Reforming SIDIS

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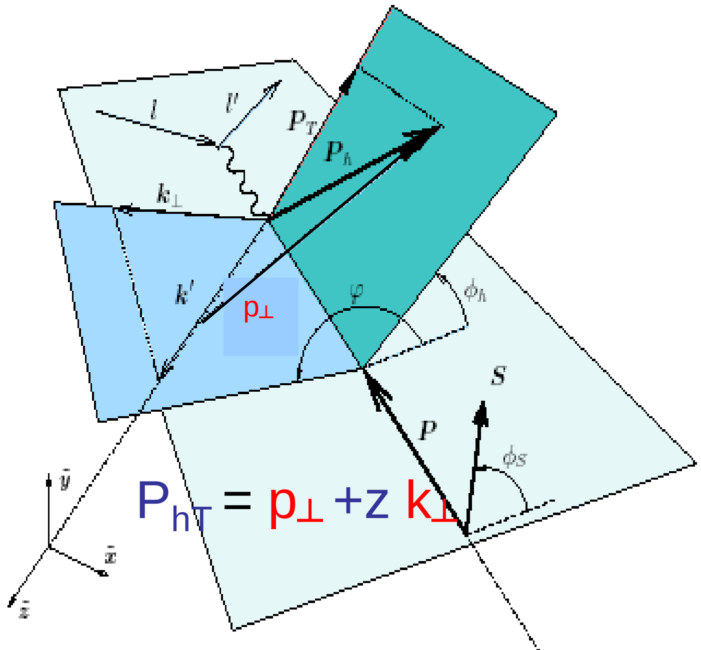
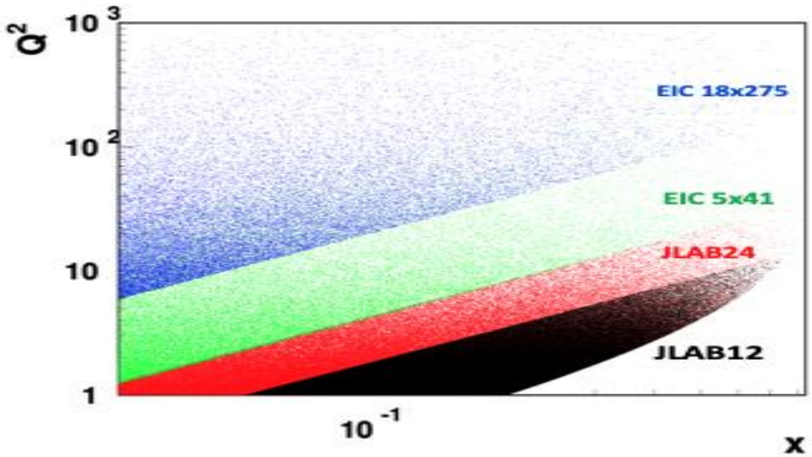
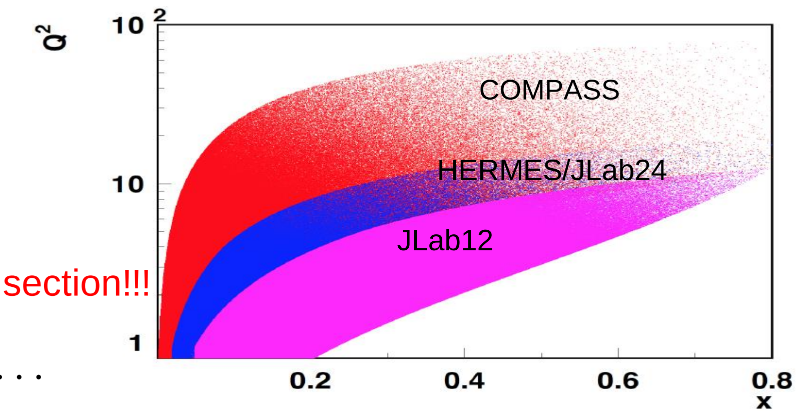
- What is SIDIS?
- Understanding of physics backgrounds→ need for multidimensional measurements critical for JLab and beyond, EIC, in particular
- Interpretation of leptoproduction require studies of hadronic correlations going from ep→e'πX to ep→e'ππX and ep→e'pπX
- SIDIS observables
- Summary

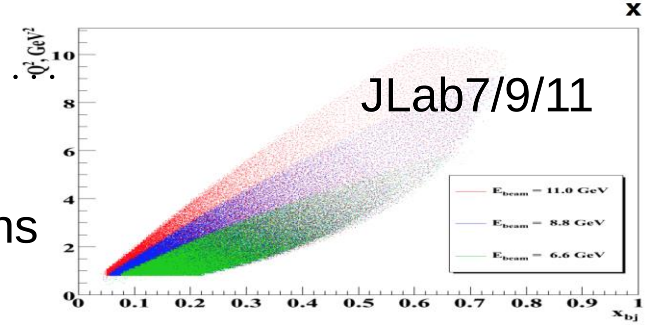
SIDIS kinematical coverage and observables



EIC







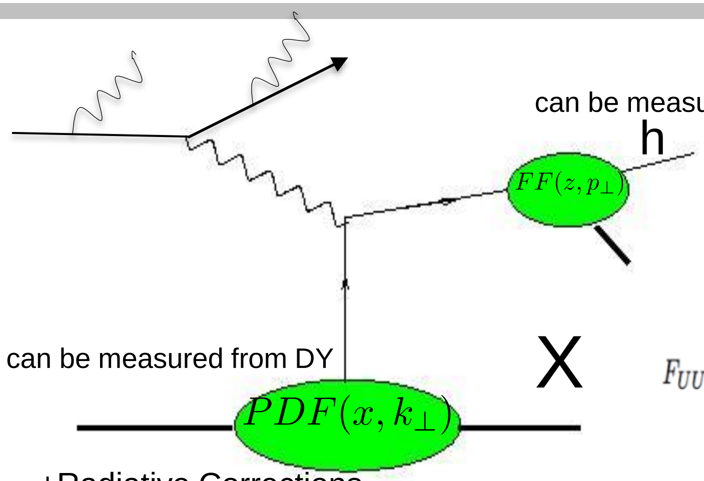
Experiments measure the full azimuthal dependence of the cross section!!!

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

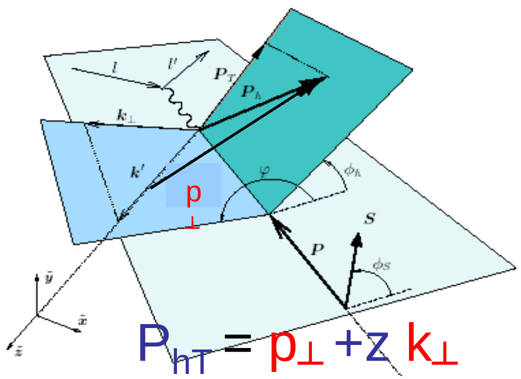
$$+\epsilon F_{UU,L} + |S_\perp|[F_{UT}^{\sin\phi-\phi_S}\sin(\phi-\phi_S) + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S] + \ldots$$

- Studies of azimuthal modulations in 6D (x,Q^2,z,P_T,ϕ,ϕ_S) space give access to underlying 3D partonic distributions
- QCD predicts only the Q^2-dependence of 3D PDFs

SIDIS as THE theory describes it



+Radiative Corrections



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

Probability to produce 1 or 2 hadrons in single photon exchange

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

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

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

hard part

Factorization 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>

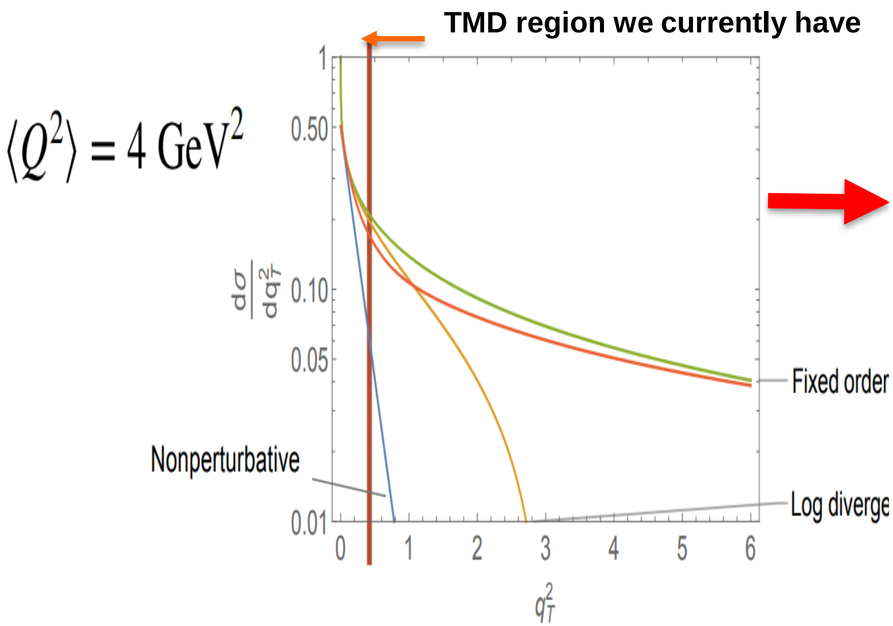
Data has it all!!! Dealing with unaccounted terms:

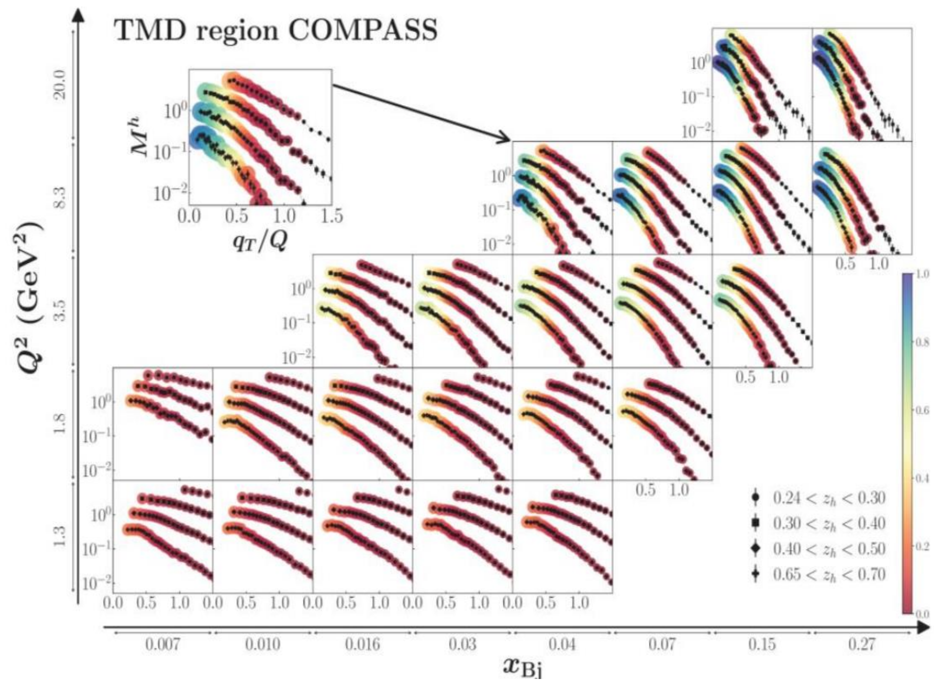
- Theory accounts for them (ex. VMs)
- Experiment measures and excludes them!!! (ex.VMs)

SIDIS of ehX: TMD theory challenges

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

Addressing challenges of TMD theory

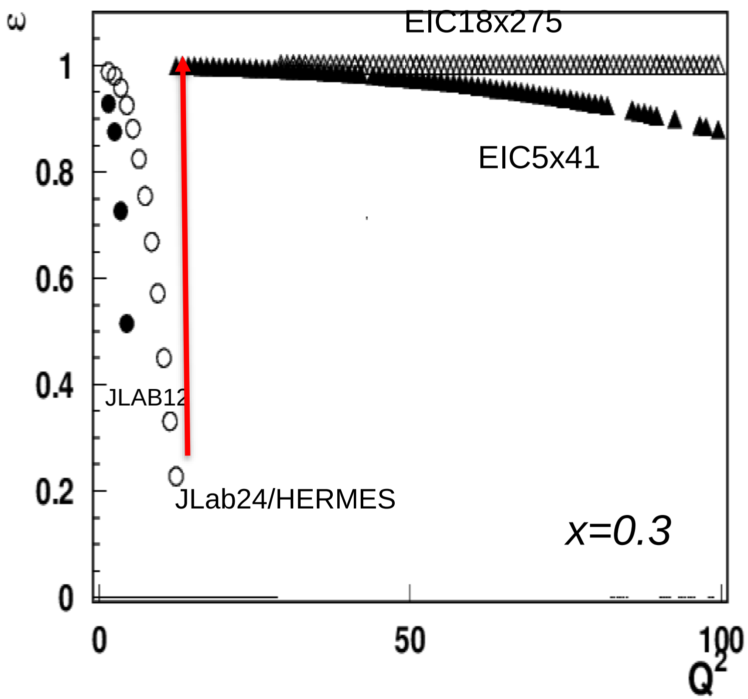
What exactly are identified so far sources of "factorization breakdown" in SIDIS and where is the evidence that "few GeV" matters?

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

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

1) Longitudinal photon

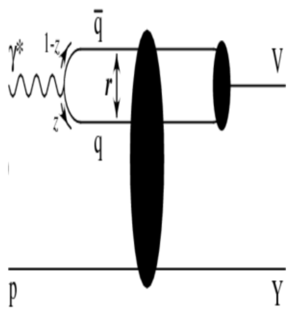
- For a given x&Q^2 the contribution from longitudinal photon increases at higher energies (ex. at EIC 5 times bigger at Q^2~10, x~0.3 than at JLab)
- JLab studies of impact of longitudinal photons critical for interpretation of polarized SIDIS, including EIC data

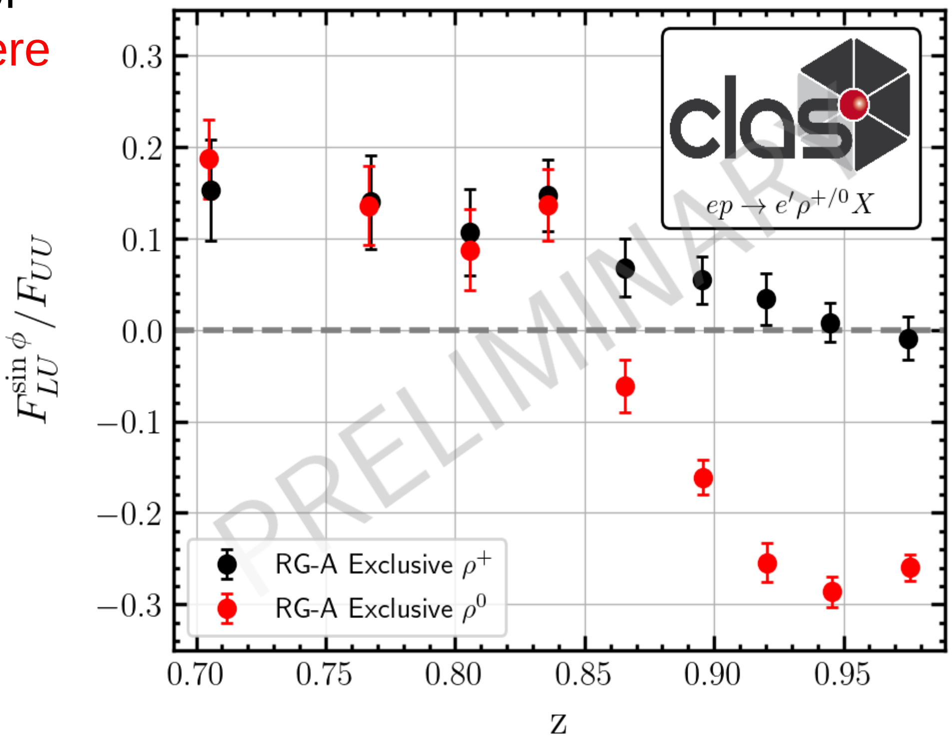


Addressing PAC/theory comments

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

2) Diffractive VMs (ρ^0)



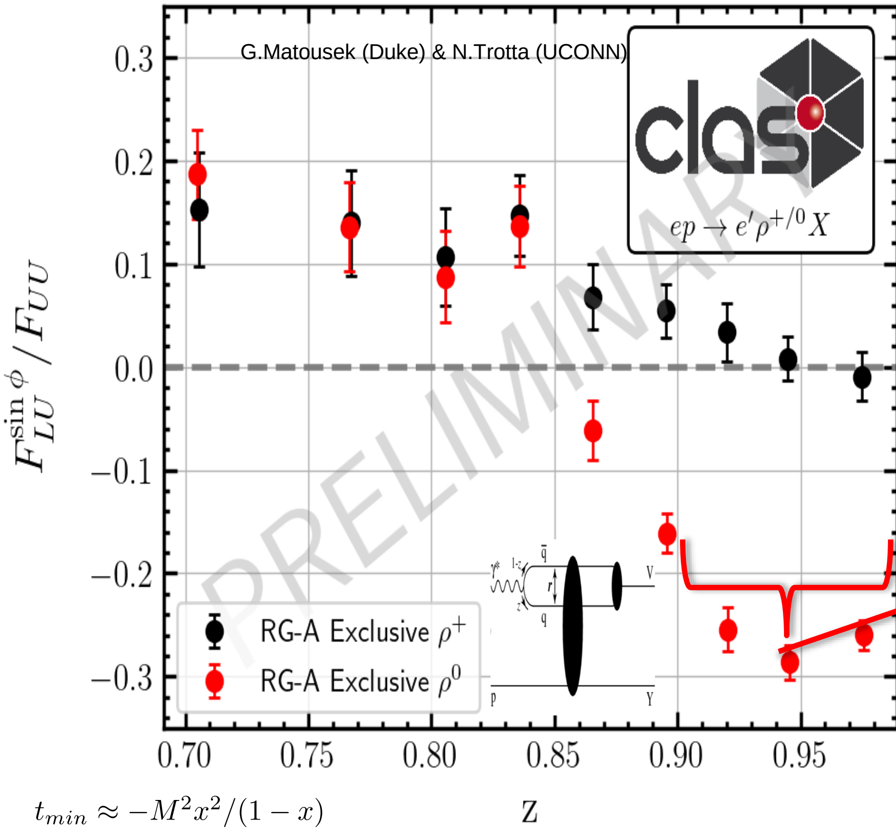


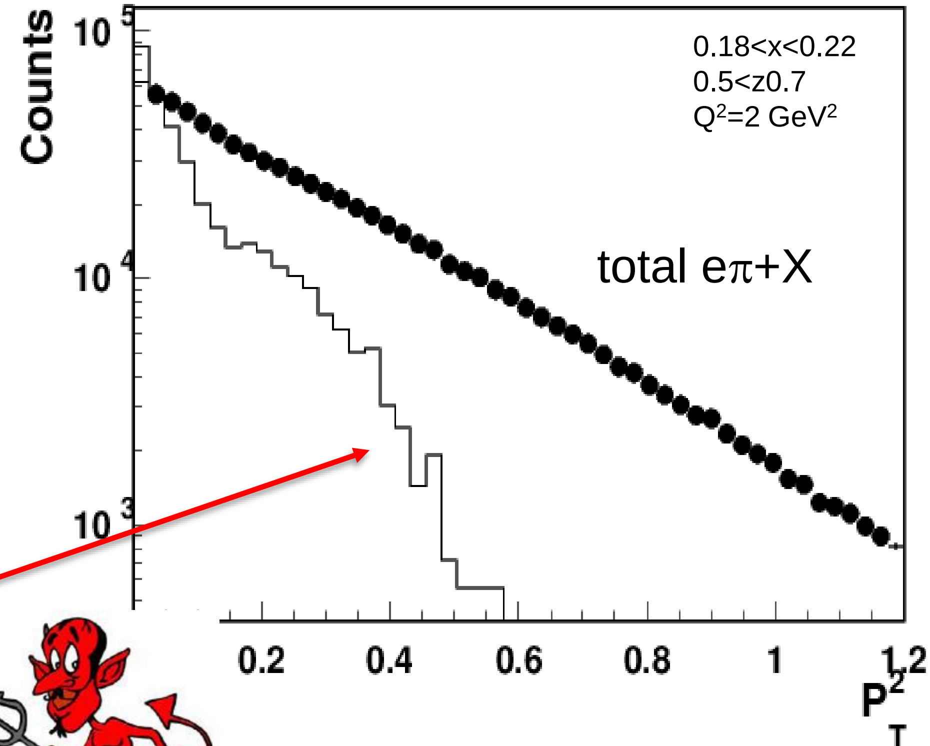
Comparison with exclusive rho+, clearly indicates the kinematics where the "diffractive rho0" shows up (increases at higher energies)

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.

