (entanglement)
- Multidimensional measurements crucial for evolution studies

TMDs IN Semi-Inclusive DIS

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$$

$$= x \sum_q \boxed{\mathcal{H}_{UU,T}^q(Q^2, \mu^2)} \int d^2\boldsymbol{k}_\perp \, d^2\boldsymbol{P}_\perp \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu^2) \, D_1^{a\to h}(z, \boldsymbol{P}_\perp^2; \mu^2) \, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp)$$

$$+ Y_{UU,T}(Q^2, \boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

Major advance in theory in last years

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^2} e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} f_1^q(x, k_\perp^2; \mu_f, \zeta_f)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \, e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\text{resum}} + g_K} f_{1\,NP}(x, b_T^2; \zeta_f, Q_0)$$

collinear PDF

matching coefficients (perturbative)

Collins-Soper kernel (perturbative and nonperturbative)

nonperturbative part of TMD

$$g_K(b_T^2) = -g_2^2 \frac{b_T^2}{4}$$

CS kernel discribes the interaction of out-going parton with the confining potential

Provides nonperturbative part of evolution for TMDs

CS-kernel→independent on any other variables

SIDIS Validation tests: Collins-Soper kernel

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

$$\int_0^\infty \frac{bdb}{(2\pi)^2}J_0\left(\frac{k_\perp b}{z}\right)\underbrace{R[b,Q\to\mu]}_{\text{Evol.factor our goal!}}|C_V(Q)|^2\sum_f e_f^2 \underbrace{f_1(x,b;\mu)d_1(z,b;\mu)}_{\text{TMDs}}$$

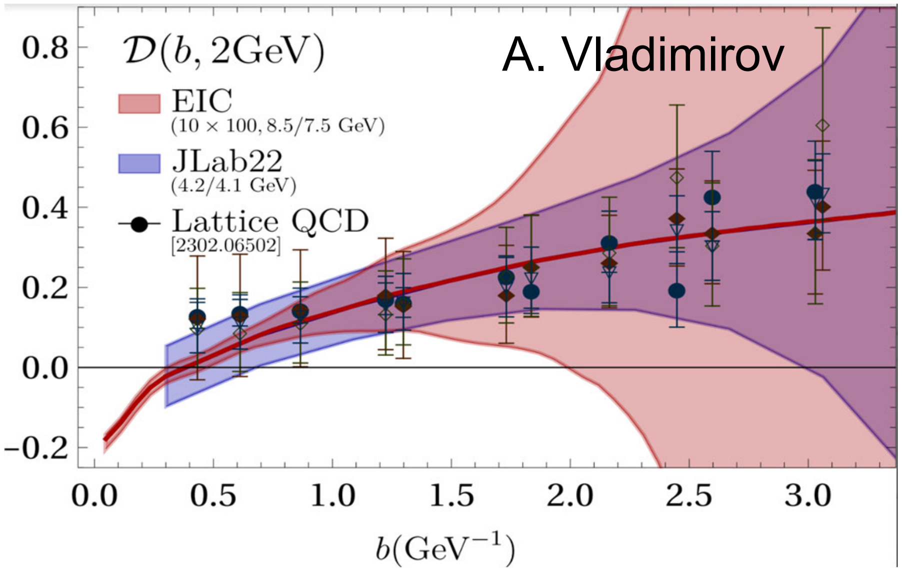
- **Ultimate test of factorization hypothesis**
  - Different (Q, x, z) MUST result into the same curve
  - Different final states $(\pi^\pm, K^\pm)$ MUST result into the same curve
  - ⇒ comparing Collins-Soper kernel obtained in different regimes we can scan the kinematic range and determine size of **TMD-factorization violation**

A. Vladimirov

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)



