Massachusetts Institute of Technology

Current Status of TMD Measurements at CLAS12

Timothy B. Hayward

European Nuclear Physics Conference 2025

September 23, 2025

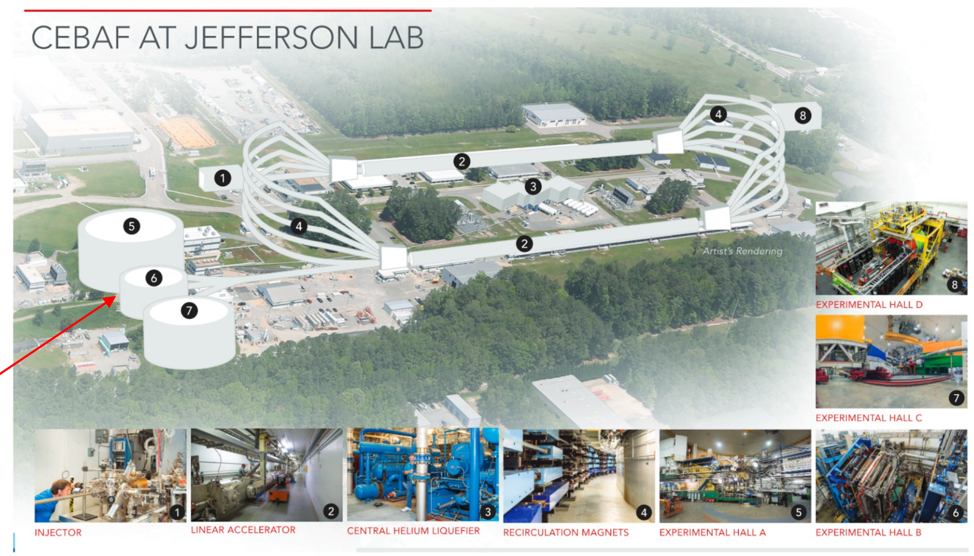
Thomas Jefferson National Accelerator Facility

- Continuous Electron Beam Accelerator Facility (CEBAF) is located in Newport News, VA.

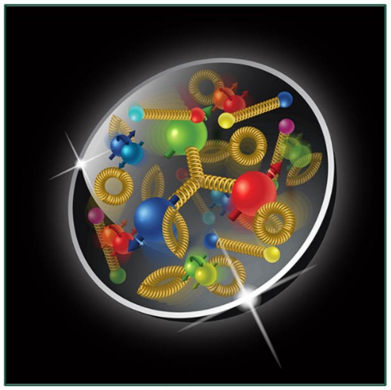
- Four experimental halls (A, B, C and D) receive a recently upgraded 12 GeV longitudinally polarized electron beam.

- Racetrack design with parallel north and south linear accelerators that pass the beam up to five times.

- CLAS12 located in Hall B.



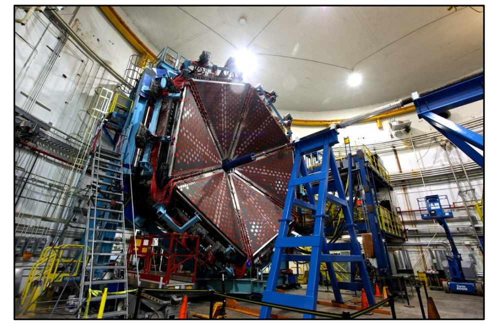
CLAS12 (Hall B) Physics Program



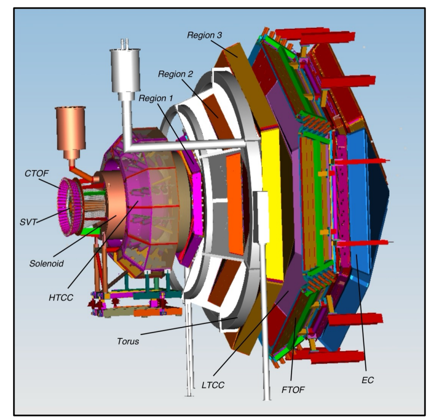
Stony Brook University News, August 2017

- International collaboration with more than 40 member institutions and 200 full members, including many European collaborators.

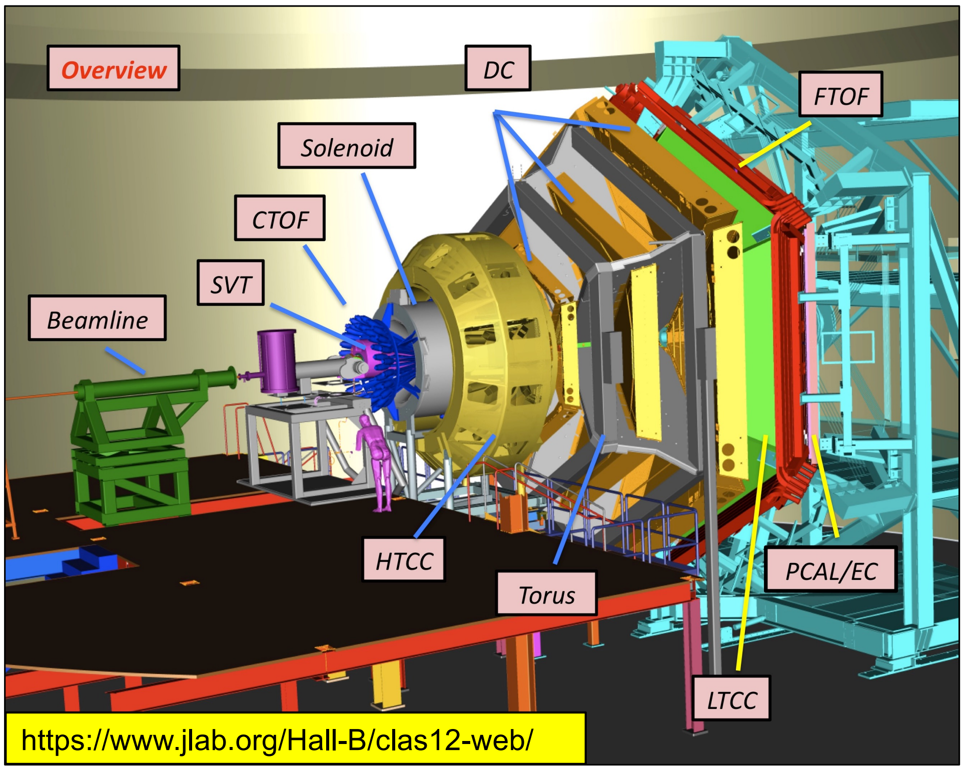
- CLAS(12) is the world's only large acceptance and high luminosity spectrometer for fixed target lepton scattering experiments.

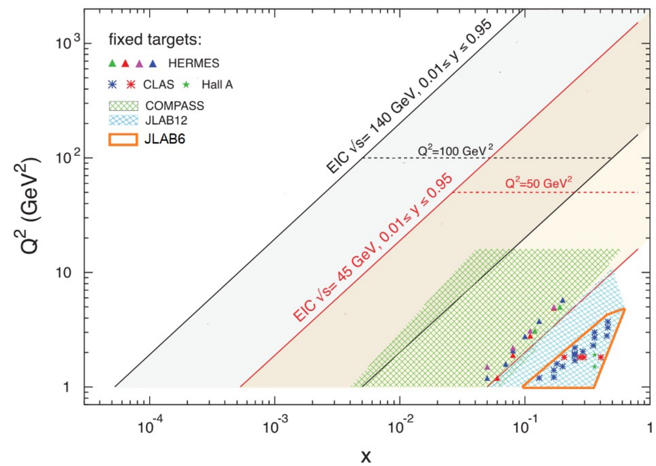


1. Study of the nucleon resonance structure and excited states, c.f. talk by Lucilla Lanza
2. Study of Generalized Parton Distributions (GPDs), (2 +1) D imaging of the proton and the study of its gravitational and mechanical structure, c.f. talks by Adam Hoballah, Li Xu Sebastian Alvarado and Pierre Chatagnon
3. Study of the Transverse Momentum Dependence (TMDs) and the of 3D structure in momentum space.
4. Hadronization in nuclear media, c.f. talk by Hayk Hakobyan
5. Study of J/ψ Photoproduction, LHCb Pentaquarks and Timelike Compton Scattering.
6. Study of meson spectroscopy in search of hybrid mesons
7. Much more!



CLAS12 Spectrometer





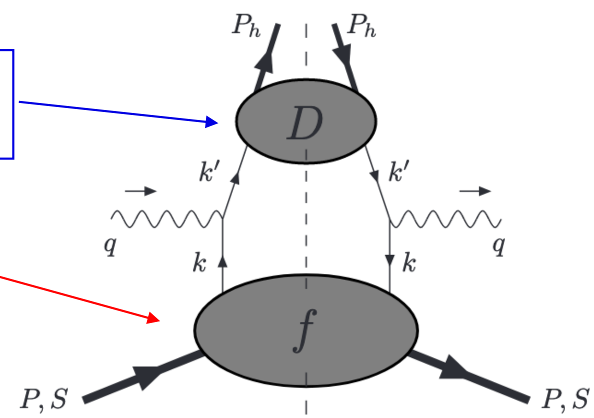
JLab: Valence quark distribution
Compass: Sea quark distribution
EIC: Gluon distribution

- CLAS12: very high luminosity (10^{34}), wide acceptance, low Q^2 (higher twist measurements)
- Began data taking in Spring 2018 – many "run periods" now available: liquid H_2, D_2, polarized NH_3 and ND_3 etc.
- ~10.5 GeV electron beam, longitudinally polarized beam.

Traditional SIDIS Measurements

- Decades of study have led to detailed mappings of the momentum distribution of partons in the nucleon in terms of 1-D and 3-D transverse-momentum dependent parton distribution functions (TMDs).
- SIDIS measurements rely on the assumption that measured hadrons are produced in the CFR.
- Cross section factorized as a convolution of PDFs and Fragmentation Functions (FFs)[1].

$$\frac{d\sigma^{\mathrm{CFR}}}{dx_B\,dy\,dz_h} = \sum_a e_a^2 \boxed{f_a(x_B)} \frac{d\hat{\sigma}}{dy} \boxed{D_a(z_h}$$



M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

- PDFs
  - Confined motion of quarks and gluons inside the nucleus
  - Orbital motion of quarks, correlations between quarks and gluons
- Fragmentation Functions
  - Probability for a quark to form particular final state particles
  - Insight into transverse momenta and polarization

1. A. Bacchetta et al., JHEP 02 (2007) 093 [hep-ph] 0611265,

SIDIS Observables at CLAS12

Run Group A (Unpolarized LH_2 target)

- ★ **unpolarized SIDIS cross section** off proton
- ★ A_{LU} **in Beam Spin Asymmetries**

Run Goup B (Unpolarized LD_2 target)

- ★ Complementary to RG-A
  → allow for ***u/d*** **quark flavor separation**

Run Group C (**longitudinally** polarized NH_3 and ND_3)

- ★ $\mathbf{F_{UL}}$ and $\mathbf{F_{LL}}$

Run Group K (Unpolarized LH_2 target)

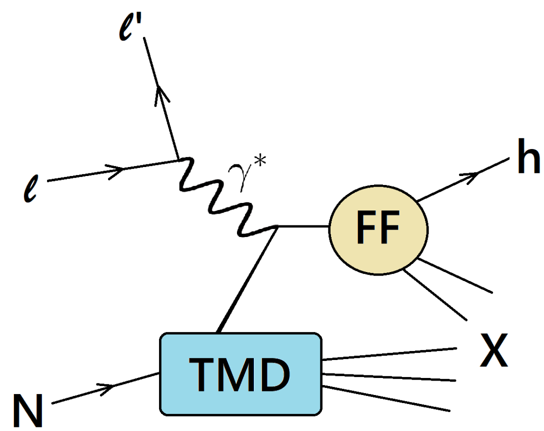
- ★ 6.5, 7.5, 8.4 GeV e- beam
- ★ $F_{UU,L}$, $F_{UU,T}$ Separation

Run Group H (**transversely** polarized NH_3)

- ★ $\mathbf{F_{UT}}$ structure function

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

The CLAS12 physics program will have access to the full SIDIS cross section including all observables in a variety of flavors.



