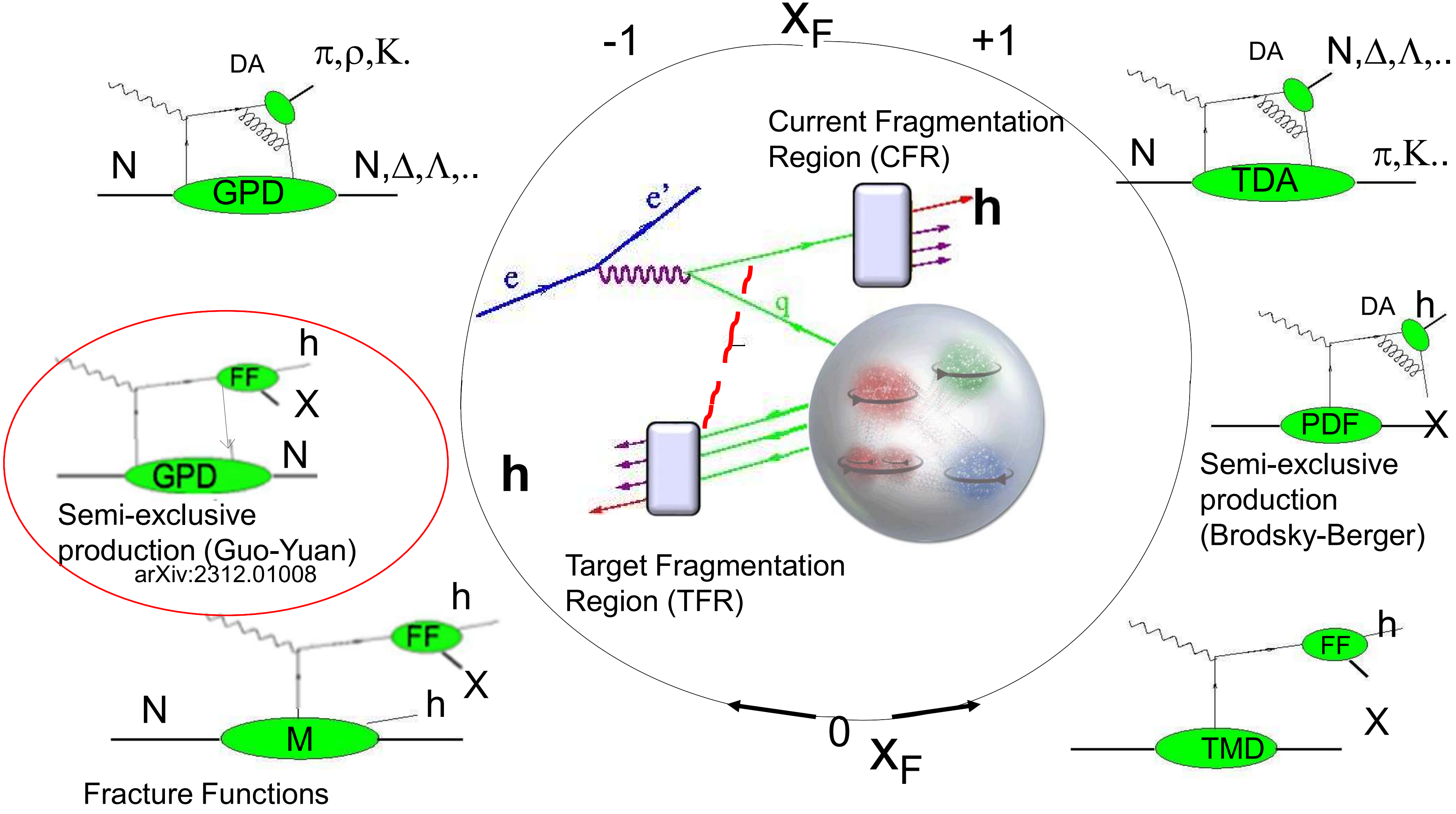
The 3D nucleon structure at JLab 12 and 22

Harut Avakian (JLab)

Trieste, June 4, 2024

- 3D studies: Theory Experiment Dialogue (TED)
- Accessing partonic structure in leptoproduction
- Motivating the JLab upgrade
- Accessing the helicity TMD
  - Studies of ep$\rightarrow$e'πX
  - Studies of ep$\rightarrow$e'pπX
- SIDIS with multiparticle detection, semi-exclusive processes
- Summary

Hadron production in hard scattering in SIDIS



Current Fragmentation Region (CFR)

Target Fragmentation Region (TFR)

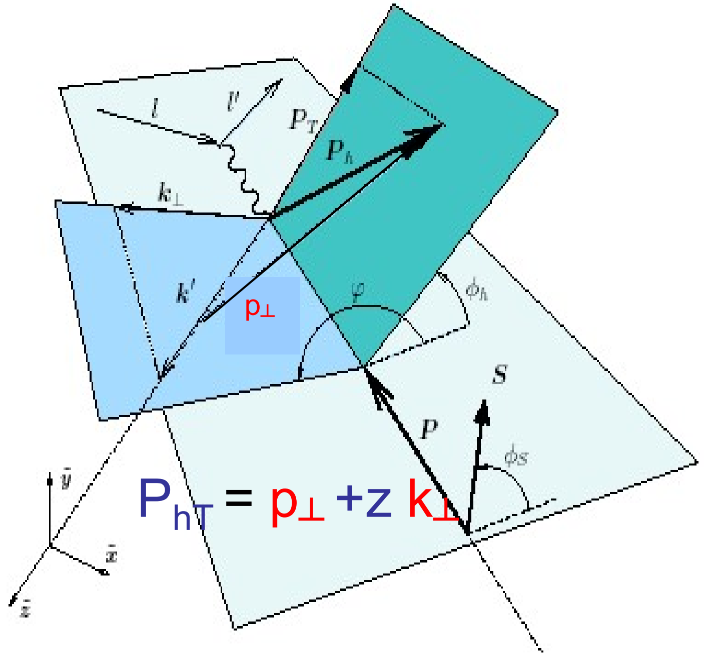
Semi-exclusive production (Guo-Yuan)
arXiv:2312.01008

Semi-exclusive production (Brodsky-Berger)

Fracture Functions

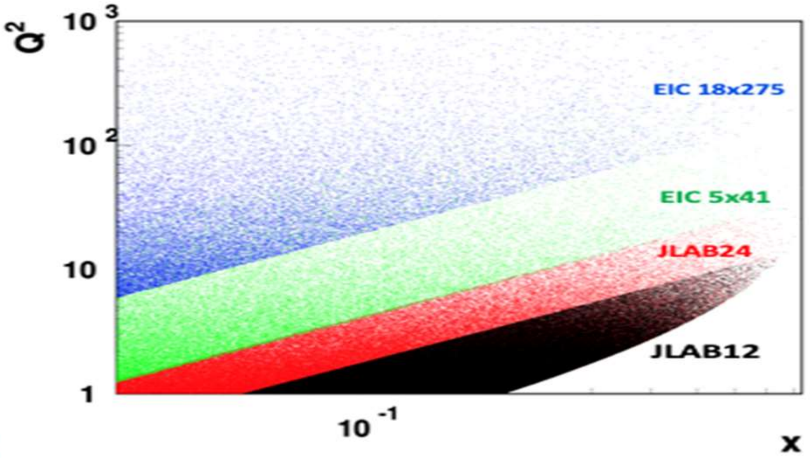
- Different non-perturbative objects may be involved in description, depending on kinematics
- Semi-Exclusive processes allow mixed descriptions, allowing access to GPDs and GTMDs

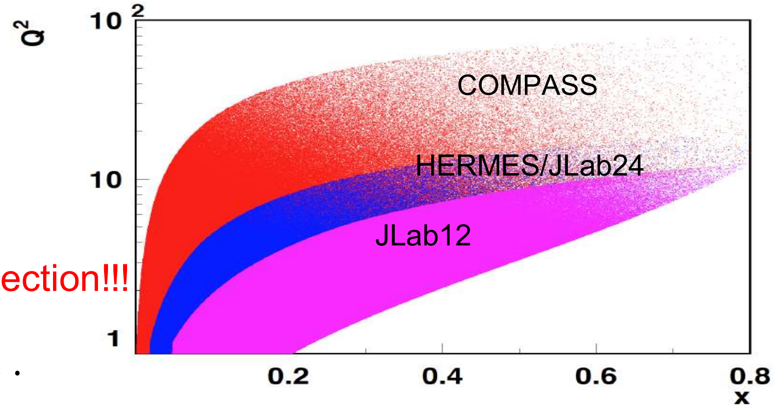
SIDIS kinematical coverage and observables



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

EIC

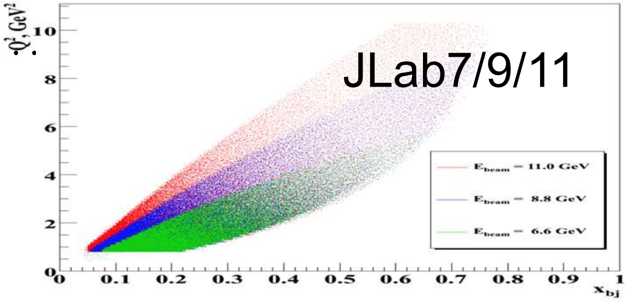




Experiments measure the full azimuthal dependence of the cross section!!!

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

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



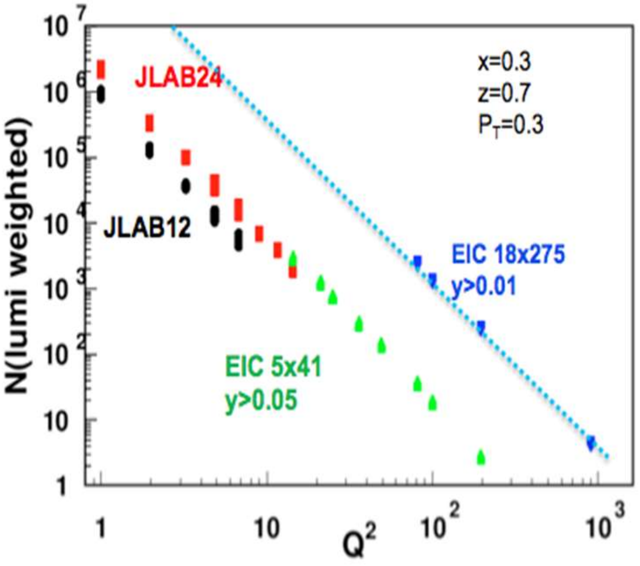
- Studies of azimuthal modulations give access to underlying 3D partonic distributions
- QCD predicts only the Q^2-dependence of 3D PDFs

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

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

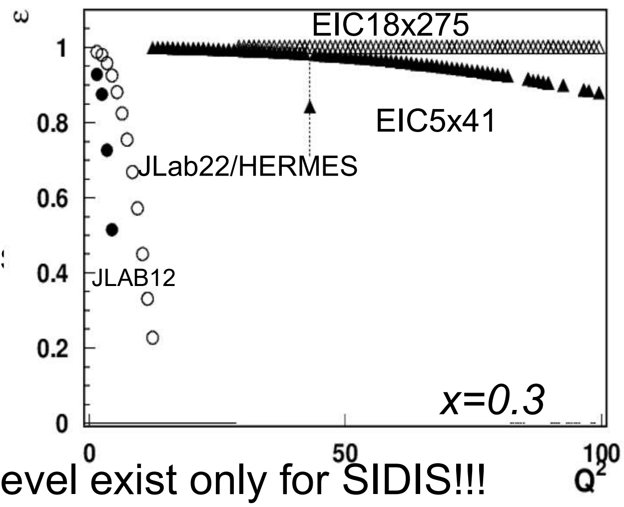


x-section from Bacchetta et al, 1703.10157

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 of SSA: (Collins effects,…) requires *separation* of VMs (JLab)



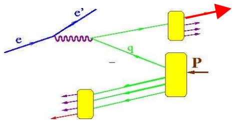
Full decomposition of SFs to underlying 3D PDFs up to twist 3 level exist only for SIDIS!!!

JLab22 white paper: Hadronization and Transverse Momentum

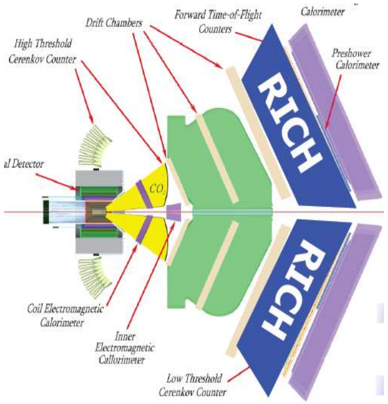
Studies of Transverse Momentum Distributions (TMDs) require studies of transverse momentum dependences of SIDIS observables (multiplicities/asymmetries) in multidimensional space.

- Understanding the systematics in SIDIS studies
- Reforming SIDIS: what we need to apply THE theory with controlled systematics?
  - –separate different contributions to x-section (locate SF of interest)
  - –separate different contributions to a given SF from different mechanisms (ex. longitudinal photon contributions)
  - –separating the kinematics of current and target fragmentation
  - –understanding the role of hadron correlations in SIDIS (impact of VMs)
  - –use Q^2-dependent measurements as a unique tool to validate the interpretation of results

Important advantages of JLab: high luminosity, high precision multiparticle detection



SIDIS at JLab12



CLAS12

Proton

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

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: π^+,π^-, K^+,K^-
C12-11-102: π^0

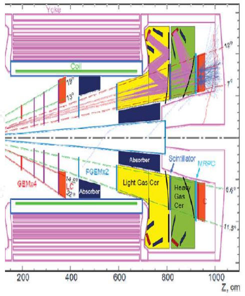
HMS
SHMS

E12-06-104
E12-23-014

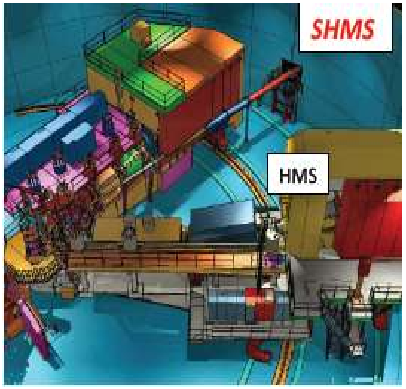
C12-11-108: π^+,π^-

Solid

H_2 | NH_3



E12-16-010C



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+

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: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS
SHMS

D_2

^{3}He

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 $h_{1T}^\perp$

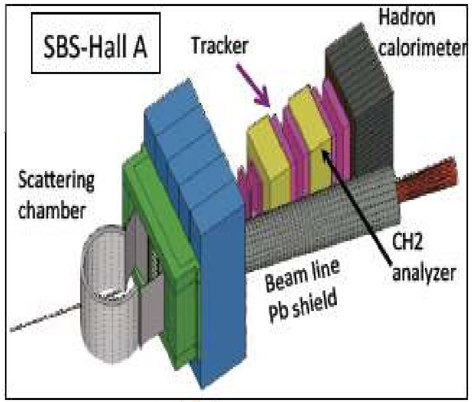
Hall A

E12-07-007: π^+, π^-

Solid

E10-006: π^+,π^-
E12-09-018: π^+,π^-, K^+,K^-

Solid
SBS



^{3}He

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

Semi-Inclusive:

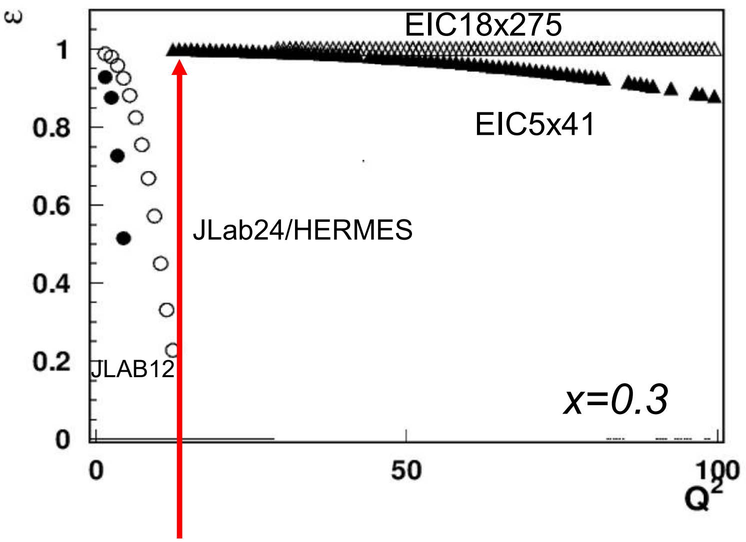
ratio of longitudinal and
transverse photon flux

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

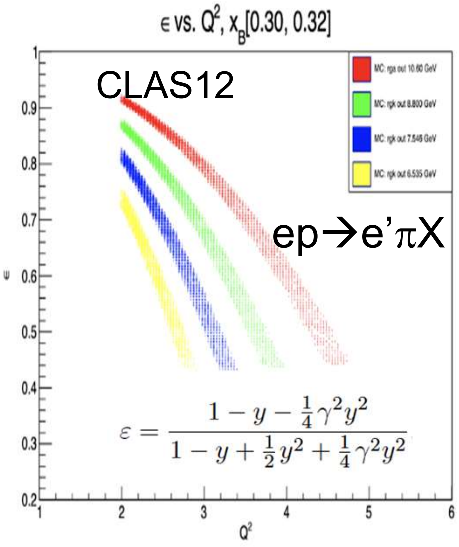
Hall-C E12-06-104
E12-23-014
Hall-B E12-16-010C

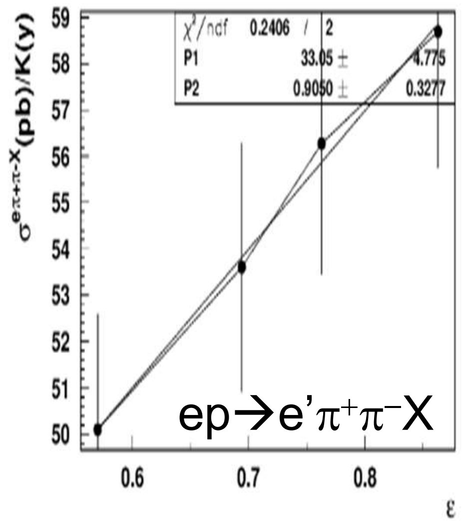
$$+ S_\| \left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] + S_\|\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL}\Big\}$$

Separation of contributions from longitudinal and transverse photons critical for interpretation



Wide ε-coverage needed!!!

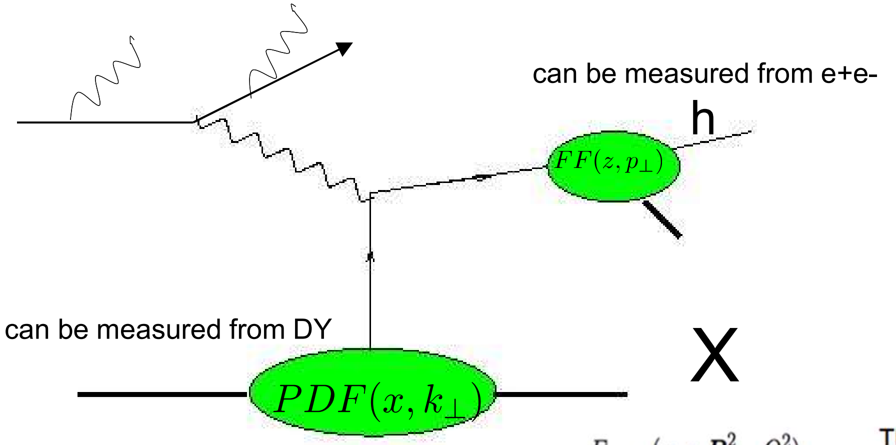




- At higher energies longitudinal photon contributions kinematically enhanced (at EIC 5 times bigger at Q^2~10)
- JLab studies critical for EIC data interpretation

$R=F_{UU,L}/F_{UU,T}$ depend on the process, need for all relevant ones, in all kinematics!

SIDIS as theory describes it



Probability to produce 1 or 2 hadrons in single photon exchange

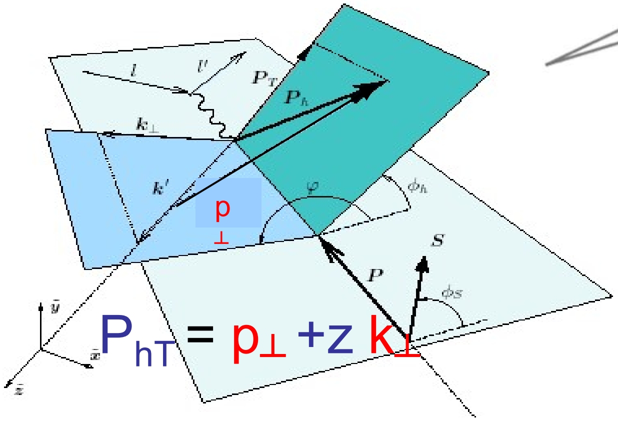
$$\frac{d\sigma^{eN \to e'hX}}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP^2_{h\perp}}$$

+Radiative Corrections

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

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



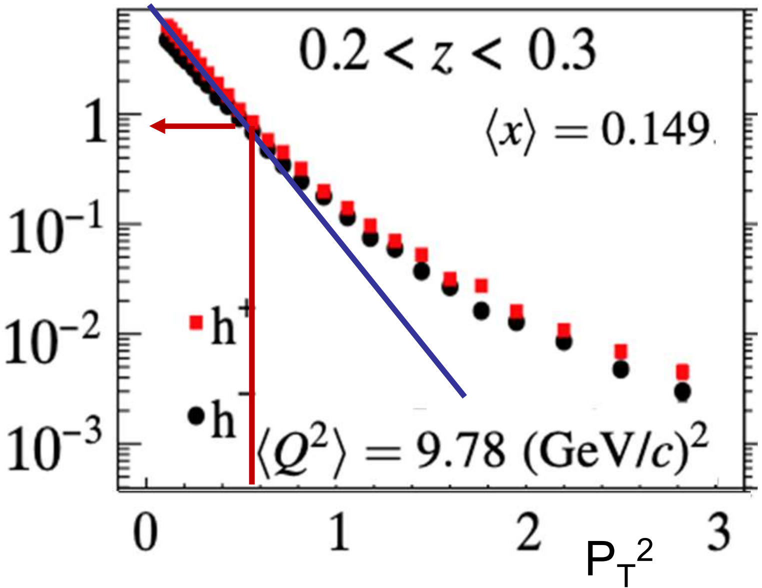
$P_{hT} = p_\perp + z\, k_\perp$

Factorization allowing description using distribution functions (TMD-PDF) and fragmentation functions (TMD FF)
X→ multiplicity of unobserved hadrons LARGE, and x-section doesn't depend on X (independent fragmentation)
Leading twist dominates, $Q^2 >> 1$
$k_\perp/Q << 1$

"much bigger/smaller" defined in comparison with experiment
in case of disagreement:
1)factorization is broken
2)unaccounted terms may contribute (assumptions are not good,…)

q_T-crisis or misinterpretation

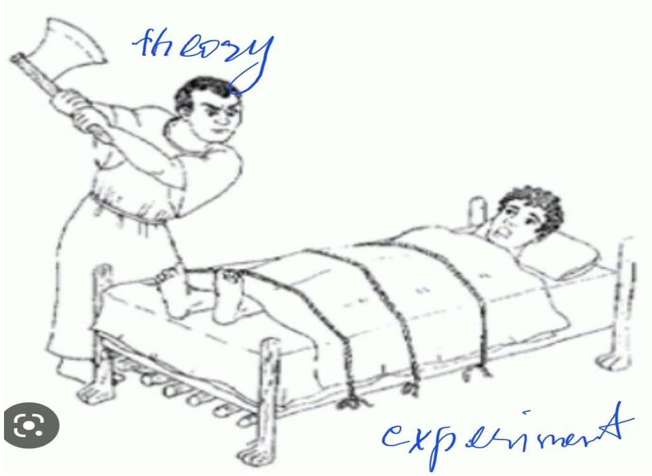
https://arxiv.org/pdf/1709.07374.pdf



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.

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



Procrustes - Greek Mythology Visit

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

Possible sources of large P_T behaviour

1) Perturbative contributions and p_T-dependence of unpolarized FFs (so far unlikely...)

2) Significantly wider in k_T distributions of u-quarks with spin opposite to proton spin (possible sign flips in asymmetries related to polarization of partons)

3) Significantly wider in k_T distributions of d-quarks (possible sign flips in asymmetries related to polarization of partons)

4) Significantly wider in k_T sea quark distributions (study contributions dominated by sea, K-,..)

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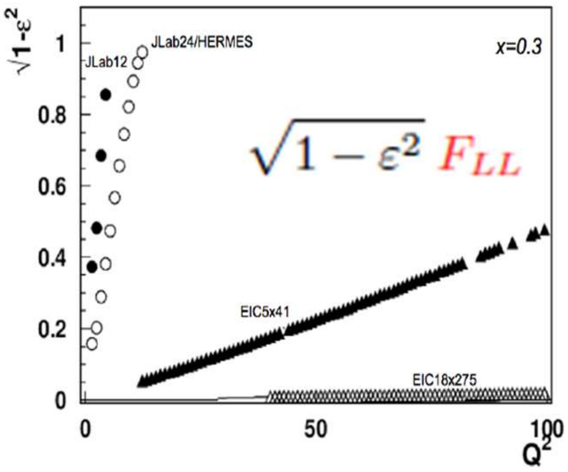
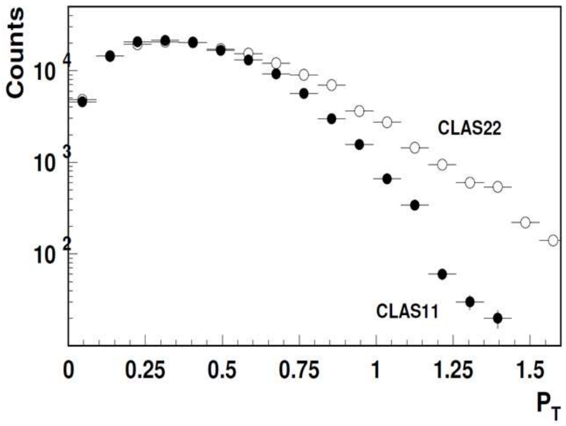
5) Increasing fraction of hadrons due to $F_{UU,L}$ (needed for proper interpretation
→ separation of $F_{UU,L}$ from total)
6) Significant contributions from VMs to low P_T pion multiplicities, with direct pions showing up at large P_T (needed for proper interpretation → much wider in k_T original parton distributions)
7) Radiative corrections (need the full x-section, typically applied to pions, while may be needed for underlying VMs,...)
8) Two photon exchange (will need positron beam)
....

Study helicity TMDs with JLab22





Accessing the quark k_T from hadron P_T

–Why helicity TMD, $g_1(x,k_T)$, matters?

