Connecting the phenomenology of 3D PDFs with experiment

Resummation, Evolution, Factorization 2024

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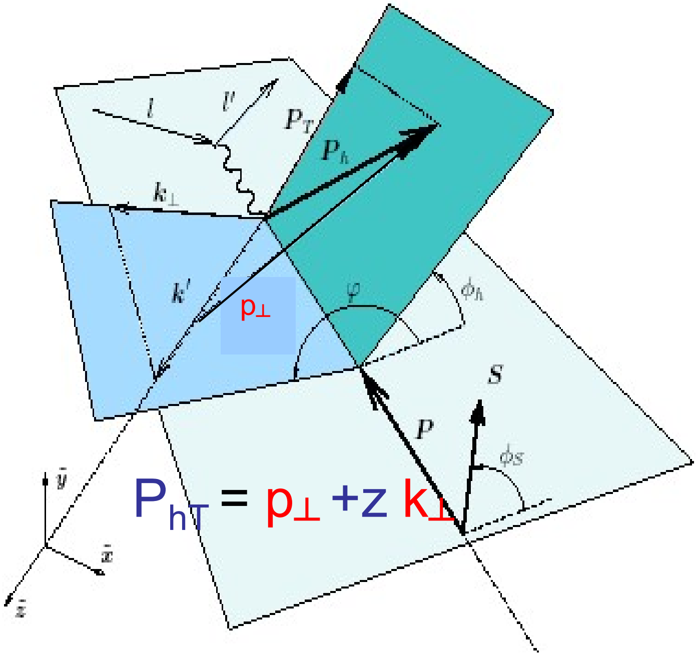
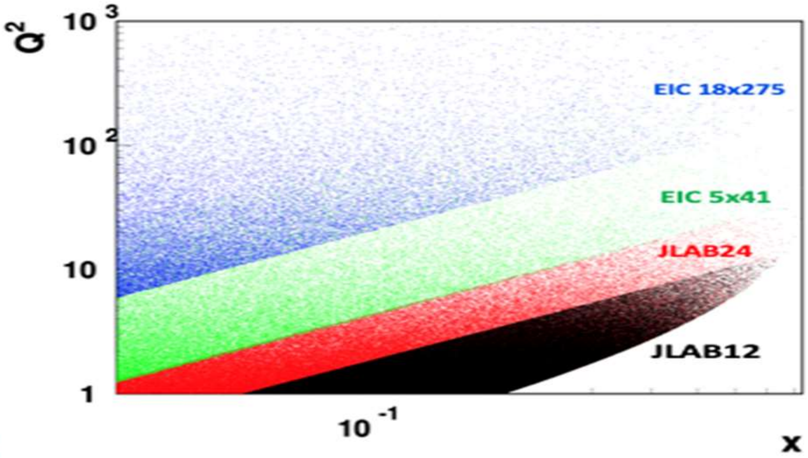
- What is SIDIS?
- Understanding of physics backgrounds→ need for multidimensional measurements critical for JLab and beyond, EIC, in particular
- Interpretation of leptoproduction requires studies of hadronic correlations going from ep→e'πX to ep→e'$\pi\pi$X and ep→e'pπX
- New SIDIS observables
- Simulations and validation procedures (AI tools instead of fits to get 3D PDFs, from data,…)
- Summary

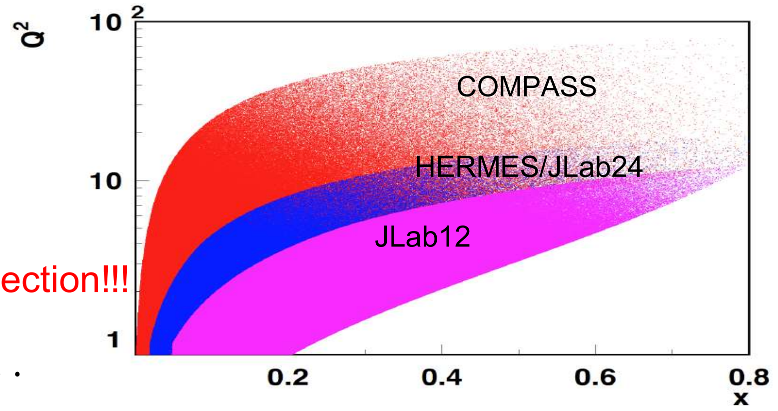
SIDIS kinematical coverage and observables



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

EIC

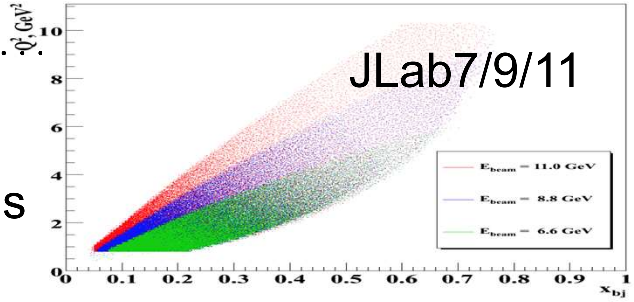




Experiments measure the full azimuthal dependence of the cross section!!!

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

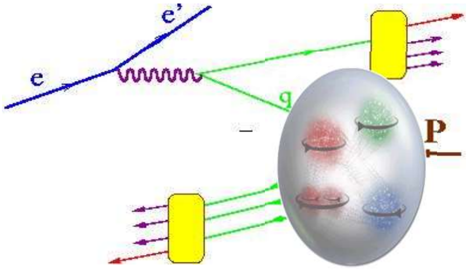
$$+\epsilon F_{UU,L} + |S_\perp|[F_{UT}^{\sin\phi-\phi_S}\sin(\phi-\phi_S) + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S] + \ldots$$



- 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

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.

- The leptoproduction, with hadrons detected in the final state, from experimental point of view, in siplest 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

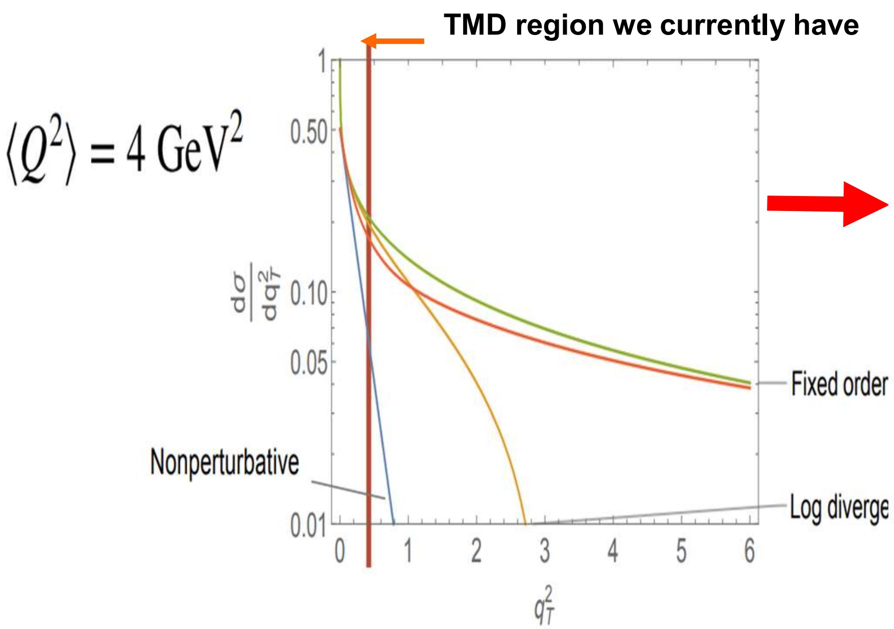
- To get a realistic physics interpretation, it is required to separate certain structure functions, and possible certain contributions to structure functions experimentally in a given multidimensional space, with controlled systematics

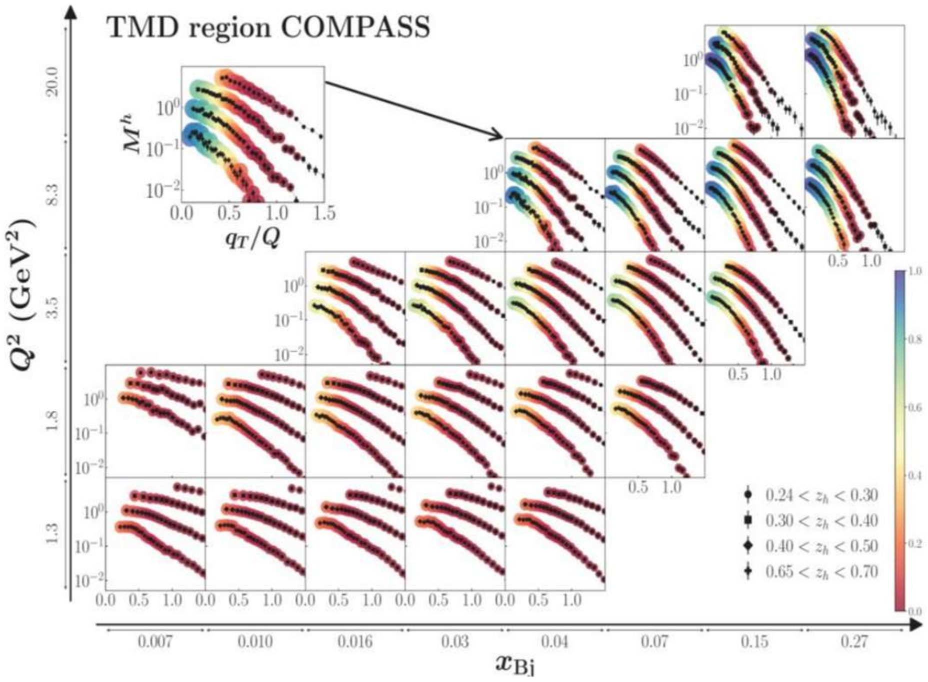
SIDIS of ehX: TMD theory problems

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

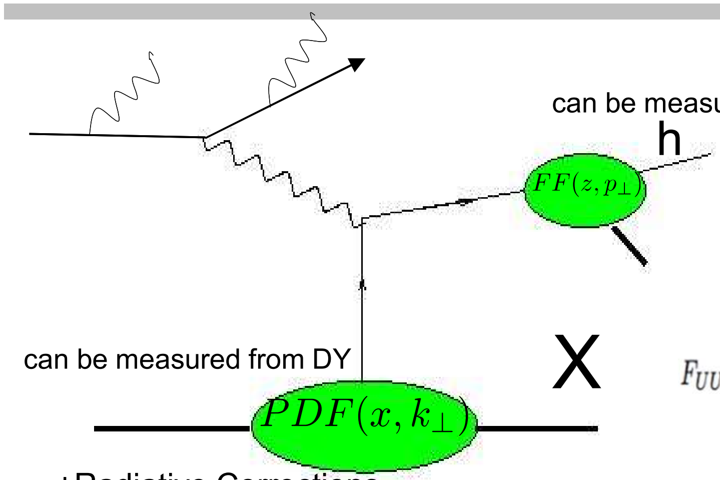
What data input exactly drives down the nonperturbative part?



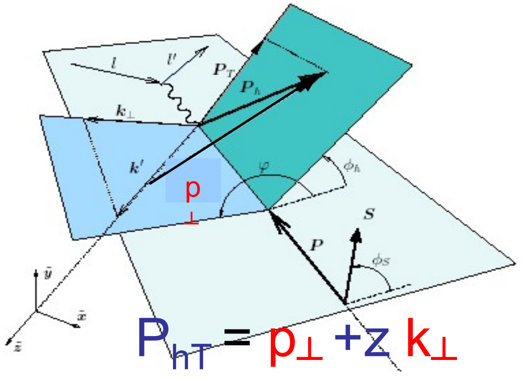


How far in P_T or q_T extends the TMD region is defined by contributions from dominant non-perturbative (blue) and perturbative parts

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

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

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

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

hard part

Factorization 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 in JLab: comments from “theory” experts

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 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]

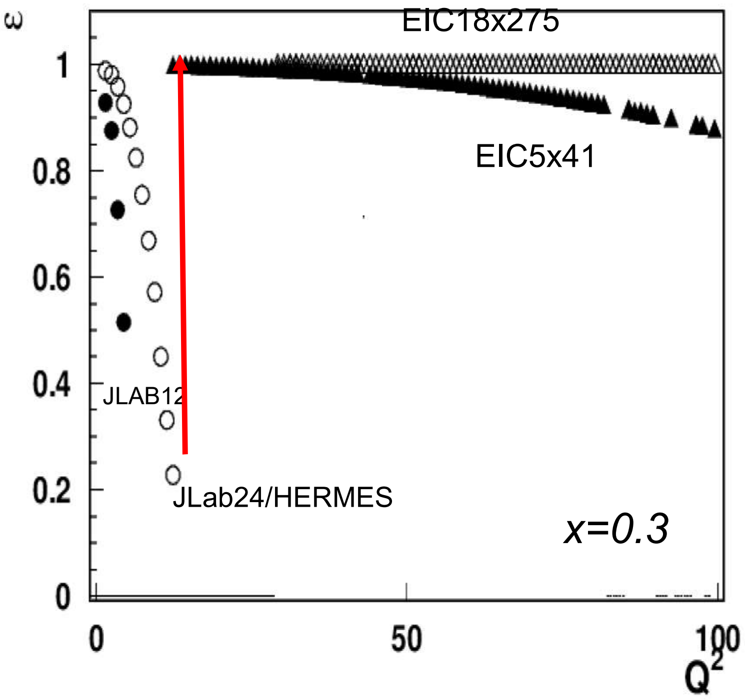
Addressing PAC/theory comments

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

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

1) Longitudinal photon

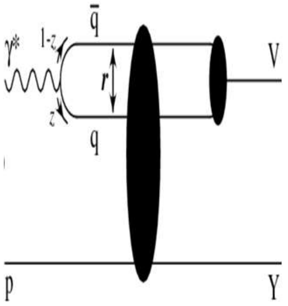
- For a given x&Q^2 the contribution from longitudinal photon increases at higher energies (ex. at EIC 5 times bigger at Q^2~10, x~0.3 than at JLab)
- JLab studies of impact of longitudinal photons critical for interpretation of polarized SIDIS, including EIC data



Addressing JLab PAC/theory comments

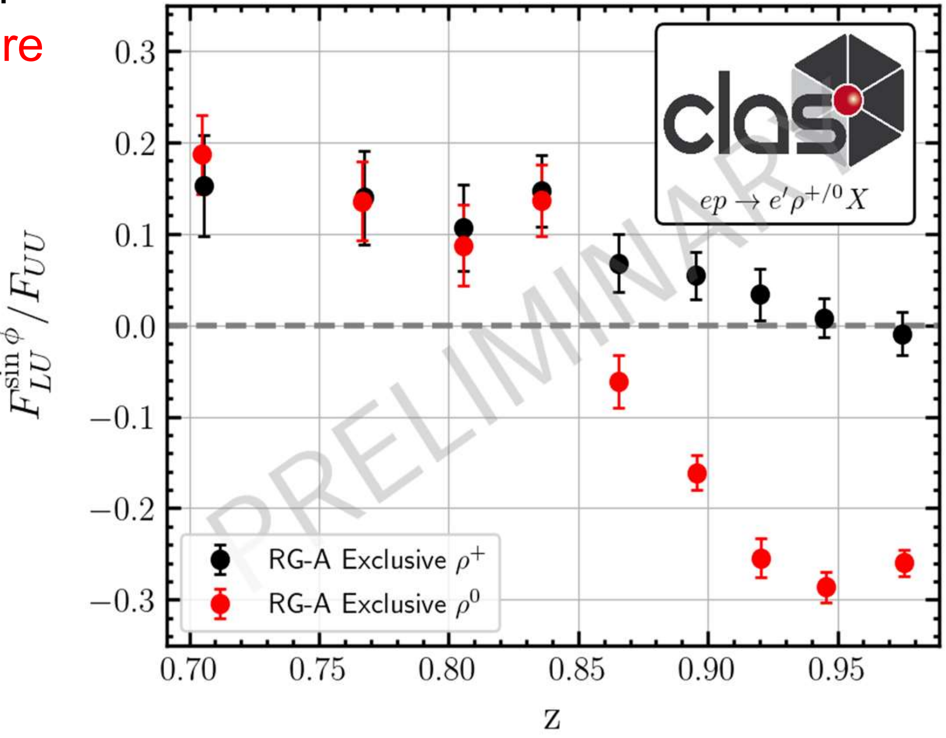
What exactly are identified so far sources of “factorization breakdown” in SIDIS and where is the evidence that “few GeV” matters?

2) Diffractive VMs (ρ^0)



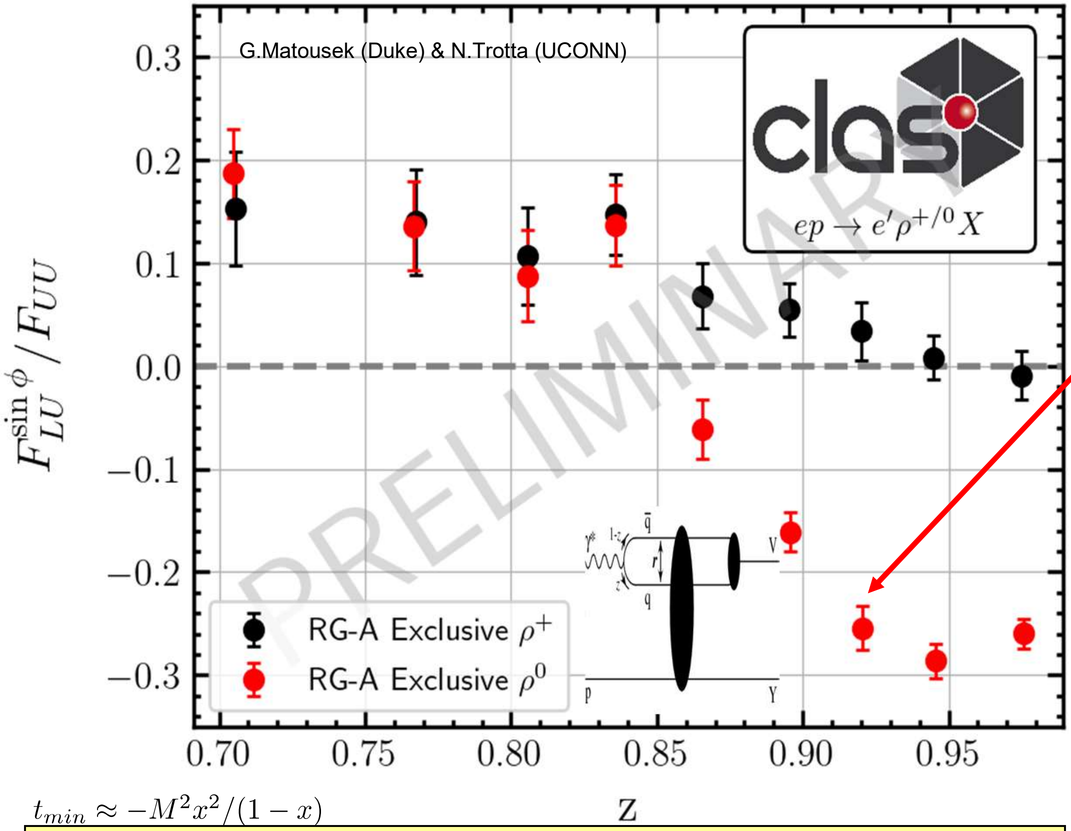
Comparison with exclusive rho+, clearly indicates the kinematics where the “diffractive rho0” shows up (increases at higher energies)

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 !!!