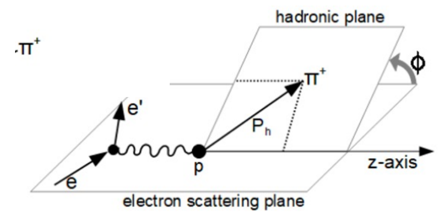
TMDs from Single Hadron Production

twist-3 pdf — unpolarized PDF — twist-3 t-odd PDF — Boer-Mulders

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(x\boxed{e}\boxed{H_1^{\perp}}+\frac{M_h}{M}\boxed{f_1}\frac{\boxed{\tilde{G}^{\perp}}}{z}\right)+\frac{\hat{h}\cdot p_T}{M}\left(x\boxed{g^{\perp}}\boxed{D_1}+\frac{M_h}{M}\boxed{h_1^{\perp}}\frac{\boxed{\tilde{E}}}{z}\right)\right]$$

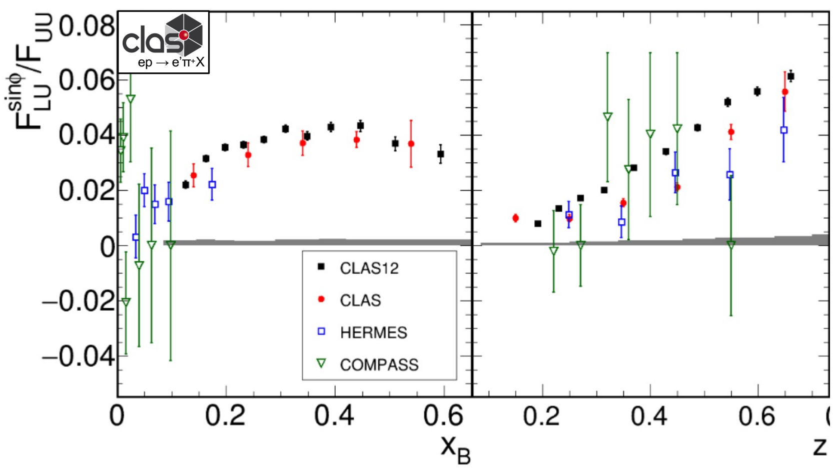
Collins FF — twist-3 FF — unpolarized FF — twist-3 FF

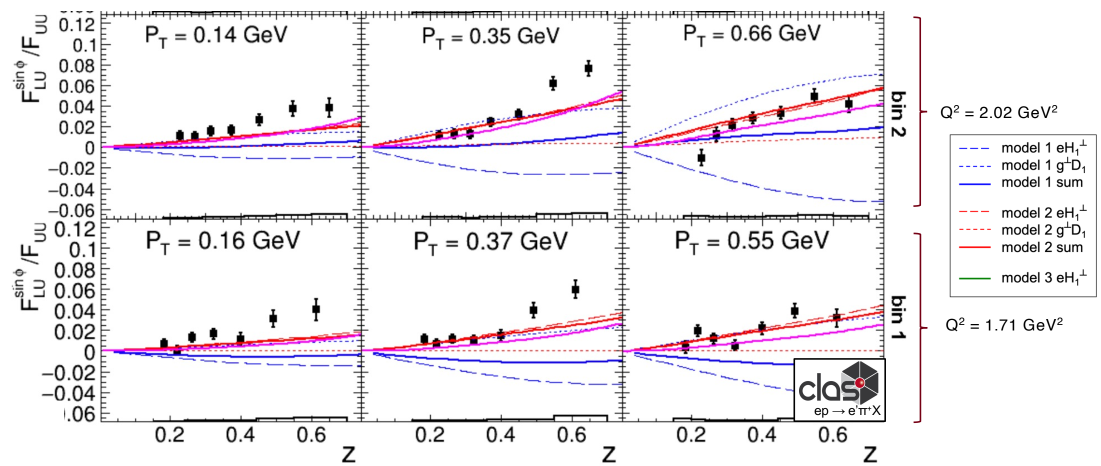
A. Bacchetta et al., *JHEP 0702*, 093 (2007).



model 1 (Mao et al., EPJ C 73) → Proton = active quark plus spectator scalar and axial-vector diquarks
model 2 (Mao et al., EPJ C 74)
$eH_1^\perp$ — $g^\perp D_1$
model 3 $eH_1^\perp$ (Schweitzer et al.) → e(x) based on the chiral quark soliton model

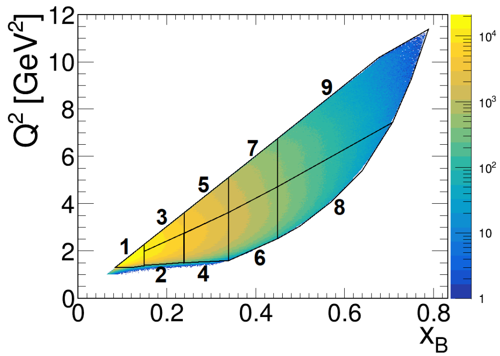
First high-precision multidimensional study: important for constraints of PDFs.





S. Diehl et al., *Phys. Rev. Lett.*, 128, 062005, (2022), [hep:ex] 2101.03544

Flavor Effects in Single Pion SIDIS



■ π⁺ ■ π⁰ ■ π⁻

model 2 prediction

★ If Collins term only **($H_1^\perp$)**

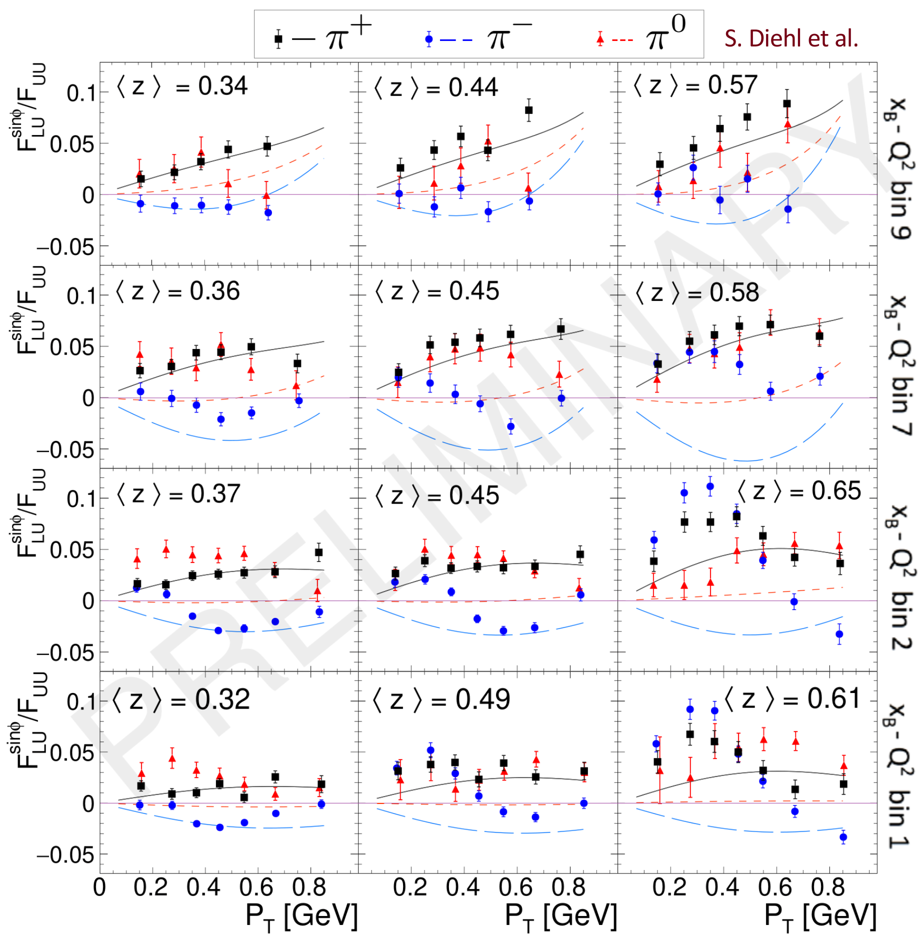
→ hierarchy of the A_{LU}'s

$A_{LU}(\pi^-) < A_{LU}(\pi^0) = 0 < A_{LU}(\pi^+)$

★ Observed is more **Sivers-like ($g^\perp$)**

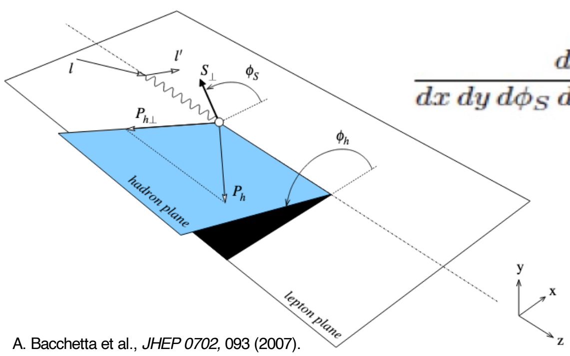
$A_{LU}(\pi^-) < A_{LU}(\pi^0) = A_{LU}(\pi^+)$

→ Asymmetry from struck u-quark



Understanding QCD, from observables to dynamics

- Goal: study the non-perturbative QCD dynamics in 3D space in details.
- Accurate physics interpretation requires separating multiple structure functions within a multidimensional space, with controlled systematics and careful evaluation of theoretical assumptions on non-perturbative quantities.



A. Bacchetta et al., *JHEP 0702,* 093 (2007).

$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)$

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = x\sum_q \boxed{\mathcal{H}^q_{UU,T}(Q^2,\mu^2)} \int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\,\delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT}+\boldsymbol{P}_\perp)$$

$$+\,Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2)+\mathcal{O}(M^2/Q^2)$$

hard part

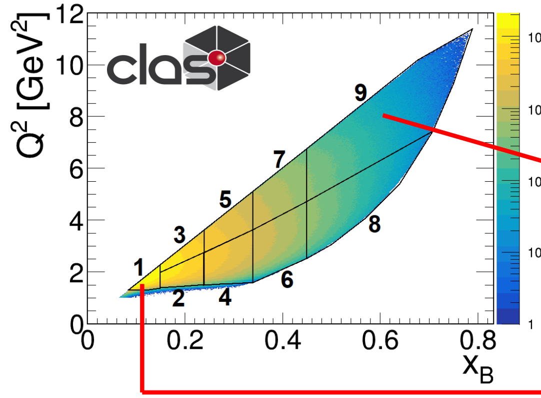
$Q^2 \gg 1,\ k_\perp/Q \ll 1$

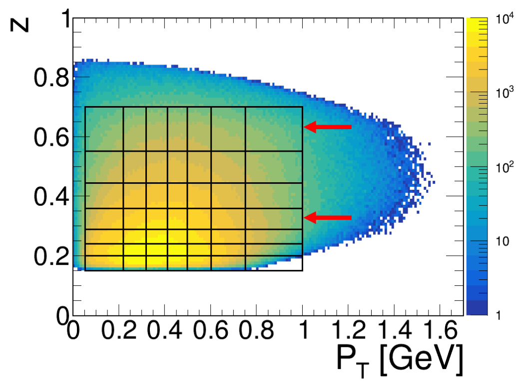
- Factorization allows the description using TMD-PDFs and TMD FFs.
- When there is disagreement:
  - Factorization is broken…? 😥
  - Unaccounted terms may contribute… 🧐

Theory should account for them… or

Experiment should measure and exclude them!

Differences between multidimensional analysis and theory

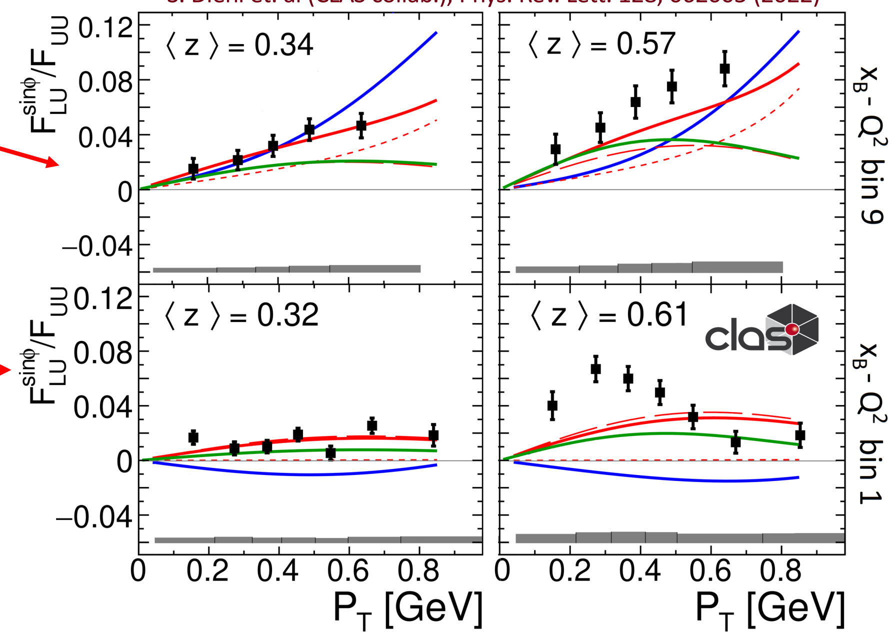




in total: 344 bins x 12 bins in ϕ

~ 4130 BSA bins

S. Diehl et. al (CLAS collab.), Phys. Rev. Lett. 128, 062005 (2022)



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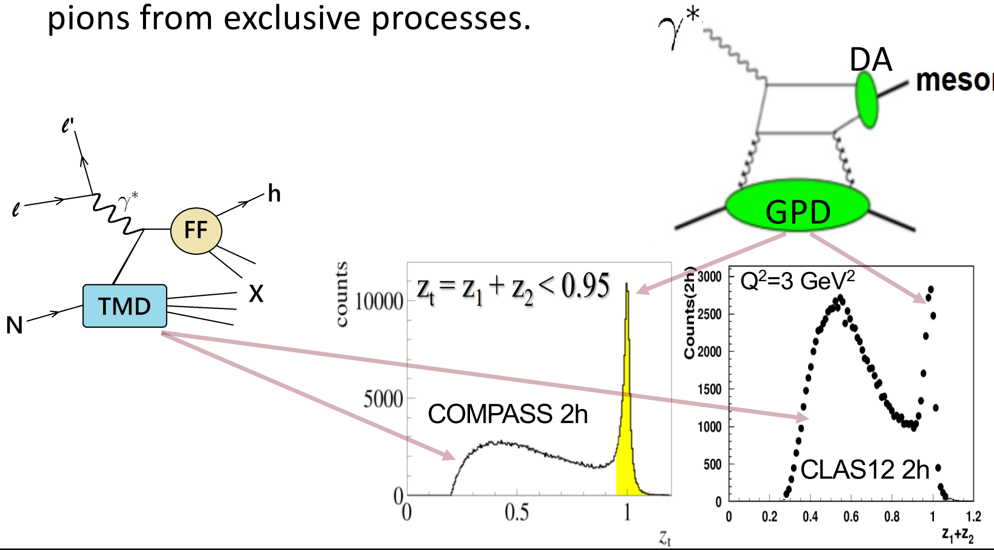
➔ Proton = active quark plus spectator scalar and axial-vector diquarks

