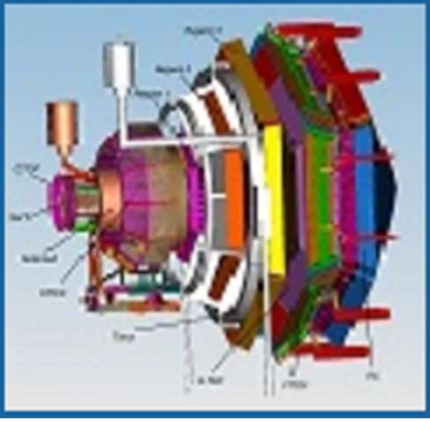
# SIDIS with CLAS12 RGA



## CLAS12 Run Group A - Retreat

**Harut Avakian (JLab)**

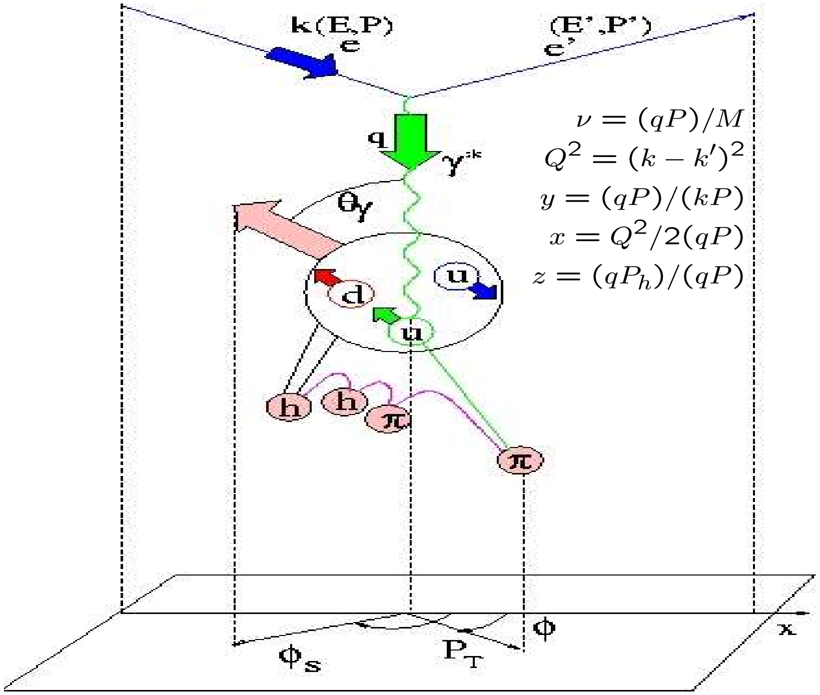
CNU, 18 Oct 2023

Introduction
– Regular SIDIS ep→e'hX ( ep→e'$\pi$+X, ep→e'K+X)
– SIDIS with 2+ hadrons in the final state (ep→e'p$\pi$+X, ep→e'$\pi^+\pi^-$X)
– Separating the kinematics of current and target fragmentation
–Separating dynamical contributions in exclusive and semi-inclusive process
Summary

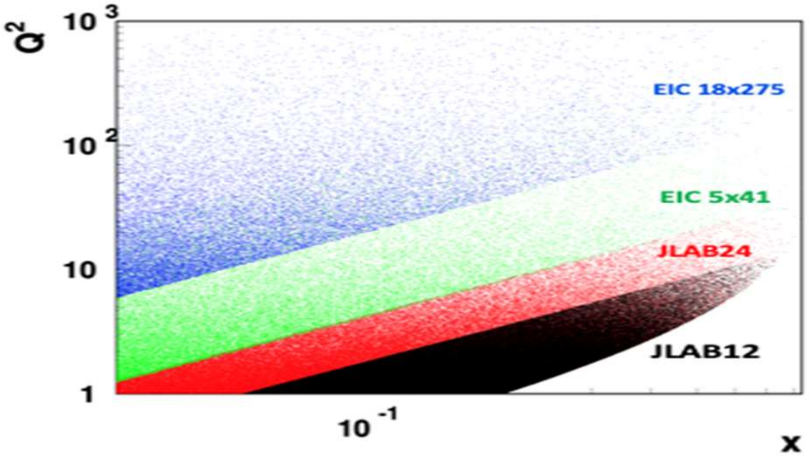
SIDIS working group (JLab, UCONN, Duke, ANL + Gissen, Ferrara, Frascati)

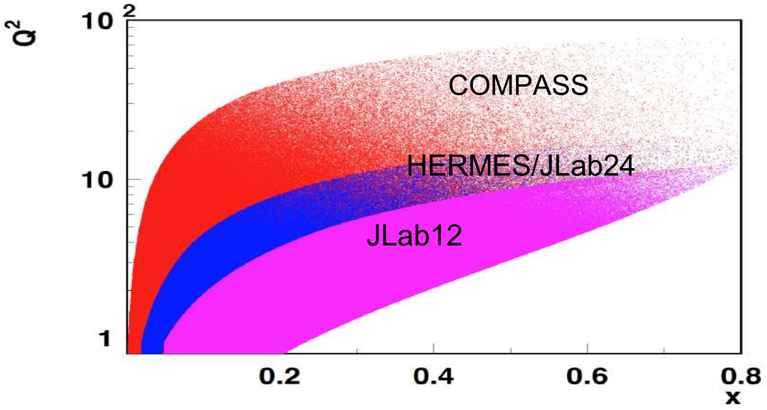
https://clasweb.jlab.org/wiki/index.php/SIDIS_Analysis_Group#tab=Overview

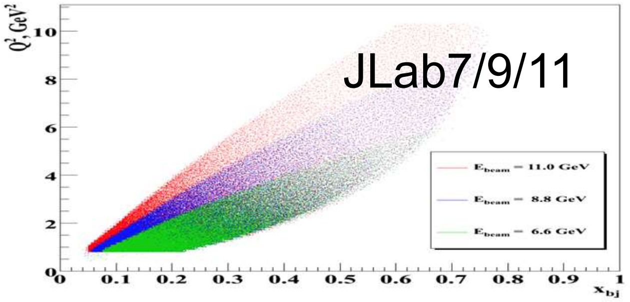
# SIDIS kinematical coverage and observables



EIC







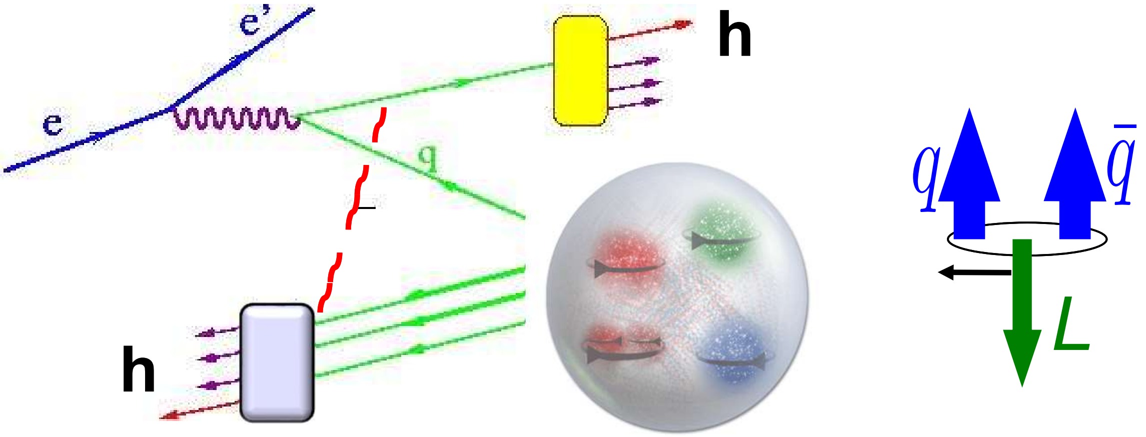
Experiments measure azimuthal dependence of the cross section as a function of $x, Q^2, z, P_T$

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

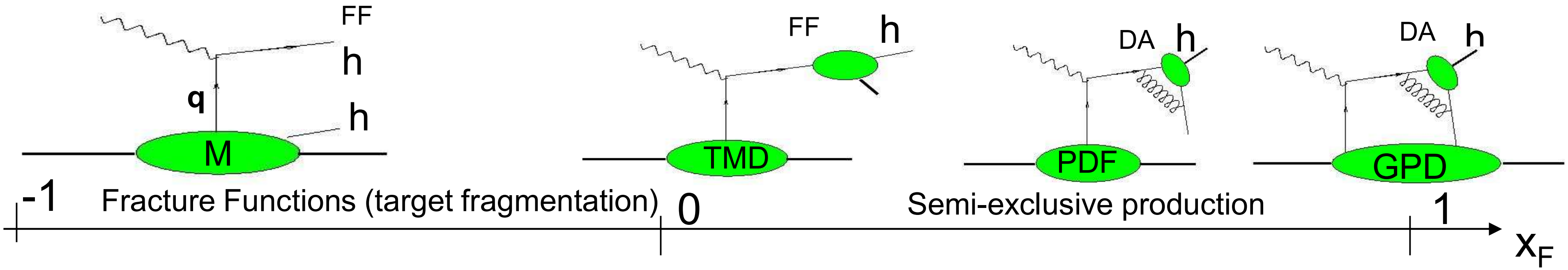
# Hadron production in hard scattering in SIDIS

$x_F$ – fractional momentum in the CM frame

$x_F$>0 (current fragmentation)



$x_F$<0 (target fragmentation)

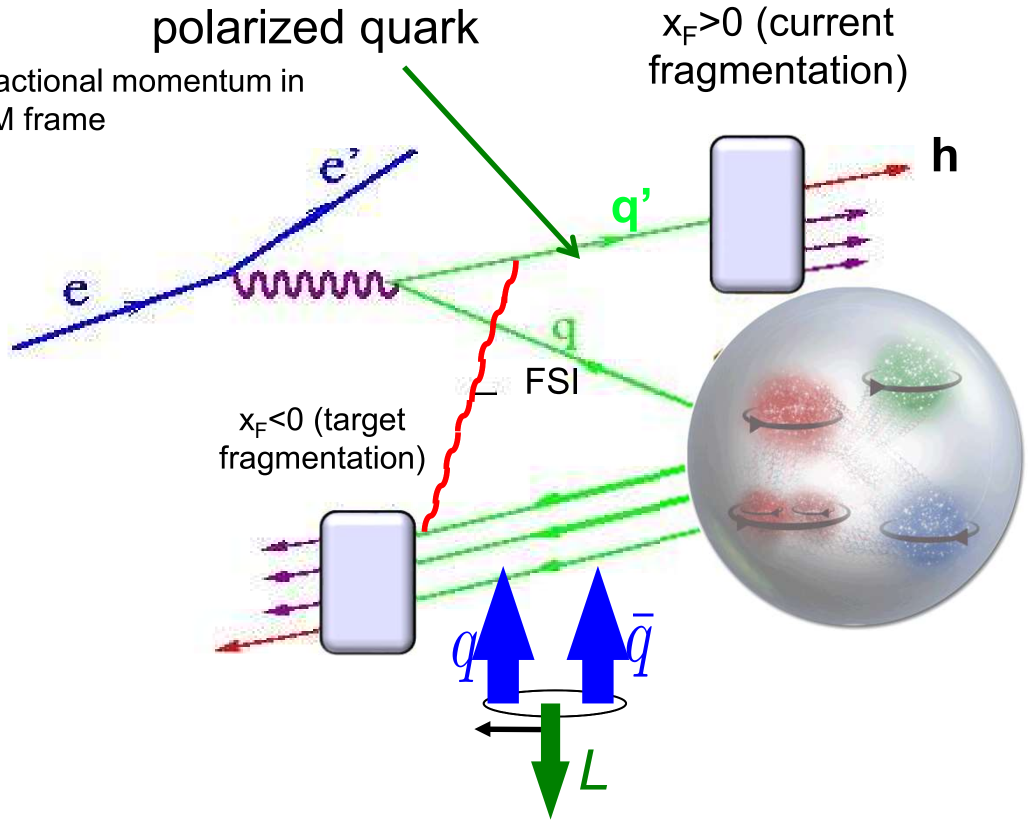


Fracture Functions (target fragmentation)

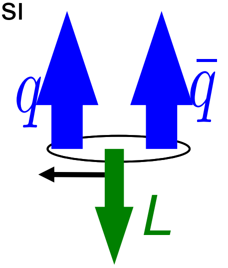
Semi-exclusive production

Different non-perturbative objects may be involved in description, depending on kinematical conditions, introducing different dependence on $Q^2$

# 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 qluon correlations described by higher twist 3D TMD PDFs, access to details of the QCD dynamics “forces”,….

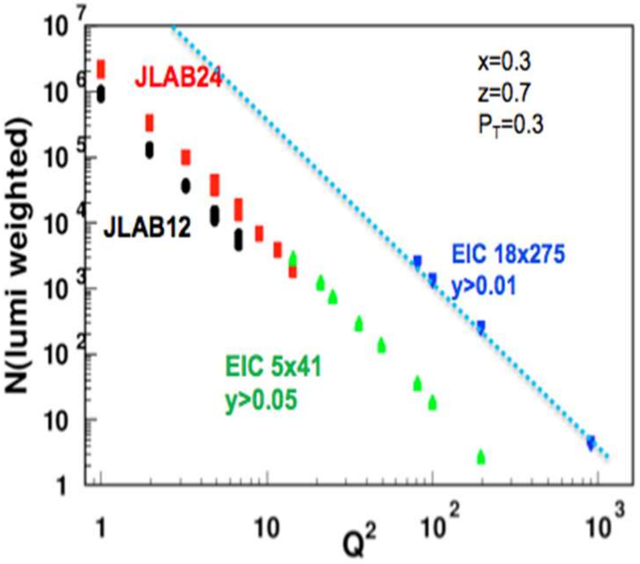
Final state interactions and quark-gluon correlations give rise to detectable spin-azimuthal modulations of produced particles

# Structure functions and depolarization factors

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

x-section for eN→e'hX

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

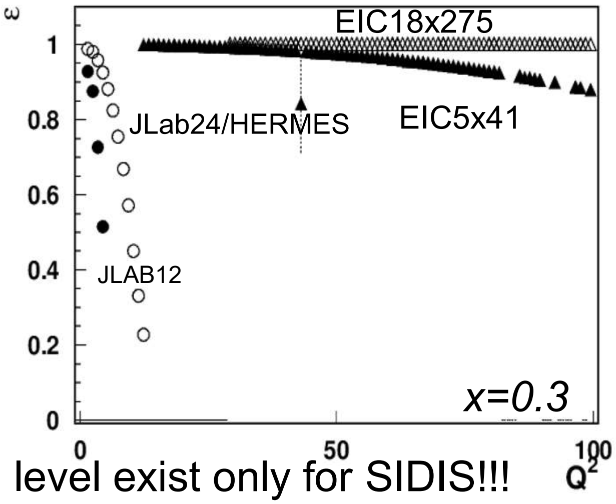


x-section from Bacchetta et al, 1703.10157

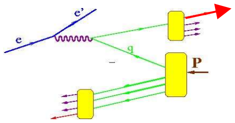
Combination of statistics and depolarization factors defines measurable SFs