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

Contributions of “diffractive rho0s” in SIDIS



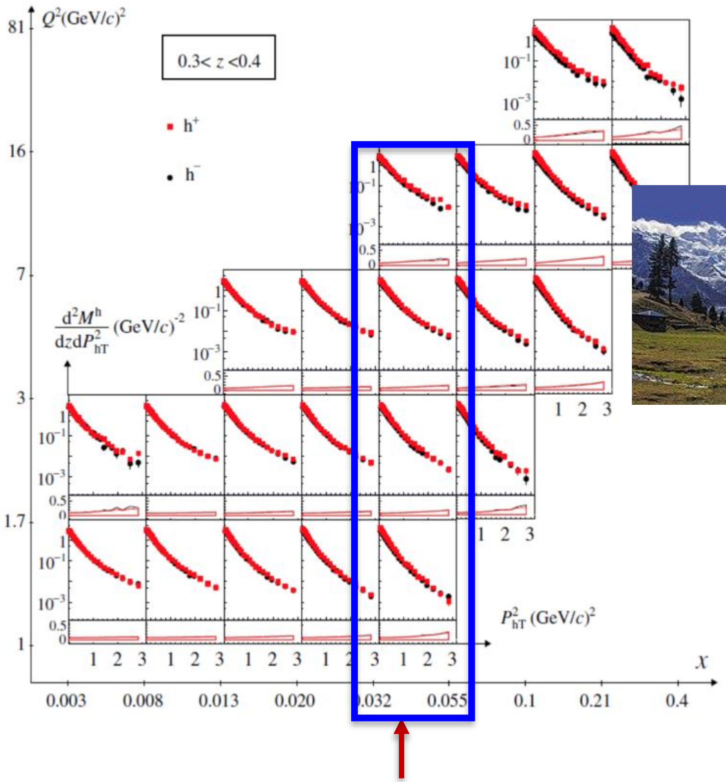


The “diffractive” rho contributes at lower P_T values in the inclusive pion sample

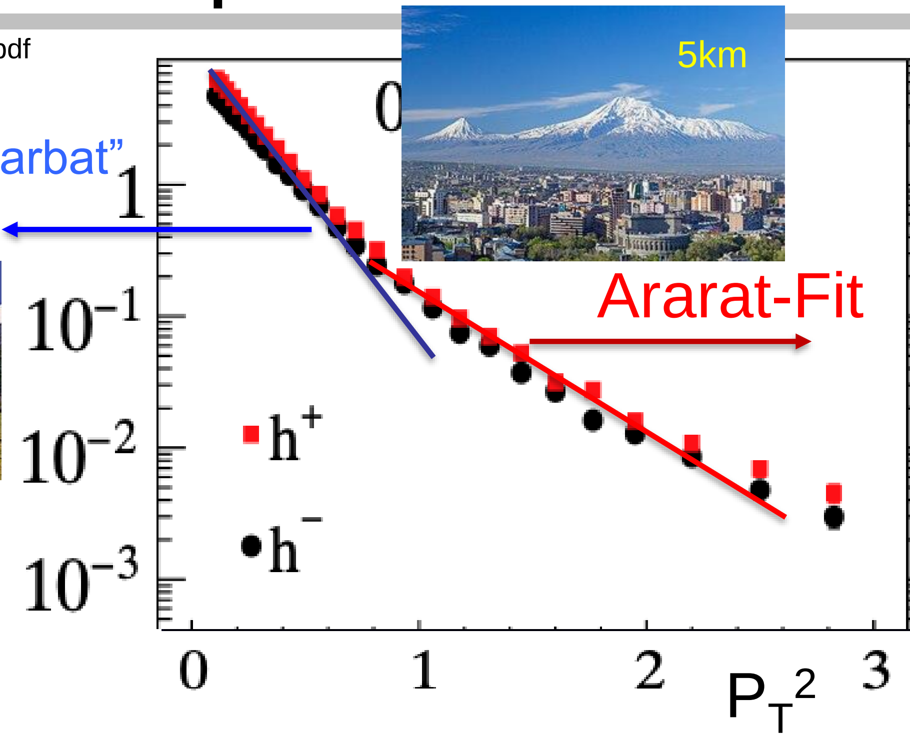
Estimated ~20% contributions from rho, consistent with ~10% in DIS

q_T-crisis or misinterpretation

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



"Nanga Parbat" 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)

Excluding the “diffractive” rho from SIDIS

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

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

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

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

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

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

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

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

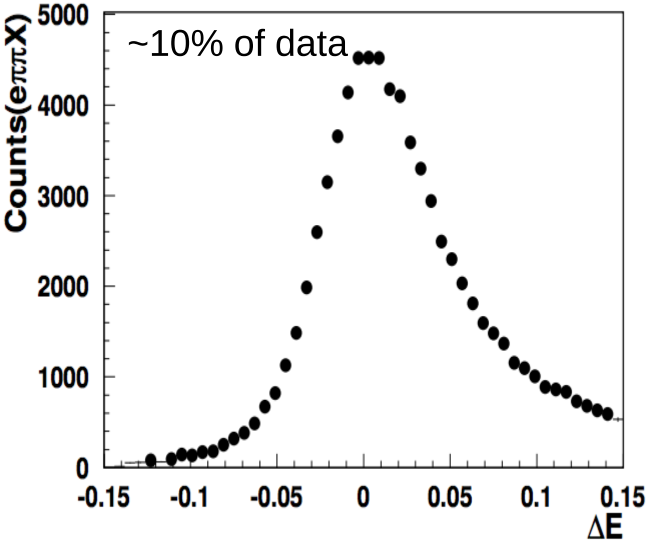
Understanding exclusive rhos and SDME validations

Exclusivity condition defined by the missing Energy:

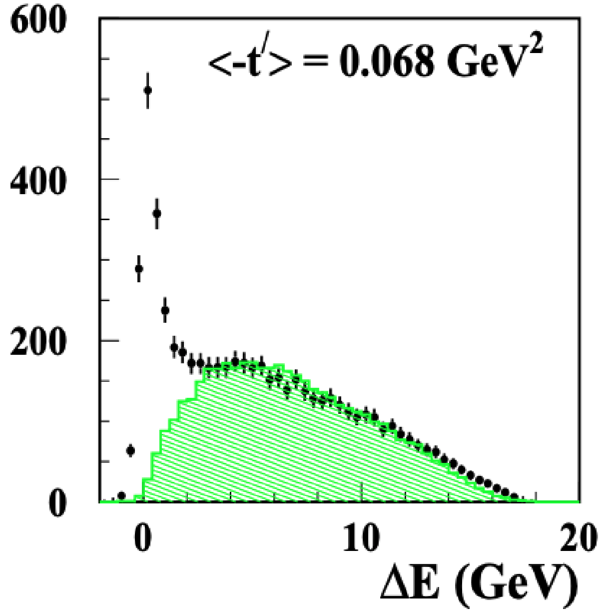
$$M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2$$

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

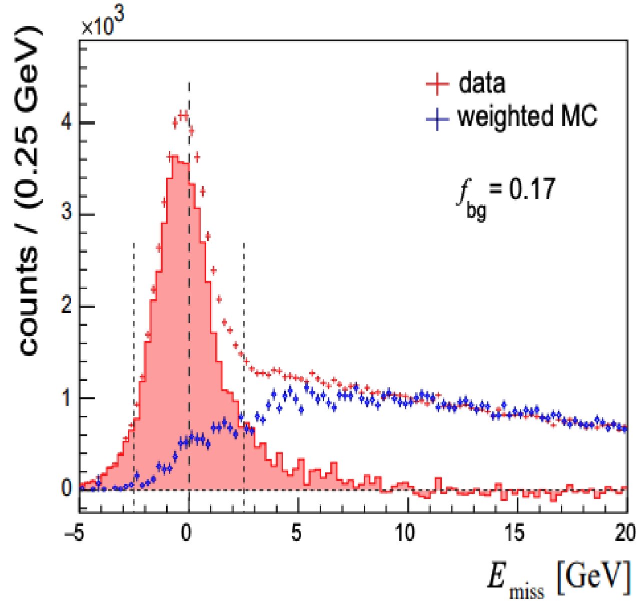
CLAS12 (width <0.1GeV)



HERMES(width ~0.6GeV)



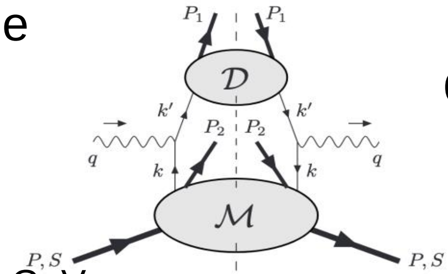
COMPASS(width ~2GeV)



- 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)

Unique ability to measure target fragments

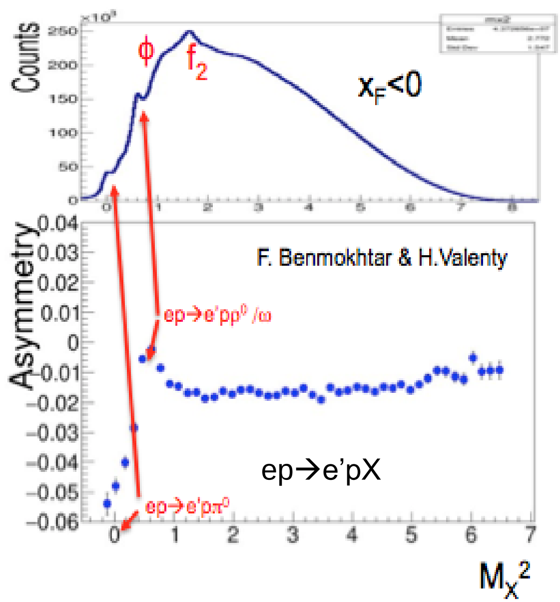
Detection of the target nucleons (B2B SIDIS) provide a powerful tool to control the contributions in CFR

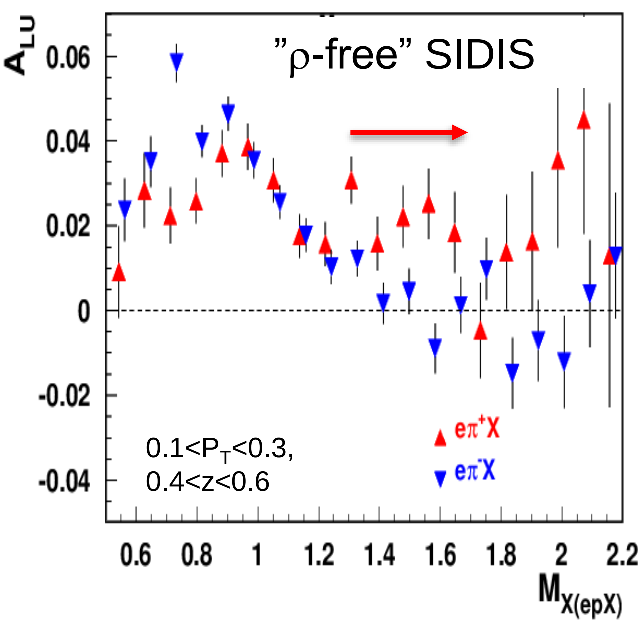


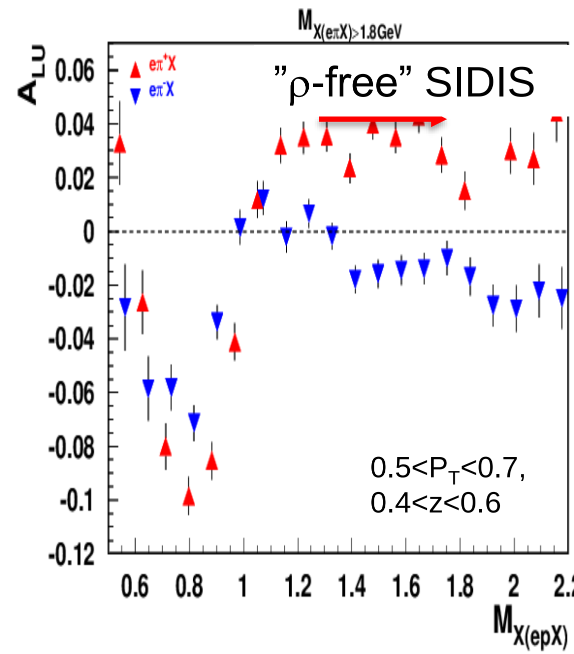
ep→e'pπX

3 processes:

- ep→e'hX (regular SIDIS)
- ep→e'NhX (SIDIS+ TFR nucleon, B2B SIDIS)
- ep→e'NhX (SIDIS+ TFR Nucleon + cut on M_X(ep→e'NX)>1.35 GeV



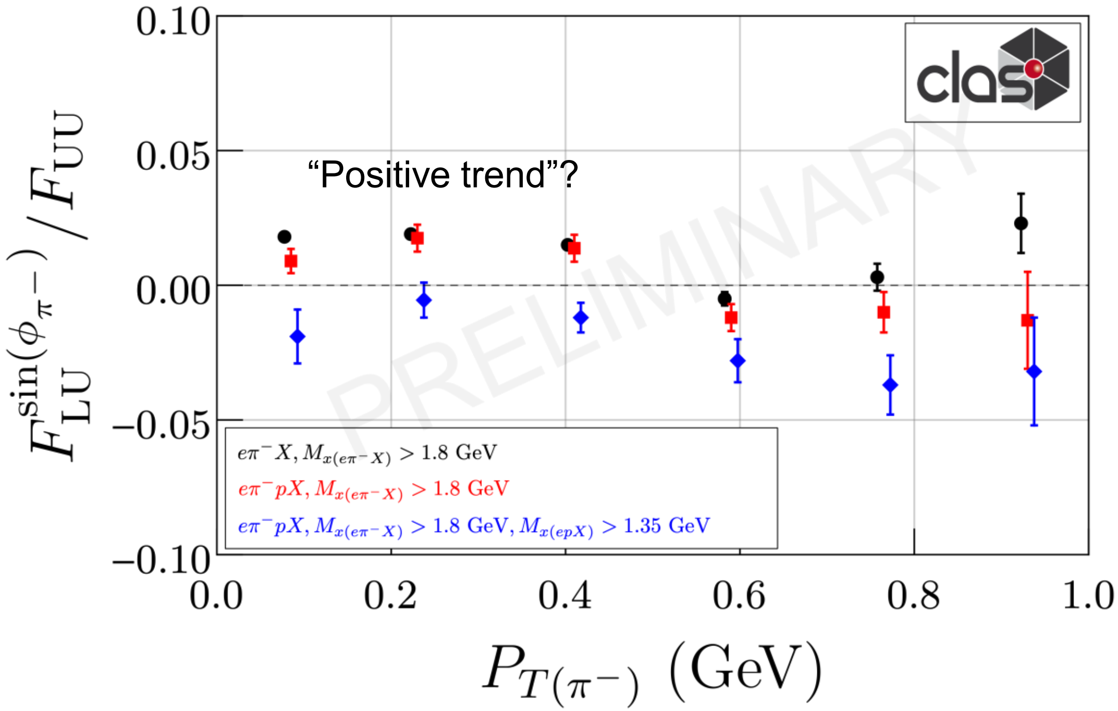




Exclusive ρ (possibly f_2) have very significant contributions to all SIDIS observables (ex. beam SSA), which **can be completely eliminated** with detection of the TFR proton

“rho-free” SIDIS and possible bias

Use sample of ep→e’p π- X and and make plots with and without M_X cut(epX) 1.35 GeV

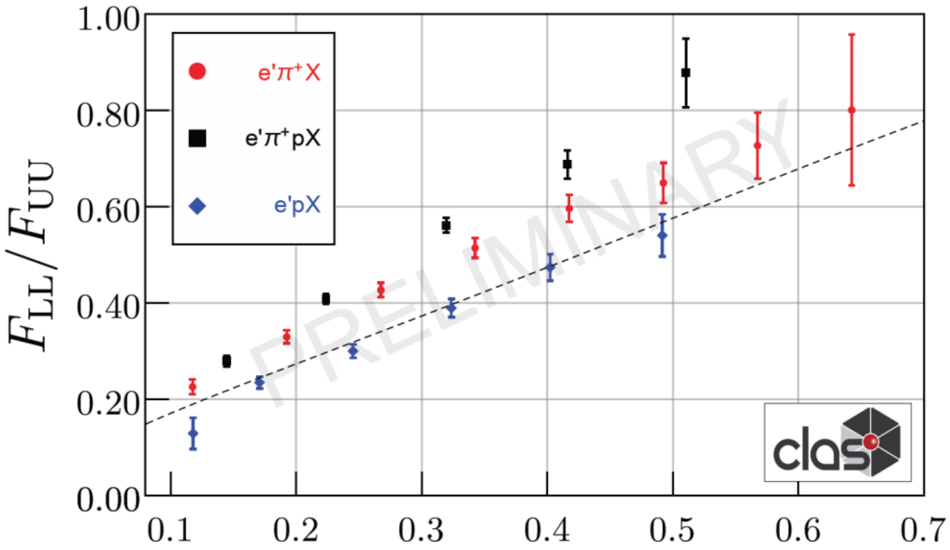


All point include
$M_X(e'\pi\text{-}X)$>1.8 GeV
→out of resonance region

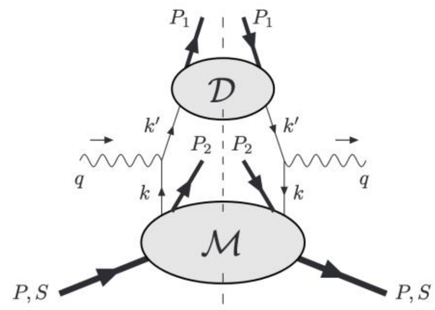
Blue squares
M_X(epX) >1.35 GeV (rho-free), significantly different and will impose much less challenge for phenomenology

- Exclusive rho-0s have very significant impact on kinematic dependences of SIDIS SSAs, in particular at low P_T
- Detection of the target proton introduces much smaller bias on the inclusive SSA, than the exclusive rho
- The procedure can be validated using direct subtraction of rho (like DVCS/π^0)

Longitudinally polarized quarks in B2B SIDIS

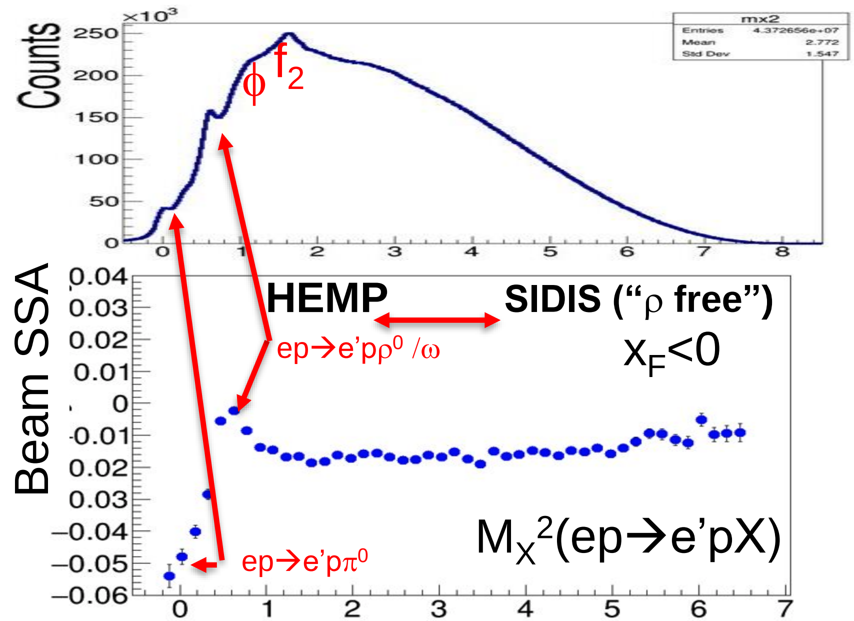


ep→e'pπX



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!



