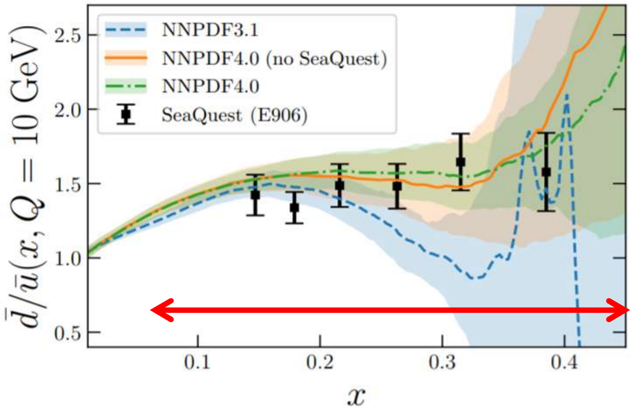
Summary: transverse momenta of hadrons

Conveners: Harut Avakian, Nobuo Sato

Frascati, Dec 13, 2024

- Main goals: relevant kinematics and observables
- What is SIDIS2.0?
  - Understanding hadronic correlations from ep→e'πX to ep→e'ππX and ep→e'pπX
  - Understanding "diffractive" contributions and impact on phenomenology
- Summary

Understanding the QCD: from observables to QCD dynamics



Moving from testing QCD to understanding it
→ Detailed studies of non-perturbative QCD dynamics in 3D space through measurements of multiplicities, and spin-azimuthal modulations

JLAB uniqueness:

- *Superior luminosity of CEBAF*
- *High resolutions of detectors*
- *Ability for multidimensional and multiparticle detection in the kinematics where non-perturbative effects are significant*

Note: eptoproduction, in simplest case of a single hadron detected in the final state, is a measurement of observables in 5D space (x,Q^2,z,P_T,ϕ), 6D for transverse target, $+\phi_S$

  - Collinear SIDIS (last 50 years), is just the proper integration of observables, over P_T,ϕ,ϕ_S

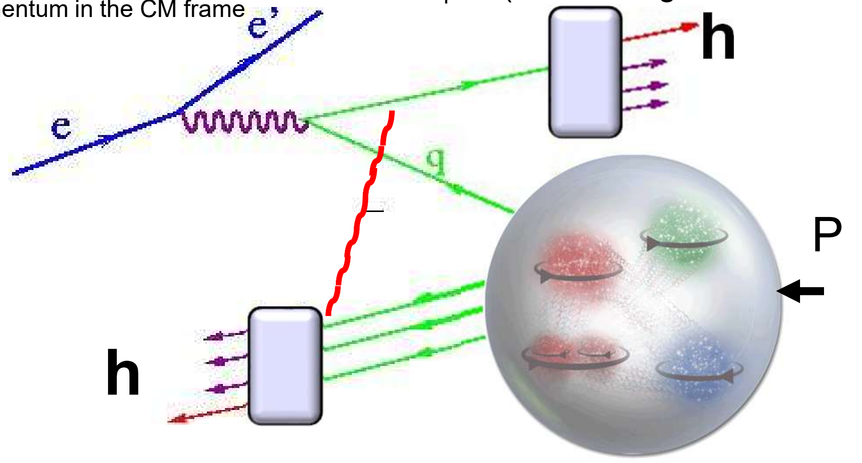
- *Dominant fraction of hard scattering data available at $Q^2<16$ GeV^2*

All the above makes JLab unique in disentangling the genuine intrinsic transverse structure of hadrons encoded in 3D partonic distributions with **controlled systematics in the kinematics dominated by valence quarks**

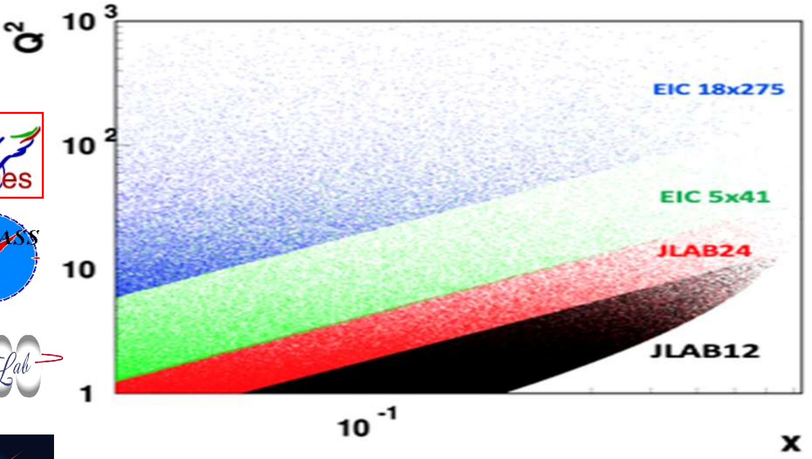
Polarized Leptoproduction

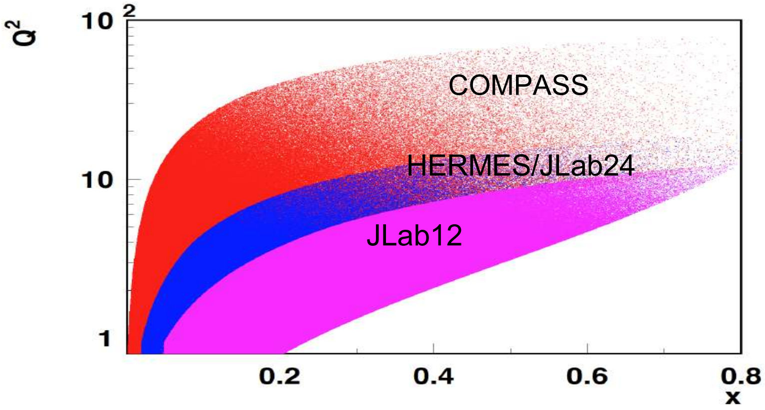
x_F– fractional longitudinal momentum in the CM frame

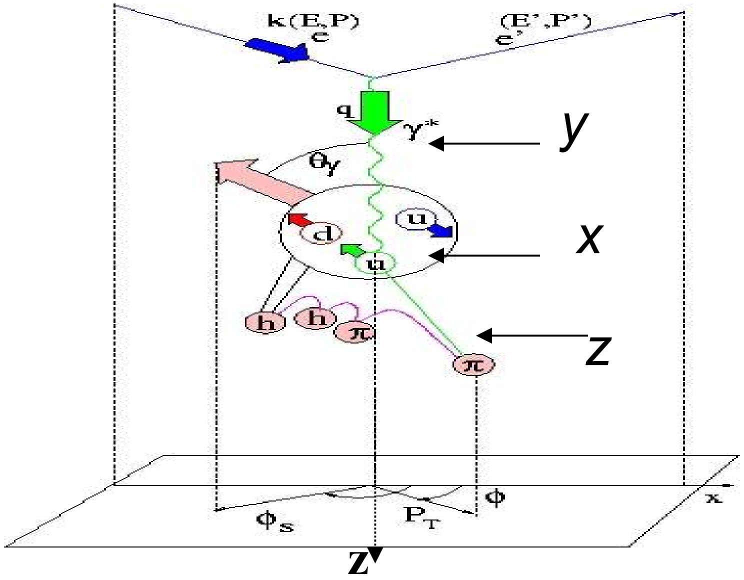
$x_F>0$ (current fragmentation, CFR)



$x_F<0$ (target fragmentation,TFR)







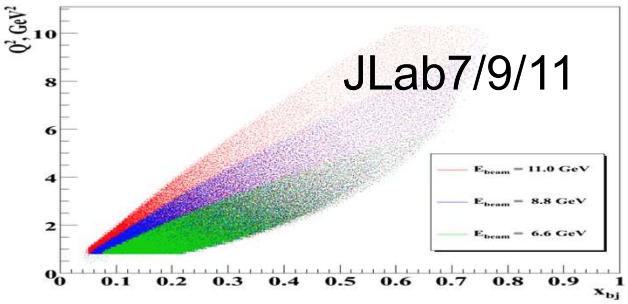
$$y=(qP)/(kP)$$

$$x=Q^2/2(qP)$$

$$z=(qP_h)/(qP)$$

in eN→e'hX

6D $(x,Q^2,z,P_T,\phi,\phi_S)$



In exclusive limit

$t = (P-P')^2$

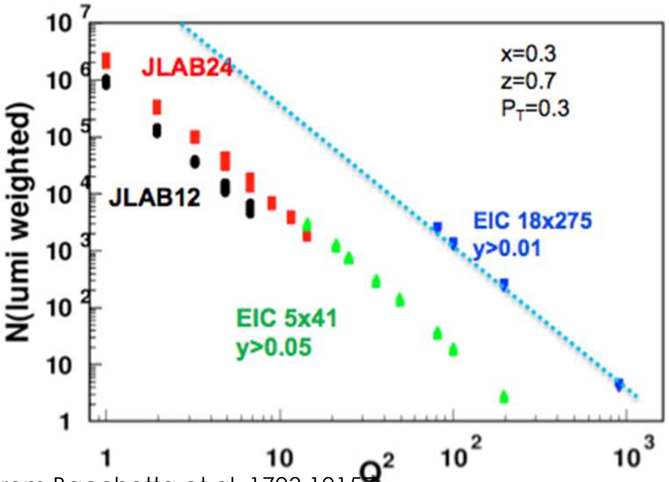
$-t=(1-z)Q^2/x$

Structure functions and depolarization factors

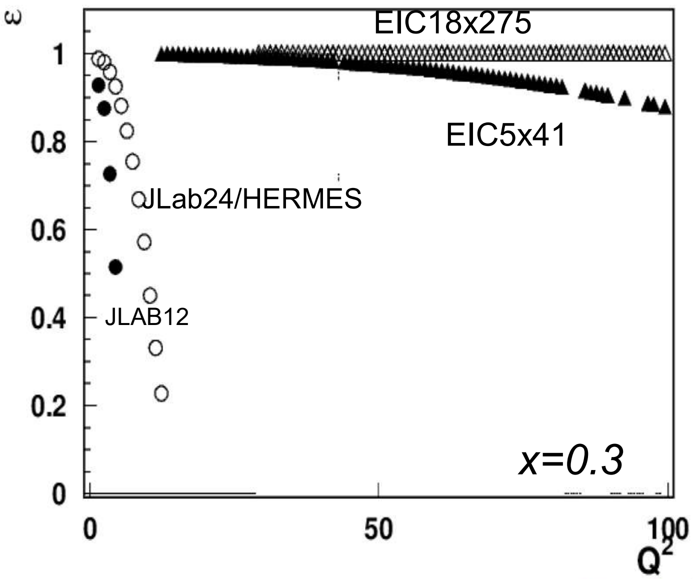
x-section for eN→e'hX

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

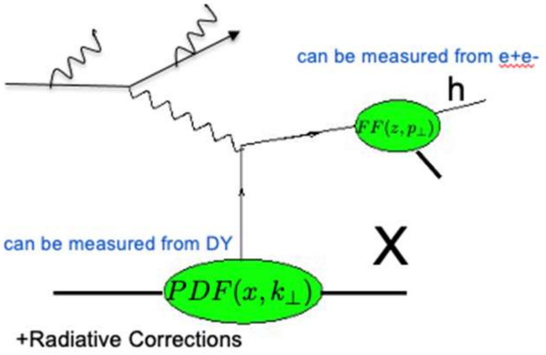
- **Measurements of correlations of spin and transverse momenta, encoded in the Structure Functions (SFs), provides direct access to details of QCD dynamics**
- Where are contributions from diffractive processes?
- Combination of statistics and depolarization factors defines measurable SFs
- At higher energies (EIC), observables surviving the ε→1 limit (FUU, FUL, Transversely pol. FUT)



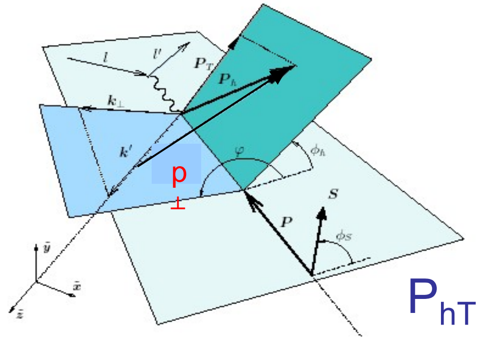
x-section from Bacchetta et al, 1703.10157



SIDIS as THE theory describes it



$eN \to e'hX$



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

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

Probability to produce 1 or 2 hadrons in single photon exchange:

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

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

hard part

- **Factorization allows 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**

Conclusions in case of apparent disagreement:

"much bigger/smaller" defined in comparison with experiment

1. **Factorization is broken?**
2. **Unaccounted terms may contribute**

Data has it all!!! Dealing with unaccounted terms:

- Theory accounts for them (ex. VMs)
- **Experiment measures and excludes them!!! (ex.VMs)**

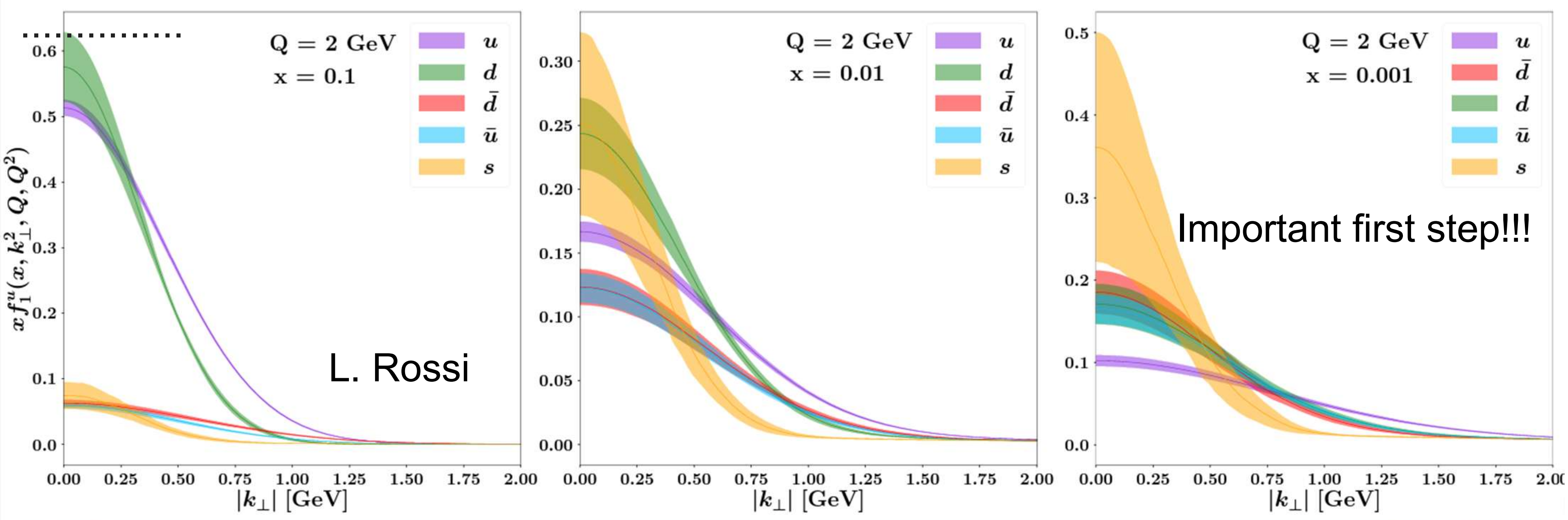
P_T distributions provide access to k_T-distributions

Understanding of P_T-distributions of hadrons in SIDIS, most critical for TMD measurements in the multidimensional space, providing access to QCD dynamics!!!

Expected:

1) Perturbative contributions in the p_T-range covered by polarized SIDIS likely minor
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-,..)