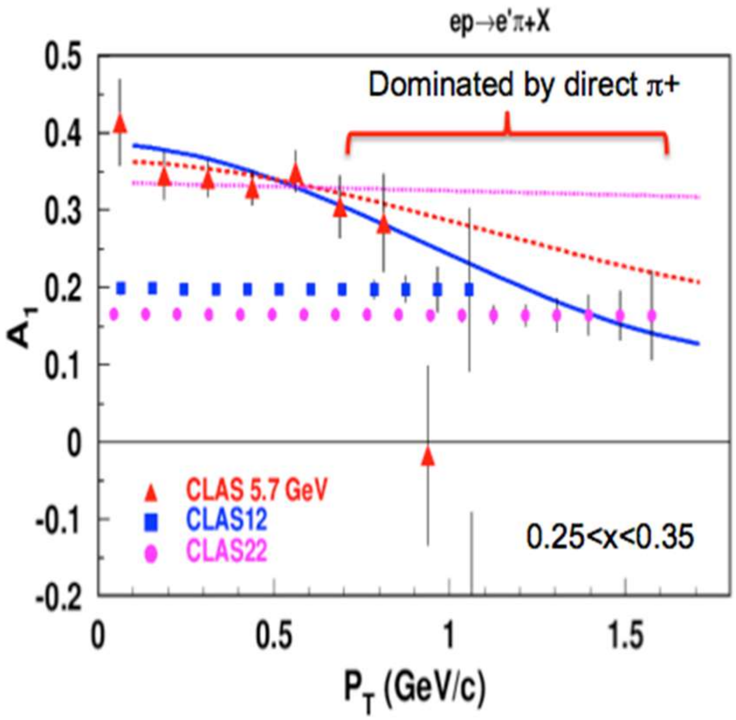
–How we measure the $g_1(x,k_T)$

–Why JLab is unique for studies of g_1 in valence region

–Why 22 GeV is critical

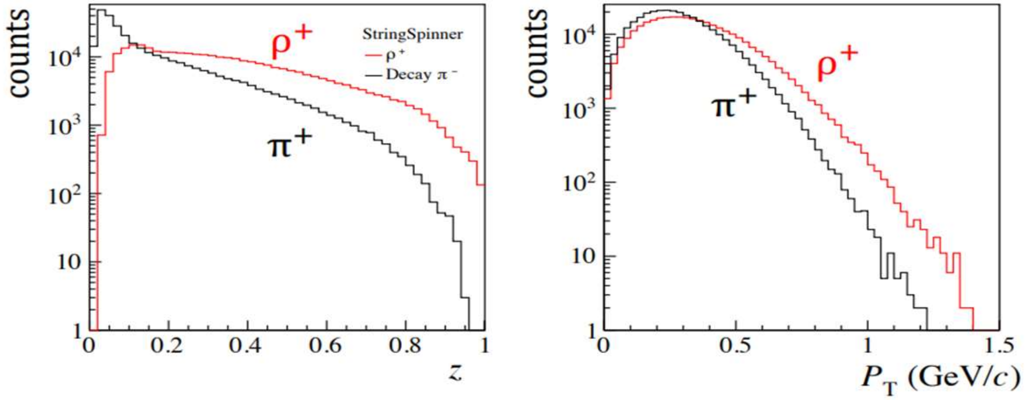
–Challenges at large P_T

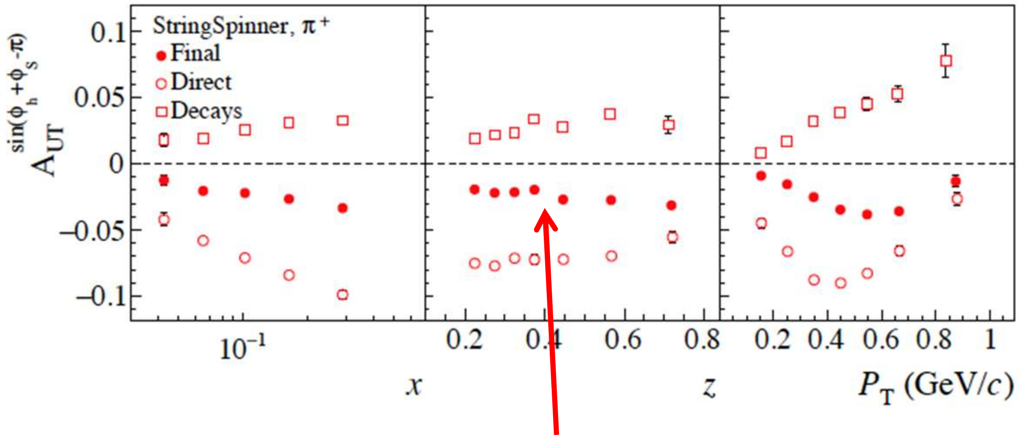
Fig. 16 in 22 GeV white paper

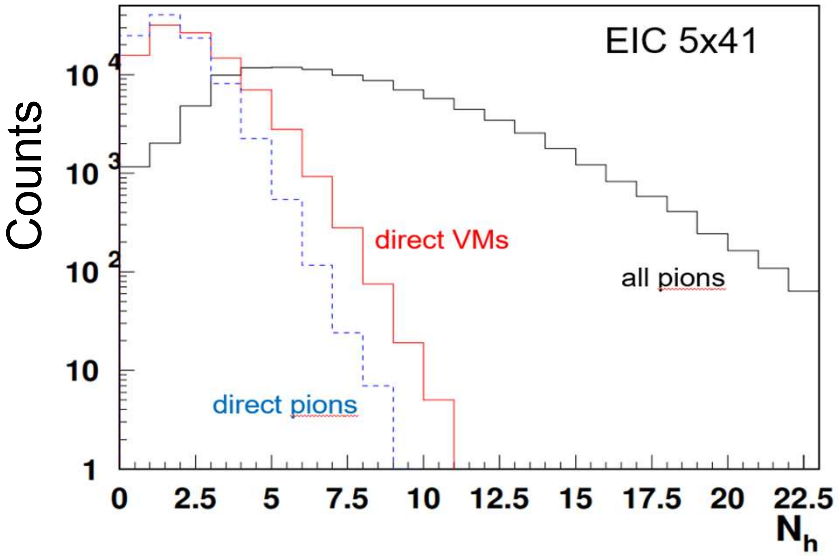


VM contributions

A. Kerbizi (Trieste U.)







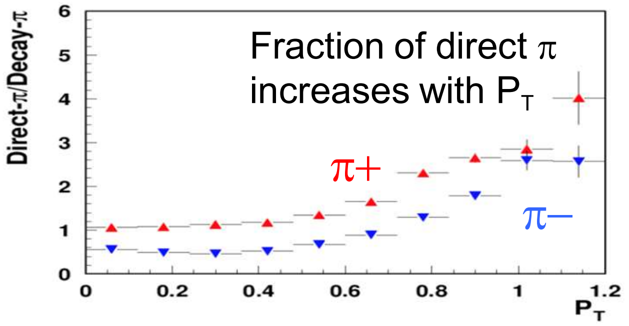
Understanding VMs is critical for interpretation even for unpolarized data

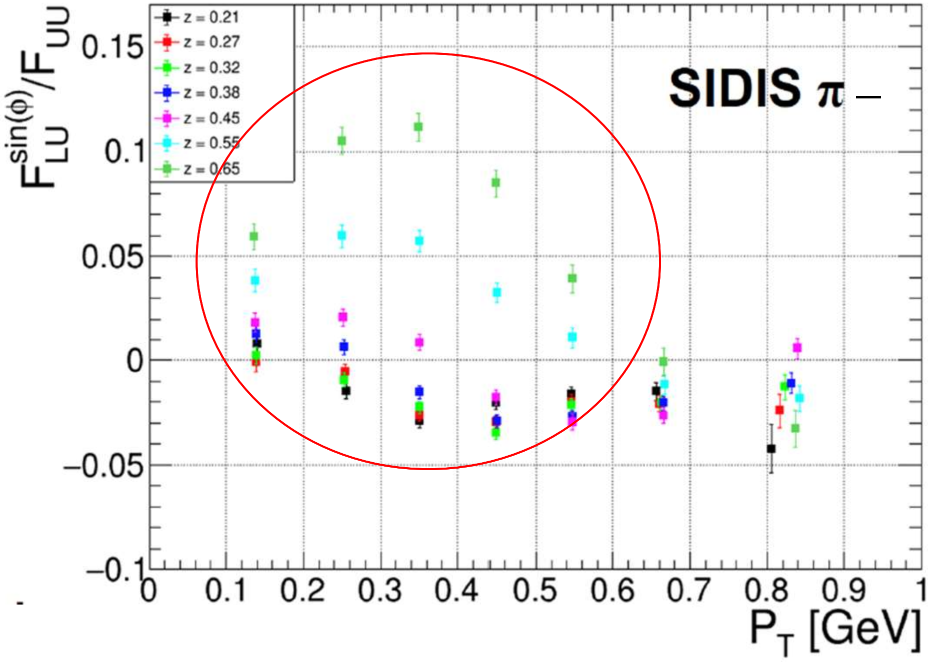
- Strong dilution of SSAs(3-5 for pions 2-3 for Kaons) due to VM decays
- Significant differences in pions vs Kaons from VMs(JLab can measure also K*, and their SSAs)

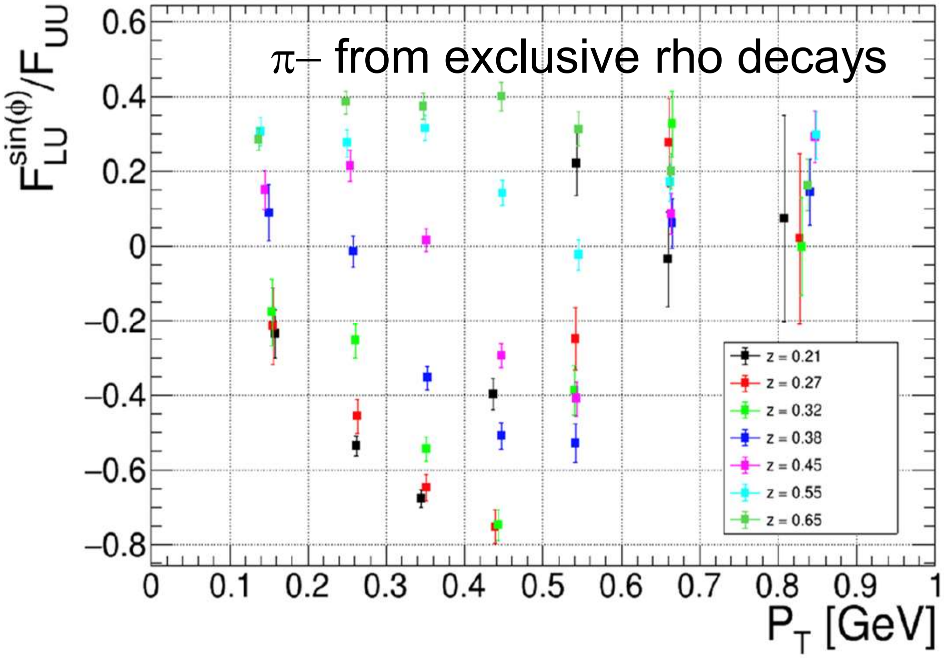
SIDIS SSAs

S. Diehl

- Biggest contributions from exclusive rhos in low P_T, large z
- Large fractions of low z pions from semi-inclusive VM decays

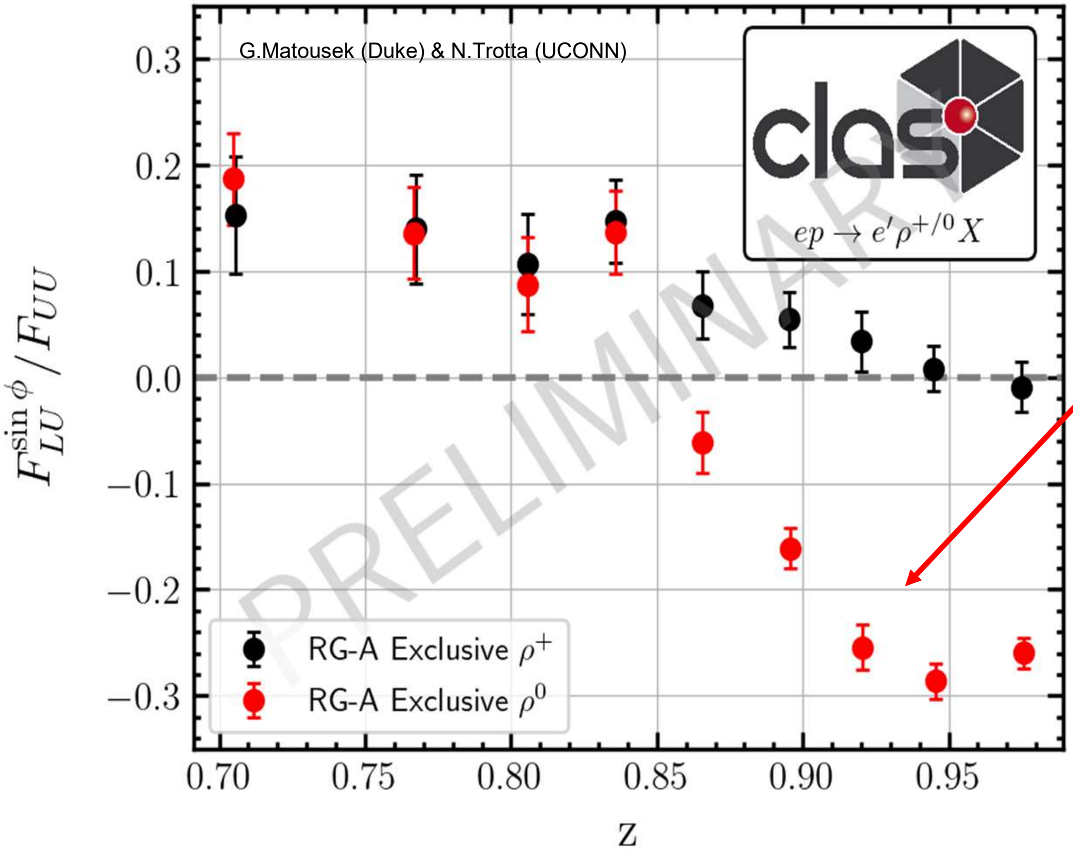






Interpretation of SSAs can be very challenging in certain kinematics
For low P_T the impact of rho can be critical even for small fractions

Quark-gluon correlations: impact of VMs



Different dynamical contributions

What are those contributions?
Other DSAs and SSAs?
How and in which kinematics they affect inclusive pions and dihadrons?

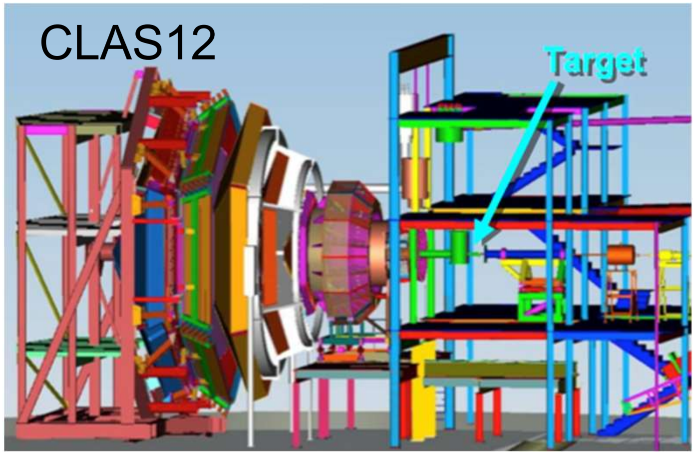
longitudinal photons?

Need theory (ex. involving HT GPDs to describe the SSA)

- Understanding of SSAs of VMs is critical in interpretation of the pion SIDIS
- A_{LU} sign change can define the dominating process!!!
- At large x the diffractive processes are suppressed by the minimum t

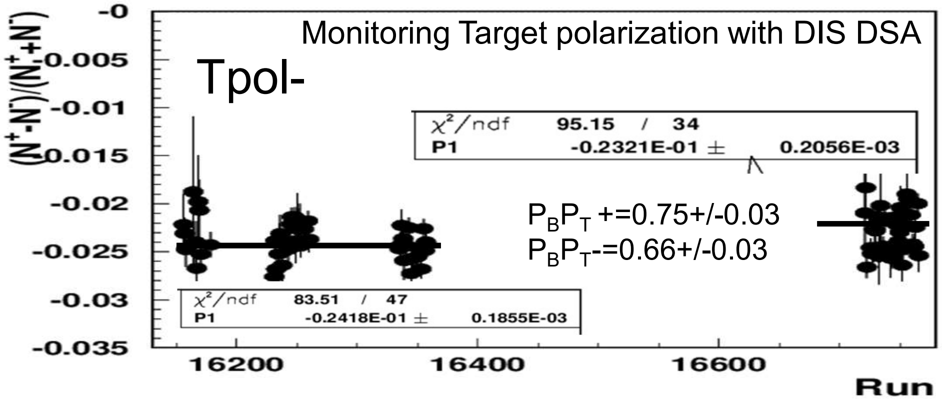
$t_{min} \approx -M^2x^2/(1-x)$

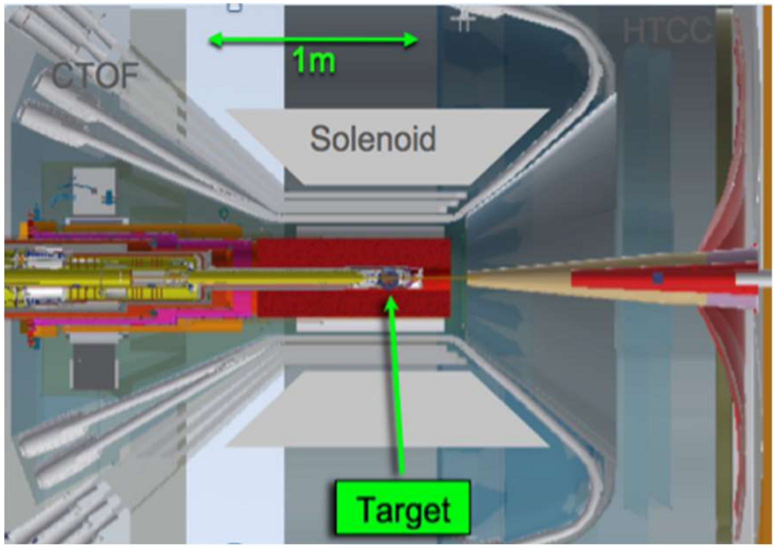
CLAS12 RGC experiment with longitudinally polarized target



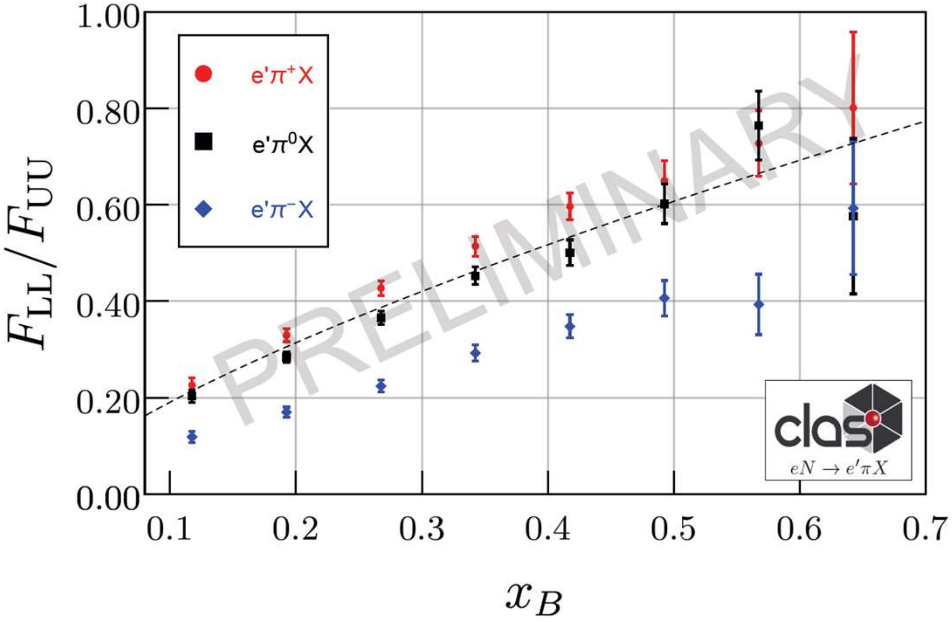
E12-06-109, E12-06-119, E12-07-107, E12-09-009

Electroproduction on longitudinally polarized NH3 and ND3



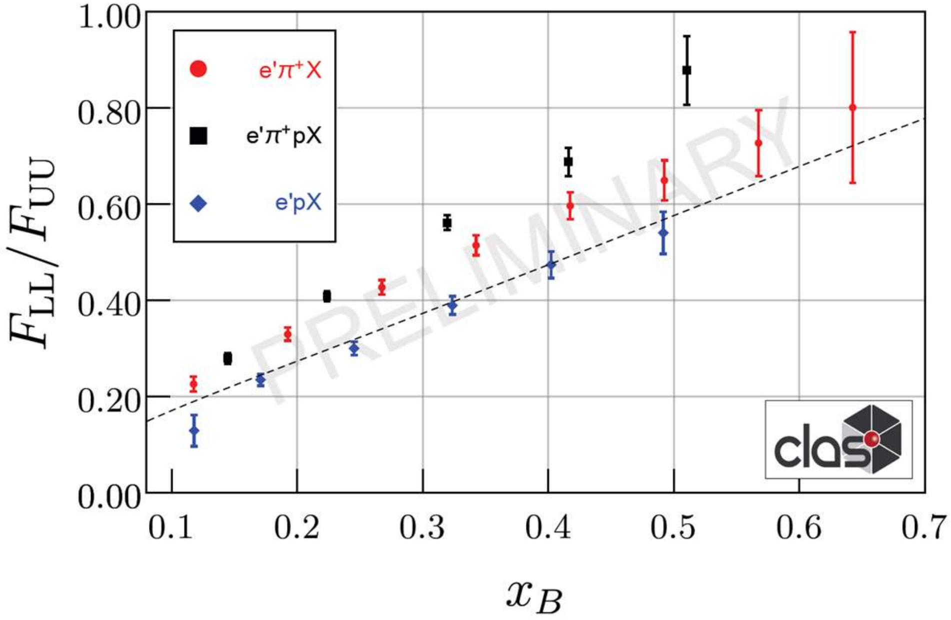


Dynamic Nuclear Polarization (DNP)

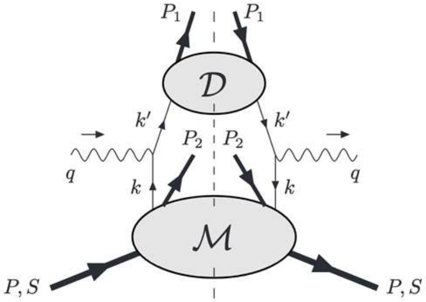


Double spin asymmetries consistent with world data

Accessing longitudinally polarized quarks

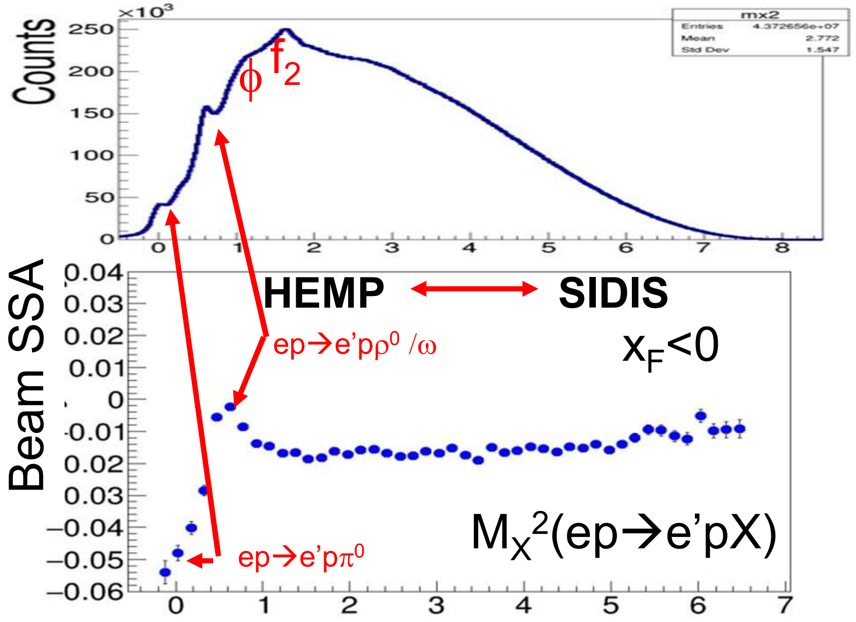


ep→e'pπX



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

Detection of proton allows elimination of exclusive rho!