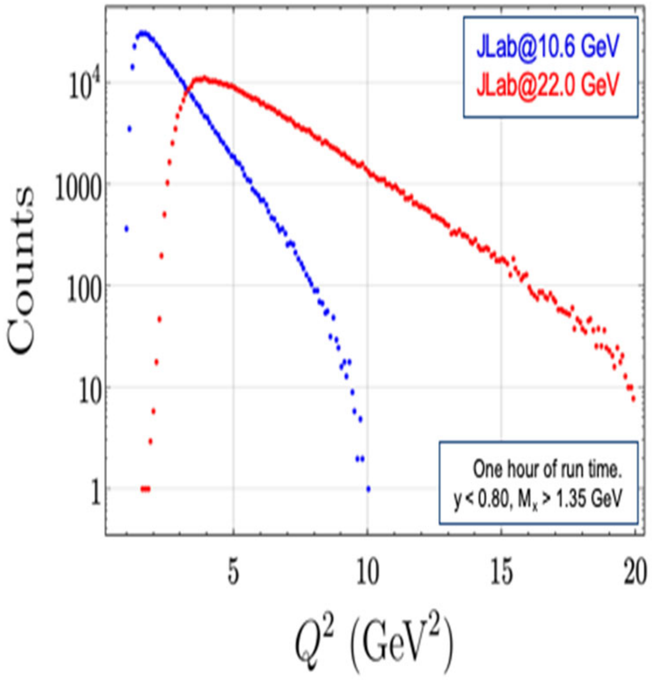
A. Vladimirov

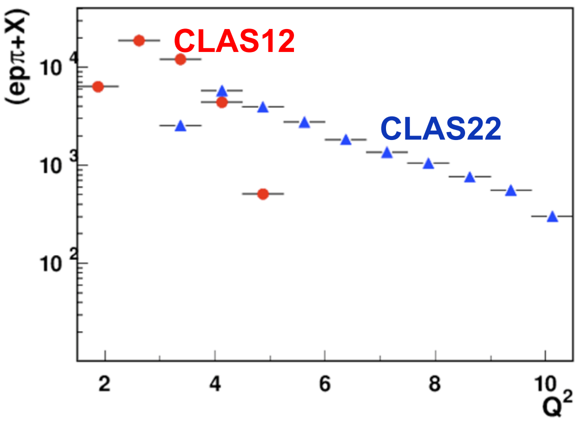
Different experiments most sensitive to different ranges in b

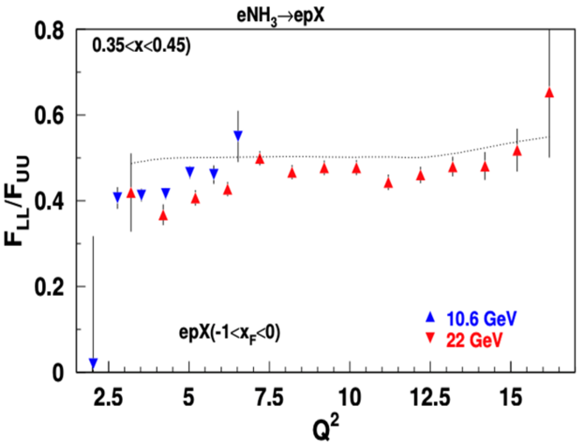
- JLab ~1<b<4
- EIC ~0.5<b<1.2
- LHC b<0.5
- COMPASS overlaps

Power corrections may shift the distributions: validation critical!!!

Accessing CS-kernel directly or through extraction of SFs







- Wide Q^2 range and high luminosity is the key for a validating separation of twist-2 contributions

- Q^2 evolution studies possible, provide superior access to critical Collins-Soper (CS) kernel
- CLAS12 at JLab20+ can provide a wide range in Q^2 combined with high lumi and superior resolution

- Kinematic correlations, (P_T and Q^2, in particular) due to trivial energy and momentum conservation, may mask the real dependences (need 4D)
- Evaluate the systematics due to factorization violation and define possible reasons (some can be easy to fix)

SUMMARY

- Studies of QCD dynamics with controlled systematics involving Semi-Inclusive DIS, requires detailed understanding of the contributions into the measured cross sections/multiplicities/asymmetries as a function of all involved kinematical variables (x,Q^2,z, P_T and ϕ)

- To evaluate the systematics of extracted TMDs, it is critical to validate the formalism, and understand main contributions violating the factorized picture based on the dominance of the leading twist contributions

- Measurements of azimuthal modulations of inclusive pions, and multiplicities of pion pairs indicate very significant part of hadrons come from decays of VMs (different in kaon case) and can provide important insight in understanding the “leading twist” observables

