Current and Target Fragmentation Region Correlations in SIDIS

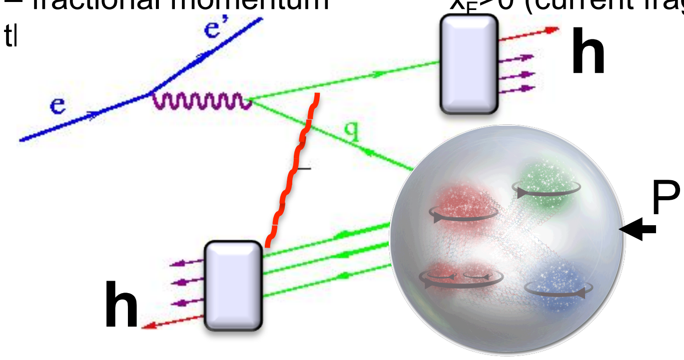
Harut Avakian (JLab)

- JLab and EIC: Complementarity and Synergy in the valence region
- Understanding of physics backgrounds→ need for multidimensional measurements critical for JLab and beyond
- Understanding the exclusive rho from identification and observables to SDMEs
- Understanding the Diffractive rho, impact on DIS/SIDIS and the need for MC
- Summary

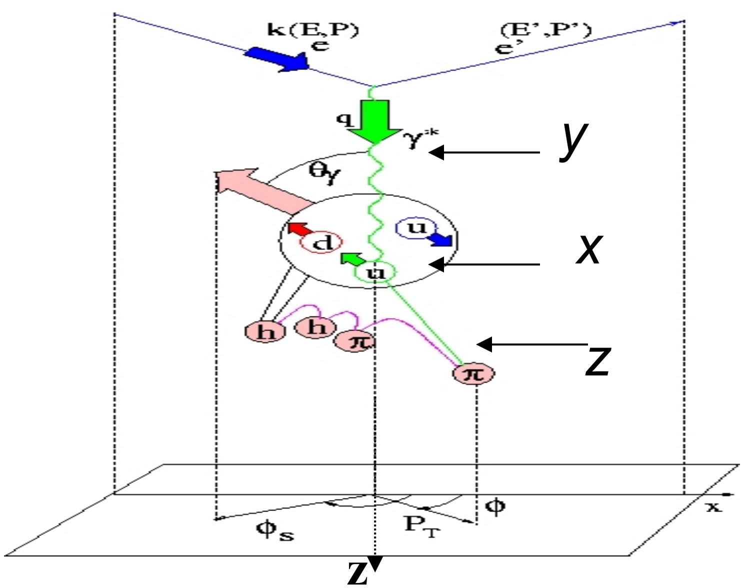
Polarized Leptoproduction

x_F – fractional momentum in tl

x_F>0 (current fragmentation, CFR)



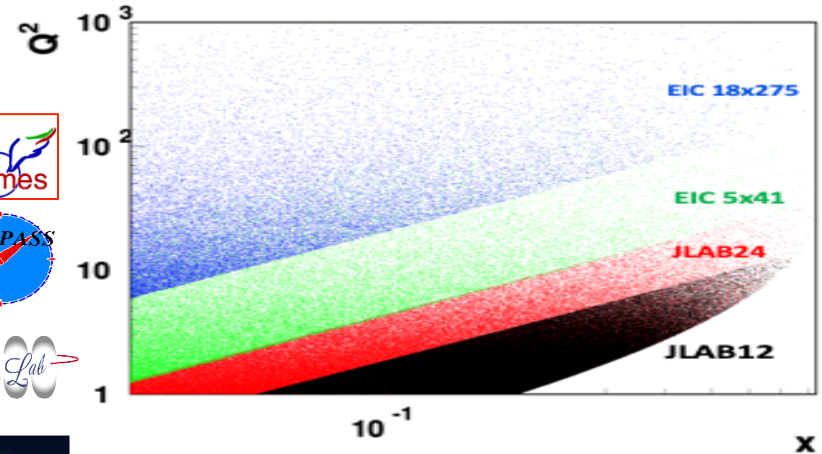
x_F<0 (target fragmentation,TFR)

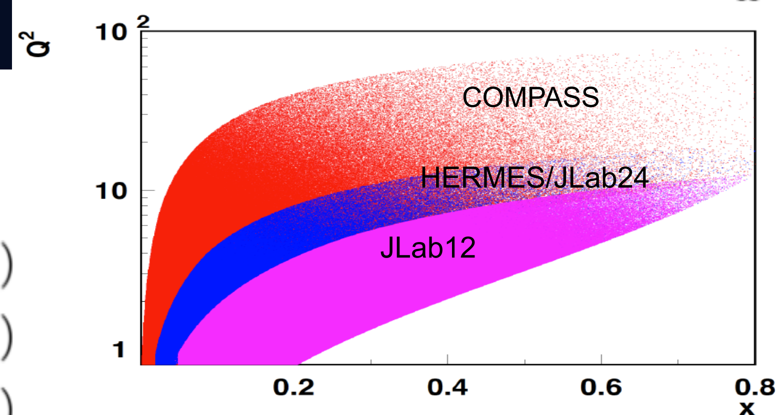


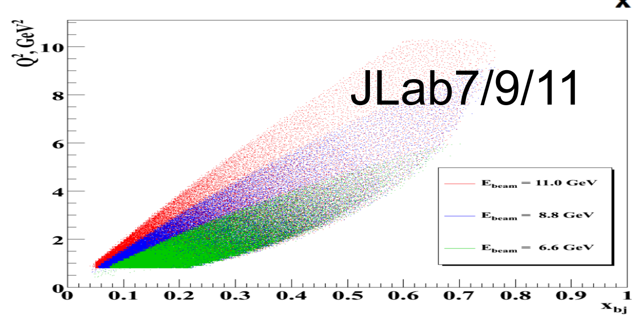
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

in eN→e'hX
6D $(x,Q^2,z,P_T,\phi,\phi_S)$

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





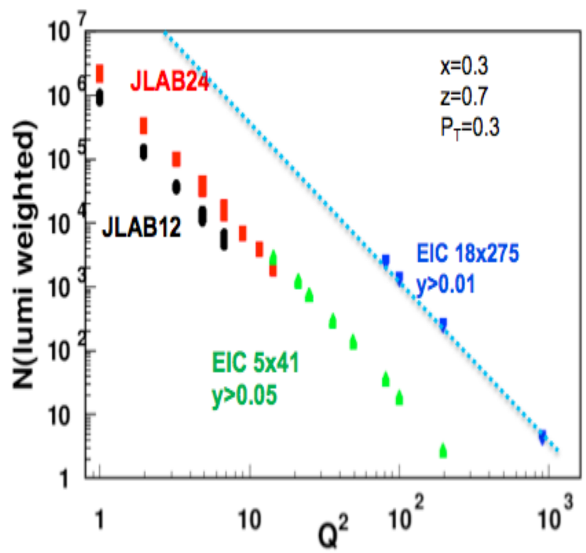


Structure functions and depolarization factors

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

x-section for eN→e'hX

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

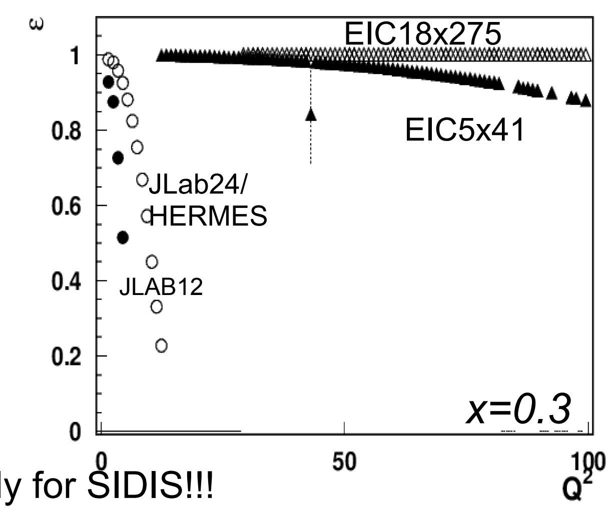


x-section from Bacchetta et al, 1703.10157

Measurements of correlations of spin and transverse momenta provides direct access to details of QCD dynamics

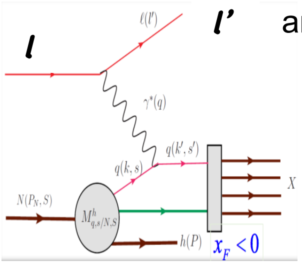
Combination of statistics and depolarization factors defines measurable SFs

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



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

Hadron production in TFR



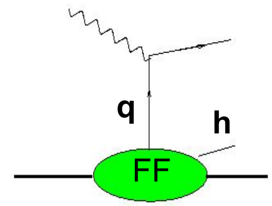
arXiv:2308.11251

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

unpolarized quarks in the longitudinally polarized proton

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

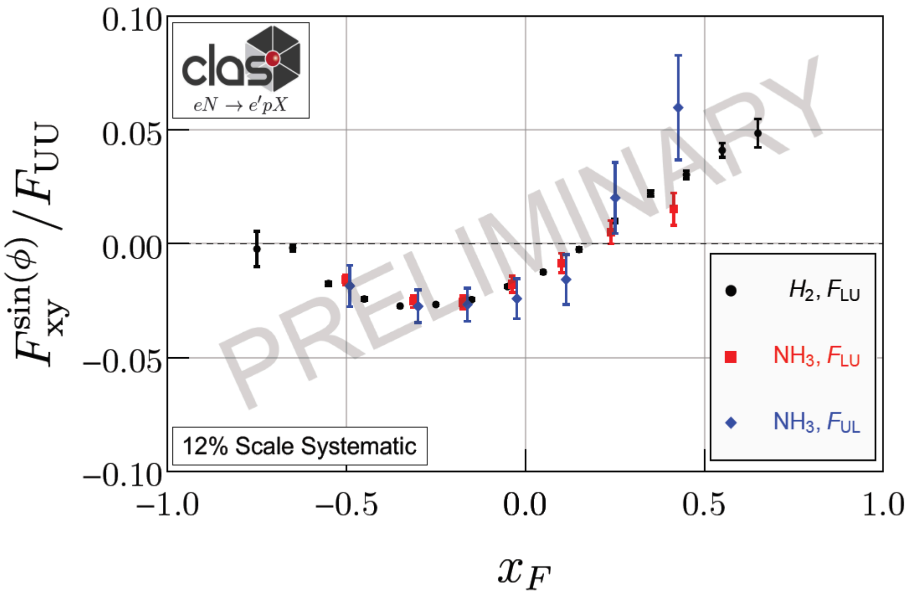
longitudinally polarized quarks in the unpolarized proton

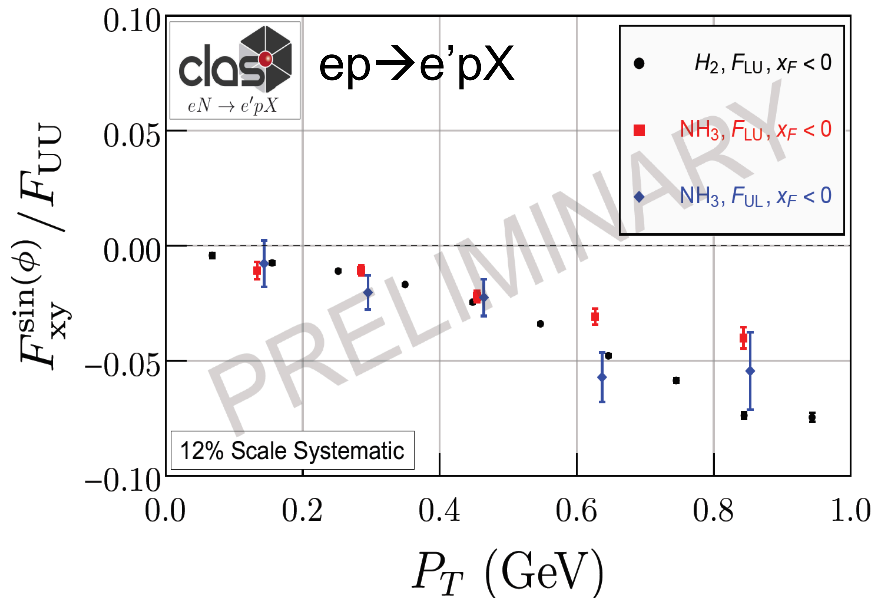


Conditional probability to produce a hadron ***h***, when kicking out quark ***q***

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

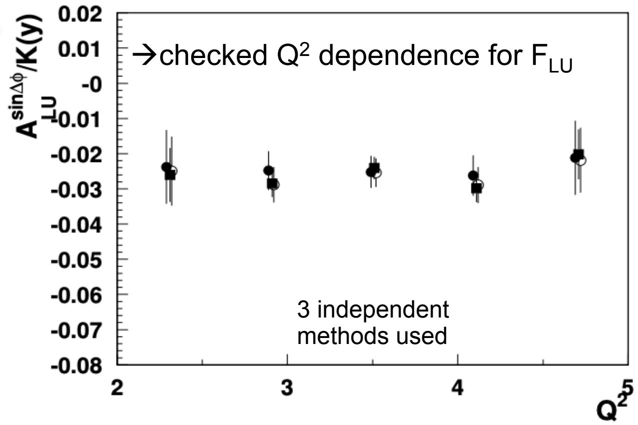
Azimuthal modulations in B2B production

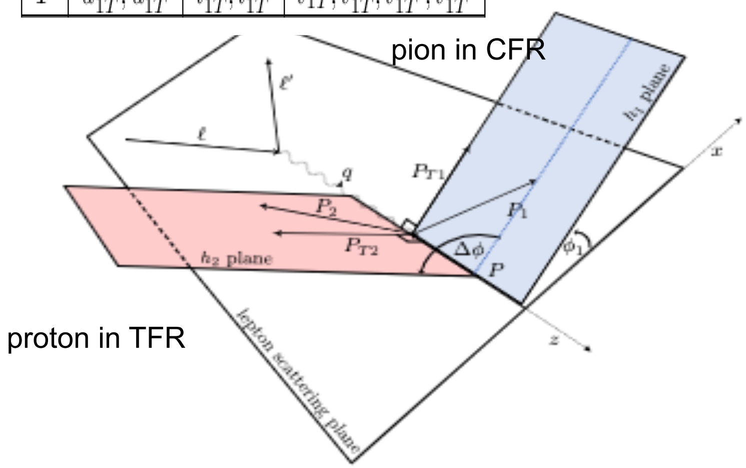
A. Kotzinian et al, arXiv:1107.2292

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

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

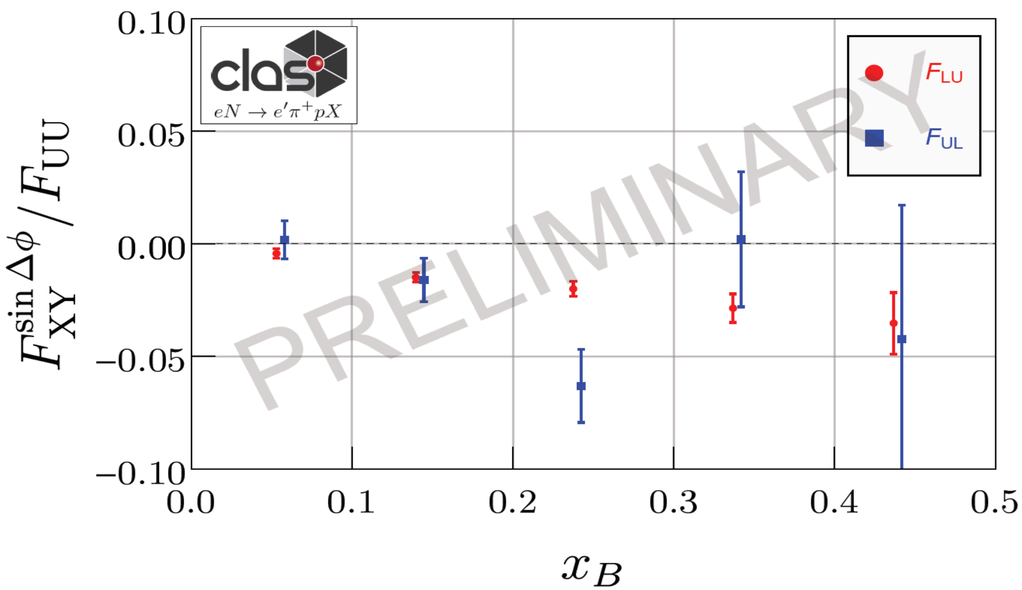
$$\sigma_{UL} = -\frac{P_{T1}P_{T2}}{m_N m_2} F_{k1}^{\hat{u}_{1L}^{\perp h}\cdot D_1} \sin(\Delta\phi)$$





→ F_{UL} and F_{LU} comparable (consistent with epX))

→ No suppression at higher energies for F_{UL}



Full CLAS12 longitudinally 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!

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

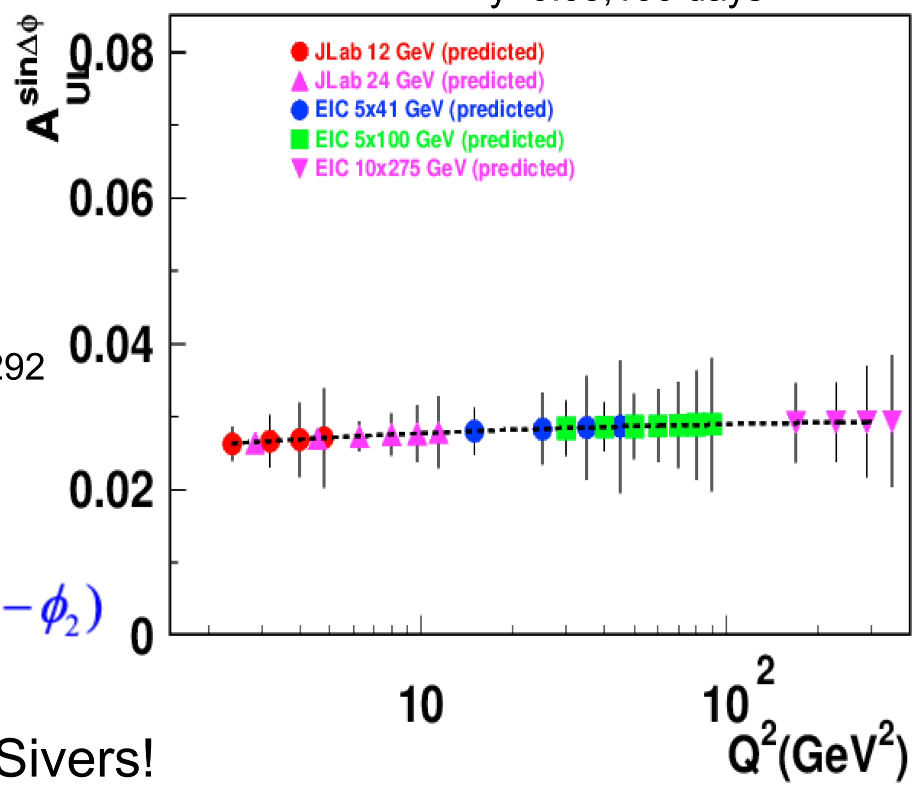
$$\sigma_{UU} = F_0^{\hat{u}\cdot D_1}$$

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

No depolarization, like Sivers!

