TMD program at JLab

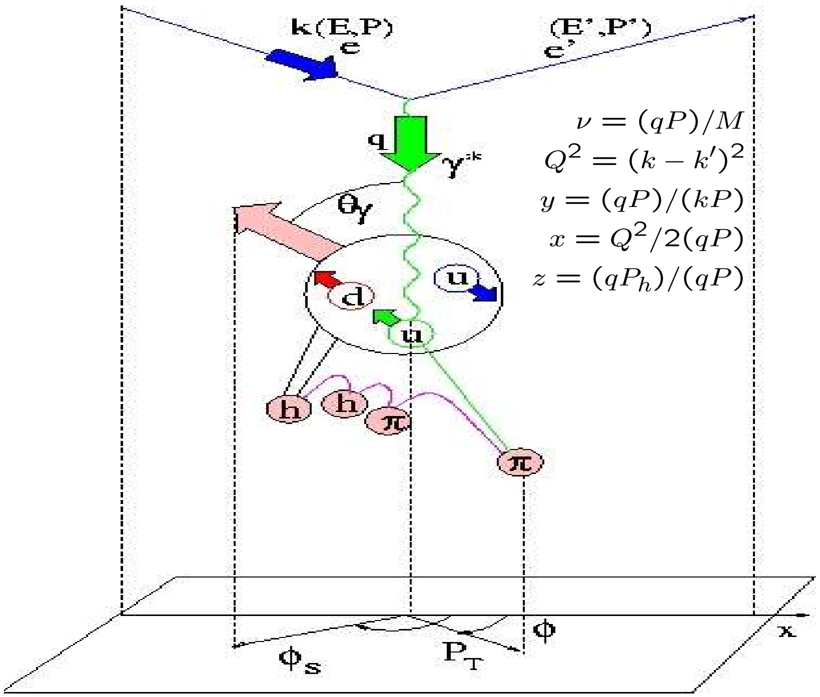
25th International Spin Symposium (SPIN 2023)

Harut Avakian (JLab)

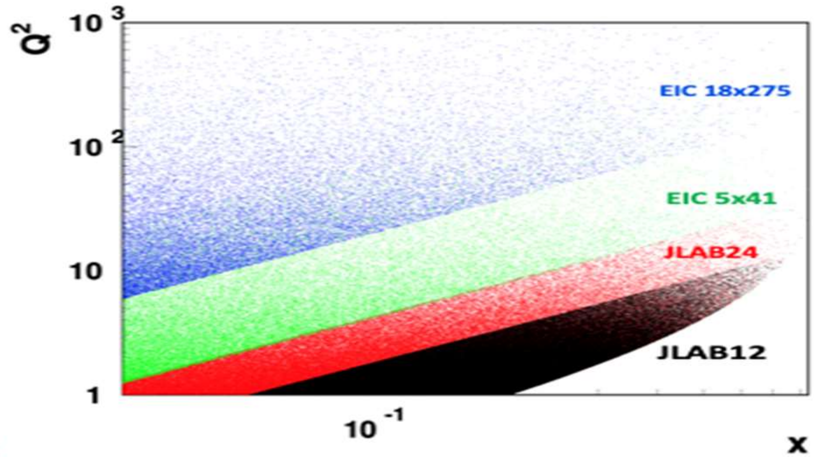
Duke, 24–29 Sept 2023

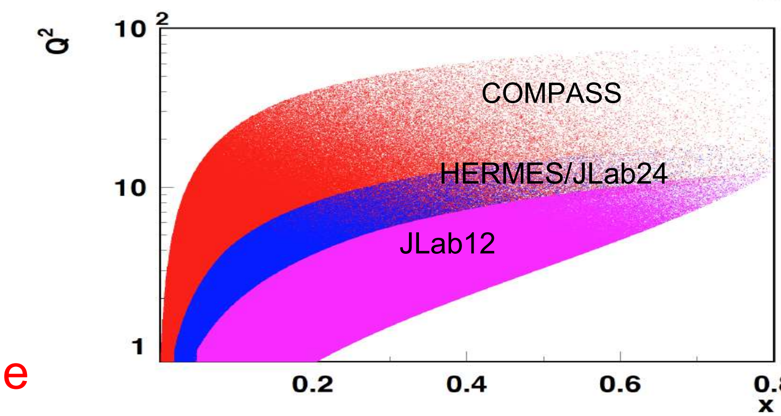
Introduction
–Dissecting the SIDIS $ep\rightarrow e'pX$, $ep\rightarrow e'\pi+X$, $ep\rightarrow e'p\pi+X$, $ep\rightarrow e'\pi^{+}\pi^{-}X$
–Separating the kinematics of current and target fragmentation
–Separating dynamical contributions in exclusive and semi-inclusive processes
–The role of hadron correlations in SIDIS
Summary

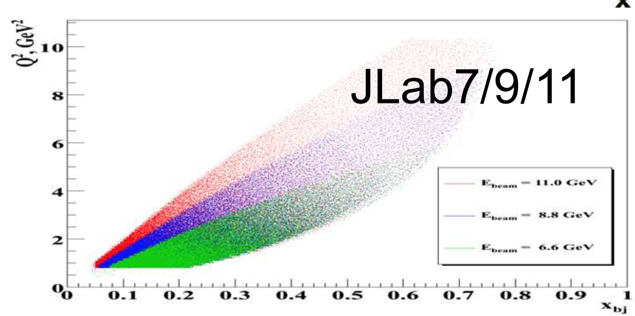
SIDIS kinematical coverage and observables



EIC



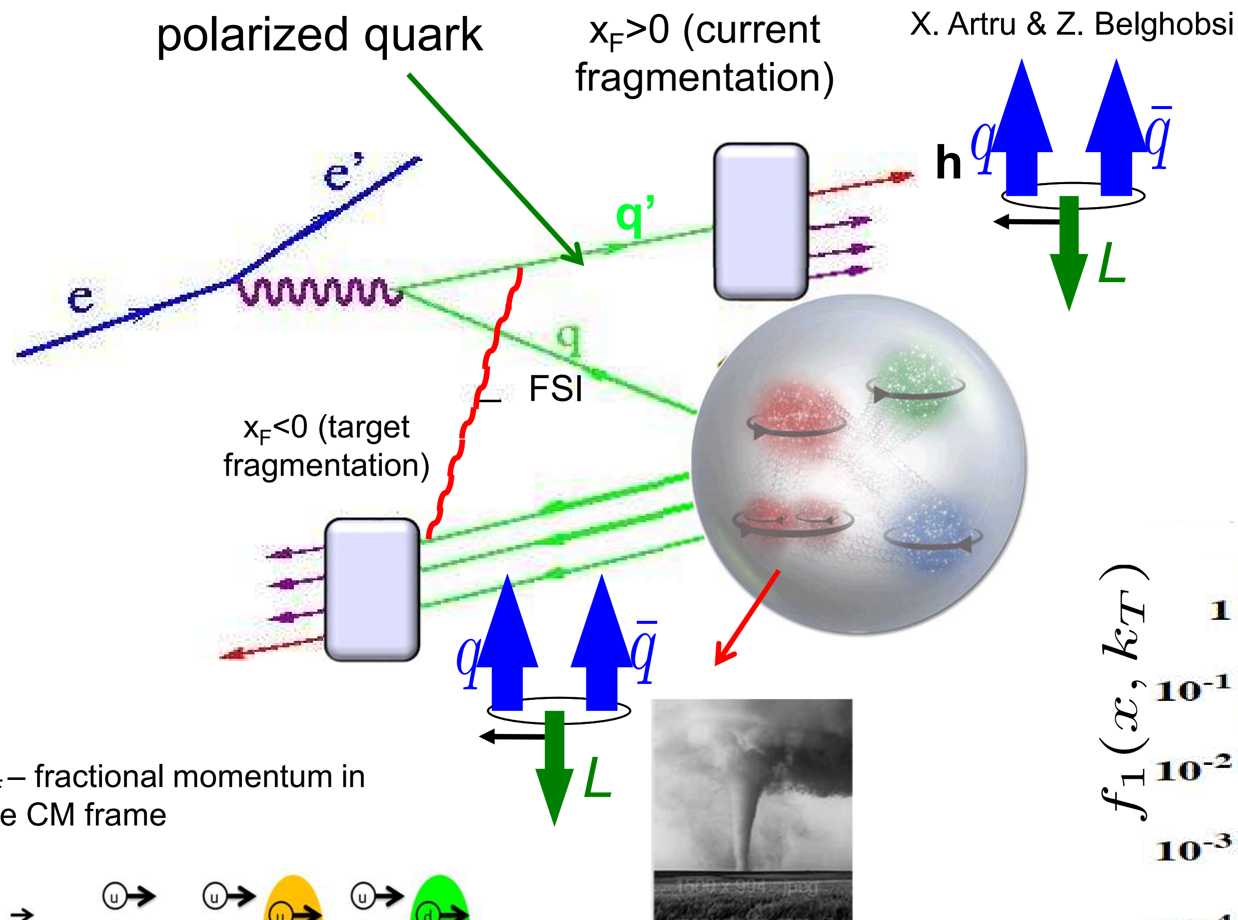


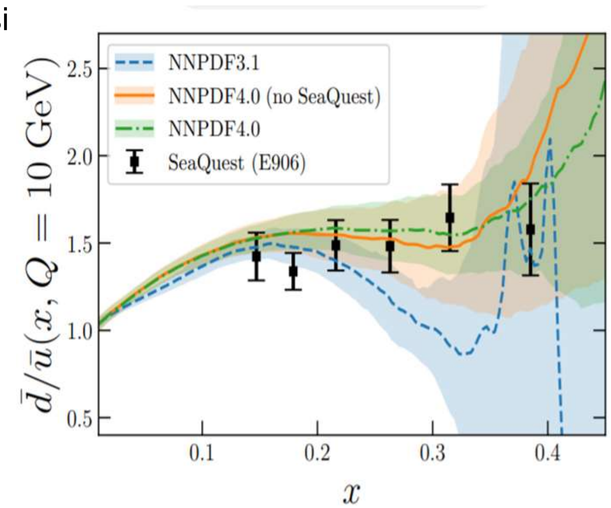


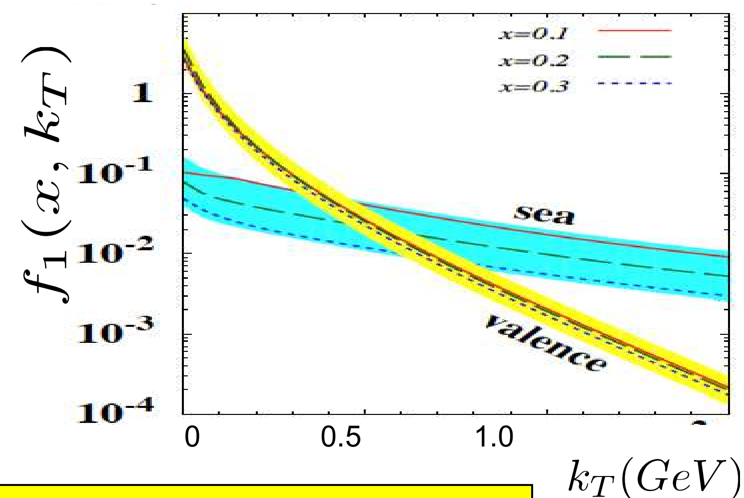
Experiments measure azimuthal dependence of the cross section as a function of x, Q^2, z, P_T

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

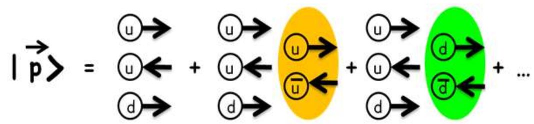
Hadron production in hard scattering





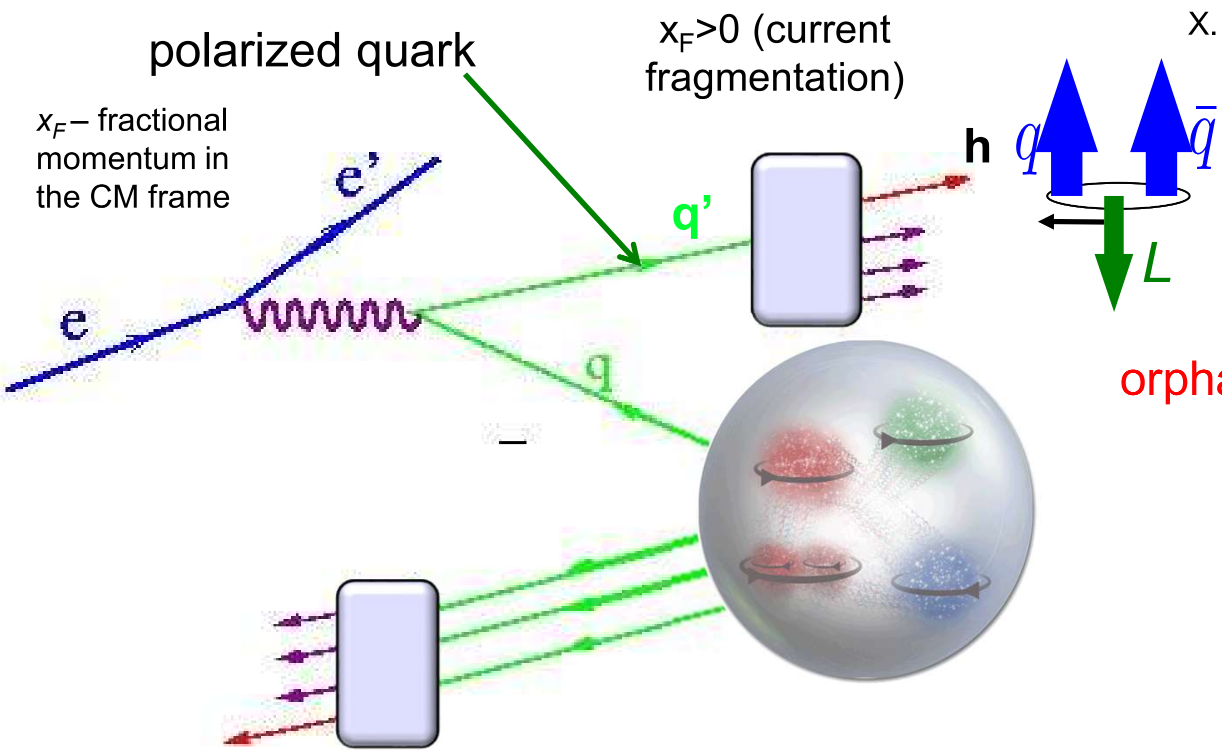


x_F – fractional momentum in the CM frame

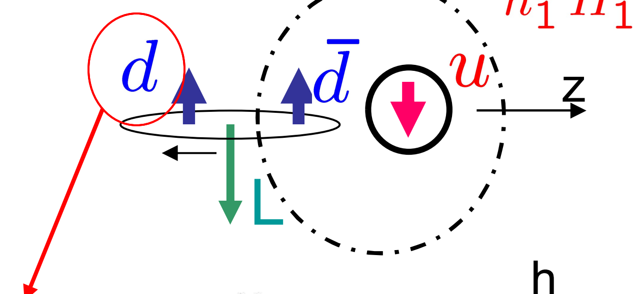


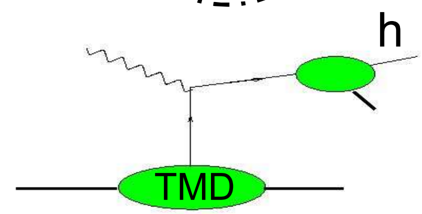
Non-perturbative sea is significant in the valence region
It contribute in spin-orbit correlations, more at large transverse momenta

Hadron production in hard scattering: SIDIS



X. Artru (Collins effect)



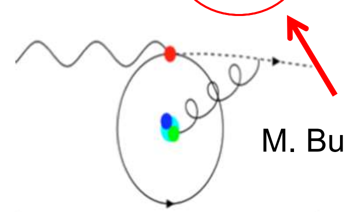


CFR/Current Fragmentation Region
→hadrons produced from struck quark

Transverse Momentum Distributions

N/q	U	L	T
U	f_1	x	$h_1^\perp$
L	x	g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

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 in SIDIS



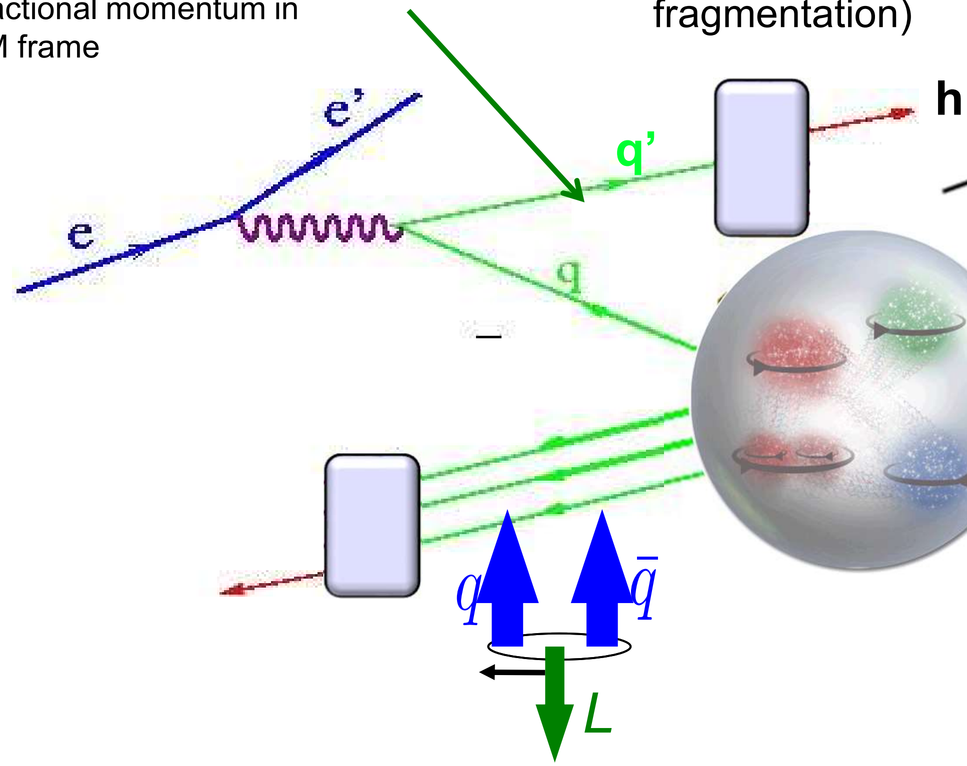
M. Burkardt (Sivers effect)

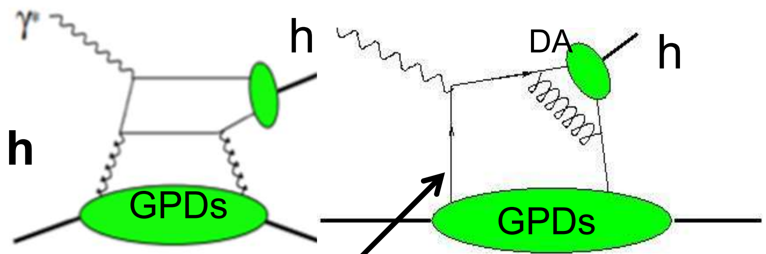
Exclusive hadron production in hard scattering

polarized quark

x_F – fractional momentum in the CM frame

x_F>0 (current fragmentation)

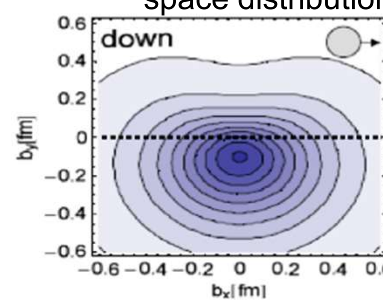




sensitive to flavor

N/q	U	L	T
U	H	X	$\mathcal{E}_T$
L	X	$\widetilde{H}$	X
T	E	X	$H_T, \widetilde{H}_T$

space distributions

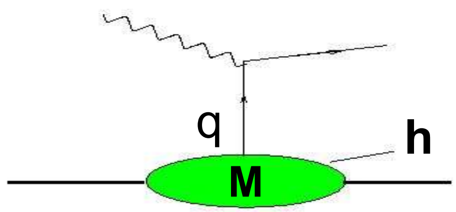


Current Fragmentation Region

→ nucleon and transition GPDs, access to properties like "pressure",….