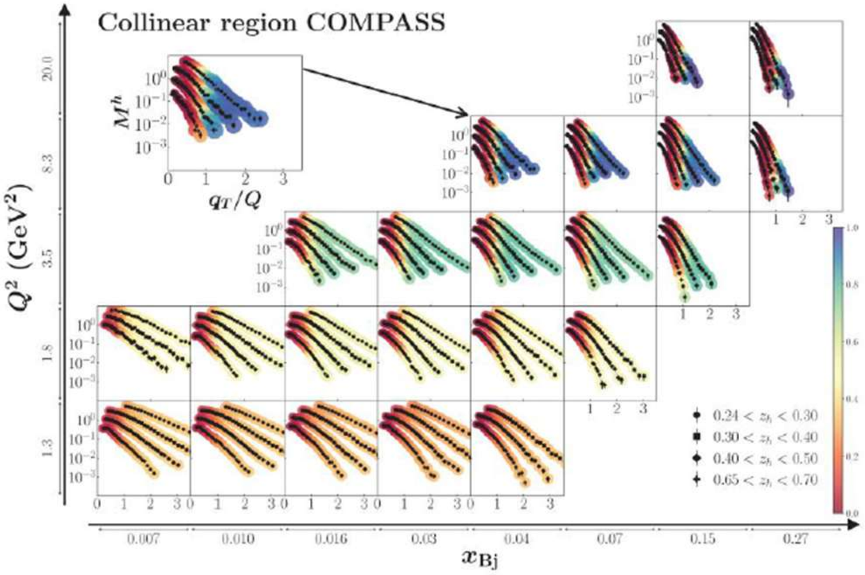
……



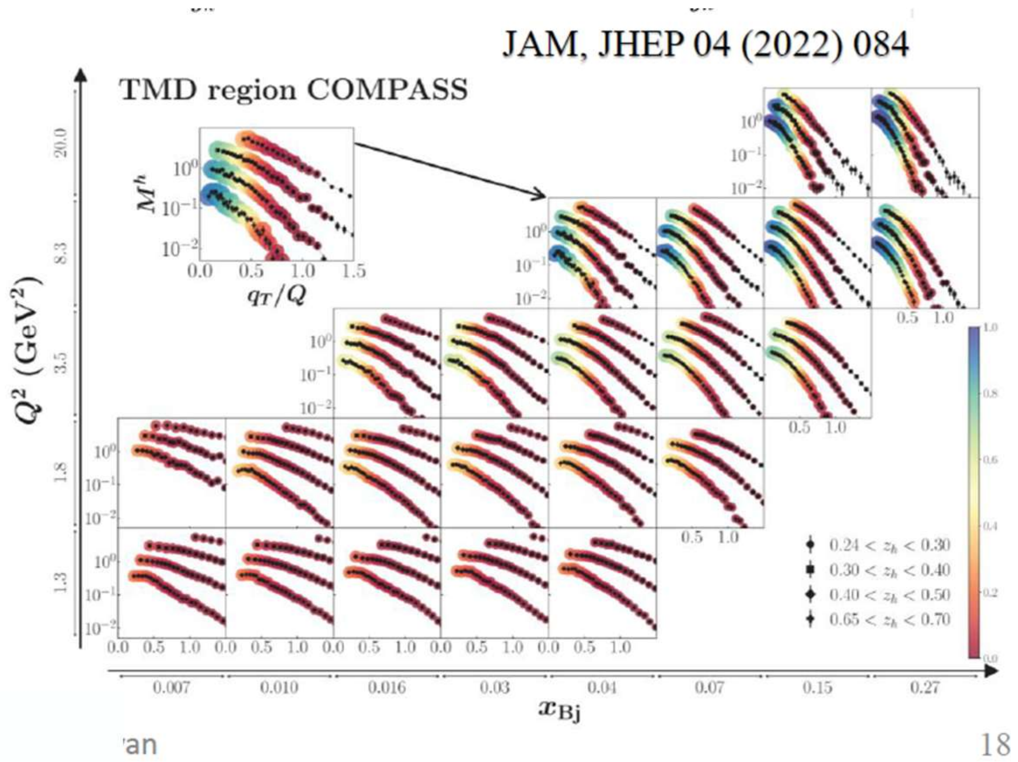
L. Rossi

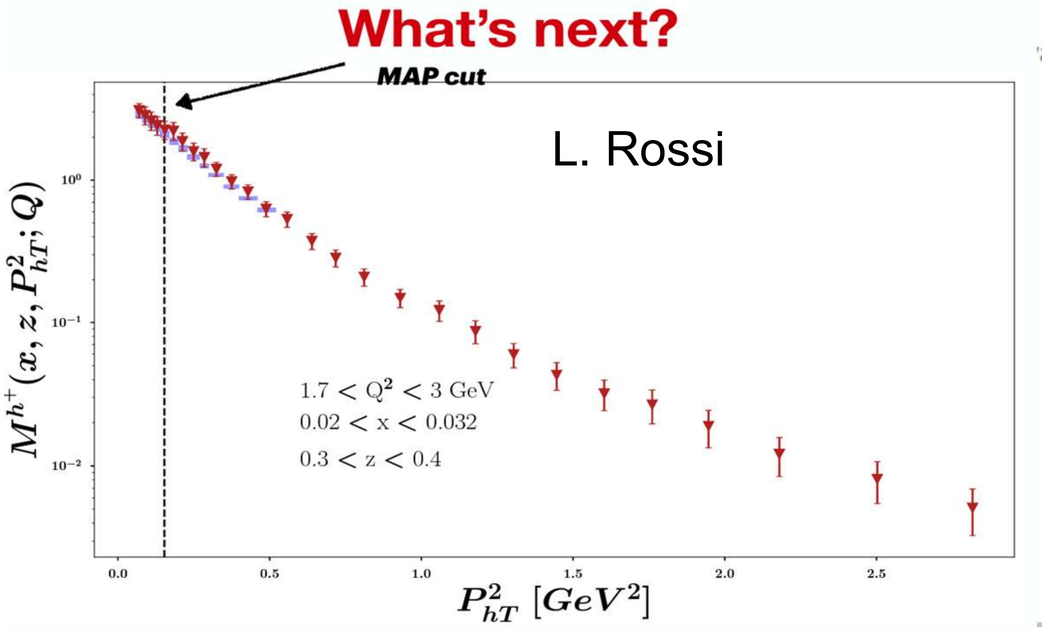
Important first step!!!

B. Parsamyan



JAM, JHEP 04 (2022) 084





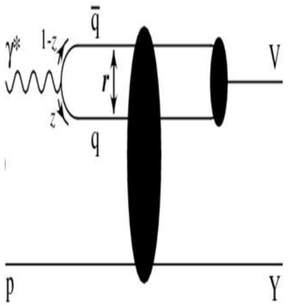
What's next?

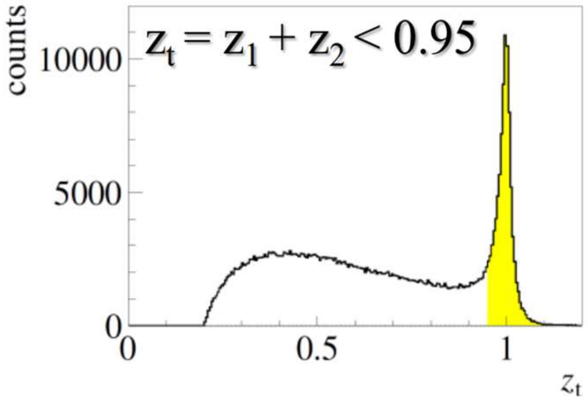
- The Theory works only for low P_T
- Need major changes in the phenomenology to capitalize on the JLab22 upgrade, increasing significantly the P_T coverage

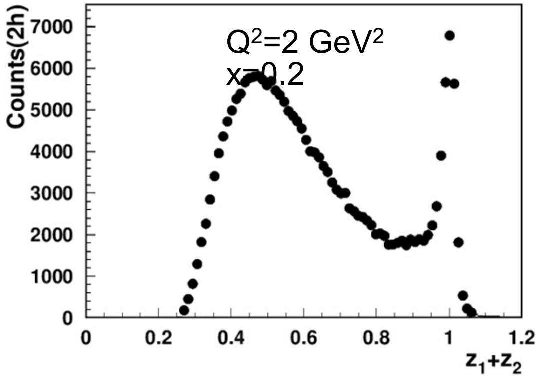
Longitudinal photons and diffractive rhos

Diffractive VMs (ρ^0)

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = K(x,Q^2,y)[F_{UU,L} + \boxed{\epsilon F_{UU,L}} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos} \ldots$$




COMPASS 2h

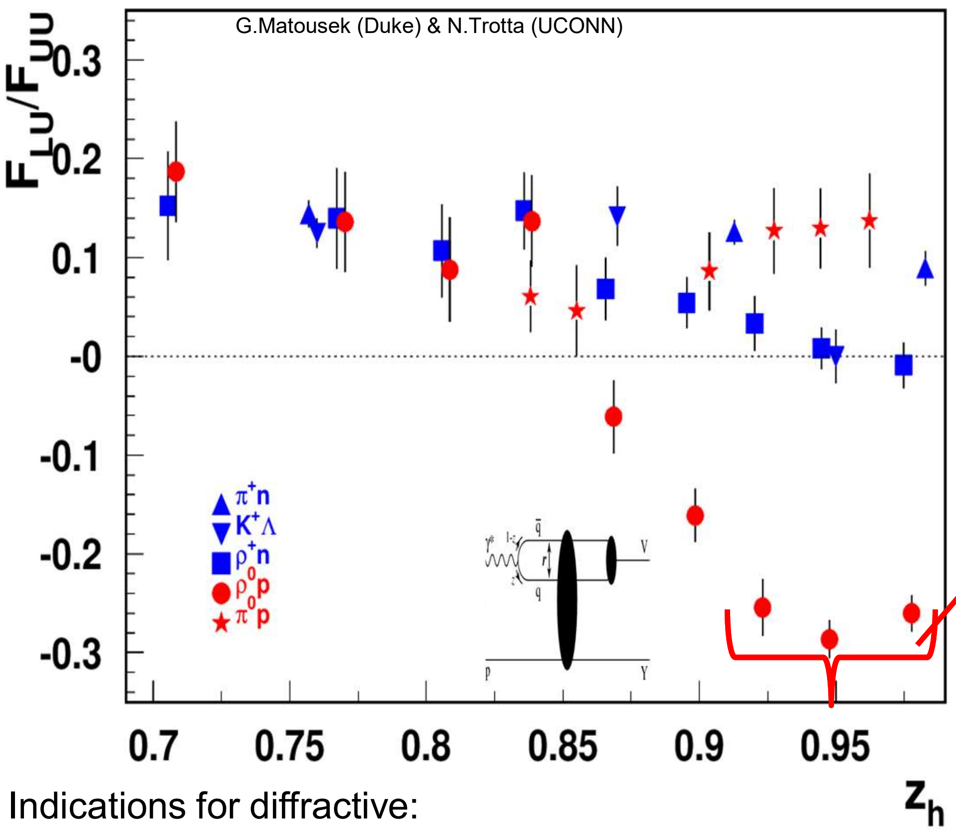

CLAS12

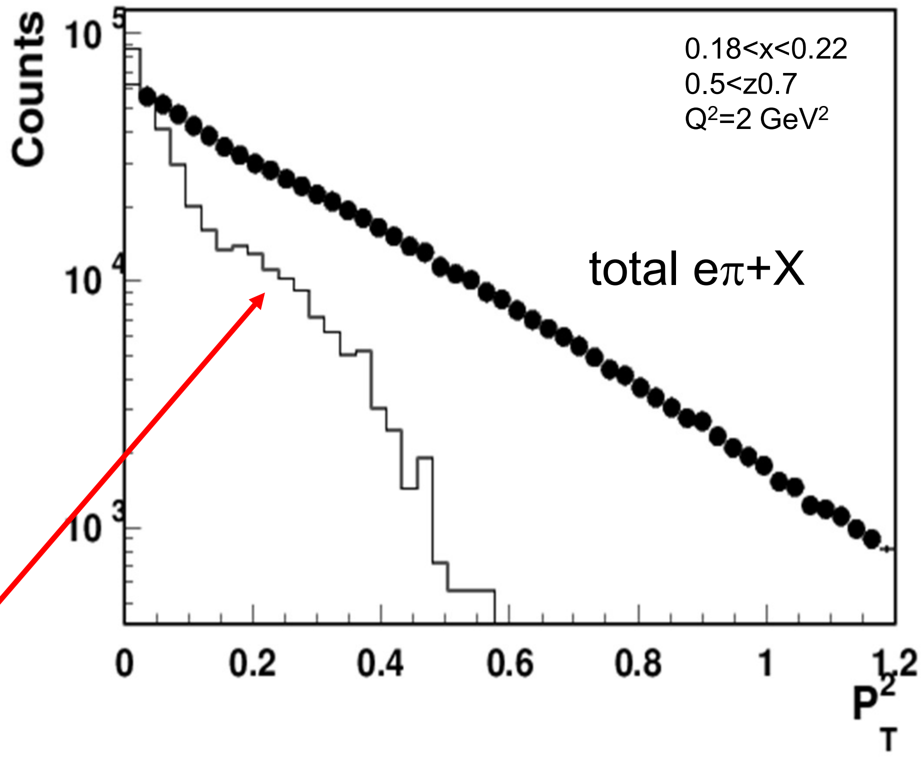
- CLAS12 measurements indicate the 2hadron exclusive sample is dominated by "diffractive ρ^0"produced at very small ***t***
- JLab provides possibility of detailed studies of those rhos, crucial for interpretation in terms of TMDs of SIDIS data in general, and for EIC in particular.

- Estimated ~20% contributions from ρ to charged pion SIDIS, consistent with ~10% of diffractive DIS in inclusive DIS
- Indication: most longitudinally polarized ρ^0
  (note: higher the Q^2 lower is ε)

Studies of exclusive processes require high resolution and multidimensional measurements !!!

Contributions of "diffractive ρ^0s" in SIDIS





Indications for diffractive:

- Major differences in observables dominated by quarks
- Major differences with charged rho+

Estimated ~20% contributions from ρ, mainly show up at low P_T in SIDIS

The "diffractive" ρ will bias extractions of TMDs, unless properly subtracted in multidimensional space of SIDIS measurements.

Excluding the “diffractive” rho from SIDIS

Depending on how we exclude the exclusive rho we can have several versions of experimental samples of inclusive hadrons, each with their own bias:

1) Standard SIDIS (eN→ehX, h=π,K,..) within the full accessible kinematics, corrected for acceptance and RC, measured in the multidimensional space

→eπX biased with respect to theory by presence of contributions from diffractive rho, contributing to ~20% of counts, in low P_T, with contributions to SSA ~10 times higher

2) Standard SIDIS (eN→eπX) within the full accessible kinematics, corrected for acceptance and RC, measured in the multidimensional space, with subtracted in multi-D bins for rho0 contributions (“rho-subtracted SIDIS”)

→requires measurements of pions from diffractive rho in multidimensional space, means detailed studies of SDMEs of rhos, requiring good precisions and huge statistics, also for all polarization observables, extensive validation needed, little known RC

3) SIDIS subsamples (eN→epπX, eN→e$\pi\pi$X) within the full accessible kinematics, allowing clear eliminiation of rho0 contributions using cuts on missing masses of epX or e$\pi\pi$X (“rho-free SIDIS”)

→biased by the presence of additional hadron in TFR (epX) or CFR (eppX), may need a new phenomenology

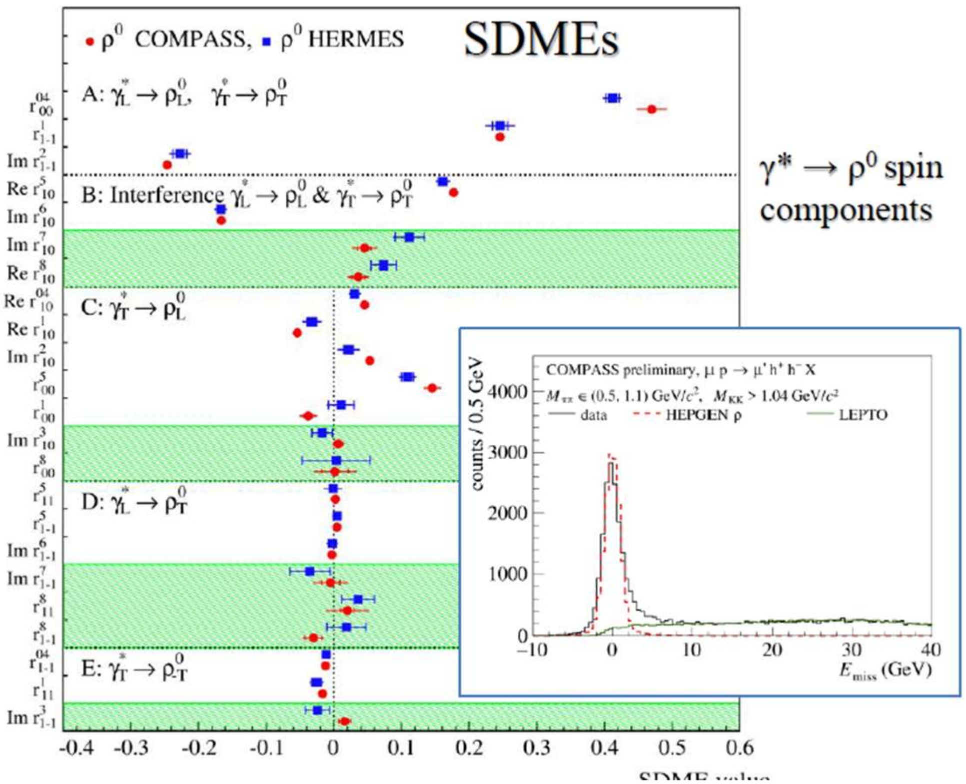
requires measurements of dependence on M_X to understand the bias,
Theory should be able to evaluate the bias from the presence of an additional hadron

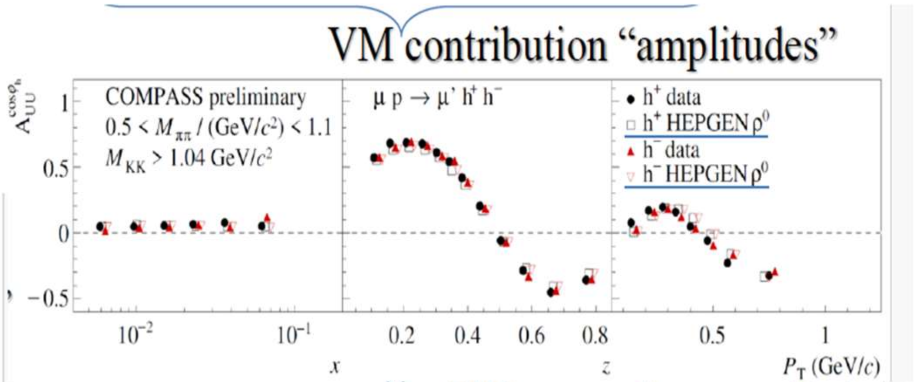
Attempts to separate the “diffractive” contributions