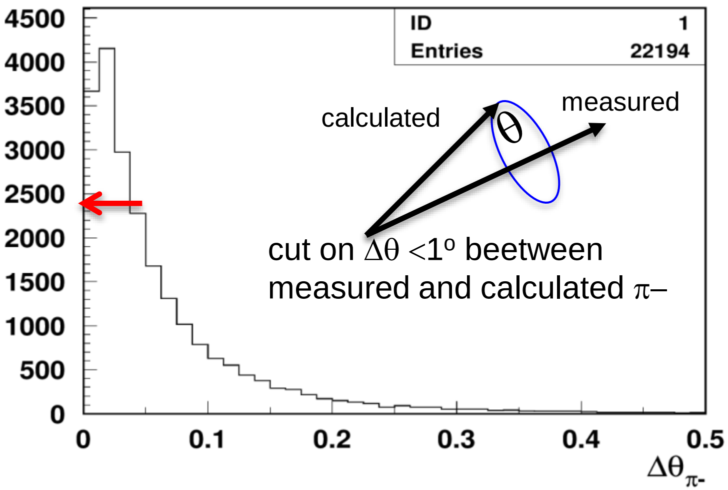
Possible theory formalisms:

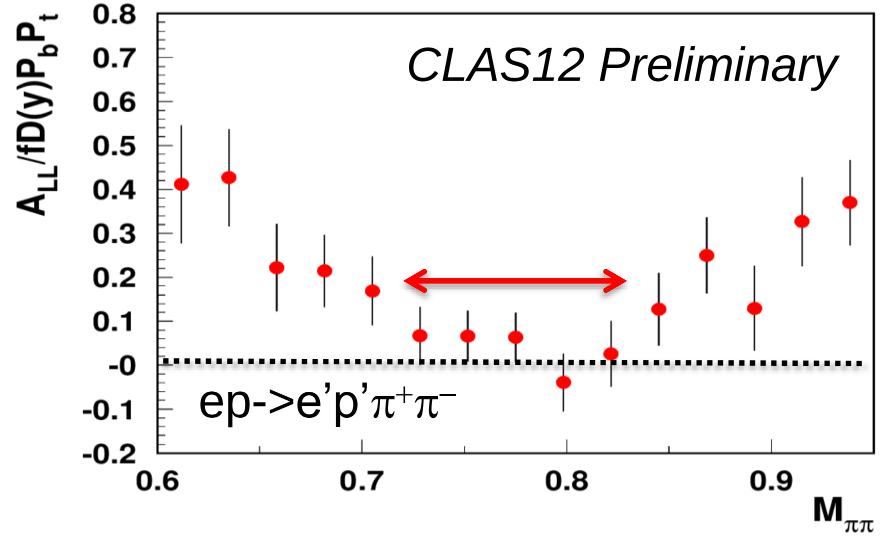
- **Formalism based on fracture functions (Anselmino, Barone, Kotzinian (back-to-back, b2b, hadron production, DSIDIS)**
- **Semi-exclusive processes, involving GPDs/GTMDs on proton side (TFR) and FFs on pion side (CFR) Yuan and Guo**

- 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)

Studies of ρ^0 impact with longitudinally polarized NH_3 target

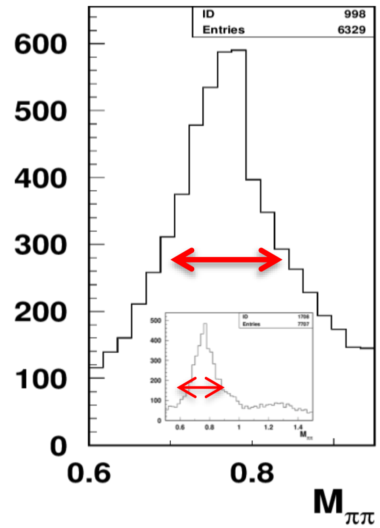
Separating exclusive dihadrons

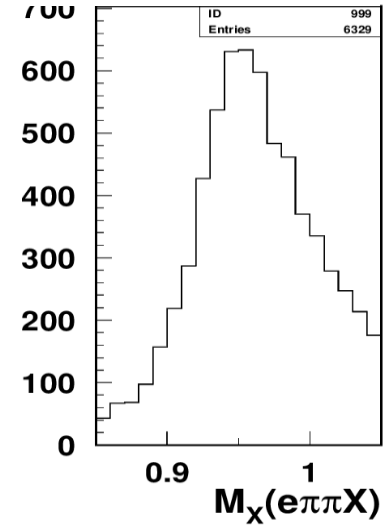




- Require the angle of negative pions is within a degree from calculated from e',p,π+ assuming exclusive e',p,π+π- event.

- 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)





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

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 proper account of VMS with either "rho-subtracted SIDIS" or the "rho-free SIDIS" will provide an important step to address the challenges of phenomenology

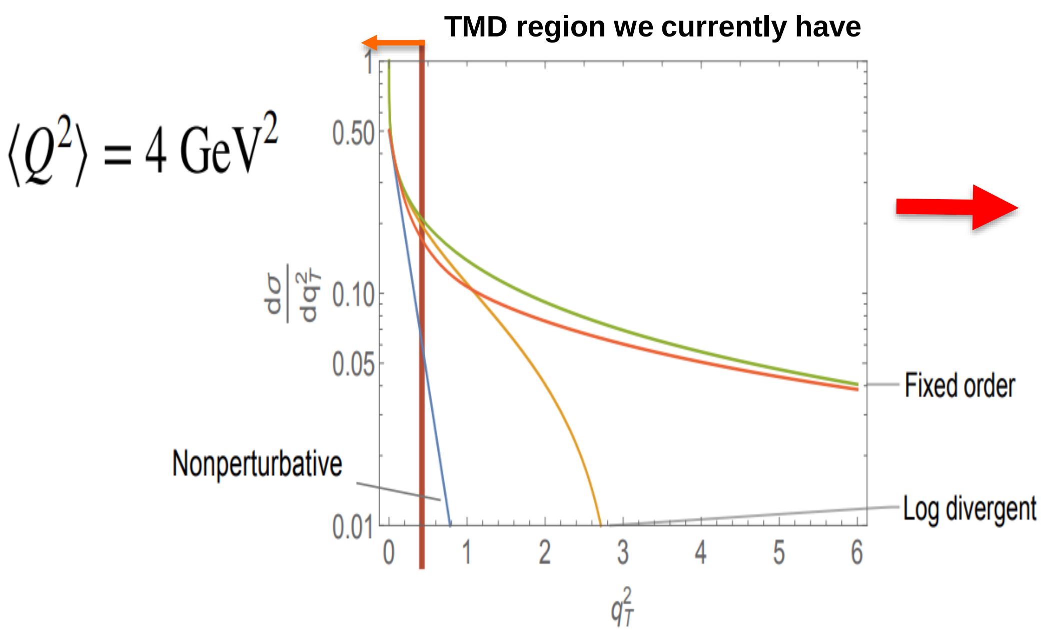
- Extraction of the full set of SDMEs for exclusive ρ^0 in multidimensional space, describing x-sections and all kind of spin dependent observables, including azimuthal modulations as a function of all relevant kinematical variables is one of the most critical tasks in electroproduction also the VM contributions

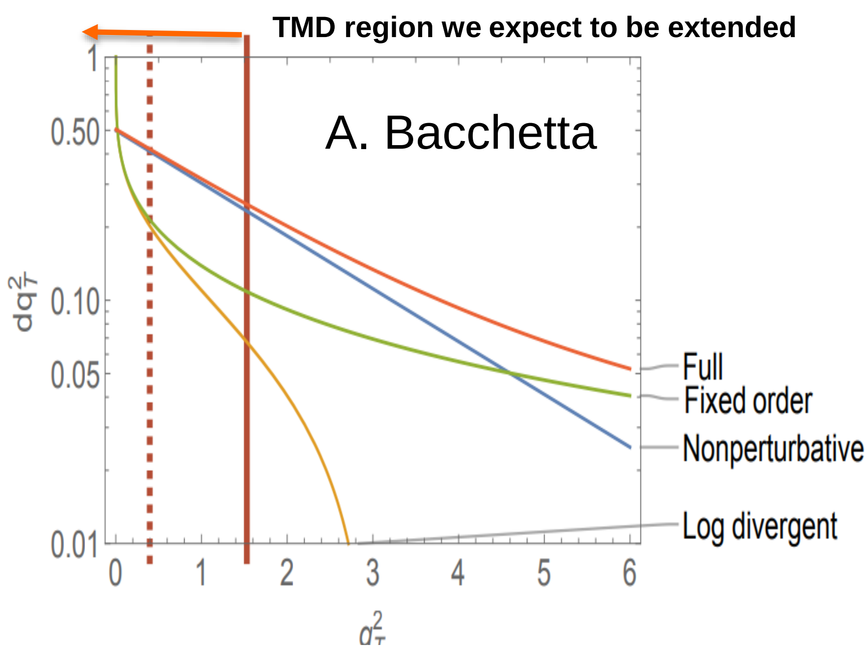
Future Plans

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?



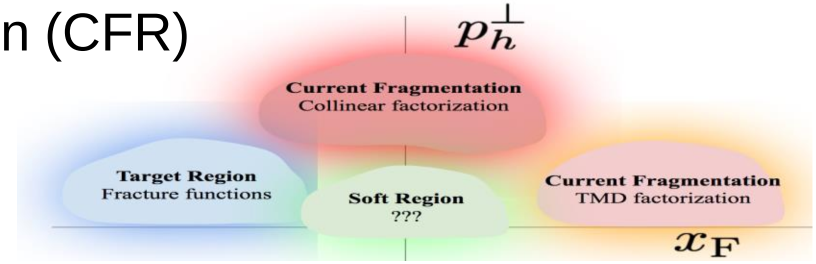


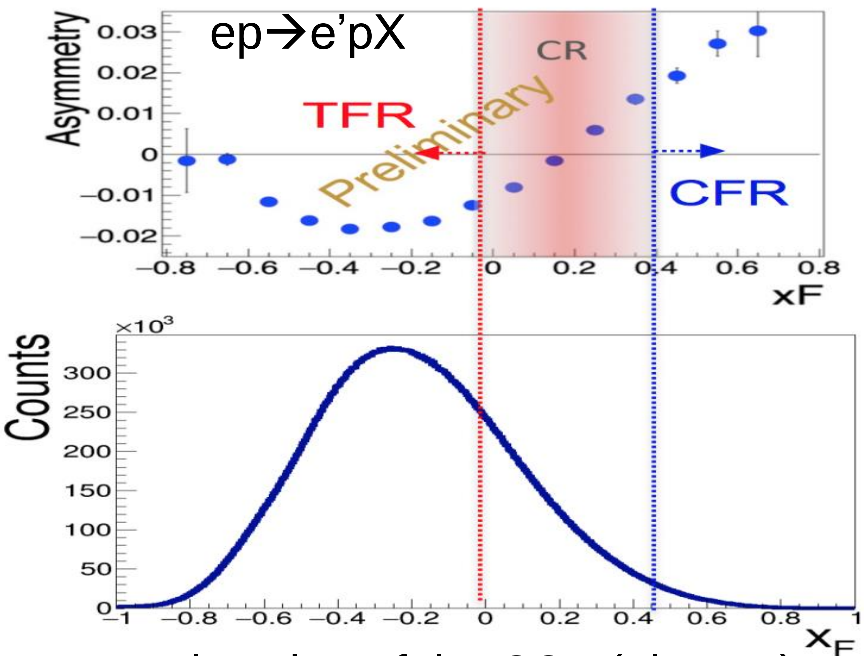
How far in P_T or q_T extends the TMD region

"they know not what they do" Luke 23:34

Beam SSAs as a tool to separate regions and contributions

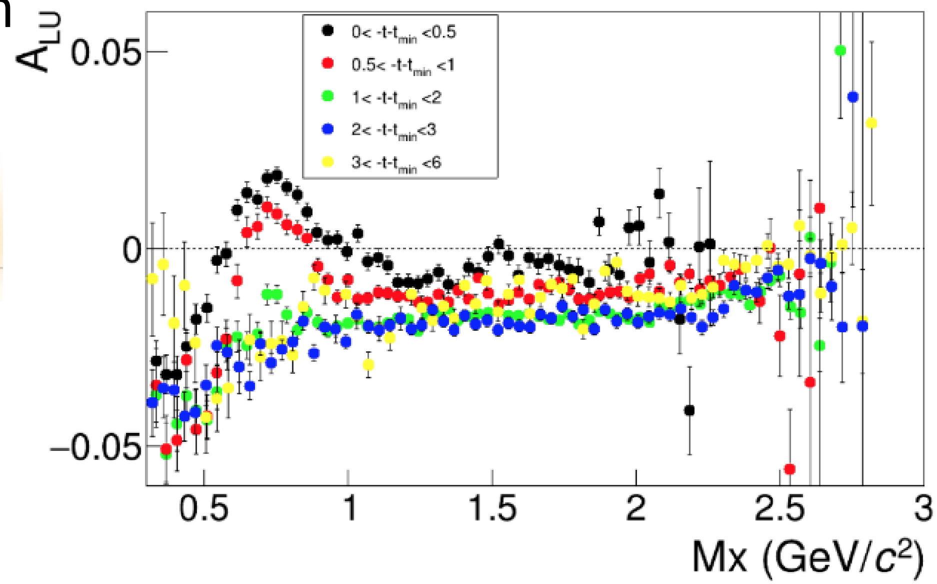
3) Separating Target Fragmentation Region TFR from Current fragmentation region (CFR)





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

F. Benmokhtar & Duquesne U.

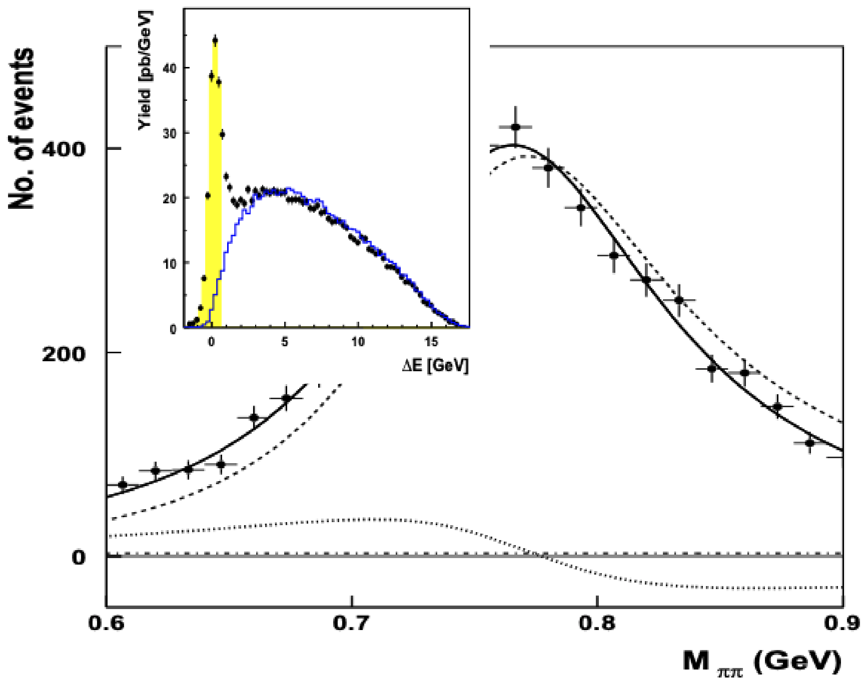


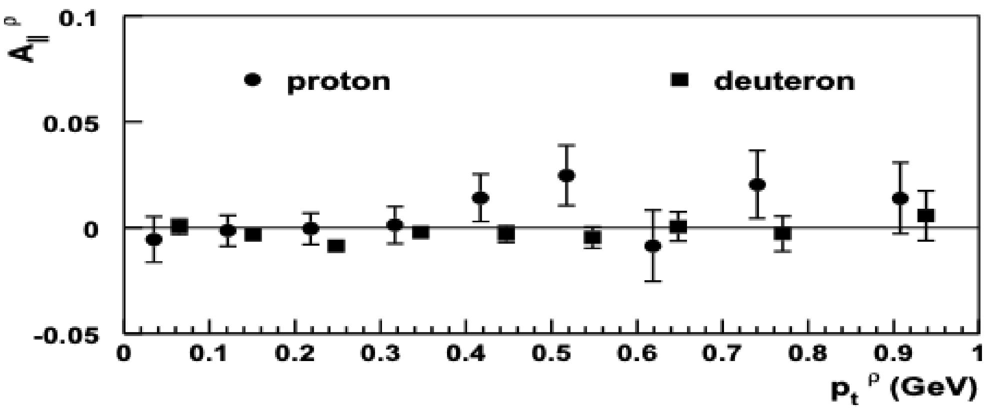
Major difference only for protons at small t!