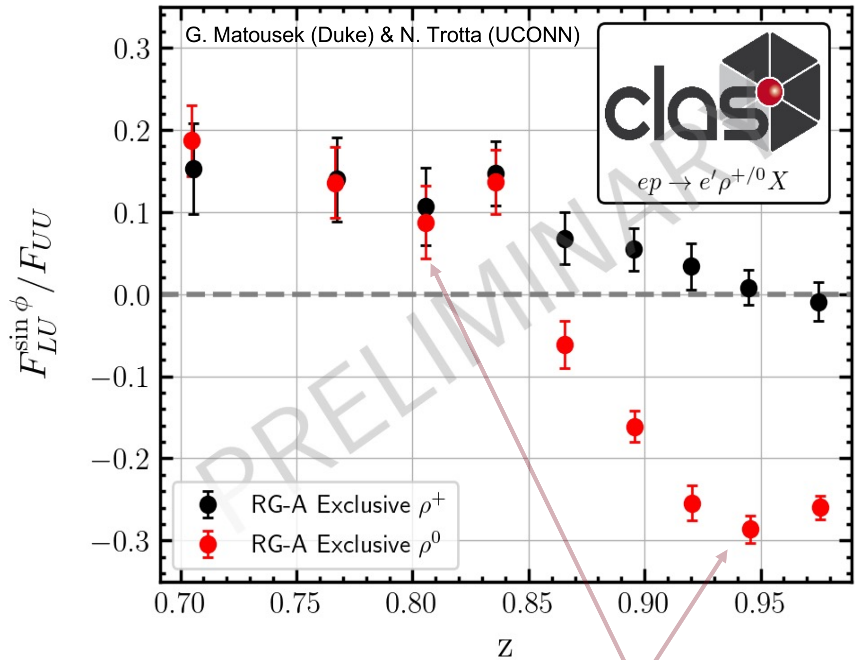
➔ e(x) based on the chiral quark soliton model

- Certain regions of multidimensional analysis agree well with predictions while others clearly diverge (typically low P_T and high z).

Quark-gluon correlations; Impact of VMs

- A TMD based description is valid *only* for pions from current fragmentation **BUT** the eπX sample also contains pions from exclusive processes.





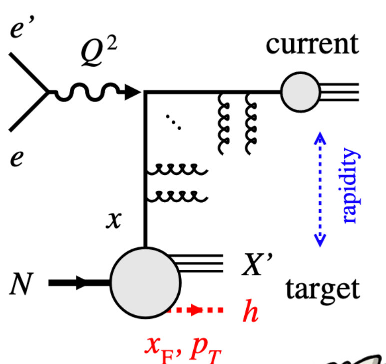
- Understanding of the SSAs of VMs is critical for interpretation of pion SIDIS.
- The fraction of diffractive mesons increases with energy.
- At large x_B the diffractive processes are suppressed by the minimum t.
- Fully evaluating the effect diffractive mesons have on the extraction of TMDs will be critical for EIC studies.

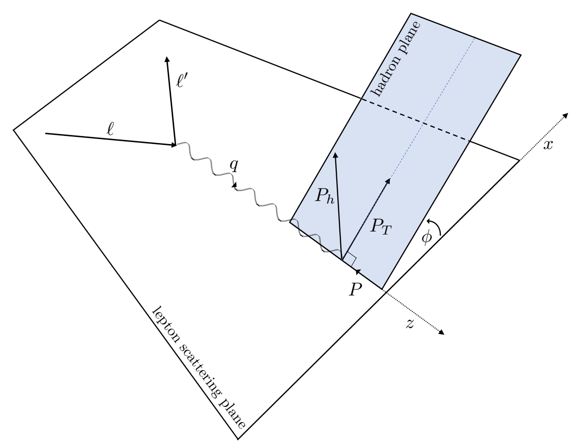
Comparison to ρ^0 indicates where the “diffractive” events are appearing. There are separate dynamical contributions with wildly different azimuthal moments that complicate the picture. Which kinematic regions are contributing to the measurements in single pion observables?

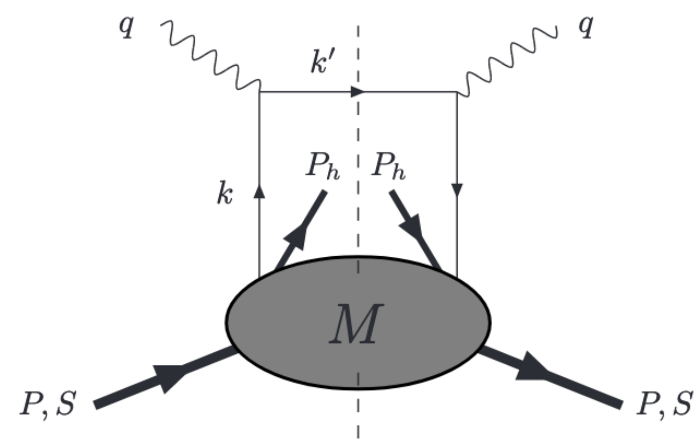
The ~~Neglected~~ Other Hemisphere – Target Fragmentation

- Final state hadrons also form from the left-over target remnant (TFR) whose partonic structure is defined by "fracture functions"[1,2]: the probability for the target remnant to form a certain hadron given a particular ejected quark.
- In the TFR, factorization into x_B and z does not hold because it is not possible to separate quark emission from hadron production. Many ramifications!

$$\frac{d\sigma^{\mathrm{TFR}}}{dx_B\,dy\,dz} = \sum_a e_a^2\,(1-x_B)\boxed{M_a(x_B,(1-x_B)z)}\,\frac{d\hat{\sigma}}{dy}$$







M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

1. L. Trentadue and G. Veneziano, Phys. Lett. B323 (1994) 201,
2. M. Anselmino et al., Phys. Lett. B. 699 (2011), 108-118, [hep-ph] 1102.4214
3. TFR/CFR Fig. from EIC Yellow Report, (2021) [physics.ins-det] 2103.05419

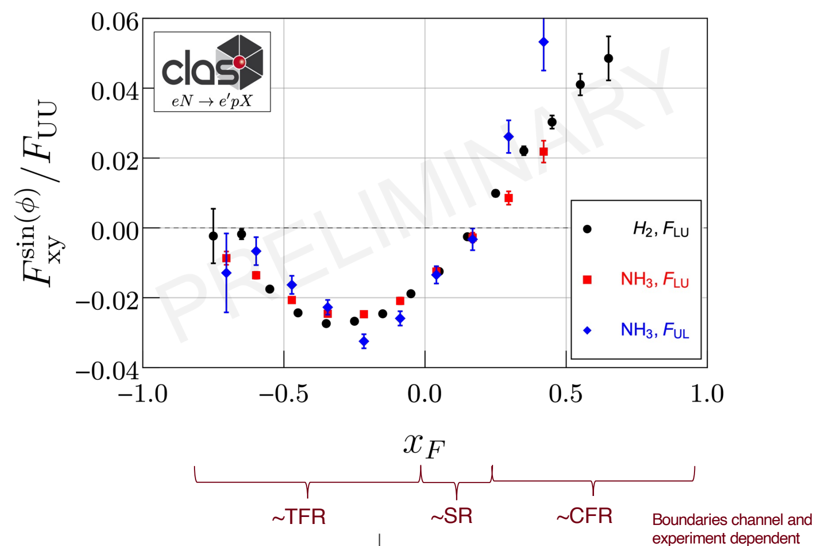
Separating the Target and Current Regimes

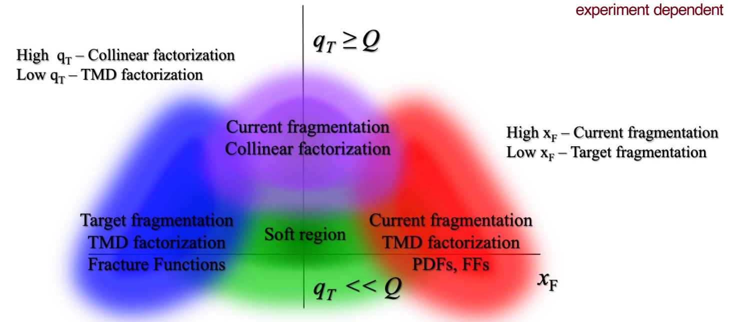
Feynman variable

$$x_F = \frac{p_h^z}{p_h^z(\text{max})} \quad \text{in CM frame } \mathbf{p} = -\mathbf{q}, \qquad -1 < x_F < 1$$

Rapidity

$$y = \frac{1}{2}\log\frac{p_h^+}{p_h^-} = \frac{1}{2}\log\frac{E_h + p_h^z}{E_h - p_h^z}$$





- No clear ***experimental*** definition of what constitutes current production versus target production.
- Fixed target SIDIS experiments lack a clear rapidity gap.
- Structure functions, with different production mechanisms in both regions, give a possible clue.
- Odd-function (sine) modulations exhibit a sign flip around the transition from target to current fragmentation.
- The positive(negative) sign of twist-3 SSAs defines the CFR(TFR) dominance.

Further reading: M. Boglione et al., JHEP 10 (2019) 122, 2019, [hep-ph] 1904.12882

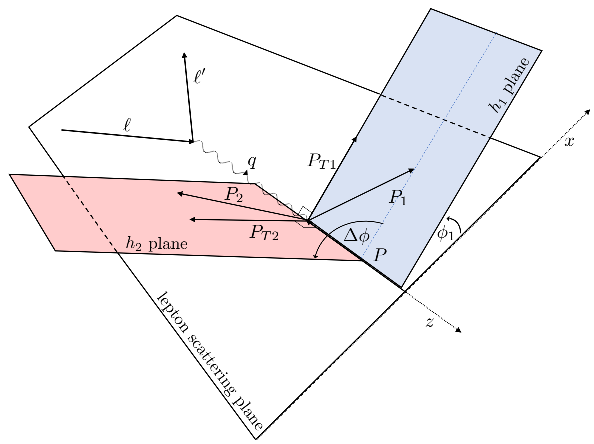
Back-to-back (dSIDIS) Formalism

- When two hadrons are produced "back-to-back"[1,2] with one in the CFR and one in the TFR the structure function contains a convolution of a fracture function and a fragmentation function.
- Leading twist beam(target)-spin asymmetry.