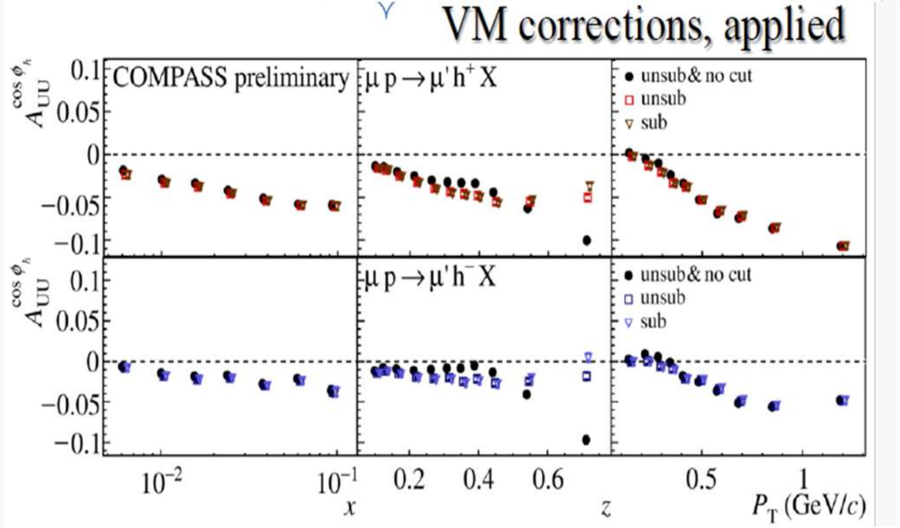
Procedure: “rho-subtracted SIDIS”(B. Parsamyan)

1) Measure exclusive rhos
2) Extract SDMEs (>20 azimuthal modulations)
3) Develop MC
4) Evaluate the correction

COMPASS, EPJC (2023) 83 924

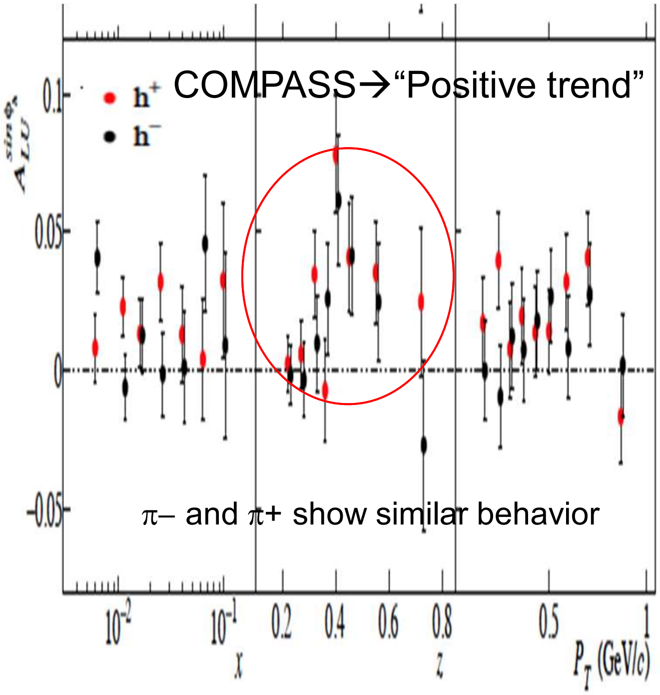






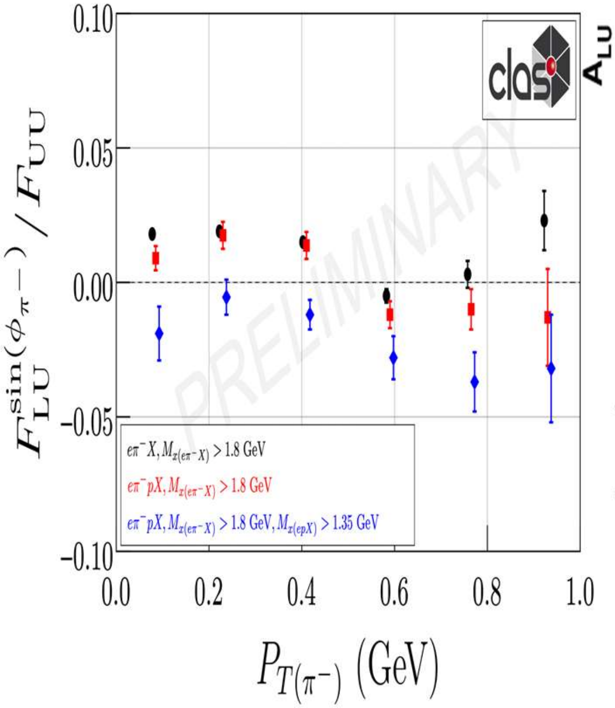
Extracted modulations have weird P_T and most importantly Q^2 dependence

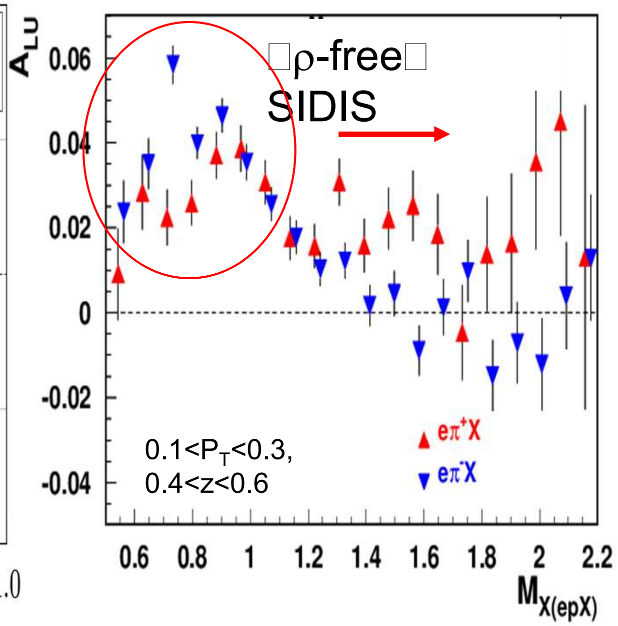
Exclusive ρ contributions to π: P_T-dependence



COMPASS→“Positive trend”

π– and π+ show similar behavior





“ρ-free” SIDIS

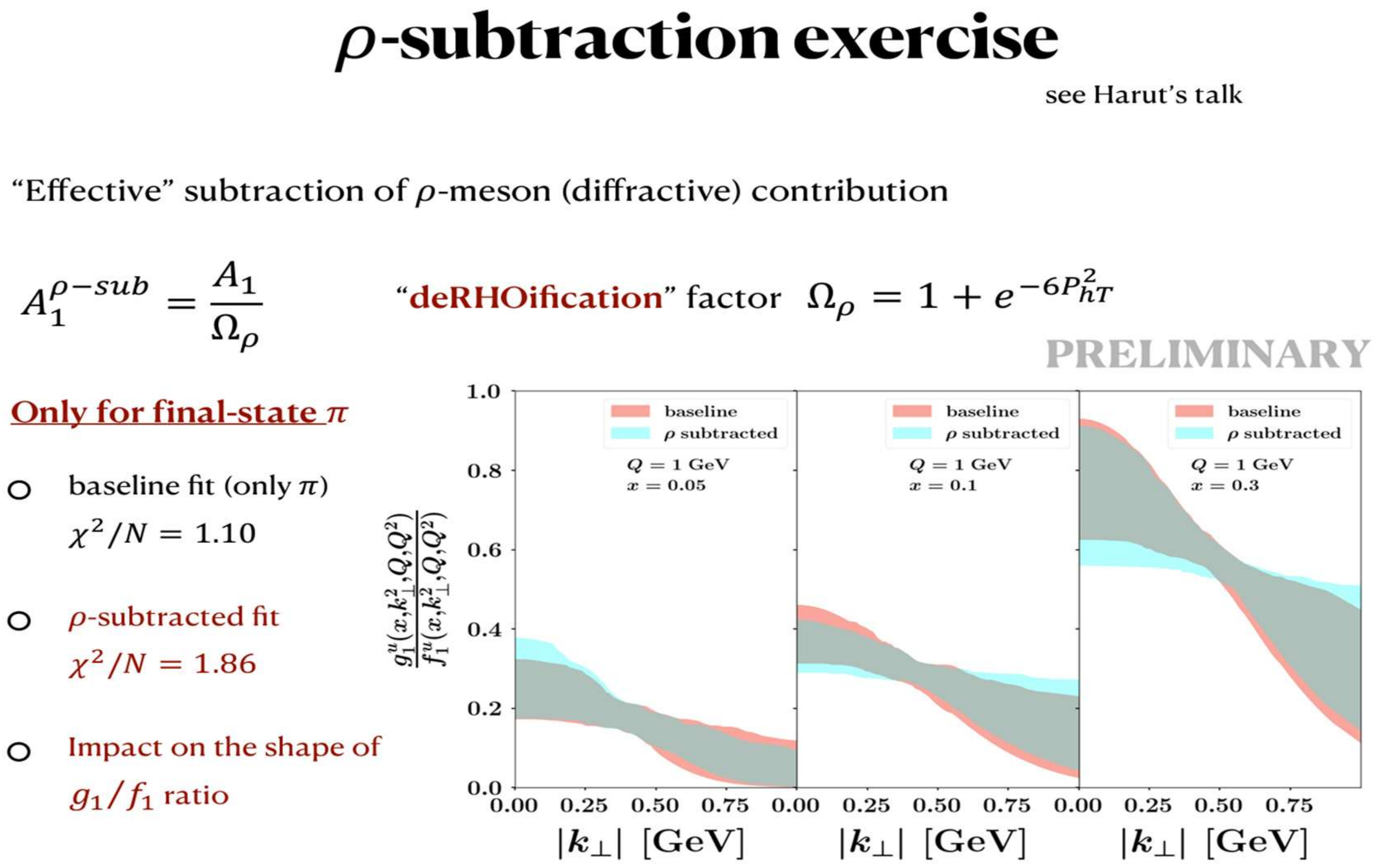
COMPASS→“Positive trend” also reproduced when additional proton in TFR detected (red)

- The same sign and size of π+ and π- SSA indicates the rho0 may not be properly subtracted(require detailed MC studies, which require proper SDMEs)
- While VM contributions are ~20% in multiplicities in SSA they can be >100%

Need proper MC for rho for all polarization states→

> “The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge.”
> — **Daniel J. Boorstin**

First attempts to account or rho (M. Cerutti)



ρ-subtraction exercise

see Harut's talk

"Effective" subtraction of ρ-meson (diffractive) contribution

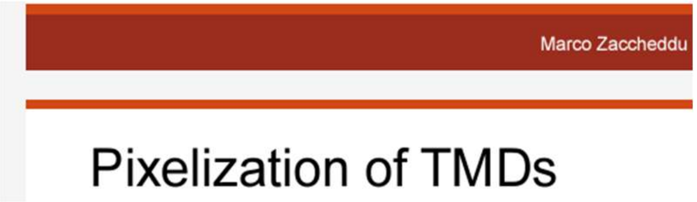
$$A_1^{\rho-sub} = \frac{A_1}{\Omega_\rho}$$

"**deRHOification**" factor $\Omega_\rho = 1 + e^{-6P_{hT}^2}$

PRELIMINARY

Only for final-state π

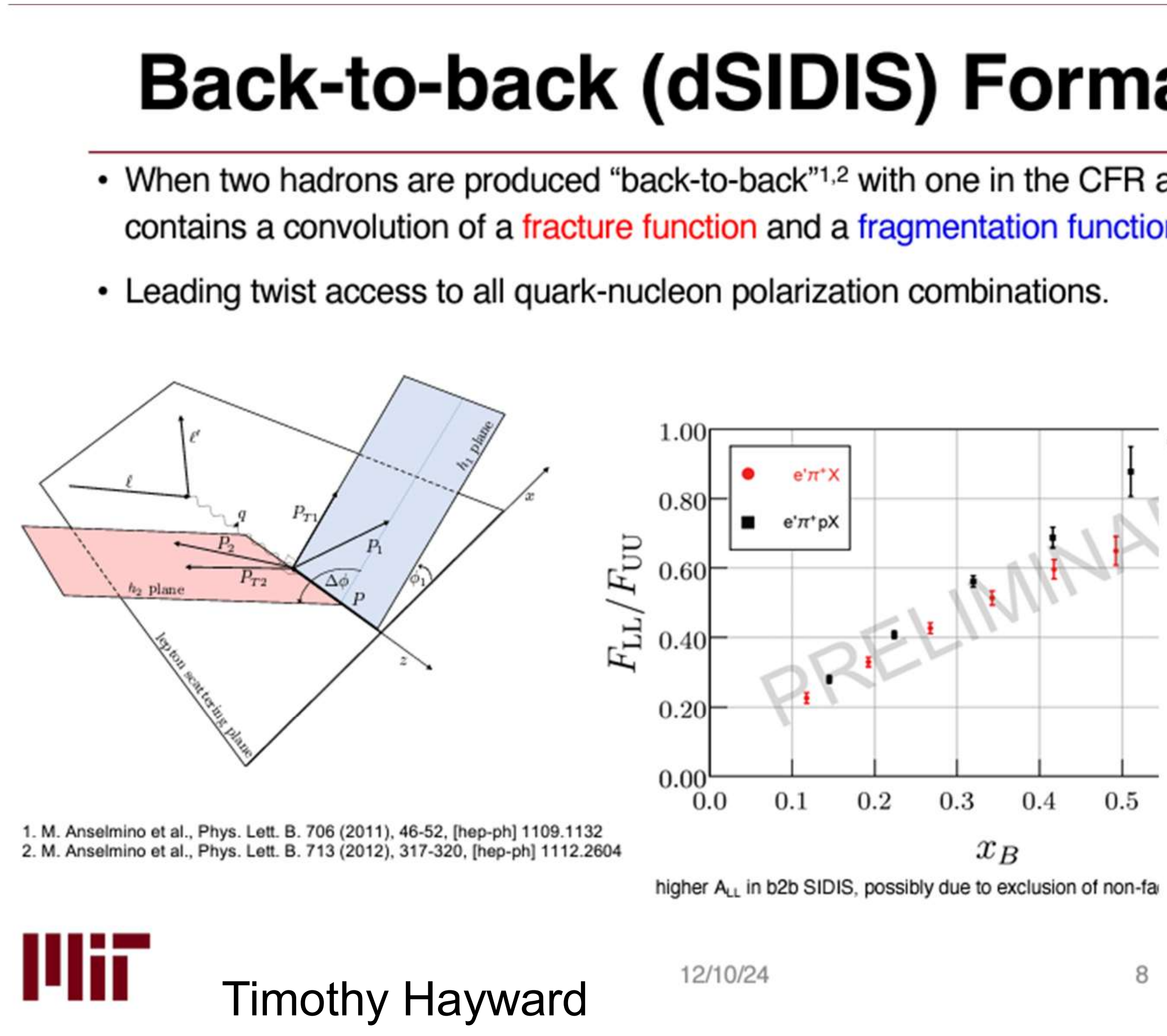
- ○ baseline fit (only π) $\chi^2/N = 1.10$
- ○ ρ-subtracted fit $\chi^2/N = 1.86$
- ○ Impact on the shape of g_1/f_1 ratio



Marco Zaccheddu

Pixelization of TMDs

Need a self consistent procedure with proper rho subtraction



Back-to-back (dSIDIS) Formalism

- When two hadrons are produced “back-to-back”[1,2] with one in the CFR and one in the
  contains a convolution of a fracture function and a fragmentation function.
- Leading twist access to all quark-nucleon polarization combinations.

