Spin structure of the nucleon: current status and future measurements

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Understanding the QCD: from observables to QCD dynamics
- Building the science case for Jlab 22+ upgrade
- Testing the QCD based frameworks for finite energies in SIDIS with experiments with polarized beams and targets
- Studies of evolution properties of observables
- Multihadron correlations

Summary

Building the science case for JLab22

Workshops to support Future Opportunities ArXiv:2306.09360

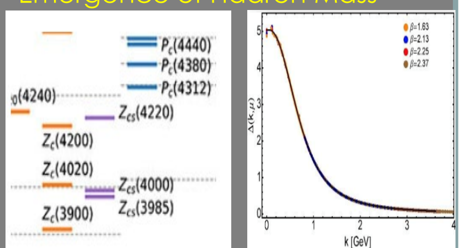
- **J-FUTURE**
  Messina (Italy) March 28-30, 2022
- **Hadron Physics Opportunities with JLab Energy and Luminosity Upgrade**
  Pohang (Korea) July 18-21, 2022
- **Opportunities with Jlab Energy and Luminosity Upgrade**
  ECT* Trento (Italy) September 26-30, 2022

- **Probe the science that would be opened up by a E_e 20+ GeV**
  Initially utilizing largely existing or already-planned Hall equipment

U = Uniqueness
E = Enrichment
C = Complementarity (EIC)

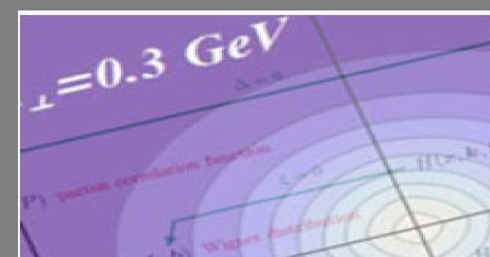
@JLab Workshops July 7-8, January 23-25

Hadron Spectroscopy and Emergence of Hadron Mass

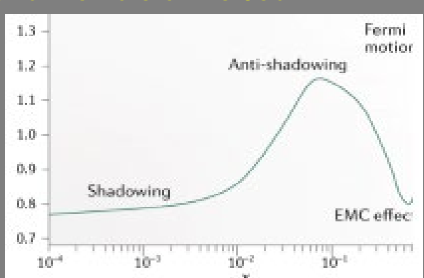


J/Psi and Beyond

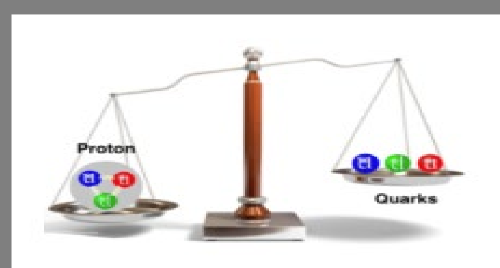
The Next Generation of 3D Imaging



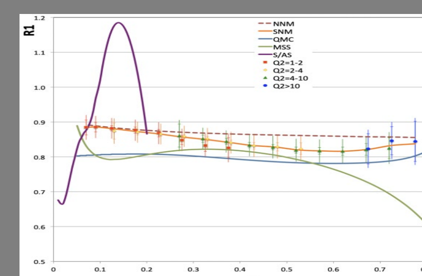
Science at Mid x: Anti-shadowing and the Role of the Sea



Physics Beyond the Standard Model



Medium modifications



Motivating the JLab 20+ upgrade

Need to classify observables, summarize the set of projection for key observables

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

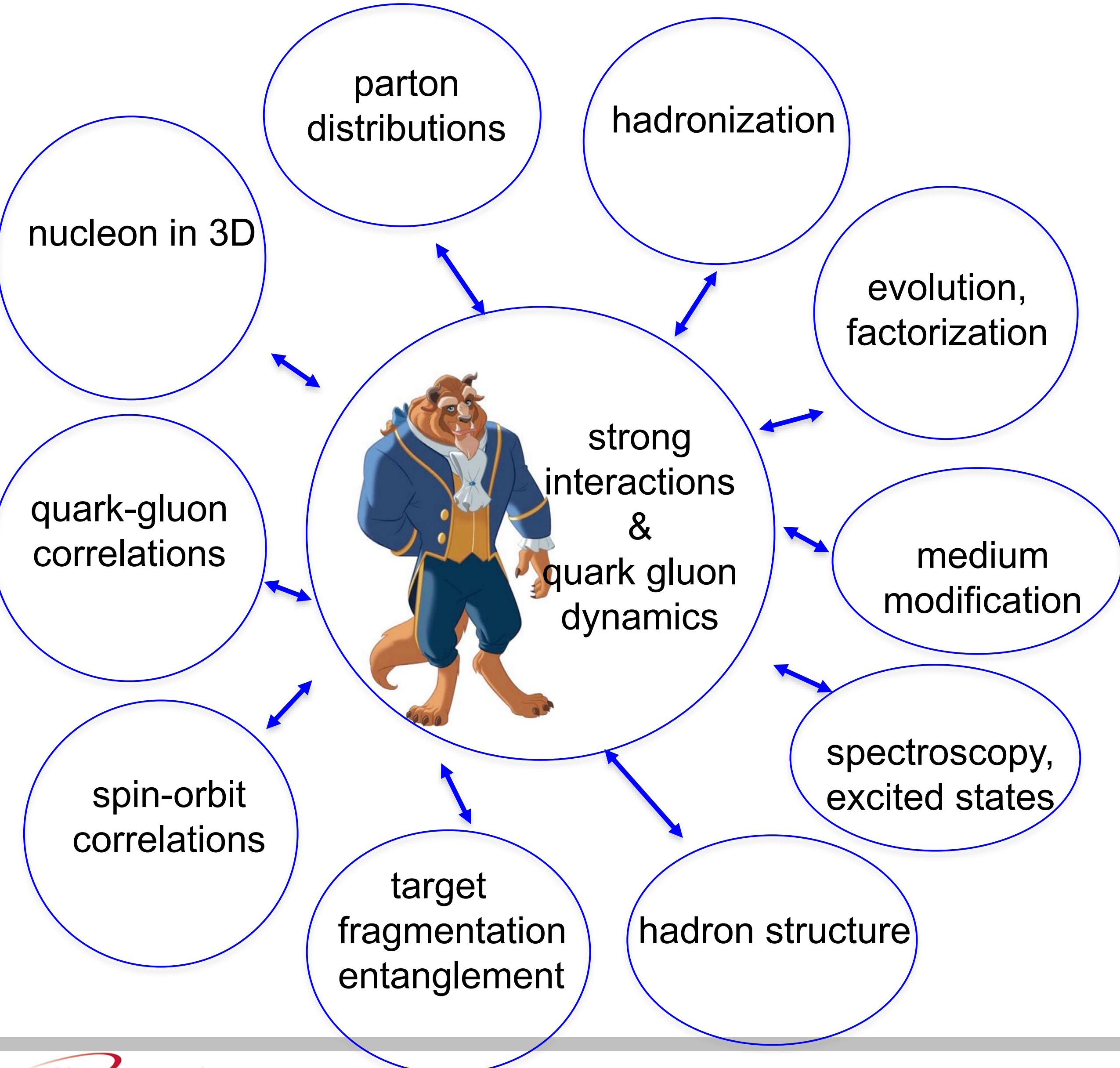
2)Identify the flagship measurements with 22 GeV that can extend, improve the 11 GeV, helping interpretation, multidimensional bins in extended kinematics

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

Projections summarize what we learned, teach us what we can do with our data, and where we need to combine it with higher energy data,

QCD: from testing to understanding



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

Understanding stage:
non-perturbative QCD, observables in the real life kinematics where most of the data is available and interactions are strong (more complex observables revealing details of the dynamics,…)

Uniqueness

- In the area of hadron spectroscopy, with real photons in Hall D and quasi-real photons in Hall B, a unique production environment of exotic states will be probed providing cross section results, complementary to high-energy facilities. Photoproduction cross sections of exotic states could be decisive in understanding the nature of a subset of the pentaquark and tetraquark candidates that contain charm and anti-charm quarks. Moreover, in Hall B the high-intensity flux of quasi-real photons at high energy will add the extra capability of studying the Q^2 evolution of any new state produced.

- JLab will be able to explore the proton's gluonic structure by unique precise measurements of the photo and electroproduction cross section near threshold of J/ψ and higher-mass charmonium states, χ_c and $\psi(2S)$. Moreover, with an increase of the polarization figure-of-merit by an order of magnitude, GlueX will be able to measure polarization observables that are critical to disentangle the reaction mechanism and draw conclusions about the mass properties of the proton.

- The JLab 22 GeV upgrade will enable high-precision measurements of the Primakoff production of pseudoscalar mesons with results: to explore the chiral anomaly and the origin and dynamics of chiral symmetry breaking; and to determine the light quark-mass ratio and the η-η' mixing angle model independently. In particular, JLab will be able, for the first time, to perform precision measurements of the radiative decay width of π^0 off an electron to reach a sub-percent precision on $\Gamma(\pi^0 \to \gamma\gamma)$, necessary to better understand the discrepancy between the existing experimental results and the high-order QCD predictions, and therefore offering a stringent test of low-energy QCD.

Enrichment and Complementarity

- The 22 GeV upgrade will be crucial for carrying out elastic and hard-exclusive process experiments. Such measurements require sufficient energy for reaching the scaling and factorization regime, high luminosity for measurements of low-rate processes and multivariable differential analysis, and excellent detector resolution for cross section measurements. Essential physics applications are:

  a) High-quality extraction of the D-term form factor of the QCD energy-momentum tensor and the "pressure" distribution inside the proton.

  b) Fully differential 3D imaging of the nucleon using novel processes such as Double Deeply Virtual Compton Scattering (DDVCS) and exclusive diphoton production.

  c) Exploring hadron structure with novel exclusive processes such as $N \to N^*$ transition GPDs and $N \to$ meson transition distribution amplitudes.

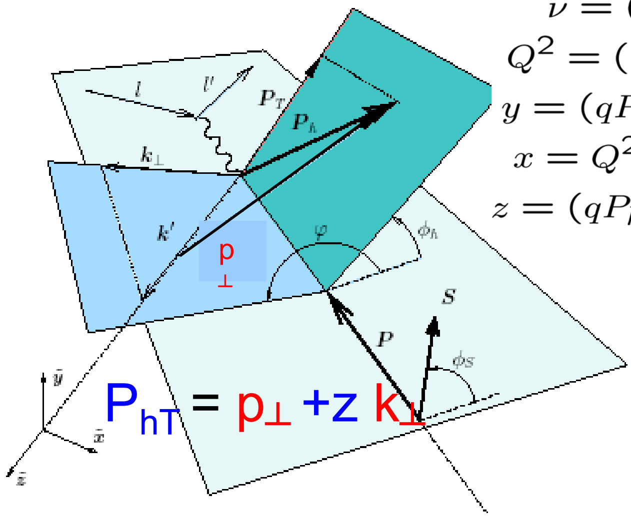
  d) Extending nucleon, pion, and resonance transition form factor measurements to momentum transfers $Q^2 \sim 30$ GeV^2, probing short-range hadron structure, QCD interactions, and the mechanism of the emergence of hadron mass.

- The 22 GeV high intensity beam will create an unprecedented opportunity for Nuclear Sciences to significantly advance our knowledge of QCD dynamics of nuclear forces at core distances. Some highlights of the JLab 22 GeV upgrade program include:

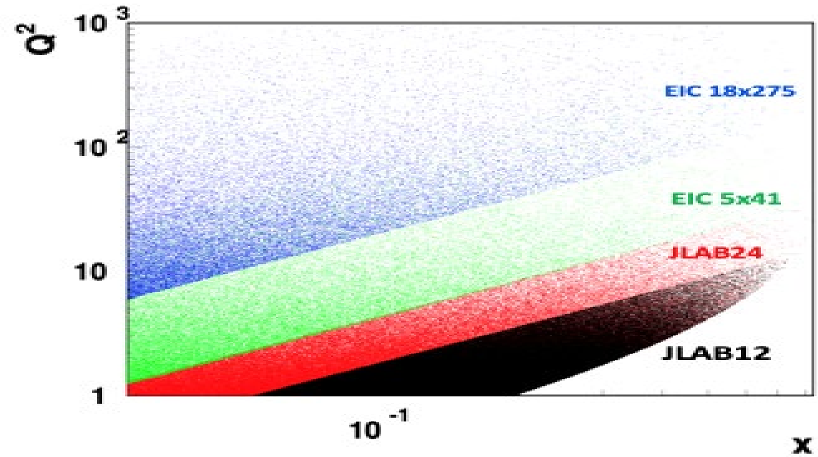
Enrichment and Complementarity

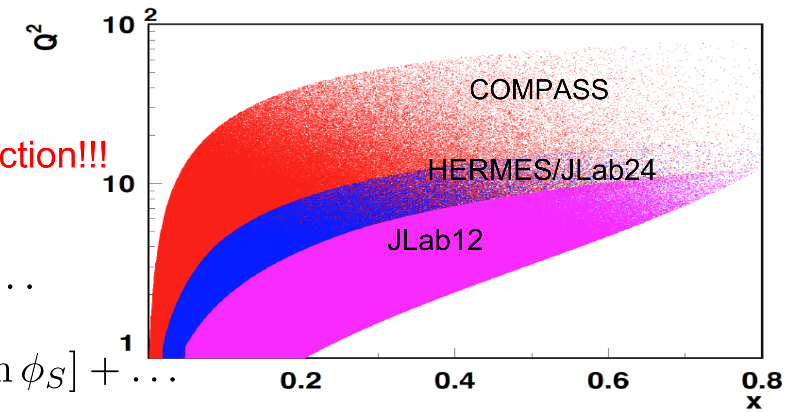
- The 22 GeV upgrade will extend the phase space, in particular in momentum transfer Q^2 and hadronic transverse momenta, for studying the momentum space tomography of nucleons and nuclei through the transverse momentum dependent (TMDs) of parton distribution functions, offering a new complementary window between the 12 GeV program and the future EIC. Combined with the high luminosity and precision detecting capabilities of multiparticle final state observables in a multidimensional space, it will make JLab unique to disentangle the genuine intrinsic transverse structure of hadrons encoded in TMDs with controlled systematics. These capabilities are critical for the interpretation of the measurements carried out both at JLab and EIC and for full understanding of the complex nature of nucleon structure properties and hadronization processes. Moreover, JLab has a uniquely fundamental role to play in the EIC era in the realm of precision separation measurements between the longitudinal (σ_L) and transverse (σ_T) photon contributions to the cross section, which are critical for studies of both semi-inclusive and exclusive processes.

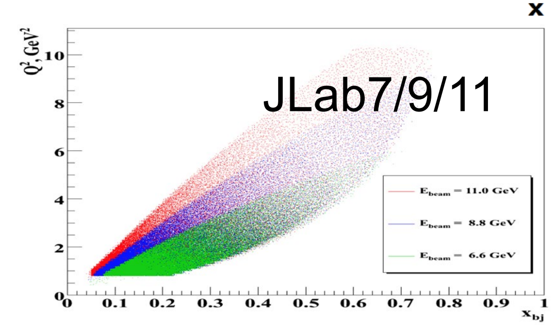
SIDIS kinematical coverage and observables



$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$







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
- All azimuthal modulations increase with P_T
- All assumptions involved in description of SFs, should be tested!
- QCD predicts only the Q^2-dependence of 3D PDFs

Steps to control the systematics in interpretation

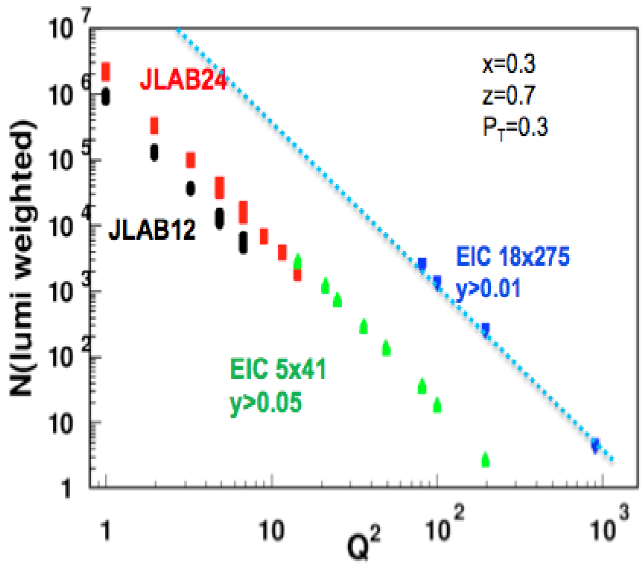
- SIDIS, with hadrons detected in the final state, from experimental point of view, is a measurement of observables in 5D space (x,Q^2,z,P_T,ϕ), 6D for transverse target, $+\phi_S$
  Collinear SIDIS, is just the proper integration, over P_T,ϕ,ϕ_S
- SIDIS observations relevant for interpretations of experimental results:
  1. Understanding of P_T-dependences of observables in the full range of P_T dominated by non-perturbative physics
  2. Understanding of phase space effects is important (additional correlations)
  3. Understanding the role of vector mesons in independent fragmentation
  4. Understanding of correlations in hadron production in hard scattering
  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

Structure functions and depolarization factors in SIDIS

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

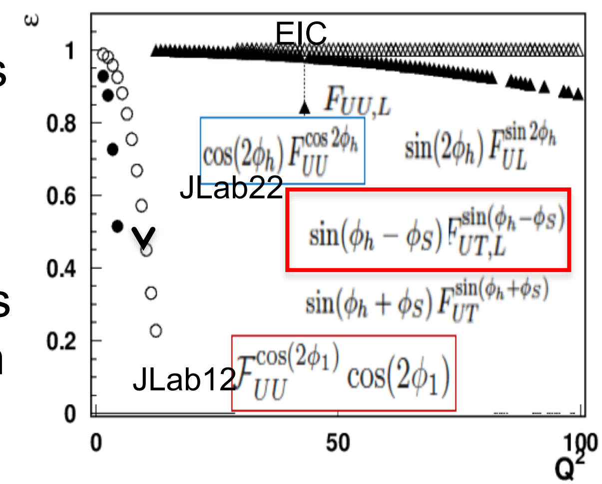
$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2\,(1-\varepsilon)}\Big\{ & F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\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



x-section from Bacchetta et al, 1703.10157

Combination of statistics and depolarization factors defines measurable SFs

1) Measurements of FUU,T and Sivers requires separation, evaluation of longitudinal photon (JLab)
2) Meaningful interpretation of the Collins effects requires separation of VMs(JLab)



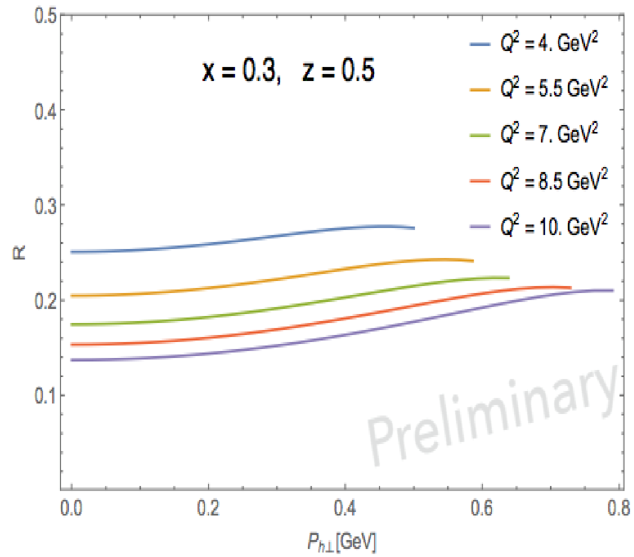
Longitudinal photon contributions in SIDIS

A. Bacchetta

	observable	twist (low P_T)	twist (high P_T)
"SIDIS F_T"	$F_{UU,T}$	2	2
"SIDIS F_L"	$F_{UU,L}$	4	2
"Cahn" - $f^\perp$	$F_{UU}^{\cos\phi_h}$	3	2
"Boer-Mulders"	$F_{UU}^{\cos 2\phi_h}$	2	2
e, $g^\perp$ and friends	$F_{LU}^{\sin\phi_h}$	3	2
	$F_{UL}^{\sin\phi_h}$	3	2
"Kotzinian-Mulders"	$F_{UL}^{\sin 2\phi_h}$	2	
"SIDIS g_1"	F_{LL}	2	2
	$F_{LL}^{\cos\phi_h}$	3	2
"Sivers"	$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	2	3
	$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	4	3
"Collins"	$F_{UT}^{\sin(\phi_h+\phi_S)}$	2	3
"Pretzelosity"	$F_{UT}^{\sin(3\phi_h-\phi_S)}$	2	3
f_T and friends	$F_{UT}^{\sin\phi_S}$	3	3
	$F_{UT}^{\sin(2\phi_h-\phi_S)}$	3	3
"Worm gear"	$F_{LT}^{\cos(\phi_h-\phi_S)}$	2	3
"SIDIS g_2" - g_T	$F_{LT}^{\cos\phi_S}$	3	
	$F_{LT}^{\cos(2\phi_h-\phi_S)}$	3	

There are several possibilities:

- Twist 2 TMD matching twist 2 PDF
- Twist 3 TMD matching twist 2 PDF
- Twist 2 TMD matching twist 3 PDF
- Expected mismatch
- Twist 4 TMD matching twist 2 PDF?