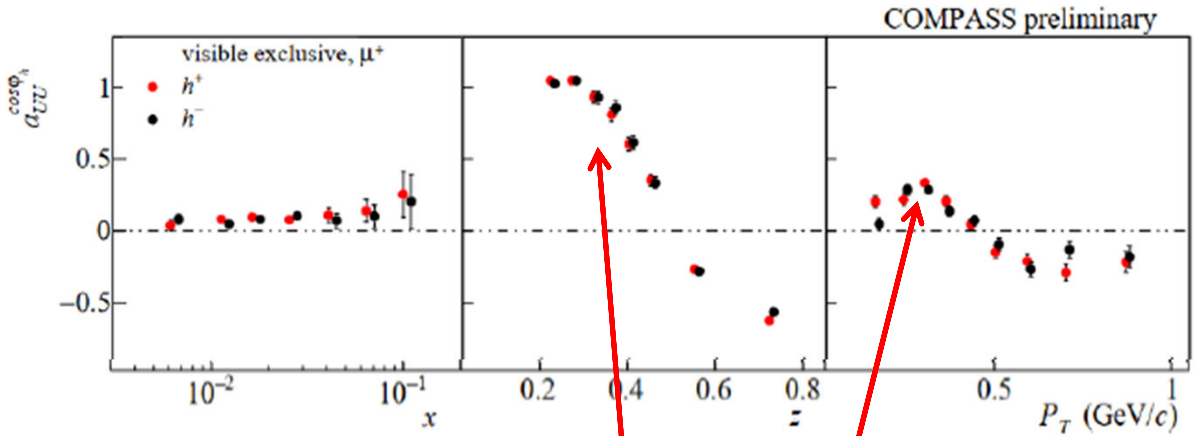
- Evolution studies observables will require multidimensional coverage of all relevant kinematics (including depolarization factors) for observables with polarized beams and targets

- Critical to have an analysis frameworks with controlled systematics to validate the phenomenology, and make credible projections for future measurements!!!

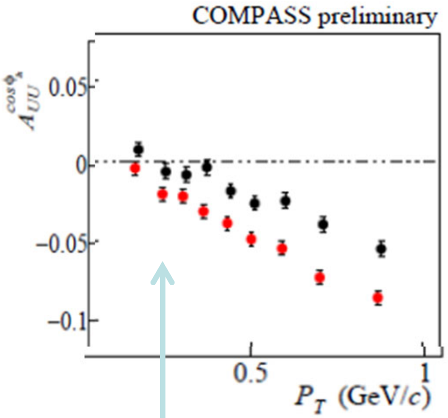
Support slides

COMAPASS multiplicities and cosine modulations

Moretti et al→ COMPASS (ECT* workshop)

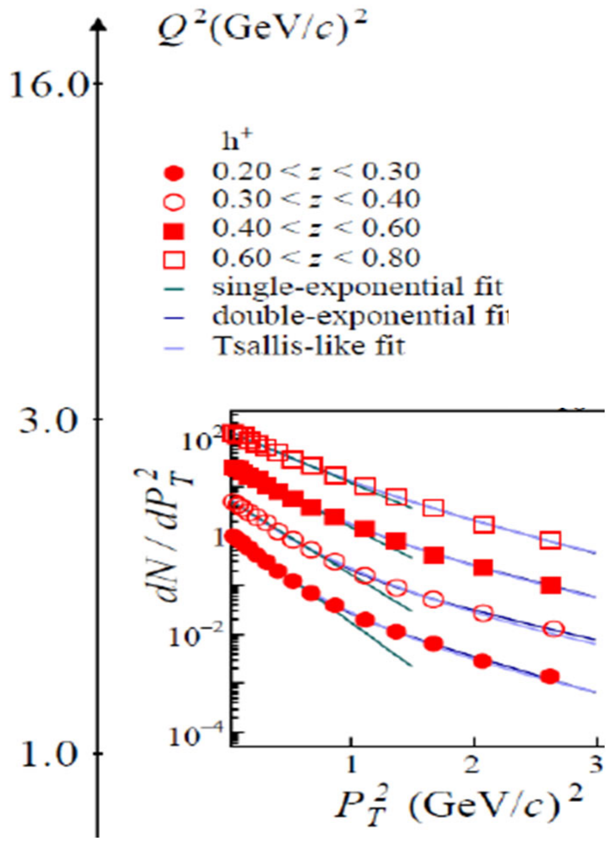


Negative cos of ρ^0 converts to positive for low P_T pions (sign flip ~z=0.5)



