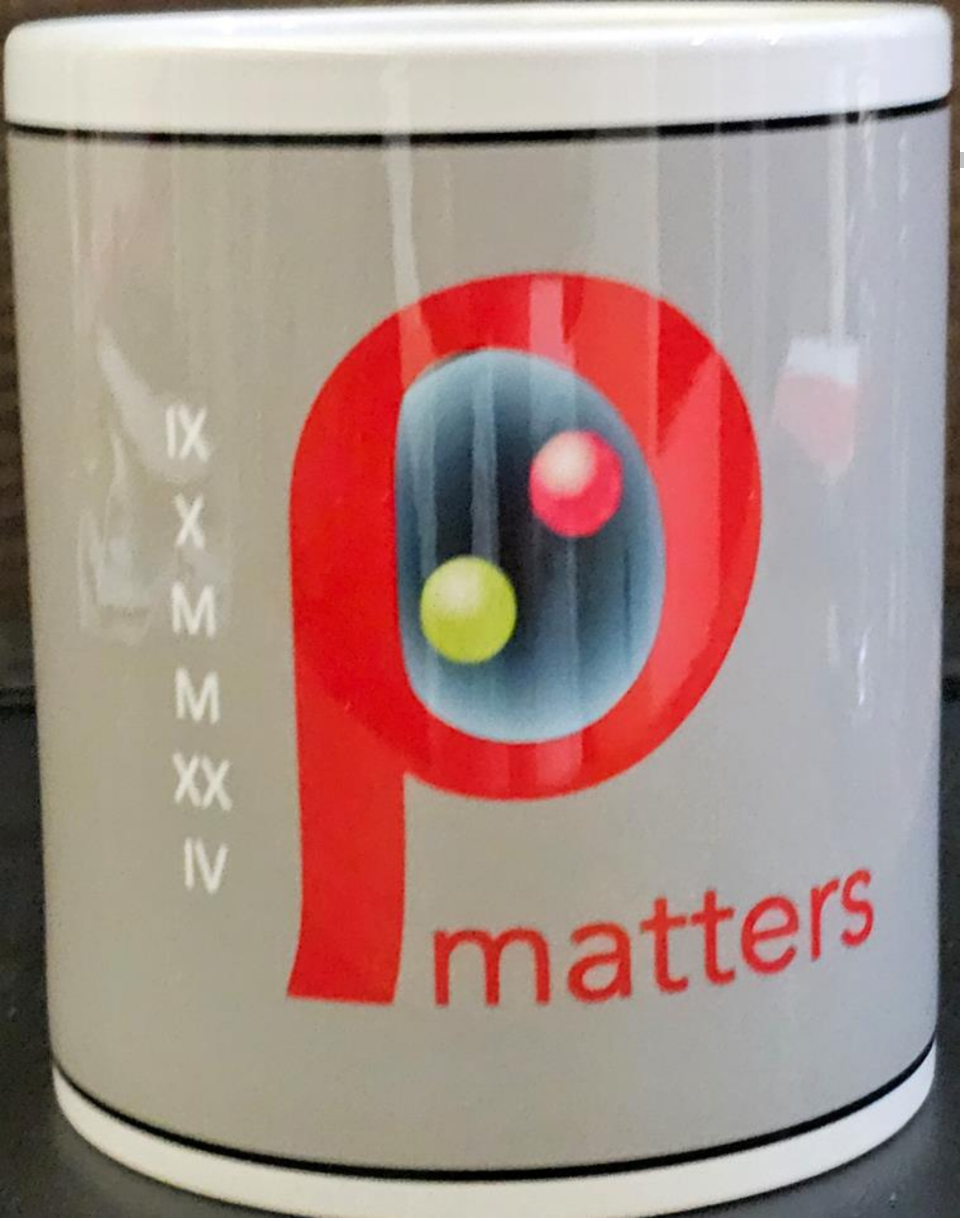
The role of the exclusive VMs in leptoproduction

Harut Avakian (JLab)

- Why rho matters in SIDIS and DIS?
- 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 and the need for MC
- Summary



Set a focus group to study exclusive VMs (JLab/HERMES/COMPASS/EIC)

Organize a dedicated workshop "Exclusive Vector mesons and SIDIS"

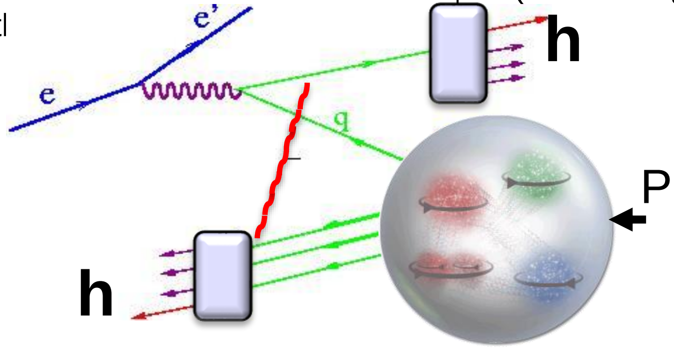
- **Set a CPHI prize for theoretical description of exclusive vector meson observables (SSA/DSA)**

Proposal for an EMMI Rapid Reaction Task Force meeting on rho in preparation

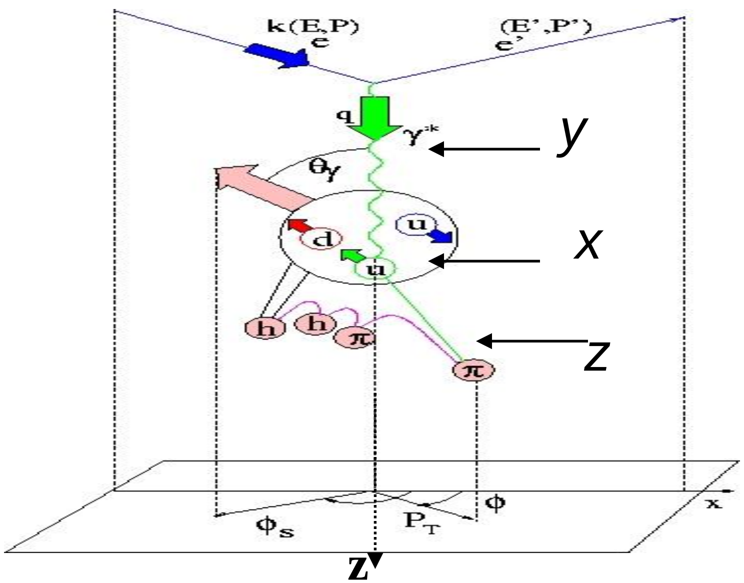
Polarized Leptoproduction

x_F – fractional momentum in tl

x_F>0 (current fragmentation, CFR)



x_F<0 (target fragmentation,TFR)

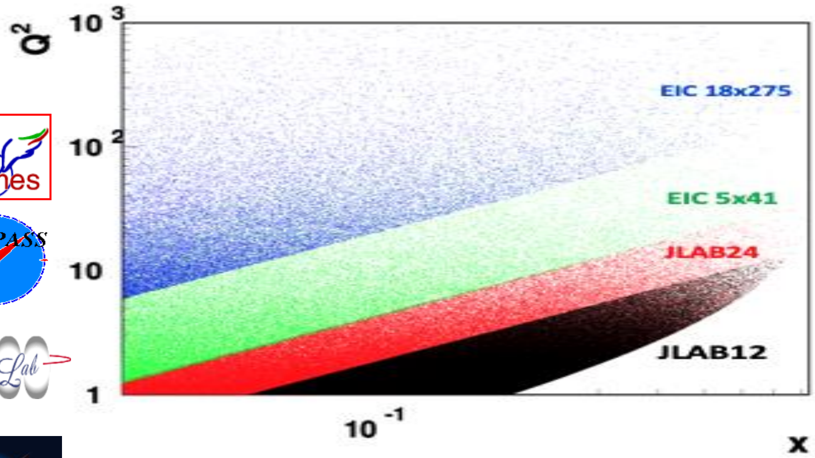


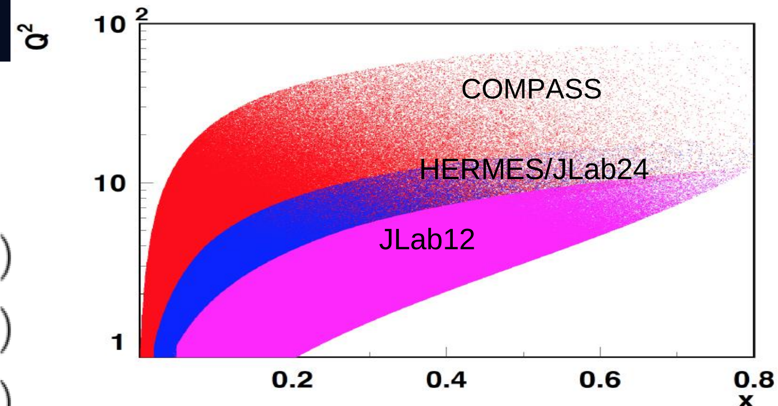
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

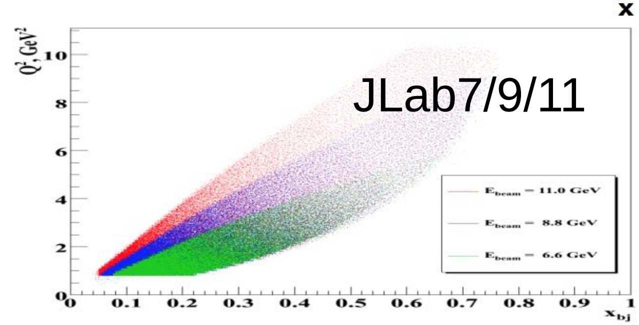
in eN→e'hX

6D (x,Q^2,z,P_T,ϕ,ϕ_S)

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

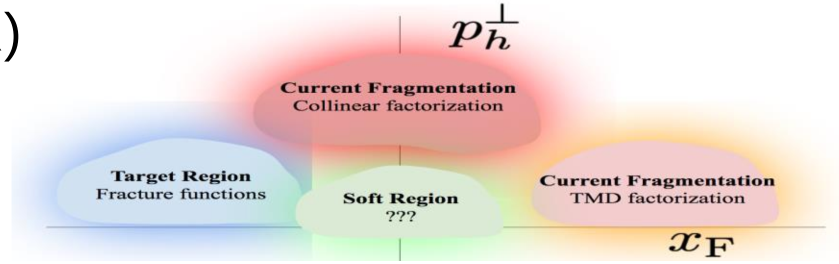


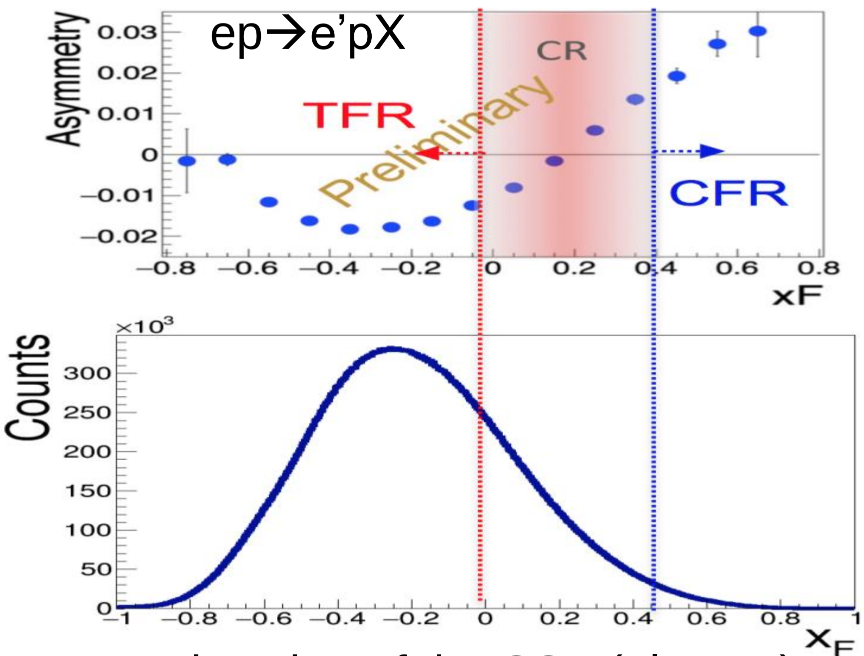




Beam SSAs as a tool to separate regions and contributions

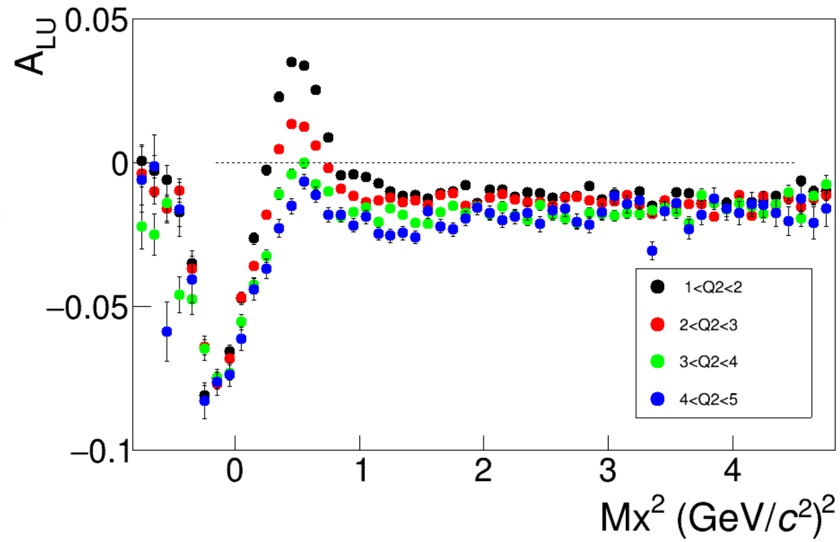
Separating Target Fragmentation Region TFR from Current fragmentation region (CFR)





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

F. Benmokhtar & Duquesne U.

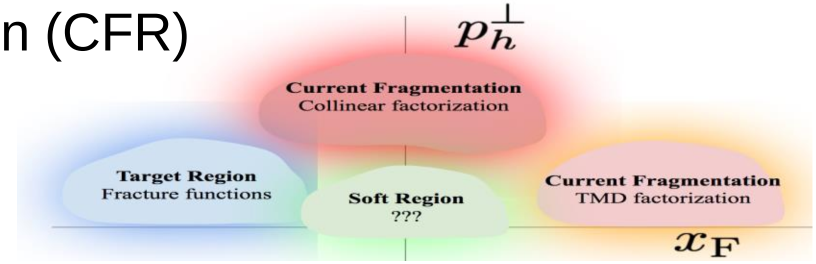


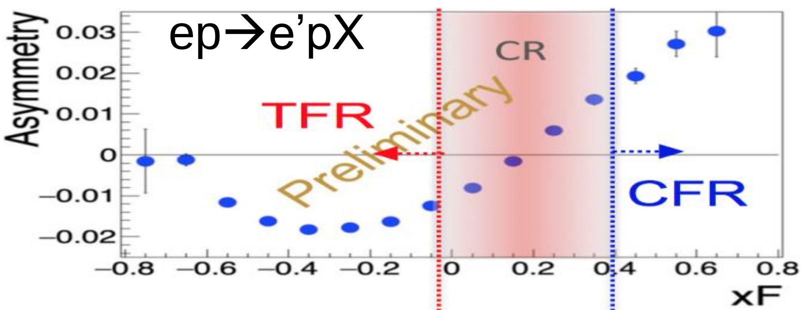
Major difference only for protons at small t!

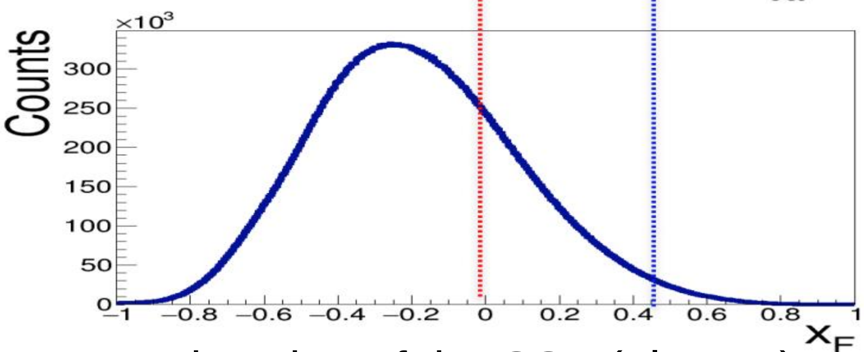
With beams in polarized SIDIS typically always polarized, beam SSA can serve as a tool to separate
1) kinematical regions (CFR/TFR)
2) Higher the Q^2, less prominent is rho

Beam SSAs as a tool to separate regions and contributions

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







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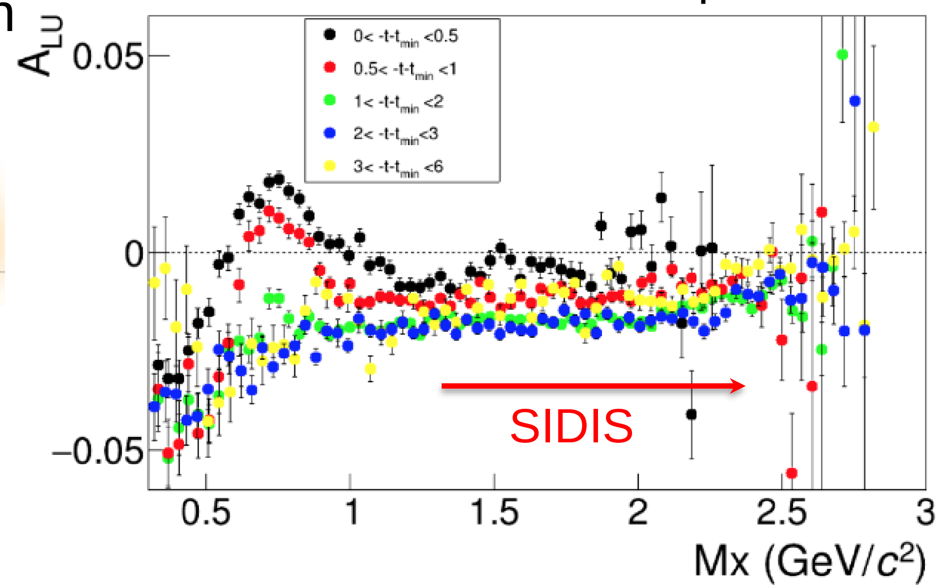
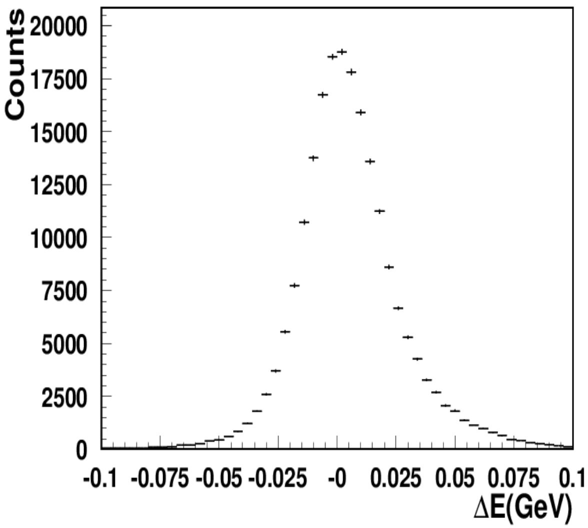


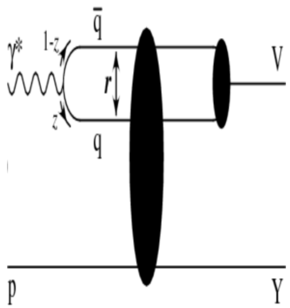
Major difference only for protons at small t!

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

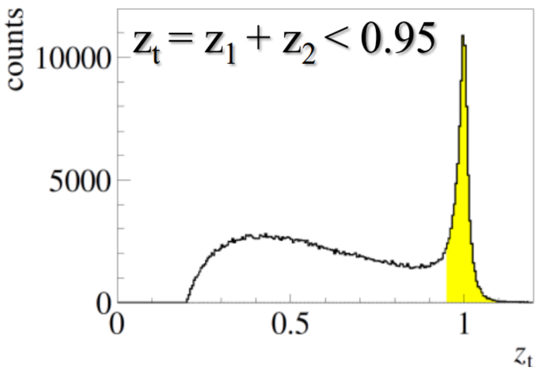
Addressing PAC/theory comments

2) Diffractive VMs (ρ^0)

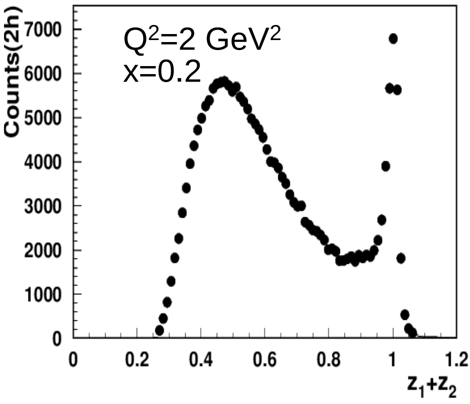




COMPASS 2h



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.