- **Formalism based on fracture functions (Anselmino, Barone, Kotzinian (back-to-back, b2b, hadron production, DSIDIS)**
- **Semi-exclusive processes, involving GPDs/GTMDs on proton side (TFR) and FFs on pion side (CFR) Yuan and Guo**

- Differences in A_{LL} , due to different weights on PDFs can provide additional info on impact of possible ingredients
- Measurements of A_{LL} for ρ^0 indicate very small values, and can be one of the reasons for higher A_{LL} with protons with a M_X cuts above 1.5 GeV (excluding exclusive ρ^0)

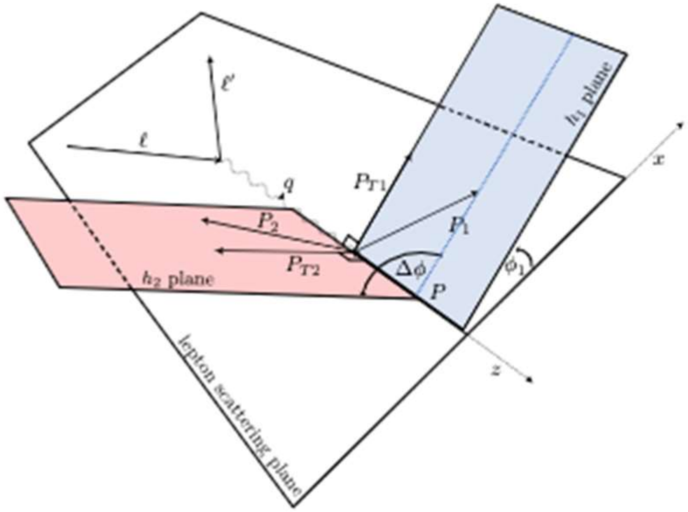
Azimuthal modulations in B2B production

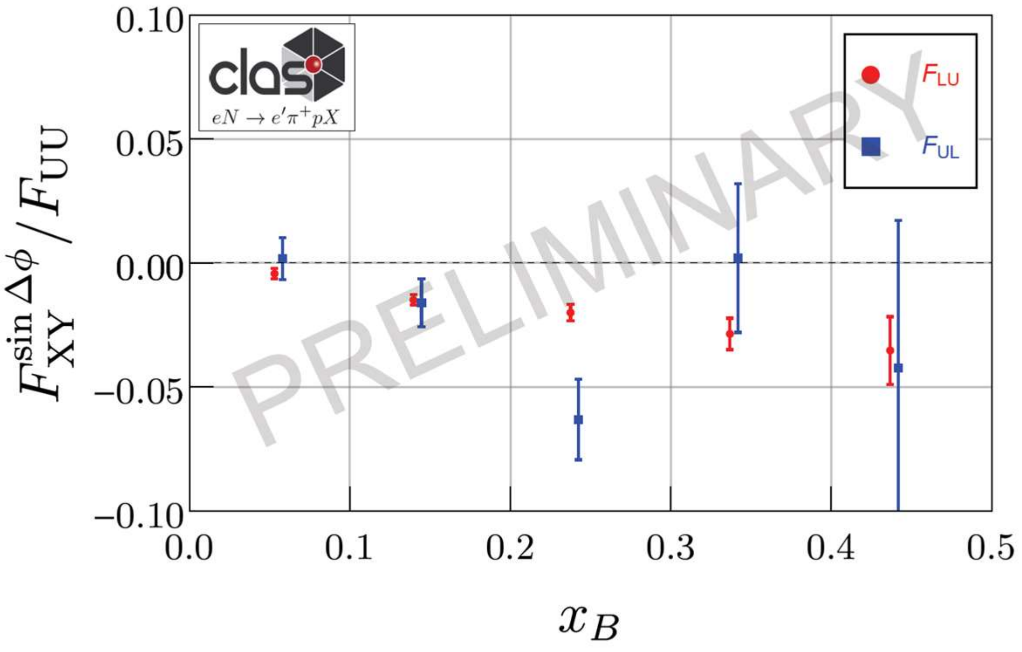
N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\boxed{\hat{u}_{1L}^{\perp h}}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp},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

$$\sigma_{LU} = -\frac{P_{T1}P_{T2}}{m_N m_2} F_{k1}^{\hat{l}_1^{\perp h}\cdot D_1} \sin(\Delta\phi),$$

$$\sigma_{UL} = -\frac{P_{T1}P_{T2}}{m_N m_2} F_{k1}^{\hat{u}_{1L}^{\perp h}\cdot D_1} \sin(\Delta\phi)$$ → No suppression at higher energies

A.Kotzinian
Transversity-2022

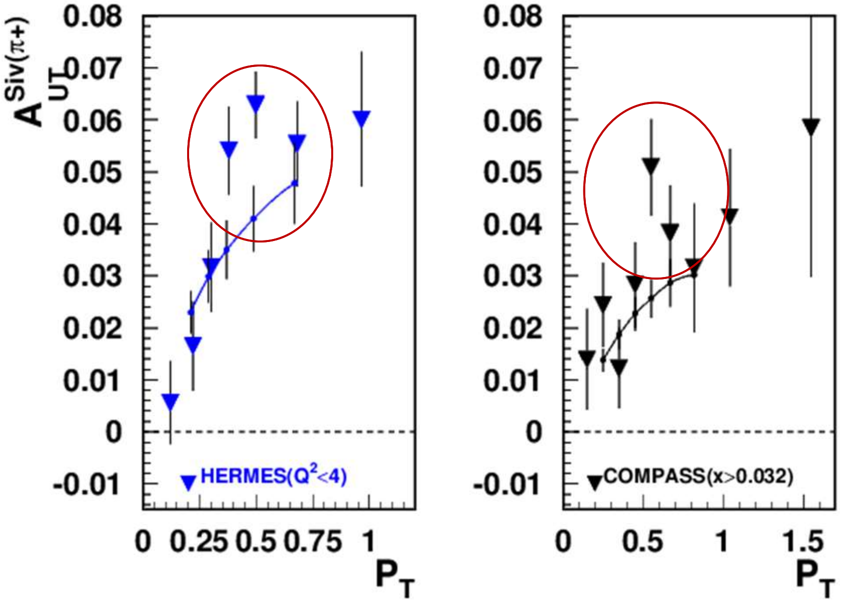




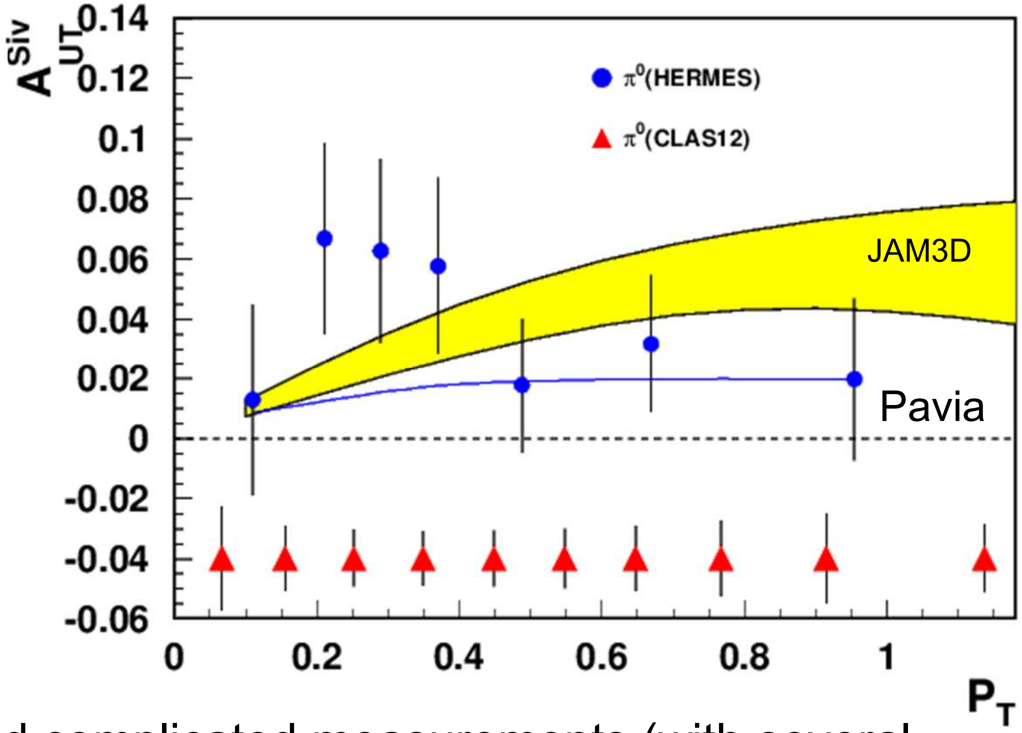
Full RGC polarized target set (x4) will provide a significant measurement of the target single spin asymmetry $A_{UL}^{\sin\Delta\phi}$, which has no suppression at higher energies and can be measured at colliders!

Sivers effect: P_T-dependence

Significant Sivers effect measured so far for charged hadrons



CLAS12 RGH experiment with Transversely polarized target

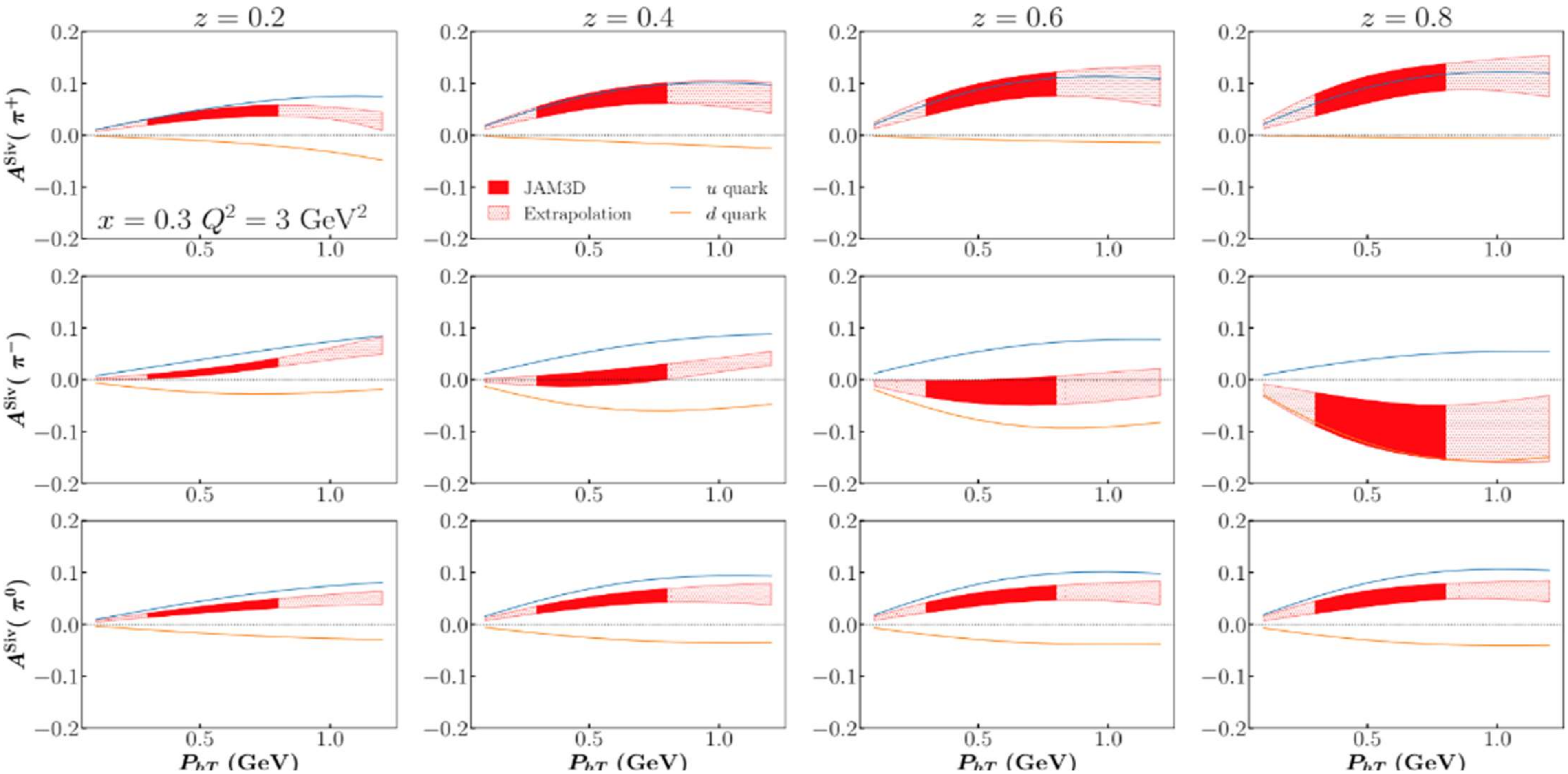


Sivers effect, one of the most exciting and complicated measurements (with several overlapping azimuthal modulations, VM and longitudinal photon contributions)

- Neutral pion measurements, with less impact from VMs and longitudinal photons, critical for validation of Sivers measurements
- Higher statistics + neutral pions would allow extraction of asymmetries for dihadron sample, also needed to control systematics from VMs

Sivers effect: P_T-dependence

JAM3D



- Higher statistics measurement with pions in the valence region can check the predictions of large π- SSAs (blue lines u-quark dominance)

SUMMARY

- Studies of QCD dynamics with controlled systematics involving Semi-Inclusive DIS, requires multidimensional measurements of cross sections/multiplicities/asymmetries as a function of all involved kinematical variables (including P_T and ϕ)

- For interpretation of the SIDIS data it is critical to separate contributions from different structure functions, as well as separation of different production mechanisms in a given structure function (including VMs)

- 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

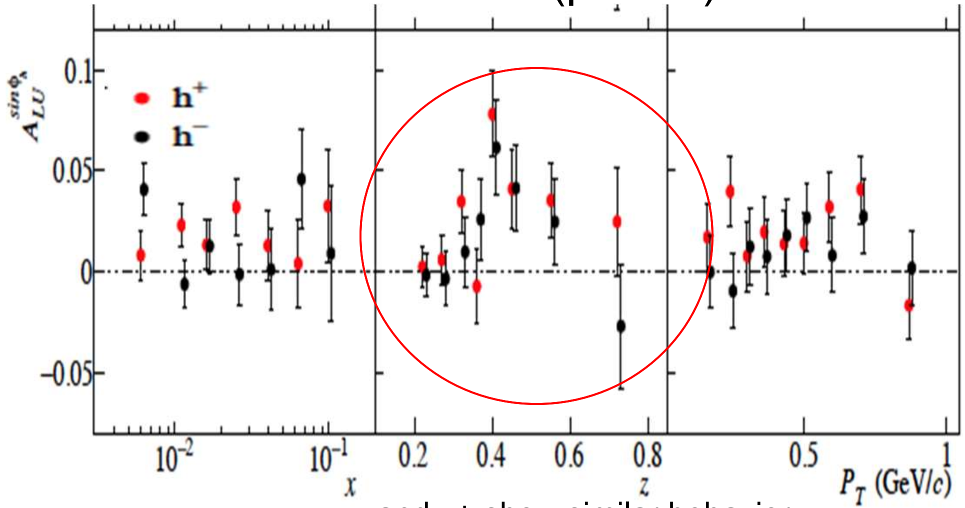
- Detection of target fragment baryon opens a new avenue for studies of the partonic structure of nucleon, allowing separation of certain contributions.

- 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.

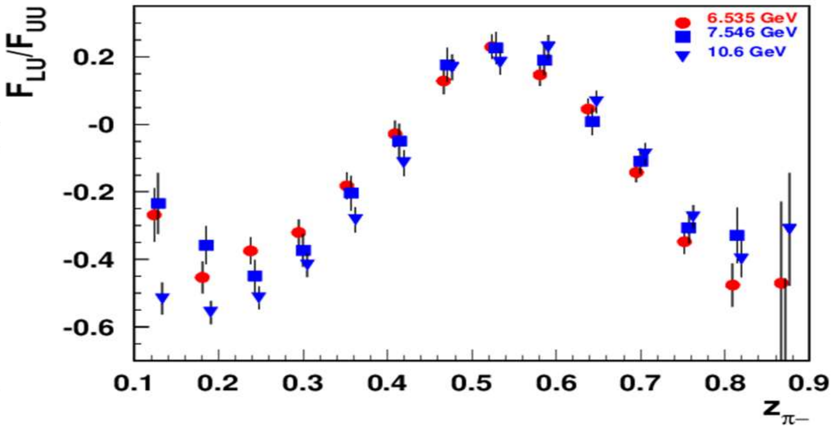
- Support Slides

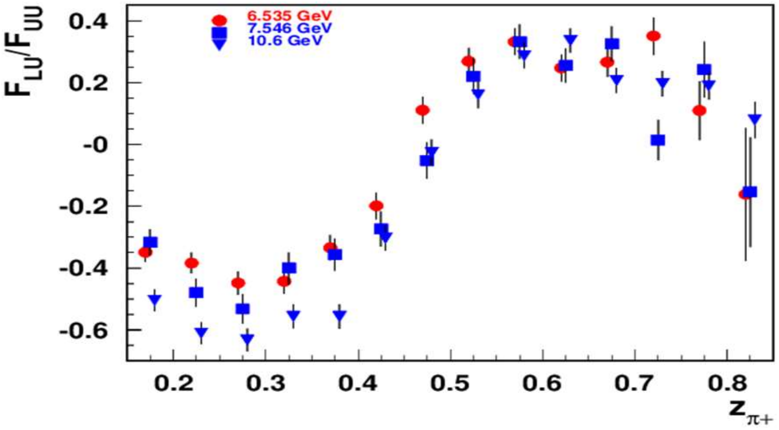
Exclusive ρ contributions to π: z-dependence

COMPASS (proton)



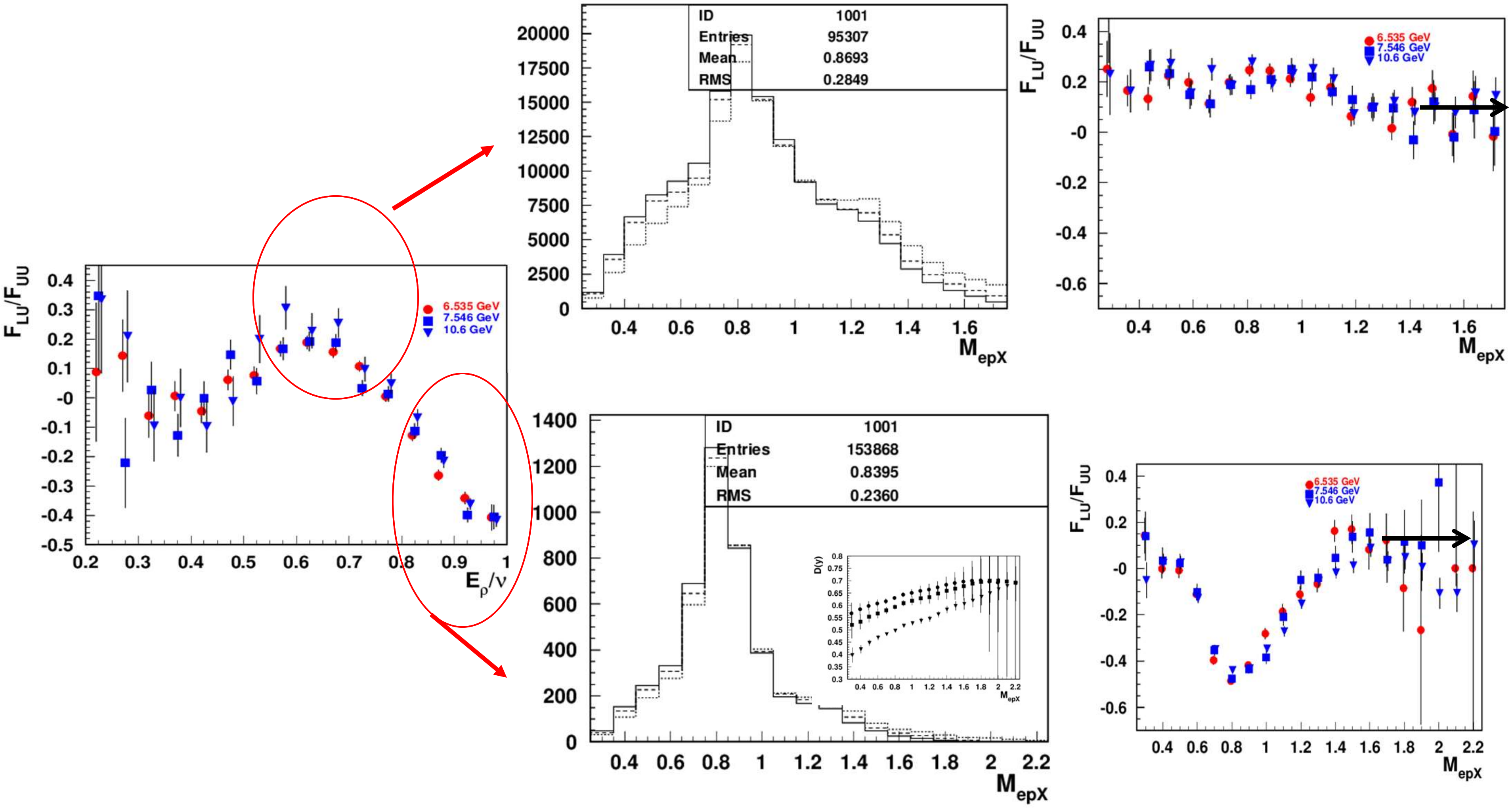
π– and π+ show similar behavior





Diffractive rho can change significantly observed pion SSAs

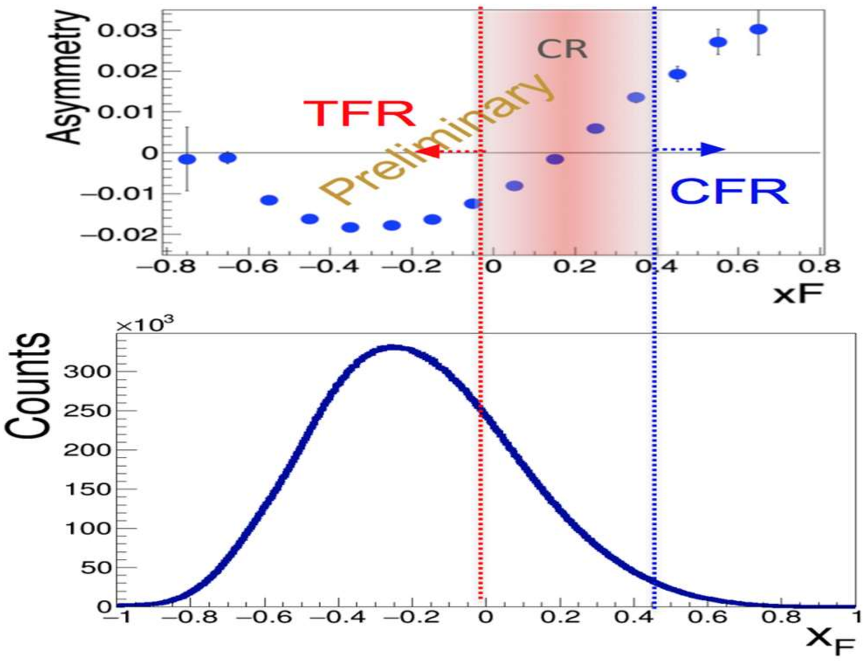
Exclusive $\pi+\pi-$: missing mass dependence

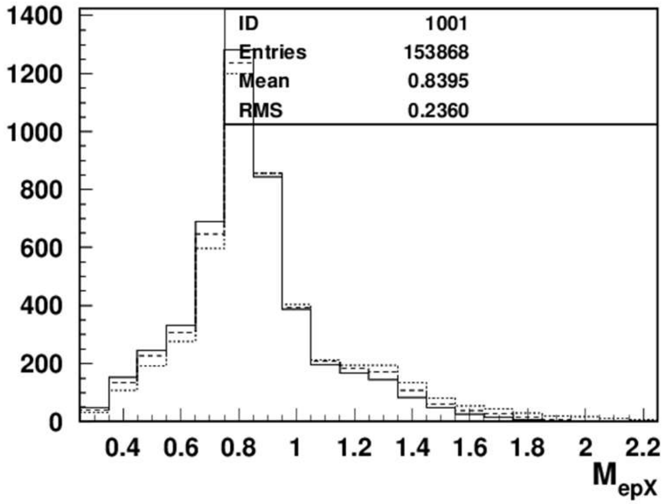


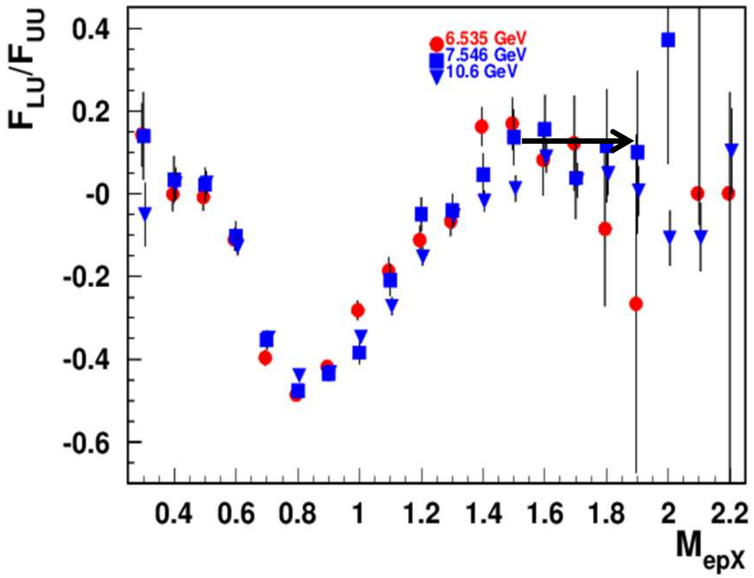
Rhos dominate both exclusive dihadron sample, contributing differently depending on z

Beam SSAs: impact of exclusive rho0

ep→e'pX





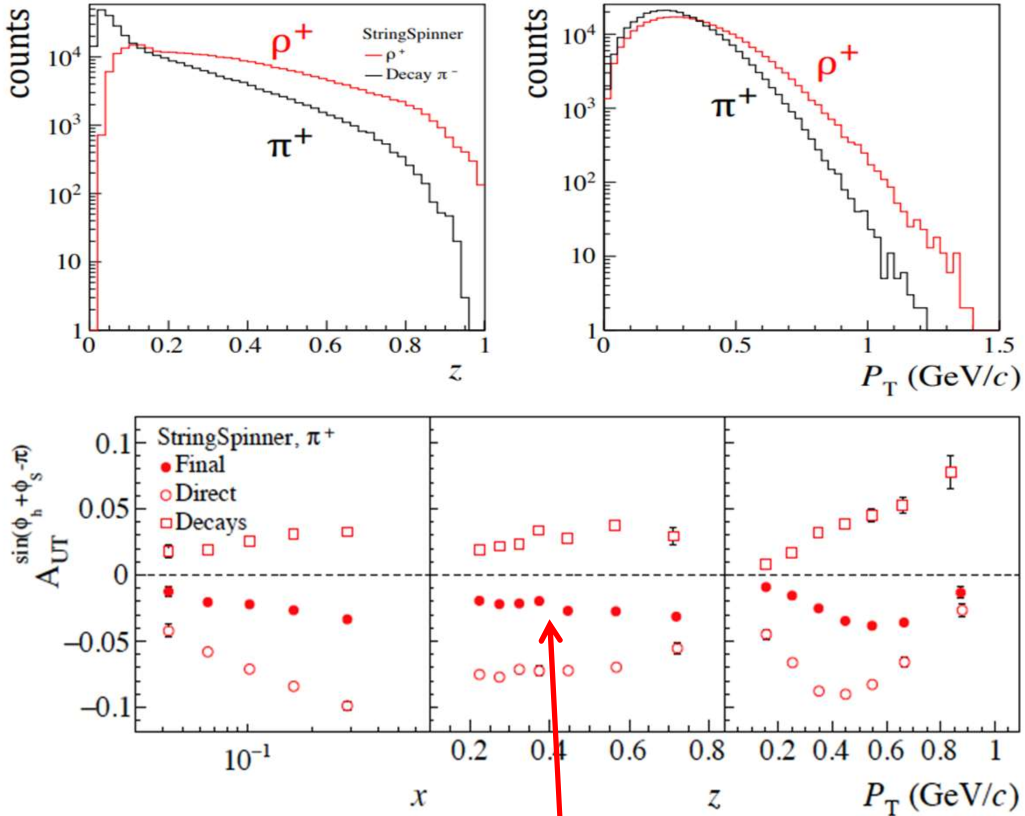


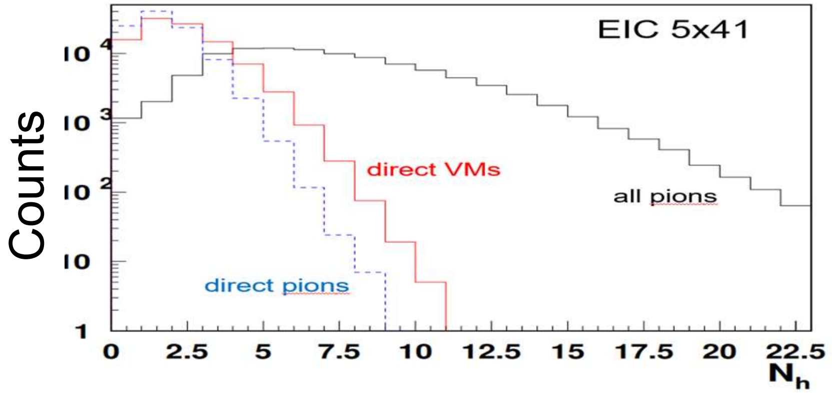
Negative sign of the SSA (plateau) for TFR particles, means positive for CFR (ex. K+)

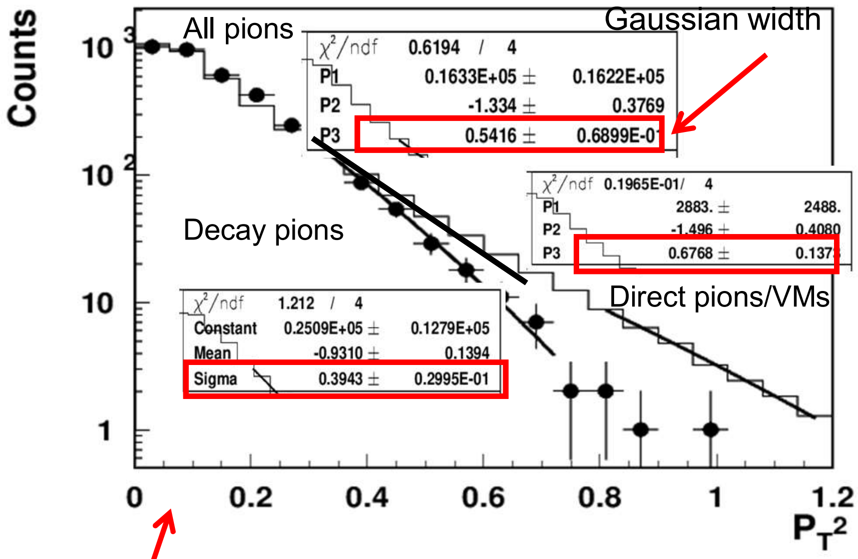
kick out of polarized u-quark most likely responsible for the negative SSA in the target fragment

