CLAS20+ simulations/projections

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July 7-8, 2022, JLab20+ Upgrade Meeting

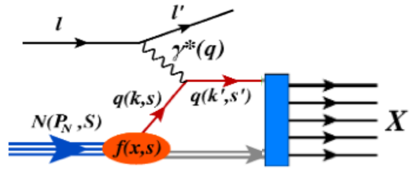
Understanding the QCD: from observables to QCD dynamics

- Projections as motivation for future studies
  - Projections for observables (x-sections, multiplicities, asymmetries)
  - Projections for underlying physics objects of interest (GPDs,TMDs,.. guts of QCD)
- Extending the phase space in P_T, Q^2 and x
- Studies of evolution properties
- Future studies of 3D

Summary

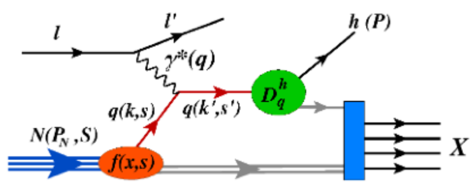
QCD: from testing to understanding

0h DIS



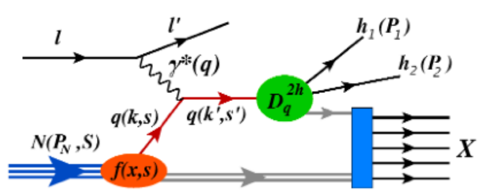
Testing stage:
pQCD predictions, observables in the kinematics where theory predictions are easier to get (higher energies, 1D picture, leading twist, IMF)

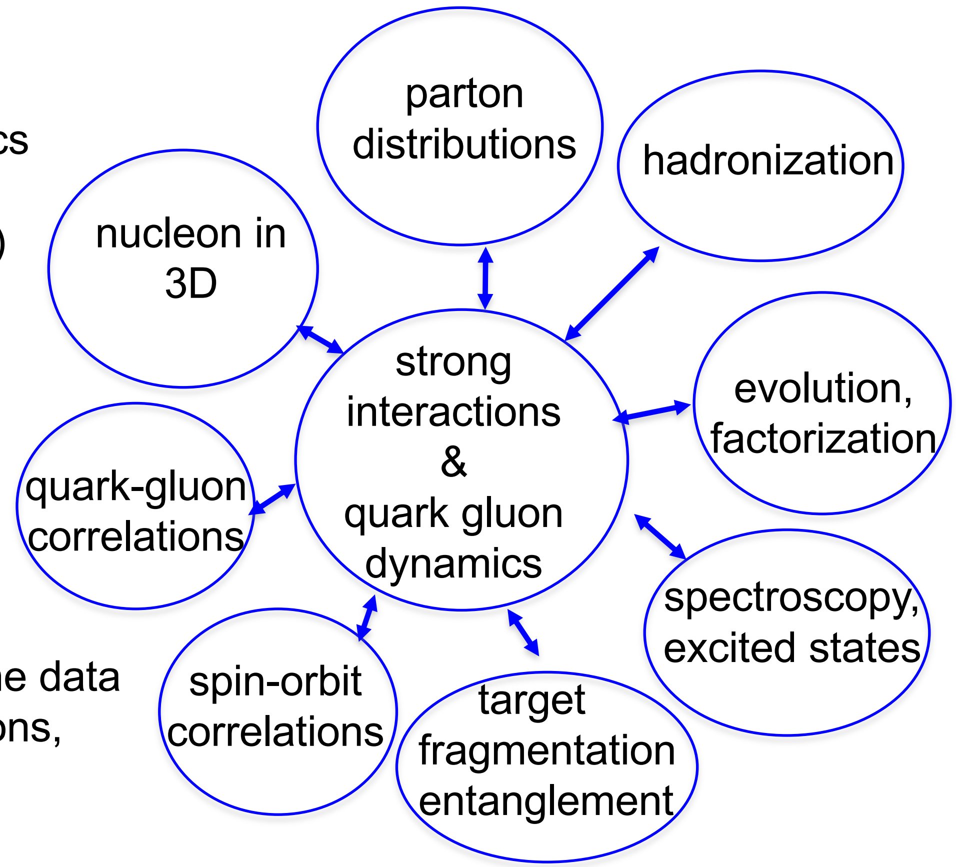
1h SIDIS/DVMP



Understanding stage:
non-perturbative QCD, strong interactions, observables in the kinematics where most of the data is available (all energies, quark-gluon correlations, orbital motion)

2h SIDIS/DVMP



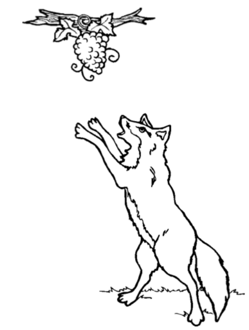


production in SIDIS provides access to correlations inaccessible in simple SIDIS (dihadron fragmentation, correlations of target and current regions, entanglement....)

Projections to motivate the JLab 20+ upgrade

Classify observables, summarize the set of projection from future facilities

1) Identify the flagship measurements that can be done only with 20+ GeV



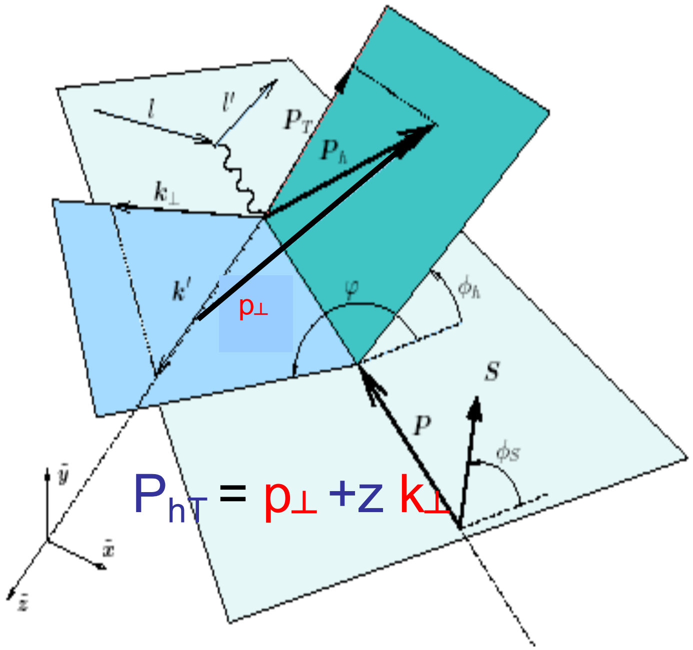
2)Identify the flagship measurements with 22 GeV that can extend, improve the 11 GeV, helping interpretation, multidimensional bins in extended kinematics

3)Identify the measurements with 22 GeV that can set the bridge between JLab12 and EIC (complementarity)

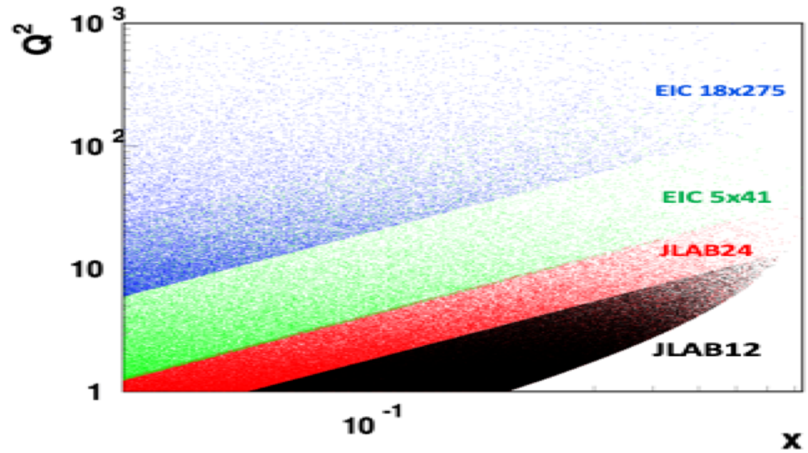
- Produce sets of event for relevant observables (SIDIS, DVCS, Large x,….) and process them using existing detector reconstructuion chains (ex. CLAS12, SoLID,Hall-A/C/D), evaluate count rates, define kinematical coverage and resolutions
  - Identify observables that can provide critical input without detector upgrades
  - Identify critical observables, that require certain detector upgrades

Most importantly: projections teach us what we can do with our JLab12 data, and where we need to combine it with higher energy data

SIDIS kinematical coverage and observables



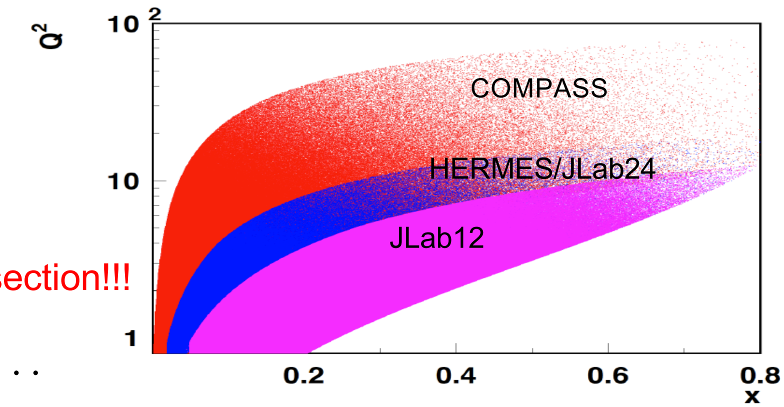
EIC

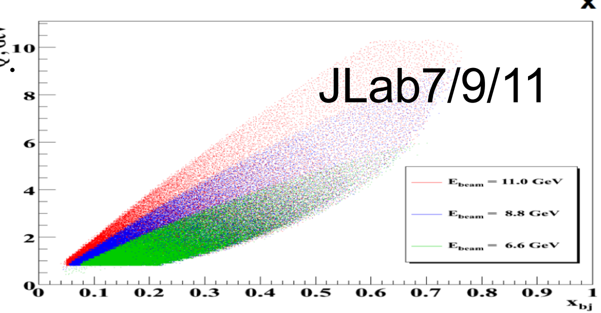


SIDIS experiments measure azimuthal dependence of the cross section!!!

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

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





- Studies of azimuthal modulations give access to underlying 3D partonic distributions
- QCD predicts only the Q^2-dependence of 3D PDFs

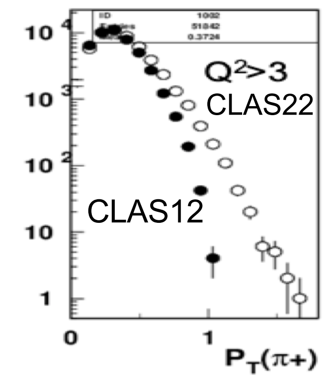
What we learned: missing parts of the mosaic

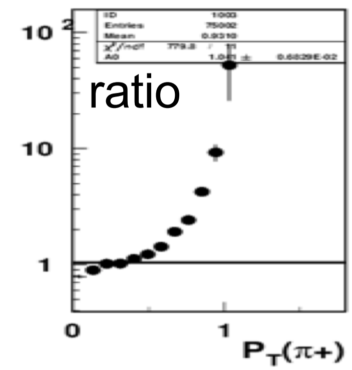
- SIDIS, with hadrons detected in the final state, from experimental point of view, is a measurement of observables in 5D space (x,Q^2,z,P_T,ϕ)
- Collinear SIDIS, is just the proper integration, over P_T,ϕ
- SIDIS observations relevant for interpretations of experimental results:
  1. Understanding the kinematic domain where non-perturbative effects of interest are significant (ex. x,P_T-range)
  2. Understanding of P_T-dependences of observables in the full range of P_T dominated by non-perturbative physics is important
  3. Understanding of phase space effects is important (additional correlations)
  4. Understanding the role of vector mesons is important
  5. Understanding of evolution properties and longitudinal photon contributions
  6. Understanding of radiative effects may be important for interpretation
  7. Overlap of modulations (acceptance, RC,…) is important in separation of SFs
  8. Multidimensional measurements with high statistics, critical for separation of different ingredients
- QCD calculations may be more applicable at lower energies when 1)-7) clarified
- Need a realistic chain for MC simulations of SIDIS to produce realistic projections with controlled systematics

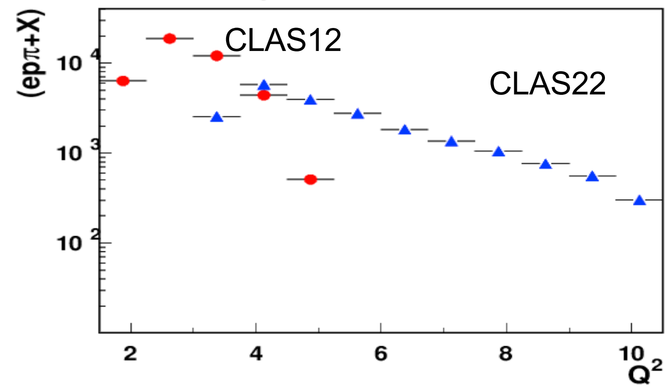
Opportunities with 20+ GeV

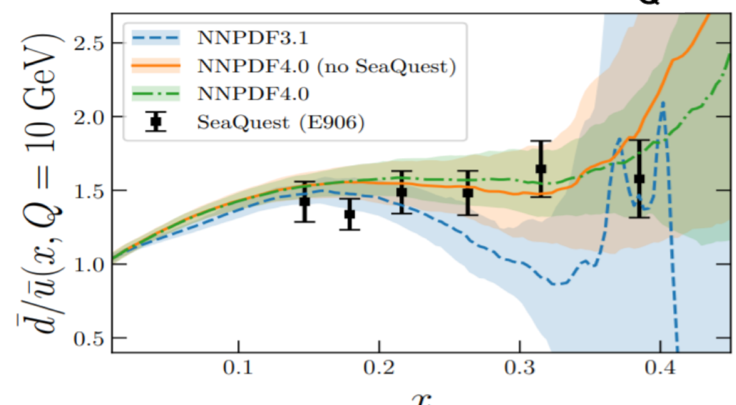
Significantly wider phase space would allow

- Enhance the range in transverse momentum P_T of hadrons
  - Access to P_T-region where the dependence of the k_T-dependences of different flavors (valence and sea) and polarization states is most significant
- Enhance the Q^2 range
  - Increase significant the range of high Q^2, where the theory is supposed to work better, and allow studies of evolution properties
- Enhance the x-range
  - Access the the full kinematical range (x>0.03) where the non-perturbative sea is expected to be significant







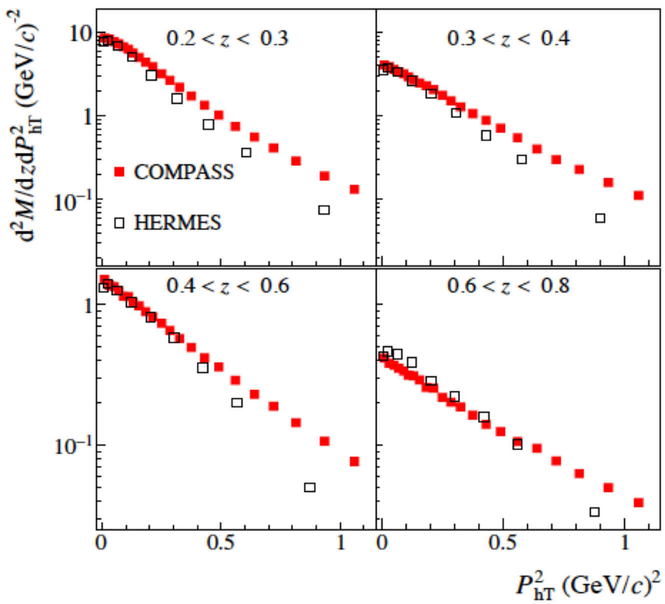


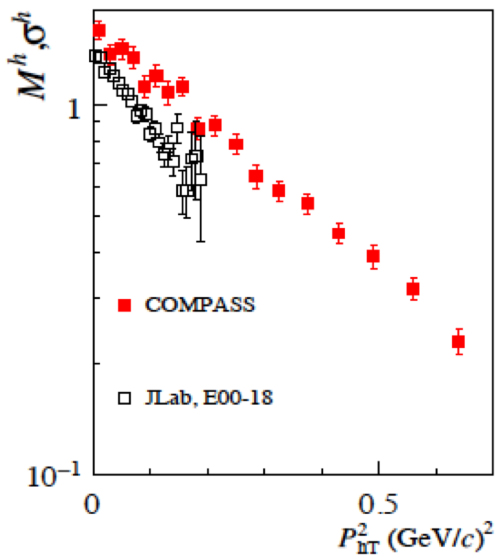
Multiplicities of hadrons in SIDIS

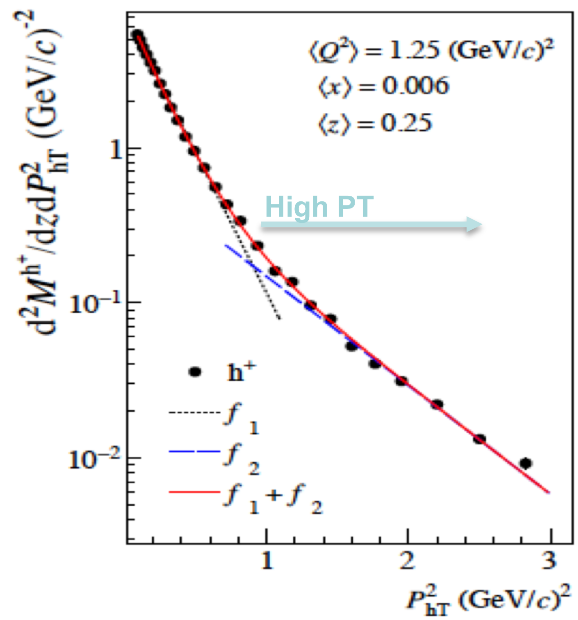
Gaussian Ansatz $\boxed{f_1^q} \otimes \boxed{D_1^{q\to h}} = x f_1^q(x)\, D_1^{q\to h}(z) \dfrac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$

TMDs universal, so what is the origin of the differences observed ?

COMPASS:1709.07374





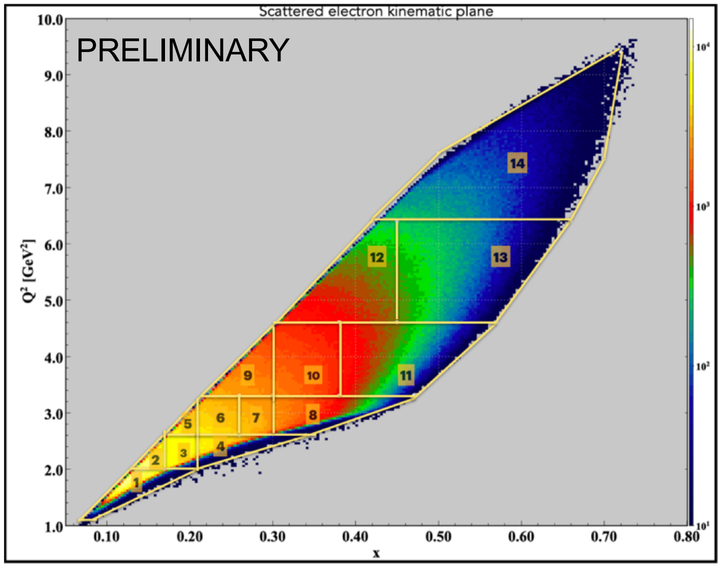


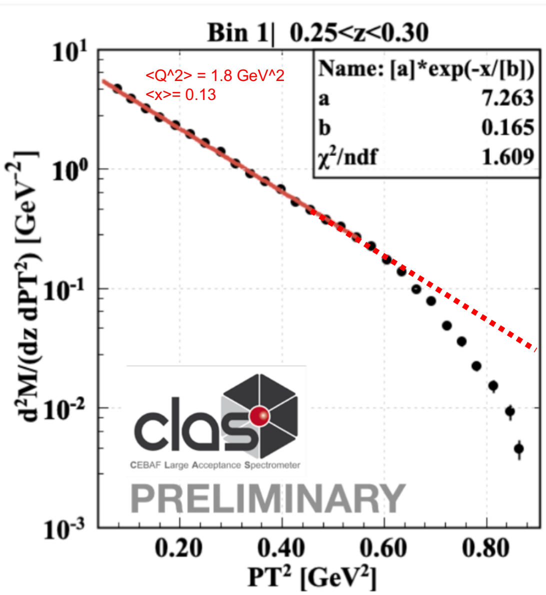
JLab: not enough energy to produce large P_T
HERMES: not enough luminosity to access large P_T

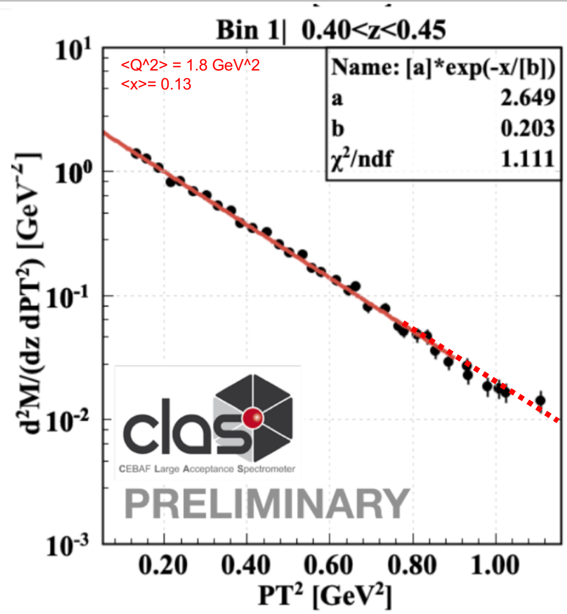
- What is the origin of the "high" P_T (0.8-1.8) tail?

1) Perturbative contributions?
2) Non perturbative contributions?

CLAS12 Multiplicities: high P_T & phase space

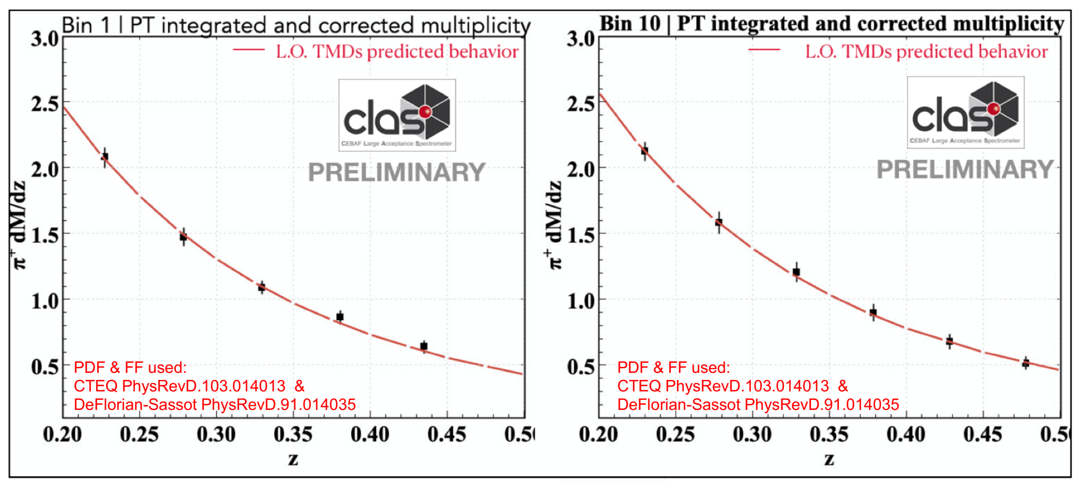






For some kinematic regions, at low z, the high P_T distribution appear suppressed: there is no enough energy in the system to produce hadron with high transverse momentum (phase space effect).

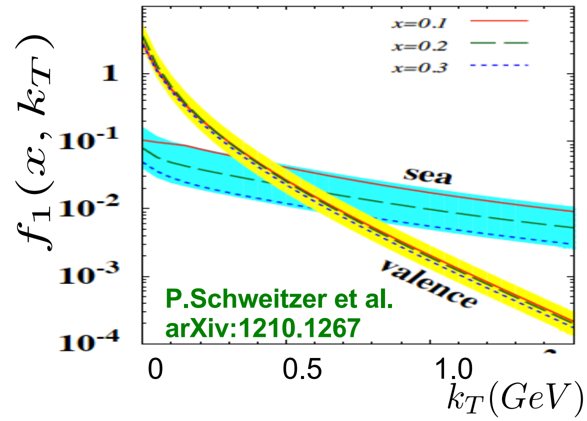
<u>If the effect is accounted, the CLAS data follows global fits.</u>

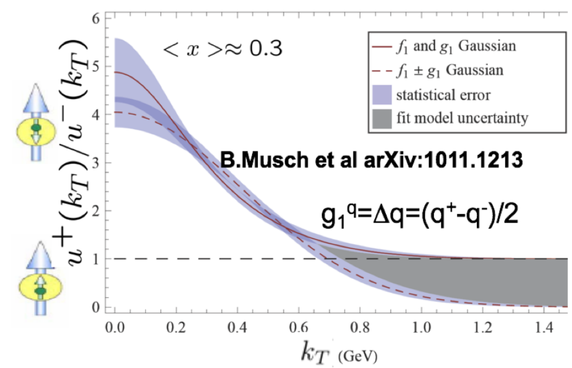


Most critical with JLab20+: access to large P_T

List if of possible sources of large non-perturabative P_T in SIDIS

1. Non perturbative sea
2. Wider in k_T u- distributions (need long.pol.target)
3. Wider in k_T d-quark distributions
4. Wider in P_T longitudinal photon contributions ($F_{UU,L}$)
5. Vector meson decay pions (low P_T) vs direct pions (high P_T)





Large P_T-coverage critical for sorting out flavor dependence of k_T-distributions of TMDs!!!

Azimuthal distributions in SIDIS (unpolarized)

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

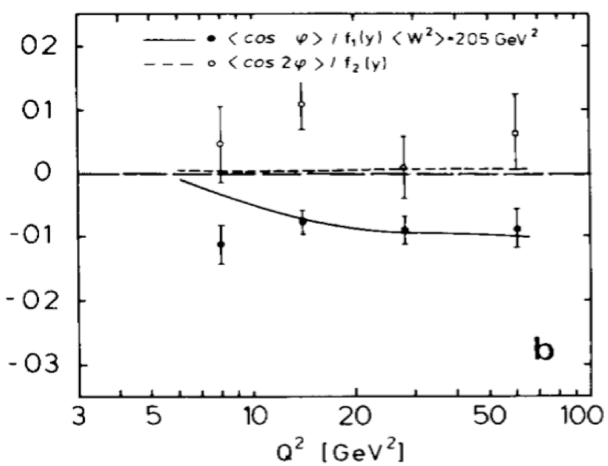
H.T. H.T.

$$\frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h}$$

H.T.

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

EMC-1983 (PL,v130,118)



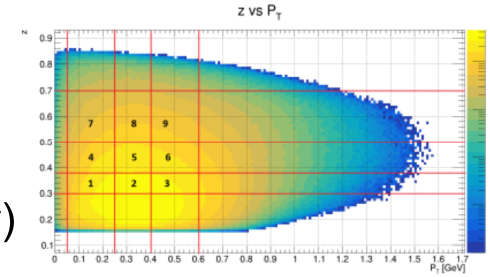
Observables: - Azimuthal Moments - Multiplicity

$$\boxed{\frac{d^4M^{\pi^\pm}(x,Q^2,z,P_T^2)}{dx\,dQ^2\,dz\,dP_T^2}=\left(\frac{d^4\sigma^{\pi^\pm}}{dx\,dQ^2\,dz\,dP_T^2}\right)\Big/\left(\frac{d^2\sigma^{DIS}}{dx\,dQ^2}\right)}$$

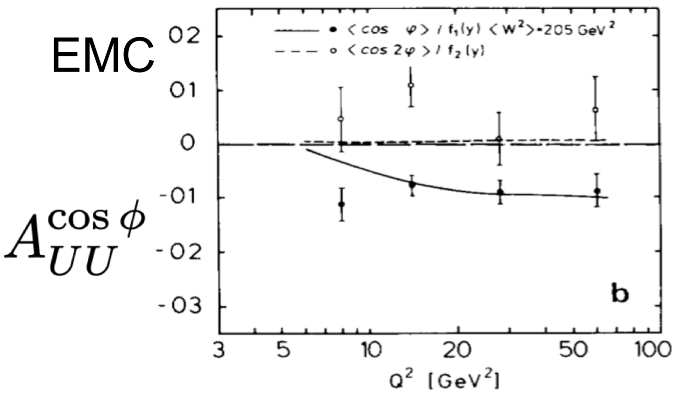
$$m^h(x,z,P_T^2,Q^2)=\frac{\pi F_{UU,T}(x,z,P_T^2,Q^2)+\pi\epsilon F_{UU,L}(x,z,P_T^2,Q^2)}{F_T(x,Q^2)+\epsilon F_L(x,Q^2)}$$

- Quark-gluon correlations are significant in electro production experiments (even if at high energy).
- Large cosϕ modulations observed in electroproduction (EMC, COMPASS, HERMES) may be a key in understanding of the QCD dynamics.