Quark-gluon correlations: impact of VMs



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

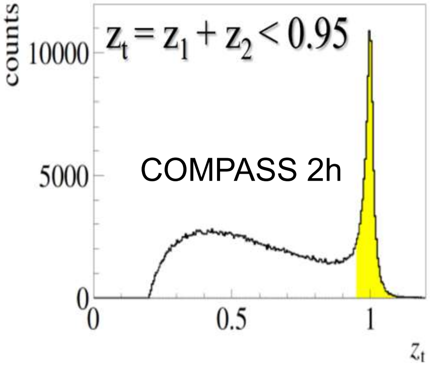
- At large z (small t) those rhos are longitudinally polarized, likely coming predominantly from longitudinal photons
- A_{LU} sign change can define the dominating process!!!
- At large x the diffractive processes are suppressed by the minimum t

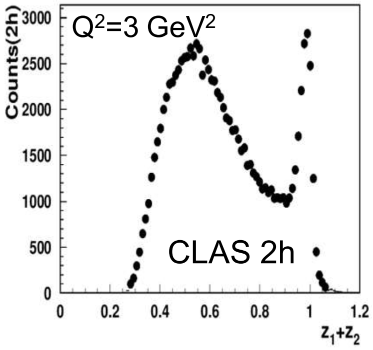
Different dynamical contributions

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

longitudinal photons?

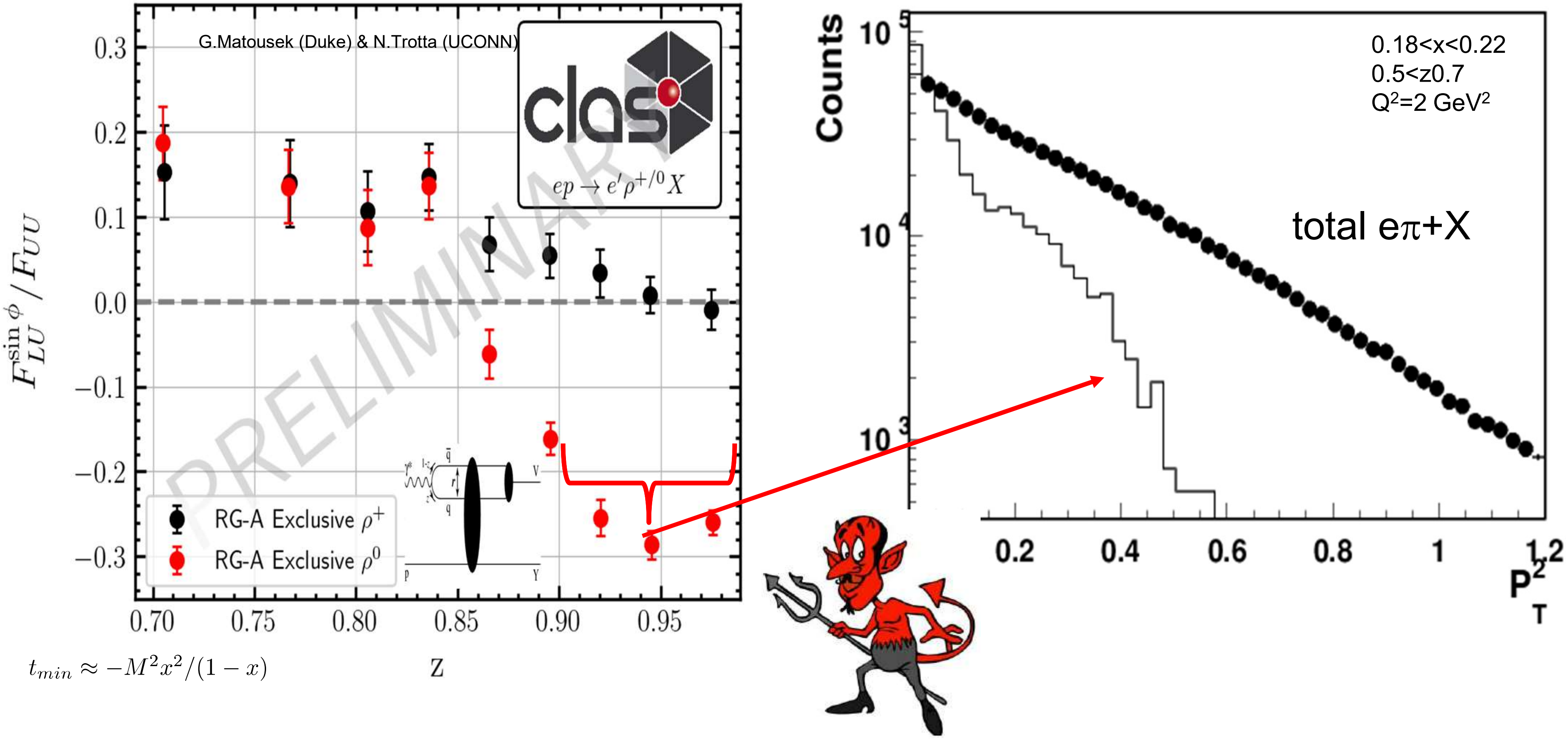
Is it going away at high energies?





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

Contributions of “diffractive rho0s” in SIDIS

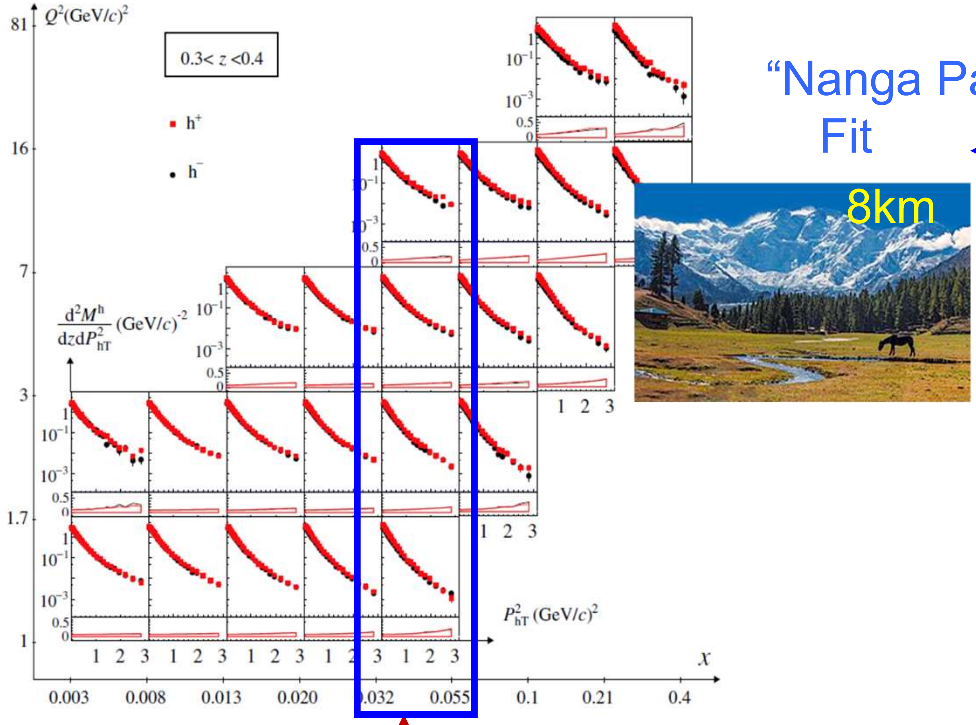


The “diffractive” rho contributes at lower P_T values in the inclusive pion sample

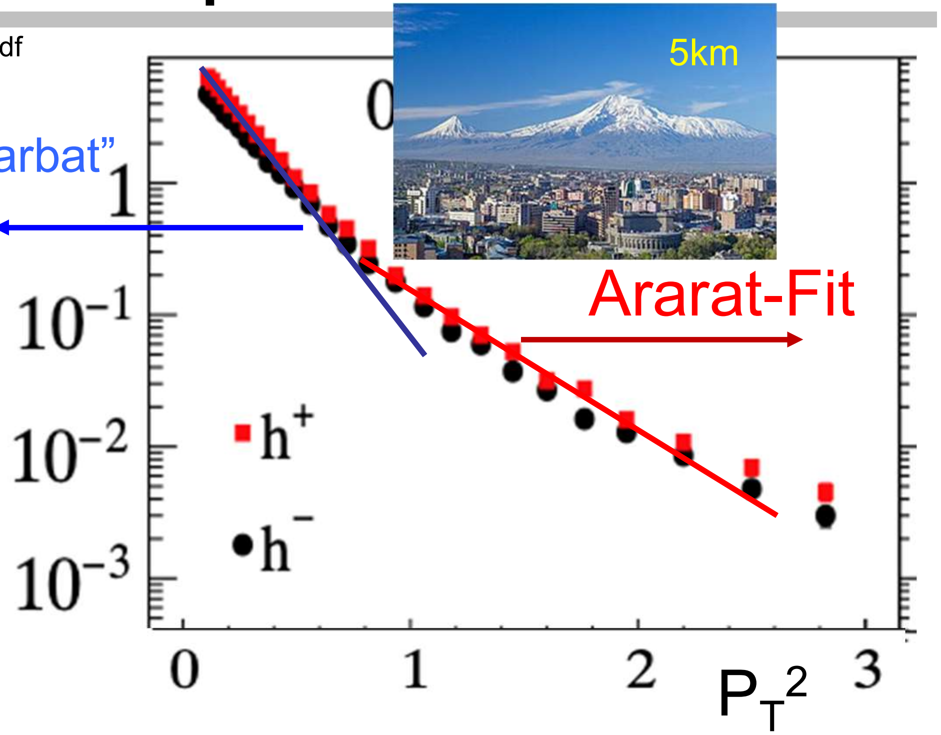
Estimated ~20% contributions from rho, consistent with ~10% in DIS

q_T-crisis or misinterpretation

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



“Nanga Parbat” Fit



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)

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 SSA ~10 times higher

2) Standard SIDIS (eN→eπhX) within the full accessible kinematics, corrected for acceptance and RC, measured in the multidimensional space, with subtracted in multi D-bins 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→eππX) within the full accessible kinematics, allowing clear eliminiation of rho0 contributions using cuts on missing masses of epX or eππX (“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 MX to understand the bias,

Theory should be able to evaluate the bias from the presence of an additioonal hadron

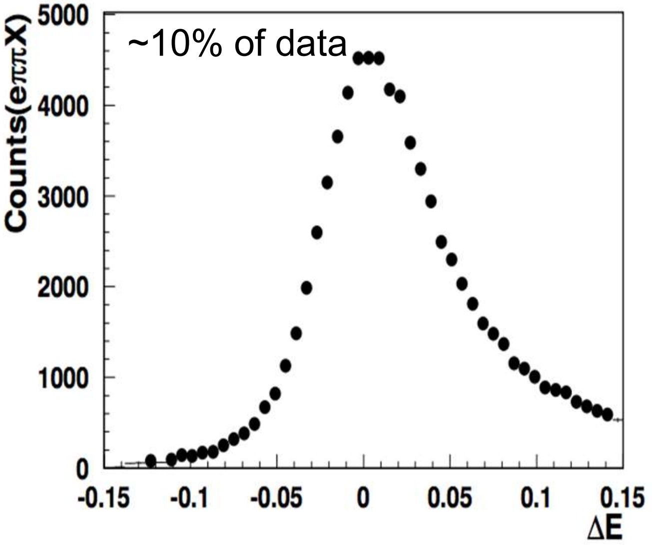
Understanding exclusive rhos and SDME validations

Exclusivity condition defined by the missing Energy:

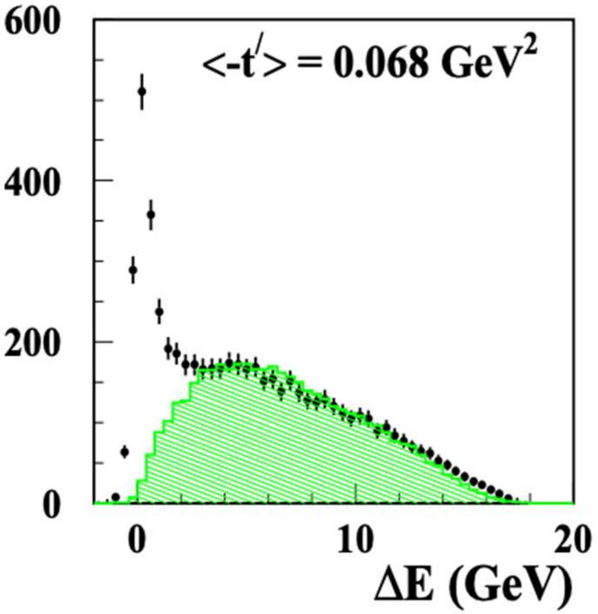
$$M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2$$

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

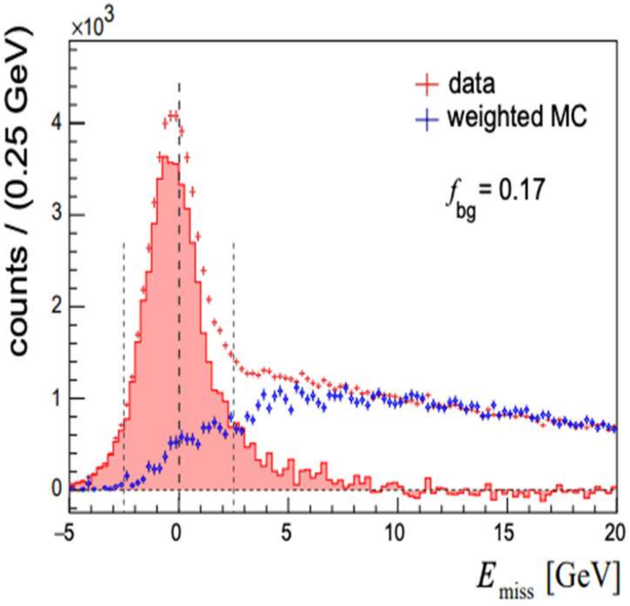
CLAS12 (width <0.1GeV)



HERMES(width ~0.6GeV)



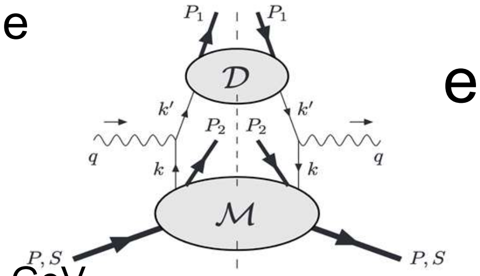
COMPASS(width ~2GeV)



- Guarantying the “exclusivity” requires good resolutions (get worse at higher energies
- All distributions have have tails, indicating the RC may not be negligible
- Extraction of SDMEs, will require validation in the multi-D space

Unique ability to measure target fragments

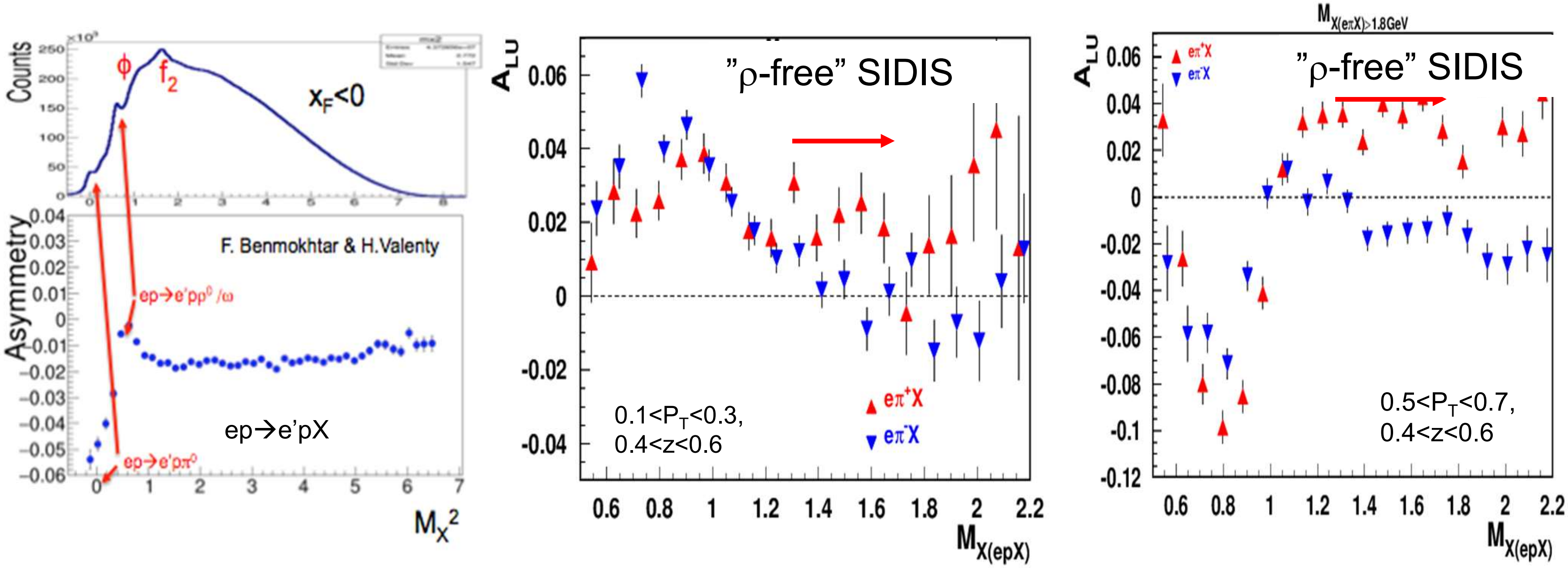
Detection of the target nucleons (B2B SIDIS) provide a powerful tool to control the contributions in CFR



ep→e’pπX

3 processes:

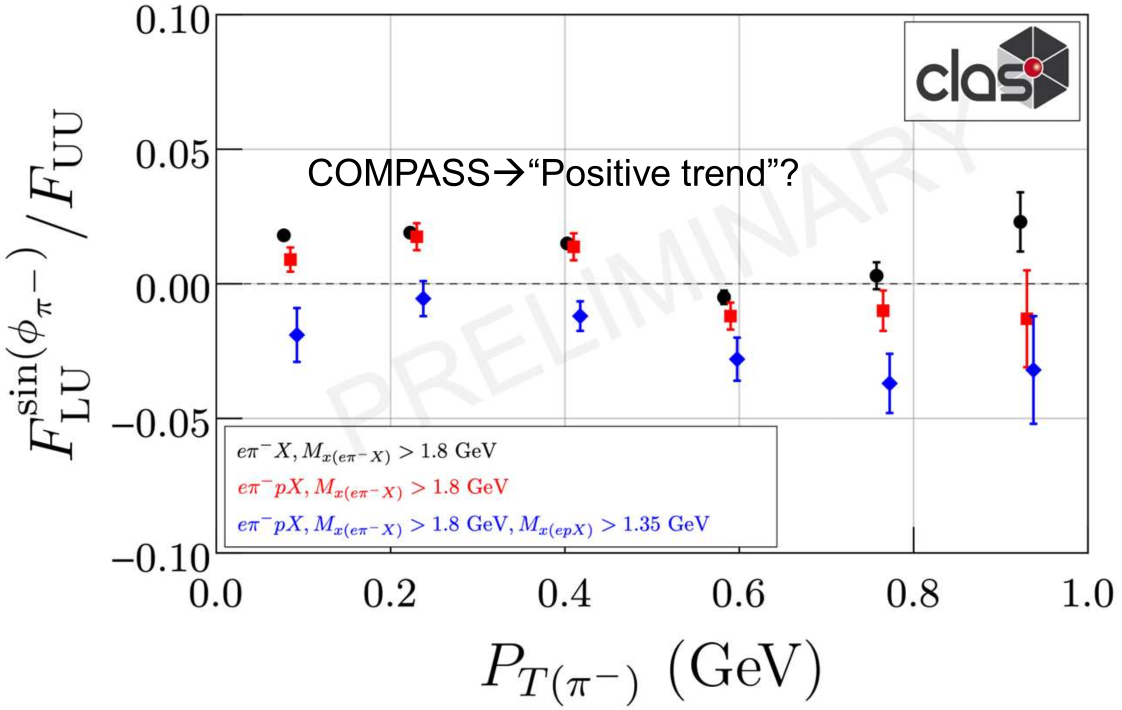
ep→e’hX (regular SIDIS)
ep→e’NhX (SIDIS+ TFR nucleon, B2B SIDIS)
ep→e’NhX (SIDIS+ TFR Nucleon + cut on M_X(ep→e’NX)>1.35 GeV



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



COMPASS→“Positive trend”?