+no known HT

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

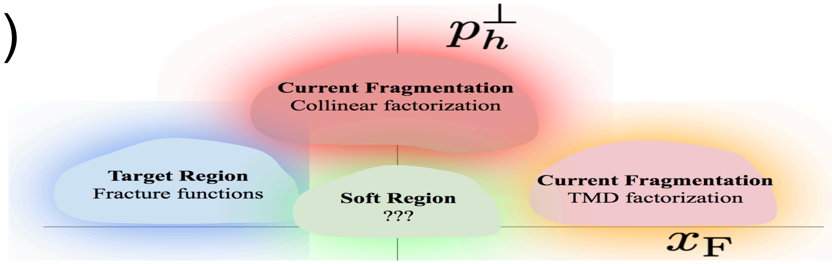
^{3}He
C12-20-002

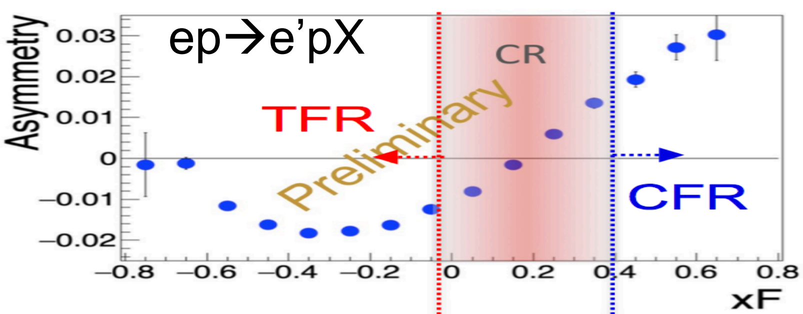
^{7}LiD
E12-14-001

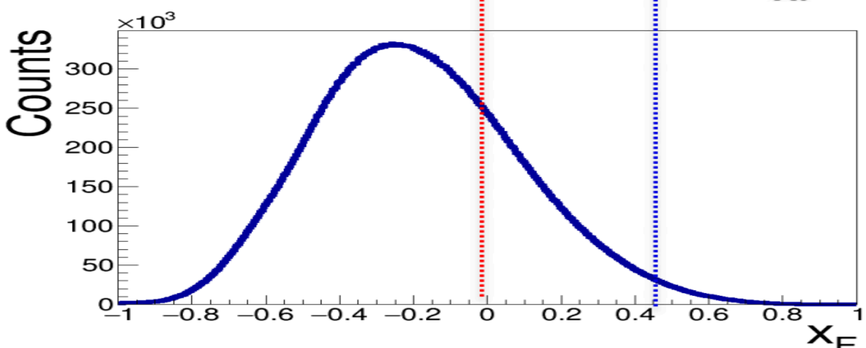
- Target SSA can be measured in the full Q^2 range, combining different facilities
- Advantages: Higher Lumi for JLab, no kinematical suppression at high Q^2 for EIC
- JLab24 will be crucial to bridge the studies of FFs between JLab12 and EIC in the valence region

Beam SSAs as a tool to separate regions and contributions

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

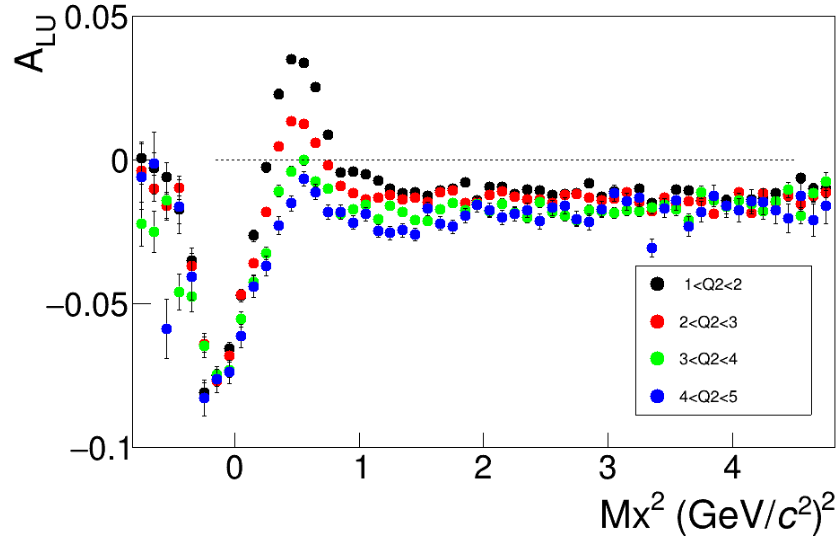






Negative sign of the SSA (plateau) defines the TFR dominance

F. Benmokhtar & Duquesne U.

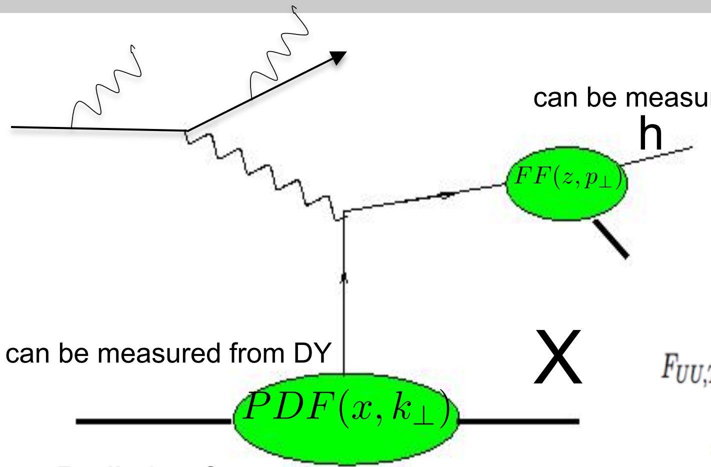


Major difference only for protons at small t!

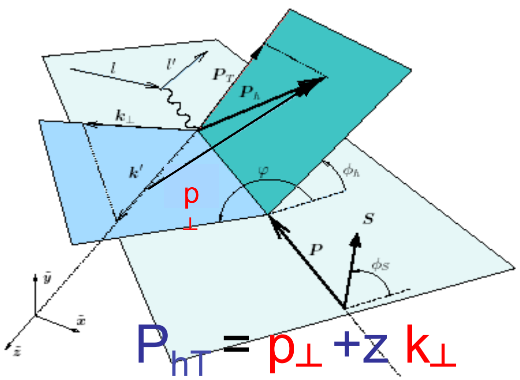
With beams in polarized SIDIS typically always polarized, beam SSA can serve as a tool to separate

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

SIDIS as THE theory describes it



+Radiative Corrections



Probability to produce 1 or 2 hadrons in single photon exchange

$$eN \to e'hX$$

$$\frac{d\sigma}{dx\, dy\, d\phi_S\, dz\, d\phi_h\, dP^2_{h\perp}}$$

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

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

hard part

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, $Q^2 >> 1$, $k_\perp/Q << 1$

Conclusions in case of apparent disagreement:

"much bigger/smaller" defined in comparison with experiment

1)factorization is broken?
2)<u>unaccounted terms may contribute (assumptions are not good in certain kinematics,…)</u>

Data has it all!!! Dealing with unaccounted terms:
- Theory accounts for them (ex. VMs)
- Experiment measures and excludes them!!! (ex.VMs)

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”)

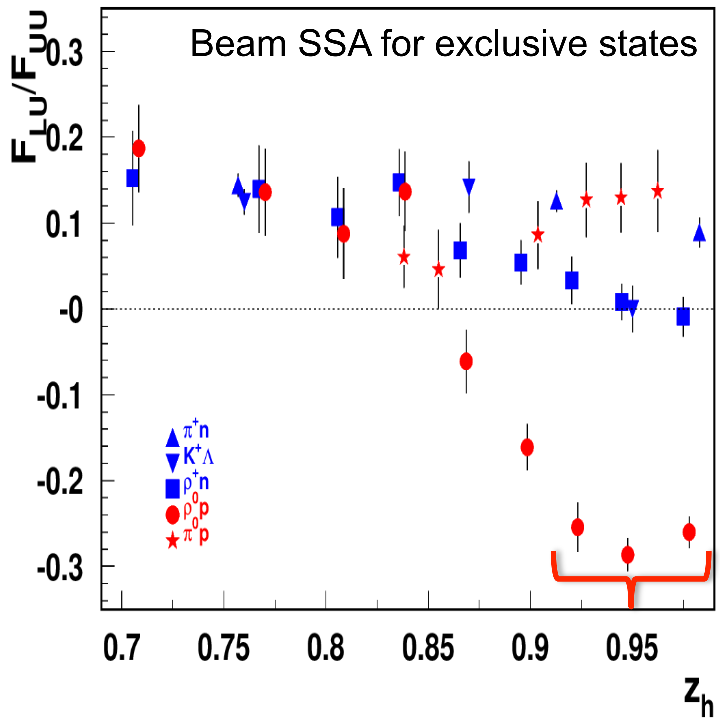
→requires measurements of pions from diffractive rho in multidimensional space, means detailed studies of SDMEs of rhos, requiring good precisions and huge statistics, develop MC (ex. HEPGEN) also for all polarization observables, extensive validation needed, little known RC

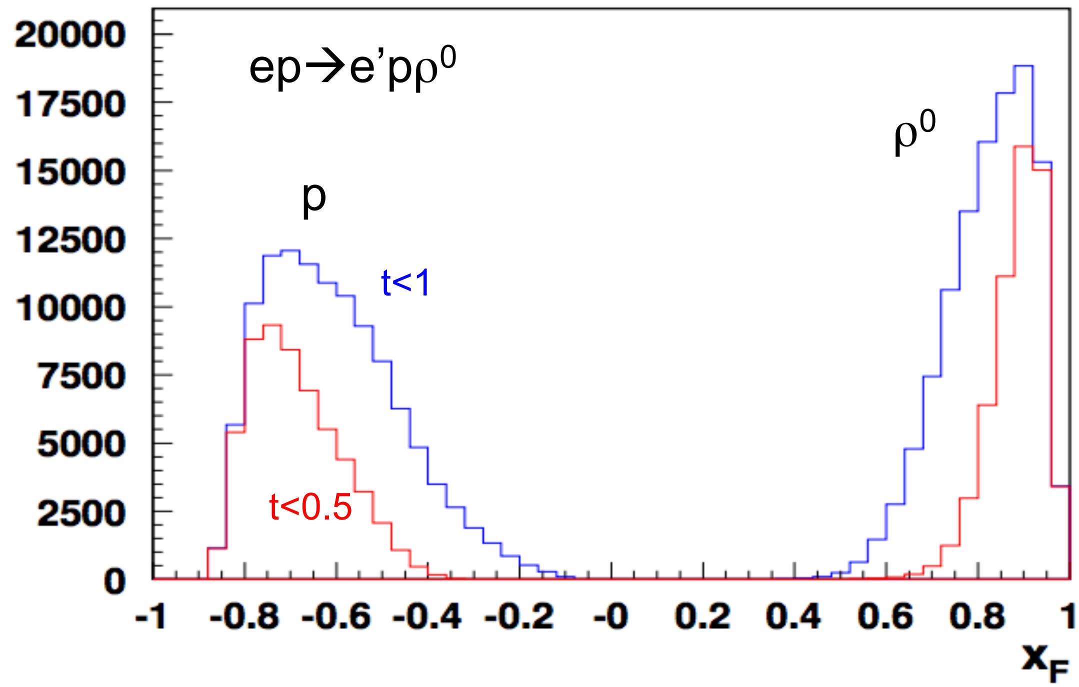
3) SIDIS subsamples (eN→epπX, eN→e$\pi\pi$X) within the full accessible kinematics, allowing clear eliminiation of rho0 contributions using cuts on missing masses of epX or e$\pi\pi$X (“rho-free SIDIS”)

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

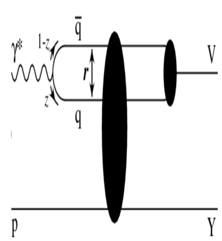
requires measurements of dependence on M_X to understand the bias,
Theory should be able to evaluate the bias from the presence of an additional hadron

"diffractive" VMs: rapidity gap





Diffractive VMs (ρ^0)



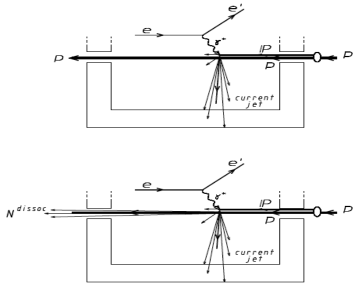
Significant rapidity gap between protons (backward) and rho (forward)

What is the fraction of VMs in DDIS?

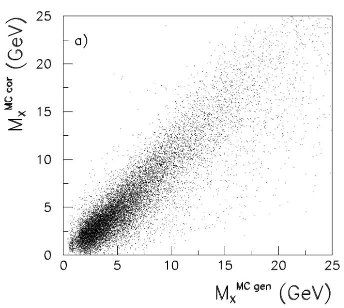
What is the relative fraction of VMs as a function of W and Q^2?

Identify kinematics of "diffractive" ρ^0 by comparison with ρ^+

Measured x-section: DDIS vs DIS

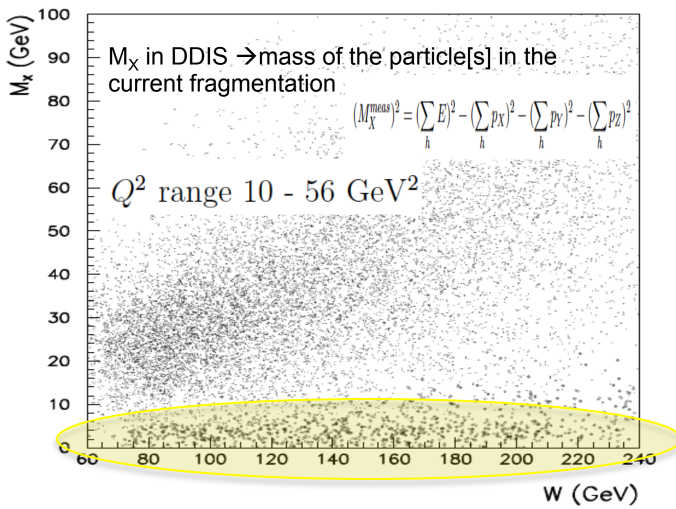


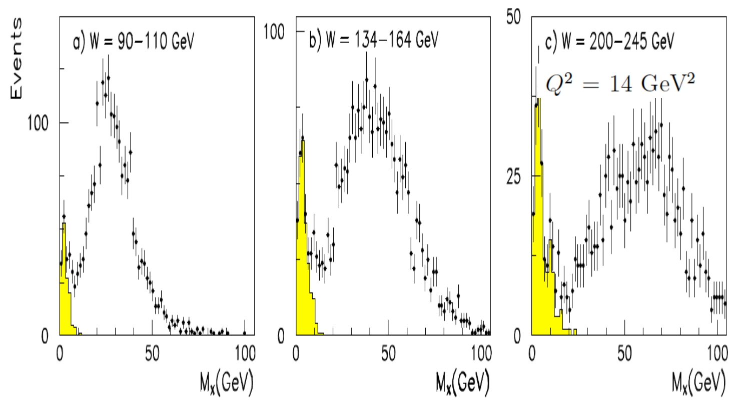
$\sigma_E/E = 18\%/\sqrt{E}$



Week increase with W in photoproduction
Strong increase in electroproduction (longitudinal rho?)

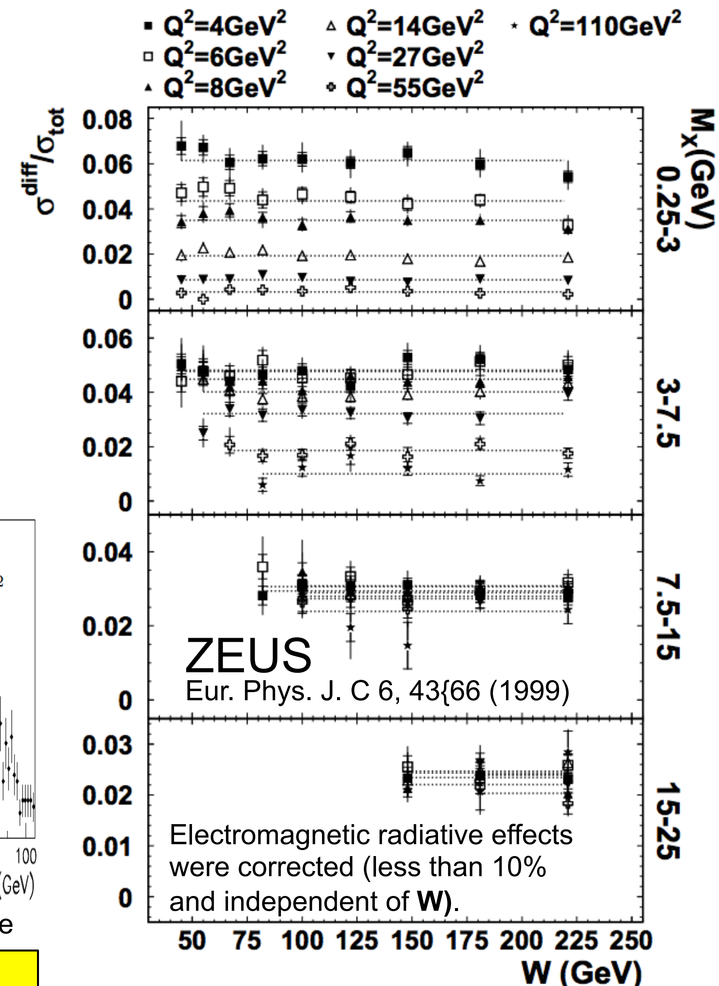
η is defined as $-\ln(\tan\frac{\theta}{2})$.