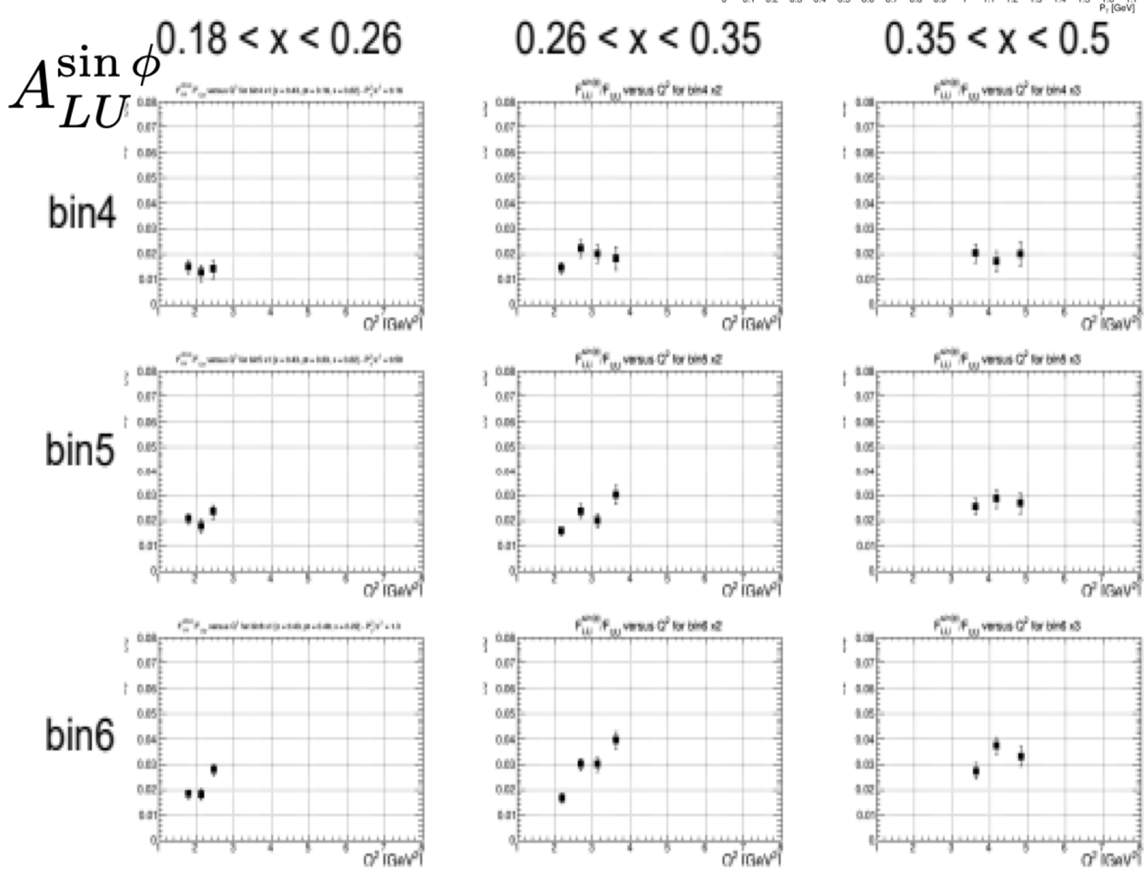
Attempts to understand Q^2-dependence of HT



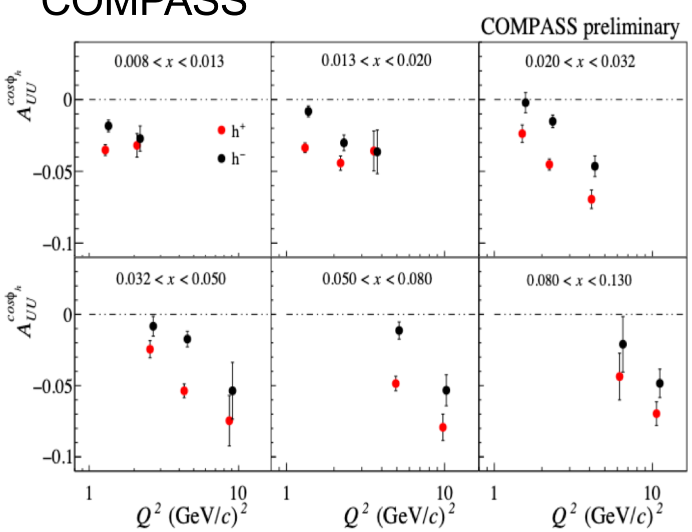
EMC



CLAS12(preliminary)



COMPASS



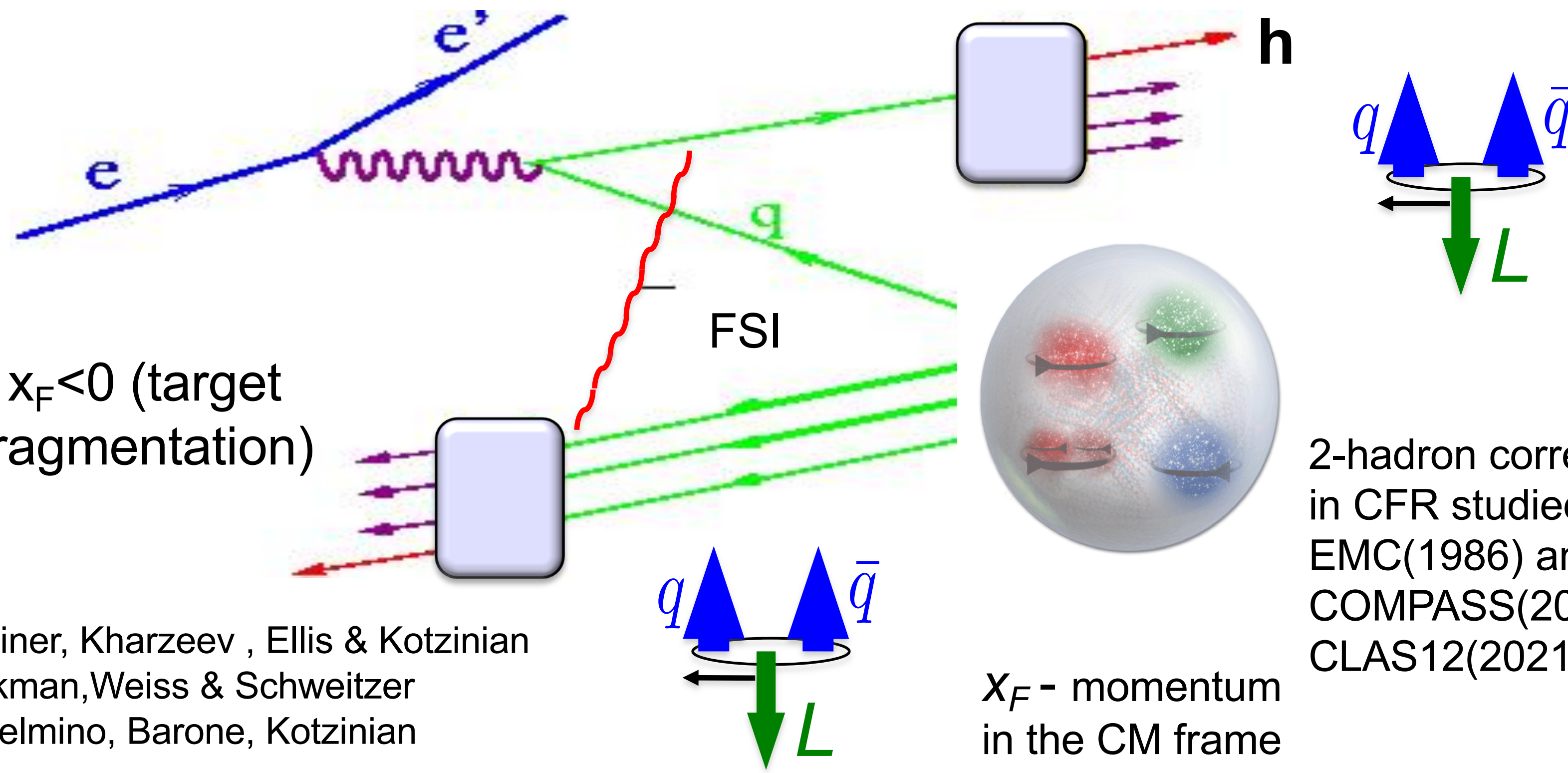
The ratios of SFs (to F_{UU}) are not decreasing with Q!!!
The HT observables, don't look much like HT observables, something missing in understanding
Understanding of these behavior can be a key to understanding of other inconsistencies

Hadron production in hard scattering

x_F – fractional momentum in the CM frame

x_F>0 (current fragmentation)

X. Artru & Z. Belghobsi



x_F<0 (target fragmentation)

Karliner, Kharzeev , Ellis & Kotzinian
Strikman,Weiss & Schweitzer
Anselmino, Barone, Kotzinian

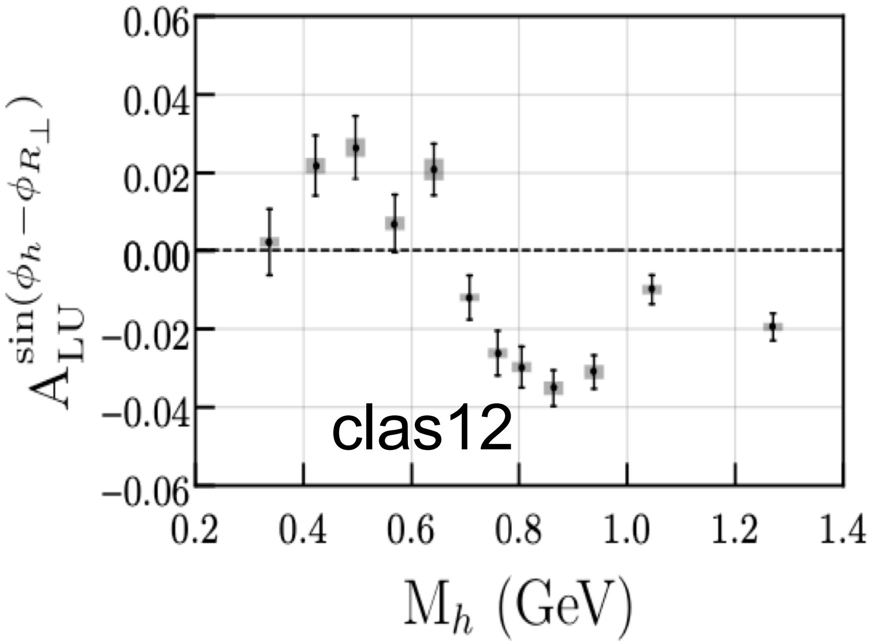
x_F - momentum in the CM frame

2-hadron correlations in CFR studied in EMC(1986) and COMPASS(2015) CLAS12(2021)

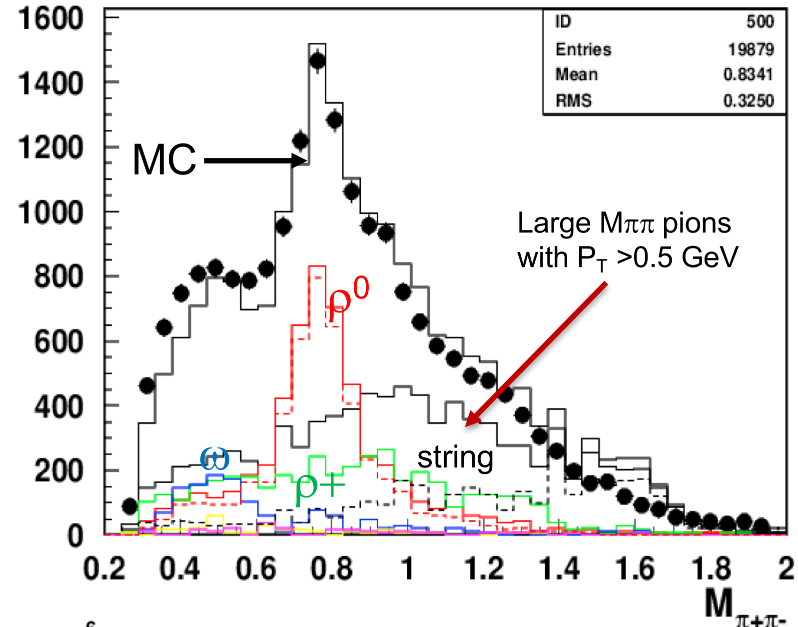
Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles

2 hadron correlations in CFR $ep \rightarrow e'\pi^+\pi^-X$

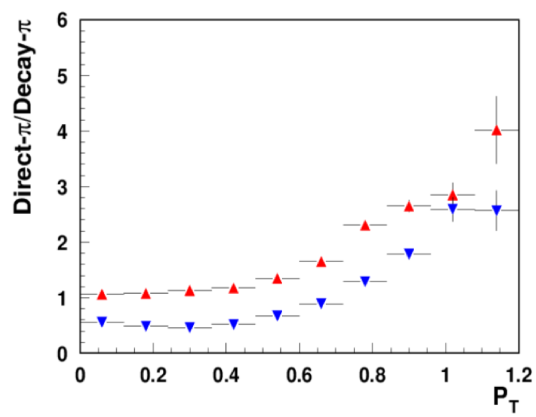
T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)



Contributions to π^+ in $e'\pi^+\pi^-X$ sample from different channels



- Spin-azimuthal correlations in hadron pair production are very significant
- Hadron pairs in SIDIS (true from JLab to LHC) are dominated by VM decays (therefore single hadron channel too)
- Direct pions dominate only at relatively high P_T, (P_T >0.6-0.7 GeV)



theory

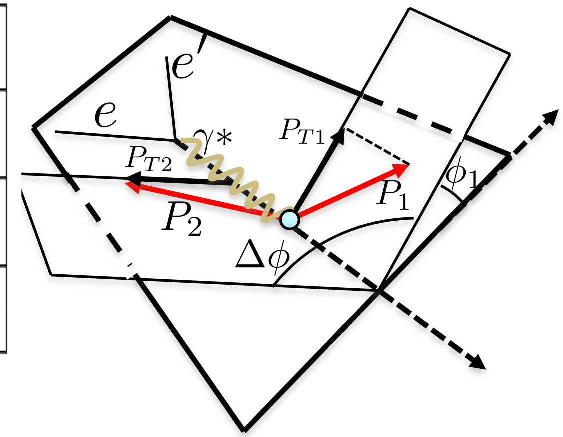
CFR/TFR correlations in 2 hadron production

In publication

M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)

$$\mathcal{A}_{LU} = -\sqrt{1-\epsilon^2}\,\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

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



- Depolarization factor becomes negligible at high energies at large x

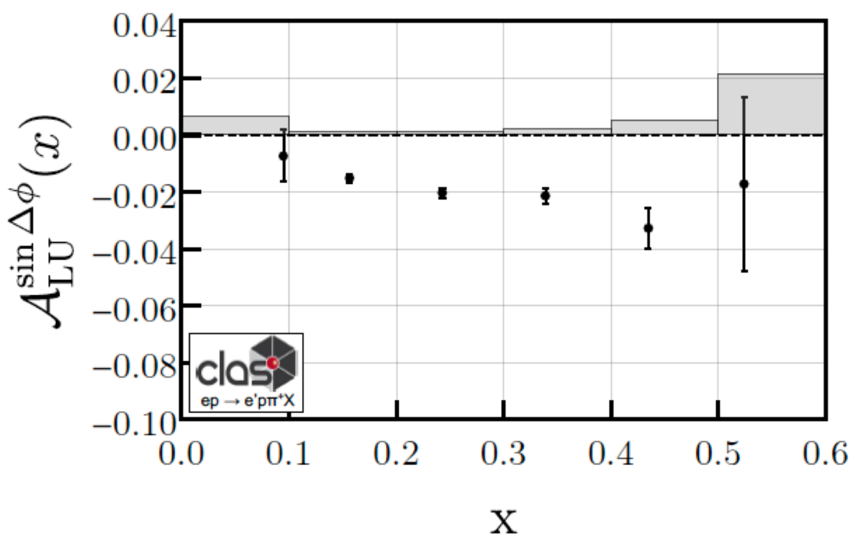
$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2}\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}$$

$$\times\frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h}D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\sin\Delta\phi,$$

correlation

modulation



The correlation is most significant at large x, where the valence quarks (non-perturbative sea?) most relevant

"Only JLab" measurements (suppressed at EIC)

Twist-2

$\boxed{A_{LL} = F_{LL}/F_{UU}}$

Double spin asymmetries in hadron production CFR and TFR

$\boxed{\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} \sin\Delta\phi}$

Beam spin asymmetries in correlations of CFR and TFR

Twist-3

$\boxed{\sin\phi_h\, F_{LU}^{\sin\phi_h}}$

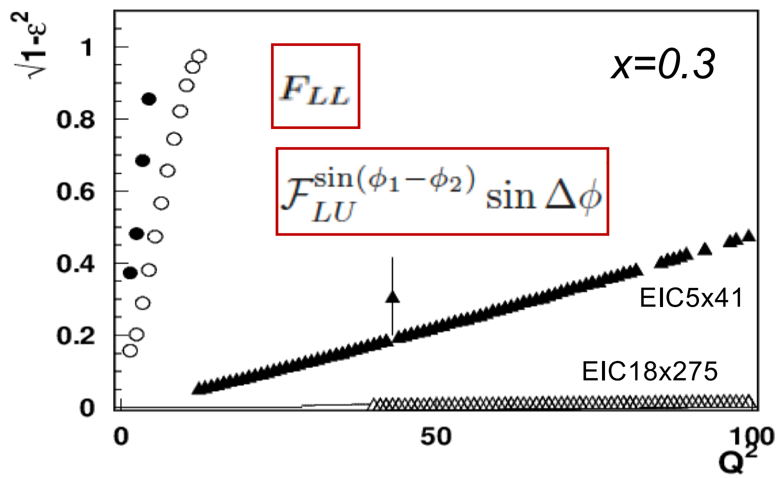
$\boxed{\mathrm{A}_{\mathrm{LU}}^{\sin\phi_{R_\perp}}}$

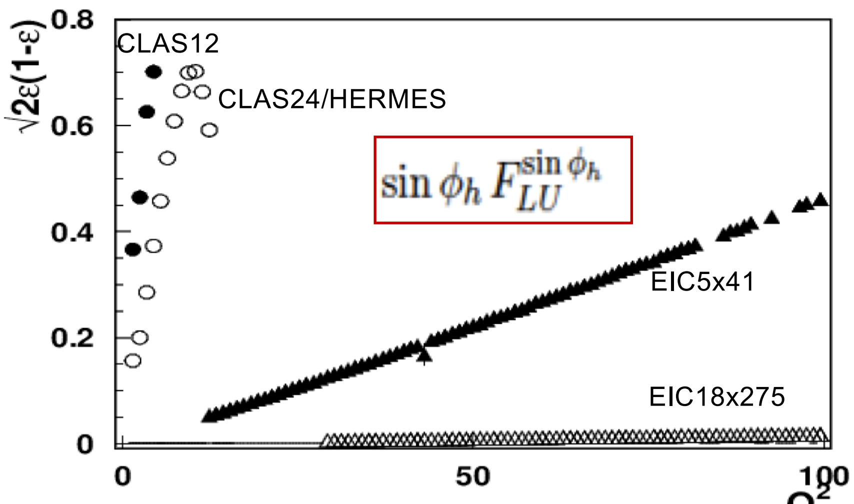
Beam spin asymmetries in CFR (single and dihadron)

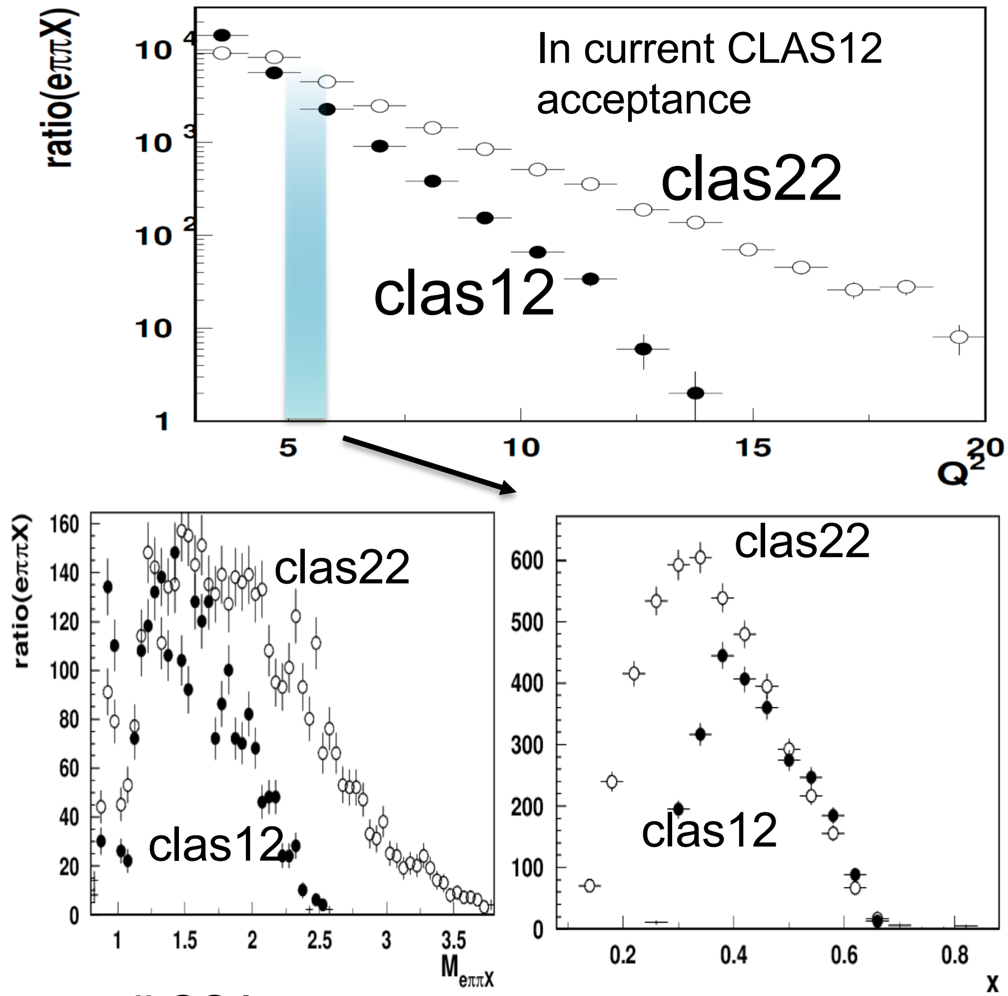
Examples in slides (10-15)

Exclusive processes in the x>0.1 domain, may most be in this category, due to resolutions and rapidly decreasing x-sections at higher energies

Beam SSAs & Kinematic suppression at large x



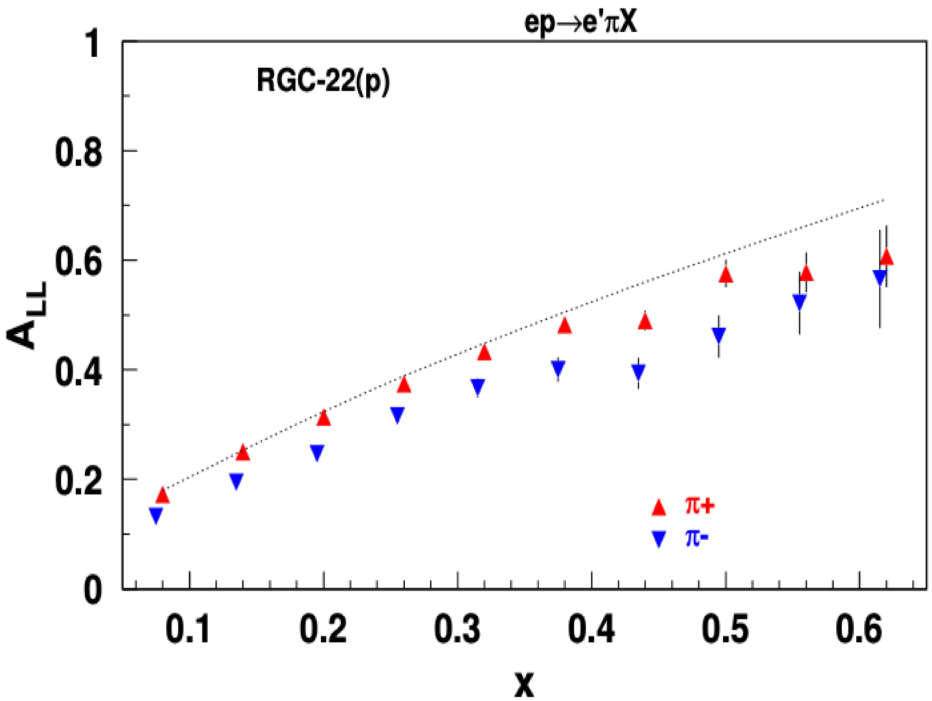


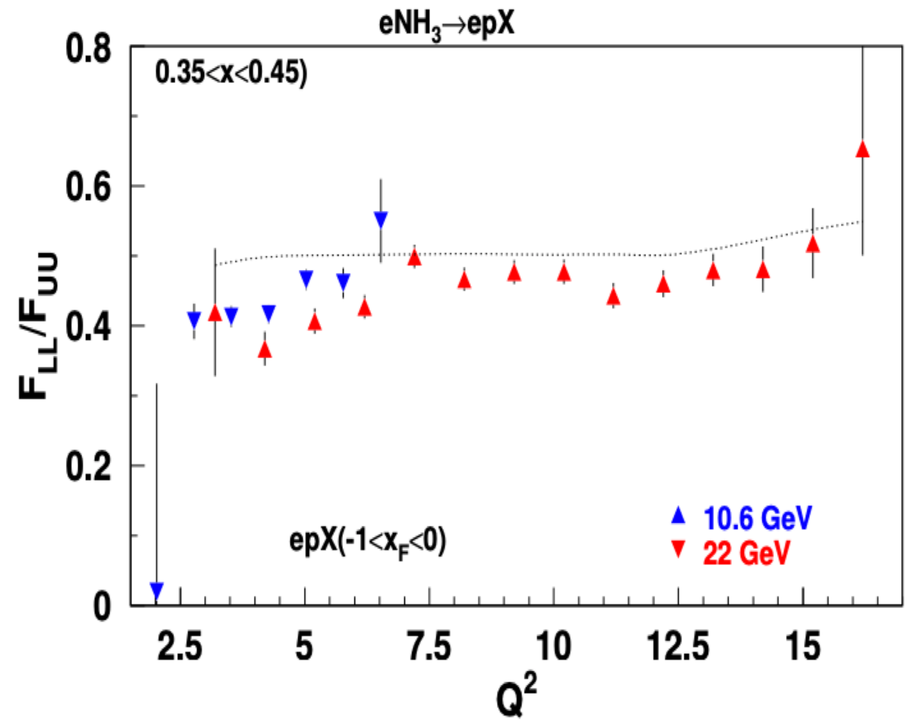


- Fixed target experiments are sensitive to all SSAs
- Higher energy opens up the phase space allowing access to, sea and large Q^2
- Measurements of beam SSAs (+some others) at large x, will be challenging at EIC

Full simulation of CLAS12 at 22 GeV with pol. target

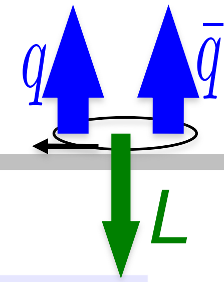
/volatile/cebaf24/sidis/reconstructed/clas12/lpol-target/..





- Studies of evolution of observed double spin asymmetries will be a critical task in validating the QCD predictions $g_1(x,k_T)$-studies CLAS12
- Asymmetries measured with input polarized and unpolarized PDFs, can be used to test the flavor decomposition capabilities
- Kinematical correlations, even for small bins relevant (multidimensional bins critical)

3D PDFs: Common features



Rodini & Vladimirov, arXiv:2204.03856, J. O. Gonzalez-Hernandez, T. Rogers, N. Sato, arXiv:2205.0575,…

CS kernel discribes the interaction of out-going parton with the confining potential
Provides nonperturbative part of evolution for TMDs

$$Q^2 \frac{dF(x,b;Q)}{dQ^2} = -\left(\frac{\gamma_V(Q)}{2} + \mathcal{D}(b,Q)\right) F(x,b;Q)$$

quark AD
perturbative
known at N^{3}LO

CS kernel
nonperturbative

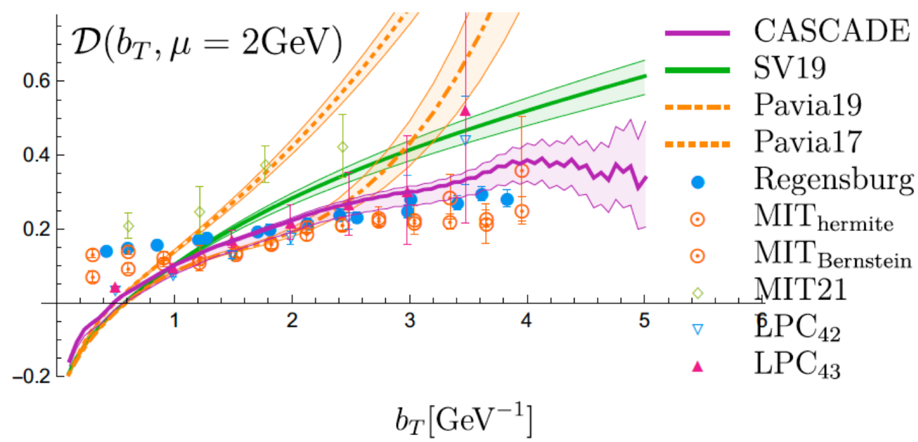
TMD distribution
any tw2
many **tw3**

Includes "e"

nonperturbative Q and x can be factorized

$$F(x,b;Q) = R[\mathcal{D},Q]F(x,b)$$

- R is known function
- $\mathcal{D}$ can de determined directly from data
  - requires dense coverage in p_T
  - requires proper adjustments of (x,z,Q)



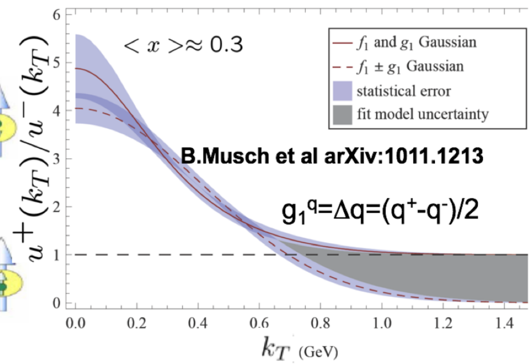
The Collins Soper kernel, defining the evolution properties of TMDs related to non-perturbative q-q
Detailed studies of evolution properties of observables in different x-range will be needed

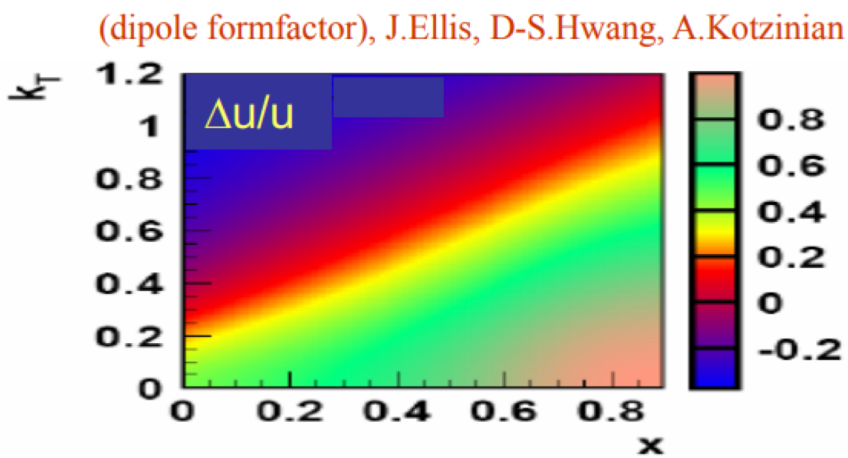
Unknown "known" f_1,g_1 TMDs

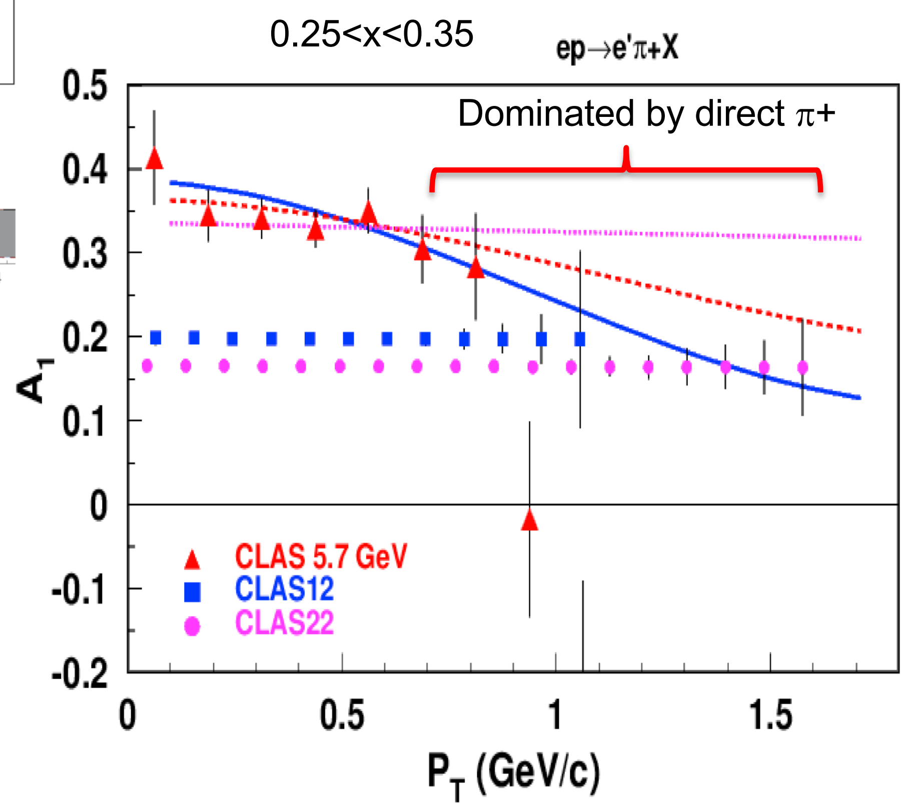
	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$