Quark polarization

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

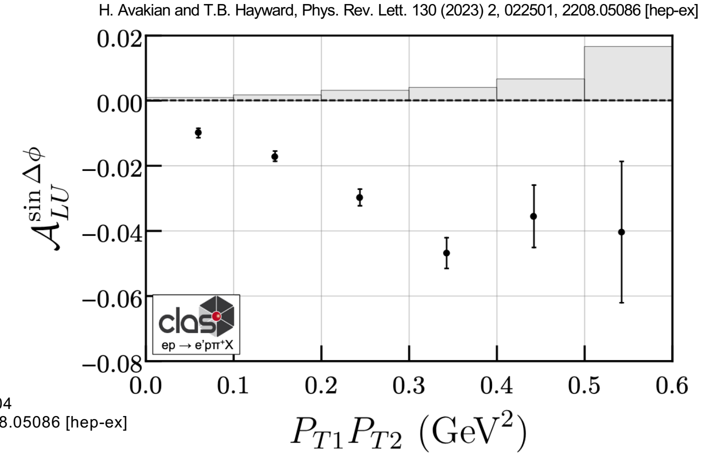
M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

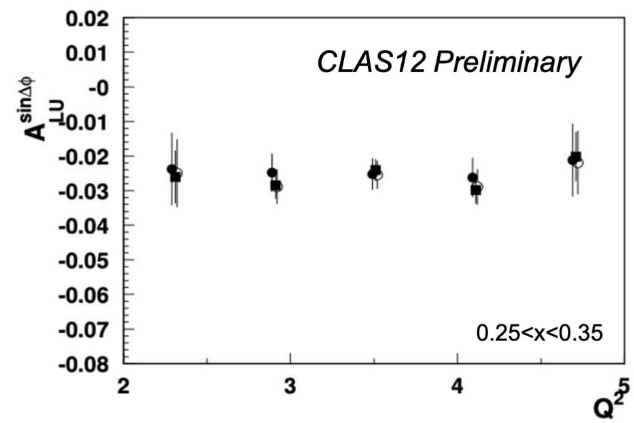


$$A_{LU} = -k(\epsilon)\frac{P_{T1}P_{T2}}{m_1 m_2}\frac{\mathcal{C}\left[w_5 \hat{l}_1^{\perp h}(x,\zeta_2,P_{T2})D_1(z_1,P_{T1})\right]}{\mathcal{C}\left[\hat{u}_1(x,\zeta_2,P_{T2})D_1(z_1,P_{T1})\right]}\sin(\Delta\phi)$$

Unique access to longitudinally polarized quarks in unpolarized nucleons… no corresponding PDF! Reverse situation in target-spin asymmetry (which uniquely has no depolarization, similar to Sivers)

H. Avakian and T.B. Hayward, Phys. Rev. Lett. 130 (2023) 2, 022501, 2208.05086 [hep-ex]

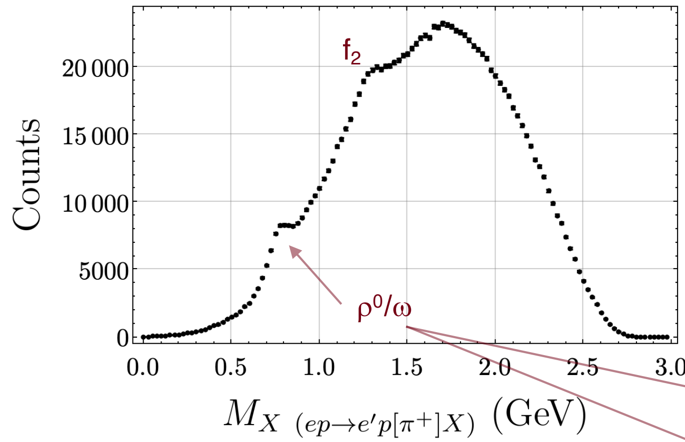




1. M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132
2. M. Anselmino et al., Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604
3. H. Avakian and T.B. Hayward, Phys. Rev. Lett. 130 (2023) 2, 022501, 2208.05086 [hep-ex]

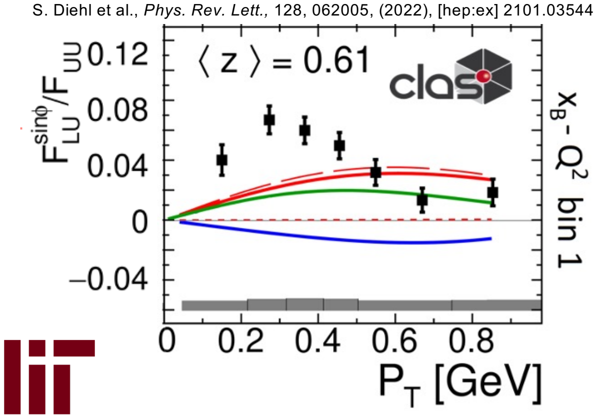
First measurement sensitive to TMD Fracture Functions

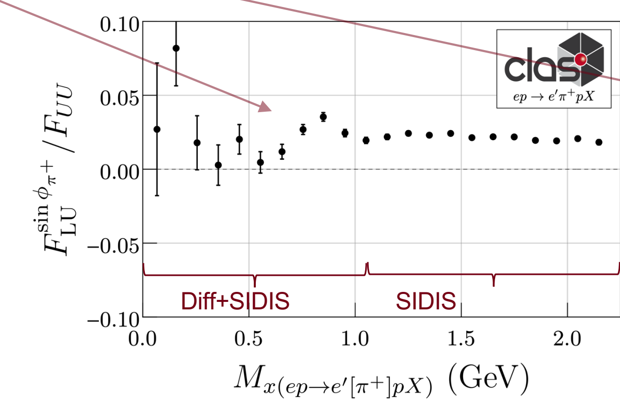
Semi-exclusive measurements

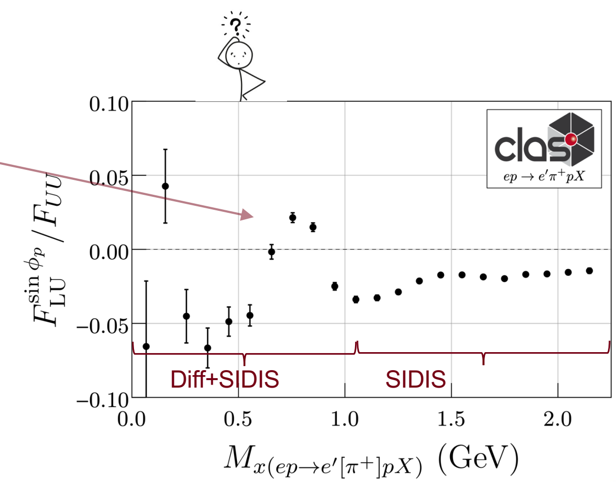


- The dSIDIS/semi-exclusive measurements with target fragment detected not only allow access to new physics observables but also enables the *explicit* removal of vector meson contributions to the single hadron channels
  - (possible alternative method; *implicit* subtraction via MC c.f. COMPASS: NPB 956 (2020)115039 [hep:ex] 1912.10322).
- Earlier observed tendency for π^+ results in certain kinematics can easily be explained by contributions of π^+ coming from the decay of ρ^0 with higher asymmetries that are not removable in single hadron SIDIS.

S. Diehl et al., *Phys. Rev. Lett.*, 128, 062005, (2022), [hep:ex] 2101.03544



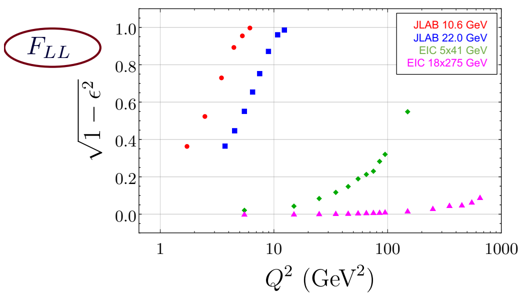




Helicity TMD (and the effect from ρ^0)

- $g_1(x,k_T)$ will be heavily kinematically suppressed at EIC.
- JLab22, with extension to higher P_T, would be critical for studies of g_1 in the valance quark region.

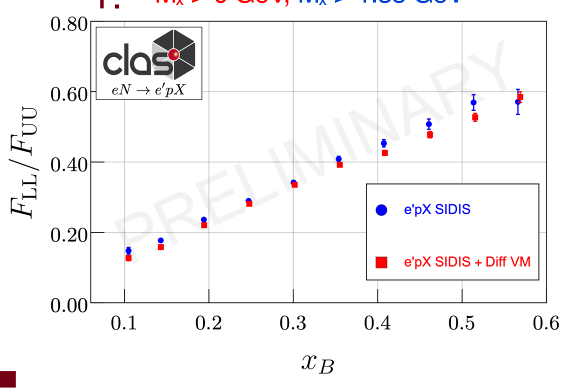
$$F_{LL} \propto g_1(x,k_T) \otimes D_1(z,p_T)$$



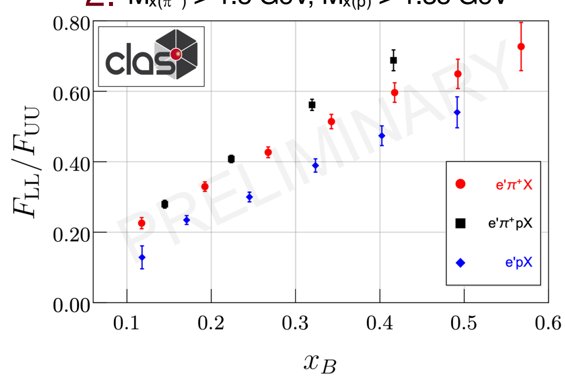
1. Measurements of epX A_{LL} systematically higher after M_x cut to remove VMs
2. Semi-exclusive e'π^+pX with ρ removed larger than e'π^+X double-spin asymmetries
3. Measurements of A_{LL} for "diffractive" ρ^0 indicate very small values (probably negative)

Contributions from VM may have caused underestimations of g_1!

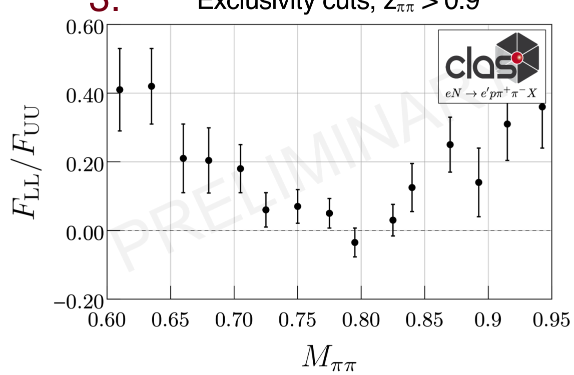
1. $M_x > 0$ GeV, $M_x > 1.35$ GeV



2. $M_{x(\pi^+)} > 1.5$ GeV, $M_{x(p)} > 1.35$ GeV
$M_{x(\pi^+)} > 1.5$ GeV, $M_{x(p)} > 1.35$ GeV



3. Exclusivity cuts, $z_{\pi\pi} > 0.9$



(Psuedo $\longleftrightarrow$ Vector) Exclusive Mesons

$$n_M = (-1)^J P$$

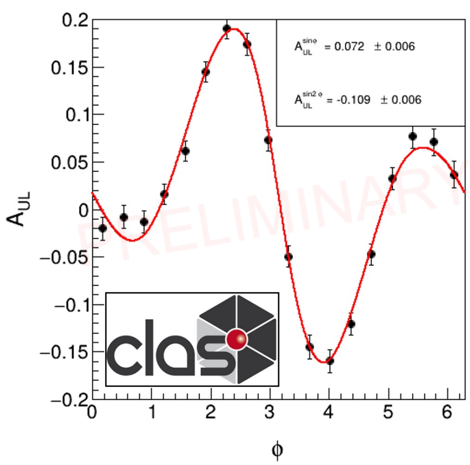
J = spin (= 0 π, 1 ρ)
P = parity (= -1)

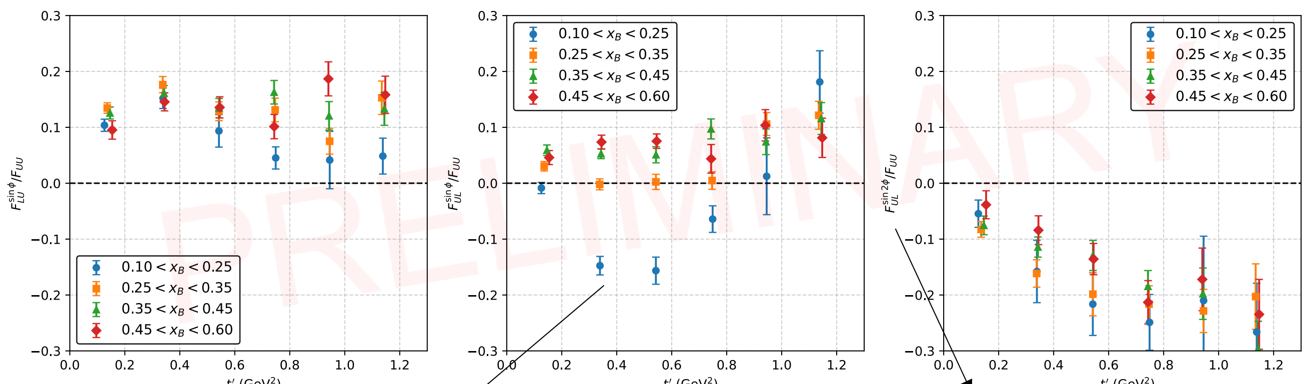
Goloskokov & Kroll, Eur. Phys. J. C **65** (2010) 137; [arXiv:0802.0822]

$$A_{LU}^{\sin\phi} = e_0^2\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Im}\left[(1+\eta_M) < \tilde{E}_T^M >^*_{TL} < H_{\mathrm{eff}}^M >_{LL} -2 < H_T^M >^*_{TL} < E^M >_{LL}\right]$$

$$A_{UL}^{\sin\phi} = e_0^2\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Im}\left[\underbrace{(1-\eta_M) < \tilde{E}_T^M >^*_{TL} < H_{\mathrm{eff}}^M >_{LL}}_{\text{different term, causes low } x_B \text{ divergence for } A_{LU} \text{ of } \rho \text{ and } A_{UL} \text{ of } \pi^+} \underbrace{-2 < H_T^M >^*_{TL} < E^M >_{LL}}_{\text{common term; likely dominates at large } x_B}\right]$$