Correlations of the spin of the target or/and the momentum and the spin of quarks define the azimuthal distributions of produced particles in hard exclusive production of hadrons

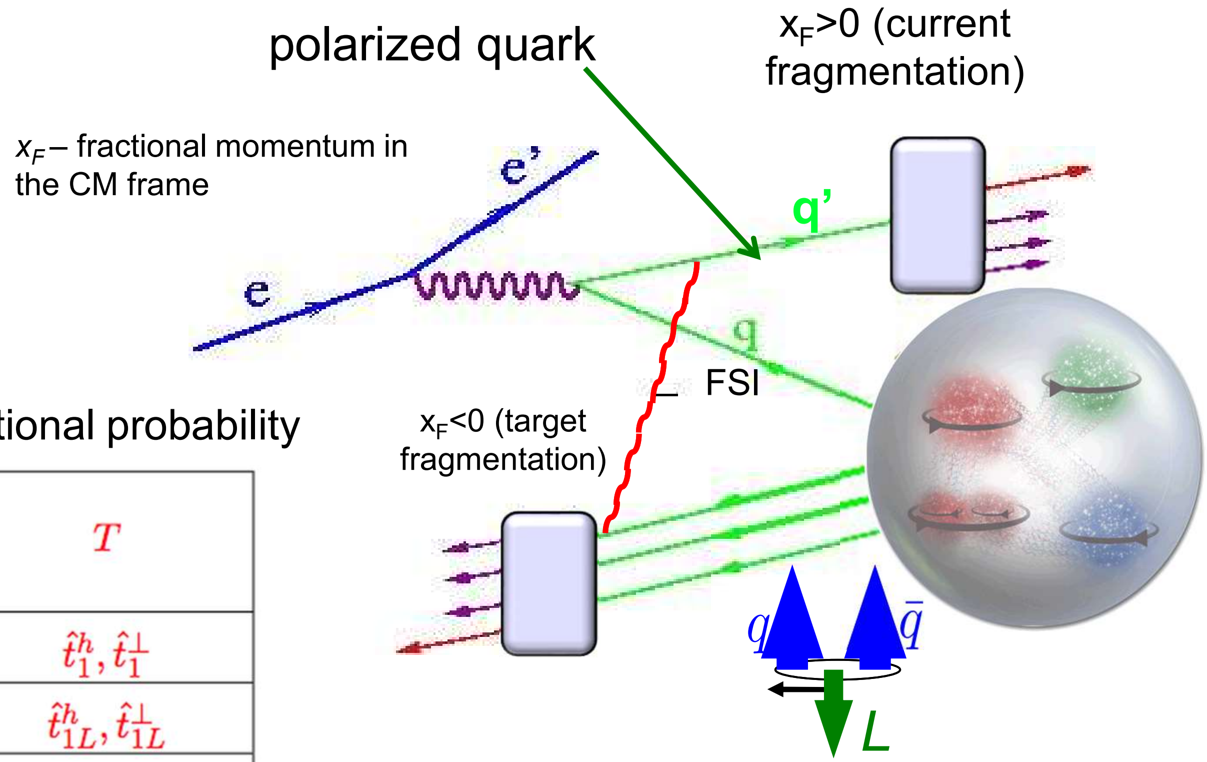
Hadron production in hard scattering: SIDIS



Fracture Function→ conditional probability

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

Anselmino, Barone, Kotzinian

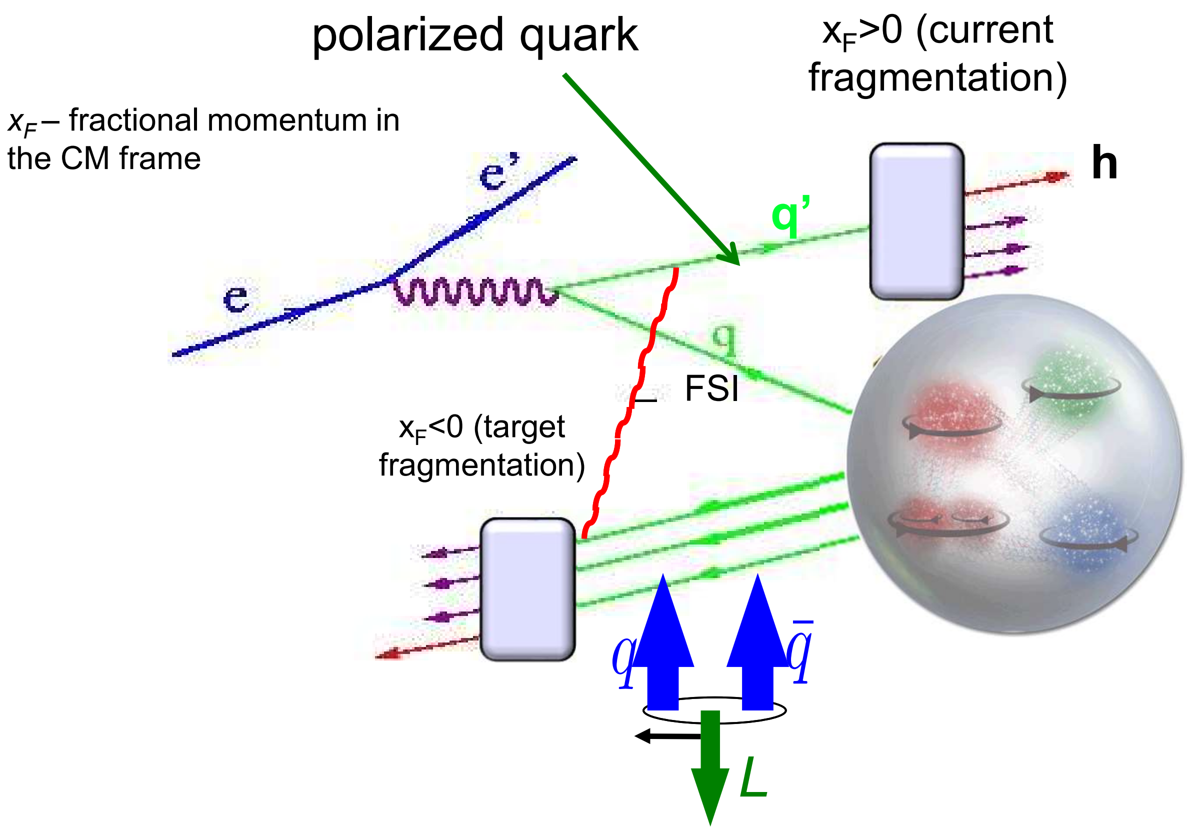


X. Zhao
T. Hayward

TFR/Target Fragmentation Region
→hadrons produced from remnant, access to entanglement,…

Correlations of the struck quark and the target remnant combined with final state interactions define the azimuthal distributions of particles in the backward hemisphere (TFR), providing complementary information on nucleon structure

Exclusive hadron production in hard scattering



Quark qluon correlations described by higher twist 3D PDFs

Twist3 GPDs

M.Constantinou

N \ q	U	L	T
U	$\mathcal{E}_{2T}$	$\mathcal{E}'_{2T}$	$\mathcal{H}_2, \mathcal{H}'_2$
L	$\tilde{\mathcal{E}}_{2T}$	$\tilde{\mathcal{E}}'_{2T}$	$\tilde{\mathcal{H}}_2, \tilde{\mathcal{H}}'_2$
T	$\mathcal{H}_{2T}, \mathcal{H}'_{2T}$	$\mathcal{H}'_{2T}, \tilde{\mathcal{H}}'_{2T}$	$\mathcal{E}_2, \tilde{\mathcal{E}}_2, \mathcal{E}'_2, \tilde{\mathcal{E}}'_2$

M.Engelhardt

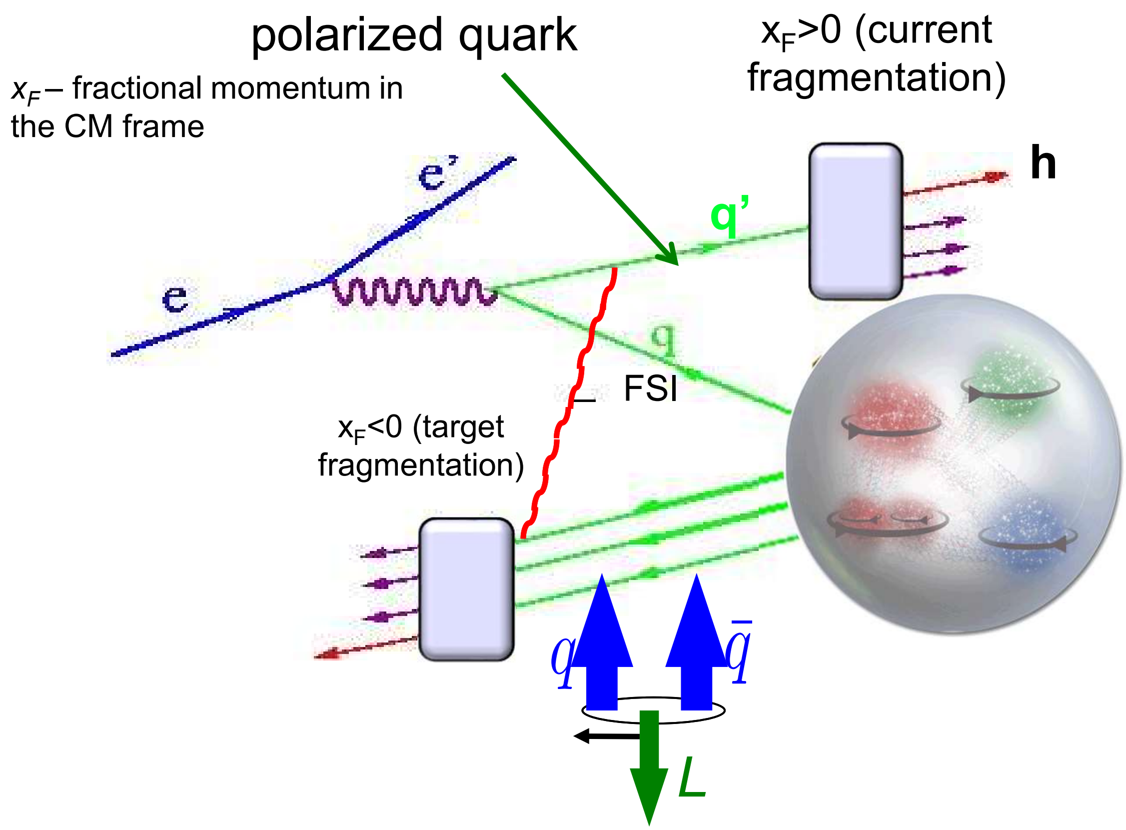
OAM

$$-\int dx\, x\, \tilde{E}_{2T}(x,0,0) = L_z^q + 2S_z^q$$

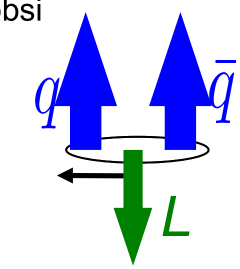
Lorce&Pasquini, arXiv:1208.3065

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 in exclusive limit

Hadron production in hard scattering: SIDIS



X. Artru & Z. Belghobsi



Higher Twist TMDs

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

Quark gluon correlations described by higher twist 3D TMD PDFs, access to details of the QCD dynamics "forces",….

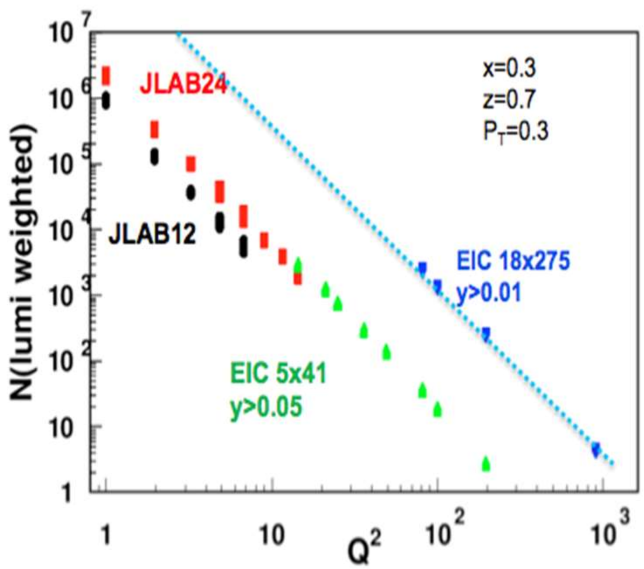
Final state interactions and quark-gluon correlations give rise to detectable spin-azimuthal modulations of produced particles

Structure functions and depolarization factors

- **At large x fixed target experiments are sensitive to ALL Structure Functions**
- **At higher energies (EIC), observables surviving the $\varepsilon \to 1$ limit (F_{UU}, F_{UL}, Transversely pol. F_{UT})**

x-section for eN→e'hX

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

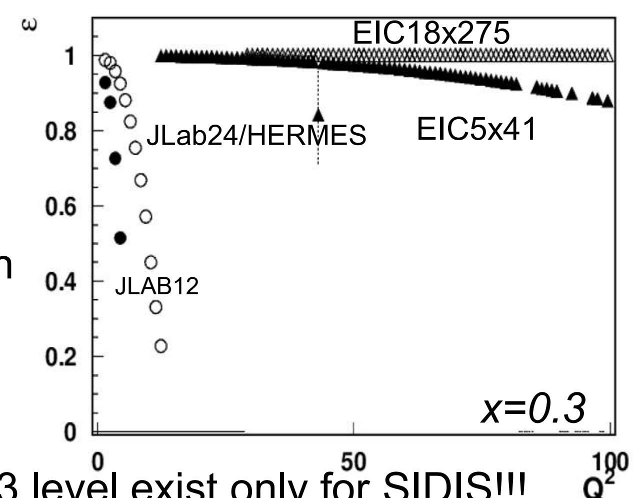


x-section from Bacchetta et al, 1703.10157

Combination of statistics and depolarization factors defines measurable SFs

1) Measurements of $F_{UU,T}$ and Sivers requires separation, evaluation of longitudinal photon (JLab)

2) Meaningful interpretation the Collins effects requires separation of VMs(JLab)



Full decomposition of SFs to underlying 3D PDFs up to twist 3 level exist only for SIDIS!!!

More…..

In addition to 3D PDFs there are similar sets for

•3D Fragmentation functions (FFs) in SIDIS
•Distributions Amplitudes (DAs) in exclusive
•Transition Distribution Amplitudes (TDAs)
•Nuclear Energy Correlations(NEEC)
•…………………

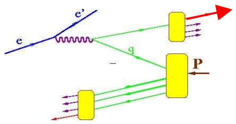
In addition all the same non-perturbative objects could be/have been defined for bound nucleons (describe medium modifications)

Interpretation of hard scattering processes requires

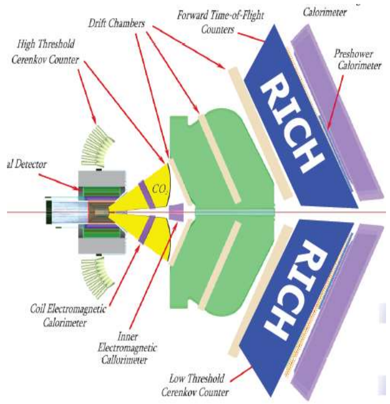
- Separating different structure functions
- Separating different contributions to given structure function
- Accounting for phase space limitations
- Understanding of Radiative effects, 2photon exchange
- Accounting impact of neglected correlations, higher twists

How do you eat an elephant?" "—> One bite at a time.

(may need upgrading existing tools)



SIDIS at JLab12



Proton

CLAS12 → E12-16-010C

- E12-06-112: π^+,π^-,π^0
- E12-09-008: K^+, K^-,K^0
- E12-07-107: π^+,π^-,π^0
- E12-09-009: K^+,K^-,K^0
- C12-11-111: π^+,π^-,π^0, K^+, K^-

H_2, NH_3, HD

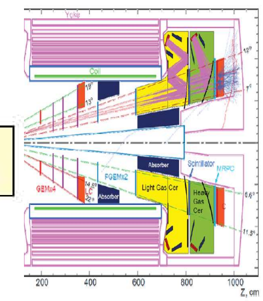
Quark spin polarization (q) / Nucleon polarization (N)

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

Hall C | Hall A

- E12-09-017: π^+,π^-, K^+,K^- — HMS SHMS
- C12-11-102: π^0
- E12-06-104
- E12-23-014
- C12-11-108: π^+,π^- — Solid

H_2 NH_3



D_2

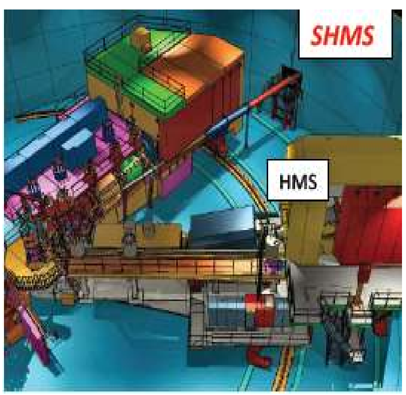
CLAS12

- E09-008: π^+,π^-,π^0 K^+, K^-,K^0
- E07-107: π^+,π^-,π^0
- E09-009: K^+,K^-,K^0

D_2, ND_3

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

E12-16-010C



Quark spin polarization (q) / Nucleon polarization (N)

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

Hall C

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

D_2

^3He

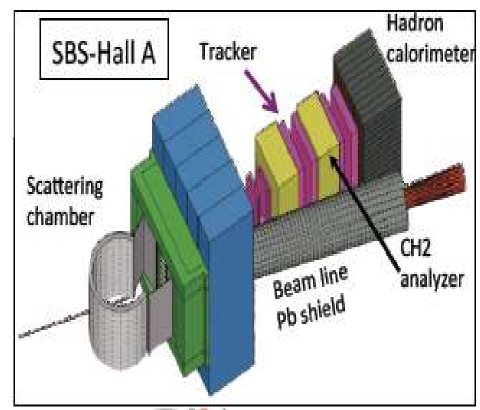
Quark spin polarization (q) / Nucleon polarization (N)

