Massachusetts Institute of Technology

SCIENCE AT THE LUMINOSITY FRONTIER:
JEFFERSON LAB AT 22 GEV

LABORATORI NAZIONALI DI FRASCATI – INFN (ITALY)
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Back-to-back SIDIS

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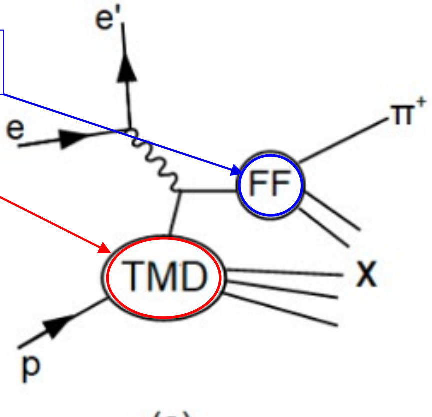
December 10th, 2024

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 (TMD) parton distribution functions (PDFs).
- Accessible in SIDIS measurements of cross sections and asymmetries; rely on the assumption that measured hadrons are produced in the current fragmentation region (CFR).
- Cross section factorized[1] as a convolution of PDFs and Fragmentation Functions (FFs) that can be modulated by the azimuthal scattering angle.

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

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



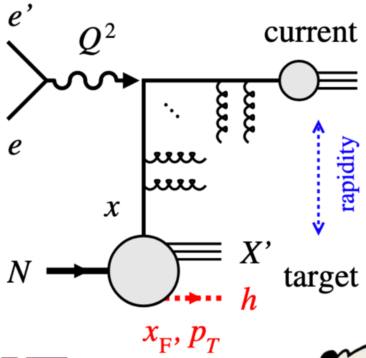
(a)

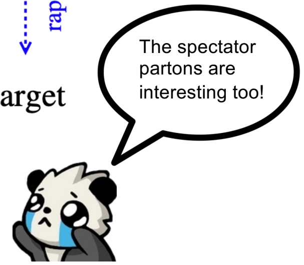
- (TMD)PDFs
  - Probability (leading twist) of finding a particular parton in a certain configuration
  - Confined motion of quarks and gluons inside the nucleus
  - Orbital motion of quarks, correlations between quarks and gluons
- Fragmentation Functions
  - Nonperturbative dynamics of hadronization
  - Probability for a parton to form particular final state hadron
  - Insight into transverse momenta and polarization

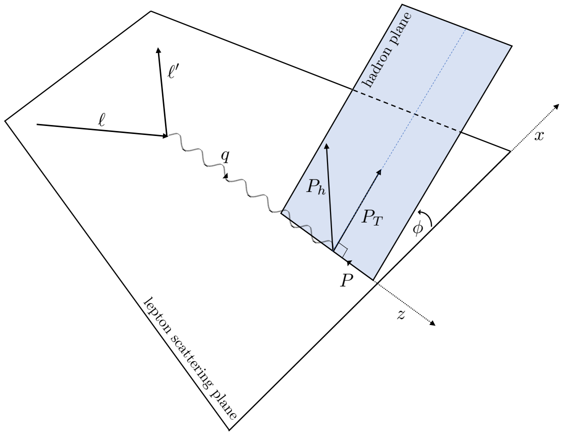
The ~~Neglected~~ Other Hemisphere – Target Fragmentation

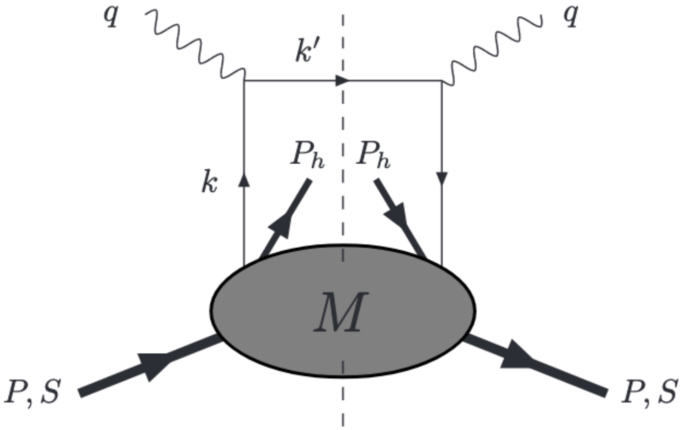
- Final state hadrons also form from the left-over target remnant (TFR) whose partonic structure is defined by “fracture functions”[1,2]: the probability for the target remnant to form a certain hadron given a particular ejected quark.
- In the TFR, factorization into x_B and z-dependent contributions 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