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

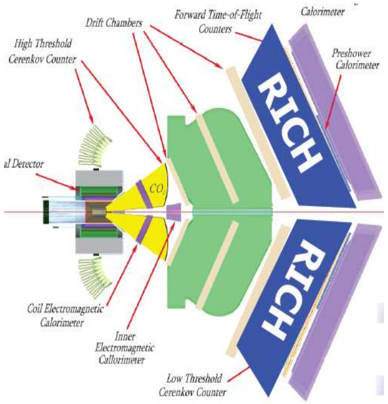
2) Meaningful interpretation the Collins effects requires separation of VMs(JLab)



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



# SIDIS at JLab12



CLAS12

**E12-16-010C**

E12-06-112: $\pi^+,\pi^-,\pi^0$
E12-09-008: $K^+, K^-,K^0$

E12-07-107: $\pi^+,\pi^-,\pi^0$
E12-09-009: $K^+,K^-,K^0$

C12-11-111: $\pi^+,\pi^-,\pi^0$
$K^+, K^-$

$H_2$, $NH_3$, HD

## Proton

Quark spin polarization

Nucleon polarization

| 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: $\pi^+,\pi^-, K^+,K^-$
C12-11-102: $\pi^0$

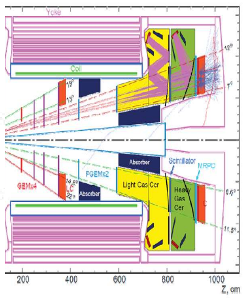
HMS
SHMS

**E12-06-104**
**E12-23-014**

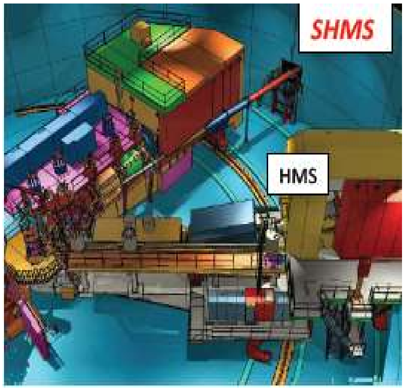
C12-11-108: $\pi^+,\pi^-$

Solid

$H_2$ | $NH_3$



E12-16-010C



CLAS12

E09-008: $\pi^+,\pi^-,\pi^0$
$K^+, K^-,K^0$

E07-107: $\pi^+,\pi^-,\pi^0$
E09-009: $K^+,K^-,K^0$

$D_2$, $ND_3$

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

## $D_2$

Quark spin polarization

Nucleon polarization

| 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: $\pi^+,\pi^-, K^+,K^-$
C12-11-102: $\pi^0$

HMS
SHMS

$D_2$

## $^3He$

Quark spin polarization

Nucleon polarization

| 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

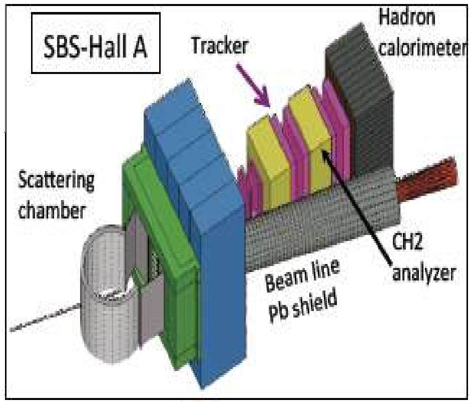
E12-07-007: $\pi^+, \pi^-$

Solid

E10-006: $\pi^+,\pi^-$
E12-09-018: $\pi^+,\pi^-, K^+,K^-$

Solid
SBS

$^3He$



# UConn Group on RG-A SIDIS (PI: Kyungseon Joo)

- **List of PhD students and subject of thesis topic completed and in progress**
  - Richard Capobianco (Ph.D. Expected in 2024) with Argonne Group: Analysis of cos\phi and cos \2phi modulations of SIDIS pi+ cross section (pass2 data).

- **Completed analyses and published articles based on pass1 data forward tracking only**
  - Timothy Hayward et al., "Observation of Beam Spin Asymmetries in the Process ep→eπ+π-X with CLAS12", Phys. Rev. Lett. 126, 152501 (2021).
  - Stefan Diehl and Kyungseon Joo et al., "Multidimensional, High Precision Measurements of Beam Single Spin Asymmetries in Semi-Inclusive π+ Electroproduction off Protons in the Valence Region", Phys. Rev. Lett. 128, 062005 (2022).
  - Timothy Hayward, and H. Avakian et al. (CLAS Collaboration), "Observation of Correlations Between Spin and Transverse Momenta in Back-to-Back Dihadron Production at CLAS12", Phys. Rev. Lett. 130, 022501 (2023).

- **Analyses based on pass1 data**
  - Stefan Diehl and Kyungseon Joo, “Flavor and kinematic effects in beam spin asymmetries from semi-inclusive pion electroproduction off protons...,” Adhoc review currently under way.
  - Aron Kripko, Stefan Diehl and Kyungseon Joo, “Multidimensional Measurements of Beam Single Spin Asymmetries in Semi-inclusive Deep In. Charged Kaon Electroproduction,” Adhoc review currently under way.
  - Fatiha Benmokhtar and Timothy Hayward, “Single Spin Asymmetries in Proton Electroproduction (ep->epX).”

- **CLAS Approved Analysis (CAA) and Analyses based on pass2 data in FY24**
  - Timothy Hayward and Harut Avakian, “Investigations of flavor dependence in the correlation of charged pion-proton pairs in back-to-back dihadron production,” CLAS Approved Analysis (CAA) proposal. Currently under review.
  - Redo all the above PASS1 analyses combining forward and central tracking together

# Justus Liebig University Giessen (Stefan Diehl)

- **List of PhD students and subject of thesis topic completed and in progress**
  - Aron Kripko (Charged Kaon SIDIS BSA with RG-A), thesis completed, graduation in Nov 2023

- **Analyses based on pass1 data**
  - S. Diehl et al., Multidimensional, High Precision Measurements of Beam Single Spin Asymmetries in Semi-Inclusive π+ Electroproduction off Protons in the Valence Region, Phys. Rev. Lett. 128, 062005 (2022).
  - S. Diehl et al., **Flavor and kinematic effects in beam spin asymmetries from semi-inclusive pion electroproduction off protons in the valence region** (pi- and pi0 SIDIS BSA), analysis note approved, paper under ad-hock review, to
  - A. Kripko et al., **Multidimensional Measurements of Beam Single Spin Asymmetries in Semi-inclusive Deep Incluisve Charged Kaon Electroproduction**, analysis note approved, paper under ad-hock review

- **Current analysis with Pass2 data and FY2024 plans**
  - S. Diehl, cos(phi) and cos(2phi) modulations from pi- SIDIS (RG-A – pass 2)
  - A. Kripko, cos(phi) and cos(2phi) modulations from charged Kaon SIDIS (RG-A – pass 2)

# Duke University (Anselm Vossen)

- **List of PhD students and subject of thesis topic completed and in progress**
- Matthew McEneaney
  - -lambda spin transfer (working on paper) —>might also do this for RGB, RGC
  - -transverse lambda polarization and lambda-K correlations
- Gregory Matousek, Connor Pecar, Kei Nagai
- -di-hadrons,harged and neutral pions
- -kaons
- -BSA and target single/double spin asymmetries (with long target), simultaneous extraction of amplitudes (obviously overlap with RGB, RGC)
- -cross-section
- -Boer Mulders
- **Analyses based on pass1 data**

Partial waves in di-hrons (C.Dilks)

- **Current analysis with Pass2 data and FY2024 plan (Greg)**
- -semi-inclusive and exclusive vector mesons
- -rho, omega,

# Argonne (Maria Zurek)

Maria Żurek (PI), Marshall B. C. Scott (postdoc), Henry Klest (postdoc, start in FY24), Richard Capobianco (grad student, UConn/Argonne)

**PhD Thesis:**

R. Capobianco, Measurements of the Cos$\varphi_h$ and Cos2$\varphi_h$ Moments of the Unpolarized SIDIS $\pi^+$ Cross-section at CLAS12 - Analysis developed on pass-1 data. Transition to pass-2 data planned. Planned analysis conclusion: FY24.

**Analyses on pass-1 data:**

M. Scott, Neutral Pion Multiplicities - Analysis developed on pass-1 data. Transition to pass-2 data planned. Planned analysis conclusion: FY24.

**Planned analyses on pass-2 data:**

Unpolarized cross-section modulation and multiplicity program to be continued with pass-2 data (extended to CD) including also deuteron target (RG-B).

H. Klest - continuation of multiplicity studies with pass-2 data in FY24. M. Scott postdoc term ends end of 2023.

# Connections with other run groups

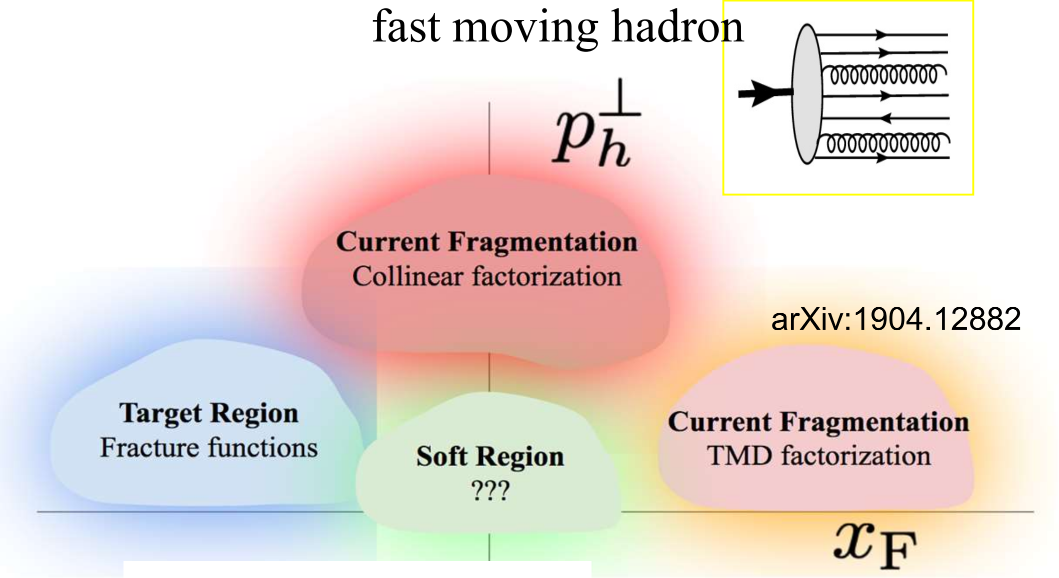
Detailed understanding of SIDIS on proton (RGA) in terms of underlying 3D PDFs and hadronization functions (Fragmentation, Distribution Amplitudes, Fracture Functions) requires measurements with neutrons (RGB) and different helicity combinations (RGC)

Interpretation of SIDIS measurements, being sum of different exclusive contributions, in particular when significant part of the energy of the virtual photon goes into a single particle, requires detailed understanding of the dominant exclusive channels

Understanding exclusive channels with complex final states (resonances, vector mesons), decaying to pions and kaons is critical for separation of different dynamical mechanisms, in particular correlations of partons and hadrons leading to azimuthal modulations in general and single spin asymmetries in particular

Detection and proper ID of final state neutrons critical!!!

# Structure functions and depolarization factors in SIDIS



fast moving hadron

$p_h^\perp$

**Current Fragmentation**
Collinear factorization

arXiv:1904.12882

**Target Region**
Fracture functions

**Soft Region**
???

**Current Fragmentation**
TMD factorization

$x_F$

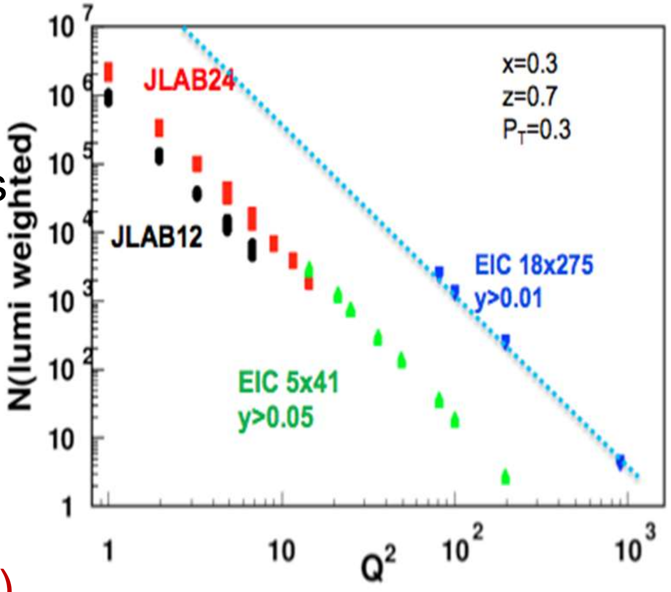
$x_F$ – fractional momentum in the CM frame

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

-----------------------------------------------------

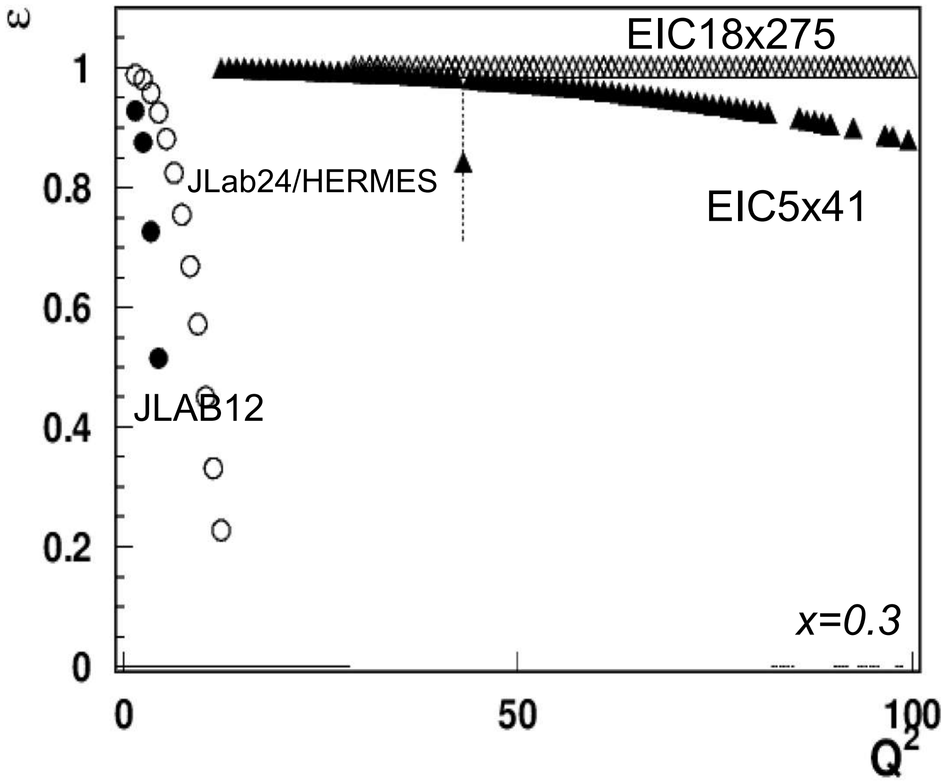
For proper interpretation *multi-dimensional and multiparticle final state* measurements critical:
requiring high lumi and large acceptance (CLAS12)

"I'm searching for my keys."