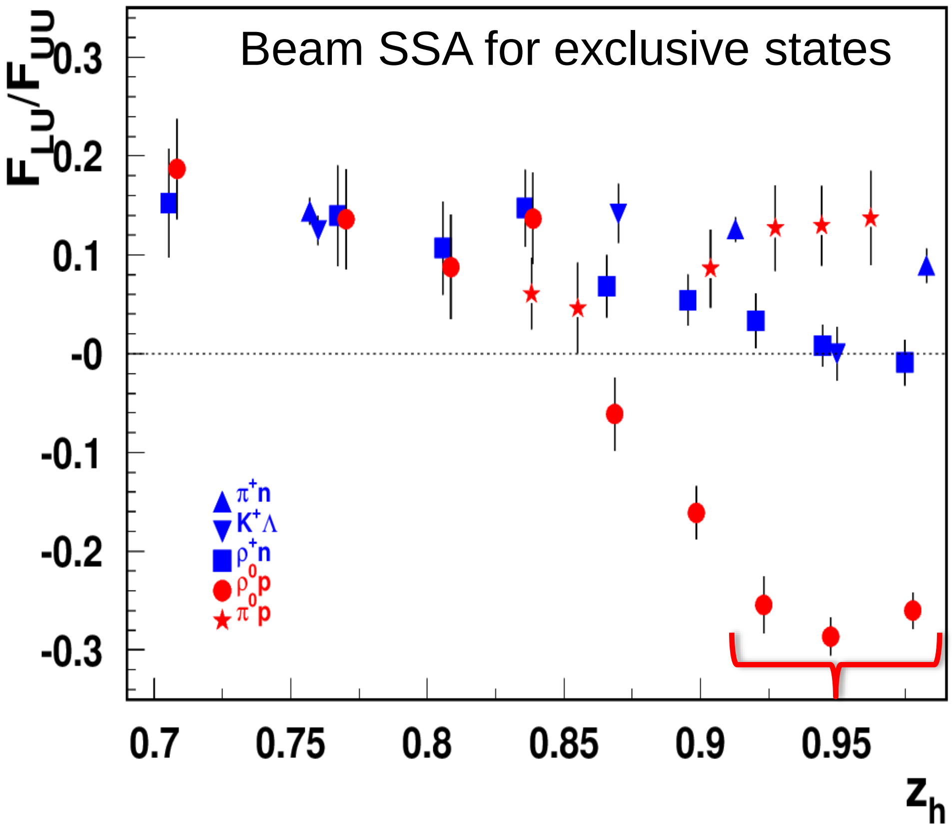
Estimated ~20% contributions from rho to charged pion SIDIS, consistent with ~10% of diffractive DIS in inclusive DIS

indication: most longitudinally polarized ρ^0

note: higher the Q^2 lower is ε

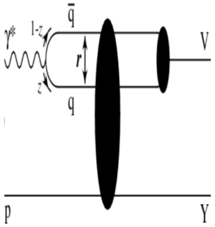
Studies of exclusive processes require high resolution and multidimensional measurements !!!

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)

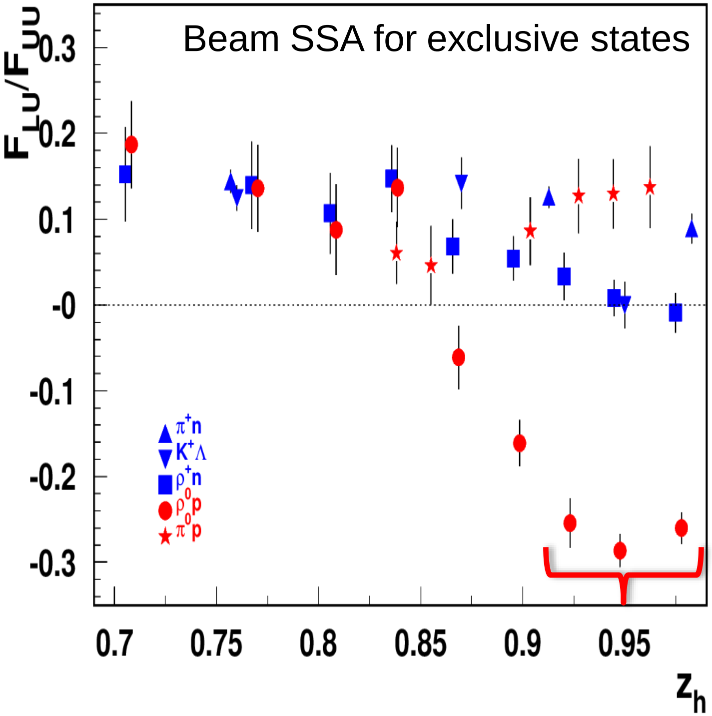


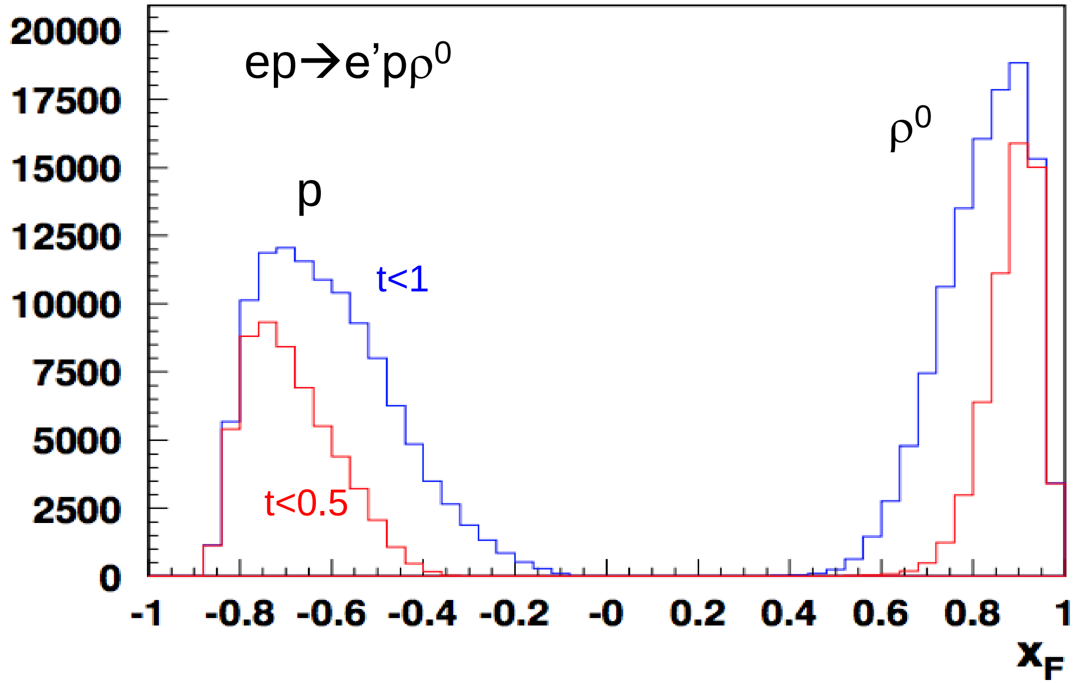
+preliminary data on ep→e'pϕ (A_{LU}=-0.084+/-0.038)

- Beam SSA can be used to separate dynamical contributions

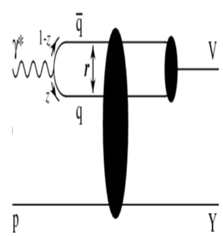
At higher energies (COMPASS/HERMES) no major effect were observed, as high resolution and multidimensional measurements are critical !!!

“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?

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 ($eN \rightarrow ehX$, $h=\pi,K,..$) within the full accessible kinematics, corrected for acceptance and RC, measured in the multidimensional space

→$e\pi X$ 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 ($eN \rightarrow e\pi X$) 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 ($eN \rightarrow ep\pi X$, $eN \rightarrow e\pi\pi X$) 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

Understanding exclusive rhos and SDME validations

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

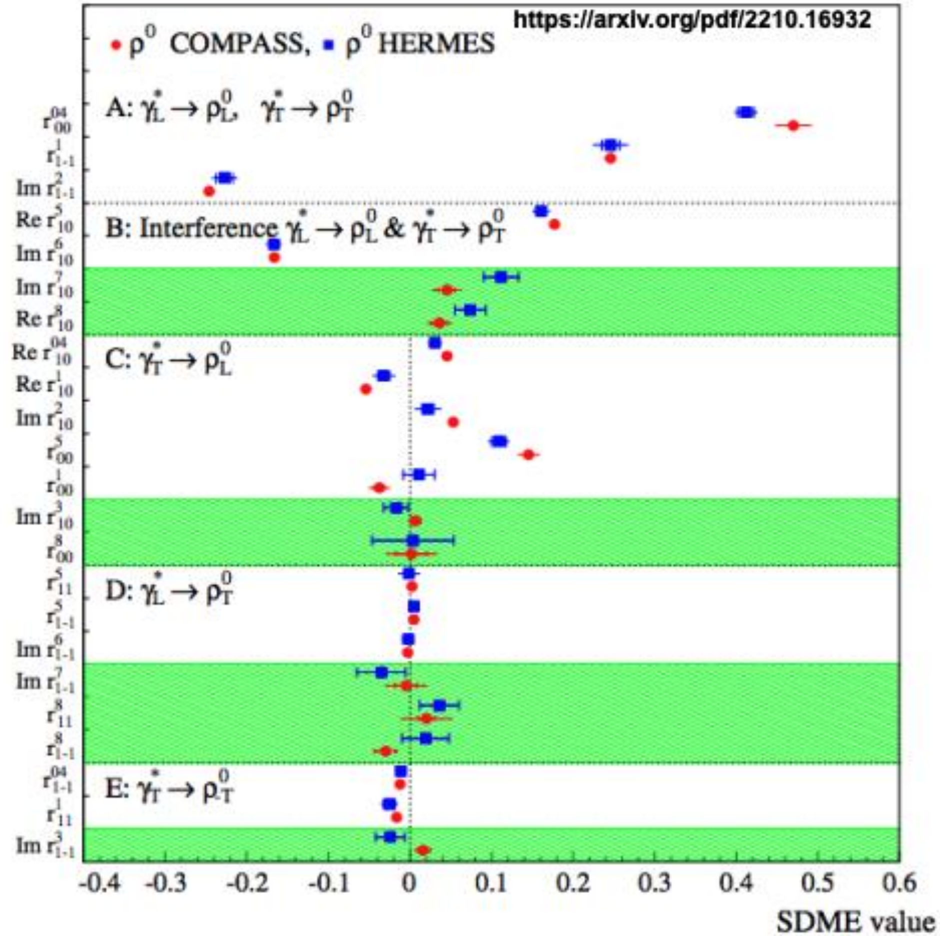


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle|t'|\rangle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

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

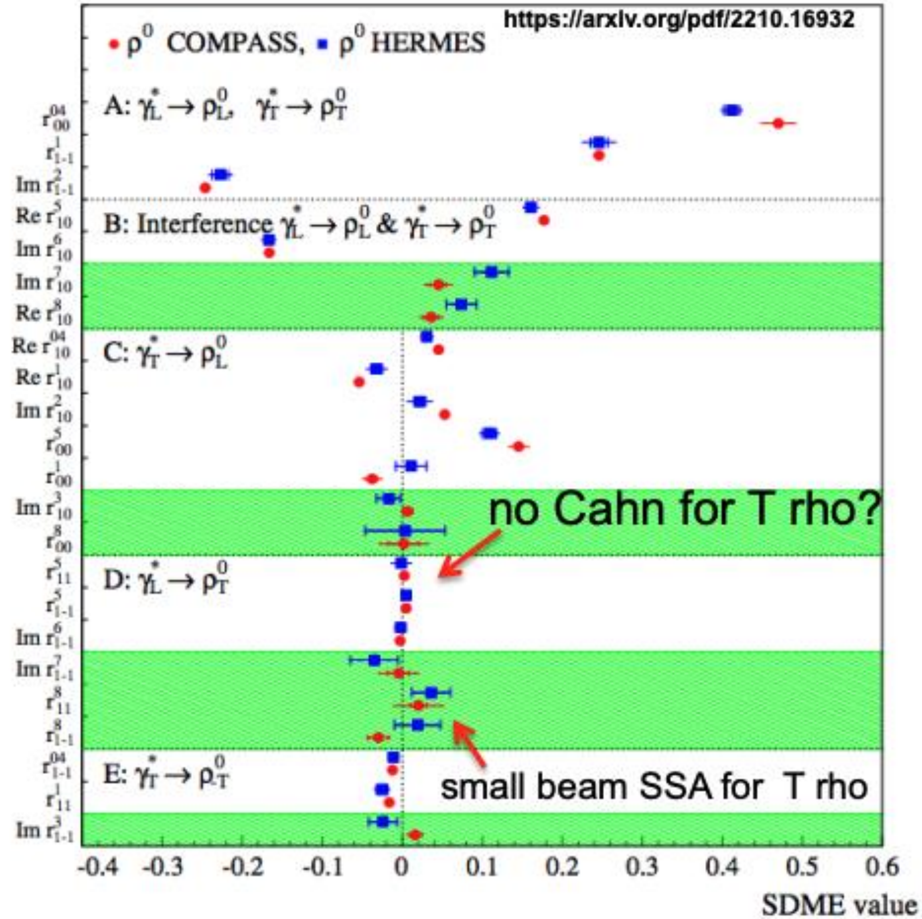
$$+ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta\right.$$

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

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)

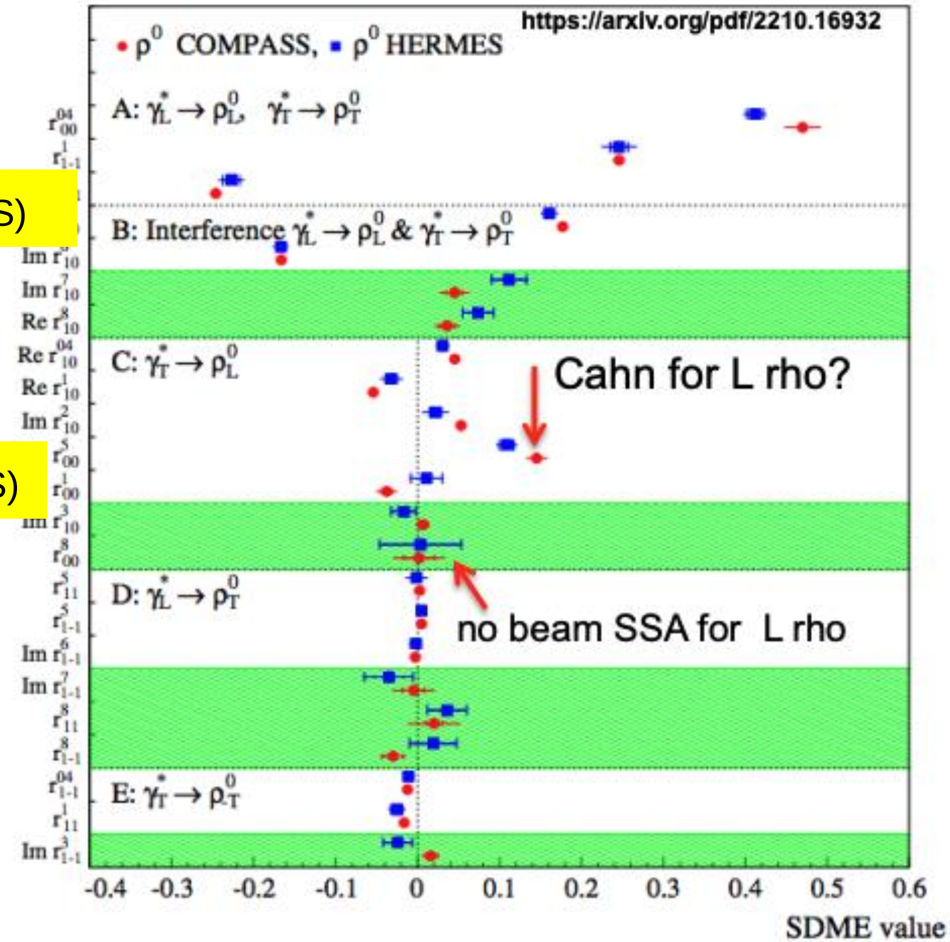
$$\mathcal{W}^L(\Phi,\phi,\cos\Theta)$$

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

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

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

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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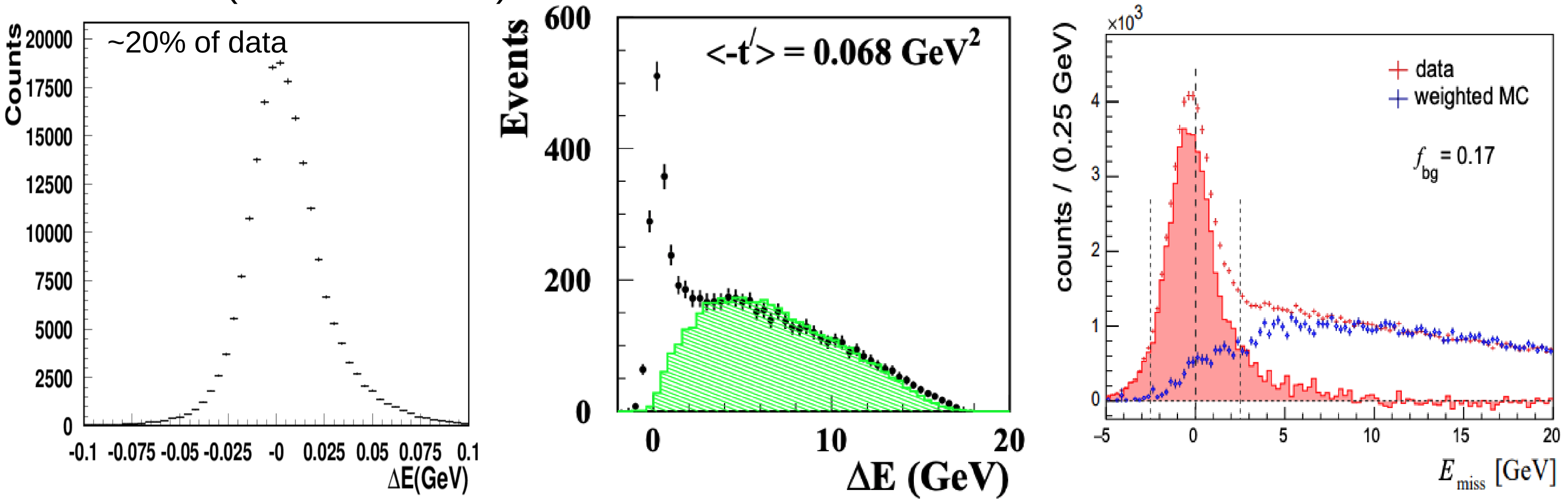
CLAS12 Experiments involved: RGA superiority

Exclusivity condition defined by the missing Energy:

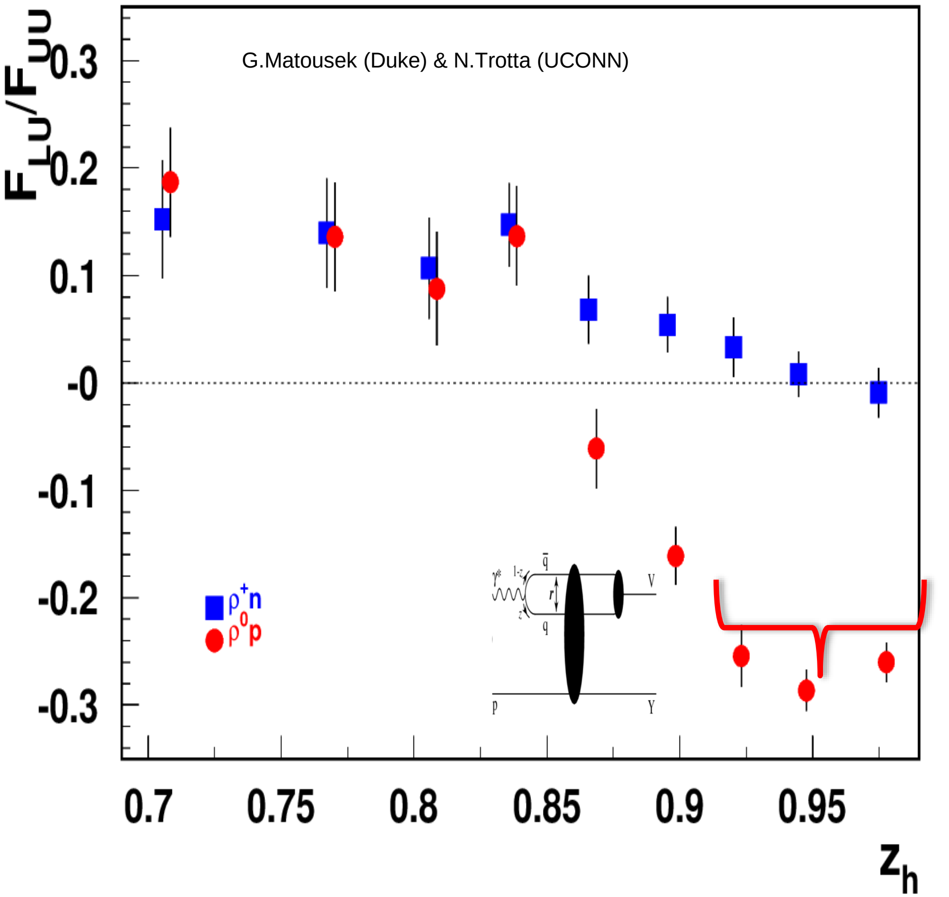
$$M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2 \qquad E_{\text{miss}} = \frac{M_X^2 - M^2}{2M}$$