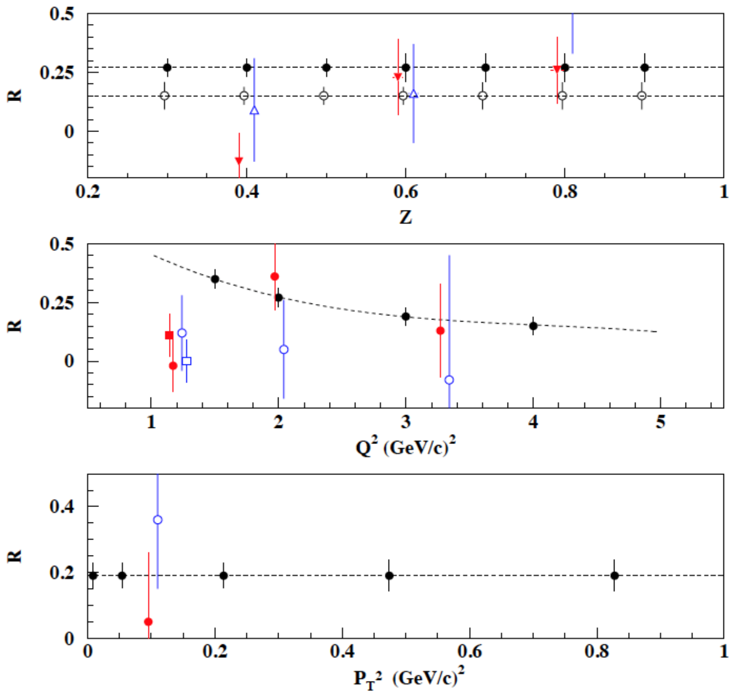
→ Contributes everywhere,
→ we know nothing!!!

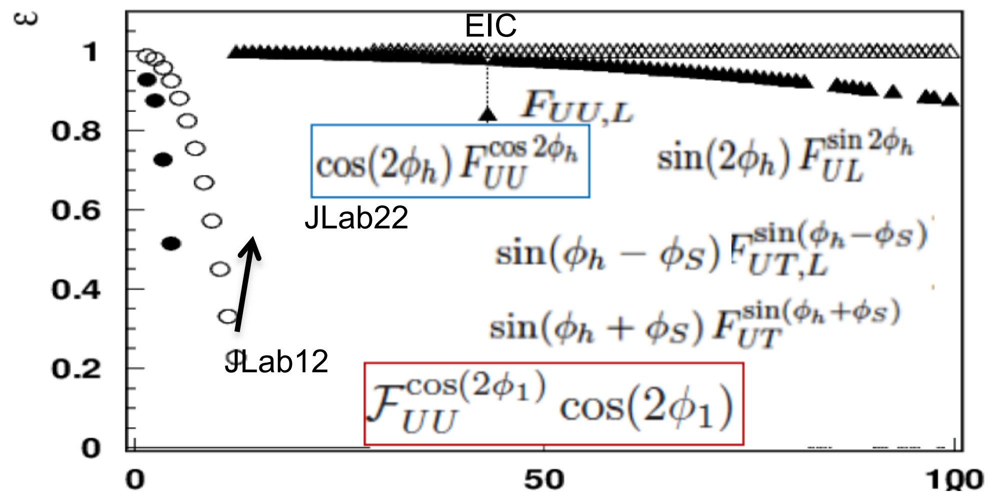
$$\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2} = \frac{2\pi\alpha^2}{x\,y\,Q^2}\frac{y^2}{2\,(1-\varepsilon)}\left\{2\pi F_{UU,T}(x,z,P_{h\perp}^2,Q^2) + \varepsilon\,2\pi F_{UU,L}(x,z,P_{h\perp}^2,Q^2)\right\}$$

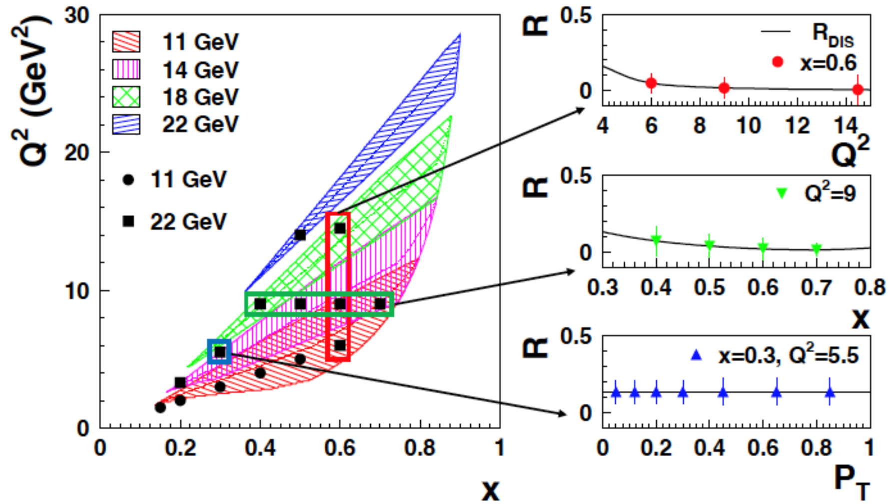
$$\frac{d\sigma}{dx\,dy\,dz} = \frac{4\pi\alpha^2}{x\,y\,Q^2}\frac{y^2}{2\,(1-\varepsilon)}\left\{F_{UU,T}(x,z,Q^2) + \varepsilon\,F_{UU,L}(x,z,Q^2)\right\}$$

$$R = \frac{F_{UU,L}}{F_{UU,T}}$$

FUU,L studies at Hall-C



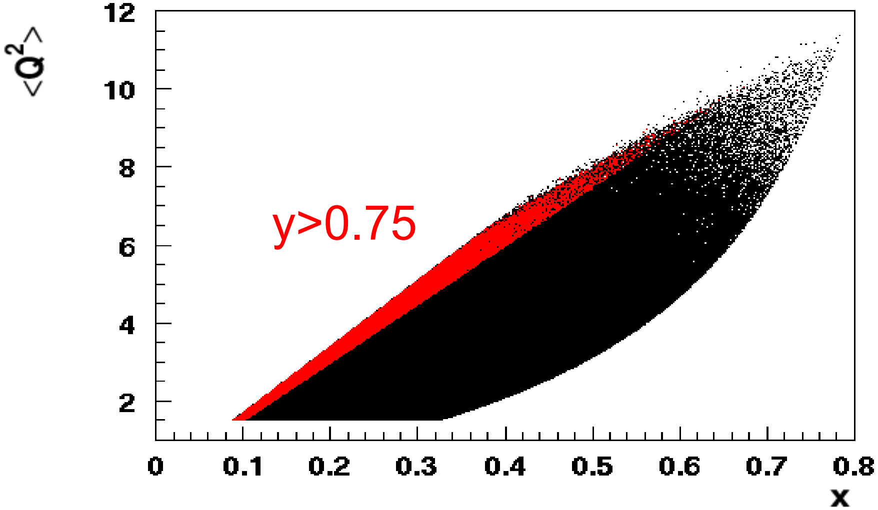


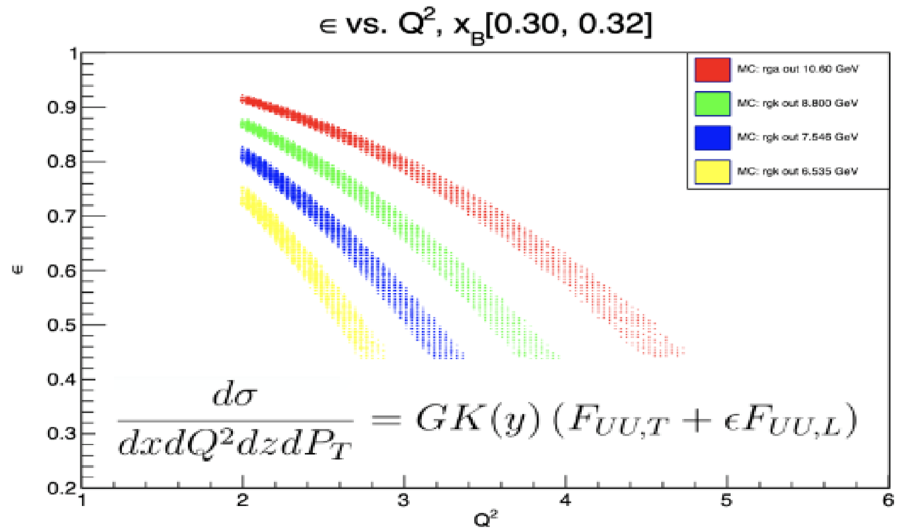


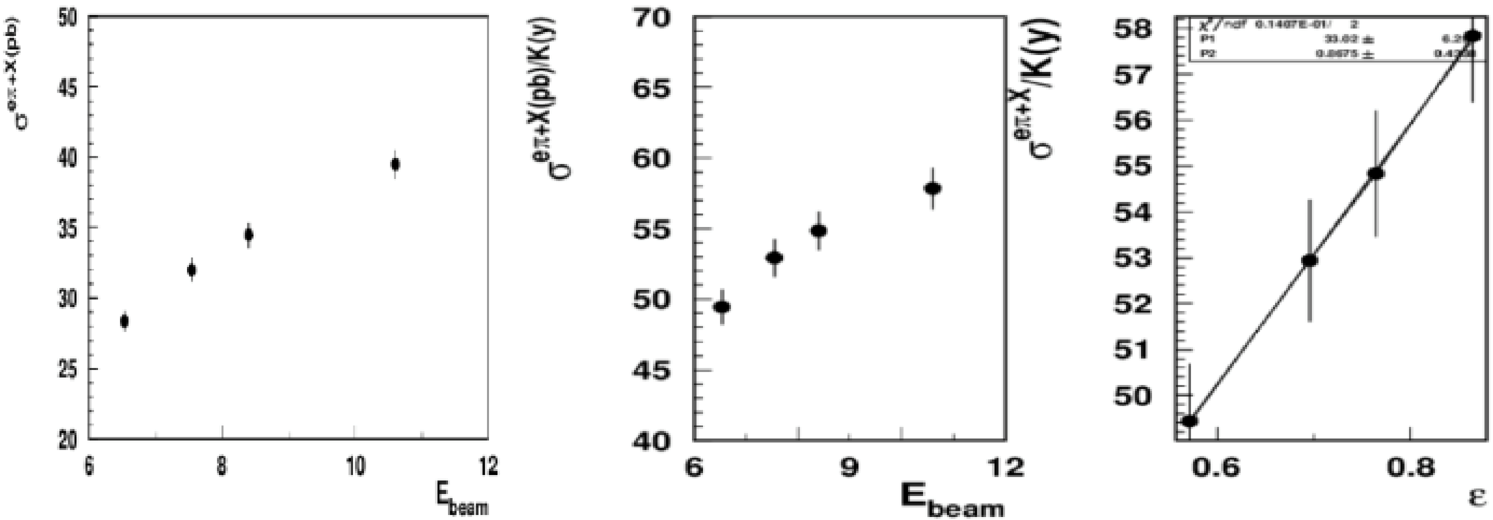
Projections for E12-06-104 vs existing Cornell Data (projections assume RSIDIS = RDIS)
Comparable 1.6% systematic uncertainties not indicated
Projections: Solid Black H, Open Black D π
Cornell:
Top panel: solid red (open blue) π! (π") on LH2
Middle : solid red (open blue) dots are π! (π") on LH2
solid red (open blue) squares are π! (π") on LD2
Bottom : solid red (open blue) dots are for π! (π") on LH2

Kinematic ranges accessible in Hall C withexisting HMS and SH MS spectrometers and thatcan achieve two ε values separated by 0.2 with aminimum ε of 0.1

FUU,L studies at Hall-B







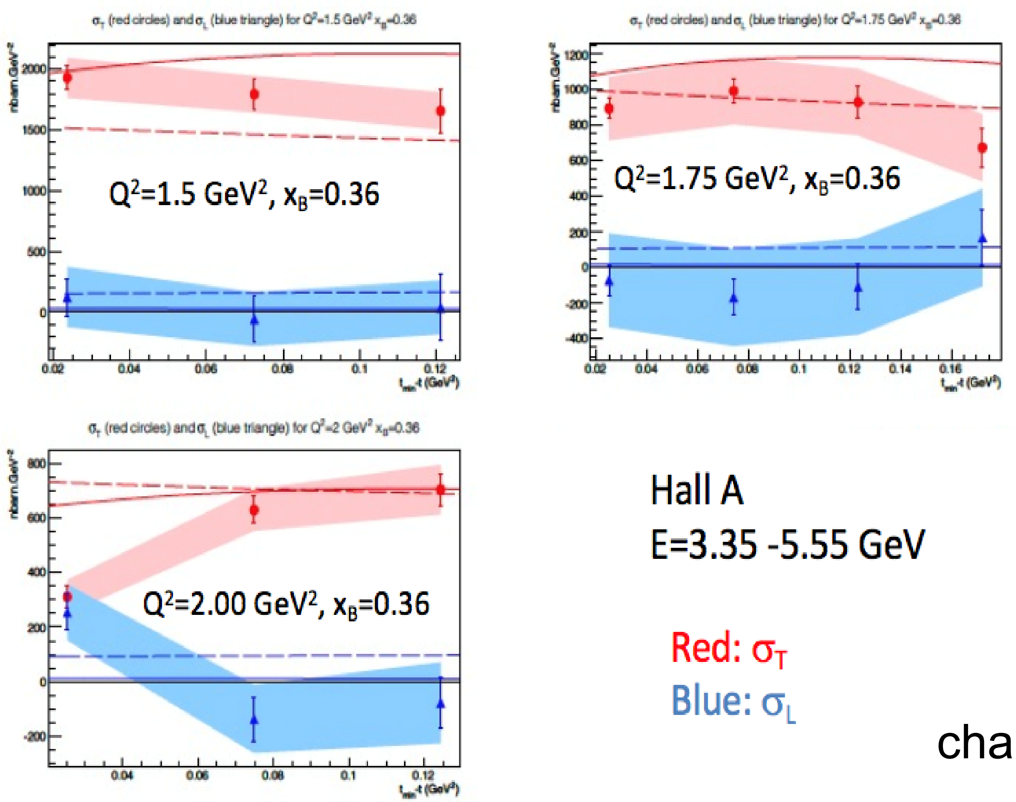
A new research proposal submitted to Jlab PAC to study the $F_{UU,L}$ with CLAS12

Suppression of longitudinal contributions for pi0s

Measured in exclusive limit

predicted in semi-exclusive limit

DVMP (π^0) L/T Separation

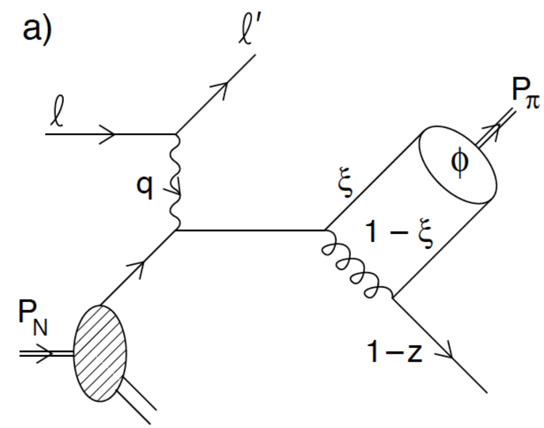


Hall A

E=3.35 -5.55 GeV

Red: σ_T

Blue: σ_L

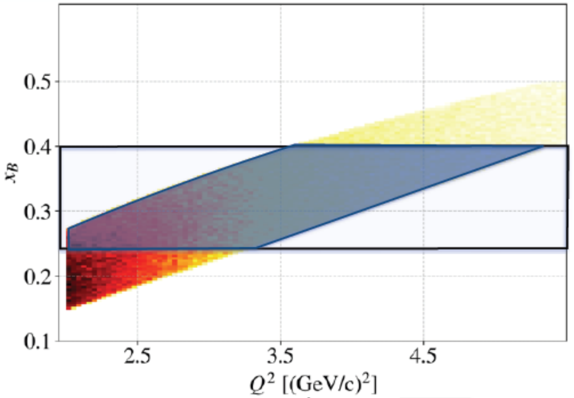


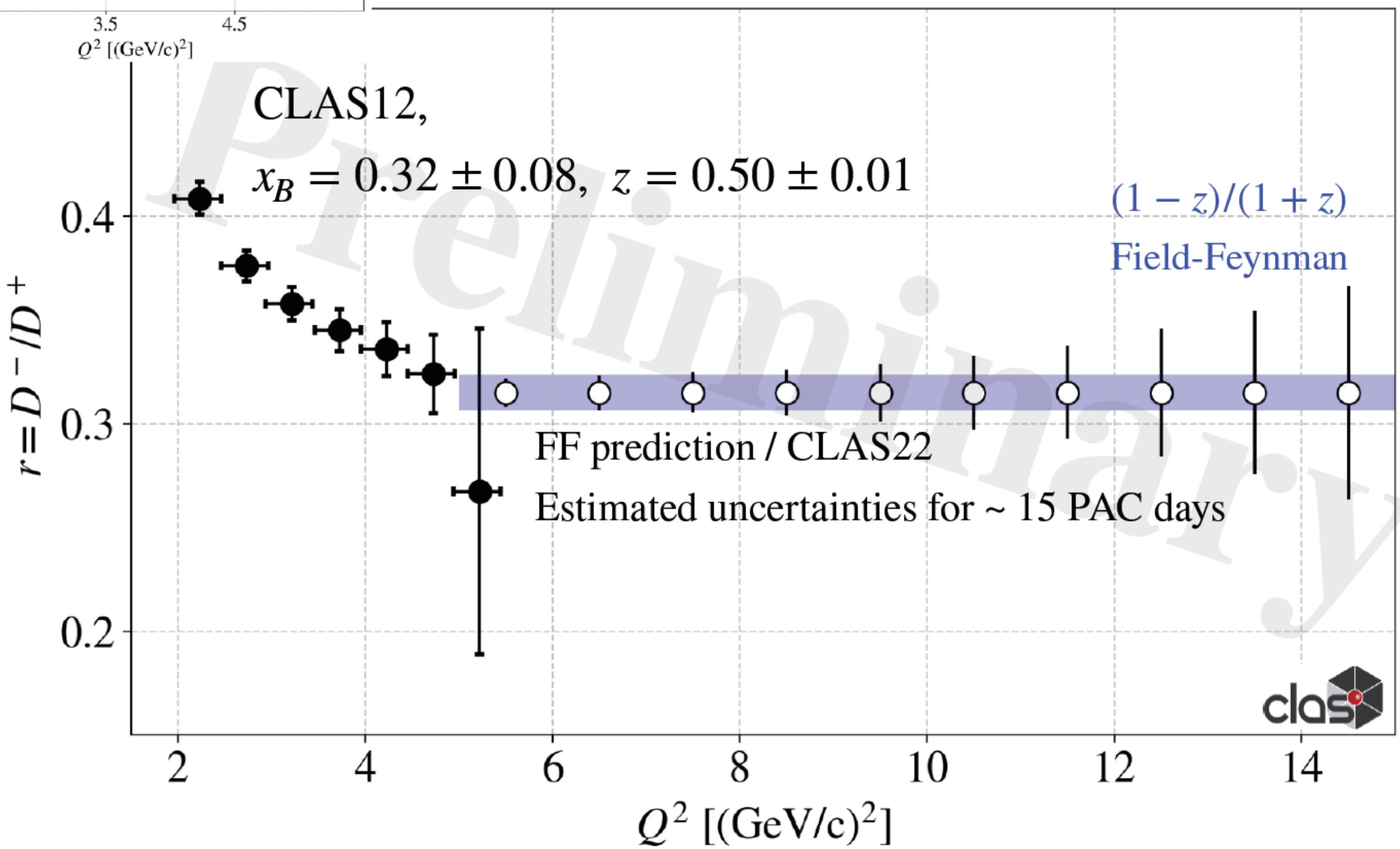
charged pions may be more affected

M. Defurne Phys. Rev. Lett. 117 (2016) 26, 262001

Q^2 evolution

E.Cohen (MIT)

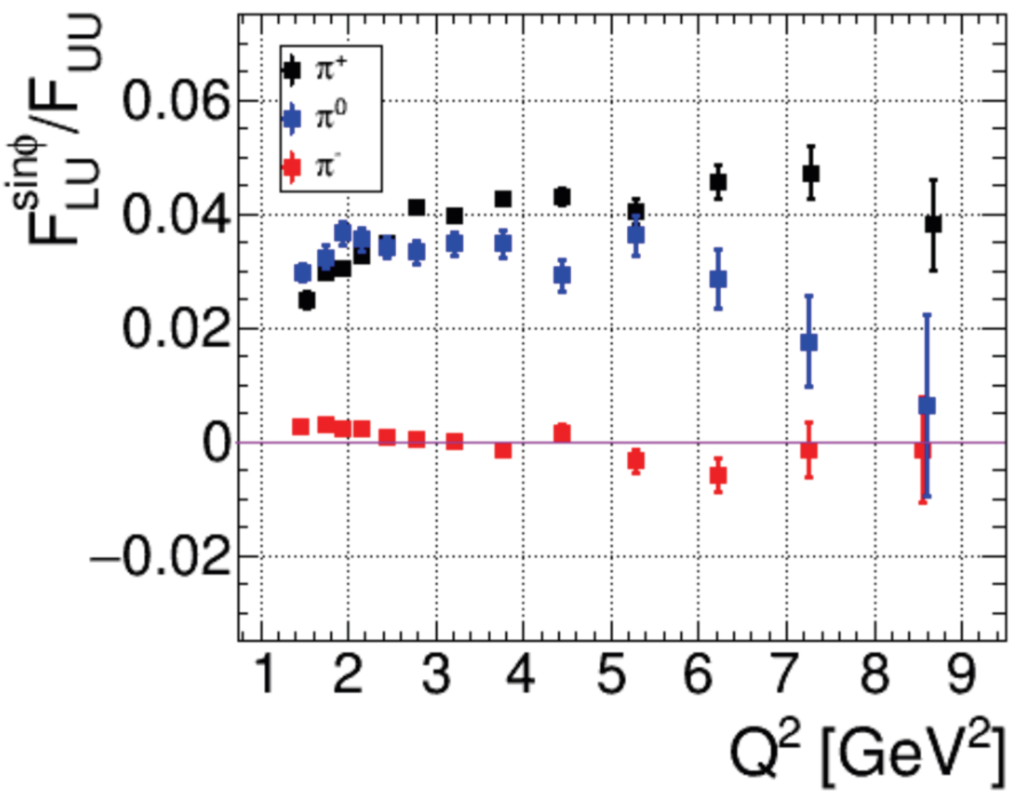




Understanding

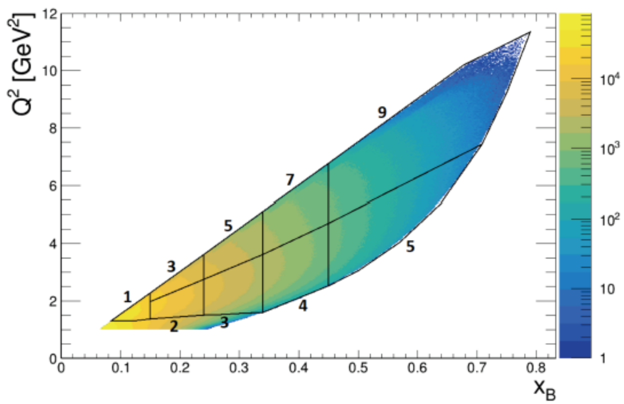
RGB + BAND: 10.2 GeV all data

Pion beam SSAs in the 1D case

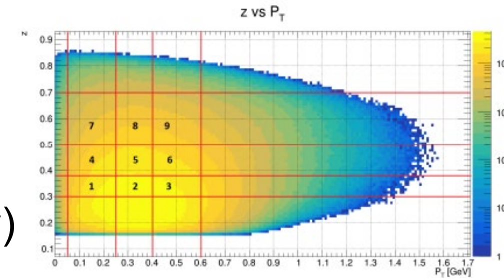


z-P_T and x_B inetgarted case

➔ Bahaviour dominated by x_B dependence (as observed in models)