# $F_{UU,L}$ 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 $F_{UU,T}$

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

Semi-Inclusive:

ratio of longitudinal and transverse photon flux

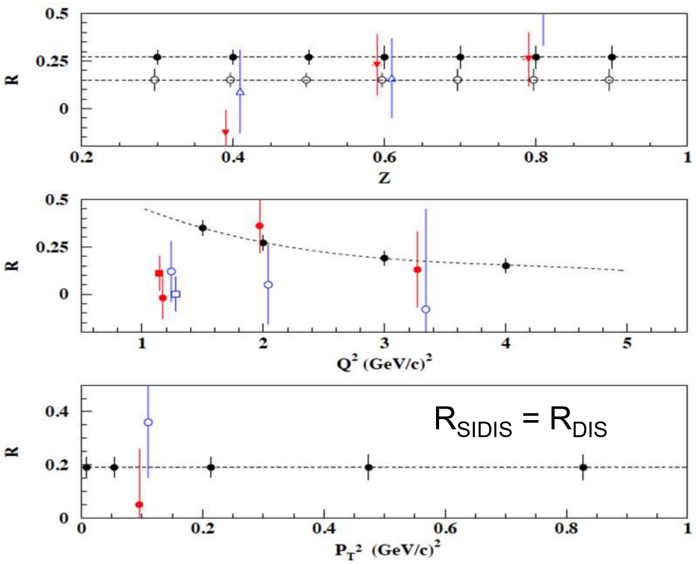
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

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

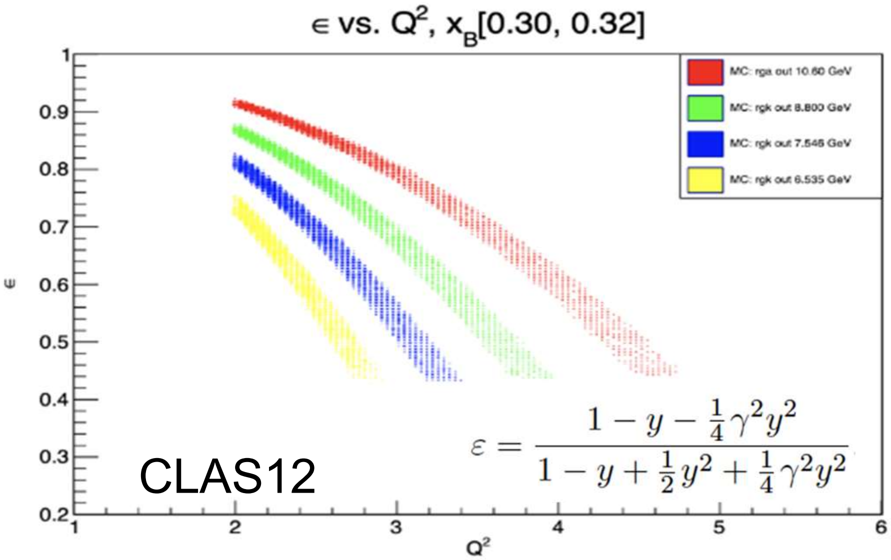
**Hall-C E12-06-104**
**E12-23-014**
**Hall-B E12-16-010C**

Separation of contributions from longitudinal and transverse photons critical for interpretation

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



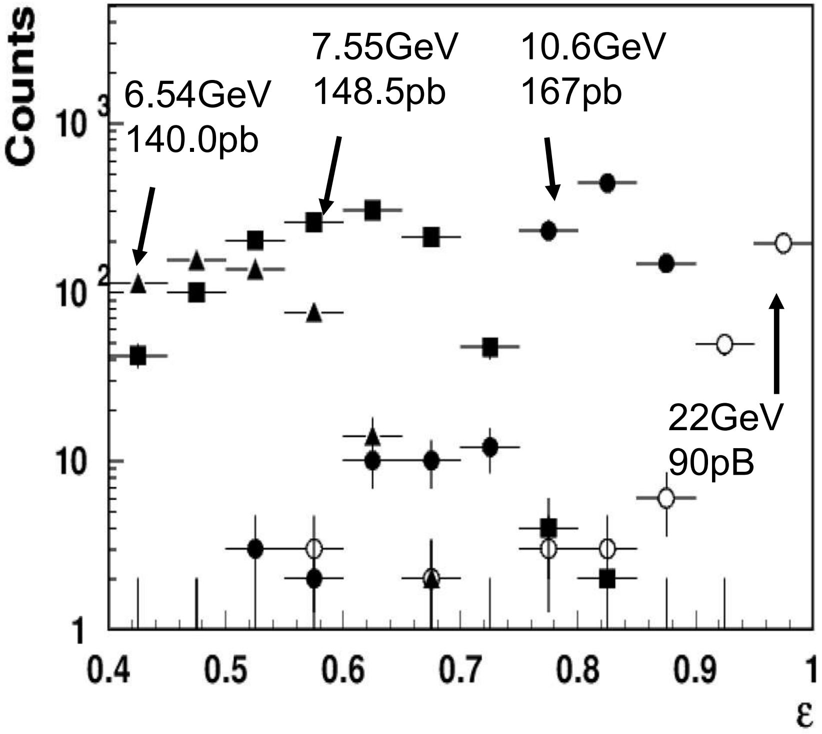
$R_{SIDIS} = R_{DIS}$



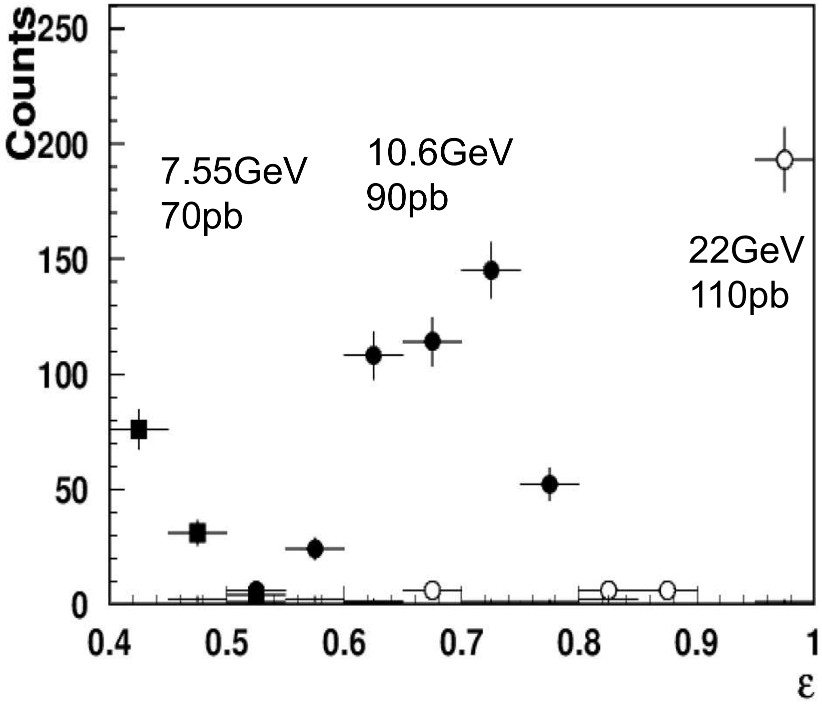
CLAS12

$$\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

# Measuring $F_{UU,L}$ with CLAS12



0.35<x<0.45, 3.4<Q^2<3.6, 0.45<z<0.55, 0.4<$P_T$<0.6

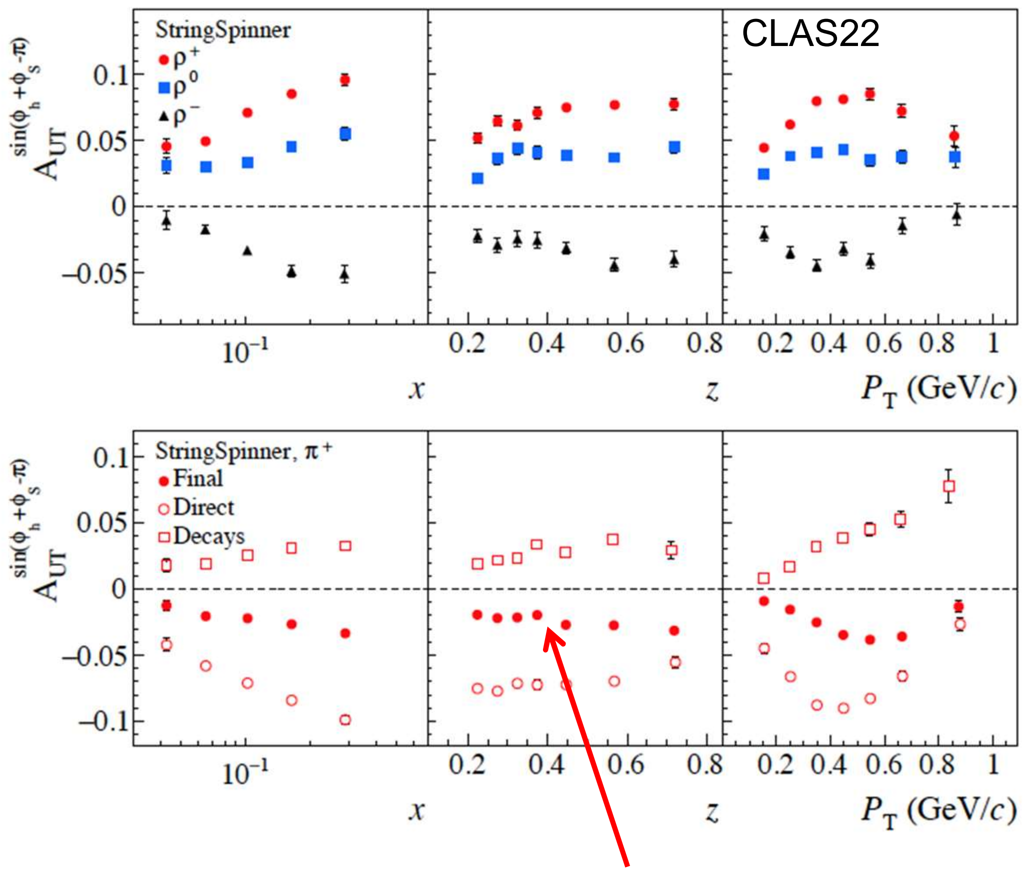


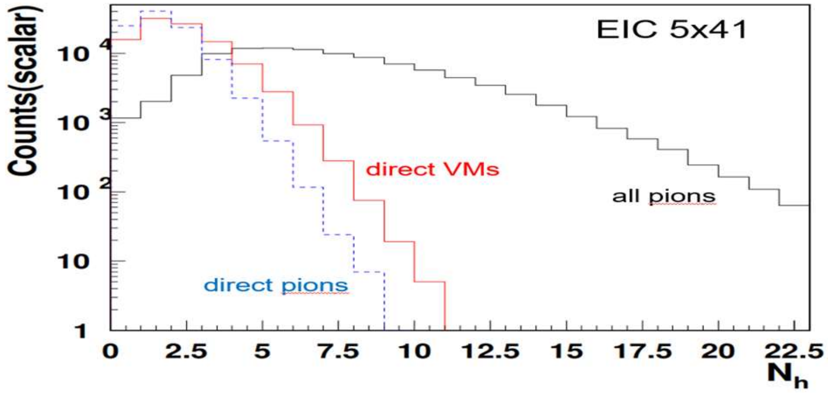
0.35<x<0.45, 4.4<Q^2<4.6, 0.45<z<0.55, 0.4<$P_T$<0.6

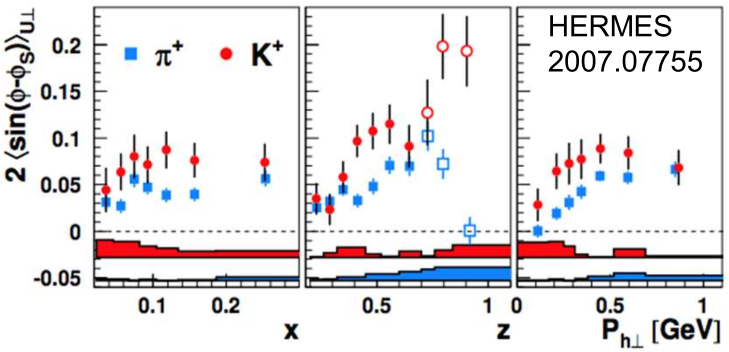
- CLAS12 measurements with 6.54, 7.55 (in future 8.8 GeV) and 10.6 GeV beams would allow to constrain the $F_{UU,L}$
- 22 GeV will be critical to understand the high $Q^2$ and high $P_T$ behavior

# VM contributions

A. Kerbizi (Trieste U.)







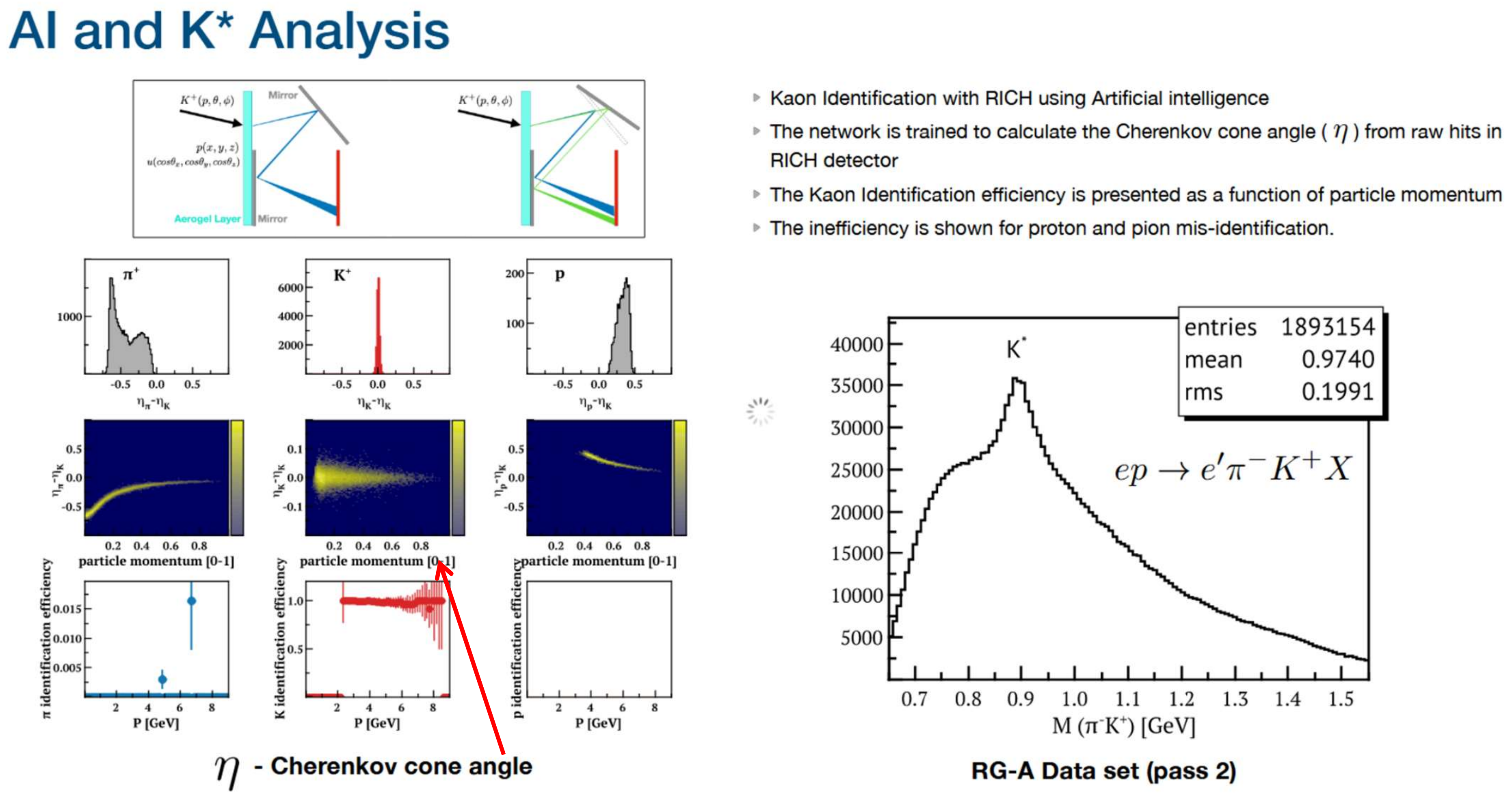
Understanding VMs is critical for interpretation

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

# VM contributions (CAAs)



## AI and K* Analysis

- Kaon Identification with RICH using Artificial intelligence
- The network is trained to calculate the Cherenkov cone angle ( $\eta$ ) from raw hits in RICH detector
- The Kaon Identification efficiency is presented as a function of particle momentum
- The inefficiency is shown for proton and pion mis-identification.