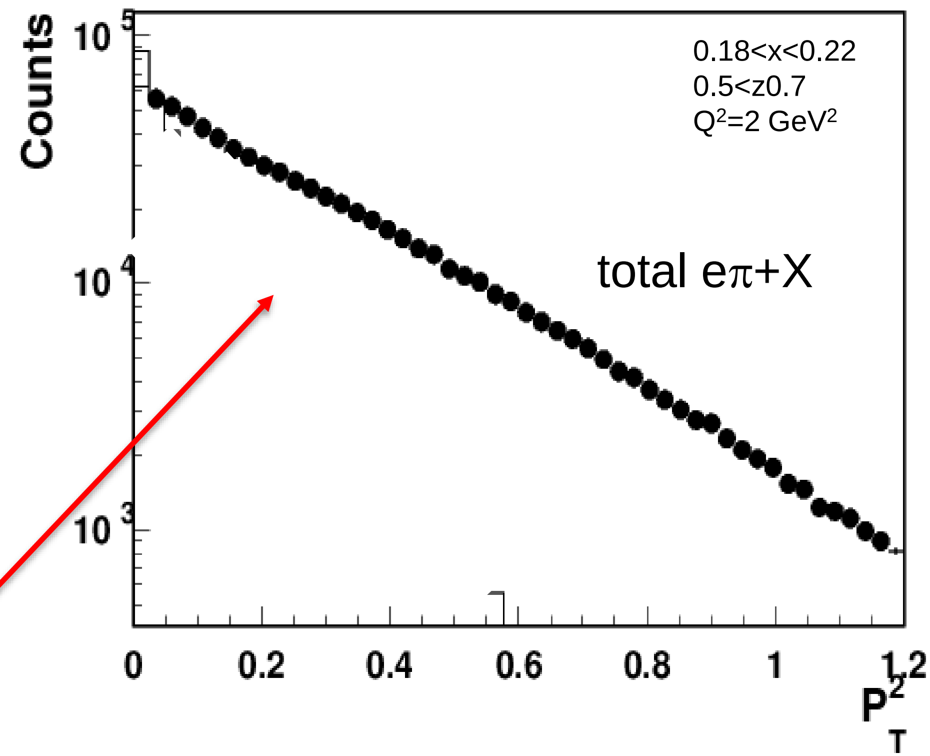
CLAS12 (width <0.1GeV) HERMES(width ~0.6GeV) COMPASS(width ~2GeV)



- 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)

“diffractive rho0s” in SIDIS multiplicities



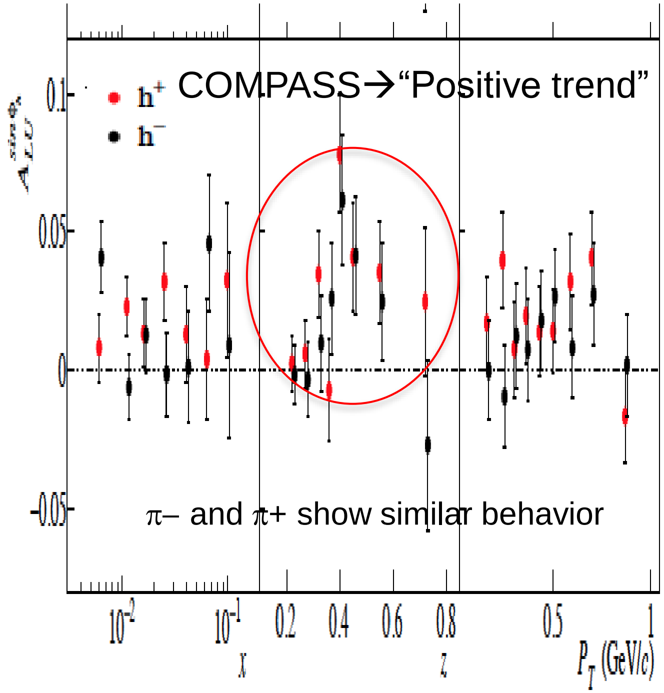


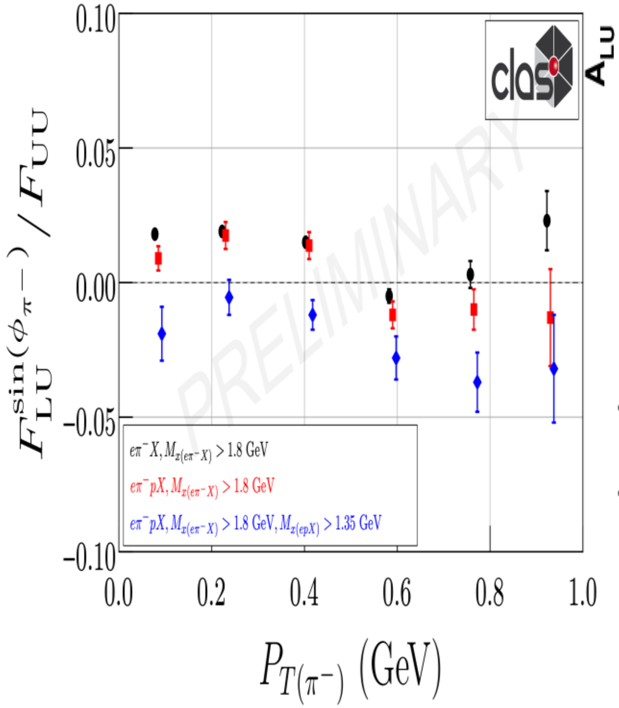
$t_{min} \approx -M^2x^2/(1-x)$

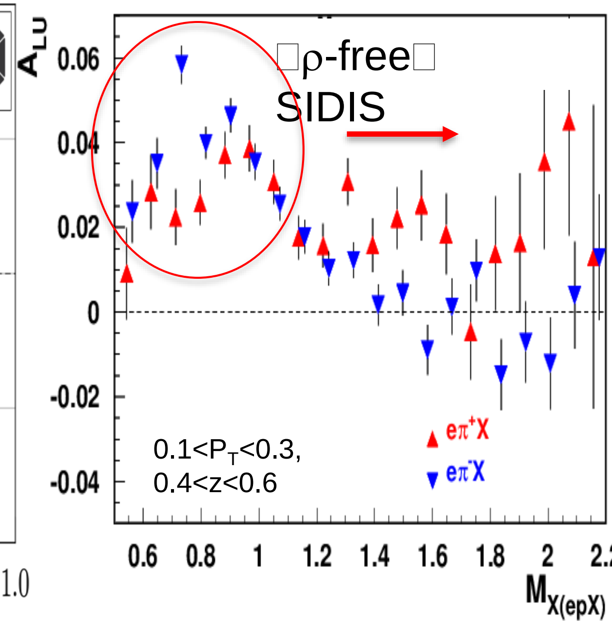
Estimated ~20% contributions from rho, mainly show up at low P_T in SIDIS

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

Exclusive ρ contributions to π: P_T-dependence



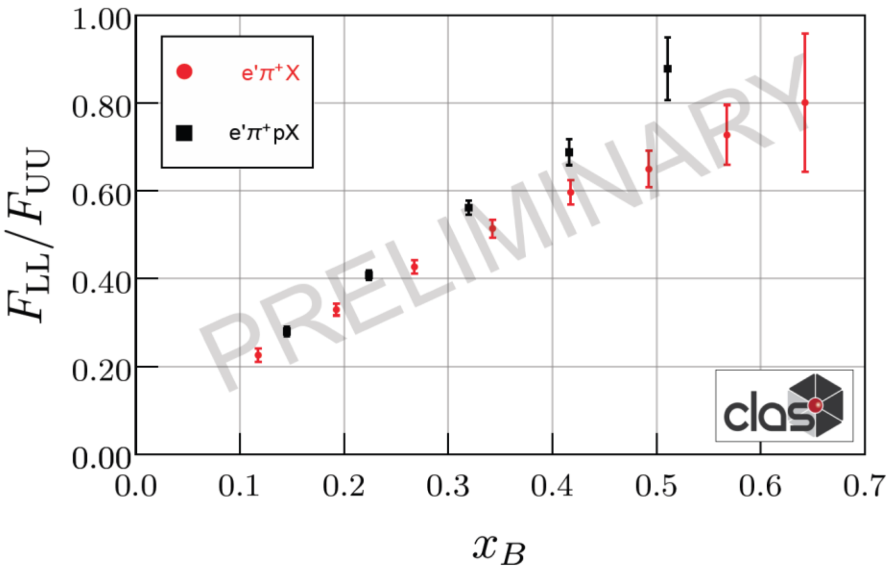




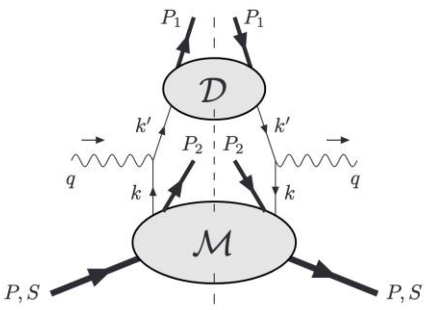
COMPASS→"Positive trend" also reproduced when additional proton in TFR detected (red)

- 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

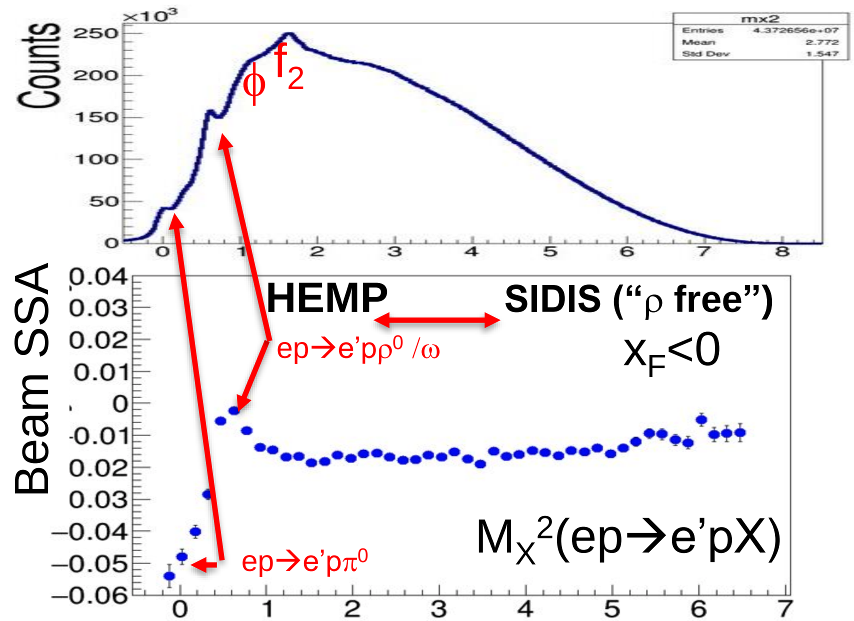


ep→e'pπX



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!

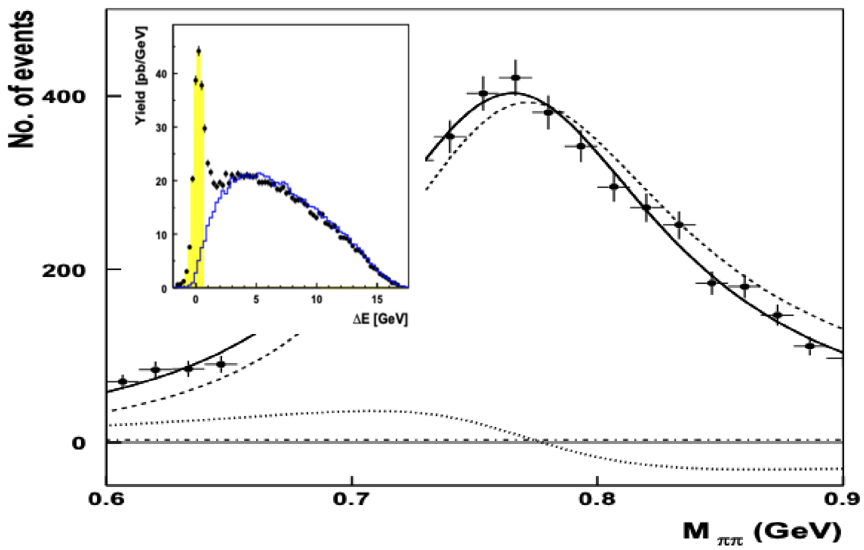


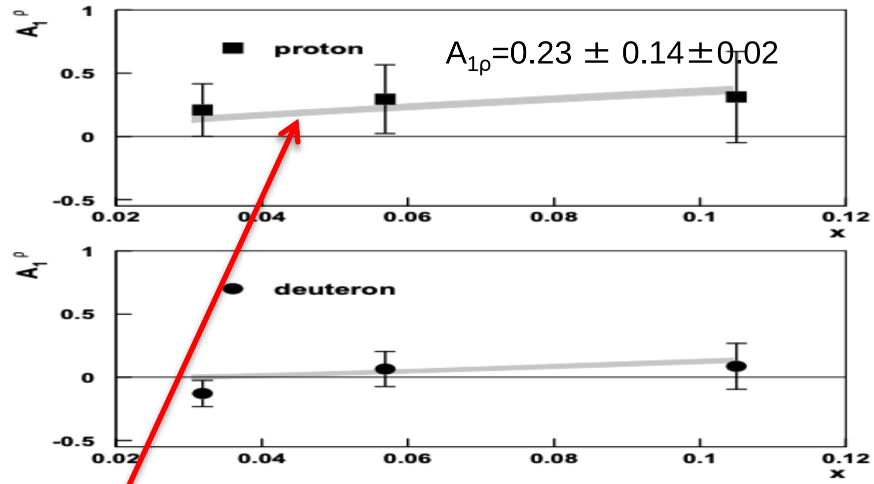
Possible theory formalisms:

- **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!!!

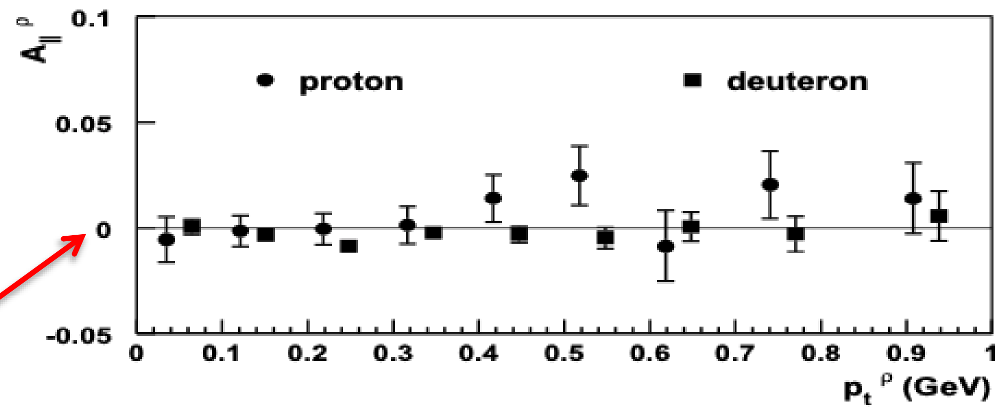
A_{LL} studies of exclusive ρ^0 : HERMES





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

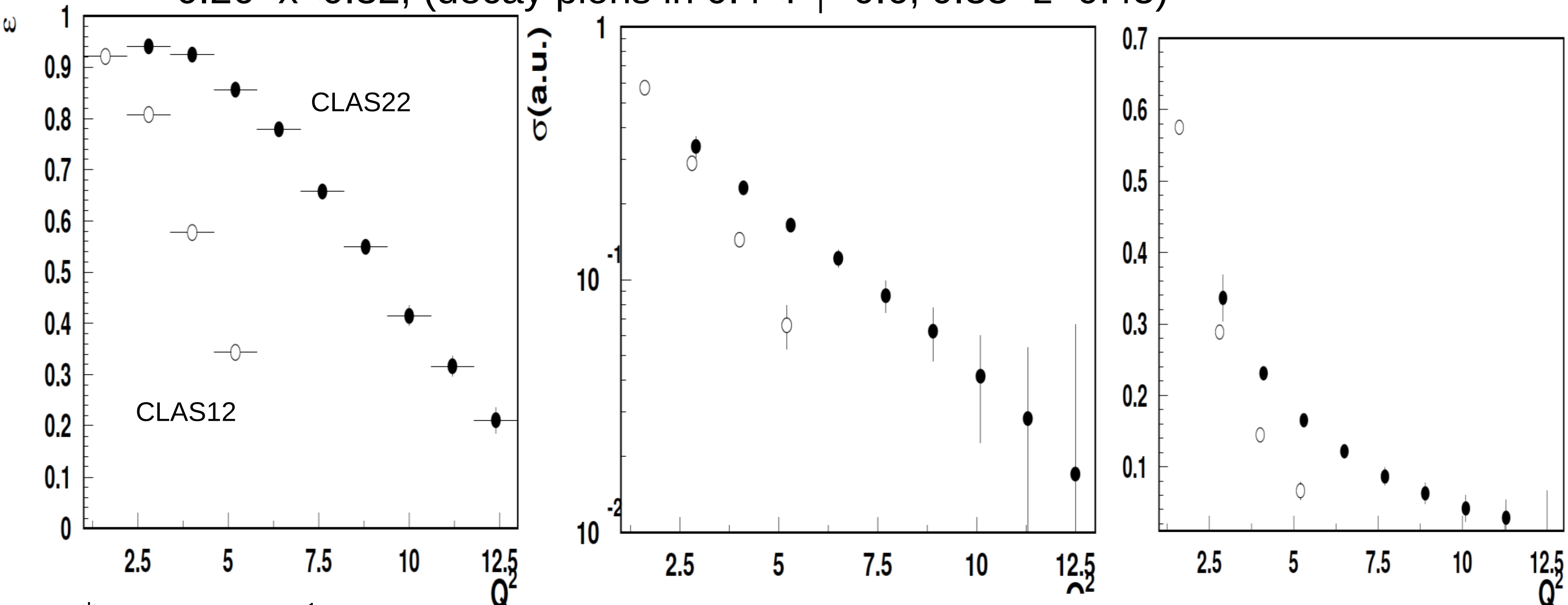


At low P_T, where the background is smaller, the asymmetry indeed tend to be negative

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

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

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



$$\gamma^*_L \rightarrow \rho_L \propto 1$$
$$\gamma^*_T \rightarrow \rho_L \propto \sqrt{-t}/Q$$

Longitudinal photon contributions enhanced at higher energies

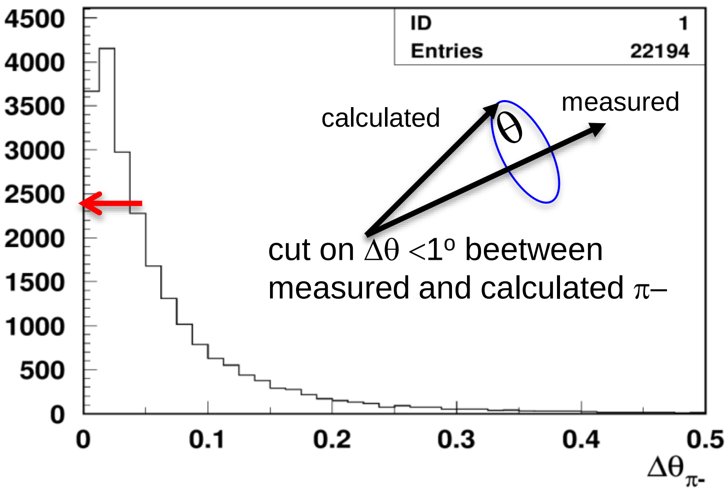
$$\gamma^*_T \rightarrow \rho^0_L \quad \tau_{01} \approx \sqrt{\epsilon}\frac{\sqrt{(r^5_{00})^2+(r^8_{00})^2}}{\sqrt{2r^{04}_{00}}}$$

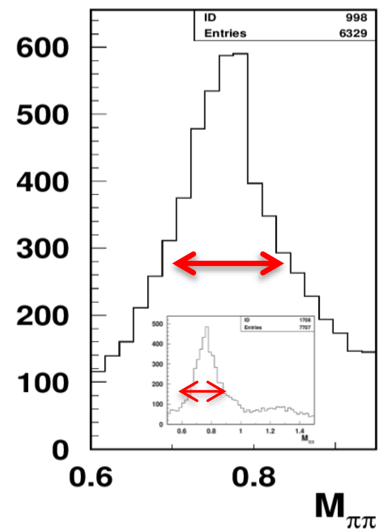
$$W^L(\Phi,\phi,\cos\Theta)$$
$$+ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta\right.$$

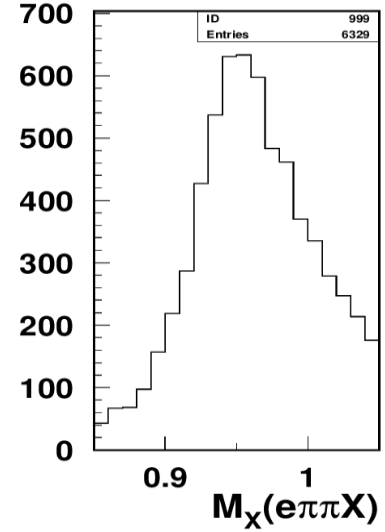
- Wider in t the range of integration, less will be relative fraction from asymmetric decays
- Range in Q^2 increases significantly allowing detailed studies at beyond 10 GeV^2