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

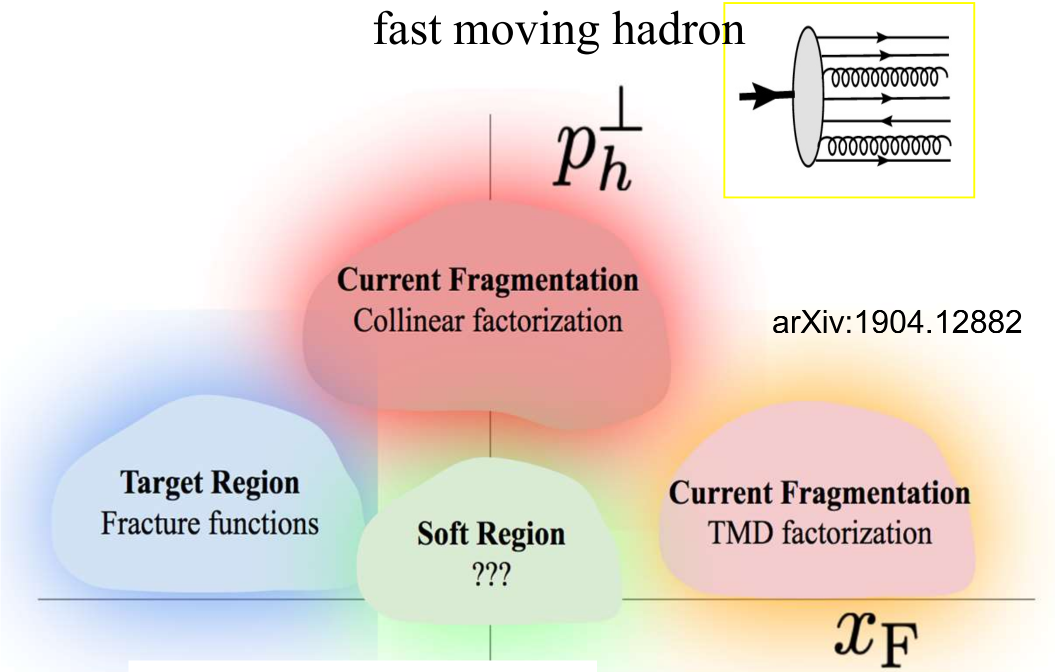
Hall A

- E12-07-007: π^+,π^- — Solid
- E10-006: π^+,π^- — Solid
- E12-09-018: π^+,π^-, K^+,K^- — SBS

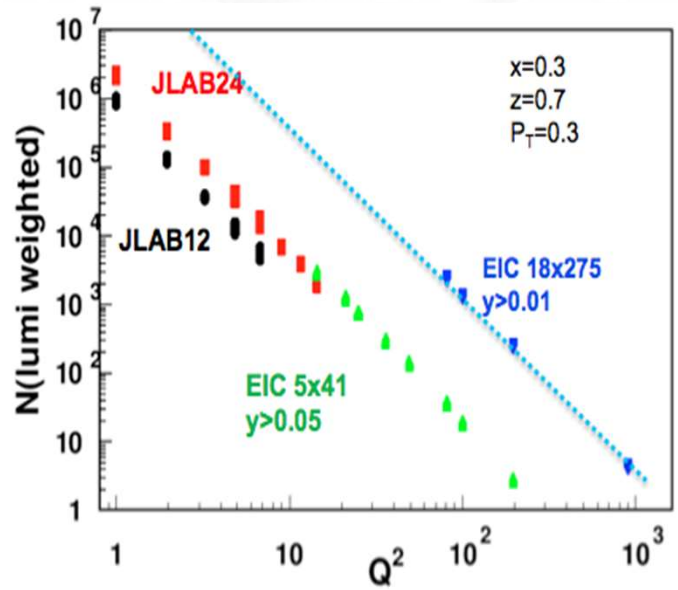
^3He



Structure functions and depolarization factors in SIDIS



x_F – fractional momentum in the CM frame



1) Theory works well for $P_T/Q<0.25$,
2) Kinematic regions not trivial to separate, in particular for polarized measurements
3) Multi-dimensional measurements critical, requiring high lumi
4) Theoretical separation of kinematic region requires some assumptions (no decays,…)

TMDs in Semi-Inclusive DIS

A. Bacchetta

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

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

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)

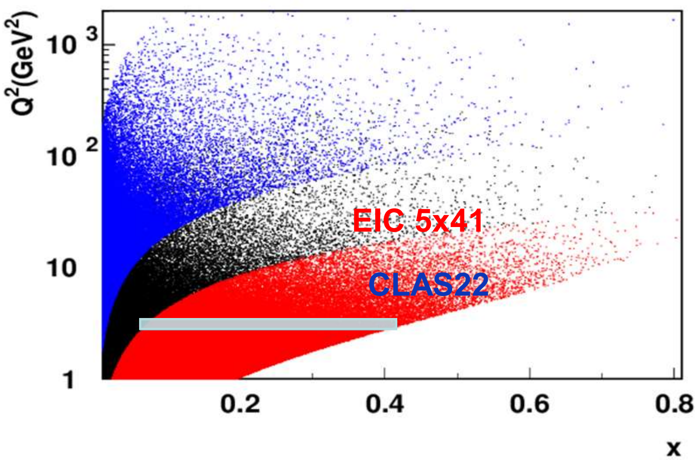
nonperturbative part of TMD

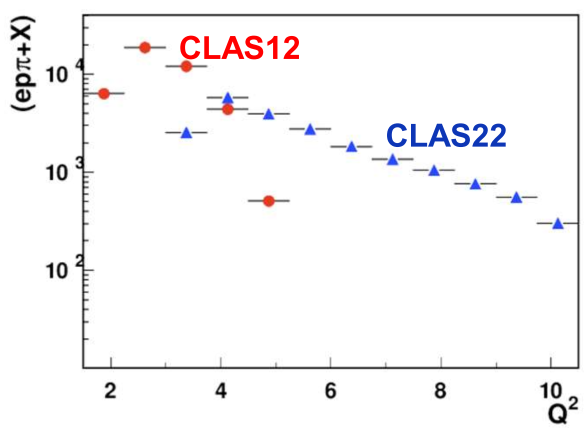
$$g_K(b_T^2) = -g_2^2\frac{b_T^2}{4}$$

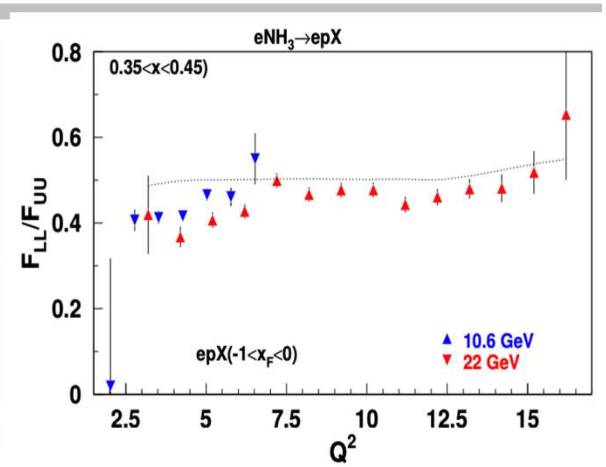
CS-kernel→independent on any other variables

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

Accessing CS-kernel directly or through extraction of SFs



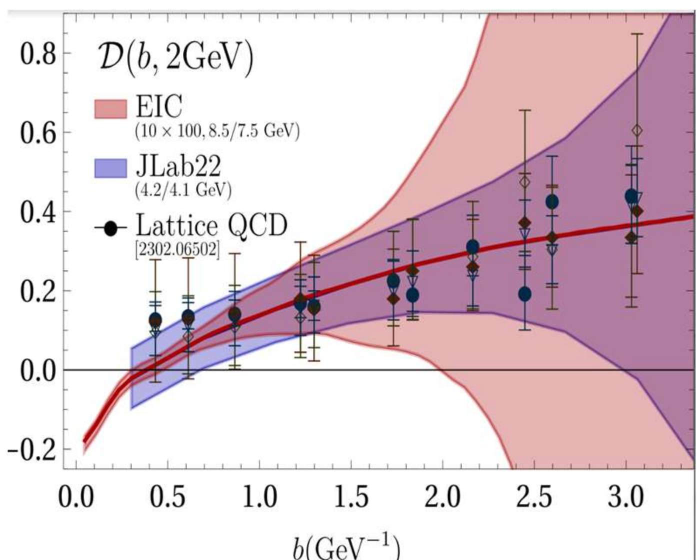




Use slices in Q^2 (good resolution needed)

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

A. Vladimirov



- 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

Sensitive to different ranges in b

- JLab ~1<b<4
- EIC ~0.5<b<1.2, COMPASS overlaps ,
- LHC b<<0.05

- Test the CS-kernel from different experiments, and for different kinematics in a given experiment
- Evaluate the systematics due to factorization violation and define possible reasons (some can be easy to fix)

SIDIS cross section: separating $F_{UU,L}$

Semi-Inclusive:

ratio of longitudinal and transverse photon flux

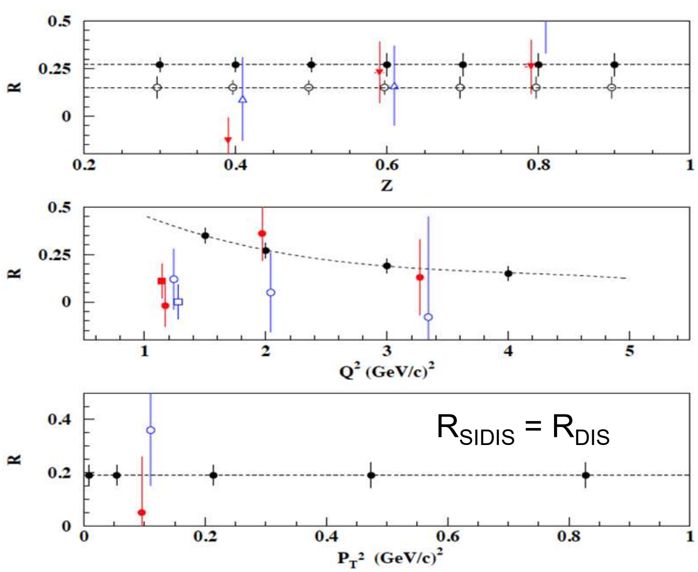
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

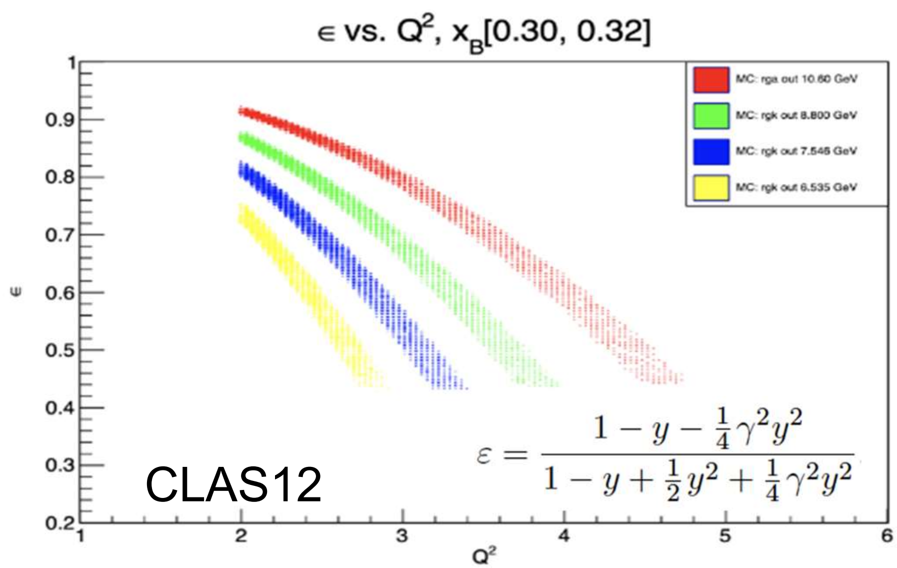
$$+ S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] + S_\parallel\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL}\Big\}$$

Hall-C E12-06-104
E12-23-014
Hall-B E12-16-010C

Separation of contributions from longitudinal and transverse photons critical for interpretation

Expected E12-06-104(Hall-C) assume R=FUU,L/FUU,T

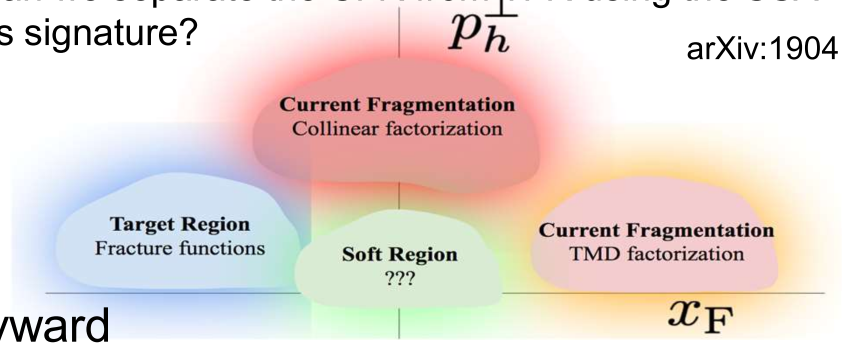




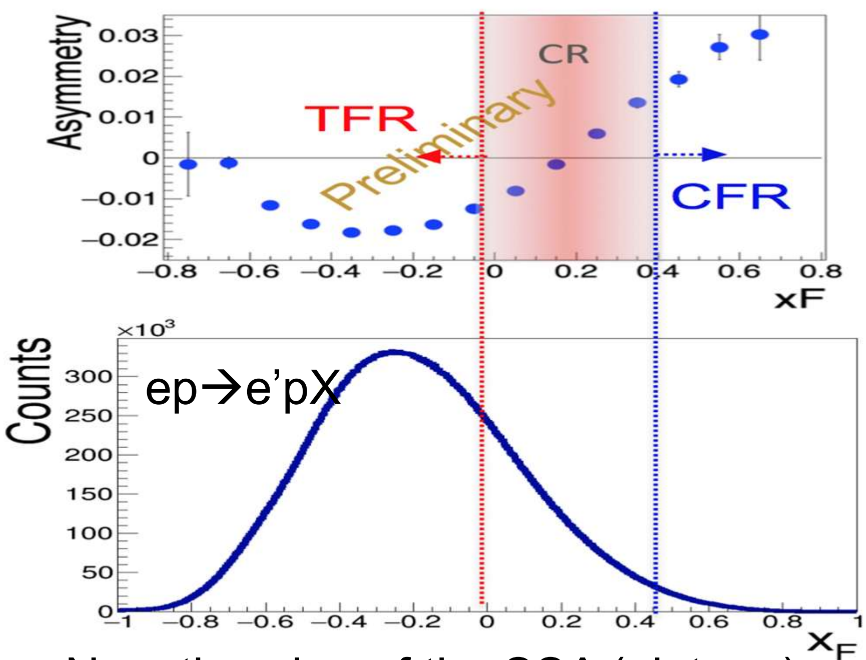
Beam SSAs: Where is the struck quark?

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

arXiv:1904.12882

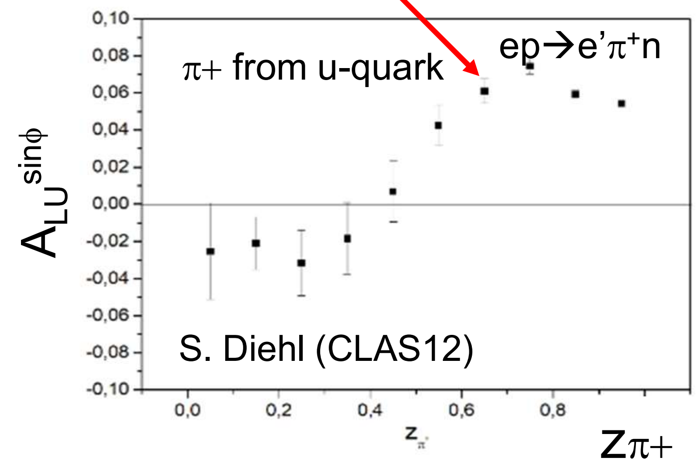


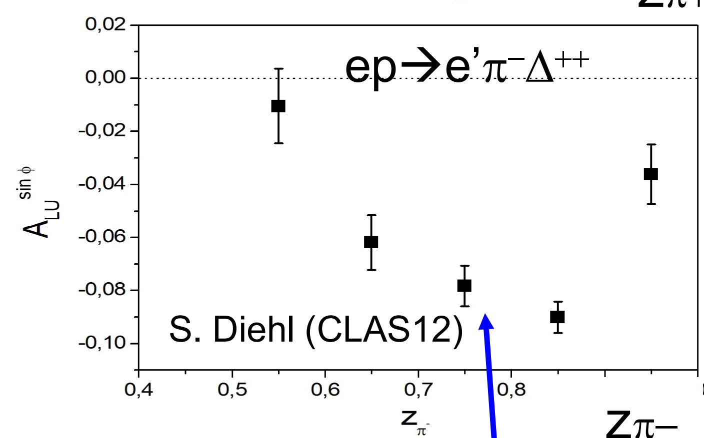
T.Hayward



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

Polarized u-quark, dominates
→ SSA positive



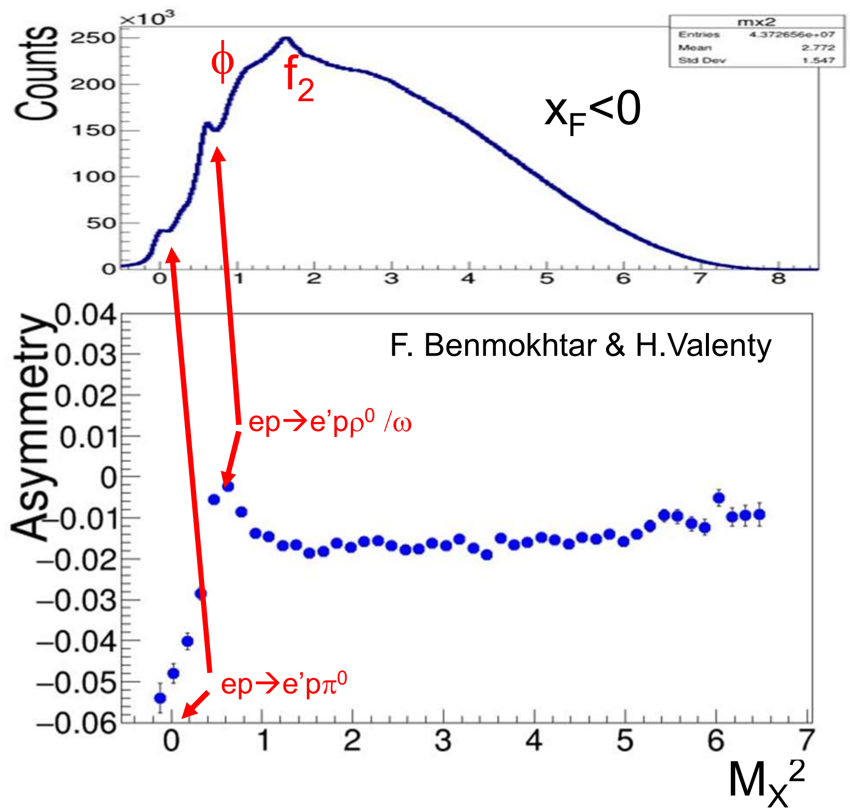


Polarized d-quark, is hard to locate, and one obvious process where we can guarantee it was hit, is the production of Δ++ (negative SSA)

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

What is SIDIS?