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

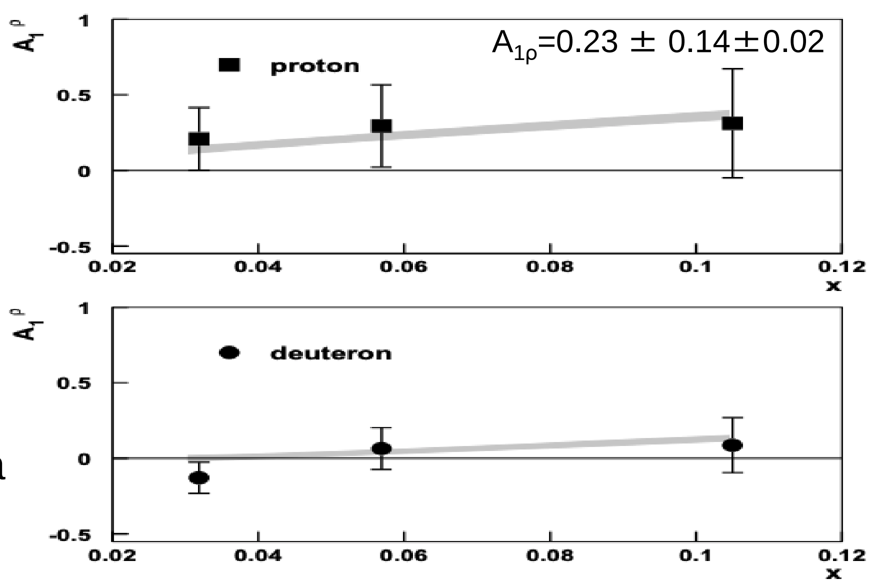
1) kinematical regions (CFR/TFR)
2) dynamical contributions
3) cut on M_X eliminate exclusive VMs

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





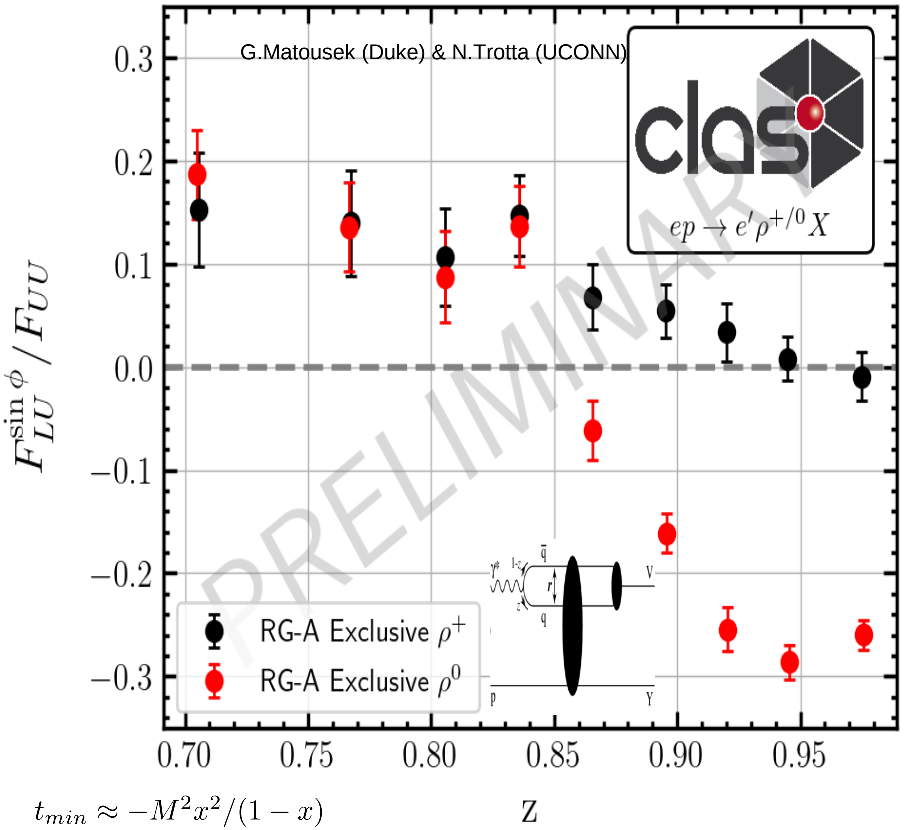
At low P_T, where the background is smaller, the asymmetry indeed tend to be negative

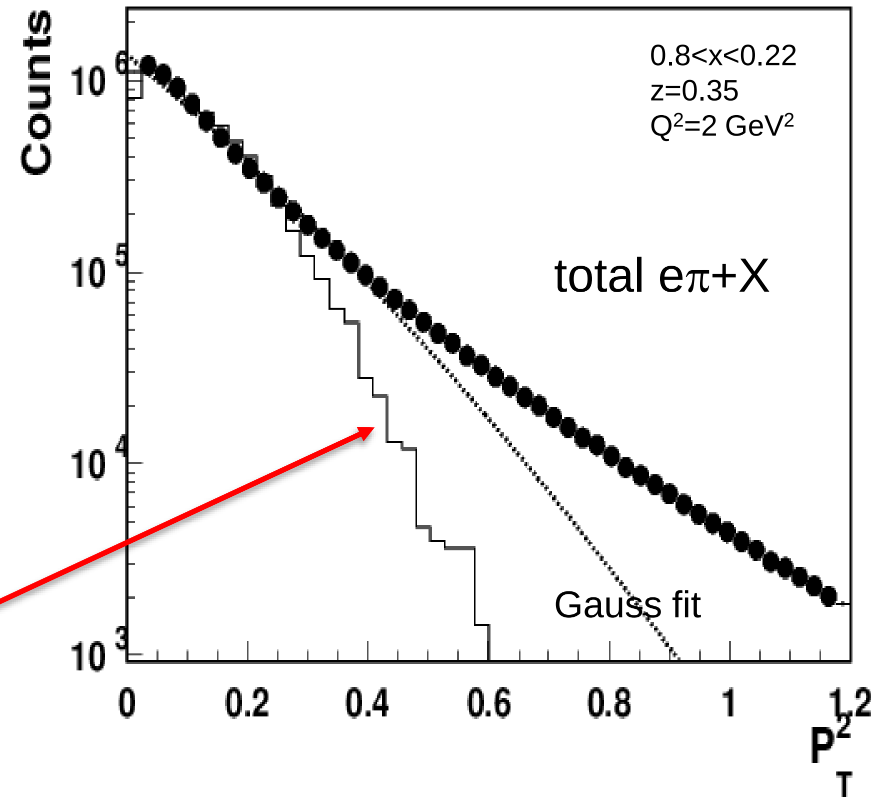


For a proper extraction of multiplicities and spin-azimuthal modulations of exclusive ρs, clean separation is needed for ρ^0, and longitudinally polarized ρ^0 signal, in particular

For a proper account of the impact on SIDIS, need a realistic MC (with validated SDMEs) for proper separation of "diffractive" exclusive ρ^0s in multi-D

Contributions of “diffractive rho0s” in SIDIS





Pions from exclusive rho0 (line) drop much faster than Gauss, while overall SIDIS pions drop slower than Gauss

The “diffractive” rho contributes at lower PT values in the inclusive pion sample

x-section

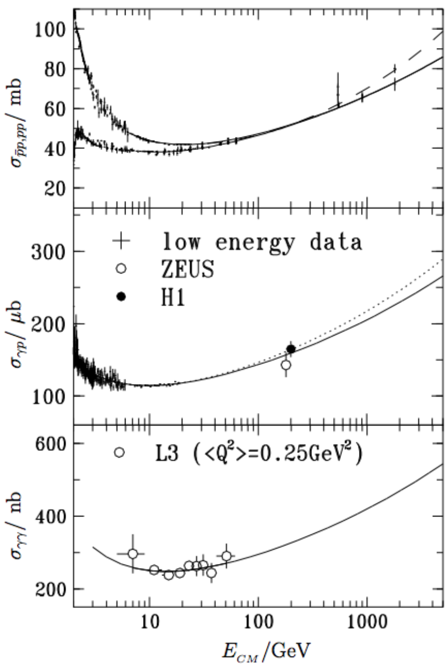


Figure 1.9: Total cross sections for pp ($p\bar{p}$), γp and $\gamma\gamma$ scattering as a function of the center of mass energy E_{CM}. The curves represent the DL parameterization with $\alpha_{IP}(0) = 1.0808$ (solid), $= 1.112$ (dashed) and $= 1.088$ (dotted).

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

$$\sigma_{tot} = A\, s^{\alpha_{IR}(0)-1} + B\, s^{\alpha_{IP}(0)-1}\,. \tag{1.38}$$

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

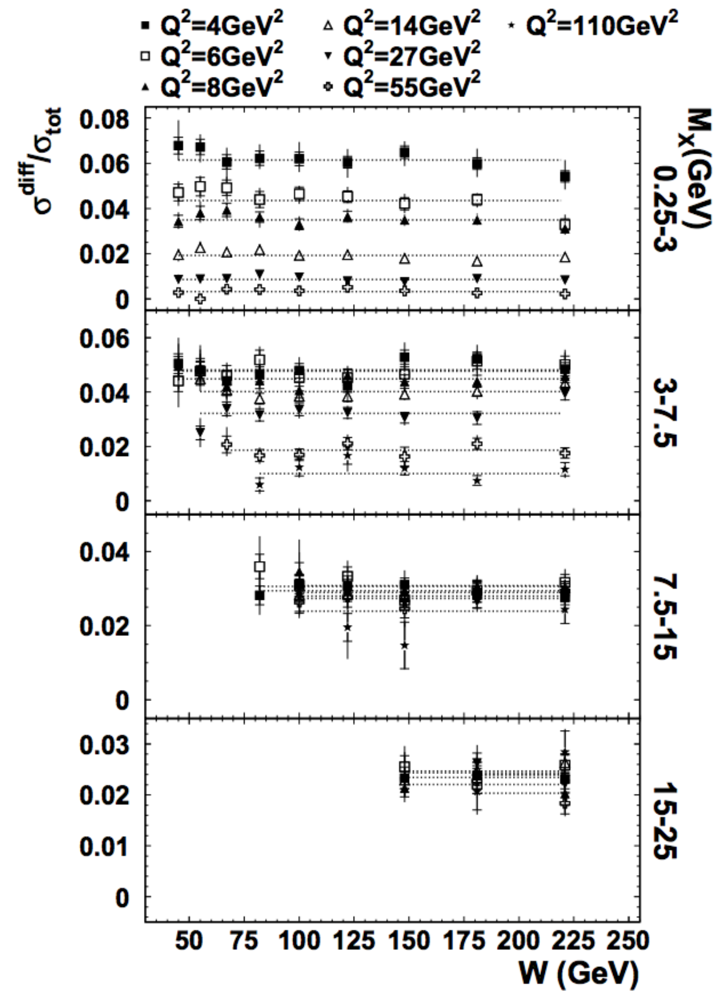


Figure 11.6: The ratio of the diffractive cross section σ^{diff}, integrated over the bin width $M_a < M_X < M_b$, and the total $\gamma^* p$ cross section σ^{tot} is shown as a function of W for different bins of M_X and Q^2. The dotted lines indicate the average values of $\sigma^{diff}/\sigma^{tot}$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

Understanding exclusive rhos and SDME validations

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

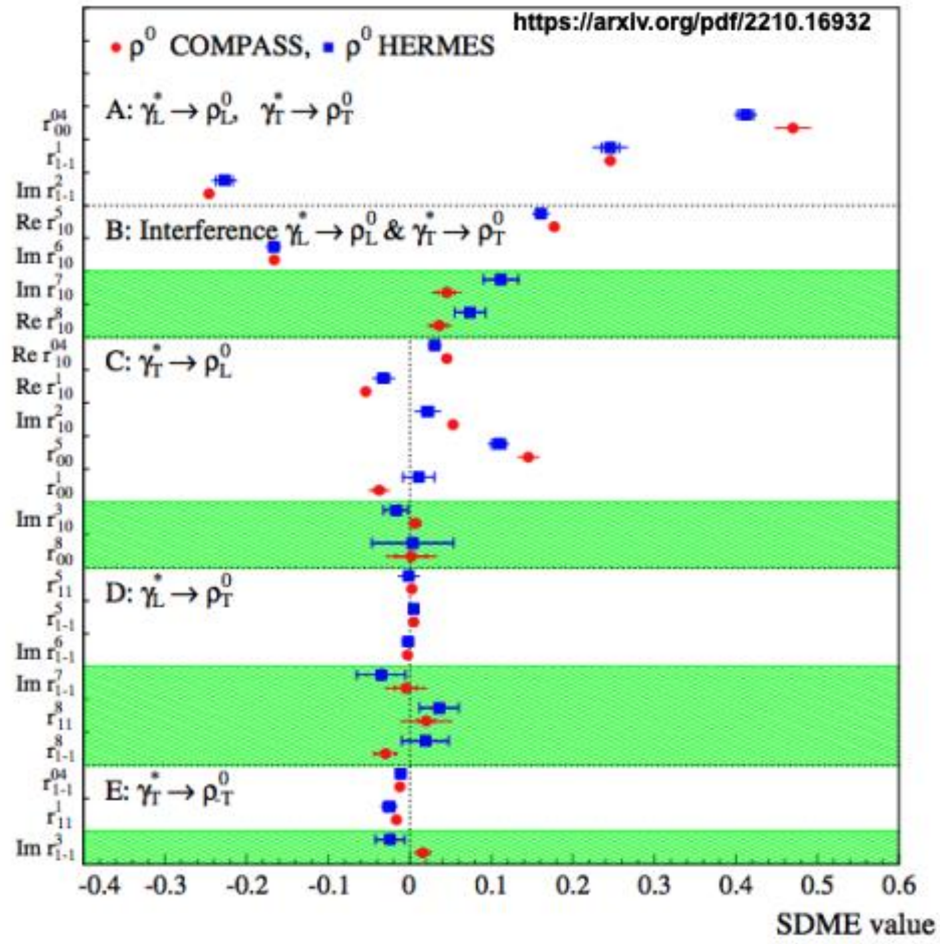


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle|t'|\rangle = 0.13$, 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 <Q²> seem to be consistent.

Understanding exclusive rhos and SDME validations

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

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

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

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

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

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

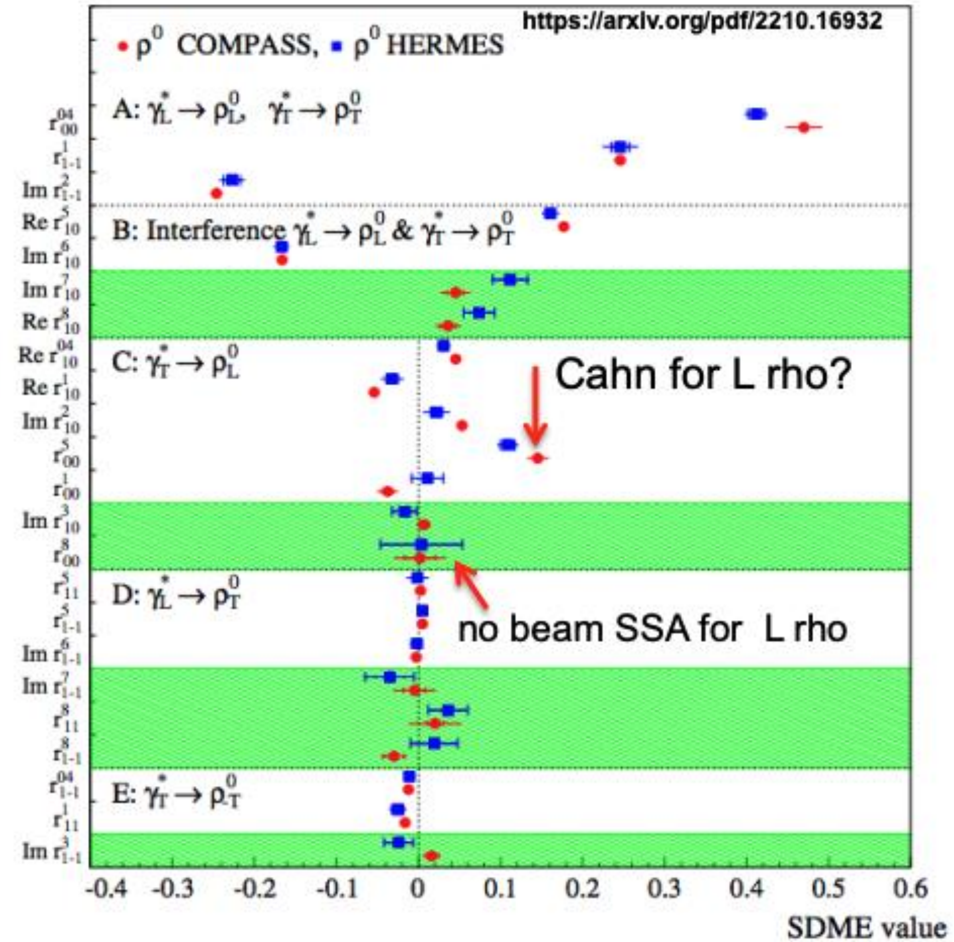


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle|t'|\rangle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