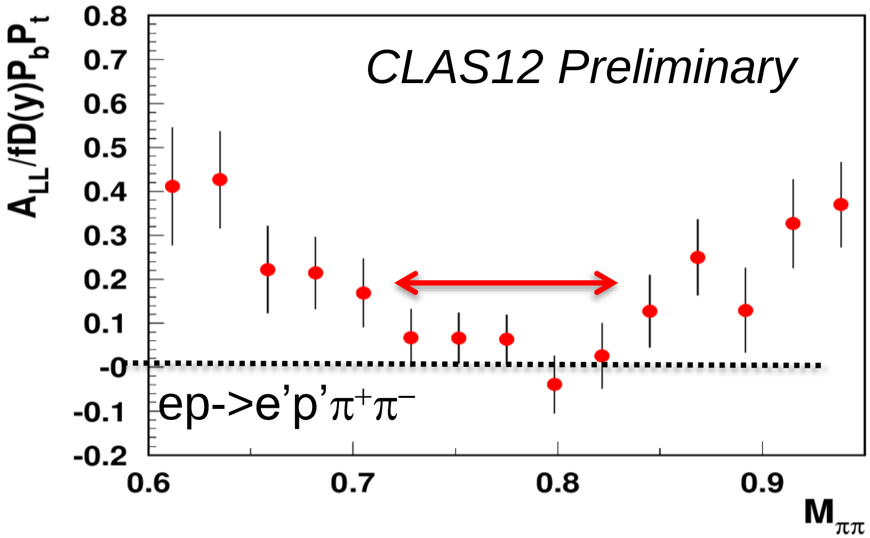
CLAS12 studies of ρ^0 using longitudinally polarized NH_3 target

Separating exclusive dihadrons



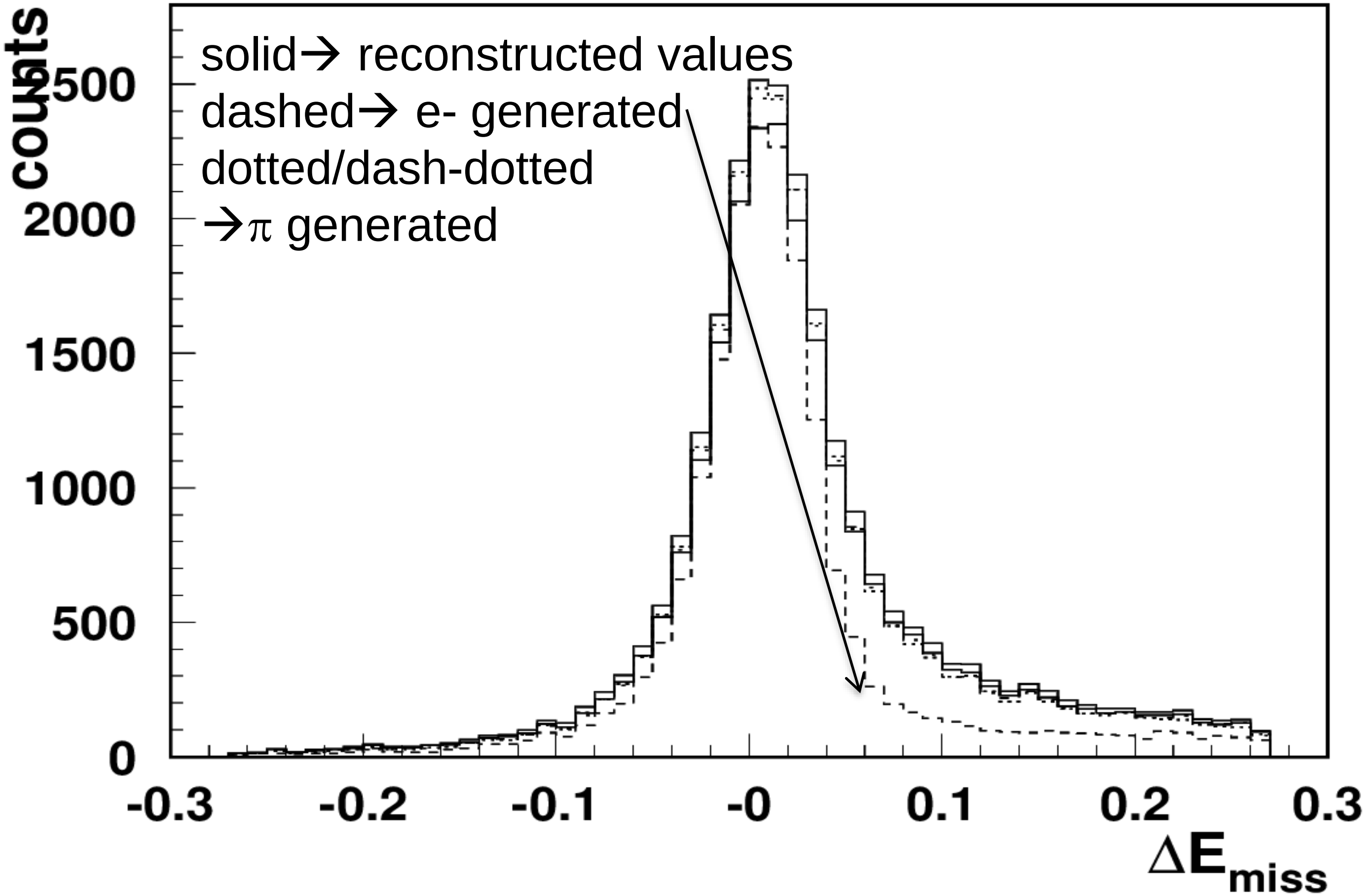




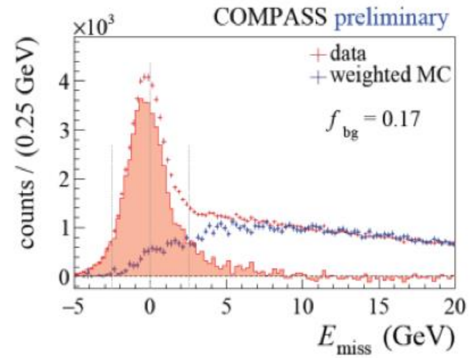


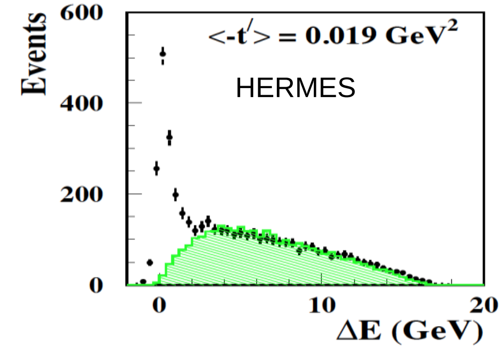
- Require the angle of negative pions is within a degree from calculated from e',p,π+ assuming exclusive e',p,π+π- event.
- Angular cuts remove the non-exclusive background and most importantly the nuclear contribution
- Measurements of exclusive rhos with polarized nuclear targets, A_{LL} in particular, require detection of the recoil proton (large positive asymmetry ~40% for "non-diffractive" component)

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)

Measured x-section: DDIS vs DIS

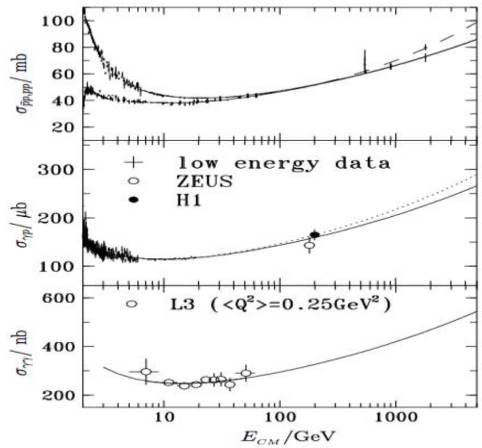
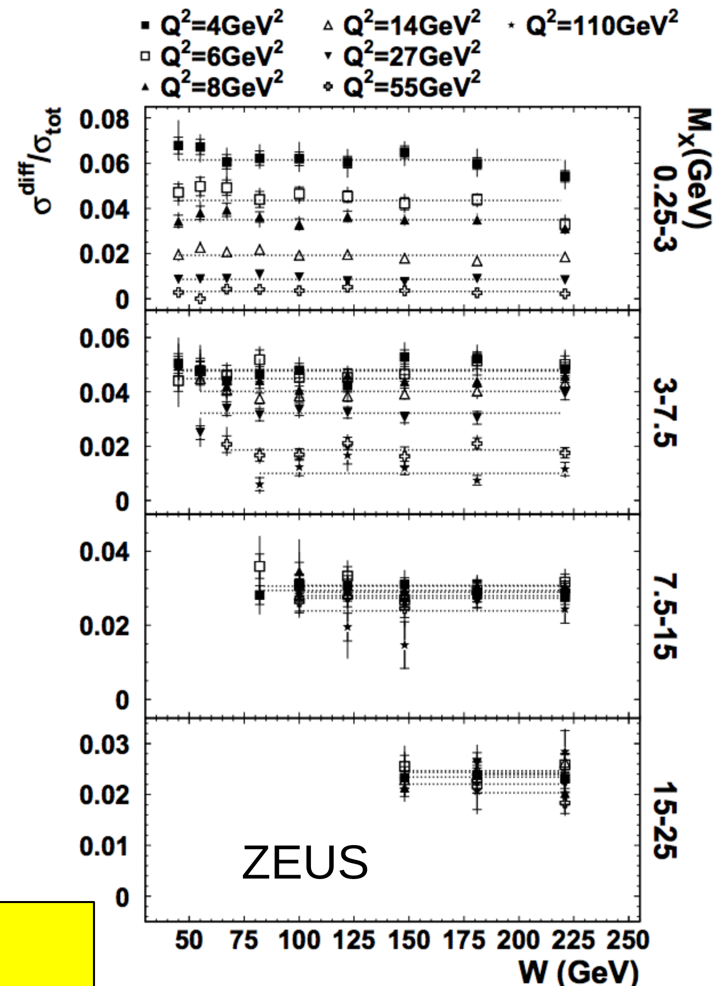


Figure 1.9: Total cross sections for pp ($p\bar{p}$), γp and $\gamma\gamma$ scattering as a function of the center of mass energy E_{CM}. The curves represent the DL parameterization with $\alpha_{I\!P}(0) =$ 1.0808 (solid), $=$ 1.112 (dashed) and $=$ 1.088 (dotted).

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

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

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].



M_X in DDIS and M_X in exclusive rho different

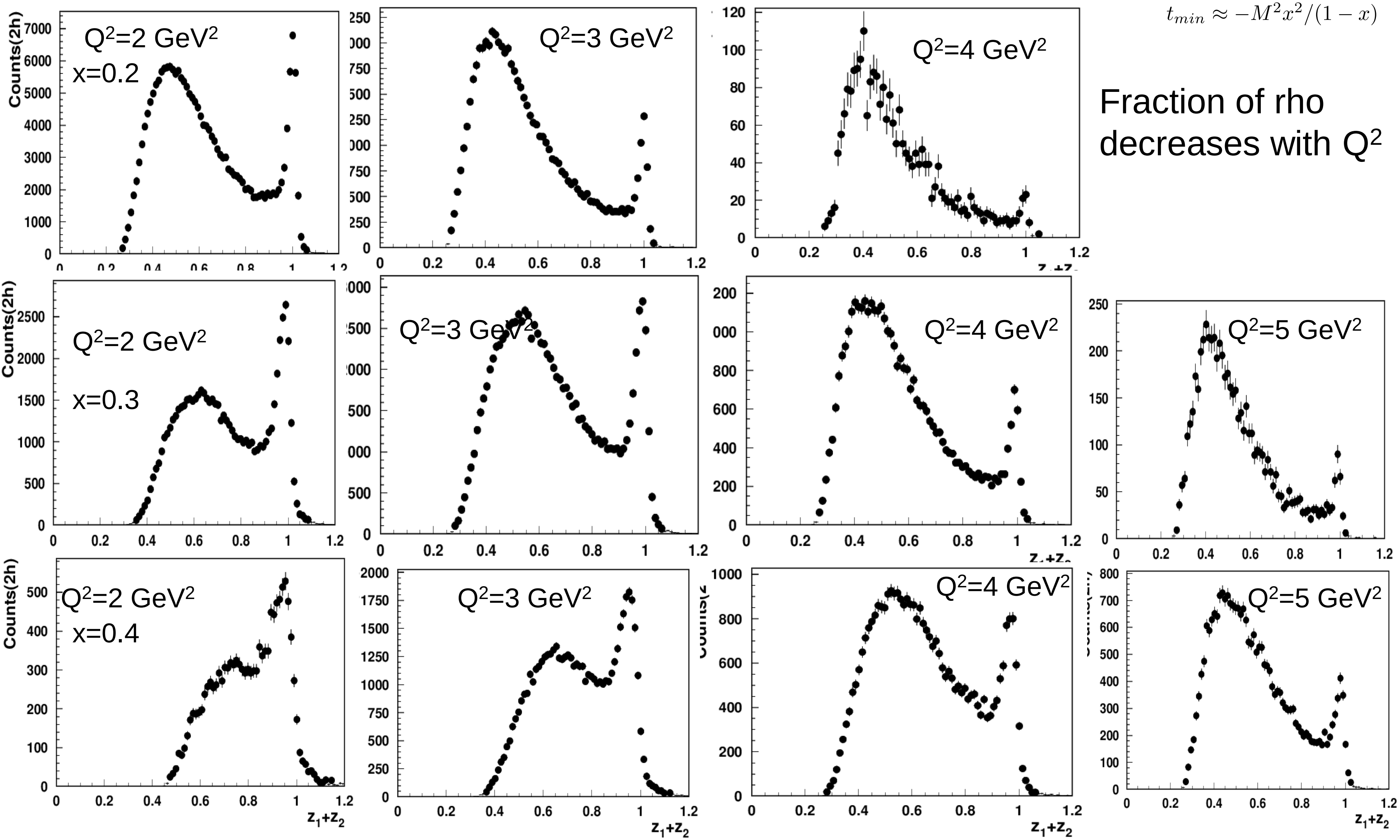
No dependence on W, decrease with Q^2 indicating the rho can be the main contributor
At higher W there seem to be no Q^2-dependence

.6: The ratio of the diffractive cross section σ^{diff}, integrated over the bin width $< M_b$, and the total $\gamma^* p$ cross section σ^{tot} is shown as a function of W for ns 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.

Exclusive dihadrons from CLAS12

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

Fraction of rho decreases with Q^2



SDMEs from theory

Nuclear Physics B61 (1973) 381–413. North-Holland Publishing Company

polarized beam unpolarized target

HOW TO ANALYSE VECTOR-MESON PRODUCTION IN INELASTIC LEPTON SCATTERING

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Preprint typeset in JHEP style - PAPER VERSION

DESY-07-049
arXiv:0704.1565 [hep-ph]

+polarized targets: Using the helicity basis for both photon and meson

Vector meson production from a polarized nucleon

M. Diehl

Deutsches Elektronen-Synchroton DESY, 22603 Hamburg, Germany

ABSTRACT: We provide a framework to analyze the electroproduction process $ep \to ep\rho$ with a polarized target, writing the angular distribution of the ρ decay products in terms of spin density matrix elements that parameterize the hadronic subprocess $\gamma^* p \to \rho p$. Using the helicity basis for both photon and meson, we find a representation in which the expressions for a polarized and unpolarized target are related by simple substitution rules.

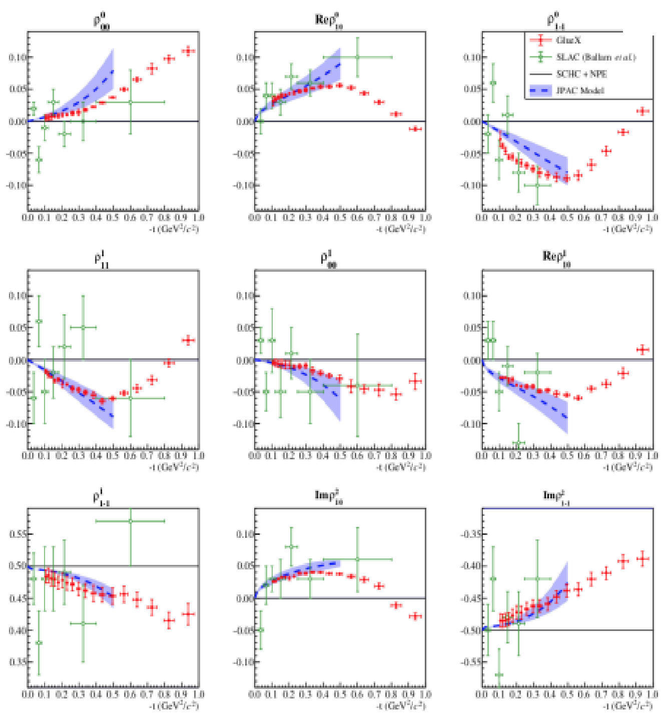
KEYWORDS: Lepton-Nucleon Scattering, Spin and Polarization Effects.

SDMEs from photoproduction

D. Glazier: https://indico.jlab.org/event/829/contributions/14273/attachments/10776/16321/PolarisedTwoPion.pdf

Spin Density Matrix Elements, ρ photoproduction

GlueX results



Measurement of Spin-Density Matrix Elements in $\rho(770)$ Production with a Linearly Polarized Photon Beam at $E_\gamma = 8.2 - 8.8\,\mathrm{GeV}$

$$W^0(\cos\vartheta,\varphi) = \frac{3}{4\pi}\Big(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\Big) \quad (10)$$

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

$$W^2(\cos\vartheta,\varphi) = \frac{3}{4\pi}\Big(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\Big)\,. \quad (12)$$

$$\rho^0_{00} = \frac{1}{3}(5H^0(20)+1)$$
$$\Re\rho^0_{10} = \frac{5}{\sqrt{12}}H^0(21)$$
$$\rho^0_{1-1} = -\frac{5}{\sqrt{6}}H^0(22)$$
$$\rho^1_{11} = -\frac{1}{3}H^1(00)$$
$$\rho^1_{00} = -\frac{5}{2}H^1(20) - \frac{1}{3}H^1(00)$$
$$\Re\rho^1_{10} = -\frac{5}{\sqrt{12}}H^1(21)$$
$$\rho^1_{1-1} = \frac{5}{\sqrt{6}}H^1(22)$$
$$\Im\rho^2_{10} = -\frac{5}{\sqrt{12}}H^2(21)$$
$$\Im\rho^2_{1-1} = \frac{5}{\sqrt{6}}H^2(22)$$
$$\Im\rho^3_{10} = -\frac{5}{\sqrt{12}}H^3(21)$$
$$\Im\rho^3_{1-1} = \frac{5}{\sqrt{6}}H^3(22)$$

This tells us what our data should look like

Link between partial waves and SDMEs

SDMEs from photoproduction

A. Austregesilo:https://indico.icc.ub.edu/event/180/contributions/2528/attachments/1234/2479/QNP24_Austregesilo.pdf

Extraction of SDMEs

with Amplitude Analysis Technique

Jefferson Lab

Thomas Jefferson National Accelerator Facility

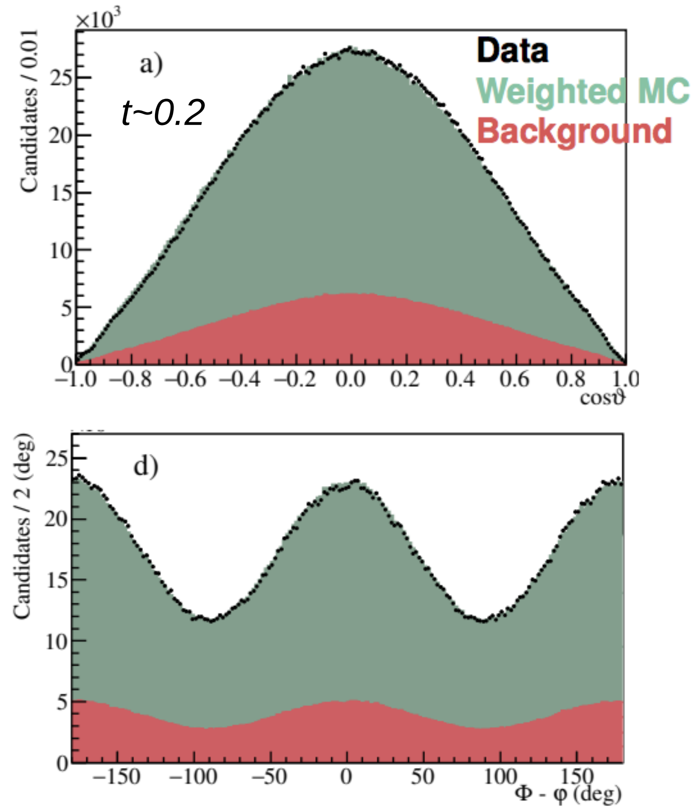
Extended Maximum-Likelihood Fit

$$\ln L = \underbrace{\sum_{i=1}^{\text{events}} \ln \mathcal{I}(\tau_i)}_{\text{Experiment}} - \underbrace{\int d\Omega\, \mathcal{I}(\tau)\, \eta(\tau)}_{\text{Normalization Integral}}$$

- Choose SDMEs such that intensity fits the observed events
- Normalization integral evaluated by a phase-space Monte Carlo sample with the acceptance $\eta(\tau) = 0/1$

Analysis Strategy

- Improve theoretical description of photoproduction process
- Understand and evaluate detector acceptance
- Prerequisites for amplitude analysis of possible exotic signals