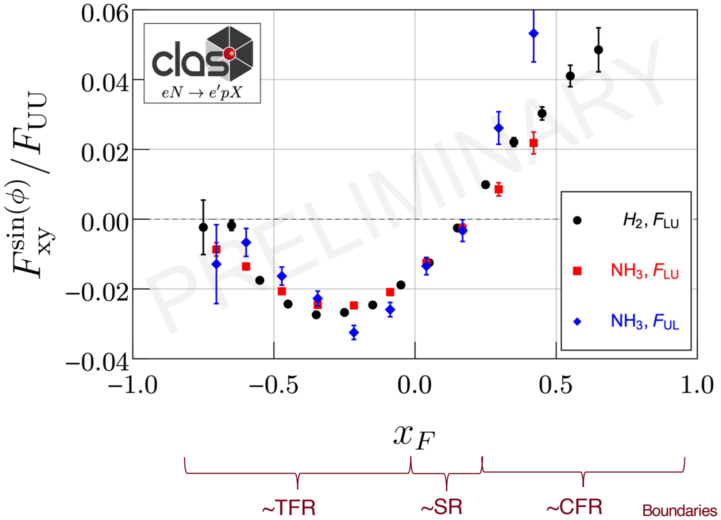
Separating the Target and Current Regimes

Feynman variable

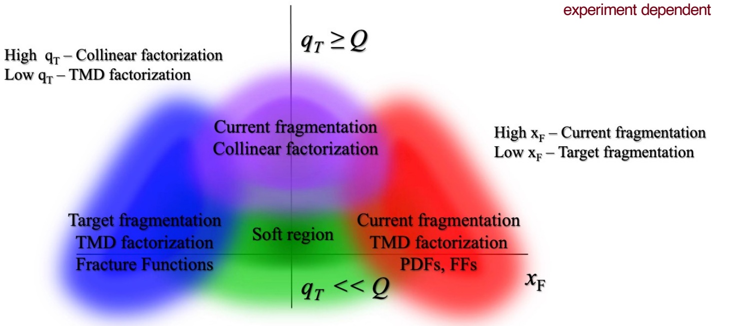
$$x_F = \frac{p_h^z}{p_h^z(\text{max})} \quad \text{in CM frame } \mathbf{p} = -\mathbf{q}, \qquad -1 < x_F < 1$$

Rapidity

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



Boundaries channel and experiment dependent



$q_T \geq Q$

High q_T – Collinear factorization
Low q_T – TMD factorization

Current fragmentation
Collinear factorization

High x_F – Current fragmentation
Low x_F – Target fragmentation

Target fragmentation
TMD factorization
Fracture Functions

Soft region

Current fragmentation
TMD factorization
PDFs, FFs

$q_T << Q$

x_F

- 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

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.
- 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

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

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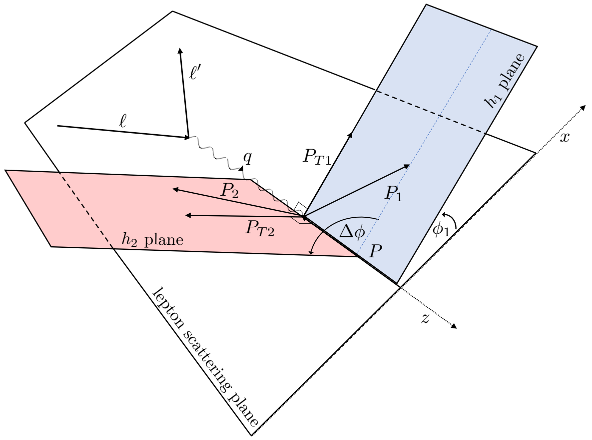
Back-to-back (dSIDIS) Formalism

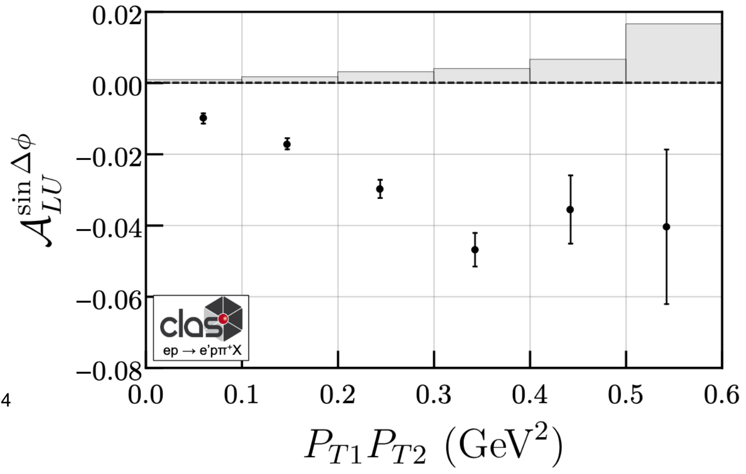
- When two hadrons are produced “back-to-back”[1,2] with one in the CFR and one in the TFR the structure function contains a convolution of a fracture function and a fragmentation function.
- Leading twist access to all quark-nucleon polarization combinations.