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$\bar{E} = 2\tilde{H}_T + E_T$
	L		$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	$H_T, \tilde{H}_T$





sin2ϕ, T-T interference (purely chiral odd GPDs)

$A_{LU} \sim A_{UL}$ at high x_B; at low x_B π^+ (shown here) A_{UL} drops sharply; similar behavior for A_{LU} of ρ

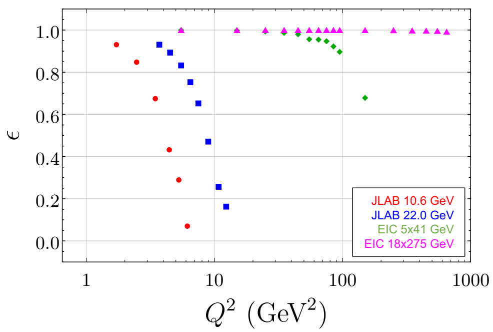
Summary

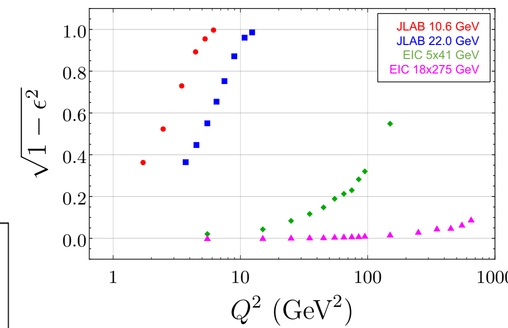
- CLAS12 can provide measurements with many orders of magnitude higher luminosity than previous experiments while also reliably measuring multiparticle final states.
- For interpreting the SIDIS data, it is critical to separate contributions from different structure functions in multidimensional space and also to distinguish between various production mechanisms within a given structure (including VMs).
- Contributions from diffractive VM challenge the factorized picture of SIDIS. Moving towards a “p-free SIDIS” might help address these challenges in phenomenology.
- The detection of target fragment baryons opens new avenues for studying the partonic structure of nucleons both by introducing new observables and by aiding in the separation of VM contributions.
- Many analyses not discussed: pion multiplicities, dihadrons (collinear and TMD, all charge combinations), kaons, etc.

Back up

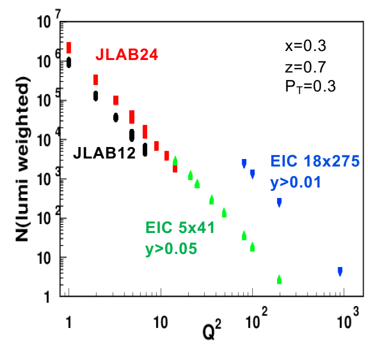
Effects of the Kinematic Factor JLab vs EIC

$F_{UU,L}$
$F_{UU}^{\cos 2\phi}$
$F_{UT}^{(3\phi-\phi_S)}$
$F_{UT,L}^{\sin(\phi-\phi_S)}$
etc



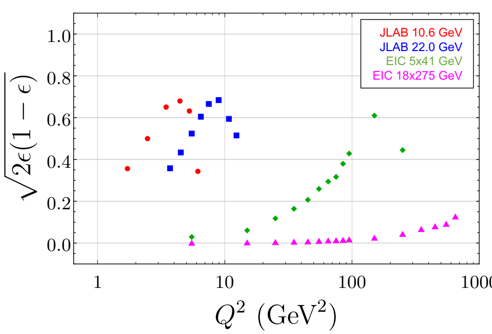


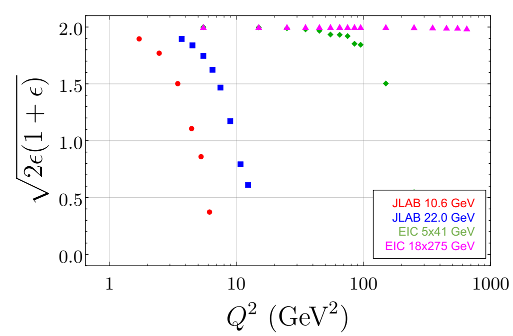
F_{LL}
$F_{LU}^{\sin \Delta\phi}$
$F_{LU}^{\sin(\phi_h-\phi_{R_\perp})}$
etc



At the premier EIC luminosity of 10x275 many observables are **heavily** suppressed.

$F_{LU}^{\sin\phi}$
$F_{LU}^{\sin\phi_{R_\perp}}$
$F_{LL}^{\cos\phi}$
etc



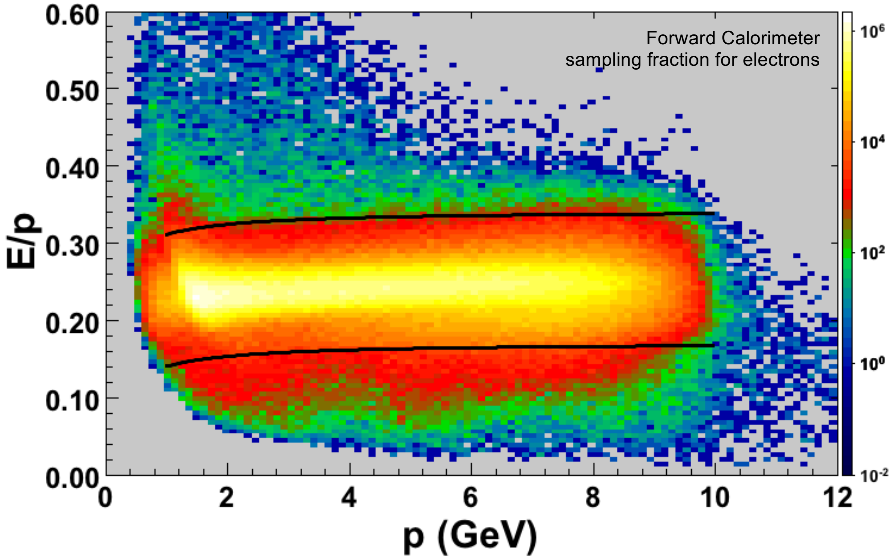


$F_{UL}^{\sin\phi}$
$F_{UU}^{\cos\phi}$
$F_{UT}^{\sin\phi_S}$
$F_{UT}^{\sin\phi_S}$
etc

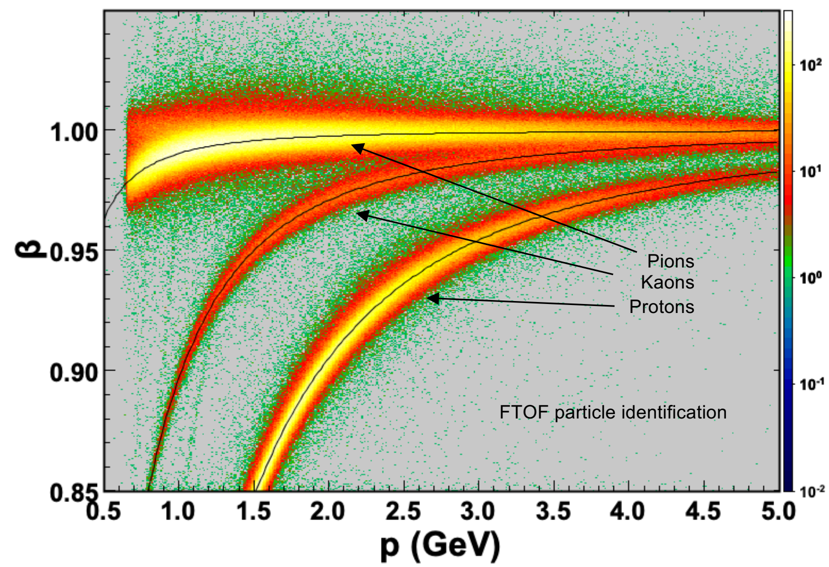
Access to several key SIDIS/TMD objects will be **extremely** difficult to measure at higher energy experiments, while others will have similar magnitudes across different energies, strengthening their interpretation.

Particle Identification

- Electron
  - Electromagnetic calorimeter.
  - Cherenkov detector.

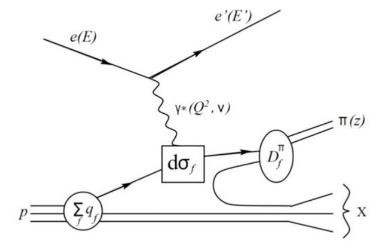


- Hadron
  - β vs p comparison between vertex timing and event start time using forward and central time of flight systems (~100 ps resolution)



Unpolarized Multiplicities of ep → eπX

$$\frac{d\sigma}{dx\,dQ^2\,dz\,dP_{h\perp}^2\,d\phi_h} \sim F_{UU,T} + \epsilon\, F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\;\cos\phi_h\; \underline{F_{UU}^{\cos\phi_h}} + \epsilon\;\cos 2\phi_h\; \underline{F_{UU}^{\cos 2\phi_h}}$$

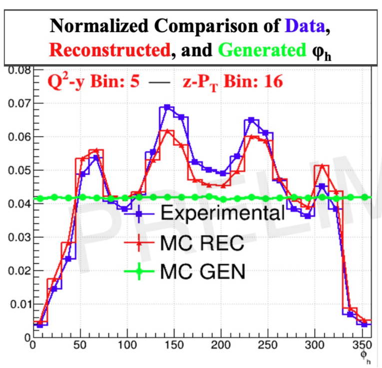


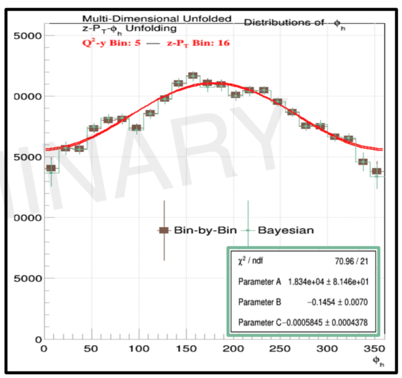
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\zeta\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}\left(x\,h\,H_1^{\perp} + \frac{M_h}{M}\,f_1\,\frac{\widetilde{D}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M}\left(x\,f^{\perp}\,D_1 + \frac{M_h}{M}\,h_1^{\perp}\,\frac{\widetilde{H}}{z}\right)\right)$$

$$F_{UU}^{\cos 2\phi_h} = \zeta\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)(\hat{\mathbf{h}}\cdot\mathbf{p}_T) - \mathbf{k}_T\cdot\mathbf{p}_T}{M\,M_h}\,h_1^{\perp}H_1^{\perp}\right]$$

➔ Leading twist

- Next to leading twist: Sensitive to the Cahn Effect
- 4-D measurements [Q^2, y, z, P_T] for pion SIDIS
- 5-D bayesian unfolding (acceptance corrections)

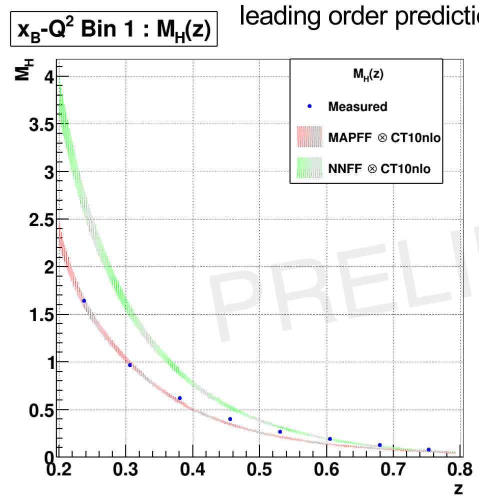


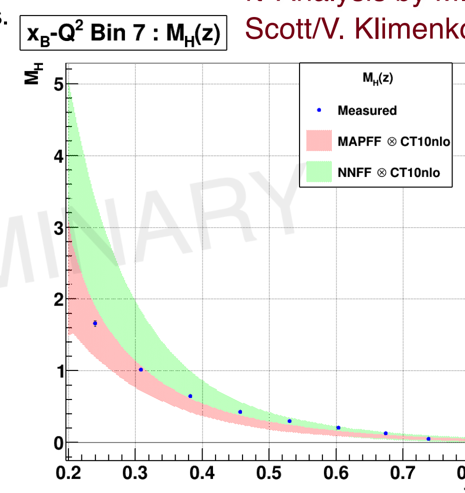


π⁺ Analysis by Richard Capobianco

The π^0 p_T^2 integrated multiplicities have been extracted and shown to be inline with the MAPFF⊗CT10nlo leading order predictions.