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

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





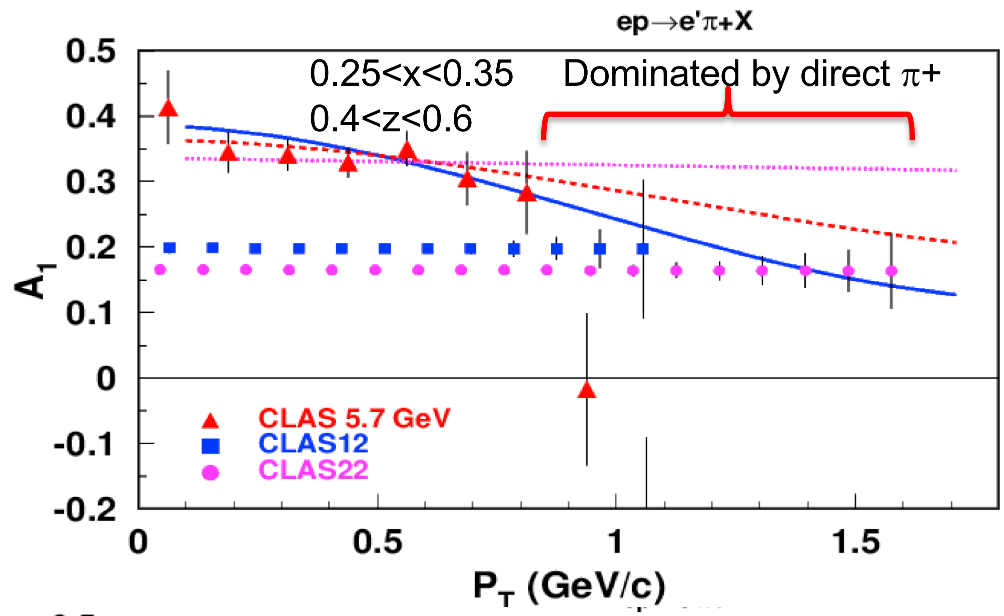


- Models and lattice predict very significant spin and flavor dependence for TMDs
- Large transverse momenta are crucial to access the large k_T of quarks
- Several CLAS12 proposals dedicated to $g_1(x,k_T)$-studies CLAS12
- Understanding of k_T-dependence of g_1 will help in modeling of f_1

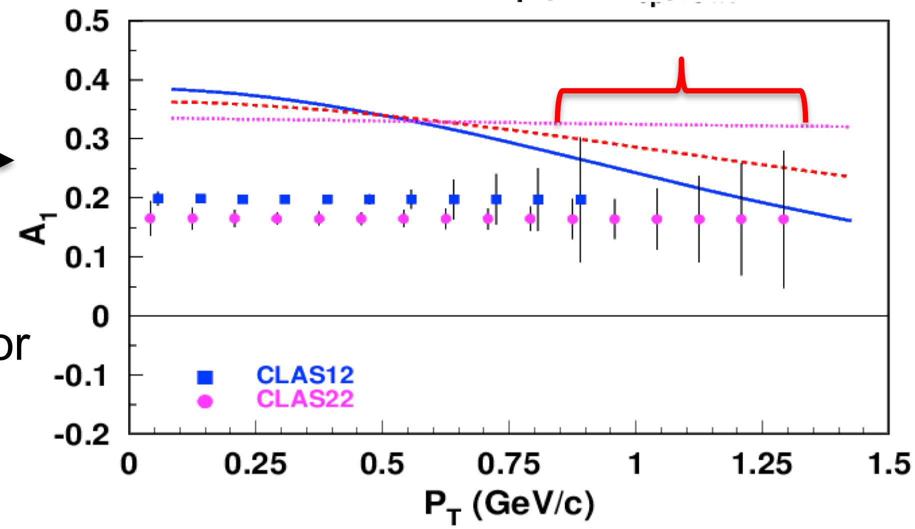
Impact of limitations from theory

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

- Gain with 22 GeV will be more critical with additional kinematical cuts imposed by theory



$P_T/z/Q<0.5$



More theory limitation, may convert the observable from major improvement (type 2) to only possible with 20+ GeV (type 1)

Summary

- Measurements of SFs from the azimuthal distributions of final state hadrons in electroproduction, requires high statistics in multidimensional bins (ex. Q^2-dep.)
- Extending JLab measurements to a wider range in Q^2 and P_T with energy upgrade, will be crucial in studies of evolution properties of underlying PDFs, and separation of higher twist contributions, critical for understanding the QCD dynamics
- Better understanding of the process of extraction of final physics quantities (motivating the measurements) can help to optimize the output format of the data (ex, multidimensional binning, providing events…)
- The 3D physics with SIDIS and hard exclusive production processes can provide a set of flagship measurements
  - Measurements superior at JLab24, in the kinematics where non-perturbative effects are relevant, will compete both with JLab12 (exclusive processes) and EIC (SIDIS in perturbative regime)
- The data used in production of projections should be available, to allow reproduction and further improvement of those projections

<u>Development of a procedure for making transparent and reproducible projections will be important for making a strong case for future experiments, and JLab20+ in particular (combined effort with computing+lattice+theory).</u>

Support slides…

Organization of projections: “Process files” txt files

Organizing a common storage

process

/volatile/cebaf24/sidis/generated/polarized-minus-22GeV-proton/

/polarized-plus-22GeV-proton/

/nitrogen-22gev-proton/

/carbon-22gev/

detector data-set

/reconstructed/clas12/lpol-target/ rgc-pplus/ inbending/gev22/hipo

/txt

/outbending/…

/rgc-pminus/…

/proton-target/…

/deuteron-target/…

/carbon-target/…

/nitrogen-target/…

/hep/…

/hsg/..

Reconstructed files stored in both reconstruction format (hipo files for clas12) and txt format

Organization of projections: “Process files” txt files

(Timothy Hayward)

Come up with as general as possible set of variables
1) event info (run#,event#,helicity)
2) 3 momenta of involved particles (momentum, polar angle, azimuthal angle)
3) all relevant variables describing the process (x,Q^2,y,W,z,PT,f, all relevant missing and invariant masses, more complex variables x_Feynman, rapidity,…)

/volatile/cebaf24gev/sidis/reconstructed/clas12/lpol-target/rgc-pplus/inbending/gev22/txt/
rgc_pplus_inbending_22GeV_eppi+X.txt
rgc_pplus_inbending_22GeV_epi+X.txt
rgc_pplus_inbending_22GeV_epX.txt

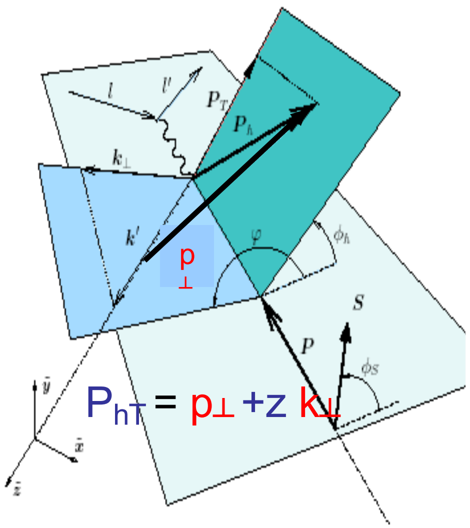
Ex. *ep->e’π+X*

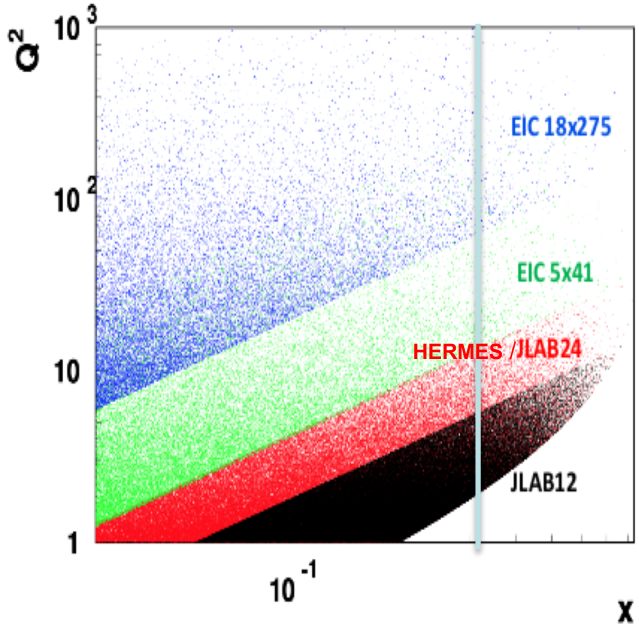
Run#,	ev#	helicity	e_p (GeV),:	e_theta	e_phi	vz_e	p_p,	p_theta,	p_phi ,	vz_p	Q2 (GeV2),	W (GeV)
11	57	0	4.51685	0.45048	3.08727	0.01404	0.93713	0.22354	0.1606	-5.56464	19.82692	3.72308
11	58	0	8.58741	0.17935	1.26198	-4.51106	1.92747	0.34164	4.75543	-0.76261	6.0608	4.47089
11	62	0	0.80435	0.59841	2.94635	-0.65328	1.95437	0.4588	5.3786	-4.55974	6.1499	5.8741
11 ………..												

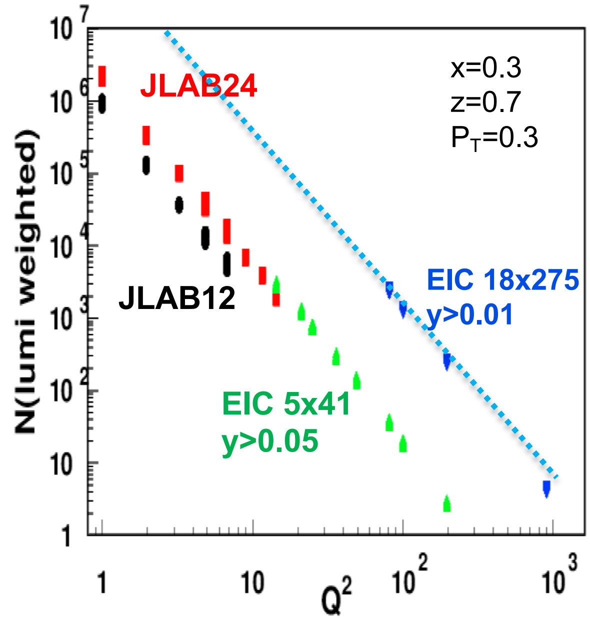
Final analysis from “process files”

- Process files, even in the text version occupy few Gb
- We can come up with a header (JSON, HepMC,…) so the analysis software will read it without major efforts.

SIDIS kinematical coverage and observables







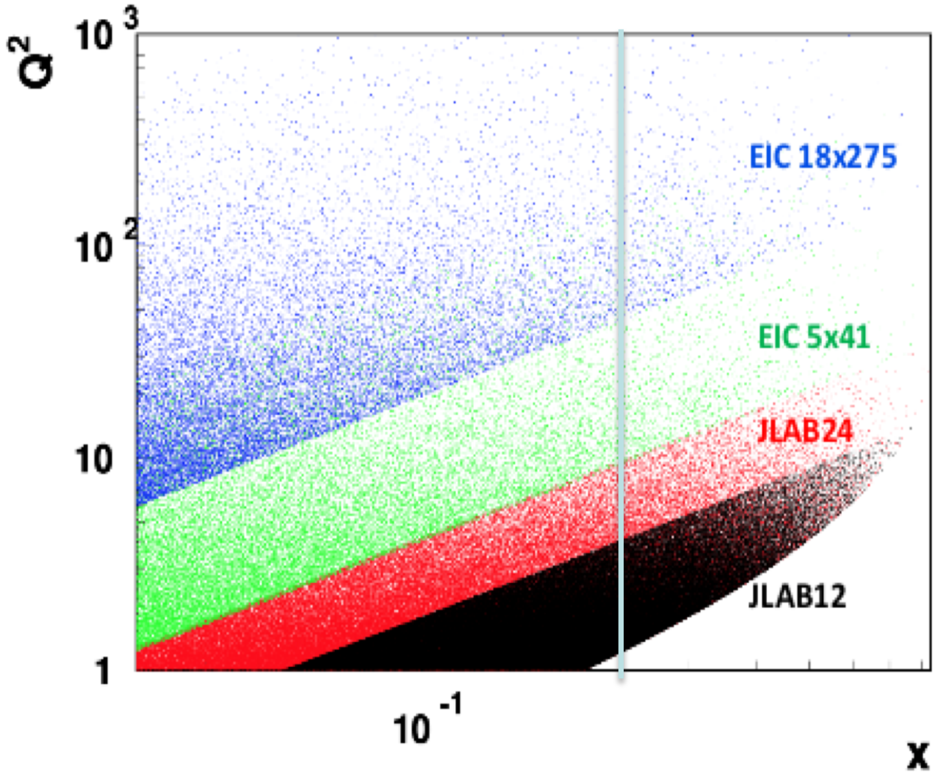
Crucial to evaluate counts in the fiducial region (resolutions, acceptance,RC,…)

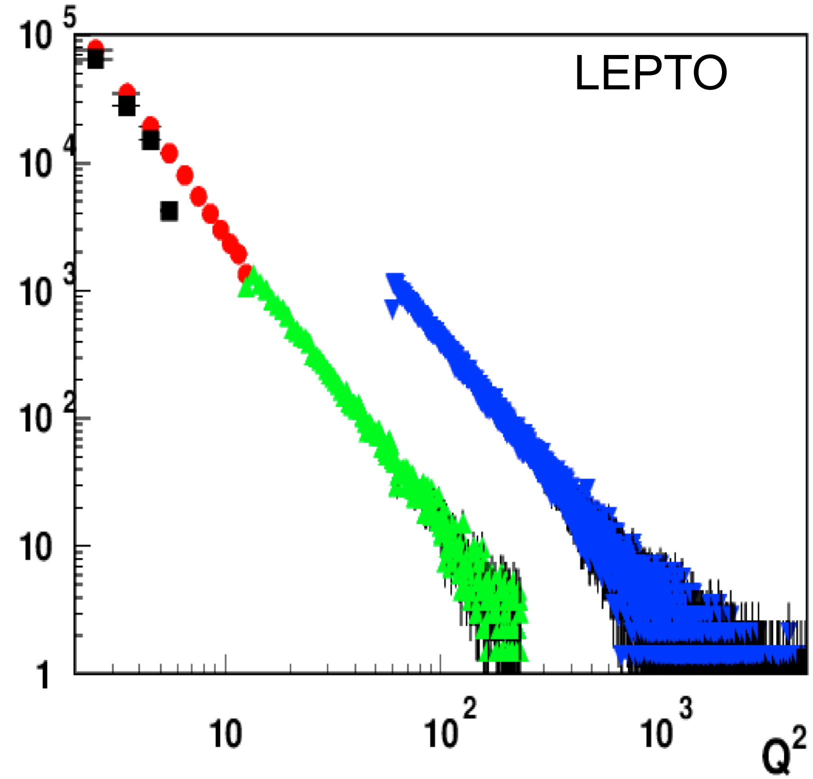
$$\sigma \propto F_{UU} + P_b\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi + P_t\epsilon F_{UL}^{\sin 2\phi}\sin 2\phi + \dots$$

- Higher energies open the phase space for large transverse momenta and Q^2, and lower x, but move events to lower y
- Wider range in Q^2- allows evolution studies of 3D PDFs
  - Higher statistics, better resolutions vs wider range in EIC (complementary)

From JLab to EIC: complementarity

2D → slice in x=0.3





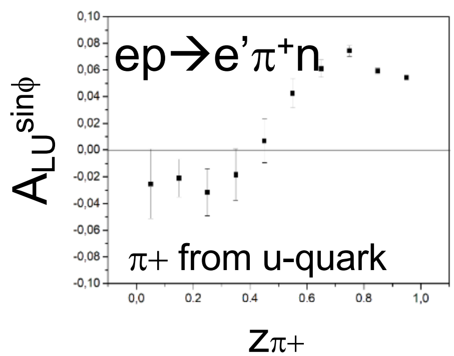
- Understanding of Q^2-dependence of multiplicities crucial for interpretation
- JLab at 24 GeV will provide critical input in evolution studies of TMDs
- Higher Q^2-coverage of “Low s” EIC running will provide validation of evolution studies at JLab at large x

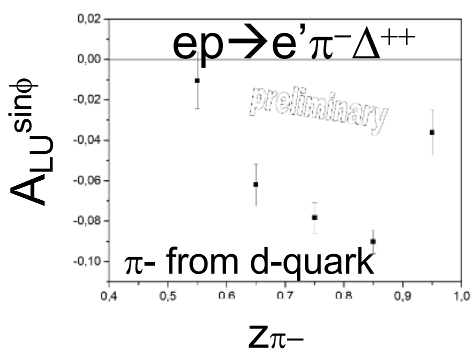
A_{LU}:New look at SSAs in ep→e'πX

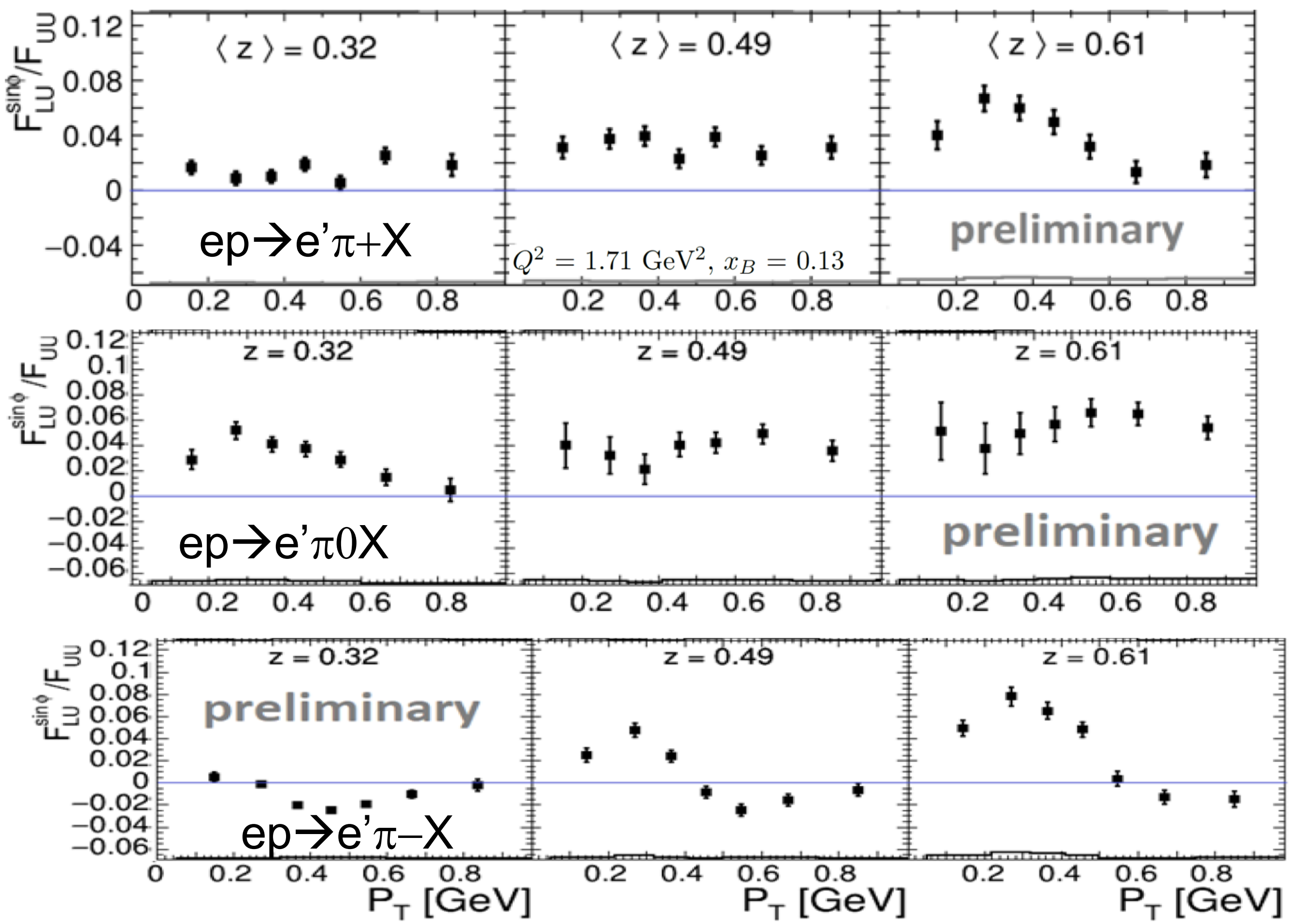
S. Diehl

Higher Twist PDFs

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







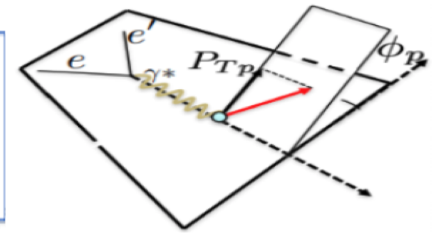
Single beam SSA tends to change the sign, when the observable is dominated by the struck u-quarks.
At small P_T the counts are dominated by VMs coming fro u-quarks

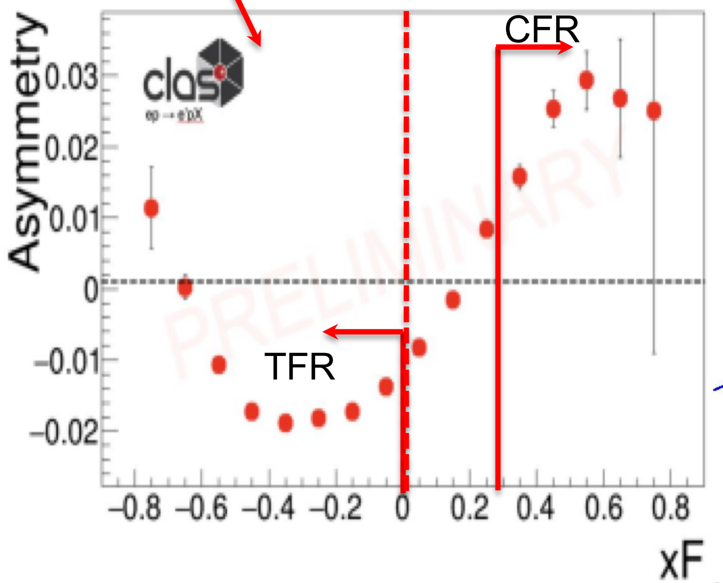
SSA in ep→e’pX production

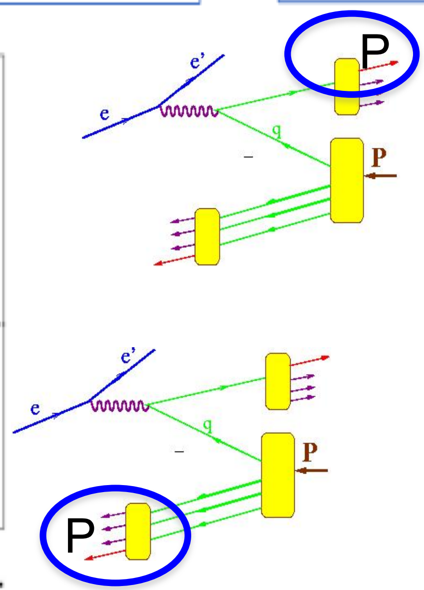
F. Benmokhtar (CPHI-2022)

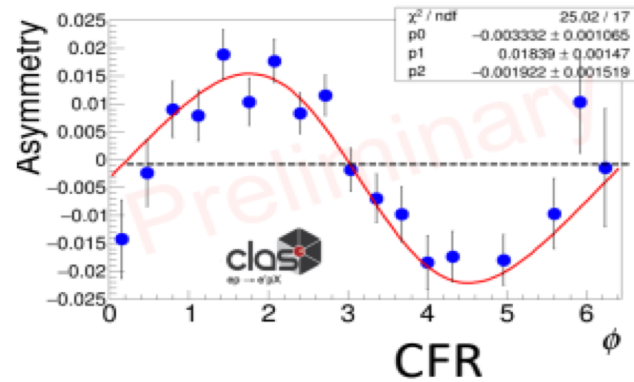
Nq	U	L	T
U	$\hat{u}_2^{\perp h}$	$\hat{l}_2^{\perp h}$	$\hat{t}_2, \hat{e}_2$
L	$\hat{u}_{2L}^{\perp h}$	$\hat{l}_{2L}^{\perp h}$	$\hat{t}_{2L}, \hat{e}_{2L}$
T	$\hat{u}_{2T}^{\perp h}, \hat{u}_{2T}^{\perp h}$	$\hat{l}_T, \hat{l}_{2T}^{\perp h}$	$\hat{t}_{2T}^h, \hat{e}_{2T}^h, \hat{t}_{2T}^{\perp h},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

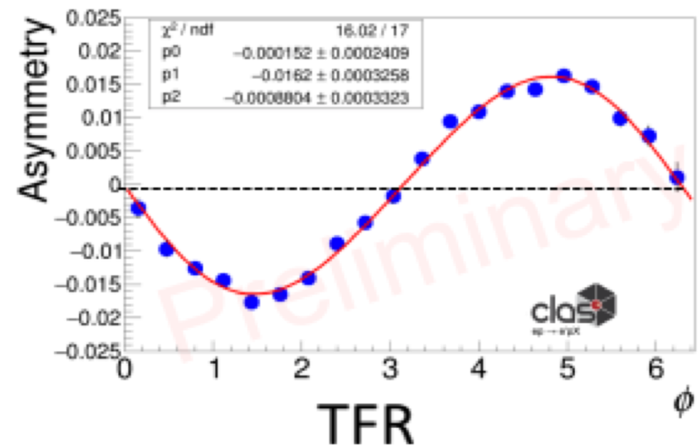
$$A(\phi)_{LU} = \frac{1}{p}\left(\frac{N^+ - N^-}{N^+ + N^-}\right) \rightarrow F_{LU}^{\sin\phi_h} = \frac{A(\phi)_{LU}}{\sqrt{2\varepsilon(1-\varepsilon)}}$$











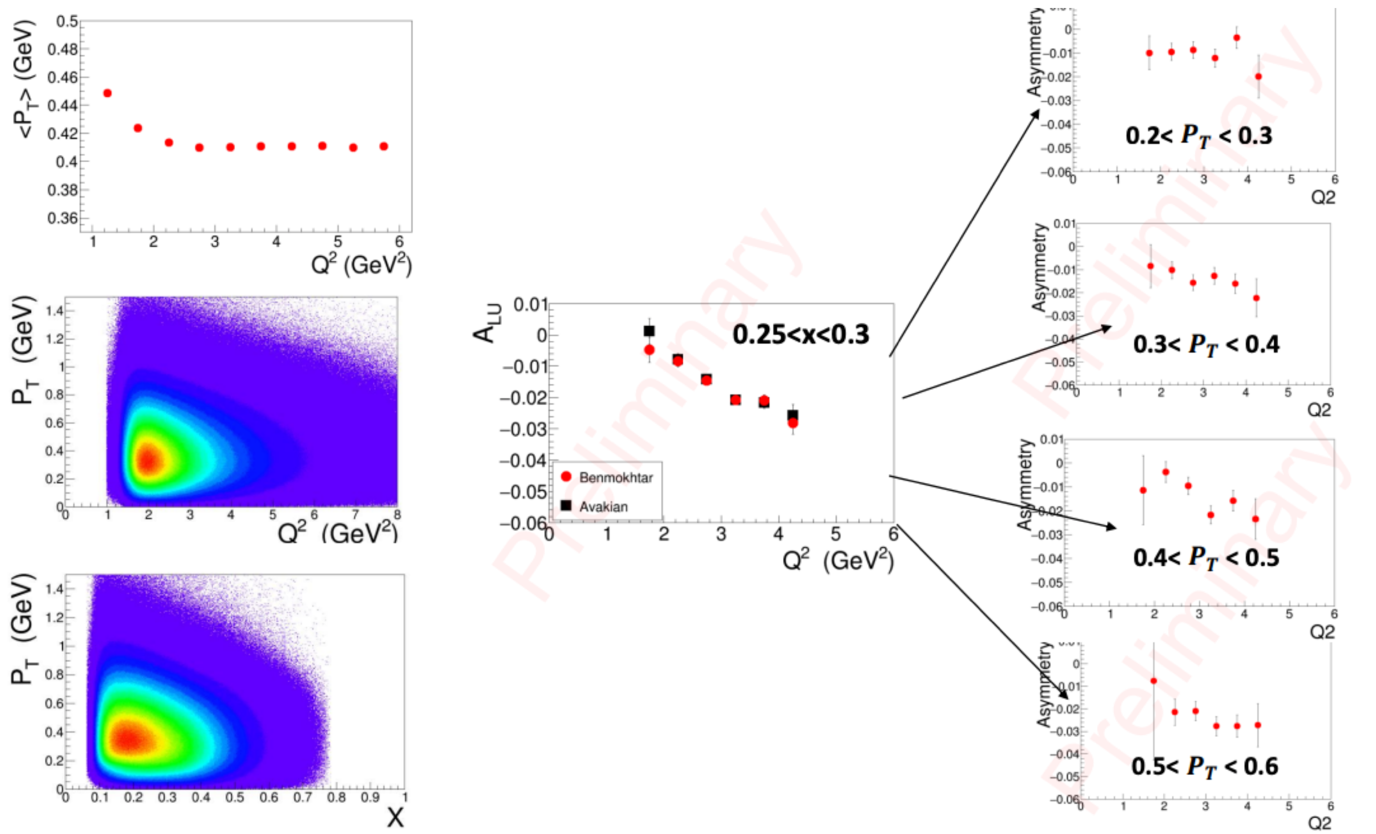
- The SSA, clearly changing the sign, may be used to define separation of TFR and CFR regions
- More baryons in the TFR, mesons in the CFR