VM contributions

A. Kerbizi (Trieste U.)







All pions

Gaussian width

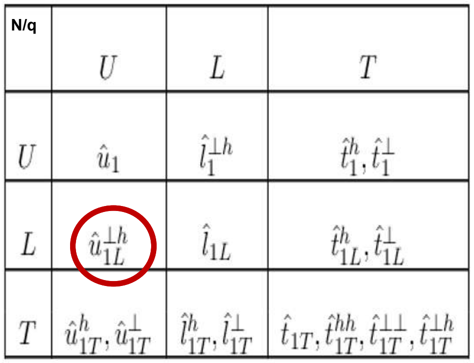
Decay pions

Direct pions/VMs

- Strong dilution of SSAs(3-5 for pions 2-3 for Kaons) due to VM decays
- Significant differences in pions vs Kaons from VMs(JLab can measure also K*, and their SSAs)

Understanding VMs is critical for interpretation even for unpolarized data

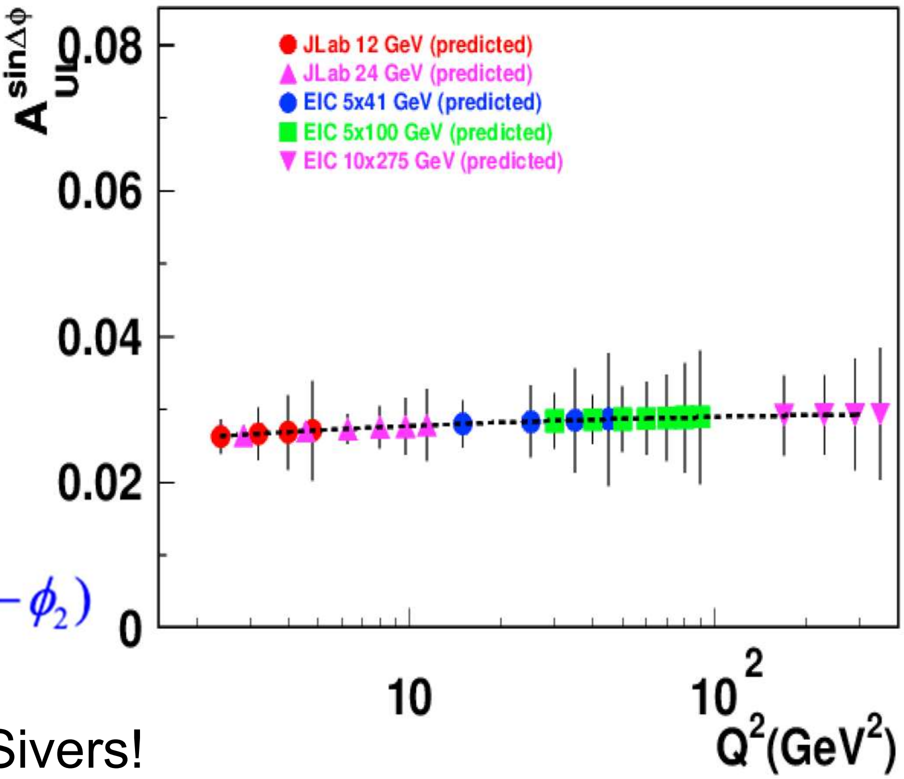
B2B correlations with longitudinally polarized target



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

A. Kotzinian et al, arXiv:1107.2292

Lumi: JLab 10^{35}, EIC4x51/5x100/10x275 0.044,0.6,1x10^{34})
y>0.05,100 days



CL AS12 proposals

NH3/ND3

E12-09-009

E12-07-107

E12-09-007A

^{3}He

C12-20-002

^{7}LiD

E12-14-001

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

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

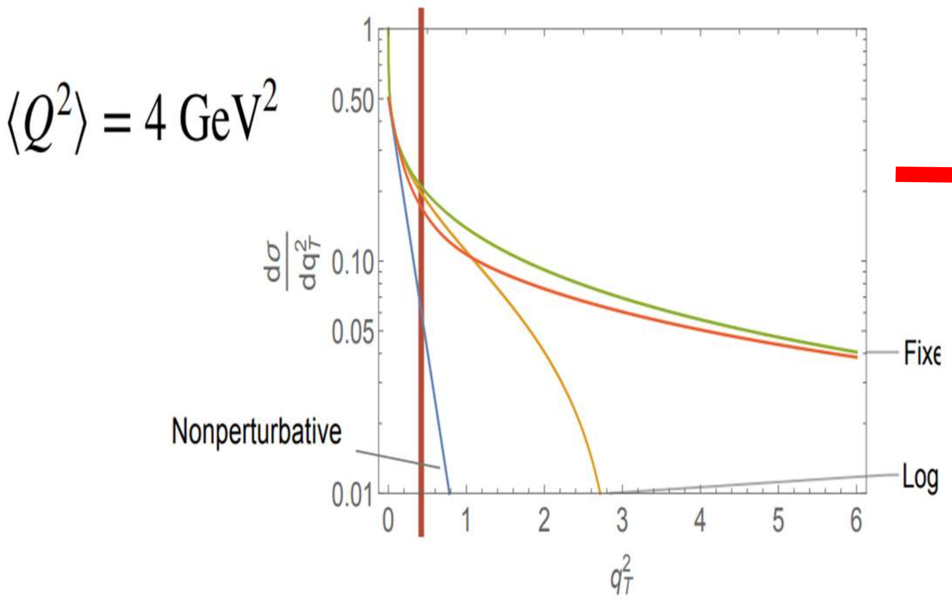
No depolarization, like Sivers!

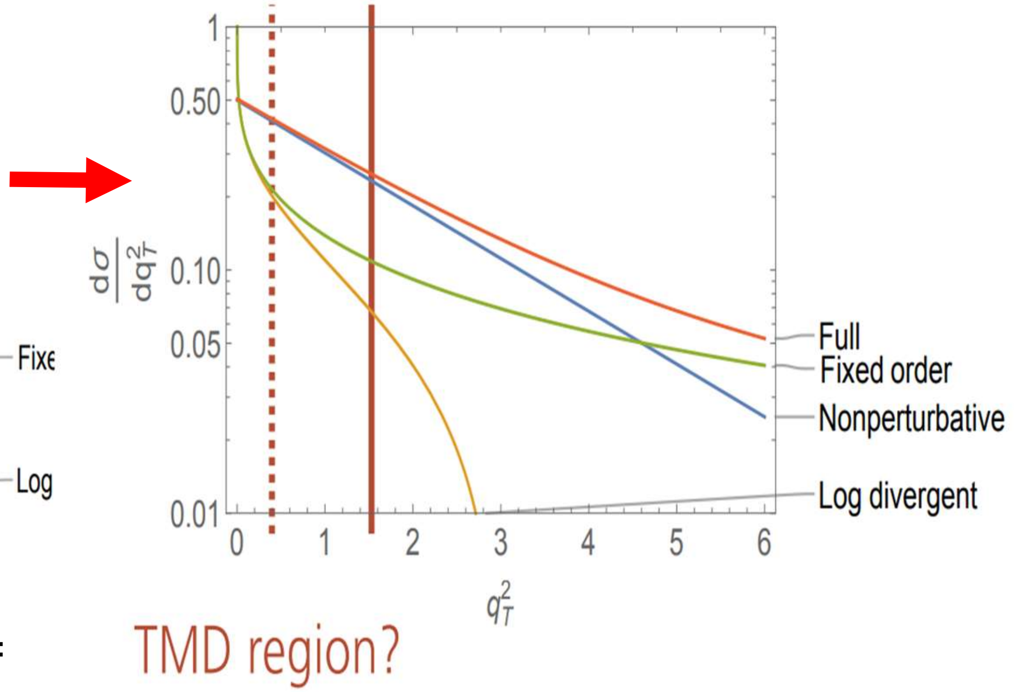
- Target SSA can be measured in the full Q^2 range, combining different facilities
- Advantages: Higher Lumi for JLab, no kinematical suppression at high Q^2 for EIC
- JLab24 will be crucial to bridge the studies of FFs between JLab12 and EIC in the valence region

TMD theory problems

Perturbative approach: TMD region = where the log divergence of the fixed-order calculation dominates (resummation is required)

A. Bacchetta





Nonperturbative approach: TMD region = where either the log divergence OR the nonperturbative contributions dominate

What data input exactly drives down the nonperturbative part?

Goals, observables,statements….

The valence region (x>0.02), where the non-perturbative effects, SSAs in particular, were measured to be significant, most critical for non-perturbative QCD studied

1) Understanding of P_T-distributions of hadrons in SIDIS is critical for extraction of k_T-dependence/distributions of partons and transverse momentum dependence of the hadronization (fragmentation functions)

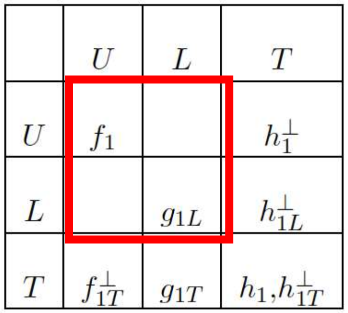
2) Measurements with longitudinally polarized target are critical for understanding of the systematics of TMD measurements in multidimensional space, including the unpolarized TMDs $(f_1^q(x,k_T))$

3) Multidimensional measurements of different hadrons are critical for understanding of measurements of hadronic P_T-dependent observables

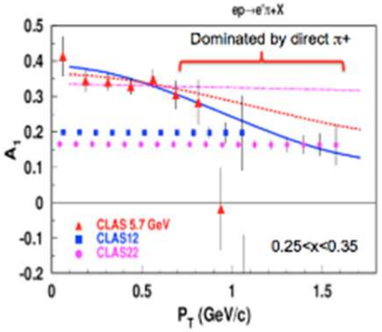
4) Higher energy experiments, colliders in particular will have major challenges in studies of longitudinal single and double spin asymmetries

5) JLab is the unique place to measure the $g_1(x,k_T)$ in the valence region

6) Upgrade to 22 GeV, is critical for studies of TMDs, increasing the critical range of P_T of pions not dominated by VM decays by an <u>order of magnitude</u>

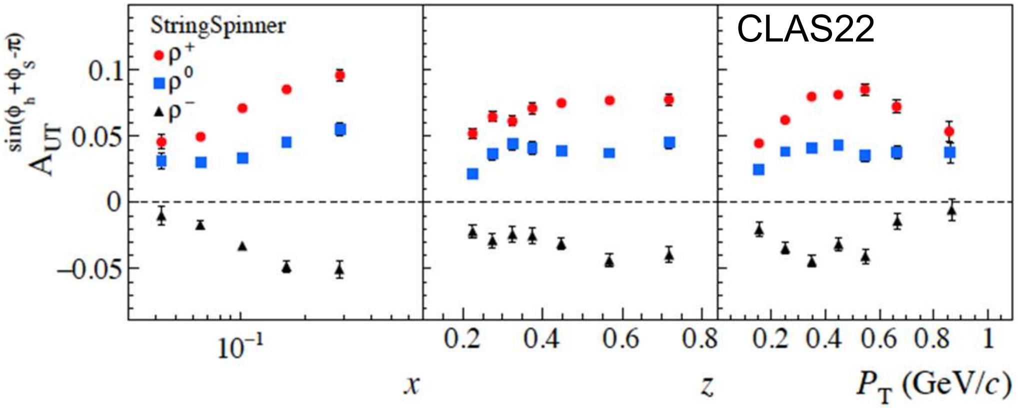


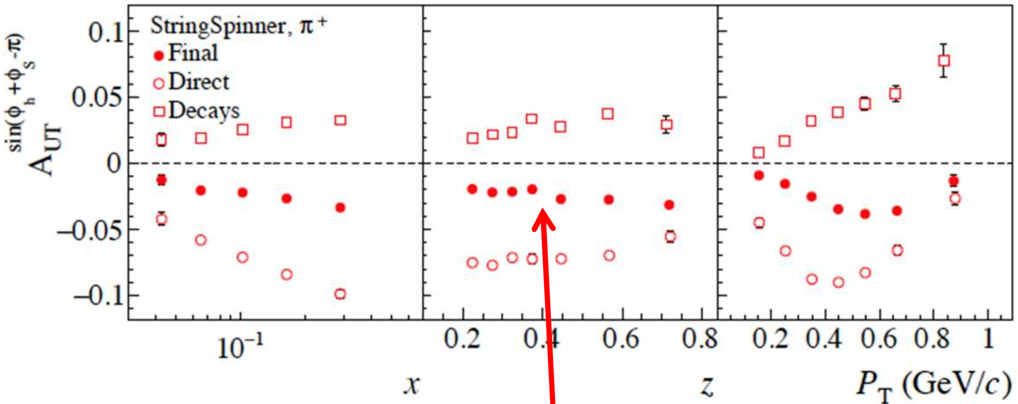
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

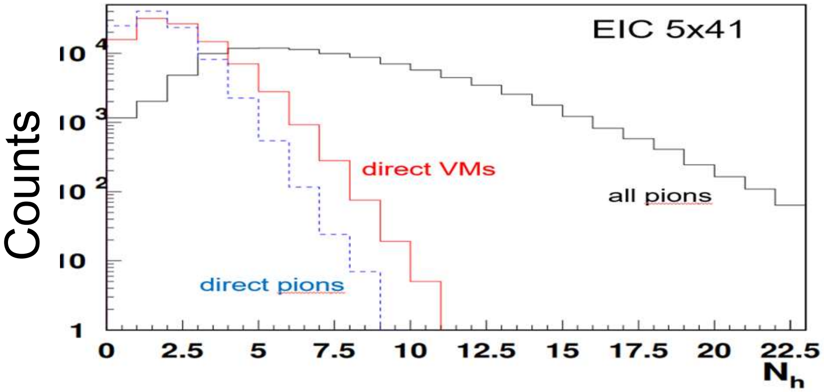


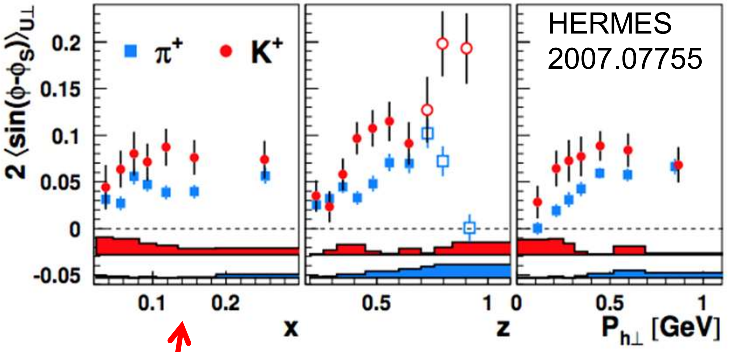
VM contributions

A. Kerbizi (Trieste U.)









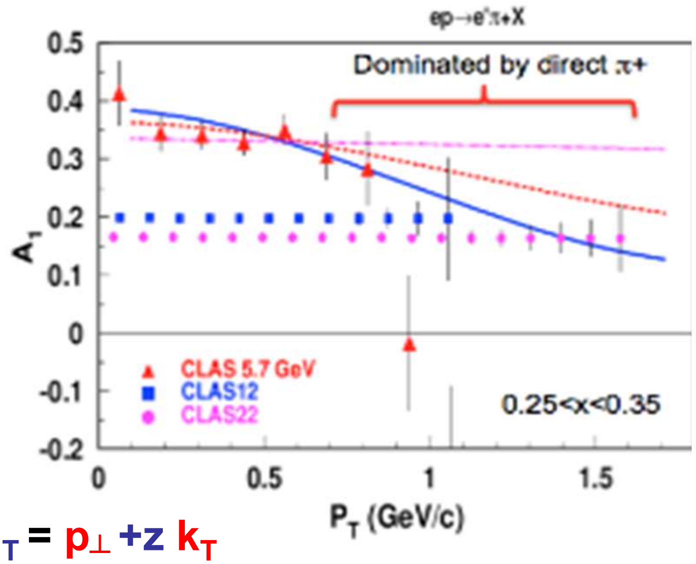
Strong dilution of SSAs(3-5 for pions 2-3 for Kaons) due to VM decays

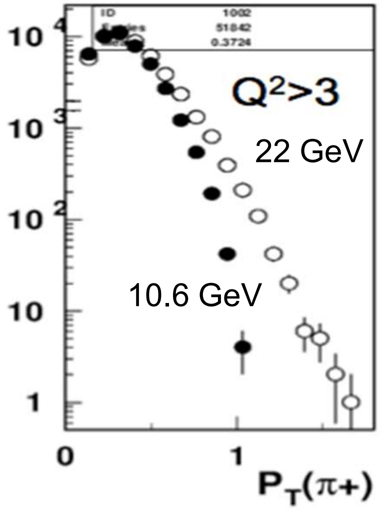
The differences in pions vs Kaons SSAs may be coming from VMs???

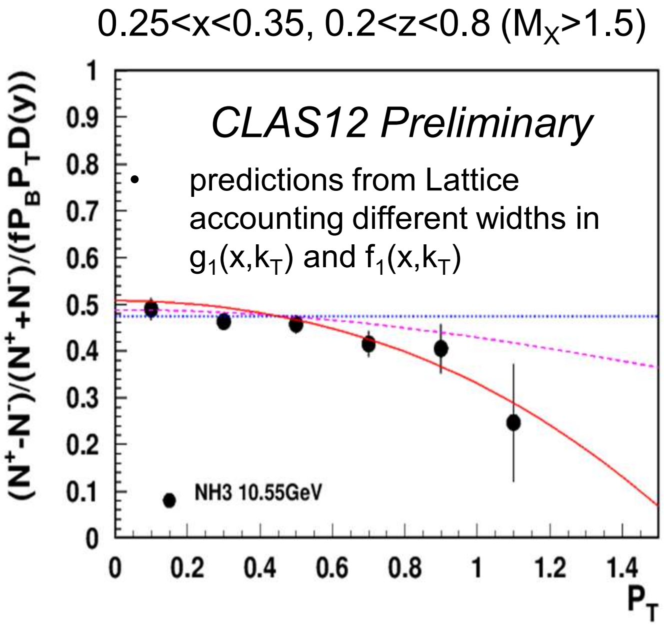
Understanding VMs is critical for interpretation What is q_T?

JLab can measure the SSA of VMs(also K*), and separate contributions

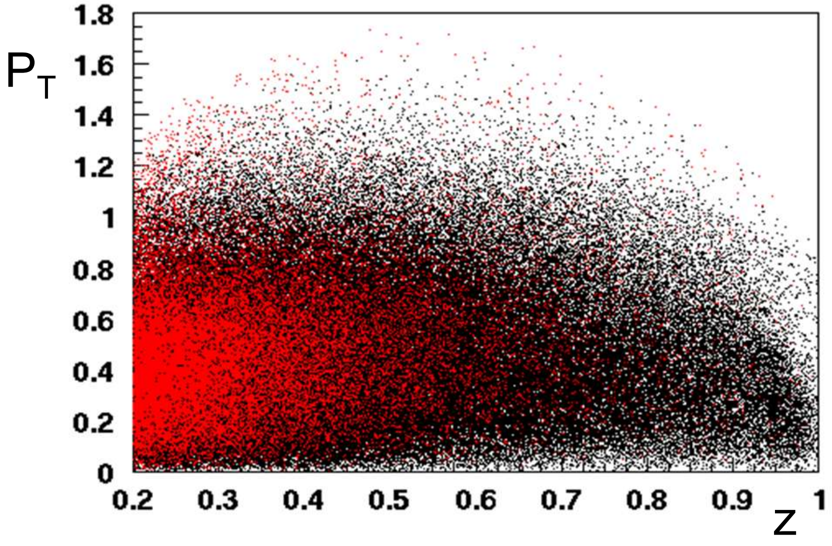
A_1 P_T-dependence







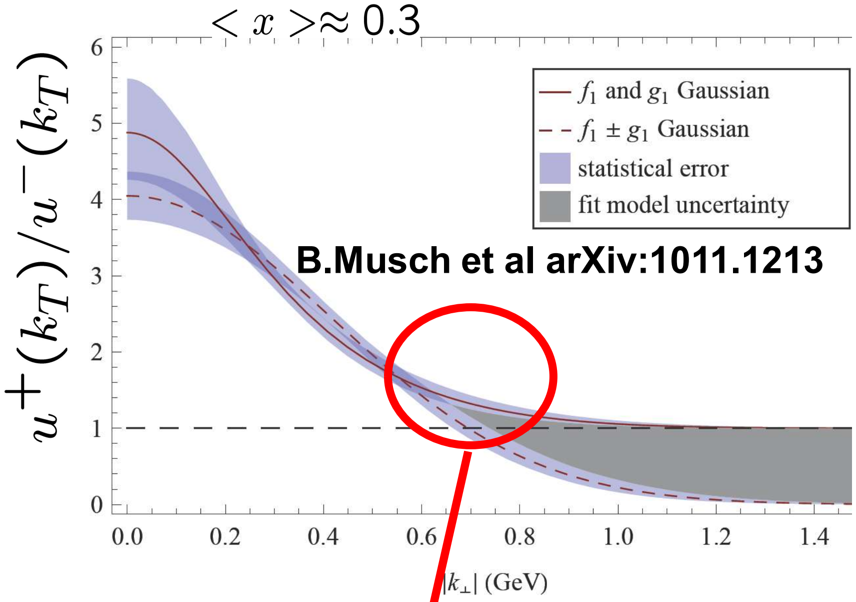
$P_T = p_\perp + z\, k_T$



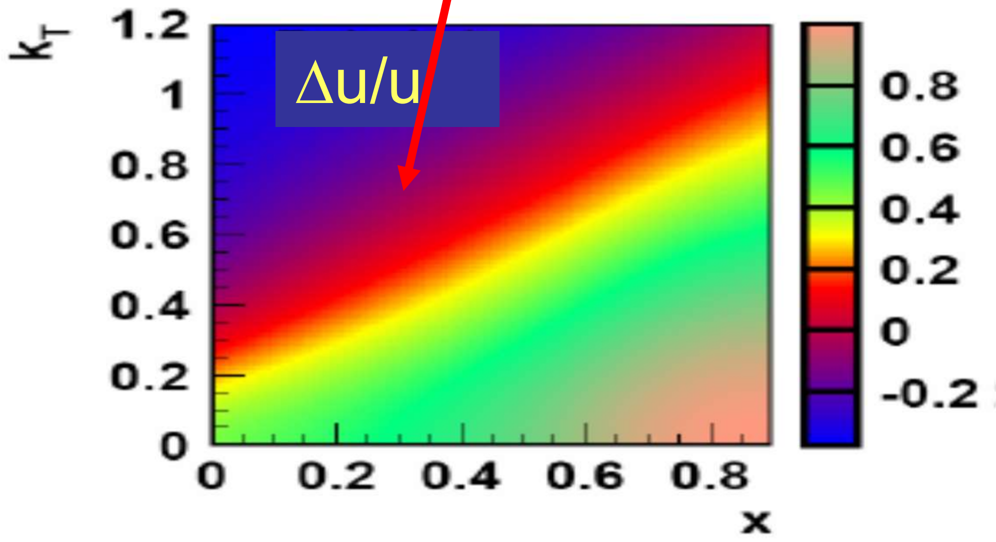
With more statistics in extended P_T range can

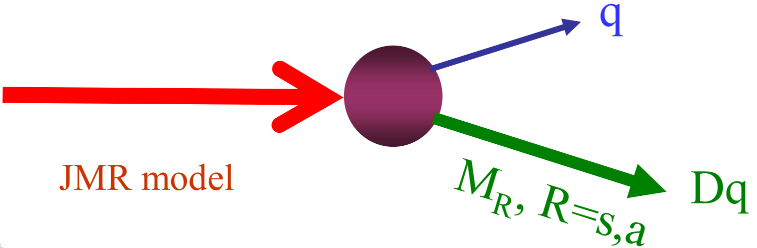
- do finer bins in x/z/P_T (correlated)
- measure Q^2-depndence needed for validation
- higher statistics would allow extraction of the same asymmetries for dihadron sample needed to control systematics from VMs

Quark distributions at large k_T: lattice



B.Musch et al arXiv:1011.1213





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

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

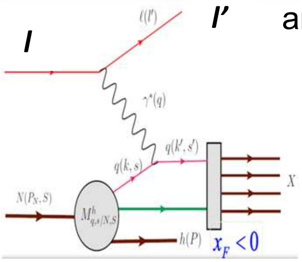
Sign change of Δu/u consistent between lattice and diquark model

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

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

More quarks with opposite to proton spin at large transverse momentum

Hadron production in TFR



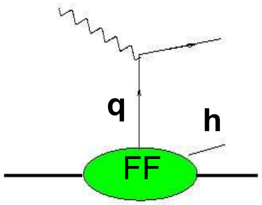
arXiv:2308.11251

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

unpolarized quarks in the longitudinally polarized proton

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

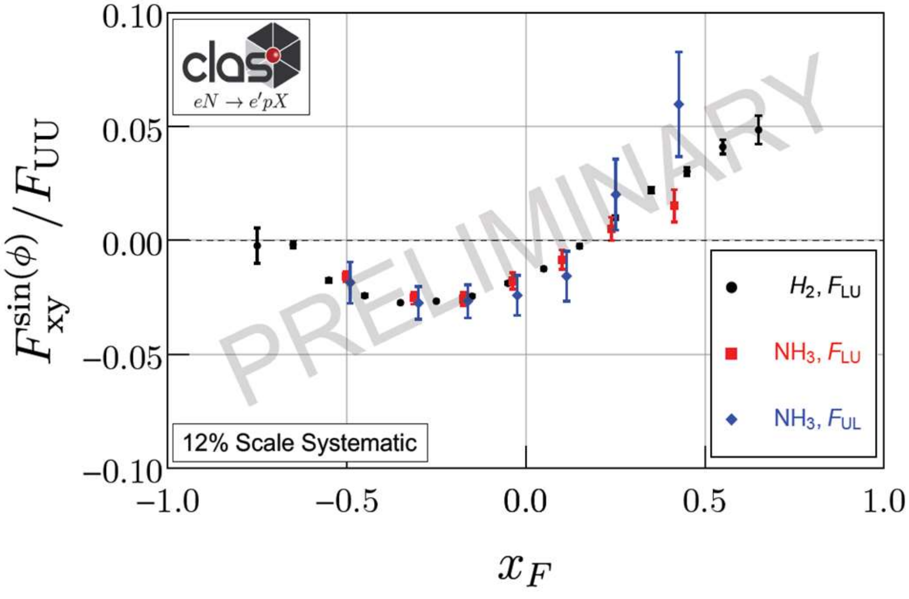
longitudinally polarized quarks in the unpolarized proton

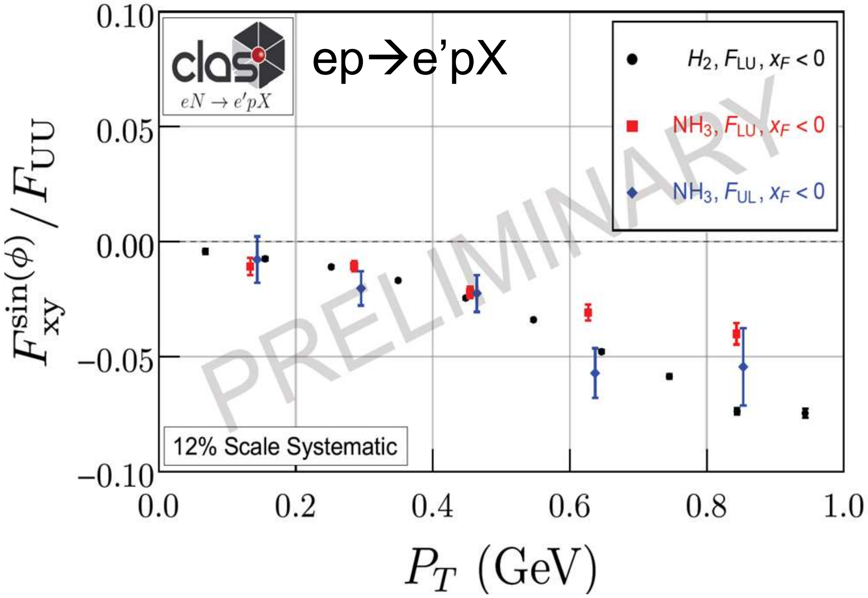


Conditional probability to produce a hadron ***h***, when kicking out quark ***q***