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

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

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

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

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

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

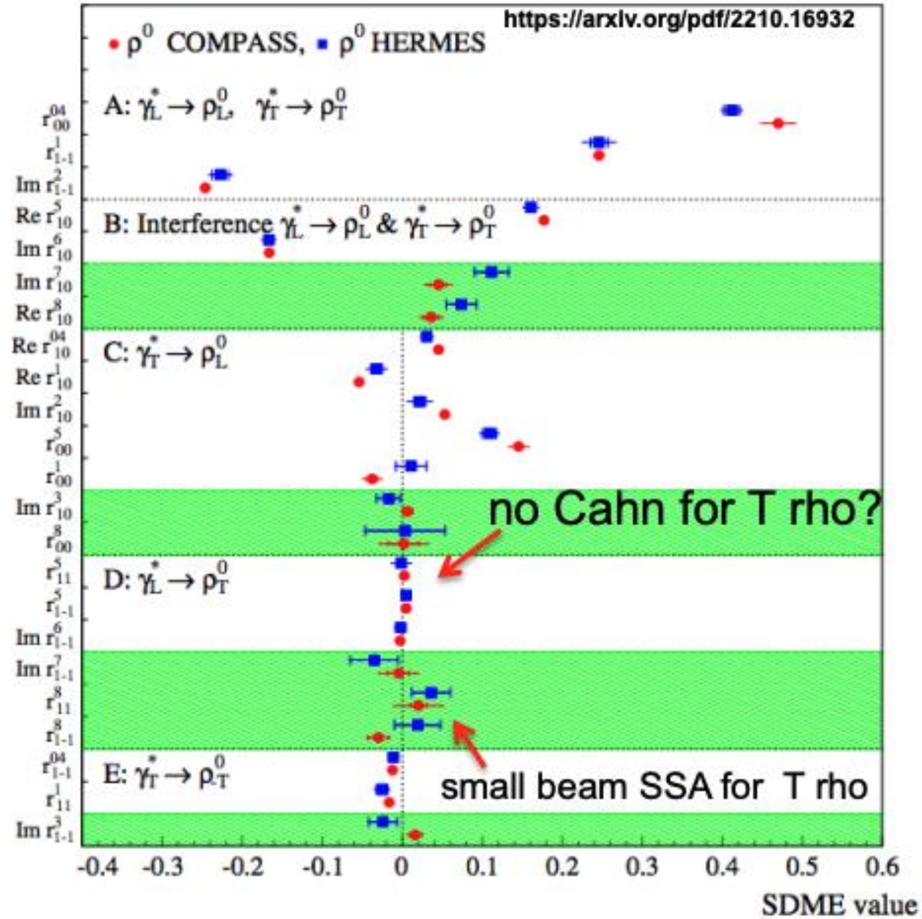
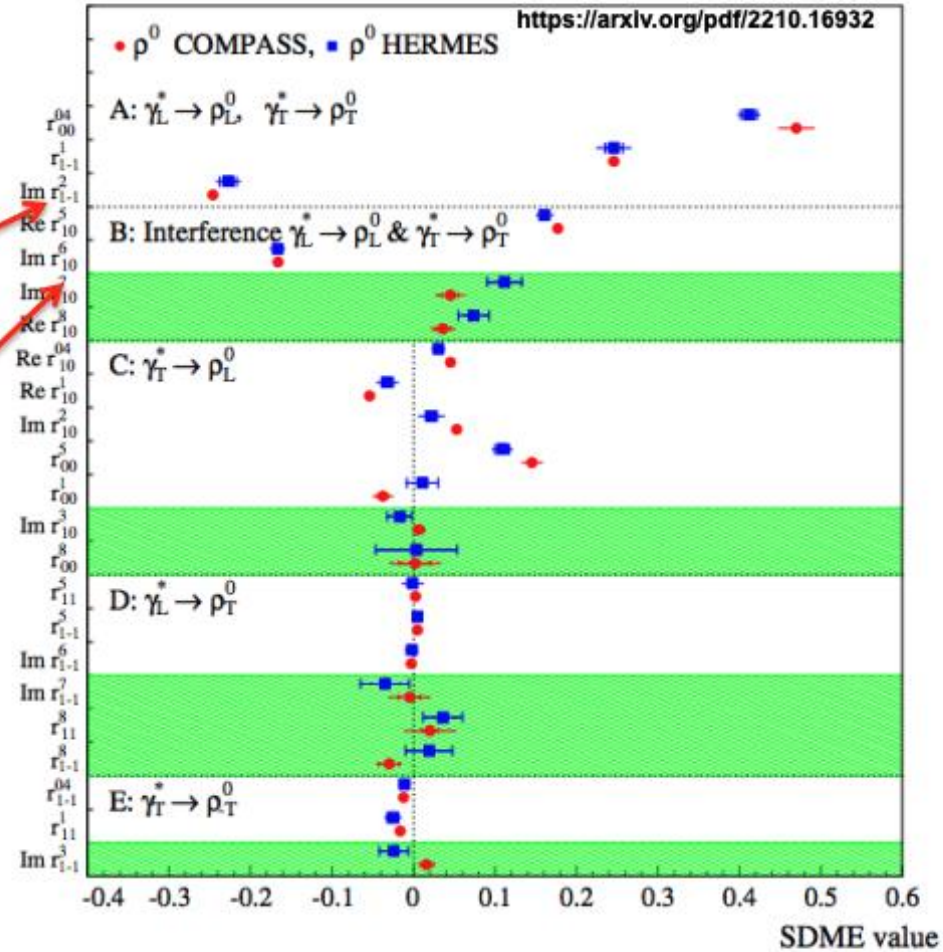


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle|t'|\rangle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

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?)

Understanding exclusive rhos and SDME validations

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

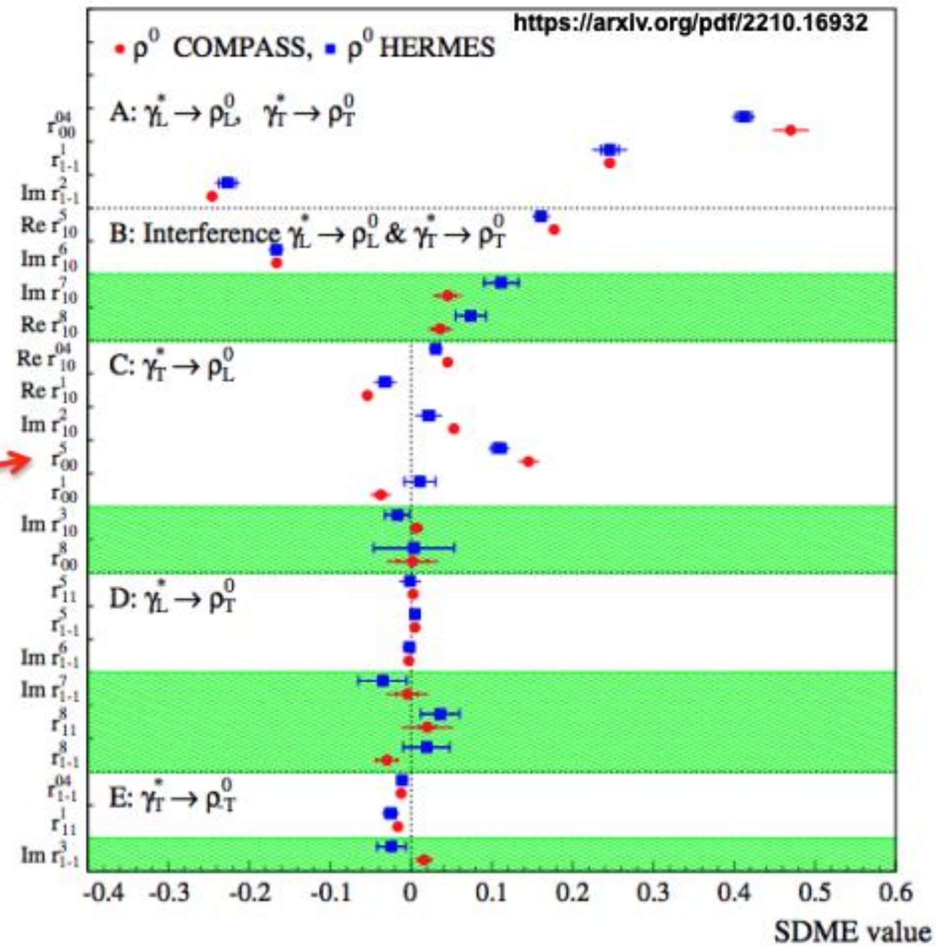


Significant sinusoidal modulations for unpolarized target. Not usual for hadrons (require parity violating effects for pion case)

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

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



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

$$
\begin{aligned}
&\mathcal{W}^{L}(\Phi,\phi,\cos\Theta) \\
&= \frac{3}{8\pi^2}\Bigg[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r^3_{10}\}\sin 2\Theta\sin\phi \\
&\qquad +\mathrm{Im}\{r^3_{1-1}\}\sin^2\Theta\sin 2\phi\Big) \\
&+\ \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^7_{10}\}\sin 2\Theta\sin\phi \\
&\qquad +\mathrm{Im}\{r^7_{1-1}\}\sin^2\Theta\sin 2\phi\Big) \\
&+\ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta \\
&\qquad -\sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi - r^8_{1-1}\sin^2\Theta\cos 2\phi\Big)\Bigg].
\end{aligned}
$$

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

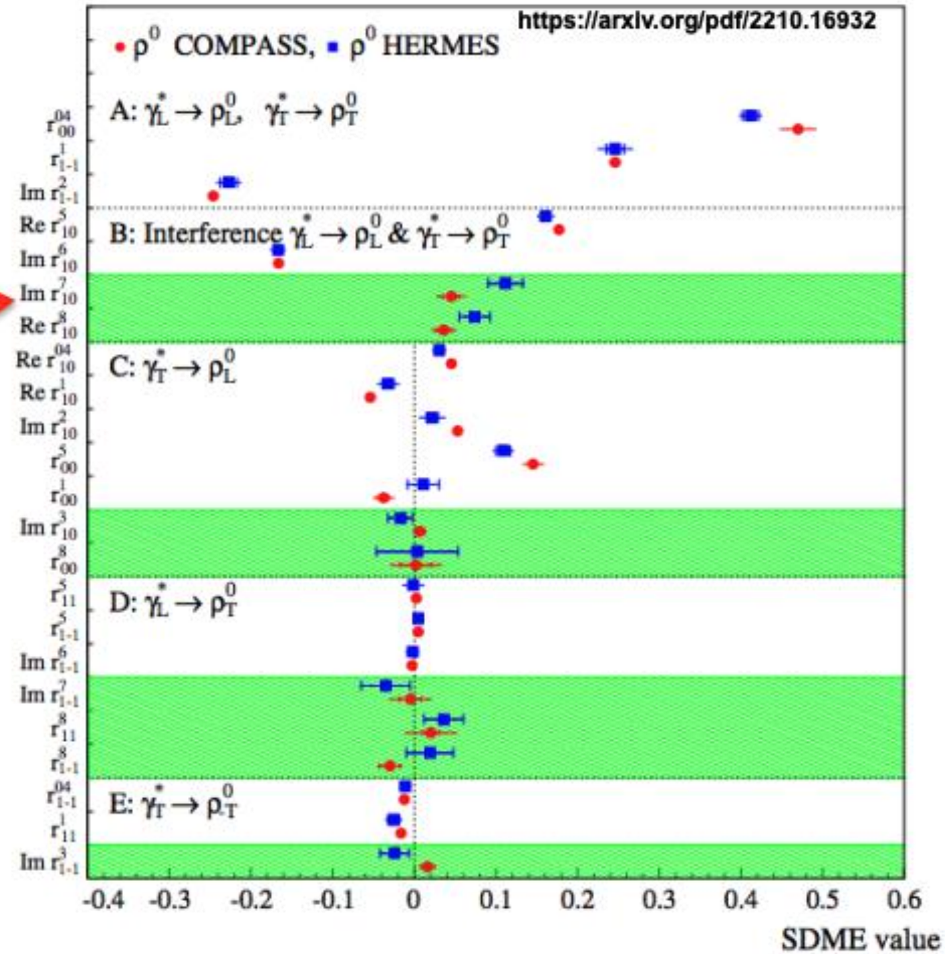


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96\ (\mathrm{GeV}/c)^2$, $\langle W\rangle = 4.8\ \mathrm{GeV}/c^2$,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

Understanding exclusive rhos and SDME validations

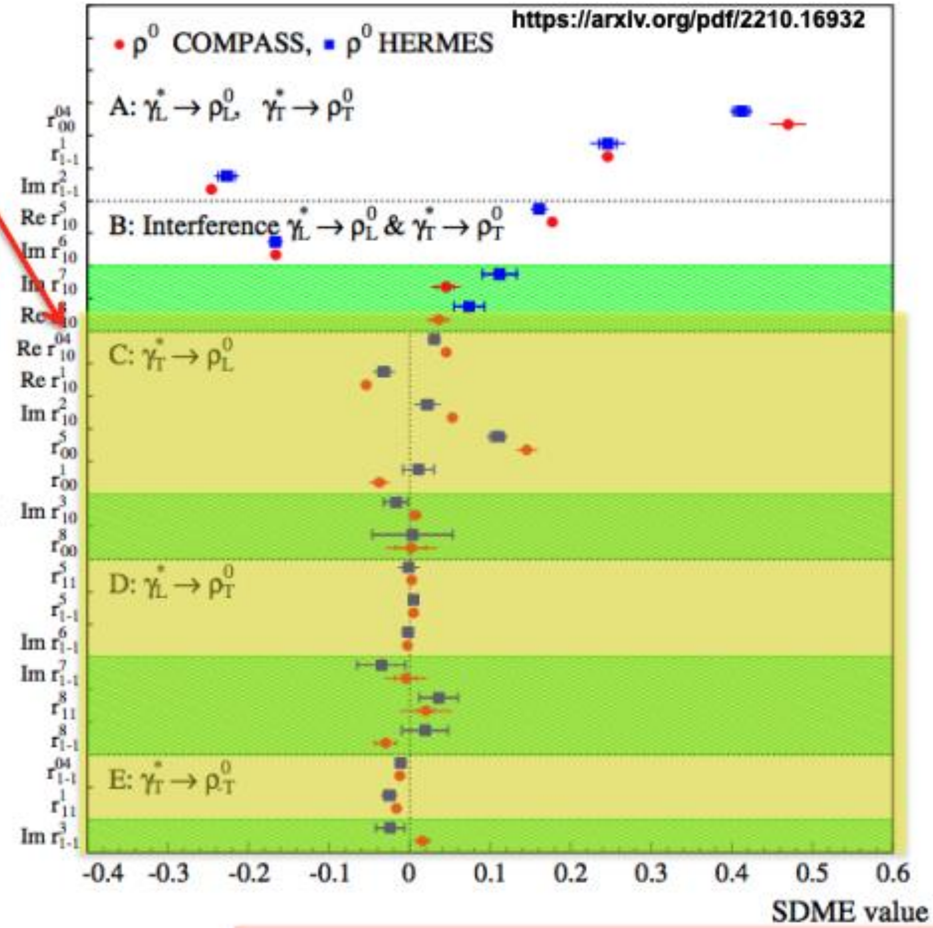
In case of SCHC (terms in yellow disappear) longitudinal-to-transverse virtual-photon cross-section ratio R

$$R = \frac{\sigma_L(\gamma_L^* \to V)}{\sigma_T(\gamma_T^* \to V)},$$ approximated by $$R' = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

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.

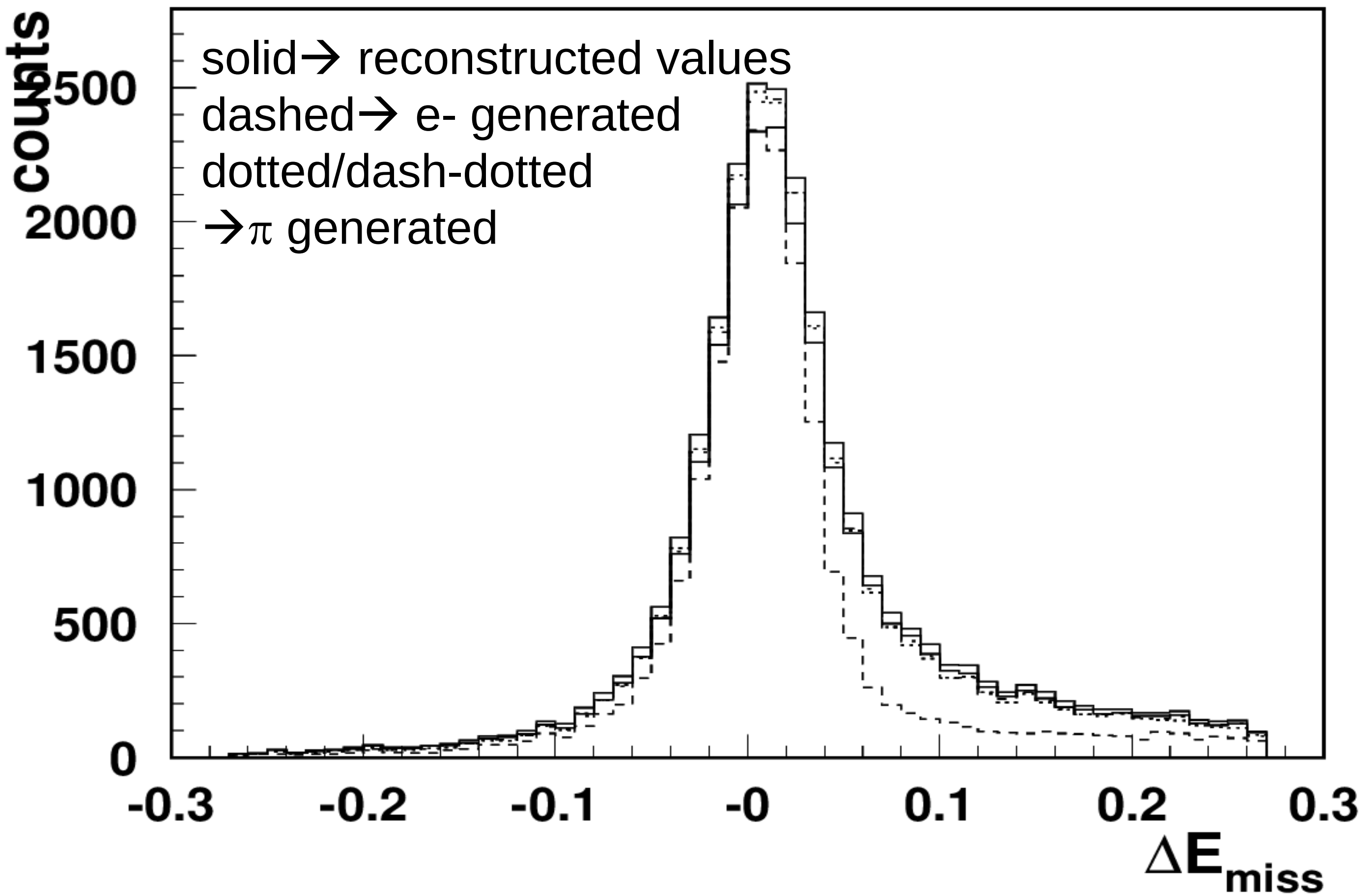
$$\widetilde{R} = R' - \frac{\eta(1+\epsilon R')}{\epsilon(1+\eta)}$$

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

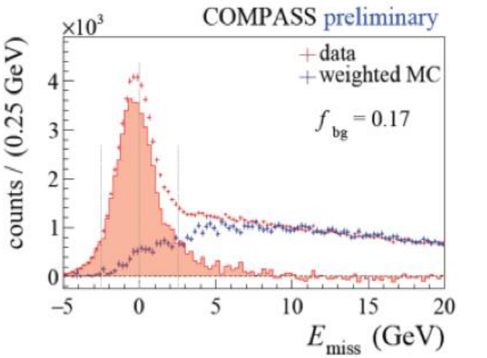


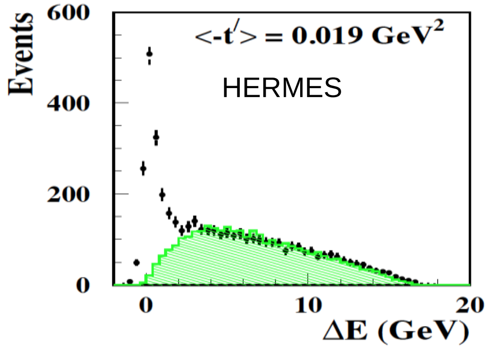
Measurements of sin and cos modulations critical for understanding the rho in general and L/T contributions, in particular

Radiative effects: impact on missing mass



Claim RC is negligible



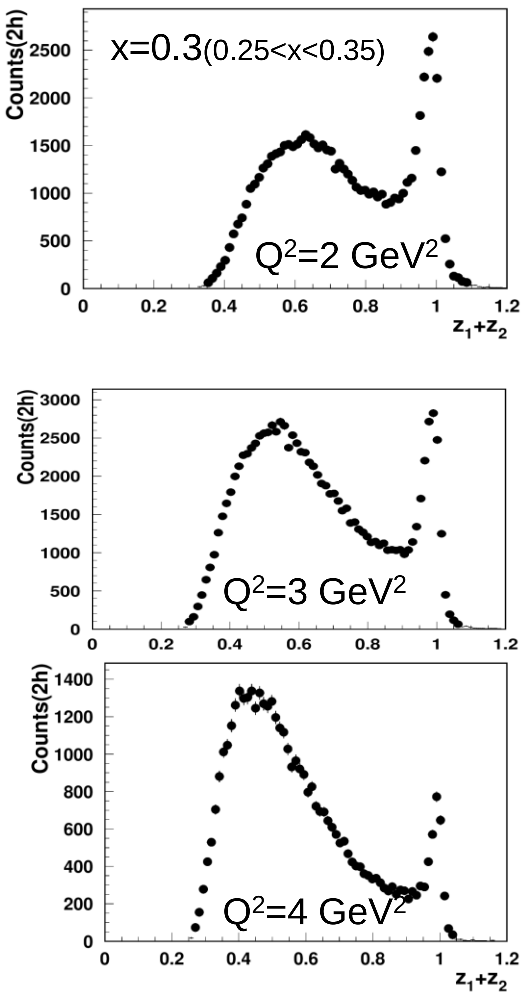


LUND-MC description of the exclusive limit will be important in evaluation of the tail.