1. M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132
2. M. Anselmino et al., Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604

higher A_{LL} in b2b SIDIS, possibly due to exclusion of non-fa

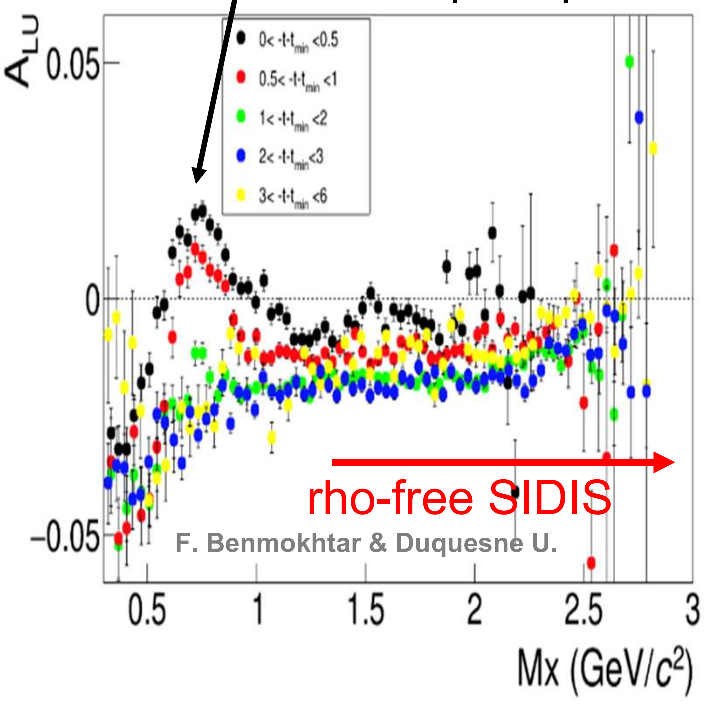
Timothy Hayward

12/10/24

8

SSA/Fraction of diffractive rho increases at small t

ep→e'pX



rho-free SIDIS

F. Benmokhtar & Duquesne U.

- Detection of the target fragment proton allows “rho free” SIDIS measurements
- Signal from rho clearly increases at small t, consistent with large negative SSA (r_{00}^{8} SDME, arising from longitudinal rhos produced from transverse photons)

SUMMARY

- The superior luminosity of CEBAF, high resolutions of detectors, and ability for multidimensional and multiparticle detection, makes the JLab unique facility to study the non-perturbative QCD dynamics in 3D space in the kinematics dominated by valence quarks
- Interpretation of observables in charged pions SIDIS, and spin and azimuthal asymmetries, require detailed understanding of longitudinal photon contributions, vector mesons, and exclusive rho0 in particular.
- Exclusive “diffractive rhos” due to sensitivity to gluon contributions, have very different from any other (quark dominated) processes spin and azimuthal asymmetries, and may provide understanding of “diffractive” phenomena
- Measurements of exclusive rhos at 22 GeV will be critical for interpretation of high energy data, also providing a bridge between JLab and EIC
- Development of “rho subtracted” SIDIS, will require detailed measurements of SDMEs in multidimensional space, validated by “rho free” measurements in multi-D space.
- Need a major upgrade for SIDIS phenomenology to extract TMDs with controlled systematics (SIDIS2.0 or reforming SIDIS) to use in most efficient way major improvements of P_T and Q^2 coverage at 22 GeV

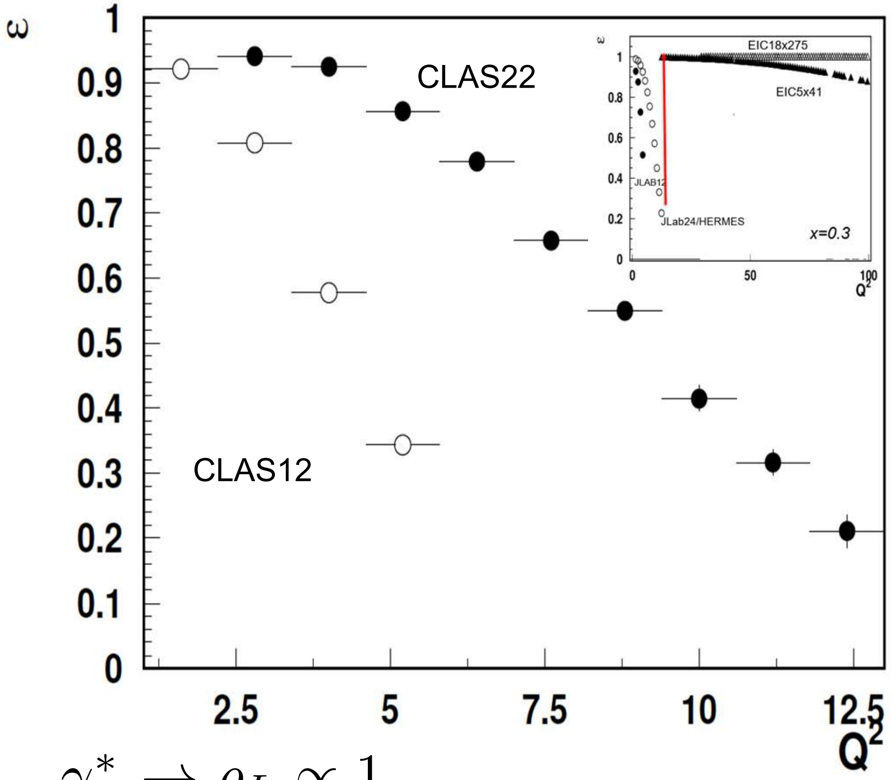
- Support slides

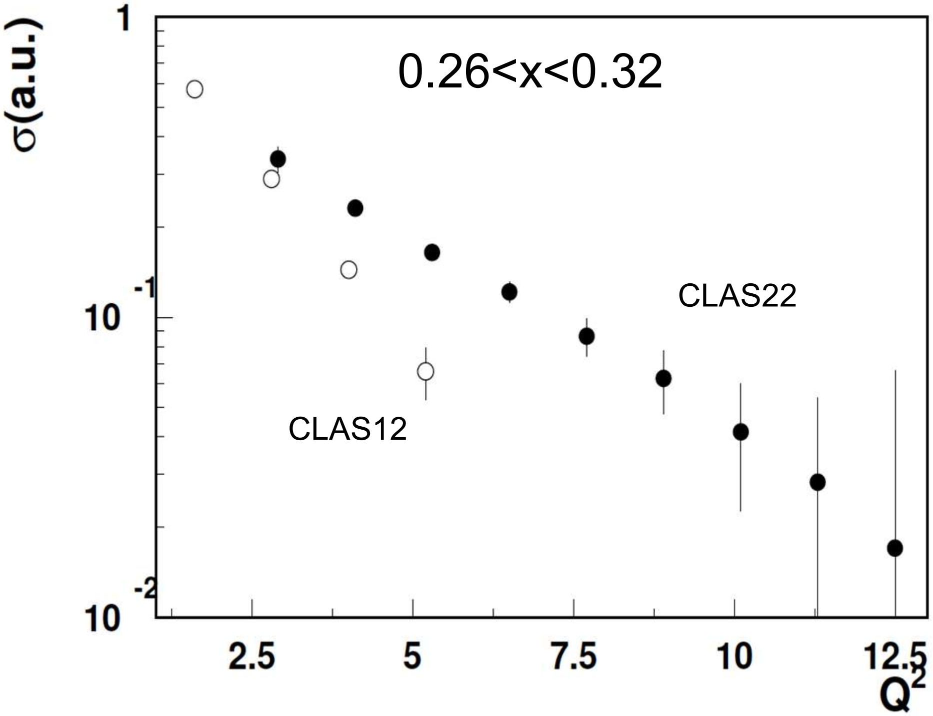
JLab22 white paper: Hadronization and Transverse Momentum

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
- physics backgrounds:
  - What is “diffractive DIS” and “diffractive 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

Exclusive ρ^0: extending the Q^2 with JLab22





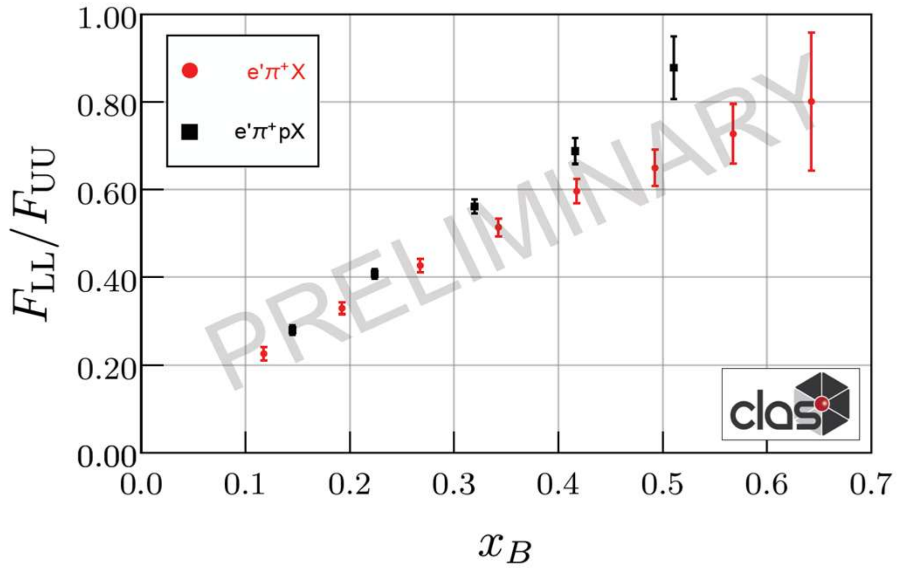
$$\gamma_L^* \to \rho_L \propto 1$$

$$\gamma_T^* \to \rho_L \propto \sqrt{-t}/Q$$

Longitudinal photon contributions kinematically enhanced at higher energies

- Beam SSA provides important info on production of longitudinal rho from transverse photons
- Range in Q^2 increases significantly with 22 GeV upgrade, allowing detailed studies at beyond 10 GeV^2 and providing a bridge to EIC

Longitudinally polarized quarks in B2B SIDIS

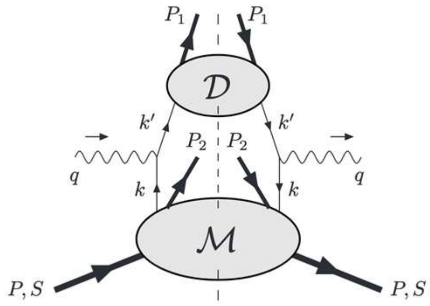


Possible theory formalisms:

- **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**

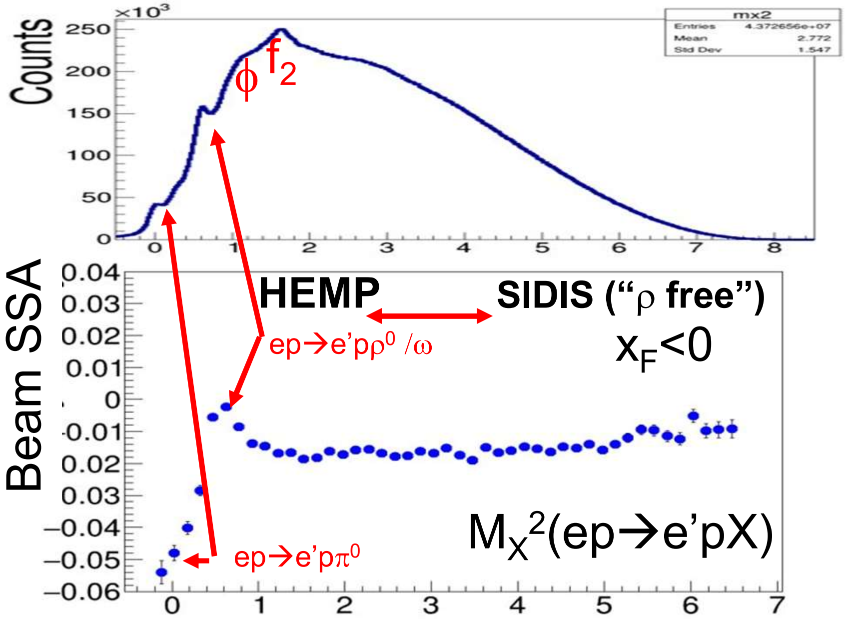
- Differences in A_{LL} , due to different weights on PDFs can provide additional info on impact of possible ingredients
- Measurements of A_{LL} for ρ^0 indicate very small values, and can be one of the reasons for higher A_{LL} with protons with a M_X cuts above 1.5 GeV (excluding exclusive ρ^0)
- Higher A_{LL} will change the phenomenology used last 40 years in DIS and SIDIS studies!!!

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!



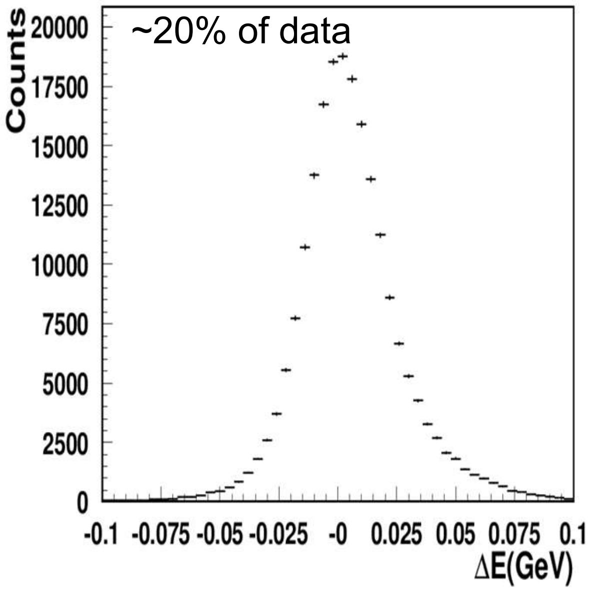
Understanding exclusive rhos and SDME validations

Exclusivity condition defined by the missing Energy:

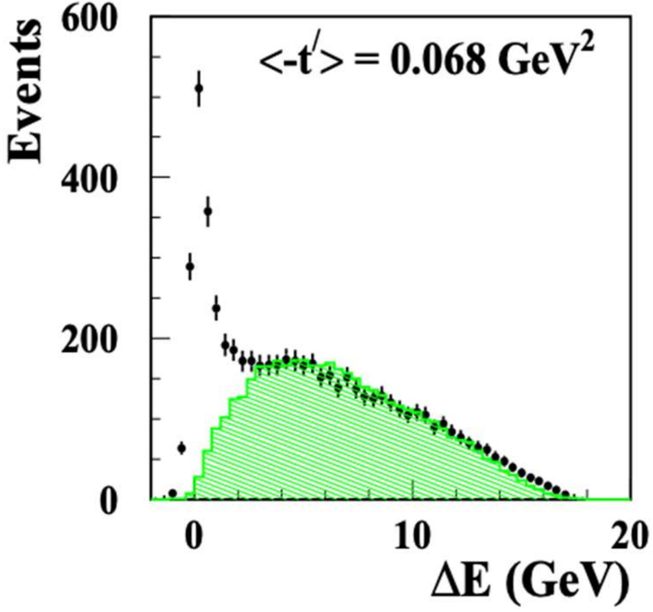
$$M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2$$

$$E_{\text{miss}} = \frac{M_X^2 - M^2}{2M}$$

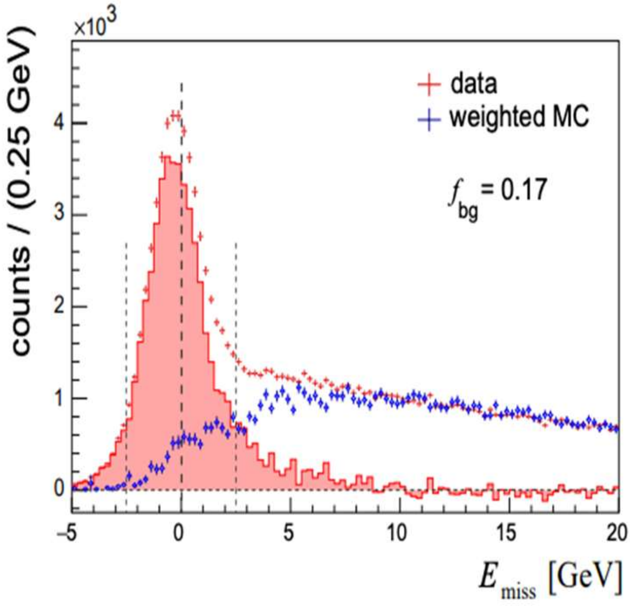
CLAS12 (width <0.1GeV)



HERMES(width ~0.6GeV)

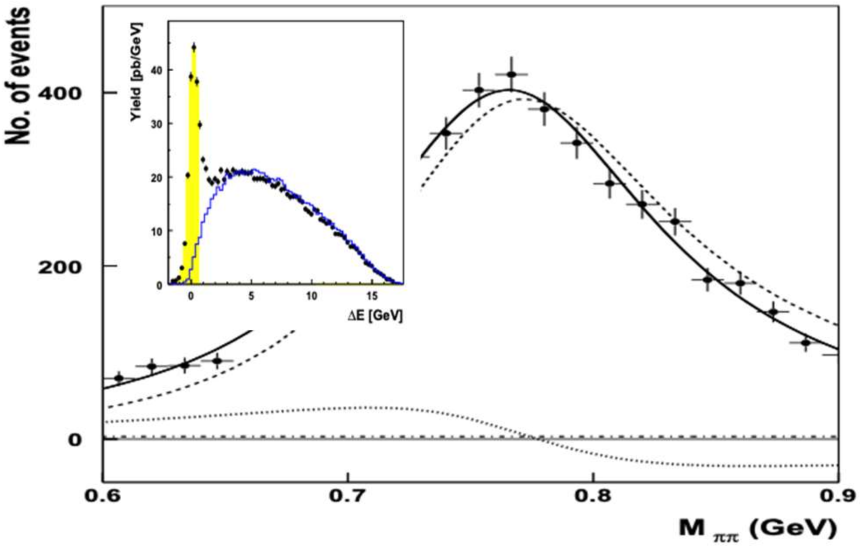


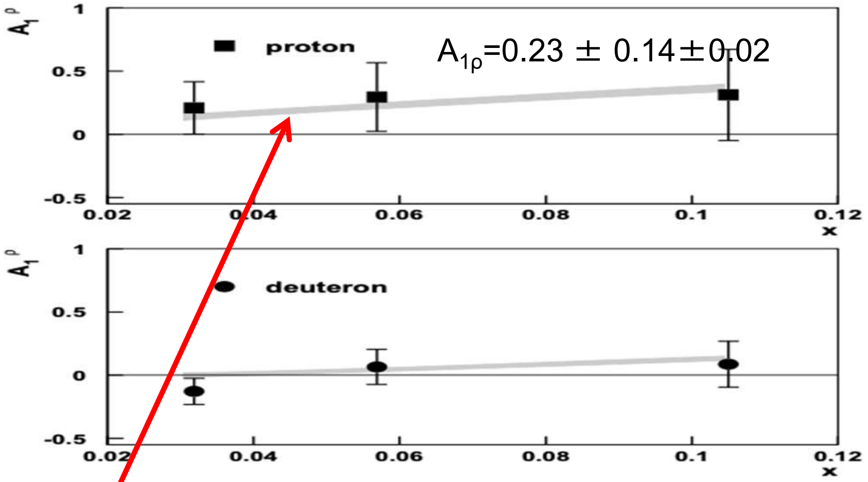
COMPASS(width ~2GeV)



- Guarantying the “exclusivity” requires good resolutions (get worse at higher energies)
- Subtraction procedure relays on normalization, based on exclusive limit of LUND-MC
- All distributions have have tails, indicating the RC may not be negligible
- Extraction of SDMEs, will require validation in the multi-D space (significant samples)