For η_{max} < 1.5 the contribution from nondiffractive scattering is expected to be negligible

No dependence of DDIS/DIS on W, decrease with Q^2 indicating the VMs can be the main contributor
At higher M_X there seem to be no Q^2-dependence



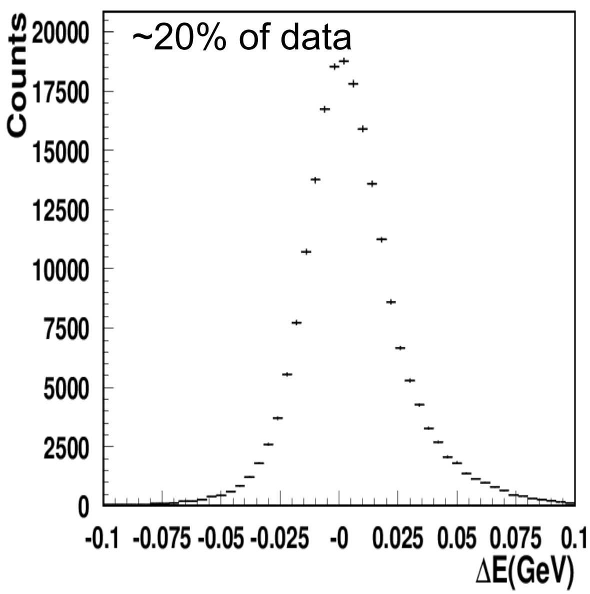
ure 11.6: The ratio of the diffractive cross section σ^{diff}, integrated over the bin width $< M_X < M_b$, and the total $\gamma^* p$ cross section σ^{tot} is shown as a function of W for erent bins of M_X and Q^2. The dotted lines indicate the average values of $\sigma^{diff}/\sigma^{tot}$ in measured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

CLAS12 Experiments involved: Exclusive rhos

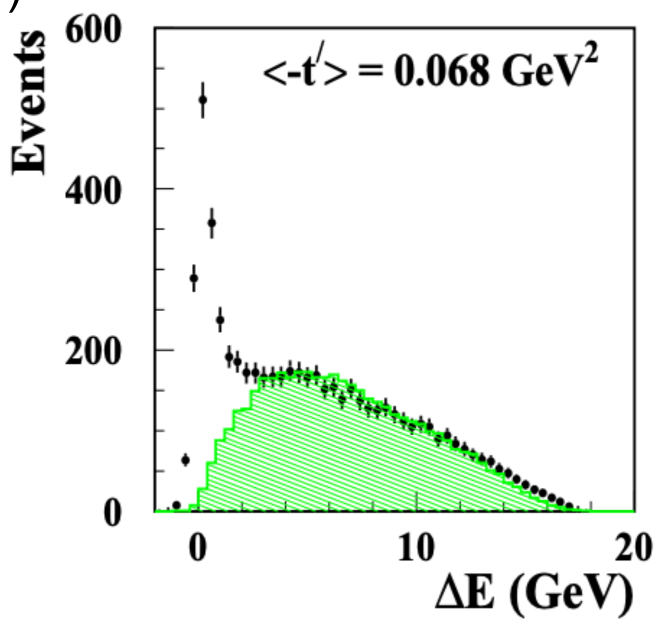
Exclusivity condition defined by the missing Energy:

$$M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2 \qquad E_{miss} = \frac{M_X^2 - M^2}{2M}$$

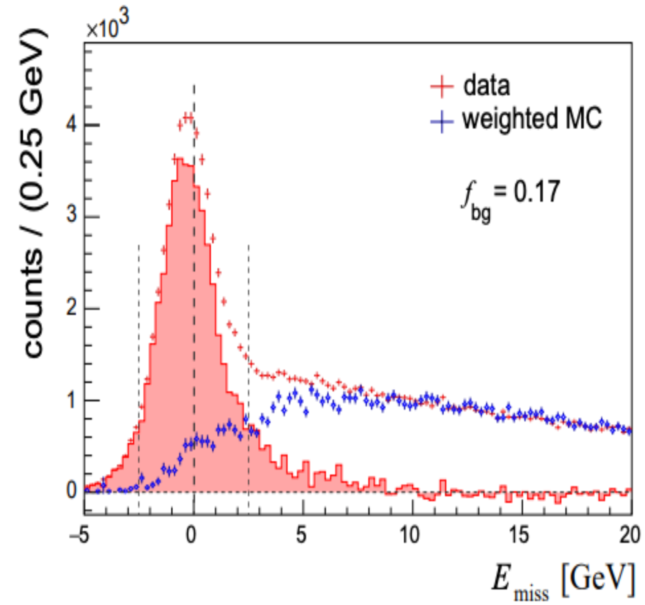
CLAS12 (width <0.1GeV)



HERMES(width ~0.6GeV)

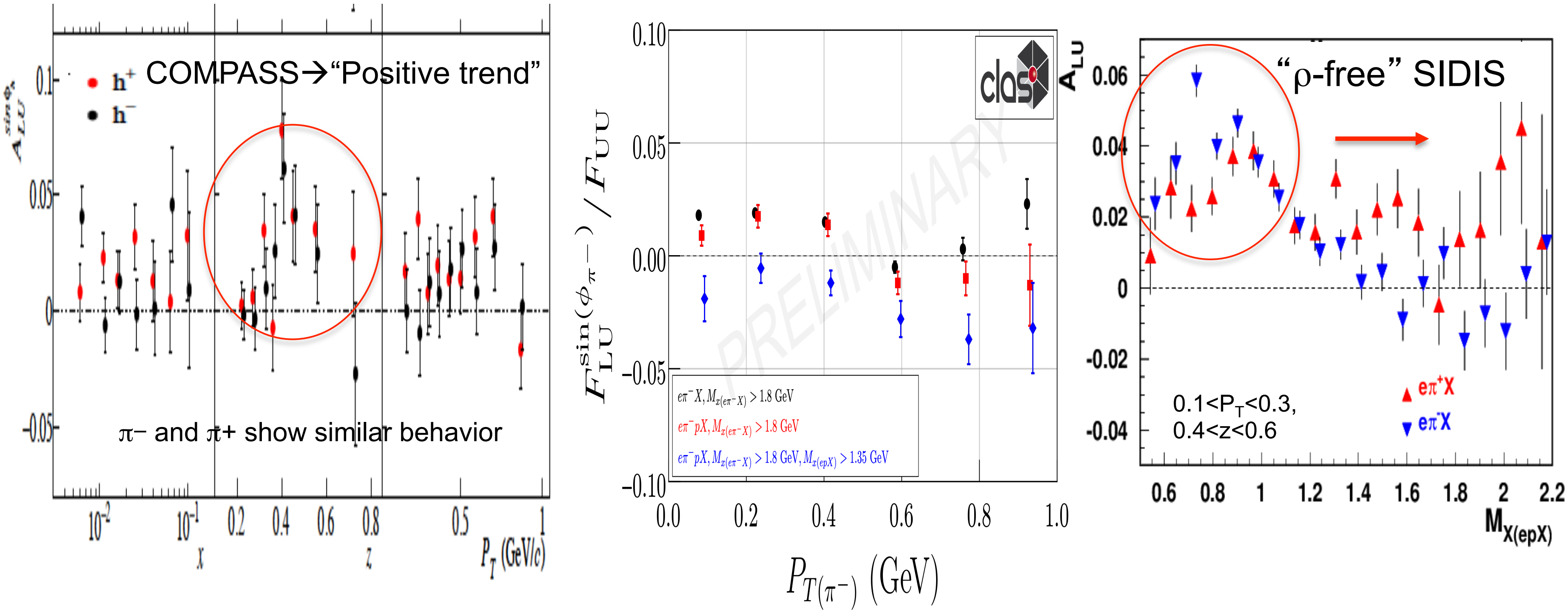


COMPASS(width ~2GeV)



- 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 tails, indicating the RC may not be negligible
- Extraction of SDMEs, will require validation in the multi-D space (significant samples)

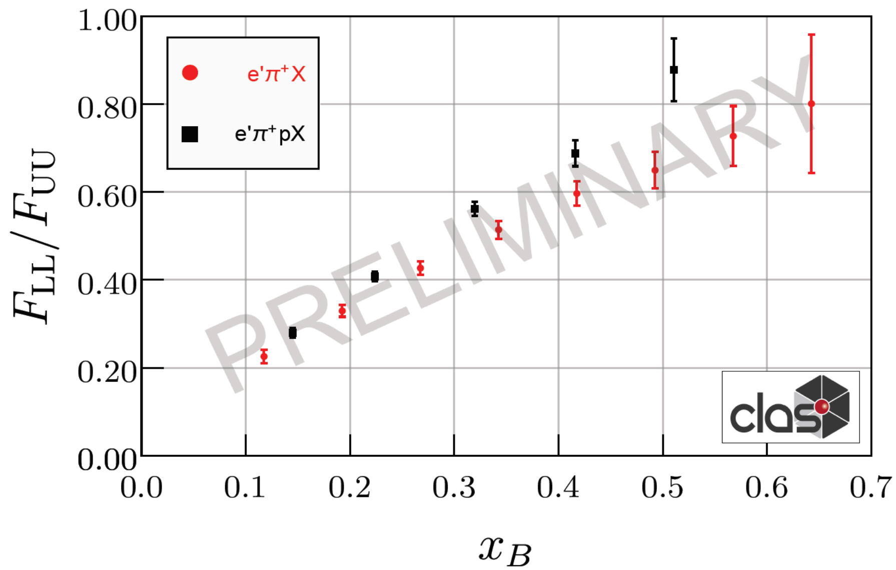
Exclusive ρ contributions to π: P_T-dependence



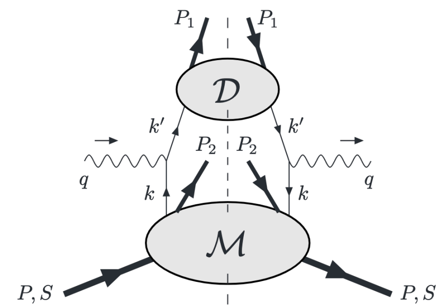
COMPASS→“Positive trend” also reproduced
when additional proton in TFR detected (red)

- 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%
- Detection of the target proton introduces much smaller bias on the inclusive charged pion SSA, than the exclusive rho contributions

Longitudinally polarized quarks in B2B SIDIS

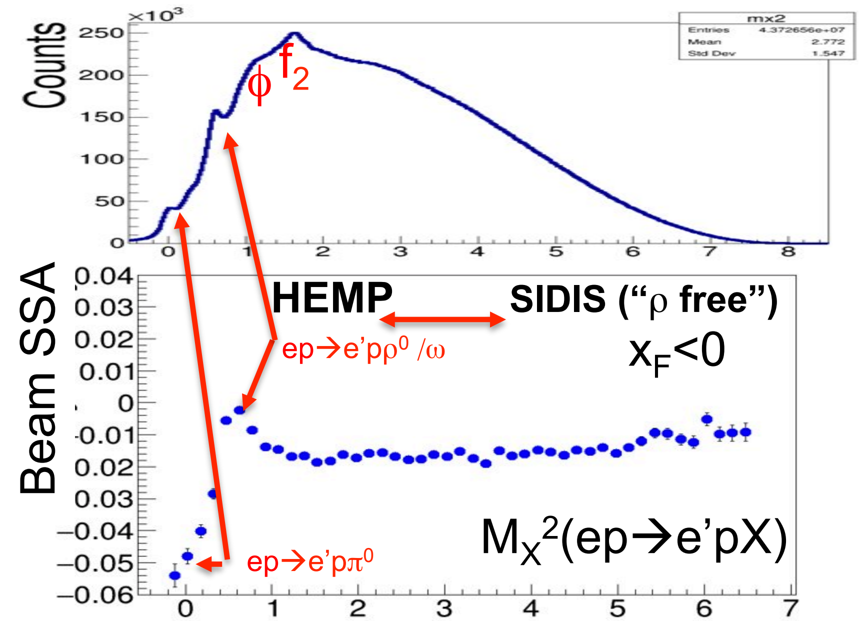


ep→e'pπX



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!



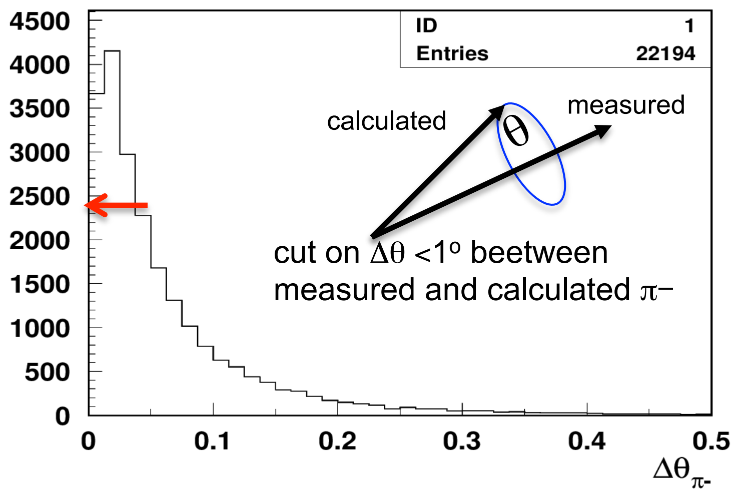
Possible theory formalisms:

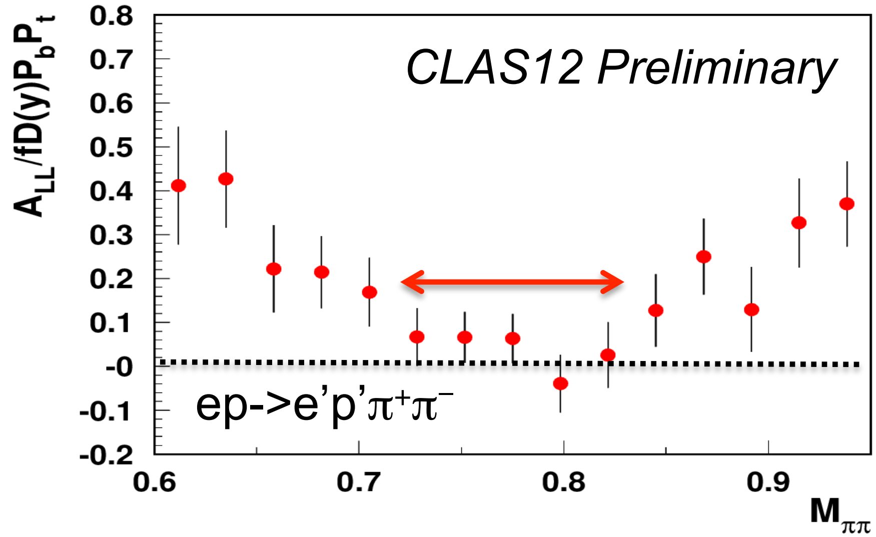
- **Formalism based on fracture functions (Anselmino, Barone, Kotzinian (back-to-back, b2b, hadron production, DSIDIS)**
- **Semi-exclusive processes, involving GPDs/GTMDs on proton side (TFR) and FFs on pion side (CFR) Yuan and Guo**

- 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!!!

Studies of ρ^0 impact with longitudinally polarized NH_3 target

Separating exclusive dihadrons

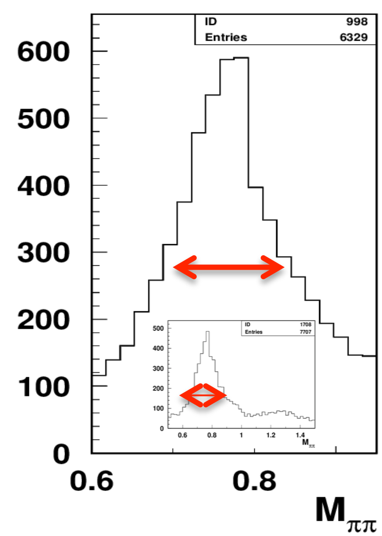


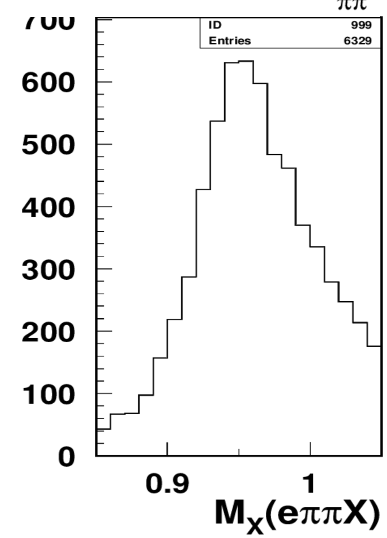


- Require the angle of negative pions is within a degree from calculated from e',p,π+ assuming exclusive e',p,π+π- event.

- Measurements of A_{LL} for ρ^0 indicate very small values (with ~10-20% bck, 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)

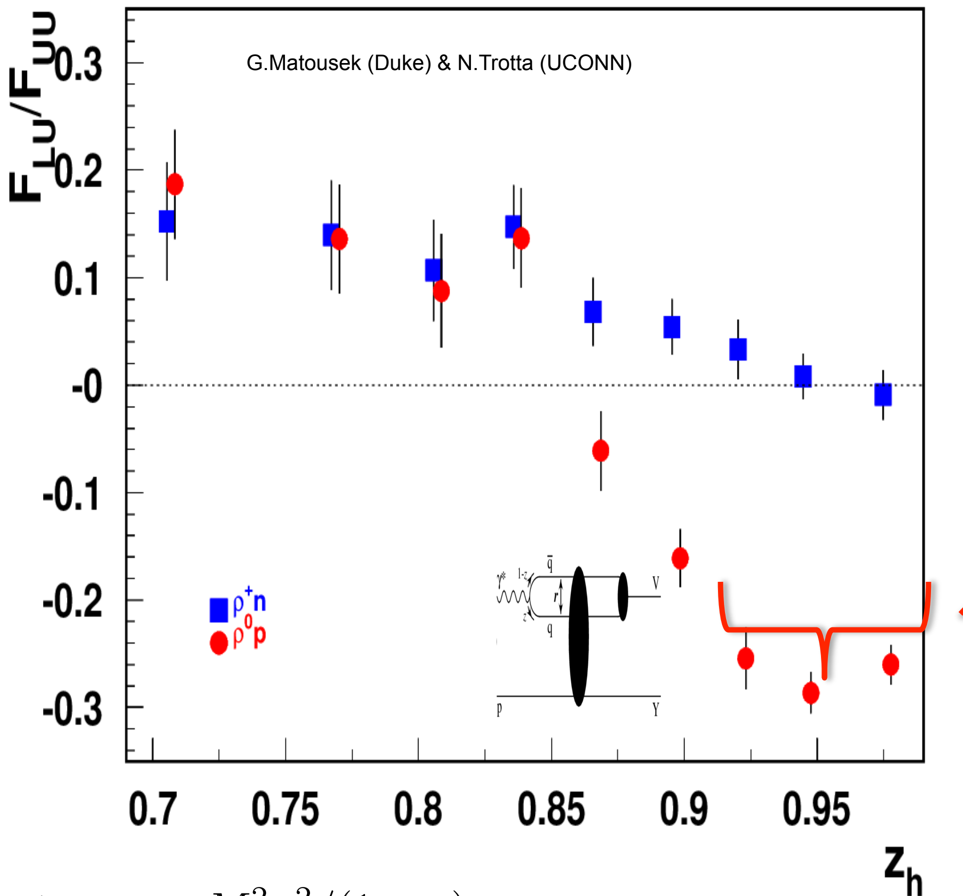
Request to theory→ evaluate the impact on $g_1(x,k_T)$ with all A_{LL}s increasing 10-20%



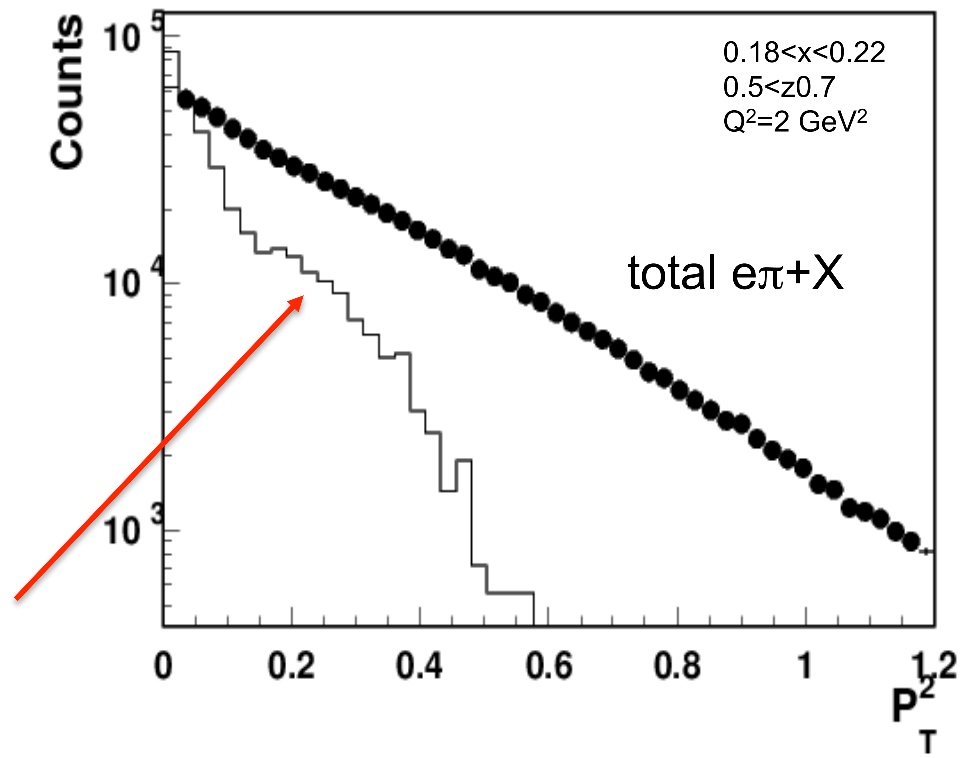


Need clear separation of hydrogen from NH_3 and diffractive exclusive ρ0s from exclusive π+π−

“diffractive rho0s” in SIDIS multiplicities



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



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

The “diffractive” rho will bias extractions of TMDs, unless properly subtracted in multidimensional space of SIDIS measurements.