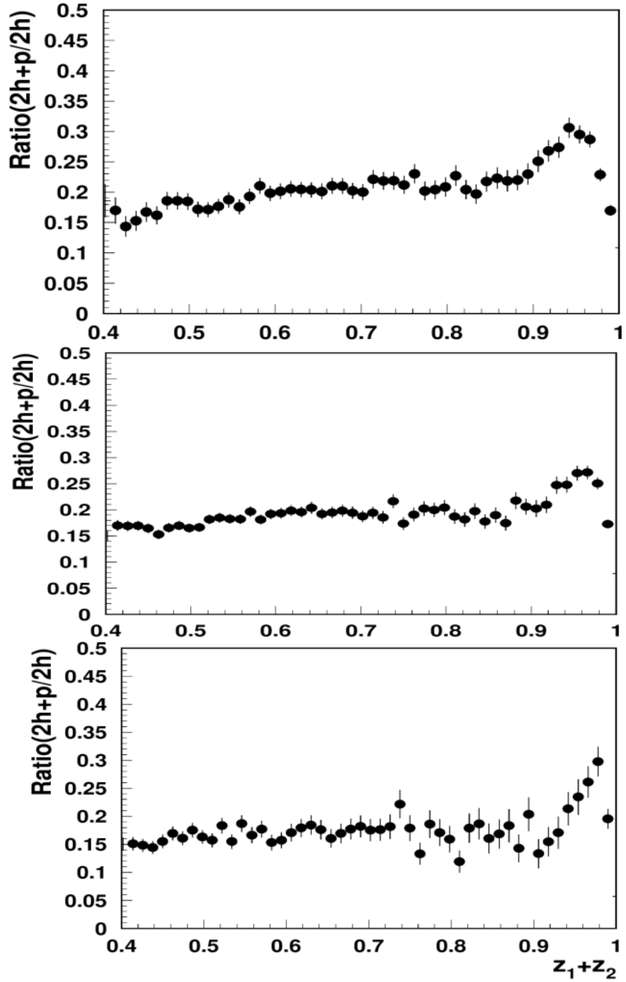
Energy loss of final state particles creates a shoulder (mainly e- for CLAS12)

“ρ-free SIDIS” free: target proton bias

ep→e’ππX

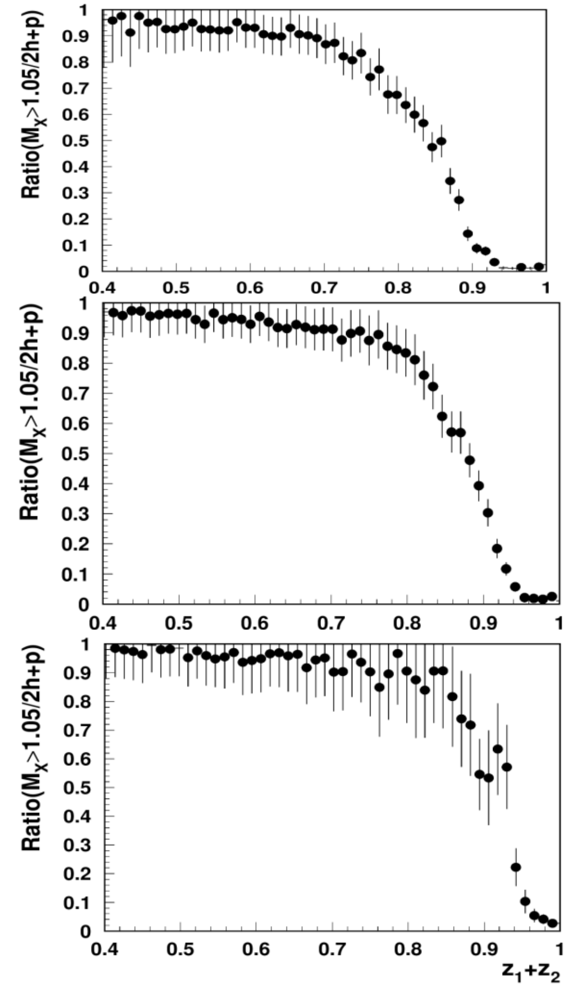


ep→e’pππX + $x_{Fproton}$<0



ep→e’pππX + $x_{Fproton}$<0

+ M_X(epX)>1.05 GeV

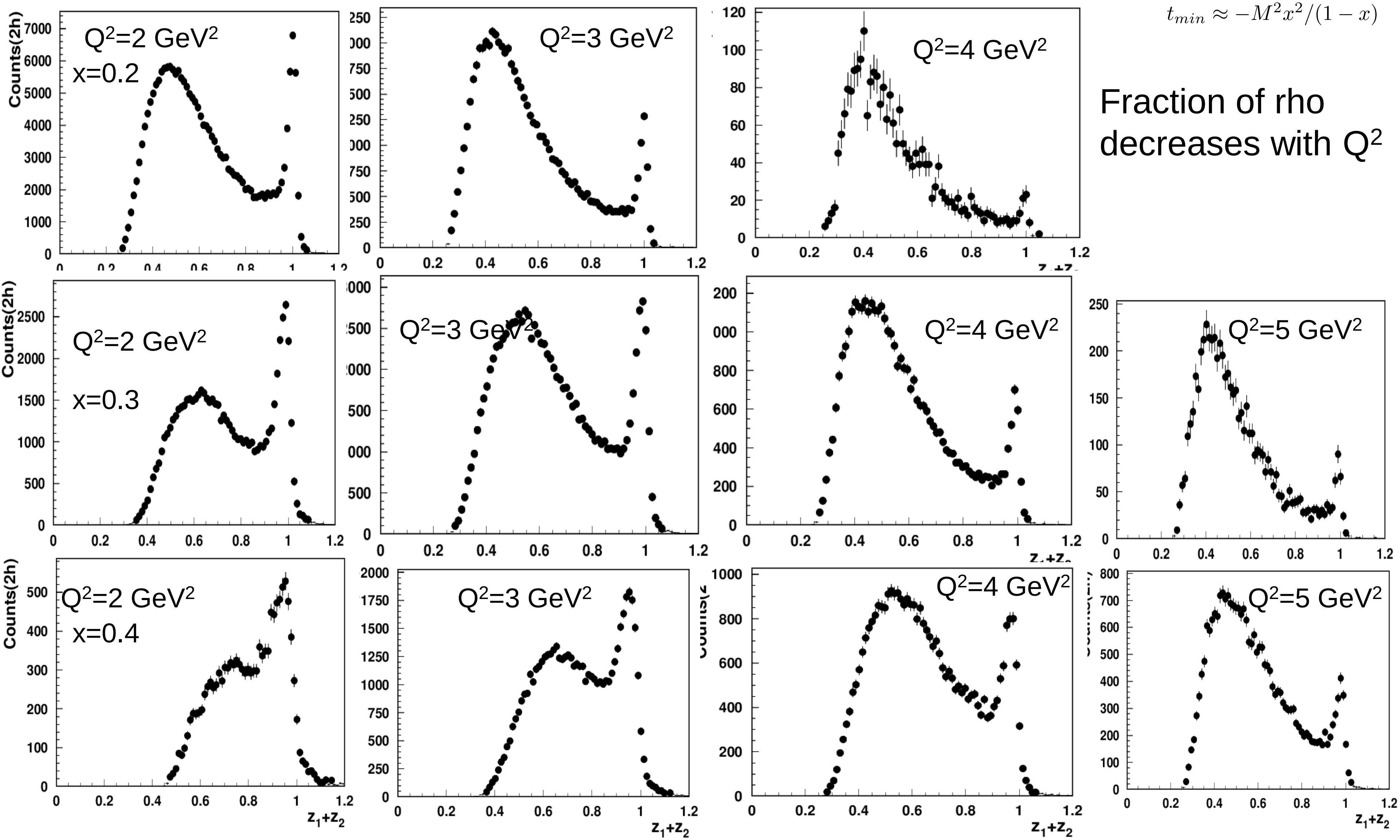


While the detected proton introduces slight difference in the kinematic distributions, the cut on the proton missing mass makes significant impact (clear at large z).

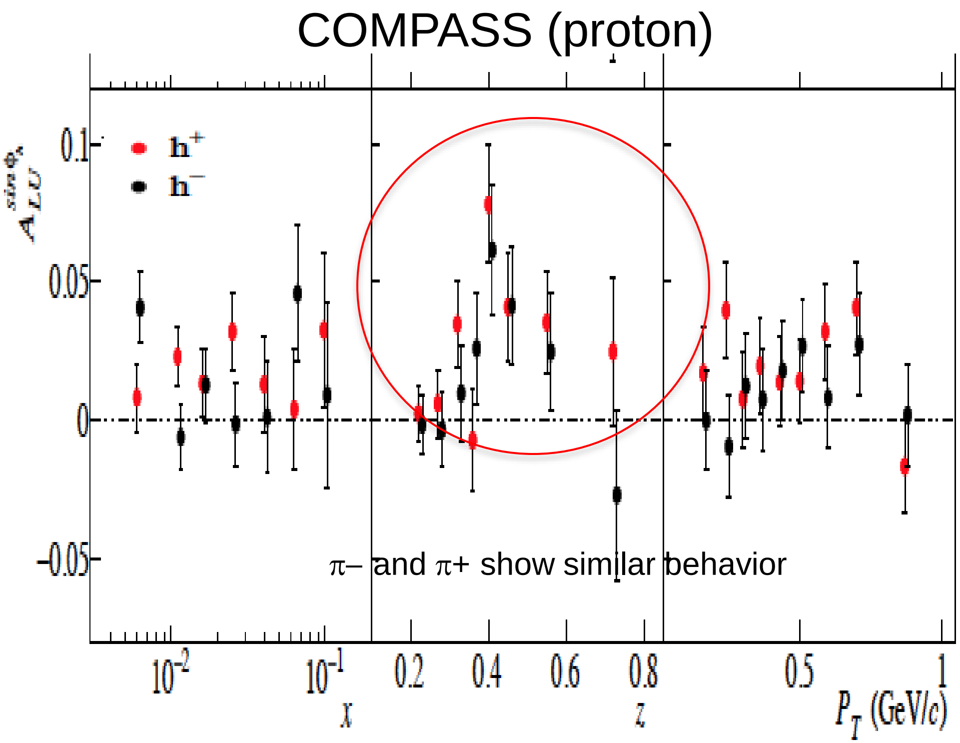
Exclusive dihadrons from CLAS12

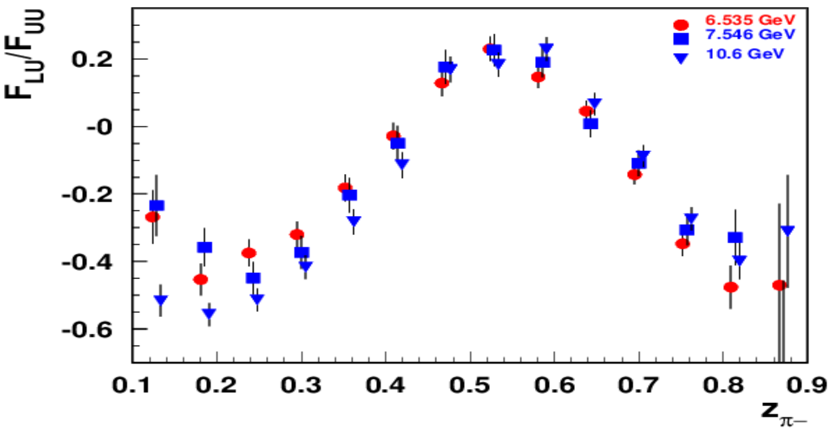
$t_{min} \approx -M^2x^2/(1-x)$

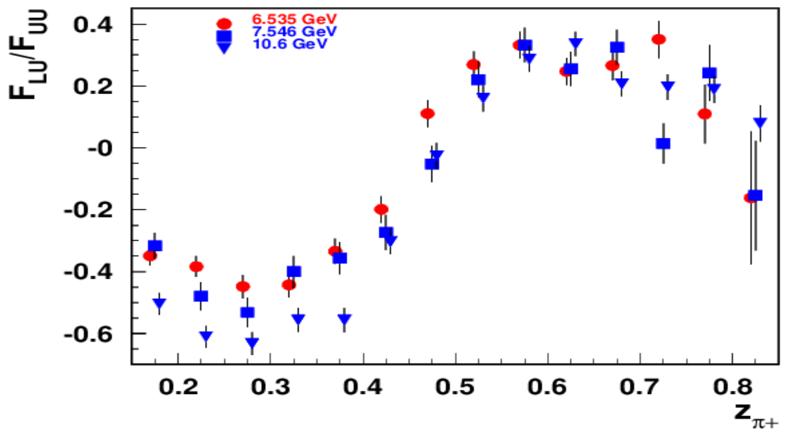
Fraction of rho decreases with Q^2



Exclusive ρ contributions to π: z-dependence



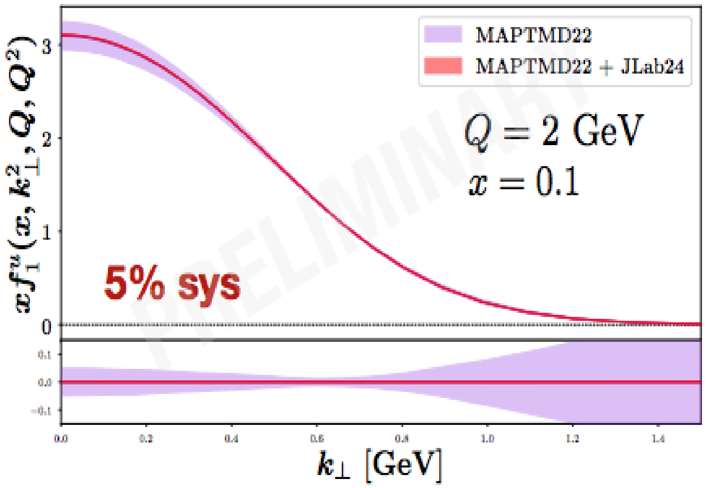


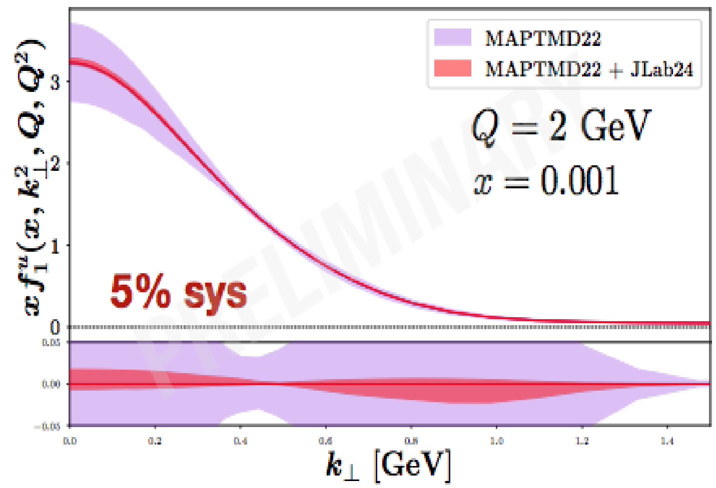


- Diffractive rho can change significantly observed pion SSAs
- The same sign and size of π+ and π- SSA indicates the rho0 may not be properly subtracted(require detailed MC studies, which require proper SDMEs)

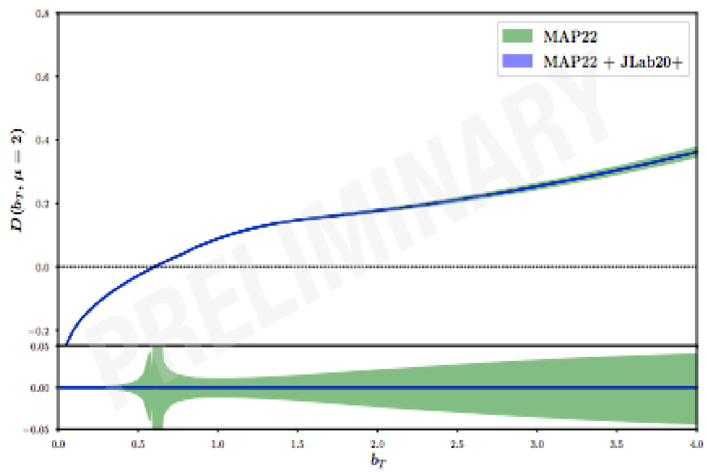
JLAB 24 IMPACT STUDIES ON TMDS

M. Cerutti, talk at Trento workshop Sep 2022





Collins-Soper kernel (driving TMD evolution)