$\eta$ - **Cherenkov cone angle**

**RG-A Data set (pass 2)**

107

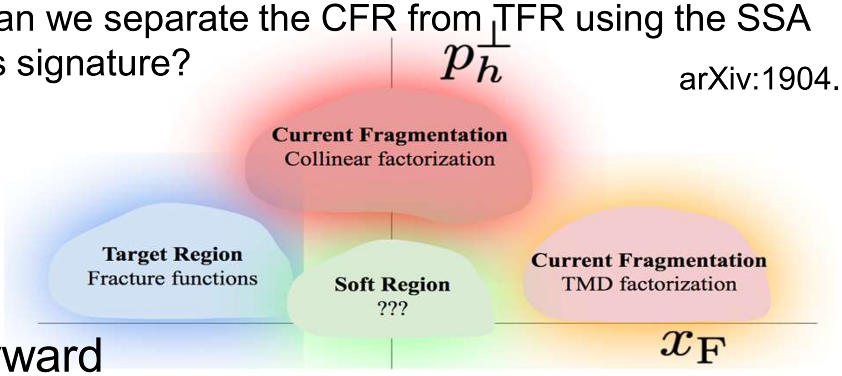
K* single spin asymmetries under way

CAA: Measure the SSA of strange VMs, and separate contributions

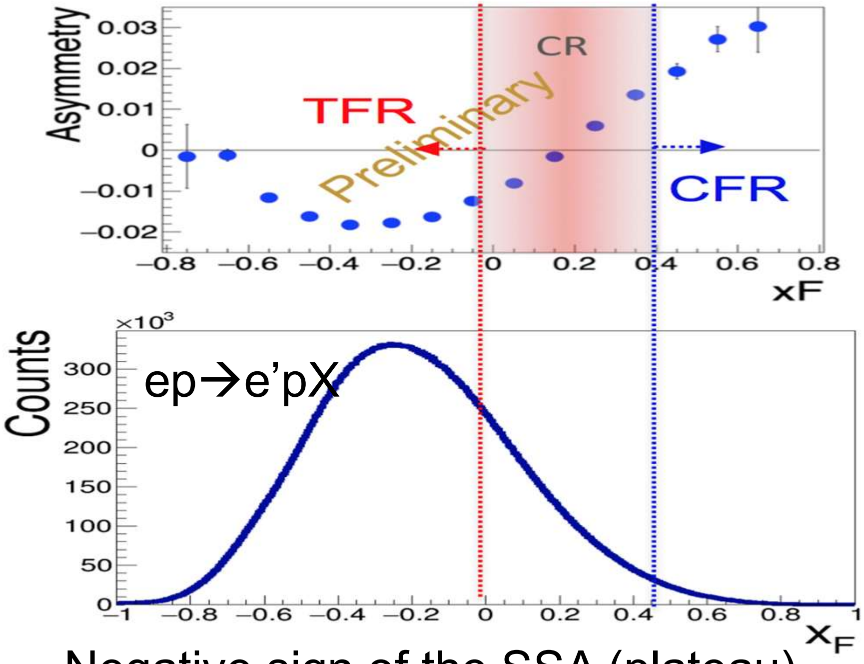
# Beam SSAs: Where is the struck quark?

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

arXiv:1904.12882



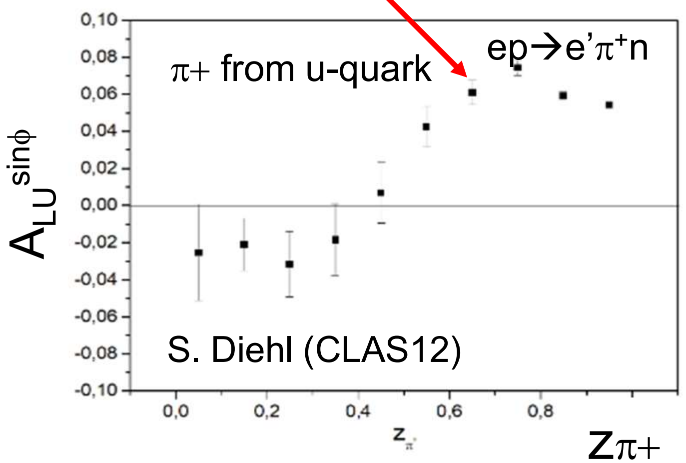
T.Hayward



ep→e'pX

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

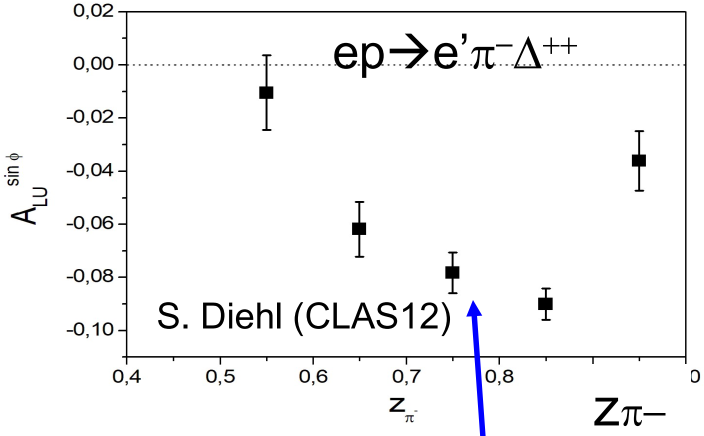
Polarized u-quark, dominates
→ SSA positive



ep→e'$\pi^+$n

π+ from u-quark

S. Diehl (CLAS12)



ep→e'$\pi^-\Delta^{++}$

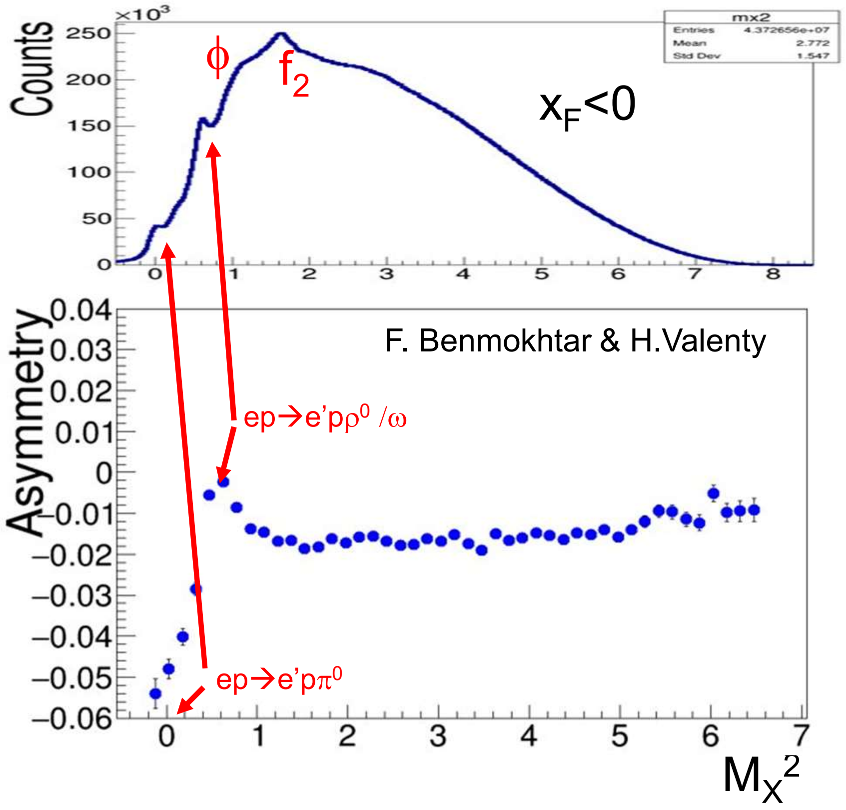
S. Diehl (CLAS12)

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. $ep \rightarrow e'p\pi^0$ or $e'p\rho^0$)
- $M_X$>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?



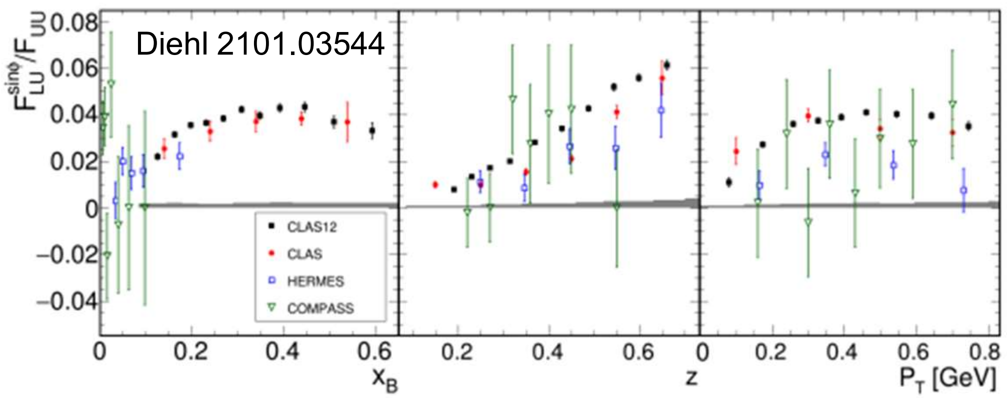
Significant beam spin SSAs observed for exclusive $ep \rightarrow e'p\pi^0$ (~8%) and $ep \rightarrow e'p\rho^0$ (~10-15%)

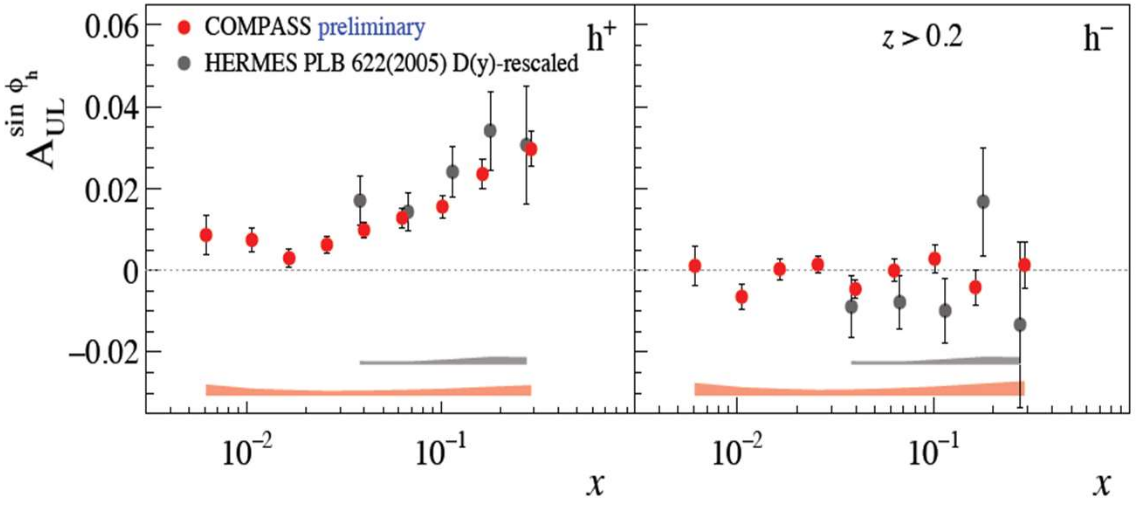
# Quark-gluon correlations: flavor dependence

## Higher Twist PDFs

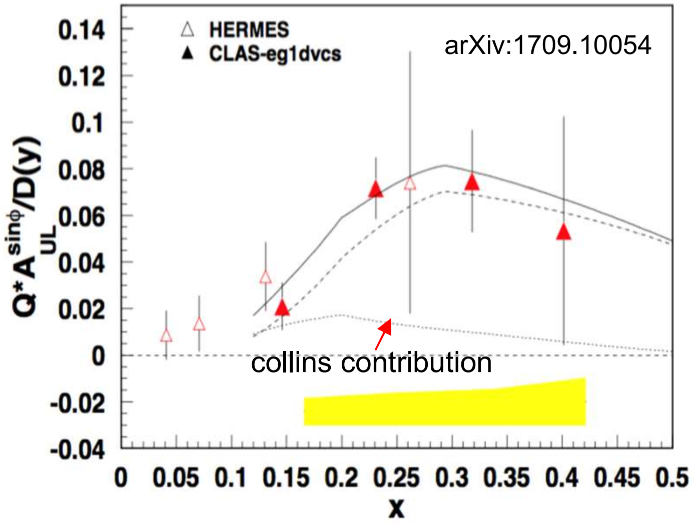
| N/q | U | L | T |
|---|---|---|---|
| U | $f^{\perp}$ | $g^{\perp}$ | $h$, e |
| L | $f_L^{\perp}$ | $g_L^{\perp}$ | $h_L, e_L$ |
| T | $f_T, f_T^{\perp}$ | $g_T, g_T^{\perp}$ | $h_T, e_T, h_T^{\perp}, e_T^{\perp}$ |