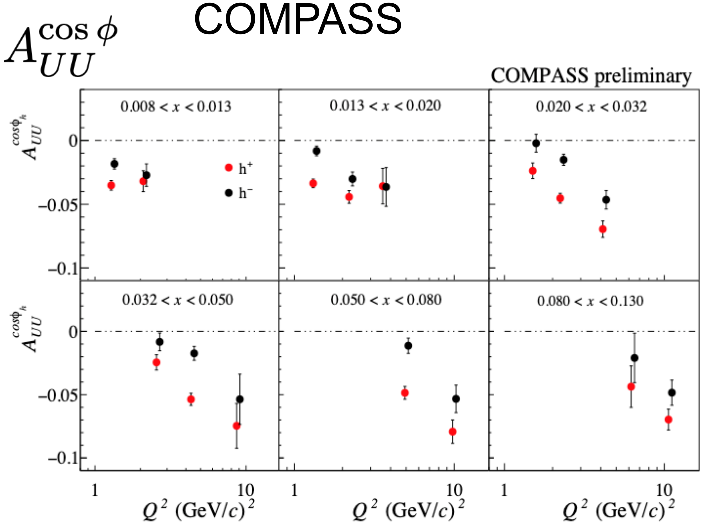


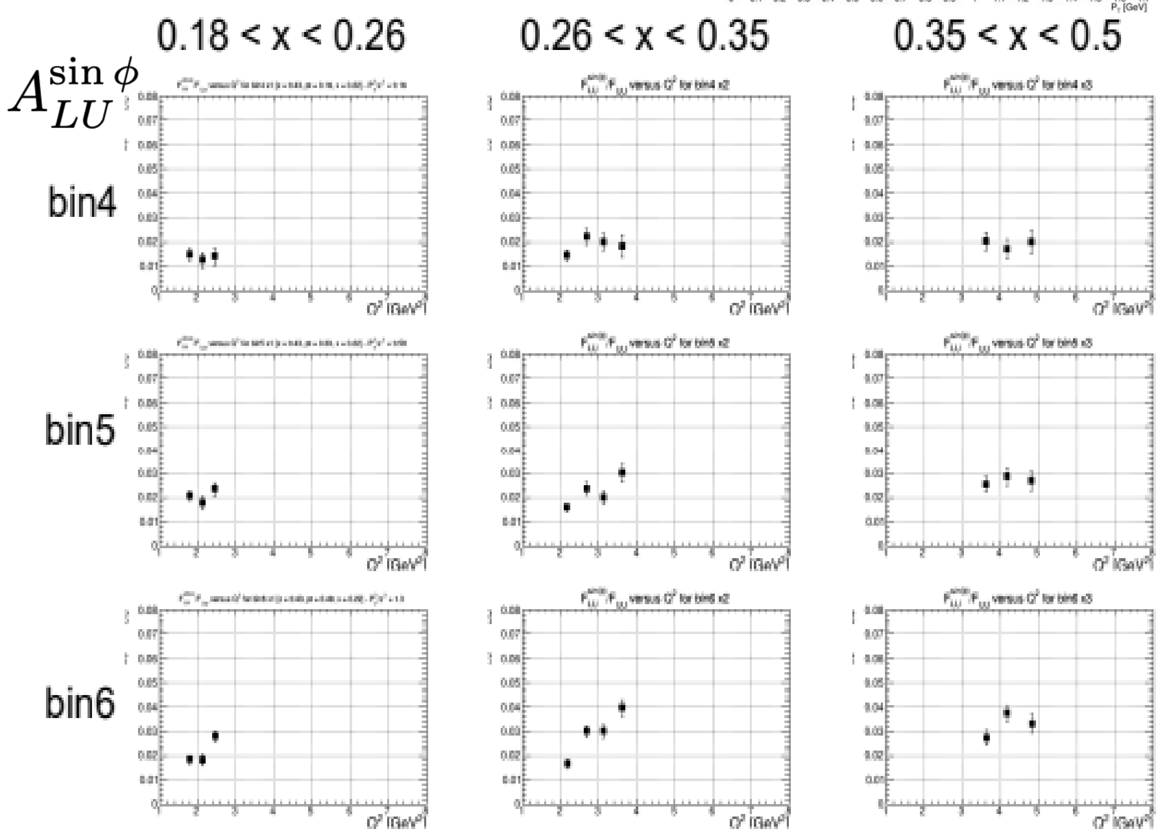
Attempts to understand Q²-dependence of HT



CLAS12(preliminary)

COMPASS



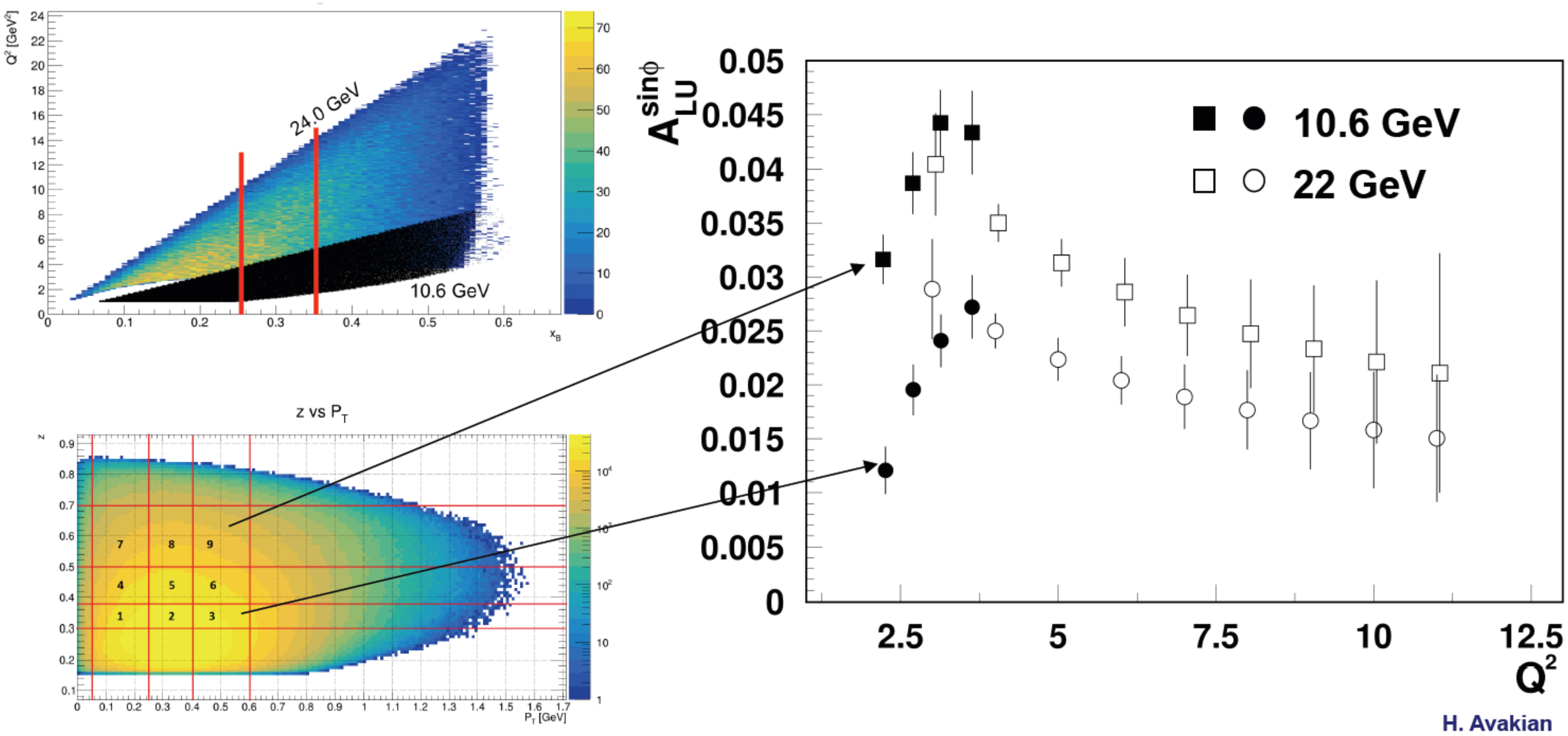


- We always measure ratio to

$$F_{UU,T} + \varepsilon F_{UU,L}$$

- The moments defined as a ratio to ϕ-independent x-section(to $F_{UU,T}$), 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**
- Checking the Q^2 and P_T-dependences of the $F_{UU,L}$ may provide crucial input for validation

Conclusion and gain from an energy upgrade



Increased range in Q2 would allow to validate the HT nature of observables

TMDs in Semi-Inclusive DIS

TMD Parton Distribution Functions

TMD Parto Fragmentation Functions

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

Major advance in theory in last years

$$\hat{f}_1^a(x,b_T^2;\mu_f,\zeta_f) = \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^2} e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} f_1^q(x,k_\perp^2;\mu_f,\zeta_f)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x,b_T^2;\mu_f,\zeta_f) = [C\otimes f_1](x,\mu_{b_*})\, e^{\int_{\mu_{b_*}}^{\mu_f}\frac{d\mu}{\mu}\left(\gamma_F-\gamma_K\ln\frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\rm resum}+g_K} f_{1\,NP}(x,b_T^2;\zeta_f,Q_0)$$

collinear PDF

matching coefficients (perturbative)

Collins-Soper kernel (perturbative and nonperturbative)

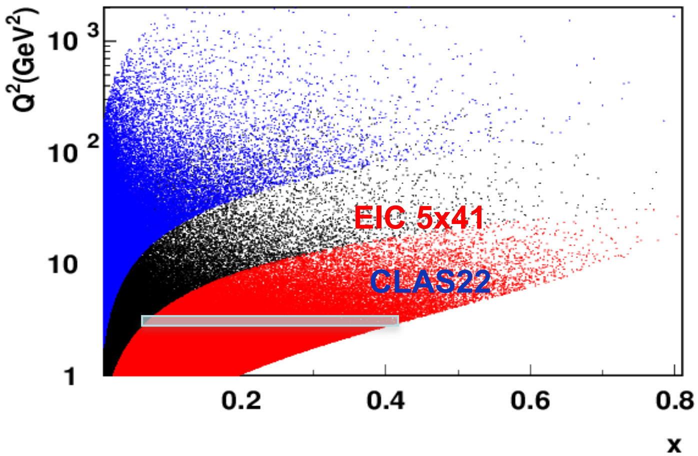
nonperturbative part of TMD

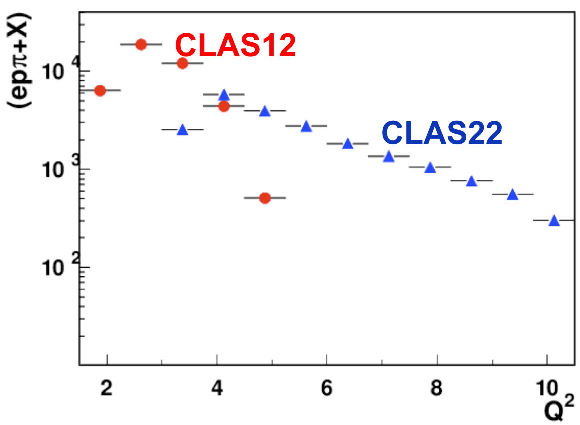
$$g_K(b_T^2) = -g_2^2\frac{b_T^2}{4}$$

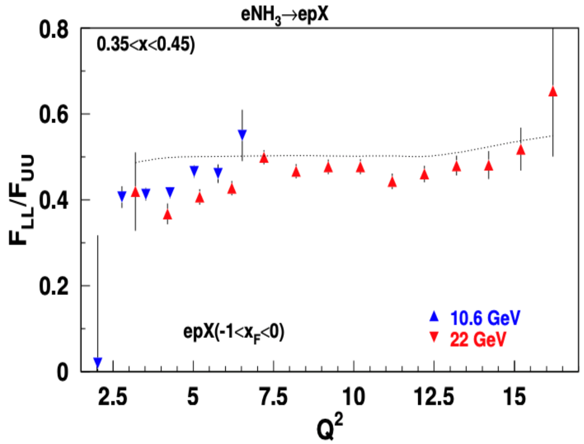
CS kernel discribes the interaction of out-going parton with the confining potential
Provides nonperturbative part of evolution for TMDs

CS-kernel→independent on any other variables

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

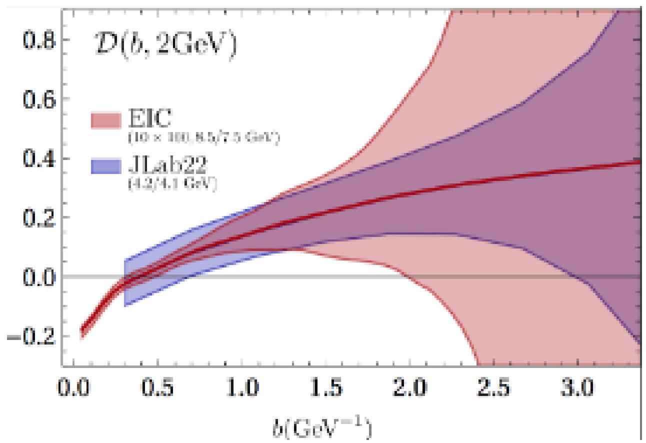


Figure 2: Extraction of the nonperturbative part of the CS using CLAS and EIC pseudo data

- 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
- Evaluate the systematics due to factorization violation and define possible reasons (some can be easy to fix)

SIDIS Validation tests: Collins-Soper kernel

$$\frac{d\sigma}{dQ^2 dx dz dk_\perp^2} = \frac{\pi \alpha_{em}^2(Q)}{Q^4} \frac{y^2}{1-\varepsilon} W(Q,x,z,k_\perp)$$

$$\int_0^\infty \frac{bdb}{(2\pi)^2} J_0\left(\frac{k_\perp b}{z}\right) R[b,Q \to \mu] |C_V(Q)|^2 \sum_f e_f^2 f_1(x,b;\mu) d_1(z,b;\mu)$$

Evol.factor
our goal!

TMDs

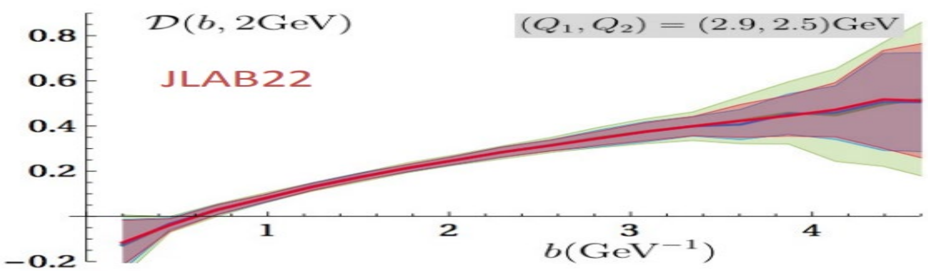
A. Vladimirov

nonperturbative Q and x can be factorized

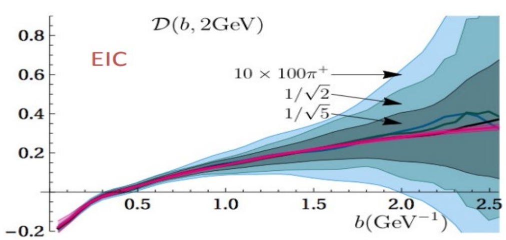
$$F(x,b;Q) = R[\mathcal{D},Q]F(x,b)$$

- 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)

- **Ultimate test of factorization hypothesis**
  - Different (Q,x,z) MUST result into the same curve
  - Different final states $(\pi^\pm, K^\pm)$ MUST result into the same curve
  - ⇒ comparing Collins-Soper kernel obtained in different regimes we can scan the kinematic range and determine size of **TMD-factorization violation**



A. Vladimirov @ APCTP22 workshop



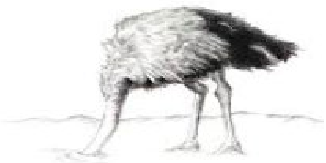
Different experiments most sensitive to different ranges in b

- JLab ~1<b<4
- EIC ~0.5<b<1.2
- LHC b<0.5
- COMPASS overlaps

Theory-Experiment: SIDIS Validation tests

$$\frac{d\sigma^{lN\to l'hX}}{dx_B dQ^2 dz dP_{h\perp}^2 d\phi_h} = \frac{\pi\alpha^2 y}{x_B y Q^2(1-\epsilon)}[F_{UU,T} + \quad \ldots\ldots]$$

theory



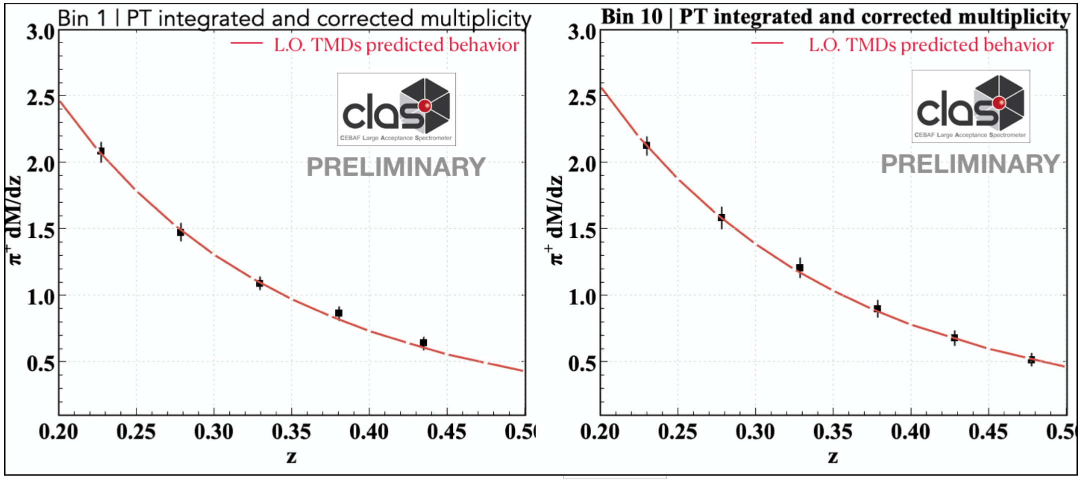
$$\left.\begin{array}{l} lN \to l'\pi^+ X \\ lN \to l'\rho^0 X \\ \ldots\ldots\ldots\ldots \end{array}\right\} \quad lN \to l'\pi^+ X$$

Fragmentation Function
→ probability to produce π+

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

Integrated over transverse momentum are well described by the formalism

the CLAS data at 10.6 GeV follows global fits (also at 6 GeV).