$$\sigma_{LU} = -\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\hat{l}_1^{\perp h}\cdot D_1} \sin(\phi_1 - \phi_2)$$



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

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



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

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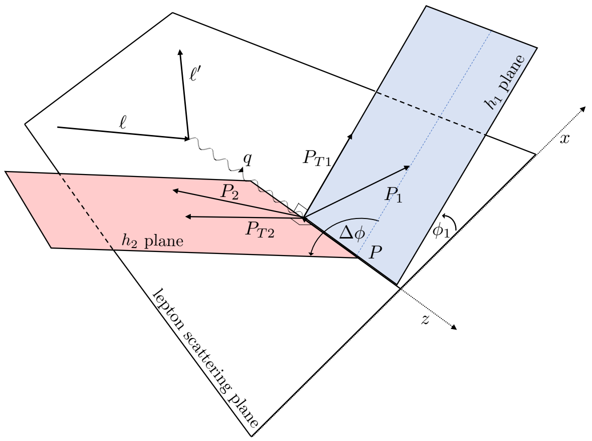
$$\sigma_{UL} = -\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\hat{u}_1^{\perp h}\cdot D_1} \sin(\phi_1 - \phi_2) + \ldots$$



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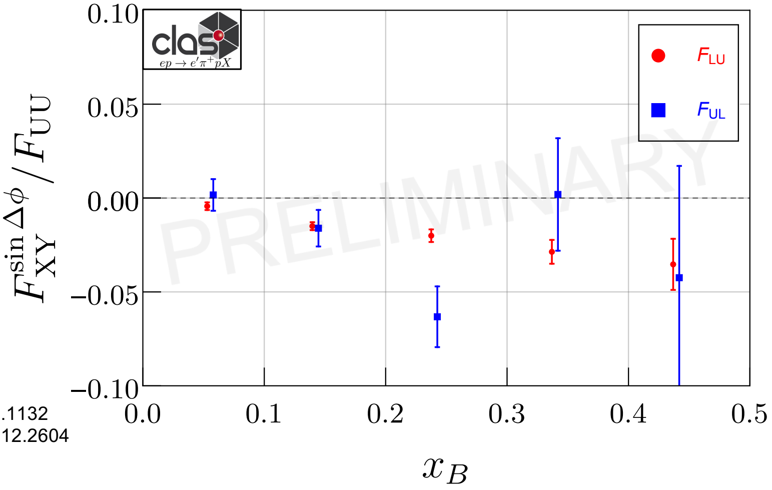

F_{UL}/F_{UU} has no “depolarization” factor, similar to Sivers!

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

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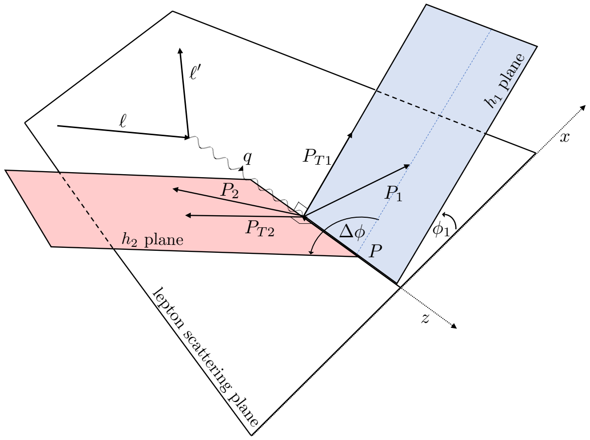
$$\sigma_{LL} = -F_0^{\hat{l}_1 \cdot D_1}$$