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



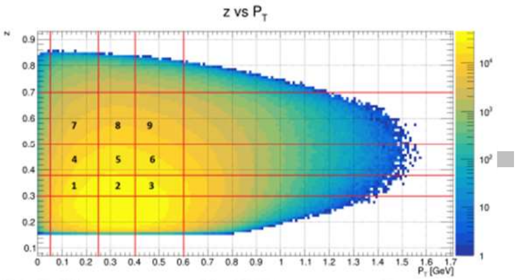


CLAS/HERMES



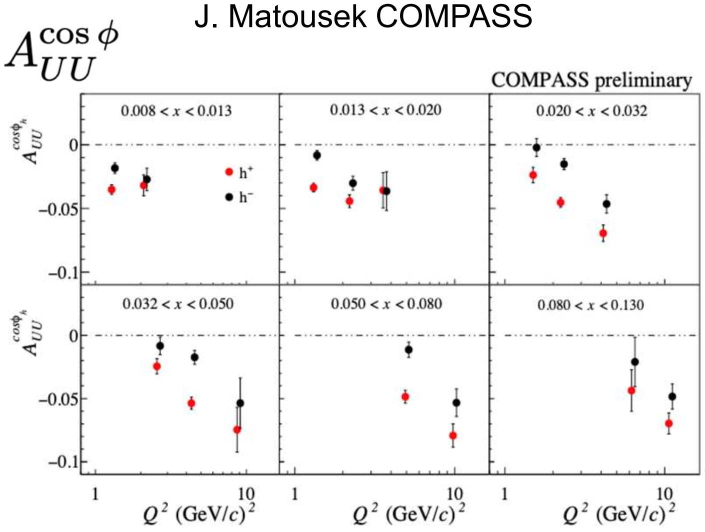
- Significant longitudinal beam and target SSA measured at HERMES, JLab and COMPASS may be related to higher twist distribution functions
- $\sin\phi$ modulations for $\pi^+\pi^0$ consistent with dominance of Sivers like mechanism (initial state effects)
- Subleading asymmetries comparable with leading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

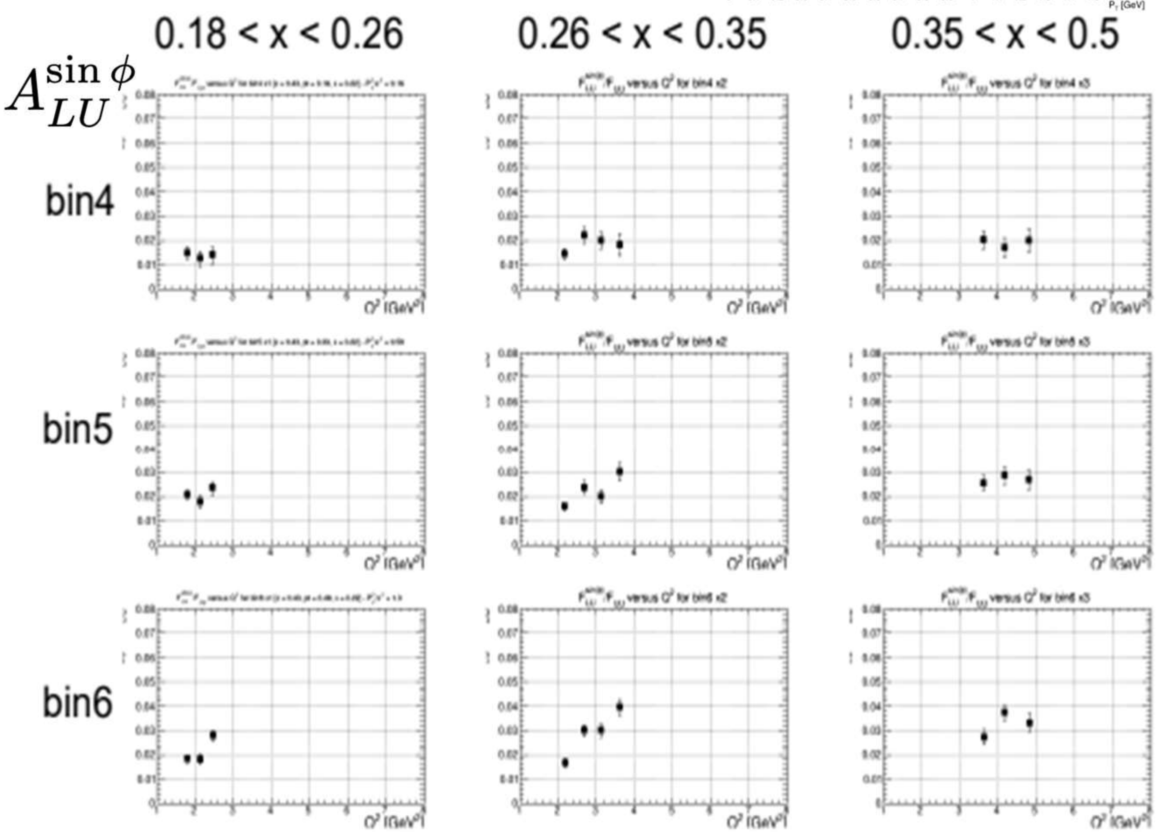
# Attempts to understand $Q^2$-dependence of HT



CLAS12(preliminary)

J. Matousek COMPASS





- We always measure ratio to

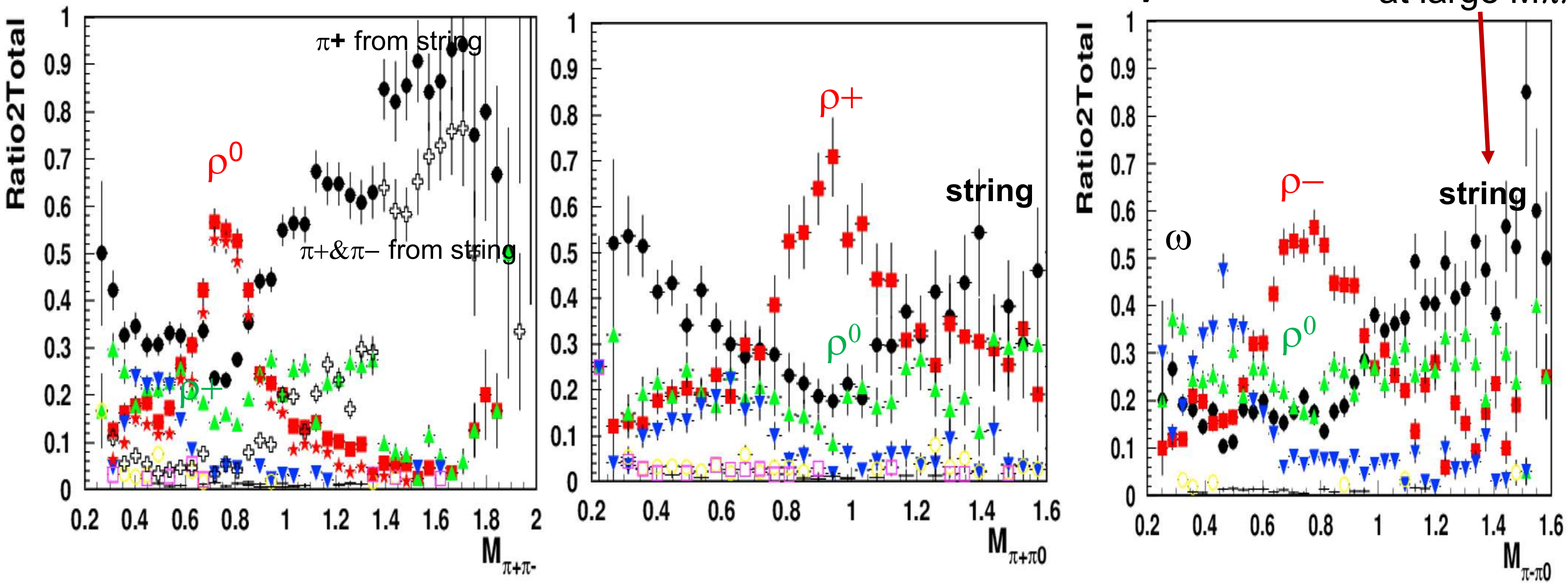
$$F_{UU,T} + \varepsilon F_{UU,L}$$

- The moments defined as a ratio to $\phi$-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 $\pi^0$s allows also studies of $\rho^{\pm}$

High $P_T$ pions at large Mππ



Dominant fraction of 2 pion combinations come from VM decays

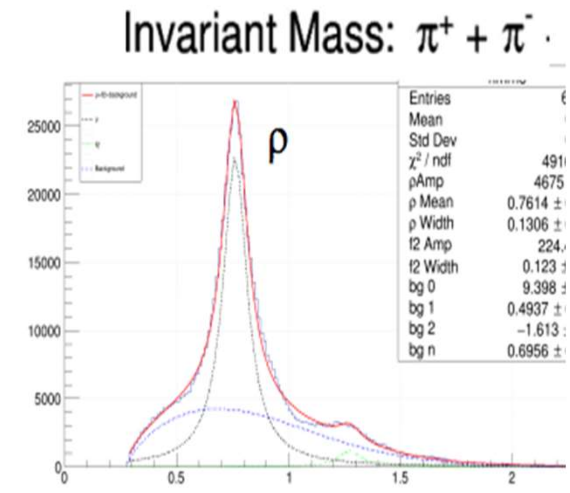
— ρ

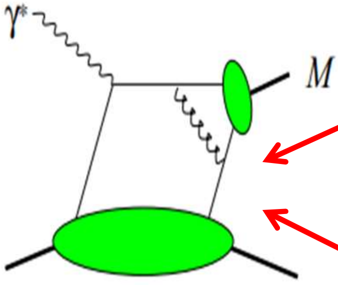
— string

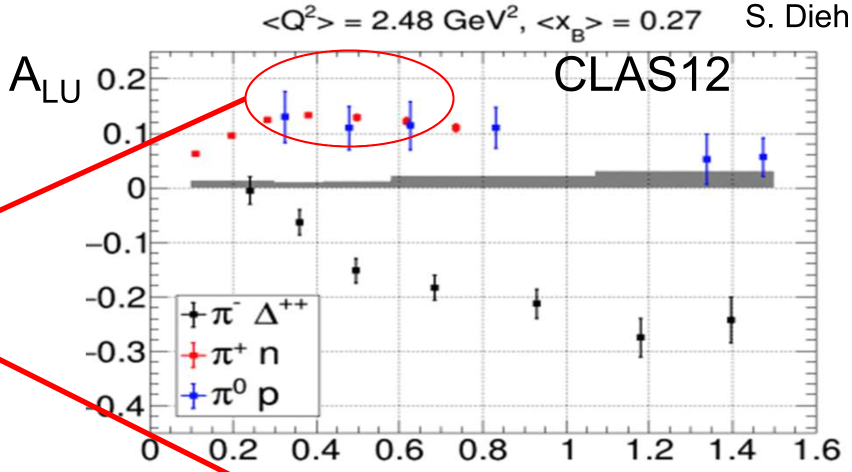
— ω

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

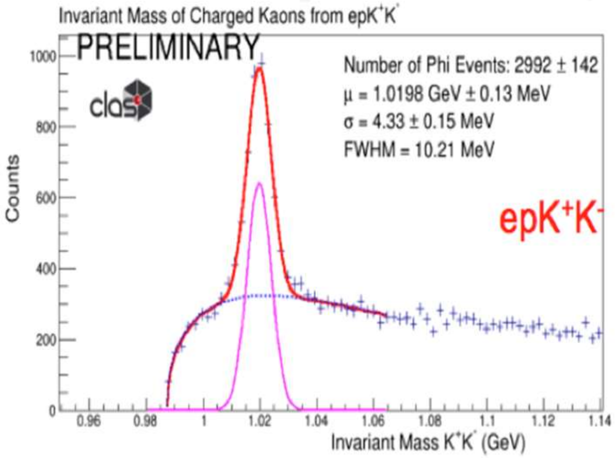
# Current hadrons: exclusive limit

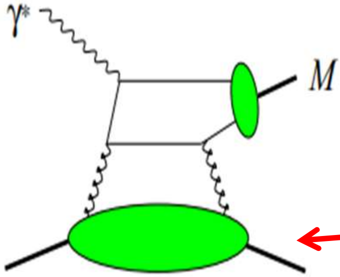




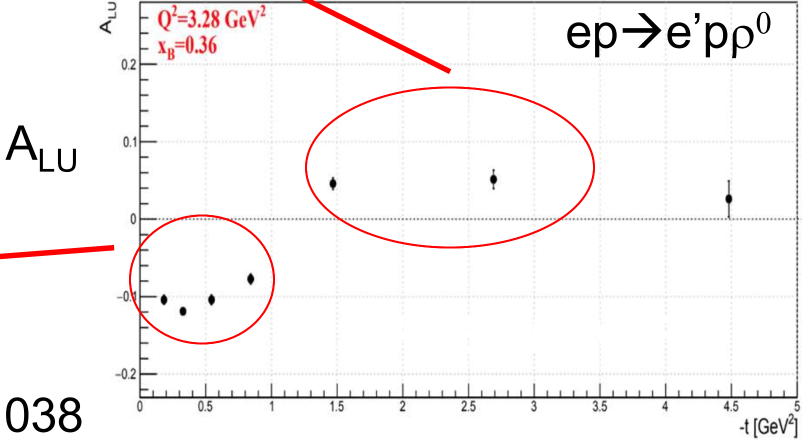


S. Diehl





N. Trotta & A. Kim



$A_{LU}$=-0.084+/-0.038

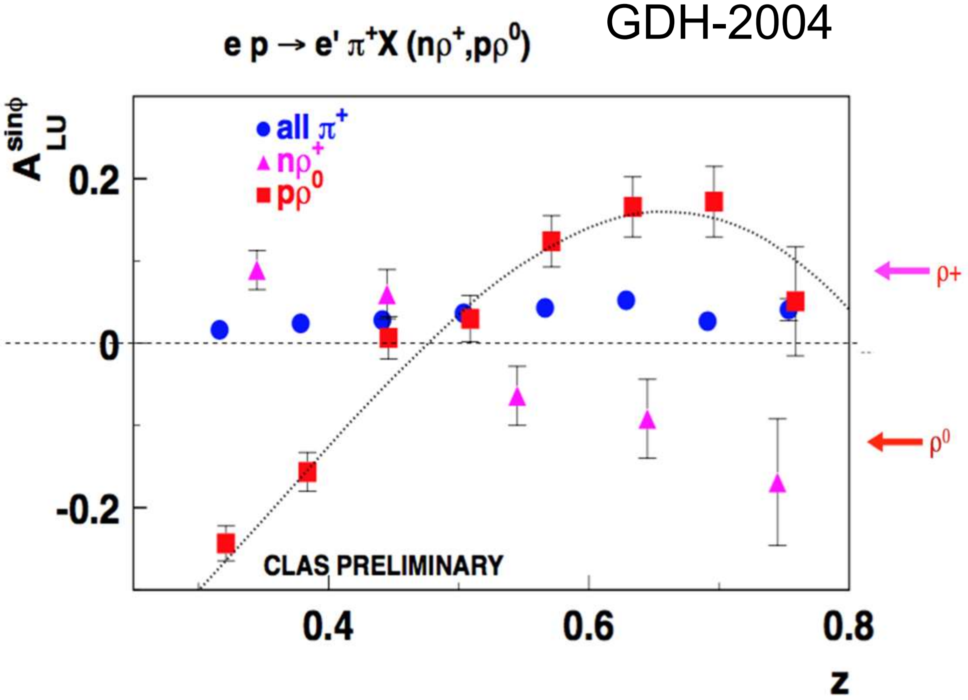
SSA negative→ΔG negative?