A_{LL} studies of exclusive ρ^0 : HERMES

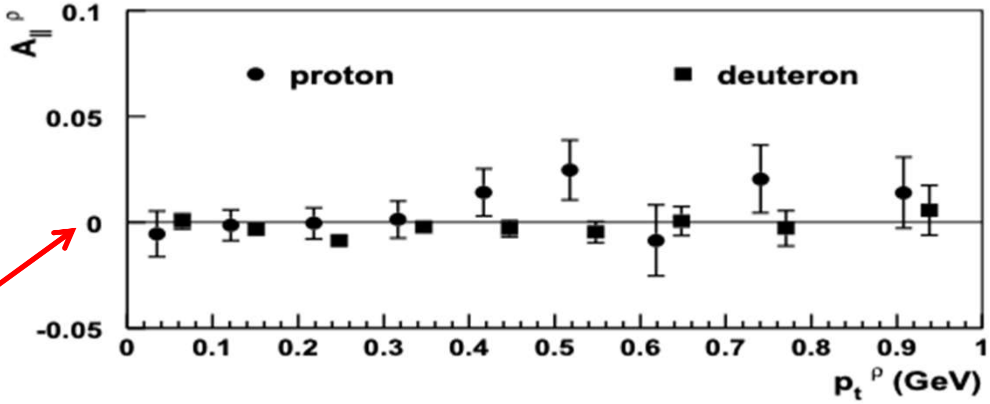




$A_{1\rho}=0.23 \pm 0.14 \pm 0.02$

1D plots can be really misleading need multi-D

For a proper extraction of multiplicities and spin-azimuthal modulations of exclusive ρs, clean separation is needed for ρ^0, and longitudinally polarized ρ^0 signal, in particular

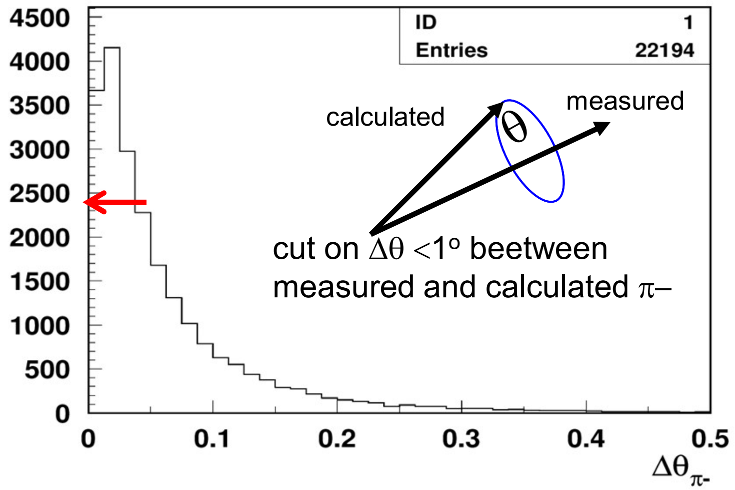


At low P_T, where the background is smaller, the asymmetry indeed tend to be negative

Accounting of ρ^0 will change the phenomenology of helicity distributions

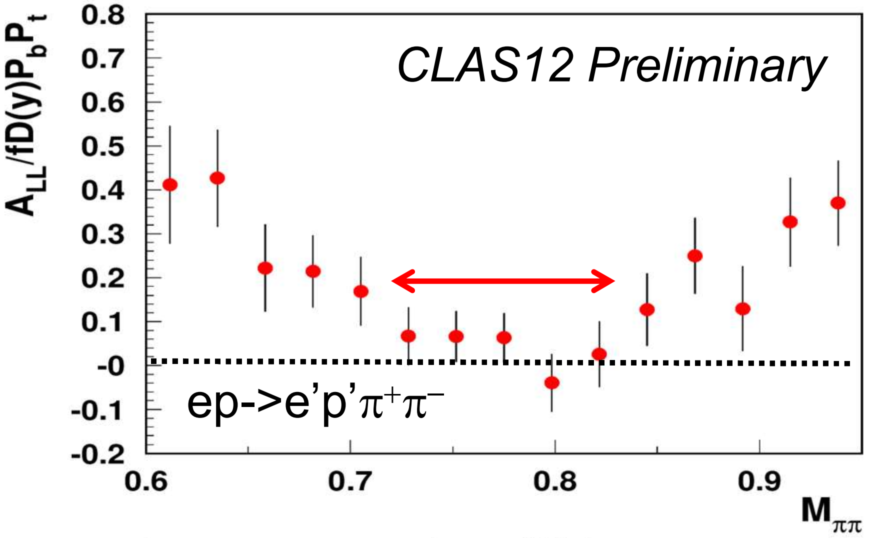
Studies of ρ^0 impact with longitudinally polarized NH_3 target

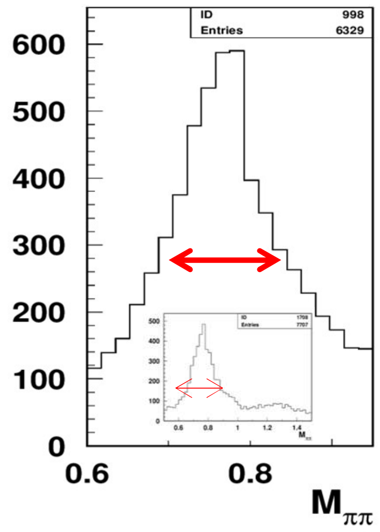
Separating exclusive dihadrons

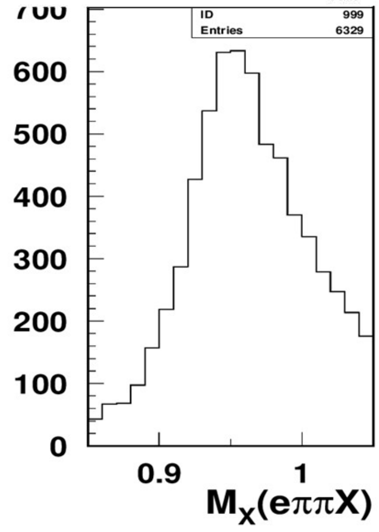


- Require the angle of negative pions is within a degree from calculated from e',p,π+ assuming exclusive e',p,π+π- event.

- Measurements of A_{LL} for ρ^0 indicate very small values (with ~10-20% bckg, likely negative ~ -2-10%), and can be one of the reasons for higher A_{LL} with protons with a M_X cuts above 1.35 GeV (excluding exclusive ρ^0)



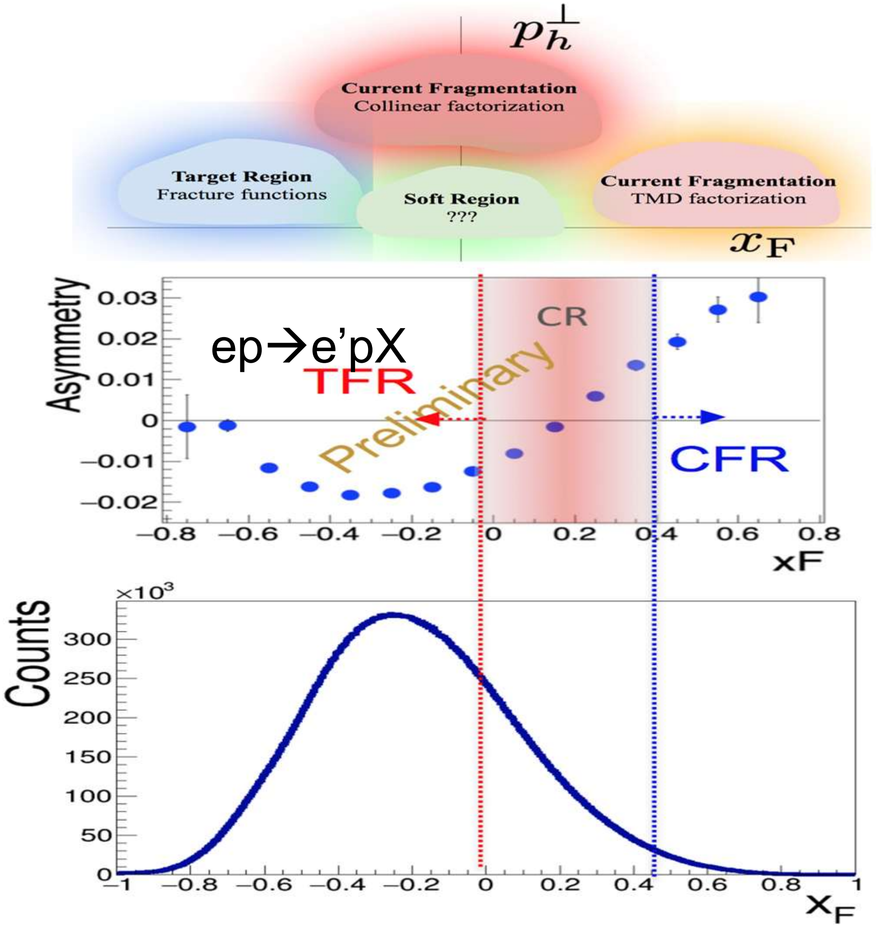




Need clear separation of hydrogen from NH_3 and diffractive exclusive ρ0s from exclusive $\pi+\pi-$

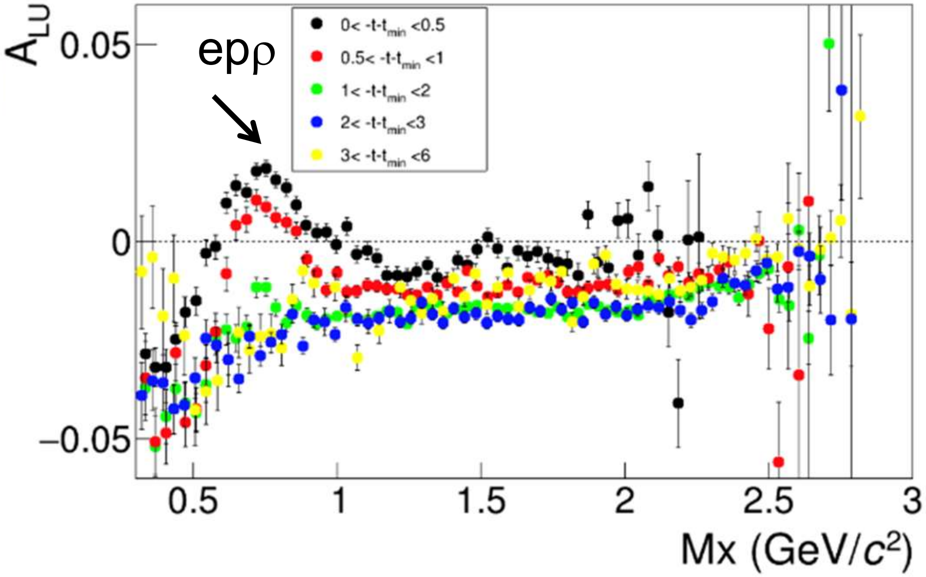
Beam SSAs as a tool to separate regions and contributions

Separating Target Fragmentation Region TFR from Current fragmentation region (CFR)



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

F. Benmokhtar & Duquesne U.



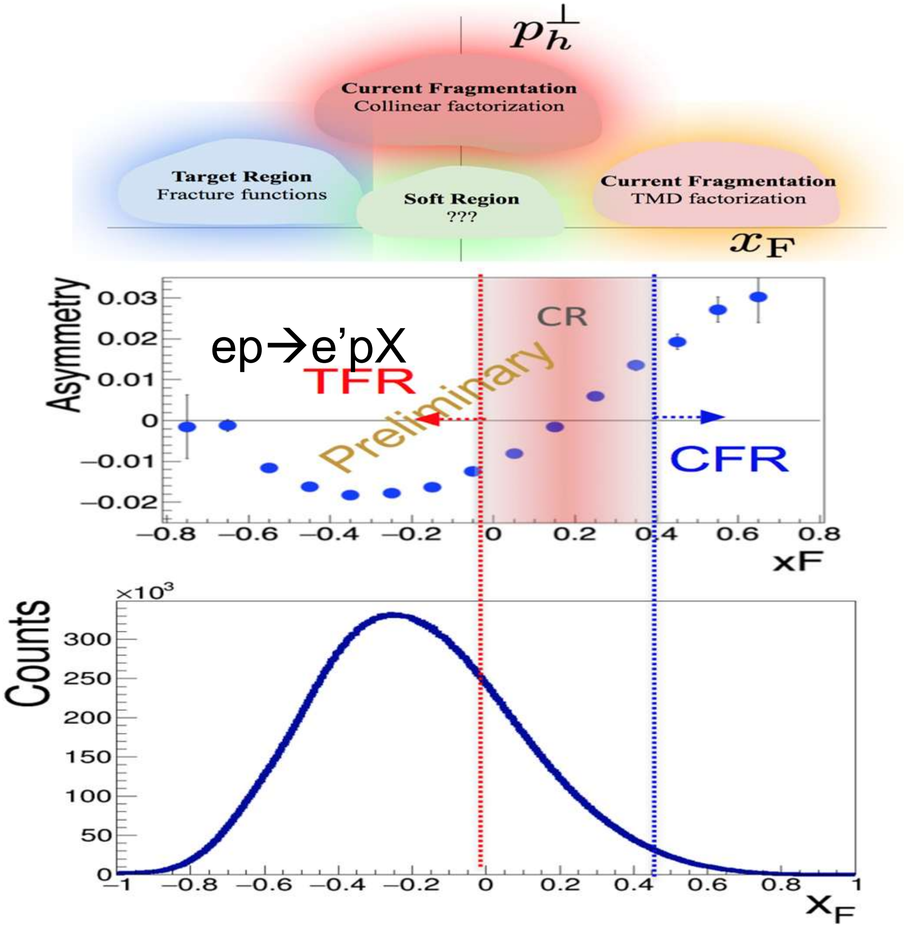
Major difference only for protons at small t!

SIDIS beam SSA can serve as a tool to separate :

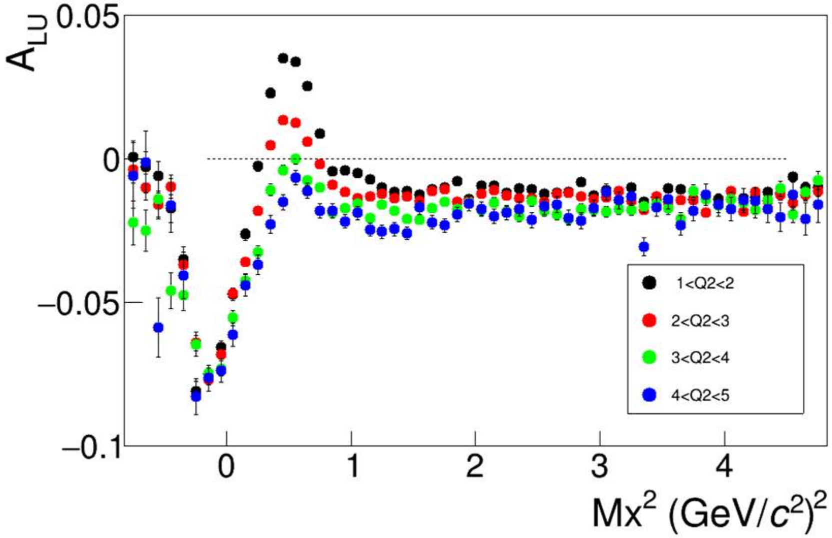
1) kinematical regions (CFR/TFR)

Beam SSAs as a tool to separate regions and contributions

Separating Target Fragmentation Region TFR from Current fragmentation region (CFR)



F. Benmokhtar & Duquesne U.



SIDIS beam SSA can serve as a tool to separate:

1) kinematical regions (CFR/TFR)
2) dynamical contributions
3) cut on M_X eliminate exclusive VMs

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

Understanding exclusive rhos and SDME validations

$$\mathcal{W}^U(\Phi,\phi,\cos\Theta)$$

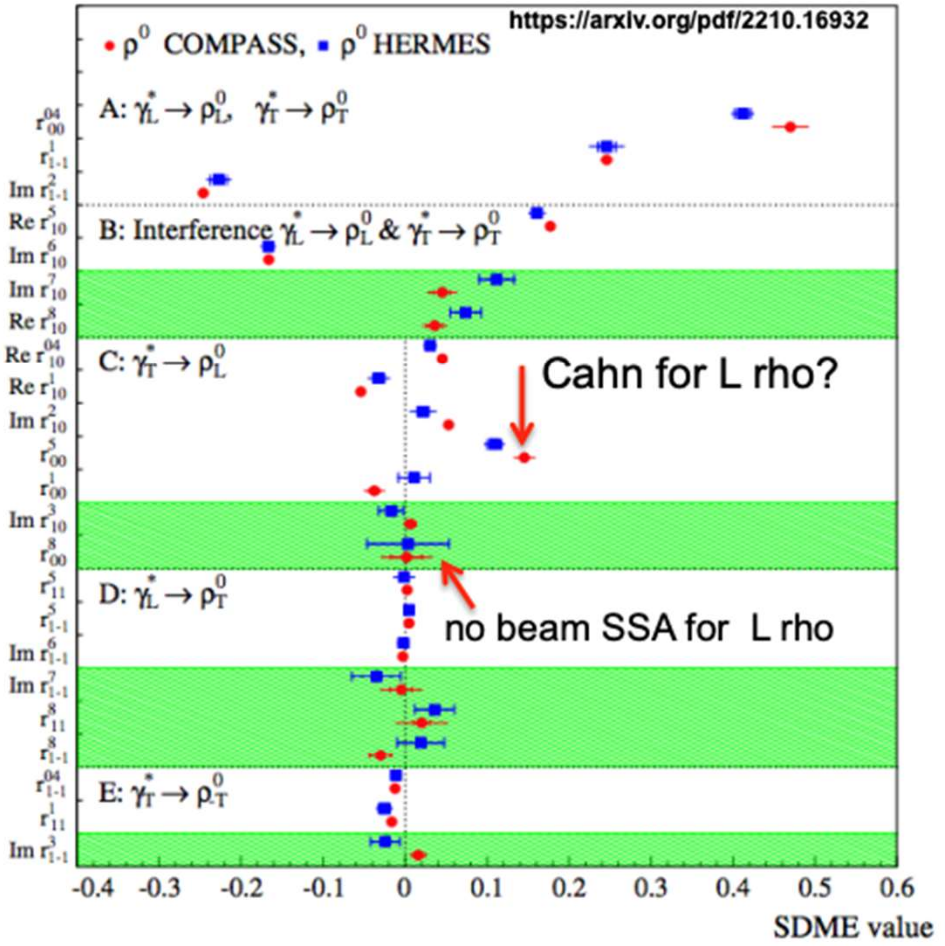
$$+\ \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\left(r^5_{11}\sin^2\Theta\boxed{+r^5_{00}\cos^2\Theta}\right.$$

$$\mathcal{W}^L(\Phi,\phi,\cos\Theta)$$

$$+\ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^8_{11}\sin^2\boxed{\Theta+r^8_{00}\cos^2\Theta}\right.$$

$$\gamma^*_T\rightarrow\rho^0_L \qquad \boxed{\tau_{01}}\approx\sqrt{\epsilon}\frac{\sqrt{(r^5_{00})^2+(r^8_{00})^2}}{\sqrt{2r^{04}_{00}}}.$$

Since the decay angle is correlated with the polarization of the rho, then r_{00}^8 and r_{00}^5 will be responsible for longitudinal rho, so tiny beam SSA expected for longitudinal rho



https://arxiv.org/pdf/2210.16932

Cahn for L rho?

no beam SSA for L rho

Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96\ (\text{GeV}/c)^2$, $\langle W\rangle = 4.8\ \text{GeV}/c^2$, $\langle|t'|\rangle = 0.13$, while those for COMPASS are $\langle Q^2\rangle = 2.40\ (\text{GeV}/c)^2$, $\langle W\rangle = 9.9\ \text{GeV}/c^2$, $\langle p_T^2\rangle = 0.18\ (\text{GeV}/c)^2$. Inner error bars represent statistical uncertainties and outer ones statistical and systematic uncertainties added in quadrature. Unpolarised (polarised) SDMEs are displayed in unshaded (shaded) areas.