SUMMARY

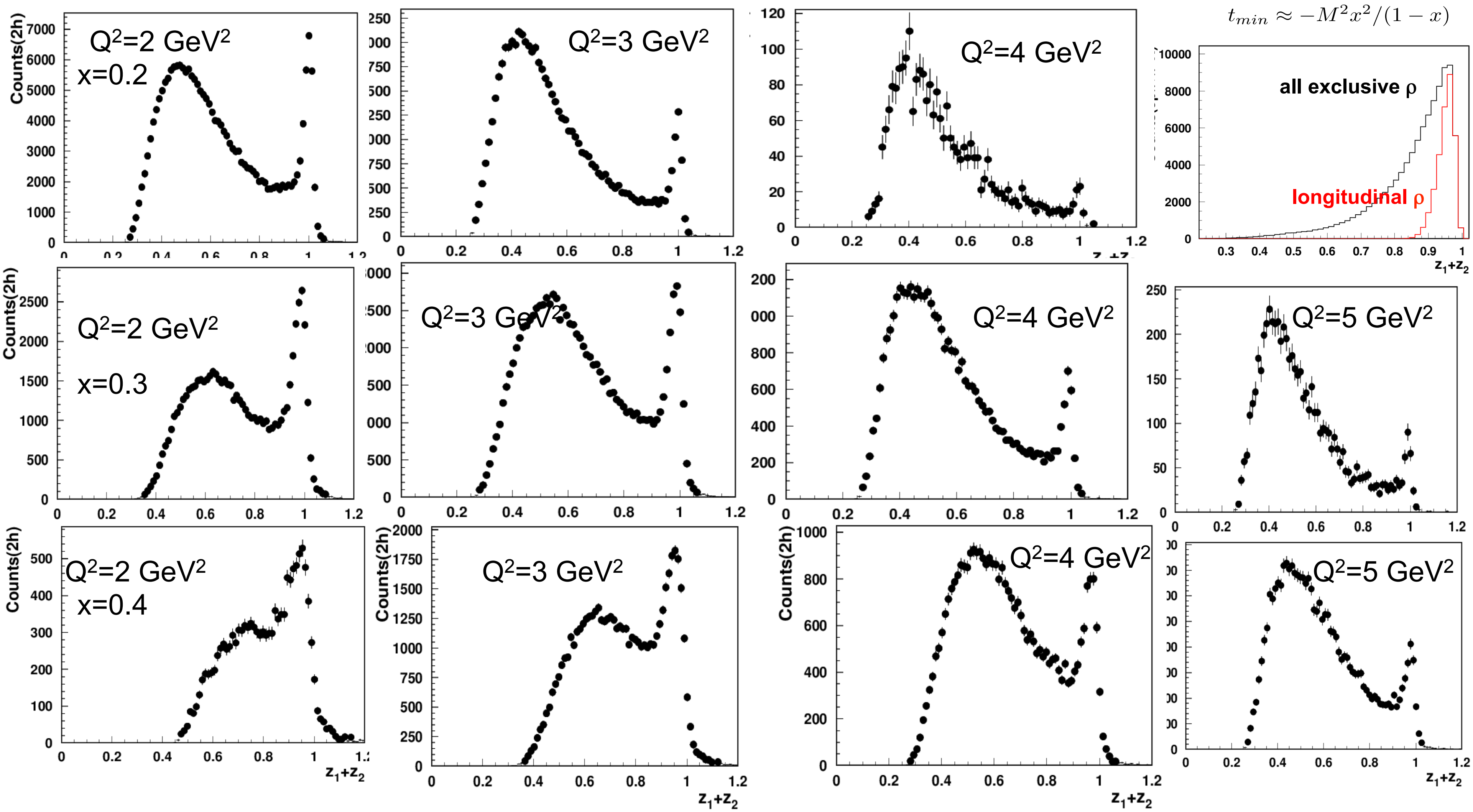
Studies of QCD dynamics with controlled systematics involving Semi-Inclusive DIS, requires multidimensional measurements of cross sections/multiplicities/asymmetries as a function of all involved kinematical variables (including P_T and ϕ).

- 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)
- New SSA observable, which is not suppressed at higher energies, providing access to polarized quarks, evaluated for EIC,
- The diffractive VM contributions, violate the factorized picture of SIDIS based on the dominance of the leading twist contributions, and the “rho free SIDIS” may help to address the challenges of phenomenology (cross checking “rho-subtracted SIDIS”)
- Need a generator to describe the exclusive rho in the accessible kinematic phase space accounting for all possible combinations of polarizations of beam, target and the final rho (Diehl: arXiv:0704.1565)

Combine efforts of SIDIS communities in understanding the diffractive ρ and sort out the impact on diffractive DIS and possible impact on PDFs, helicity PDF, in particular

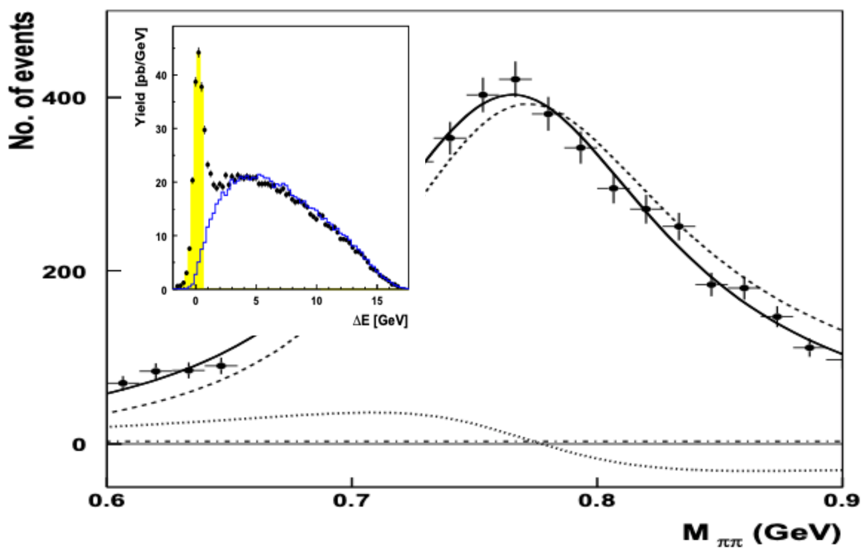
support slides

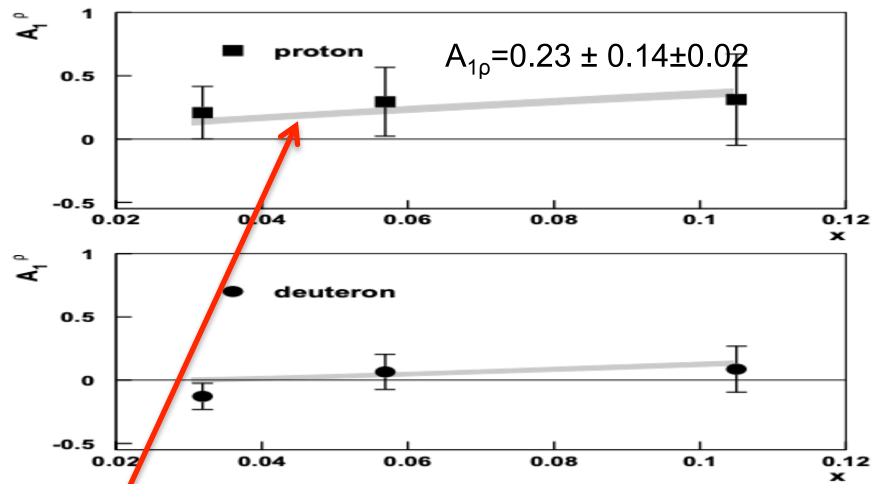
Exclusive dihadrons from CLAS12



The exclusive rho contributions in SIDIS drop with Q^2 (~$1/Q^2$)

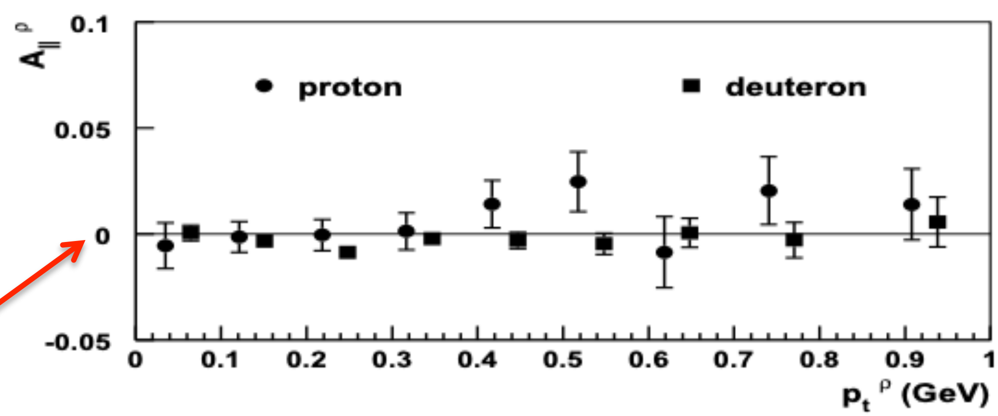
A_{LL} studies of exclusive ρ^0 : HERMES





1D plots can be really misleading need multi-D

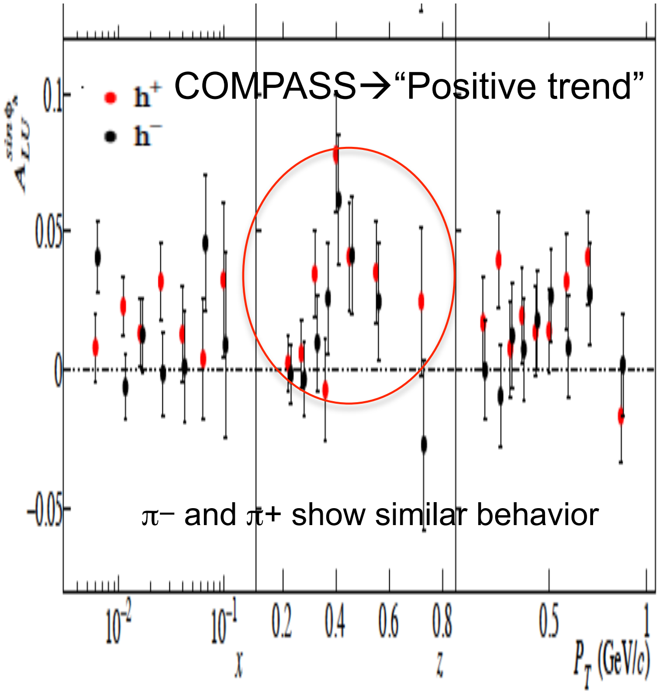
For a proper extraction of multiplicities and spin-azimuthal modulations of exclusive ρs, clean separation is needed for ρ^0, and longitudinally polarized ρ^0 signal, in particular

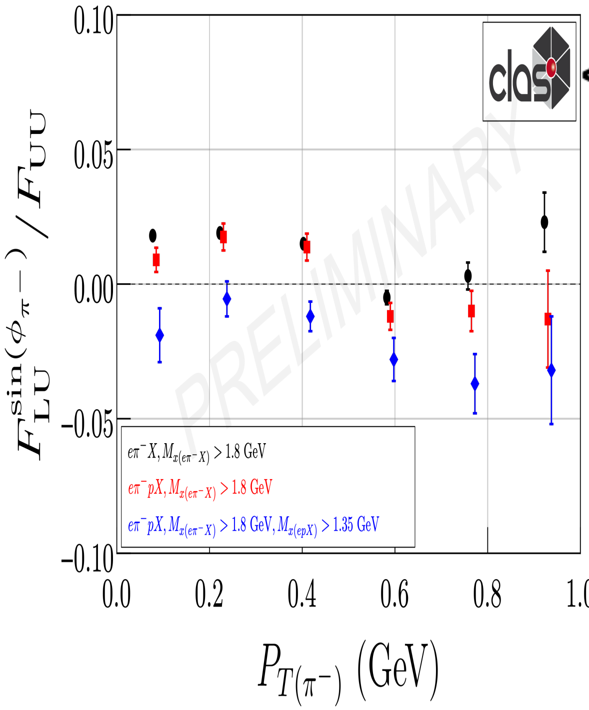


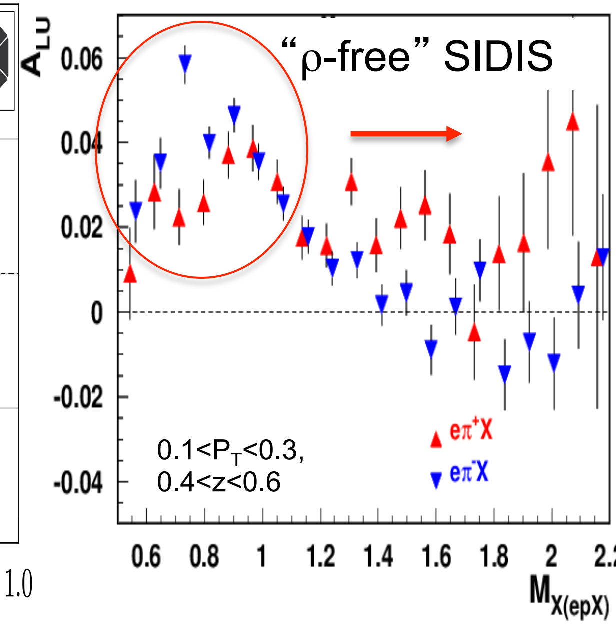
At low P_T, where the background is smaller, the asymmetry indeed tend to be negative

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

Exclusive ρ contributions to π: P_T-dependence



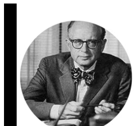




COMPASS→"Positive trend" also reproduced when additional proton in TFR detected (red)

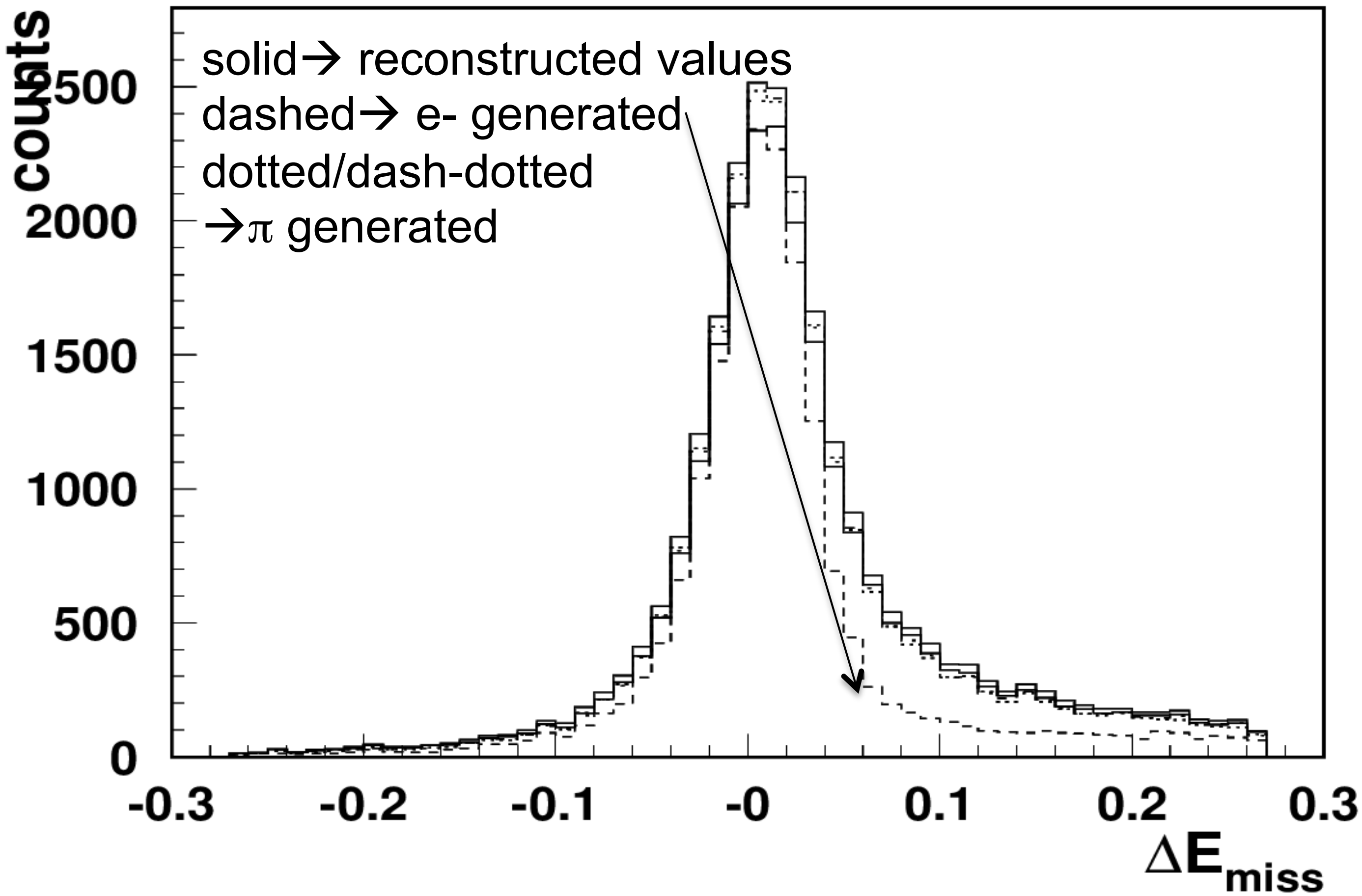
- The same sign and size of π+ and π- SSA indicates the rho0 may not be properly subtracted(require detailed MC studies, which require proper SDMEs)
- While VM contributions are ~20% in multiplicities in SSA they can be >100%

Need proper MC for rho for all polarization states→

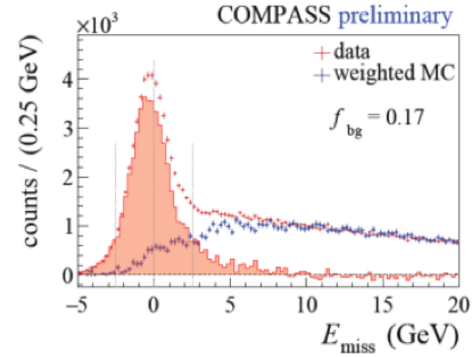


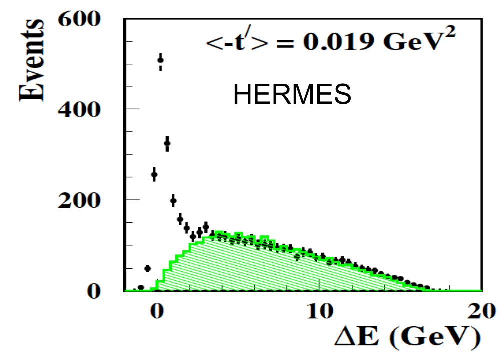
"The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge."
— Daniel J. Boorstin

Radiative effects: impact on missing mass



Claim RC is negligible



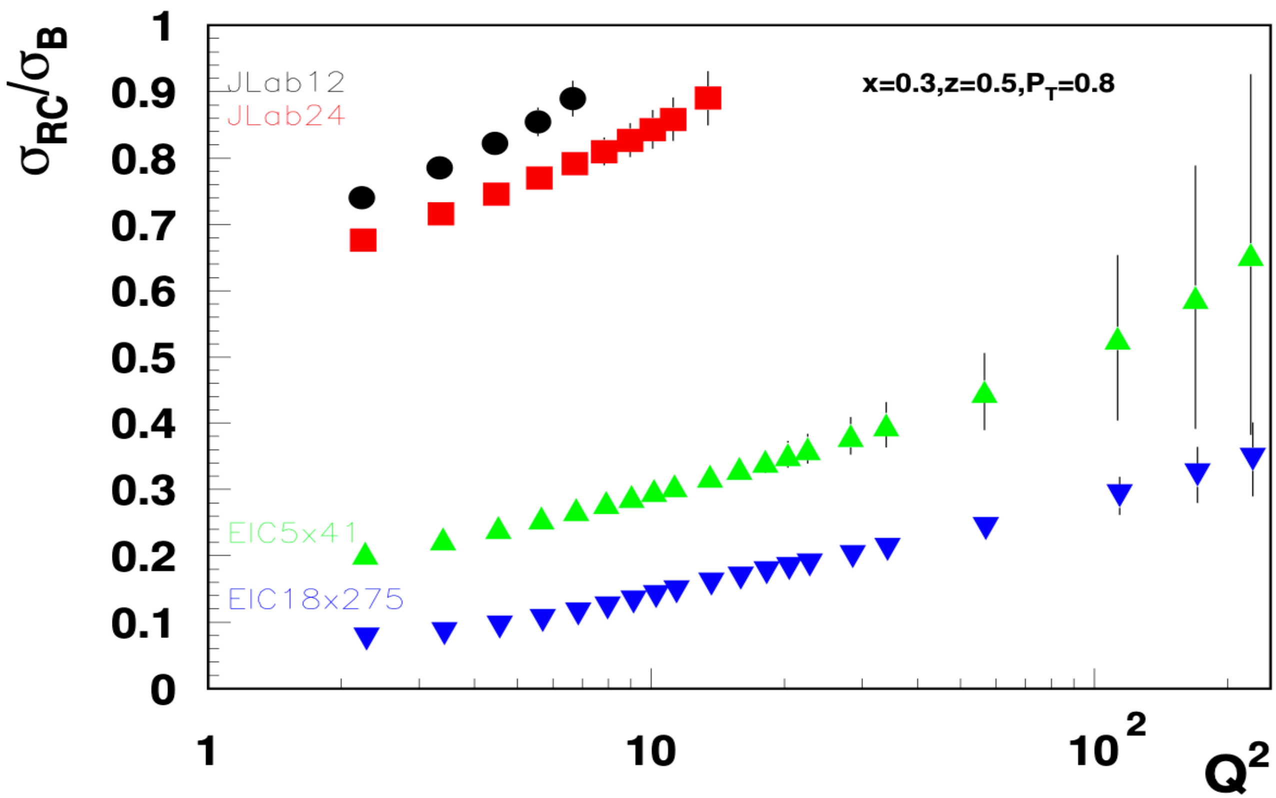


LUND-MC description of the exclusive limit will be important in evaluation of the tail.