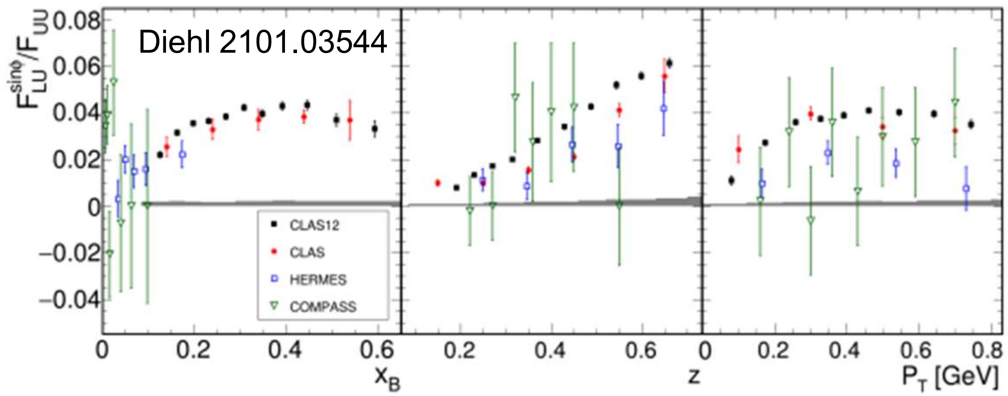
Significant beam spin SSAs observed for exclusive ep→e'pπ^0 (~8%) and ep→e'pρ^0 (~10-15%)

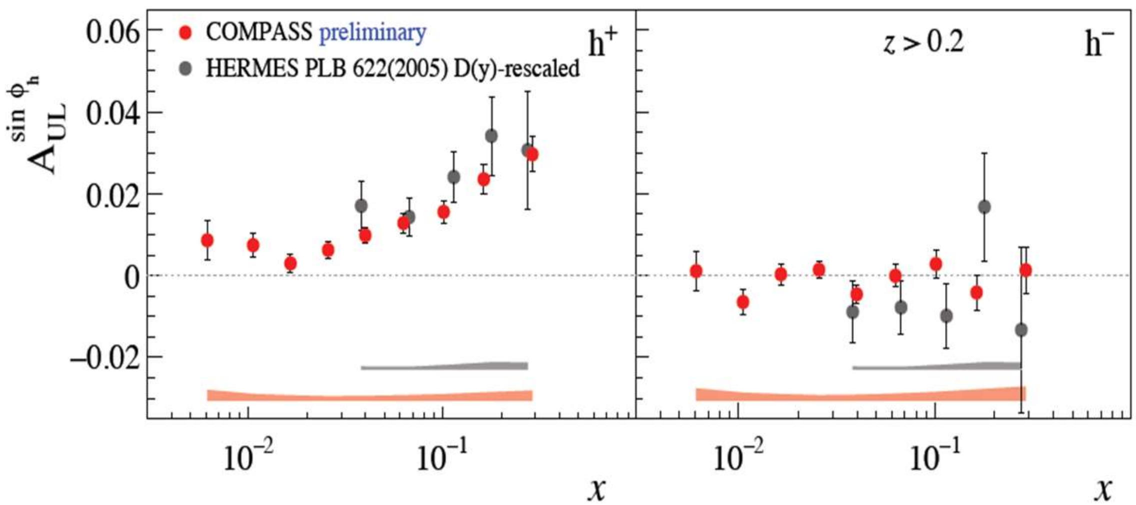
Quark-gluon correlations: flavor dependence

Higher Twist PDFs

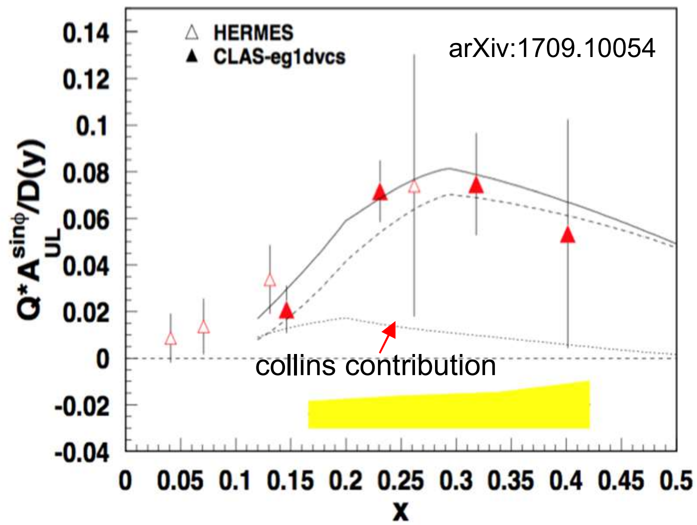
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

1) roughly equal $\pi^+\pi^0$ SS
2) π^- SSA much smaller, consistent with 0 or<0



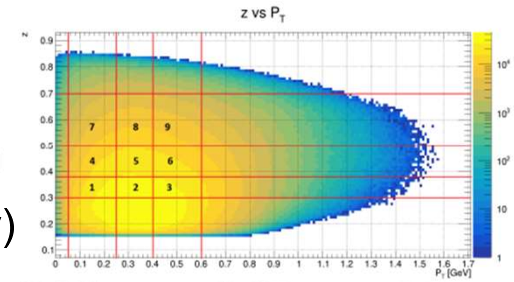


CLAS/HERMES



- Significant longitudinal beam and target SSA measured at HERMES, JLab and COMPASS may be related to higher twist distribution functions
- $\sin\phi$ modulations for $\pi^+\pi^0$ consistent with dominance of Sivers like mechanism (initial state effects)
- Subleading asymmetries comparable with leading ones (1/Q terms should be accounted)

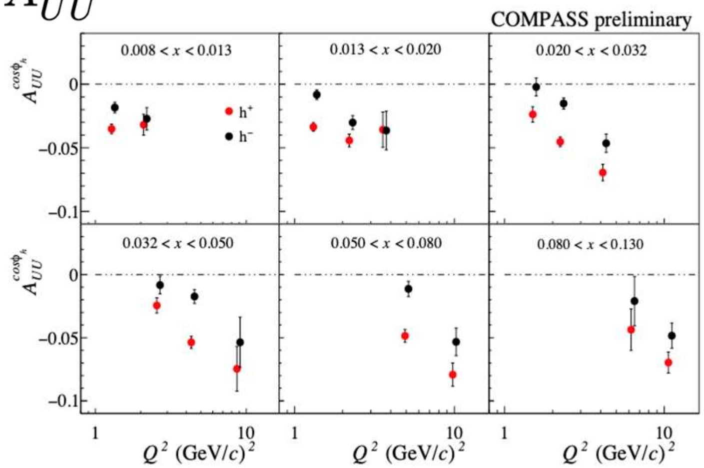
Attempts to understand Q^2-dependence of HT

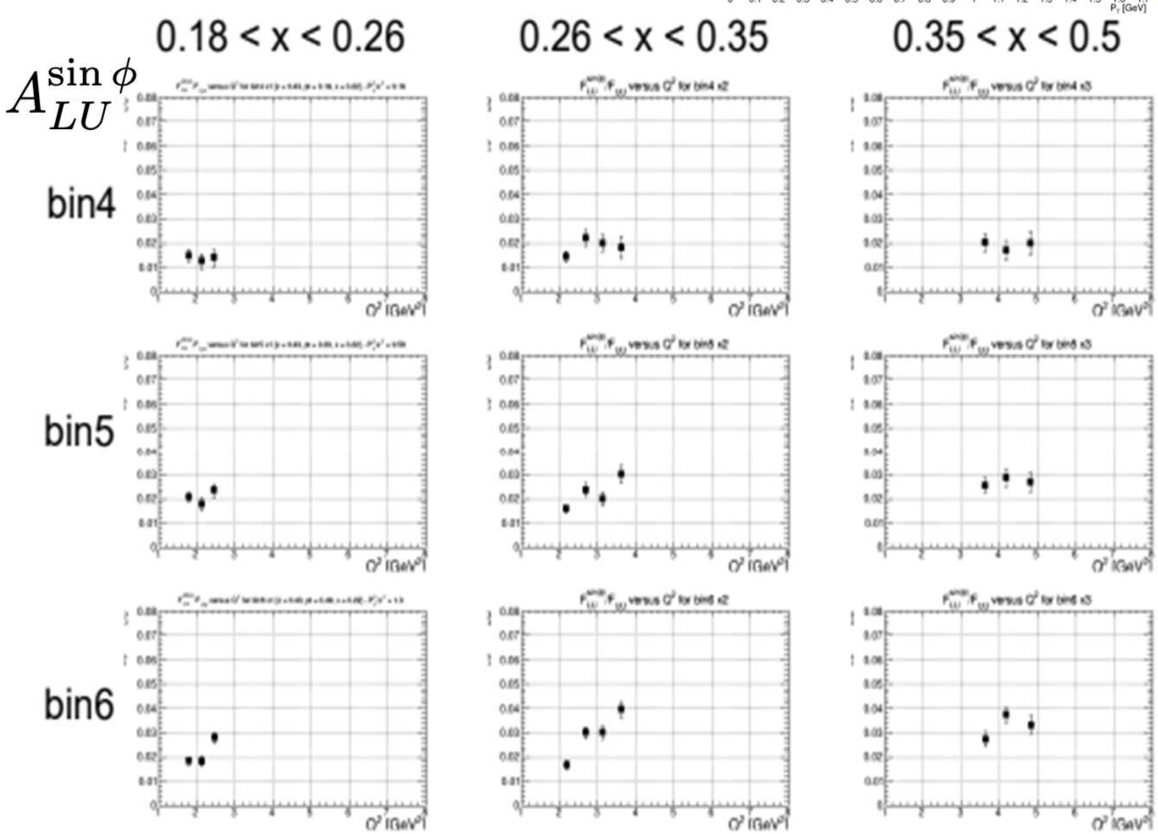


CLAS12(preliminary)

J. Matousek COMPASS

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





- We always measure ratio to

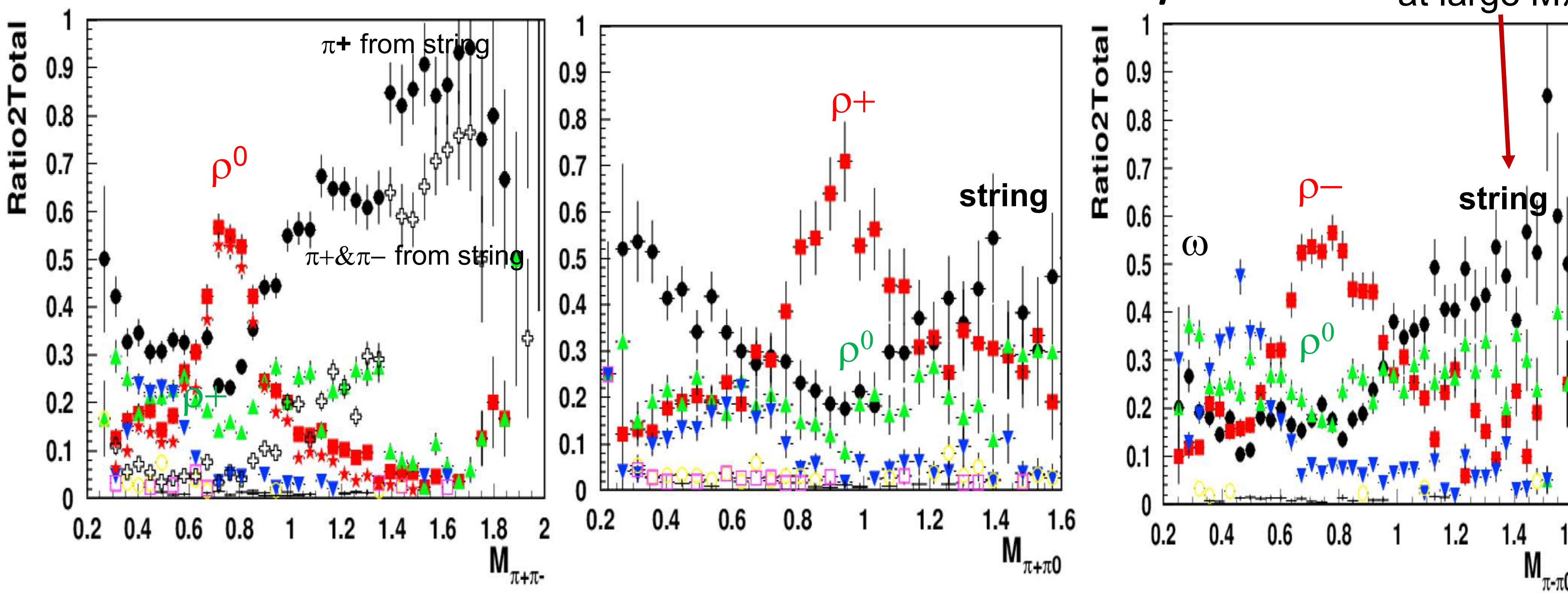
$$F_{UU,T} + \varepsilon F_{UU,L}$$

- 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

Sources of inclusive pions: CLAS12 MC

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

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

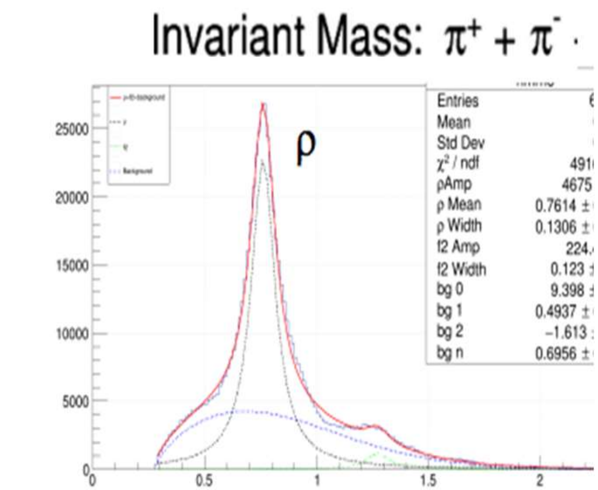


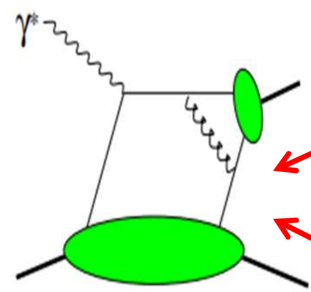
Dominant fraction of 2 pion combinations come from VM decays

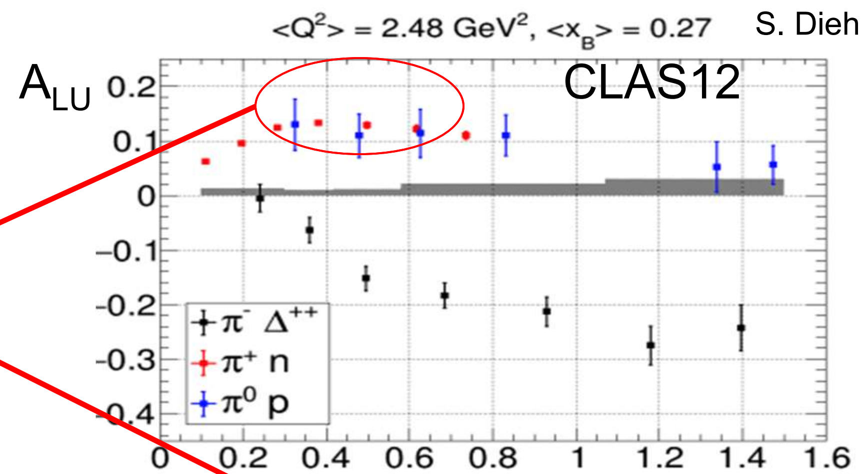
ρ
string
ω

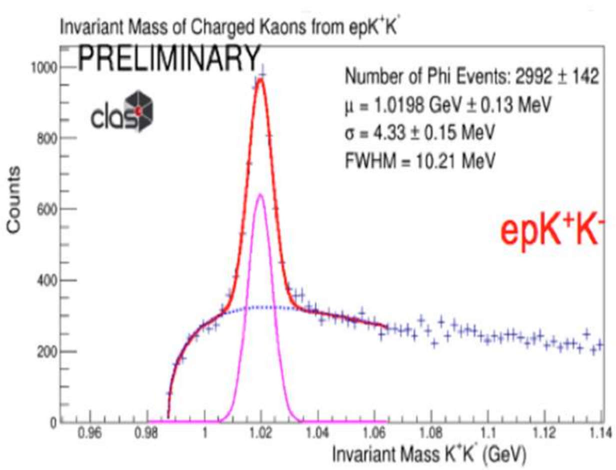
All measured 2 pion combinations are dominated by VM decays, indicate that all inclusive pions are dominated by VM decays at small P_Ts, and in particular at lower z!!!

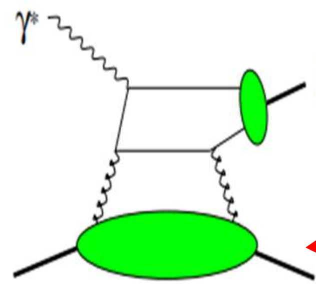
Current hadrons: exclusive limit

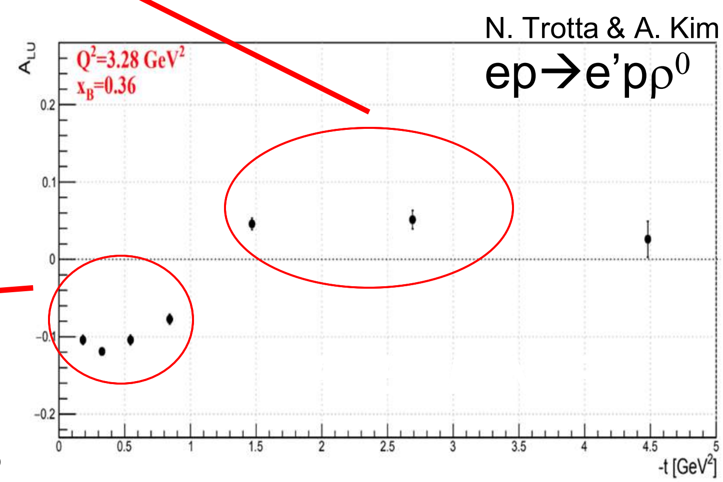












A_{LU}=-0.084+/-0.038

SSA negative→ΔG negative?