Evolution in TFR

Fatiha's talk at CPHI-2022

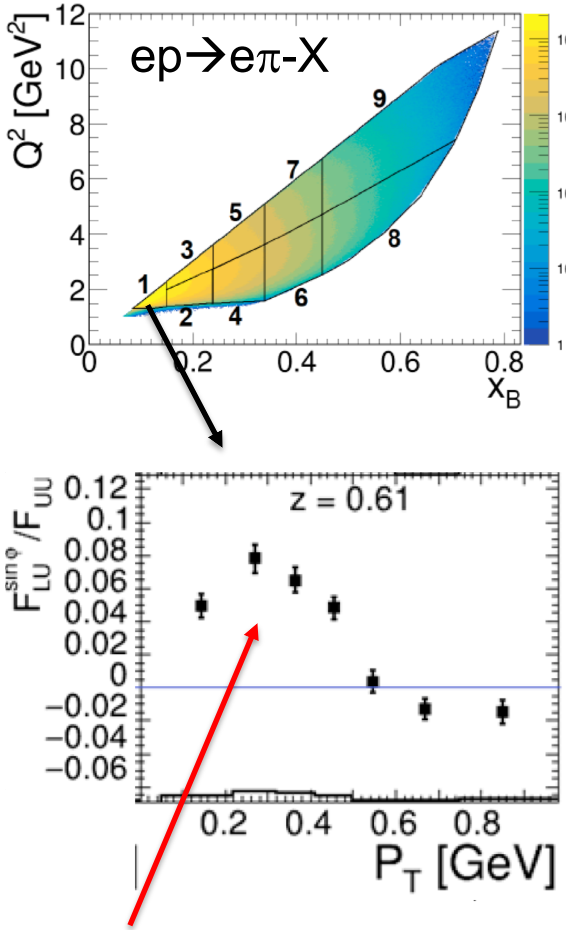
https://indico.jlab.org/event/498/contributions/9470/attachments/7650/10679/Benmokhtar-ep-epX-CPHI-2022c.pdf

***More Q^2* Dependence Studies**



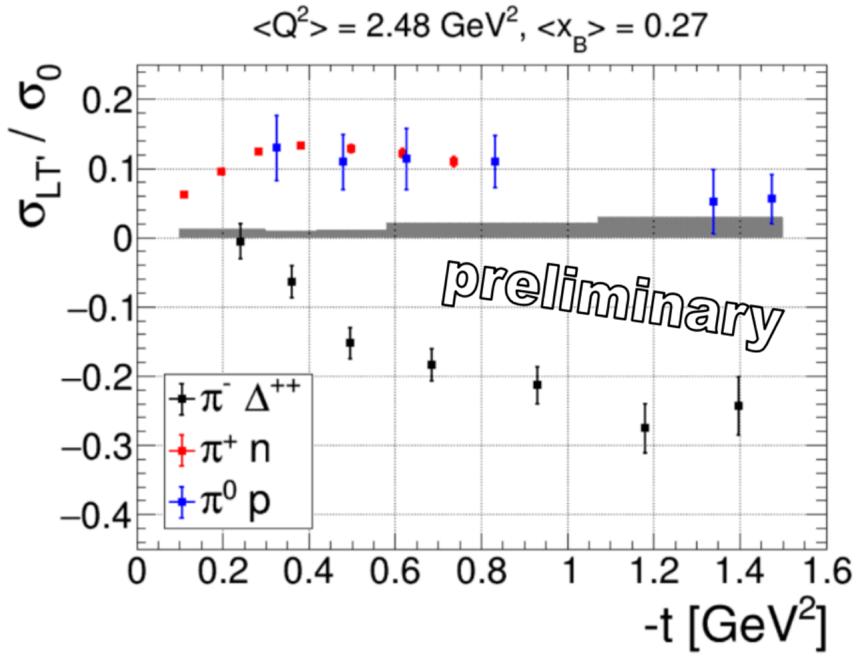
Accounting for correlation between Q^2 and P_T

Multidimensional measurements



Low P_T dominated by VM decays from u-quarks

Beam SSAs as a tool to access the longitudinally polarized quarks



π- has sensitivity to polarized d-quarks, but require multidimensional measurements

Projections for involved processes

Steps for making transparent, reproducible projections, to convince ourselves, first, before trying to convince others

- Define the cross sections for a given process
  - Collect realistic sets of Structure Functions (to be stored on common disk space)
  - Test with existing data (HERMES/CLAS/….)
  - Test with available full event generators (PYTHIA,…)
- Generate events of interest base on x-section defined by SFs
- Reconstruct particles in a given framework (CLAS12/SoLID/Hall-A/C/D) with actual resolutions and phase space (to be stored on common disk space)
- Make projections of extraction of relevant objects from the reconstructed data sets, with a well documented set of assumptions

Ex. of SIDIS with single hadron production for polarized targets

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

Making projections: extraction procedure

Pseudo data set (counts)

Some prediction (parameterization?)

Extraction procedure

Projection for measurements

Extraction procedure should have clear definition of systematics

- <u>The role of multidimensional measurements should be well defined, accounted in the extraction</u>
  - The same parameterization used in production of data and extraction of TMDs will have practically unconstrained systematics
  - Using statistical errors from simulation to evaluate the errors on a given TMDs can produce absolutely unrealistic projections, in particular in boundaries.

Making projections: data set

Pseudo data set (counts)

Some prediction (parameterization?)

Extraction procedure

Projection for measurements

Data set

Full statistics

Fiducial volume

Full cuts (E_{min},y_{min},y_{max},…) may reduce the sample from ~50% to 1-2%

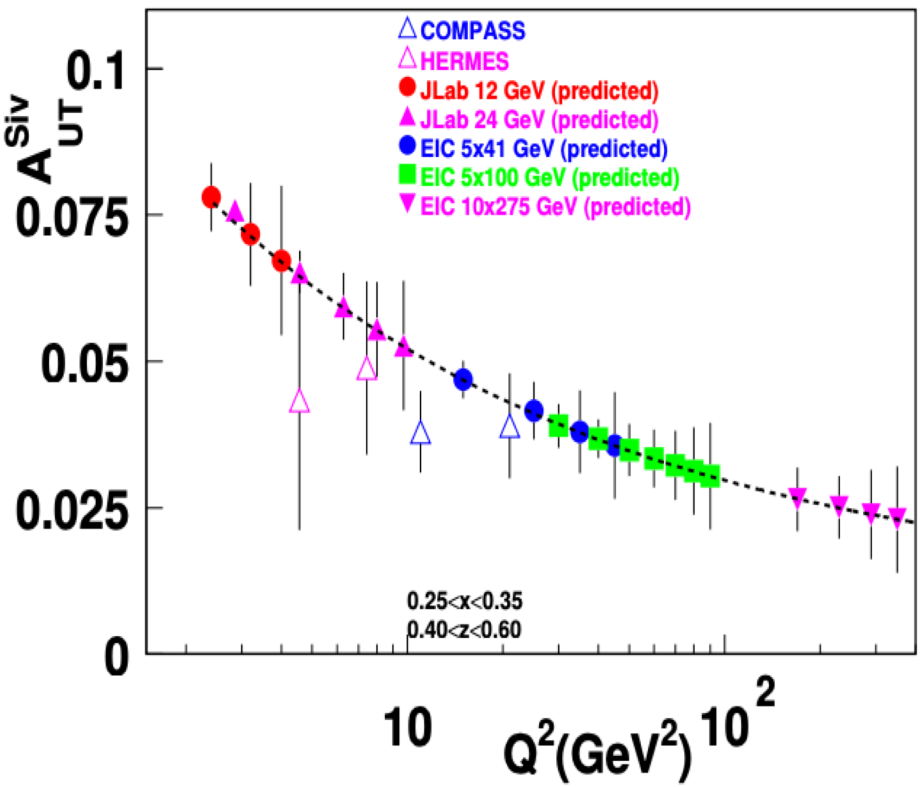
Quality

- Cross sections + geometrical cuts
- Generated events (real phase space)
- Reconstructed after GEANT (ideal)
- GEANT simulation + resolutions+ID
- Generate the physics and detector backgrounds
- Generated full x-section + <u>radiative effects</u>
- Reconstructed with realistic detector (trigger, tracking, efficiencies, resolutions, particle ID,….)

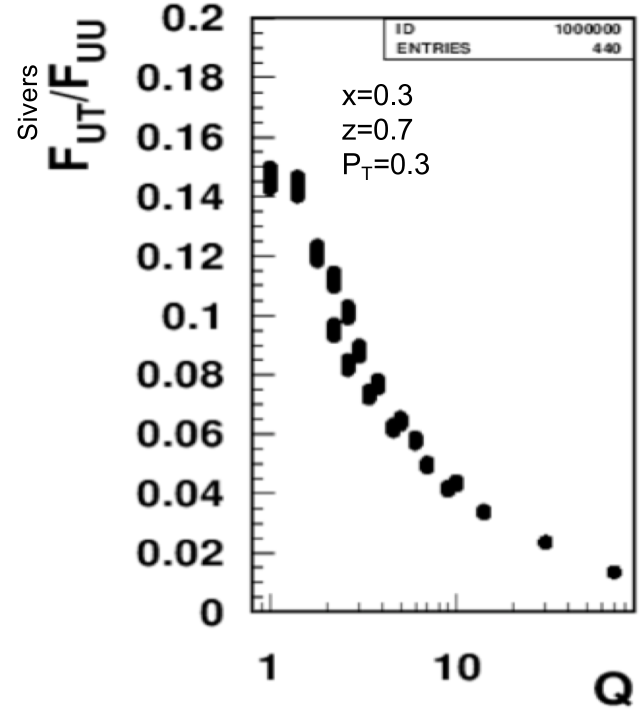
Contributions for 3D structure studies: Sivers

y>0.05,100 days (corrected for EIC official lumi)

H.A./C.Pecar/A.Vossen



Pavia grids



- Measurements of Q^2-dependence of SSAs will be crucial in validation of the theory
- JLab24 will be crucial to bridge the TMD studies between JLab12 and EIC in the valence region

B2B correlations with long. Pol. 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	$\hat{u}_{1T}^h, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^h, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

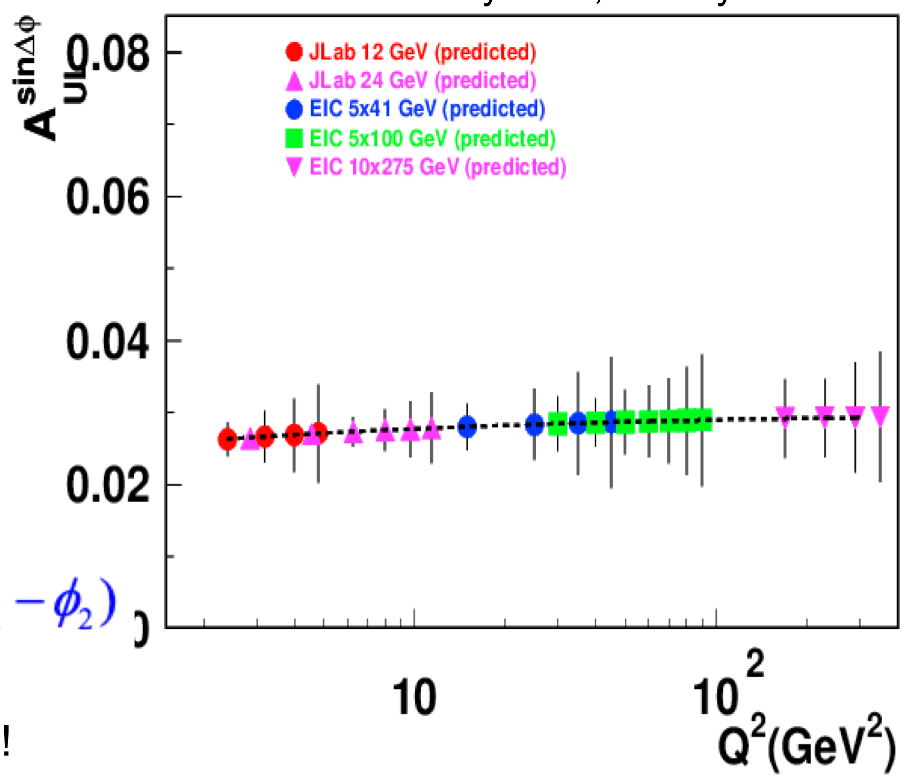
A. Kotzinian, arXiv:1107.2292

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

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

No depolarization, like Sivers!

Lumi: JLab 10^{35}, EIC4x51/5x100/10x275 0.044,0.6,1x10^{34})
y>0.05,100 days



CLAS12 proposals

NH3/ND3
E12-09-009

E12-07-107
E12-09-007A

^{3}He
C12-20-002

^{7}LiD
E12-14-001

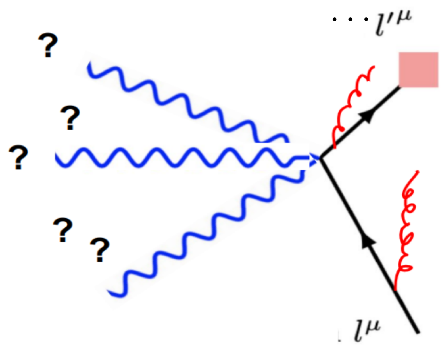
- Target SSA can be measured in the full Q^2 range, combining different facilities
- Advantages: Higher Lumi for JLab, less suppression at high Q^2 for EIC
- JLab24 will be crucial to bridge the studies of FFs between JLab12 and EIC in the valence region

Relevance of RC in studies of complex azimuthal modulations

N.Sato(CPHI-2022)

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

ignored



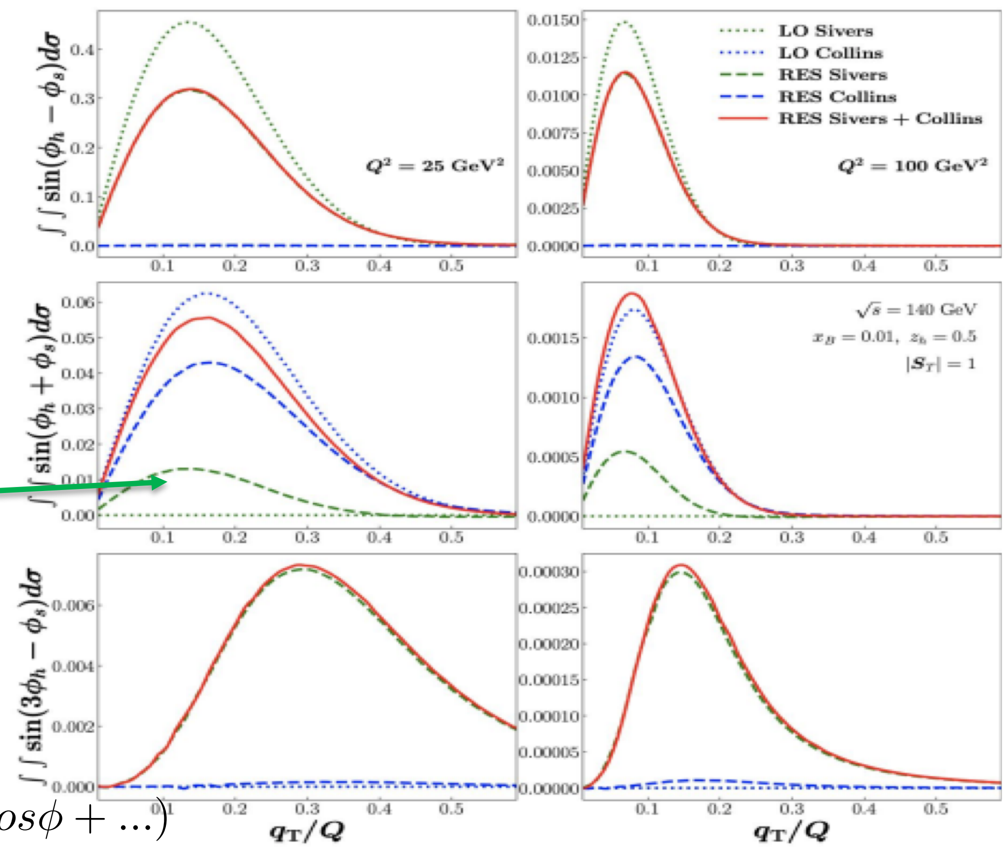
$$\boxed{\int d\phi_h d\phi_S \;\sin(\phi_h-\phi_S)\;\sin(\phi_h+\phi_S)=0}$$

BUT with QED this does not hold!

$$\boxed{\int d\phi_h\, d\phi_S\, \sin(\phi_h-\phi_S)\sin(\hat{\phi}_h+\hat{\phi}_S)\neq 0}$$

In the presence of QED radiation, the q direction is not fixed

Overlap of modulations from RC (Sivers→Collins)



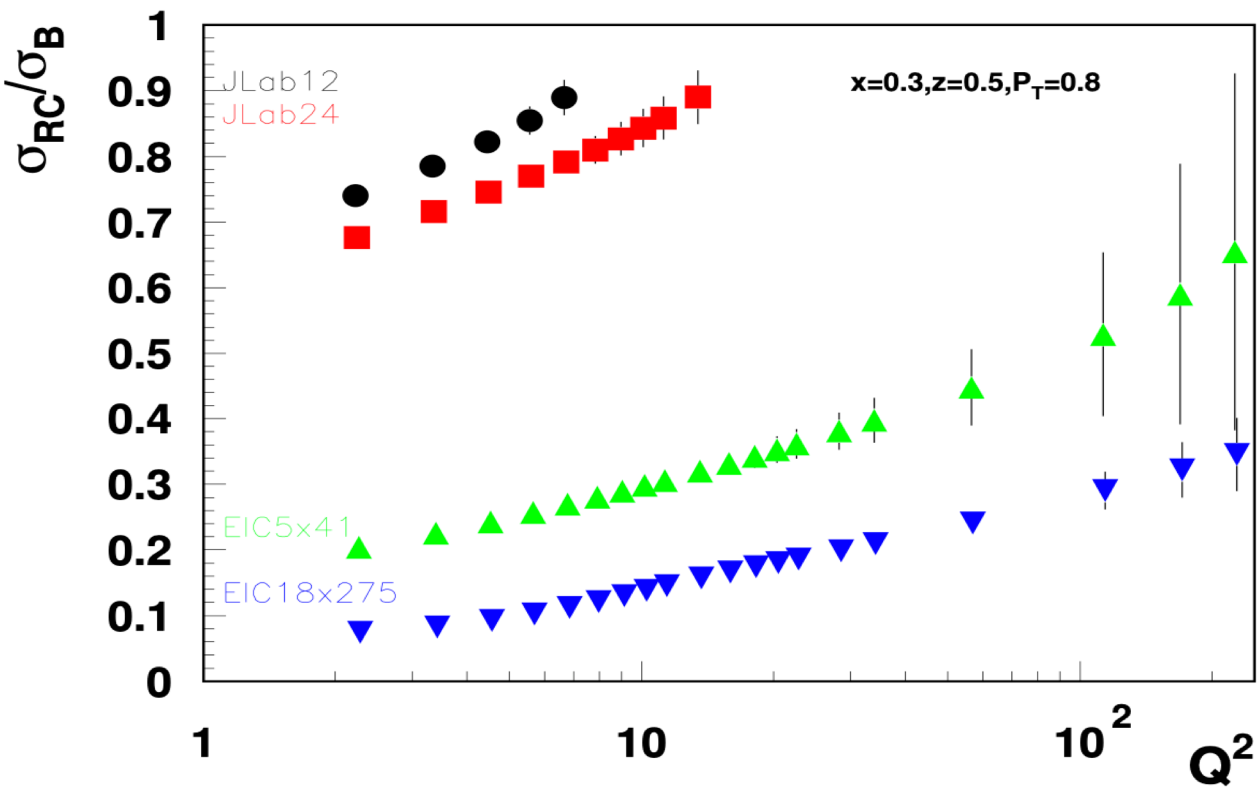
$$\sigma^h_{XY}(x,z,P_T)\to\sigma^{B,h}_{XY}(x,z,P_T)\times R(x,z,P_T,\phi_h)+\sigma^{R,h}_{XY}(\ldots).$$

$$R(x,z,P_T,\phi)=f_{XY}(x,z,P_T)*(1+a_{XY}*cos\phi+\ldots)$$

From JLab to EIC: complementarity

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

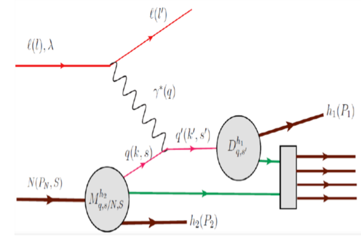
T. Liu et al
JHEP 11 (2021) 157
Gaussian F_{UU} (ϕ_h=0)



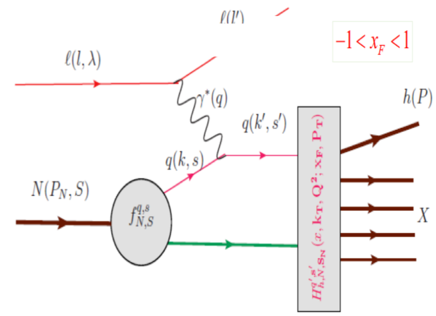
Cross section at low Q^2 suppressed at higher CM energies

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

MC simulations: Why LUND works?



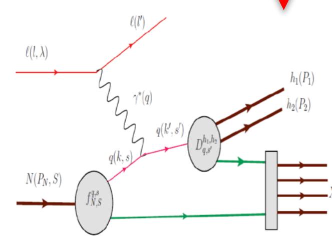
- A single-hadron MC with the SIDIS cross-section where widths of k_T-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.

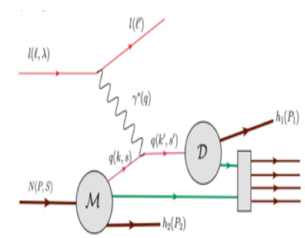


So why the LUND-MCs are so successful in description of hard scattering processes, and SIDIS in the first place?

- The hadronization into different hadrons, in particular Vector Mesons is accounted (full kinematics)
- Accessible phase space properly accounted
- The correlations between hadrons, as well a as target and current fragments accounted
- ….

subsamples

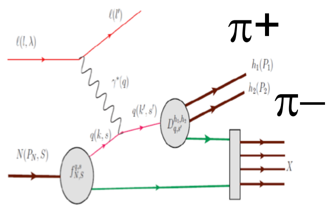




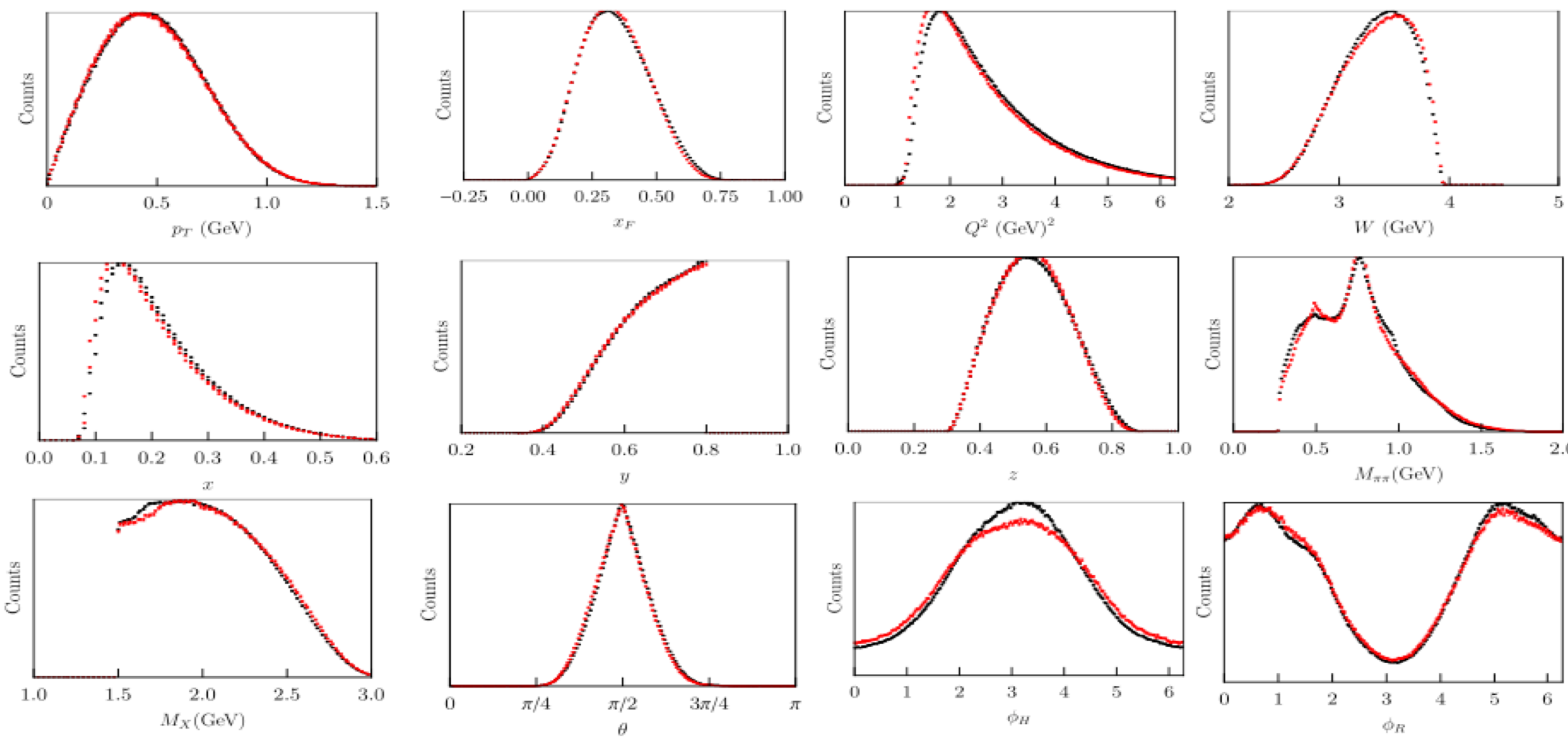
To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!

SIDIS ehhX: CLAS12 data vs MC

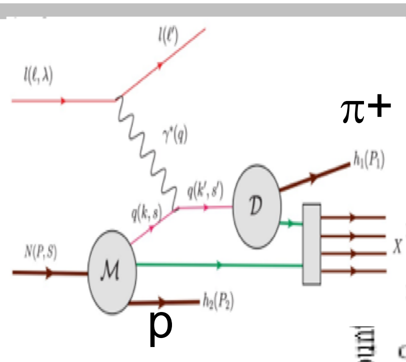


CLAS12 dihadron production ep→ehhX



CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters ”default” is in a good agreement with CLAS12 measurements for all relevant distributions

SIDIS ehhX: CLAS12 data vs MC



CLAS12 dihadron production ep→ephX (CFR/TFR)

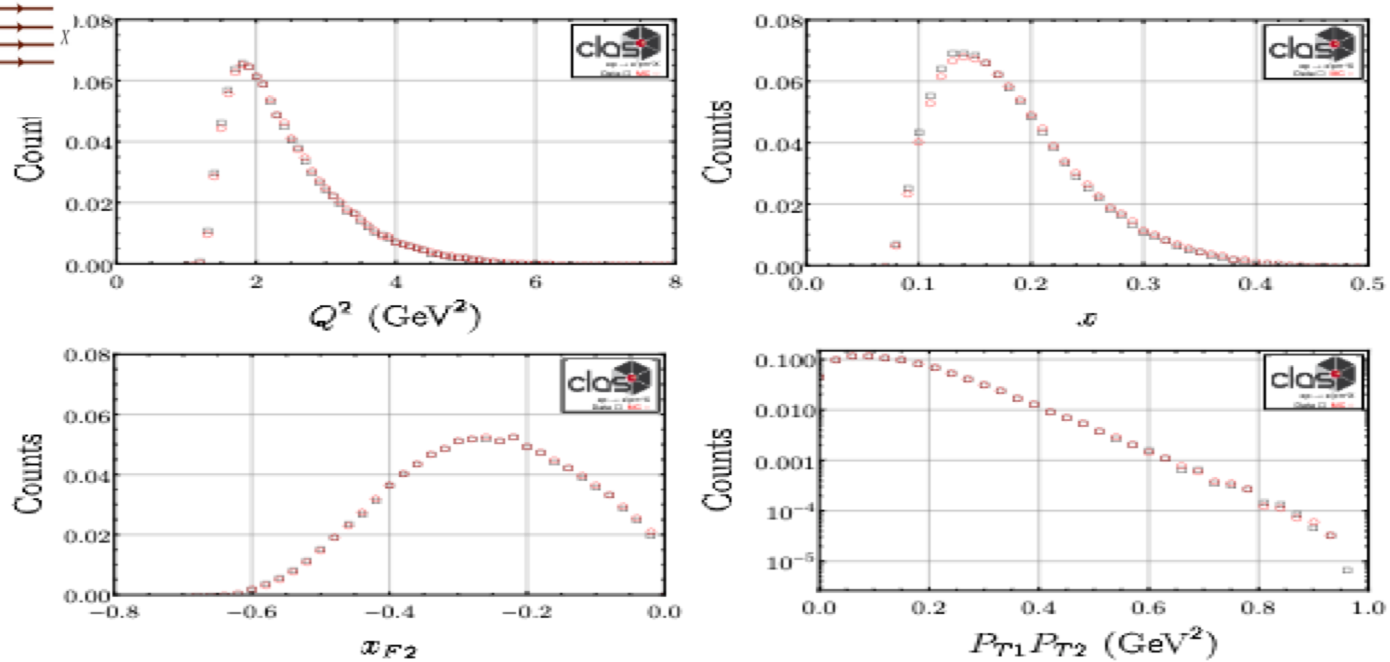
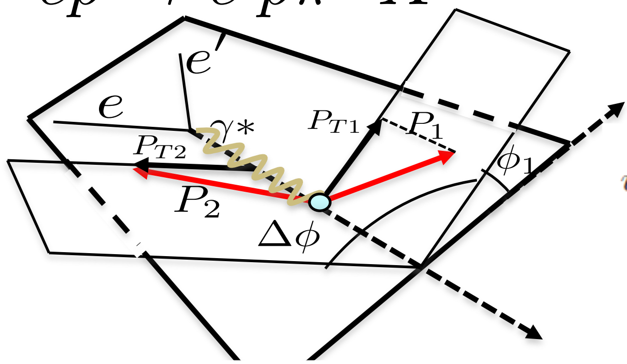


FIG. 12: Comparison between data (black squares) and Monte Carlo (red circles) for Q^2 (top left), x (top right), x_{F2} (bottom left) and $P_{T1}P_{T2}$ (bottom right, log scale). Counts are normalized to the total number of dihadron pairs. Excellent agreement is observed.