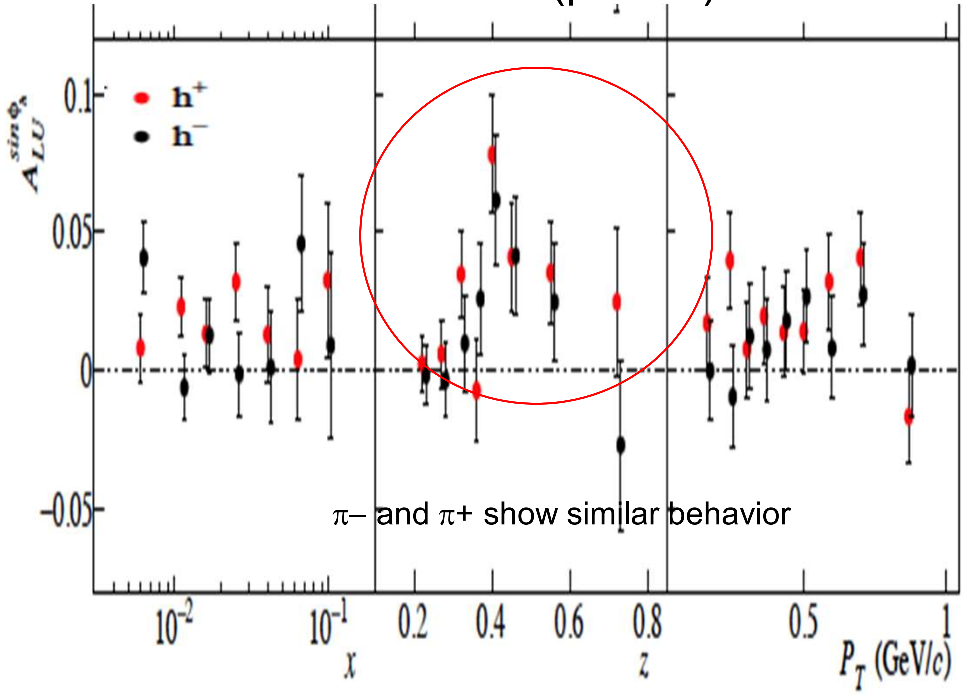
All point include
M_X(e’π-X)>1.8 GeV
→out of resonance region

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

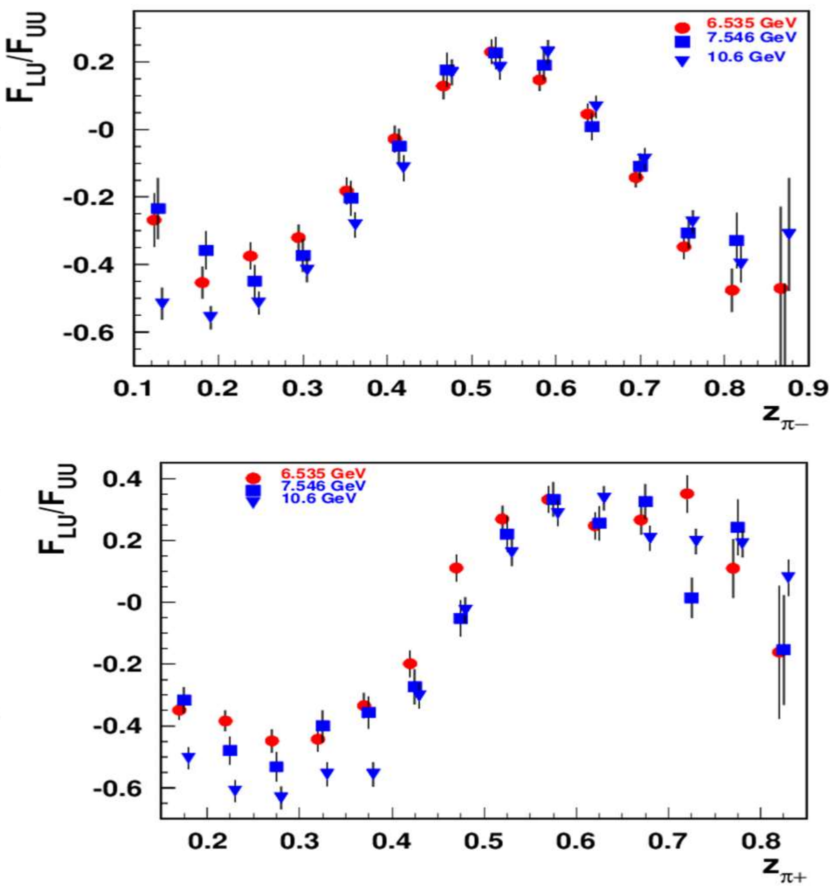
- **Exclusive rho-0s have very significant impact on kinematic dependences of SIDIS SSAs, in particular at low P_T**
- **While VM contributions are ~20% in multiplicities in SSA they can be >100%**
- **Detection of the target proton introduces much smaller bias on the inclusive charged pion SSA, than the exclusive rho contributions**

Exclusive ρ contributions to π: z-dependence

COMPASS (proton)



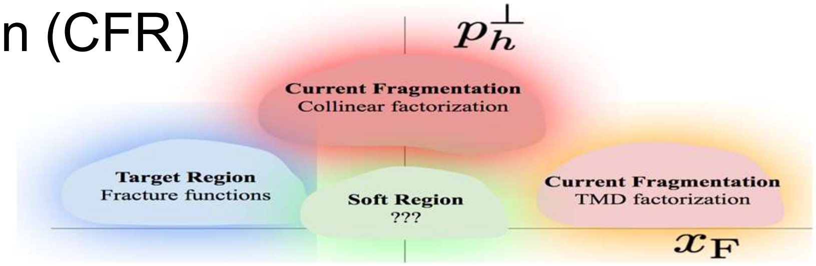
$\pi-$ and $\pi+$ show similar behavior

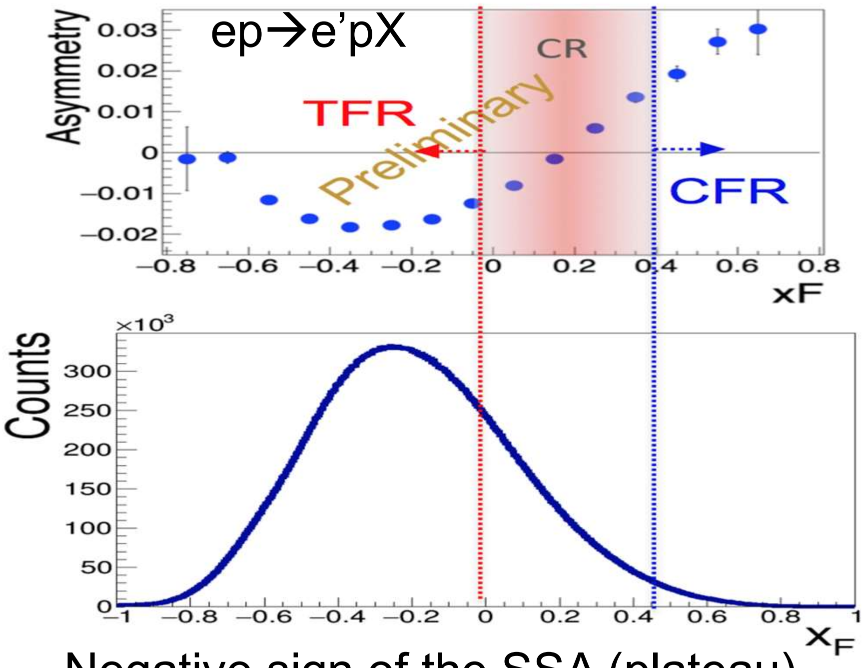


- Diffractive rho can change significantly observed pion SSAs
- The same sign and size of π+ and π- SSA indicates the rho0 may not be properly subtracted(require detailed MC studies, which require proper SDMEs)

Beam SSAs as a tool to separate regions and contributions

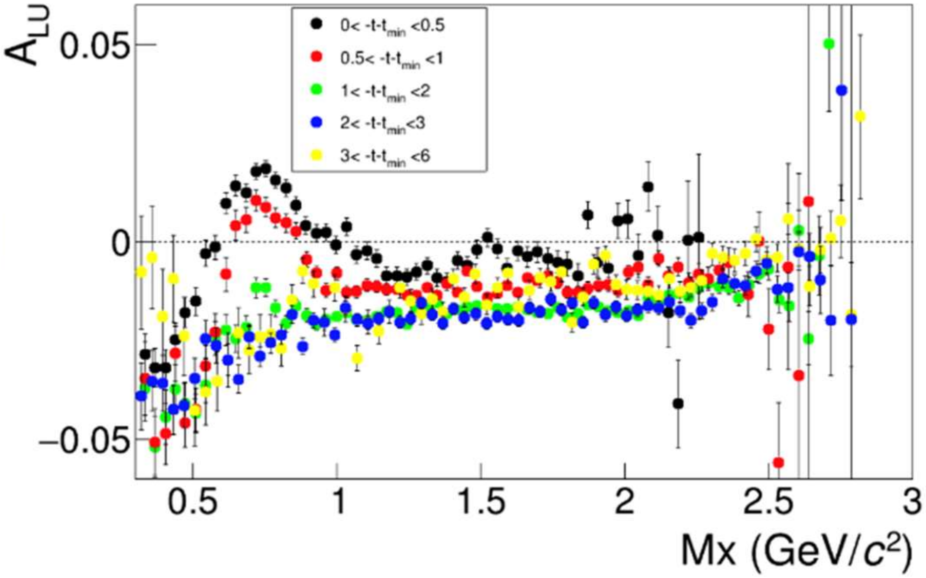
3) Separating Target Fragmentation Region TFR from Current fragmentation region (CFR)





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

F. Benmokhtar & Duquesne U.

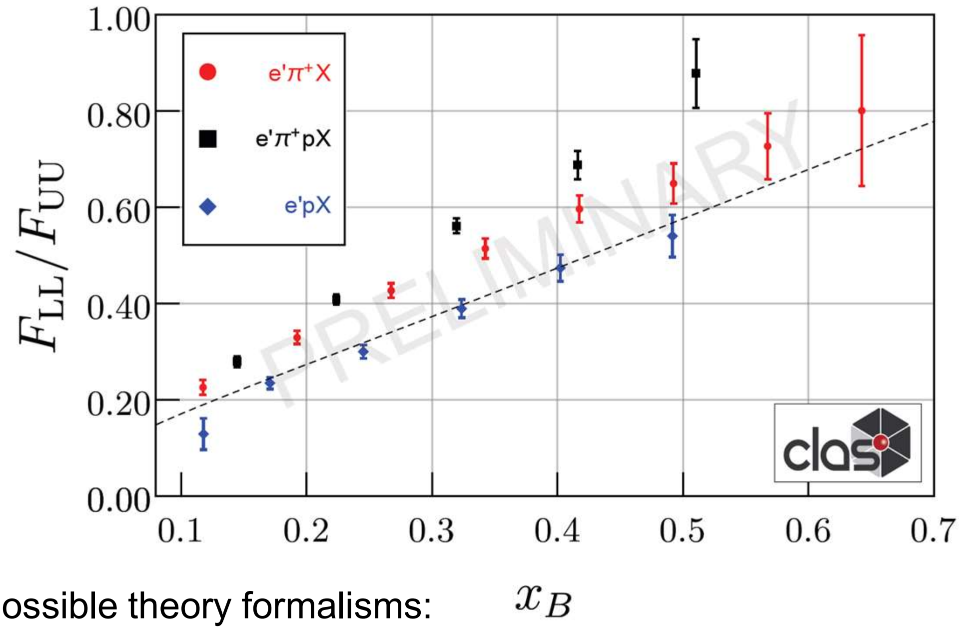


Major difference only for protons at small t!

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

Longitudinally polarized quarks in B2B SIDIS

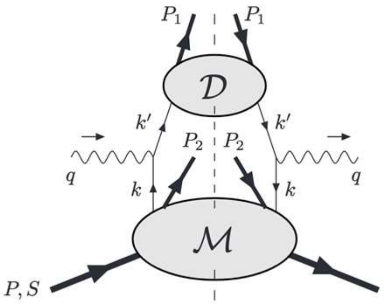


Possible theory formalisms:

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

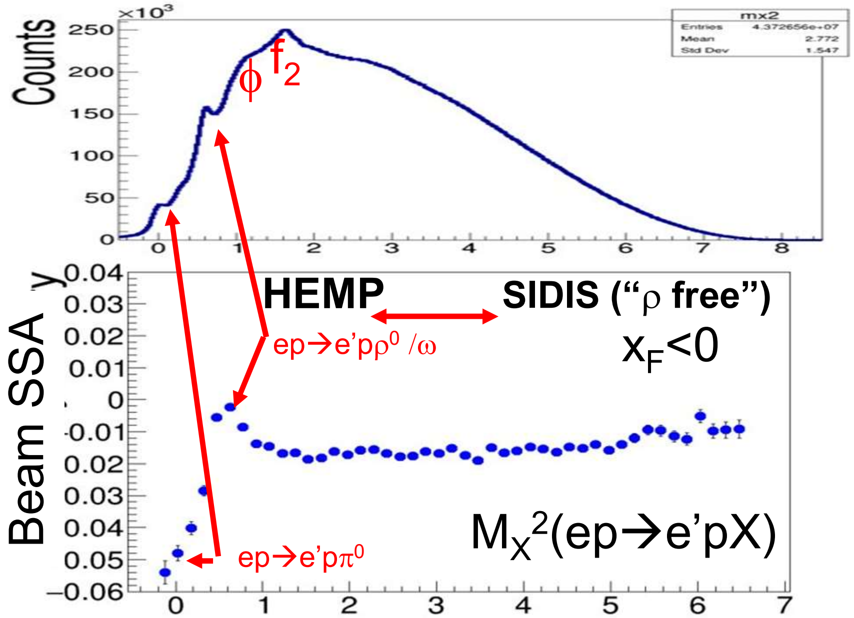
- Differences in A_{LL} , due to different weights on PDFs can provide additional info on impact of possible ingredients
- Measurements of A_{LL} for ρ^0 indicate very small values, and can be one of the reasons for higher A_{LL} with protons with a M_X cuts above 1.5 GeV (excluding exclusive ρ^0)

ep→e'pπX



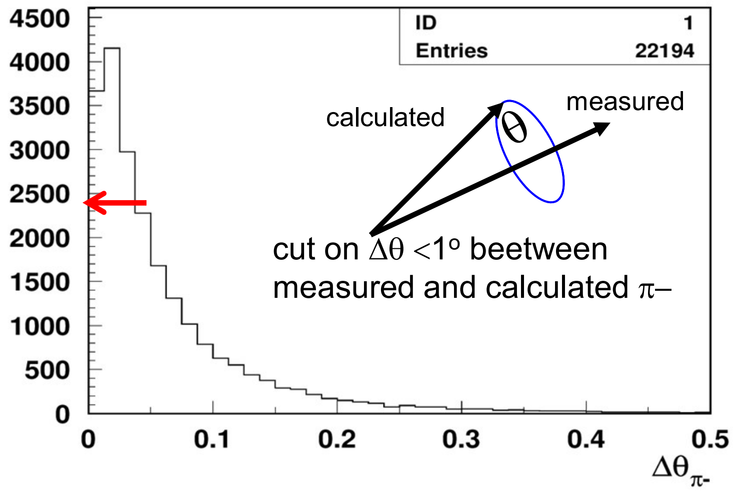
N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp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

Detection of proton allows elimination of exclusive rho!