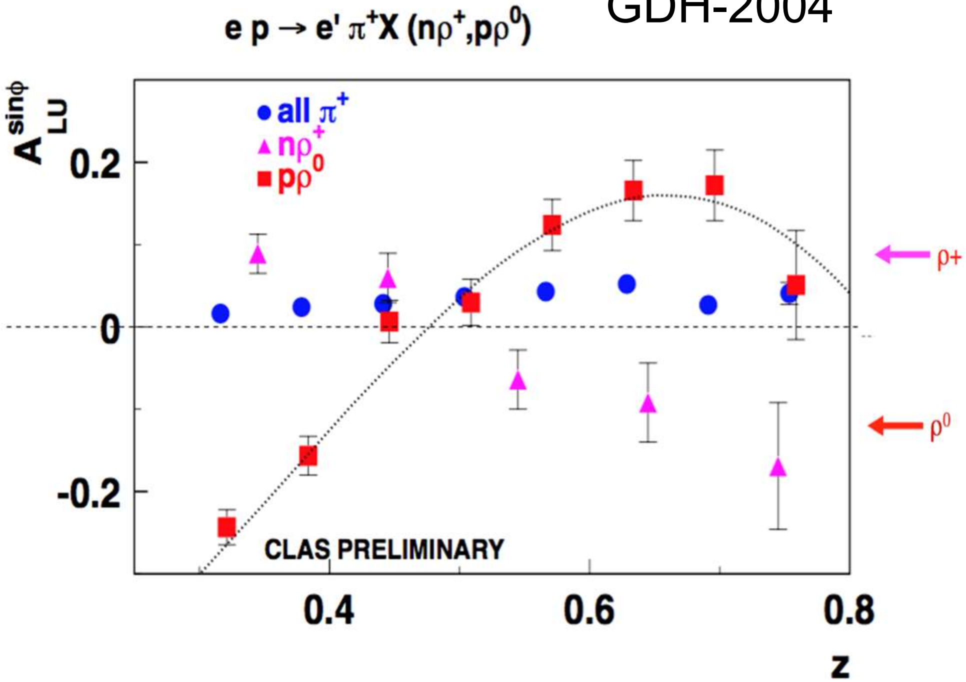
-t(GeV²)

CLAS can measure all final states in exclusive production

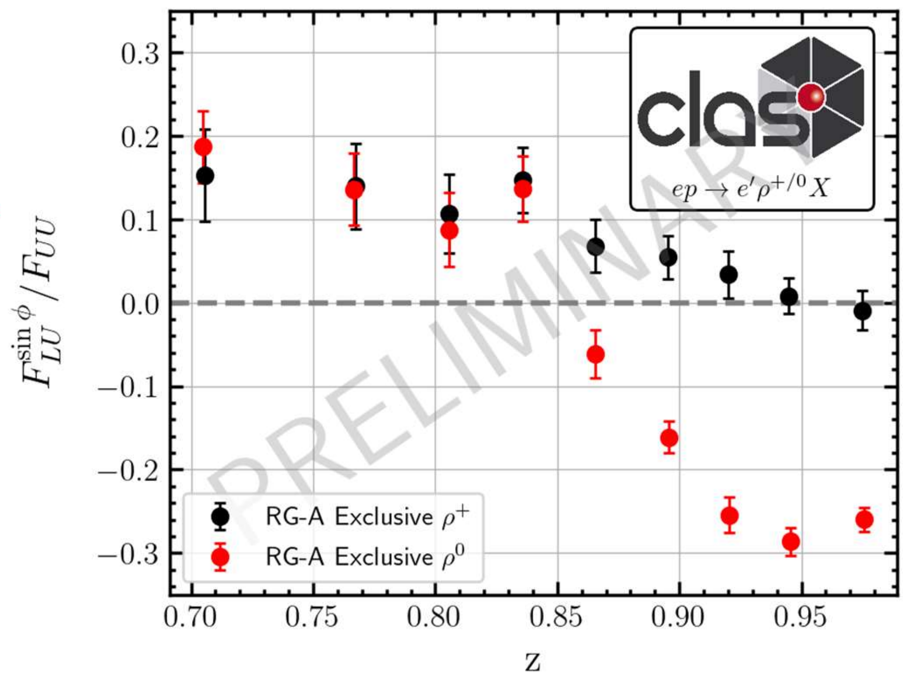
Hadrons produced fro u-quark have positive SSA, d-quarks and gluons negative.

Quark-gluon correlations: flavor dependence

GDH-2004



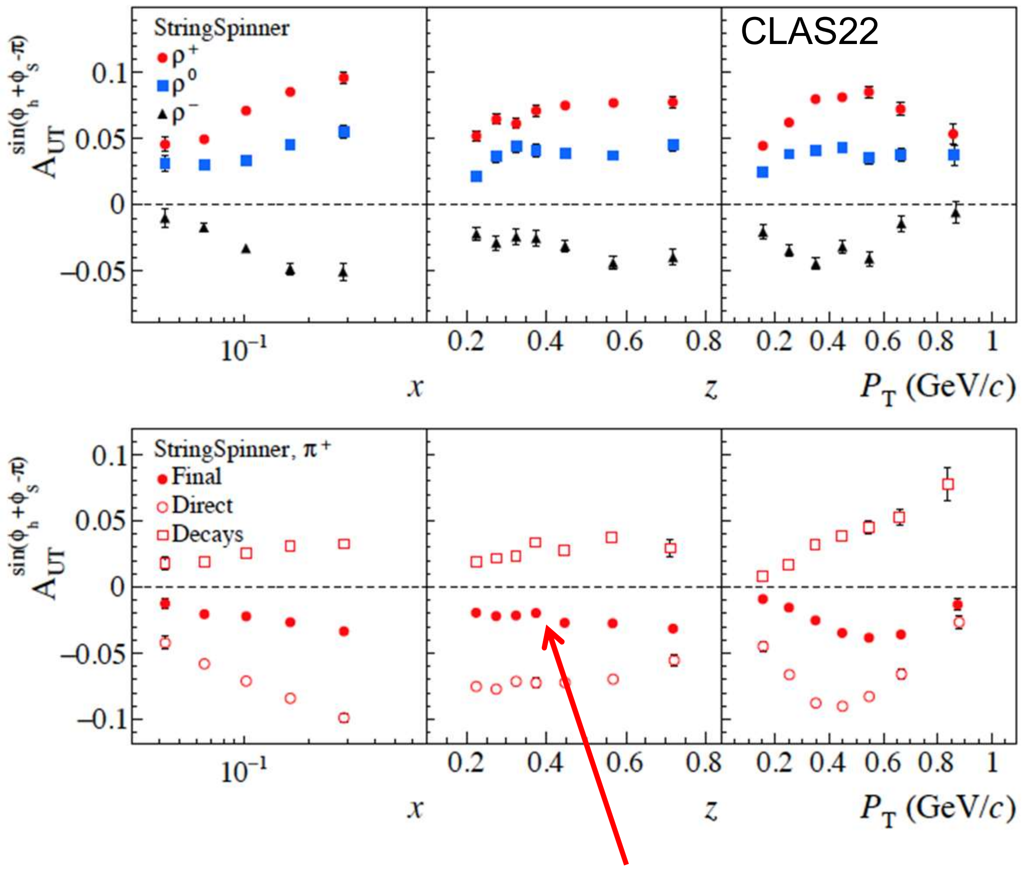
G.Matousek (Duke) & N.Trotta (UCONN)

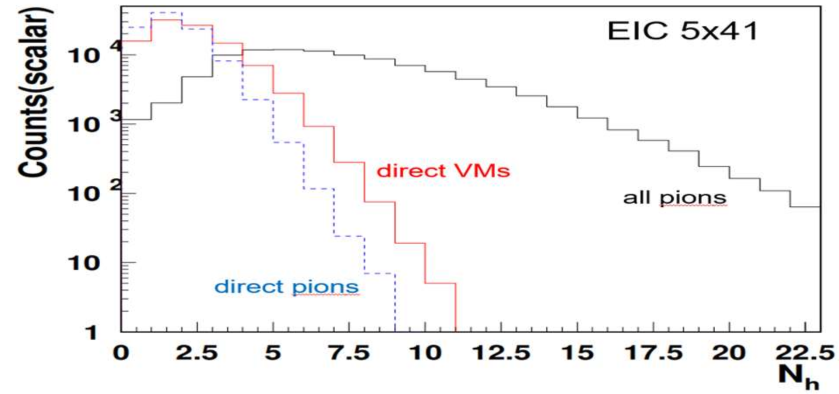


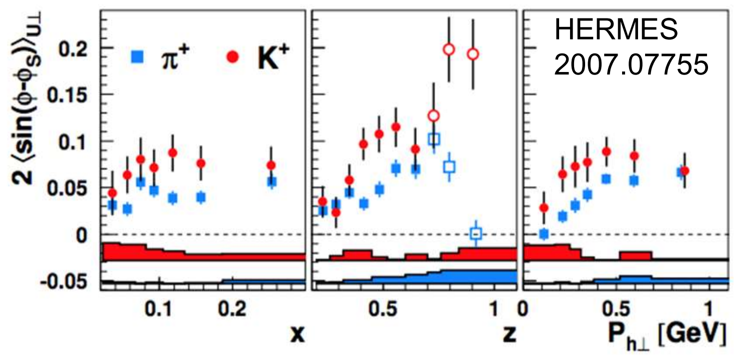
- Understanding the SSAs of VMs is critical in interpretation of the pion SIDIS

VM contributions

A. Kerbizi (Trieste U.)







Understanding VMs is critical for interpretation

Strong dilution of SSAs due to VM decays

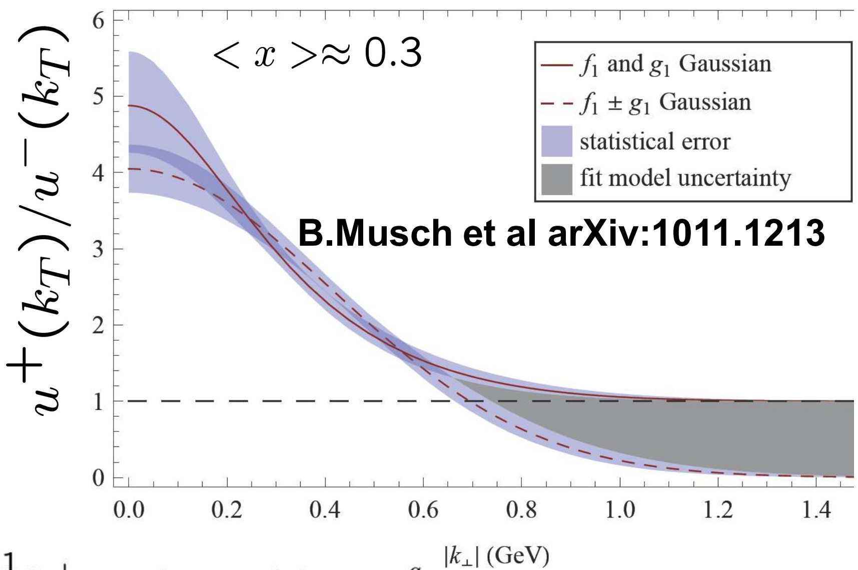
JLab can measure the SSA of VMs, and separate contributions

Are the differences in pions vs Kaons coming from VMs???
K* single spin asymmetries under way

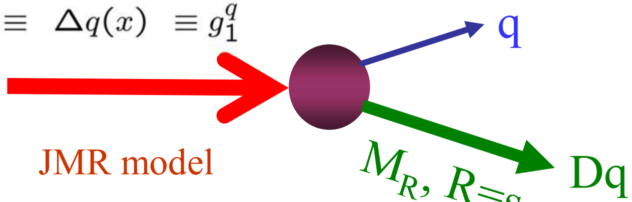
A_1 P_T-dependence

G.Matousek

- dfferent widths in $g_1(x,k_T)$ and $f_1(x,k_T)$

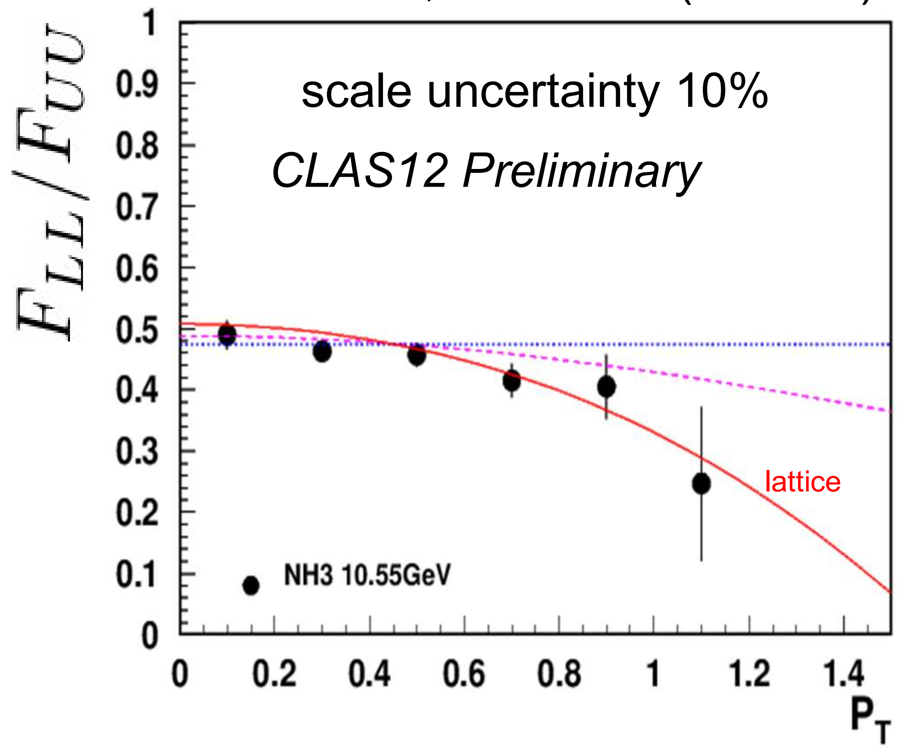


$$\frac{1}{2}(q^+ + q^-) \equiv \quad q(x) \quad \equiv f_1^q$$
$$\frac{1}{2}(q^+ - q^-) \equiv \quad \Delta q(x) \quad \equiv g_1^q$$



$$u^+(x, \mathbf{k}_T^2) \quad \propto \quad \frac{(xM+m)^2}{(\mathbf{k}_T^2 + \lambda_R^2)^{2\alpha}} \; ,$$
$$u^-(x, \mathbf{k}_T^2) \quad \propto \quad \frac{\mathbf{k}_T^2}{(\mathbf{k}_T^2 + \lambda_R^2)^{2\alpha}} \; ,$$

0.25<x<0.35, 0.2<z<0.8 (MX>1.5)

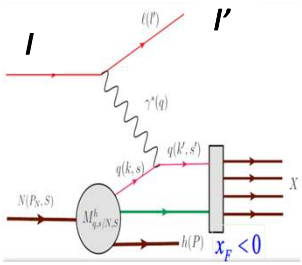


With more statistics can

- check with finer bins in P_T,
- extract the the same for dihadron sample

T.Hayward

Hadron production in TFR



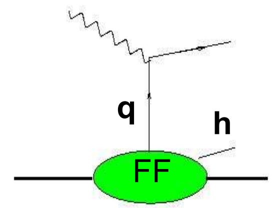
arXiv:2308.11251

$$F_{UL}^{\sin\phi_h} = -\frac{2|\vec{P}_{h\perp}|}{Q} x_B^2 u_L^h$$

unpolarized quarks in the longitudinally polarized proton

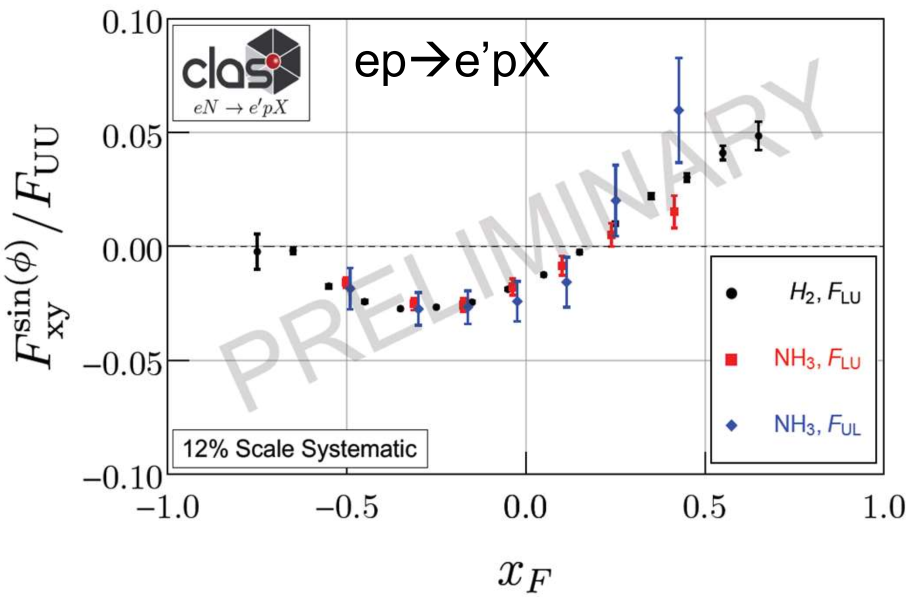
$$F_{LU}^{\sin\phi_h} = \frac{2|\vec{P}_{h\perp}|}{Q} x_B^2 l^h$$

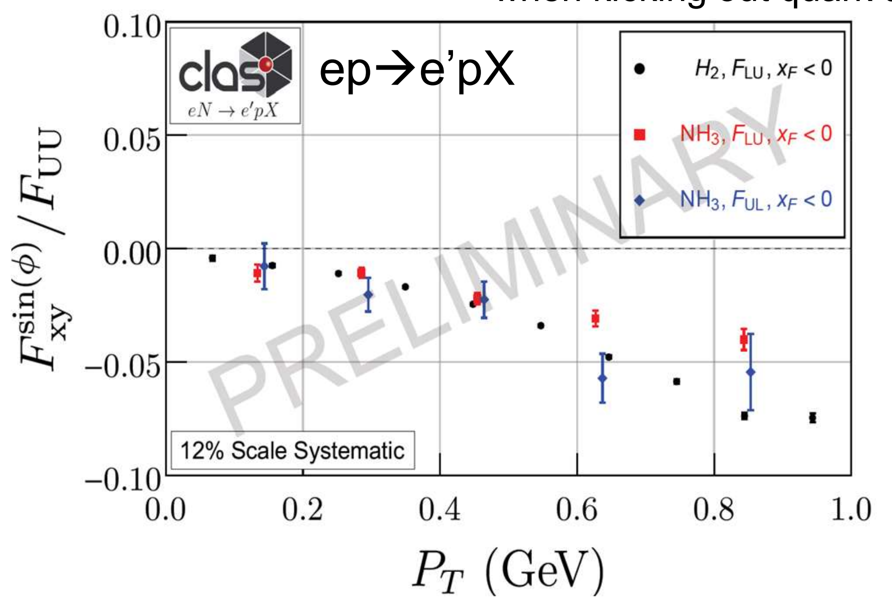
longitudinally polarized quarks in the unpolarized proton



The Twist-3 Fracture Functions responsible for SSAs A_{LU} and A_{UL}

Conditional probability to produce a hadron ***h***, when kicking out quark ***q***



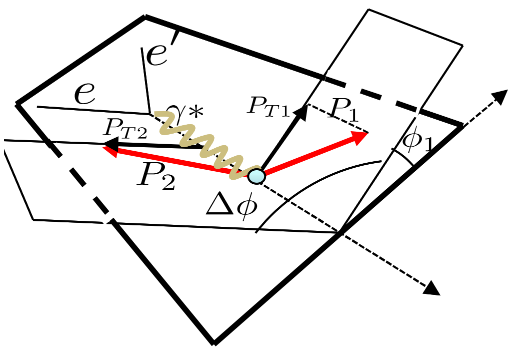


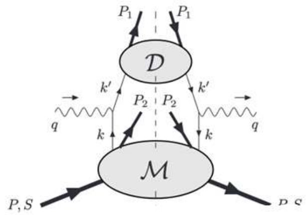
Significant asymmetries measured in Target Fragmentation Region (TFR), described by Fracture Functions provide complementary information on dynamics of polarized quarks

- F_{UL} and F_{LU} practically equal, indicating similar underlying distributions (unpolarized/longitudinally pol.)
- F_{LU} on hydrogen and NH3 practically the same, indicating medium modifications are smaller in TFR