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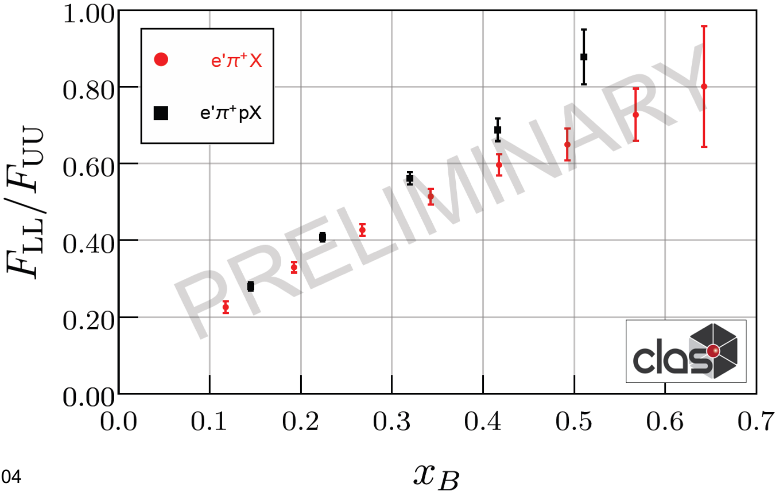

higher A_{LL} in b2b SIDIS, possibly due to exclusion of non-factorizable ρ^0 production.

Quark polarization

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

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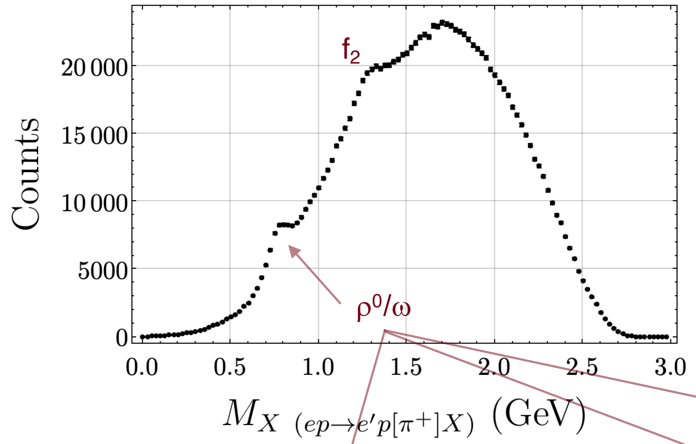
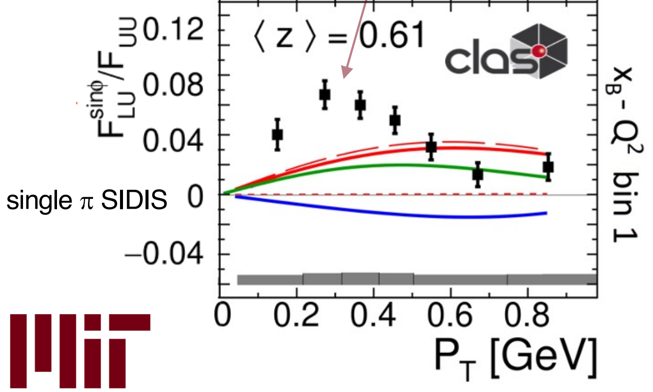
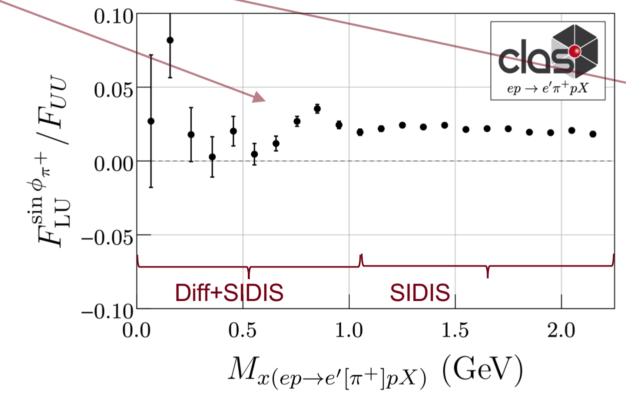
Semi-exclusive measurements

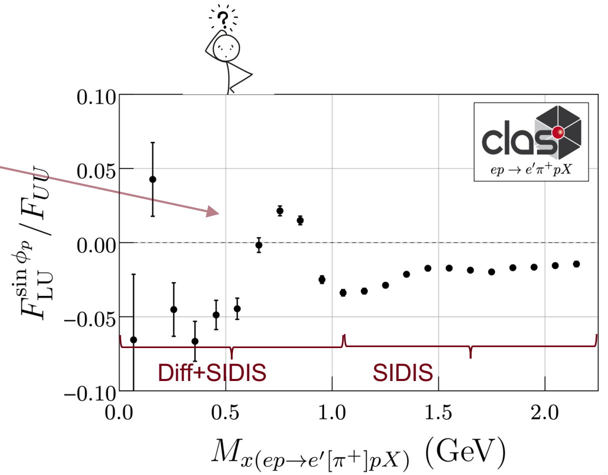


- The dSIDIS/semi-exclusive measurements with target fragment detected not only allow access to new physics observables but also enables the *explicit* removal of vector meson contributions to the single hadron channels
  - (possible alternative method; *implicit* subtraction via MC c.f. COMPASS: NPB 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.