SIDIS at JLab: the theorists’ comments

Statement:

“… SIDIS data has shown that there are basic open questions concerning the semi-inclusive pion/kaon production mechanisms at few-GeV energies, regarding e.g vector mesons and longitudinal photons....

Meaning:

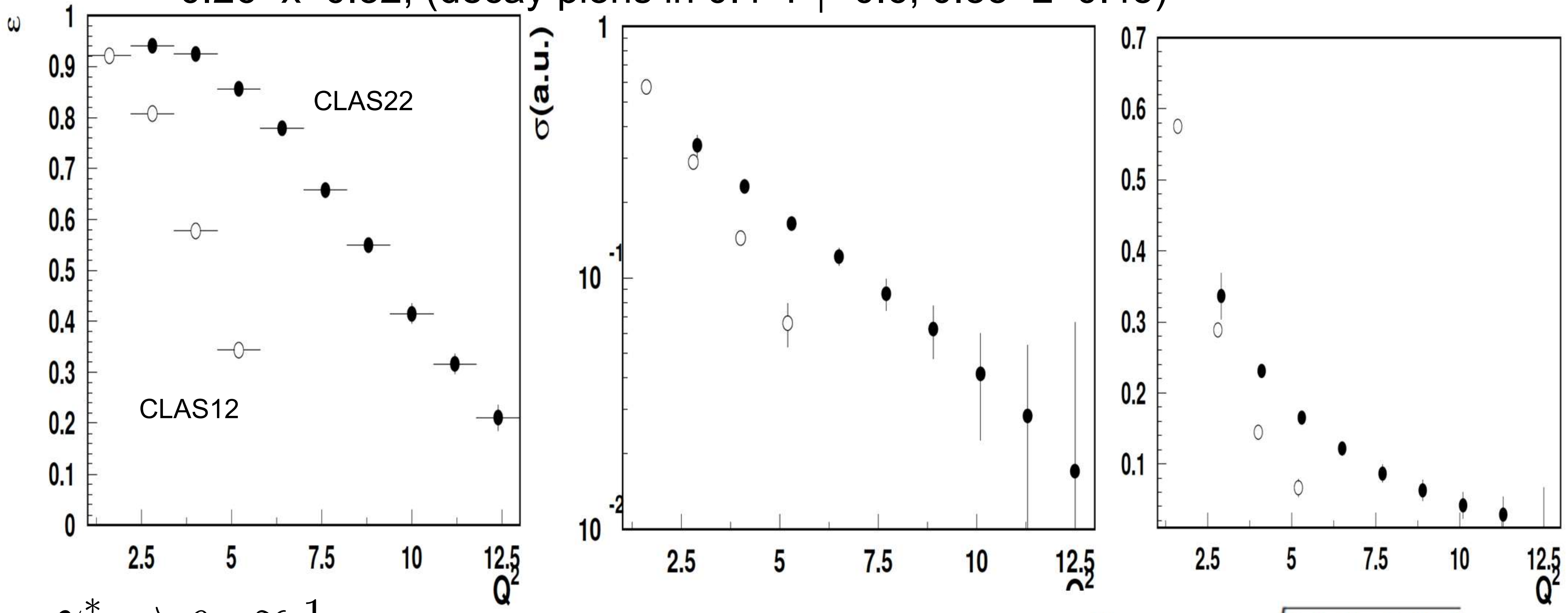
JLab has problems specific for low energies, which should be solved, before THE theory of TMDs could be applied

Possible conclusion:

All problems are due to “few-GeV”, will magically vanish at higher energies, and TMDs can be studied in the valence region [in multidimensional space] at higher Q^2 using THE theory [no need to deal with higher twists/correlations of quarks/hadrons/…....]

Exclusive ρ^0: extending the Q^{2}with JLab22

0.26<x<0.32, (decay pions in 0.4<P$_T$<0.6, 0.35<z<0.45)



$$\gamma_L^* \to \rho_L \propto 1$$
$$\gamma_T^* \to \rho_L \propto \sqrt{-t}/Q$$

Longitudinal photon contributions
enhanced at higher energies

$$\gamma_T^* \longrightarrow \rho_L^0 \qquad \tau_{01} \approx \sqrt{\epsilon}\frac{\sqrt{(r^5_{00})^2+(r^8_{00})^2}}{\sqrt{2r^{04}_{00}}}$$

$$\mathcal{W}^L(\Phi,\phi,\cos\Theta)$$
$$+ \quad \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta$$

Range in Q^2 increases significantly allowing
detailed studies at beyond 10 GeV^2

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-,..)

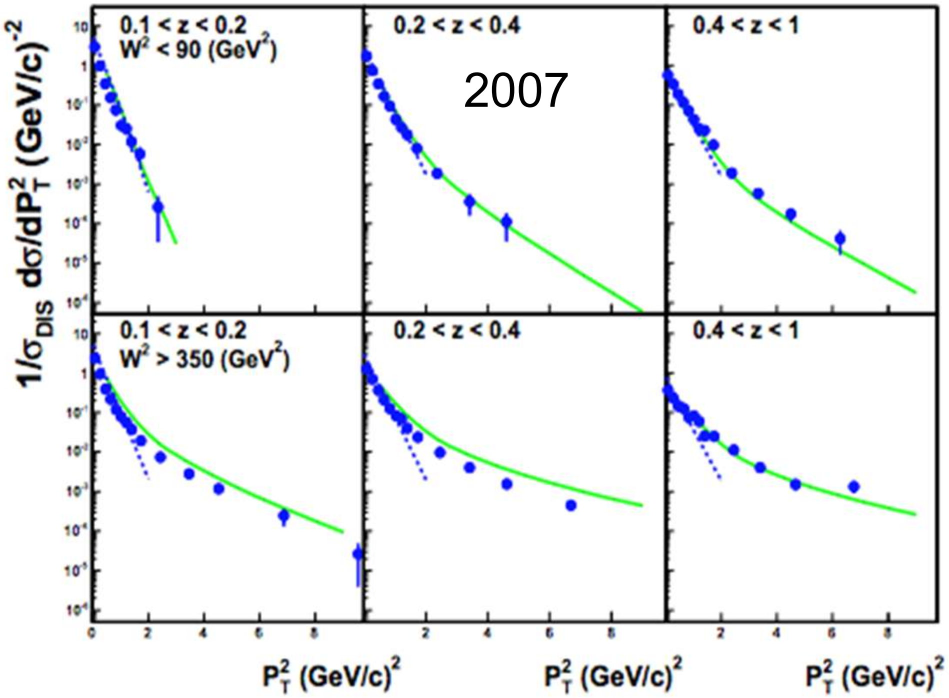
5) Increasing fraction of hadrons due to $F_{UU,L}$ (needed for proper interpretation
→ separation of $F_{UU,L}$ from total)
6) Significant contributions from VMs to low P_T pion multiplicities, with direct pions showing up at large P_T (needed for proper interpretation → much wider in k_T original parton 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)
....

Multiplicities of hadrons in SIDIS

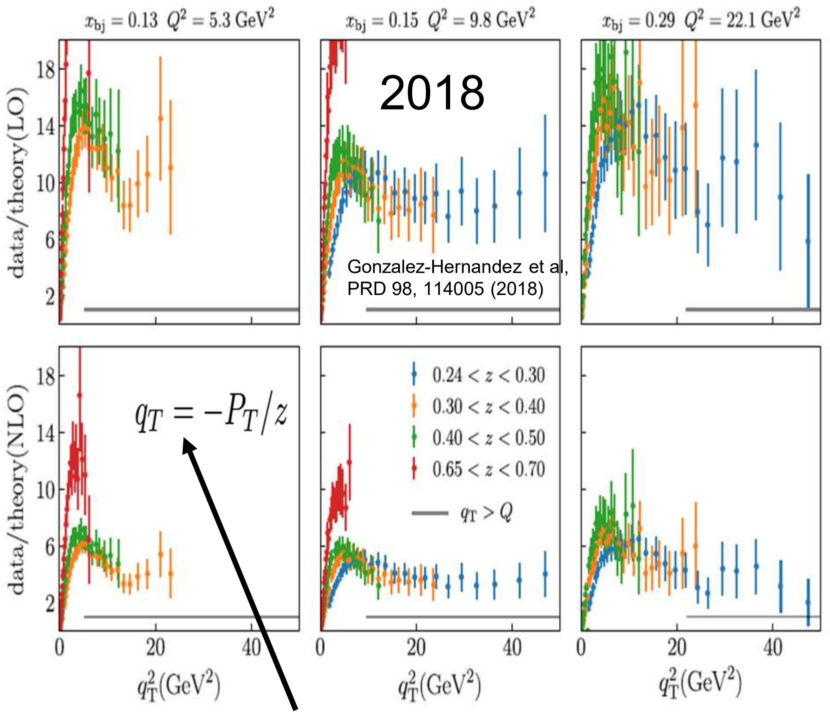
Anselmino et. al: hep-ph/0606286

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

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



Early attempts to use collinear and pQCD contributions (solid line) to fit EMC data



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

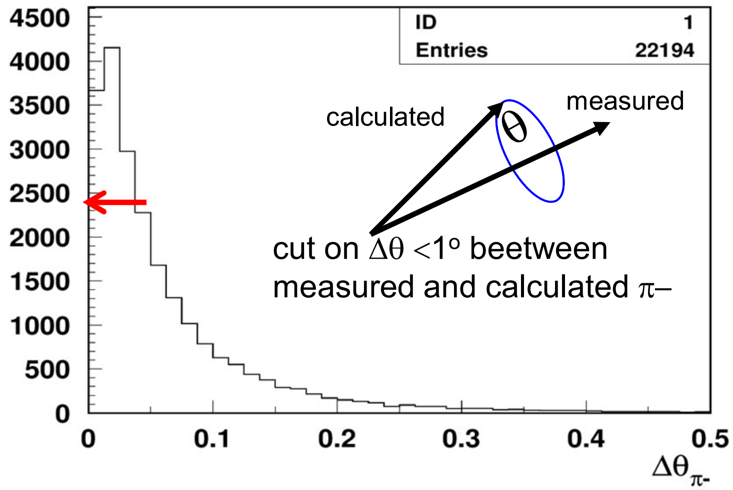
$q_T = -P_T/z$

quark transverse momentum, assuming a direct link with pion transverse momentum

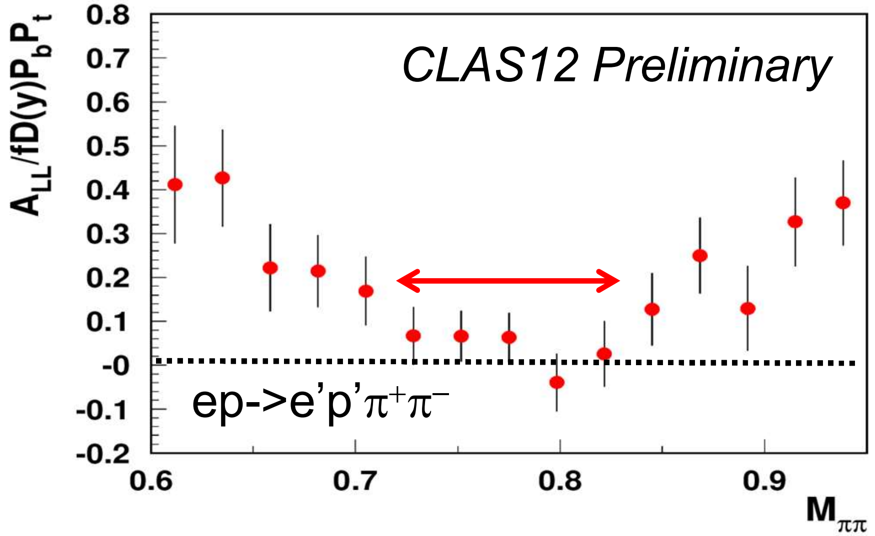
Perturbative contributions underestimate the multiplicities by an order of magnitude for all accessible kinematics at COMPASS

Studies of ρ^0 impact with longitudinally polarized NH_3 target

Separating exclusive dihadrons

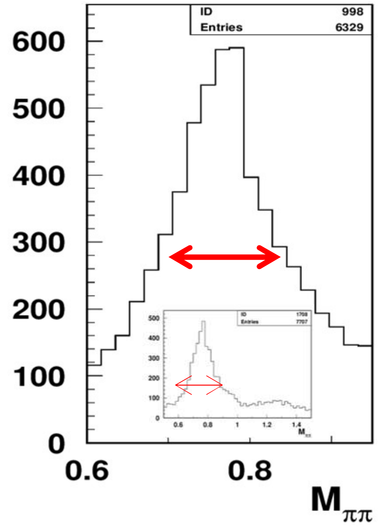


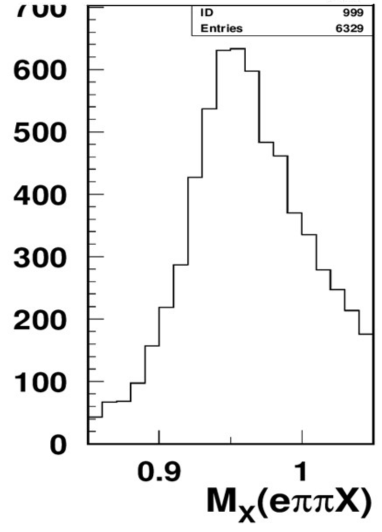
cut on $\Delta\theta < 1^o$ beetween measured and calculated $\pi-$



CLAS12 Preliminary

$ep \to e'p'\pi^+\pi^-$





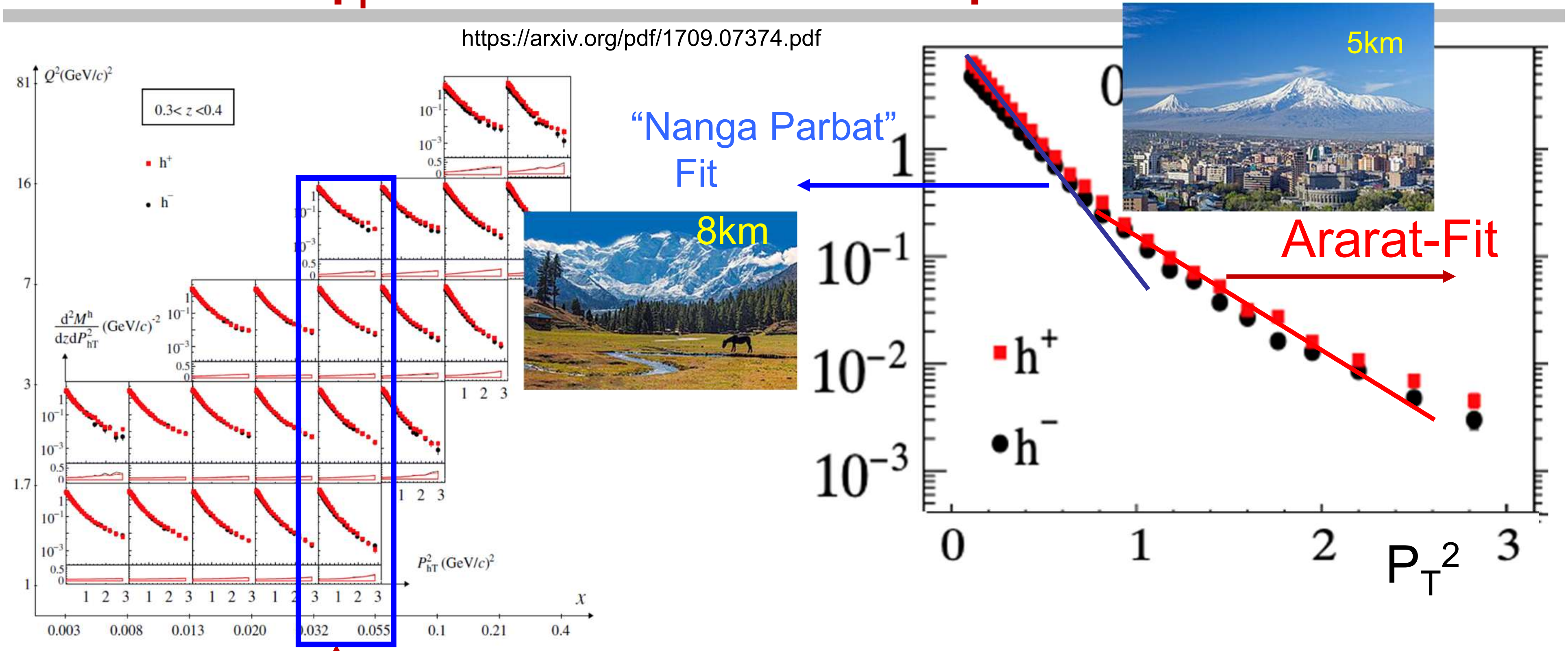
- Require the angle of negative pions is within a degree from calculated from e’,p,π+ assuming exclusive e’,p,π+π- event.