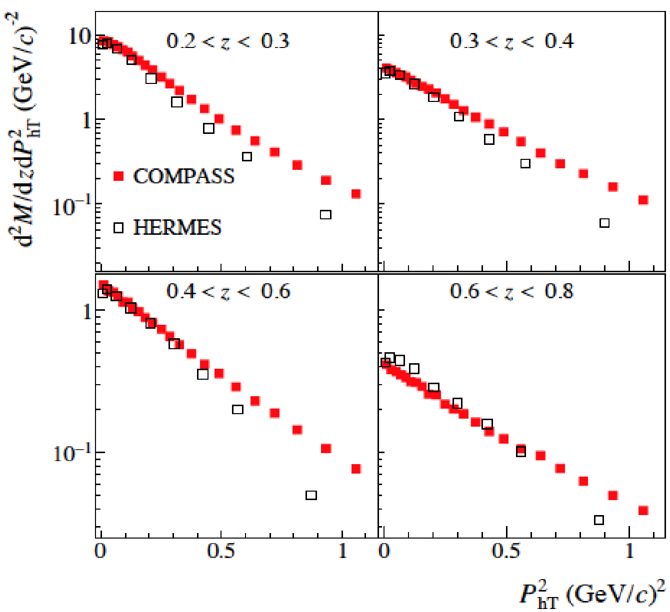


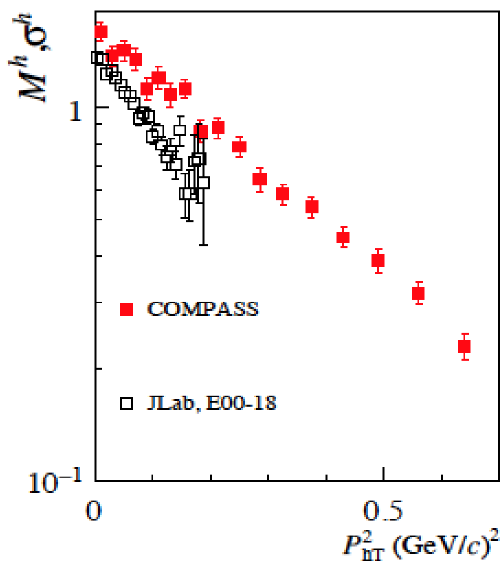
Multiplicities of hadrons in SIDIS

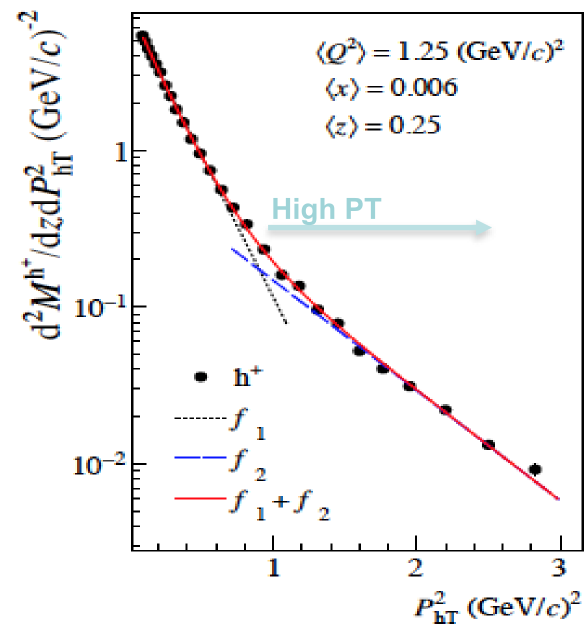
Gaussian Ansatz $$f_1^q \otimes D_1^{q\to h} = x f_1^q(x)\, D_1^{q\to h}(z) \frac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$$

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

COMPASS:1709.07374



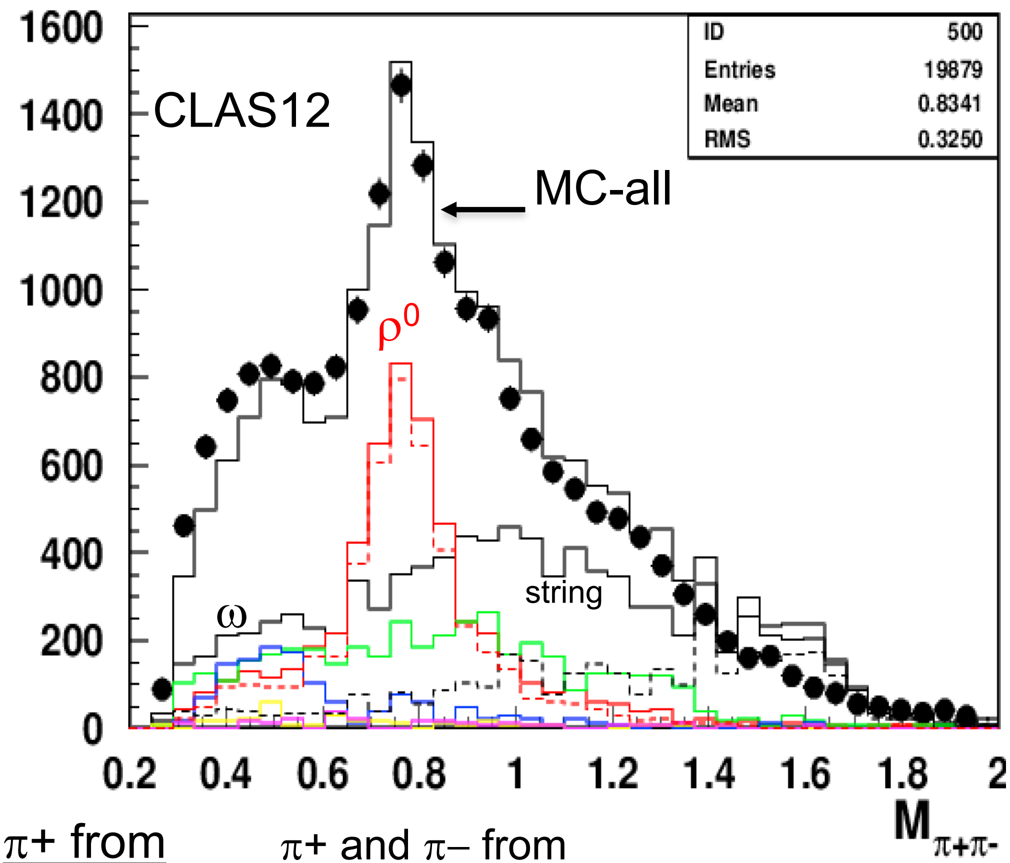


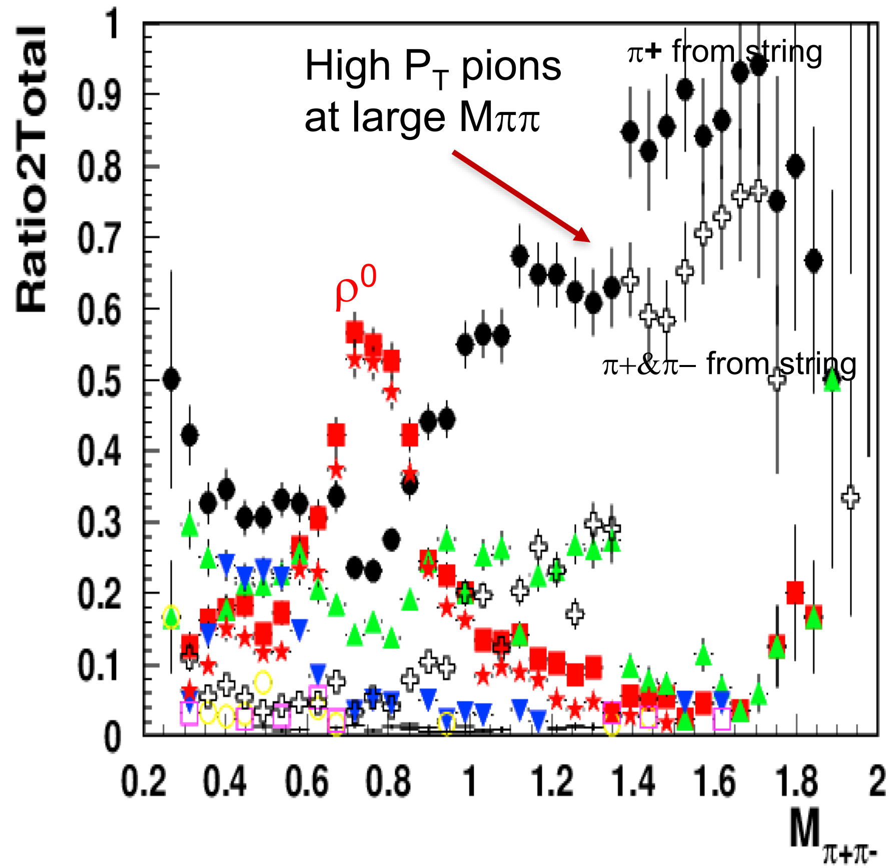


JLab: not enough energy to produce large P_T
HERMES: not enough luminosity to access large P_T

- What is the origin of the "high" P_T (0.8-1.8) tail?
  1) Perturbative contributions?
  2) Non perturbative contributions?

Sources of inclusive pions: CLAS12 vs MC





π+ from		π+ and π− from
(solid red)	ρ0	(dashed red)
(solid black)	string	(dashed black)
(solid green)	ρ+	
(solid blue)	ω	

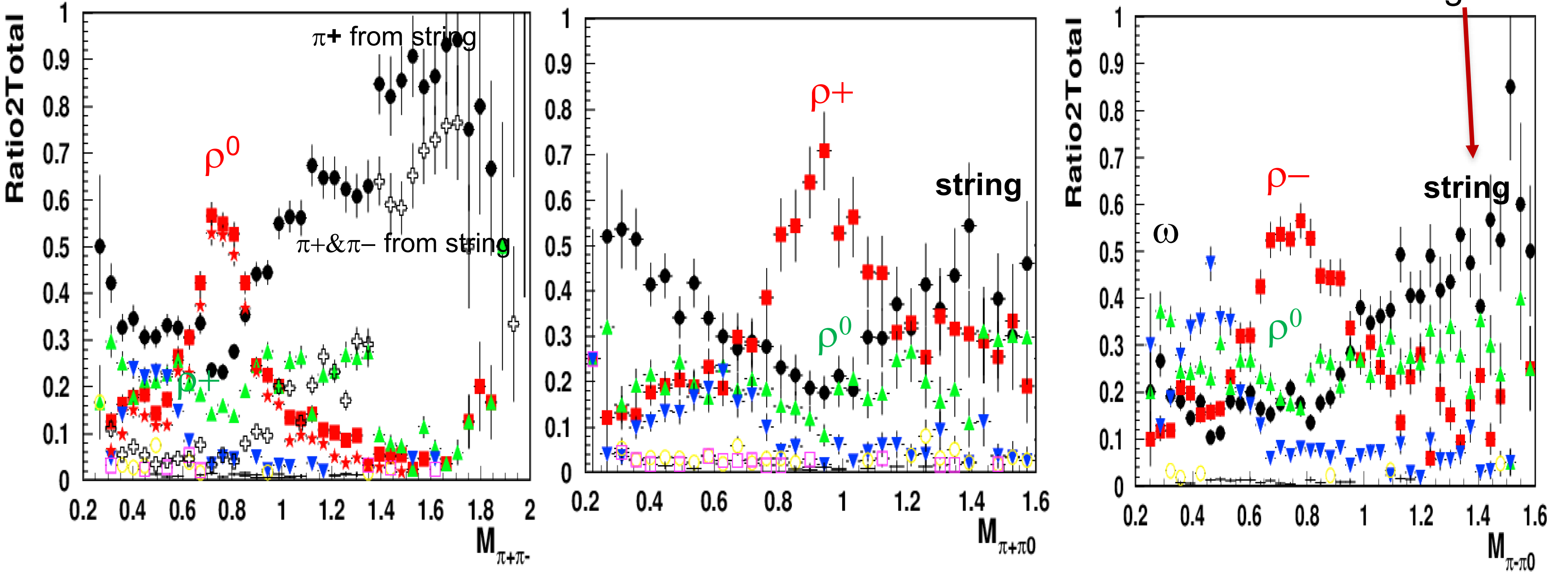
- Dominant fraction of inclusive pions come from VM decays
- Relative fraction by default in JETSET ~50%

Very important to have multidimensional TMD Fragmentation Functions!

Sources of inclusive pions: CLAS12 MC

Detection of π^0s allows also studies of $\rho^{\pm}$

High P_T pions at large $M\pi\pi$

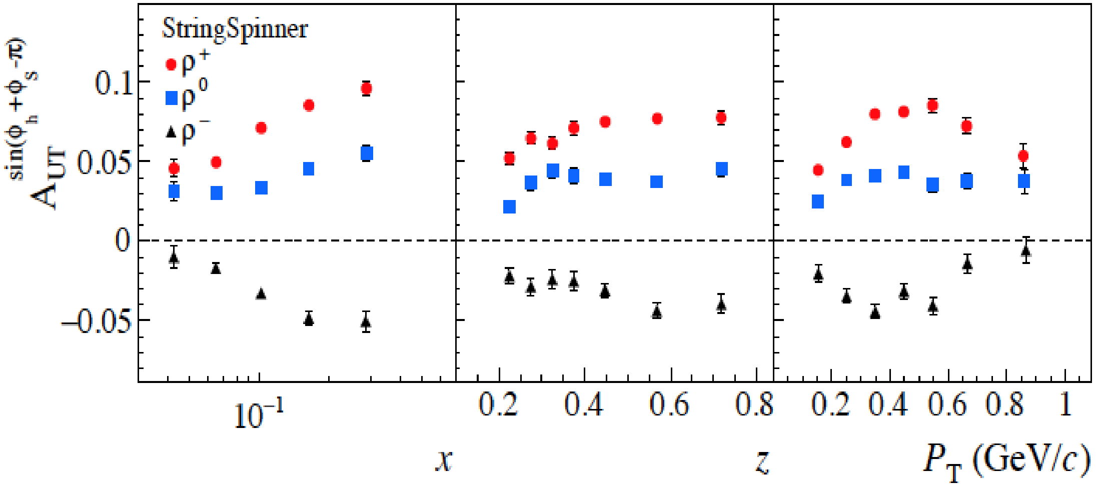


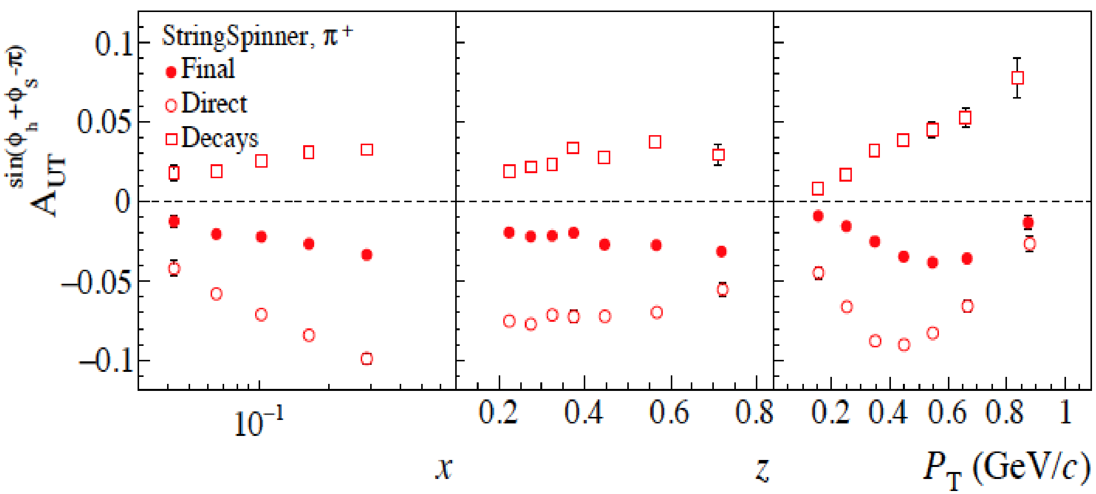
Dominant fraction of 2 pion combinations come from VM decays

- ρ
- string
- ω

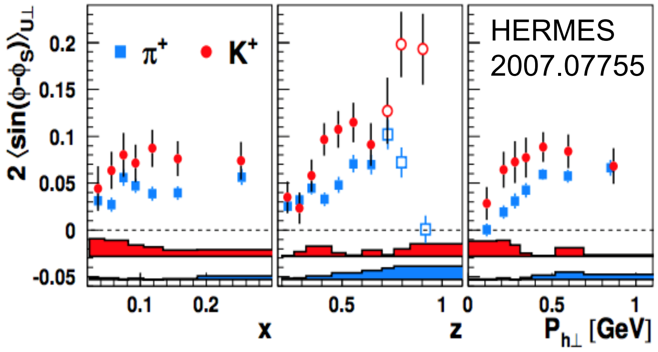
All measured 2 pion combinations are dominated by VM decays, indicate that all inclusive pions are dominated by VM decays at small P_Ts, and in particular at lower z!!!

VM contributions





e+e- will have similar composition, and with high statistics may be able to describe the spectra



Understanding VMs is critical for interpretation

JLab cam measure the SSA of VM, and separate contributions

Are the differences in pions vs Kaons coming from VMs???

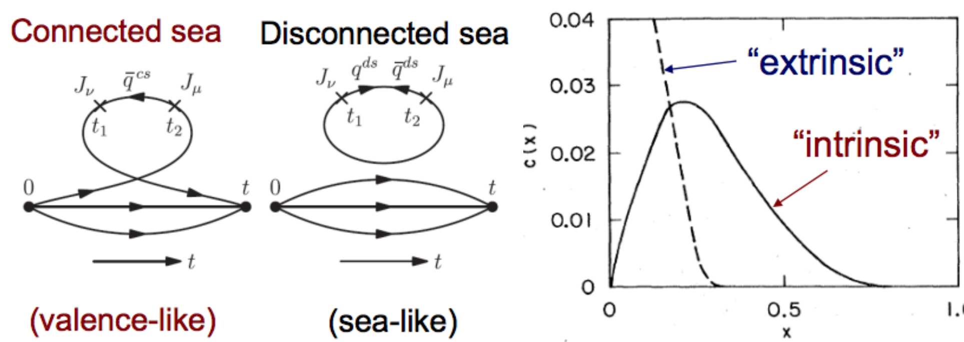
Non perturbative sea

$$P_{5q}^2 \sim 1/m_Q^2$$

$$|p\rangle = P_{3q}\,|uud\rangle + P_{5q}\,|uudQ\bar{Q}\rangle + \cdots\cdots$$

J.-C. Peng

PRL 109, 252002 (2012)



"Intrinsic sea" and "extrinsic sea" are expected to have different x-distributions

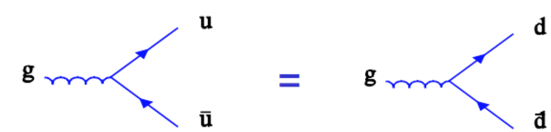
- Intrinsic sea is "valence-like" and is more abundant at larger x
- Extrinsic sea is more abundant at smaller x

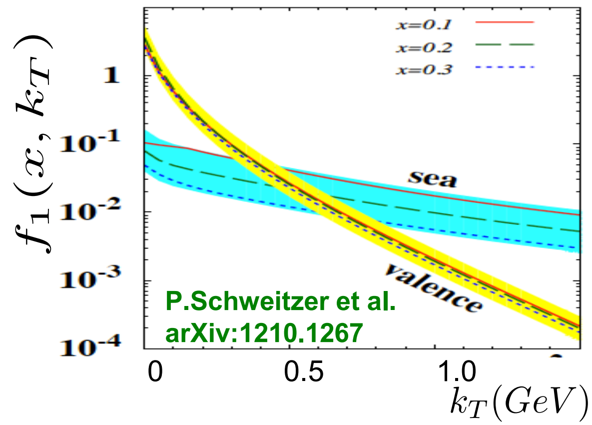
Important to identify kinematics, where the non-perturbative effects dominate!!!

The "intrinsic" sea for lighter quarks have larger probabilities!

$$P_5^{uudd\bar{d}} = 0.240;\ P_5^{uudu\bar{u}} = 0.122;\ P_5^{uuds\bar{s}} = 0.024$$

$\bar{d} - \bar{u}$ has no contribution from extrinsic sea ($g \to \bar{q}q$) and is sensitive to "intrinsic sea" only





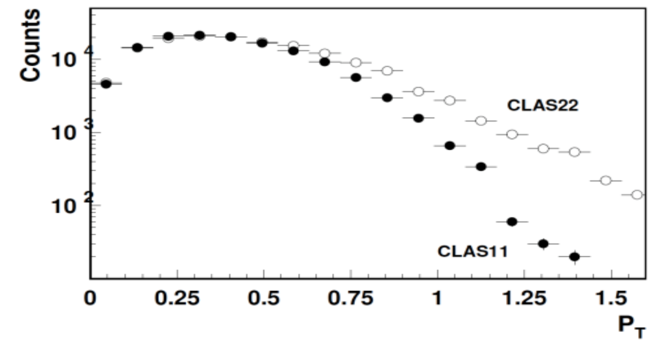
Also very different k_T-distributions

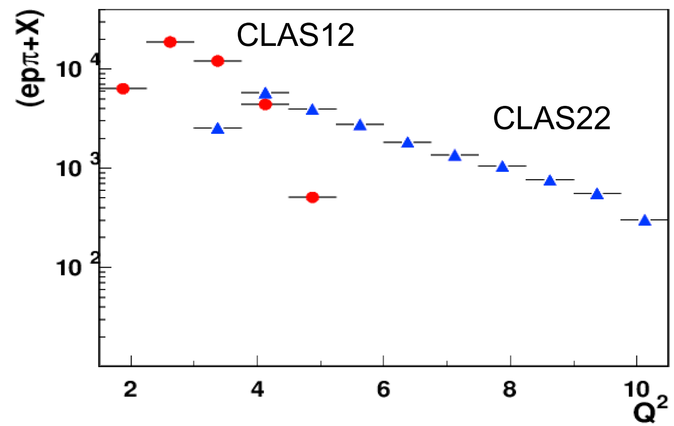
Large P_T-critical!!!