CLAS12 MC, based on the PEPSI(LEPTO) simulation with <u>most parameters "default"</u> is in a good agreement with CLAS12 measurements for all relevant distributions

b2b SSAs

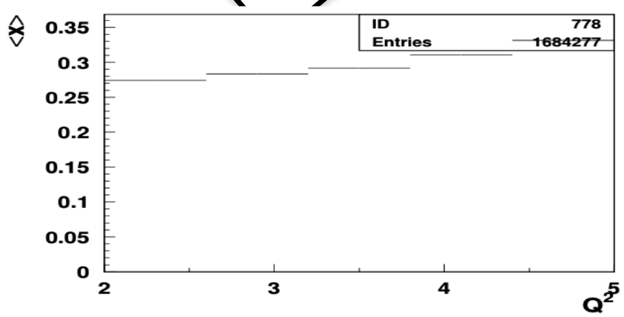
$$ep \to e'p\pi^+X$$

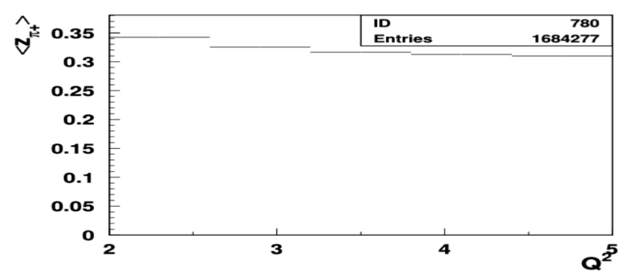


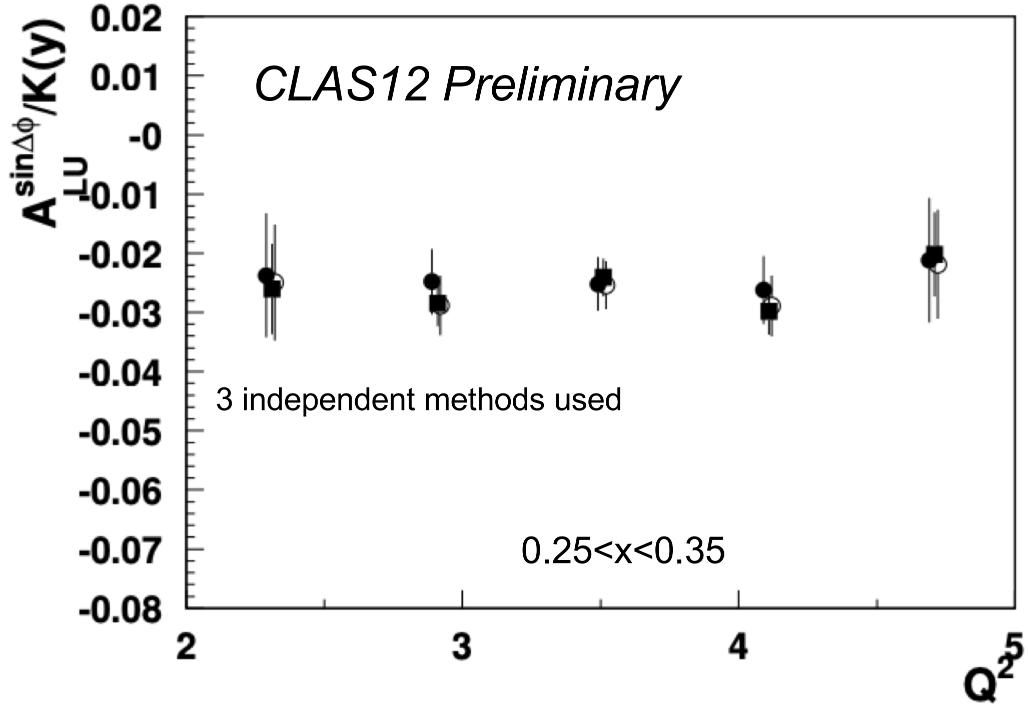
$$\mathcal{A}_{LU}^{\sin(\phi_1-\phi_2)} \propto \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}$$

$$w_5 = \frac{(\mathbf{k}_\perp \cdot \mathbf{P}_{2\perp})(\mathbf{P}_{1\perp}\cdot\mathbf{P}_{2\perp}) - (\mathbf{k}_\perp\cdot\mathbf{P}_{1\perp})\mathbf{P}_{2\perp}^2}{(\mathbf{P}_{1\perp}\cdot\mathbf{P}_{2\perp})^2 - \mathbf{P}_{1\perp}^2\mathbf{P}_{2\perp}^2}$$

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







No significant Q^2-dependence observed for b2b A_{LU}

First indication in large x SIDIS of a LT observable

Sensitivity of d-quark structure to ^{3}He: Simulation

Statistics for 30 days
Bin:
$< x >= 0.425$
$< Q^2 >= 5.0$
$< z >= 0.44$.

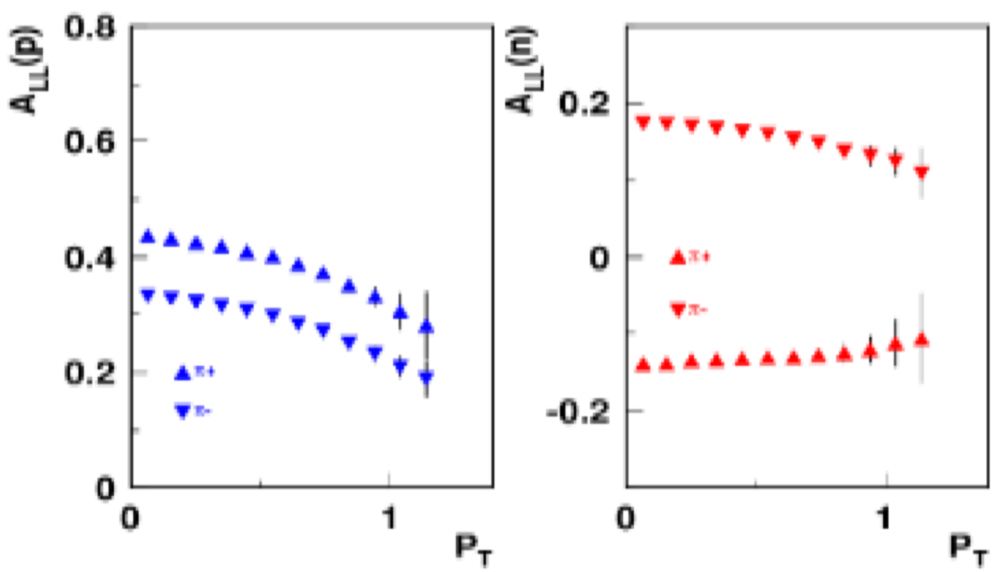
$$f_1^{q/N}(x,k_T) = f_1^{q/N}(x)\,\frac{e^{-k_T^2/\langle k_T^2\rangle_q}}{\pi\langle k_T^2\rangle_q},$$

$$g_1^{q/N}(x,k_T) = g_1^{q/N}(x)\,\frac{e^{-k_T^2/\langle k_T^2\rangle_{\Delta q}}}{\pi\langle k_T^2\rangle_{\Delta q}},$$

$$F_{LL}^N = x\sum_q e_q^2 g_1^q(x,Q^2) D^q(z,Q^2)\ P_{\Delta q}$$

Using:
LO GRV for PDF x,Q^2

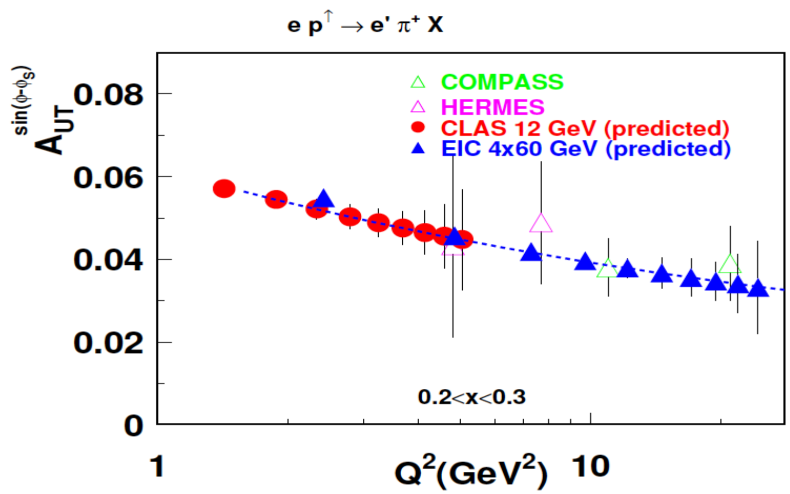
LO DSS for $D_1(z,Q^2)$
$\langle p_T^2\rangle=0.16$
$< k_T^2>u=0.3$
$< k_T^2>u=0.33$
$< k_T^2>\Delta u=0.22$
$< k_T^2>\Delta d=0.25$



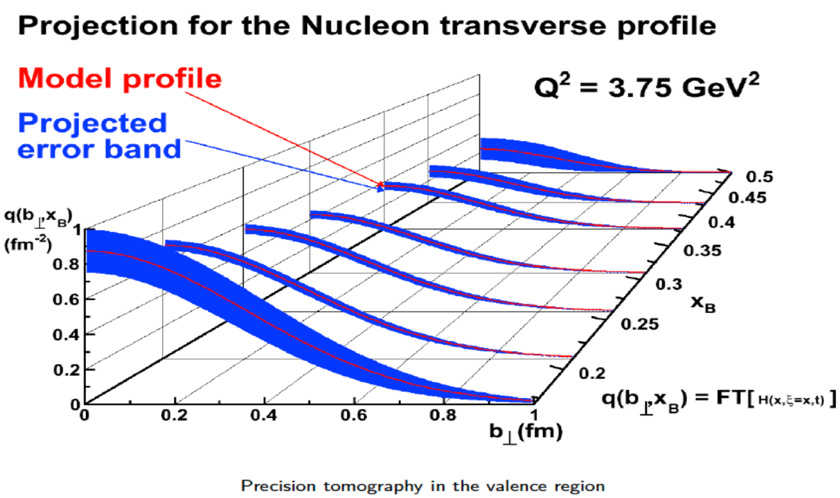
Note: for proton $\pi+$ (triangle up) $\pi-$ (triangle down) A_LLs have the same sign for proton and opposite signs for neutron

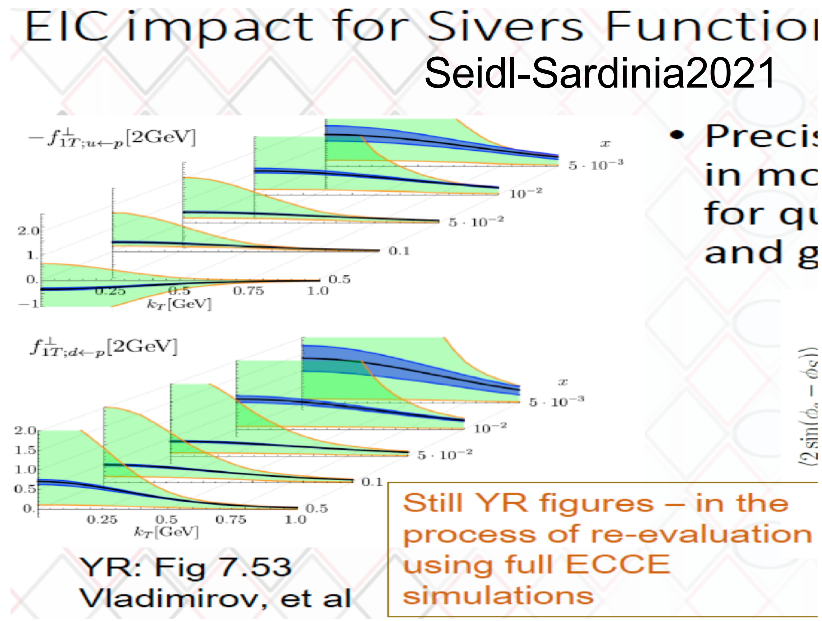
We all contributed….

H.Avakian (~10 years old)



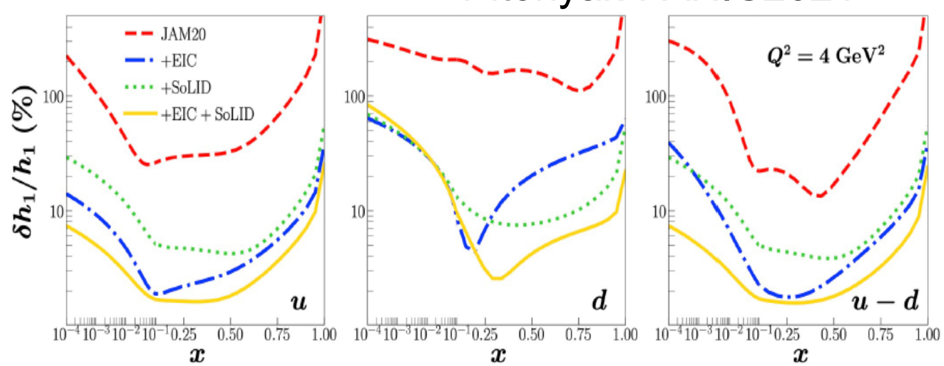
Girod-StrongQCD-2021





Gamberg, Kang, DP, Prokudin, Sato, Seidl, PLB **816** (2021)

Pitonyak-PANIC2021



Polarized quark structure from proton and ^{3}He

The k_T-dependent width of polarized d-quarks has significantly smaller uncertainty from neutron data due to order of magnitude large and canceling contributions in proton (input values for u→0.22, d→0.25)

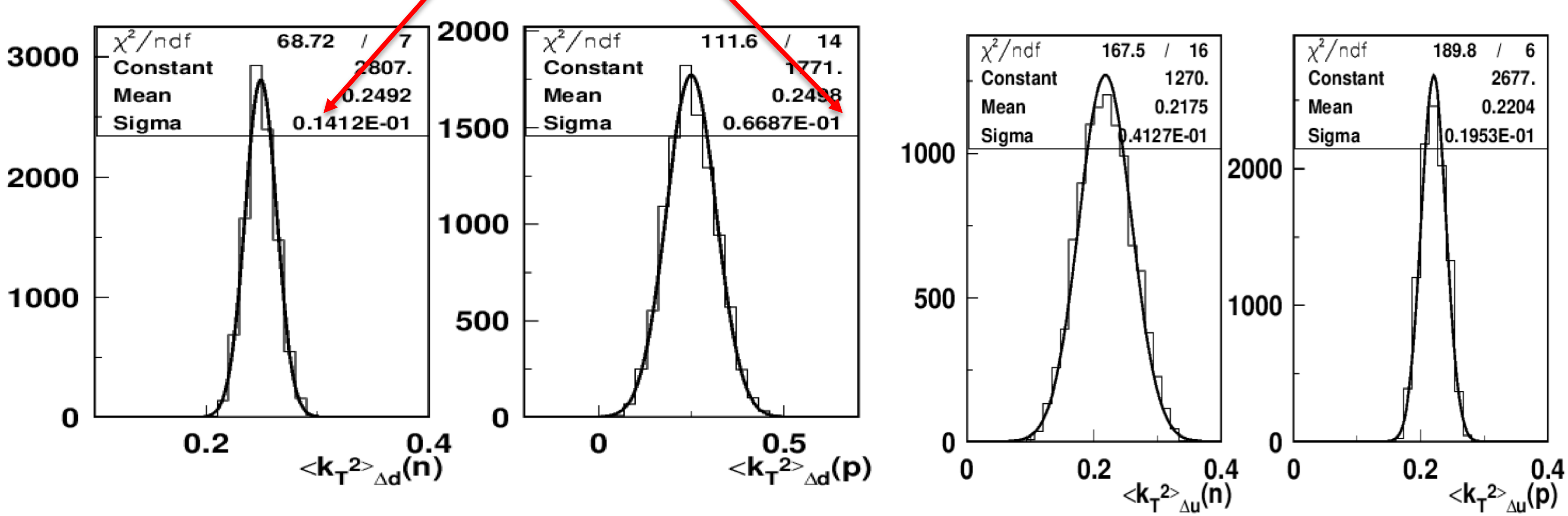
$$P_{\Delta d} = -\frac{e^{\frac{P_T^2}{\langle k_T^2\rangle_{\Delta d} z^2 + \langle p_T^2\rangle}}}{\pi(\langle k_T^2\rangle_{\Delta d} z^2 + \langle p_T^2\rangle)}$$

$$P_{\Delta u} = -\frac{e^{\frac{P_T^2}{\langle k_T^2\rangle_{\Delta u} z^2 + \langle p_T^2\rangle}}}{\pi(\langle k_T^2\rangle_{\Delta u} z^2 + \langle p_T^2\rangle)}$$

- unpolarized widths for u and d known within 10%
- Δd/Δu at large x known within 20%
- 1sigma spread of ALLs

neutron proton

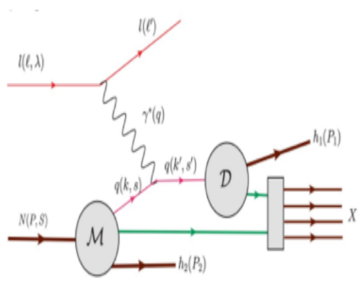
Decent extraction for u-quarks

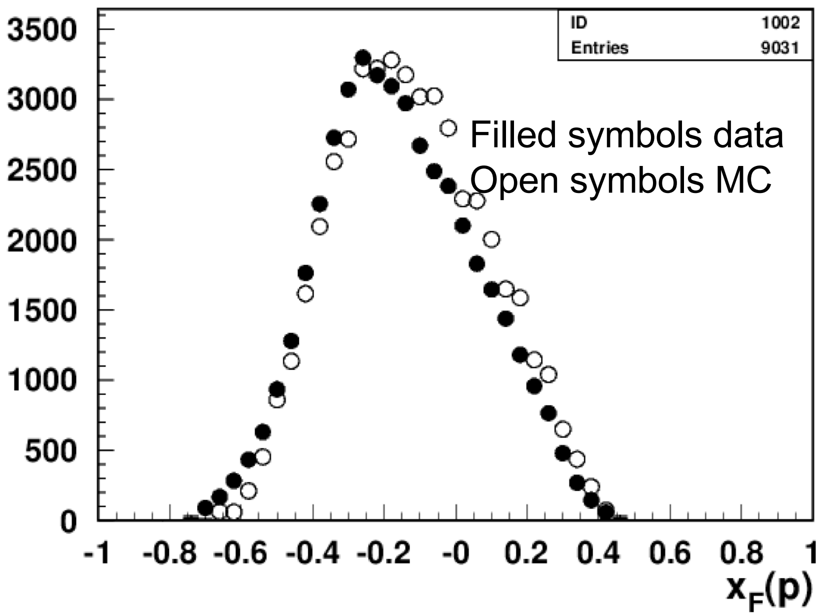


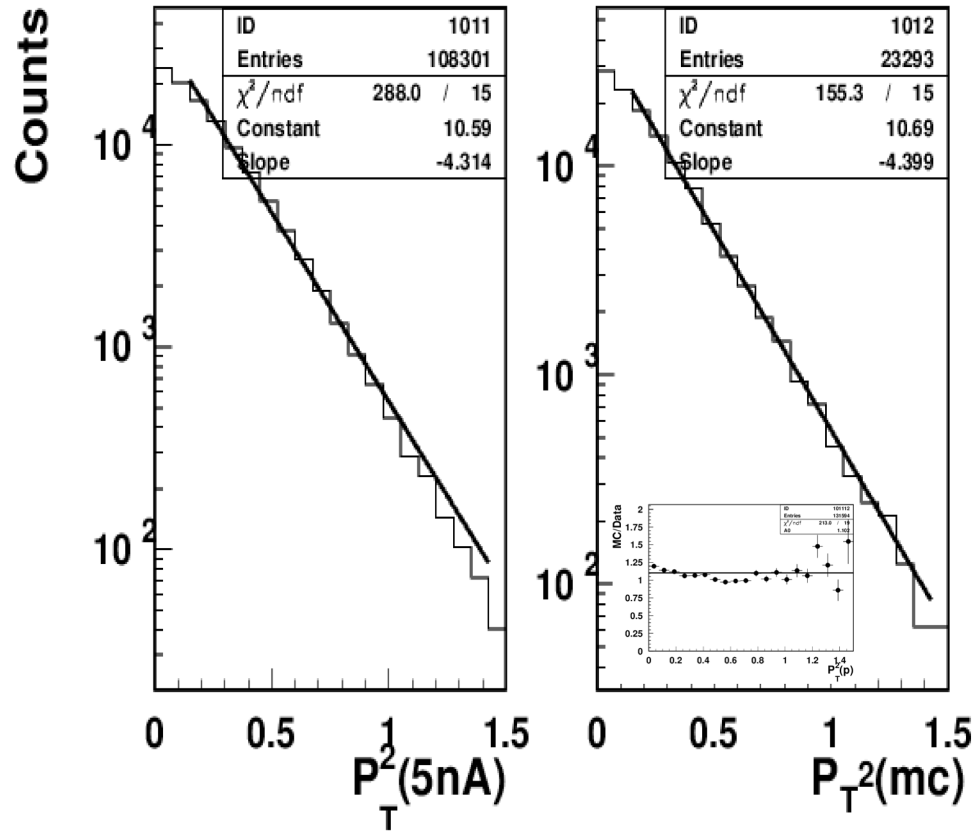
Extractions of TMDs (both Δd and Δu) can be performed within model assumptions

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator







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

CLAS12 data preservation

https://clasweb.jlab.org/wiki/index.php/Hall-B_Task_Forces_2020#Data_Preservation

Layers of data abstraction hierarchy

Raw data (production) → Recons. Software Pass1 DSTs → Reconstructed data

Reconstructed data
Relevant train(pass1):
- id: 4
- forward: 11:X+:X-:Xn
- RGA electron: Q2>1 && W>2 && p>2 && vz>-25 && vz<20
- RGB electron: Q2>0.95, W>1.95 && p>2 && vz>-25 && vz<20

→ Data selection software, java/C++)
1) SSA set (1^{st} publications)
2) Multiplicity set (Giovanni,Orlando,…)
3) x-section set (Nick)

Process file ep→e'pπ+X → Analysis software

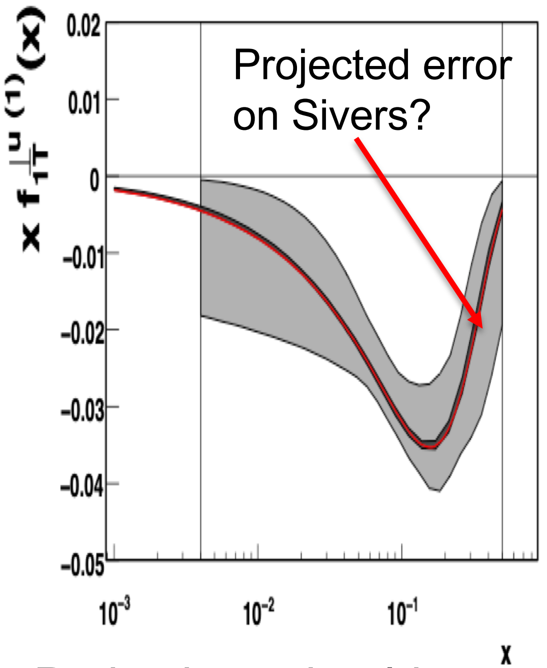
Process file ep→e'π+X → Analysis software

Process file ep→e'π+π–X → Analysis software

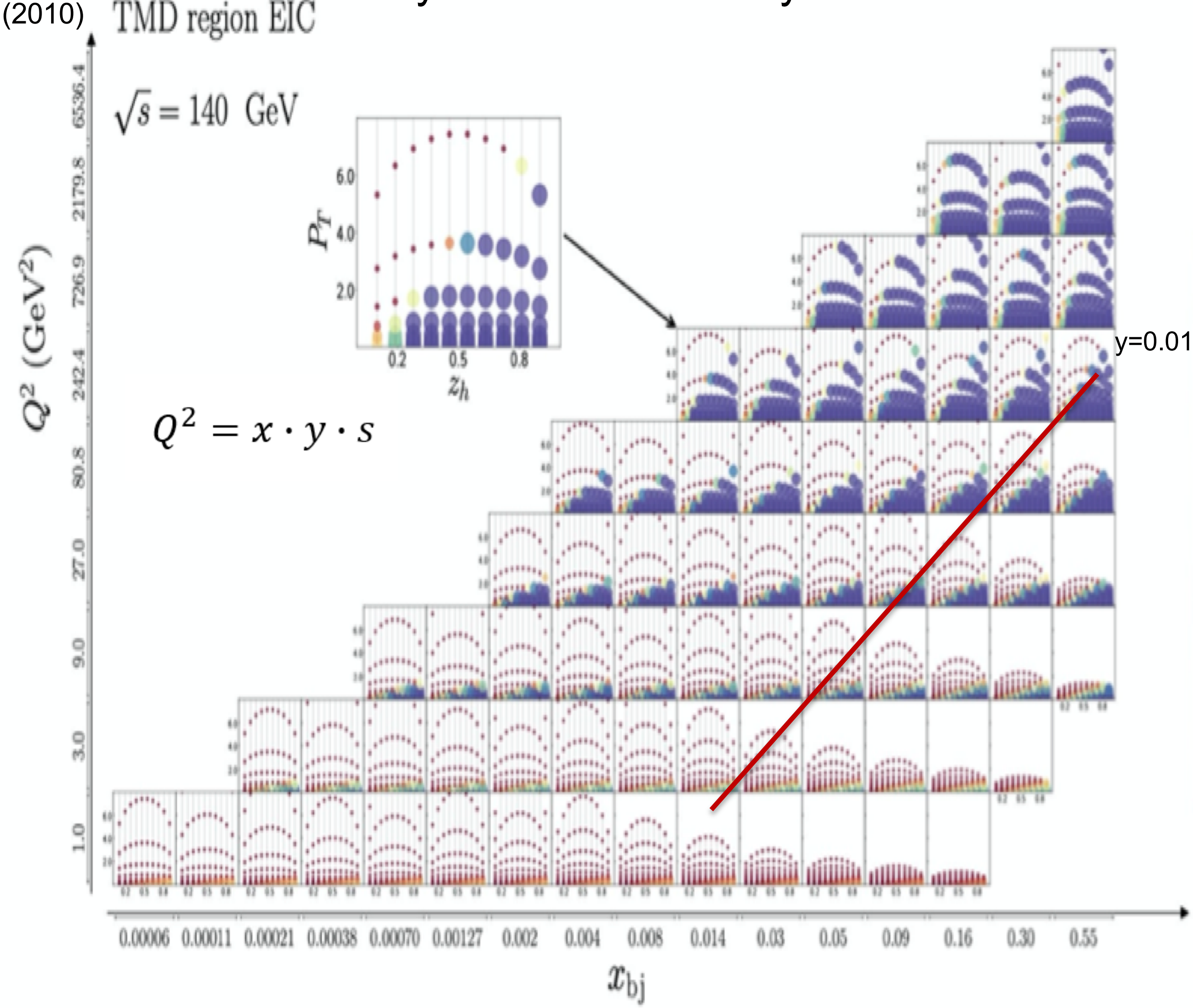
- Publication plots from analysis note and corresponding publication

Projections from 1D to 4D

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



"affinity"→ how well theory works

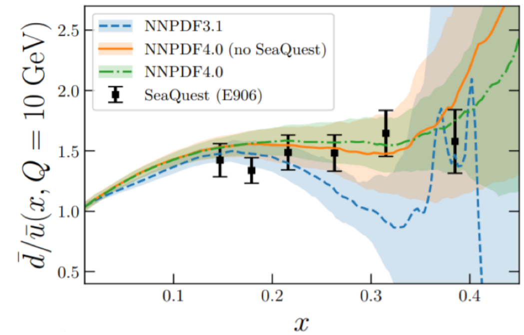


Projections should contain the size of the effect and the counts for a given interval of time
For SIDIS the x-section is defined by F_{UU}, for Sivers effect F_{UT}/F_{UU}

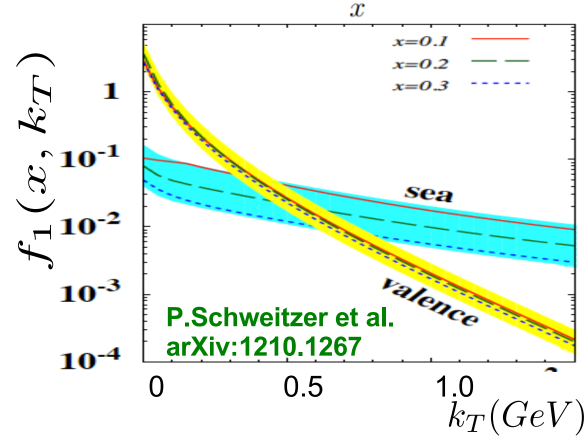
Non-perturbative contributions

Non-perturbative sea ("tornado"/$^3P_0$) in nucleon is a key to understand the nucleon structure

$$\bar{d} > \bar{u}$$

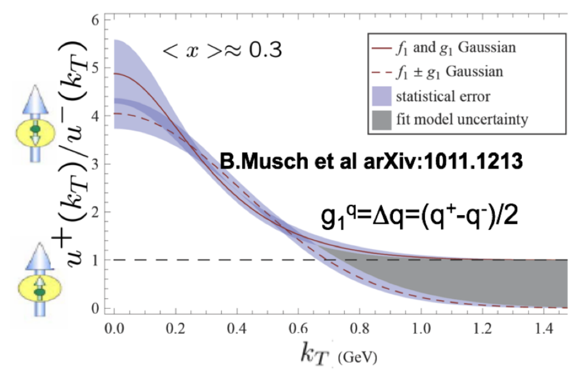


- Spin-Orbit correlations so far were shown (measurements and model calculations) to be significant in the region where non-perturbative effects dominate (x>0.02)
- Large transverse momenta of hadrons most relevant for understanding the non-perturbative QCD dynamics



- Predictions from dynamical model of chiral symmetry breaking [Schweitzer, Strikman, Weiss JHEP 1301 (2013) 163]

  -- k_T (sea) >> k_T (valence)
  -- short-range correlations between partons (small-size q-qbar pairs)
  -- may be directly observable in P_T-dependence of hadrons in SIDIS



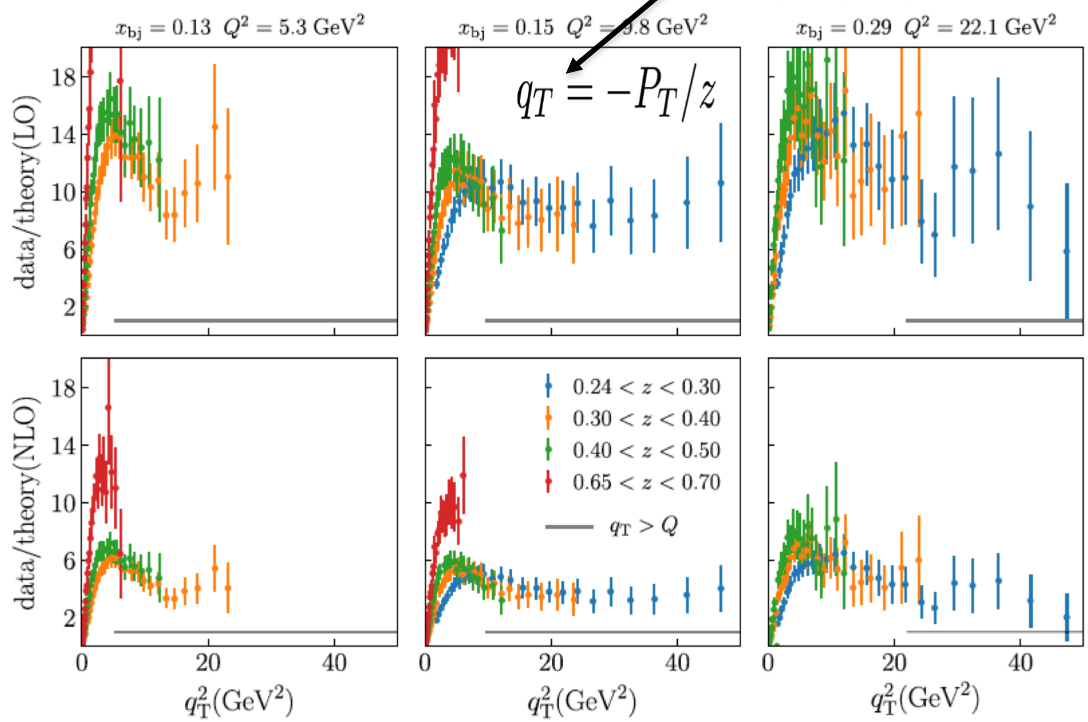
Understanding of the evolution of transverse momentum dependence most critical in validation of the theory