- Measurements of A_{LL} for ρ^0 indicate very small values (with ~10-20% bckg, likely negative ~ -2-10%), and can be one of the reasons for higher A_{LL} with protons with a M_X cuts above 1.35 GeV (excluding exclusive ρ^0)

Need clear separation of hydrogen from NH_3 and diffractive exclusive ρ0s from exclusive $\pi+\pi-$

q_T-crisis or misinterpretation

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



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

Higher the Q^2 lower the ε

→ less diffractive rho at higher Q^2 filling the low P_T in pion SIDIS.

Challenging for theory to explain the correlation of P_T and Q

need experimental subtraction of rhos (proton detection will help)

New procedure: Fit from P_{Tmin} up

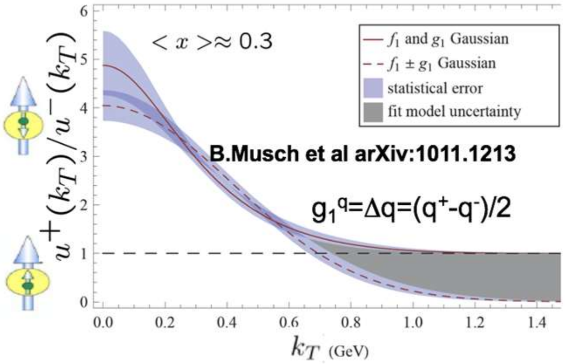
$P_T$min can be lower at higher Q^2, as the contributions from diffractive rho decreases with Q^2

Unknown “known” f_1,g_1 TMDs

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

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

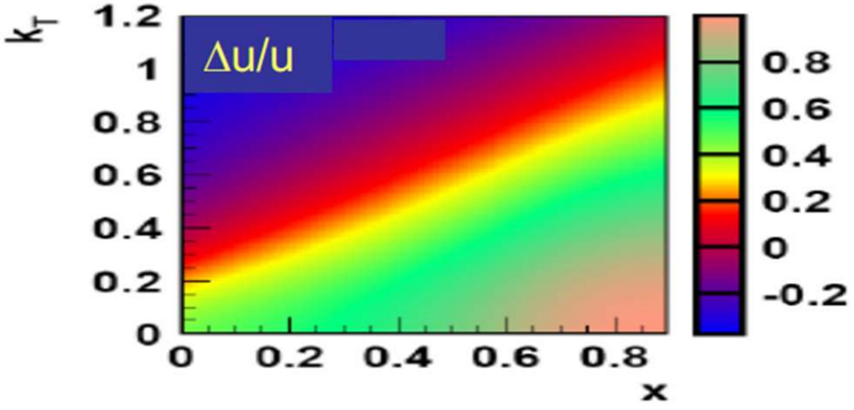
$$u^-(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$$

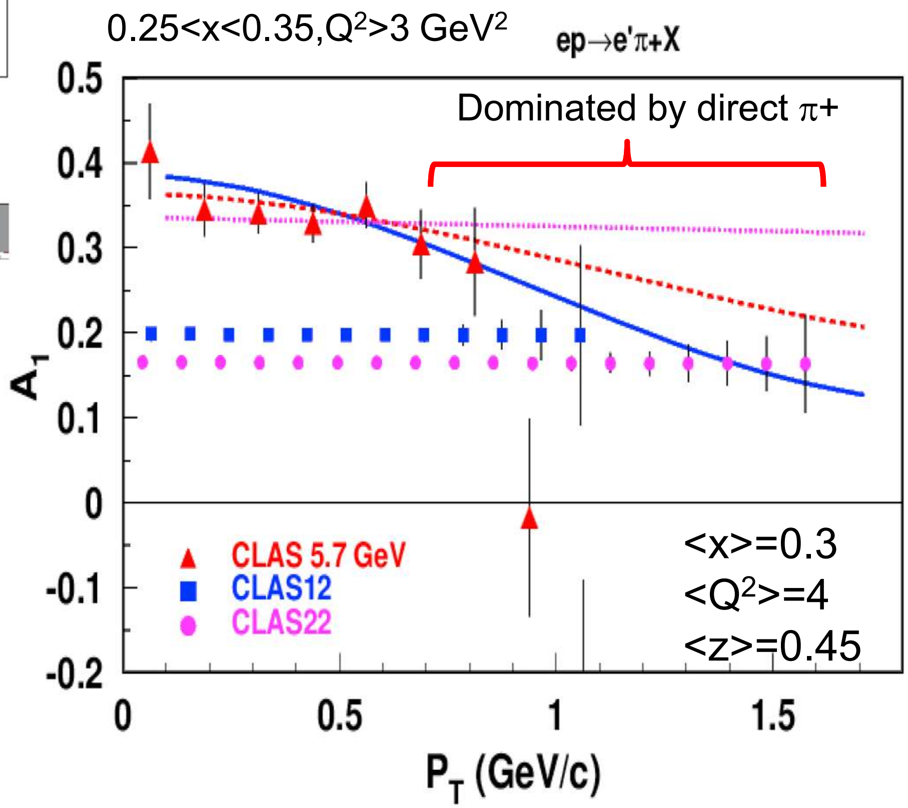


B.Musch et al arXiv:1011.1213

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

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

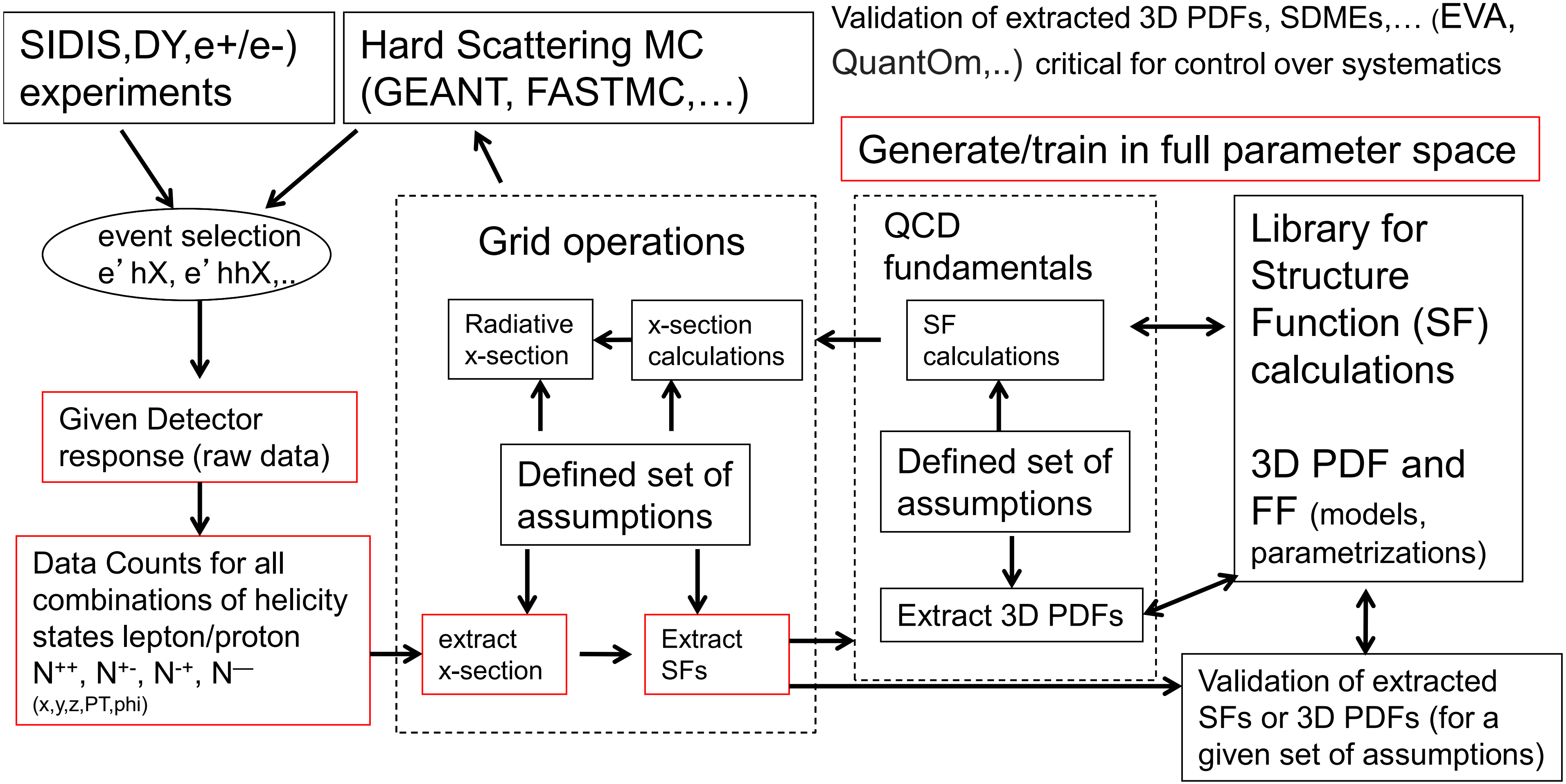




- Models and lattice predict very significant spin and flavor dependence for TMDs
- Large transverse momenta are crucial to access the large k_T of quarks
- Several CLAS12 proposals dedicated to $g_1(x,k_T)$-studies CLAS12
- Understanding of k_T-dependence of g_1 will help in modeling of f_1

3D PDF Extraction and VAlidation (EVA) framework

Validation of extracted 3D PDFs, SDMEs,… (EVA, QuantOm,..) critical for control over systematics



SIDIS,DY,e+/e-) experiments

Hard Scattering MC (GEANT, FASTMC,…)

Generate/train in full parameter space

event selection e’ hX, e’ hhX,..

Given Detector response (raw data)

Data Counts for all combinations of helicity states lepton/proton N^{++}, N^{+-}, N^{-+}, N^{--} (x,y,z,PT,phi)

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)

Direct extraction of a given parameter sets from all steps (marked red) using AI tools 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

x-section

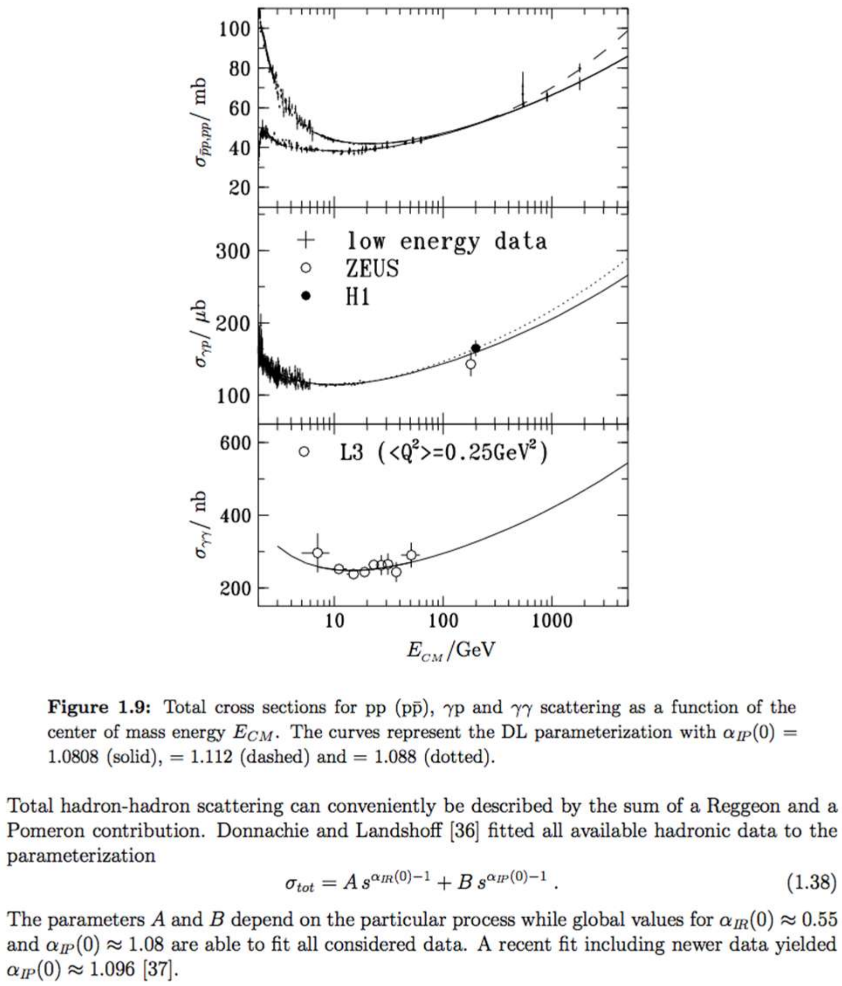


Figure 1.9: Total cross sections for pp ($p\bar{p}$), γp and $\gamma\gamma$ scattering as a function of the center of mass energy E_{CM}. The curves represent the DL parameterization with $\alpha_{I\!P}(0) = 1.0808$ (solid), $= 1.112$ (dashed) and $= 1.088$ (dotted).

Total hadron-hadron scattering can conveniently be described by the sum of a Reggeon and a Pomeron contribution. Donnachie and Landshoff [36] fitted all available hadronic data to the parameterization

$$\sigma_{tot} = A\, s^{\alpha_{I\!R}(0)-1} + B\, s^{\alpha_{I\!P}(0)-1} \,. \tag{1.38}$$

The parameters A and B depend on the particular process while global values for $\alpha_{I\!R}(0) \approx 0.55$ and $\alpha_{I\!P}(0) \approx 1.08$ are able to fit all considered data. A recent fit including newer data yielded $\alpha_{I\!P}(0) \approx 1.096$ [37].