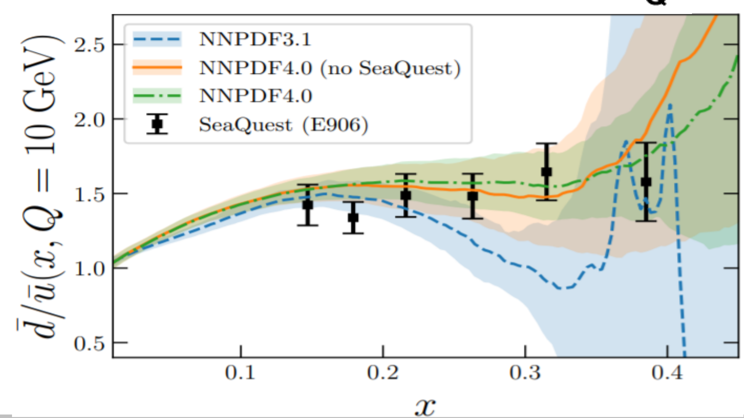
Opportunities with 20+ GeV: Summary

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, validation tests, CS-kernel
- Enhance the x-range
  - Access the the full kinematical range (x>0.03) where the non-perturbative sea is expected to be significant
- Studies of correlations between Current and Target Fragmentation regions (entanglement) with better separation of CFR and TFR (validating JLab12)





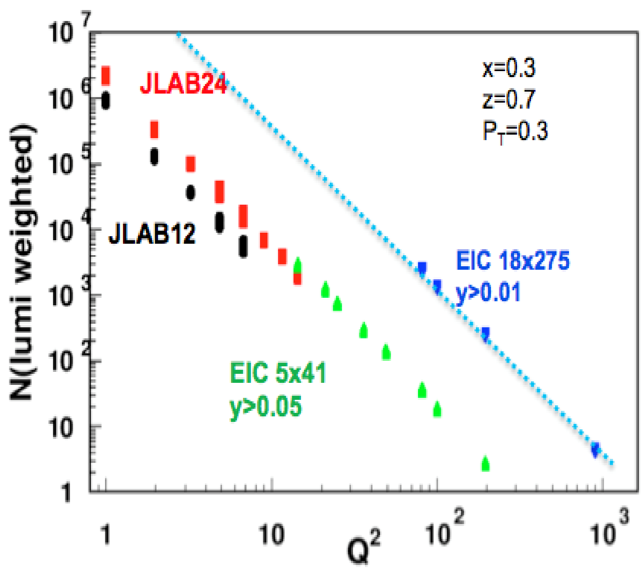


Structure functions and depolarization factors in SIDIS

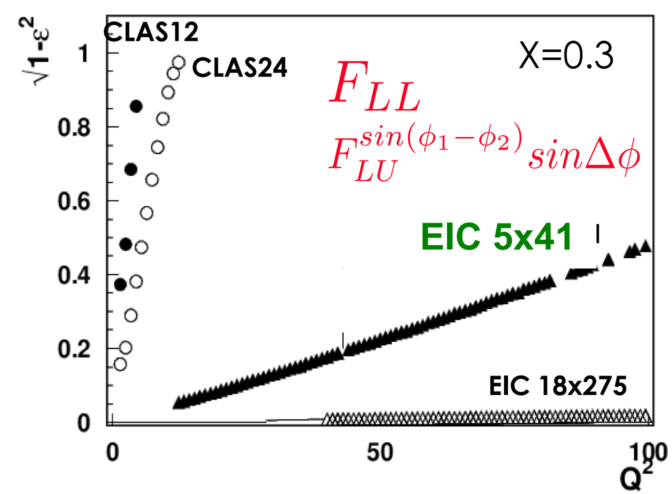
SIDIS at Large x : JLab domain!

- 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})

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



x-section from Bacchetta et al, 1703.10157

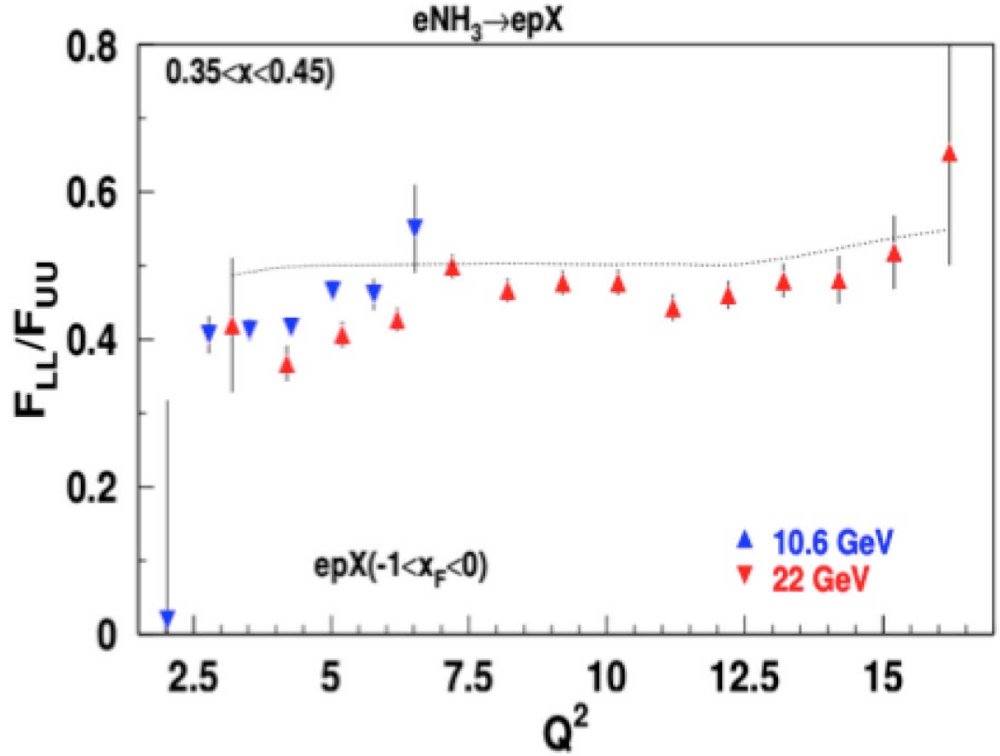


Combination of statistics and depolarization factors defines measurable SFs: FLL in focus

Understanding g1(x,k_T)

From JLAB-22 GeV upgrade document (ArXiv:2306.09360)

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



Critical capability to measure the double spin asymmetry in multidimensional bins

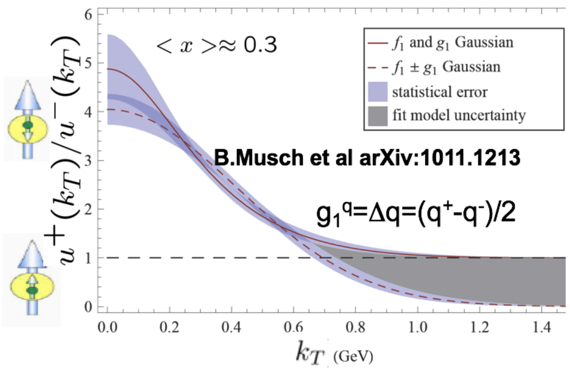
- Q^2-dependence → understand systematics, prove the observable is under control
- P_T-dependence → access the k_T-dependence of helicity distributions, $g_1(x,k_T)$

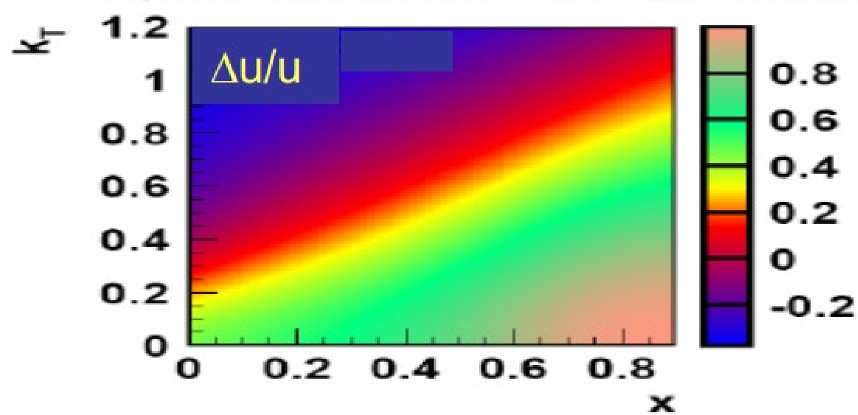
Understanding the g_1 TMDs

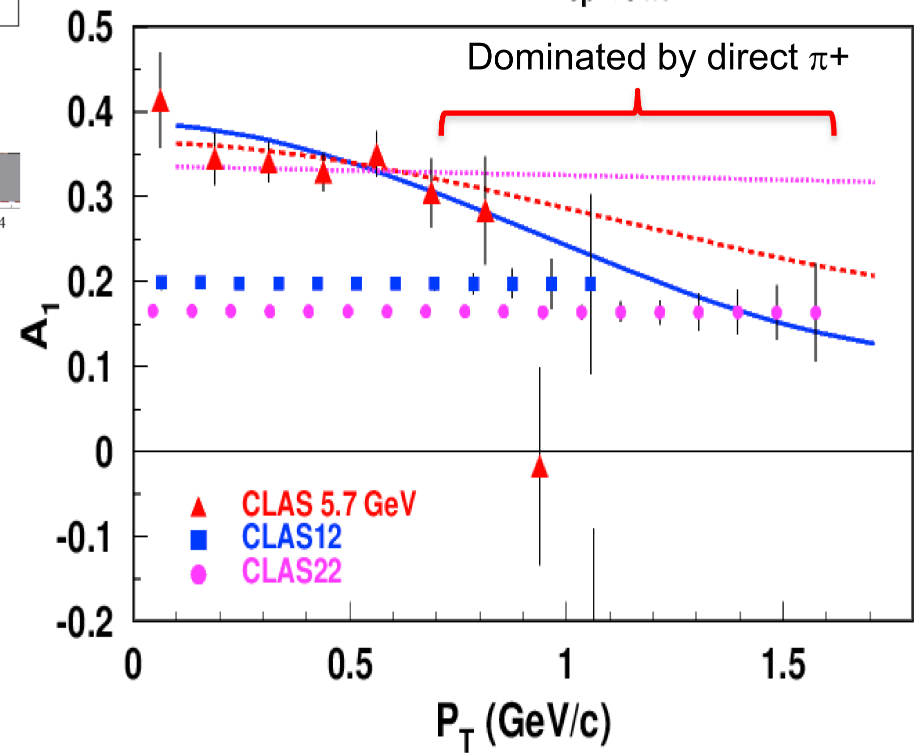
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

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

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

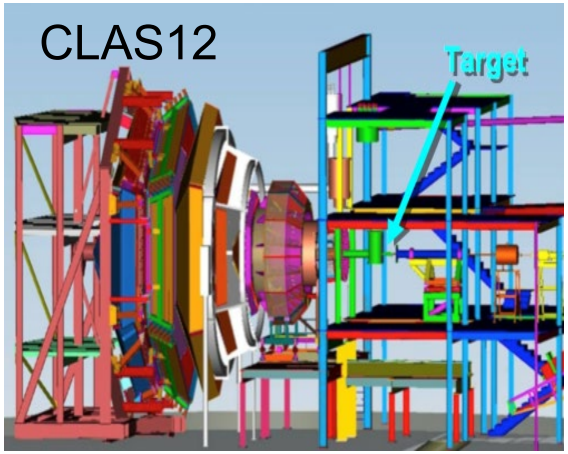


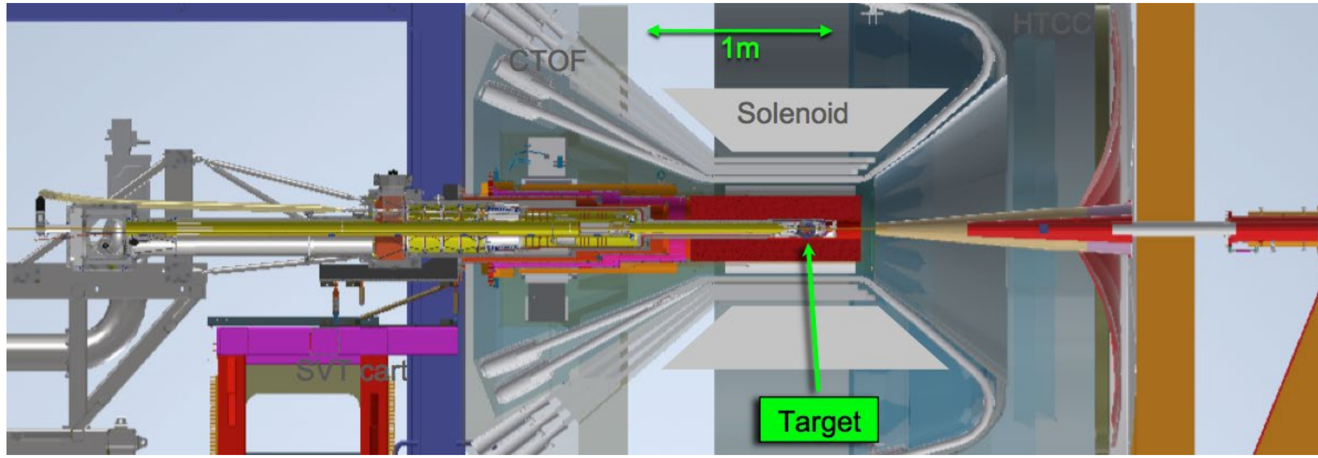


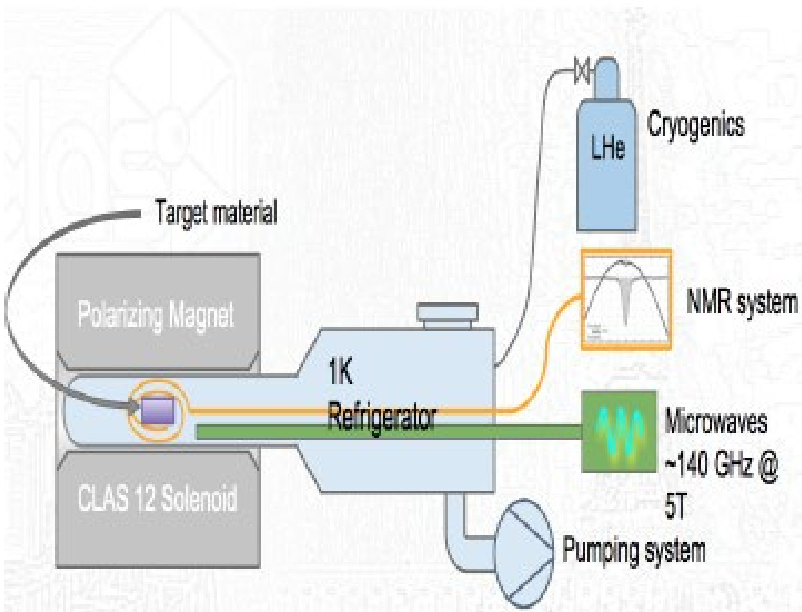


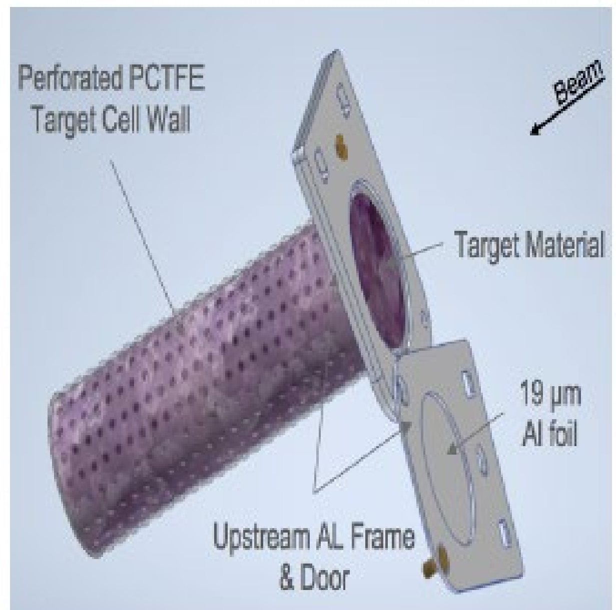
- Models and lattice predict very significant spin and flavor dependence for TMDs
- Large transverse momenta are crucial to access the large k_T of quarks
- Several CLAS12 proposals dedicated to $g_1(x,k_T)$-studies CLAS12
- Understanding of k_T-dependence of g_1 will help in modeling of f_1

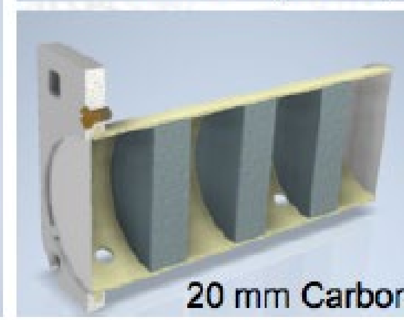
RGC polarized target: E12-06-109, E12-06-119, E12-07-107, E12-09-009





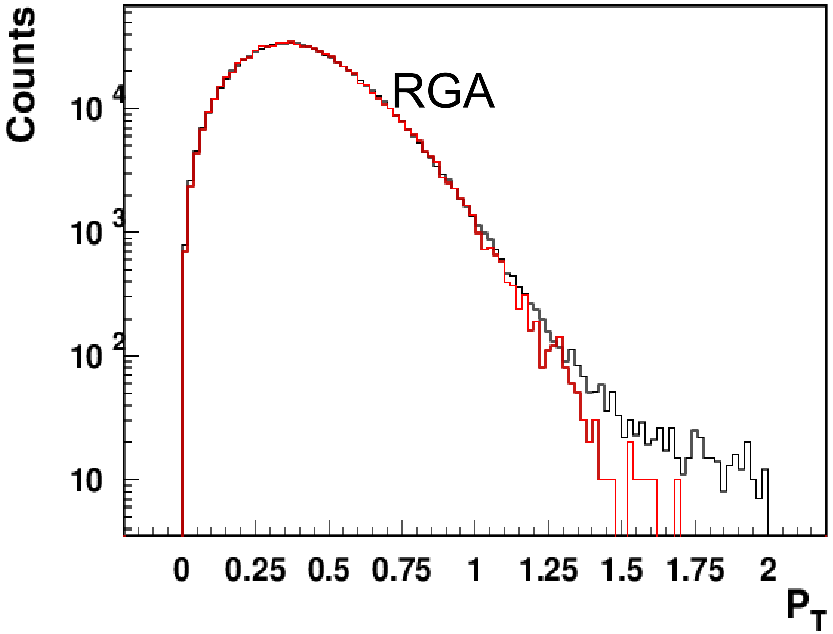


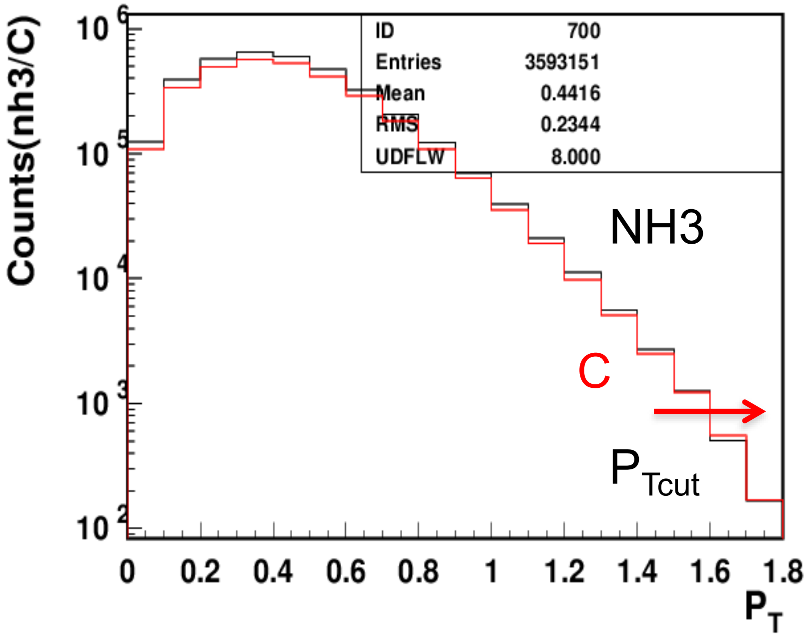




A Dynamic Nuclear Polarized

Normalized distributions

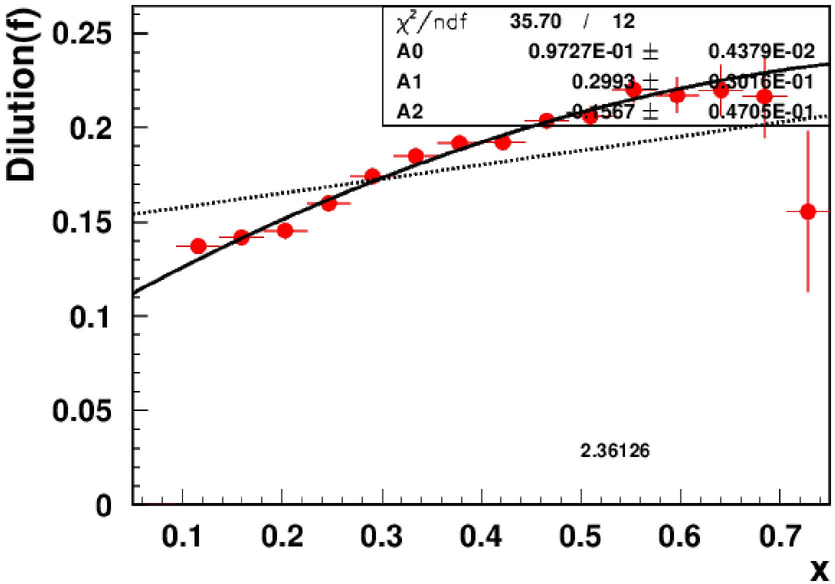




- Nuclear background can be different for different processes
- P_T above 1.5 are mainly from nuclear background, and can be used to normalize the nuclear part

Procedure for normalization: move cut in P_T and normalize NH3 and C counts

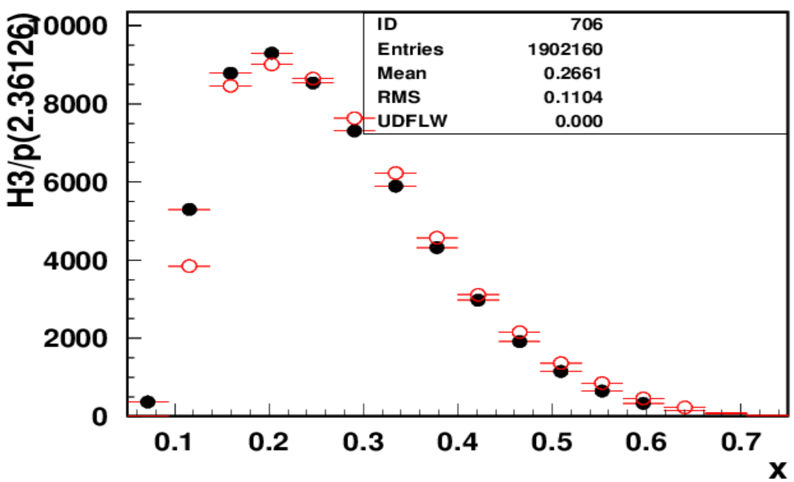
DSA from NH3: understanding dilution

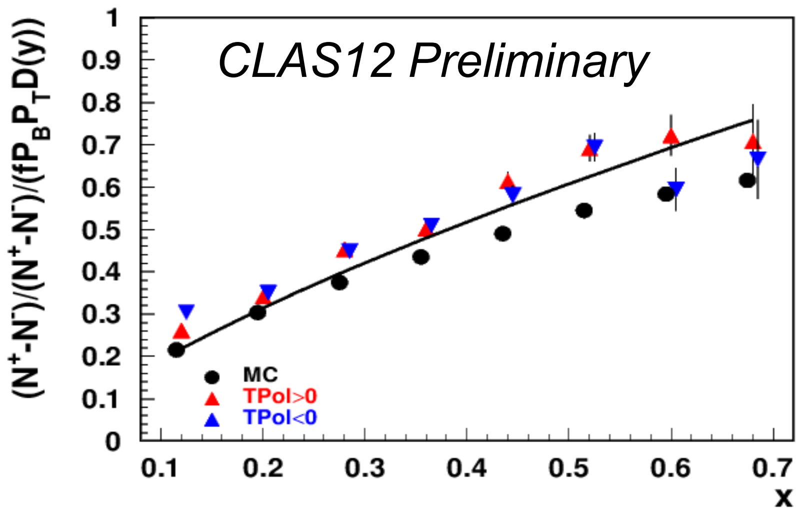


Asymmetry may scaled up/down additional 10%, with variation of polarization and dilution product