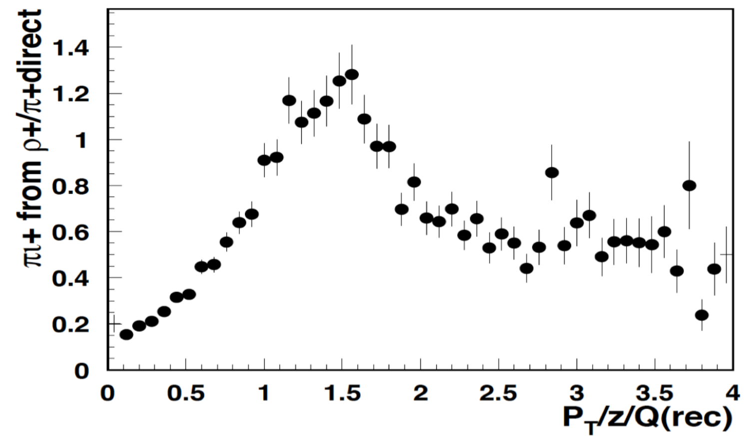
TMD formalism applicability and the impact of q_T cut

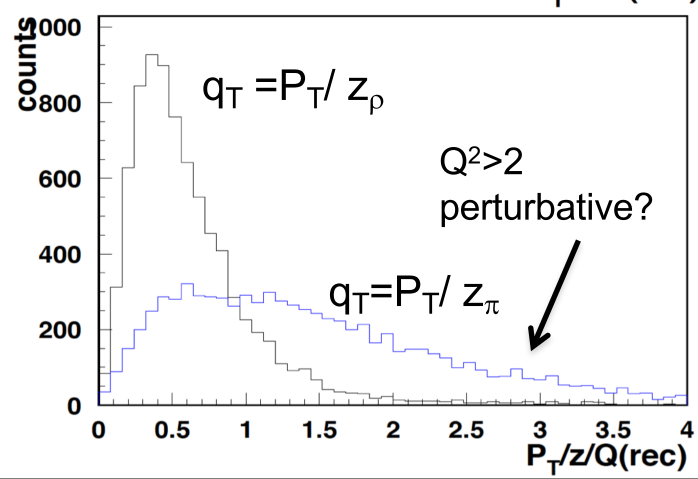
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

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)

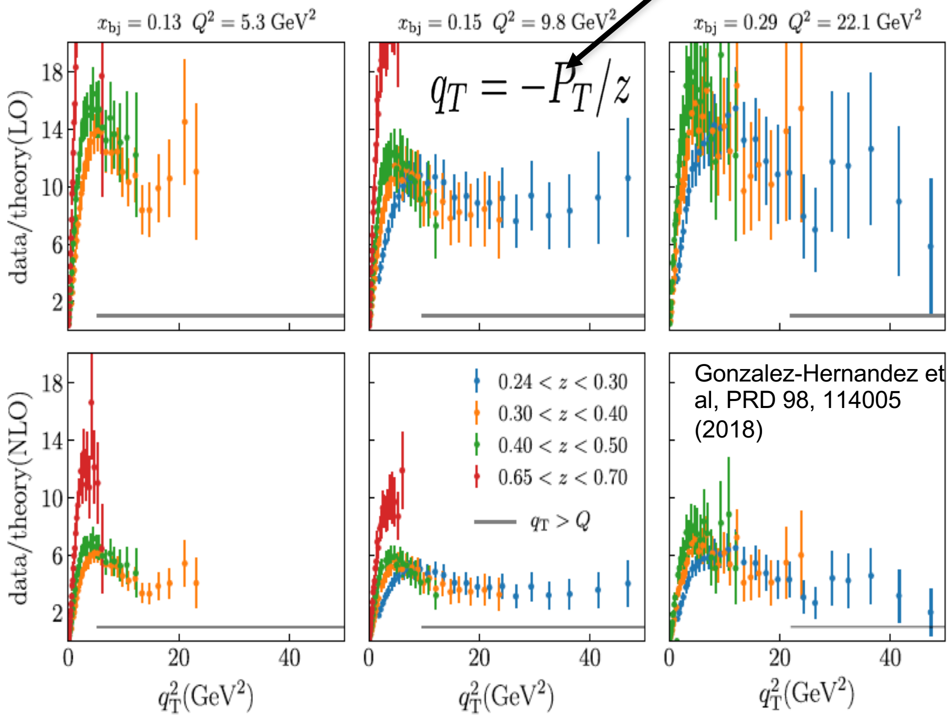
understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of q_T distributions

FO vs data for $q_T \gtrsim Q$

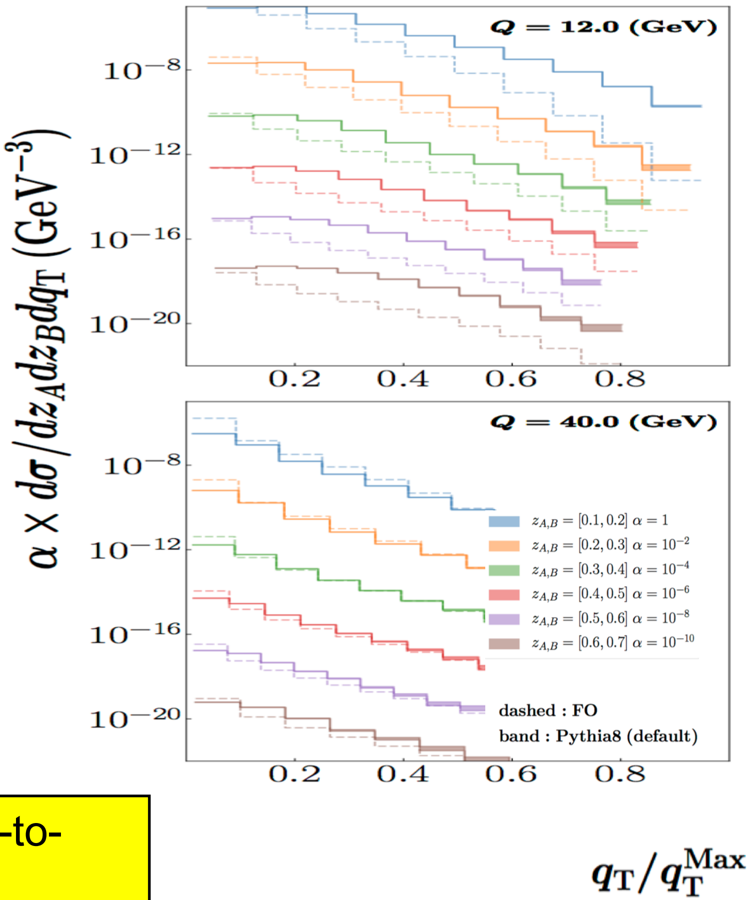
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

quark transverse momentum

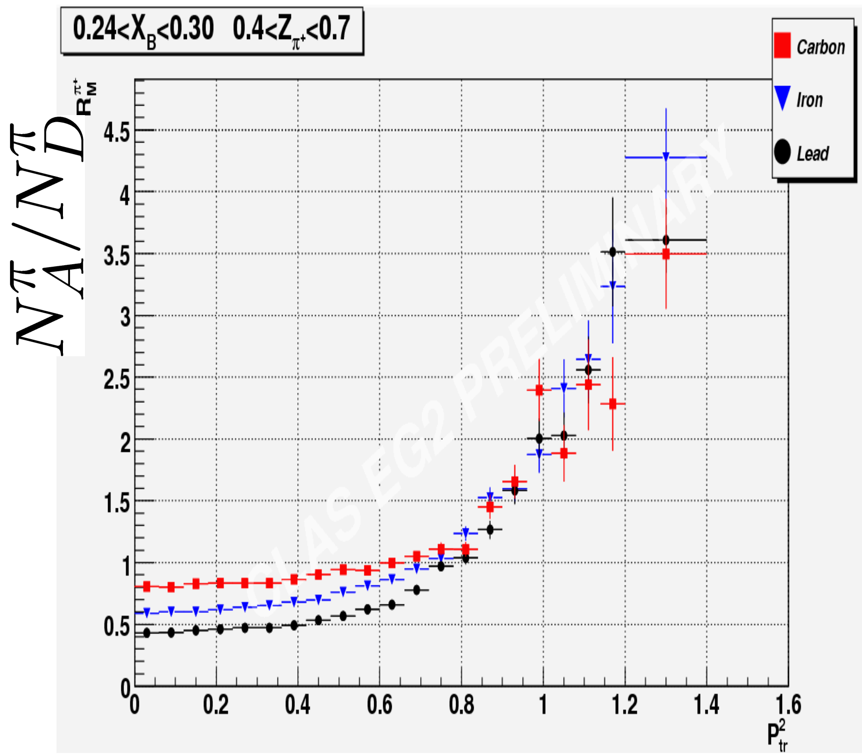


$e^+e^- \to h_1h_2X$ - Moffat et. al 1909.02951



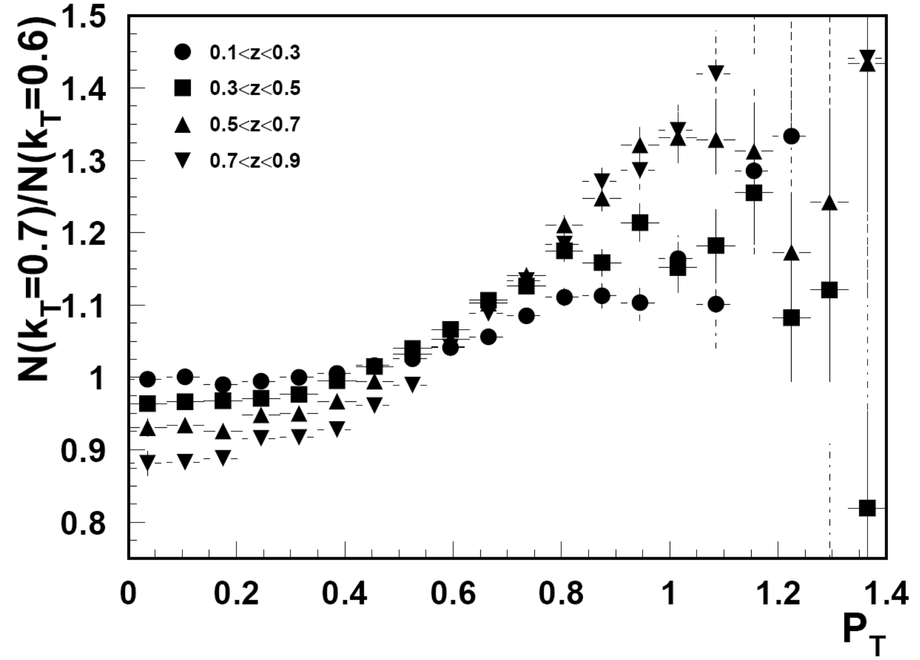
The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

Quark distributions at large k_T



bigger effect at large z

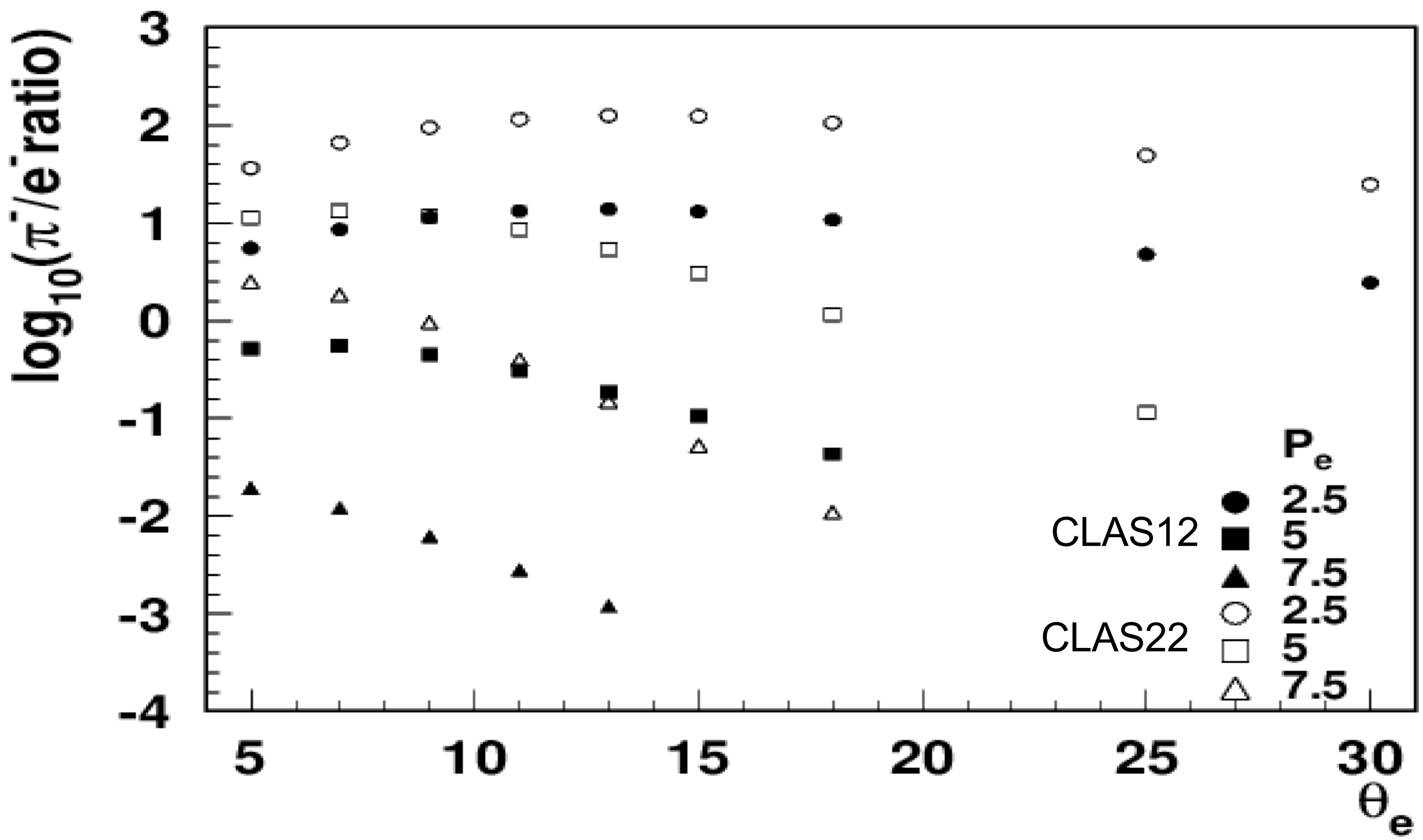
$P_T = p_\perp + z k_T$



Higher probability to find a hadron at large P_T in nuclei

k_T-distributions may be wider in nuclei?

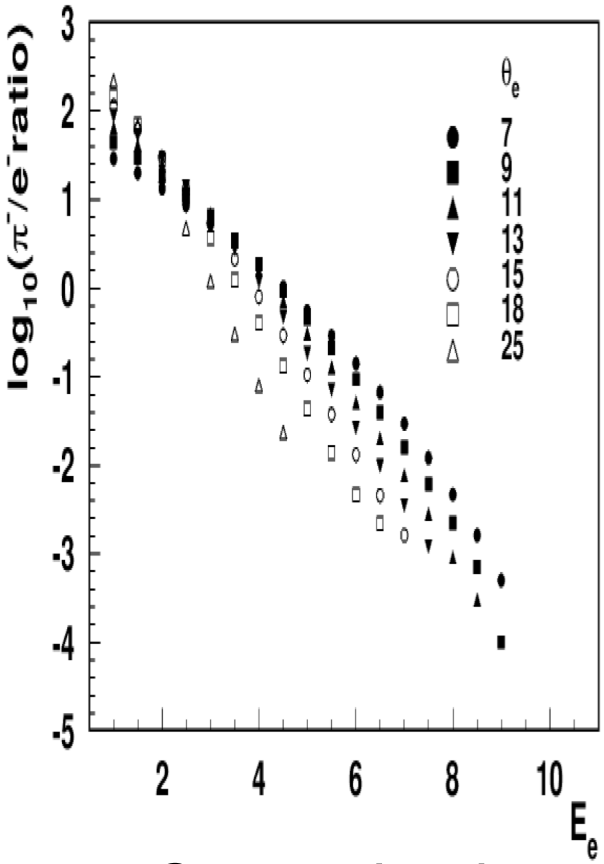
Relative fluxes: e- vs pi-



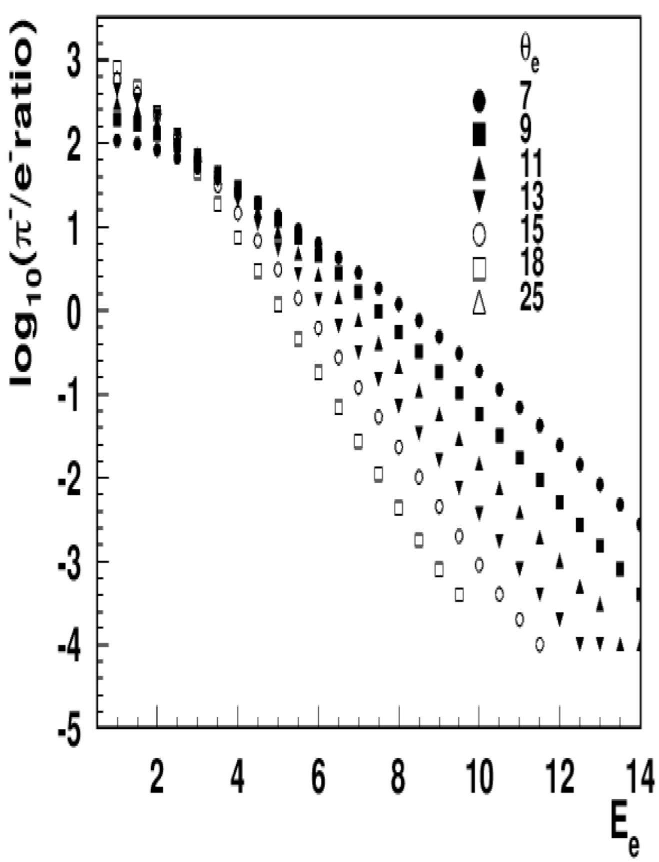
Relative fraction of pi- increases for a fixed energy
For a constant y (y<0.75 used) they are consistent

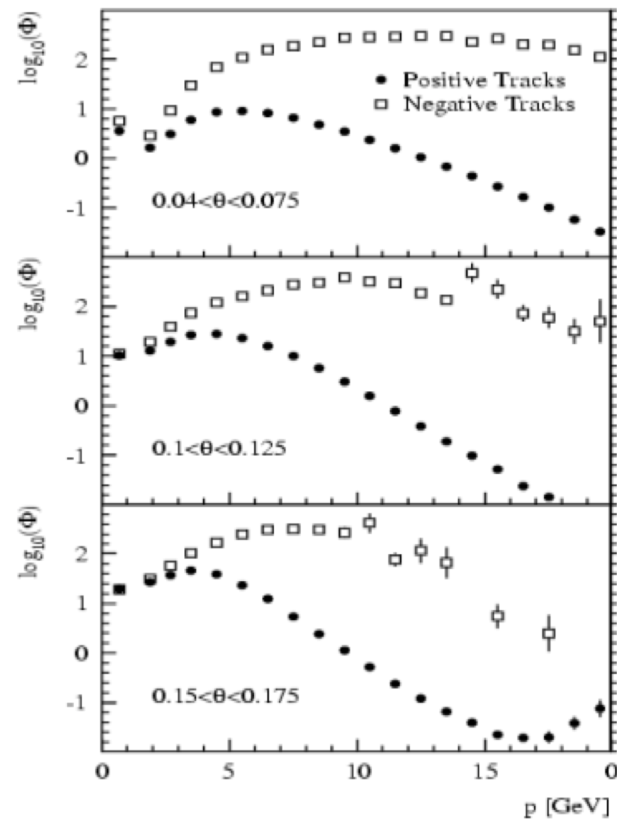
Relative fluxes: e- vs pi-

CLAS12



CLAS22





Contamination at low energies will be ~50% higher
(electrons <2 GeV may not be much useful anyway)

Projections for Sivers

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

$\sin(\phi - \phi_S)$

arXiv:1208.1244

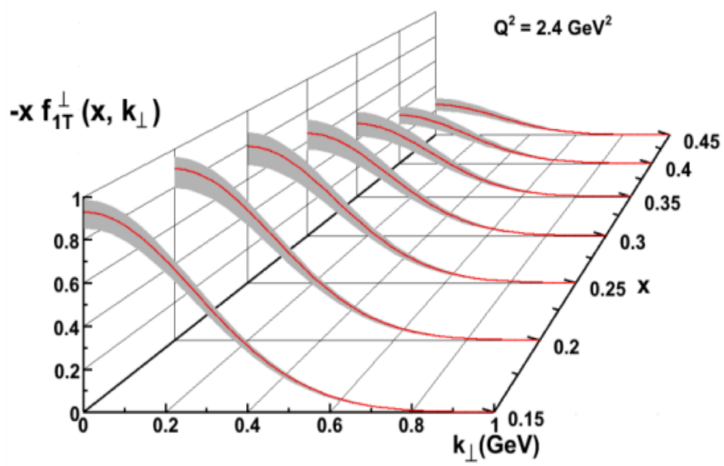


Figure 3.4 The Sivers function for the up quark as a function of $k_\perp$ at different values of x as determined by analysis of JLab 12 pseudo data generated for ^{3}He target. The central line is the model profile of [3-35]; real Jefferson Lab 12 GeV data will eventually reveal the actual shape of the distribution. The error bands have been projected about the model profile.

arXiv:1212.1701

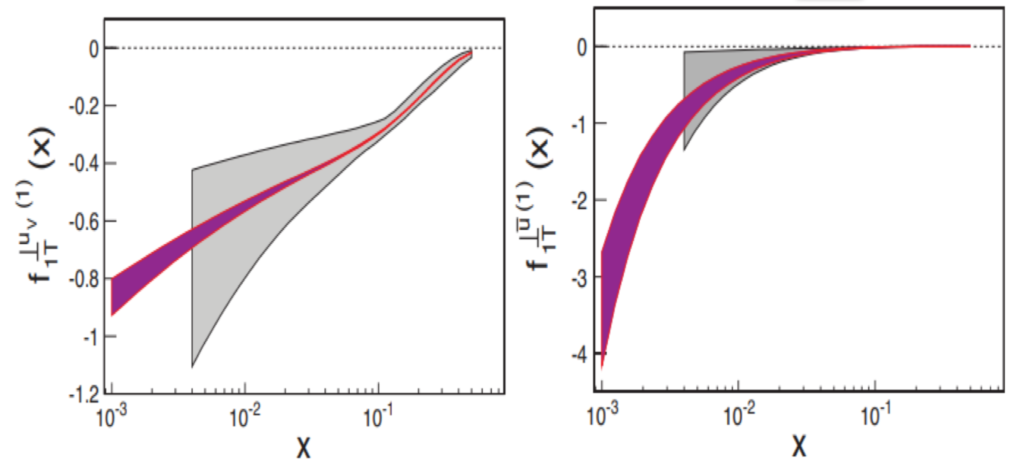


Figure 2.16: Comparison of the precision (2-σ uncertainty) of extractions of the Sivers function for the valence (left) $u_v = u - \bar{u}$ and sea (right) $\bar{u}$ quarks from currently available data [77] (grey band) and from pseudo-data generated for the EIC with energy setting of $\sqrt{s} = 45$ GeV and an integrated luminosity of 10 fb^{-1} (purple band with a red contour). The uncertainty estimates are for the specifically chosen underlying functional form.

Without clear understanding of systematics from separation of different modulations, and impact of model assumptions/approximations used in their production, this projections suppressed development of proper extraction frameworks with controlled systematics for years.

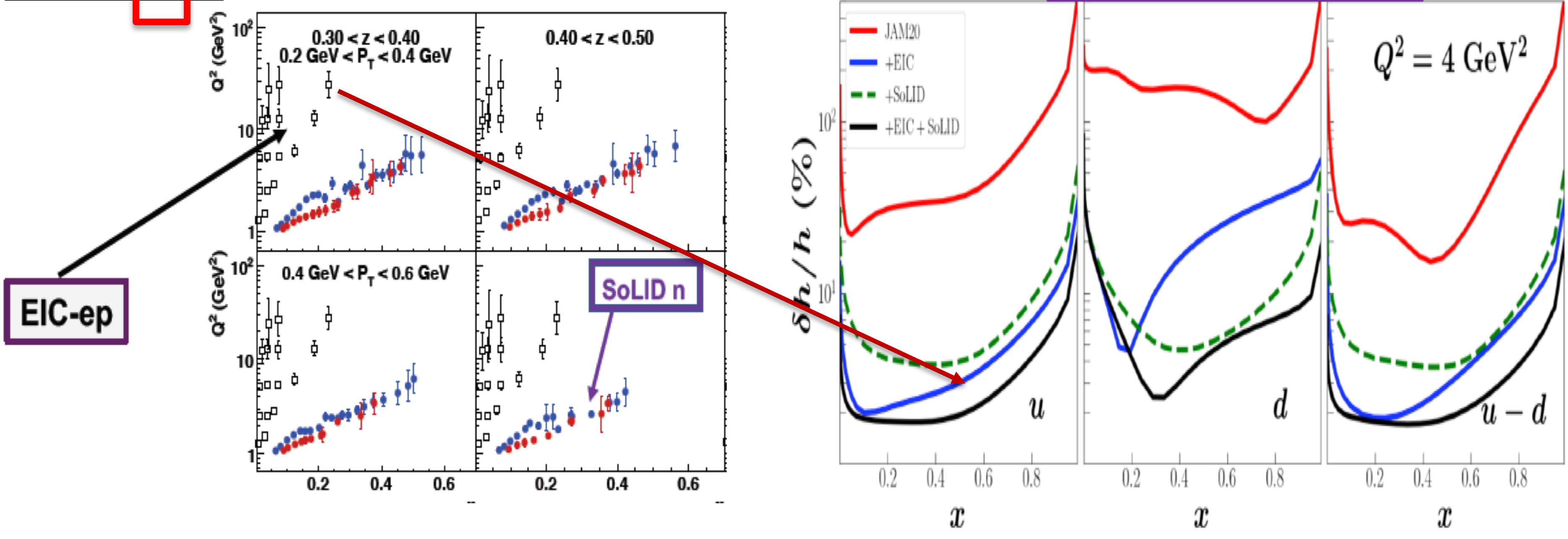
TMDs sensitivity to transversity: large x

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

$\sin(\phi + \phi_S)$

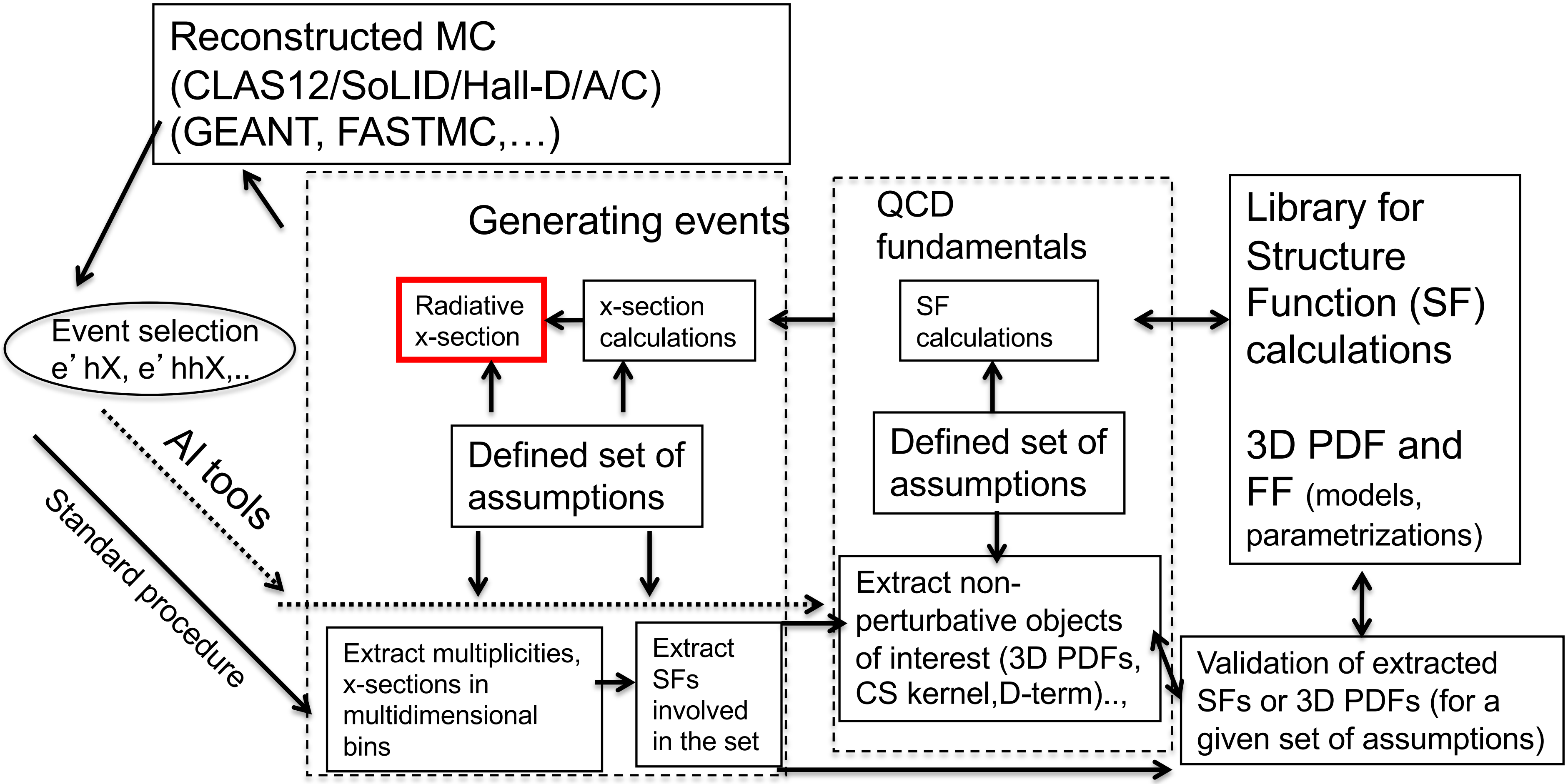
Plots from : “SoLID DOE review”

Transversity distribution



- JLab measurements with transversely polarized targets will provide crucial input at large x
- Complementarity of JLab and EIC at large x should be carefully examined for better coordination (theory+experiment)
- Systematics from parameterizations, providing “sensitivity” to kinematical regions not covered by data should be carefully evaluated

Framework: from SFs to projections



A procedure for realistic and reproducible projections for non-perturbative objects of interest (3D PDFs, FFs,FrF,…) from the multidimensional experimental observables with controlled systematics could be used by all interested

TMD extractions, parameterizations, grids

Important note from theorists: parametrizations should be used in the kinematics they are applicable. Validations mostly done for given Fragmentation Functions, by variations of experimental data within errors(TMD extraction talks).