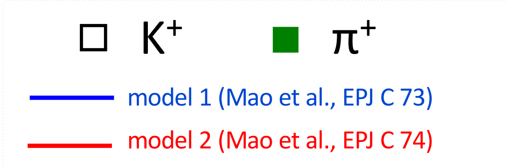
π⁰ Analysis by M. Scott/V. Klimenko

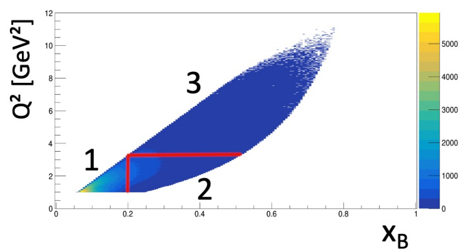




Kaon SIDIS

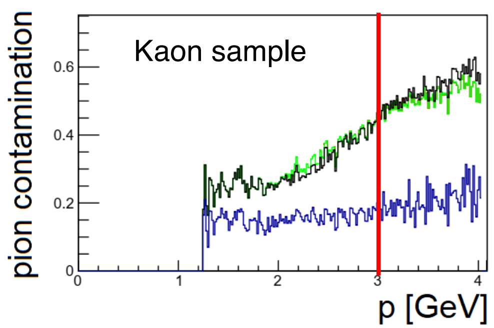
eK⁺X

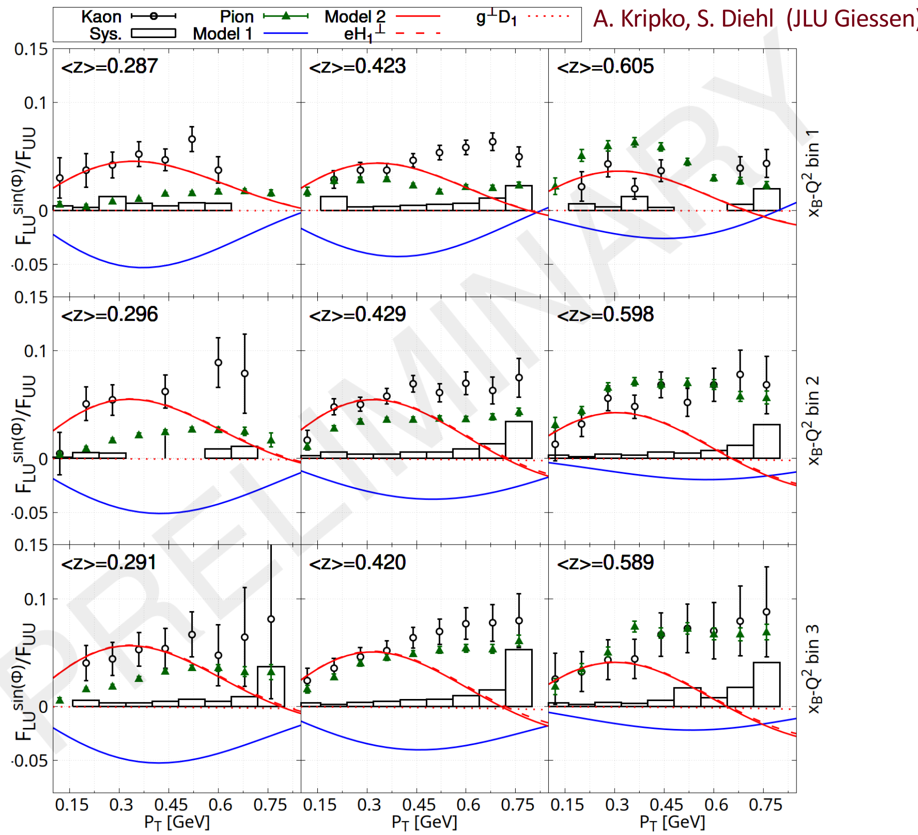




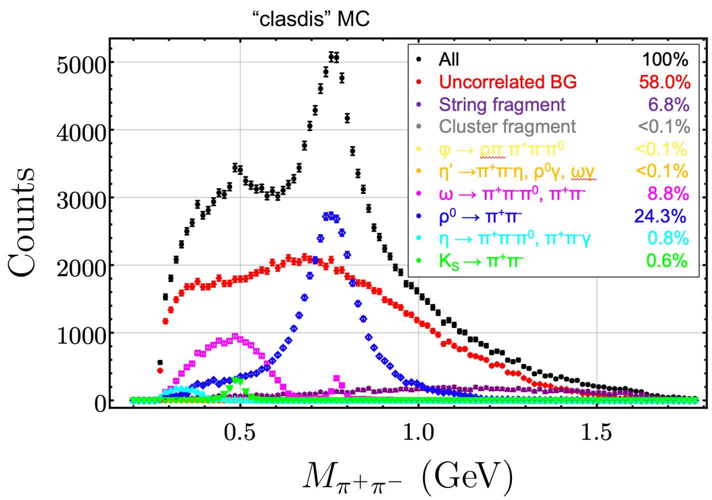
- Reasonable assumption of u-quark dominance
- Differences either from fragmentation functions or distinct VM contributions

For Kaon SIDIS: Kaon PID based on a deep neural network

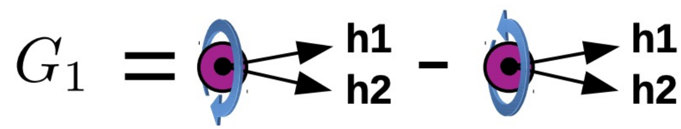


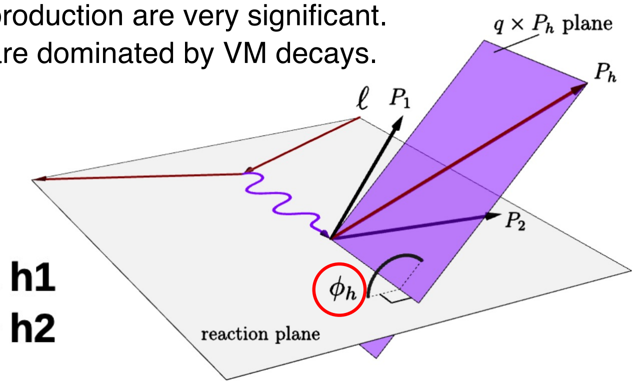


TMD Dihadron Fragmentation Functions



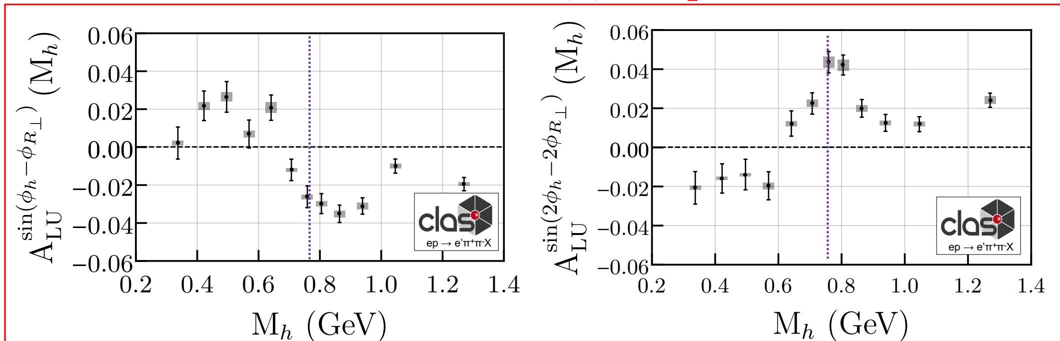
- Spin-azimuthal correlations in hadron pair production are very significant.
- Hadron pairs in SIDIS (from JLab to LHC) are dominated by VM decays.





- Dihadron studies allow for the existence of FFs with no single hadron analog.
- $G_1^{\perp}$ describes the azimuthal dependence of an unpolarized hadron pair on the helicity of the struck quark.
- First ever observation.

Twist 2, $f_1(x) \otimes G_1^{\perp|\ell,m>}$



T. B. Hayward et al., *Phys. Rev. Lett.*, 126, 152501, (2021), hep:ex/2101.04842

TFR Single Spin Asymmetries with Polarized NH_3

1. epX sample, M_x > 1.35 GeV ("VM free")
2. Near identical magnitude for F_{LU} and F_{UL}.
3. Twist-3 observables; simpler tensor structure in TFR.

$$F_{UL}^{\sin\phi_h} = -\frac{2|\vec{P}_{h\perp}|}{Q} x_B^2 u_L^h$$

unpolarized quarks in a longitudinally polarized proton

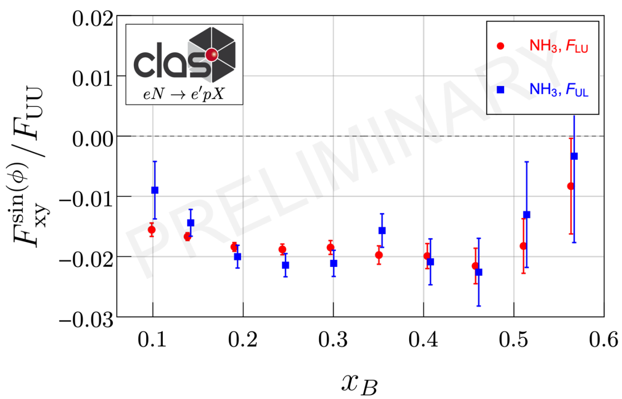
$$F_{LU}^{\sin\phi_h} = \frac{2|\vec{P}_{h\perp}|}{Q} x_B^2 l^h$$

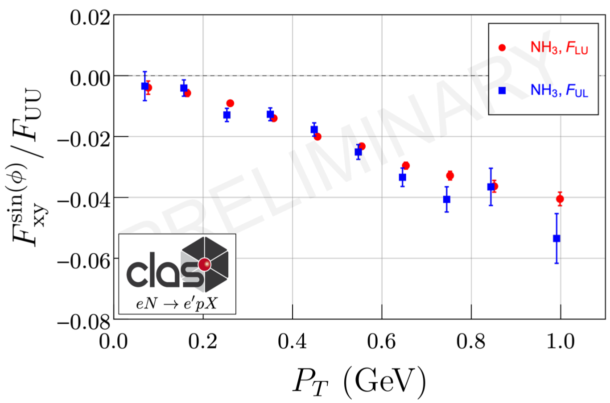
longitudinally polarized quarks in an unpolarized proton

Quark polarization (columns) / Nucleon polarization (rows)

	U	L
U	u^h	l^h
L	u_L^h	l_L^h

Twist-3 Collinear terms;
Chen, K. B., Ma, J. P. and Tong, X. B., [hep-ph] 2308.11251





Situation in CFR more complicated

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\Big[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\Big(xe\,H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z}\Big) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\Big(xg^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z}\Big)\Big],$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\Big[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\Big(xh_L H_1^\perp + \frac{M_h}{M} g_{1L} \frac{\tilde{G}^\perp}{z}\Big) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\Big(xf_L^\perp D_1 - \frac{M_h}{M} h_{1L}^\perp \frac{\tilde{H}}{z}\Big)\Big]$$

A. Bacchetta et al., *JHEP 0702*, 093 (2007).

Where is there disagreement?

J12-24-RunGroupA

J12-24-RunGroupA: *"11 GeV Polarized Electrons on Liquid Hydrogen Target to Study Proton Structure, 3D Imaging, and Gluonic Excitations"*

C. Weiss, N. Sato

Semi-inclusive DIS and TMDs: Phenomenological analysis of JLab 12 GeV SIDIS data has shown that there are basic open questions concerning the semi-inclusive pion/kaon production mechanism at few-GeV energies, regarding e.g. the role of vector meson decays (hadronic interactions), L/T photon cross sections, and current vs. target fragmentation dynamics. These questions are very interesting and reveal various aspects of nonperturbative dynamics in hadron production. They need to be addressed for a controlled use of the JLab SIDIS data in QCD factorization-based TMD analysis. Measurements of the basic semi-inclusive pion/kaon cross sections and multiplicity distributions will be essential for answering these questions. The analysis of the Run Group data should focus on providing these basic quantities. (Spin asymmetries or other ratio observables are often not sufficient for answering basic questions about the production mechanism, as deviations from theoretical expectations in such observables can result from various effects that cannot be disentangled.) With this focus, the SIDIS results from the Run Group could have a major impact on our understanding of the SIDIS mechanism and transform this field of research.