Beam pol 82%
Negative pol(blue). 70-77%
positive polarization(red) 82-90%

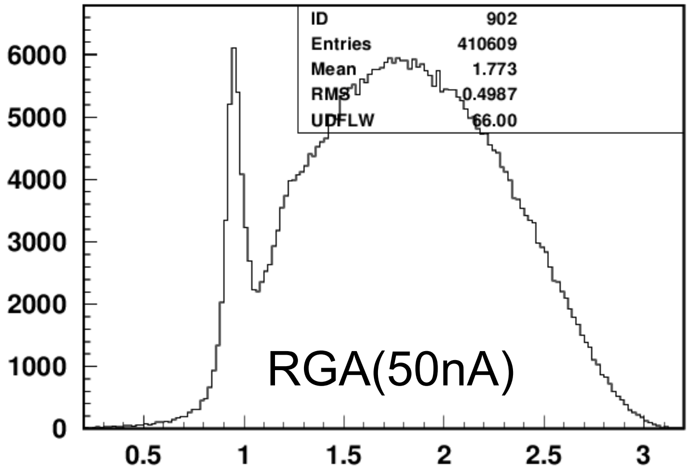
Scale uncertainty ~10% from f*D(y)*Tpol

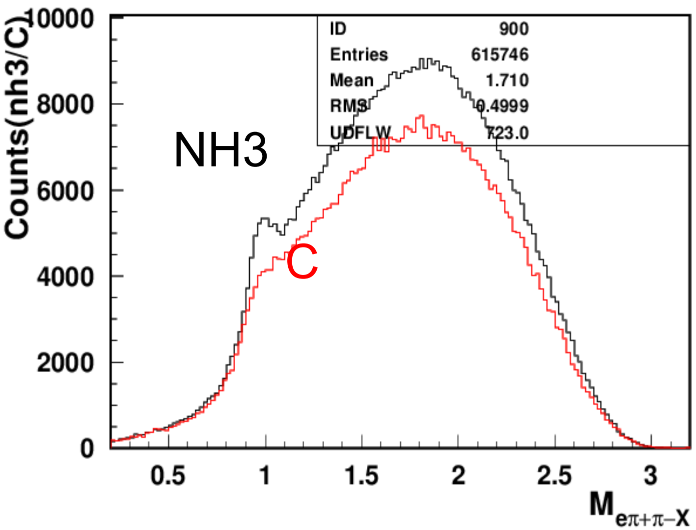


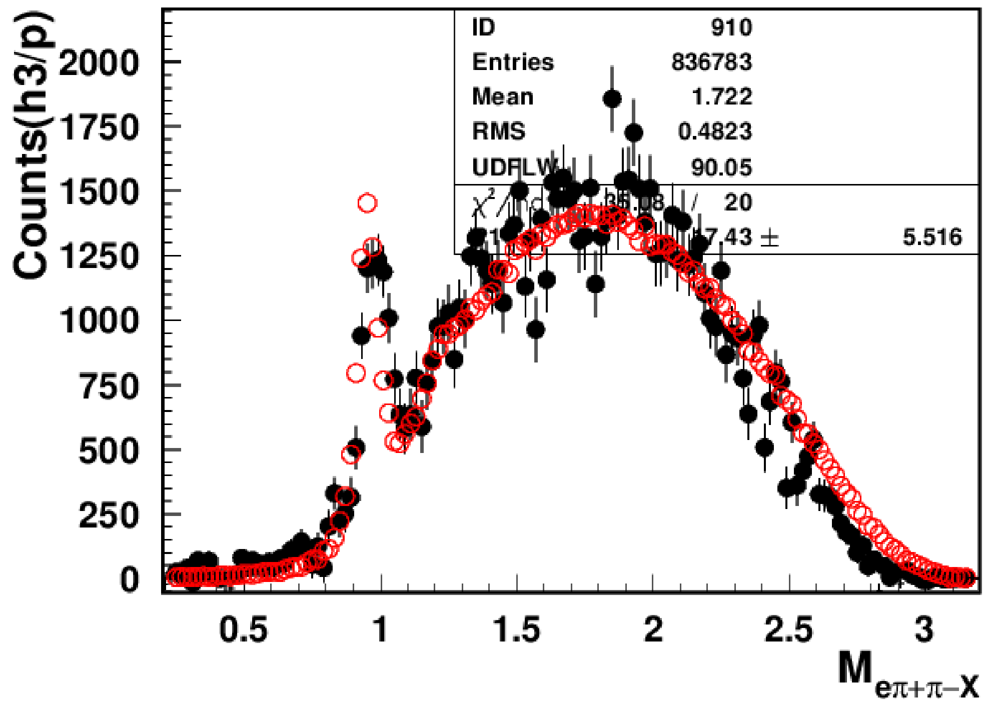


average kinematics identical in data/mc (black circles)

NH3-C vs proton in RGA

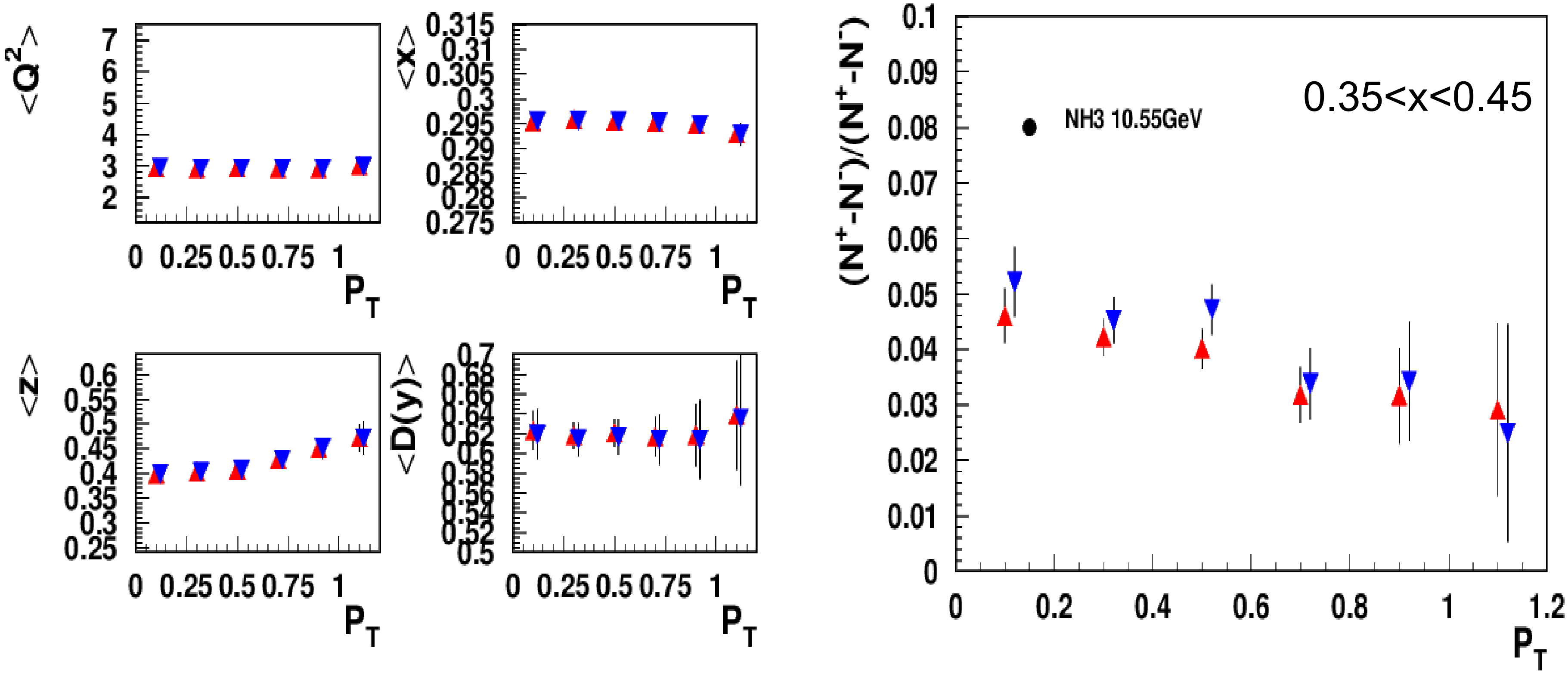






After subtraction hydrogen from NH3 and p from RGA look similar (with some shifts, also slightly better resolutions in RGA)

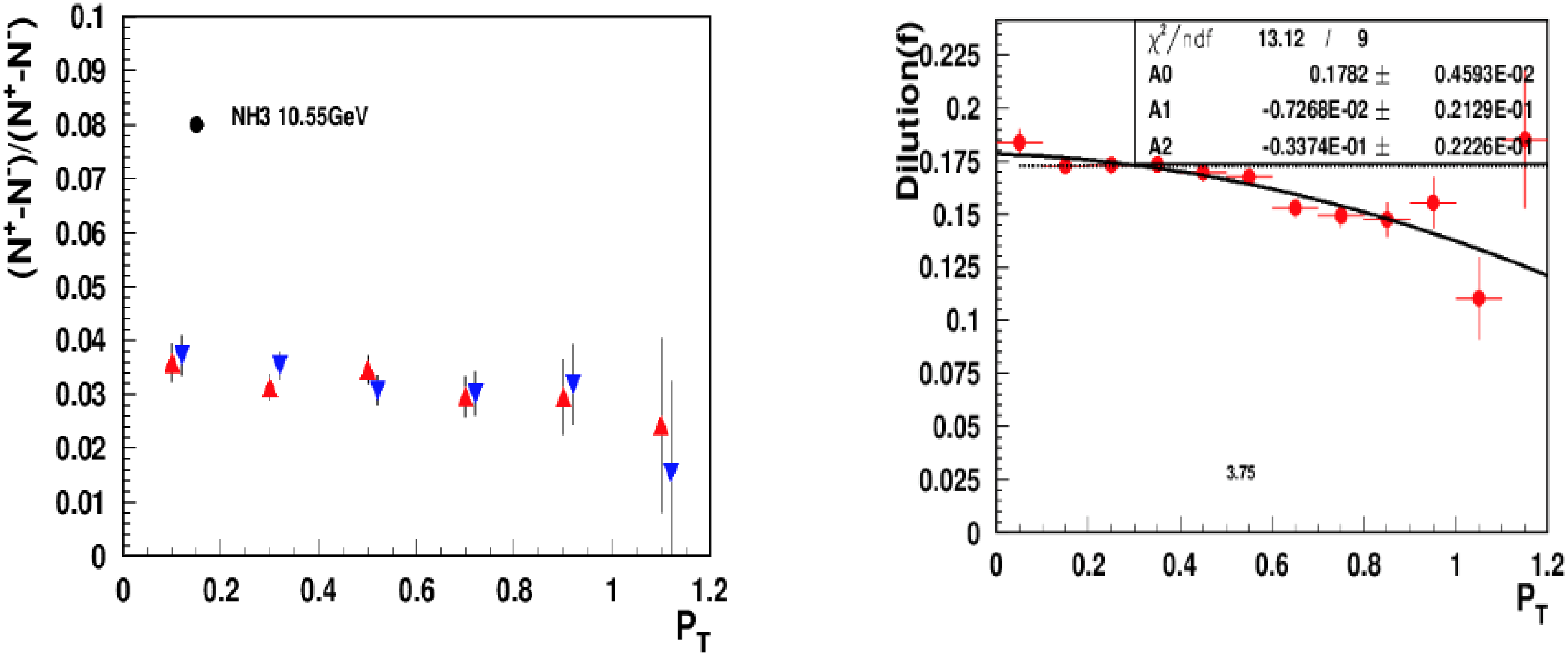
A_1 P_T-dependence



Need proper account of the P_T-dependence of the dilution factor

A_1 P_T-dependence

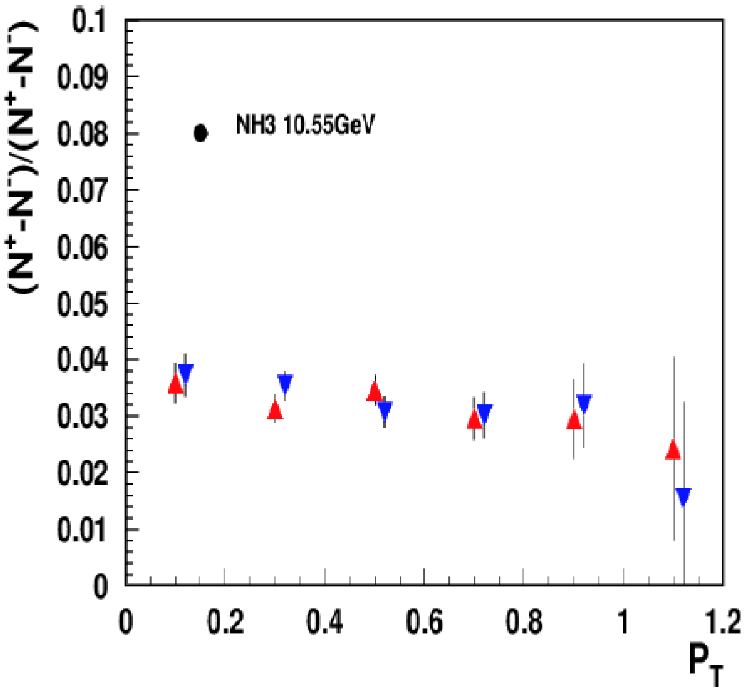
0.25<x<0.35, 0.2<z<0.8 (MX>1.5)

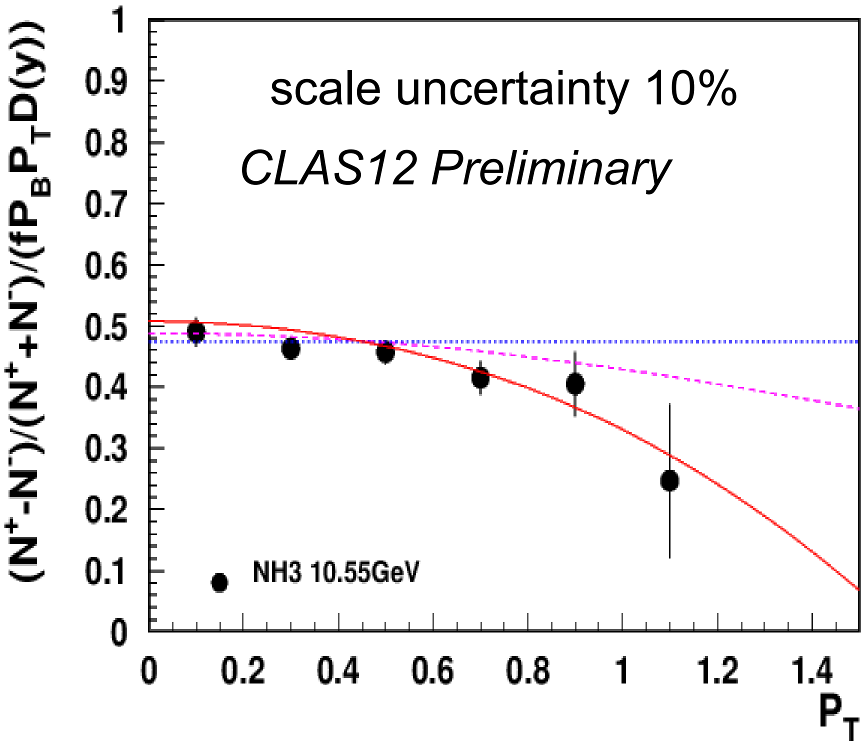


Apply dilution factor to get the DSA on the polarized hydrogen

A_1 P_T-dependence

0.25<x<0.35, 0.2<z<0.8 (MX>1.5)





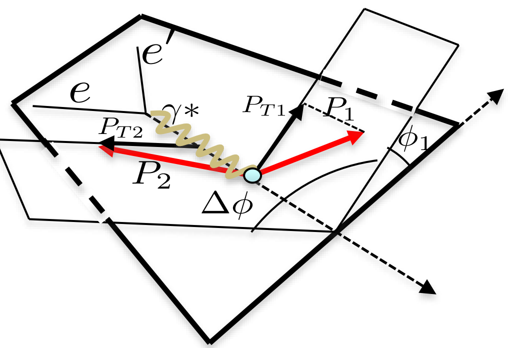
With more statistics can

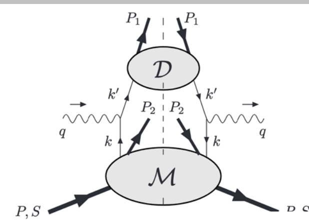
- check with finer bins in P_T,
- extract the the same for dihadron sample

- Red curve predictions from Lattice accounting different widths in $g_1(x,k_T)$ and $f_1(x,k_T)$

Correlations in back-to-back 2 hadron production

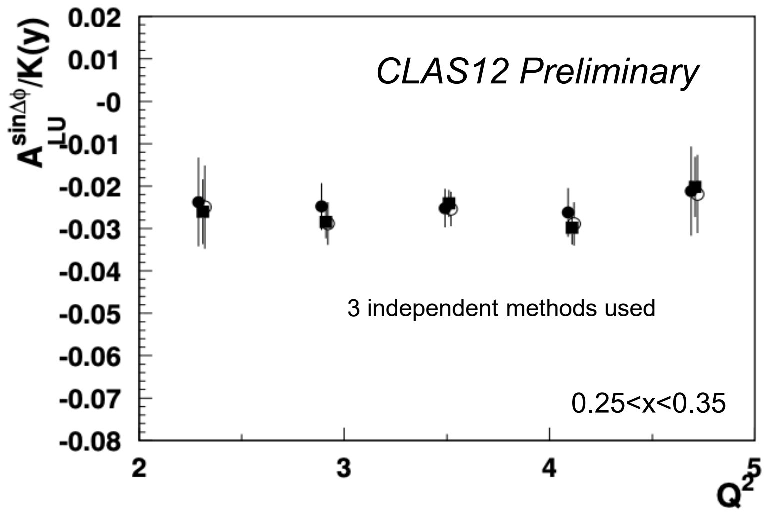
M. Anselmino, V. Barone and A. Kotzinian, Physics Letters B 713 (2012)





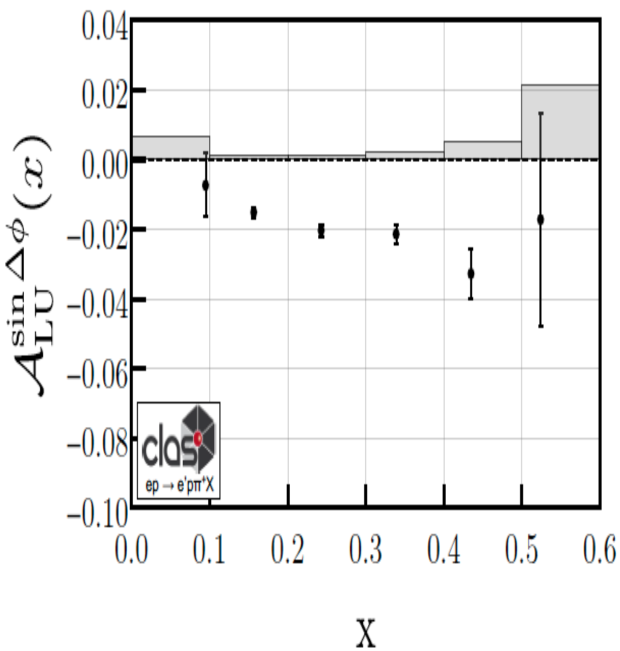
$$A_{LU} \propto \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin \Delta\phi$$

arXiv: 2208.05086
Submitted to PRL



Twist-2 table
(Fracture Functions)

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



- SSA significant at large x, where the valence quarks (non-perturbative sea) dominate?
- Correlation asymmetry is linked to Leading Twist(LT) distributions of longitudinally polarized quarks
- First indication in large x SIDIS of a LT observable
- Correlation between the struck quark and the remnant produces correlation between hadrons (entanglement)
- Multidimensional measurements crucial for evolution studies

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

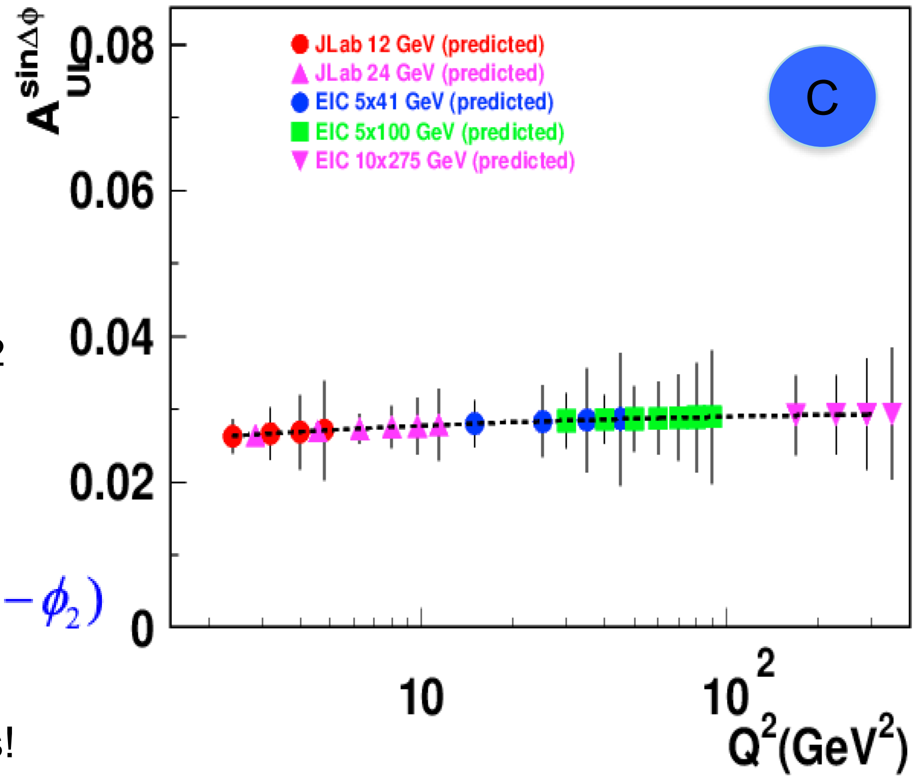
A. Kotzinian et al, arXiv:1107.2292

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

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

No depolarization, like Sivers!