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

ep→e'pX

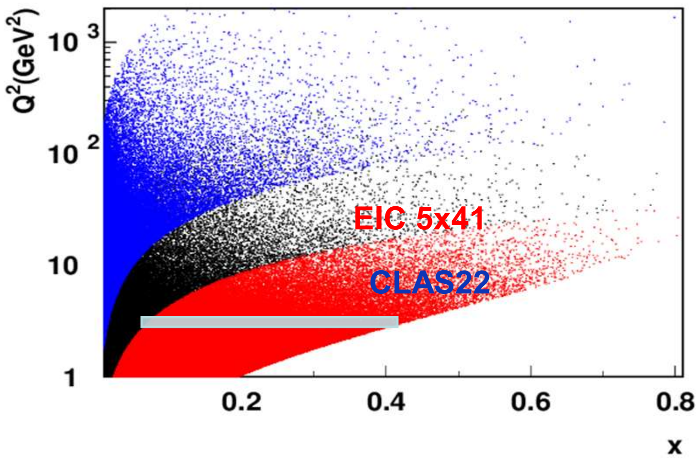


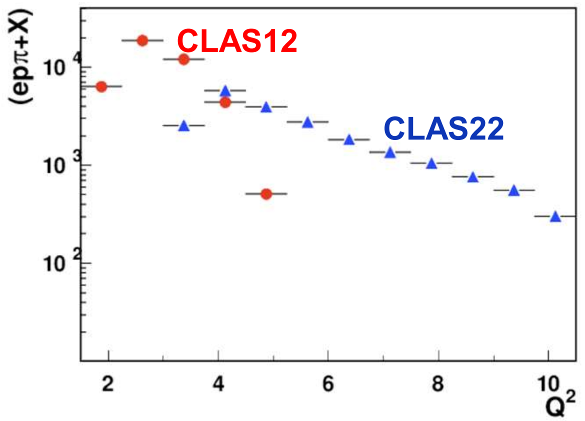


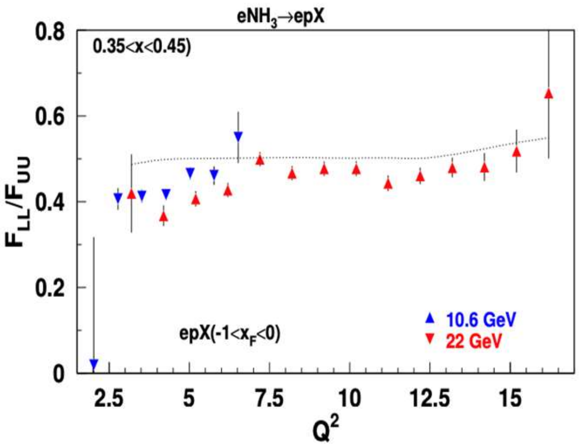
Asymmetries in epX are generated by unpolarized quarks in the longitudinally polarized target (RGC) F_{UL} or longitudinally polarized quarks in the unpolarized target (RGA) F_{LU} (consistent with each other)

Note: F_{LU} for Nitrogen practically the same as for proton → no medium modification

Accessing CS-kernel directly or through extraction of SFs



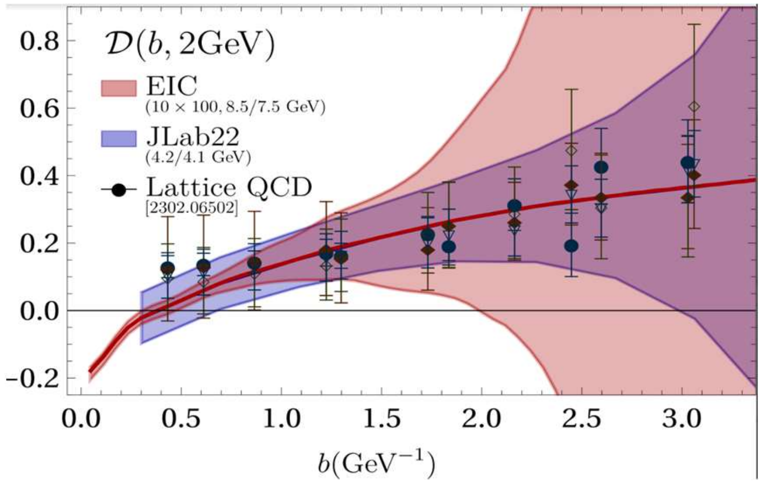




Use slices in Q^2 (good resolution needed)

- 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

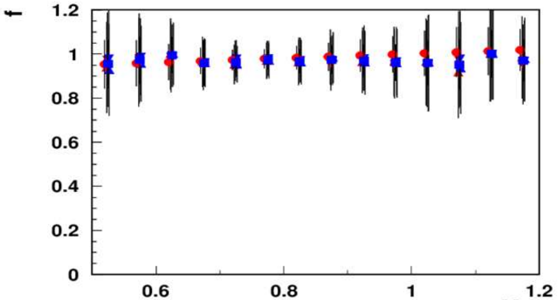
Sensitive to different ranges in b

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

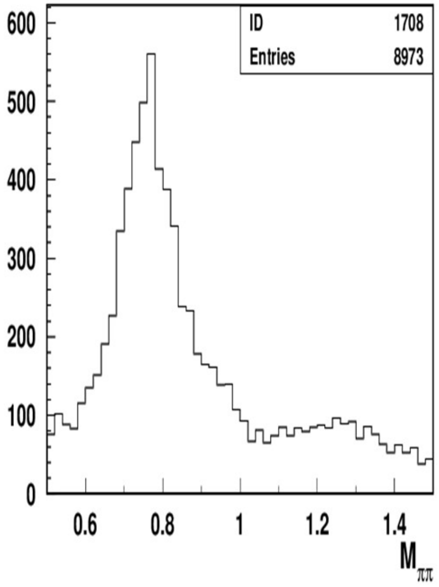
- Test the CS-kernel from different experiments, and for different kinematics in a given experiment
- Evaluate the systematics due to factorization violation and define possible reasons (some can be easy to fix)

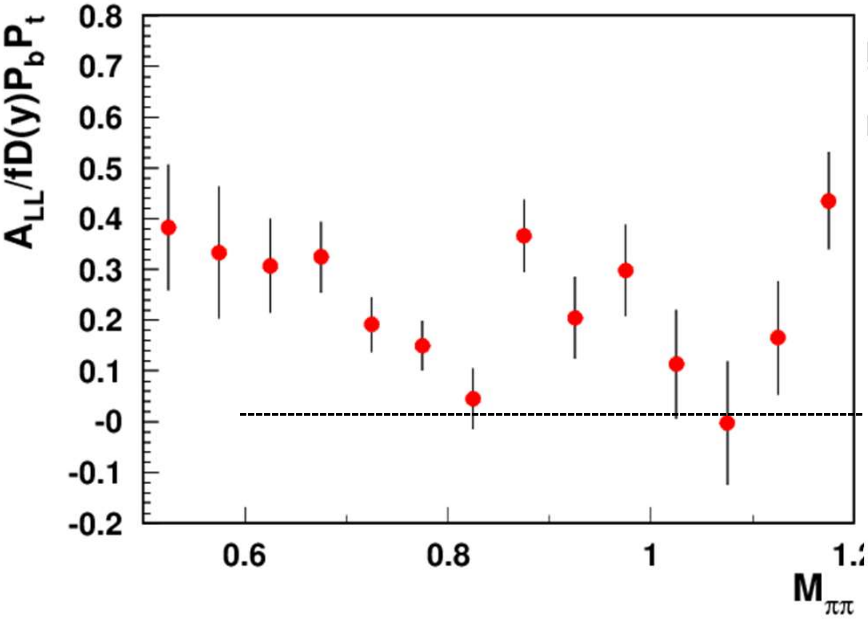
Exclusive π+π–: mass dependence of RGC A_{LL}

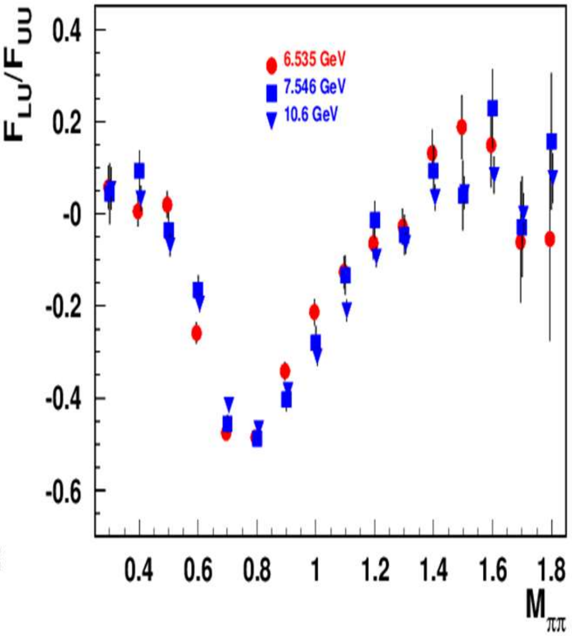
Detect 2pions and proton
use missing mass of 2pions (|M_X-0.95|<0.06)
use a cut on cone angle of pi- calculated versus measured <0.05
In the plot cut z>0.9 was use (can be relaxed to ~0.8)
Can also use M_x\pi+/->1.4 (not used by me)



carbon washed out with cuts tiny dilution.

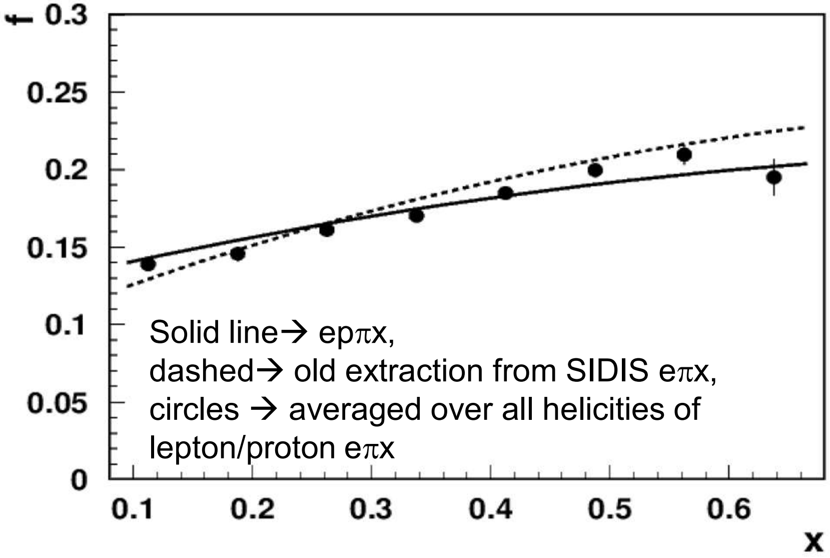




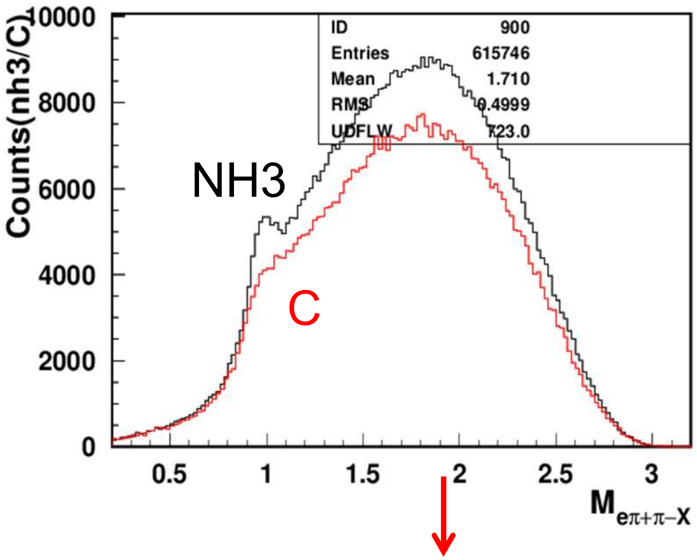


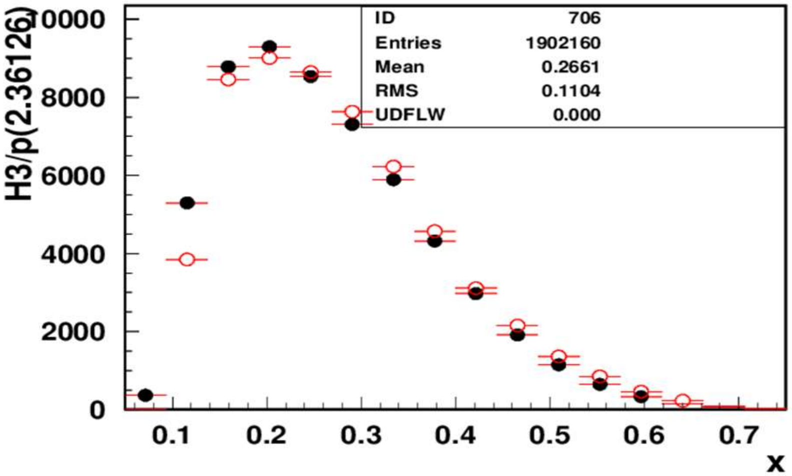
Exclusive rho0 and possibly phi have tiny (with proper subtraction of bck A_{LL} may be negative)

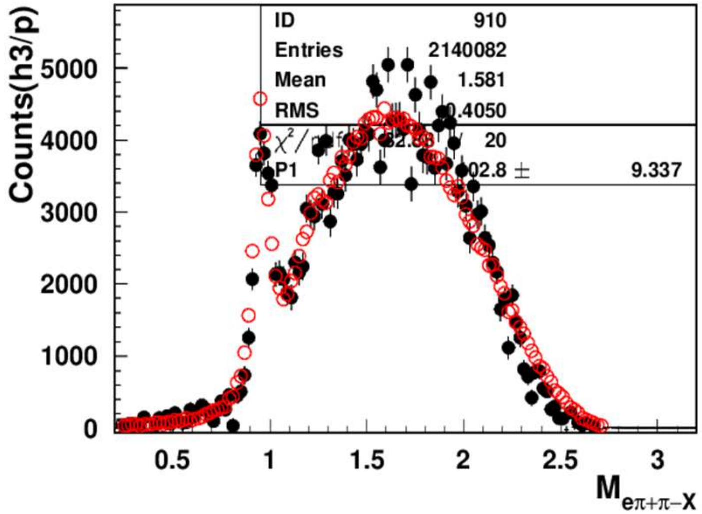
DSA from NH3: understanding dilution



Solid line→ epπx,
dashed→ old extraction from SIDIS eπx,
circles → averaged over all helicities of lepton/proton eπx







comparable with RGA(red)

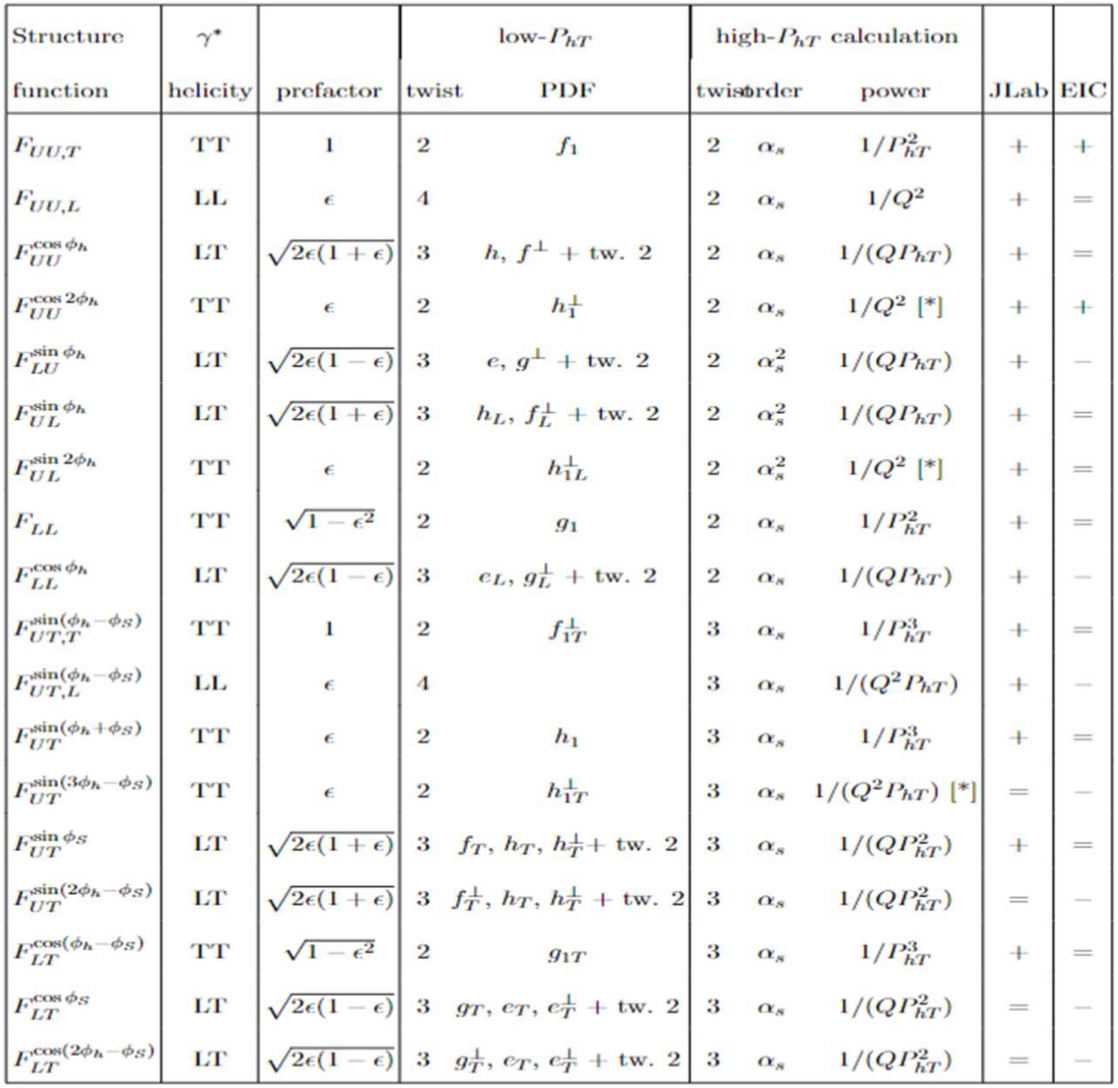
average kinematics identical in data/mc (black circles)

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

Trnaverse & Longitudinal photons



Structure	γ^*		low-P_{hT}		high-P_{hT} calculation				
function	helicity	prefactor	twist	PDF	twist	order	power	JLab	EIC
$F_{UU,T}$	TT	1	2	f_1	2	α_s	$1/P_{hT}^2$	+	+
$F_{UU,L}$	LL	ϵ	4		2	α_s	$1/Q^2$	+	=
$F_{UU}^{\cos\phi_h}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$h,\ f^\perp$ + tw. 2	2	α_s	$1/(QP_{hT})$	+	=
$F_{UU}^{\cos 2\phi_h}$	TT	ϵ	2	$h_1^\perp$	2	α_s	$1/Q^2$ [*]	+	+
$F_{LU}^{\sin\phi_h}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$e,\ g^\perp$ + tw. 2	2	α_s^2	$1/(QP_{hT})$	+	−
$F_{UL}^{\sin\phi_h}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$h_L,\ f_L^\perp$ + tw. 2	2	α_s^2	$1/(QP_{hT})$	+	=
$F_{UL}^{\sin 2\phi_h}$	TT	ϵ	2	$h_{1L}^\perp$	2	α_s^2	$1/Q^2$ [*]	+	=
F_{LL}	TT	$\sqrt{1-\epsilon^2}$	2	g_1	2	α_s	$1/P_{hT}^2$	+	=
$F_{LL}^{\cos\phi_h}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$e_L,\ g_L^\perp$ + tw. 2	2	α_s	$1/(QP_{hT})$	+	−
$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	TT	1	2	$f_{1T}^\perp$	3	α_s	$1/P_{hT}^3$	+	=
$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	LL	ϵ	4		3	α_s	$1/(Q^2P_{hT})$	+	−
$F_{UT}^{\sin(\phi_h+\phi_S)}$	TT	ϵ	2	h_1	3	α_s	$1/P_{hT}^3$	+	=
$F_{UT}^{\sin(3\phi_h-\phi_S)}$	TT	ϵ	2	$h_{1T}^\perp$	3	α_s	$1/(Q^2P_{hT})$ [*]	=	−
$F_{UT}^{\sin\phi_S}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$f_T,\ h_T,\ h_T^\perp$+ tw. 2	3	α_s	$1/(QP_{hT}^2)$	+	=
$F_{UT}^{\sin(2\phi_h-\phi_S)}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$f_T^\perp,\ h_T,\ h_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−
$F_{LT}^{\cos(\phi_h-\phi_S)}$	TT	$\sqrt{1-\epsilon^2}$	2	g_{1T}	3	α_s	$1/P_{hT}^3$	+	=
$F_{LT}^{\cos\phi_S}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$g_T,\ e_T,\ e_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−
$F_{LT}^{\cos(2\phi_h-\phi_S)}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$g_T^\perp,\ e_T,\ e_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−

Very few pure transverse

Impact of Radiative corrections

Proper RC involves the full x-section

$$\sigma_{Rad}^{ehX}(x,y,z,P_T,\phi,\phi_S) \rightarrow \sigma_0^{ehX}(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

Simplest rad. correction

$$R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$$

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

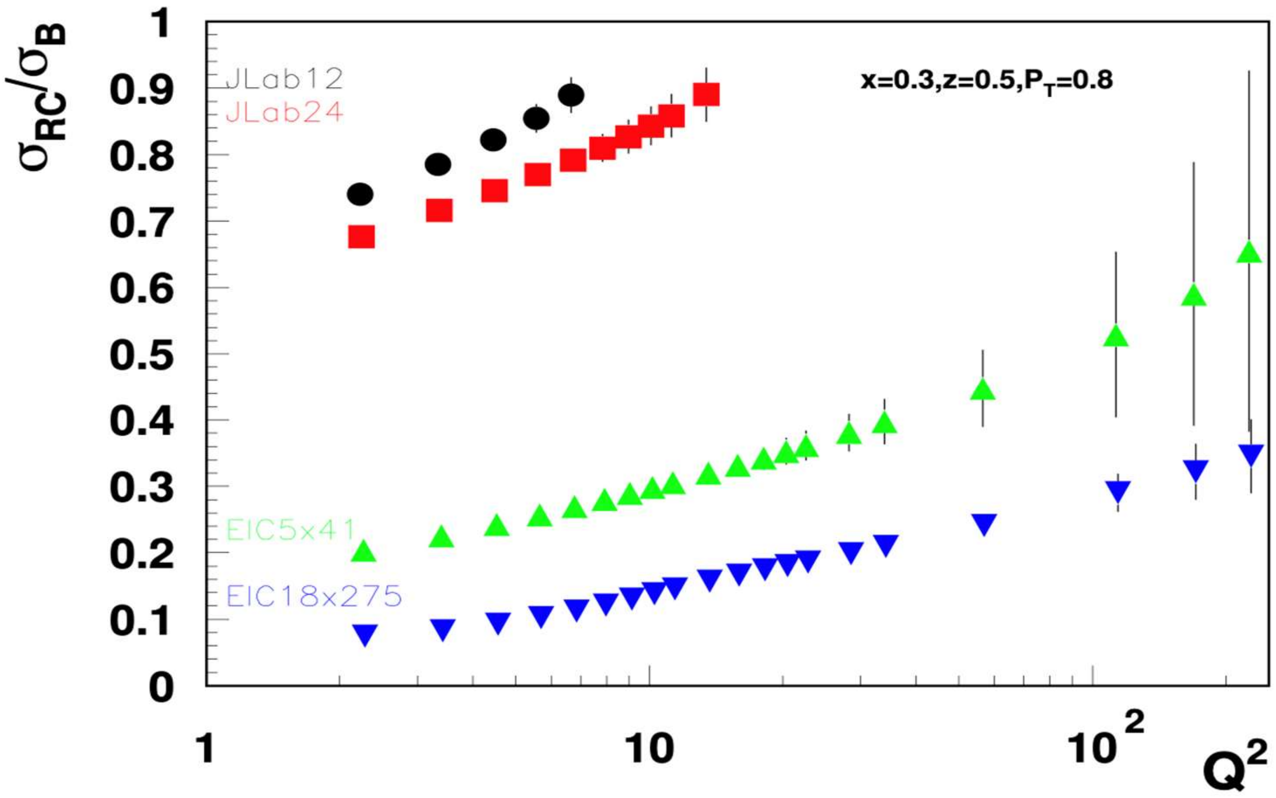
- L/T interference
- Not suppressed at high energies
- Measured to be huge in exclusive limit ~100%
- May couple to radiative cos\phi producing bck SSAs

Ex. Correction to SSA

$$\sigma_0(1 + sS_T\sin\phi_S)R_0(1 + r\cos\phi_h) \rightarrow \sigma_0 R_0(1 + sr/2S_T\sin(\phi_h - \phi_S) + sr/2S_T\sin(\phi_h + \phi_S))$$

From JLab to EIC: complementarity

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



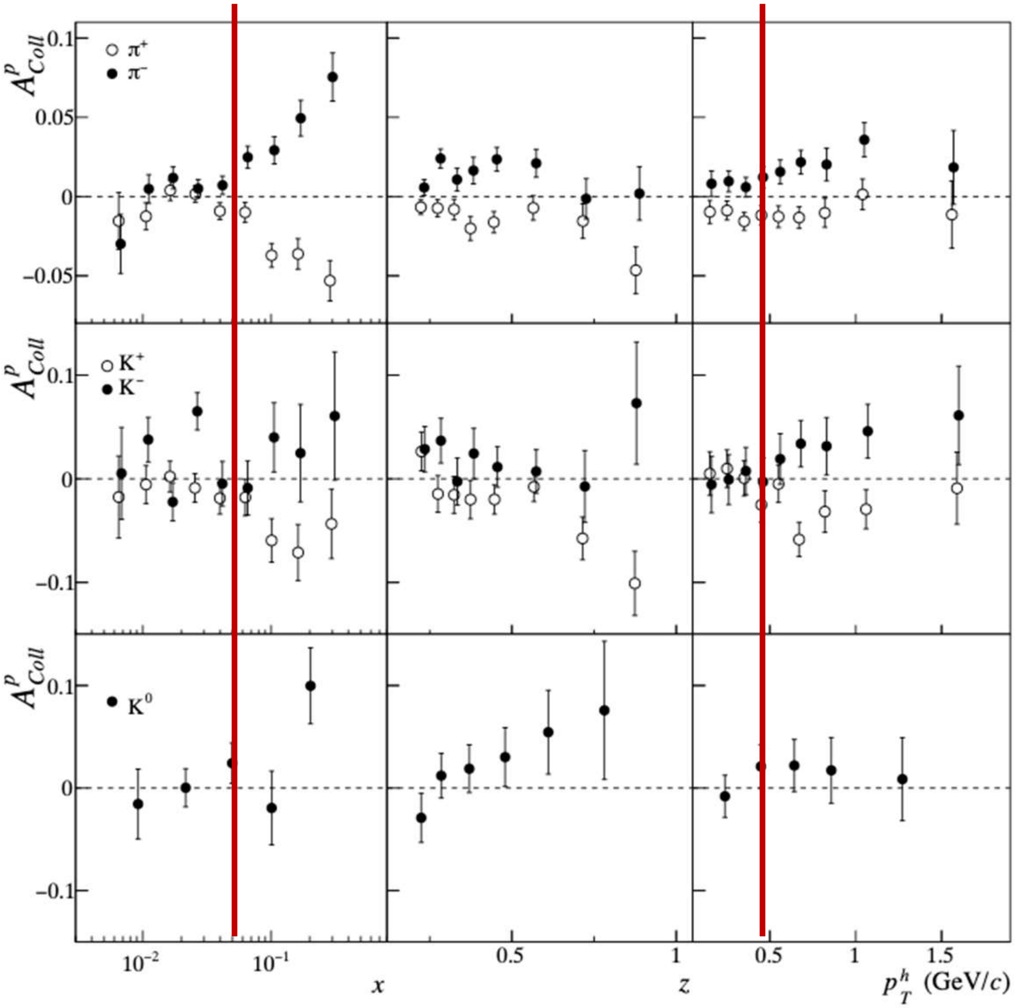
T. Liu et al
JHEP 11 (2021) 157
Gaussian F_{UU} (ϕ_h=0)