-t(GeV²)

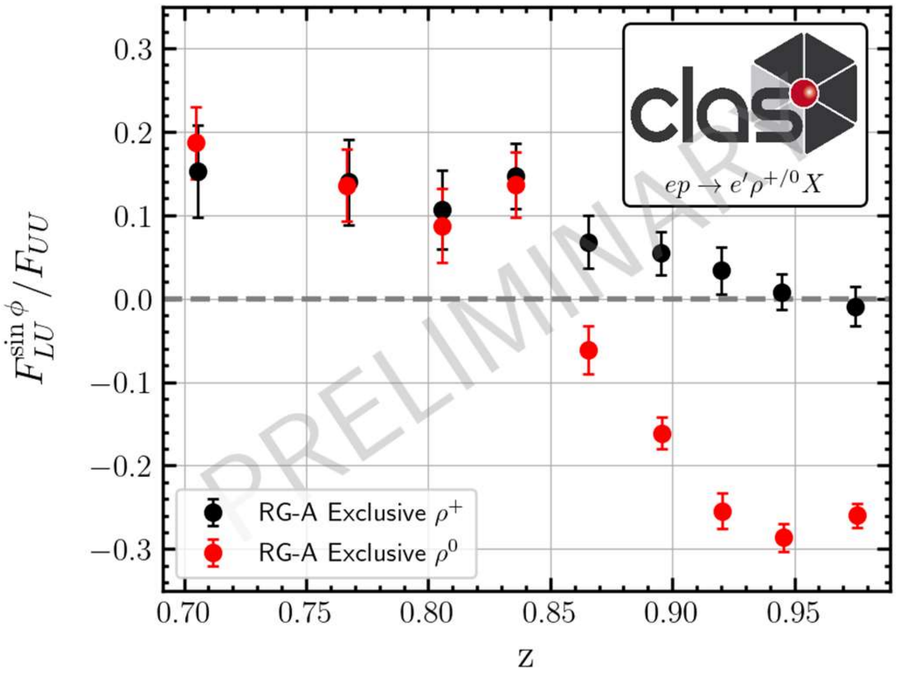
CLAS can measure all final states in exclusive production
Hadrons produced fro u-quark have positive SSA, d-quarks and gluons negative.

# Quark-gluon correlations: flavor dependence

GDH-2004



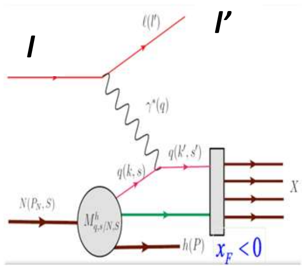
G.Matousek (Duke) & N.Trotta (UCONN)



- Understanding the SSAs of VMs is critical in interpretation of the pion SIDIS (CAA RGA+RGK)

T.Hayward

# Hadron production in TFR



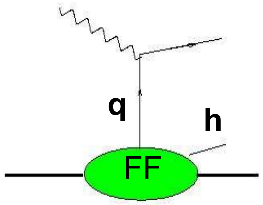
arXiv:2308.11251

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

unpolarized quarks in the longitudinally polarized proton

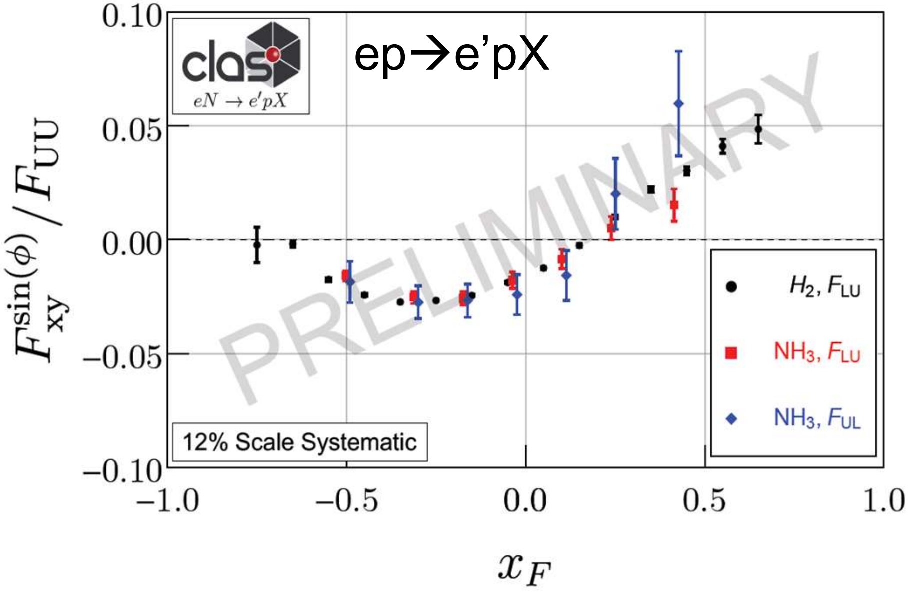
$$F_{LU}^{\sin\phi_h} = \frac{2|\vec{P}_{h\perp}|}{Q} x_B^2 l^h$$

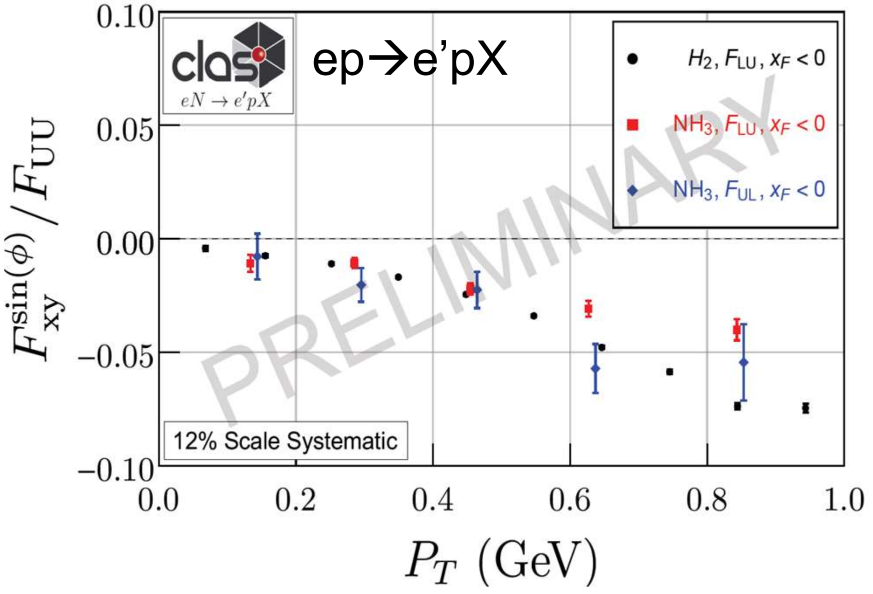
longitudinally polarized quarks in the unpolarized proton



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***





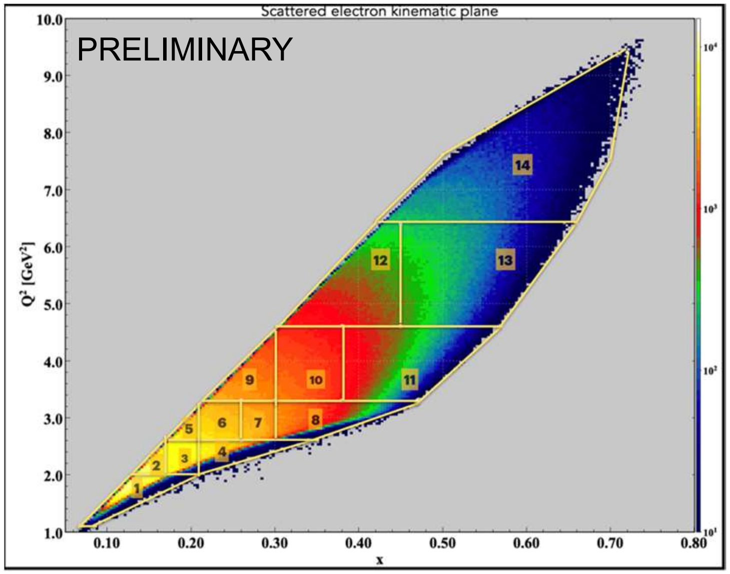
Significant asymmetries measured in Target Fragmentation Region (TFR), described by Fracture Functions provide complementary information on dynamics of polarized quarks

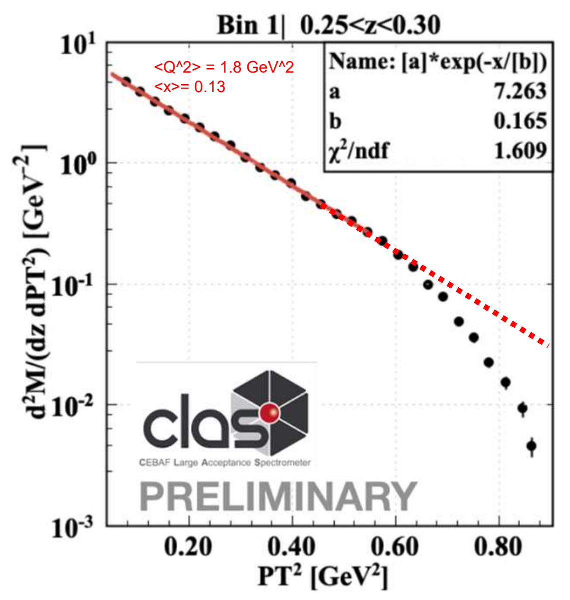
- $F_{UL}$ and $F_{LU}$ practically equal, indicating similar underlying distributions (unpolarized/longitudinally pol.)
- $F_{LU}$ on hydrogen and NH3 practically the same, indicating medium modifications are smaller in TFR

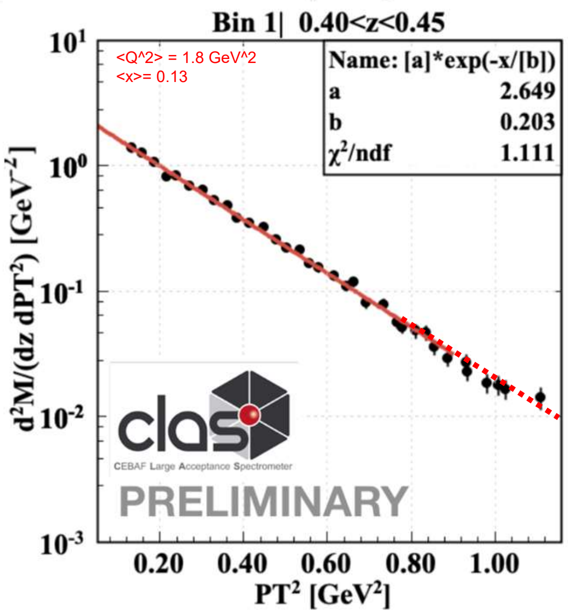
# What we learned: missing parts of the mosaic

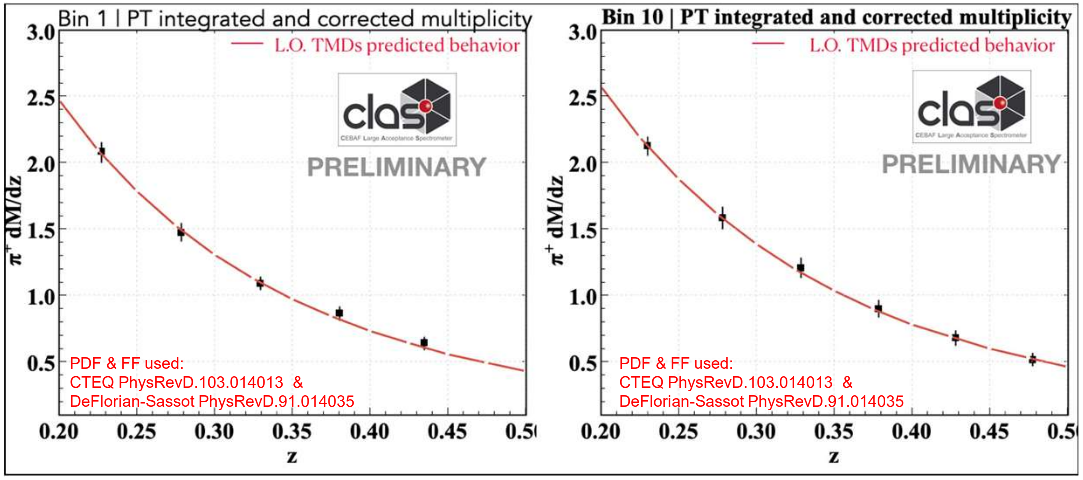
- SIDIS, with hadrons detected in the final state, from experimental point of view, is a measurement of observables in 5D space ($x,Q^2,z,P_T,\phi$), 6D for transverse target, $+\phi_S$
  Collinear SIDIS, is just the proper integration, over $P_T,\phi,\phi_S$
- SIDIS observations relevant for interpretations 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

# 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.

# Neutral Pion Multiplicity

Marshall B. C. Scott (Argonne)

- Neutral pion multiplicities describe the number of produced neutral pions in the five-dimensional SIDIS phase space (x, $Q^2$, z, $p_T^2$, $\varphi_h$) per number of DIS events in (x, $Q^2$) phase space.
- These measurements are directly related to the $D_1(z)$ fragmentation function describing the probability of quarks fragmenting into neutral pions, and further serve as a test on the isospin symmetry between $D^0(z)$ and the charged pion fragmentation functions.
- The current status of the analysis is extracting the cosine moments from the $\varphi_h$ dependence and utilizing multidimensional SVD and Bayesian unfolding methods for acceptance corrections within an updated 13 x-$Q^2$ binning scheme.
- The analysis note is located on: https://clas12-docdb.jlab.org/cgi-bin/DocDB/private/ShowDocument?docid=1065
- Publication timeline: FY24. Analysis developed on pass-1 data. Transition to pass-2 data soon.