Energy loss of final state particles creates a shoulder (mainly e- for CLAS12)

From JLab to EIC: complementarity

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



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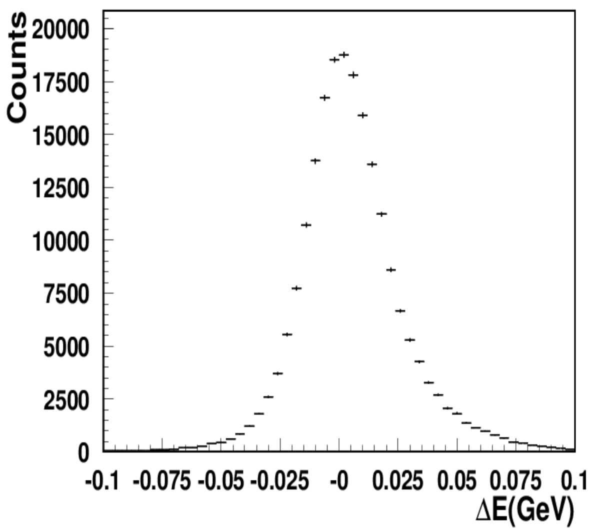
Gaussian F_{UU}
(ϕ_h=0)

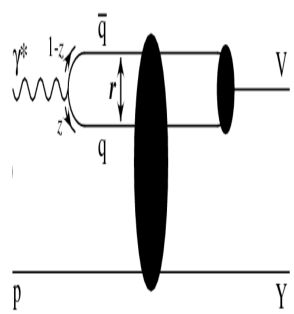
Cross section at low Q^2 suppressed at higher CM energies

- 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

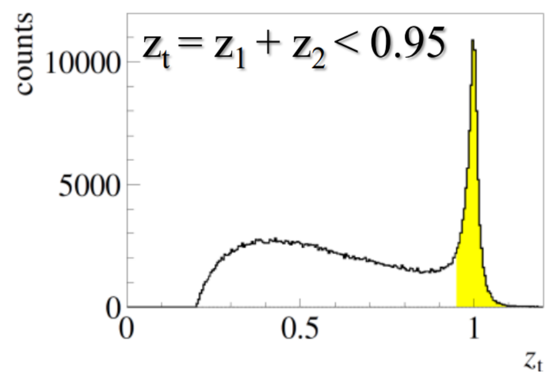
Addressing PAC/theory comments

2) Diffractive VMs (ρ^0)

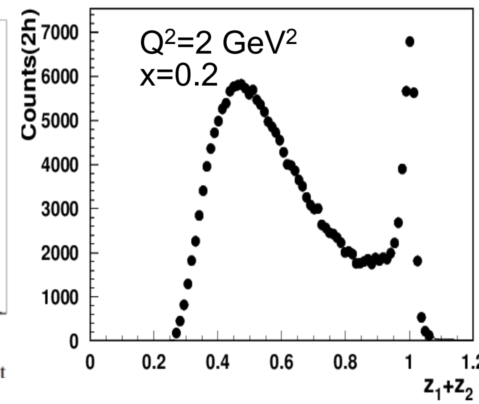




COMPASS 2h



CLAS12



CLAS12 measurements indicate the 2hadron exclusive sample is dominated by "diffractive rho0"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 rho to charged pion SIDIS, consistent with ~10% of diffractive DIS in inclusive DIS

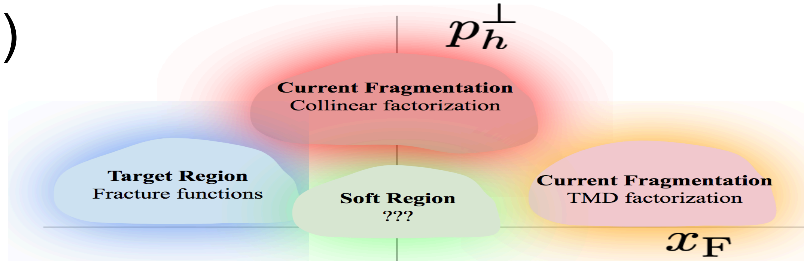
indication: most longitudinally polarized ρ^0

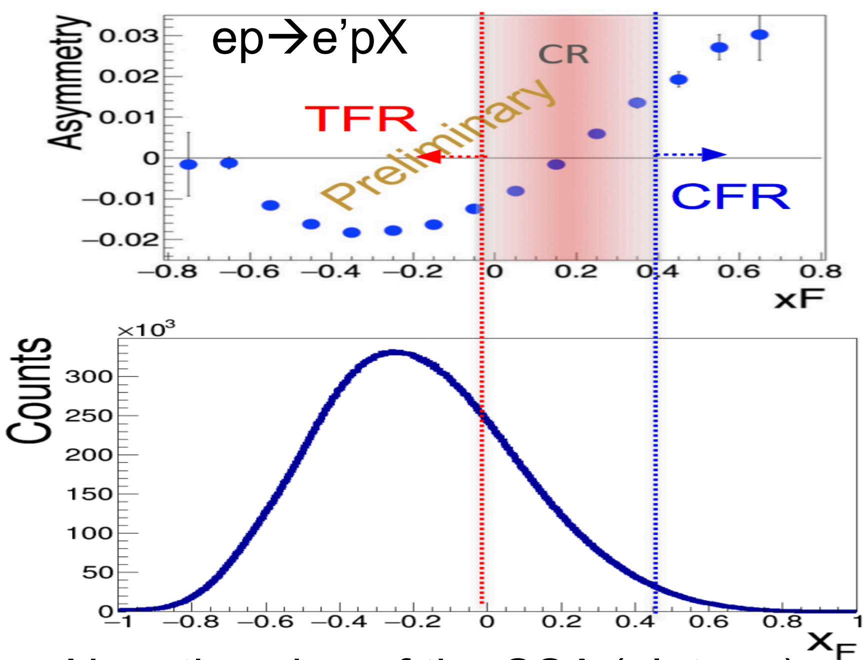
note: higher the Q^2 lower is ε

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

Beam SSAs as a tool to separate regions and contributions

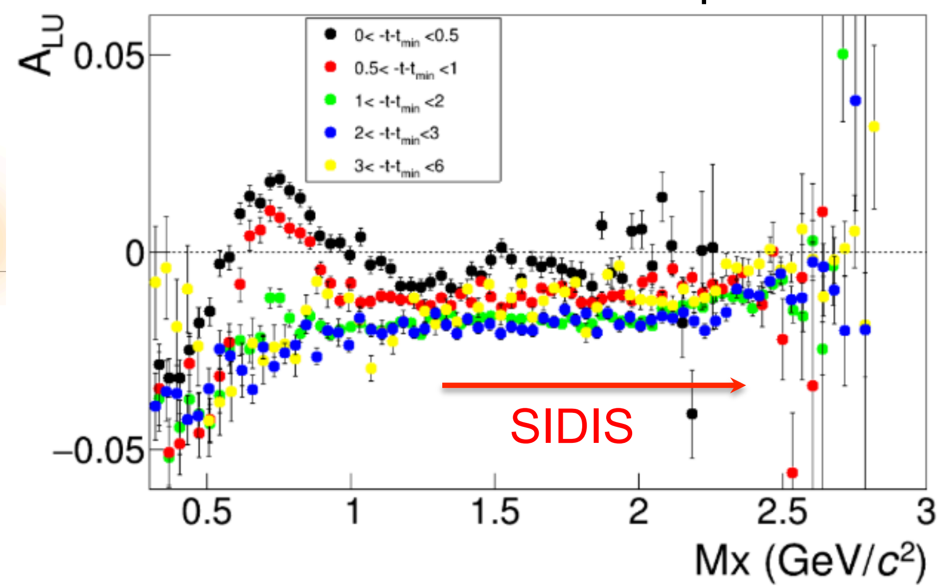
2) Separating Target Fragmentation Region TFR from Current fragmentation region (CFR)





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

F. Benmokhtar & Duquesne U.

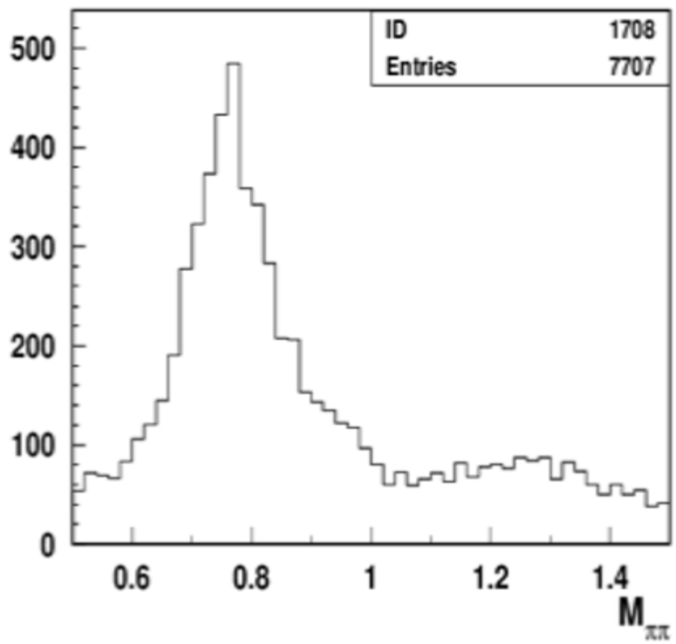


Major difference only for protons at small t!

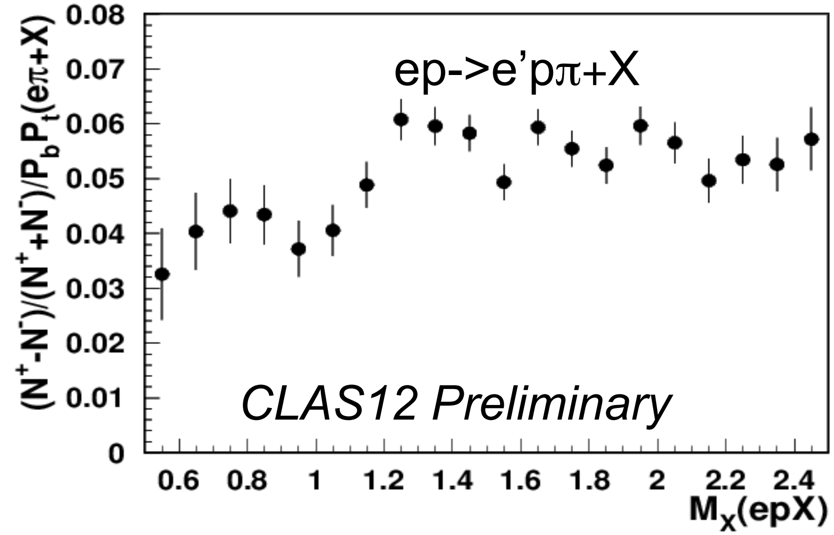
With beams in polarized SIDIS typically always polarized, beam SSA can serve as a tool to separate
1) kinematical regions (CFR/TFR)
2) dynamical contributions
3) cut on M_X eliminate exclusive VMs

Studies of ρ^0 impact with longitudinally polarized target

Separating exclusive dihadrons



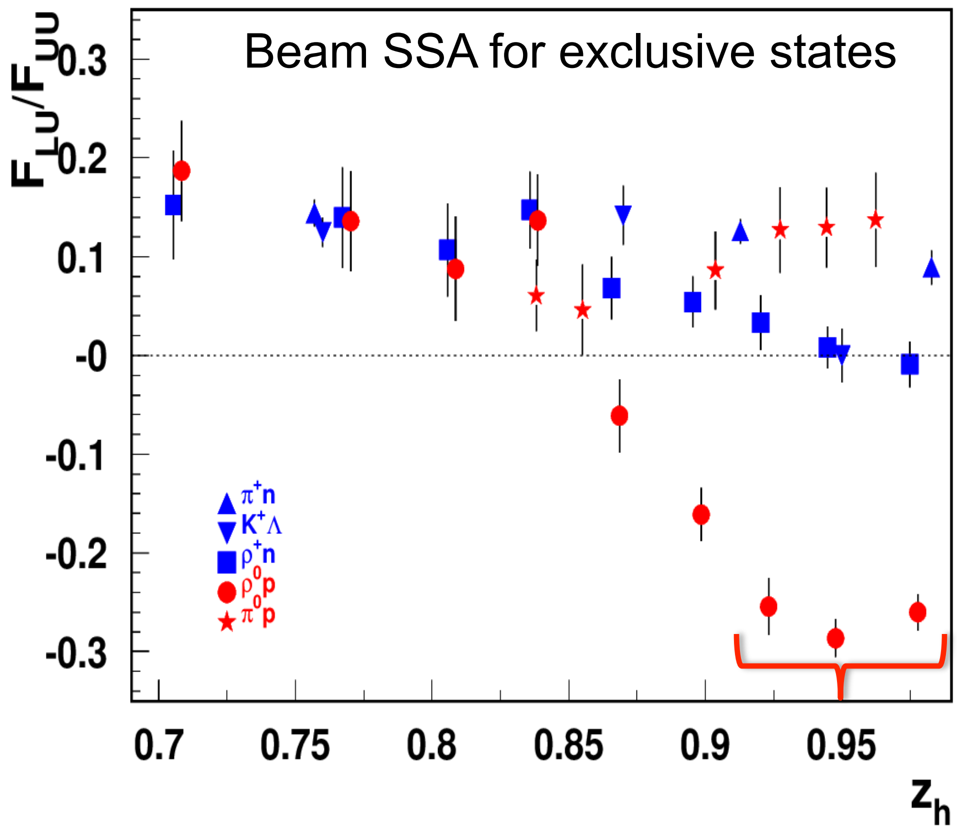
ep->e'ππX



- Measurements of A_{LL} for ρ^0 indicate very small values (most likely negative with ~10-15% bck), 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)

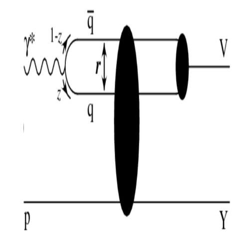
significant suppression of DSA ~rho mass

Separating the "diffractive" kinematics



- Comparison with exclusive $\rho+$ and other non-diffractive channels clearly indicates the kinematics where the "diffractive rho0" shows up (increases at higher energies)
- Comparison with other exclusive states, including the ρ^0 at higher t, indicate the contributions from quark exchange mechanisms negligible in large z kinematics

Diffractive VMs (ρ^0)



+preliminary data on $ep \rightarrow e'p\phi$ (A_{LU}=-0.084+/-0.038)

- Beam SSA can be used to separate dynamical contributions

At higher energies (COMPASS/HERMES) no major effect were observed, as high resolution and multidimensional measurements are critical !!!