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

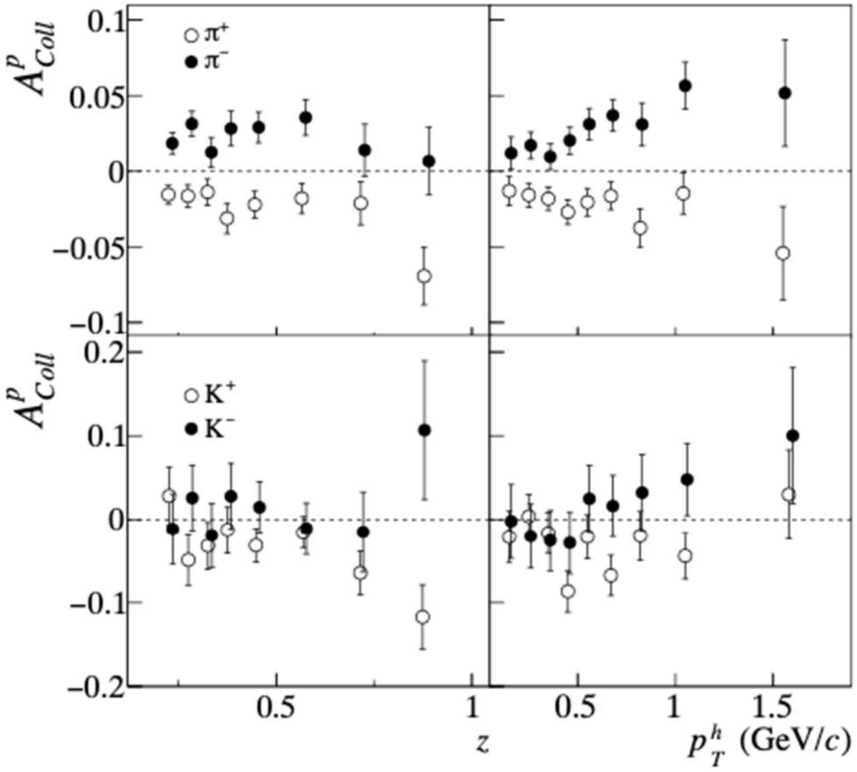
- The radiative effects in SIDIS may be very significant and measurements in multidimensional space at different facilities will be crucial for understanding the systematics in evolution studies.
- Most sensitive to RC will be all kind of azimuthal modulations sensitive to cosines

COMPASS transversity

https://arxiv.org/pdf/1408.4405.pdf



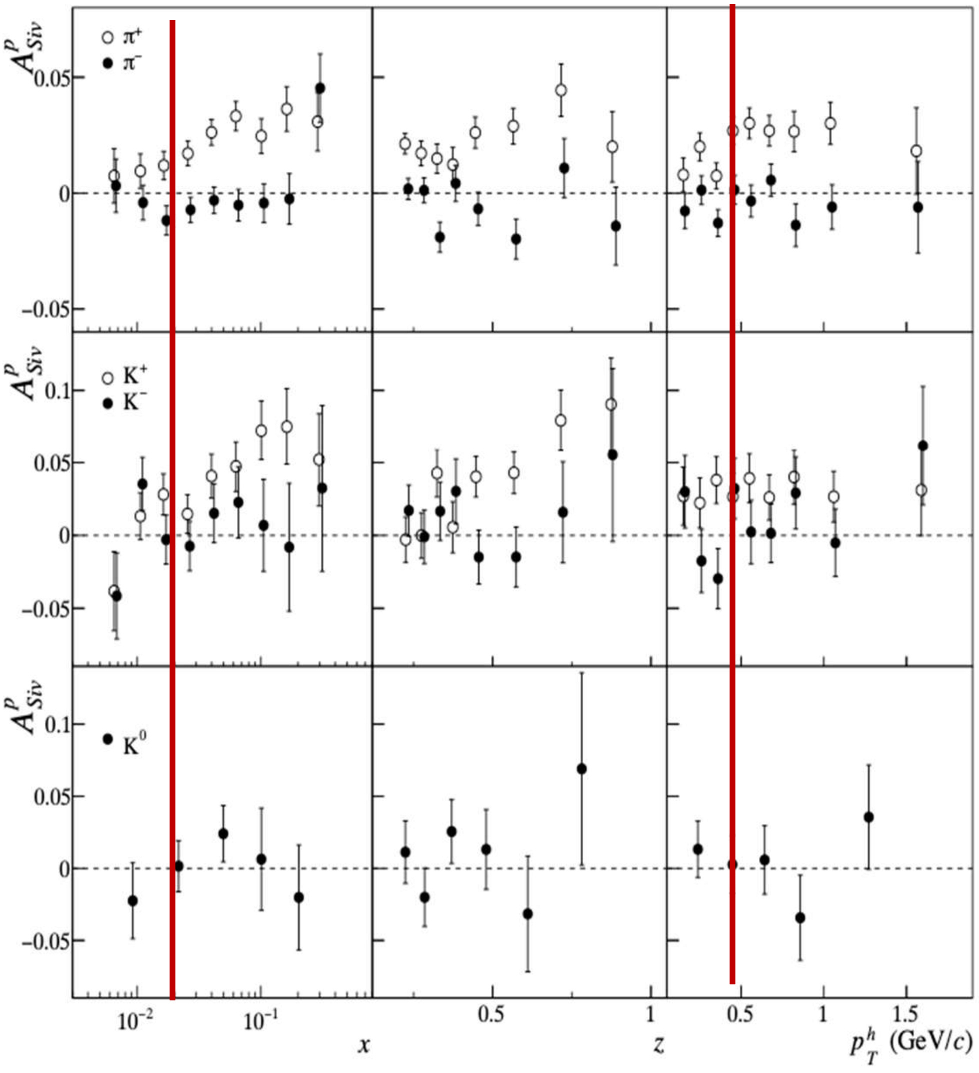
x>0.03



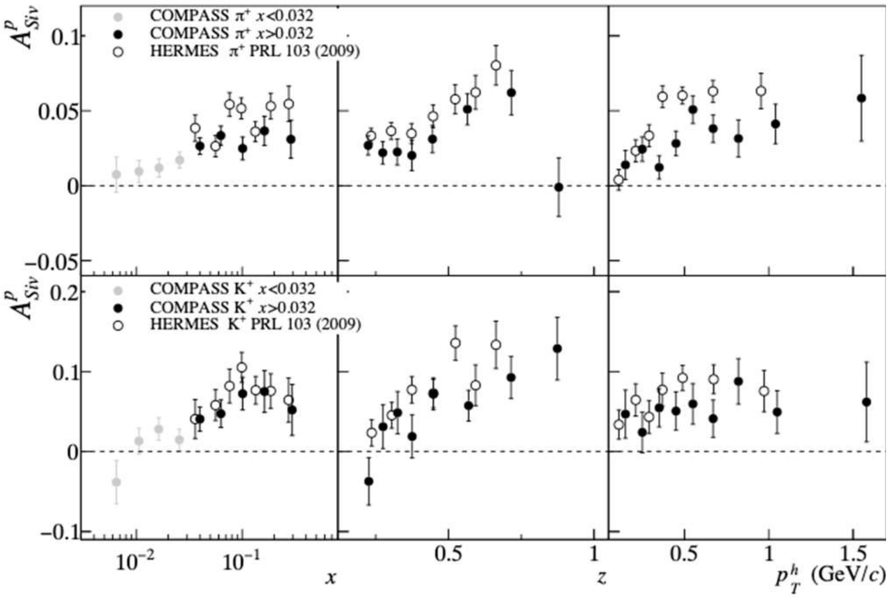
No significant effects for x<0.05, and P_T<0.5

COMPASS Sivers

https://arxiv.org/pdf/1408.4405.pdf

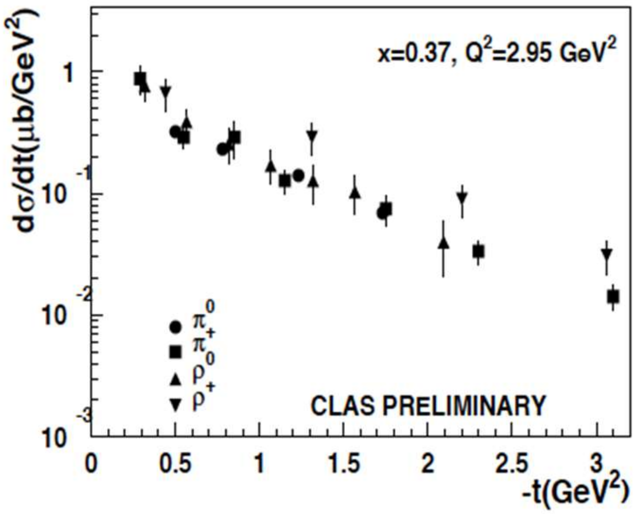


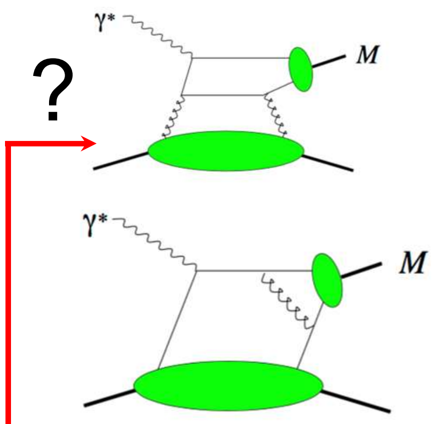
x>0.03

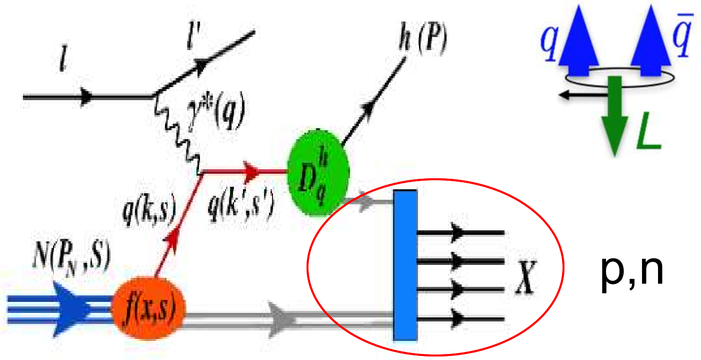


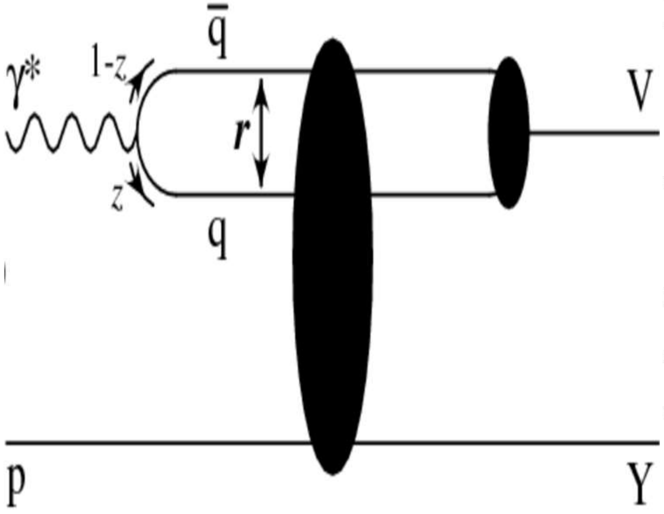
No significant effects for x<0.05, and P_T<0.5

Exclusive π/ρ production at large x/t







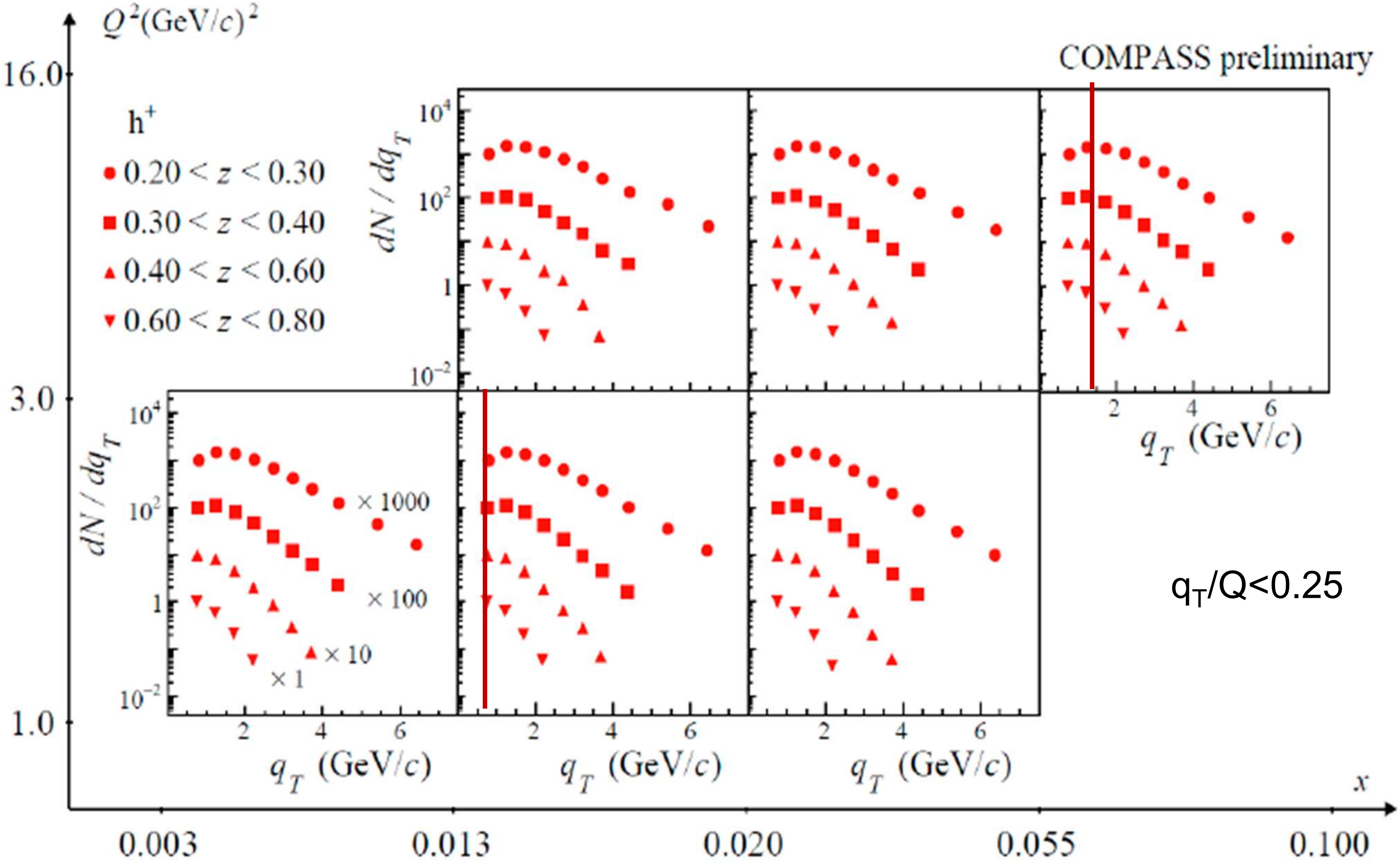


Implications

x-section of measured exclusive process at large t exhibit similar pattern

- ρ+>ρ^0 →Diffractive production suppressed at large t production mechanism most likely is similar to SIDIS
- Slightly higher rho x-sections indicate the fraction of SIDIS pions from VM > 60%
- consistent with LUND-MC in fraction of pions from VMs
- Integrating in total counts (different Q^2-dependence)?
- ………

COMPASS vs q_T-cuts

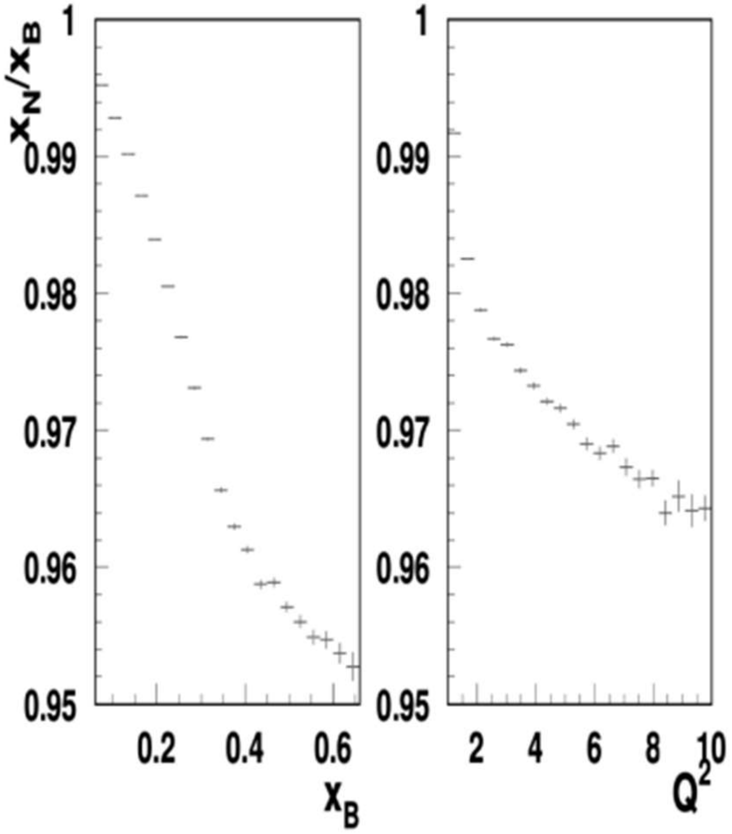


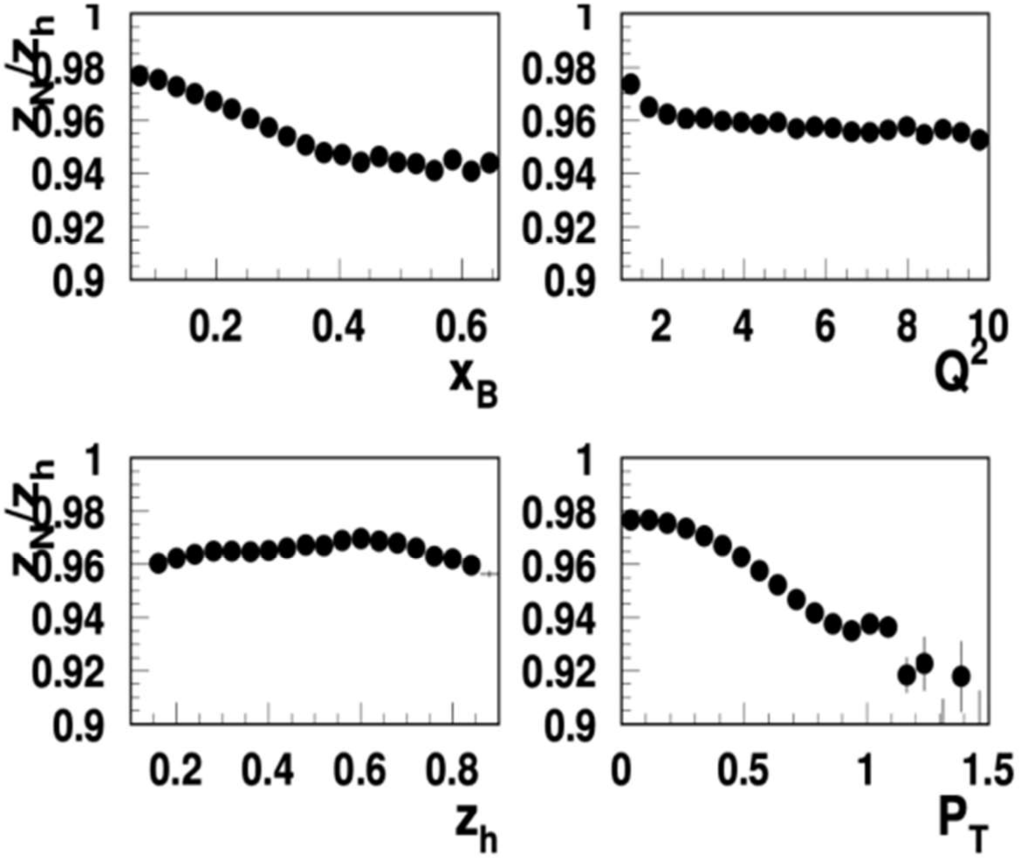
$q_T/Q<0.25$

CLAS12: Mass corrections to x_B and z_h

$$x_{\mathrm{N}} = -\frac{q^+}{P+} = \frac{2x_{\mathrm{Bj}}}{1+\sqrt{1+\frac{4x_{\mathrm{Bj}}^2 M^2}{Q^2}}}$$

$$z_{\mathrm{N}} = \frac{Q^4 x_{\mathrm{N}} z_{\mathrm{h}} \left(1 \pm \sqrt{1 - \frac{4M^2 M_{\mathrm{B}}^2 x_{\mathrm{Bj}}^2 (Q^4 + x_{\mathrm{N}}^2 M^2 \mathbf{q}_{\mathrm{T}}^2)}{Q^8 z_{\mathrm{h}}^2}}\right)}{2x_{\mathrm{Bj}}(Q^4 + x_{\mathrm{N}}^2 M^2 \mathbf{q}_{\mathrm{T}}^2)}$$





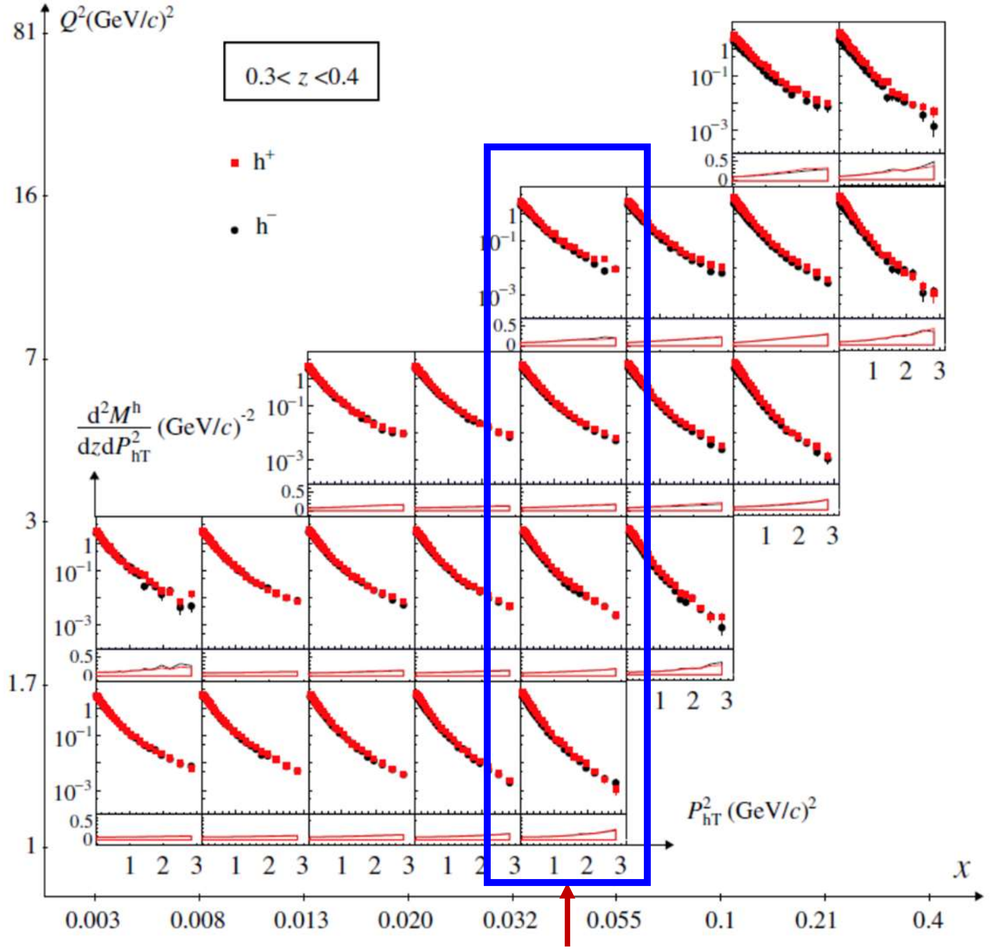
q_T-crisis or misinterpretation

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

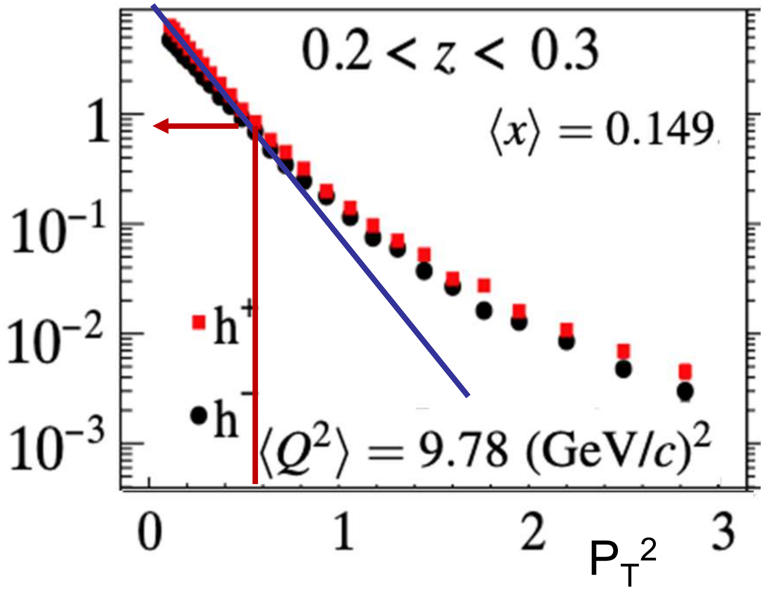
3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P_T samples , including ones from HERMES COMPASS, and even EIC.



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

Theory unable to explain the correlation of P_T and Q

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



SFs up to twist 3

For SIDIS we have the full set of contributions from twist-2 and twist-3 including (Twist-2TMD x Twist-3FF) and (Twist-3TMD x Twist-2 FF)

ex.