ENERGY JSA A. Austregesilo (aaustreg@jlab.org) — The Search for Exotic Hadrons at GlueX 17/36

Clear dominance of transverse rhos in photoproduction at low t

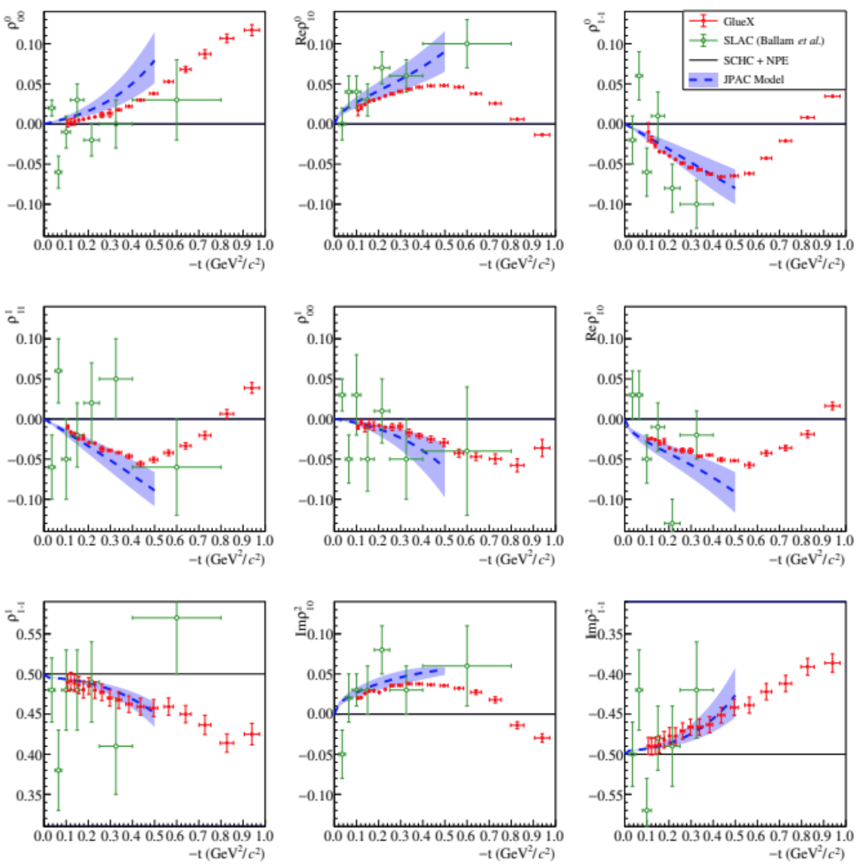
SDMEs from photoproduction

A. Austregesilo:https://indico.icc.ub.edu/event/180/contributions/2528/attachments/1234/2479/QNP24_Austregesilo.pdf

$\rho(770)$ Meson SDMEs

PRC 108, 055204 (2023)

Jefferson Lab
Thomas Jefferson National Accelerator Facility



$\gamma p \to \rho(770)p$

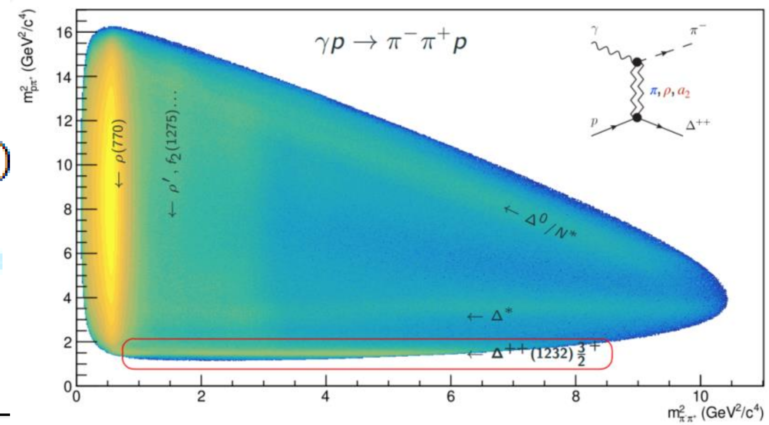
- High precision with only fraction of data set
- Orders of magnitude more precise than previous measurements
- Uncertainties dominated by systematics
- Agree with Regge model up to $-t \approx 0.5\,\mathrm{GeV}^2/c^2$ [JPAC, PRD 97 094003 (2018)]
- Studies of mass and energy dependence

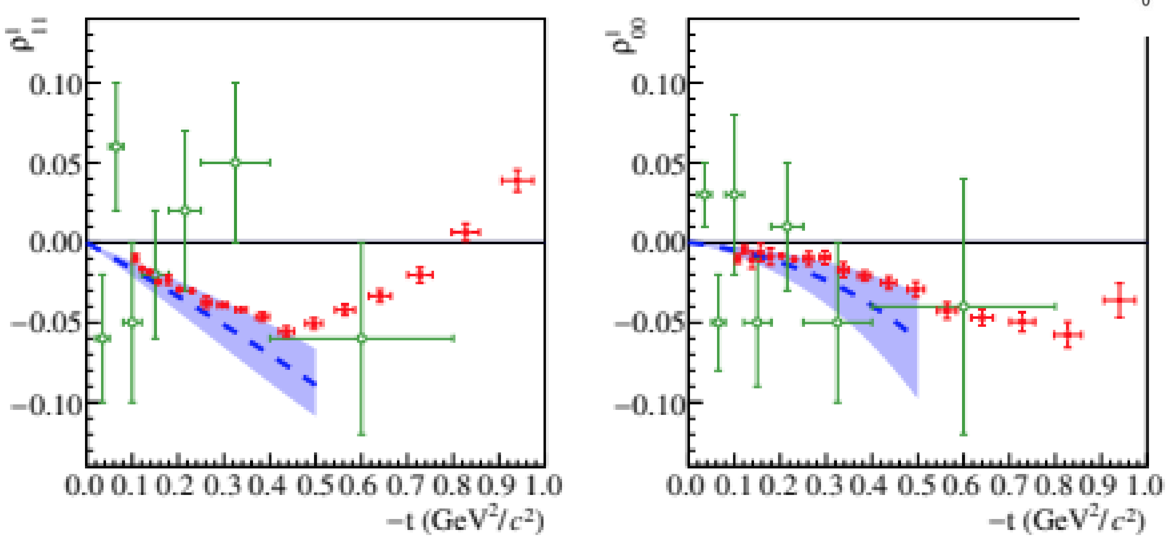
ENERGY JSA A. Austregesilo (aaustreg@jlab.org) — The Search for Exotic Hadrons at GlueX 18/36

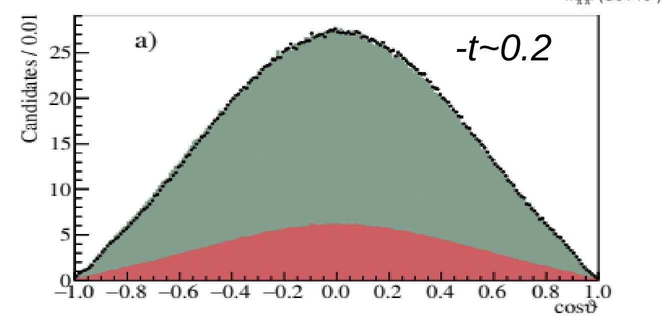
SDMEs from photoproduction

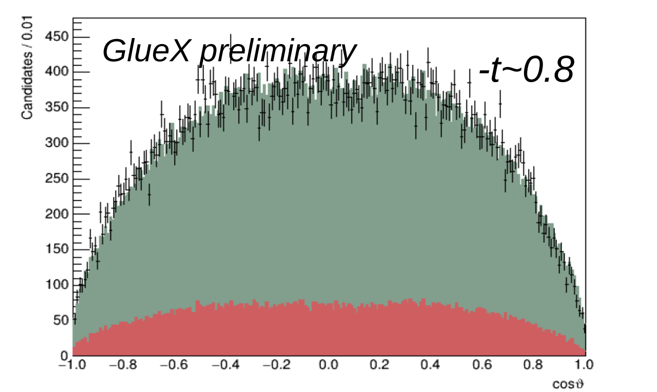
JLab/GlueX, S. Adhikari et al, Phys.Rev.C 108 (2023), 055204: ArXiv:2305.09047

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





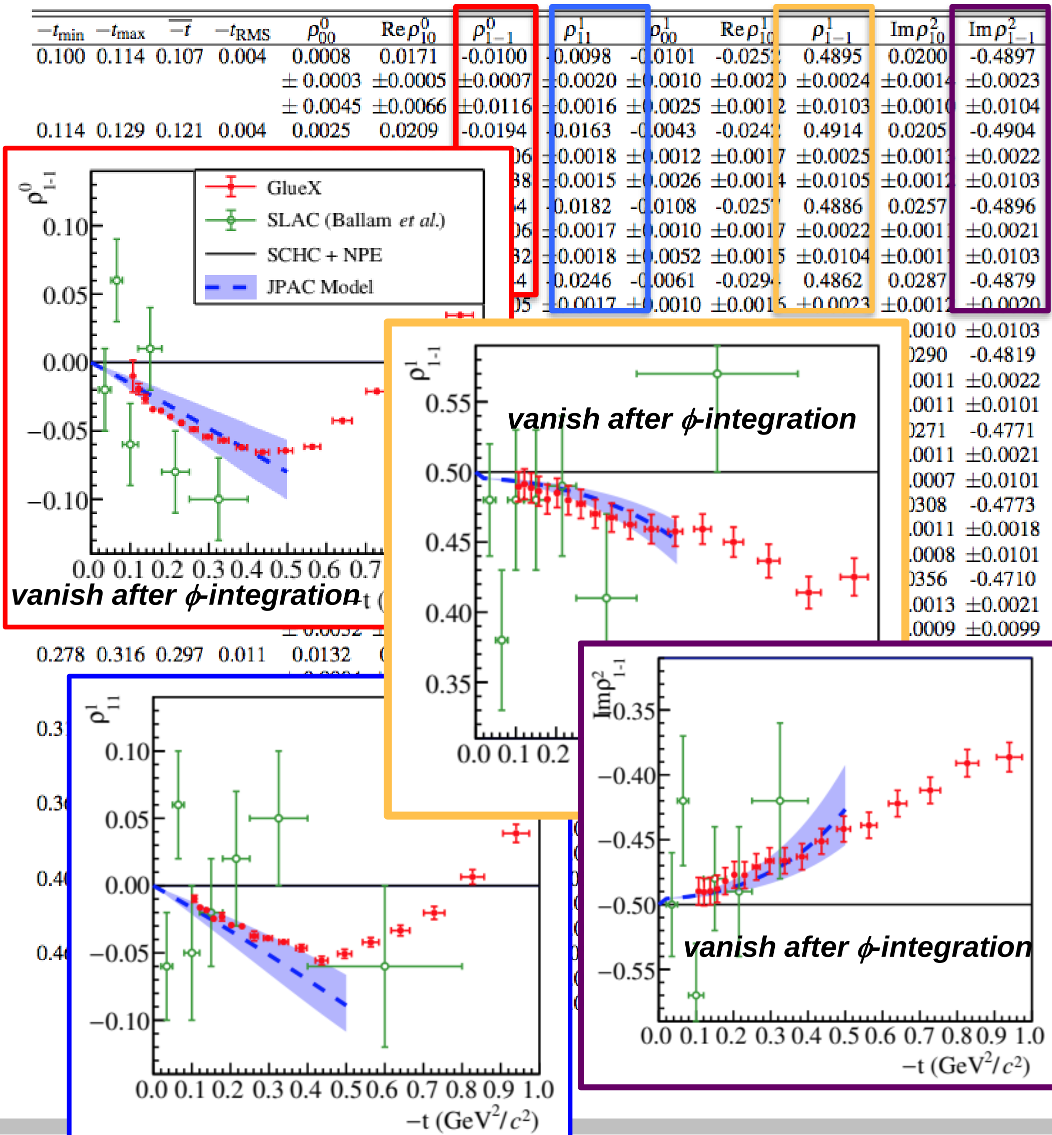


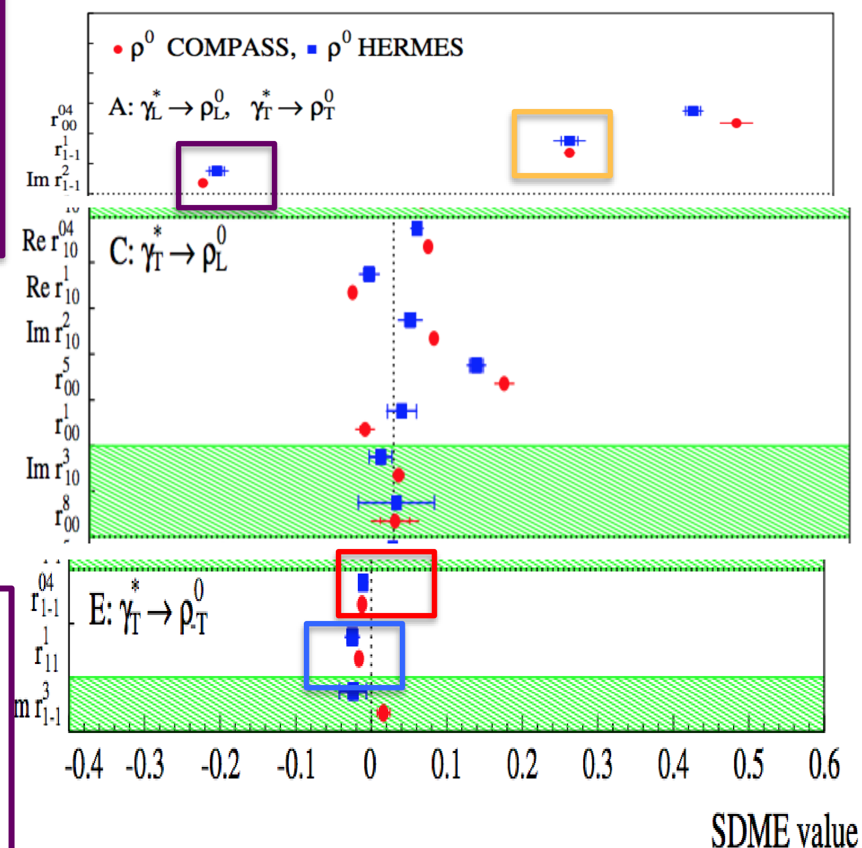


While at small t (dominant part of the statistics) the transverse rhos dominate, at large t the contribution from transverse photons going to longitudinal rho becomes more significant

SDMEs from photoproduction

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



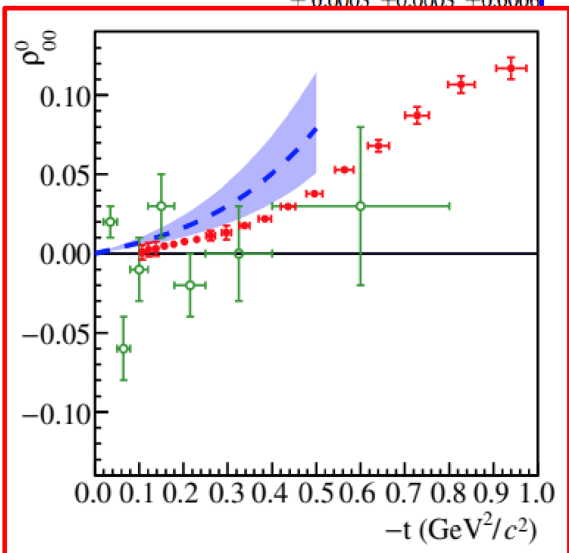


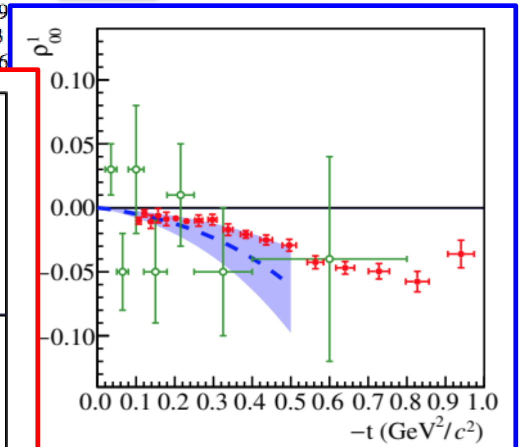
The SDMEs for transverse photons with $\sin^2\theta$ (to transverse rho?) at $Q^2>0$ seem to be smaller (detailed comparison vs Q^2).

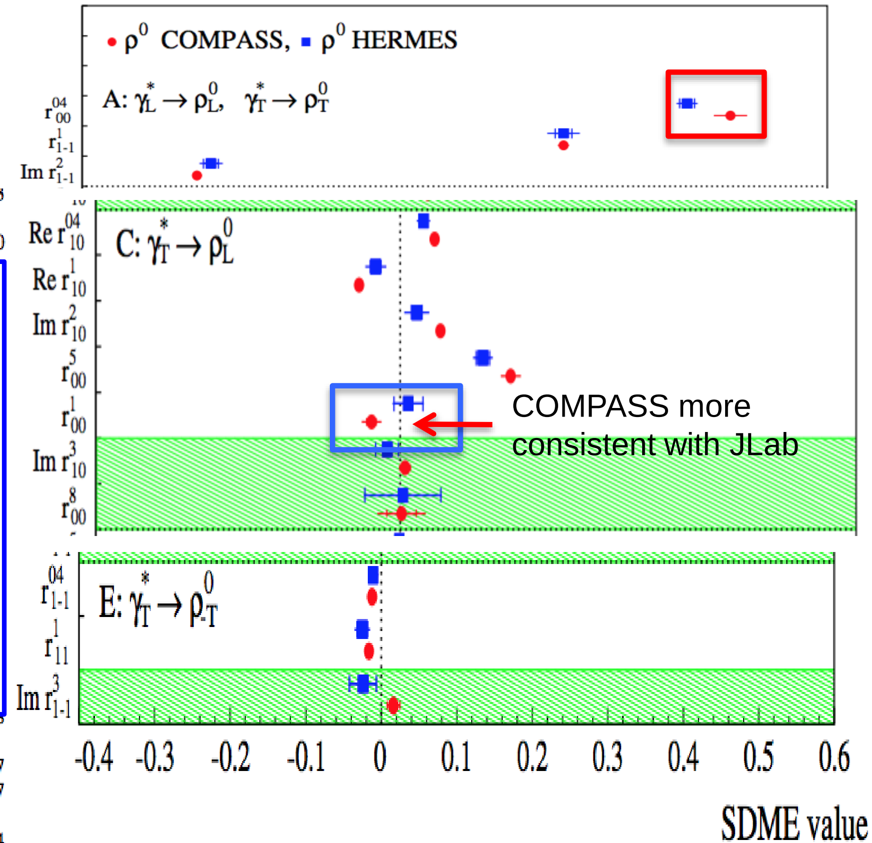
SDMEs from photoproduction

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

$-t_{min}$	$-t_{max}$	$\overline{-t}$	$-t_{RMS}$	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	-0.0[illegible]98	-0.01[illegible]1	-0.0252	0.4895	0.0200	-0.4897
				± 0.0003	±0.0005	±0.0007	±0.0[illegible]20	±0.00[illegible]10	±0.0020	±0.0024	±0.0014	±0.002[illegible]
				± 0.0045	±0.0066	±0.0116	±0.0[illegible]16	±0.00[illegible]25	±0.0012	±0.0103	±0.0010	±0.010[illegible]
0.114	0.129	0.121	0.004	0.0025	0.0209	-0.0194	-0.0[illegible]63	-0.00[illegible]3	-0.0242	0.4914	0.0205	-0.4904
				± 0.0003	±0.0004	±0.0006	±0.0[illegible]18	±0.00[illegible]12	±0.0017	±0.0025	±0.0013	±0.002[illegible]
				± 0.0042	±0.0030	±0.0038	±0.0[illegible]15	±0.00[illegible]26	±0.0014	±0.0105	±0.0012	±0.010[illegible]
0.129	0.147	0.138	0.005	0.0030	0.0244	-0.0264	-0.0[illegible]82	-0.01[illegible]8	-0.0257	0.4886	0.0257	-0.489[illegible]
				± 0.0003	±0.0004	±0.0006	±0.0[illegible]17	±0.00[illegible]10	±0.0017	±0.0022	±0.0011	±0.002[illegible]
				± 0.0044	±0.0023	±0.0032	±0.0[illegible]18	±0.00[illegible]52	±0.0015	±0.0104	±0.0011	±0.010[illegible]
0.147	0.167	0.157	0.006	0.0047	0.0283	-0.0344	-0.0[illegible]46	-0.00[illegible]1	-0.0294	0.4862	0.0287	-0.4879
				± 0.0002	±0.0004	±0.0005	±0.0[illegible]17	±0.00[illegible]10	±0.0016	±0.0023	±0.0012	±0.0020
				± 0.0022	±0.0011	±0.0009	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.167	0.190	0.178	0.007	0.0058	0.0295	-0.0353	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
				± 0.0003	±0.0003	±0.0006	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].0464	-0.0208	-0.0449	0.4624	0.0378	-0.4631
				[illegible]	[illegible]	[illegible]	[illegible].0022	±0.0017	±0.0017	±0.0031	±0.0014	±0.0027
				[illegible]	[illegible]	[illegible]	[illegible].0014	±0.0025	±0.0010	±0.0097	±0.0011	±0.0097
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible].0557	-0.0251	-0.0507	0.4592	0.0366	-0.4513
				[illegible]	[illegible]	[illegible]	[illegible].0026	±0.0020	±0.0020	±0.0036	±0.0017	±0.0024
				[illegible]	[illegible]	[illegible]	[illegible].0018	±0.0033	±0.0016	±0.0098	±0.0012	±0.0095
0.464	0.527	0.496	0.018	0.0379	0.0480	-0.0647	-0.0507	-0.0293	-0.0519	0.4575	0.0356	-0.4417
				± 0.0006	±0.0005	±0.0008	±0.0029	±0.0029	±0.0020	±0.0042	±0.0019	±0.0033
				± 0.0022	±0.0019	±0.0013	±0.0017	±0.0037	±0.0015	±0.0097	±0.0014	±0.0093





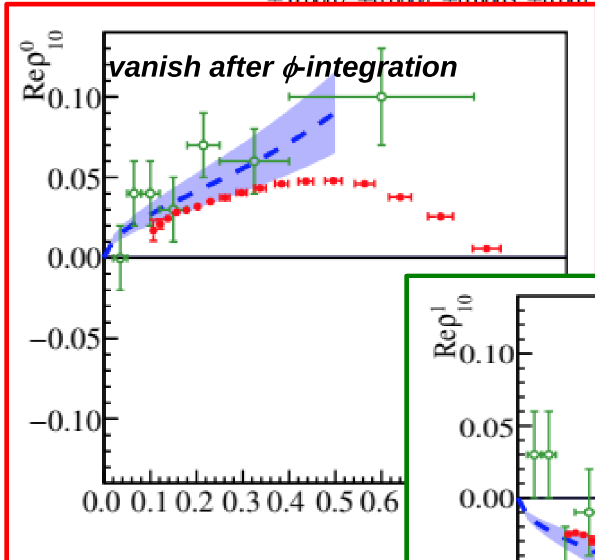


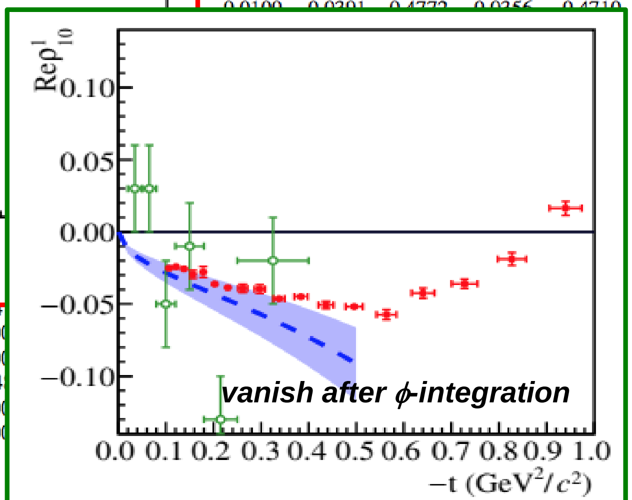
The SDMEs for transverse photons with $\cos^2\theta$ (to longitudinal rho?) at $Q^2>0$ different, in particular r_{00}^1 (relevant for BM).