Understanding exclusive rhos and SDME validations

$$
\begin{aligned}
&\mathcal{W}^{U}(\Phi,\phi,\cos\Theta)\\
=\ & \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1-r^{04}_{00})+\frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta\\
&\quad -\sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi\\
-\ & \epsilon\cos 2\Phi\Big(r^{1}_{11}\sin^2\Theta + r^{1}_{00}\cos^2\Theta\\
&\quad -\sqrt{2}\mathrm{Re}\{r^{1}_{10}\}\sin 2\Theta\cos\phi - r^{1}_{1-1}\sin^2\Theta\cos 2\phi\Big)\\
-\ & \epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{2}_{10}\}\sin 2\Theta\sin\phi\\
&\quad +\mathrm{Im}\{r^{2}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\\
+\ & \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^{5}_{11}\sin^2\Theta + r^{5}_{00}\cos^2\Theta\\
&\quad -\sqrt{2}\mathrm{Re}\{r^{5}_{10}\}\sin 2\Theta\cos\phi - r^{5}_{1-1}\sin^2\Theta\cos 2\phi\Big)\\
+\ & \sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r^{6}_{10}\}\sin 2\Theta\sin\phi\\
&\quad +\mathrm{Im}\{r^{6}_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Bigg],
\end{aligned}
$$

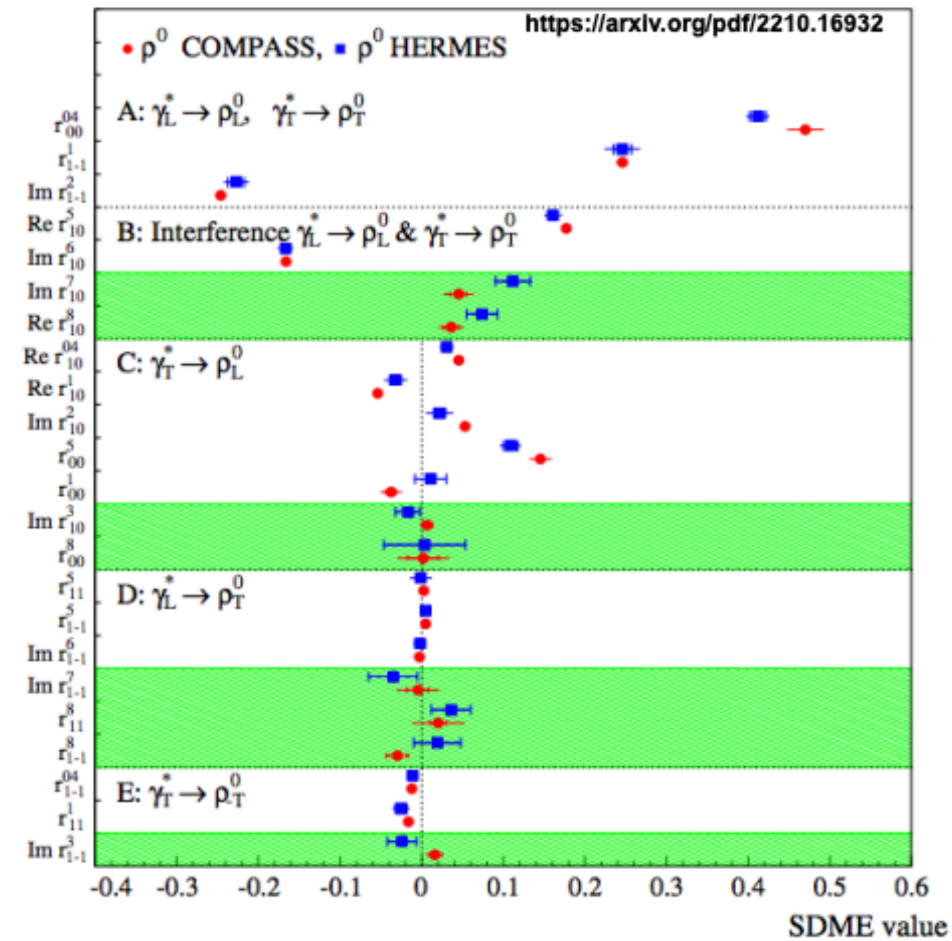


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96\ (\mathrm{GeV}/c)^2$, $\langle W\rangle = 4.8\ \mathrm{GeV}/c^2$, $\langle|t'|\rangle = 0.13$, while those for COMPASS are $\langle Q^2\rangle = 2.40\ (\mathrm{GeV}/c)^2$, $\langle W\rangle = 9.9\ \mathrm{GeV}/c^2$, $\langle p_T^2\rangle = 0.18\ (\mathrm{GeV}/c)^2$. 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.

The SDMEs from HERMES and COMPASS extracted at different <x> and <Q²> seem to be consistent.

Understanding exclusive rhos and SDME validations

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

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

corr. with r_{1-1}^{5} , r_{1-1}^{6} ,r_{00}^{5} (Hermes, COMPASS)

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

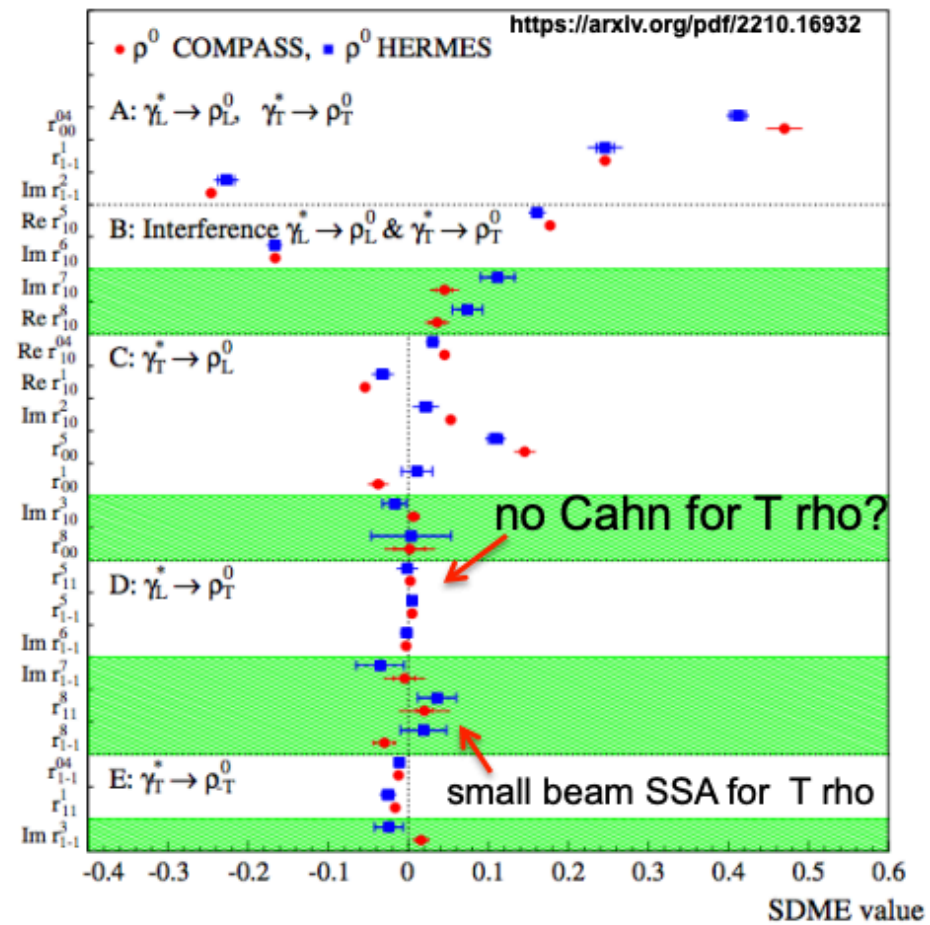
$$+ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta\right.$$

$$\left. -\sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi - r^8_{1-1}\sin^2\Theta\cos 2\phi\right)\Bigg].$$

corr. with r_{1-1}^{8} ,r_{00}^{8} (Hermes, COMPASS)

$$\gamma^*_L \to \rho^0_T, \quad \tau_{10} \approx \frac{\sqrt{(r^5_{11}+\mathrm{Im}\{r^6_{1-1}\})^2 + (\mathrm{Im}\{r^7_{1-1}\} - r^8_{11})^2}}{\sqrt{2(r^1_{1-1} - \mathrm{Im}\{r^2_{1-1}\})}}$$

Since the decay angle is correlated with the polarization of the rho, then r_{11}^{8} and r_{11}^{5} will be responsible for transverse rho (no Cahn?)



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Understanding exclusive rhos and SDME validations

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

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

corr. with r_{10}^5 (Hermes) no corr (COMPASS)

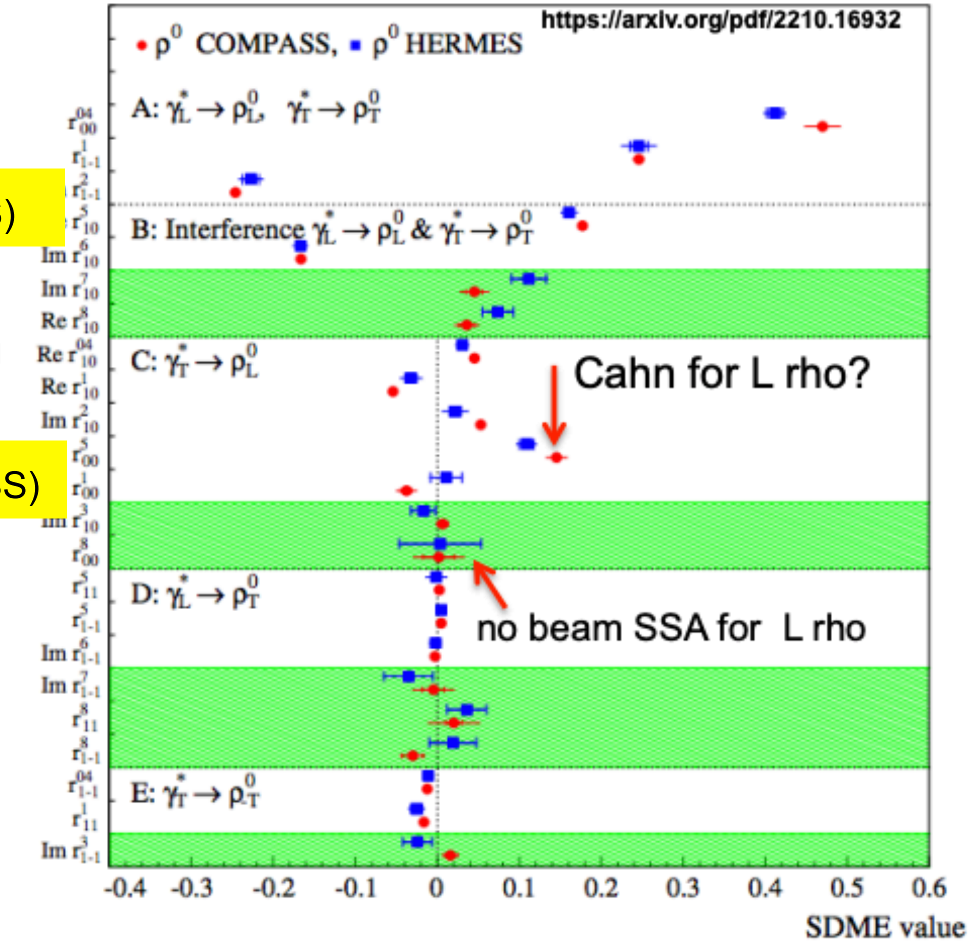
$\mathcal{W}^L(\Phi, \phi, \cos\Theta)$

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

corr. with r_{1-1}^8 (Hermes) no corr (COMPASS)

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

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



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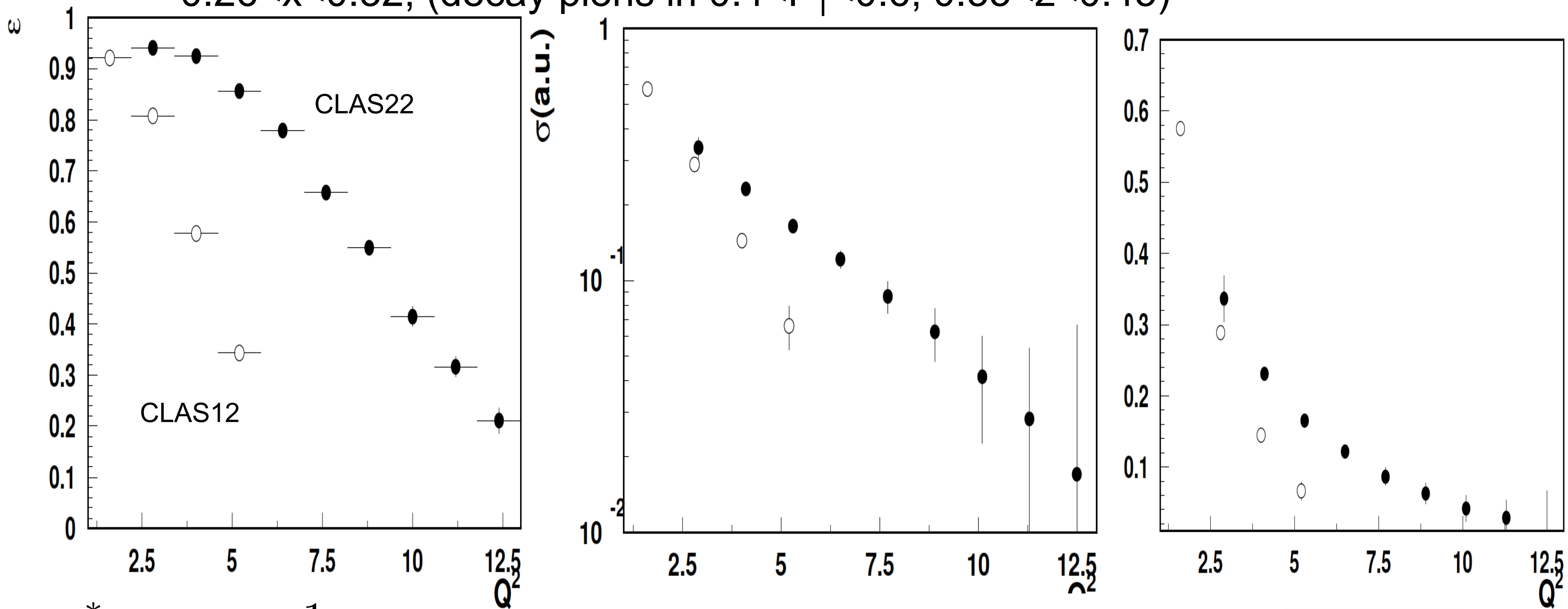
Exclusive ρ^0: extending the Q^2 with JLab22

$0.26<x<0.32$, (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

$$\gamma_T^* \to \rho_L^0 \quad \tau_{01} \approx \sqrt{\epsilon}\frac{\sqrt{(r_{00}^5)^2+(r_{00}^8)^2}}{\sqrt{2r_{00}^{04}}}$$

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

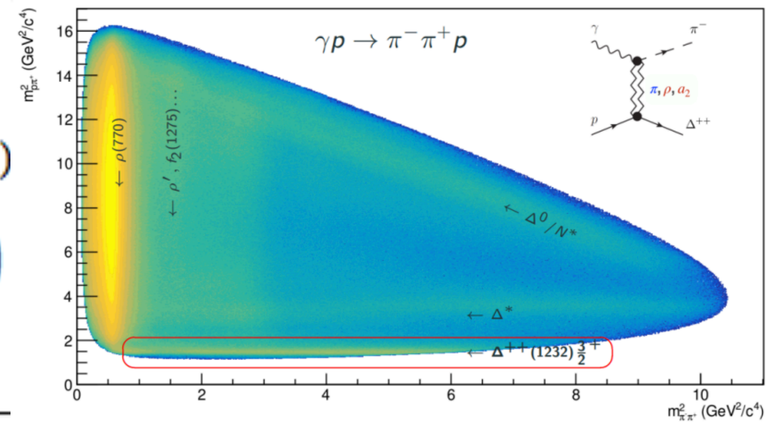
$$+ \quad \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r_{11}^8\sin^2\Theta+r_{00}^8\cos^2\Theta$$

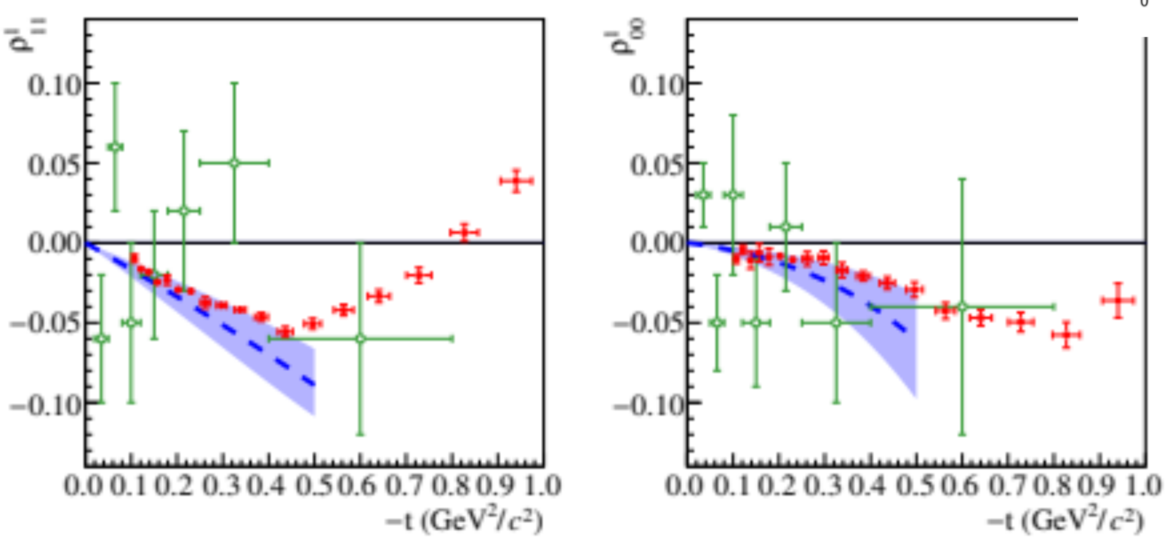
- Wider in t the range of integration, less will be relative fraction from asymmetric decays
- Range in Q^2 increases significantly allowing detailed studies at beyond 10 GeV^2

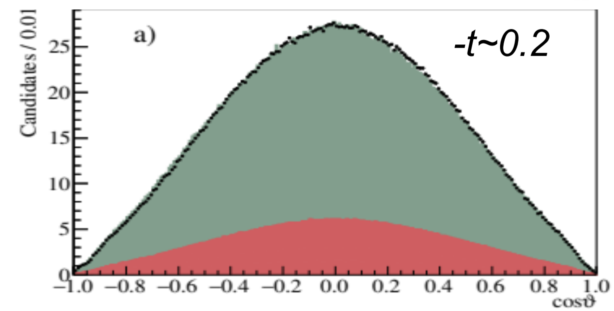
SDMEs from photoproduction

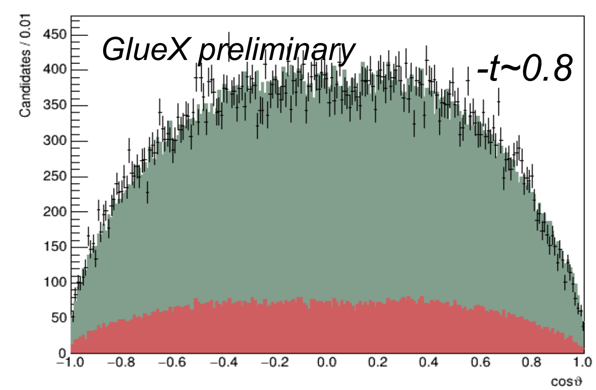
JLab/GlueX, S. Adhikari et al, Phys.Rev.C 108 (2023), 055204: ArXiv:2305.09047

$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\Big(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\Big) \quad (11)$$