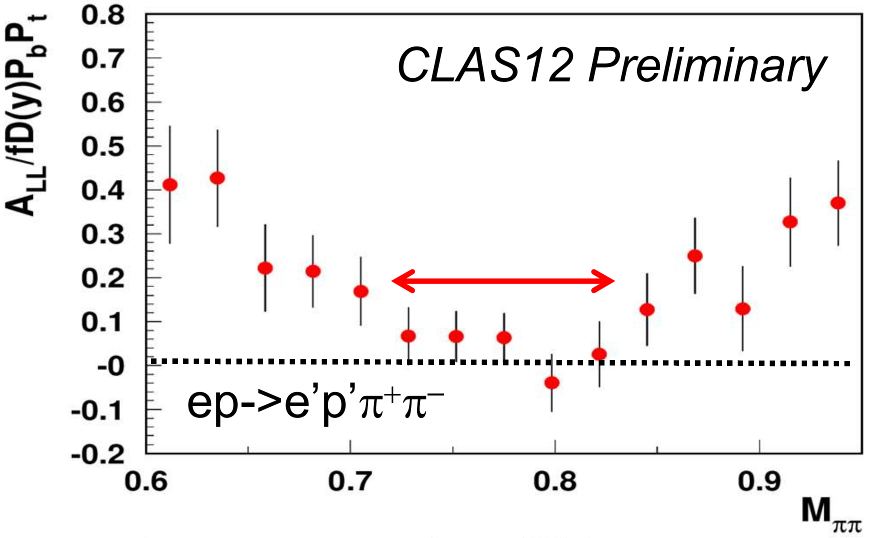


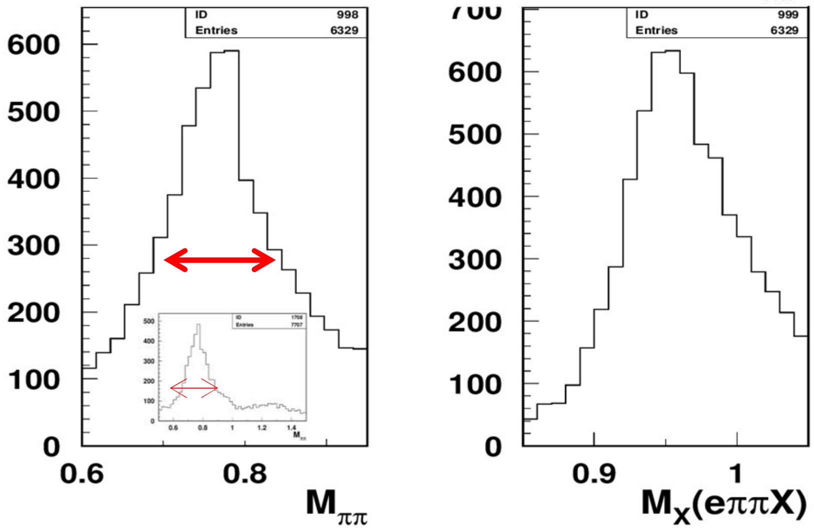
Studies of ρ^0 impact with longitudinally polarized NH_3 target

Separating exclusive dihadrons



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





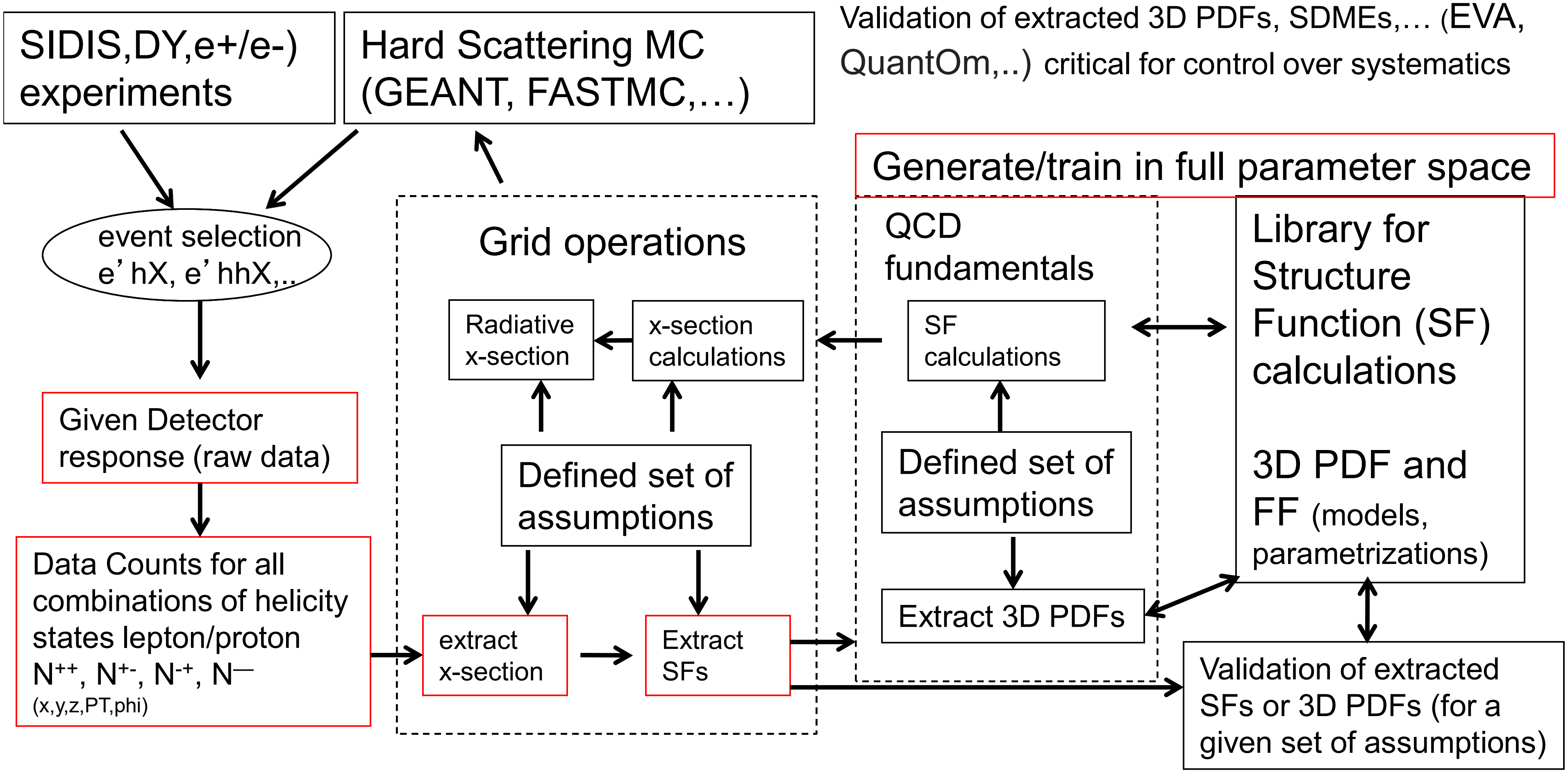
- Require the angle of negative pions is within a degree from calculated from e',p,π+ assuming exclusive e',p,$\pi+\pi$- event.
- Measurements of A_{LL} for ρ^0 indicate very small values (with ~10-20% bck, likely negative ~ -2-10%), and can be one of the reasons for higher A_{LL} with protons with a M_X cuts above 1.35 GeV (excluding exclusive ρ^0)

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

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

3D PDF Extraction and VAlidation frameworks

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



SIDIS,DY,e+/e-) experiments

Hard Scattering MC (GEANT, FASTMC,…)

event selection e’ hX, e’ hhX,..

Given Detector response (raw data)

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

Grid operations

Radiative x-section

x-section calculations

Defined set of assumptions

extract x-section

Extract SFs

Generate/train in full parameter space

QCD fundamentals

SF calculations

Defined set of assumptions

Extract 3D PDFs

Library for Structure Function (SF) calculations

3D PDF and FF (models, parametrizations)

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

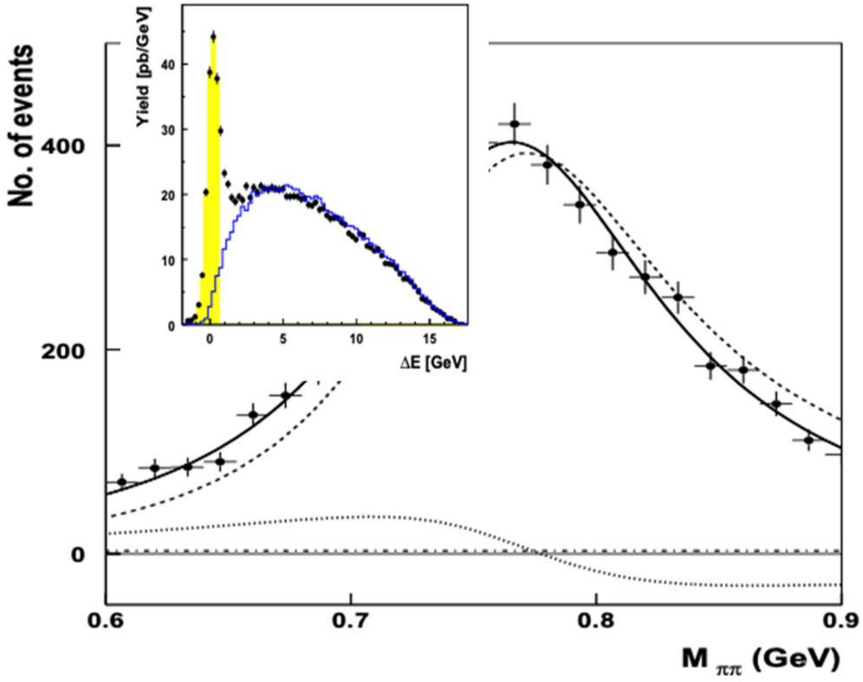
Direct extraction of a given parameter sets from all steps (marked red) using AI tools techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing

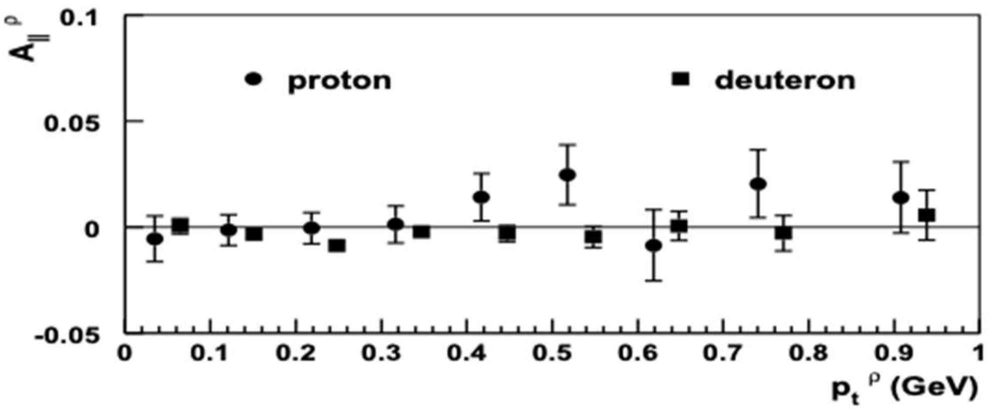
SUMMARY

- 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), likely moving to event based analysis→ 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, with cotributions ~10% in DIS, 20% in SIDIS, ~100% in SIDIS SSAs)
  - 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 and validation (also using AI tools) of the full set of TMD PDFs, also 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 in interpretation of the VM contributions and observables in terms of GPDs

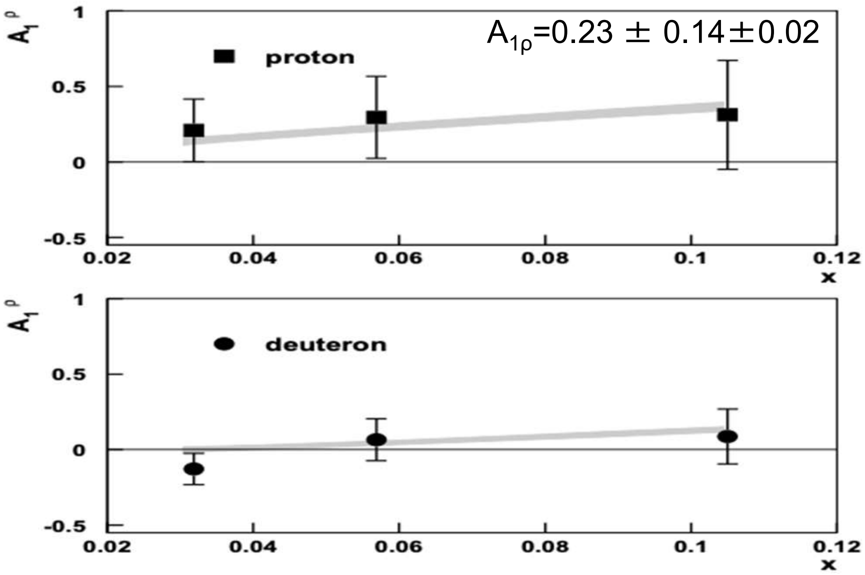
- Support slides

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





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


$A_{1\rho}$=0.23 ± 0.14±0.02

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

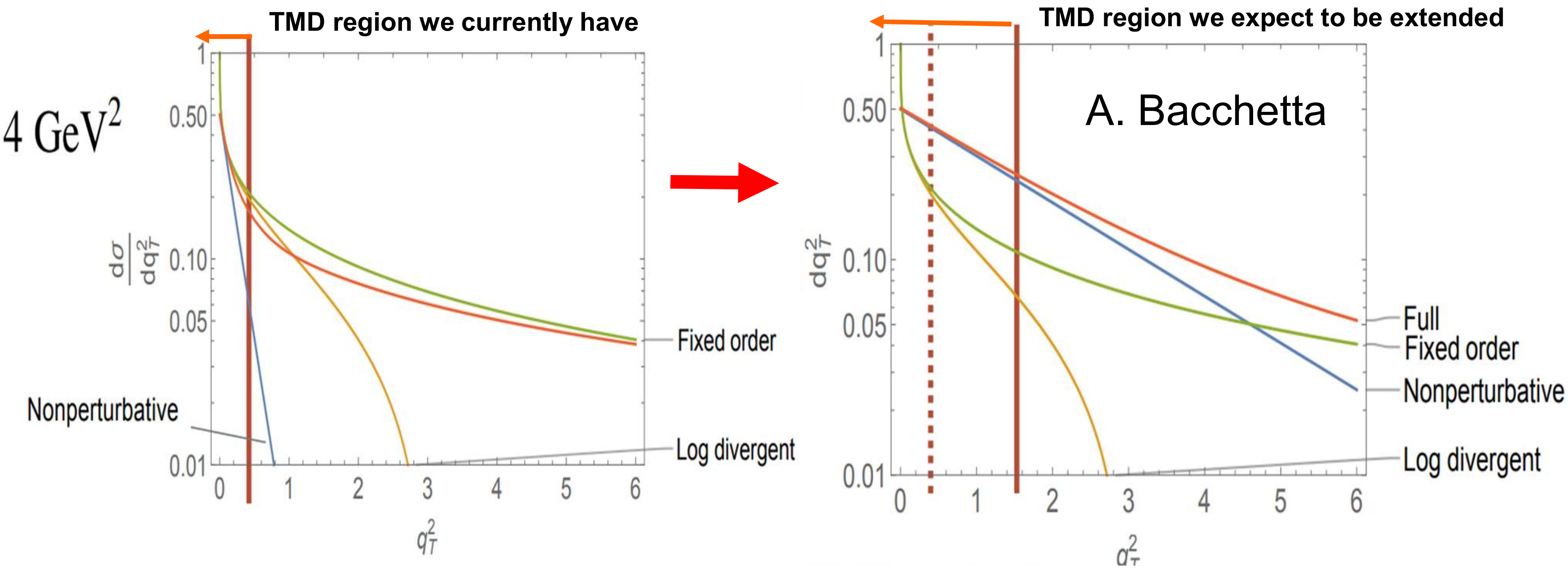
For a proper account of the impact on SIDIS, need a realistic MC (with validated SDMEs) for proper separation of "diffractive" exclusive ρ^0s in multi-D

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?

$\langle Q^2 \rangle = 4\ \mathrm{GeV}^2$



How far in P_T or q_T extends the TMD region

“they know not what they do” Luke 23:34

x-section

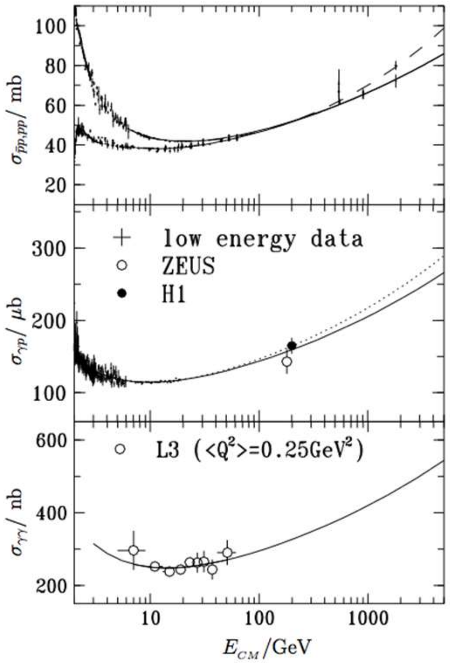


Figure 1.9: Total cross sections for pp ($p\bar{p}$), γp and $\gamma\gamma$ scattering as a function of the center of mass energy E_{CM}. The curves represent the DL parameterization with $\alpha_{I\!P}(0) = 1.0808$ (solid), $= 1.112$ (dashed) and $= 1.088$ (dotted).

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

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

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

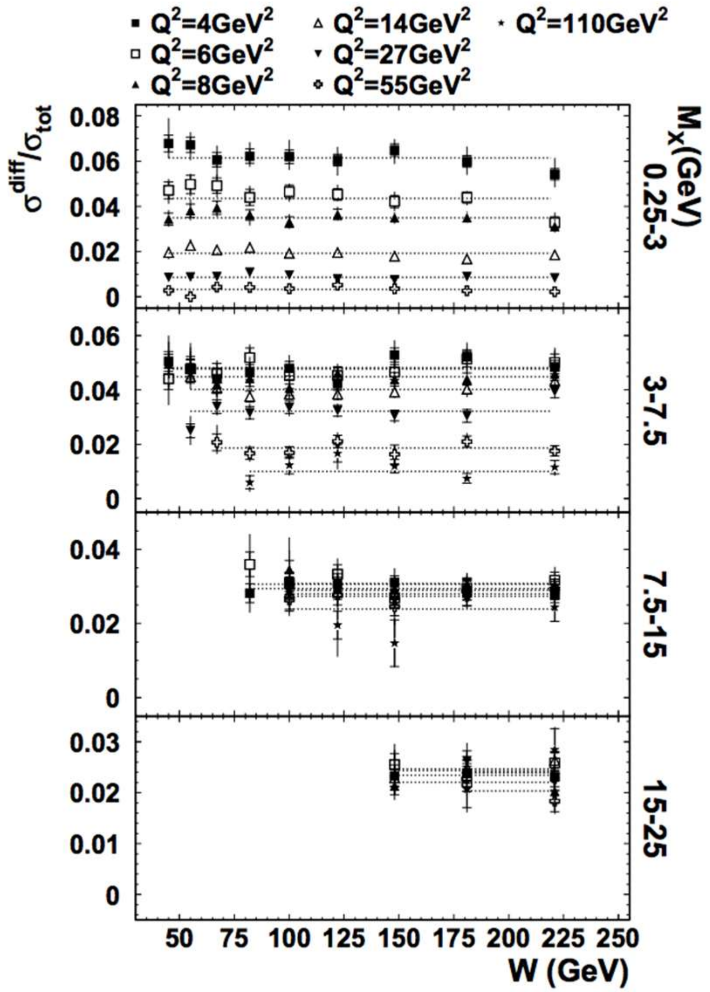


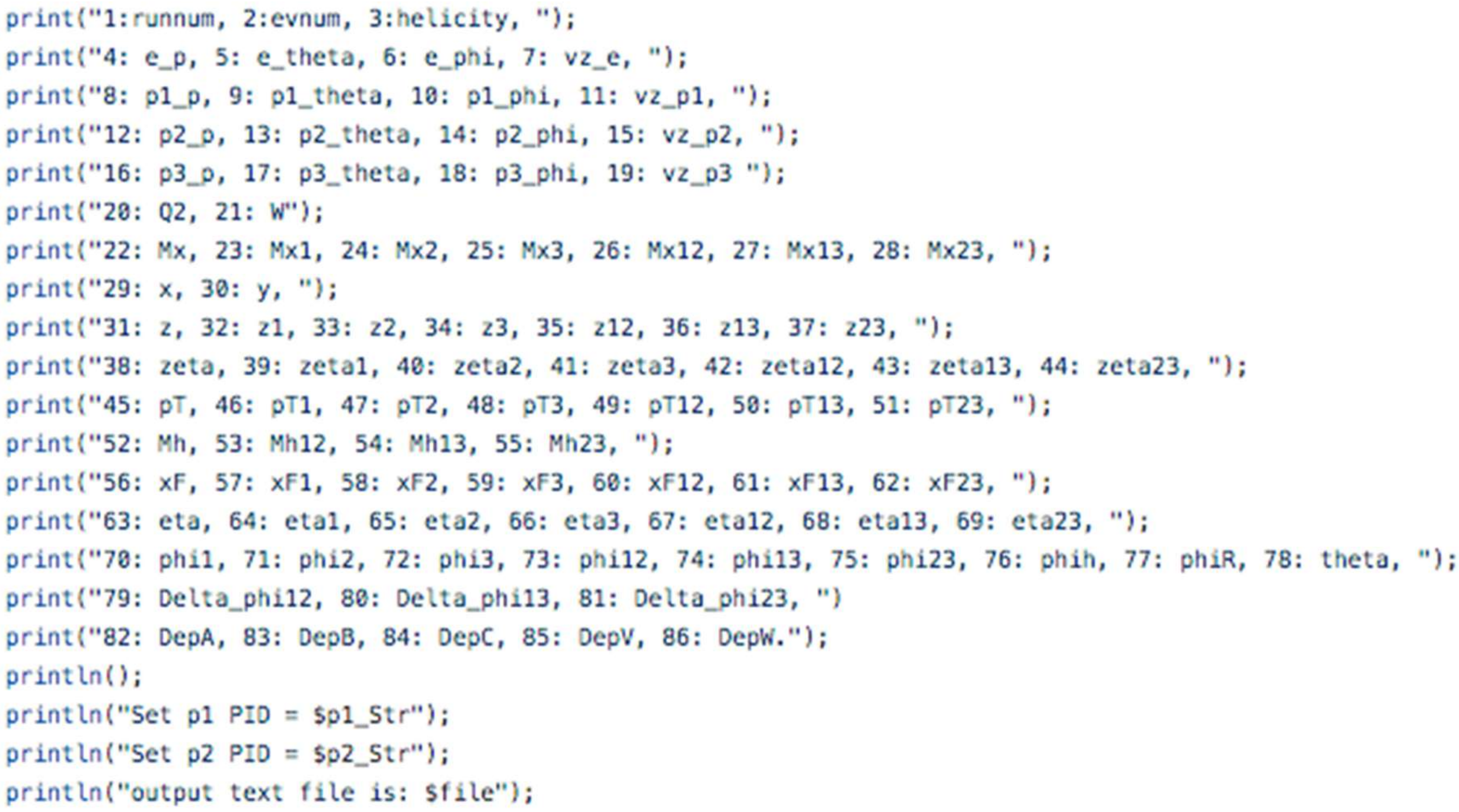
Figure 11.6: The ratio of the diffractive cross section σ^{diff}, integrated over the bin width $M_a < M_X < M_b$, and the total $\gamma^* p$ cross section σ^{tot} is shown as a function of W for different bins of M_X and Q^2. The dotted lines indicate the average values of $\sigma^{diff}/\sigma^{tot}$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