SIDIS cross section: separating $F_{UU,L}$

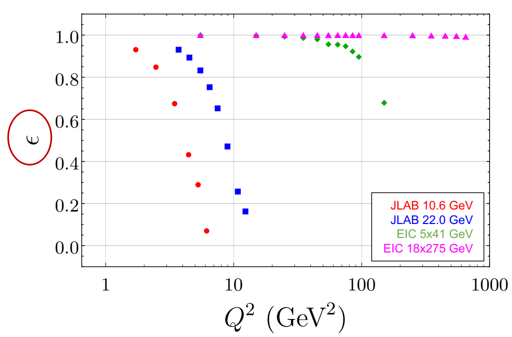
Semi-Inclusive:

ratio of longitudinal and transverse photon flux

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

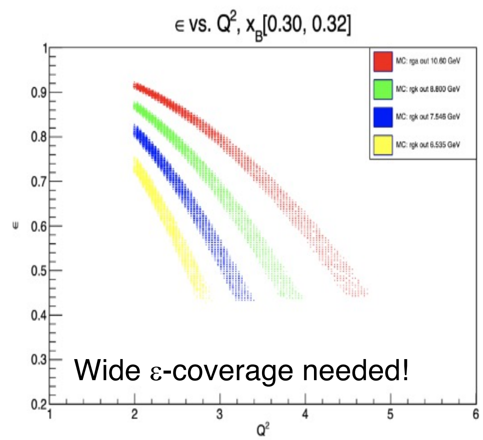
Hall-C E12-06-104
E12-23-014
Hall-B E12-16-010C

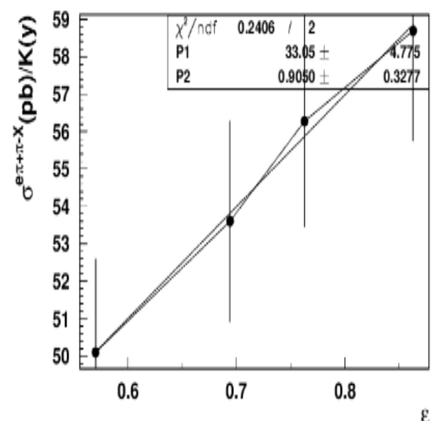
$$+ S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] + S_\parallel\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL}$$

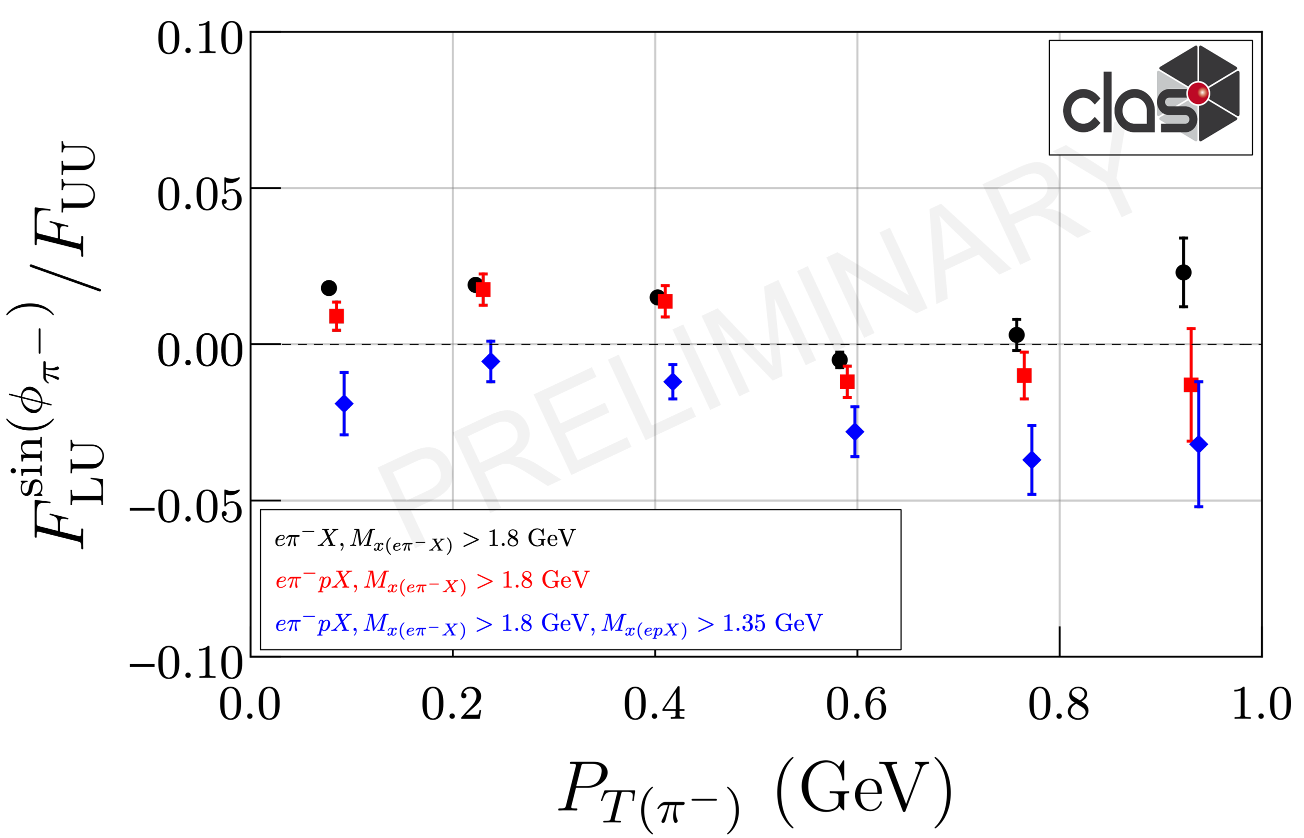


- At higher energies longitudinal photon contributions are kinematically enhanced (at EIC 5 times bigger at Q^2~10)
- JLab studies critical for EIC data interpretation

Separation of contributions from longitudinal and transverse photons critical for interpretation $R=F_{UU,L}/F_{UU,T}$ depend on the process






0.10
0.05
0.00
−0.05
−0.10
0.0
0.2
0.4
0.6
0.8
1.0
$F_{\mathrm{LU}}^{\sin(\phi_{\pi^-})}/F_{\mathrm{UU}}$
$P_{T(\pi^-)}$ (GeV)
$e\pi^- X, M_{x(e\pi^- X)} > 1.8$ GeV
$e\pi^- pX, M_{x(e\pi^- X)} > 1.8$ GeV
$e\pi^- pX, M_{x(e\pi^- X)} > 1.8$ GeV$, M_{x(epX)} > 1.35$ GeV
PRELIMINARY

Potential Ambiguities

$$\frac{\mathrm{d}\sigma^{\mathrm{TFR}}}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}\zeta\,\mathrm{d}^2\boldsymbol{P}_{h\perp}\,\mathrm{d}\phi_S} = \frac{2\alpha_{\mathrm{em}}^2}{Q^2 y}\left\{\left(1-y+\frac{y^2}{2}\right)\right.$$
$$\times\sum_a e_a^2\left[M(x_B,\zeta,\boldsymbol{P}_{h\perp}^2) - |\boldsymbol{S}_\perp|\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,M_T^h(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)\,\boxed{\sin(\phi_h-\phi_S)}\right]$$
$$\hat{u}_{1T}^{\perp}$$
$$+\lambda_l\,y\left(1-\frac{y}{2}\right)\sum_a e_a^2\left[S_\parallel\,\Delta M_L(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)\right.$$
$$\left.\left.+\ |\boldsymbol{S}_\perp|\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,\Delta M_T^h(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)\,\boxed{\cos(\phi_h-\phi_S)}\right]\right\}.$$

M. Anselmino et al., Phys. Lett. B. 699 (2011), 108-118, [hep-ph] 1102.4214

Sivers-like modulation!

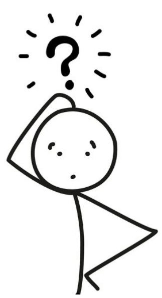
$$\left[F_{UT,T}^{\sin(\phi_h-\phi_S)}\right]_{\mathrm{TFR}} = -\sum_a e_a^2\,x_B\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,M_T^h(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$\left[F_{UT,T}^{\sin(\phi_h-\phi_S)}\right]_{\mathrm{CFR}} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp}{m_N}\,f_{1T}^\perp\,D_1\right]$$

$$\left[F_{LT}^{\cos(\phi_h-\phi_S)}\right]_{\mathrm{TFR}} = \sum_a e_a^2\,x_B\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,\Delta M_T^h(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$\left[F_{LT}^{\cos(\phi_h-\phi_S)}\right]_{\mathrm{CFR}} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\perp}{m_N}\,g_{1T}\,D_1\right]$$

The same azimuthal asymmetries can appear in both the CFR and TFR complicating their interpretation…

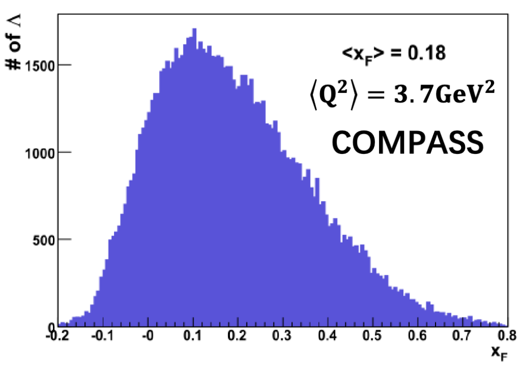


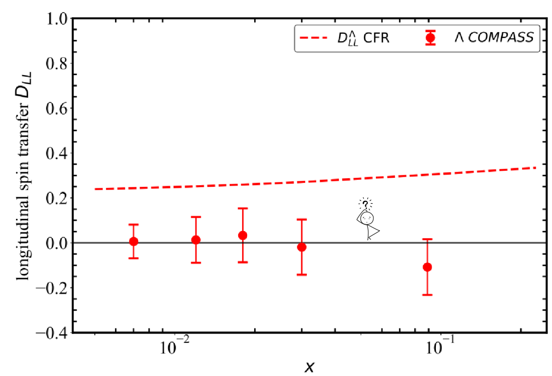
… while some asymmetries uniquely appear in a single kinematic region, strengthening their interpretation.

Potential Ambiguities; An Example

- The self analyzing Λ-baryon decay allows for the targeted extraction of information on polarization transfer from struck quark to produced hadrons.
- The spin-transfer coefficient, D_{LL}, serves as a stringent test for QCD (Quantum Chromodynamics) predictions, especially those involving polarized parton distributions and fragmentation functions.

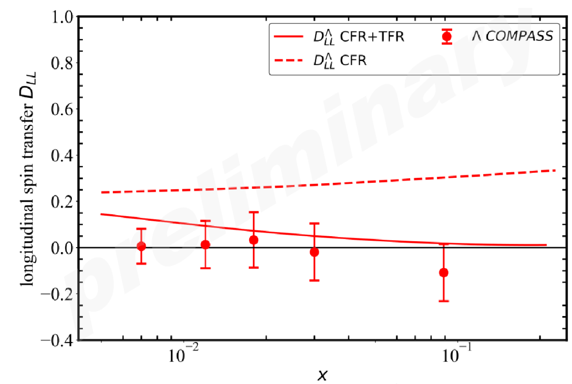
$$P_L(x,z,Q^2) = \frac{d\sigma_{\Downarrow} - d\sigma_{\Uparrow}}{d\sigma_{\Downarrow} + d\sigma_{\Uparrow}} = \frac{F_{UL}}{F_{UU}} = D(y)D_{LL'}$$





$$D_{LL'} = \frac{\sum_a e_a^2 f_a(x,Q^2) G_a(z,Q^2)}{\sum_a e_a^2 f_a(x,Q^2) D_a(z,Q^2)}\ \omega_q(z_\Lambda, P_{h\perp})$$

COMPASS data from Eur. Phys. J. C64, 171-179 (2009)
CFR+TFR analysis by X. Zhao, T. Liu, Y. Zhou, SPIN-2023



$$D^{\Lambda}_{LL}(x,z,Q^2) = \frac{\sum_q e_q^2 z^2 f_{1q}(x_B,Q^2) G^{\Lambda}_{1Lq}(z_\Lambda,Q^2)}{\sum_q e_q^2 \left[z^2 f_{1q}(x_B,Q^2) D^{\Lambda}_{1q}(z_\Lambda,Q^2) + \underbrace{\tfrac{\zeta}{z} M_q^{\Lambda}(x_B,\zeta,Q^2)}_{\text{Target fragmentation contribution!}} \right]}.$$

Categorizing Fracture Functions

- At leading twist fracture functions exist that can be organized into tables of quark and nucleon polarizations just like the more familiar PDFs.
- Access to *both* k_T and p_T effects gives 2 x 8 = 16 FrFs.

Quark polarization

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

CFR $\longleftrightarrow$ TFR

Quark polarization

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

M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

Analog to PDFs; Momentum Sum Rules

- A direct relationship exists to the eight leading twist PDFs after the fracture functions are integrated over the fractional longitudinal nucleon momentum, ζ.

$$\sum_h \int_0^{1-x} d\zeta \zeta M_a(x,\zeta) = (1-x) f_a(x)$$

M. Anselmino et al., Phys. Lett. B. 699 (2011), 108, [hep-ph] 1102.4214

Quark polarization (columns); Nucleon polarization (rows)

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

Unpolarized PDF analog

helicity PDF analog

etc. etc.

Quark polarization (columns); Nucleon polarization (rows)

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

M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

CFR ⟷ TFR

Single hadron limitations

- FrFs describing transversely polarized quarks are chiral odd and inaccessible in TFR single hadron production where there is no access to a chiral odd FF.
- Functions with double superscripts containing h and ⊥ have give the unique possibility of measuring longitudinal polarized quarks in unpolarized nucleons (and vice versa) but disappear after integration over either momentum.