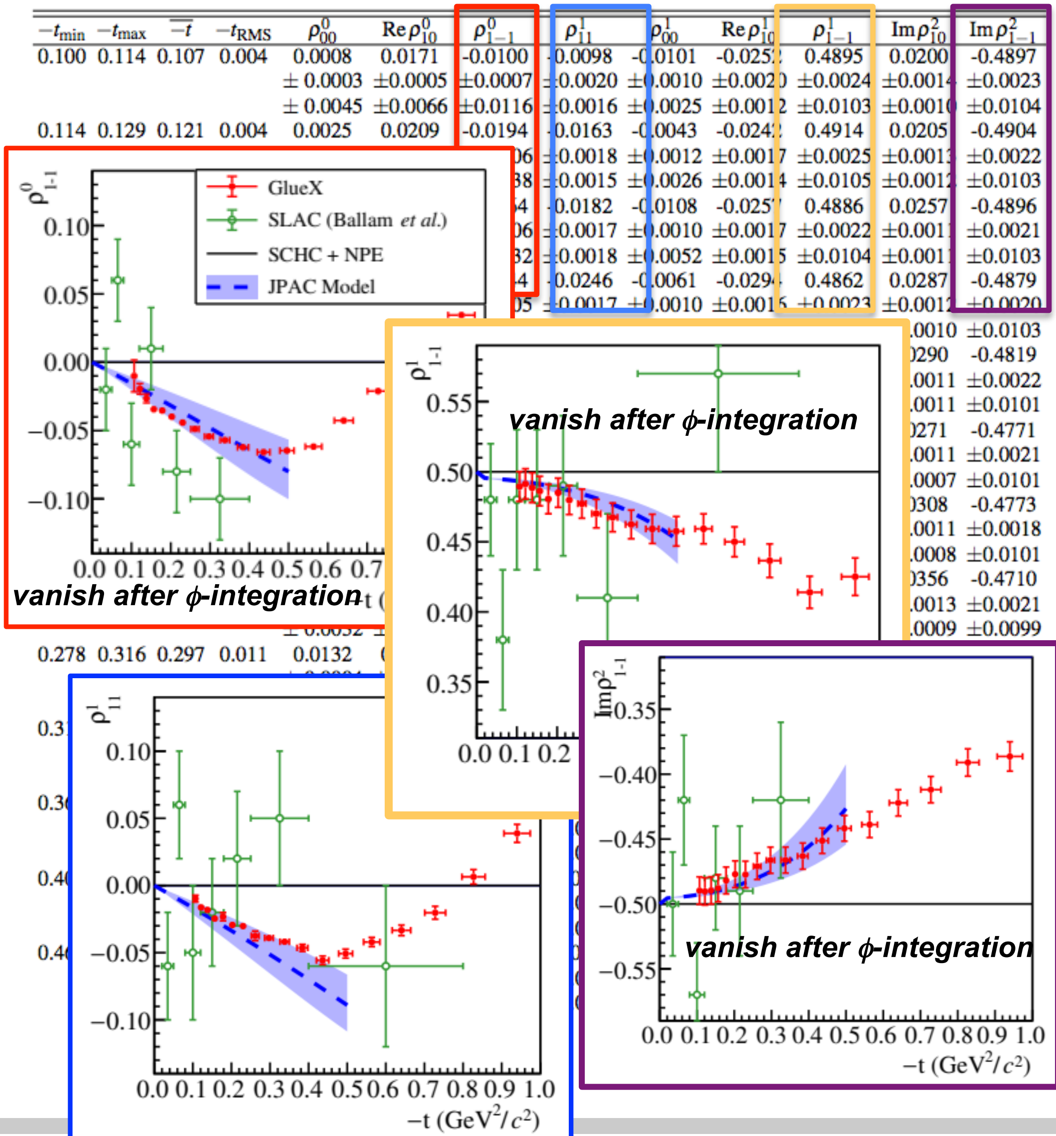


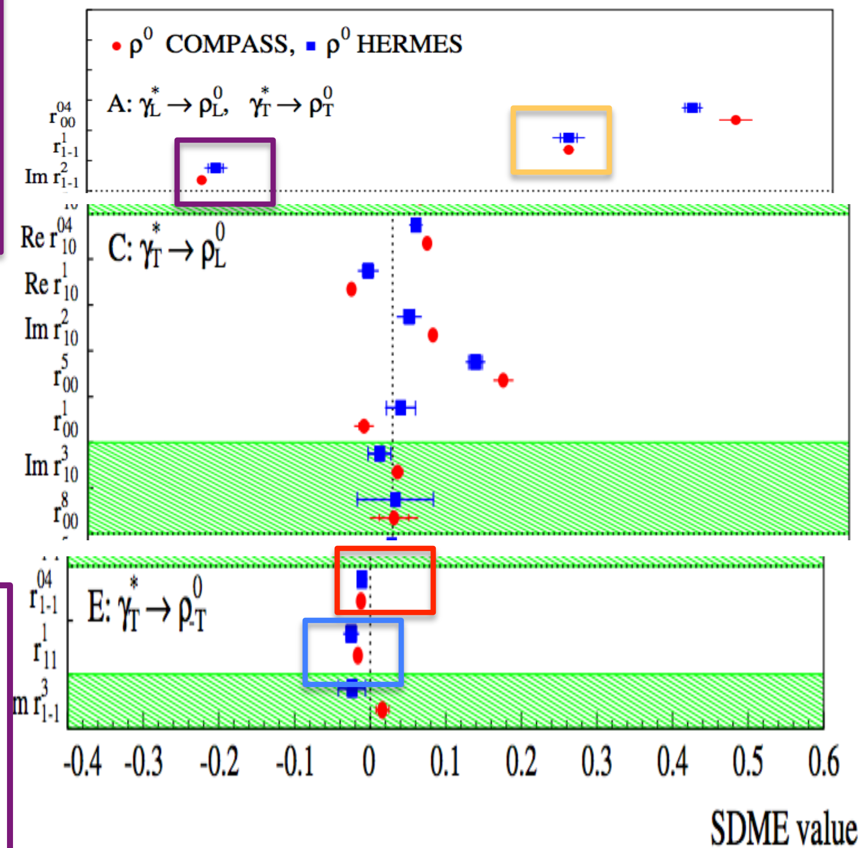


While at small t (dominant part of the statistics) the transverse rhos dominate, at large t the contribution from transverse photons going to longitudinal rho becomes more significant

SDMEs from photoproduction

JLab/GlueX, S. Adhikari et al: https://arxiv.org/pdf/2305.09047

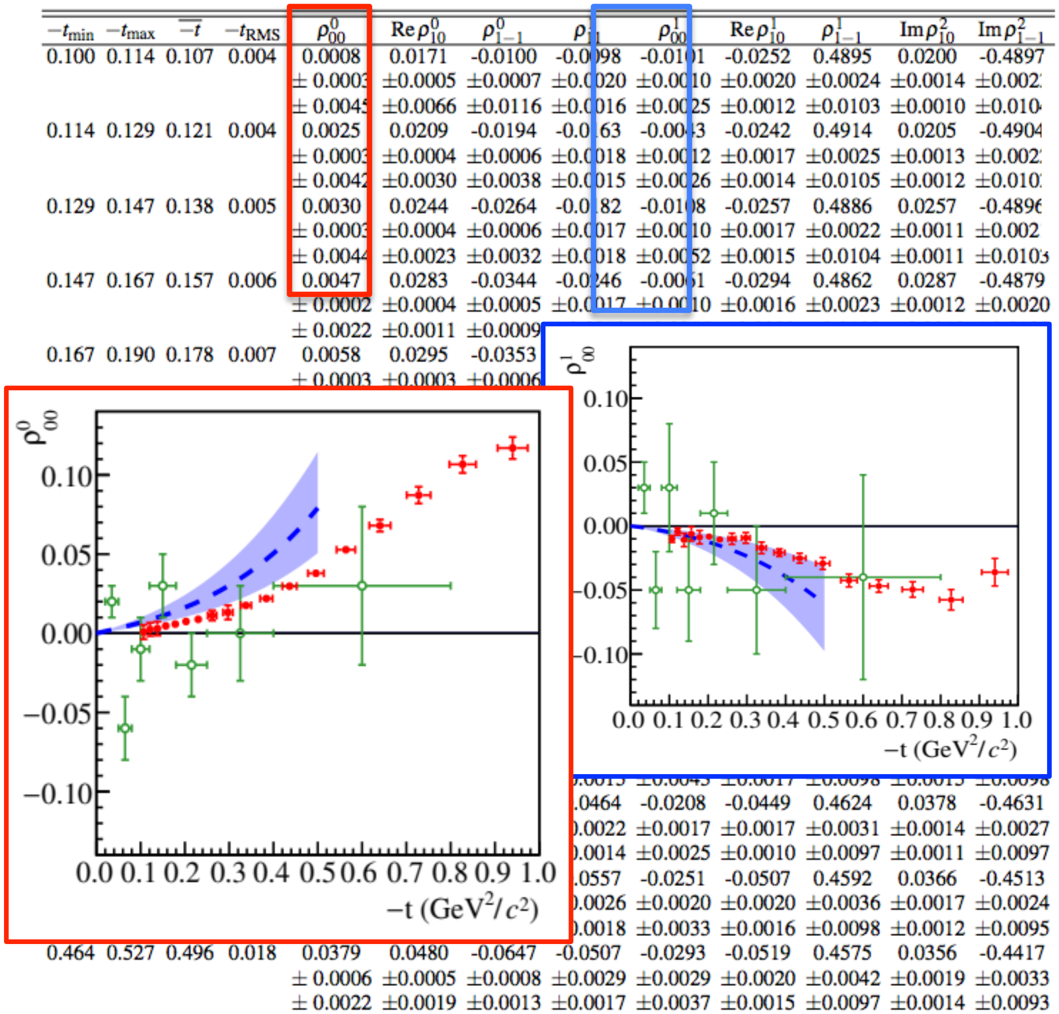


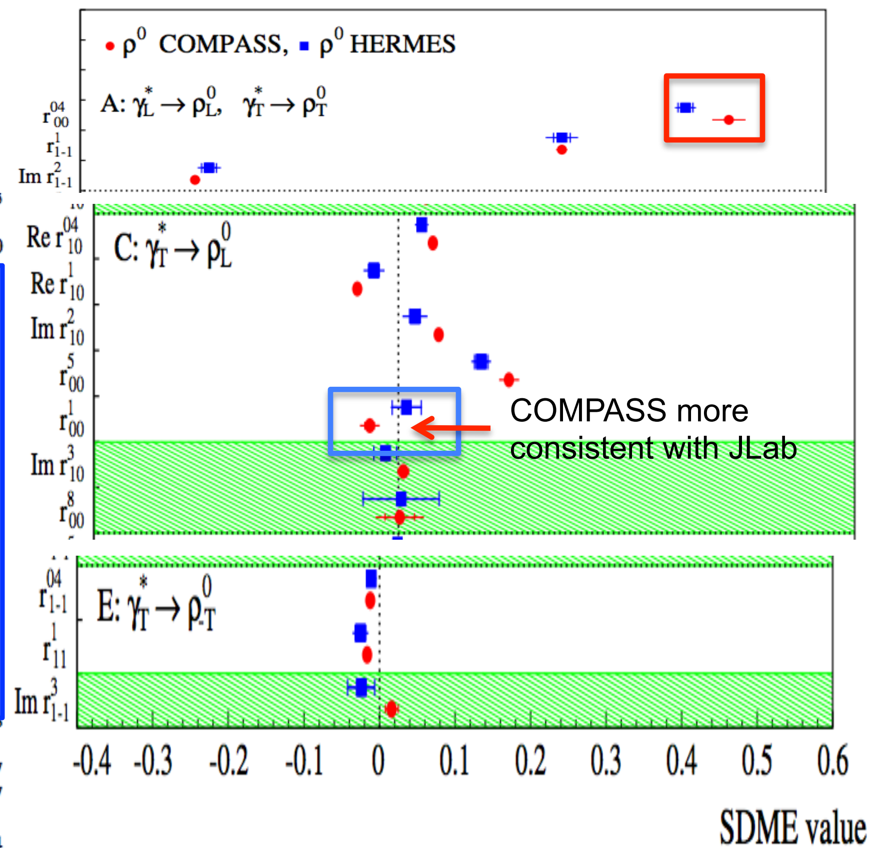


The SDMEs for transverse photons with $\sin^2\theta$ (to transverse rho?) at $Q^2>0$ seem to be smaller (detailed comparison vs Q^2).

SDMEs from photoproduction

JLab/GlueX, S. Adhikari et al: https://arxiv.org/pdf/2305.09047



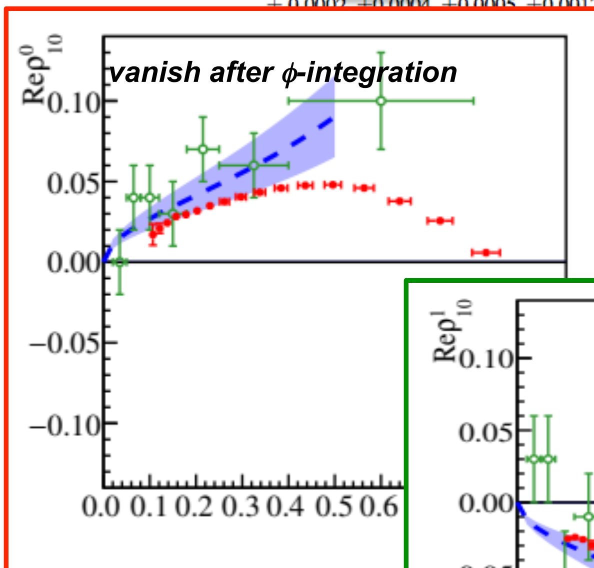


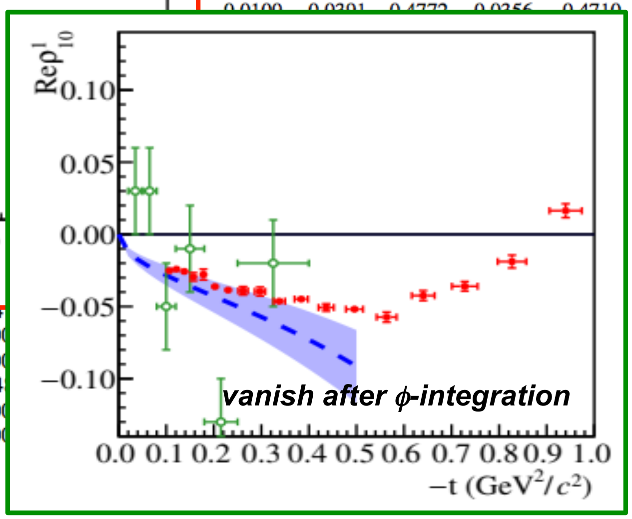
The SDMEs for transverse photons with $\cos^2\theta$ (to longitudinal rho?) at $Q^2>0$ different, in particular r_{00}^1 (relevant for BM).

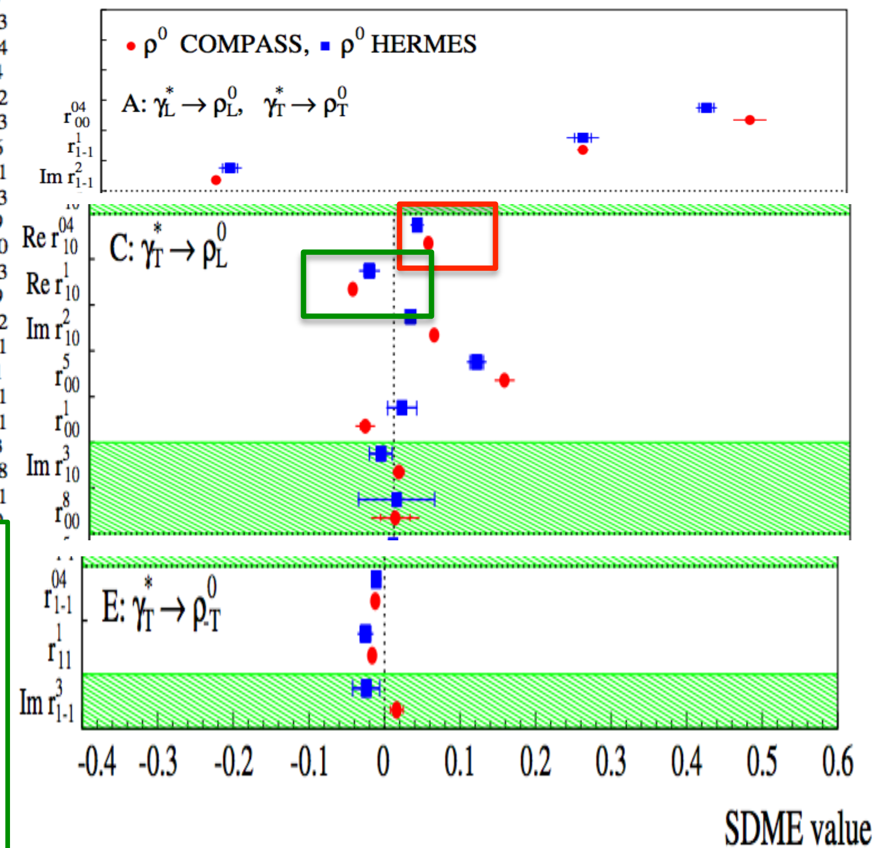
SDMEs from photoproduction

JLab/GlueX, S. Adhikari et al: https://arxiv.org/pdf/2305.09047

$-t_{min}$	$-t_{max}$	$\overline{-t}$	$-t_{RMS}$	ρ^0_{00}	$\mathrm{Re}\,\rho^0_{10}$	ρ^0_{1-1}	ρ^1_{11}	ρ^1_{00}	$\mathrm{Re}\,\rho^1_{10}$	ρ^1_{1-1}	$\mathrm{Im}\,\rho^2_{10}$	$\mathrm{Im}\,\rho^2_{1-1}$
0.100	0.114	0.107	0.004	0.0008	0.0171	-0.0100	-0.0098	-0.0101	-0.0252	0.4895	0.0200	-0.4897
				± 0.0003	±0.0005	±0.0007	±0.0020	±0.0010	±0.0020	±0.0024	±0.0014	±0.0023
				± 0.0045	±0.0065	±0.0116	±0.0016	±0.0025	±0.0012	±0.0103	±0.0010	±0.0104
0.114	0.129	0.121	0.004	0.0025	0.0209	-0.0194	-0.0163	-0.0043	-0.0242	0.4914	0.0205	-0.4904
				± 0.0003	±0.0004	±0.0006	±0.0018	±0.0012	±0.0017	±0.0025	±0.0013	±0.0022
				± 0.0042	±0.0030	±0.0038	±0.0015	±0.0026	±0.0014	±0.0105	±0.0012	±0.0103
0.129	0.147	0.138	0.005	0.0030	0.0244	-0.0264	-0.0182	-0.0108	-0.0257	0.4886	0.0257	-0.4896
				± 0.0003	±0.0004	±0.0006	±0.0017	±0.0010	±0.0017	±0.0022	±0.0011	±0.0021
				± 0.0044	±0.0023	±0.0032	±0.0018	±0.0052	±0.0015	±0.0104	±0.0011	±0.0103
0.147	0.167	0.157	0.006	0.0047	0.0283	-0.0344	-0.0246	-0.0061	-0.0294	0.4862	0.0287	-0.4879
					±0.0004	±0.0005	±0.0017	±0.0010	±0.0016	±0.0023	±0.0012	±0.0020
								±0.0055	±0.0023	±0.0103	±0.0010	±0.0103
								-0.0087	-0.0278	0.4805	0.0290	-0.4819
								±0.0010	±0.0017	±0.0020	±0.0011	±0.0022
								±0.0051	±0.0034	±0.0103	±0.0011	±0.0101
								-0.0082	-0.0362	0.4850	0.0271	-0.4771
								±0.0012	±0.0013	±0.0021	±0.0011	±0.0021
								±0.0010	±0.0013	±0.0102	±0.0007	±0.0101
								-0.0105	-0.0386	0.4798	0.0308	-0.4773
								±0.0011	±0.0015	±0.0022	±0.0011	±0.0018
								±0.0012	±0.0013	±0.0101	±0.0008	±0.0101
0.409	0.464	0.436	0.016	0.0297	0.04							
				± 0.0005	±0.0							
				± 0.0016	±0.0							
0.464	0.527	0.496	0.018	0.0379	0.04							
				± 0.0006	±0.0							
				± 0.0022	±0.0							







The SDMEs for transverse photons with $\sin 2\theta\cos\phi$ (to longitudinal rho?) at $Q^2>0$ consistent with HERMES/COMPASS

Ongoing activities in SIDIS, “rho-subtracted”/”rho free” SIDIS

Measurements of multiplicities, single-spin and double spin dependent observables of forward “current” dihadrons with separation of exclusive and semi-inclusive fractions

Measurements of multiplicities, single-spin and double spin dependent observables of back-to-back hadron “current” and baryon “target” with separation of exclusive and semi-inclusive fractions

Comparison of the SDMEs extracted in photoproduction with SDMEs for electroproduction at low Q^2, to see if we can efficiently use part of their t-dependences.