Example of a “process file”

https://github.com/tbhayward/clas12_analysis_software/blob/91f1d8f0360dc3b42446580af3899ff51eefe037/processing_scripts/processing_trihadrons.groovy

“process file” contains all 3 momenta of relevant particles, with corrections (ex. energy loss) + some relevant kinemati variables, and either combined with similar MC file or including acceptance/RC/… for given bin settings

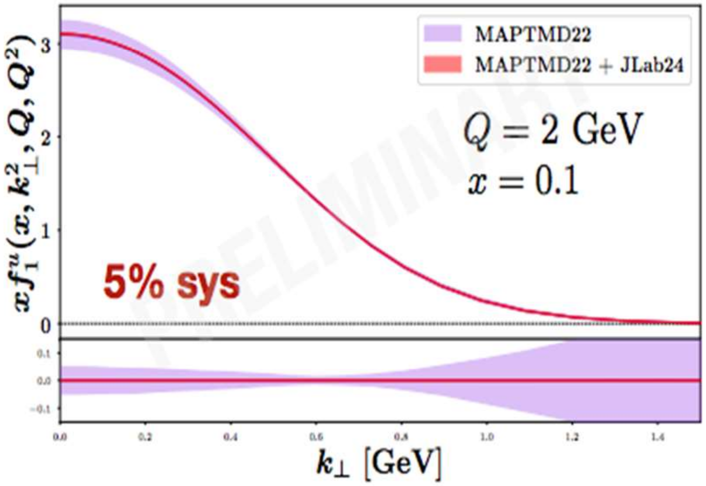
Ex. from Tim Hayward for ep→e’pπ+π-X (similar files for ep→e’pπ+X ep→e’π+π-X,…)

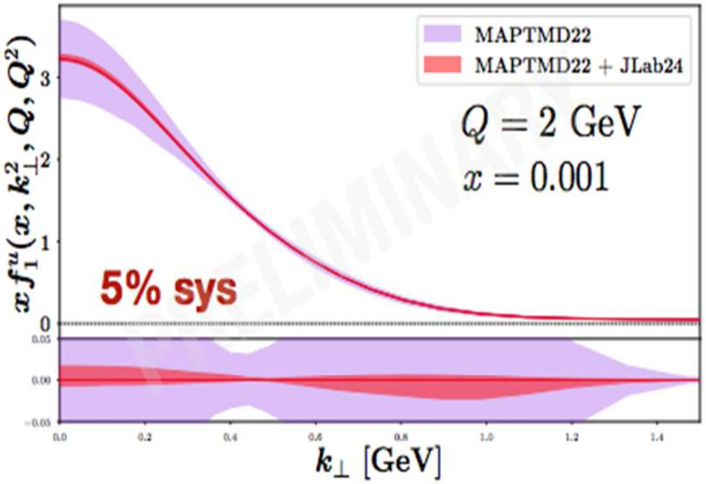


```
print("1:runnum, 2:evnum, 3:helicity, ");
print("4: e_p, 5: e_theta, 6: e_phi, 7: vz_e, ");
print("8: p1_p, 9: p1_theta, 10: p1_phi, 11: vz_p1, ");
print("12: p2_p, 13: p2_theta, 14: p2_phi, 15: vz_p2, ");
print("16: p3_p, 17: p3_theta, 18: p3_phi, 19: vz_p3 ");
print("20: Q2, 21: W");
print("22: Mx, 23: Mx1, 24: Mx2, 25: Mx3, 26: Mx12, 27: Mx13, 28: Mx23, ");
print("29: x, 30: y, ");
print("31: z, 32: z1, 33: z2, 34: z3, 35: z12, 36: z13, 37: z23, ");
print("38: zeta, 39: zeta1, 40: zeta2, 41: zeta3, 42: zeta12, 43: zeta13, 44: zeta23, ");
print("45: pT, 46: pT1, 47: pT2, 48: pT3, 49: pT12, 50: pT13, 51: pT23, ");
print("52: Mh, 53: Mh12, 54: Mh13, 55: Mh23, ");
print("56: xF, 57: xF1, 58: xF2, 59: xF3, 60: xF12, 61: xF13, 62: xF23, ");
print("63: eta, 64: eta1, 65: eta2, 66: eta3, 67: eta12, 68: eta13, 69: eta23, ");
print("70: phi1, 71: phi2, 72: phi3, 73: phi12, 74: phi13, 75: phi23, 76: phih, 77: phiR, 78: theta, ");
print("79: Delta_phi12, 80: Delta_phi13, 81: Delta_phi23, ")
print("82: DepA, 83: DepB, 84: DepC, 85: DepV, 86: DepW.");
println();
println("Set p1 PID = $p1_Str");
println("Set p2 PID = $p2_Str");
println("output text file is: $file");
```

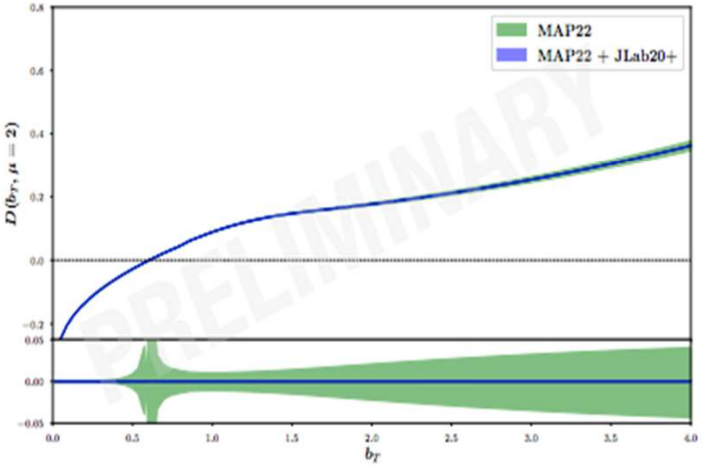
JLAB 24 IMPACT STUDIES ON TMDS

M. Cerutti, talk at Trento workshop Sep 2022





Collins-Soper kernel
(driving TMD evolution)



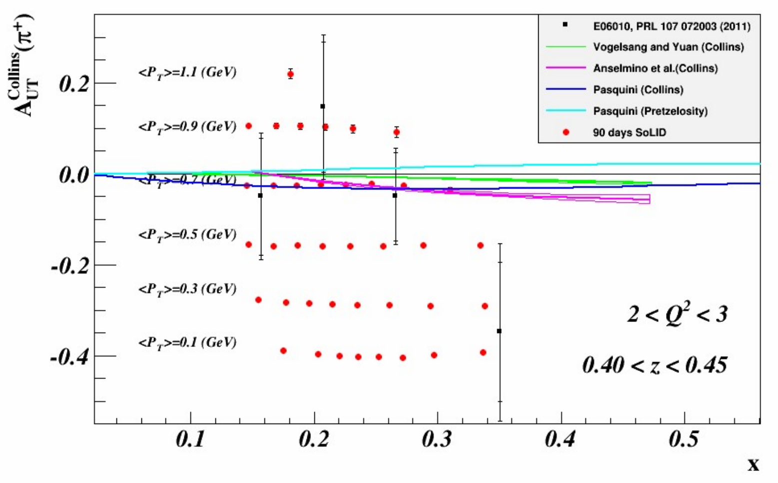
JLab 24 can have a very significant impact in reducing the errors on TMDs and their evolution

Parameterization used in extraction of TMDs will have practically unconstrained systematics

Transversity from SoLID

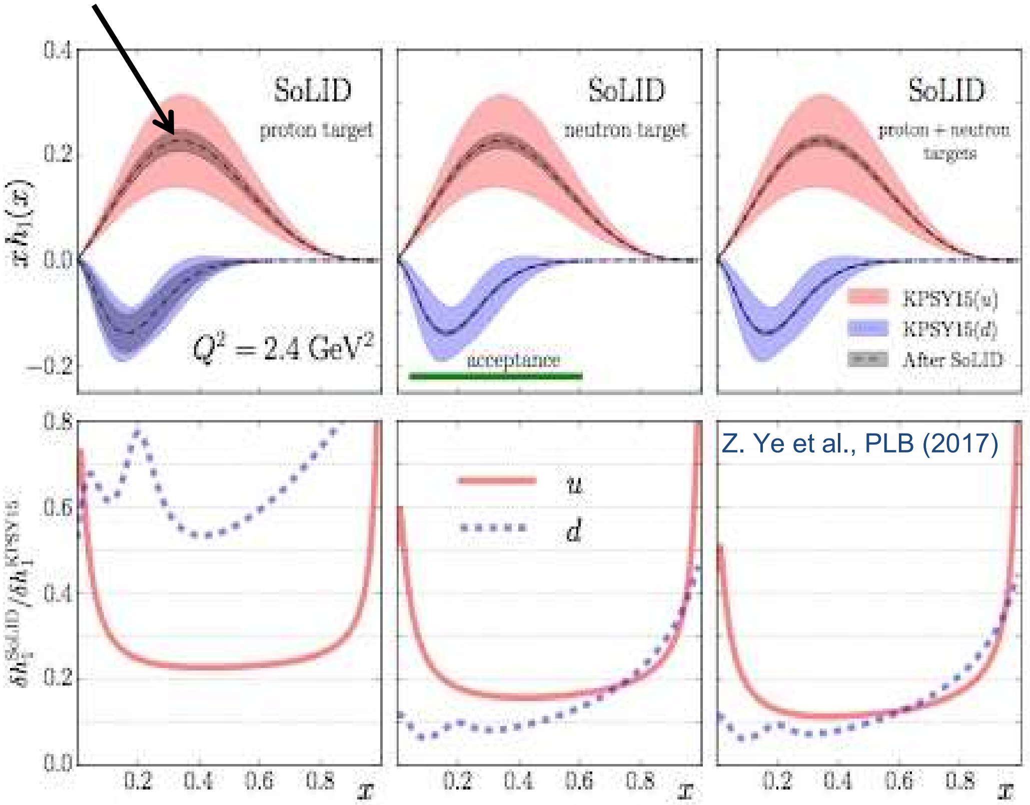
- Collins Asymmetries ~ Transversity (x) Collins Function
- SoLID with trans polarized n & p → Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, …) on impact study

Collins Asymmetries



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

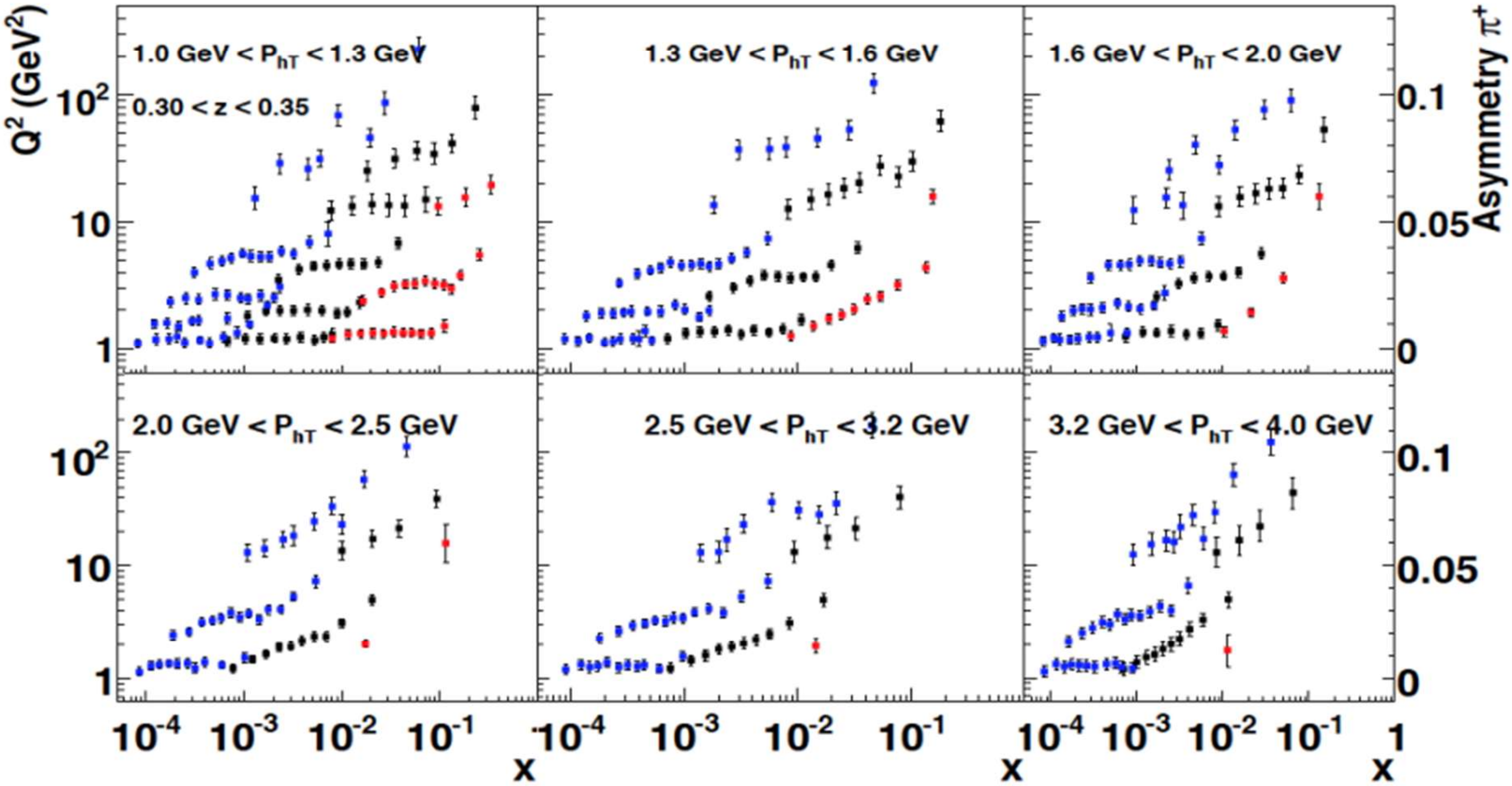
Significant improvement, but need to quantify the systematics from modeling (underlying assumptions)



Z. Ye et al., PLB (2017)

Projections for Sivers asymmetry

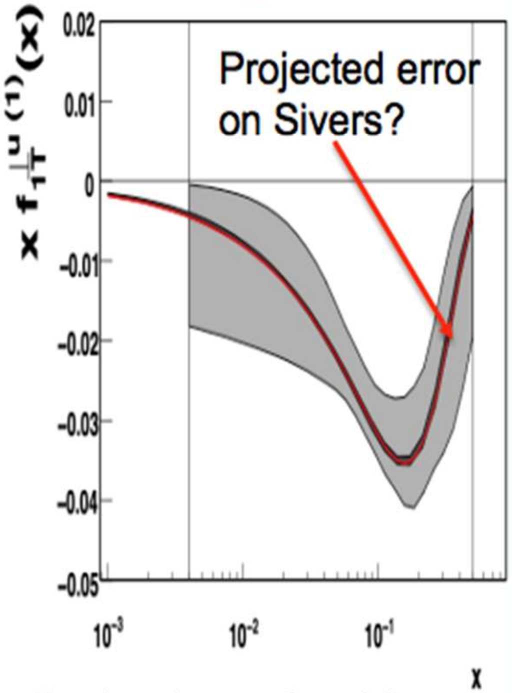
luminosity 120 fb^{-1} $\sqrt{s} = 140$ GeV, $\sqrt{s} = 50$ GeV and $\sqrt{s} = 15$ https://arxiv.org/pdf/1101.4199