CFR ⟷ TFR

CFR — Quark polarization (columns), Nucleon polarization (rows)

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

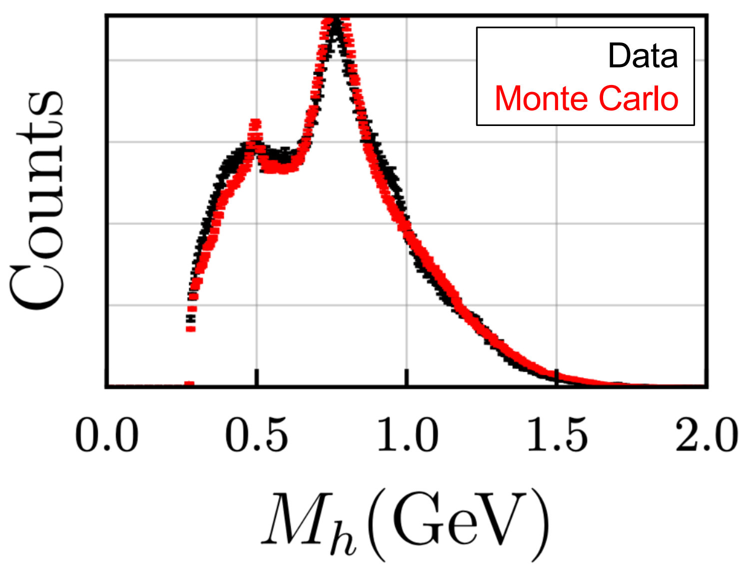
TFR — Quark polarization (columns), Nucleon polarization (rows)

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

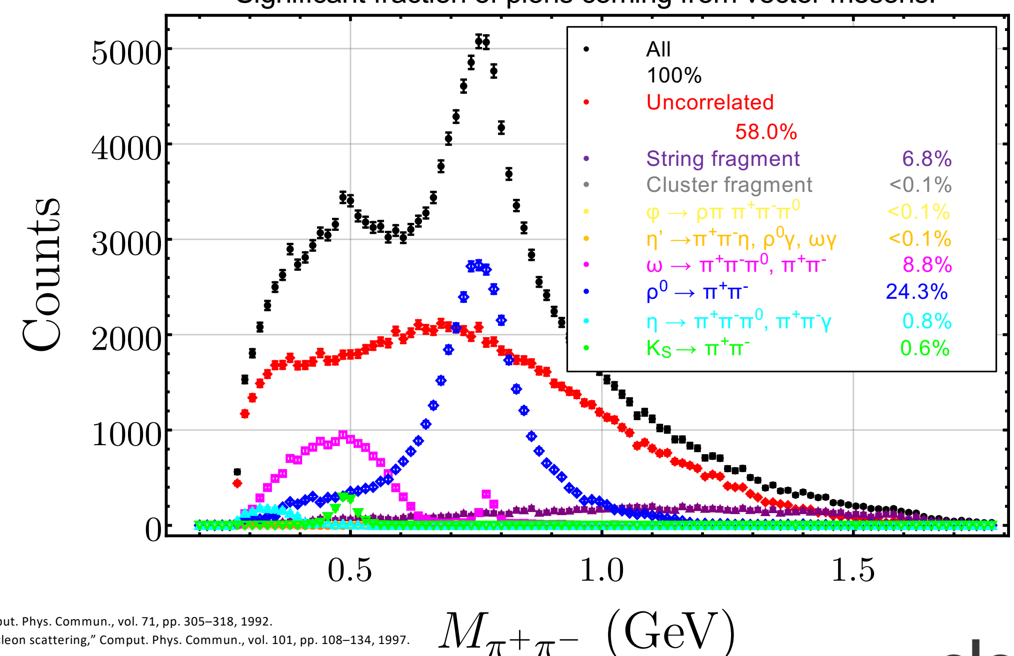
M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

Monte Carlo and Vector Mesons

- SIDIS MC "clasdis"[1] based on PEPSI[2] generator, the polarized version of the well-known LEPTO[3] generator.
- Parameters changed to reproduce observed distributions include average transverse momentum, fraction of spin-1 light mesons and fraction of spin-1 strange mesons.
- CLAS12 detector system described in "GEMC"[4], a detailed GEANT4 simulation package.



Significant fraction of pions coming from vector mesons!



1. H. Avakian, "clasdis." https://github.com/JeffersonLab/clasdis, 2020.
2. L. Mankiewicz, A. Schafer, and M. Veltri, "Pepsi: A monte carlo generator for polarized leptoproduction," Comput. Phys. Commun., vol. 71, pp. 305–318, 1992.
3. G. Ingelman, A. Edin, and J. Rathsman, "LEPTO 6.5: A Monte Carlo generator for deep inelastic 912 lepton - nucleon scattering," Comput. Phys. Commun., vol. 101, pp. 108–134, 1997.
4. M. Ungaro et al., "The CLAS12 Geant4 simulation," Nucl. Instrum. Meth. A, vol. 959, p. 163422, 2020.

π^+ double spin asymmetry

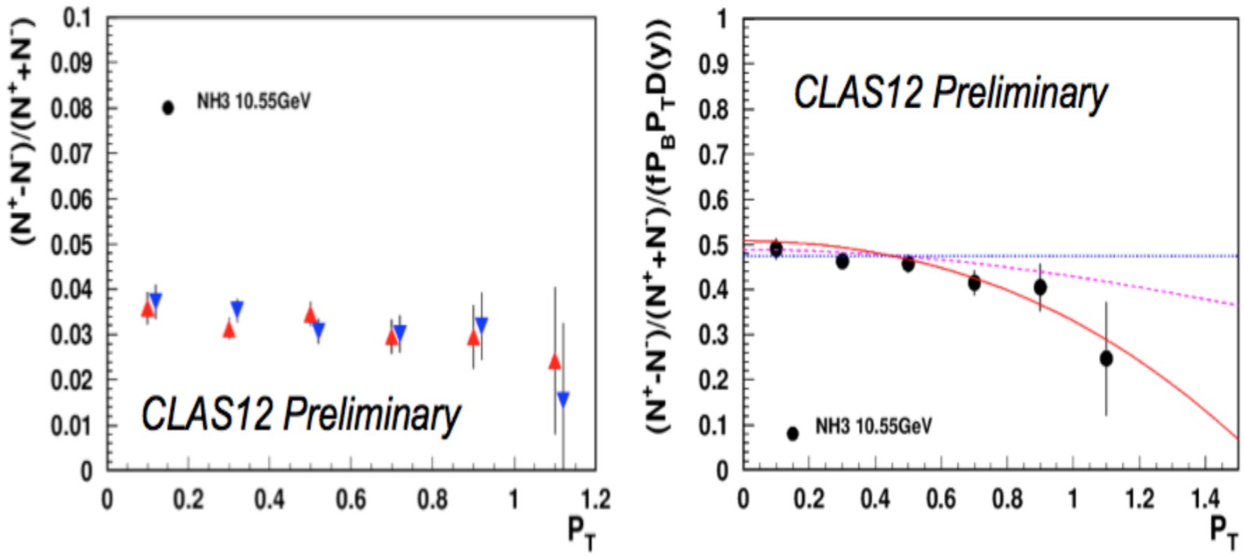


Figure 11: The P_T-dependence of the raw asymmetry in a bin in (left) and the double spin asymmetry corrected for polarization, dilution,and depolarization factors (right). Dotted line is for the equal widths of $f_1(x, k_T)$, dashed magenta line for 10% difference in Gaussian widths, and the red curve corresponds to widths predicted by lattice [Mus05] (see APPENDIX:A)

COMPASS LiD BSAs

COMPASS: Nucl. Phys. B, 886, 1046—1077. 2014. [hep-ex] 1401.6284

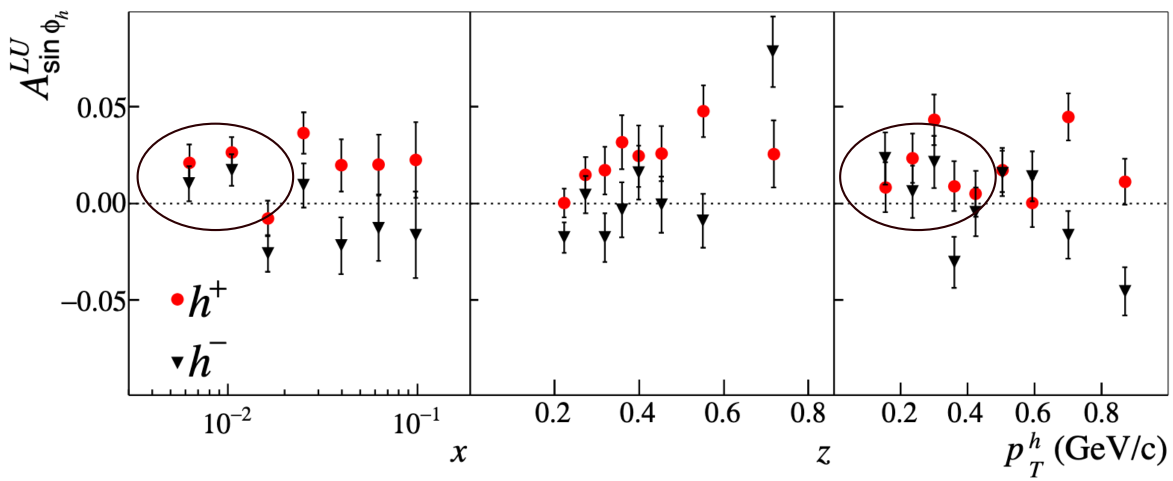


Fig. 9: $A^{LU}_{\sin\phi_h}$ integrated asymmetries for positive (red points) and negative (black triangles) hadrons as functions of x, z and p_T^h. The error bars show statistical uncertainties only.

Low x (low Q^2), high z, or low P_T show evidence of possible ρ^0 contributions

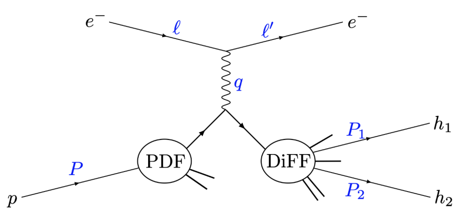
Collinear Dihdaron Production

twist-3 pdf — unpolarized pdf

$$F_{LU}^{\sin\phi_{R_\perp}} = -x\frac{\vec{R}\sin\theta}{Q}\left[\frac{M}{M_h}x\boxed{e^q(x)}\boxed{H_1^{\sphericalangle q}(z,\cos\theta,M_h)}+\frac{1}{z}\boxed{f_1^q(x)}\boxed{\tilde{G}(z,\cos\theta,M_h)}\right]$$

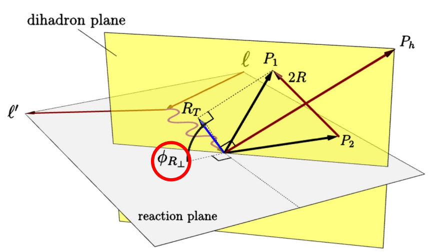
"Interference Fragmentation Function" — twist-3 FF

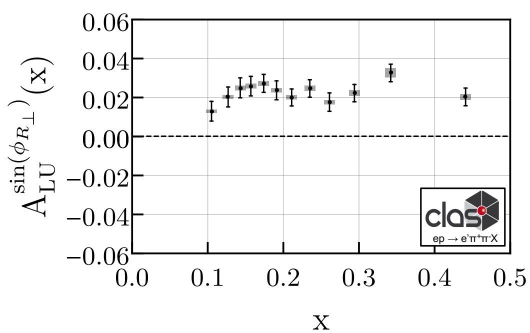
A. Bacchetta and M. Radici, *Phys Rev. D.*, 67, 094002, (2003). hep:ex/021300



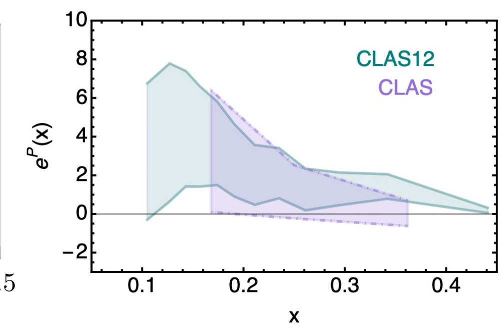
First measurement of dihadron A_{LU}, first extraction of e(x)

- IFF measured at Belle combined with F_{LU} from CLAS12
- Twist-3 PDF (quark gluon correlations)
- Related to quark contributions to nucleon mass
- ⊥ force on ⊥ polarized quarks in a unpolarized nucleon (similar to Boer-Mulders)





T. B. Hayward et al., *Phys. Rev. Lett.*, 126, 152501, (2021), [hep:ex] 2101.04842



A. Courtoy et al., *Phys. Rev. D.*, 106, 014027, (2022), [hep:ph] 2203.14975