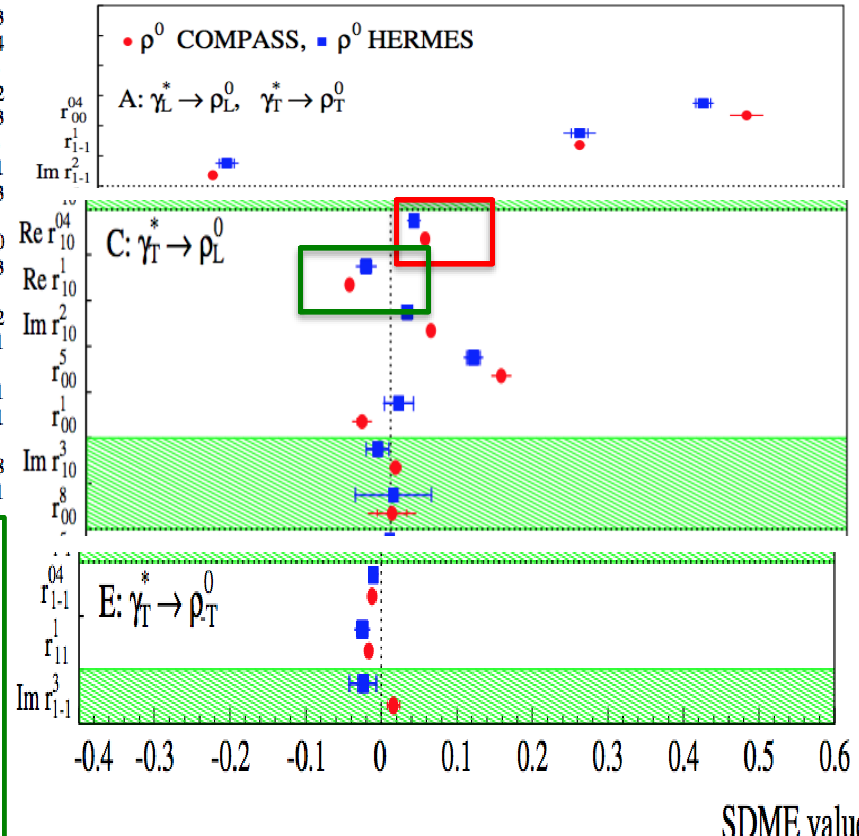
SDMEs from photoproduction

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

$-t_{min}$	$-t_{max}$	$-\bar{t}$	$-t_{RMS}$	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	.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	.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	.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	.4862	0.0287	-0.4879
								±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	±0.00							
				±0.0016	±0.00							
0.464	0.527	0.496	0.018	0.0379	0.04							
				±0.0006	±0.00							
				±0.0022	±0.00							







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

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)

- 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)

Understanding the diffractive rho contribution will help to sort out the diffractive DIS and possible impact on PDFs, helicity PDF in particular

support slides

Multiplicities of hadrons in SIDIS

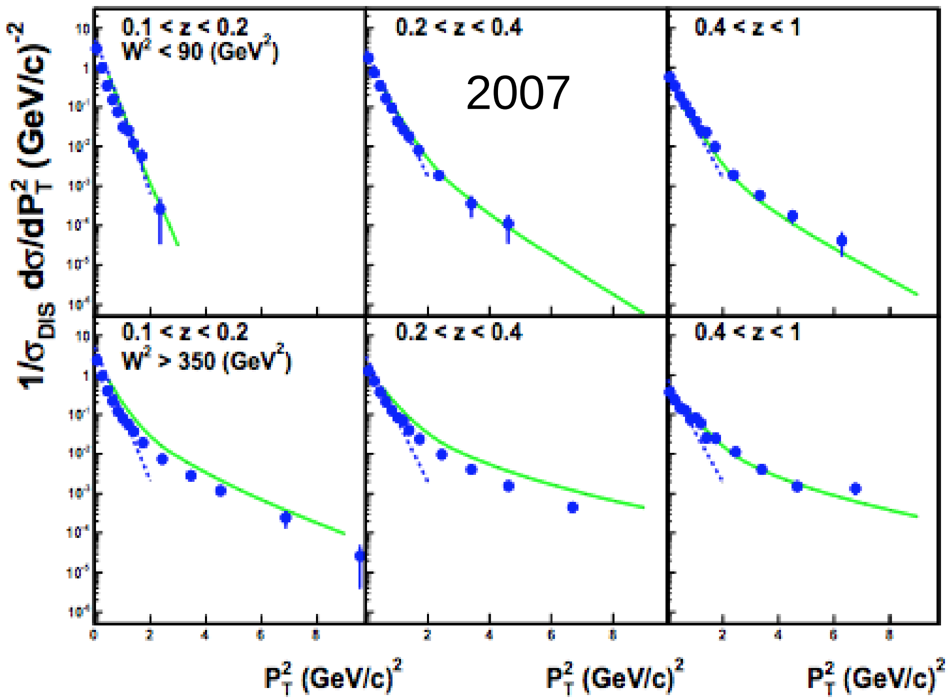
Anselmino et. al: hep-ph/0606286

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

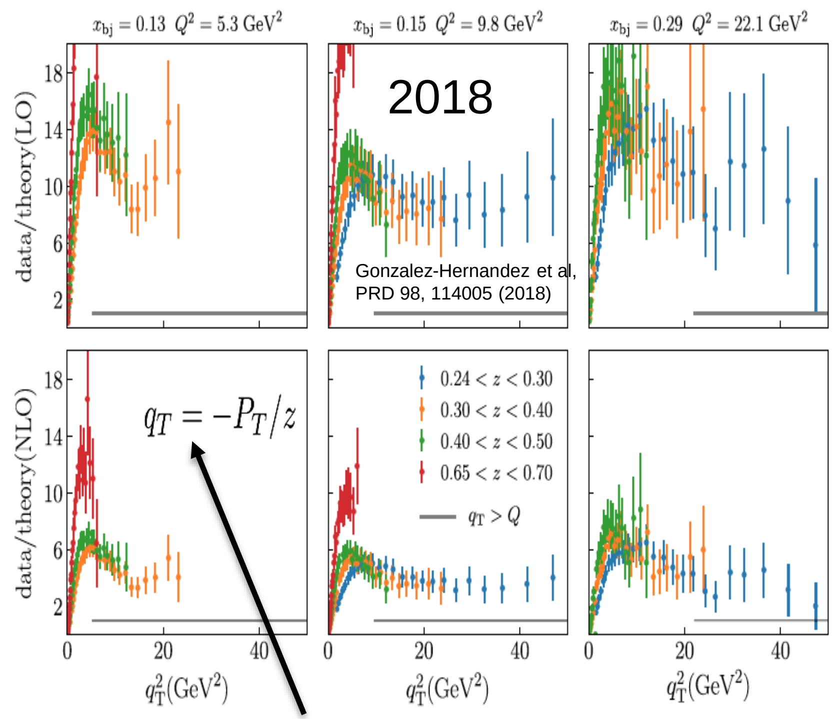
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

non-perturbative

perturbative



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



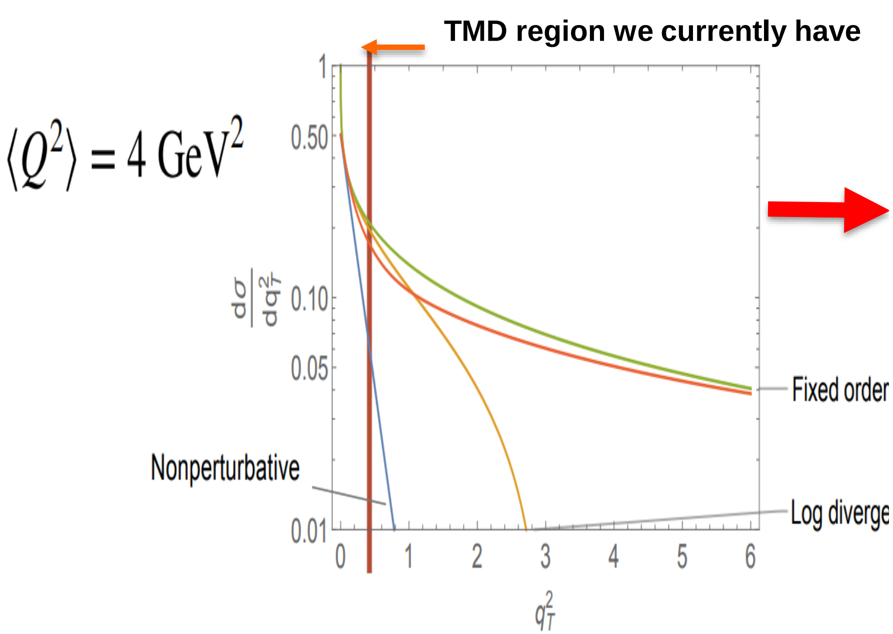
quark transverse momentum, assuming a direct link with pion transverse momentum

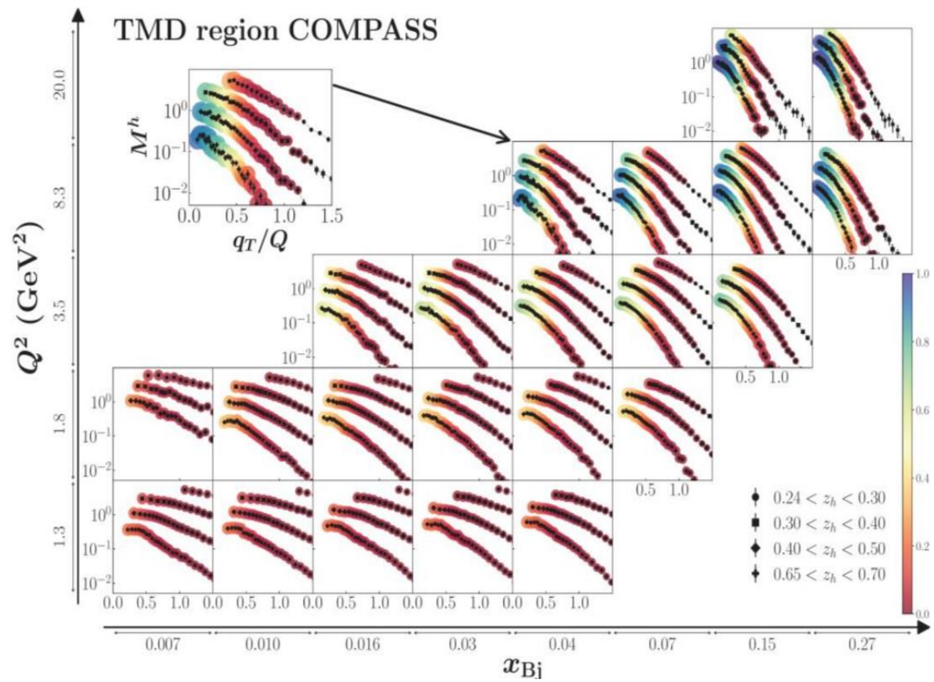
Perturbative contributions underestimate the multiplicities by an order of magnitude for all accessible kinematics at COMPASS

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

SIDIS in JLab: comments from theory

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/…....]

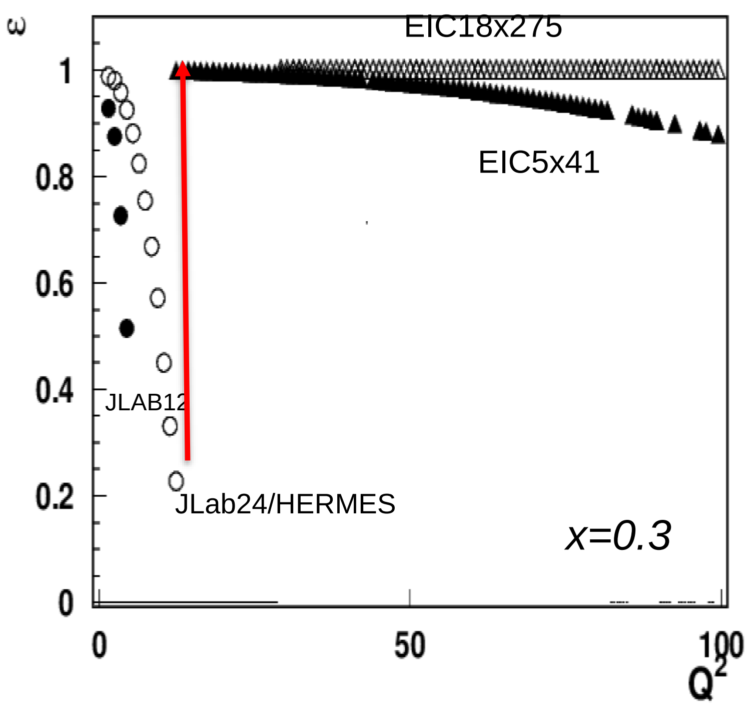
Addressing PAC/theory comments

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

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

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

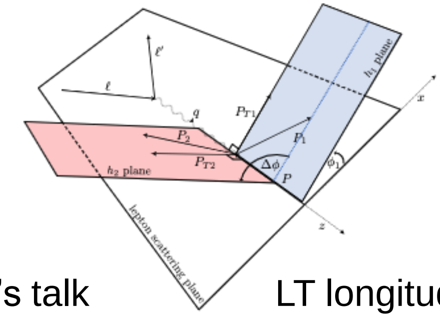
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

TFR→Higher Twist Fracture Functions

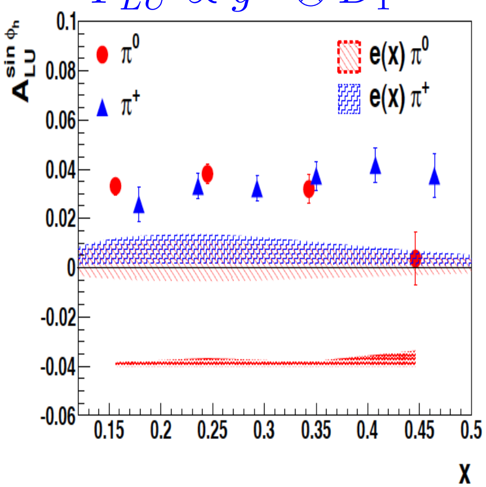
Nq	U	L	T
U	$\hat{u}_2^{\perp h}$	$\hat{l}_2^{\perp h}$	$\hat{t}_2, \hat{e}_2$
L	$\hat{u}_{2L}^{\perp h}$	$\hat{l}_{2L}^{\perp h}$	$\hat{t}_{2L}, \hat{e}_{2L}$
T	$\hat{u}_{2T}^{\perp h}, \hat{u}_{2T}^{\perp h}$	$\hat{l}_T, \hat{l}_{2T}^{\perp h}$	$\hat{t}_{2T}^{h}, \hat{e}_{2T}^{h}, \hat{t}_{2T}^{\perp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

TFR/CFR→Leading Twist Fracture Functions

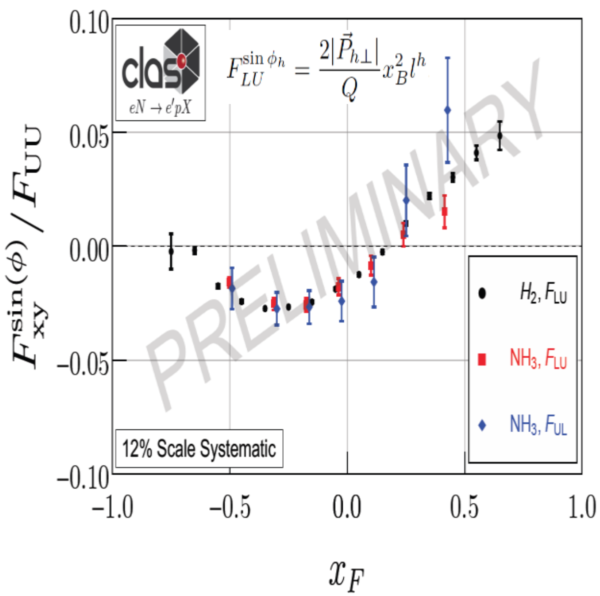
N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^{h}, \hat{t}_1^{\perp}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^{h}, \hat{t}_{1L}^{\perp}$
T	$\hat{u}_{1T}^{h}, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^{h}, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp},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



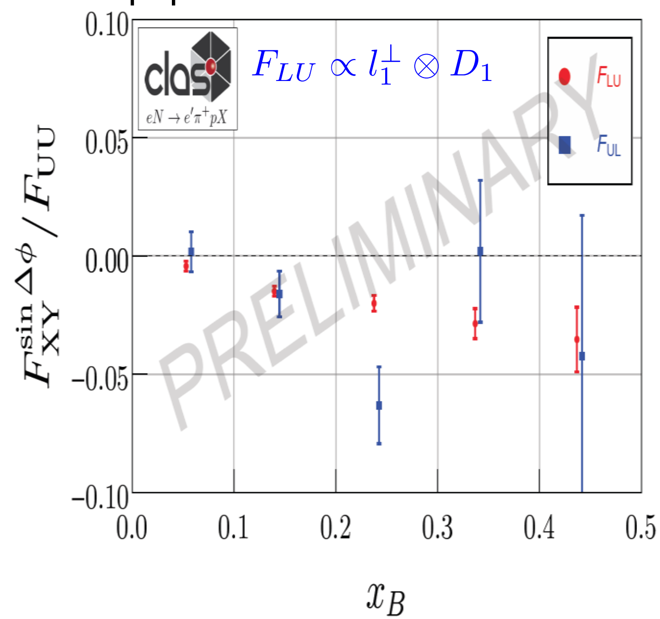
$F_{LU} \propto g^{\perp} \otimes D_1$



Fatiha's talk



LT longitudinally pol. quarks in Unp. proton

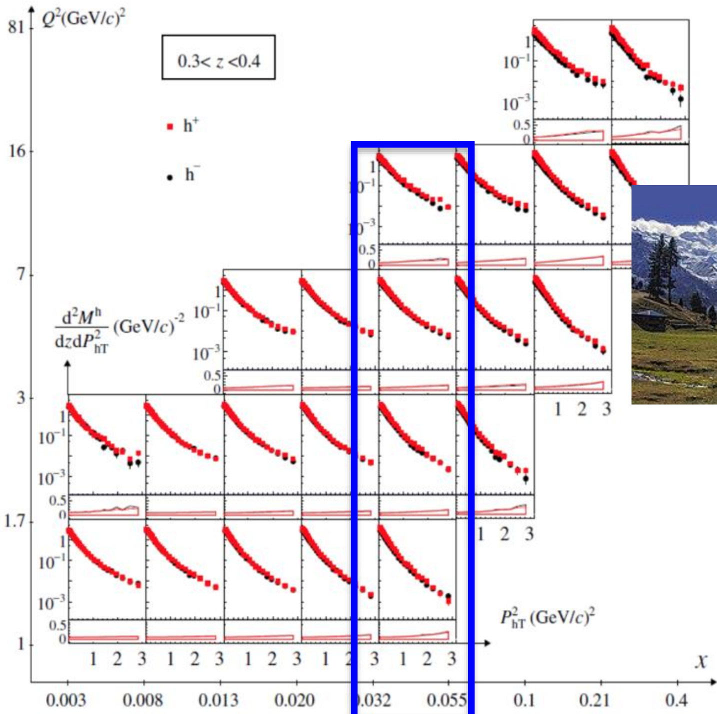


$$A(\phi)_{LU} = \frac{1}{p}\left(\frac{N^+ - N^-}{N^+ + N^-}\right) \rightarrow F_{LU}^{\sin\phi_h} = \frac{A(\phi)_{LU}}{\sqrt{2\varepsilon(1-\varepsilon)}}$$