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

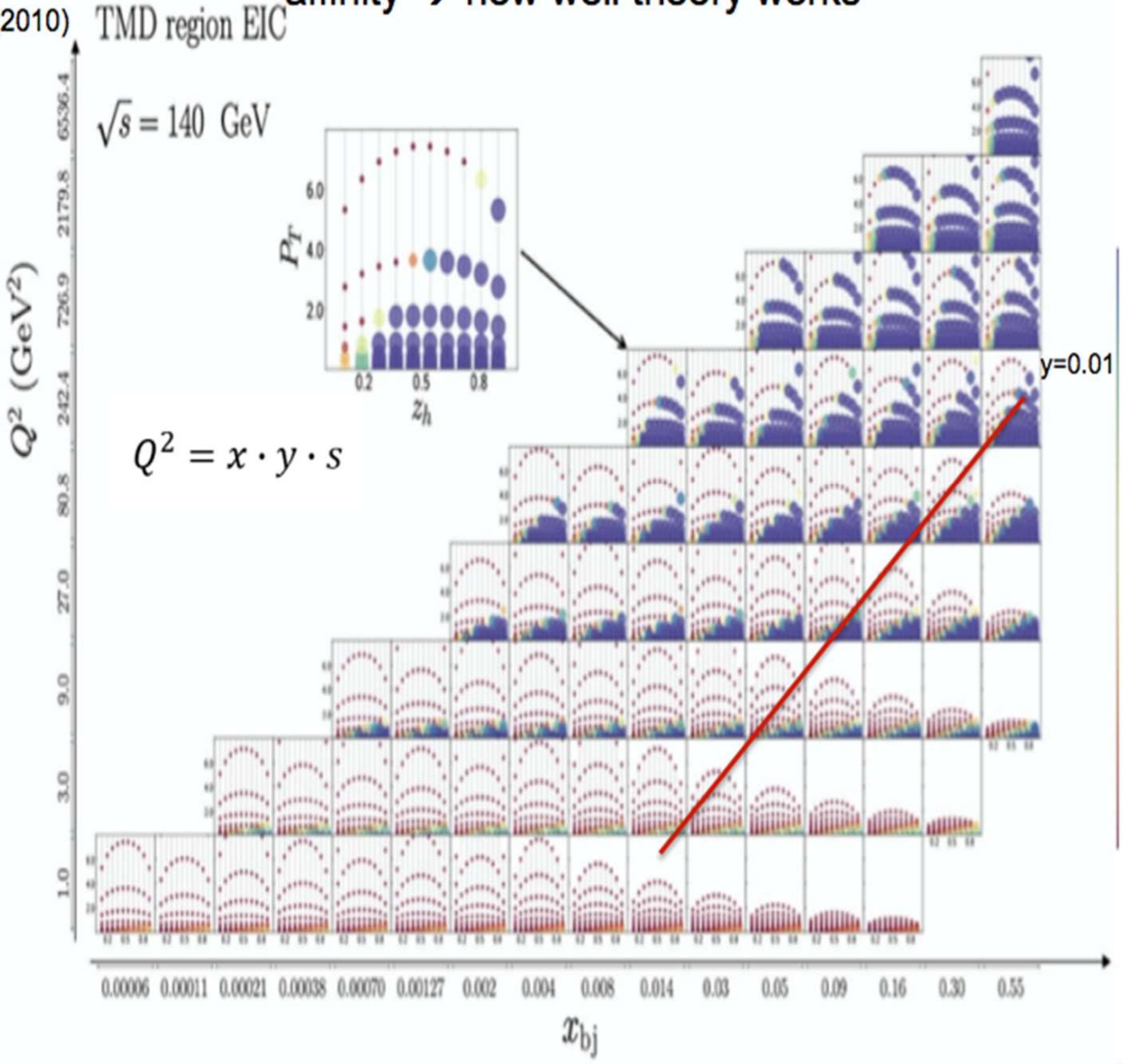
Projections from 1D to 4D

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



Projected error on Sivers?

“affinity”→ how well theory works



$Q^2 = x \cdot y \cdot s$

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

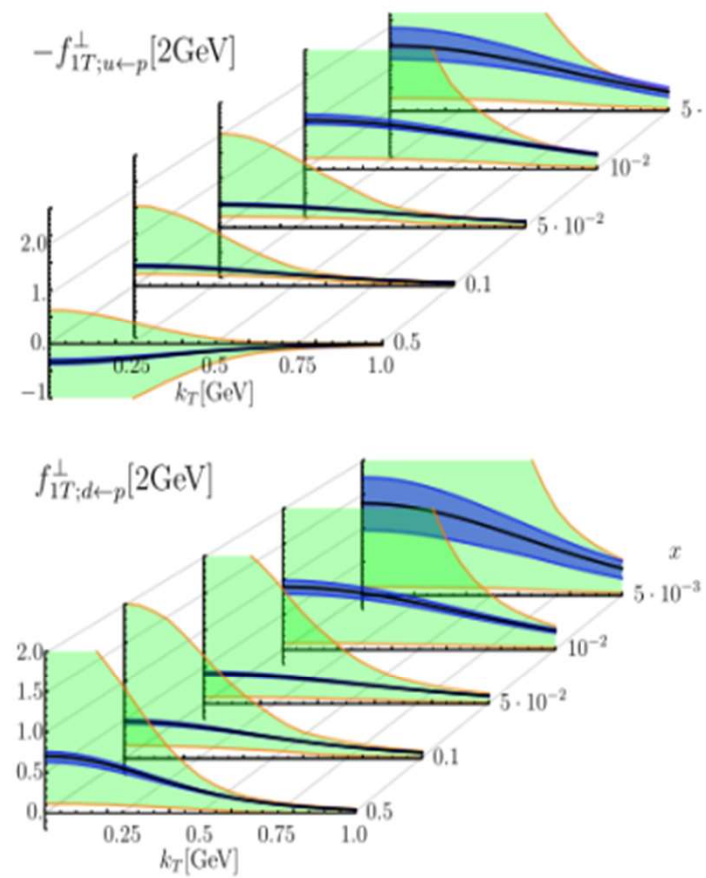


Figure 7.53: Expected impact on up and down quark Sivers distributions as a function of the transverse momentum k_T for different values of x, obtained from SIDIS pion and kaon EIC pseudodata, at the scale of 2 GeV. The green-shaded areas represent the current uncertainty, while the blue-shaded areas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

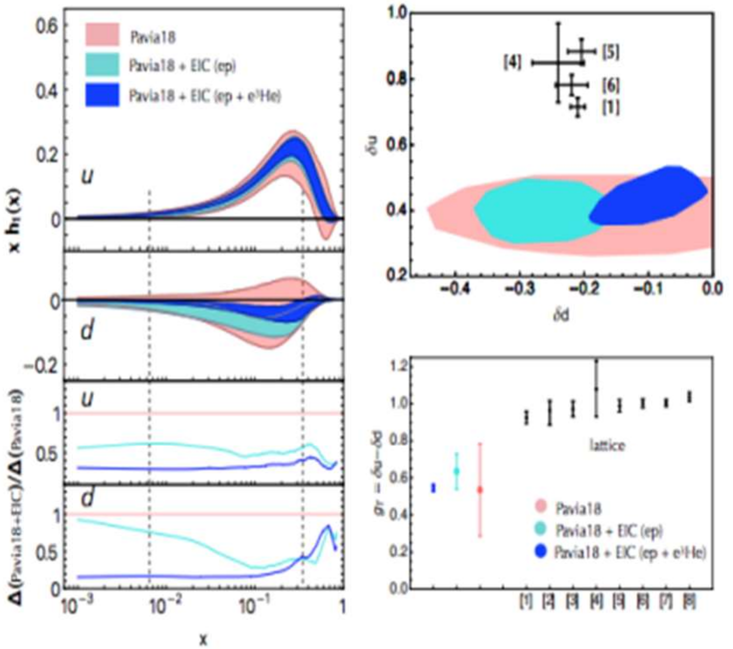
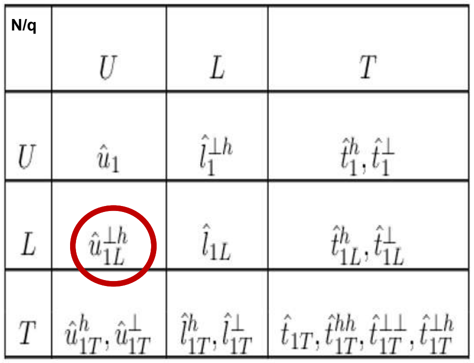


Figure 7.56: Left upper panel: The transversity $xh_1(x)$ as a function of x at $Q^2 = 2.4$ GeV^2 for up and down valence quarks. Uncertainty bands for 68% of all fitted replicas of data (see text). Pink band for the Pavia18 global extraction of Ref. [584], light-blue and blue bands when including EIC 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]

B2B correlations with longitudinally polarized target



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

A. Kotzinian et al, arXiv:1107.2292

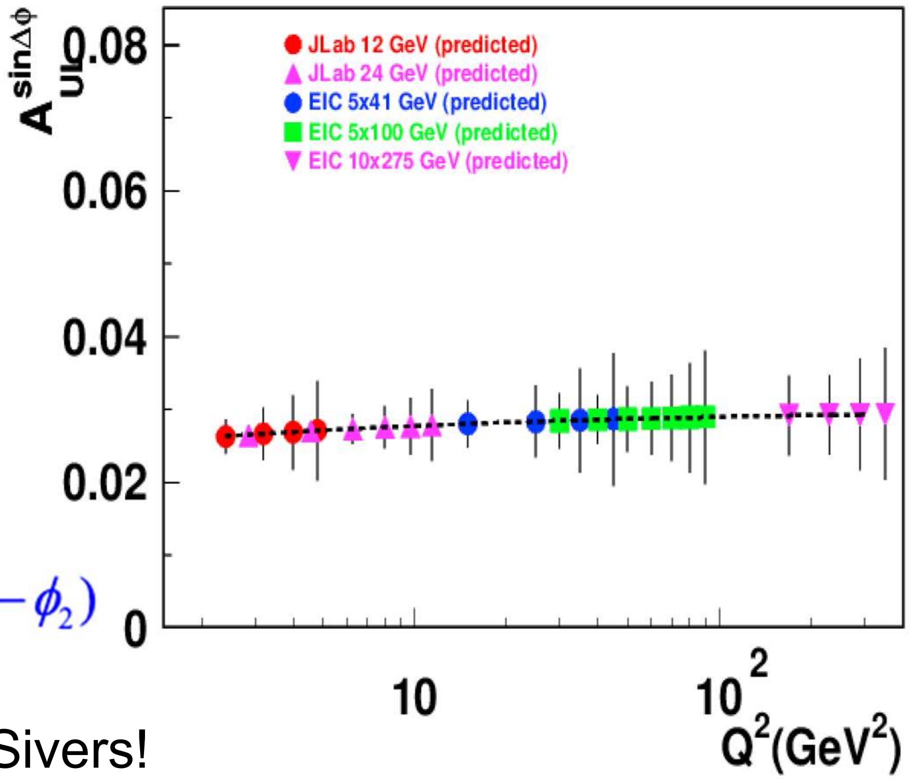
$$\sigma_{UU} = F_0^{\hat{u}\cdot D_1}$$

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

No depolarization, like Sivers!

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

y>0.05,100 days



CL AS12 proposals

NH3/ND3

E12-09-009

E12-07-107

E12-09-007A

^{3}He

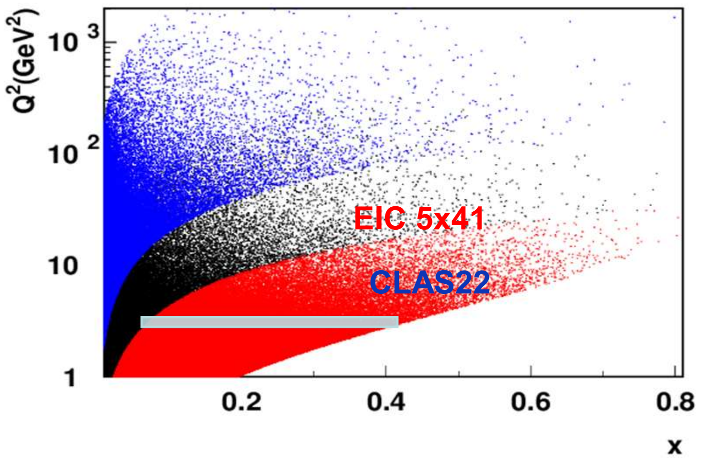
C12-20-002

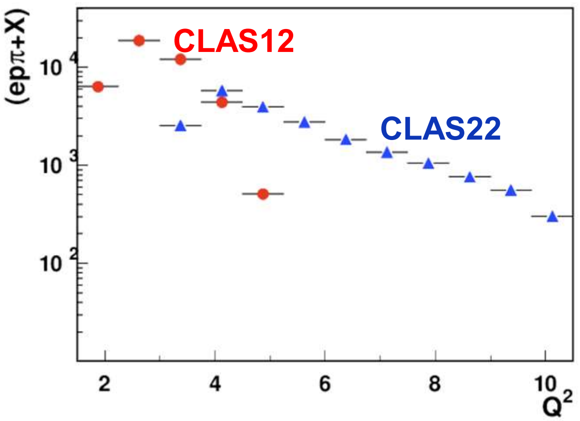
^{7}LiD

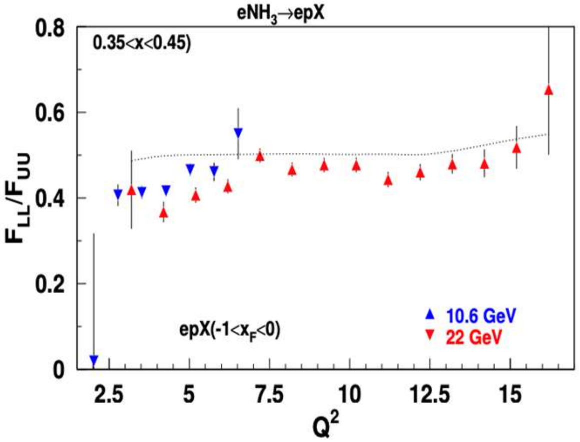
E12-14-001

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

Accessing CS-kernel directly or through extraction of SFs







Use slices in Q^2 (good resolution needed)

- Wide Q^2 range and high luminosity is the key for a validating separation of twist-2 contributions

A. Vladimirov

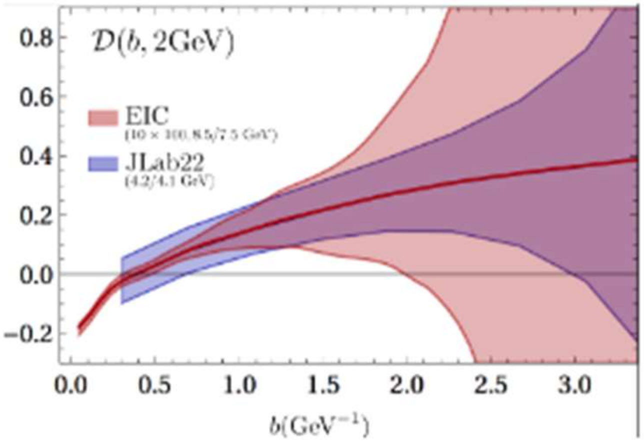
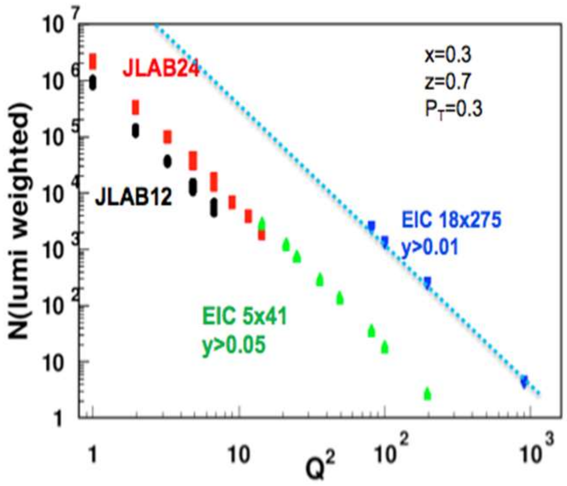


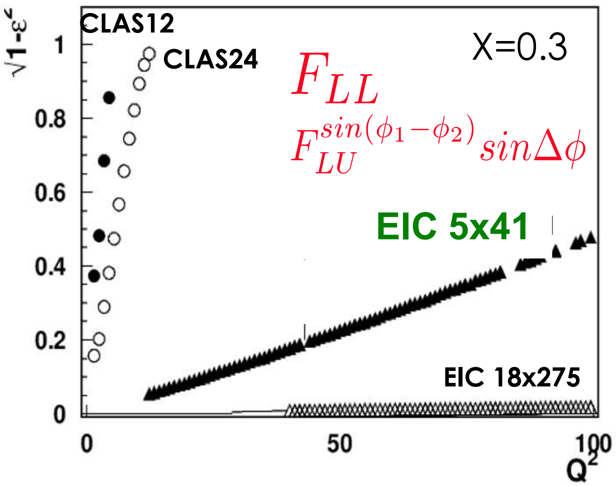
Figure 2: Extraction of the nonperturbative part of the CS using CLAS and EIC pseudo data

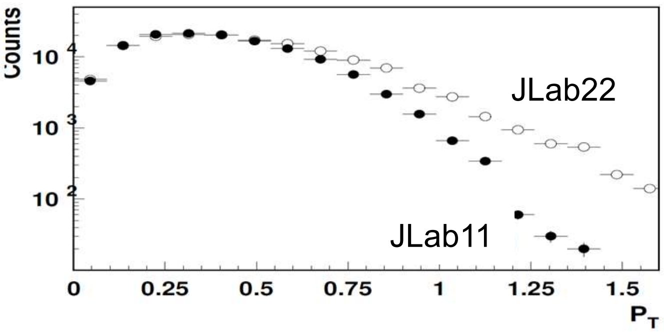
- Q^2 evolution studies possible, provide superior access to critical Collins-Soper (CS) kernel
- CLAS12 at JLab20+ can provide a wide range in Q^2 combined with high lumi and superior resolution

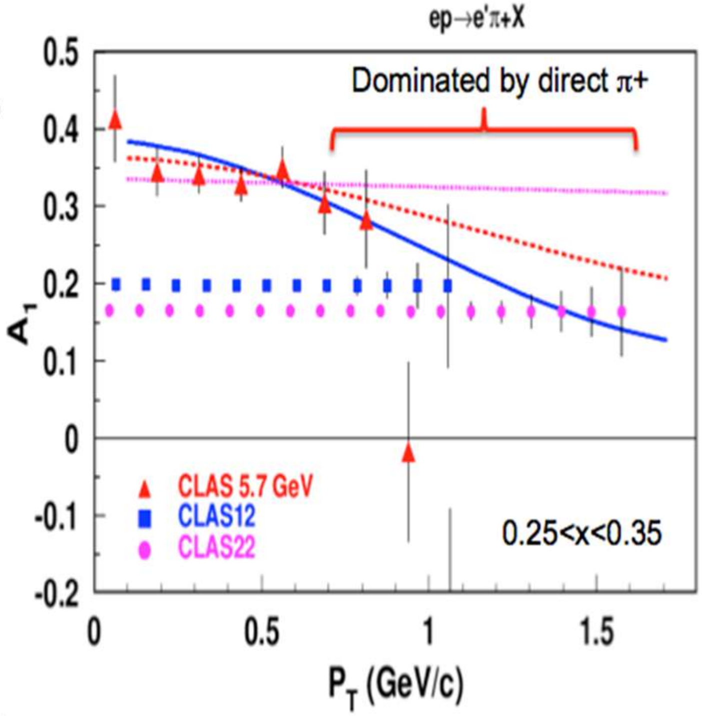
- Test the CS-kernel from different experiments, and for different kinematics in a given experiment
- <u>Evaluate the systematics due to factorization violation and define possible reasons</u> (some can be easy to fix)

Study helicity TMDs with JLab22









Accessing the quark k_T from hadron P_T
- –Why helicity TMD, $g_1(x,k_T)$, matters?
- –How we measure the $g_1(x,k_T)$
- –Why JLab is unique for studies of g_1 in valence region
- –Why 22 GeV is critical
- –Challenges at large P_T