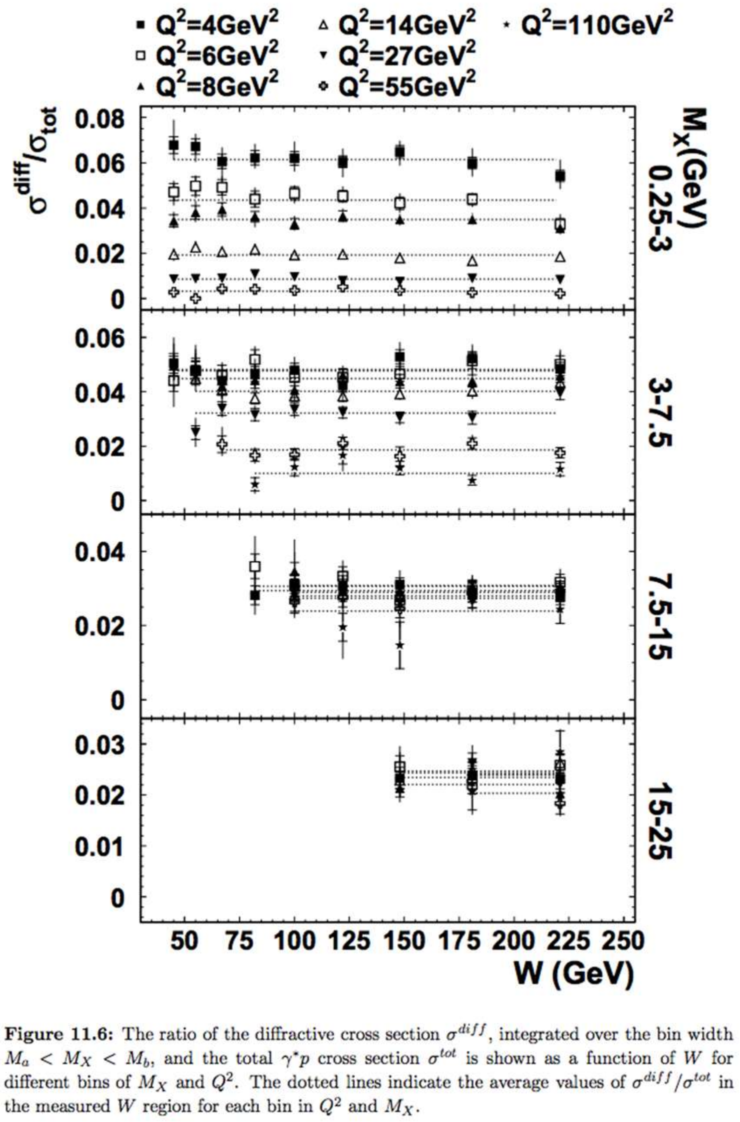
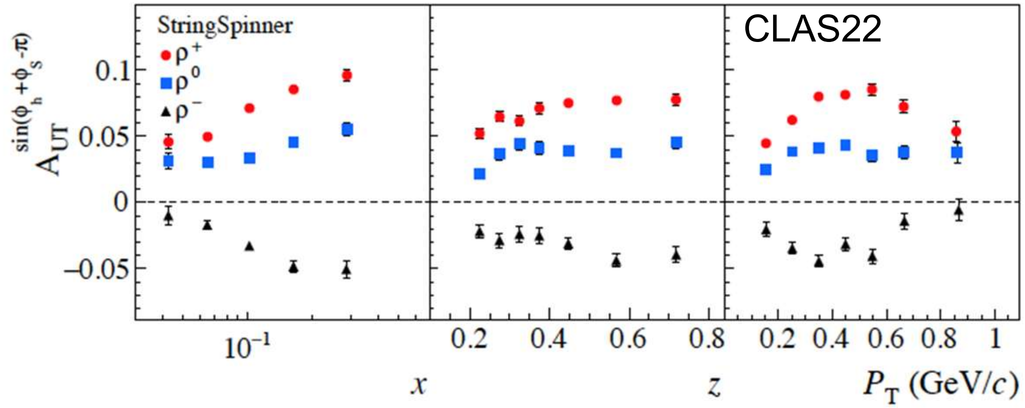
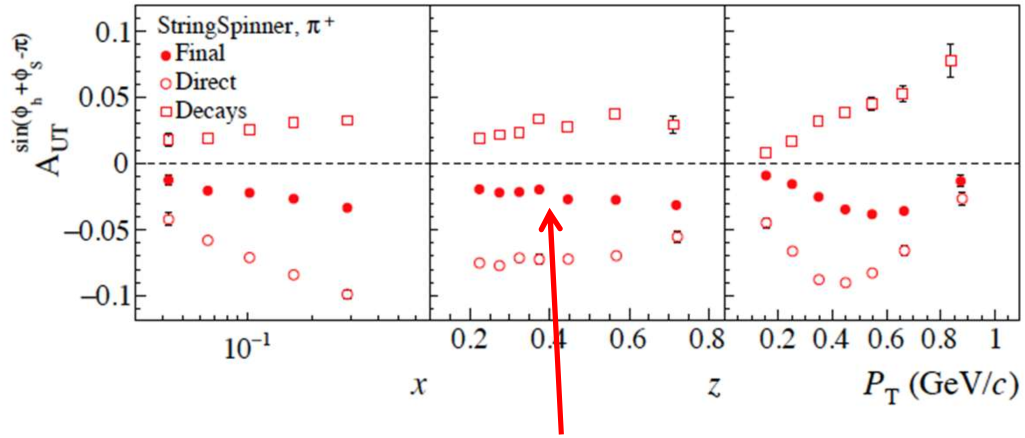


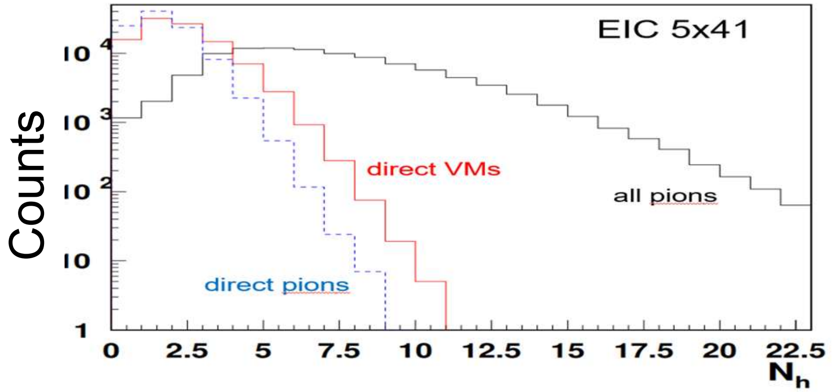
Figure 11.6: The ratio of the diffractive cross section σ^{diff}, integrated over the bin width $M_a < M_X < M_b$, and the total $\gamma^* p$ cross section σ^{tot} is shown as a function of W for different bins of M_X and Q^2. The dotted lines indicate the average values of $\sigma^{diff}/\sigma^{tot}$ in the measured W region for each bin in Q^2 and M_X.

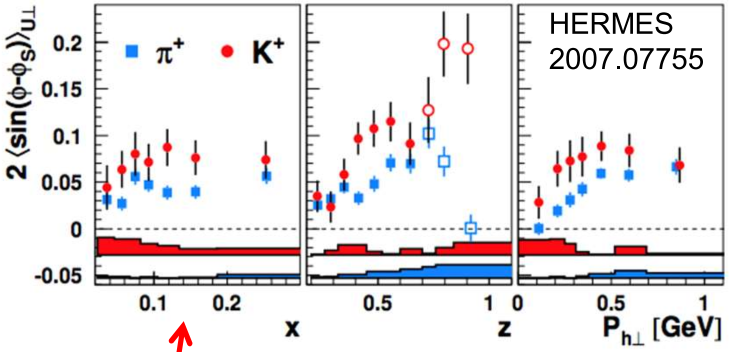
VM contributions

A. Kerbizi (Trieste U.)









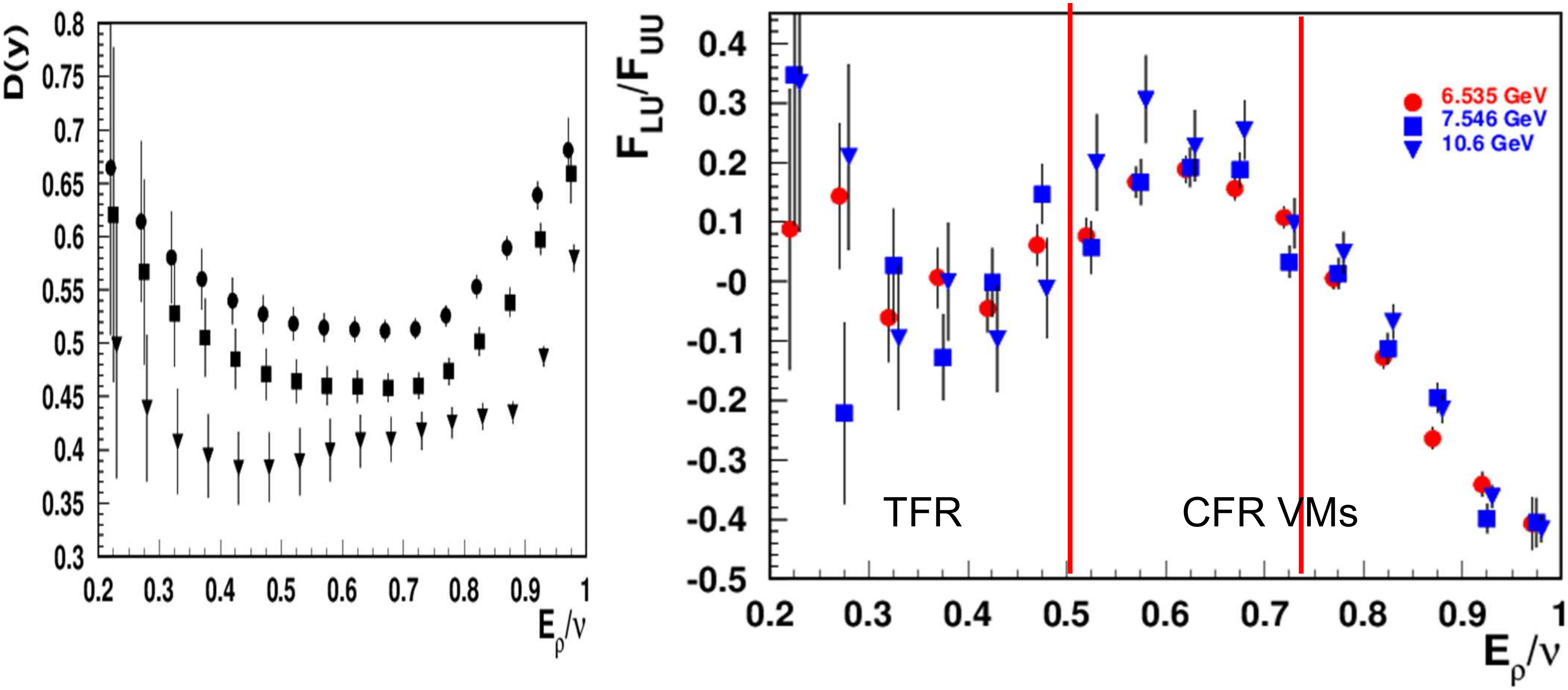
Strong dilution of SSAs(3-5 for pions 2-3 for Kaons) due to VM decays

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

VM contributions: z-dependence

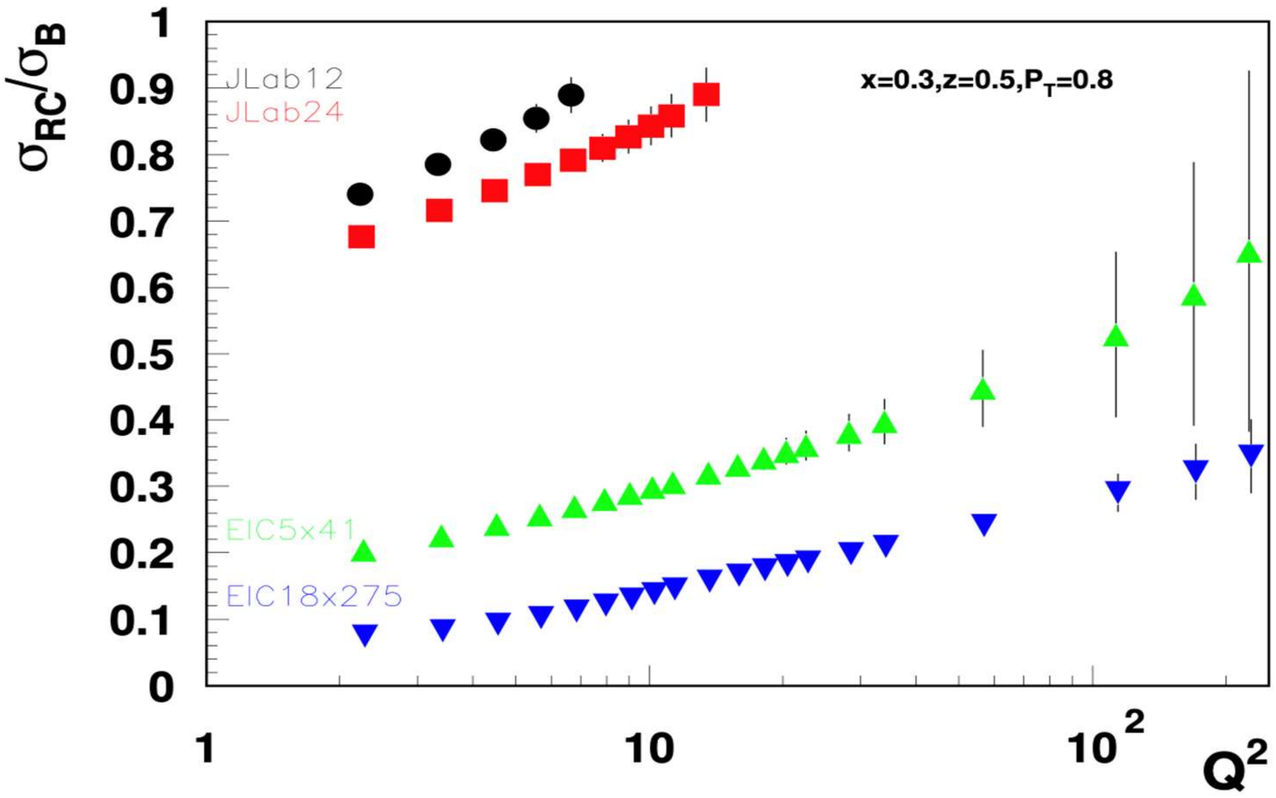


SSA significant, and changing sign in 2 points separating 3 distinct regions, which have completely different impact on π+ SSAs

From JLab to EIC: complementarity

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

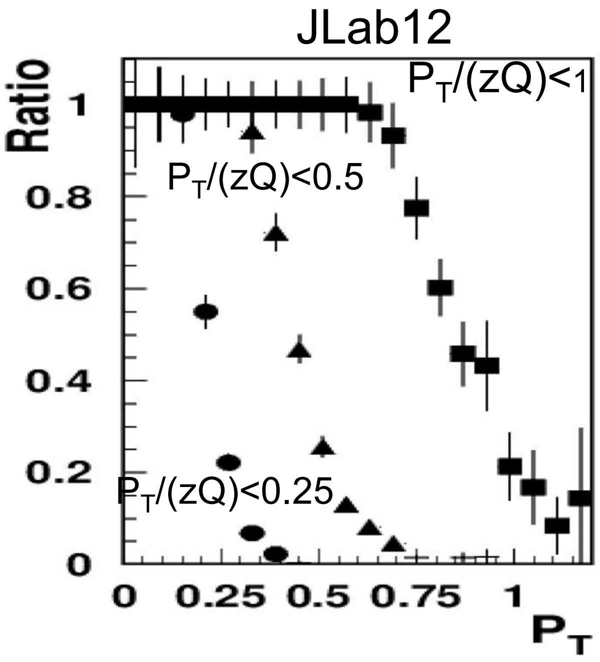
T. Liu et al
JHEP 11 (2021) 157
Gaussian F_{UU} (ϕ_h=0)

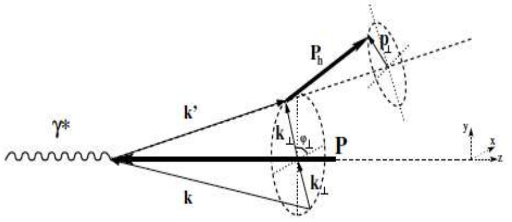


Cross section at low Q^2 suppressed at higher CM energies

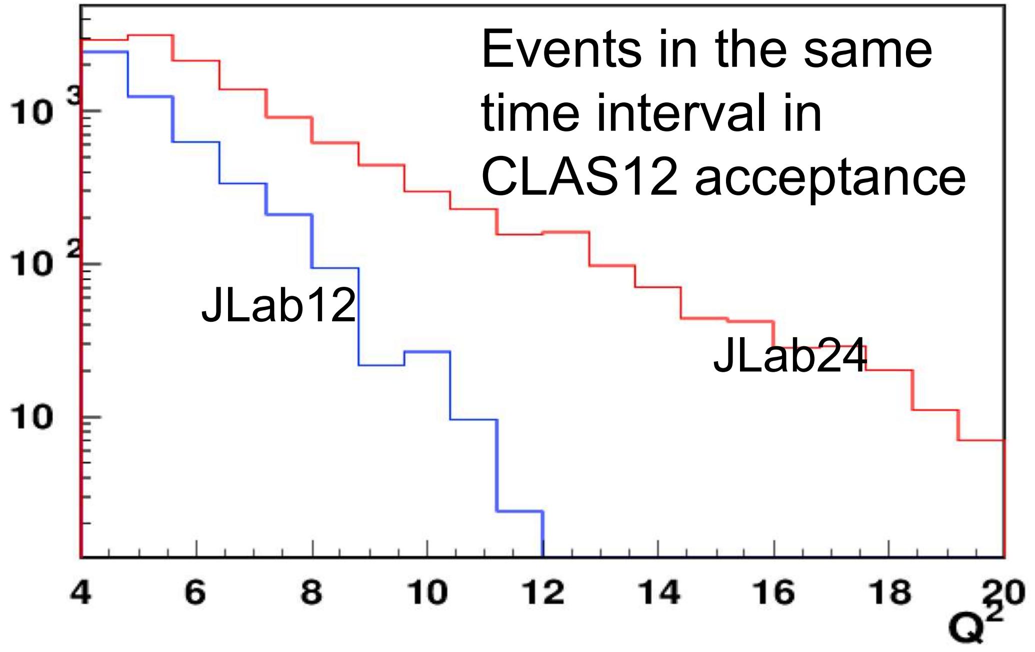
- The radiative effects in SIDIS may be very significant and measurements in multidimensional space at different facilities will be crucial for understanding the systematics in evolution studies.
- Most sensitive to RC will be all kind of azimuthal modulations sensitive to cosines

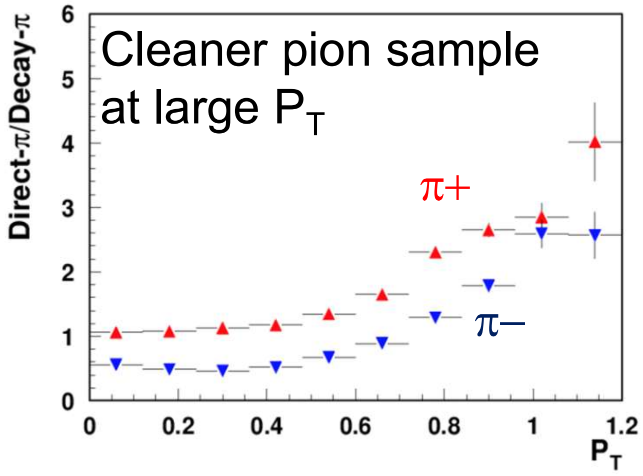
From JLa12 to JLab24 Larger Q^2 at large P_T





$$f_1^q(x, k_T) \otimes D_1^{q\to h}(z, p_T)$$


Events in the same time interval in CLAS12 acceptance


Cleaner pion sample at large P_T

JLab24 will significantly increase the the Q^2 range, allowing detailed separation of higher twist SFs, needed for understanding the QCD