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



CLAS12 proposals

NH3/ND3

E12-09-009

E12-07-107

E12-09-007A

^3He

C12-20-002

^7LiD

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

SUMMARY

- Studies of QCD dynamics with controlled systematics involving Semi-Inclusive DIS, requires detailed understanding of the contributions into the measured cross sections/multiplicities/asymmetries as a function of all involved kinematical variables (including P_T and ϕ)

- For interpretation of the SIDIS data it is critical to separate contributions from different structure functions, as well as separation of different production mechanisms in a given structure function

- To evaluate the systematics of extracted TMDs, it is critical to validate the formalism, and understand main contributions violating the factorized picture based on the dominance of the leading twist contributions

- Measurements of azimuthal modulations of inclusive pions, and multiplicities of pion pairs indicate very significant part of hadrons come from decays of VMs (even more in kaon case)

- Evolution studies observables will require multidimensional coverage of all relevant kinematics (including depolarization factors) for observables with polarized beams and targets

Support slides

Summary

The energy upgrade to the CEBAF with its high luminosity and probing precision at the hadronic scale, would enable the only facility worldwide, planned or foreseen, that can address the complexity at the scientific frontier of emergent hadron structure

JLab at the luminosity frontier will be critical to understand the rich and extraordinary variety of non-perturbative effects manifested in hadronic structure.

Upgraded JLab will be unique facility capable of exploring the emergent phenomena of QCD and its associated effective degrees of freedom.

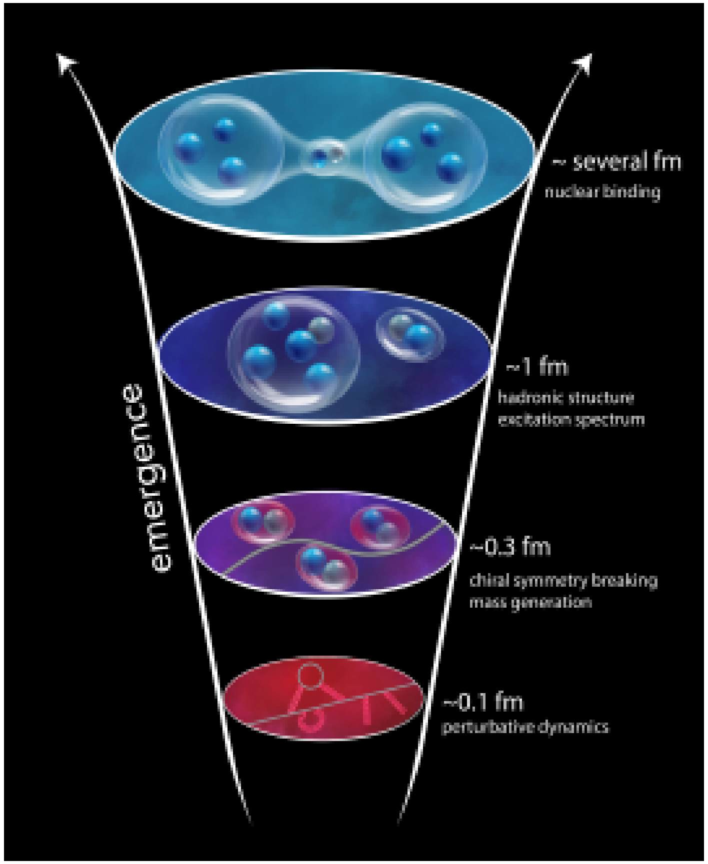
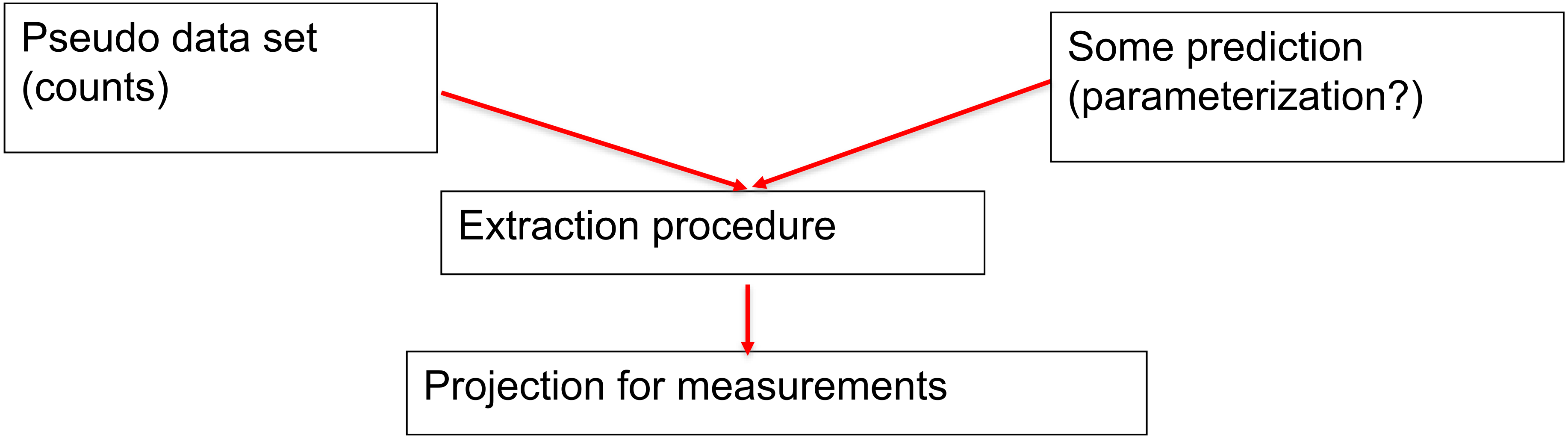


Figure 1: The emergence of structure in QCD from the perturbative regime of quarks and gluons to bound hadrons to hadrons bound in nuclei.

Making projections: extraction procedure

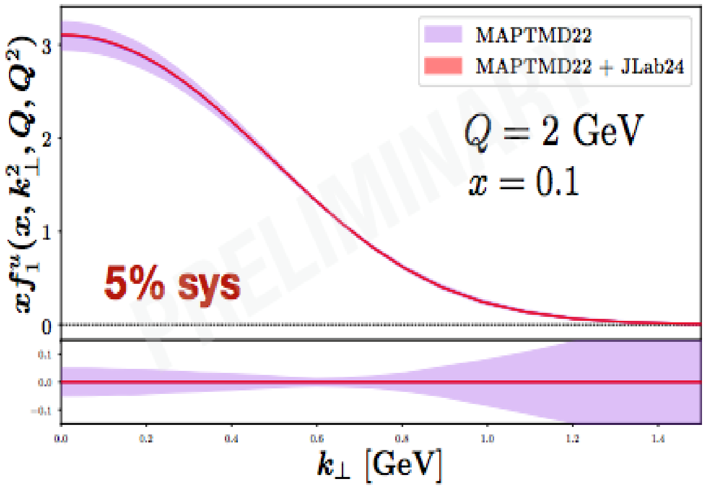


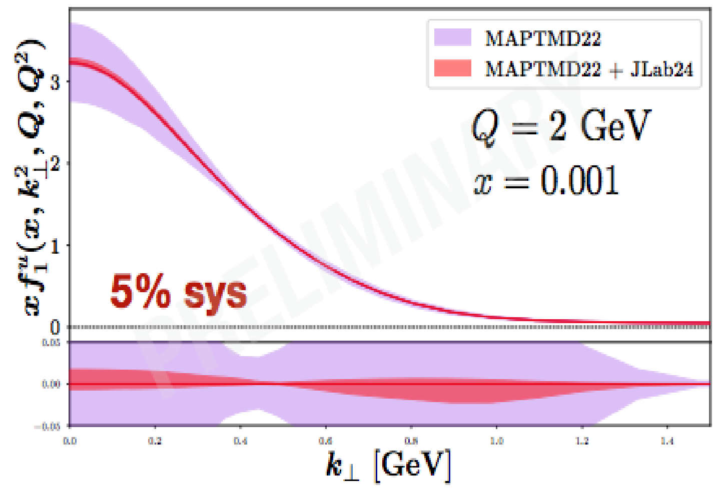
Extraction procedure should have clear definition of systematics related to assumptions and approximations!!!!

- The role of multidimensional measurements should be well defined, accounted in the extraction
  - 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.

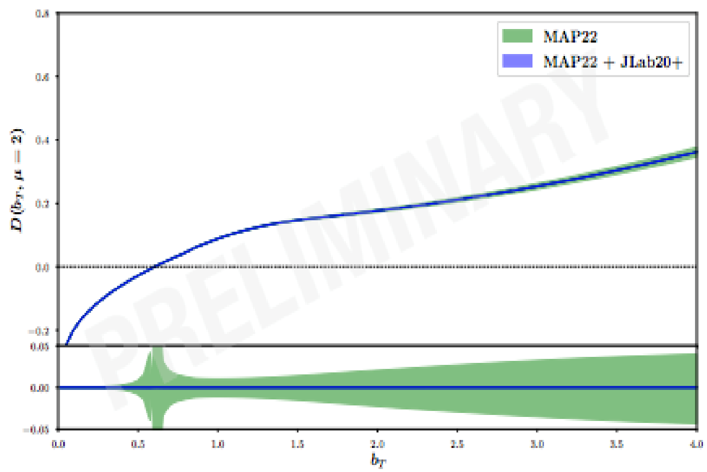
JLAB 24 IMPACT STUDIES ON TMDS

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

Projections for Sivers

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

$\sin(\phi - \phi_S)$

arXiv:1208.1244

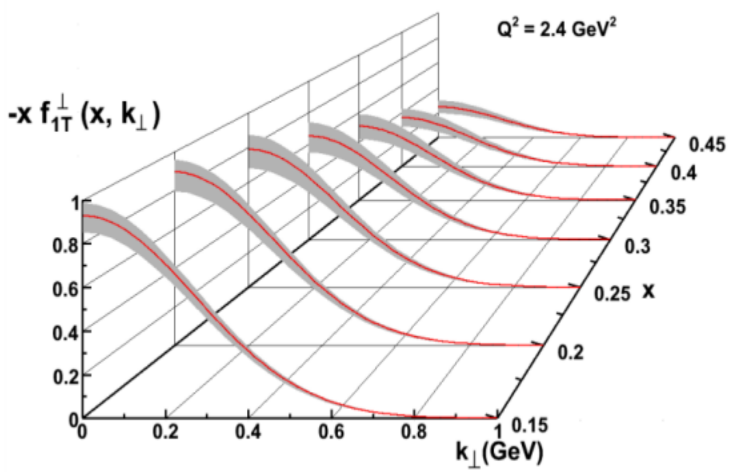


Figure 3.4 The Sivers function for the up quark as a function of $k_{\perp}$ at different values of x as determined by analysis of JLab 12 pseudo data generated for [3]He target. The central line is the model profile of [3-35]; real Jefferson Lab 12 GeV data will eventually reveal the actual shape of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

arXiv:1212.1701

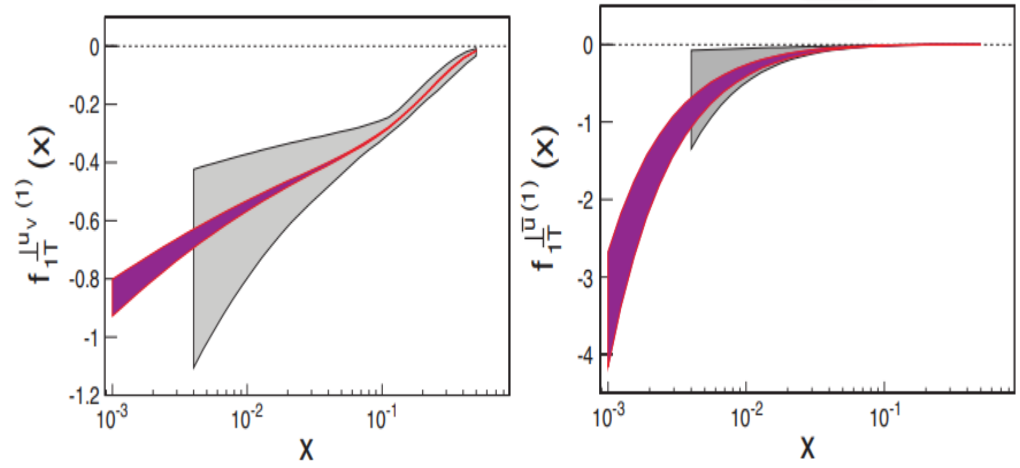


Figure 2.16: Comparison of the precision (2-σ uncertainty) of extractions of the Sivers function for the valence (left) $u_v = u - \bar{u}$ and sea (right) $\bar{u}$ quarks from currently available data [77] (grey band) and from pseudo-data generated for the EIC with energy setting of $\sqrt{s} = 45$ 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, <u>this projections suppressed development of proper extraction frameworks with controlled systematics for years.</u>

Defining the current status of SIDIS

Proposal of a new project requires clear understanding of the current status

a) Identify problems we have in interpretation of what we already observed

Possible path to address (more or better quality data, improved analysis frameworks,..)

b) Identify new problems that can be addressed with new observables, new kinematics that can provide a critical input in understanding of the QCD dynamics

To produce a realistic and convincing physics program we should be able to simulate the observables, their physics and detector backgrounds, to claim understanding of observables and validate the interpretation

$F_{UU,L}$ possible behavior

A. Bacchetta

Low transverse momentum

$$F_{UU,T} = \mathcal{C}\big[f_1 D_1\big]$$

Twist 2

$$F_{UU,L} = \mathcal{O}\left(\frac{M^2}{Q^2}, \frac{P_{h\perp}^2}{Q^2}\right)$$

Twist 4

High transverse momentum

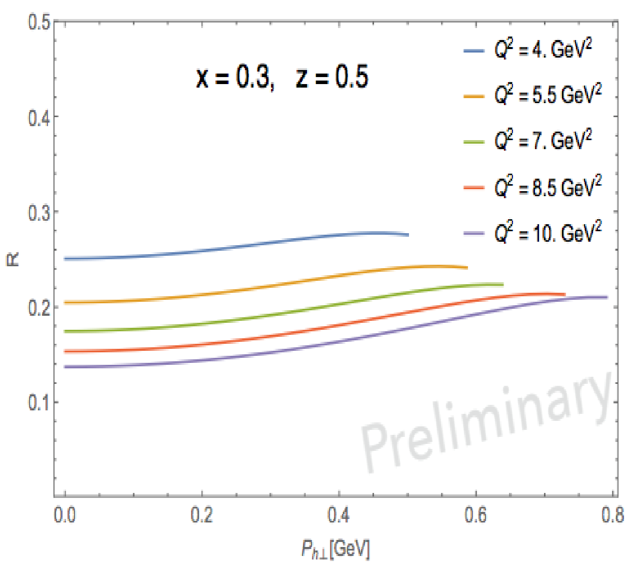
$$F_{UU,T} = \frac{\alpha_s}{P_{h\perp}^2}\big[f_1 \otimes D_1\big]_A$$

$$F_{UU,L} = \frac{\alpha_s}{P_{h\perp}^2}\frac{P_{h\perp}^2}{Q^2}\big[f_1 \otimes D_1\big]_B = 2\, F_{UU}^{\cos 2\phi_h}$$

Integrated

$$F_{UU,T} = x f_1 D_1 + \alpha_s \big[f_1 \otimes D_1\big]_C$$

$$F_{UU,L} = \alpha_s \big[f_1 \otimes D_1\big]_D$$



$$F_{UU,L} = \frac{M^2}{Q^2}\mathcal{C}\left[\frac{4k_T^2}{M^2} f_1 D_1 + \frac{m^2}{M^2} f_1 D_1 + \tilde{f}_2 D_1 + f_1 \tilde{D}_2 + \ldots\right]$$

kinematic twist 4 (à la Wandzura-Wilczek)

mass corrections

dynamic twist 4

sometimes denoted with f_3

factorization breaking terms?

$F_{UU,L}$ tends to stay large even at Q^2>100GeV^2 !!!

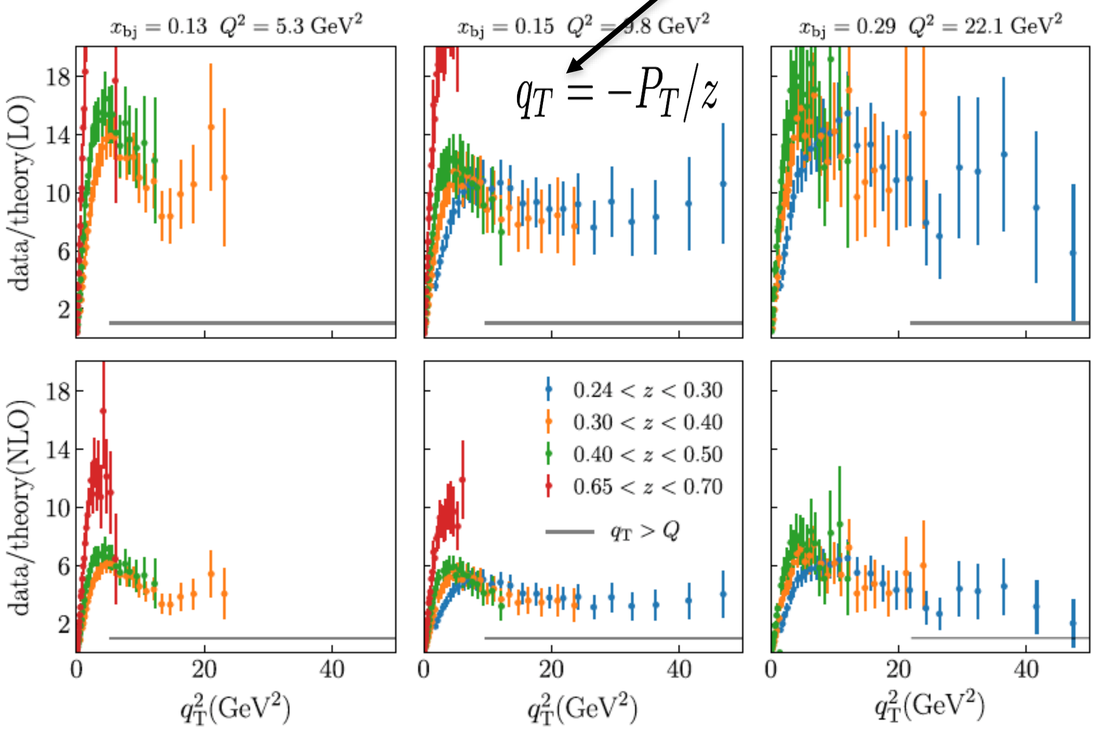
Does it matter if the pion comes from correlated pairs?