Understanding exclusive rhos and SDME validations

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

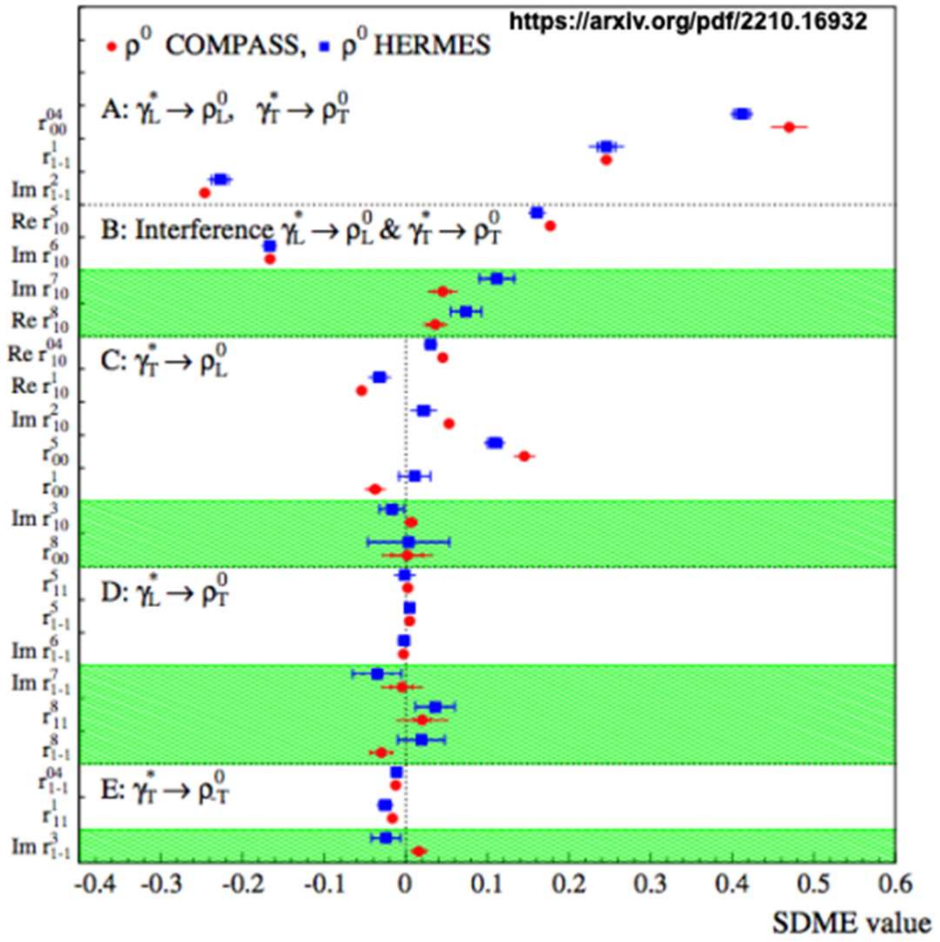


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle|t'|\rangle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

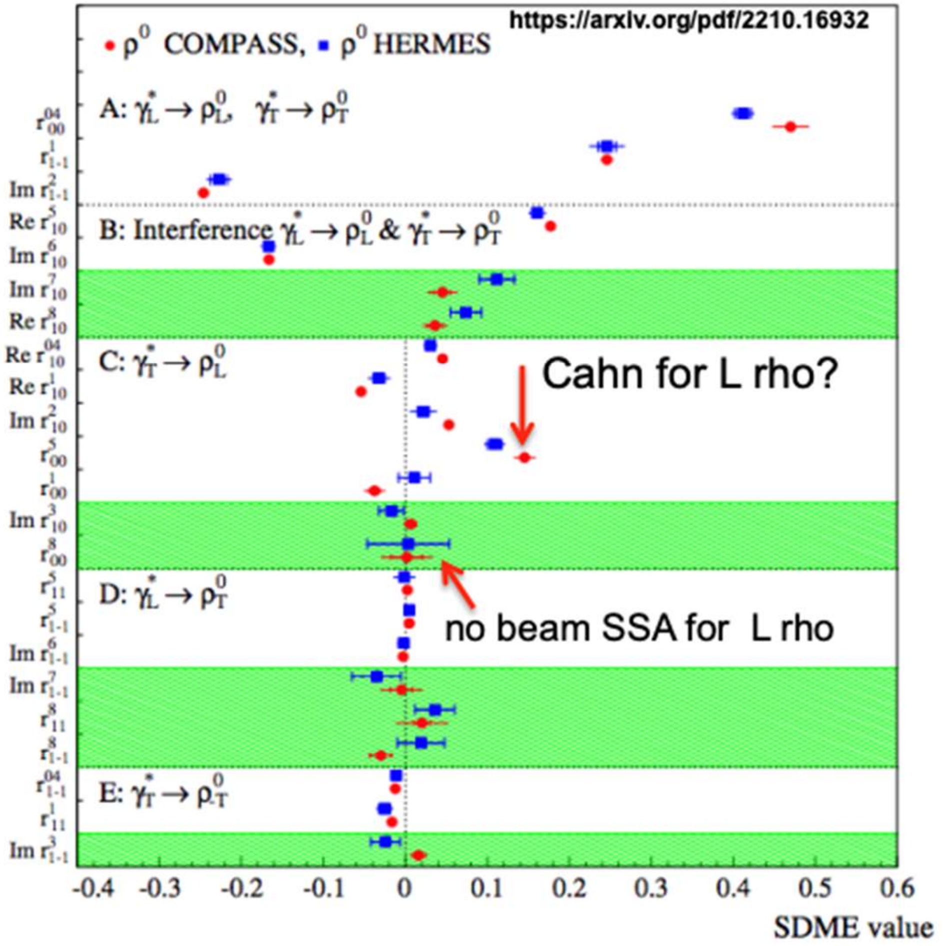
$$\mathcal{W}^U(\Phi,\phi,\cos\Theta)$$

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

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

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

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



https://arxiv.org/pdf/2210.16932

Cahn for L rho?

no beam SSA for L rho

Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (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_{00}^8 and r_{00}^5 will be responsible for longitudinal rho, so tiny beam SSA expected for longitudinal rho

Understanding exclusive rhos and SDME validations

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

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

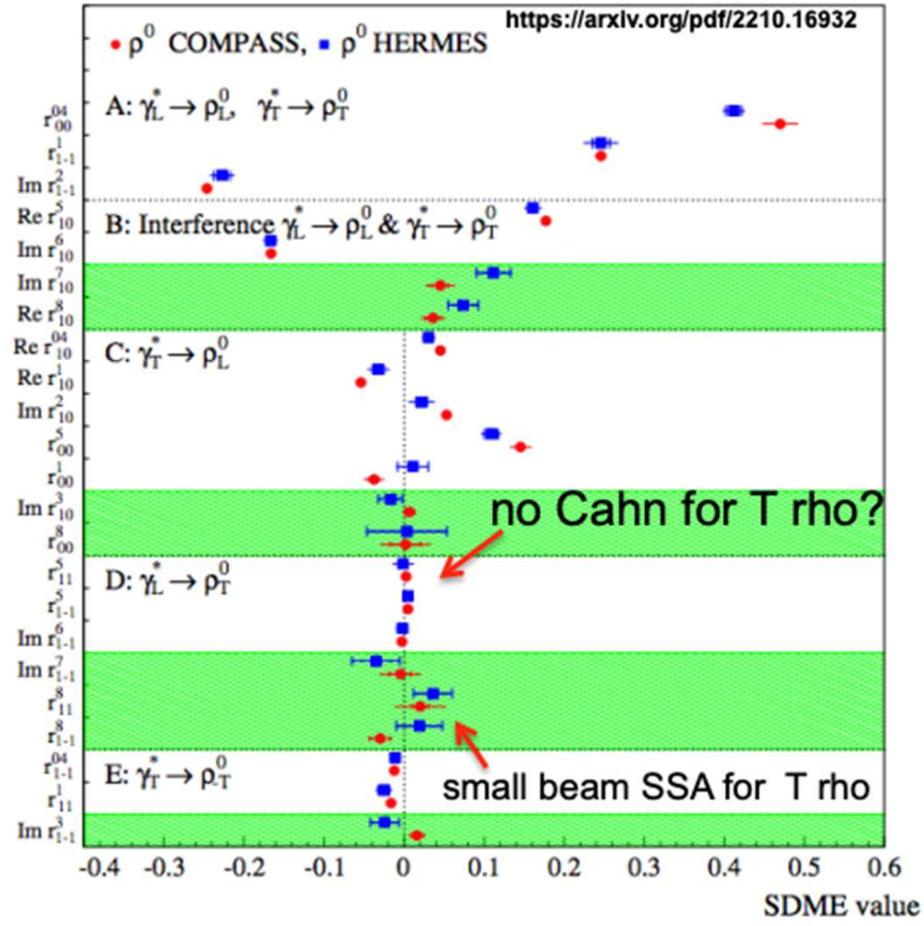
$$\mathcal{W}^L(\Phi,\phi,\cos\Theta)$$

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

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

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

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?)

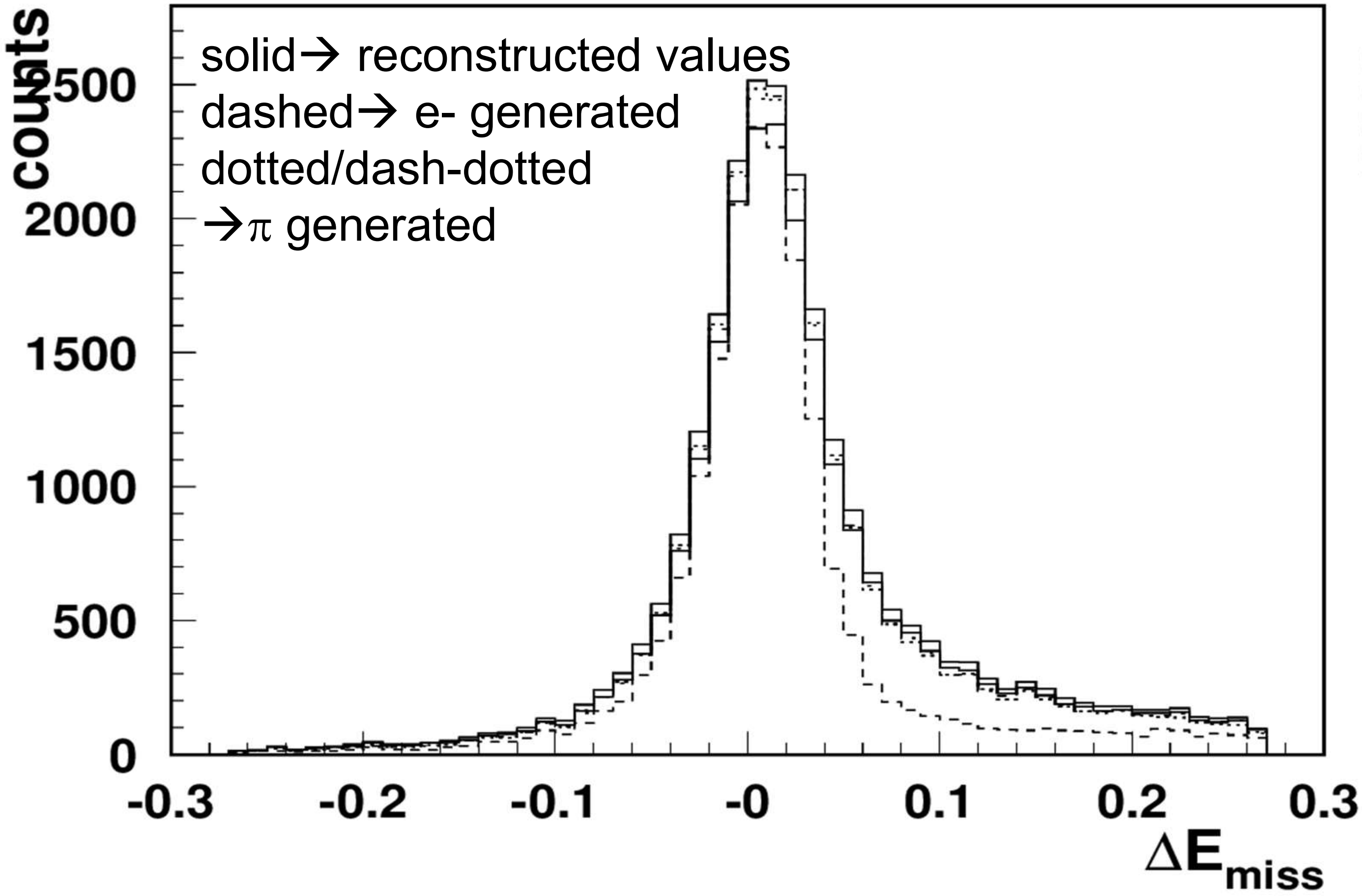


no Cahn for T rho?

small beam SSA for T rho

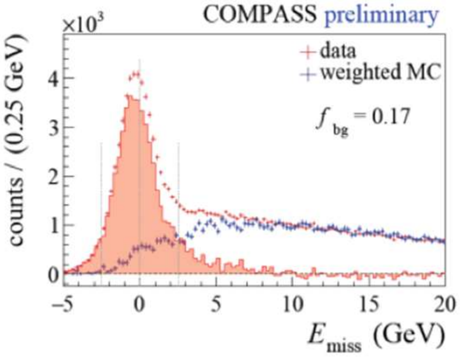
Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle|t'|\rangle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

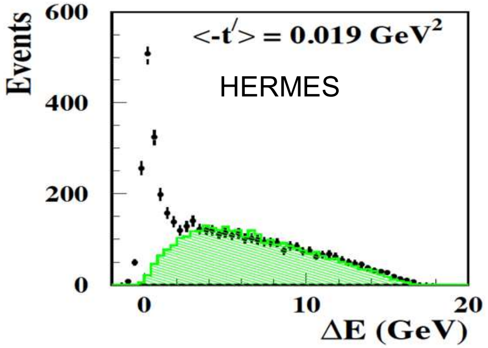
Radiative effects: impact on missing mass



solid→ reconstructed values
dashed→ e- generated
dotted/dash-dotted
→π generated

Claim RC is negligible





HERMES

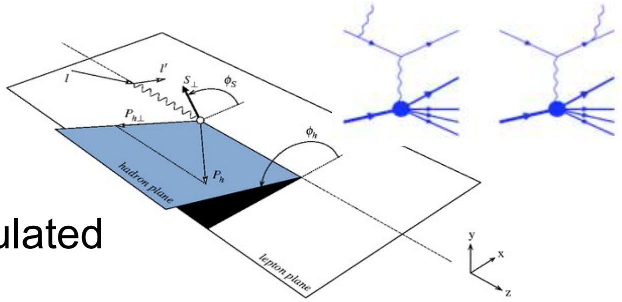
LUND-MC description of the exclusive limit will be important in evaluation of the tail.

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

Additional complications: Experiment can’t measure just 1 SF

I. Akushevich et al (LDRD-2018)

$$\sigma = \sigma_{UU} + \sigma_{UU}^{\cos\phi} cos\phi + S_T \sigma_{UT}^{\sin\phi_S} \sin\phi_S + \ldots$$



Due to radiative corrections, ϕ-dependence of x-section will get multiplicative R_M and additive R_A corrections, which could be calculated from the full Born (σ_0) cross section for the process of interest

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

Due to radiative corrections, ϕ-dependence of x-section will get more contributions
- •Some moments will modify
- •New moments may appear, which were suppressed before in the x-section

Simplest rad. correction

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

Correction to normalization

$$\sigma_0(1 + \alpha\cos\phi_h)R_0(1 + r\cos\phi_h) \to \sigma_0 R_0(1 + \alpha r/2)$$

Correction to SSA

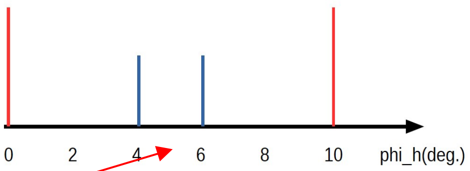
$$\sigma_0(1 + sS_T\sin\phi_S)R_0(1 + r\cos\phi_h) \to \sigma_0 R_0(1 + sr/2S_T\sin(\phi_h - \phi_S) + sr/2S_T\sin(\phi_h + \phi_S))$$

Correction to DSA

$$\sigma_0(1 + g\lambda\Lambda + f\lambda\Lambda\cos\phi_h)R_0(1 + r\cos\phi_h) \to \sigma_0 R_0(1 + (g + fr/2)\lambda\Lambda)$$

Simultaneous extraction of all moments is important also because of correlations!

From data to phenomenology: EBC

bin#	x	Q^2	y	W	M_X	ϕ	z	P_T	λ	Λ	N(counts)	RC
1 … N												

For precision studies of TMDs we need x-sections/muliplicities in smallest possible bins in x,y,z,P_T,ϕ for all hadrons and all relevant polarization states

Elementary Bins vs macroscopic bins

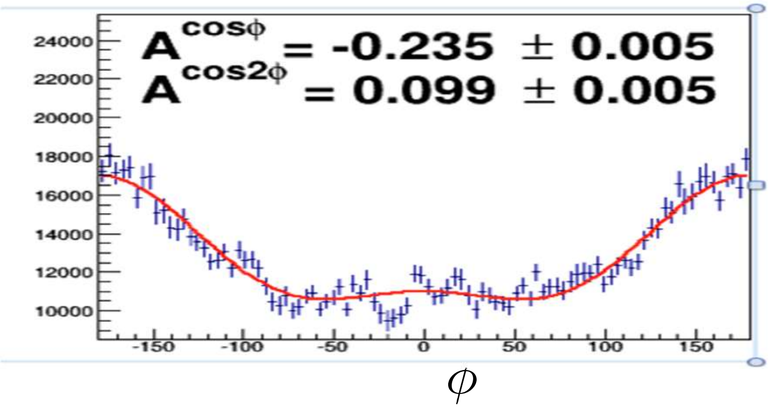
Pros:

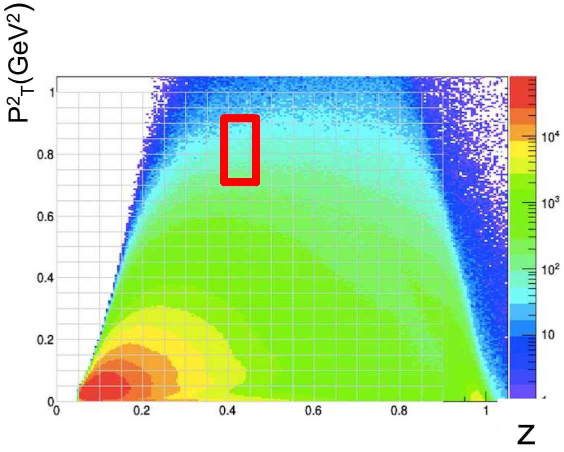
1)can go to wider bins,
2)smaller bin centering corrections
3) smaller acceptance/radiative correcions.
4) can perform also Bessel weighting
5)Can re-calculate for any other kinematical variables (η,P_T/z,…)
……………………..