ρ□decay pions mess up linear dependence at low P_T

Indication of dominant VM contributions in the inclusive hadron samples, in particular at low P_T, critical for understanding of the QCD dynamics



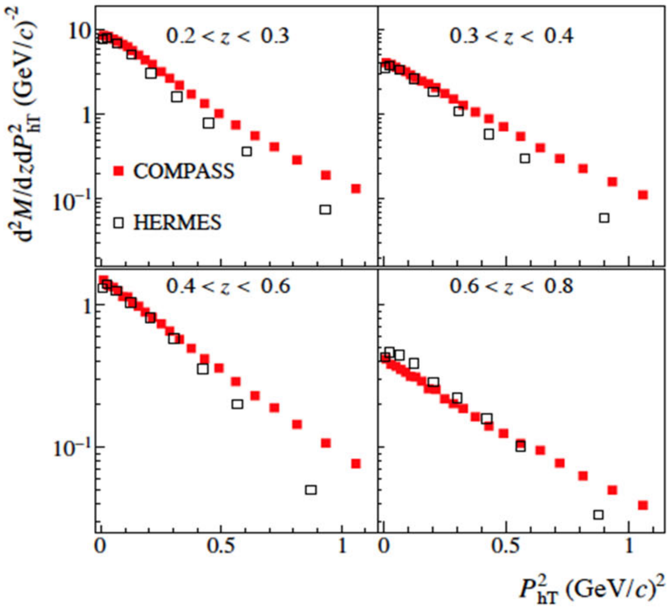
Theory is not able to explain the large P_T behavior of pion multiplicities !!!

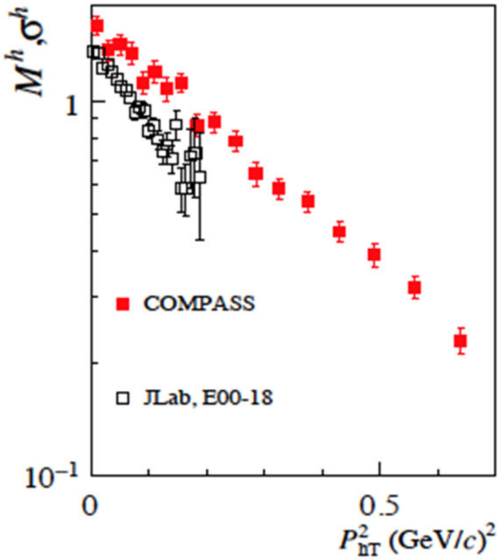
Multiplicities of hadrons in SIDIS

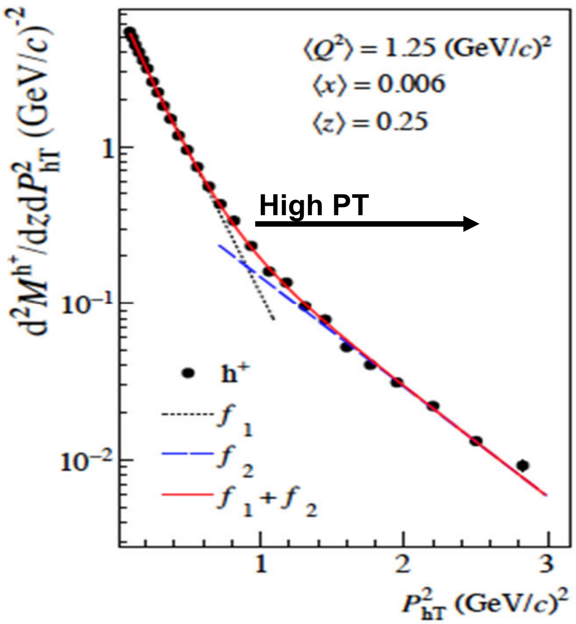
Gaussian Ansatz $\boxed{f_1^q} \otimes \boxed{D_1^{q\to h}} = x f_1^q(x)\, D_1^{q\to h}(z) \frac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$