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h}h_1^{\perp}H_1^{\perp}\right],$$

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp}+\frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1+\frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Twist-3 TMD

Most likely dominant in SSA

Higher Twist TMDs

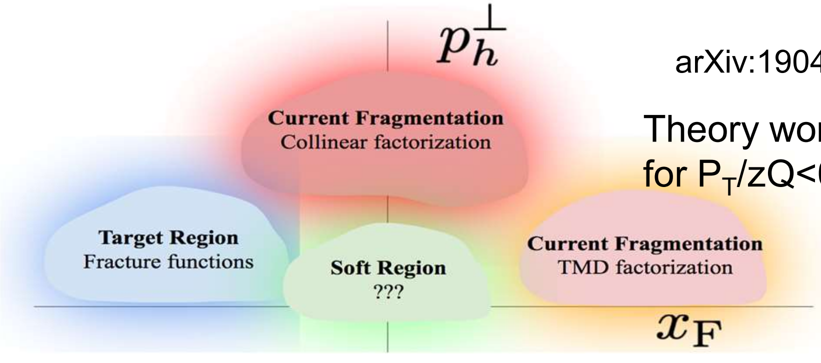
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, $\mathbf{e}$
L	$f_L^{\perp}$	$g_L^{\perp}$	$\mathbf{h_L}$, e_L
T	f_T, $f_T^{\perp}$	$\mathbf{g_T}$, $g_T^{\perp}$	h_T, e_T, $h_T^{\perp}$, $e_T^{\perp}$

Twist3 GPDs (also calculated on lattice)

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

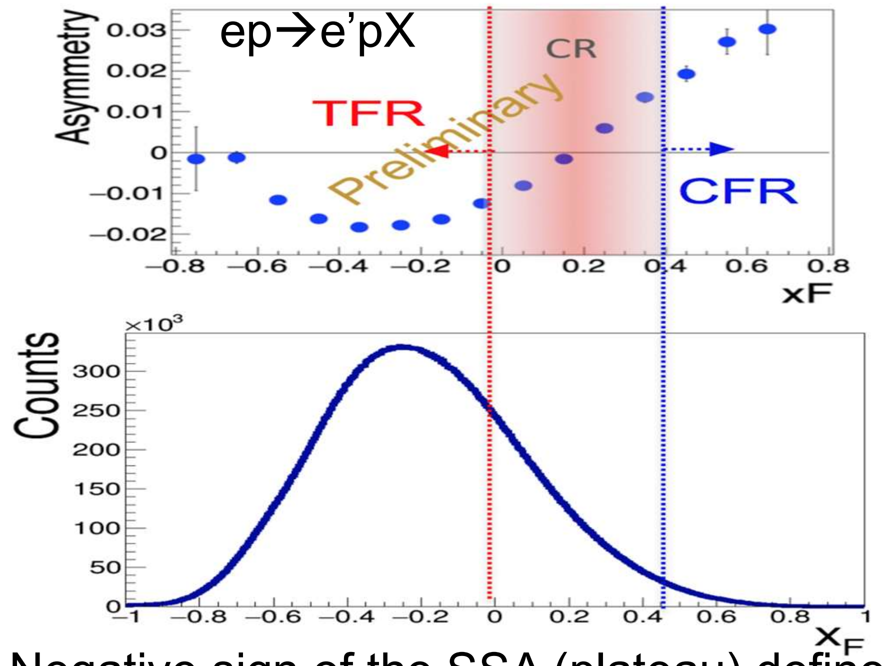
Request to theory to provide similar contributions for the exclusive hadron production. So far only Twist-3 contributions from Twist-2 GPDs (Kroll&Goloskokov,…)

Beam SSAs: Separating kinematic regions



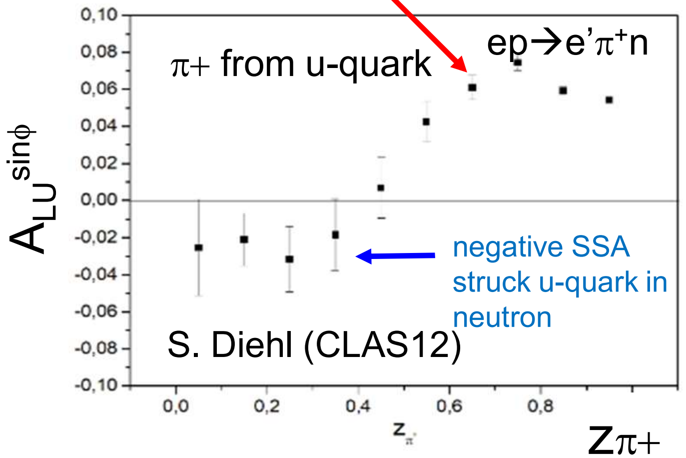
arXiv:1904.12882

Theory works well for $P_T/zQ<0.25$



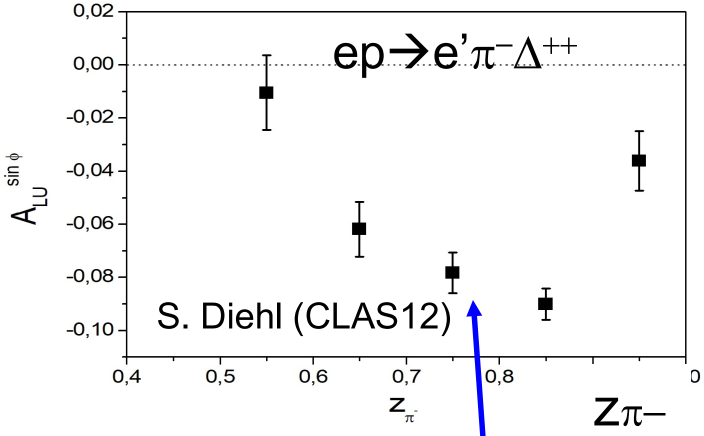
Negative sign of the SSA (plateau) defines the TFR dominance (use to separate!!!)

Polarized u-quark, dominates
→ SSA positive



negative SSA struck u-quark in neutron

S. Diehl (CLAS12)



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)

TMDs in Semi-Inclusive DIS

TMD Parton Distribution Functions

TMD Parto Fragmentation Functions

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

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

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

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

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

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

Impact of Radiative corrections

Proper RC involves the full x-section

$$\sigma_{Rad}^{ehX}(x,y,z,P_T,\phi,\phi_S) \to \sigma_0^{ehX}(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

Simplest rad. correction

$$R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$$

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

- L/T interference
- Not suppressed at high energies
- Measured to be huge in exclusive limit ~100%
- May couple to radiative cos\phi producing bck SSAs

Ex. Correction to SSA

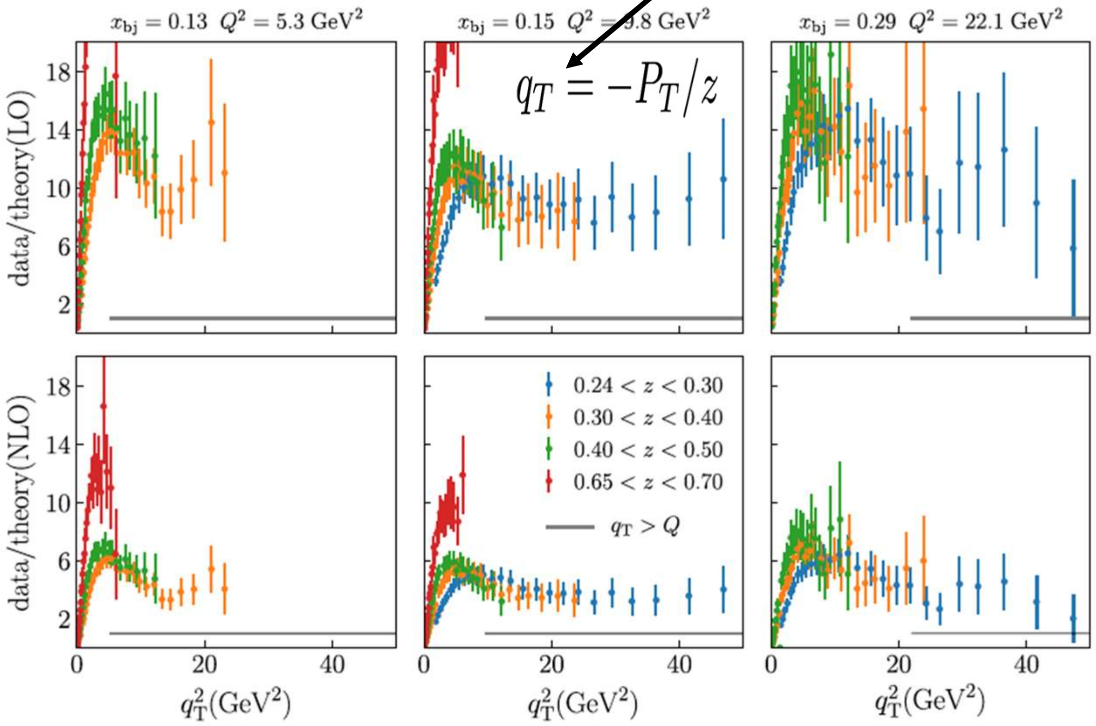
$$\sigma_0(1 + sS_T\sin\phi_S)R_0(1 + r\cos\phi_h) \to \sigma_0 R_0(1 + sr/2S_T\sin(\phi_h - \phi_S) + sr/2S_T\sin(\phi_h + \phi_S))$$

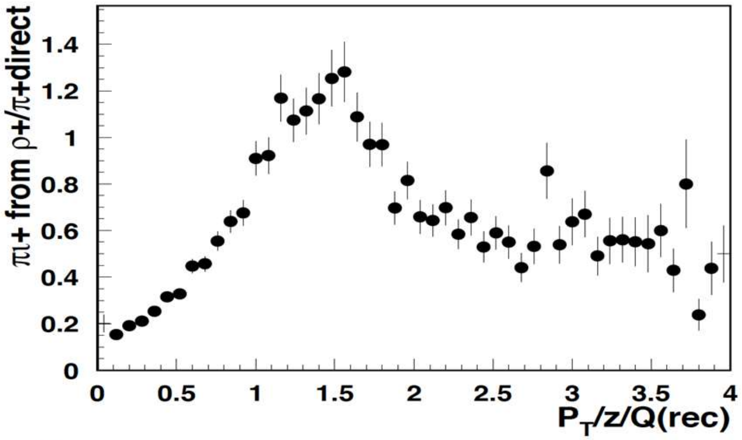
Does it matter if the pion comes from correlated pairs?

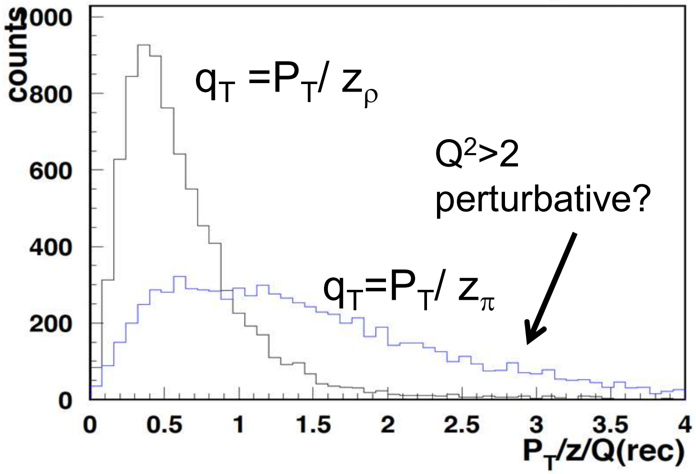
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

quark transverse momentum







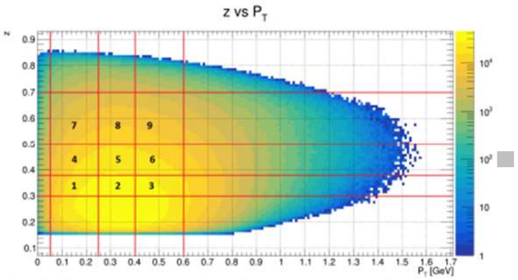
$Q^2>2$
perturbative?

The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

Gonzalez-Hernandez et al, PRD 98, 114005 (2018)

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

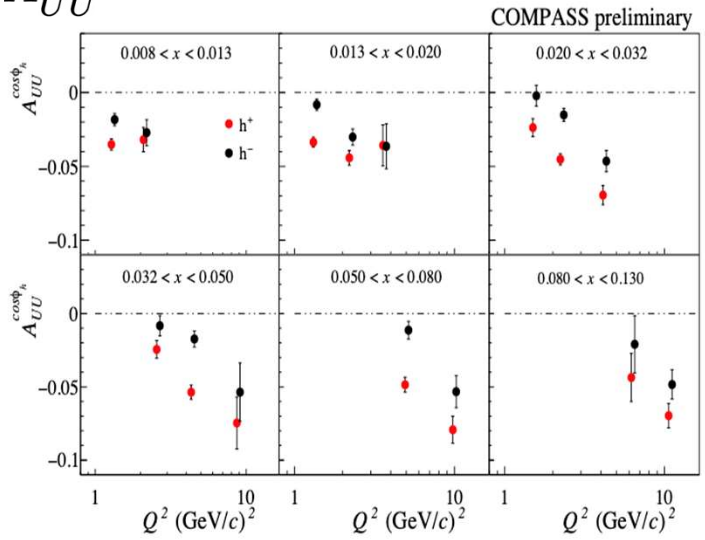
Attempts to understand Q^2-dependence of HT



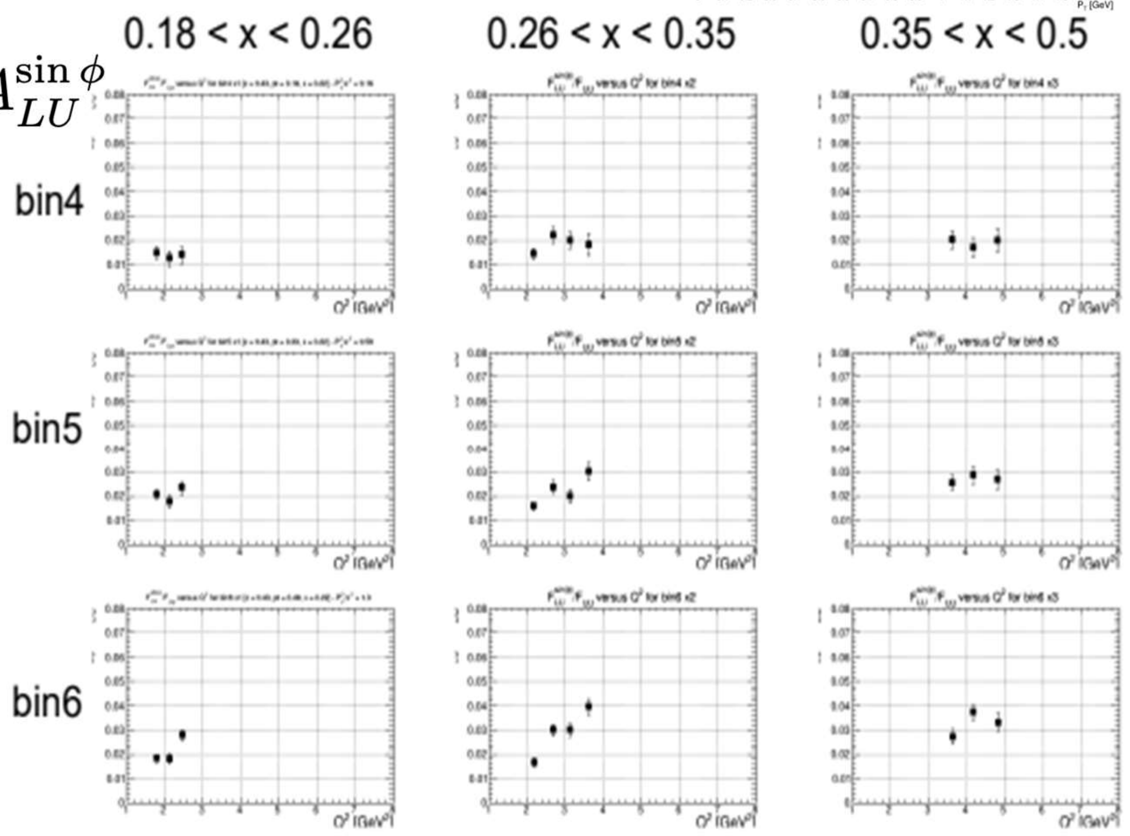
CLAS12(preliminary)

$\sqrt{2\,\varepsilon(1+\varepsilon)}$ $\rightarrow$ $A_{UU}^{\cos\phi}$

COMPASS



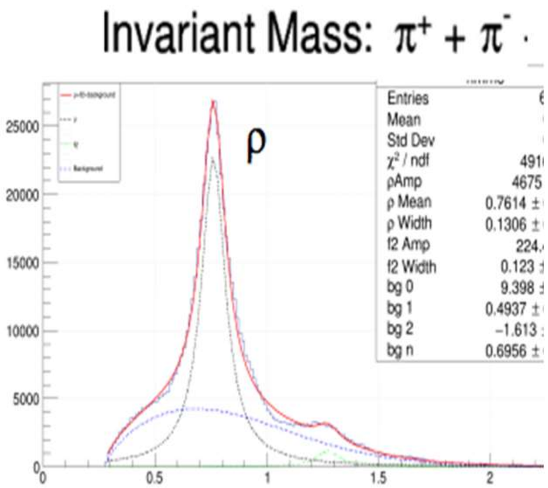
$\sqrt{2\,\varepsilon(1-\varepsilon)}$ $\rightarrow$ $A_{LU}^{\sin\phi}$

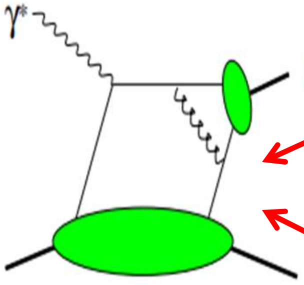


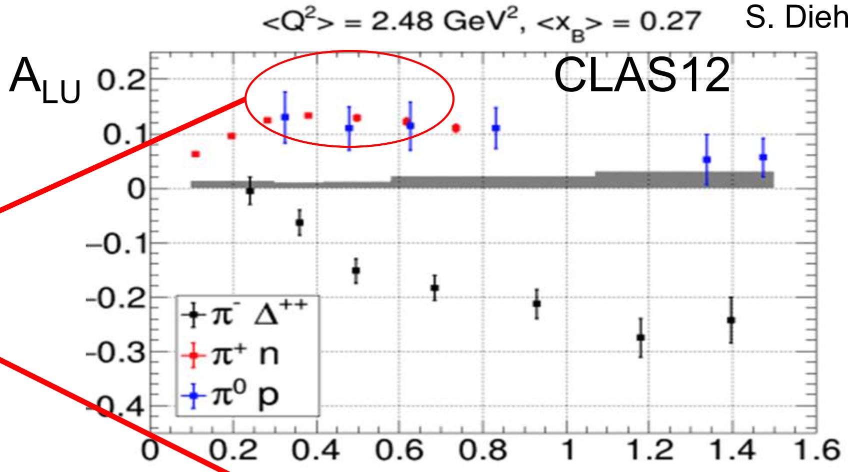
- We always measure ratio to $F_{UU,T}+\varepsilon F_{UU,L}$

- 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

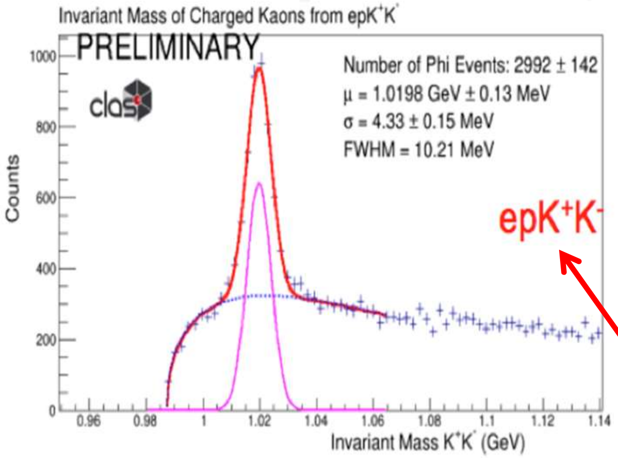
Current hadrons: exclusive limit

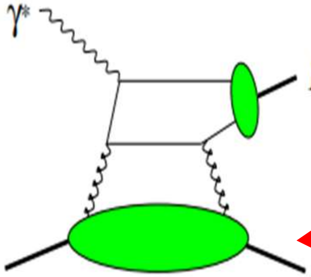




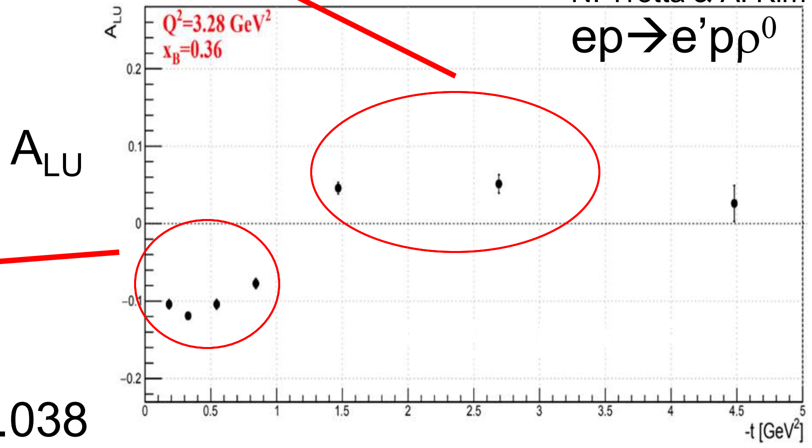


S. Diehl





N. Trotta & A. Kim



A_{LU}=-0.084+/-0.038

SSA negative→ΔG negative?

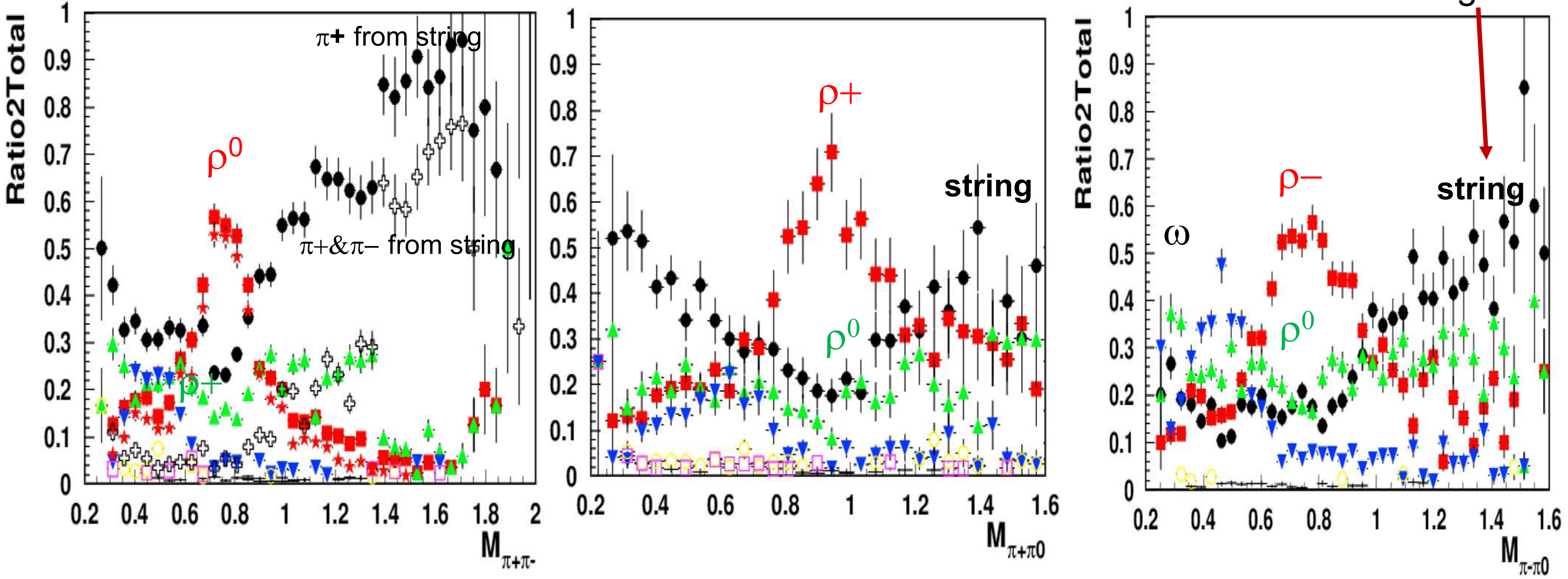
-t(GeV²)

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

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

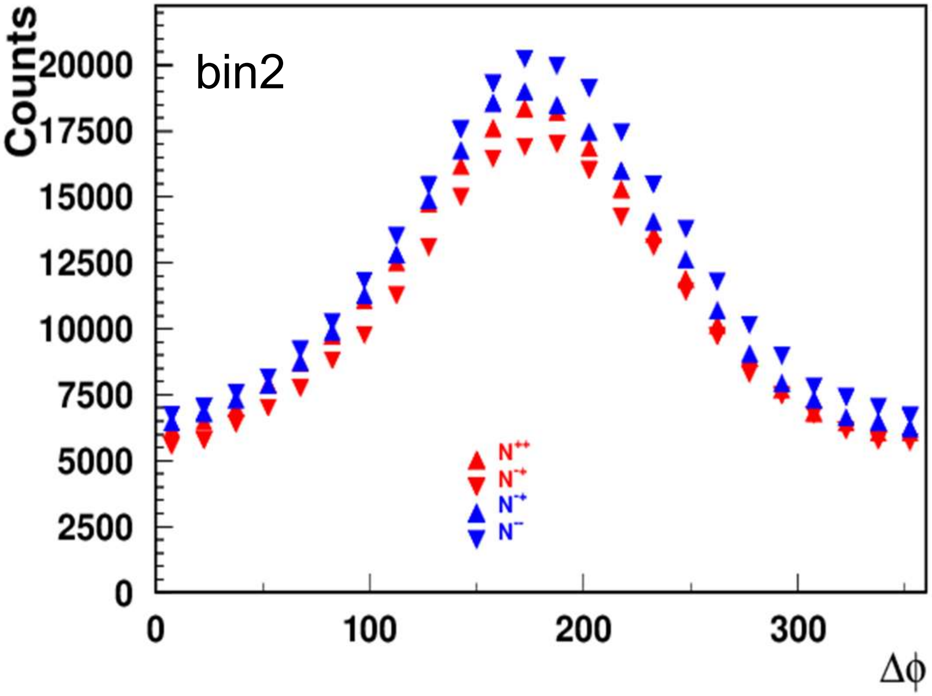
— ρ

— string

— ω

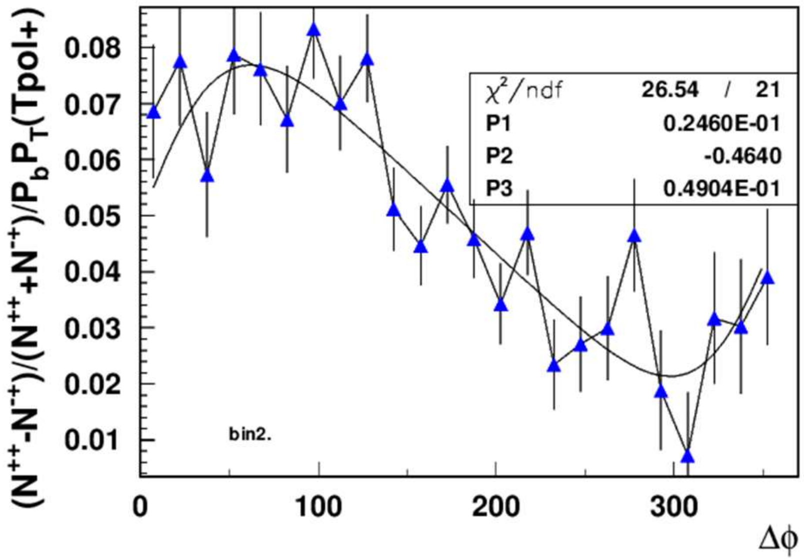
All measured 2 pion combinations are dominated by VM decays, indicate that all inclusive pions are dominated by VM decays at small P_Ts, and in particular at lower z!!!