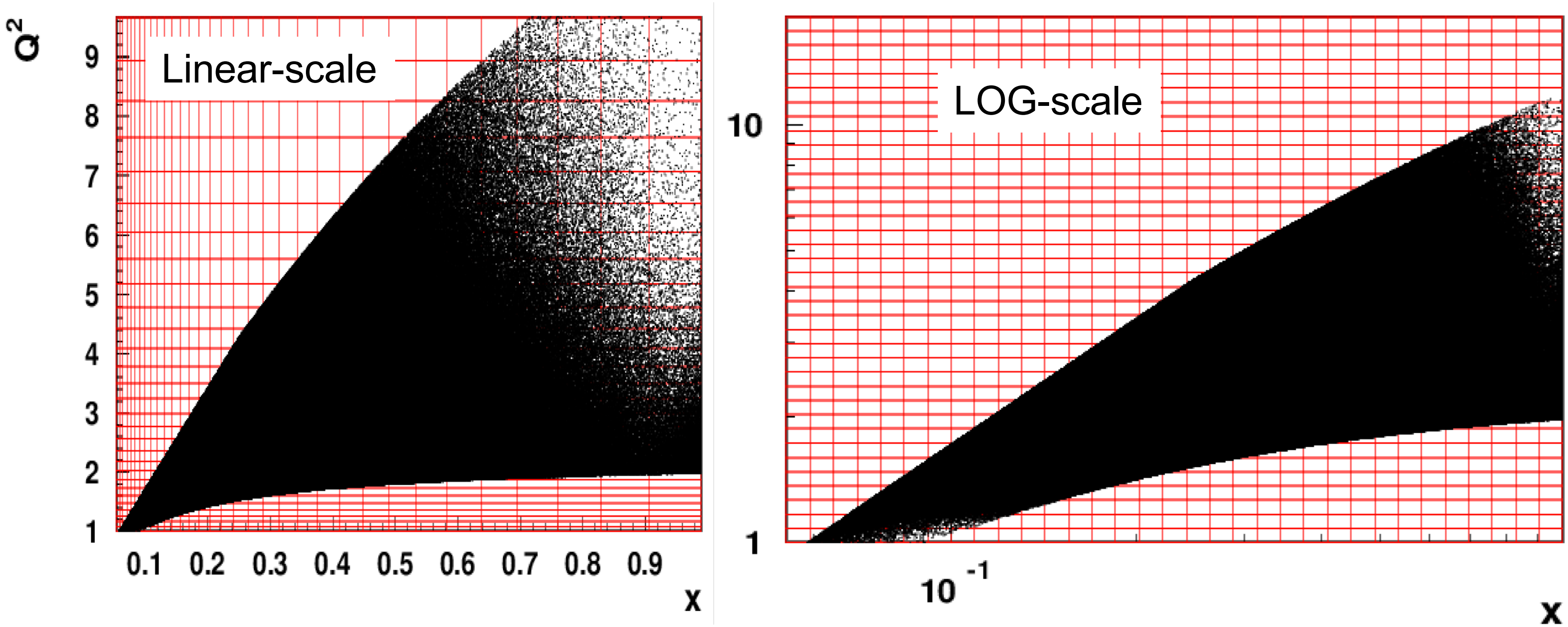
How to validate the TMD parameterization in 3D (discussion session):

- Compare kinematic dependences with new data (ex. P_T,Q^2-dependences)
- Compare kinematical dependences with direct calculations and lattice
- Compare kinematical dependences with other extractions
- Compare kinematical dependences with QCD inspired model predictions
- Common sense & intuition about non-perturbative kinematics

Use MC validation: generate pions with probabilities from extracted SFs for a given experiment, including the RC and compare multiplicities and SSAs with a given experiment (accounting phase space limitations & correlations between variables)

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

Coverage and binning



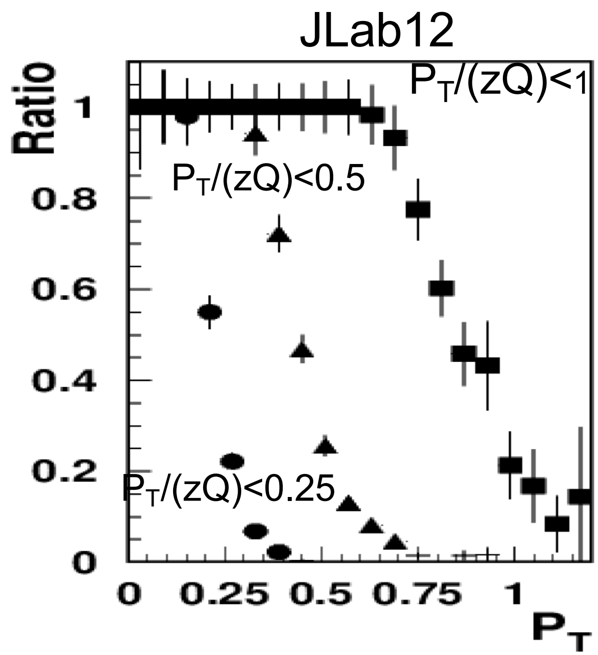
Grids for N+1 values from i=0,N

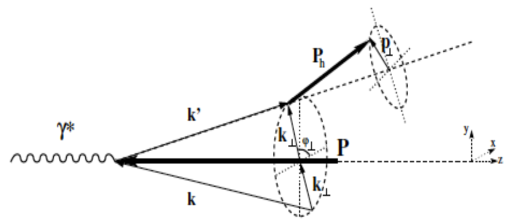
$$\Delta x = ln(x_{max}/x_{min})/N_x$$
$$\Delta Q^2 = ln(Q^2_{max}/Q^2_{min})/N_q$$
$$Q^2_i = Q^2_{min} e^{i\Delta Q^2}$$
$$x_i = x_{min} e^{i\Delta x}$$

$$\Delta z = (z_{max} - z_{min})/(2N_z)$$
$$\Delta P_T = (P_{Tmax} - P_{Tmin})/(2N_P)$$
$$z_i = z_{min} + (2i+1)\Delta z$$
$$P_{Ti} = P_{Tmin} + (2i+1)\Delta P_T$$

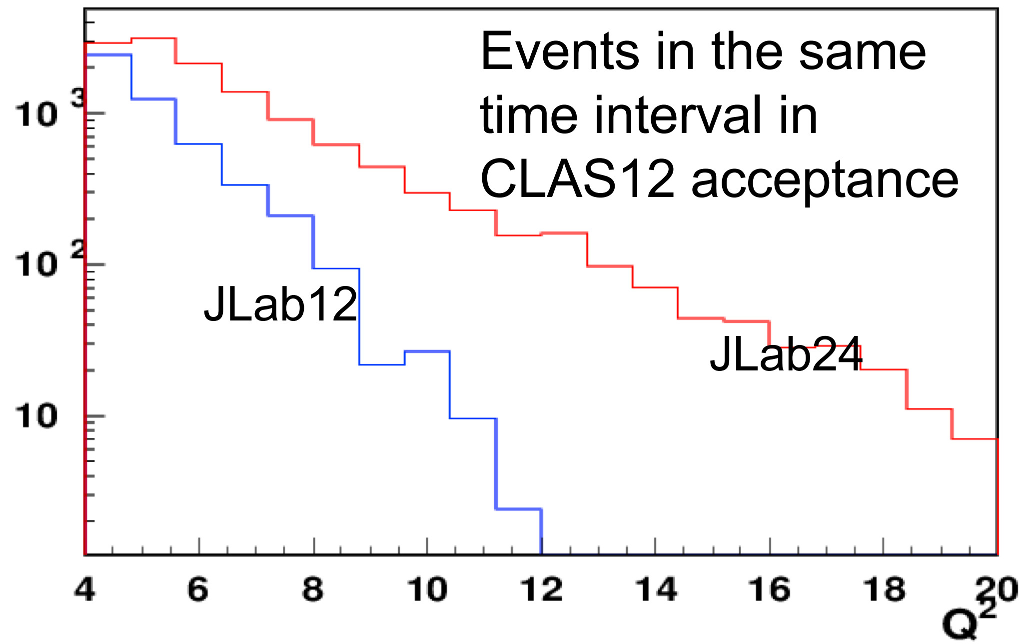
N_x=200,N_q=200
N_z=20,N_P=40
x_{min}/x_{max} (0.02 / 0.98)
Q^2_{min}/Q^2_{max}(1.0 / 40)
z_{min}/z_{max} (0.05 / 0.95)
P_{Tmin}/P_{Tmax}(0.0 / 2.0)

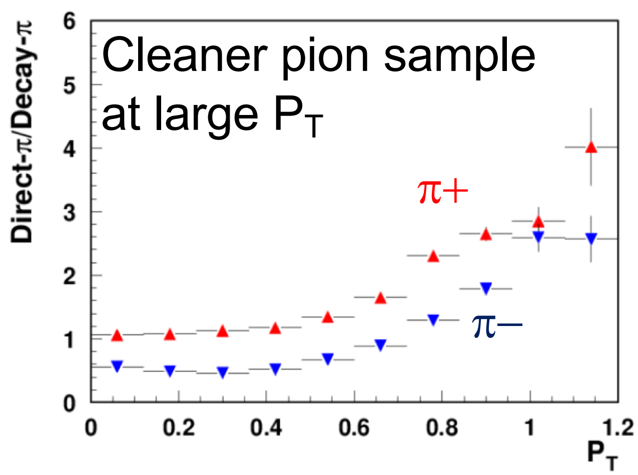
From JLa12 to JLab24 Larger Q^2 at large P_T





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

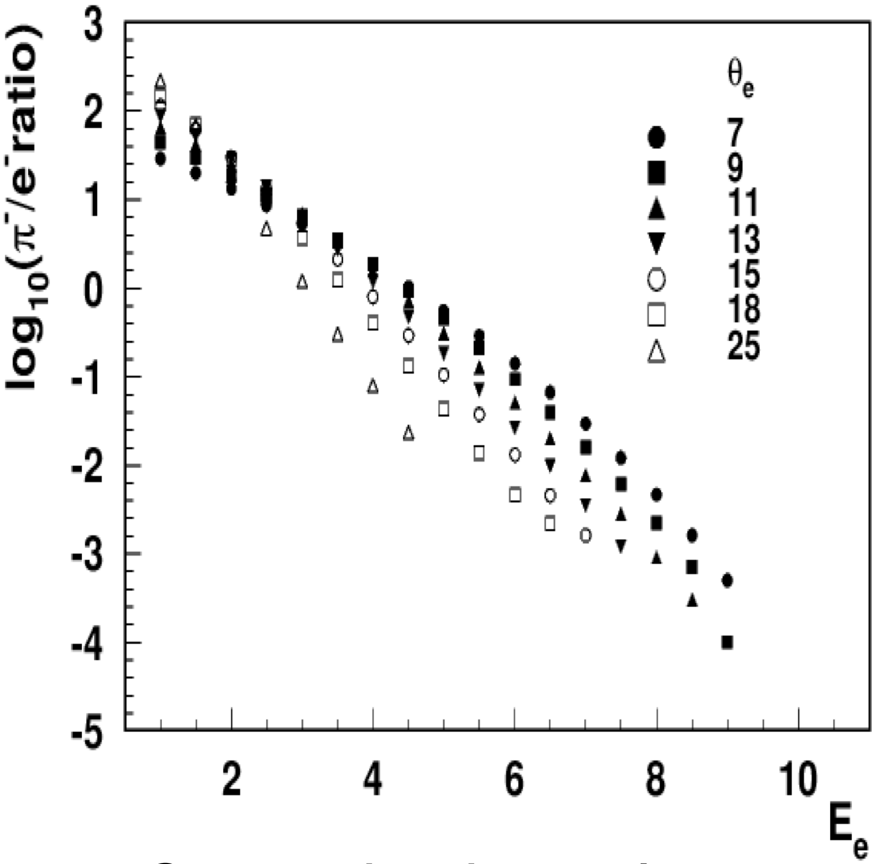




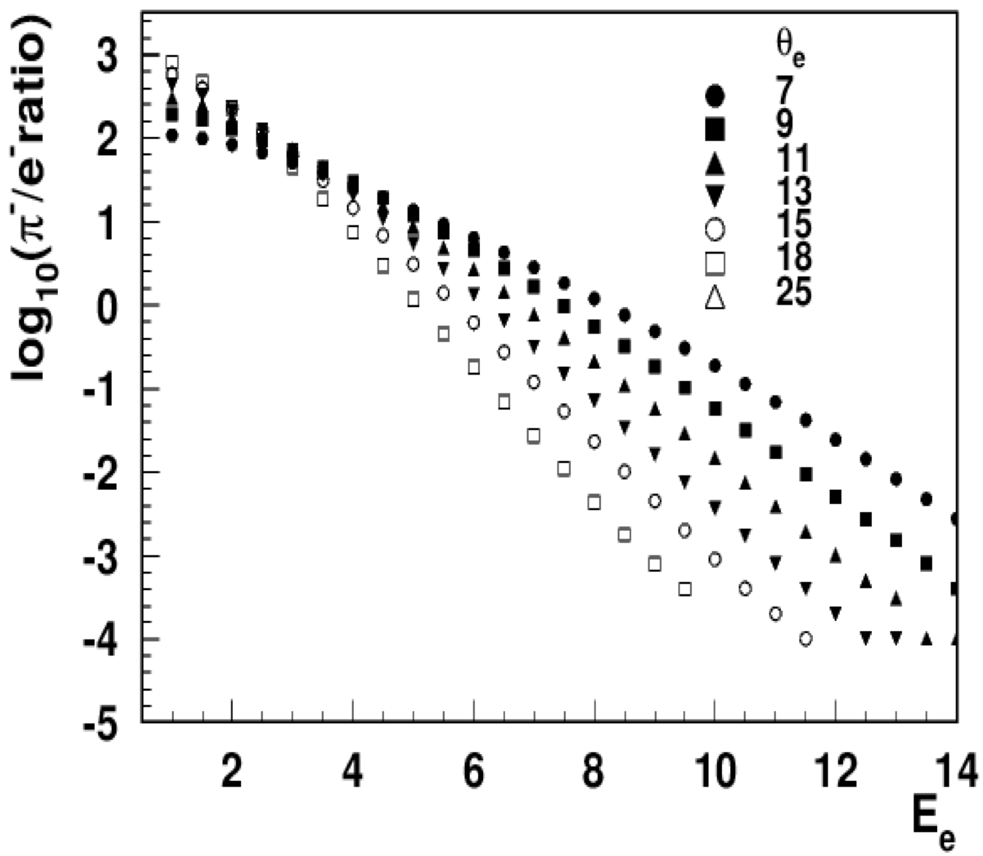
JLab24 will significantly increase the the Q^2 range, allowing detailed separation of higher twist SFs, needed for understanding the QCD

Relative fluxes: e- vs pi-

CLAS12

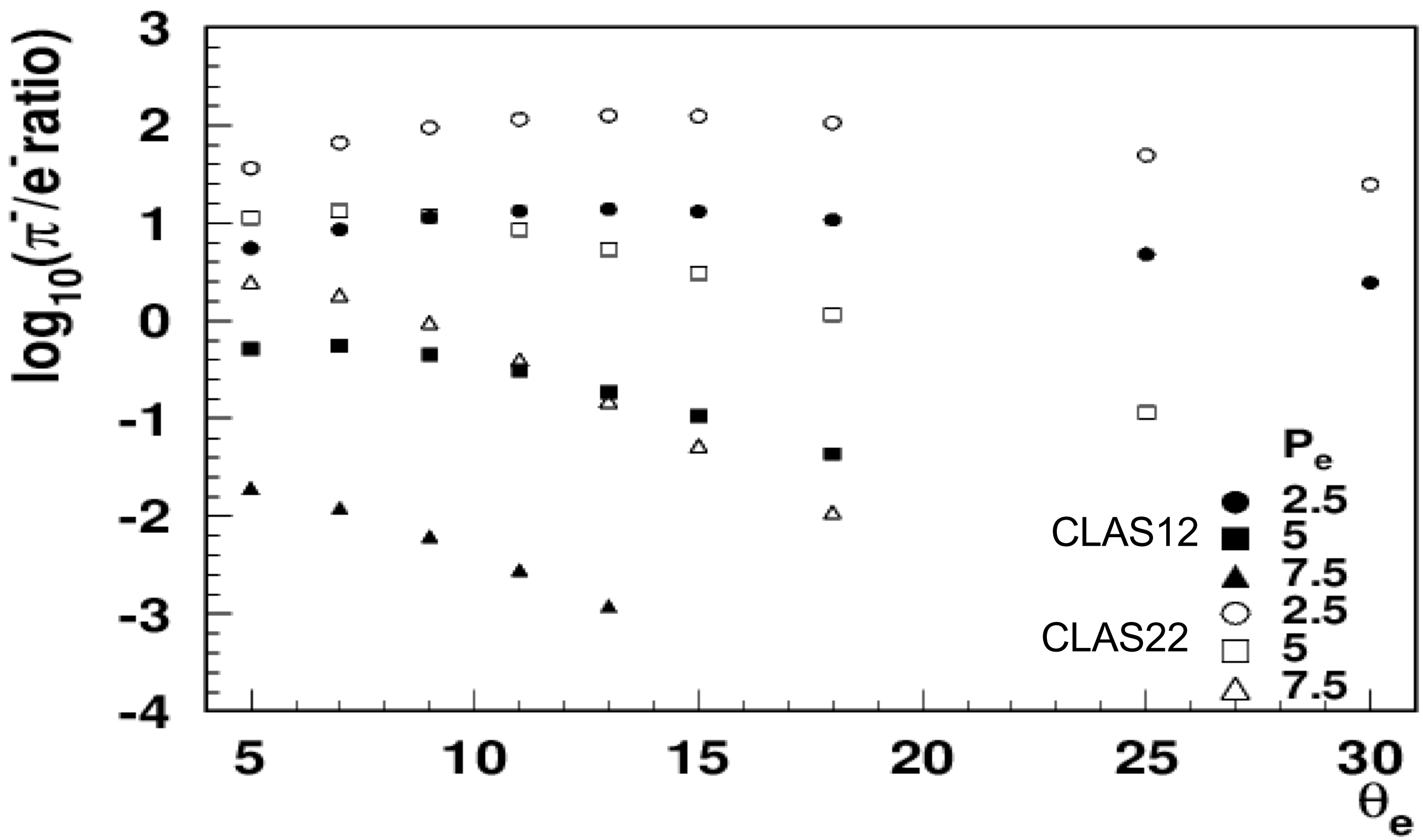


CLAS22



Contamination at low energies will be ~50% higher
(electrons <2 GeV may not be much useful anyway)

Relative fluxes: e- vs pi-



Relative fraction of pi- increases for a fixed energy
For a constant y (y<0.75 used) they are consistent

Current theory limitations (q_T/Q)

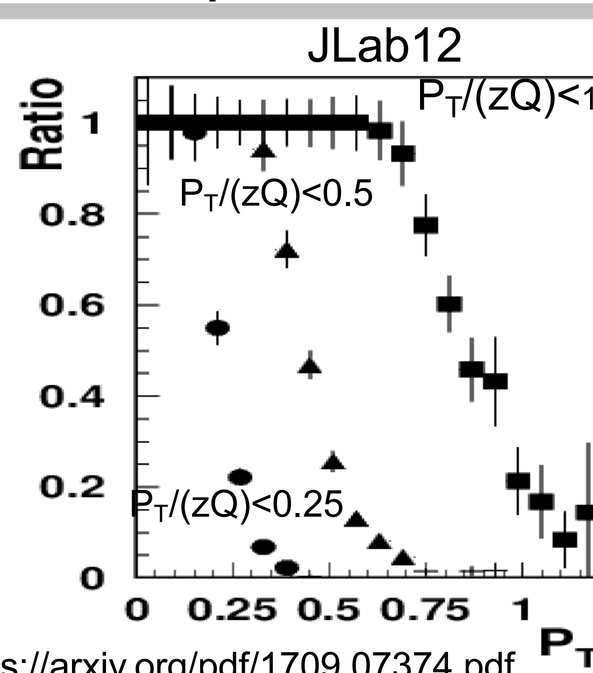
estimates of their effects. For example, the TMD description of SIDIS is valid in the small-p_T regime when $p_T^2/(zQ)^2 \ll 1$, and in a recent study [JHEP 06 (2020) 137] finding that $p_T^2/(zQ)^2 \lesssim 0.06$ approximately demarcates the boundary to large p_T, where a description in terms of TMD PDFs may not be trustworthy. By comparison, values for this ratio as

The $q_T=P_T/z$ theory "trustworthy" cut:

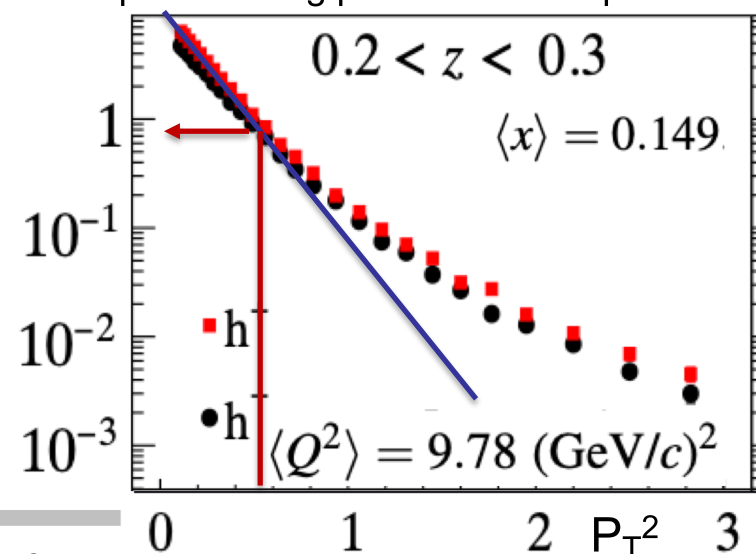
1) Suppresses moderate Q^2 and large P_T (sensitive to k_T), where all kind of azimuthal modulations are most significant
2) Enhances large z region (ex. Exclusive Events) in TMD and low z in FO calculations

3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P_T samples , including ones from HERMES COMPASS, and even EIC.

Details available from https://indico.jlab.org/event/439/
JLab/HERMES/COMPASS/EIC talks



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



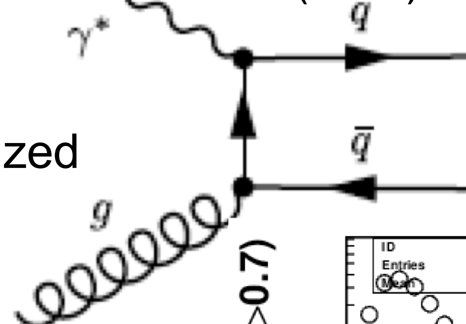
“JLab only”

Gluon polarization at large x

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

A.Bravar, D. von Harrach, A. Kotzinian,
Phys.Lett.B 421 (1998) 349-359

photon–gluon fusion (PGF).



HERMES Collaboration (M.Amaryan)
Phys. Rev. Lett. **84**, 2584

COMPASS collaboration
Physics Letters B 718 (2013) 922–930
Use P_T>0.7 GeV for leading hadron

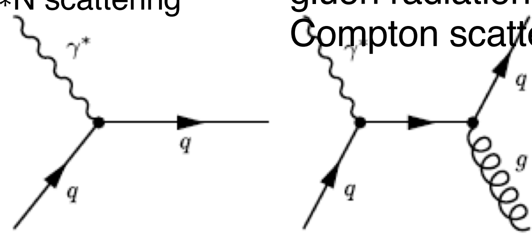
Photon gluon fusion (PGF) process direct measurements of the unpolarized gluon structure function $G(x_G)$.

- charm production
- production of jets with high transverse momentum P_T .

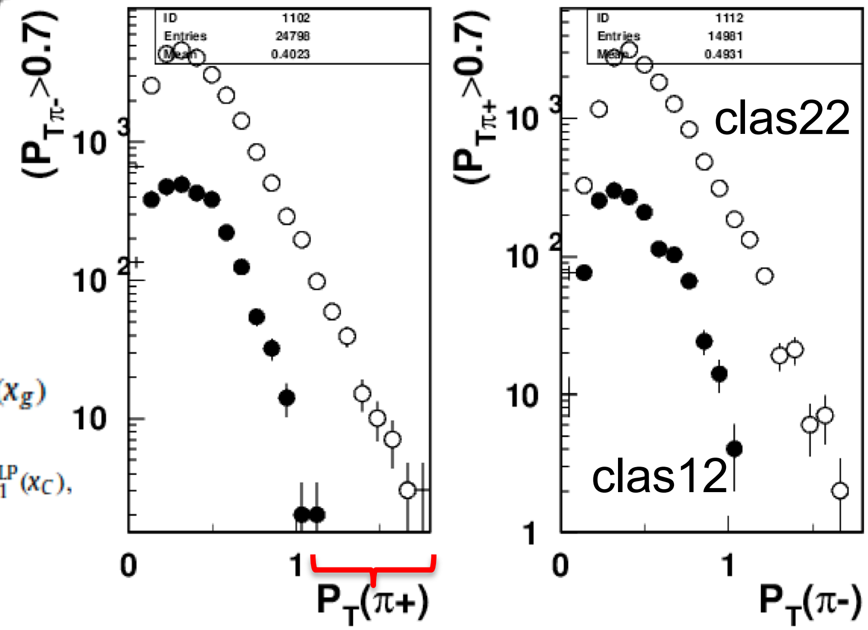
Background processes

γ ∗N scattering

gluon radiation (QCD Compton scattering)



$$A_{LL}^{2h}(x_{Bj}) = R_{PGF}\, a_{LL}^{PGF} \frac{\Delta g}{g}(x_g) + R_{LP} D A_1^{LP}(x_{Bj}) + R_{QCDC}\, a_{LL}^{QCDC} A_1^{LP}(x_C),$$



Depending on required kinematical cuts can be type 1) or type 2) observable

- Can be studied in electroproduction and quasi-real electroproduction at sufficiently high P_T reflect the high P_T of the quark and antiquark produced in the PGF process.