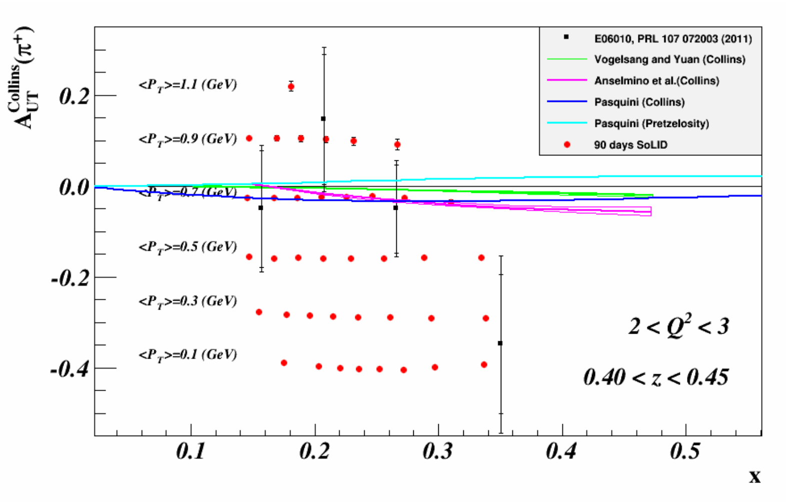
JLab 24 can have a very significant impact in reducing the errors on TMDs and their evolution

Parameterization used in extraction of TMDs will have practically unconstrained systematics

Transversity from SoLID

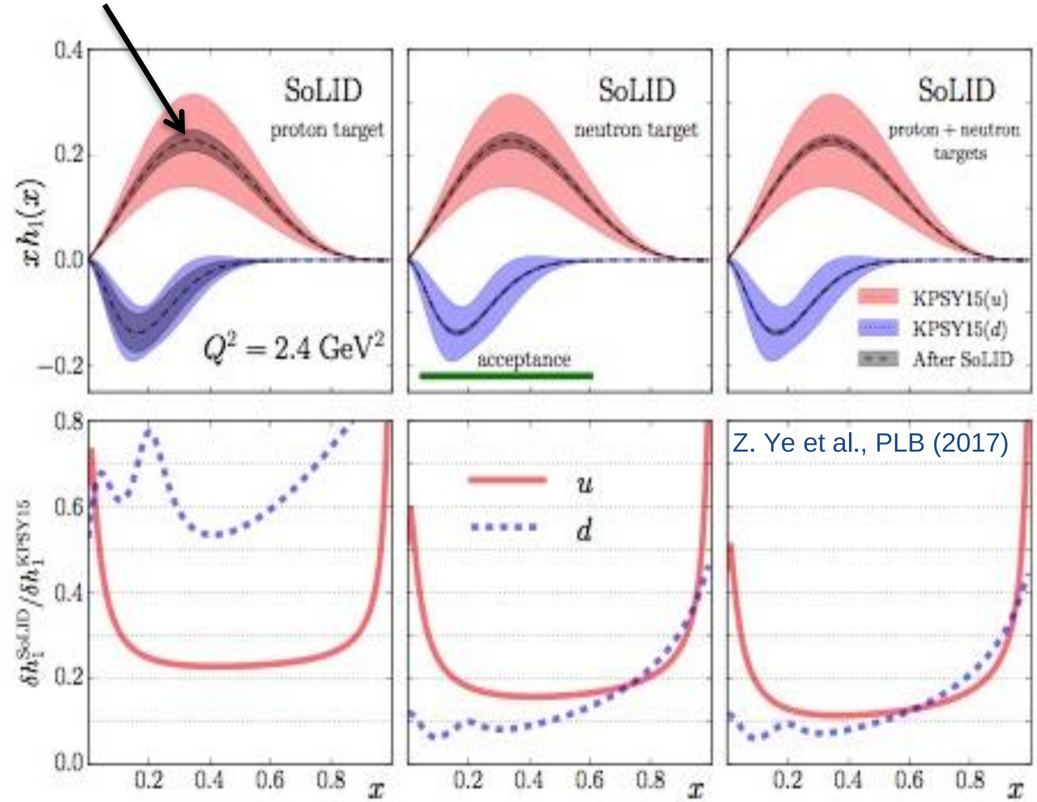
- Collins Asymmetries ~ Transversity (x) Collins Function
- SoLID with trans polarized n & p → Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, …) on impact study

Collins Asymmetries



P_T vs. x for one (Q^2, z) bin
Total > 1400 data points

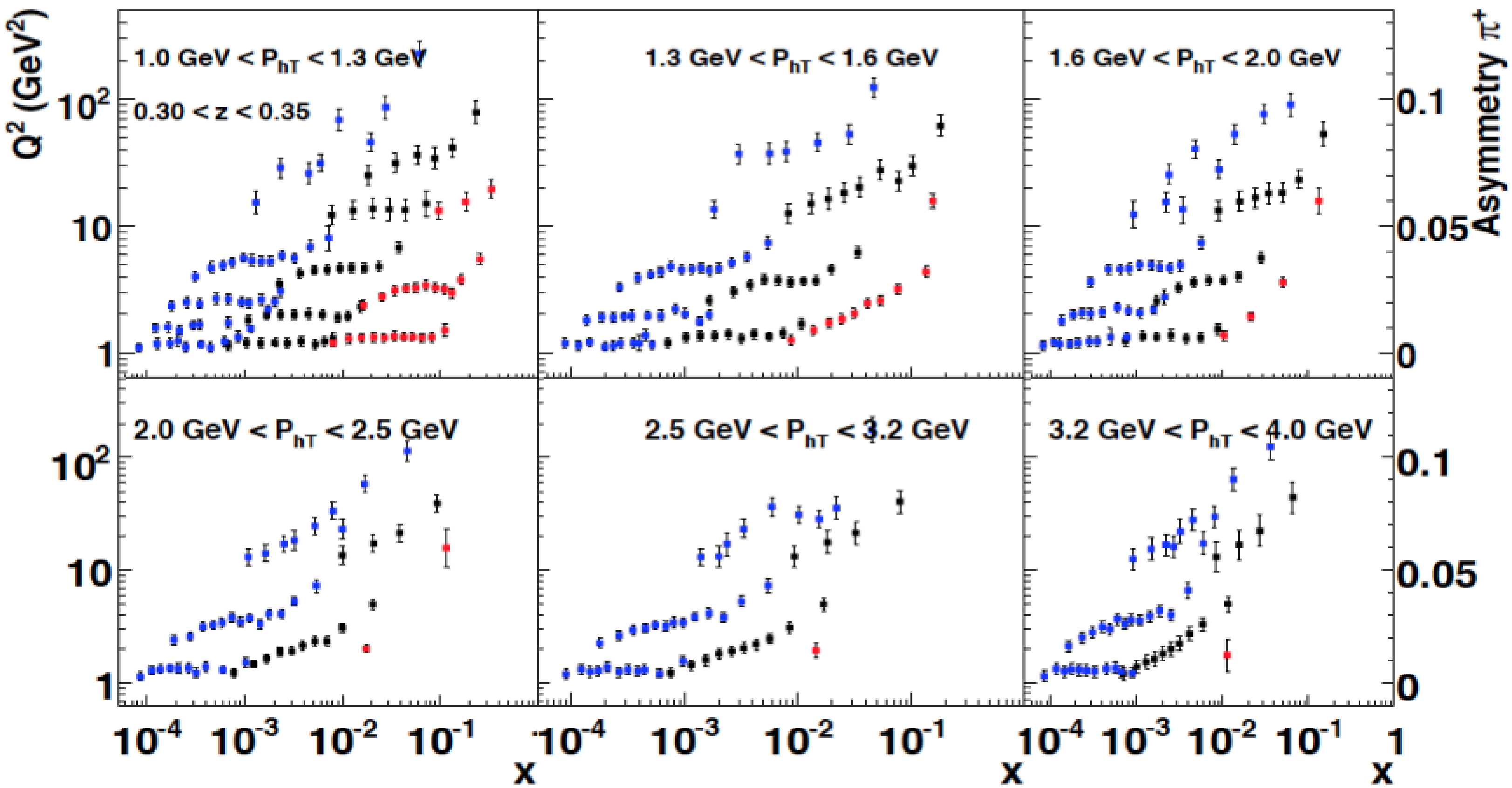
Significant improvement, but need to quantify the systematics from modeling (underlying assumptions)



Z. Ye et al., PLB (2017)

Projections for Sivers asymmetry

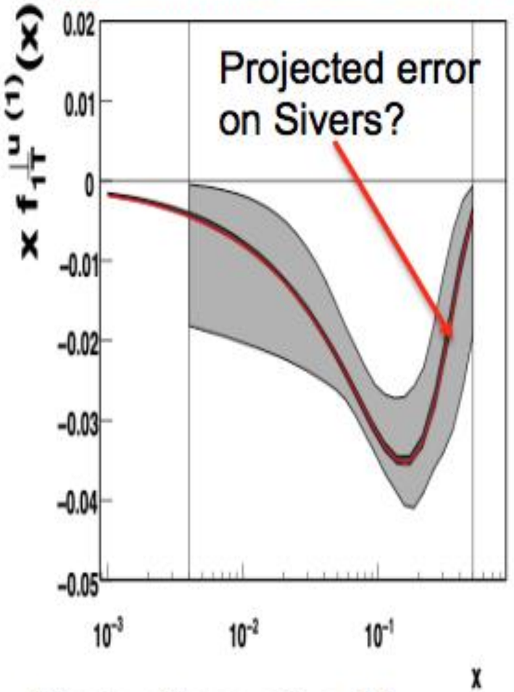
luminosity 120 fb^{-1} $\sqrt{s} = 140$ GeV, $\sqrt{s} = 50$ GeV and $\sqrt{s} = 15$ https://arxiv.org/pdf/1101.4199



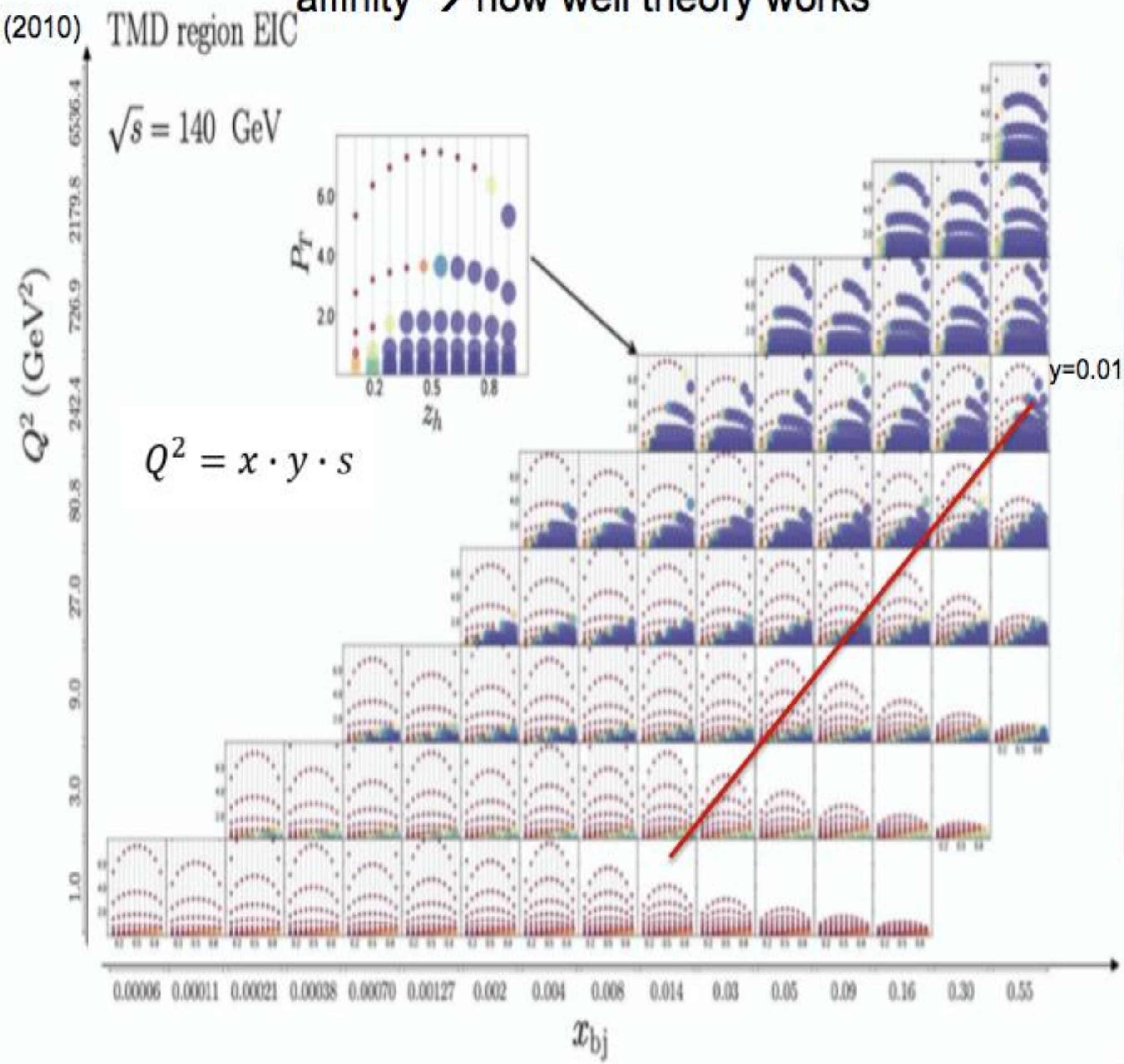
Study the transverse momentum dependence of the SSA for a wide range, we shall explore the transition from the perturbative region to the nonperturbative region

Projections from 1D to 4D

https://arxiv.org/pdf/1108.1713.pdf (2010)



“affinity”→ how well theory works



Projections should contain the size of the effect and the counts for a given interval of time

For SIDIS the x-section is defined by F_{UU}, for Sivers effect F_{UT}/F_{UU}

We can do even better!!!

https://arxiv.org/pdf/2103.05419

Quark Sivers and Collins measurements

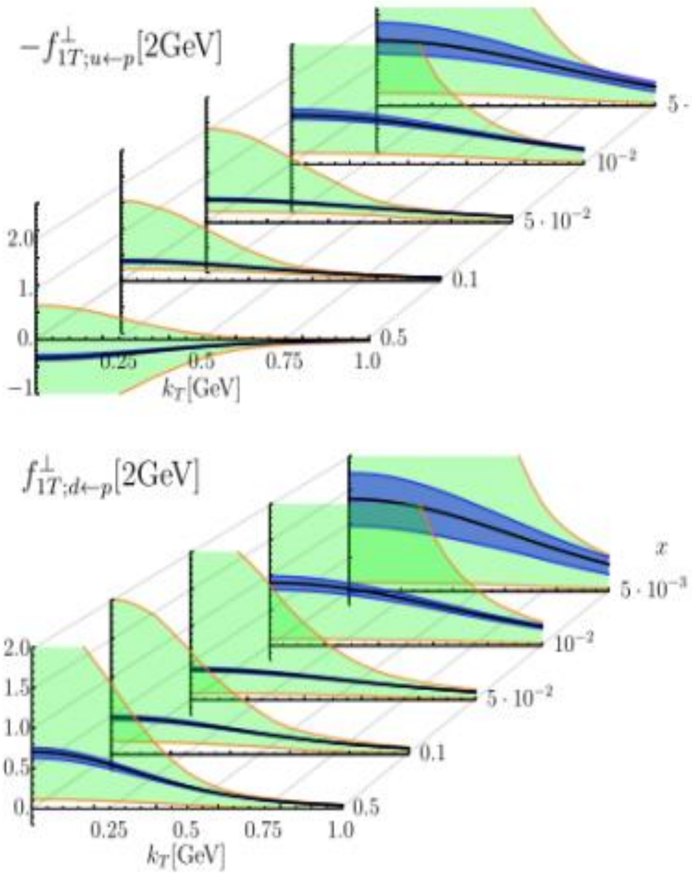


Figure 7.53: Expected impact on up and down quark Sivers distributions as a function of the transverse momentum k_T for different values of x, obtained from SIDIS pion and kaon EIC pseudodata, at the scale of 2 GeV. The green-shaded areas represent the current uncertainty, while the blue-shaded areas are the uncertainties when including the EIC pseudodata.

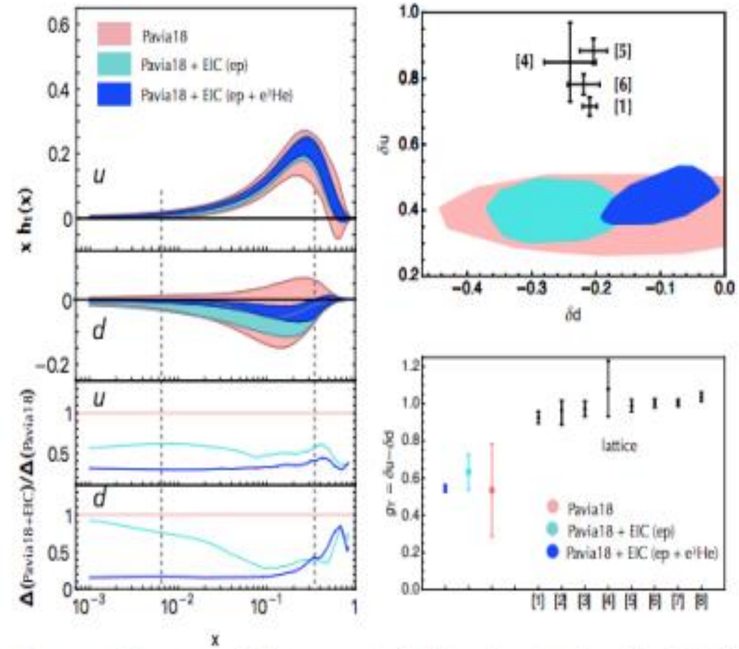


Figure 7.56: Left upper panel: The transversity $xh_1(x)$ as a function of x at $Q^2 = 2.4$ GeV^2 for up and down valence quarks. Uncertainty bands for 68% of all fitted replicas of data (see text). Pink band for the Pavia18 global extraction of Ref. [584], light-blue and blue bands when including EIC SIDIS di-hadron pseudodata from ep and e^3He collisions, respectively, with electron/ion beam energy 10×100 GeV; vertical dashed lines indicate the x-range covered by existing data. Left lower panel: ratio of the size of uncertainties with respect to the Pavia18 extraction, with same color codes as before. Right panel: impact of EIC SIDIS di-hadron pseudodata on the up quark (δu) vs. down quark (δd) tensor charges, and on the isovector tensor charge g_T (same color codes as before), in comparison with some recent lattice calculations, represented by black points and labeled as: [1] Ref. [528], [2] Ref. [585], [3] Ref. [586], [4] Ref. [587], [5] Ref. [527], [6] Ref. [588], [7] Ref. [589], [8] Ref. [590]. For more information on the EIC impact studies, see Ref. [591]

PAC48 comments and consequences

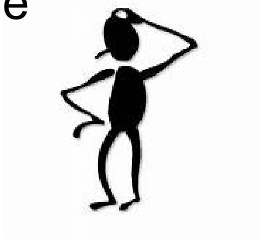
Statement:

"Several of this data covers the same x but higher Q^2 compared with RG C, which make the theoretical interpretation of the data significantly easier".