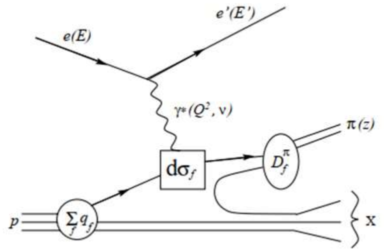
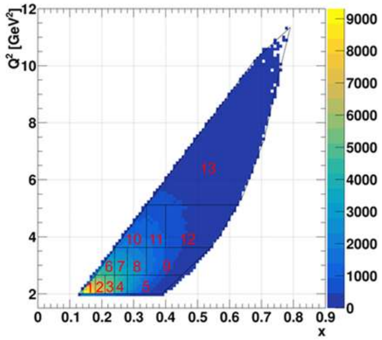
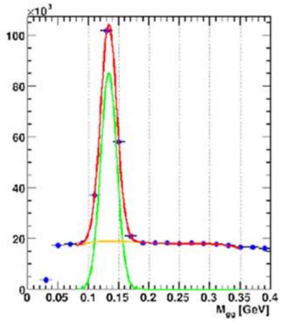
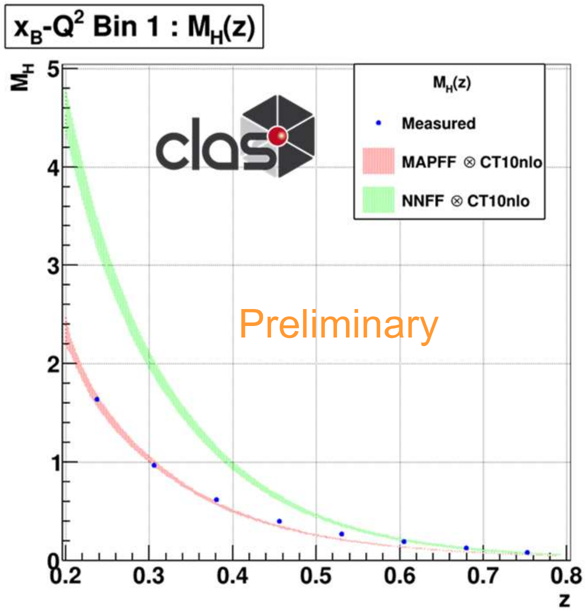


Fig. 1. Semi-inclusive pion electroproduction diagram





Example $p_T^2$ integrated multiplicity for one x-$Q^2$ Bin 1 with LO 1σ theory curves



(x,$Q^2$) phase space : triangular bin from point (0.15, 2.28) to (0.24, 2.75) to (0.24, 3.63)

# 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 $\phi$)

- To evaluate the systematics of extracted 3D PDFs (TMDs and GPDs) , multidimensional measurements are 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

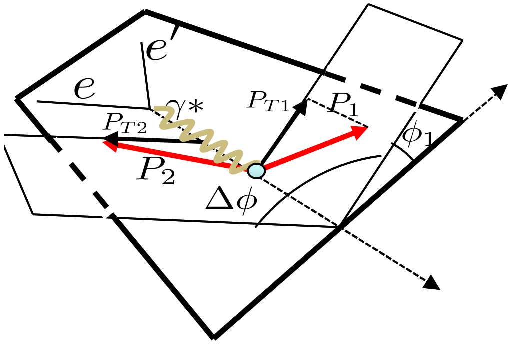
- Measurements of azimuthal modulations of inclusive pions, and multiplicities of pion pairs indicate very significant part of hadrons come from decays of VMs (even more in kaon case) supporting a completely different dynamics in hadronization

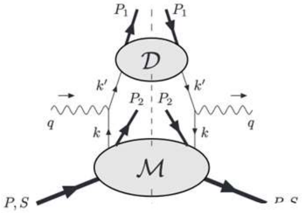
- With RGA pass2 finalize the multiplicities of single and dihedron final states in exclusive and semi-inclusive production (potentially with L/T separation)

- support slides

# Correlations in back-to-back 2 hadron production

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



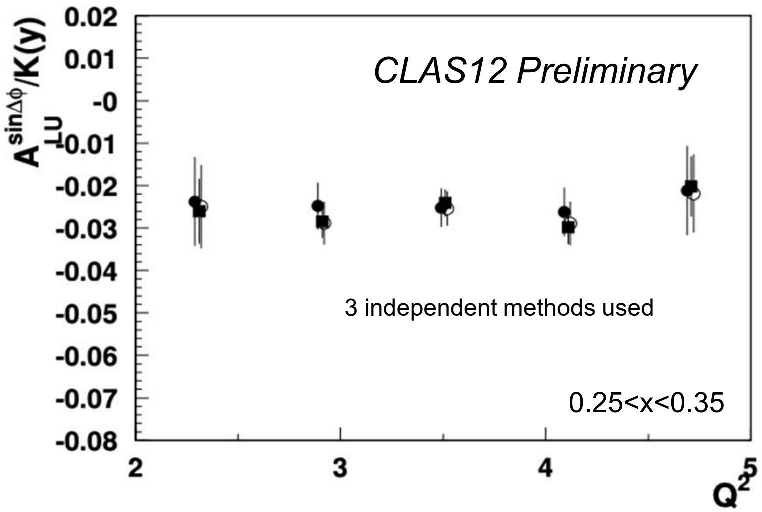


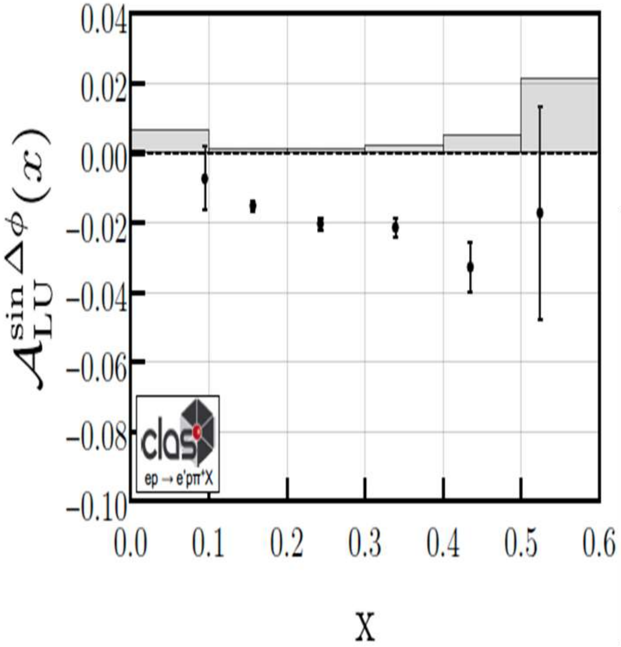
$$A_{LU} \propto \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi$$

arXiv: 2208.05086

Twist-2 table
(Fracture Functions)

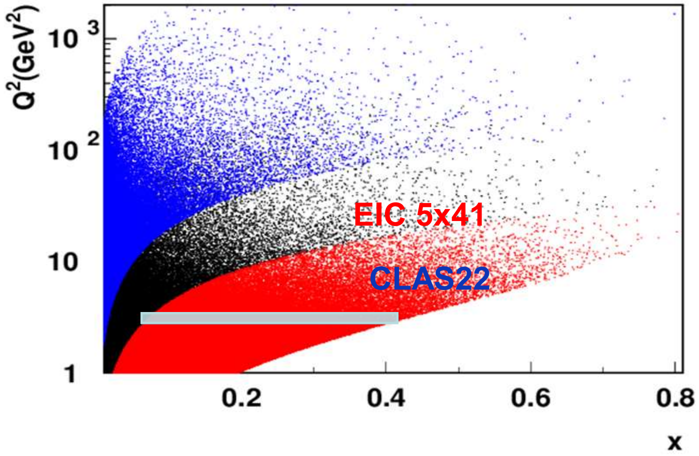
| N/q | $U$ | $L$ | $T$ |
|---|---|---|---|
| $U$ | $\hat{u}_1$ | $\hat{l}_1^{\perp h}$ | $\hat{t}_1^h, \hat{t}_1^\perp$ |
| $L$ | $\hat{u}_{1L}^{\perp h}$ | $\hat{l}_{1L}$ | $\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$ |
| $T$ | $\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$ | $\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$ | $\hat{t}_{1T},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

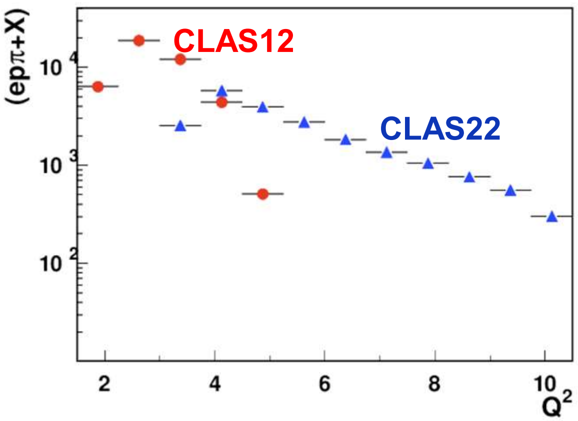


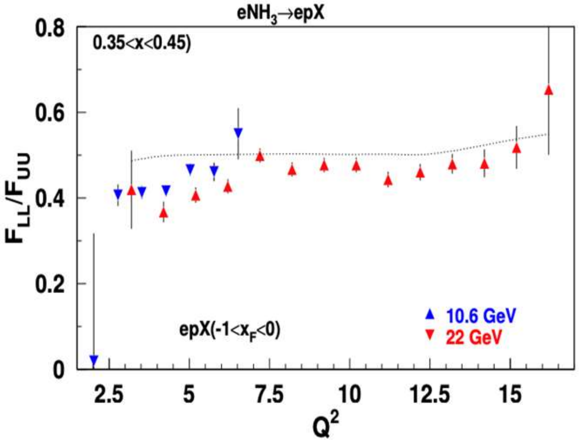


- SSA significant at large x, where the valence quarks (non-perturbative sea) dominate?
- Correlation asymmetry is linked to Leading Twist(LT) distributions of longitudinally polarized quarks
- First indication in large x SIDIS of a LT observable
- Correlation between the struck quark and the remnant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

# Accessing CS-kernel directly or through extraction of SFs



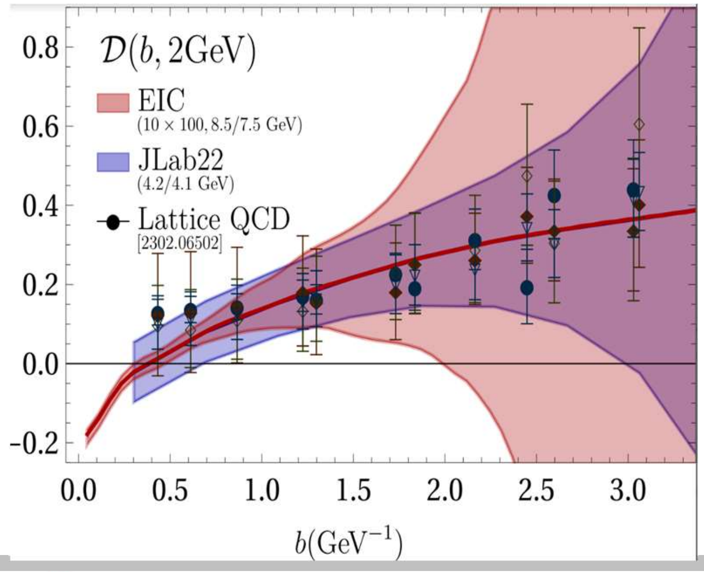




Use slices in $Q^2$ (good resolution needed)

- 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

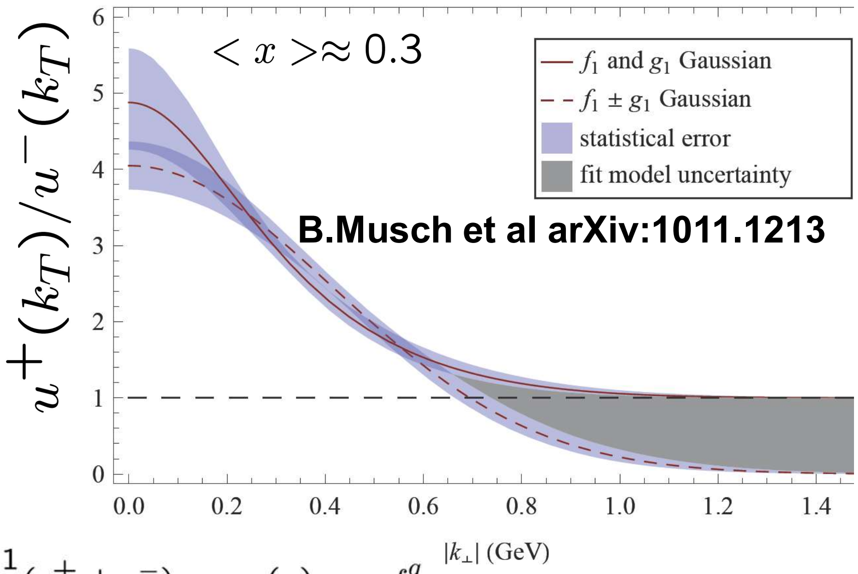
- JLab ~1<b<4
- EIC ~0.5<b<1.2, COMPASS overlaps ,
- LHC b<<0.05

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

# $A_1$ $P_T$-dependence

G.Matousek

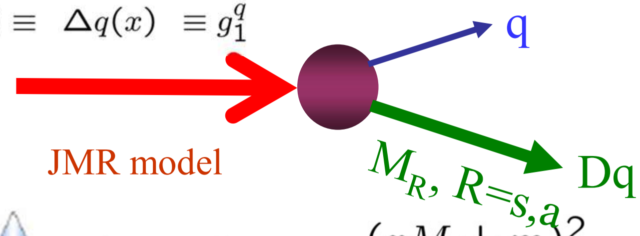
- dfferent widths in $g_1(x,k_T)$ and $f_1(x,k_T)$



**B.Musch et al arXiv:1011.1213**

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

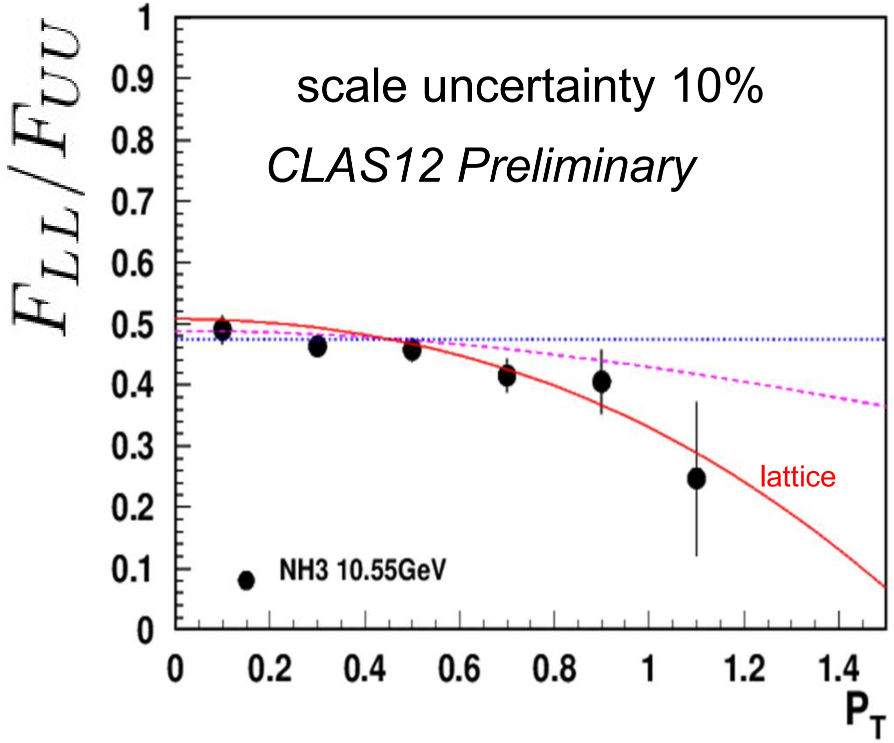
$$\frac{1}{2}(q^+ - q^-) \equiv \quad \Delta q(x) \quad \equiv g_1^q$$