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

COMPASS:1709.07374







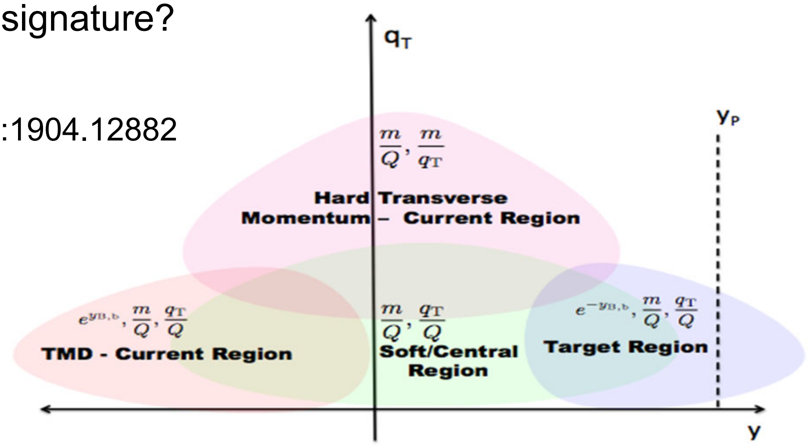
JLab: not enough energy to
produce large P_T
HERMES: not enough luminosity
to access large P_T

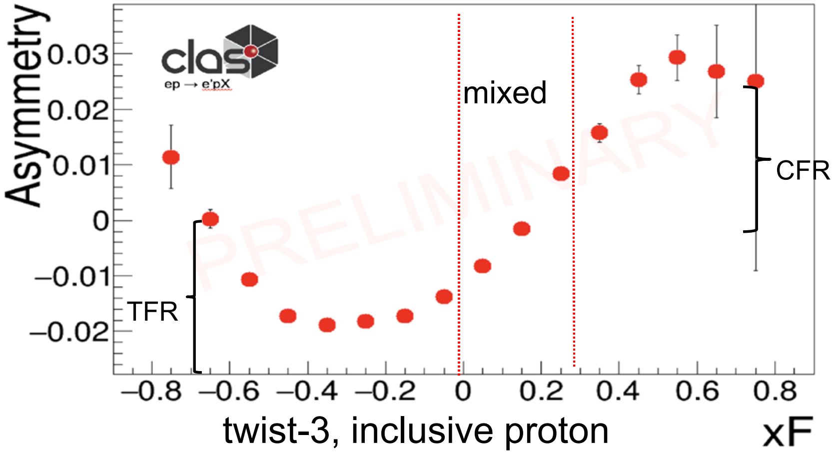
- What is the origin of the "high" P_T (0.8-1.8) tail?
  1) Perturbative contributions?
  2) Non perturbative contributions?

Beam SSAs: Where is the struck quark?

- Can we separate the CFR from TFR using the SSA as signature?