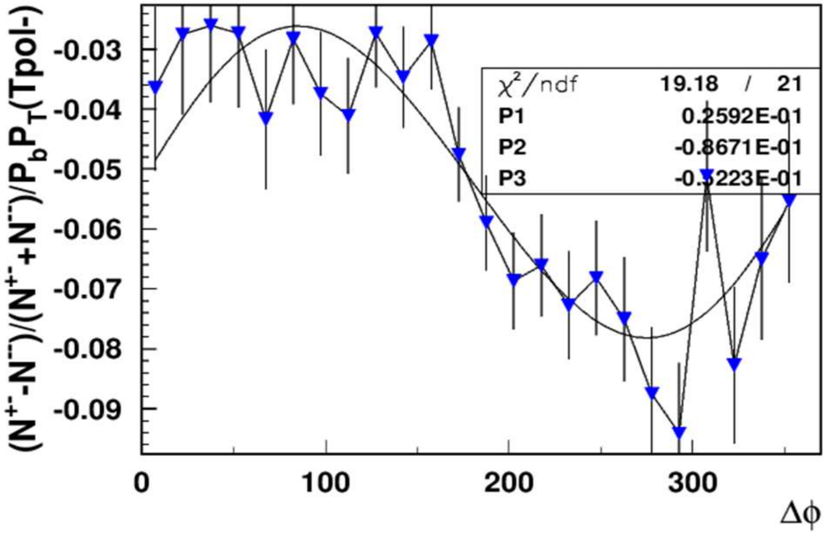
b2b protons and pions



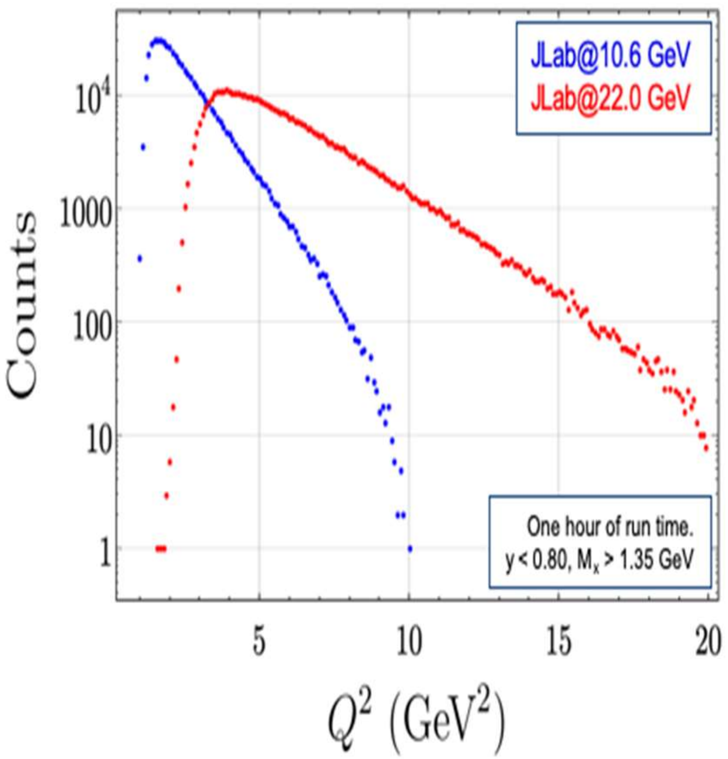
ep->e'pπ+X Counts and asymmetries

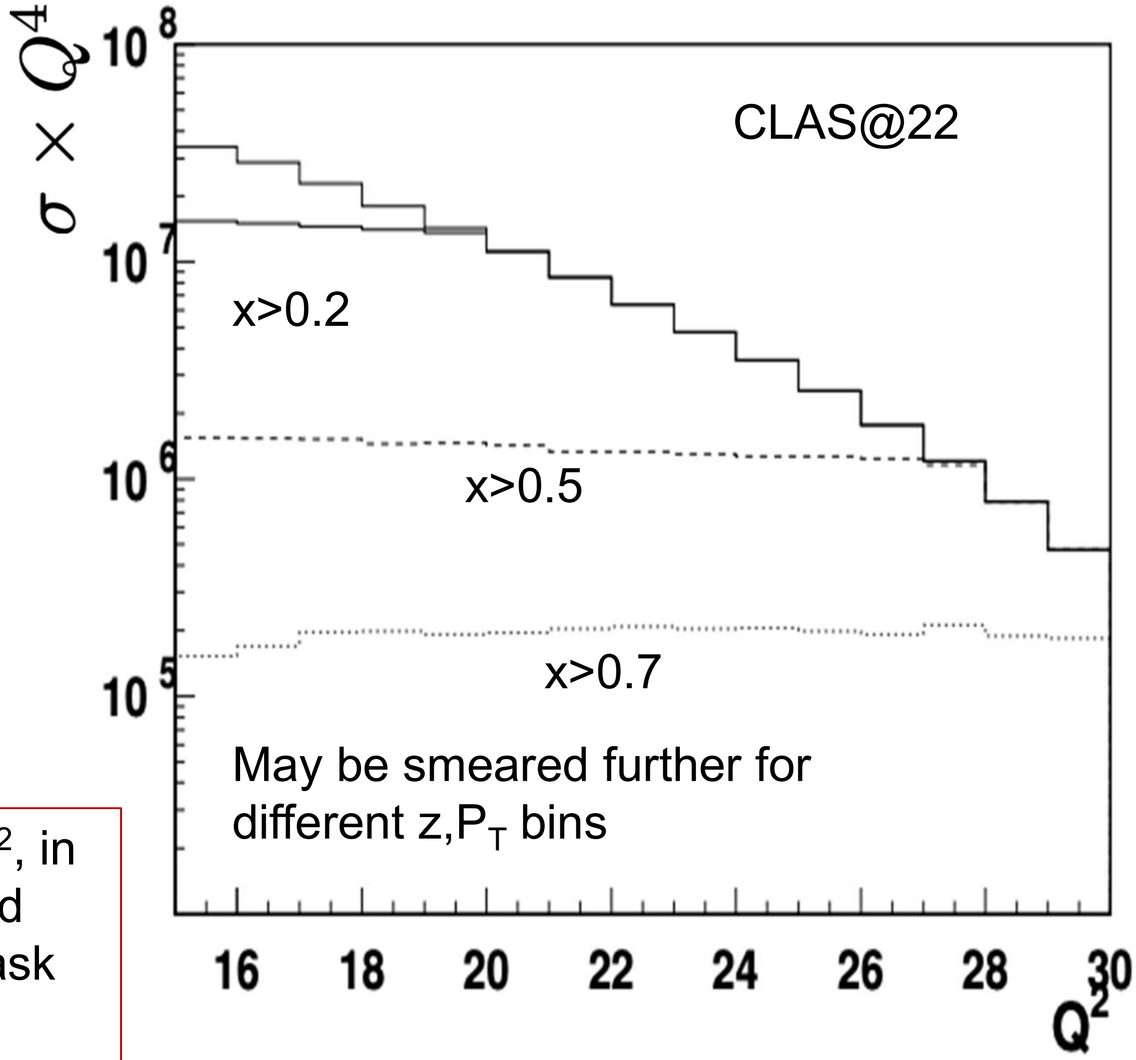
Constant term corresponds to A_{LL}





Finite energy: Kinematic limitations



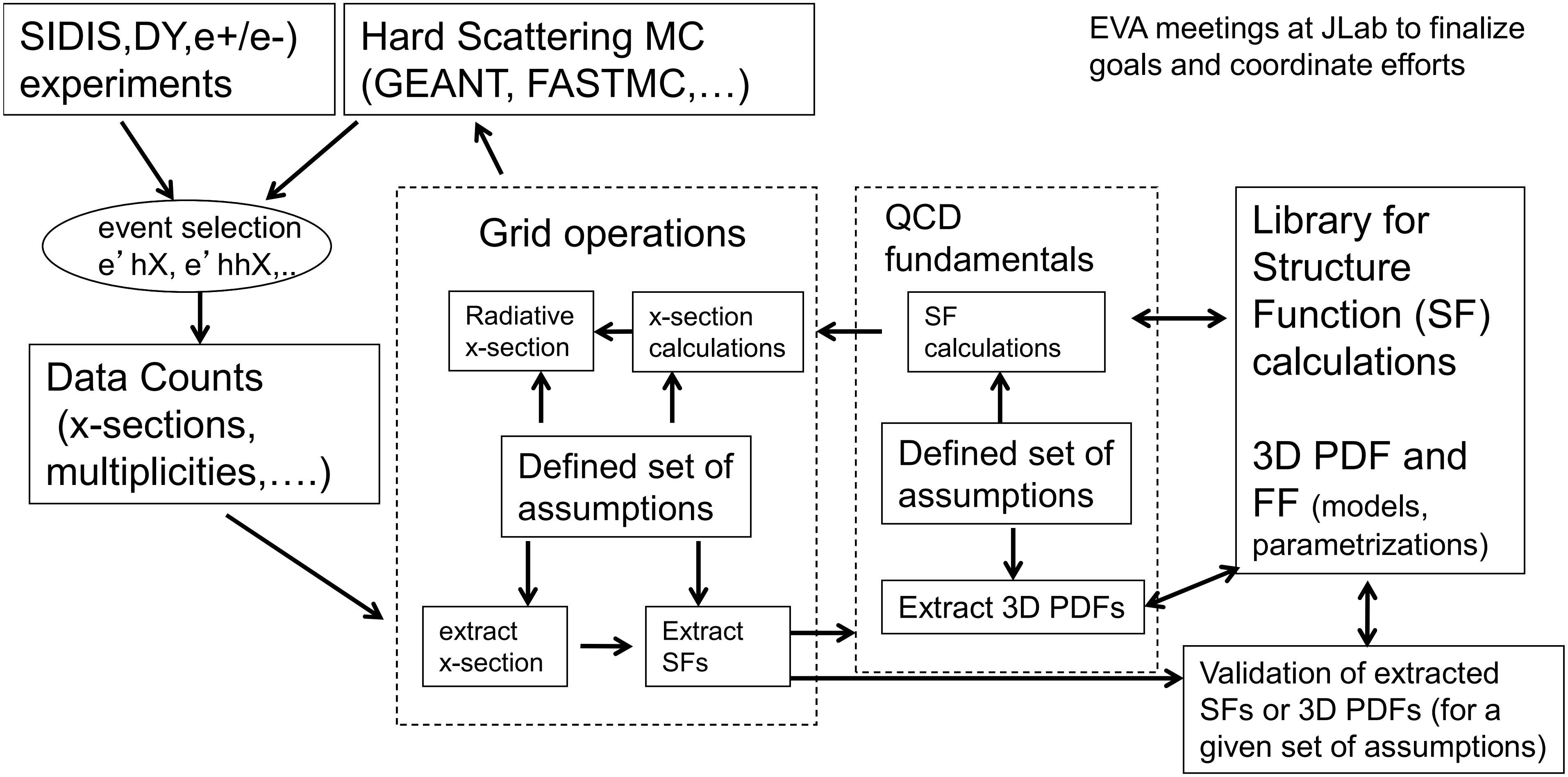


May be smeared further for different z,P_T bins

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

3D PDF Extraction and VAlidation (EVA) framework



SIDIS,DY,e+/e-) experiments

Hard Scattering MC (GEANT, FASTMC,…)

EVA meetings at JLab to finalize goals and coordinate efforts

event selection e’ hX, e’ hhX,..

Data Counts (x-sections, multiplicities,….)

Grid operations

Radiative x-section

x-section calculations

Defined set of assumptions

extract x-section

Extract SFs

QCD fundamentals

SF calculations

Defined set of assumptions

Extract 3D PDFs

Library for Structure Function (SF) calculations

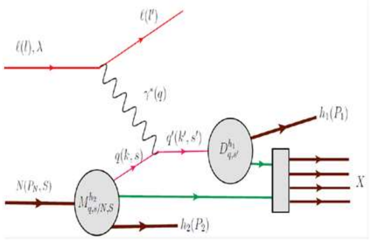
3D PDF and FF (models, parametrizations)

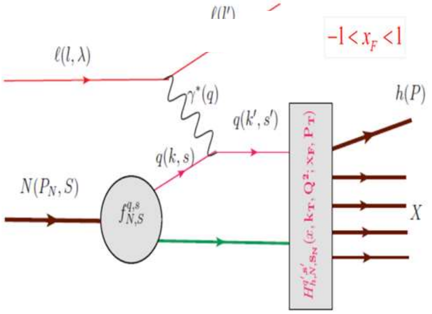
Validation of extracted SFs or 3D PDFs (for a given set of assumptions)

Development of a reliable techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing

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.

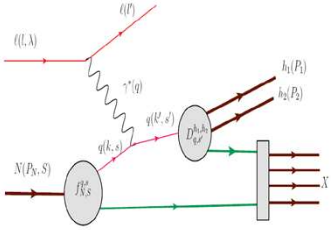


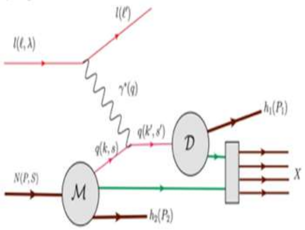


So why the LUND-MCs are so successful in description of hard scattering processes, and SIDIS in the first place?

•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

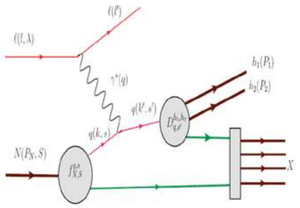




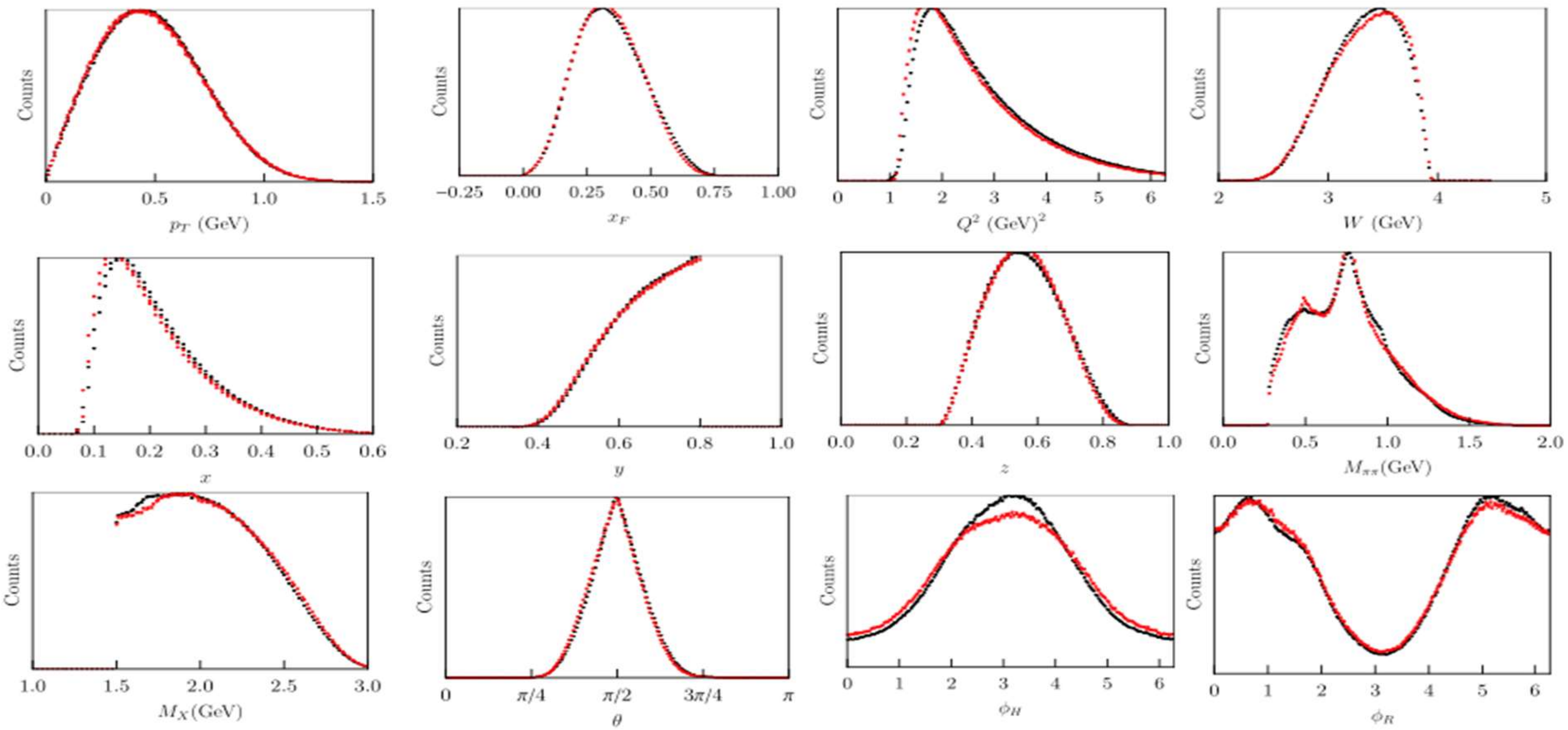
To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

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

SIDIS ehhX: CLAS12 data vs MC



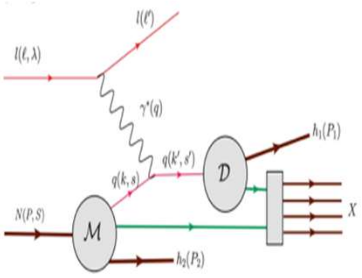
CLAS12 dihadron production ep→ehhX

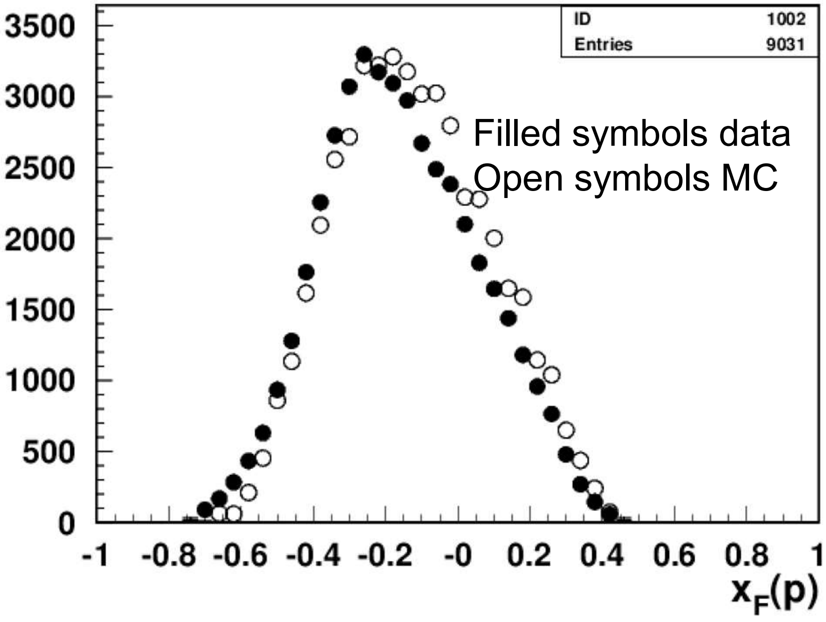


CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters "default" is in a good agreement with CLAS12 measurements for all relevant distributions

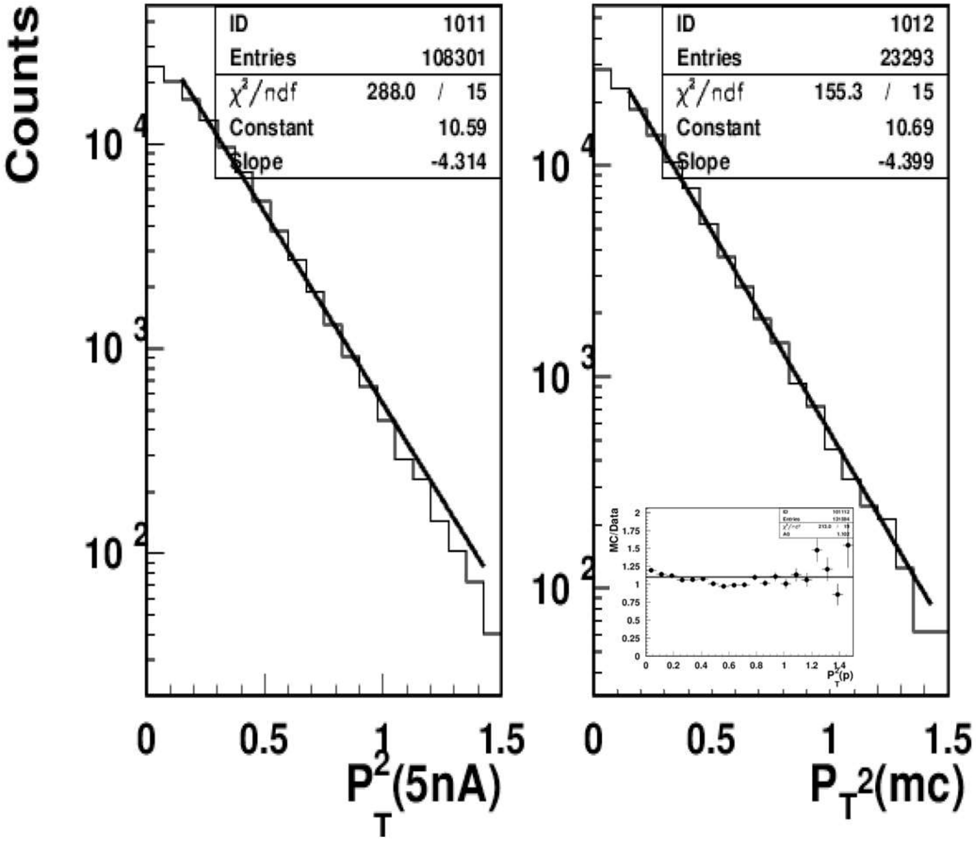
CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator



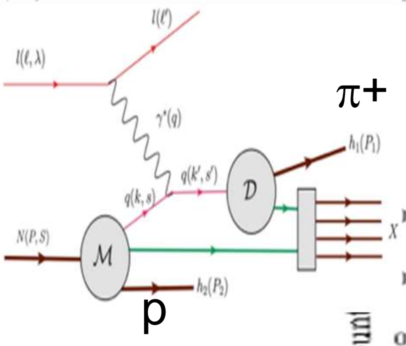


Filled symbols data
Open symbols MC



- 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

SIDIS ehhX: CLAS12 data vs MC



CLAS12 dihadron production ep→ephX (CFR/TFR)

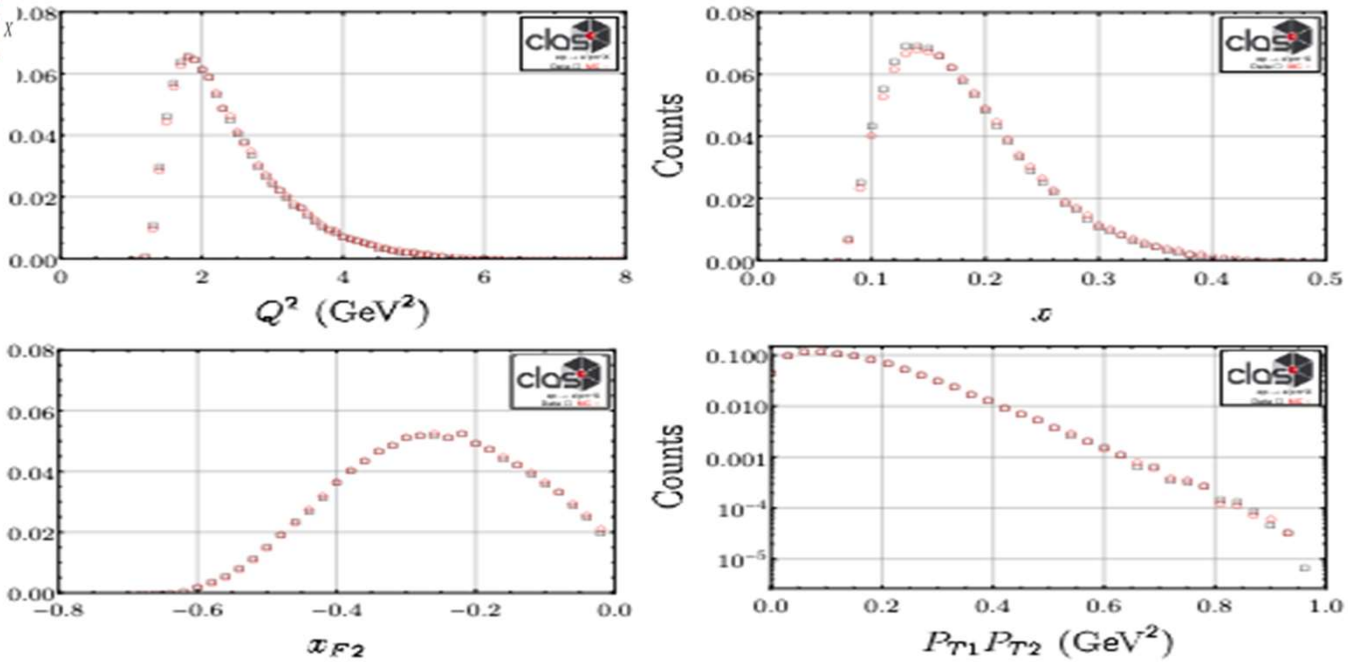
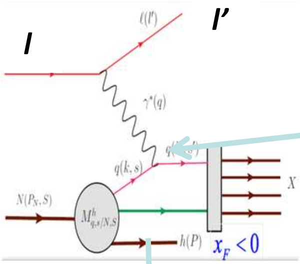


FIG. 12: Comparison between data (black squares) and Monte Carlo (red circles) for Q^2 (top left), x (top right), x_{F2} (bottom left) and $P_{T1}P_{T2}$ (bottom right, log scale). Counts are normalized to the total number of dihadron pairs. Excellent agreement is observed.

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

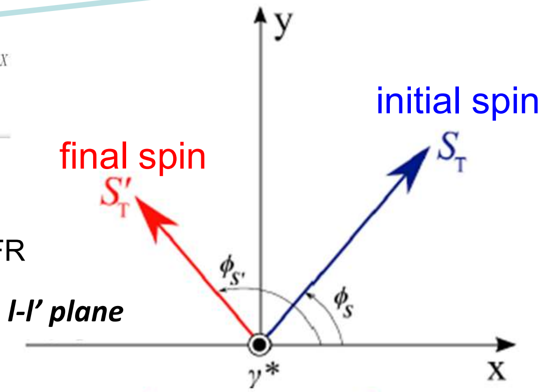
Hadron production in TFR

X. Tong (ECT* 2022)



opposite modulations in CFR and TFR

main difference between CFR and TFR
→ scattering



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

$$F_{UU}^{\cos(\phi_h)} = -2\sum_a e_a^2\, x_B^2 \frac{|k_\perp|}{Q} u(x_B,\xi,k_\perp),$$

$$F_{LU}^{\sin(\phi_h)} = 2\sum_a e_a^2\, x_B^2 \frac{|k_\perp|}{Q} l(x_B,\xi,k_\perp)$$

$$F_{LL}^{\cos(\phi_h)} = -2\sum_a e_a^2\, x_B^2 \frac{|k_\perp|}{Q} l_L(x_B,\xi,k_\perp)$$

$$F_{UL}^{\sin(\phi_h)} = -2\sum_a e_a^2\, x_B^2 \frac{|k_\perp|}{Q} u_L(x_B,\xi,k_\perp)$$

Collins SSAs, sin(ϕ+ϕ_S),sin2ϕ

spin-flip causing Collins contributions in CFR

Target fragmentation provides complementary information on proton structure and is simpler in interpretation (no Collins effect, both in leading and *subleading* contributions)

4 contributions for each in CFR!!!

- Two with unpolarized target; Two with longitudinally polarized target;