Meaning:

THE Theory will work at much higher energies also in the valence region→
no need in digging in "low energy" data where factorization is likely broken

May not be worth spending resources now, instead the 3D community can focus on analysis of measurements of GPDs and TMDs of quarks in the "bright future"



Consequences:

•JLab ("less equal" partner)

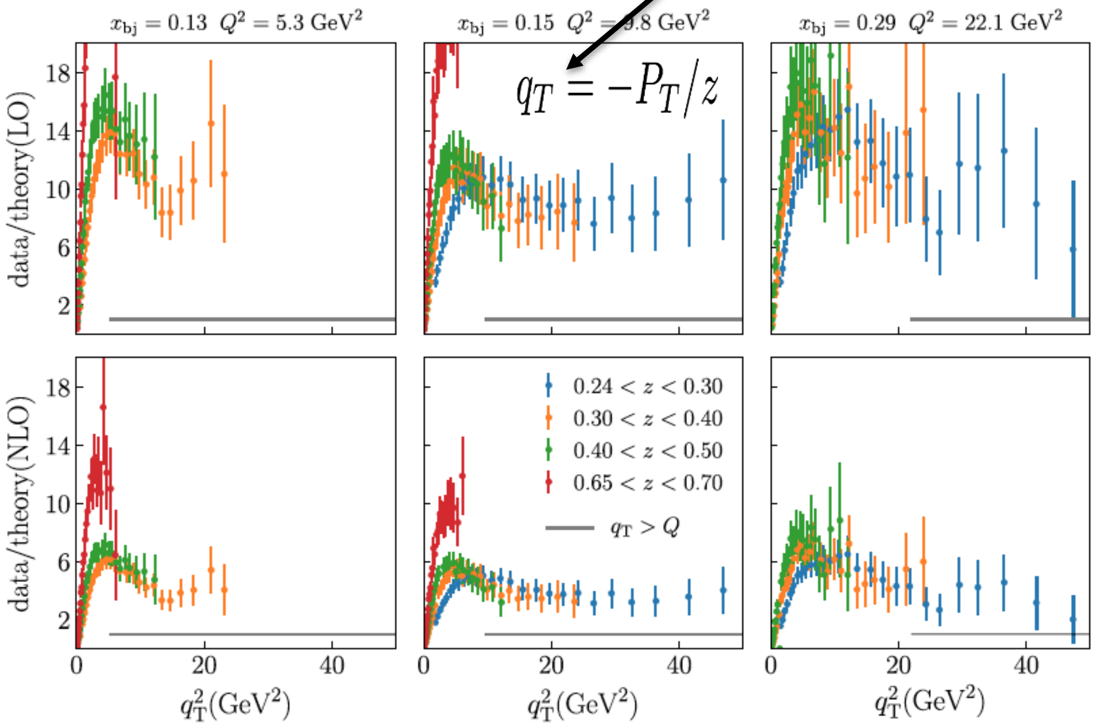
Redirection of resources to "Physics analysis of EIC data", pushing most SIDIS groups to be involved in EIC, with little focus on huge amount of precious data already accumulated or planned from incoming JLab experiments

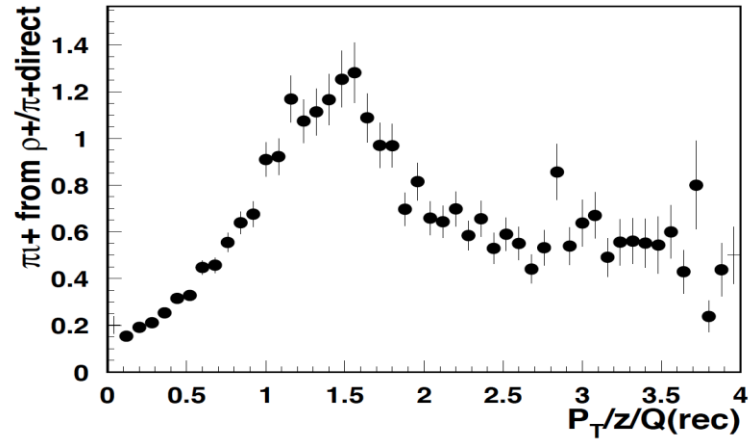
Does it matter if the pion comes from correlated pairs?

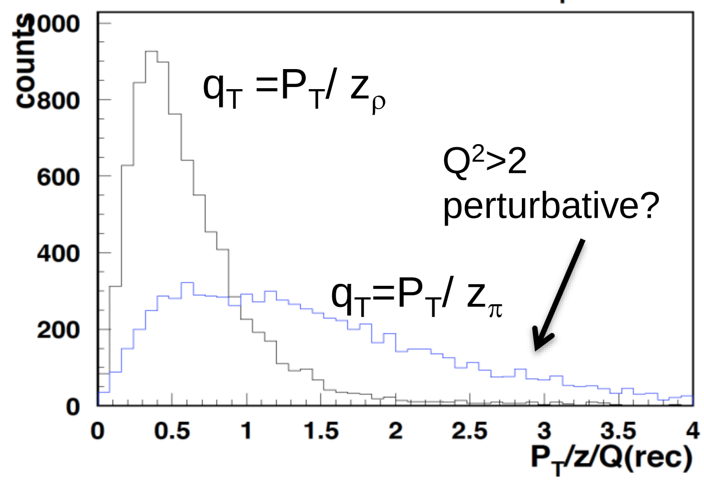
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

quark transverse momentum







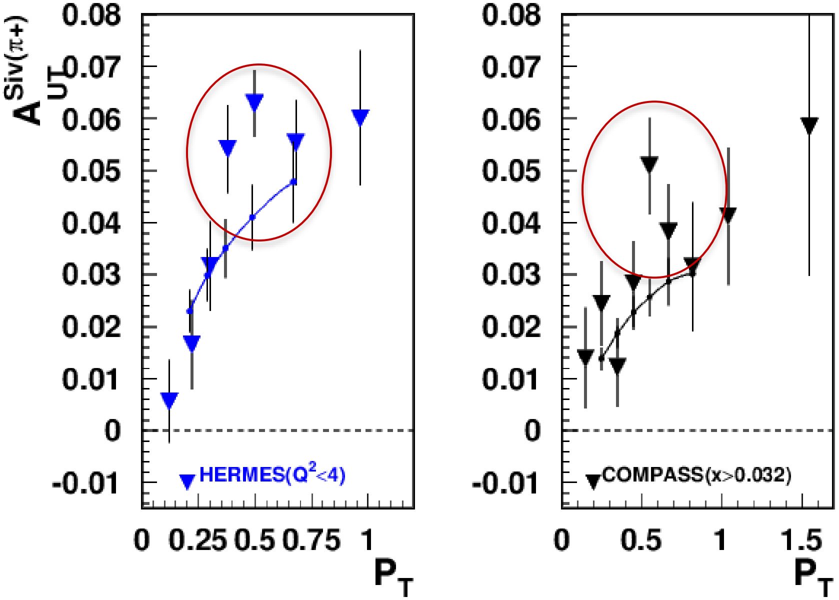
The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

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

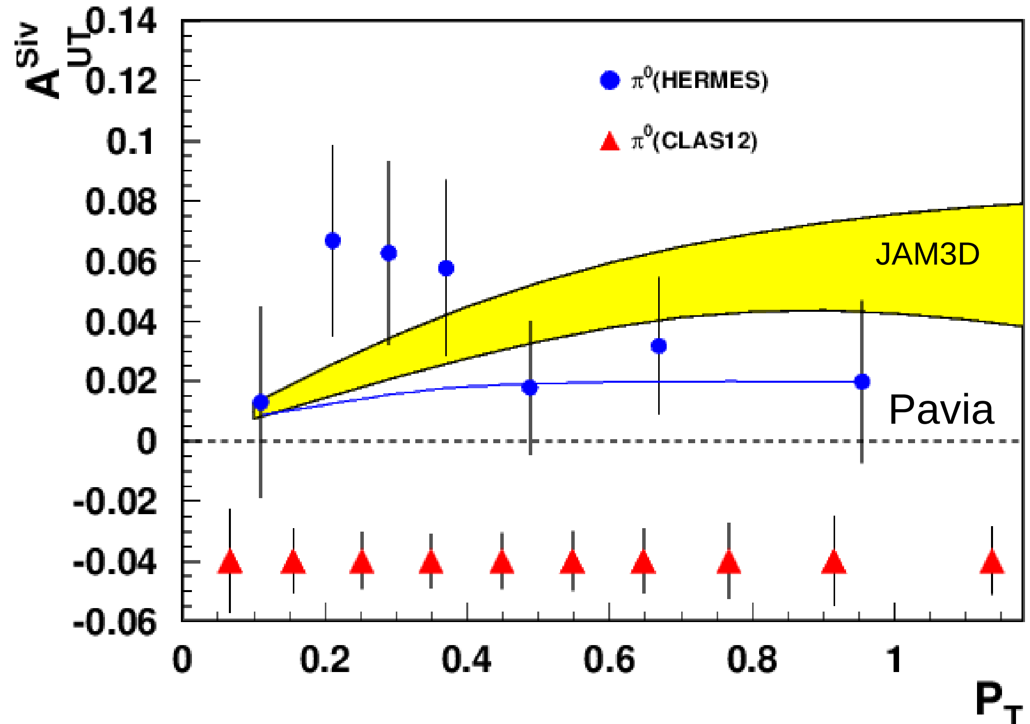
understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of q_T distributions

Sivers effect: P_T-dependence

Significant Sivers effect measured so far for charged hadrons



CLAS12 RGH experiment with Transversely polarized target



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

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

Impact of Radiative corrections

Proper RC involves the full x-section

$$\sigma^{ehX}_{Rad}(x,y,z,P_T,\phi,\phi_S) \to \sigma^{ehX}_0(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

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

Simplest rad. correction

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

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

Ex. Correction to SSA

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

Studies of rhos at COMPASS

Selection of exclusive ρ^0 sample for SDMEs analysis

$\mu\, p \rightarrow \mu'\, \rho^0\, p'$, with $\rho^0 \rightarrow \pi^+ \pi^-$

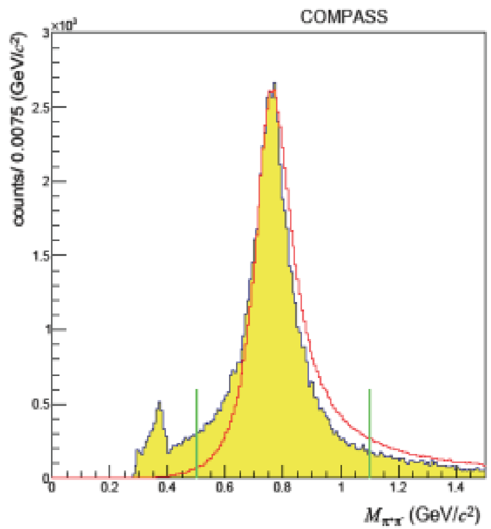
Topological selection: scattered muon
+ two hadrons with opposite charges

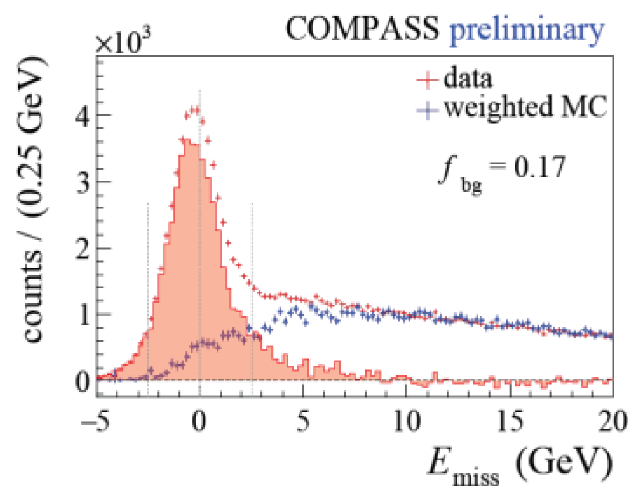
$1 < Q^2 < 10$ GeV/c^2
$W > 5$ GeV
$0.01 < p_T^2 < 0.5$ (GeV/c)^2
$0.1 < y < 0.9$
$\nu > 20$ GeV
$|E_{miss}| < 2.5$ GeV

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

After all selections and cuts
≈ 52 200 evts

Recoil proton detector
not included in selections

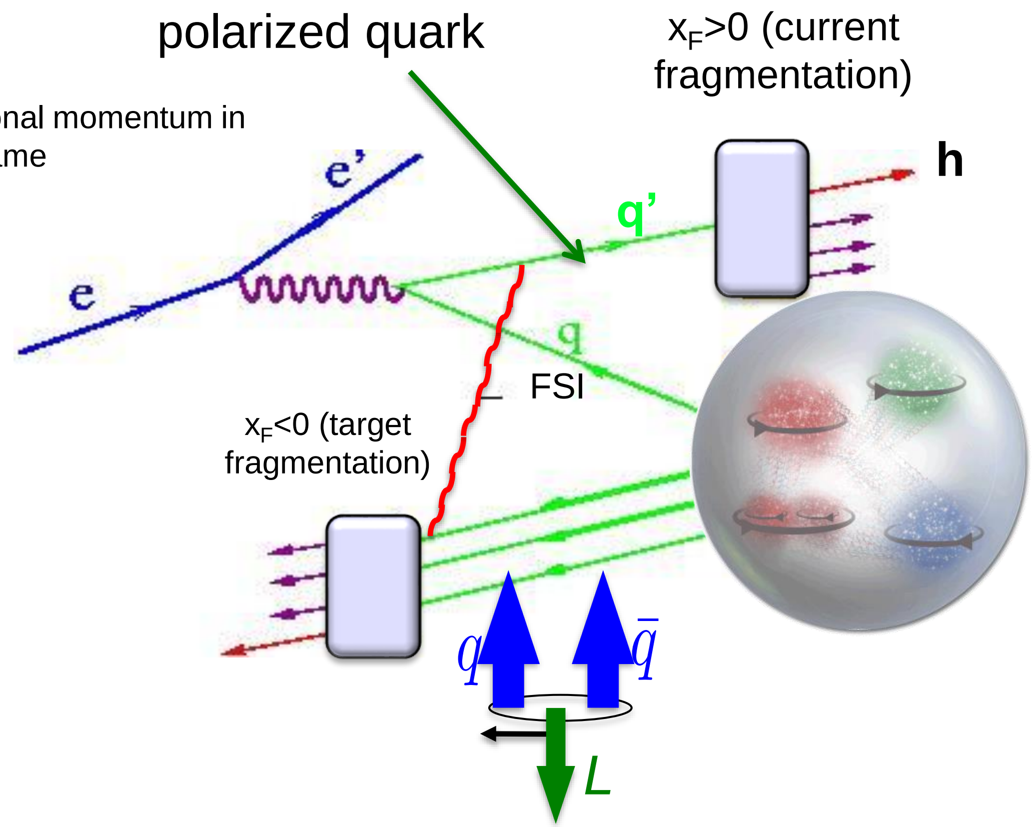




tails may be significant, also because of RC

Exclusive hadron production in hard scattering

x_F – fractional momentum in the CM frame



Quark qluon correlations described by higher twist 3D PDFs

Twist3 GPDs

M.Constantinou

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	$\mathcal{H}_{2T}, \mathcal{H}_{2T}$	$\mathcal{H}'_{2T}, \tilde{\mathcal{H}}'_{2T}$	$\mathcal{E}_2, \tilde{\mathcal{E}}_2, \mathcal{E}'_2, \tilde{\mathcal{E}}'_2$

M.Engelhardt

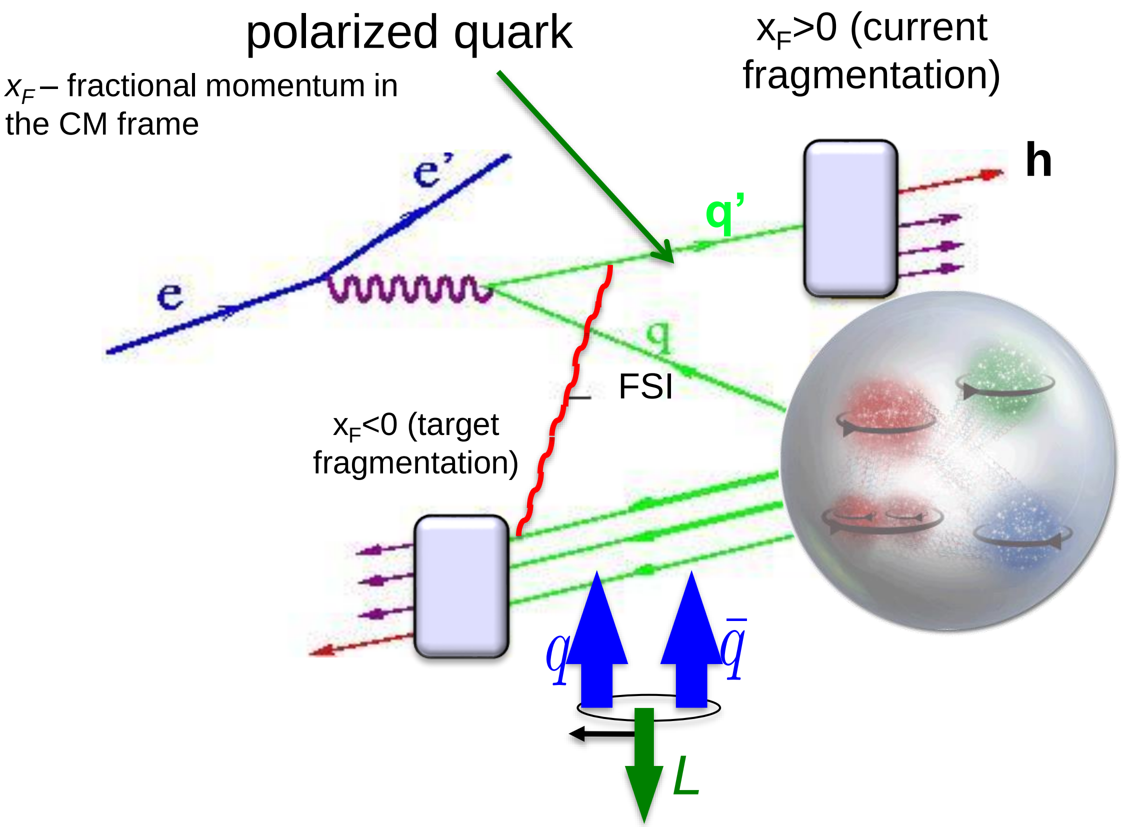
OAM

$$-\int dx\, x\, \tilde{E}_{2T}(x,0,0) = L_z^q + 2S_z^q$$

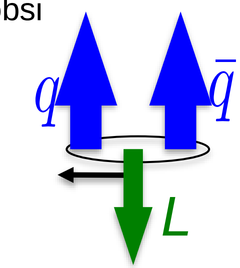
Lorce&Pasquini, arXiv:1208.3065

Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles in exclusive limit

Hadron production in hard scattering: SIDIS



X. Artru & Z. Belghobsi



Higher Twist TMDs

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

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

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