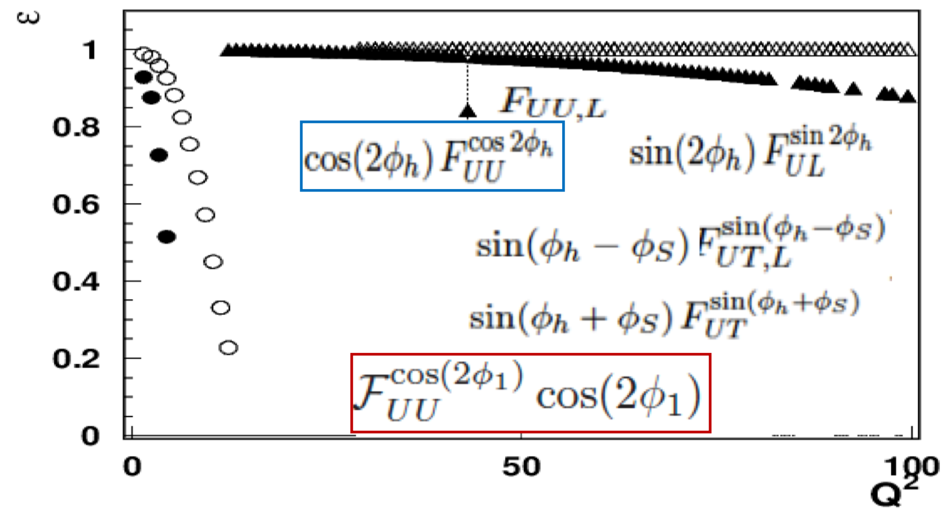
Complementarity between JLab and EIC

$F_{UU,T}$ Multiplicities, evolution of unpolarized SFs

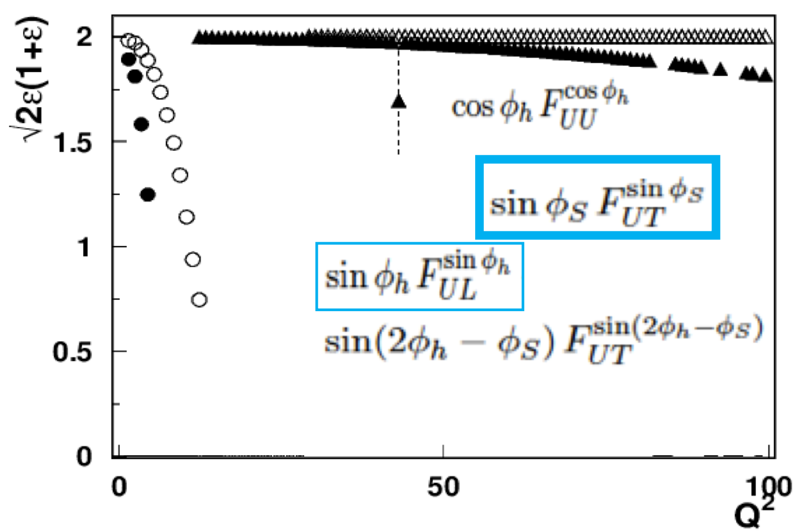
$F_{UT,T}^{\sin(\phi_h-\phi_S)}$ Sivers and Collins SSAs (Transverse target)

$\boxed{\mathcal{F}_{UL}^{\sin(\phi_1-\phi_2)} \sin\Delta\phi}$ Longitudinally polarized Target spin asymmetries in correlations of CFR and TFR (single and dihadron)

Observables with no ε-dependence or not suppressed at low ***y*** provide complementarity set



x=0.3

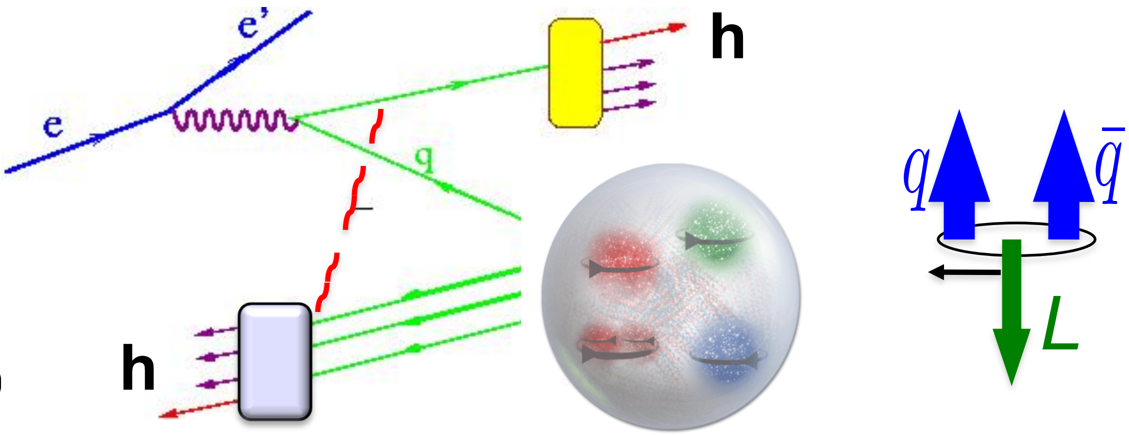


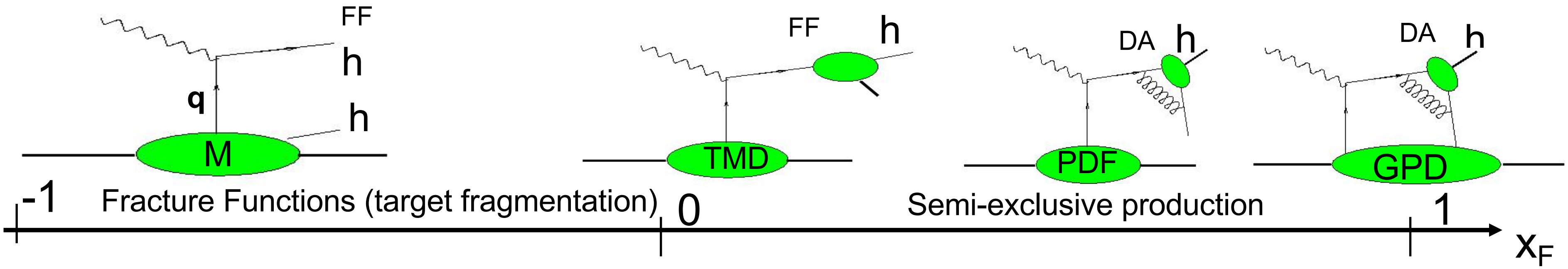
Hadron production in hard scattering in SIDIS

x_F – fractional momentum in the CM frame

$x_F>0$ (current fragmentation)

$x_F<0$ (target fragmentation)

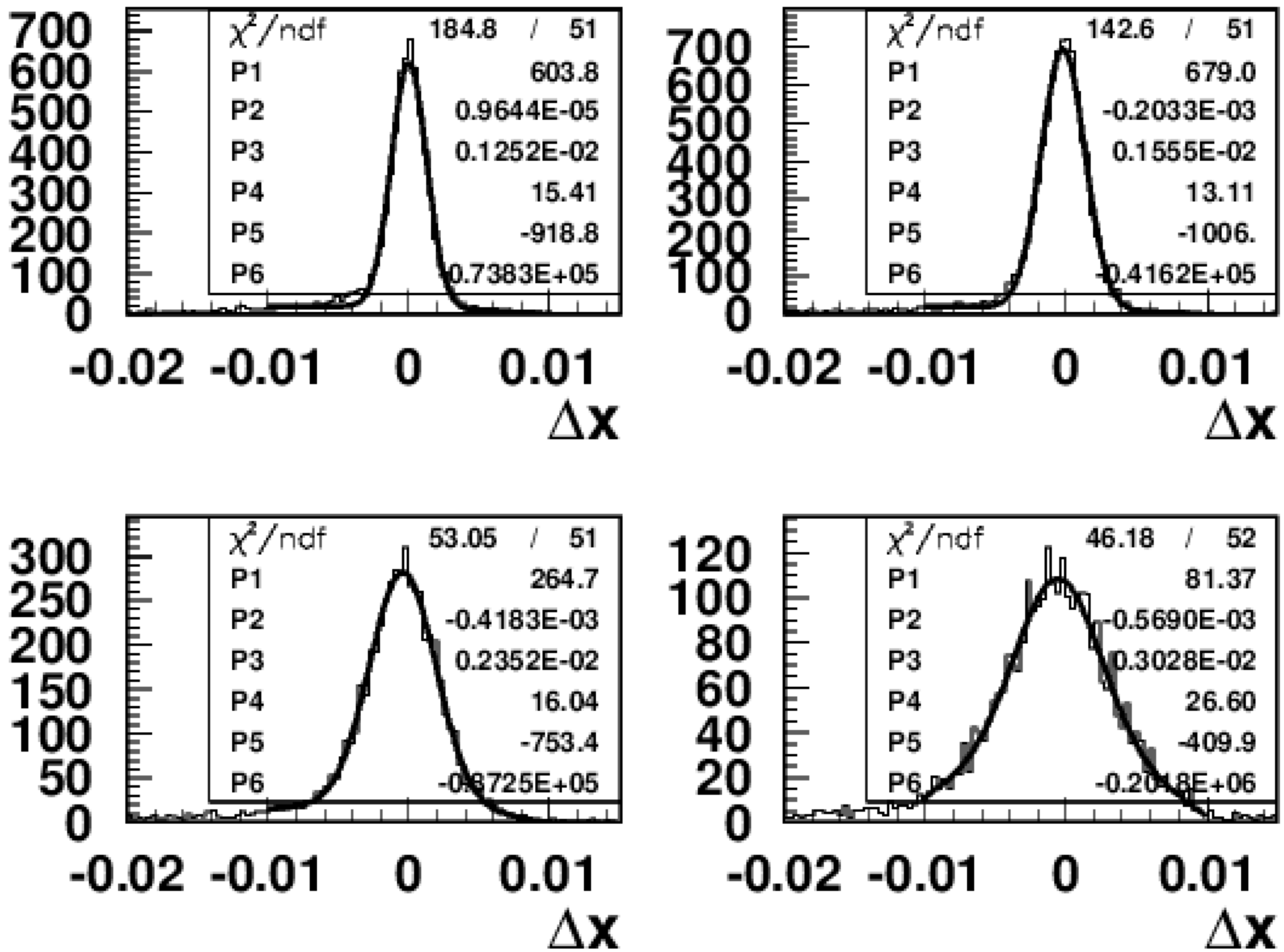




Different non-perturbative objects may be involved in description, depending on kinematical conditions, introducing different dependence on Q^2

Resolutions in x

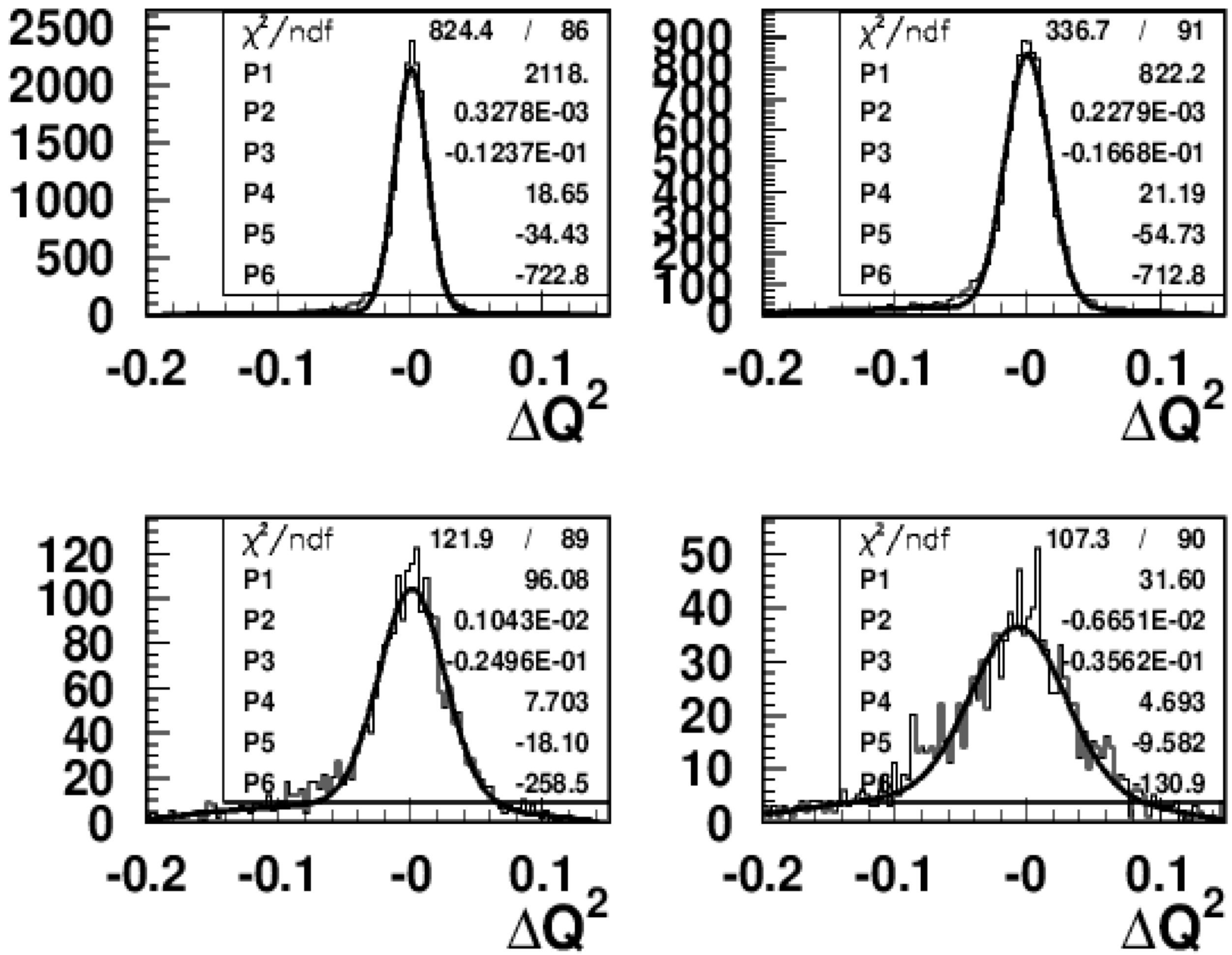
X-bins
0.0540
0.0590
0.0644
0.0704
0.0768
0.0839
0.0917
0.1001
0.1093
0.1194
0.1304
0.1424
0.1555
0.1699
0.1855
0.2026
0.2213
0.2417
0.2639
0.2882
0.3148
0.3438
0.3755
0.4101
0.4479
0.4891
0.5342
0.5834
0.6372
0.6959
0.7600



Bins ~4sigma

Resolutions in Q^2

1.000
1.0814
1.1694
1.2646
1.3675
1.4788
1.5991
1.7292
1.8700
2.0222
2.1867
2.3647
2.5571
2.7652
2.9903
3.2336
3.4968
3.7814
4.0891
4.4219
4.7818
5.1709
5.5917
6.0468
6.5389
7.0711
7.6465
8.2688
8.9418
9.6695
10.4564
11.3074
12.2276
13.2227
14.2988
15.4625
16.7209
18.0816



Bins ~5sigma

Observation of SSAs in ep→e'$\pi^+\pi^-$X

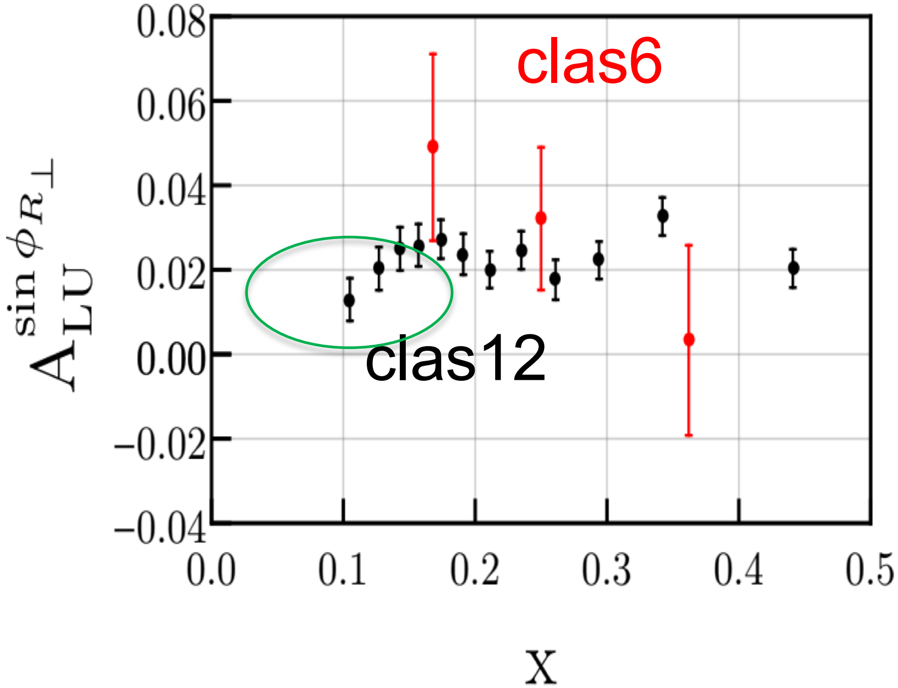
T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)

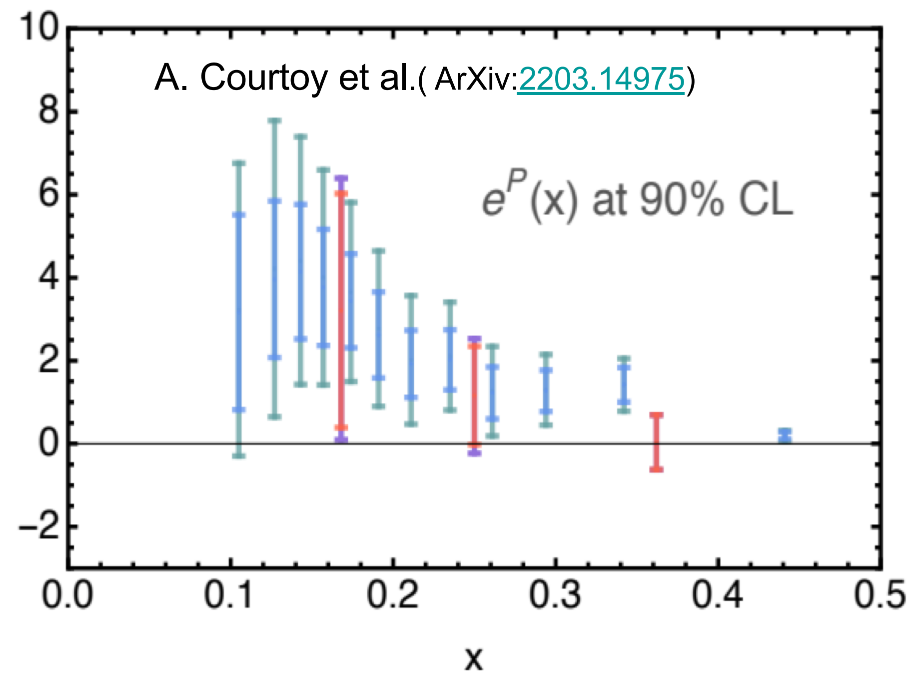
$H_1^{\sphericalangle}$ = h1 h2 - h1 h2

$$d\sigma_{LU} \propto \lambda_e \sin(\phi_{R_\perp}) \left(xe(x) H_1^{\sphericalangle}(z, M_h) + \frac{1}{z} f_1(x) \tilde{G}^{\sphericalangle}(z, M_h) \right)$$

Bacchetta&Radici: arXiv:hep-ph/0311173

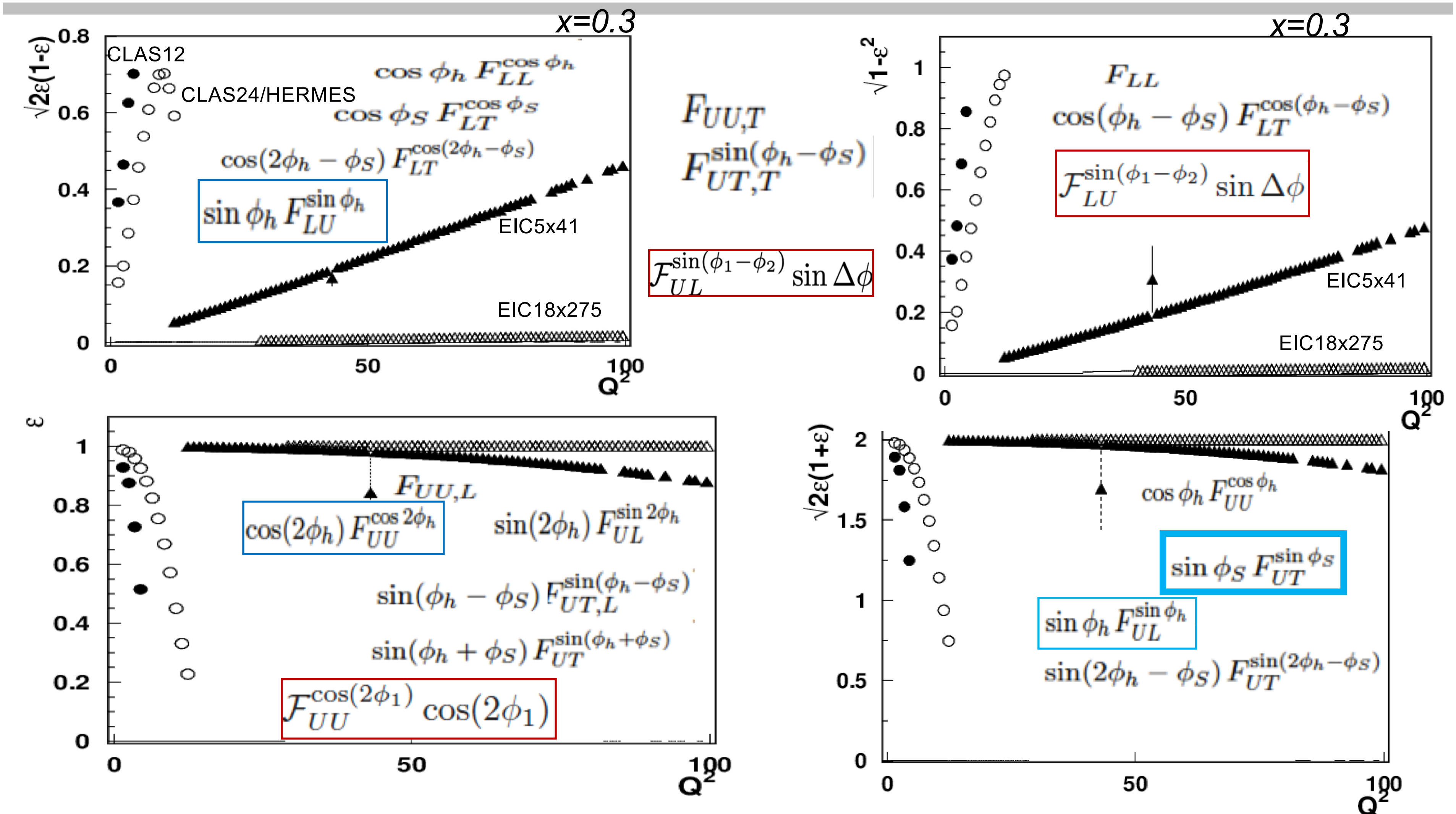
evolution→Rodini & Vladimirov, arXiv:2204.03856





- Doubling the JLab beam energy, opens the phase space for SIDIS dihadrons (low x)
- First extractions support: quark gluon correlations may be very significant,
- PDF e describes the force on the transversely polarized quark after scattering, factorization and evolution studies by Vladimirov et al (in preparation)

SIDIS: Kinematic factors at large x



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

From CLAS12 to CLAS24: Trento and focused workshops

FONDAZIONE BRUNO KESSLER
ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Opportunities with JLab Energy and Luminosity Upgrade

Sep 26 – 30, 2022
ECT* - Villa Tambosi
Europe/Rome timezone

https://indico.ectstar.eu/event/126/

Physics Items

a)Measurements of evolution of 3D partonic distribution and fragmentation functions
b) Correlated hadrons and their impact on hadronization
c) Studies of 3D PDFs using combination of the Lattice QCD with the phenomenology and QCD based modeling needed for interpretation of the experimental data, and development of new observables.
d) Advances in the exploration of the structure of excited nucleon states.
e) In-medium modifications of fundamental QCD processes
f) Studies of light meson structure
g) Charm production near the threshold
h) Spectroscopy at the intensity frontier
i) Large x physics
j) Electroweak Physics at 24~GeV

Messina Workshop

Organizers

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John Arrington (Lawrence Berkeley National Laboratory, Berkeley/US)
JArrington@lbl.gov
Alessandro Bacchetta (Pavia University, Pavia/I)
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kyungseon.joo@uconn.edu
Xiaochao Zheng (University of Virginia (UVa), Charlottesville/US)
xiaochao@jlab.org

Key speakers/physics items

1) Jianwei Qiu (QCD)
2) Jen-Chieh Peng (non-perturbative sea)
3) Pasquale Dinezza (the LHC fixed target experiments, large x)
4) Simonetta Liuti (GPDs)
5) Marco Battaglieri, Alessandro Pilloni (spectroscopy)
6) Moskov Amaryan/ Goldstein (charm)
7) Lubomir Penchev (Hall-D physics/detectors)
8) Ralf Gothe (Hall-B physics/detectors)
9) Jiang-Ping Chen (Hall-A/C physics/detectors)
10) Eric Voutie (positron beam)
11) Carlos Munoz Camacho (exclusive processes)
12) Gunar Schnell/Marco Contalbrigo (HERMES)
13) Moretti/Parsamyan (COMPASS)
14) Signori/Vladimirov/Yuan (TMDs)
15) Yong Zhao/Martha Constantinou (Lattice studies)
16) Misak Sargsian (Medium effects/theory)
17) Lamiaa el Fassi (Medium effects/experiment)
18) Barbara Pasquini (GTMDs)
19) Anselm Vossen (Complementarity with EIC)

Set of dedicated workshops/meeting to develop projections

Observation of SSAs in ep→e'$\pi^+\pi^-$X

evolution→Rodini & Vladimirov, arXiv:2204.03856

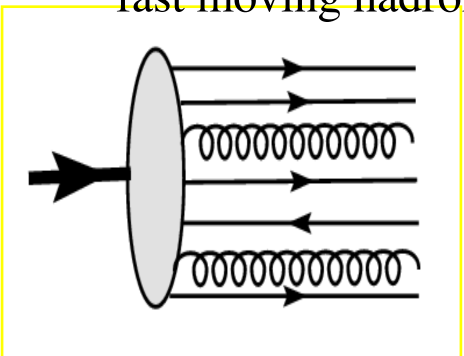
	U	L	$T_{J=0}$	$T_{J=1}$	$T_{J=2}$
U	$f_\bullet^\perp$	$g_\bullet^\perp$		$h_\bullet$	$h_\bullet^\perp$
L	$f_{\bullet L}^\perp$	$g_{\bullet L}^\perp$	$h_{\bullet L}$		$h_{\bullet L}^\perp$
T	$f_{\bullet T}$, $f_{\bullet T}^\perp$	$g_{\bullet T}$, $g_{\bullet T}^\perp$	$h_{\bullet T}^{D\perp}$	$h_{\bullet T}^{A\perp}$	$h_{\bullet T}^{S\perp}$, $h_{\bullet T}^{T\perp}$

Table 1. Quark TMD distributions of twist-three sorted with respect to polarization properties of both the operator (columns) and the hadron (rows). The labels U, H, and T are for the unpolarized, longitudinal and transverse polarizations. The subscript J differentiates different angular momentum for the transversely-polarized case. The bullet $\bullet$ stands for the $\oplus$, $\ominus$ labels.

$$\mu^2\frac{d}{d\mu^2}e=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)e\,,$$
$$\mu^2\frac{d}{d\mu^2}e_T^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)e_T^\perp\,,$$
$$\mu^2\frac{d}{d\mu^2}e_L=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)e_L\,,$$
$$\mu^2\frac{d}{d\mu^2}e_T=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)e_T\,,$$
$$\mu^2\frac{d}{d\mu^2}f_T=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)f_T-\frac{2a_sC_F}{x}\left(f_{1T}^\perp+\frac{b^2M^2}{2}\mathring{f}_{1T}^\perp\right)\,,$$
$$\mu^2\frac{d}{d\mu^2}f_L^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)f_L^\perp\,,$$
$$\mu^2\frac{d}{d\mu^2}f^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)f^\perp+\frac{2a_sC_F}{x}\mathring{f}_1\,,$$
$$\mu^2\frac{d}{d\mu^2}f_T^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)f_T^\perp+\frac{2a_sC_F}{x}\mathring{f}_{1T}^\perp\,,$$
$$\mu^2\frac{d}{d\mu^2}g_T=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)g_T+\frac{2a_sC_F}{x}\left(g_{1T}+\frac{b^2M^2}{2}\mathring{g}_{1T}\right)\,,$$
$$\mu^2\frac{d}{d\mu^2}g_L^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)g_L^\perp+\frac{2a_sC_F}{x}\mathring{g}_1\,,$$
$$\mu^2\frac{d}{d\mu^2}g^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)g^\perp\,,$$
$$\mu^2\frac{d}{d\mu^2}g_T^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)g_T^\perp+\frac{2a_sC_F}{x}\mathring{g}_{1T}\,,$$
$$\mu^2\frac{d}{d\mu^2}h_T^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)h_T^\perp+\frac{2a_sC_F}{x}\left(\mathring{h}_1-h_{1T}^\perp-\frac{b^2M^2}{4}\mathring{h}_{1T}^\perp\right)\,,$$
$$\mu^2\frac{d}{d\mu^2}h=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)h-\frac{4a_sC_F}{x}\left(h_1^\perp+\frac{b^2M^2}{2}\mathring{h}_1^\perp\right)\,,$$
$$\mu^2\frac{d}{d\mu^2}h_L^\perp=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)h_L^\perp-\frac{2a_sC_F}{x}\left(h_{1L}^\perp+\frac{b^2M^2}{4}\mathring{h}_{1L}^\perp\right)\,,$$
$$\mu^2\frac{d}{d\mu^2}h_T=\left(\frac{\Gamma_{\text{cusp}}}{2}\ln\left(\frac{\mu^2}{\zeta}\right)+a_sC_F\right)h_T-\frac{2a_sC_F}{x}\left(\mathring{h}_1+h_{1T}^\perp+\frac{b^2M^2}{4}\mathring{h}_{1T}^\perp\right),$$

Proton structure from 1D to 3D

fast moving hadron

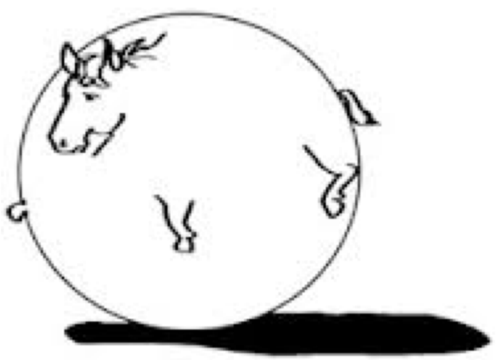


Universality of PDFs
Evolution properties
QCD tested confirmed!!!

real life

- FAMOUS QUOTE OF YURI DOKSHITZER
  - "FOLKS, WE NEED TO STOP "TESTING" QCD AND START UNDERSTANDING IT", ICHEP 1998, VANCOUVER, BC , CONFERENCE SUMMARY TALK

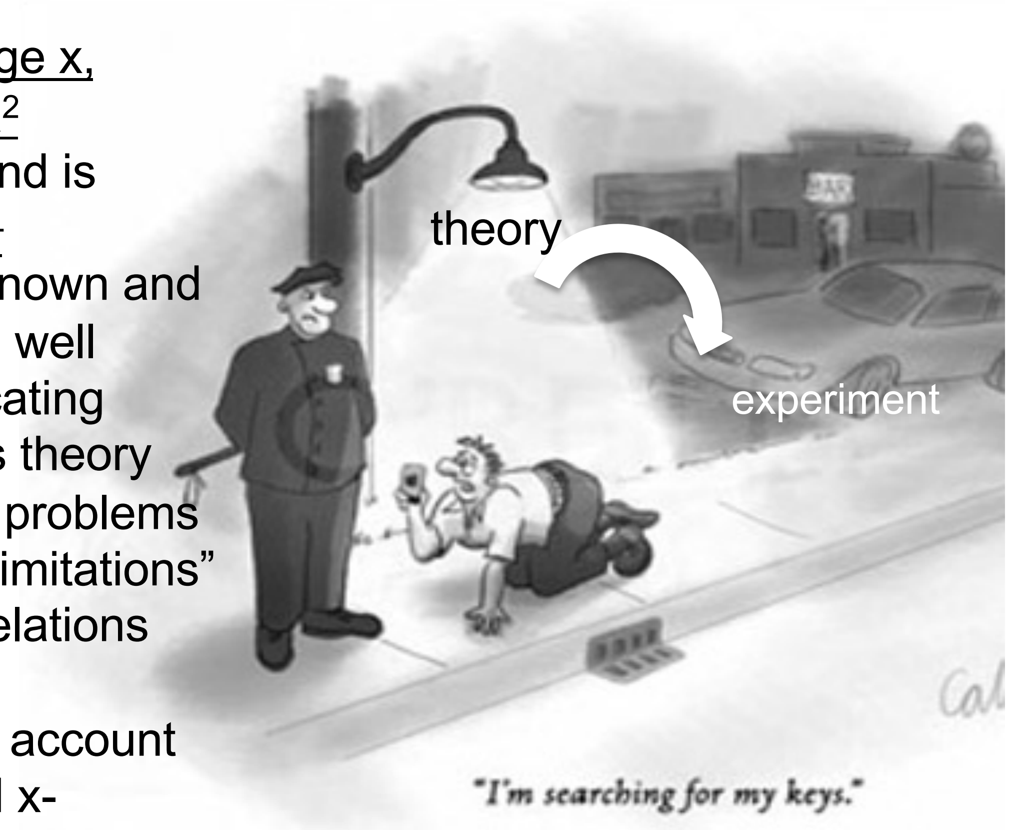
spherical horse in vacuum



For real data description understanding the dynamics and related interactions and correlations (Higher Twists) will be important

Nucleon structure, TMDs and SSAs

- Large effects observed at relatively large x, relatively large P_T and relatively low Q^2
- Theoretical framework works better, and is "trustworthy" at higher Q^2 and lower P_T
- TMD Fragmentation functions poorly known and understood, systematics not controlled well
- Higher twist SSAs are significant, indicating strong quark-gluon correlations, issues theory has, may become a key to resolve the problems
- Real experiments have "phase space limitations" due to finite energies, introducing correlations between kinematical variables
- Impact of radiative corrections with full account of azimuthal moments in the polarized x-sections still in development



The main goal of SIDIS measurements is the study of non-perturbative QCD, through spin-orbit correlations, where they are significant enough to be measurable
Understanding of the limitations of the current TMD framework with all its assumptions and approximations, is important for predictions, and projections for future experiments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