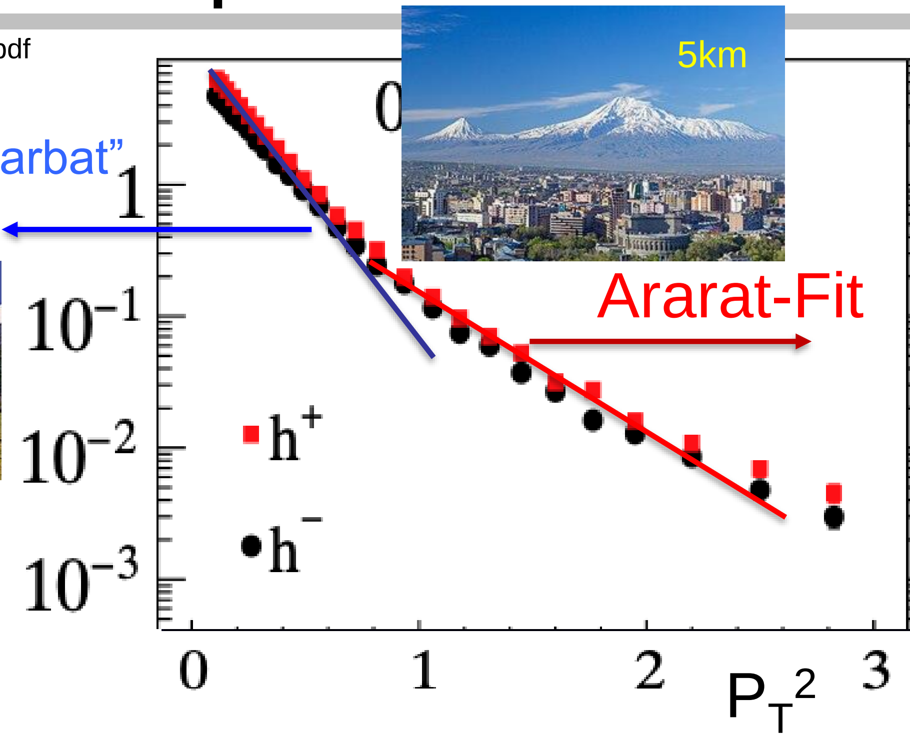
Longitudinally polarized quarks most likely responsible for observed Single Beam Spin asymmetries

q_T-crisis or misinterpretation

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



“Nanga Parbat” Fit



Ararat-Fit

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)

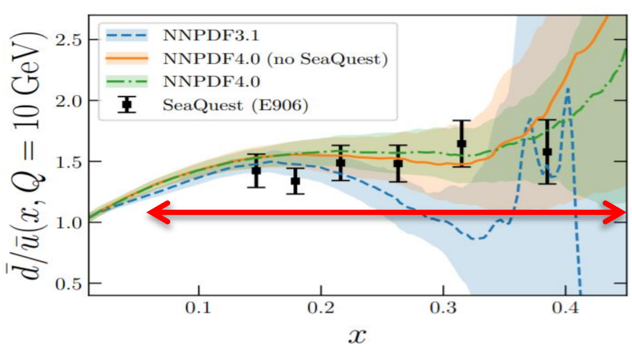
SUMMARY

- 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). Need reform in theory-phenomenology-experiment coordination
  - 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)
  - 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

- Need better coordination of efforts in theory-phenomenology-experiment
- New tools, such as AI,ML,… combined with enhanced hardware resources would allow qalitatively new methods for data analysis (LoI suggested). The JLab current and incoming data is absolutely critical for future studies of 3D and can be utilized to test the new approaches.

Understanding the QCD: from observables to QCD dynamics

Main goal to study the non-perturbative QCD dynamics in 3D space in details



JLAB uniqueness:

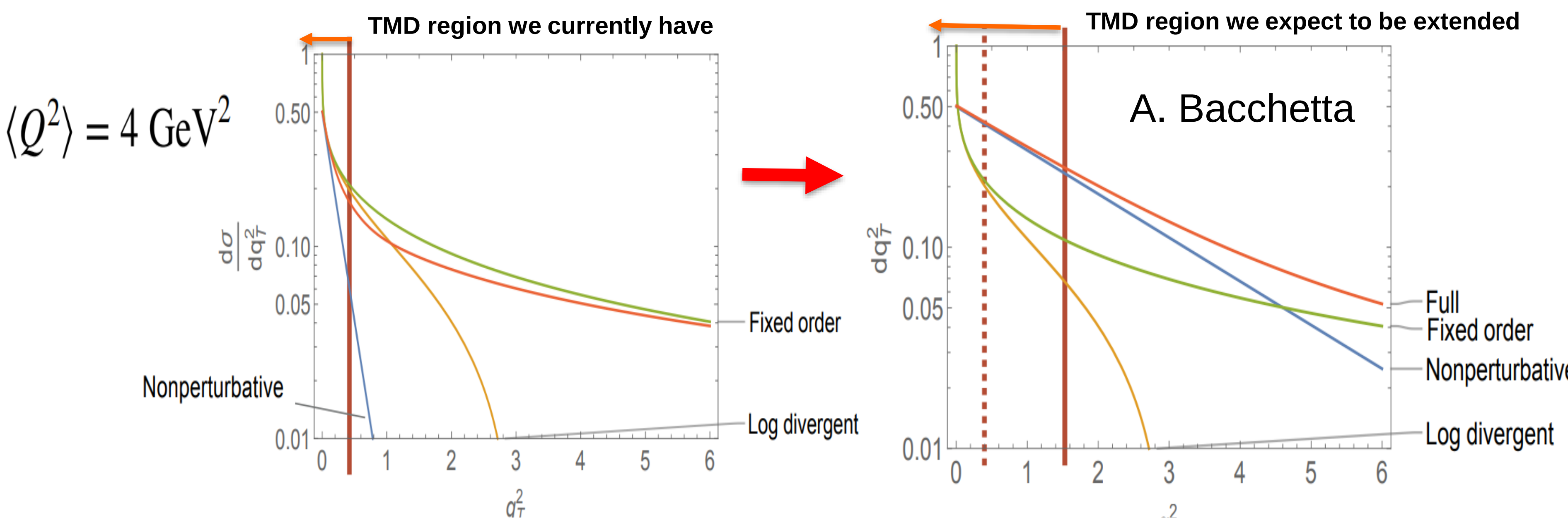
The superior luminosity of CEBAF, high resolutions of detectors, and ability for multidimensional and multiparticle detection, makes the JLab unique in disentangling the genuine intrinsic transverse structure of hadrons encoded in 3D partonic distributions (TMDs and GPDs) with controlled systematics in the kinematics dominated by valence quarks.

- Understanding of hard scattering data at Q^2<10 GeV^2 critical for multidimensional measurements, needed for understanding the QCD dynamics
- The leptoproduction, with hadrons detected in the final state, from experimental point of view, in simplest case of a single hadron, 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

TMD theory problems

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 extends the TMD region

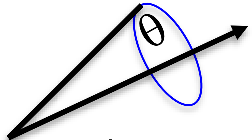
Further steps to increase the coverage of large P_T critical for SIDIS, JLab in particular

Exclusive ρ^0 ($\pi+\pi-$) contributions

Given detector resolutions and possible backgrounds the best option for studies of ep→e'p ρ^0 will be detection of all 4 particles e'p,$\pi+$,$\pi-$

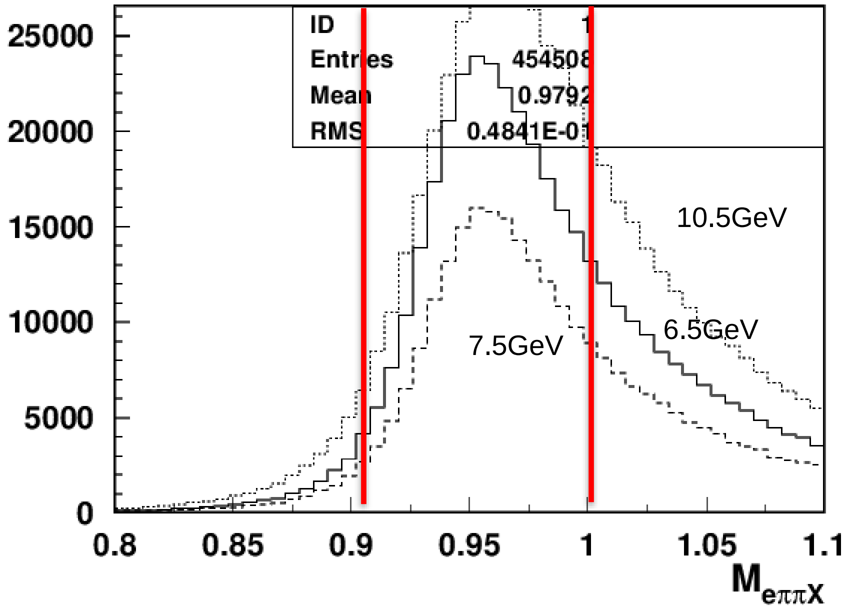
One can make invariant masses and missing masses of all combinations
ex. M_X (e'$\pi+\pi-$X) or $M_{\pi+/\pi-}$, M_X(e'p $\pi+$), M_X(e'p $\pi-$) also cuts calculated vs measured θs

Plans: publish x-sections/multiplicities and SSAs of exclusive $\rho(\pi+\pi-)$

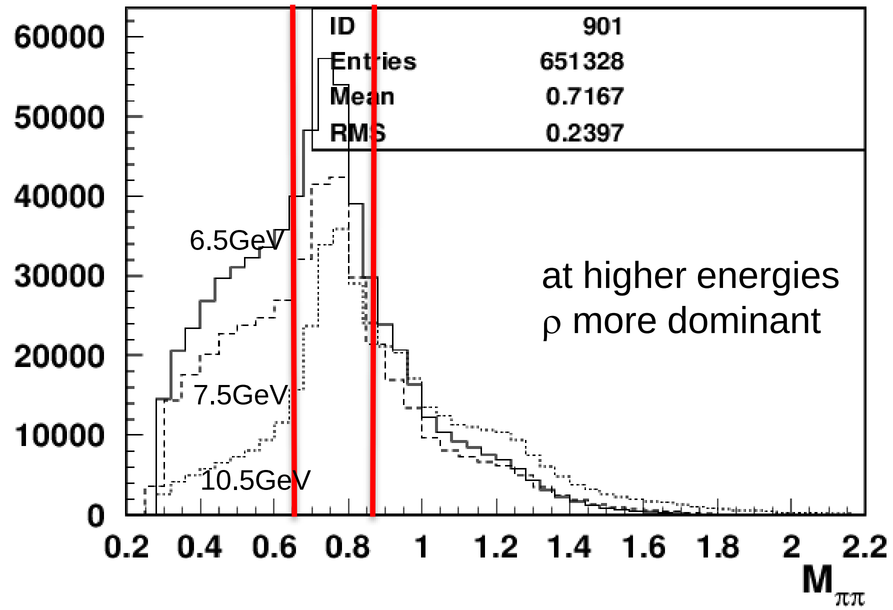


cut on $\Delta\theta < 2^o$ beetween measured and calculated $\pi-$

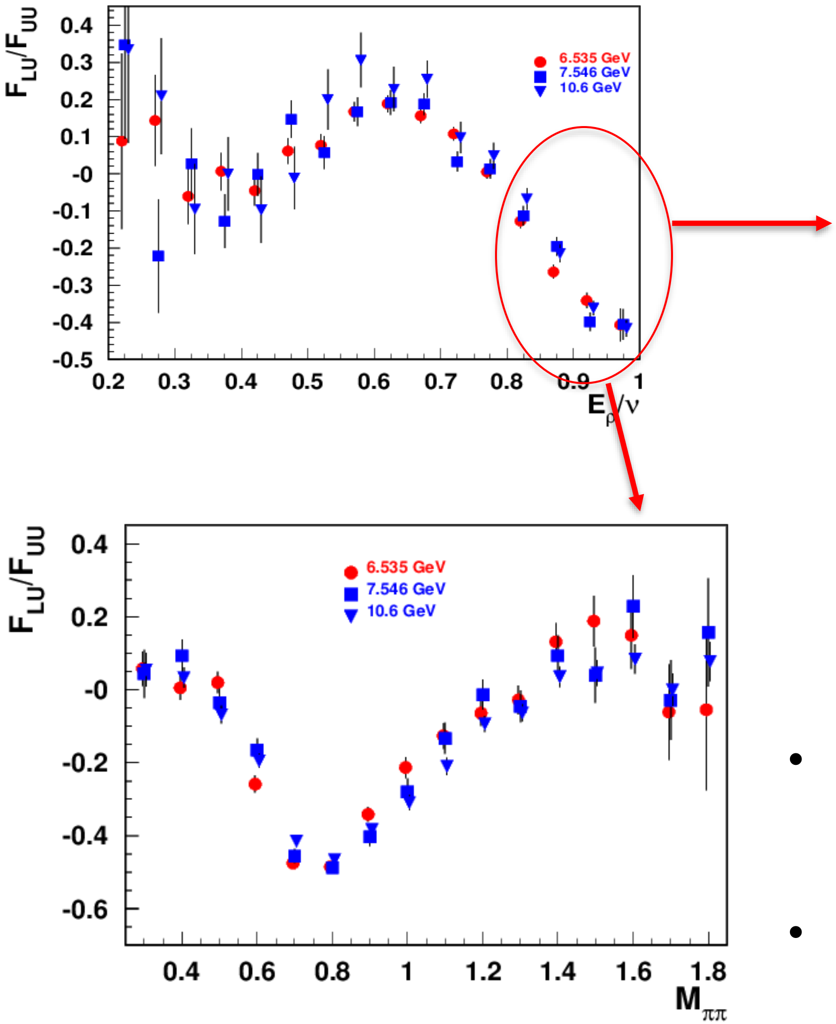
cuts on missing masses

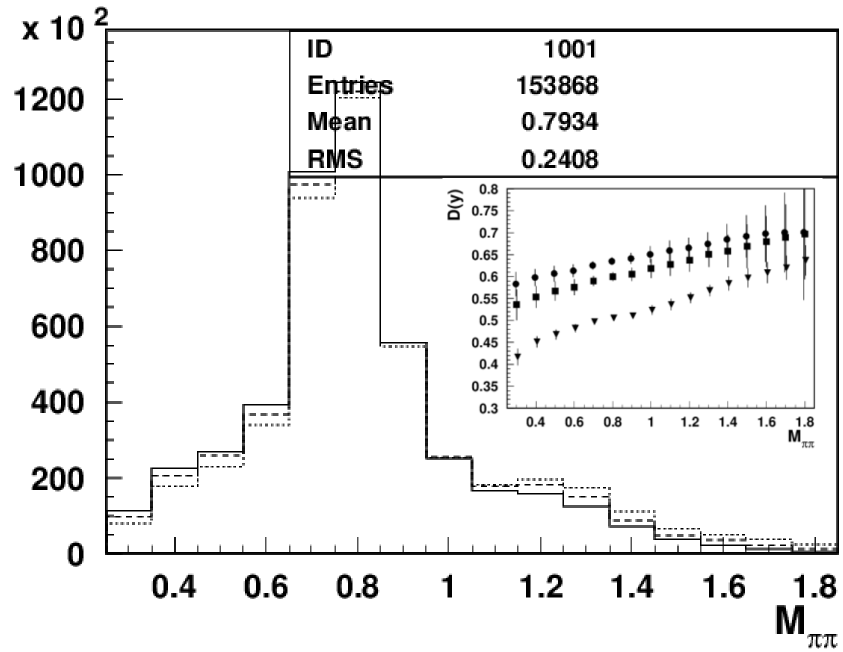


cuts on invariant masses



Beam SSA in exclusive $\pi+\pi-$

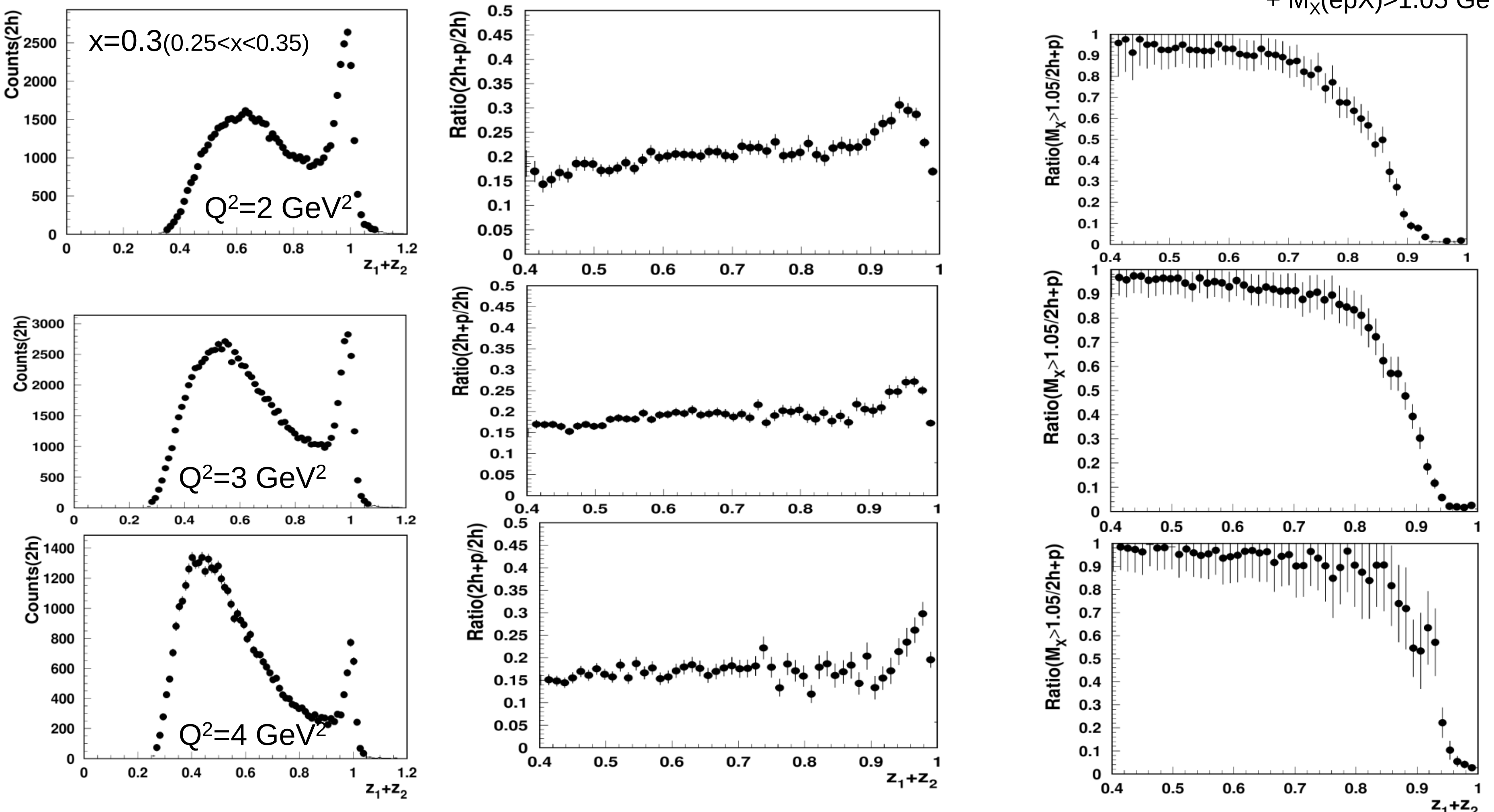




- At large z (small t) the beam SSA of exclusive dihadrons goes sharply negative indicating dominance of some (non u-quark) contributions
- Most SSA for the large z dihadron sample localized around the rho-mass (dominated by the exclusive rho)
- →The beam SSA is related to exclusive rho0s

□ρ-free SIDIS” free: target proton bias

ep→e’ππX | ep→e’pππX + $x_{Fproton}<0$ | ep→e’pππX + $x_{Fproton}<0$ + $M_X(epX)>1.05$ GeV



While the detected proton introduces slight difference in the kinematic distributions, the cut on the proton missing mass makes significant impact (clear at large z).