Development of exclusive VM MC including beam and target polarizations, longitudinal and transverse (need for preparation of the proposal for clas12) describing the photoproduction, and electroproduction data on exclusive rho in the full kinematical range of x,t,Q^2

Comparison of SIDIS observables for “rho-subtracted” and “rho-free” samples

Multiplicities of hadrons in SIDIS

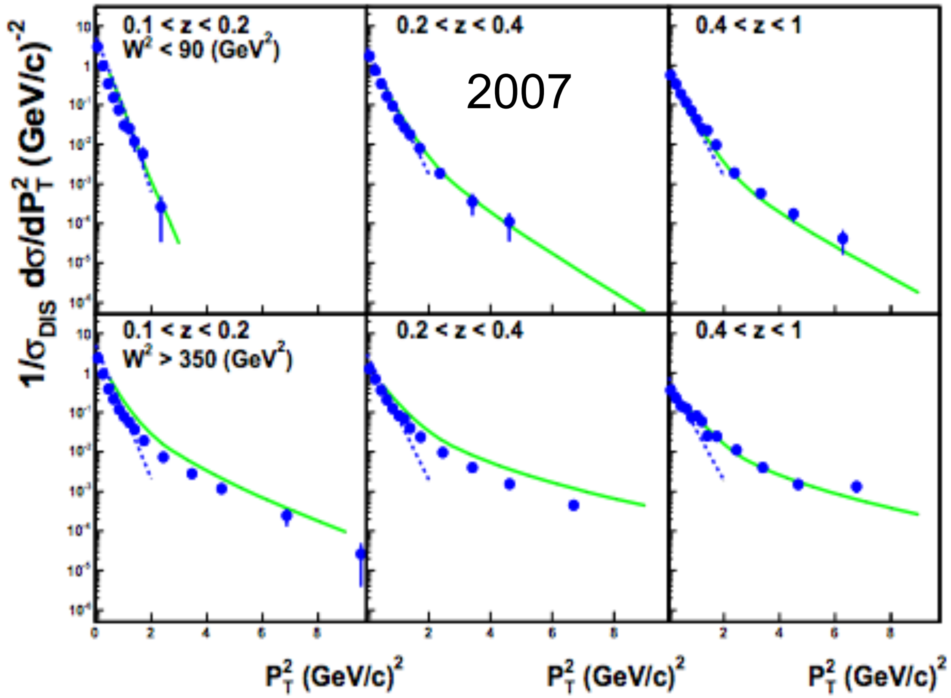
Anselmino et. al: hep-ph/0606286

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

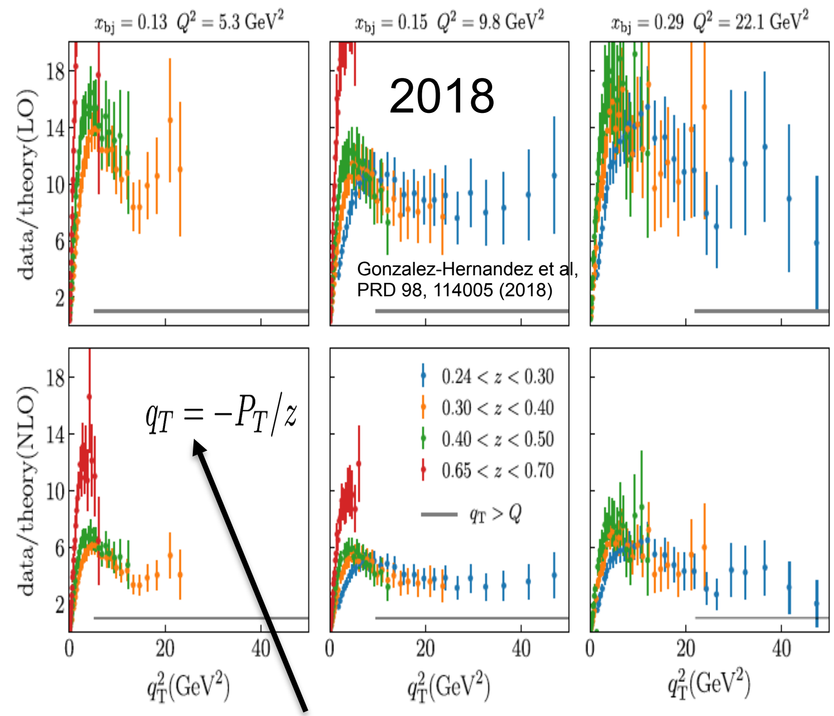
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

non-perturbative

perturbative



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



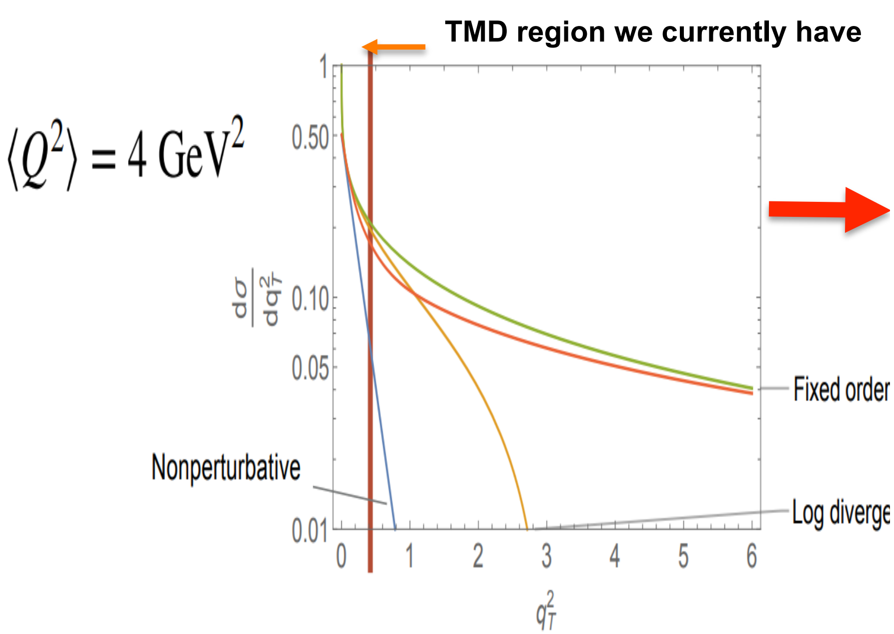
quark transverse momentum, assuming a direct link with pion transverse momentum

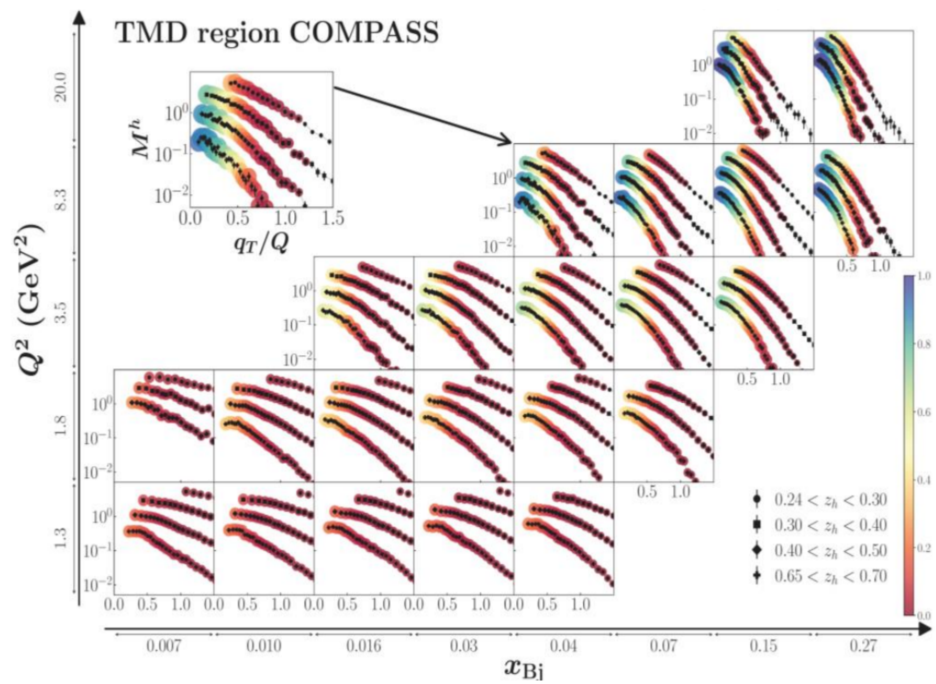
Perturbative contributions underestimate the multiplicities by an order of magnitude for all accessible kinematics at COMPASS

SIDIS of ehX: q_T-crisis in TMD theory

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

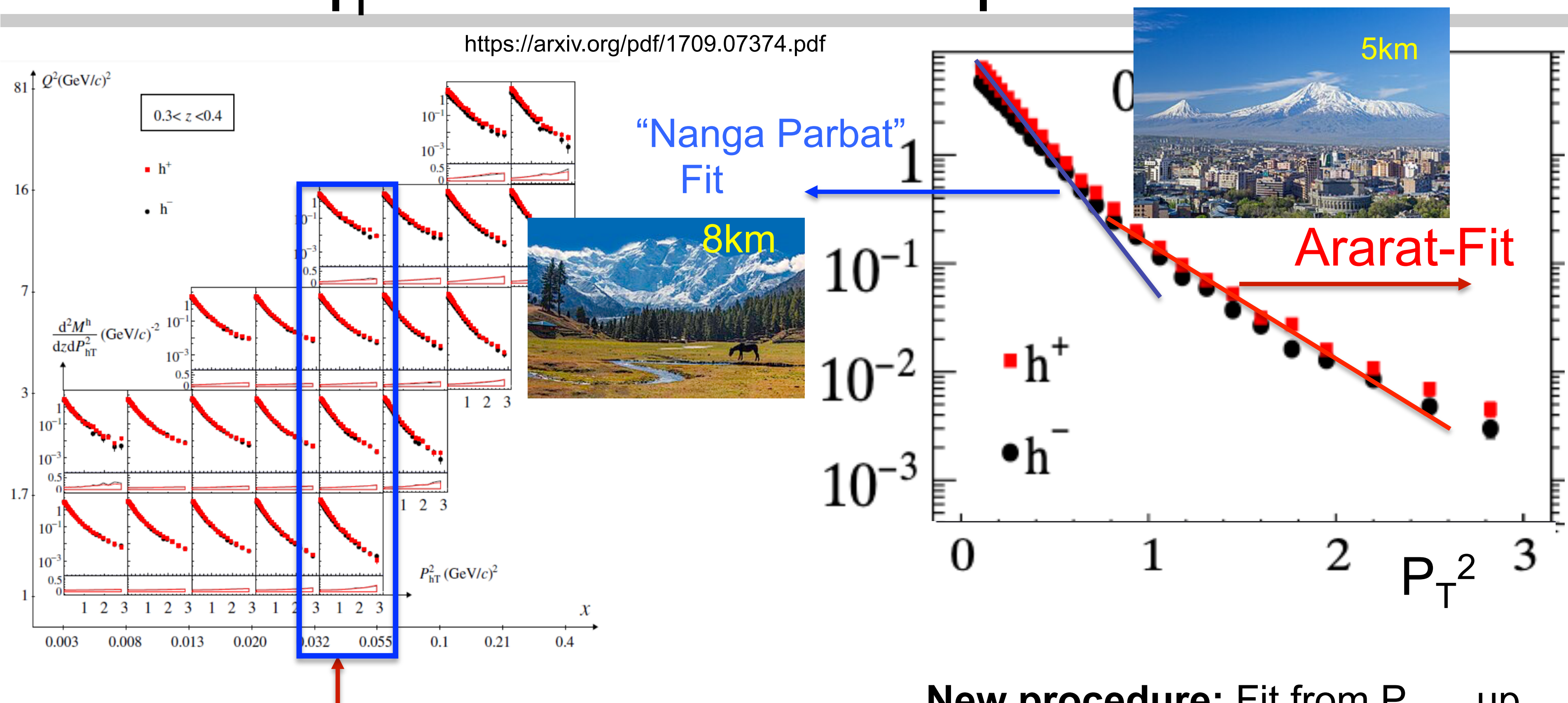
Significant fraction of polarized SIDIS data is currently considered by phenomenology to be outside of the TMD region
What data input exactly drives down the nonperturbative part?





How far in P_T or $q_T = P_T/z$, extends the TMD region

q_T-crisis or misinterpretation



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.

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

Challenging for theory to explain the correlation of P_T and Q

need experimental subtraction of rhos (proton detection will help)

Nucleon structure & TMDs at leading twist

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} +$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin$$

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

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

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\,\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\mathrm{co}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

theory

Extraction of leading twist TMDs limited to formalism accounting for only leading twists will require some mechanisms for controlling the systematics (need to measure and simulate background effects).

What we miss in the leading twist picture?

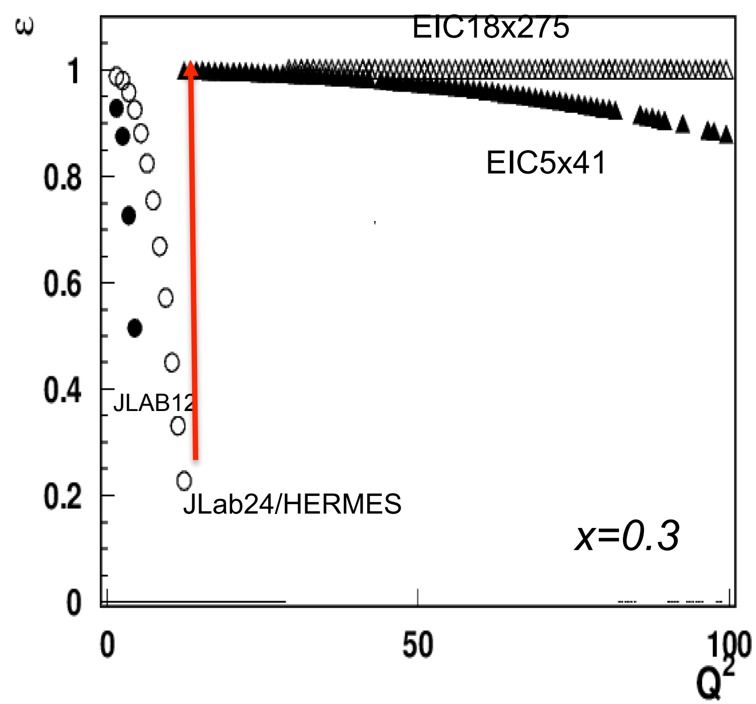
Addressing PAC/theory comments

What exactly are identified so far sources of "factorization breakdown" in SIDIS and where is the evidence that "few GeV" matters?

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$K(x,Q^2,y)[F_{UU,L} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos}\ldots]$$

1) Longitudinal photon



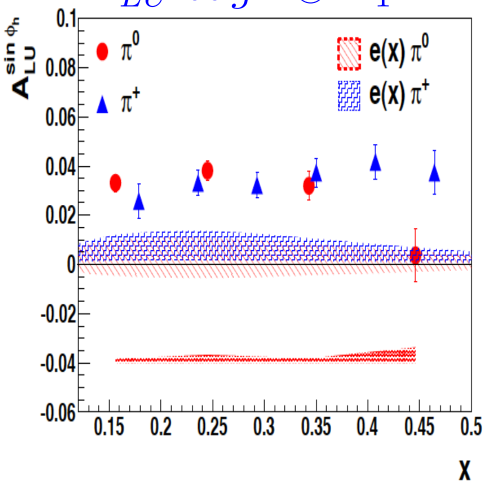
- For a given x&Q^2 the contribution from longitudinal photon increases at higher energies (ex. at EIC 5 times bigger at Q^2~10, x~0.3 than at JLab)
- JLab studies of impact of longitudinal photons critical for interpretation of polarized SIDIS, including EIC data

Longitudinal Beam SSA in CFR/TFR

CFR→Higher Twist TMDs

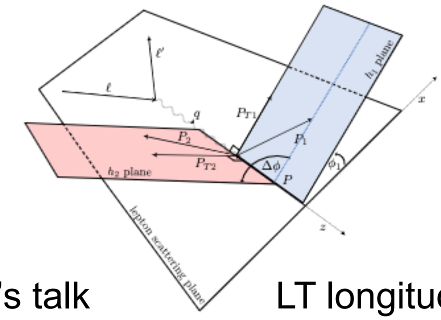
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

$F_{LU} \propto g^{\perp} \otimes D_1$

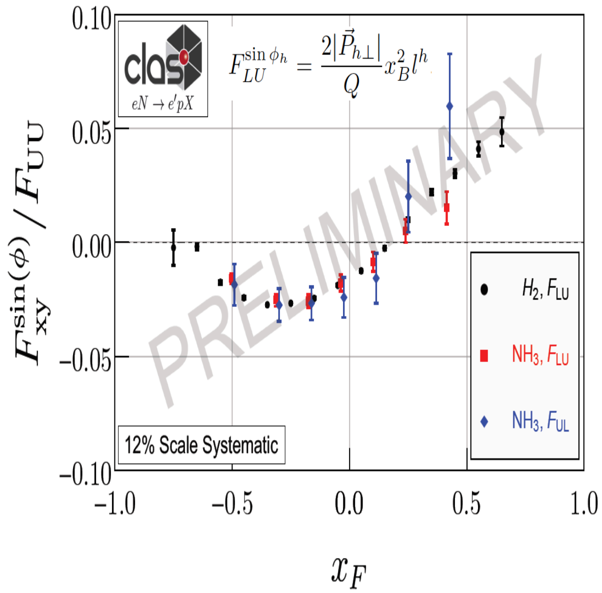


TFR→Higher Twist Fracture Functions

Nq	U	L	T
U	$\hat{u}_2^{\perp h}$	$\hat{l}_2^{\perp h}$	$\hat{t}_2, \hat{e}_2$
L	$\hat{u}_{2L}^{\perp h}$	$\hat{l}_{2L}^{\perp h}$	$\hat{t}_{2L}, \hat{e}_{2L}$
T	$\hat{u}_{2T}^{\perp h}, \hat{u}_{2T}^{\perp h}$	$\hat{l}_T, \hat{l}_{2T}^{\perp h}$	$\hat{t}_{2T}^{h}, \hat{e}_{2T}^{h}, \hat{t}_{2T}^{\perp h}, \hat{e}_{2T}^{\perp h}$



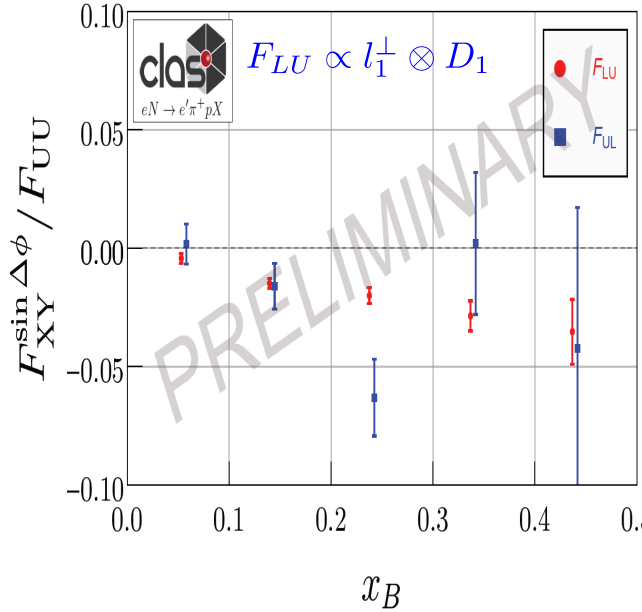
Fatiha's talk



TFR/CFR→Leading Twist Fracture Functions

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

LT longitudinally pol. quarks in Unp. proton



$$A(\phi)_{LU} = \frac{1}{p}\left(\frac{N^+ - N^-}{N^+ + N^-}\right) \rightarrow F_{LU}^{\sin\phi_h} = \frac{A(\phi)_{LU}}{\sqrt{2\varepsilon(1-\varepsilon)}}$$

Longitudinally polarized quarks most likely responsible for observed Single Beam Spin asymmetries