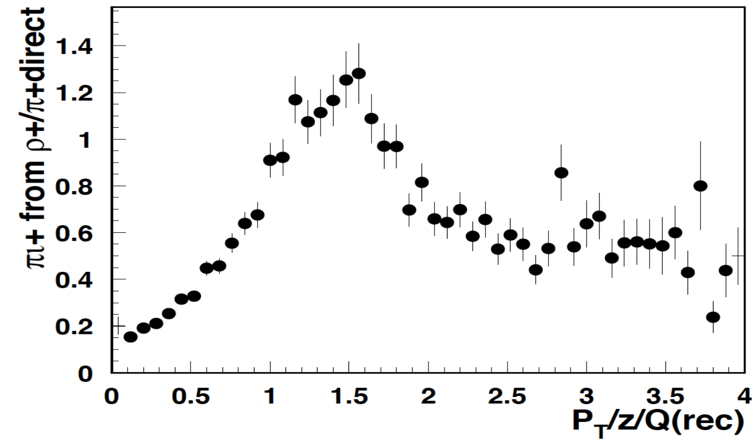
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

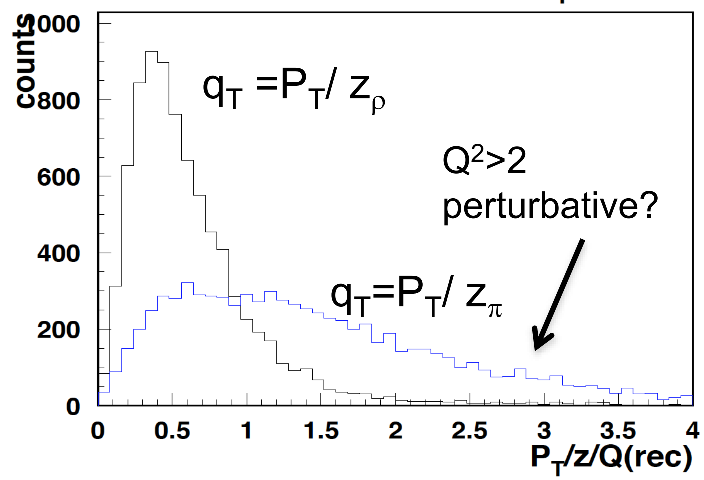
$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

quark transverse momentum

$q_T = -P_T/z$





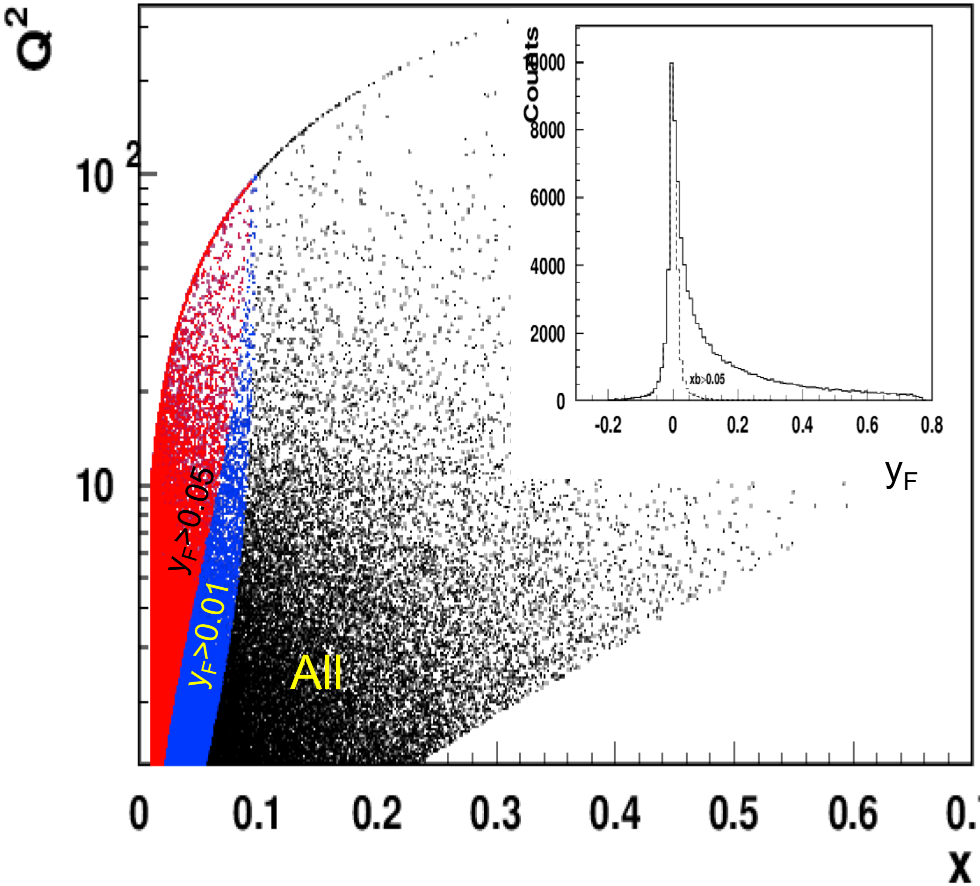


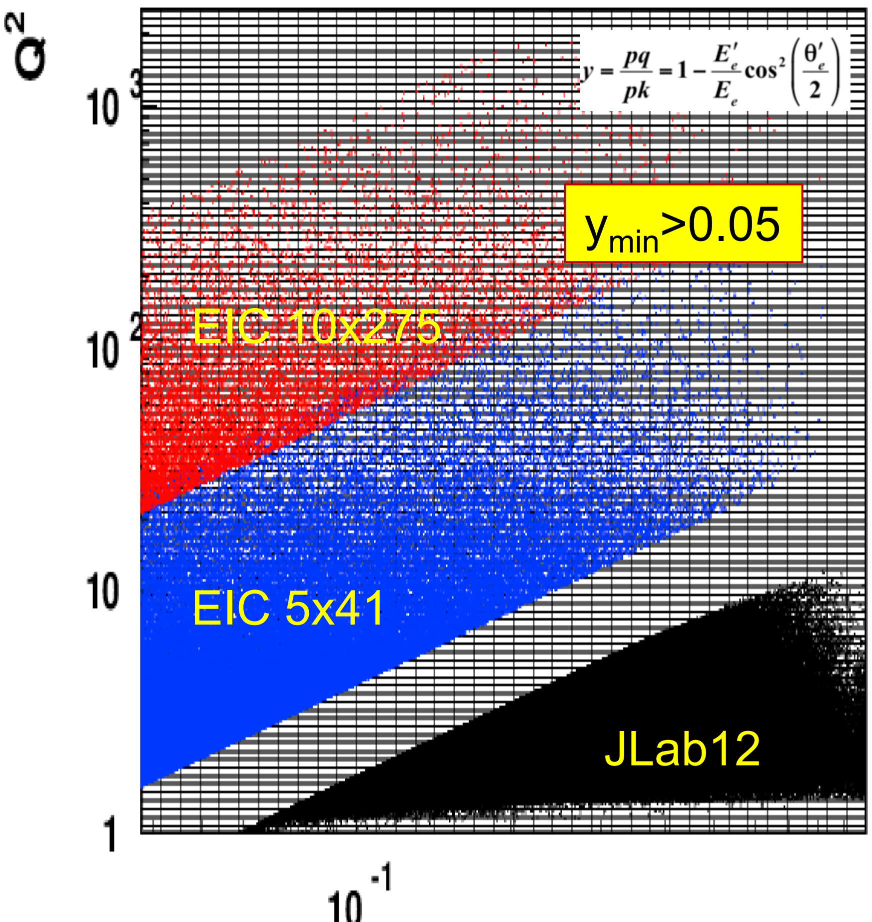
The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

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

X vs Q^2 from JLab to EIC

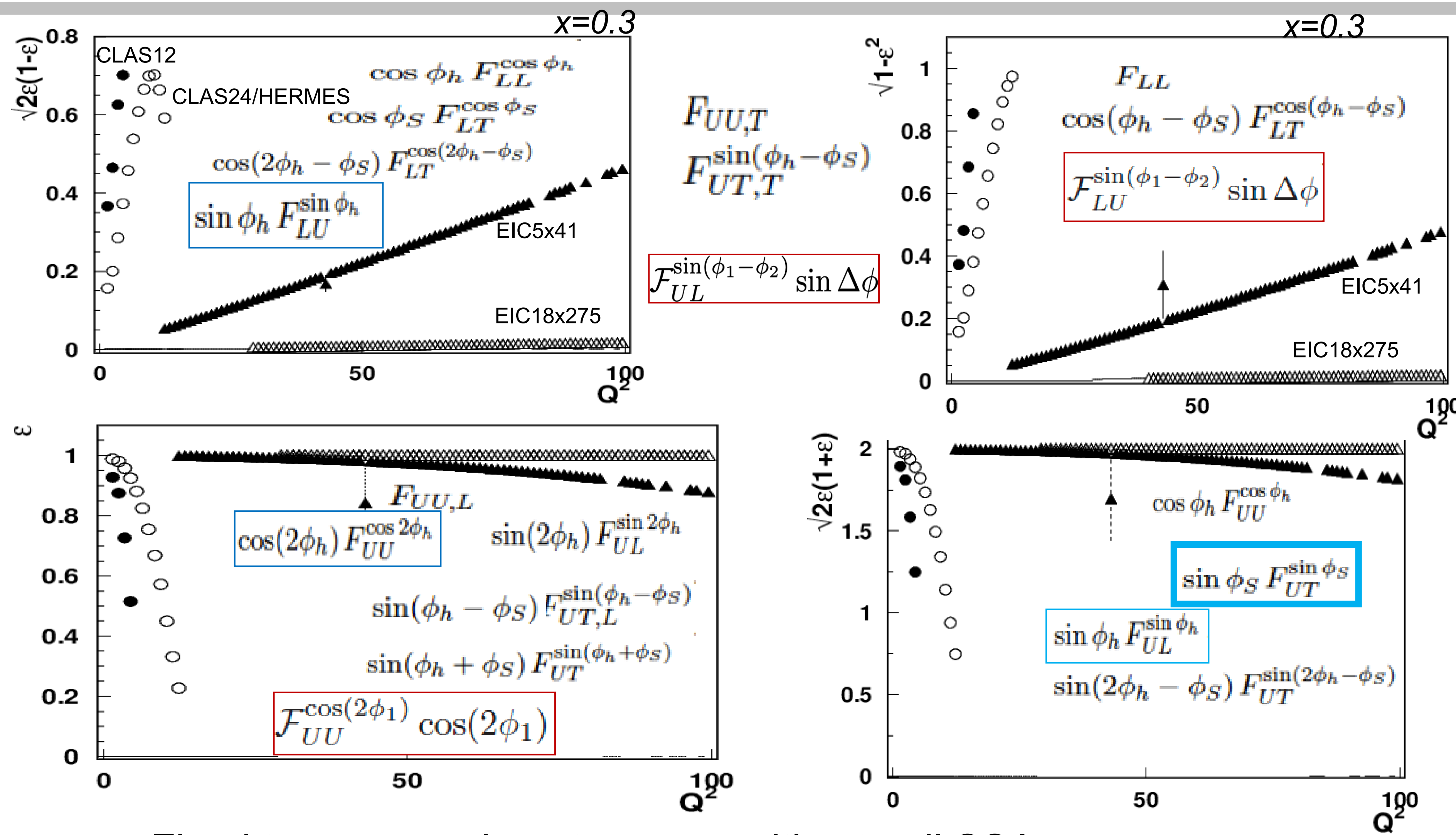




Large x events all in region of small y_F=1.0-E'/Ebeam

Non overlapping ranges of EIC (machine dedicated to gluon studies) and JLab may be a problem for evolution studies, which are most critical for the 3D structure

Kinematic factors at large x

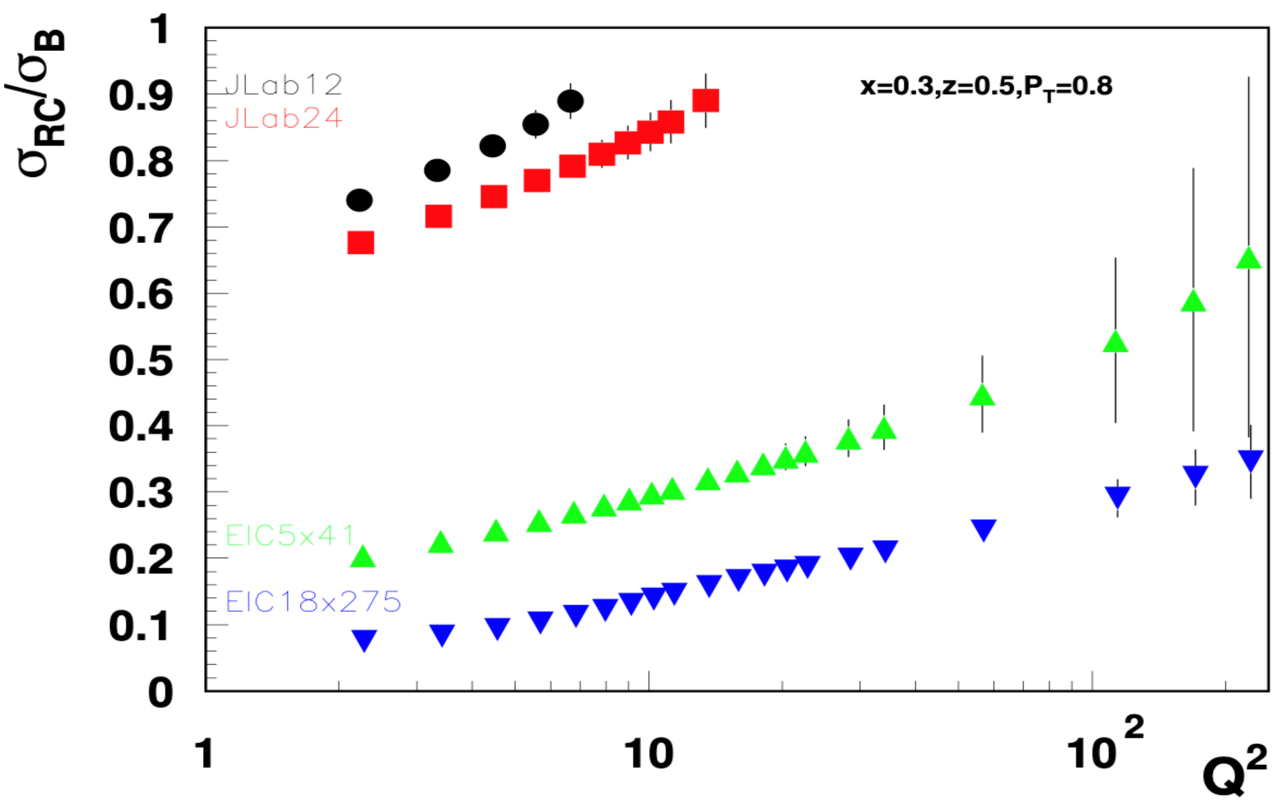


- Fixed target experiments are sensitive to all SSAs
- For EIC, observables surviving the $\varepsilon \rightarrow 1$ limit could be used

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)



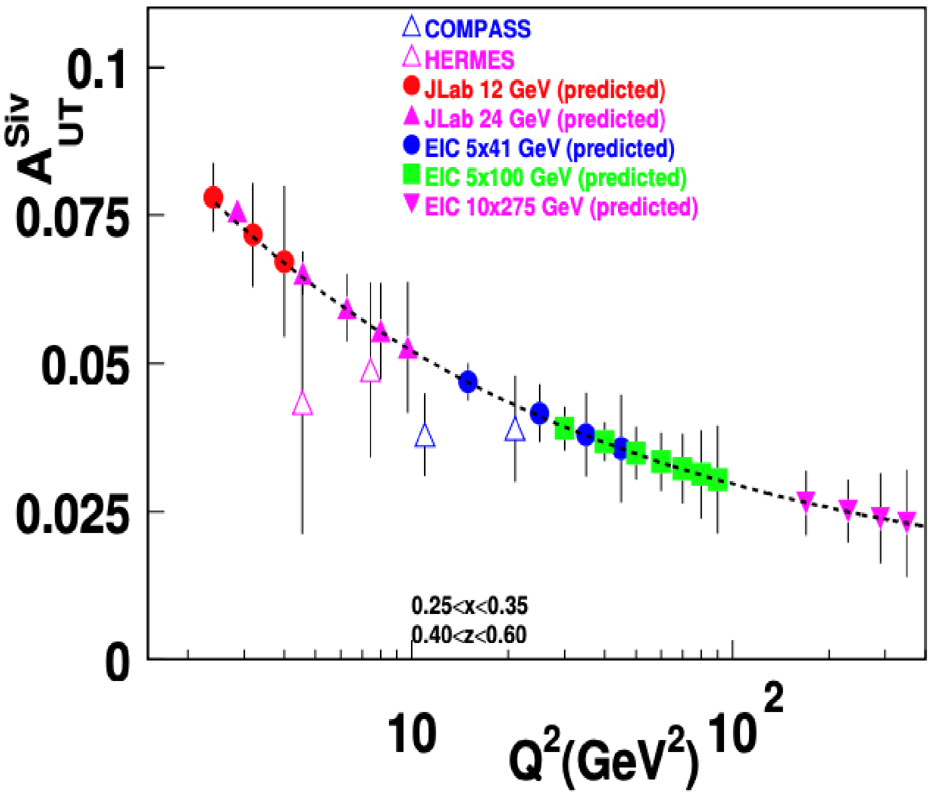
Cross section at low Q^2 suppressed at higher CM energies

- 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

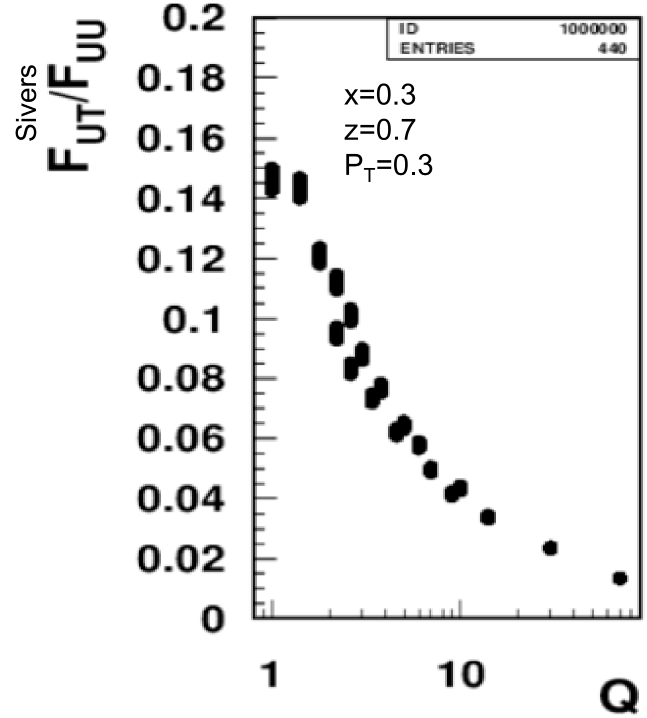
Contributions for 3D structure studies: Sivers

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

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



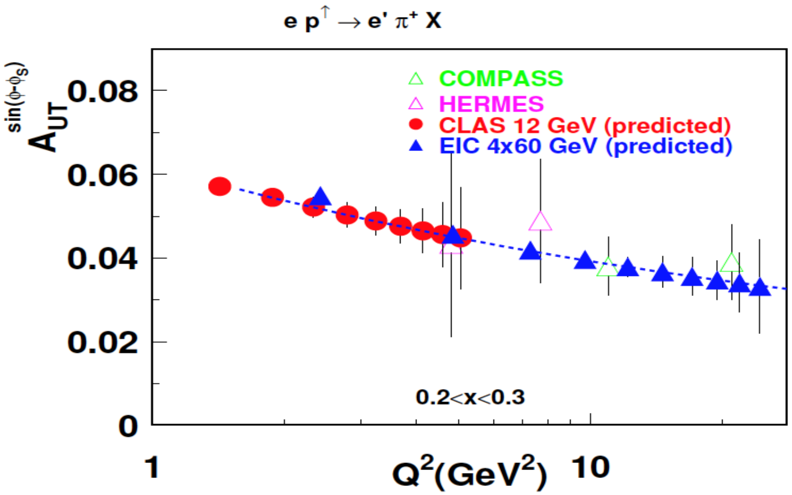
Pavia grids



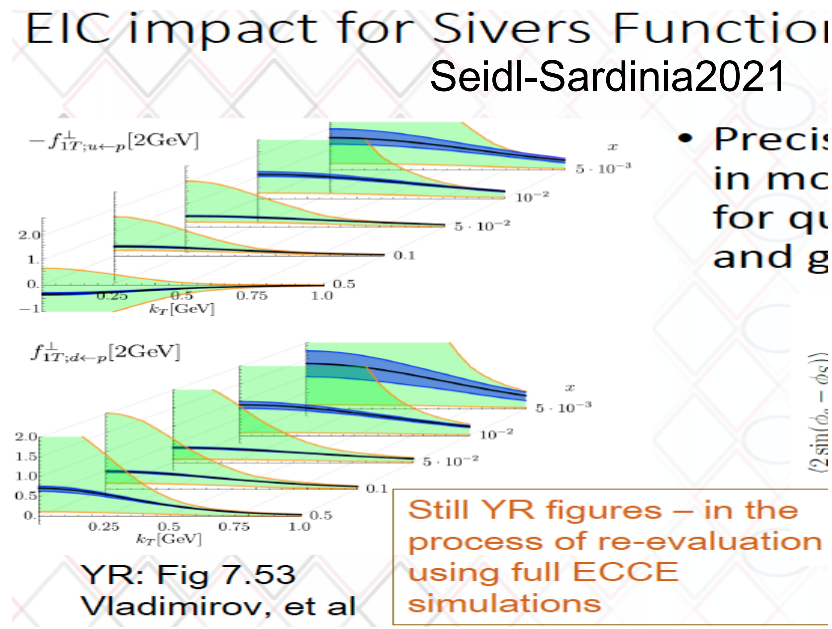
- Measurements of Q^2-dependence of SSAs will be crucial in validation of the theory
- JLab24 will be crucial to bridge the TMD studies between JLab12 and EIC in the valence region

We all contributed….

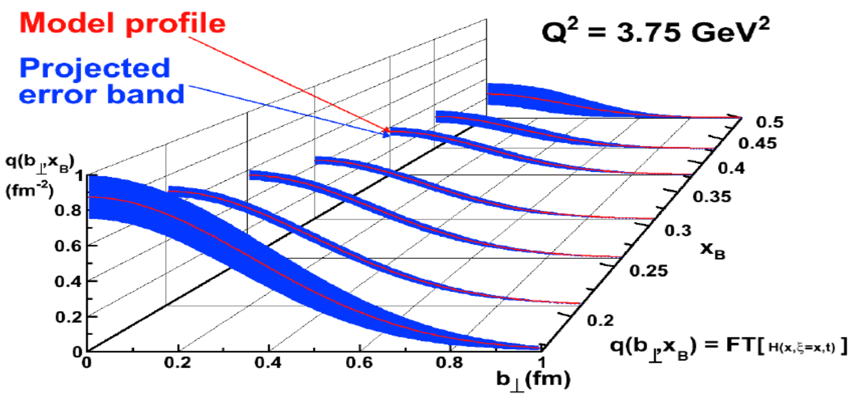
H.Avakian (~10 years old)



Girod-StrongQCD-2021



Projection for the Nucleon transverse profile



Precision tomography in the valence region

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

Pitonyak-PANIC2021