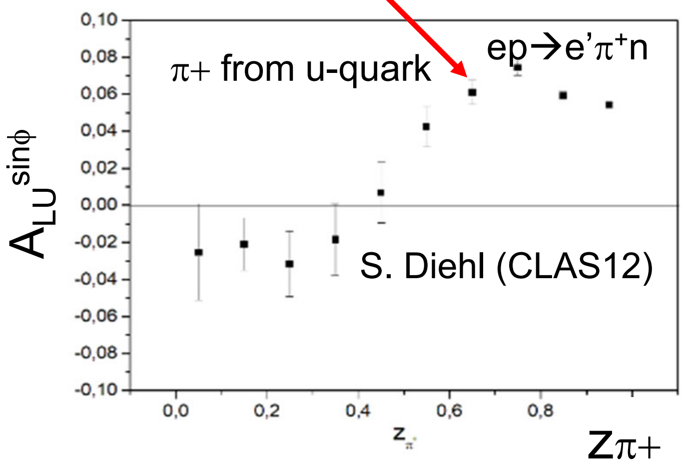
arXiv:1904.12882

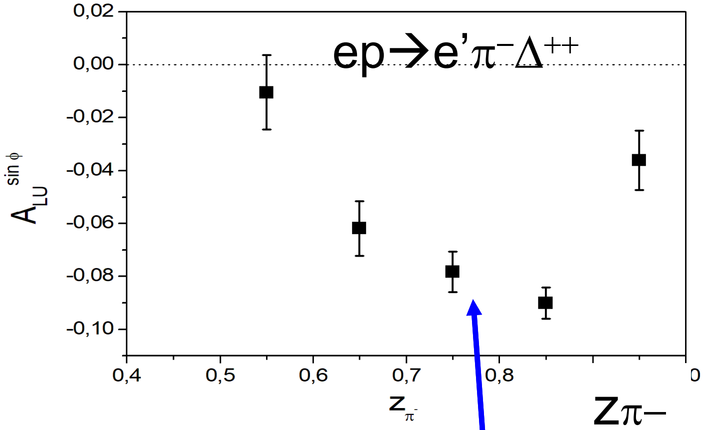




Negative sign of the SSA (plateau) defines the TFR dominance

Polarized u-quark, dominates
→ SSA positive



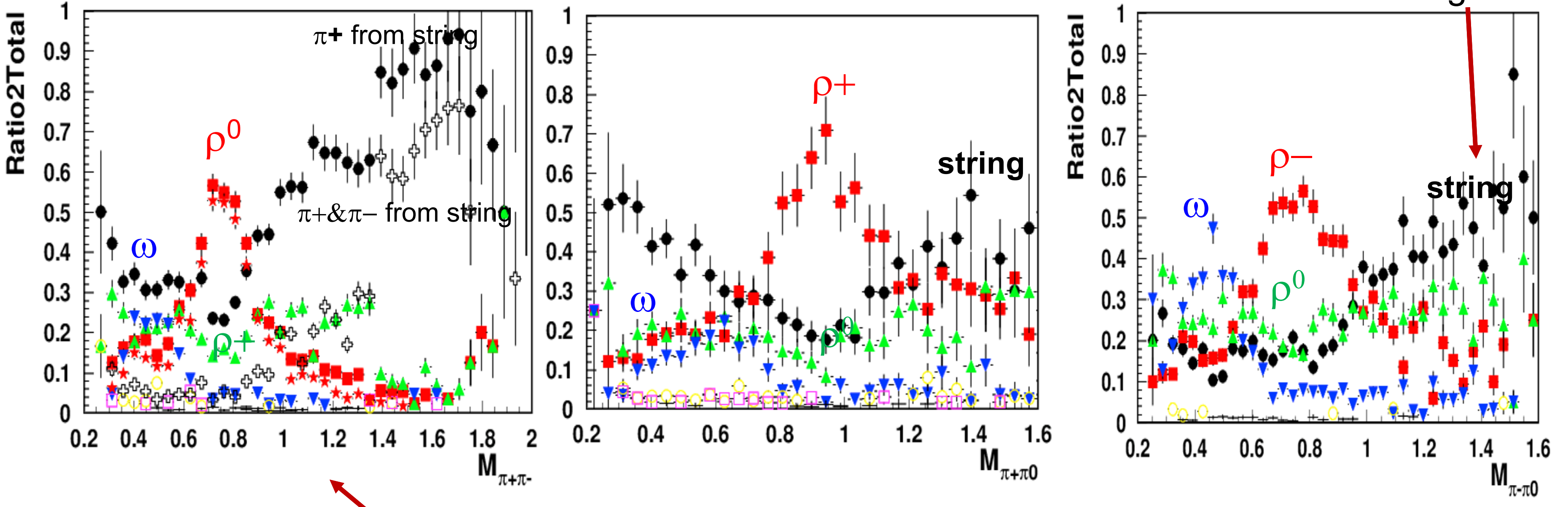


Polarized d-quark, is hard to locate, and one obvious process where we can guarantee it was hit, is the production of Δ++ (negative SSA)

Correlations of hadrons in current fragmentation region

Detection of π^0s allows also studies of $\rho^{\pm}$

High P_T pions at large $M\pi\pi$



- All measured 2 pion combinations are dominated by VM decays, indicate that all inclusive pions are dominated by VM decays at small P_Ts, and in particular at lower z!!!
- SSAs can change sign depending on the source of hadrons