Correlations in back-to-back 2 hadron production

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



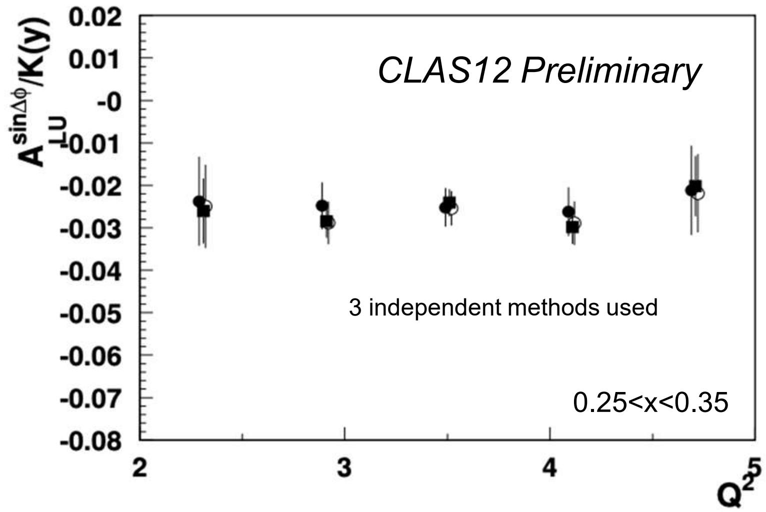


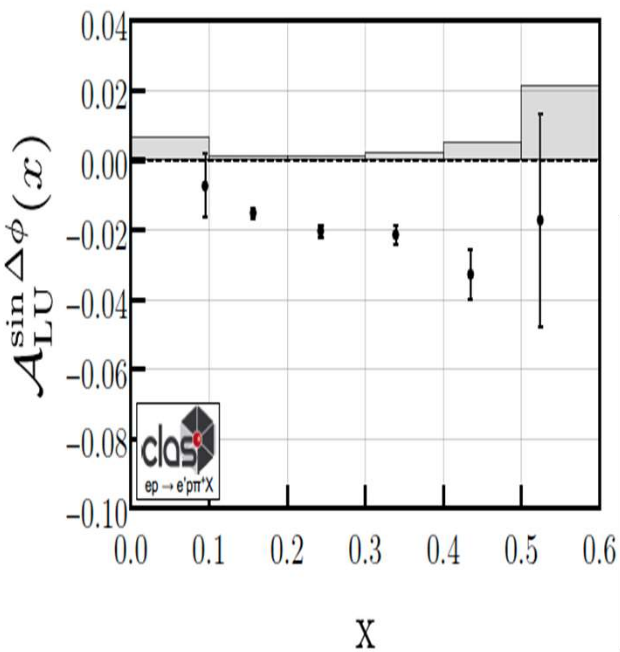
$$A_{LU} \propto \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi$$

arXiv: 2208.05086

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





- 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

SUMMARY

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

- To evaluate the systematics of extracted 3D PDFs (TMDs and GPDs) , it is critical to validate the formalism (ex. evolution studies), 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 (even more in kaon case) supporting a different dynamics in hadronization

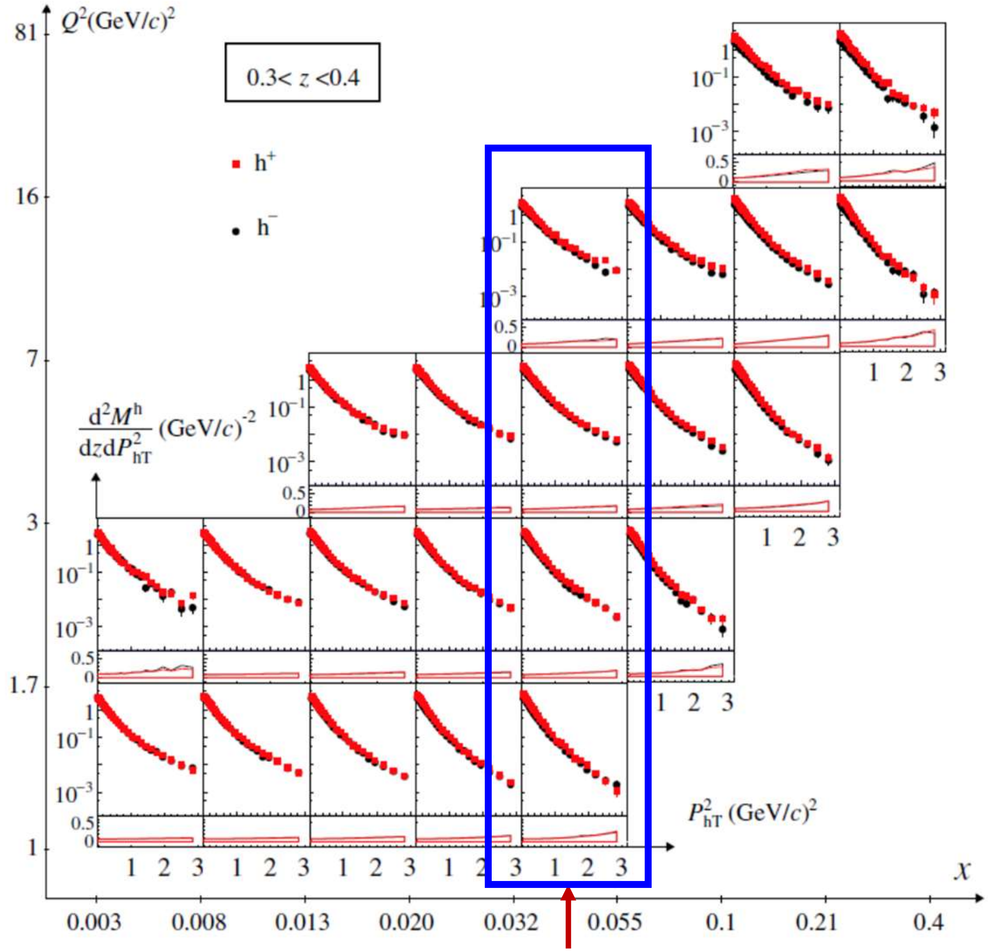
- Progress in theory and lattice calculations in describing the higher twist observables will be crucial for future precision studies of the 3D structure of nucleon using the GPD and TMD formalisms.

- support slides

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

q_T-crisis or misinterpretation



at higher Q^2 the slope in P_T changes, why?

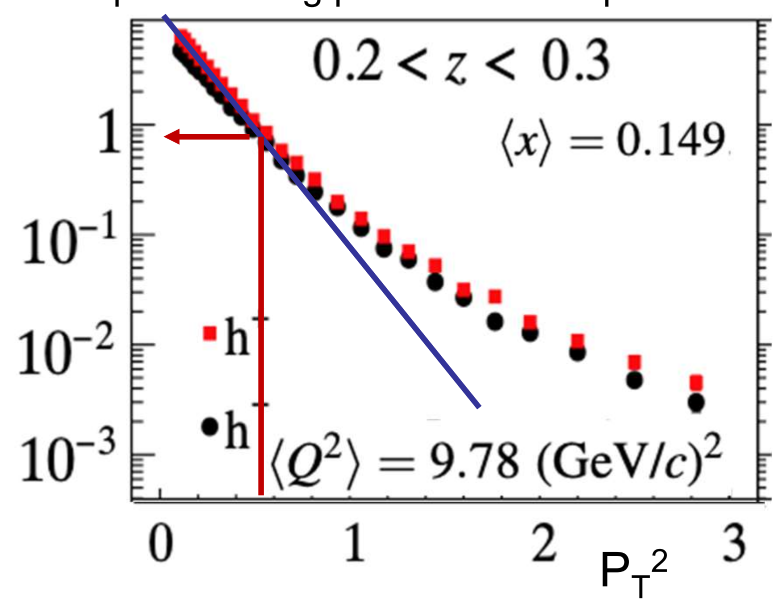
The q_T=P_T/z theory "trustworthy" cut:

1)Suppresses moderate Q^2 and large P_T (sensitive to k_T), where all kind of azimuthal modulations are most significant

2)Enhances large z region (ex. Exclusive Events) in TMD and low z in FO calculations

3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P_T samples , including ones from HERMES COMPASS, and even EIC.

https://arxiv.org/pdf/1709.07374.pdf



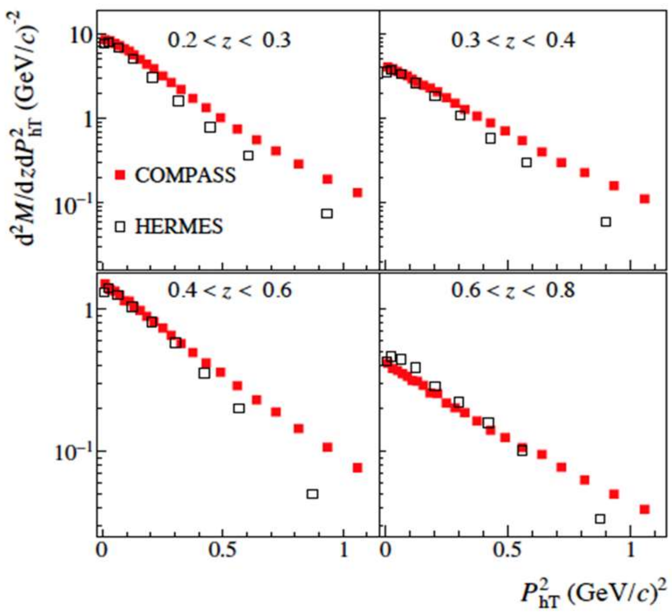
Theory unable to explain the correlation of P_T and Q

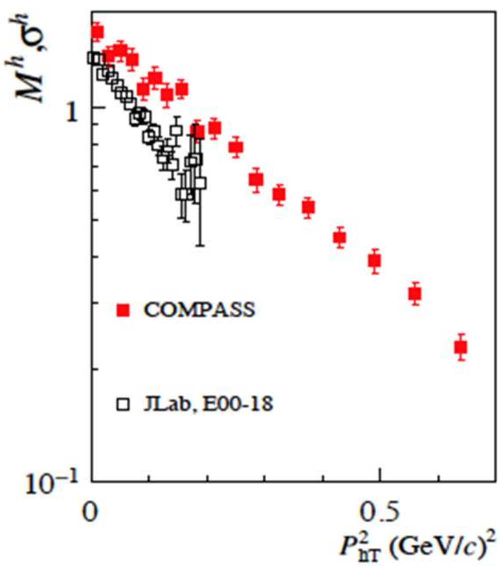
Multiplicities of hadrons in SIDIS

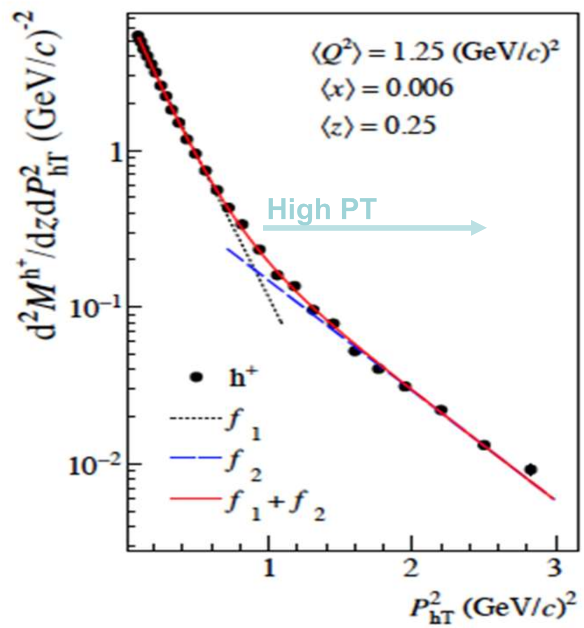
Gaussian Ansatz for $F_{UU,T}$ $\quad f_1^q \otimes D_1^{q\to h} = x f_1^q(x)\, D_1^{q\to h}(z) \dfrac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$

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

COMPASS:1709.07374



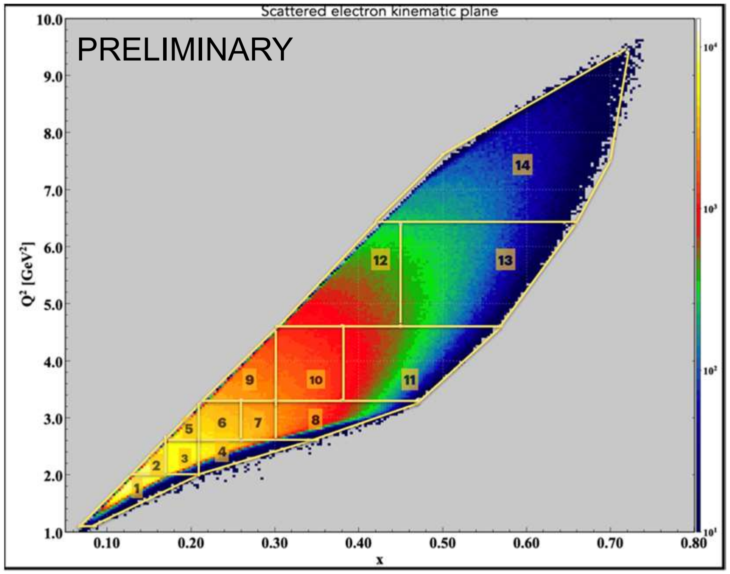


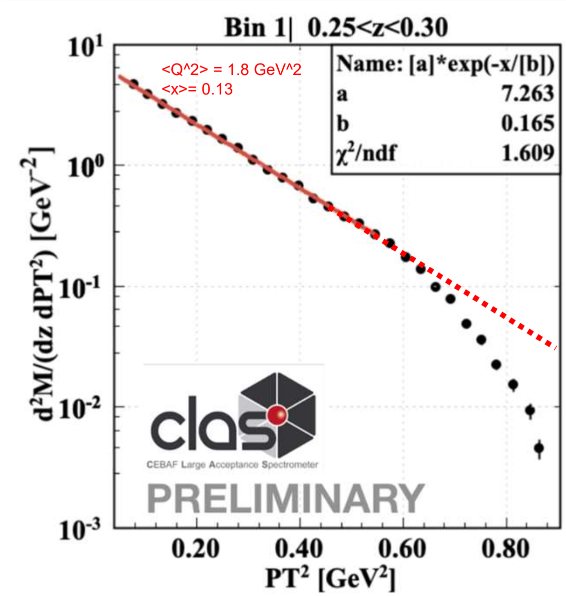


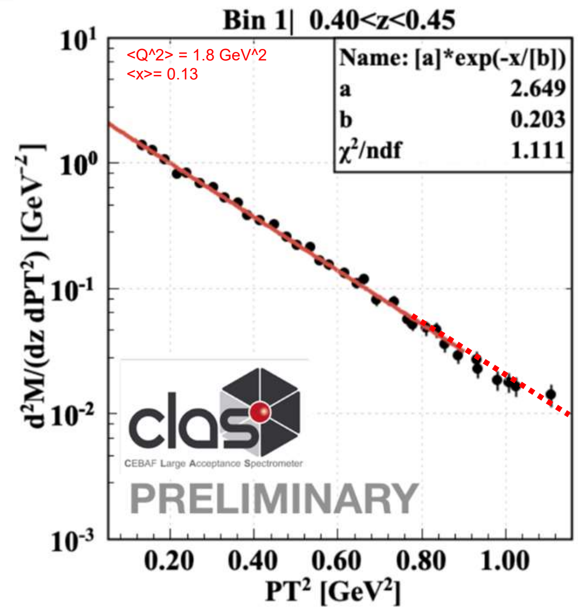
JLab: not enough energy to produce large P_T
HERMES: not enough luminosity to access large P_T

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

CLAS12 1h Multiplicities: high P_T & phase space

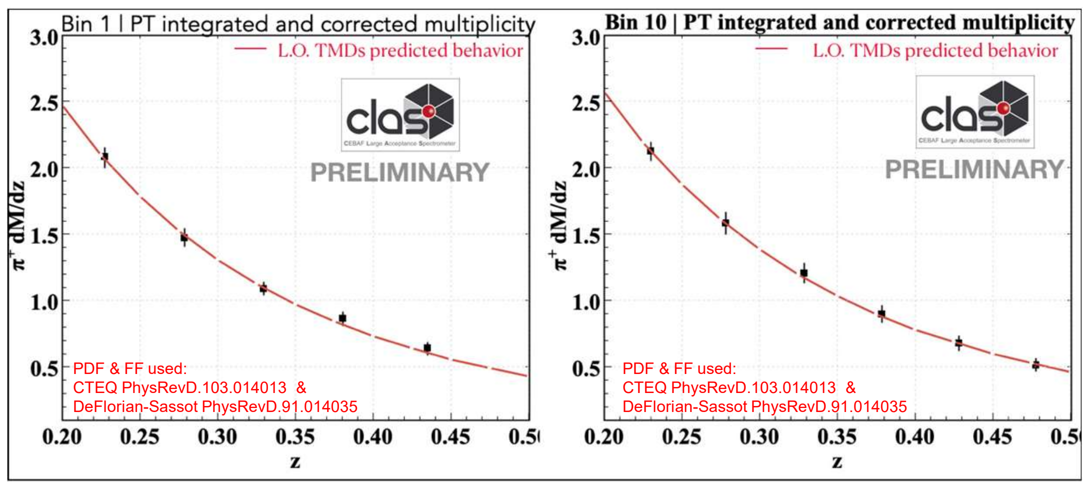






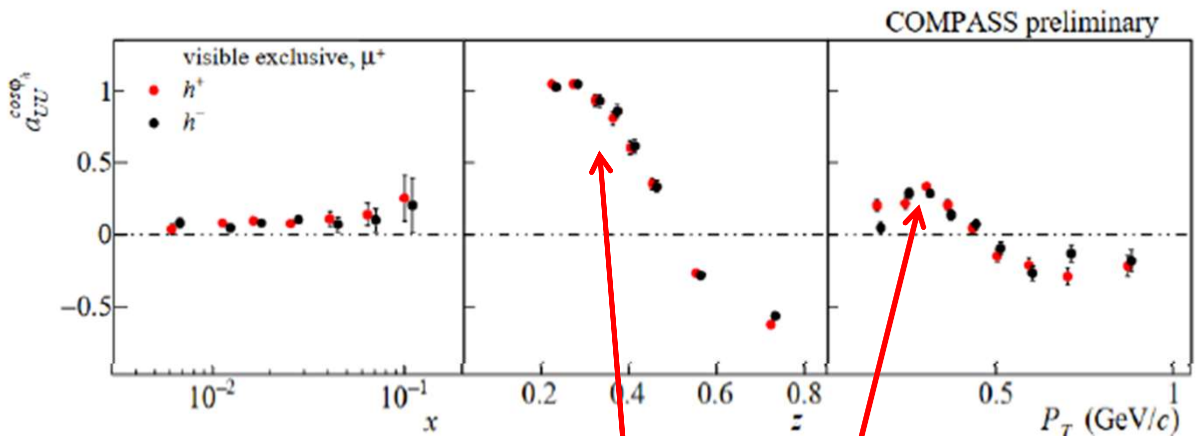
For some kinematic regions, at low z, the high P_T distribution appear suppressed: there is no enough energy in the system to produce hadron with high transverse momentum (phase space effect).