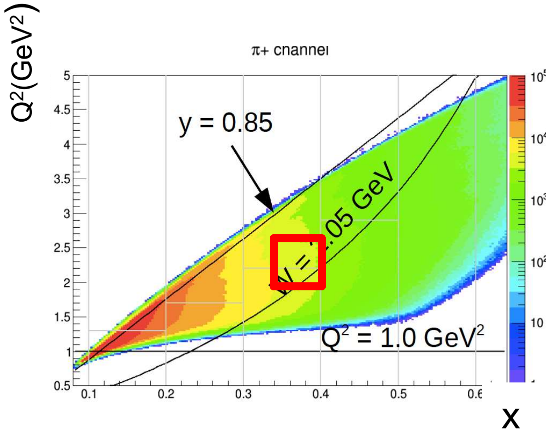
Cons:

1)Requires huge MC sample

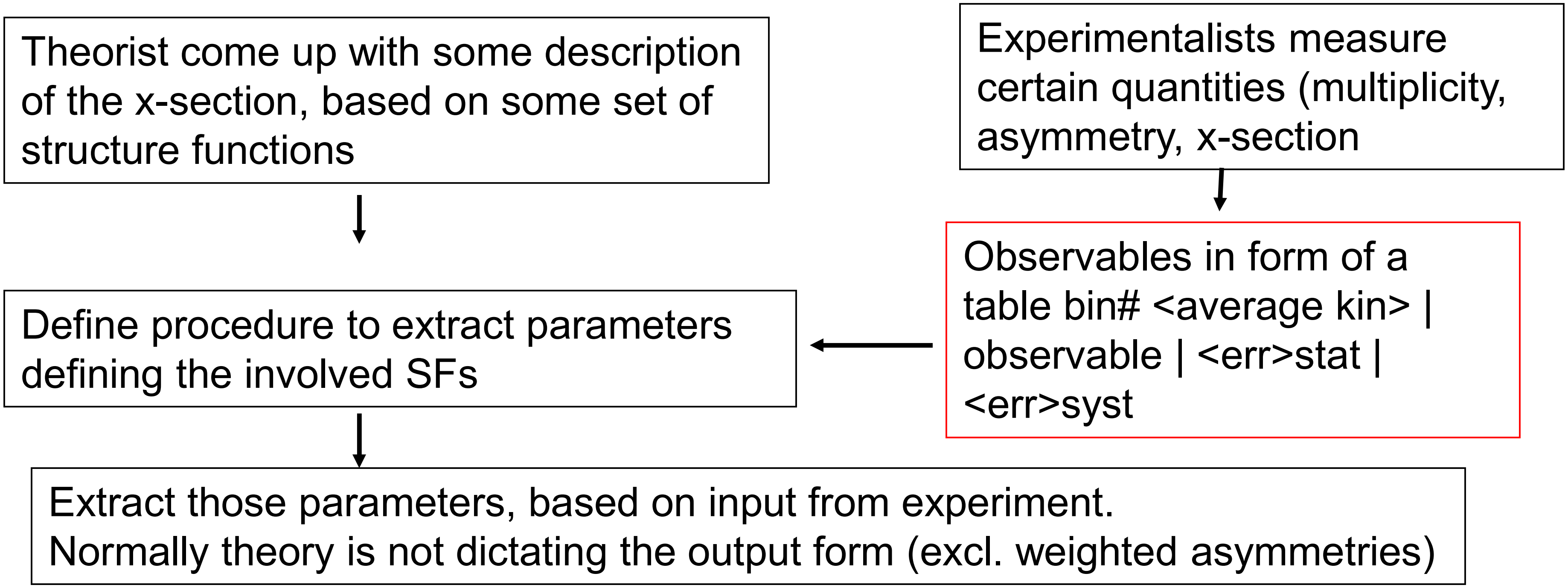
EBC: bin sizes limited by resolutions and computing resources (x10)







Experiment-Theory interaction



Theorist come up with some description of the x-section, based on some set of structure functions

Experimentalists measure certain quantities (multiplicity, asymmetry, x-section

Observables in form of a table bin# <average kin> | observable | <err>stat | <err>syst

Define procedure to extract parameters defining the involved SFs

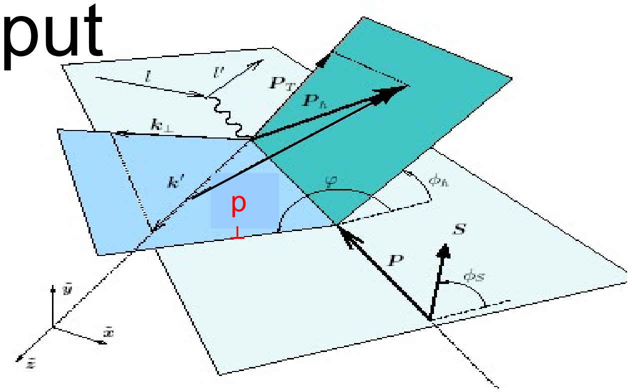
Extract those parameters, based on input from experiment.
Normally theory is not dictating the output form (excl. weighted asymmetries)

What will be the most efficient format for the data (and metadata)?

- Data required for certain analysis may require event by even info
- How to store and preserve the data (for unbinned analysis)
- Alternative to store full events (all tracks) event level analysis (ELA)?
  - Should provide easy access for theory

MC Generator to simulate SIDIS output

SIDIS MC in 7D (10D)



$$\frac{d\sigma_{\lambda\Lambda}^{eN\to e'hX}}{dx\,dQ^2\,dz\,dP_{hT}^2\,d\phi_h\,d\phi_l\,d\phi_s} = \sum_{l=1}^{L} SF_l$$

Theory

Provide a set of SF$_l$

For a given model/theory based on underlying non-perturbative input and assumptions calculate SF$_l$

$$F_l(x_1, x_2, x_3, ...x_N, P_1, P_2, ...P_M)$$

step-1 $x_i, Q_i^2 z_i P_{hT}^{i2} \phi_h^i \phi_l^i \phi_s^i$

step-2 (for a given E$_{\text{beam}}$,λ,Λ) P_i^{el}, P_i^h

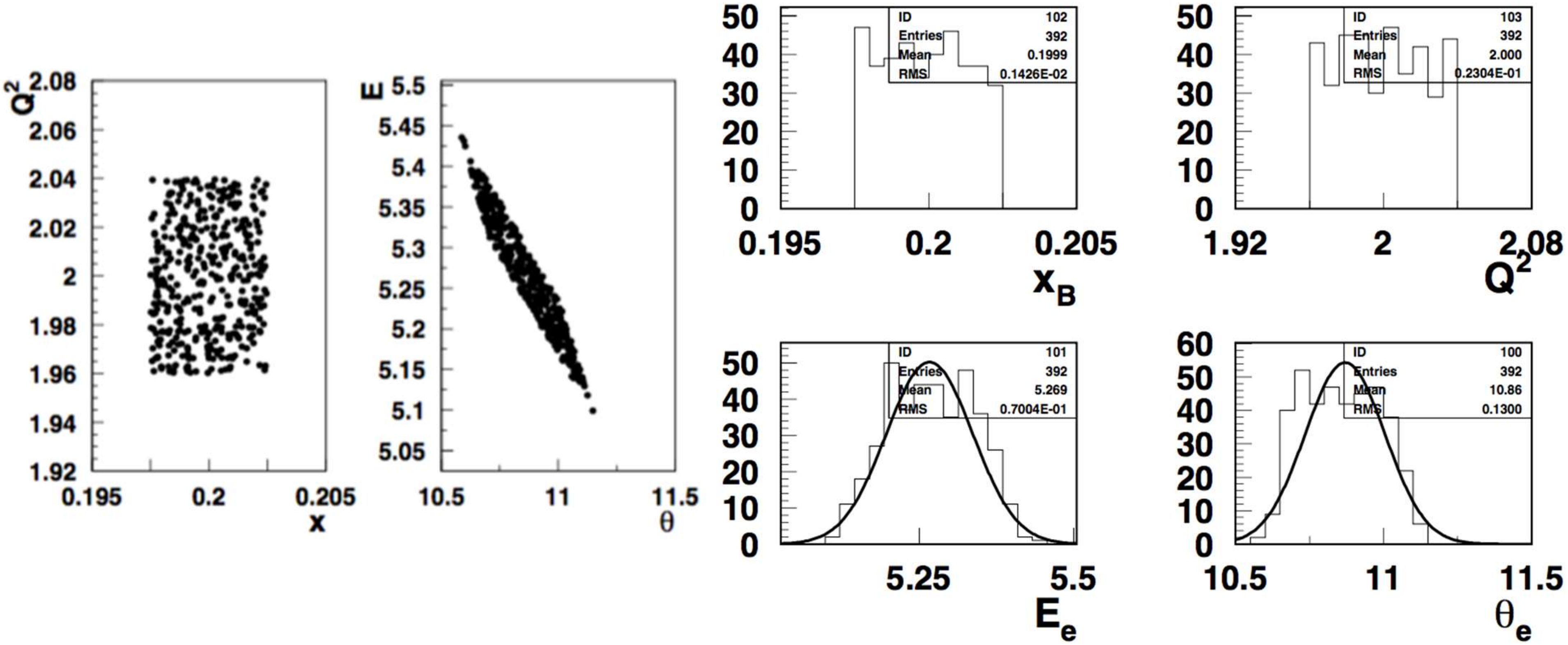
step-3 (detected for a given Detector configuration)

$$x_j, Q_j^2 z_j P_{hT,j}^2 \phi_h^j \phi_l^j \phi_s^j$$

$$F_l(x_1, x_2, x_3, ...x_N, P_1^*, P_2^*, ...P_M^*)$$

Need criteria to compare the input and output parameter spaces (validate)

Binning in DIS



For small bins in x-Q^2 or x-y, spread in other kinematical variables is becoming small (x2-3 resolution in θ and E'), reducing the role of bin-centering corrections and variations of structure functions in the bin

Main focus in building the support for upgrade

Identify the flagship measurements that can be done only with 20+ GeV and its science impact (Uniqueness)

→ impact of JLab measurements on overall 3D studies

Identify the flagship measurements with 20+ GeV that can extend and improve the 11 GeV measurements, helping the physics interpretation through multidimensional bins in extended kinematics (Enrichment)

→ for SIDIS major impact from wider Q^2 and P_T of hadrons

Identify the measurements with 20+ GeV that can set the bridge between JLab12 and EIC (Complementarity)

→ complementarity & uniqueness

PAC48 comments and consequences

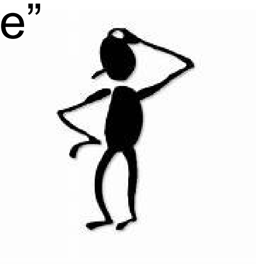
Statement:

“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)

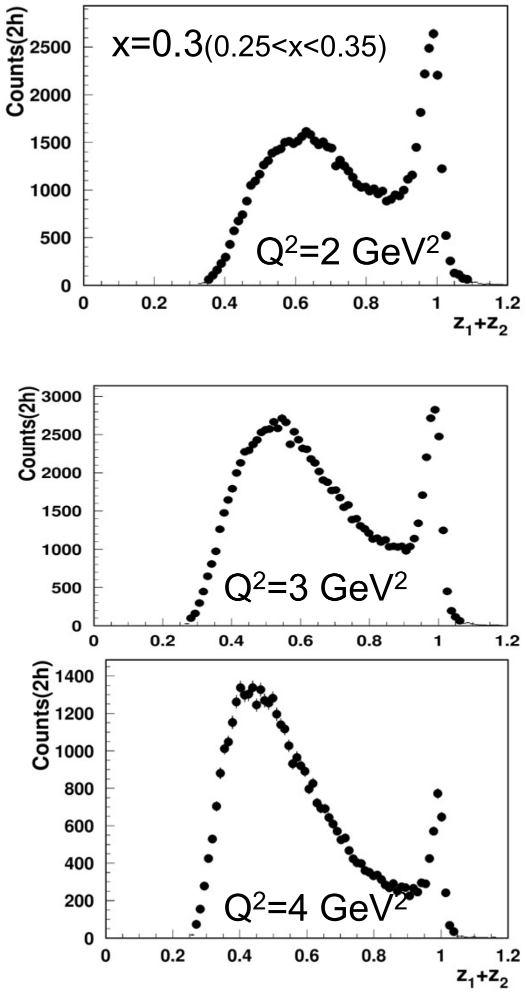
Redirection of resources to “Physics analysis of EIC data”, pushing most SIDIS groups to be involved in EIC, with little focus on huge amount of precious data already accumulated or planned from incoming JLab experiments

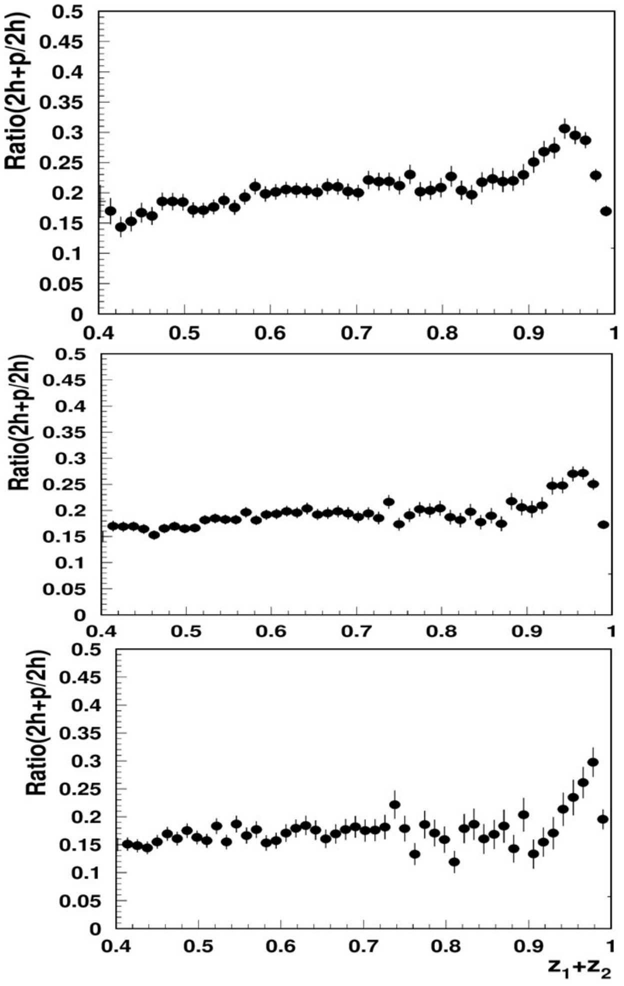
□ρ-free SIDIS” free: target proton bias

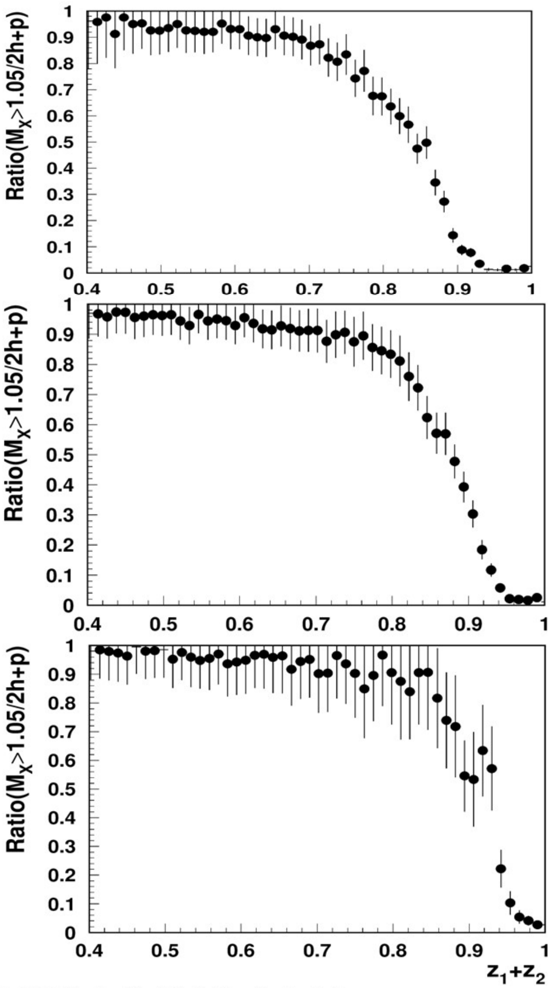
ep→e’ππX

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).

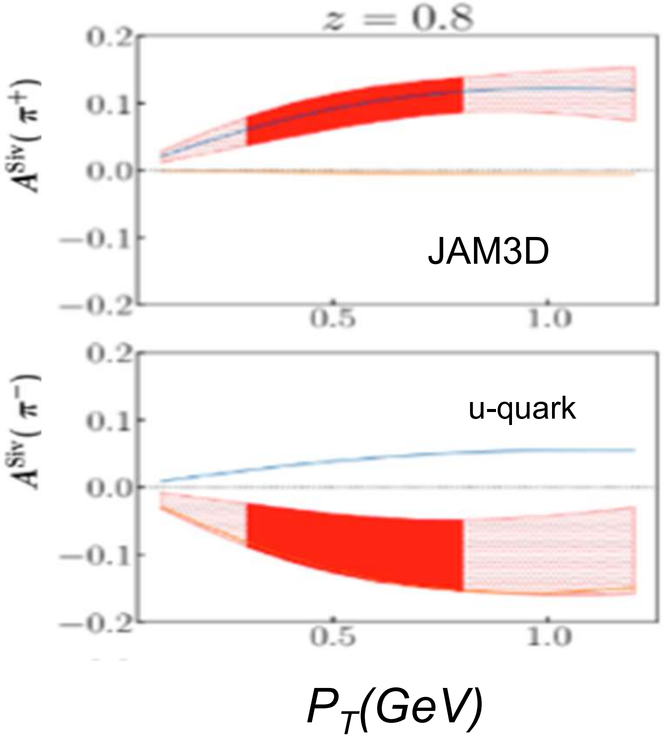
Measurements with transverse target

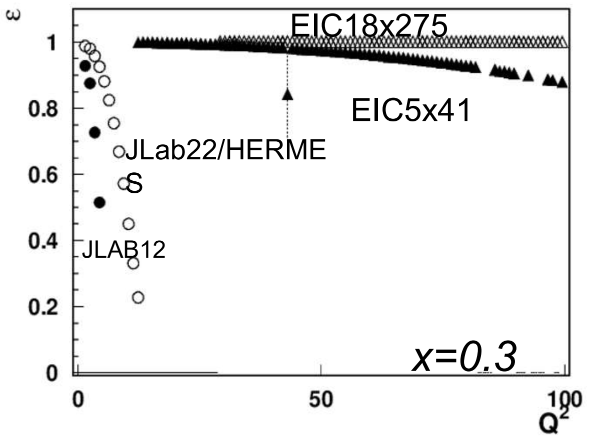
x-section for eN→e’hX

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

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

2) Meaningful interpretation of SSAs (Collins effects,…) requires *separation* of VMs (JLab)





Transversely polarized case involves most modulations to separate

Separation of exclusive contributions would allow large z measurements of Sivers/Collins effects

JLab22 white paper: Hadronization and Transverse Momentum

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

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

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