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

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

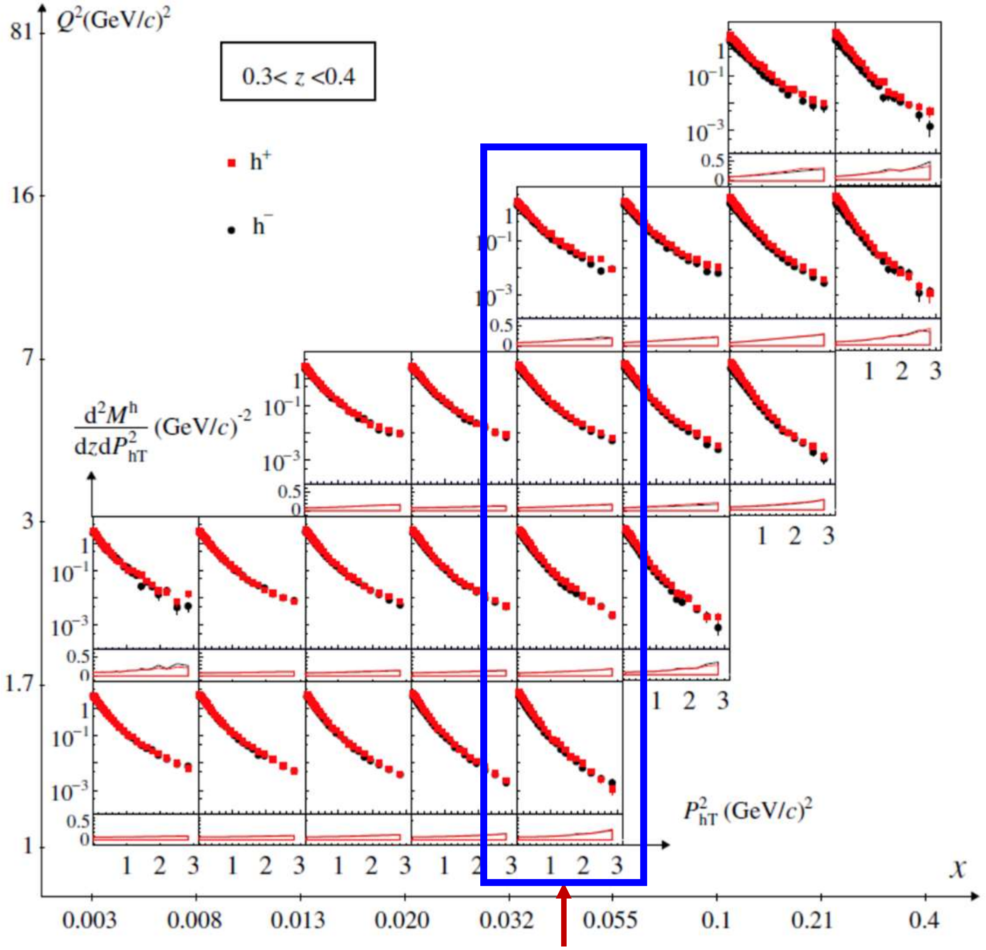
0.25<x<0.35, 0.2<z<0.8 (MX>1.5)



With more statistics can

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

# $q_T$-crisis or misinterpretation



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

Theory unable to explain the correlation of $P_T$ and Q

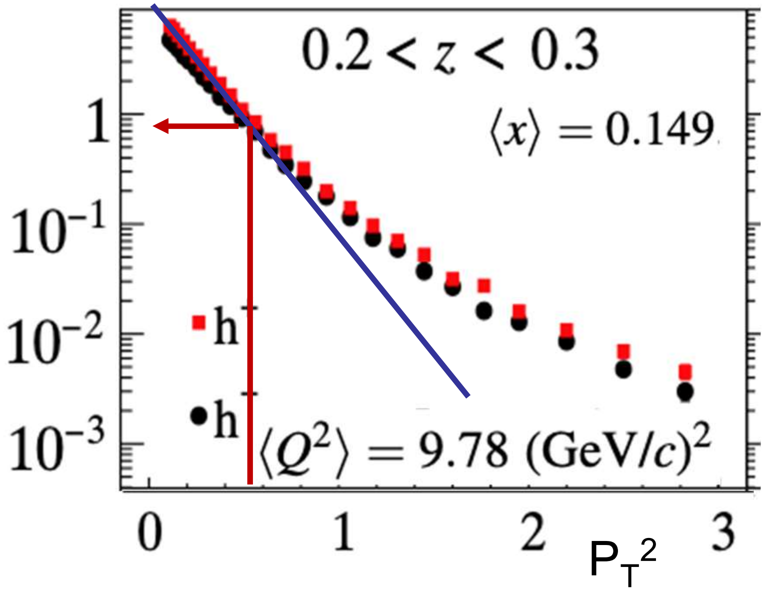
The $q_T=P_T/z$ theory “trustworthy” cut:

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

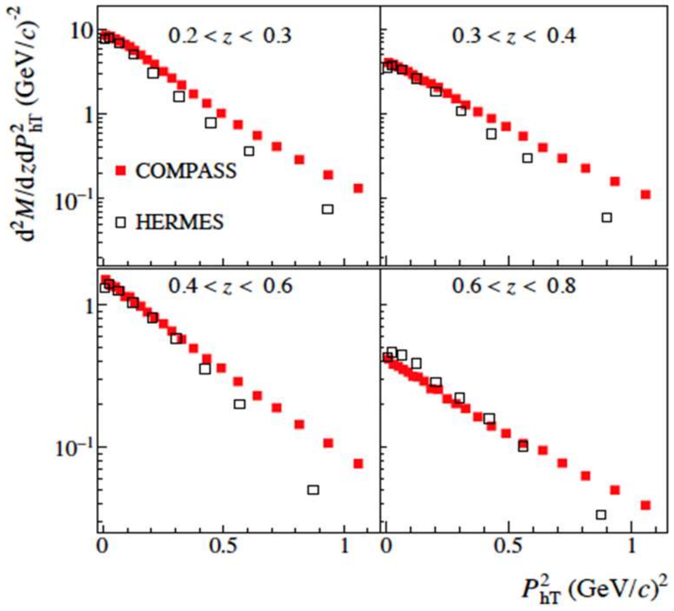


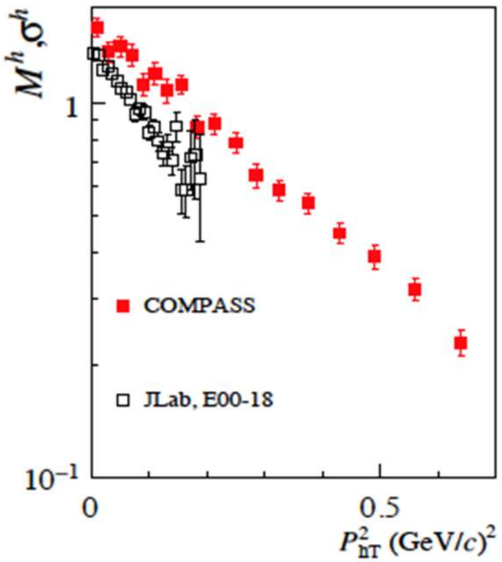
# Multiplicities of hadrons in SIDIS

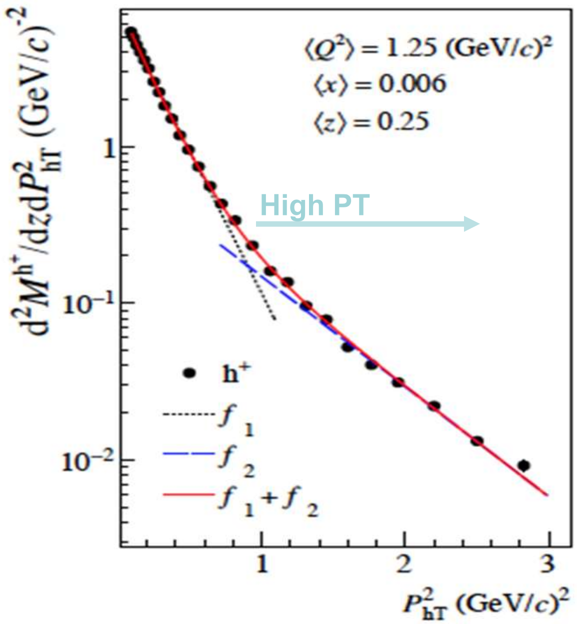
Gaussian Ansatz for $F_{UU,T}$ $\boxed{f_1^q} \otimes \boxed{D_1^{q\to h}} = x f_1^q(x)\, D_1^{q\to h}(z) \frac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$

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

COMPASS:1709.07374





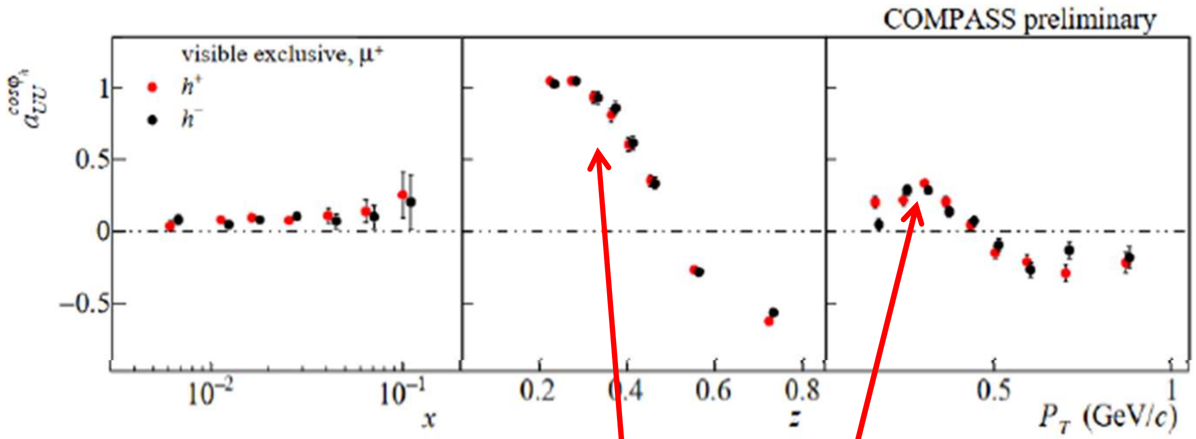


JLab: not enough energy to
produce large $P_T$
HERMES: not enough luminosity
to access large $P_T$

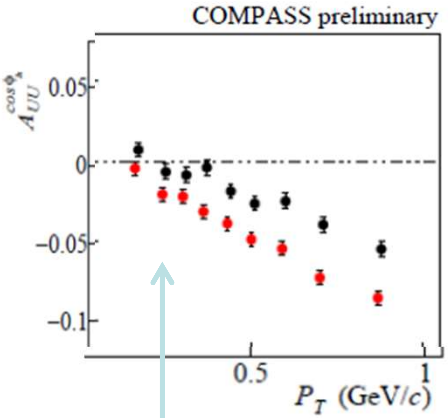
- What is the origin of the "high" $P_T$ (0.8-1.8) tail?
  1) Perturbative contributions?
  2) Non perturbative contributions?

# COMAPASS multiplicities and cosine modulations

J. Matousek→ COMPASS

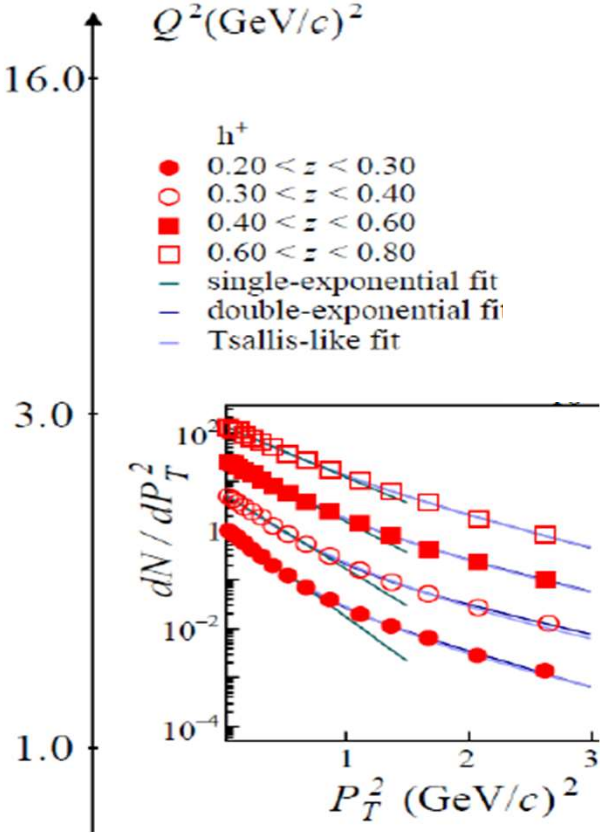


Negative cos of $\rho^0$ converts to positive for low $P_T$ pions (sign flip ~z=0.5)



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

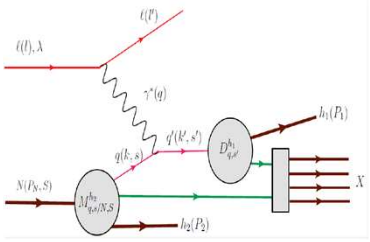
ρ–decay pions mess up linear dependence at low $P_T$

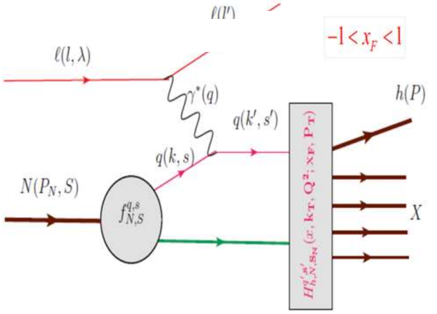


Theory is not able to explain the large $P_T$ behavior of pion multiplicities !!!

# MC simulations: Why LUND works?

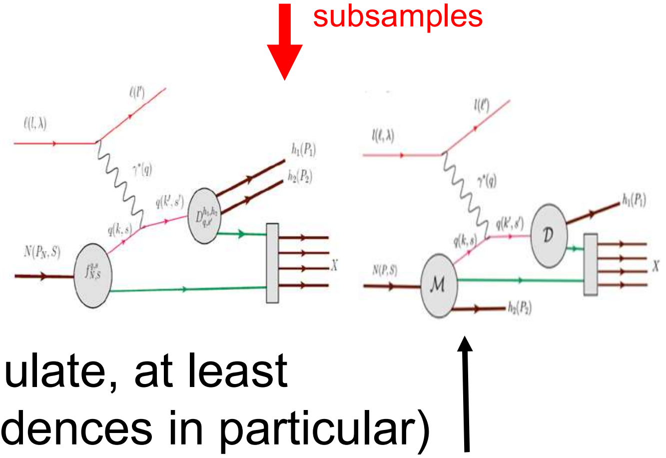
- A single-hadron MC with the SIDIS cross-section where widths of $k_T$-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.





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
•….



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 !!!