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

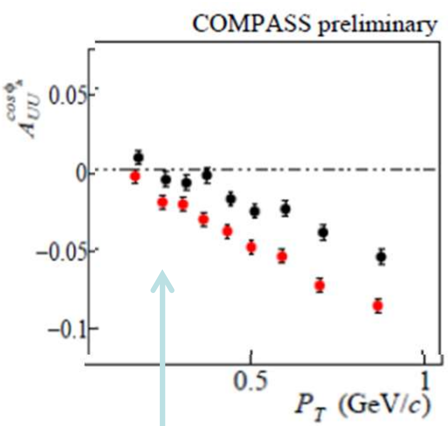


COMAPASS multiplicities and cosine modulations

J. Matousek→ COMPASS

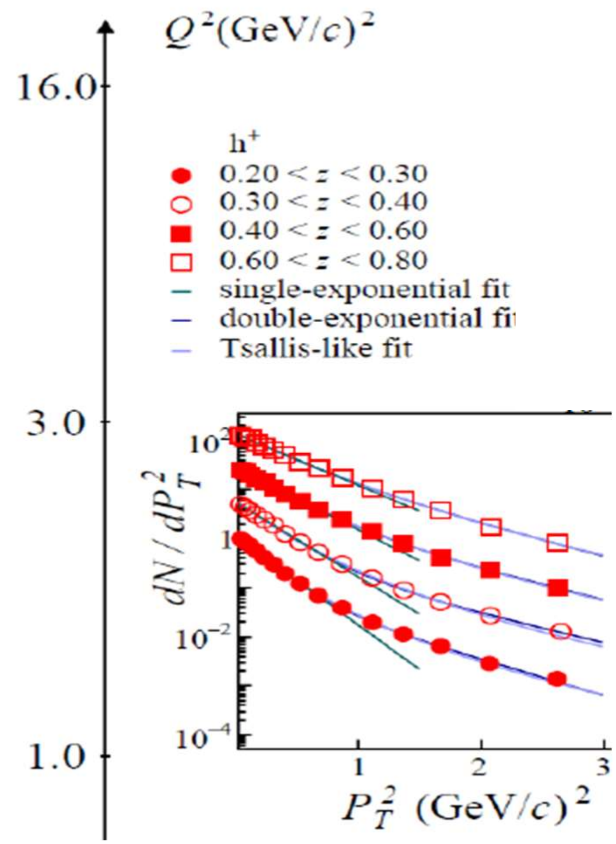


Negative cos of ρ^0 converts to positive for low P_T pions (sign flip ~z=0.5)



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

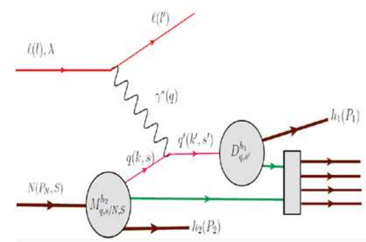
ρ–decay pions mess up linear dependence at low P_T

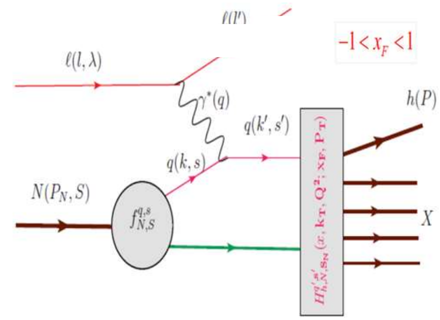


Theory is not able to explain the large P_T behavior of pion multiplicities !!!

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.

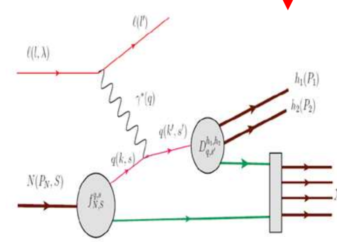


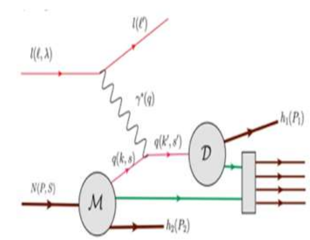


So why the LUND-MCs are so successful in description of hard scattering processes, and SIDIS in the first place?

•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

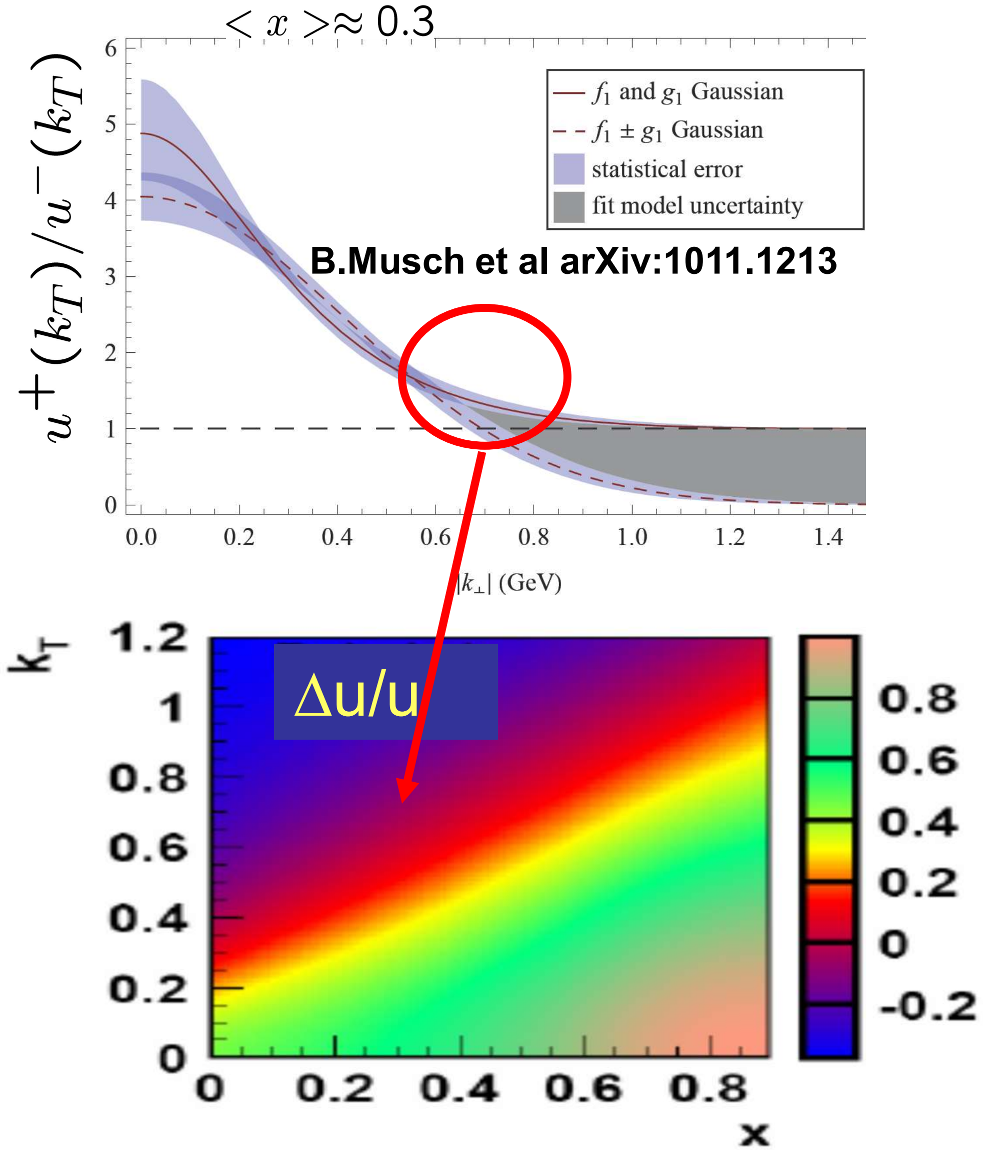


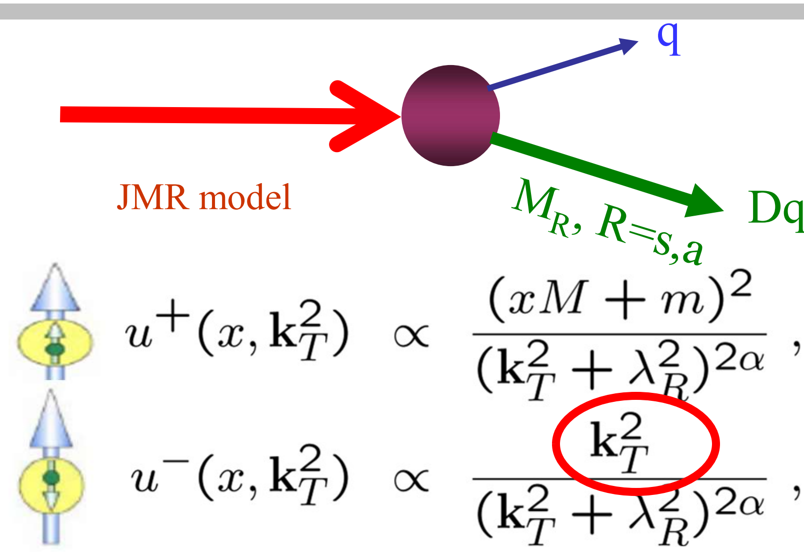


To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

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

Quark distributions at large k_T: lattice





$$u^+(x, \mathbf{k}_T^2) \propto \frac{(xM+m)^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

$$u^-(x, \mathbf{k}_T^2) \propto \frac{\mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

Sign change of Δu/u consistent between lattice and diquark model

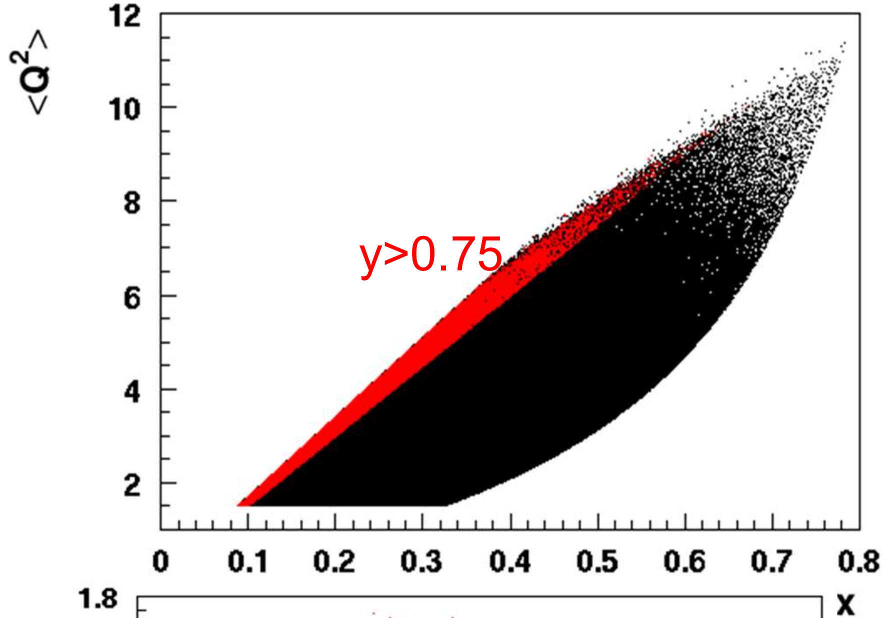
$$\frac{1}{2}(q^+ + q^-) \equiv q(x) \equiv f_1^q$$
$$\frac{1}{2}(q^+ - q^-) \equiv \Delta q(x) \equiv g_1^q$$

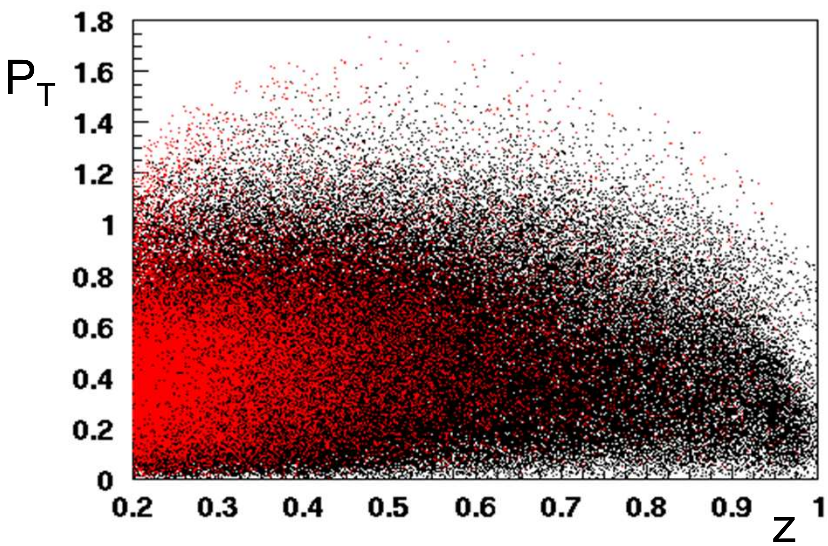
35

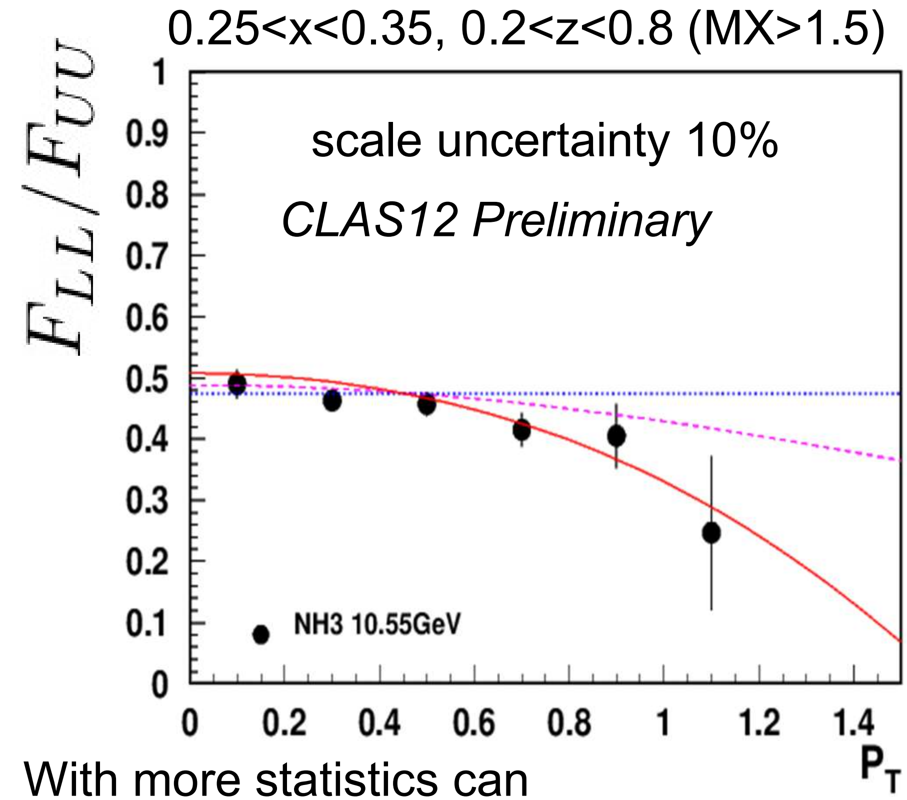
More quarks with opposite to proton spin at large transverse momentum

A_1 P_T-dependence

G.Matousek





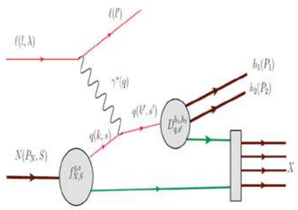


With more statistics can

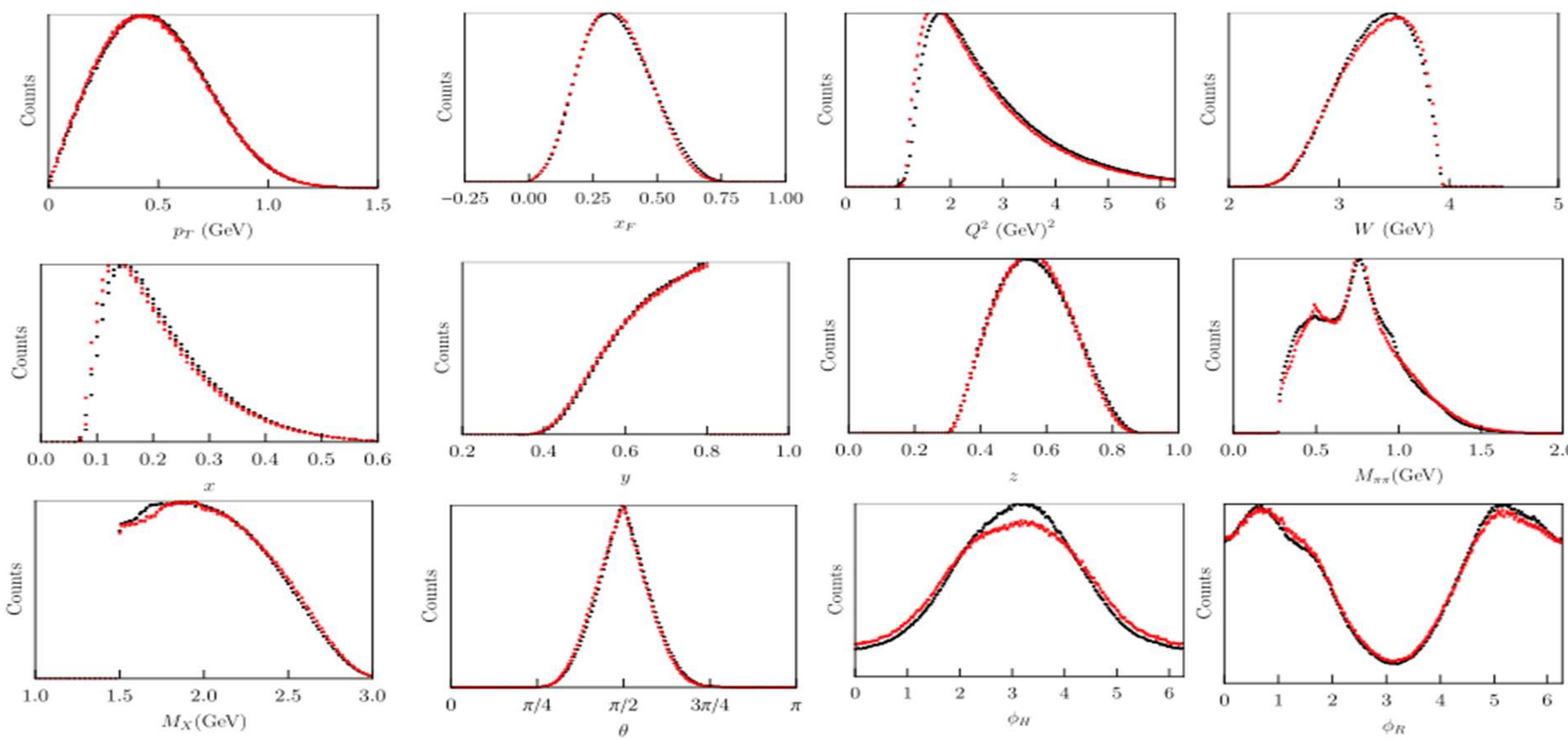
- check with finer bins in P_T,
- extract the the same for dihadron sample

Red curve predictions from Lattice accounting different widths in $g_1(x,k_T)$ and $f_1(x,k_T)$

SIDIS ehhX: CLAS12 data vs MC

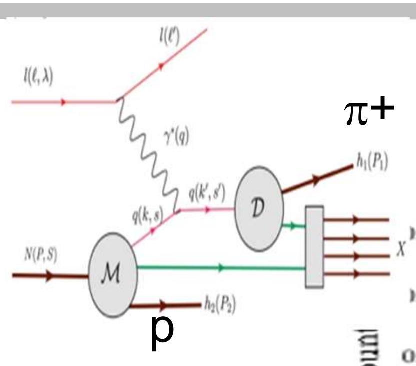


CLAS12 dihadron production ep→ehhX



CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters "default" is in a good agreement with CLAS12 measurements for all relevant distributions

SIDIS ehhX: CLAS12 data vs MC



CLAS12 dihadron production ep→ephX (CFR/TFR)