Understanding exclusive rhos and SDME validations

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

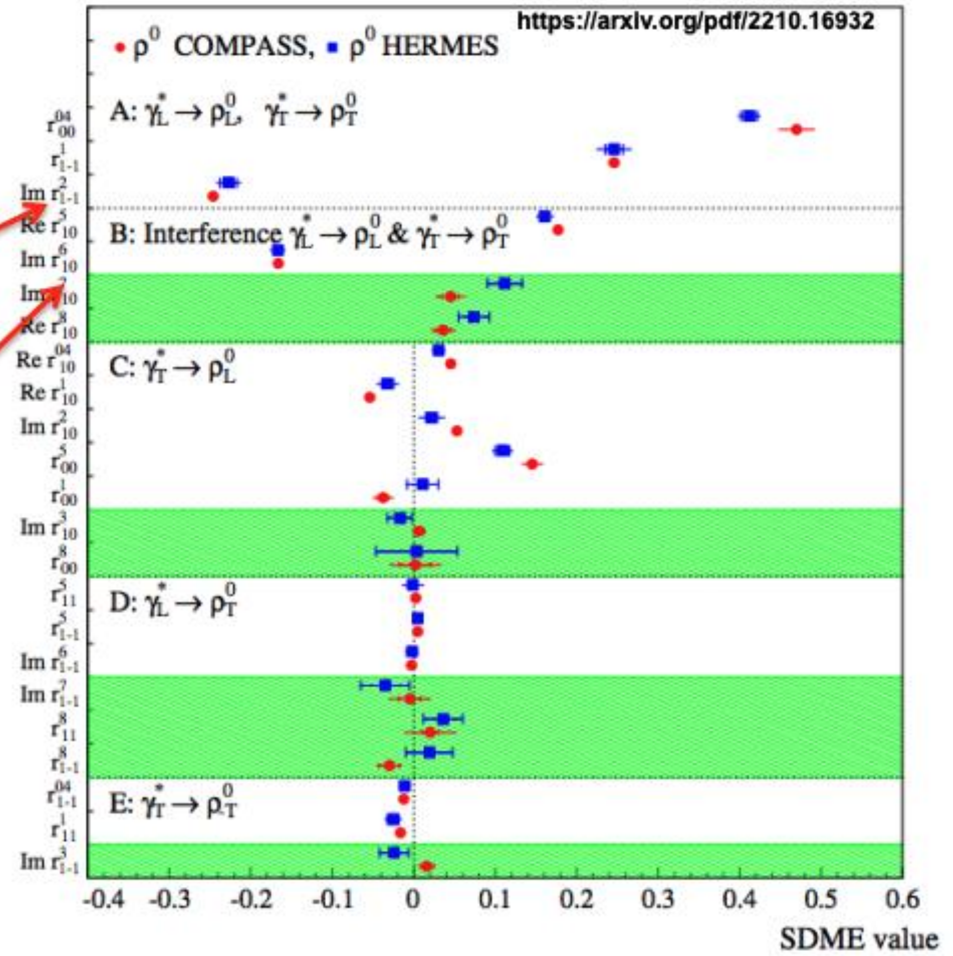
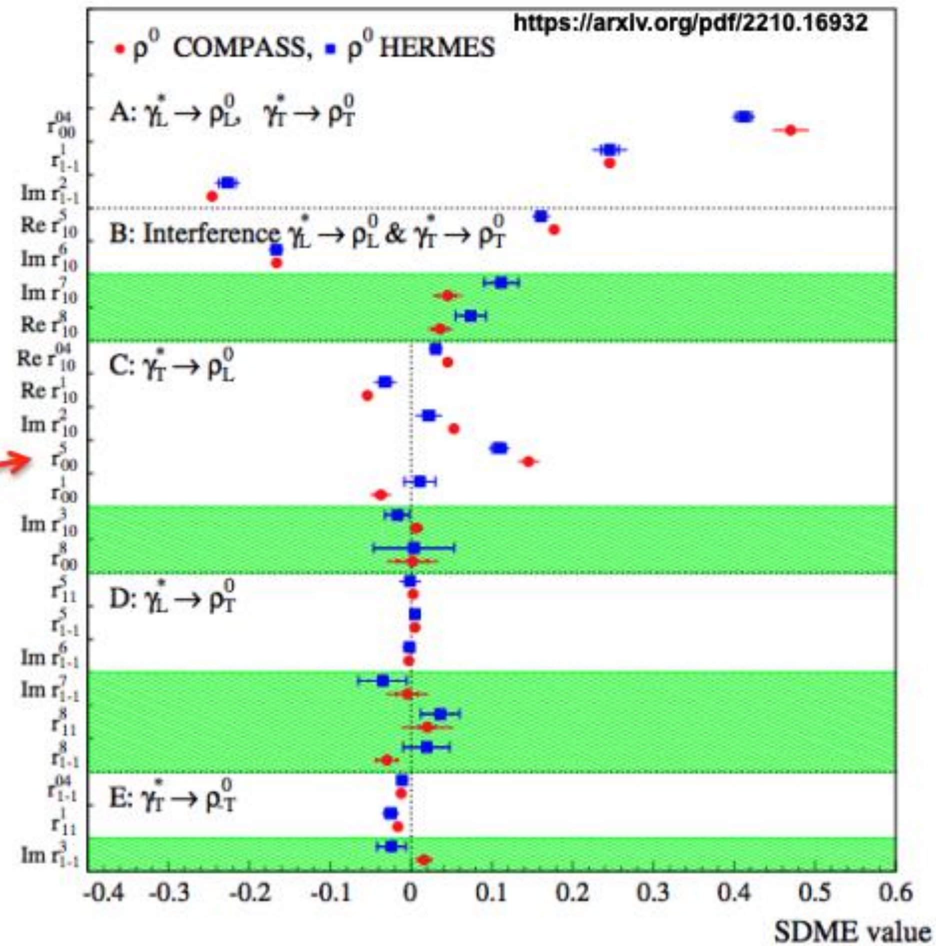


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle |t'|\rangle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

Significant sinusoidal modulations for unpolarized target. Not usual for hadrons (require parity violating effects for pion case)

Understanding exclusive rhos and SDME validations

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



Large cosine for unpolarized x-section (Cahn) expected, but normally requires a strict control over RC

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 $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle|t'|\rangle = 0.13$, while those for COMPASS are $\langle Q^2\rangle = 2.40$ (GeV/c)^2, $\langle W\rangle = 9.9$ GeV/c^2, $\langle p_T^2\rangle = 0.18$ (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.

Understanding exclusive rhos and SDME validations

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

$$= \frac{3}{8\pi^2}\Big[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r^3_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^3_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$

$$+ \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^7_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^7_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$

$$+ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi - r^8_{1-1}\sin^2\Theta\cos 2\phi\Big)\Big].$$

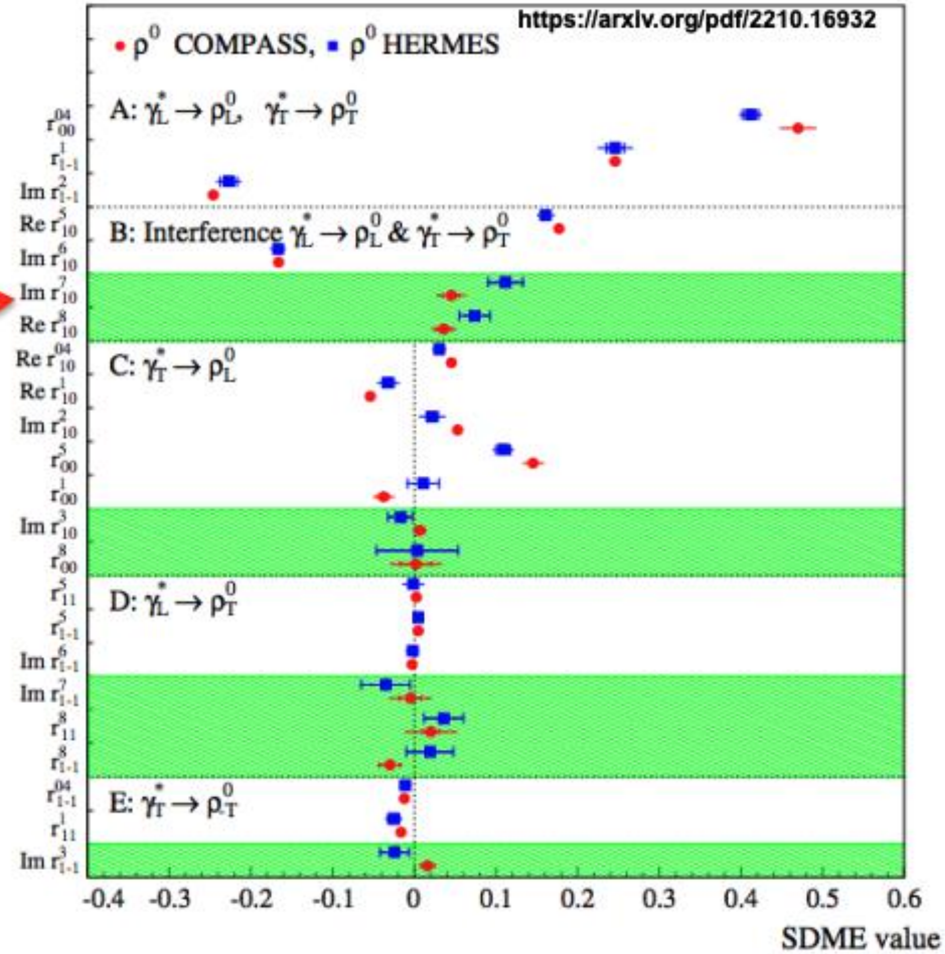


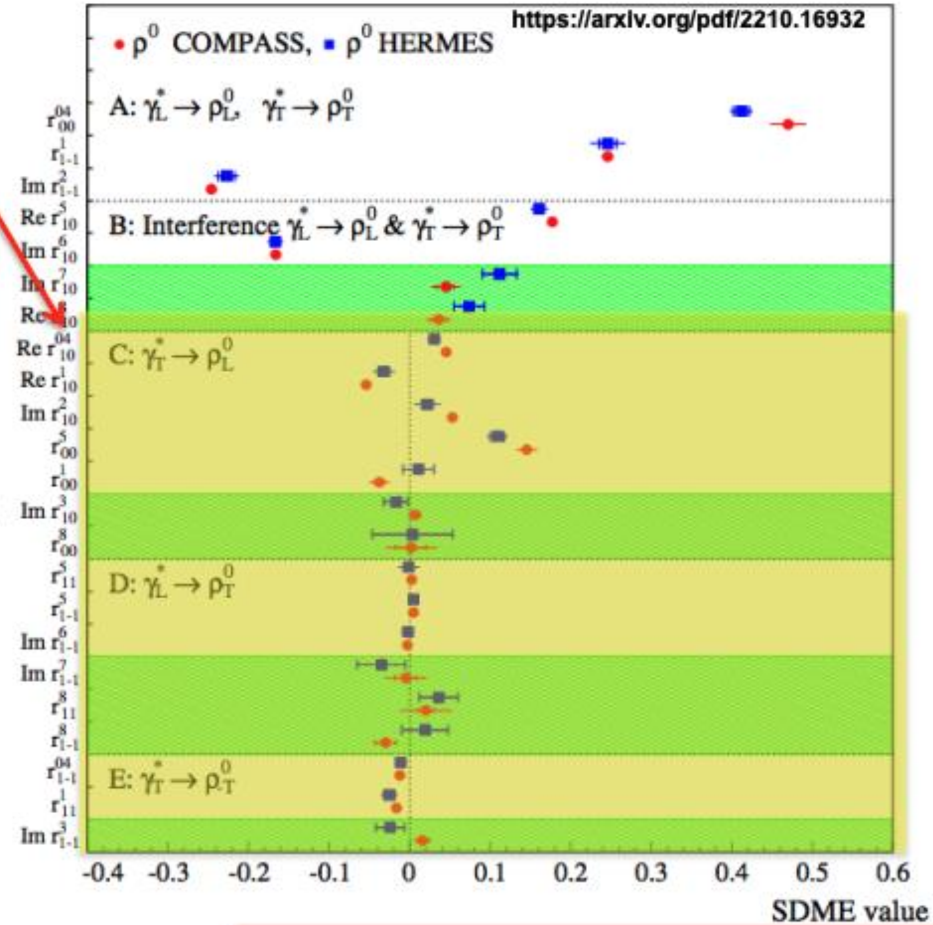
Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle |t'|\rangle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

Significant cosine single spin dependent modulation, never observed for pions (requires weak interactions)

Understanding exclusive rhos and SDME validations

In case of SCHC (terms in yellow disappear) longitudinal-to-transverse virtual-photon cross-section ratio R

$$R = \frac{\sigma_L(\gamma^*_L \to V)}{\sigma_T(\gamma^*_T \to V)},$$ approximated by $$R' = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}$$



The R in the case of SCHC violation is not surprisingly related to the terms generating the beam SSA and Cahn (L/T interference terms), indicating that the precision measurement of the beam SSA may be critical for that.

$$\widetilde{R} = R' - \frac{\eta(1+\epsilon R')}{\epsilon(1+\eta)}$$

With a correction factor defined by L→T and T→L transitions $\eta \approx (1+\epsilon R')(\tau^2_{01} - 2\epsilon\tau^2_{10}).$

Measurements of sin and cos modulations critical for understanding the rho in general and L/T contributions, in particular

Studies of rhos at COMPASS

Selection of exclusive ρ^0 sample for SDMEs analysis

$\mu\, p \rightarrow \mu'\, \rho^0\, p'$

$\quad \hookrightarrow \pi^+ \pi^-$

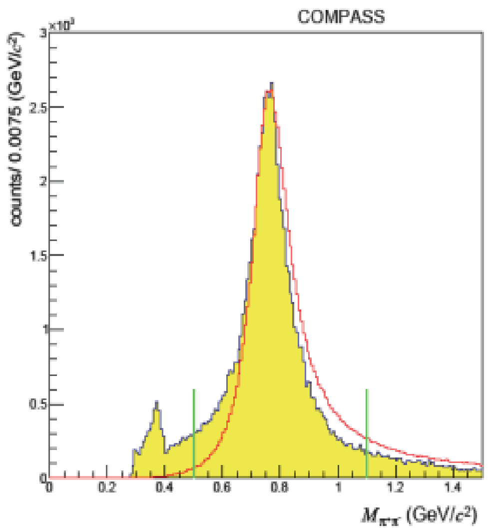
Topological selection: scattered muon
+ two hadrons with opposite charges

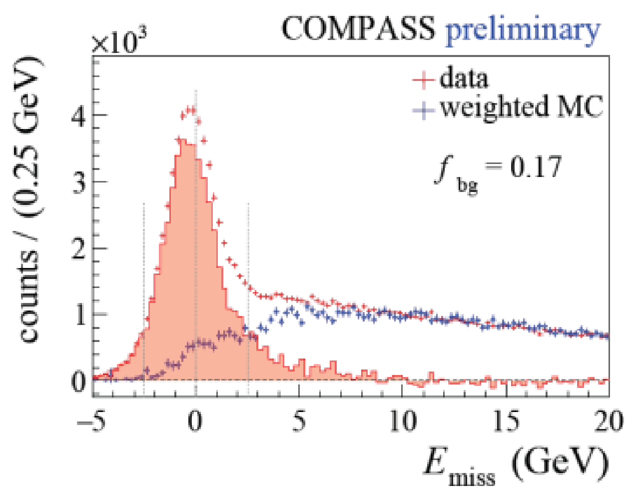
$1 < Q^2 < 10$ GeV/c^2
$W > 5$ GeV
$0.01 < p_T^2 < 0.5$ (GeV/c)^2
$0.1 < y < 0.9$
$\nu > 20$ GeV
$|E_{miss}| < 2.5$ GeV

$$E_{miss} = \frac{(M_X^2 - M_p^2)}{(2M_p)}$$

After all selections and cuts
≈ 52 200 evts

Recoil proton detector
not included in selections





tails may be significant, also because of RC

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, 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, $h_T^{\perp}$, $e_T^{\perp}$

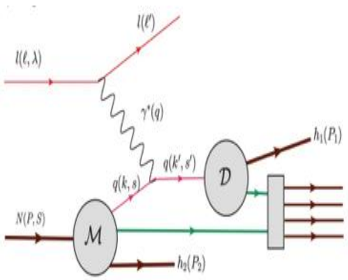
Twist3 GPDs (also calculated on lattice)

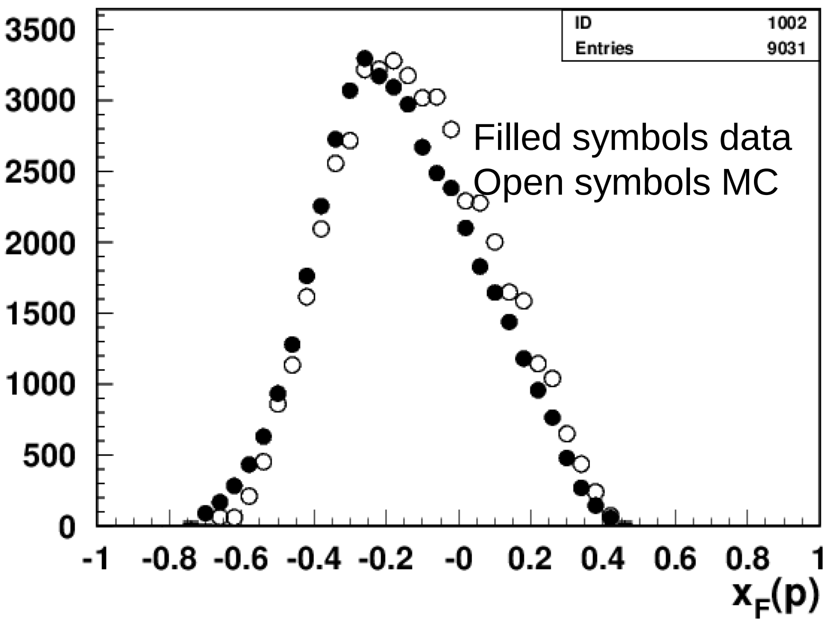
N \ q	U	L	T
U	$\mathcal{E}_{2T}$	$\mathcal{E}'_{2T}$	$\mathcal{H}_2$, $\mathcal{H}'_2$
L	$\tilde{\mathcal{E}}_{2T}$	$\tilde{\mathcal{E}}'_{2T}$	$\tilde{\mathcal{H}}_2$, $\tilde{\mathcal{H}}'_2$
T	$\mathcal{H}_{2T}$, $\tilde{\mathcal{H}}_{2T}$	$\mathcal{H}'_{2T}$, $\tilde{\mathcal{H}}'_{2T}$	$\mathcal{E}_2$,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

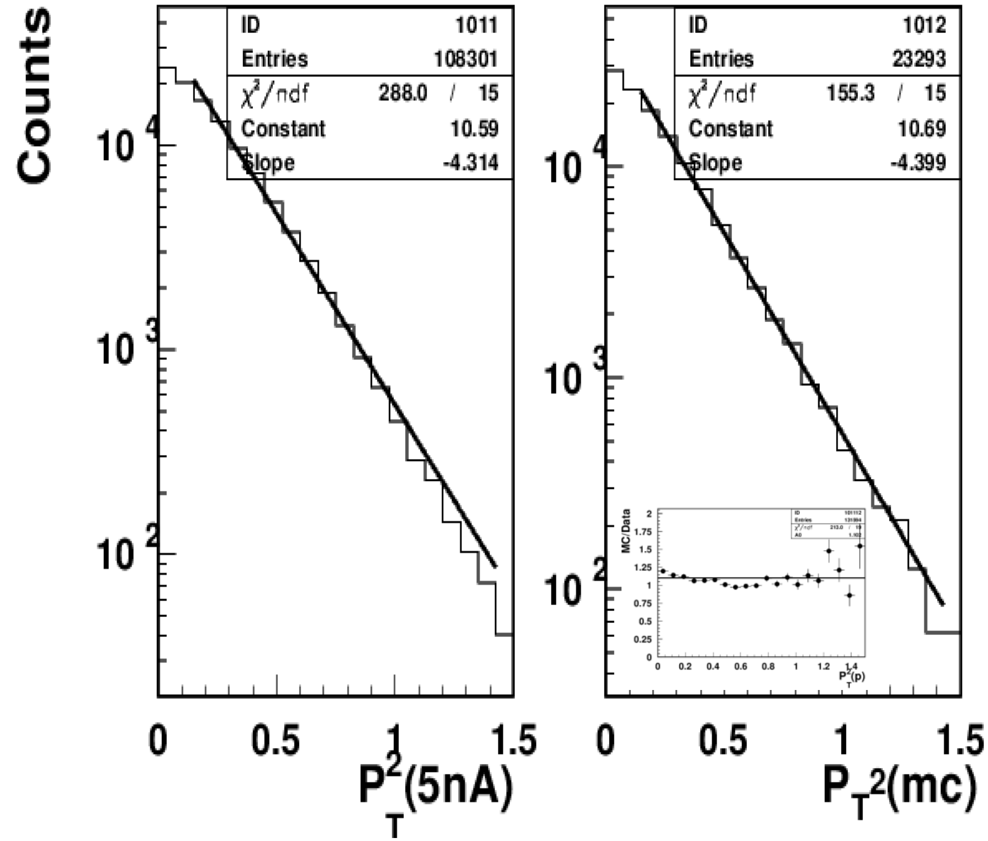
Request to theory to provide similar contributions for the exclusive hadron production. So far only Twist-3 contributions from Twist-2 GPDs (Kroll&Goloskokov,…)

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator







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