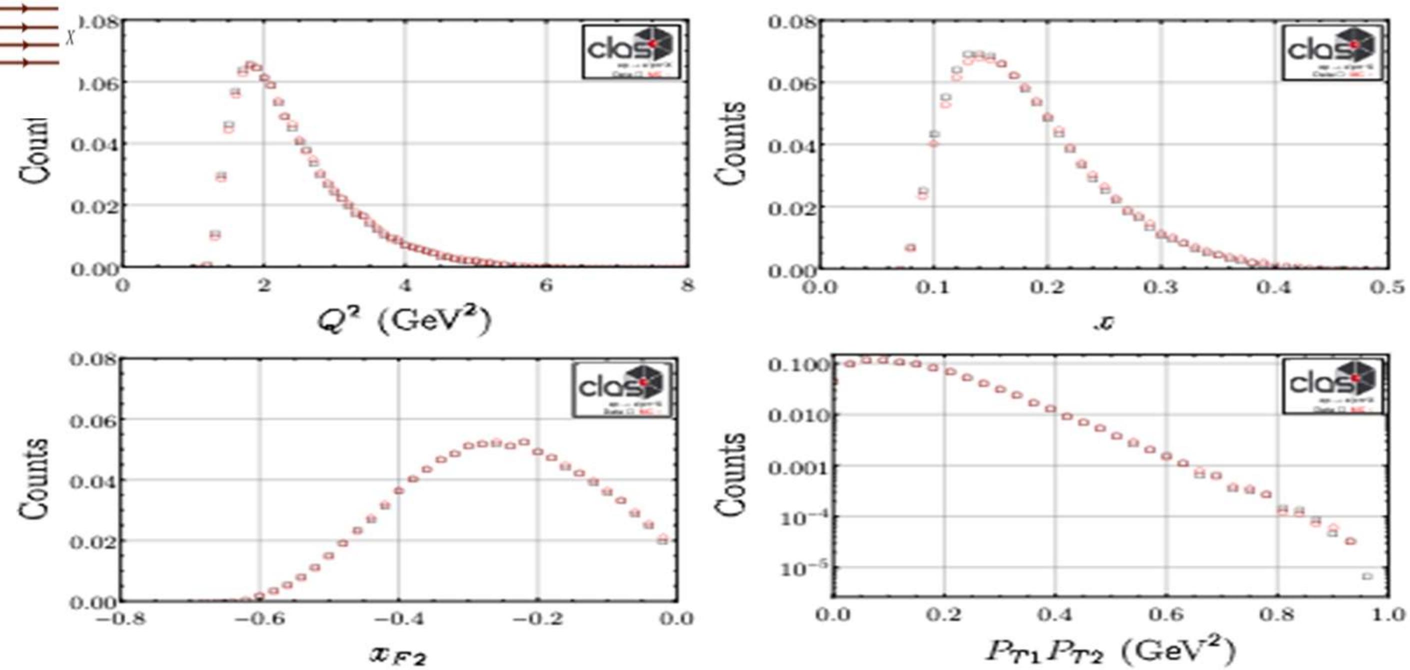
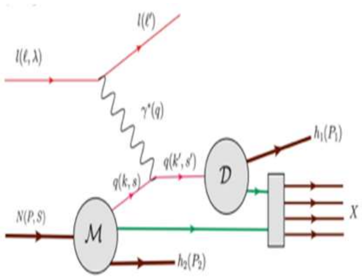


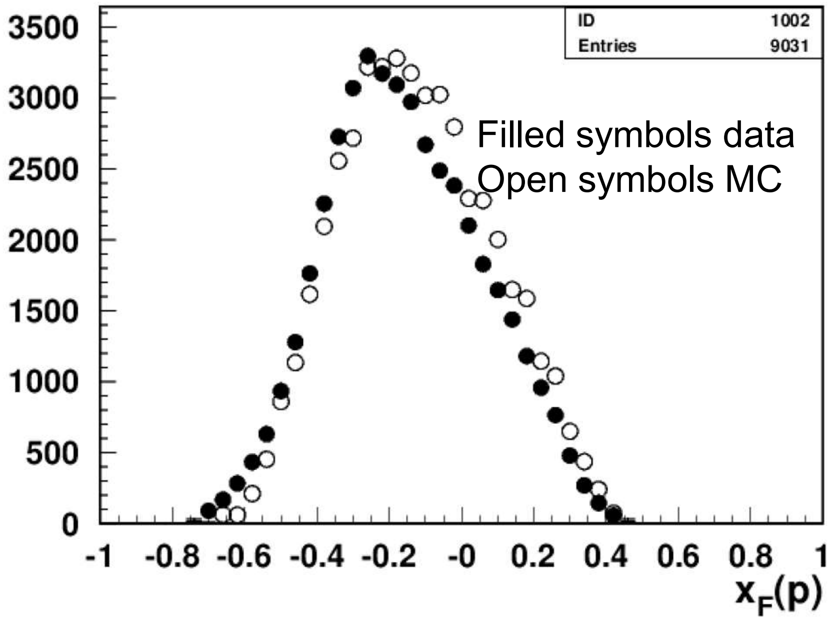
FIG. 12: Comparison between data (black squares) and Monte Carlo (red circles) for Q^2 (top left), x (top right), x_{F2} (bottom left) and $P_{T1}P_{T2}$ (bottom right, log scale). Counts are normalized to the total number of dihadron pairs. Excellent agreement is observed.

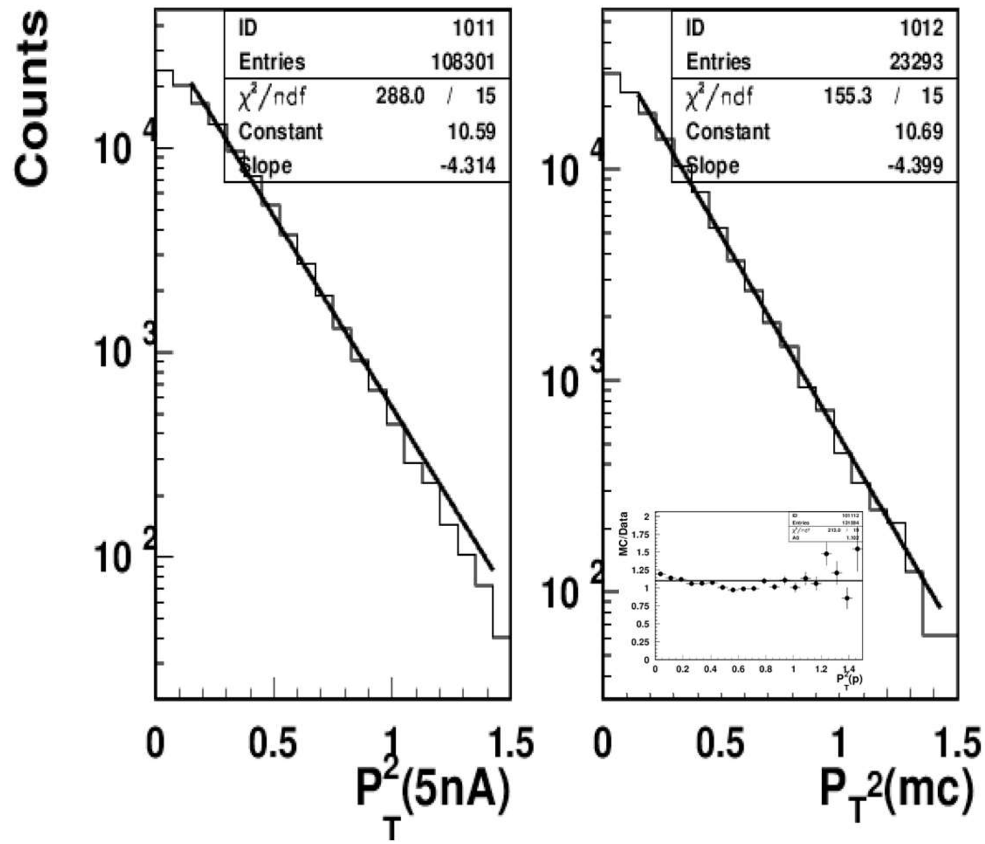
CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters ”default” is in a good agreement with CLAS12 measurements for all relevant distributions

CLAS12 Studies: Data vs MC



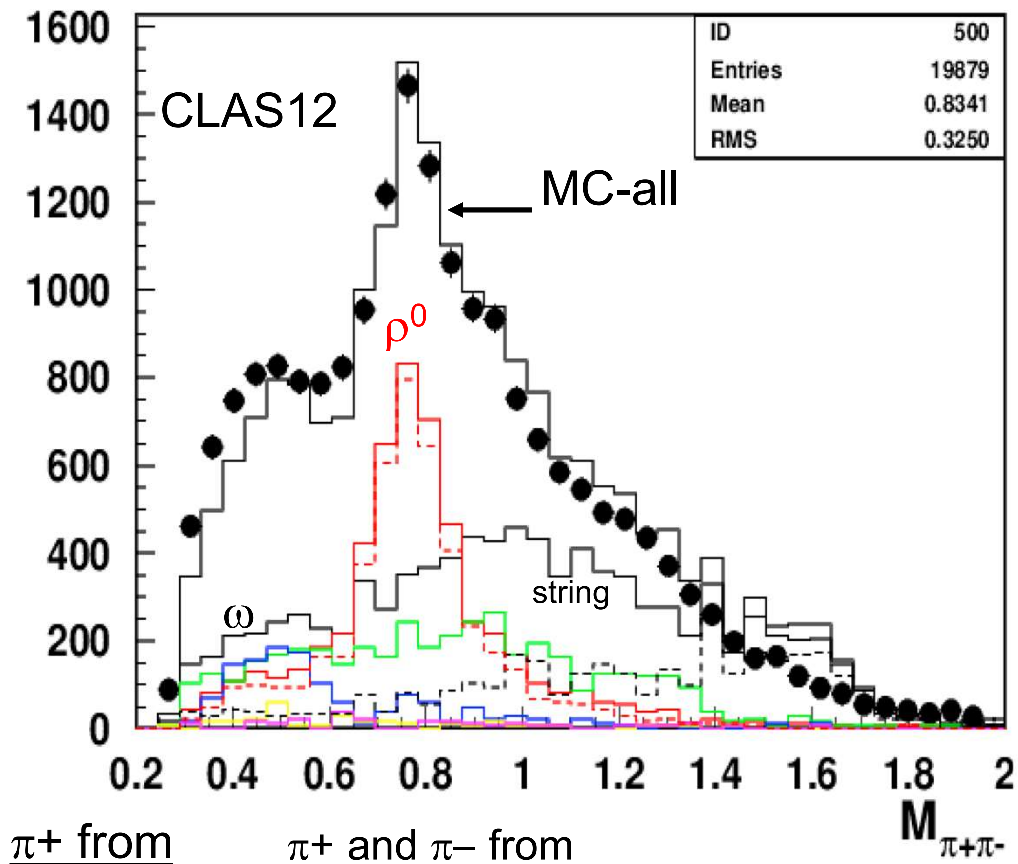
Using PEPSI (LUND) generator

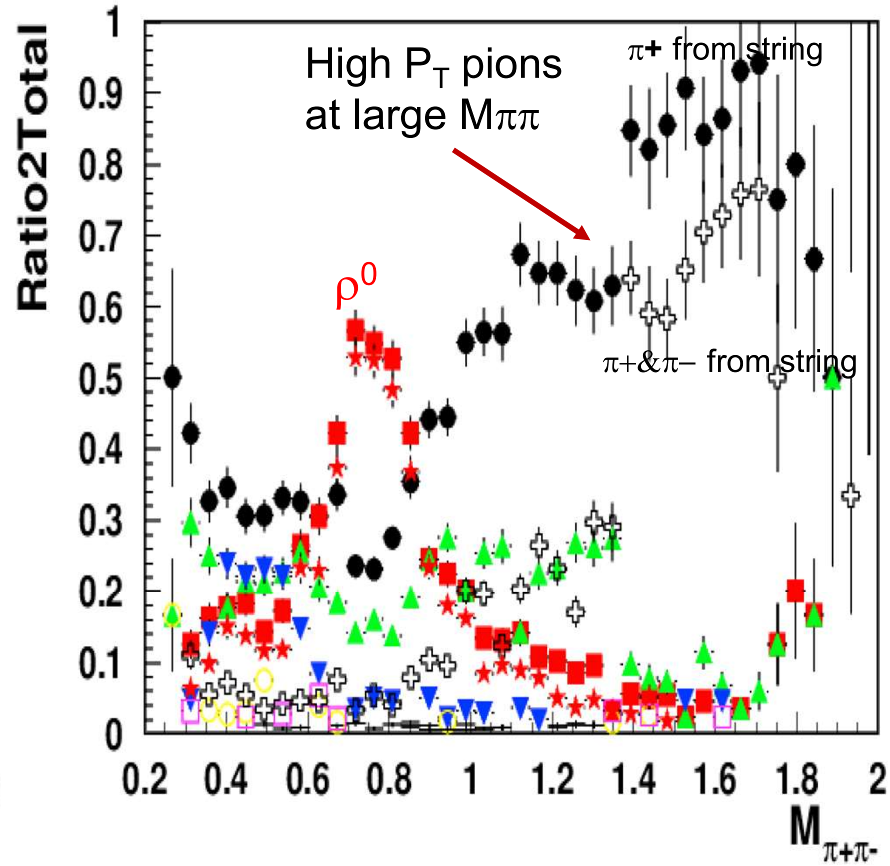




- Kinematic distributions, z,x_F,P_T-distributions of protons, and widths are in good agreement with LEPTO
- TFR may be a valuable source for studies of widths in hadronization
- Expect significantly better separation of TFR and CFR at JLab24

Sources of inclusive pions: CLAS12 vs MC





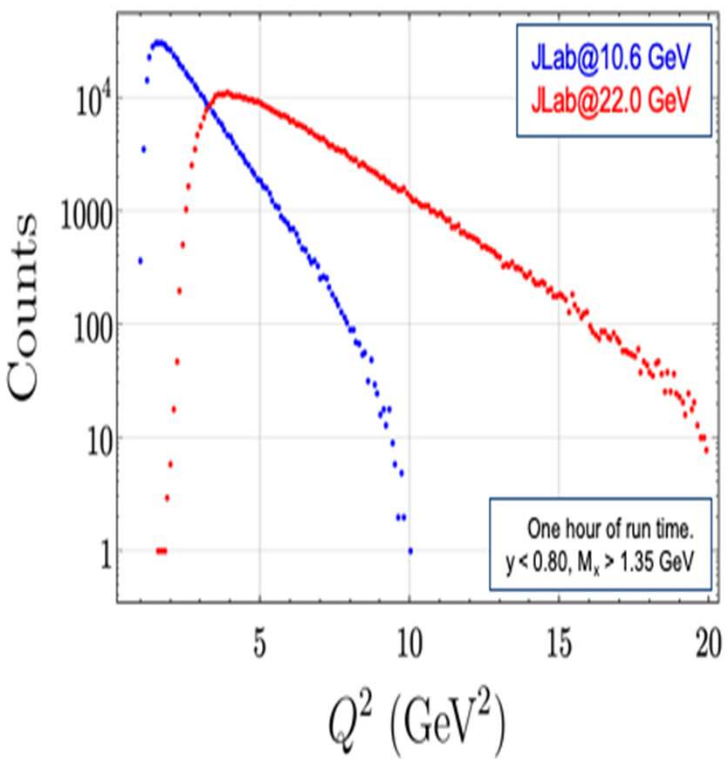
π+ from — ρ0, string, ρ+, ω

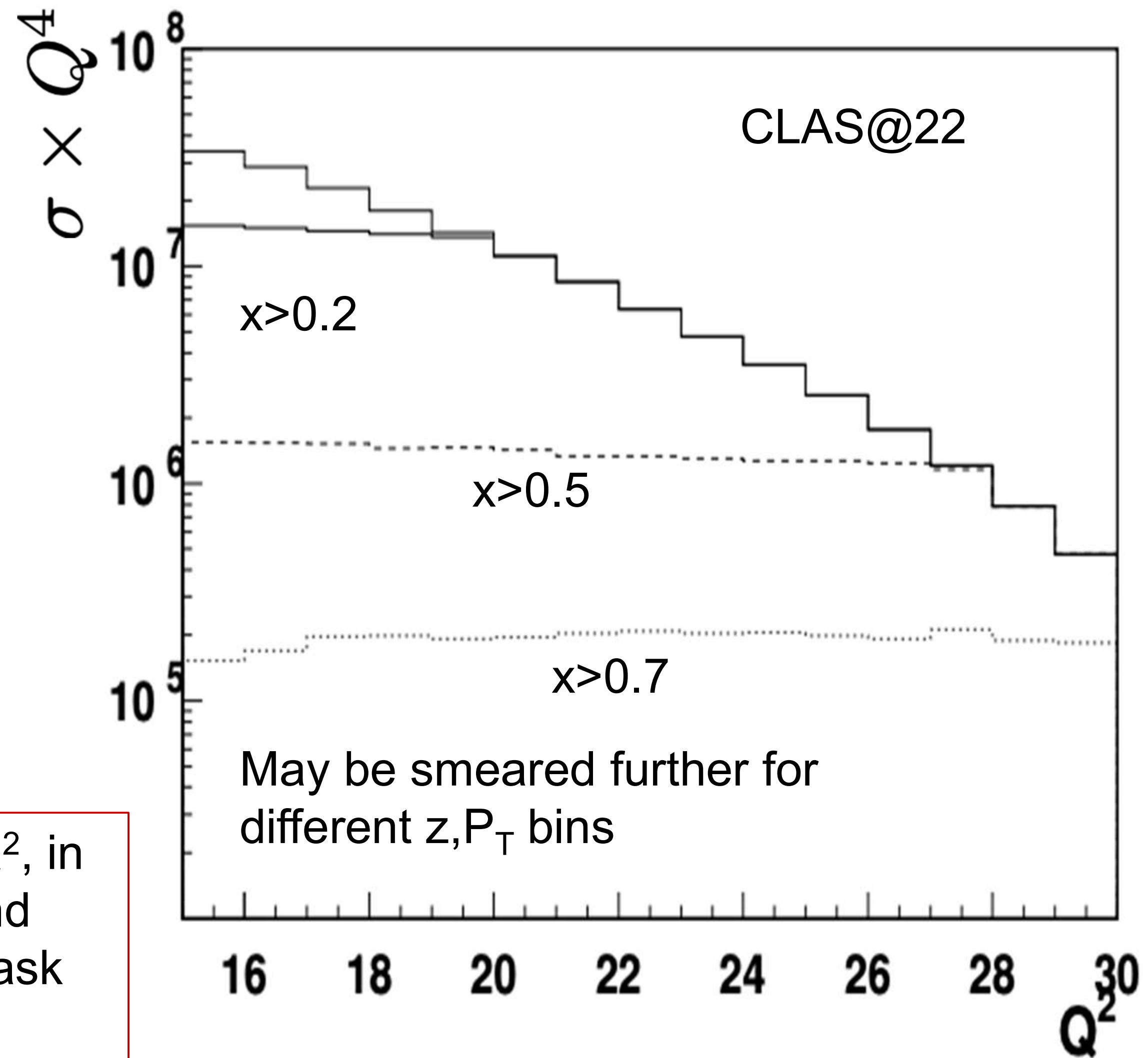
π+ and π− from

- Dominant fraction of inclusive pions come from VM decays
- Relative fraction by default in JETSET ~50%

Very important to have multidimensional TMD Fragmentation Functions!

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