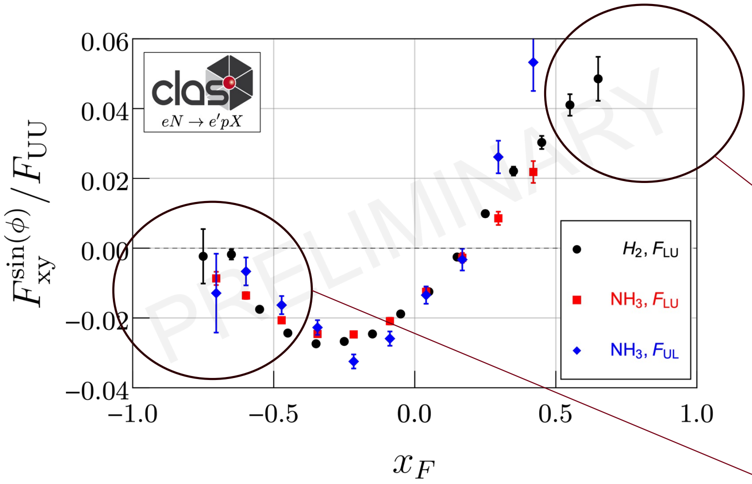
S. Diehl et al., *Phys. Rev. Lett.*, 128, 062005, (2022), [hep:ex] 2101.03544

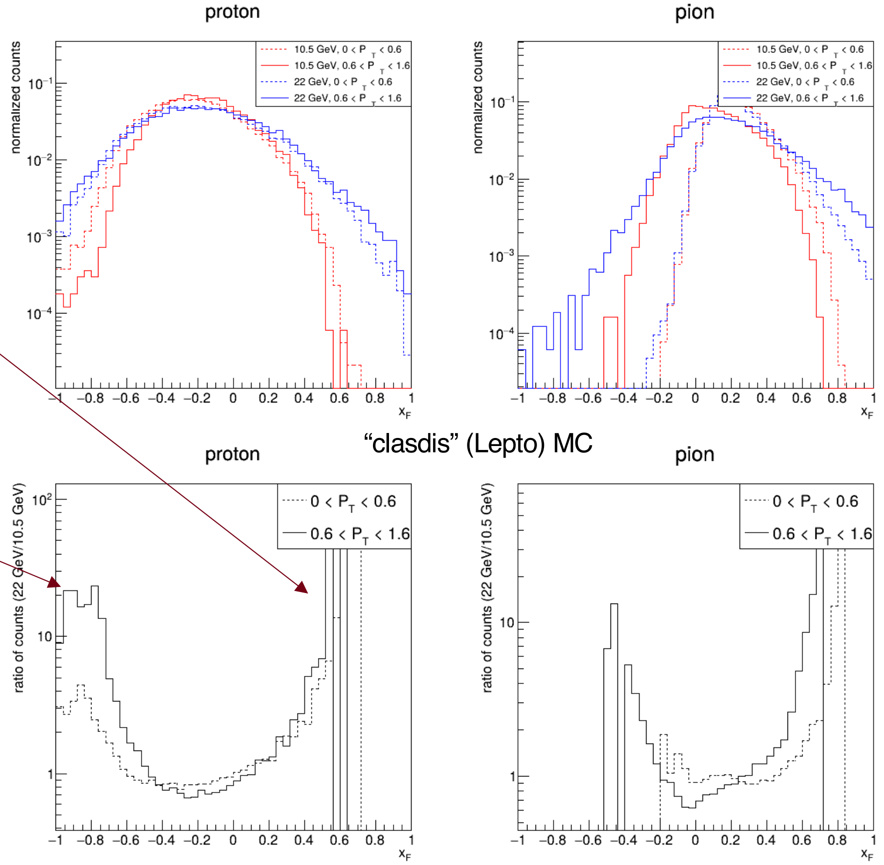






Increased phase space at 22 GeV





“clasdis” (Lepto) MC

At 22 GeV there is over an order of magnitude more data at the highest and lowest x_F, particularly at higher P_T:

1. Allow for the exploration of the full range of x_F from -1 to 1.
2. Significantly more statistics for protons at the smallest –t values.
3. Extension of pions to significantly negative x_F.
4. Increased sensitivity to gluon-TMDs[1,2] (low –t, large negative x_F values).

1. K.B. Chen et al., JHEP 05 (2024) 298 (2024), [hep-ph] 2402.15112
2. X. Tong, CPHI2024

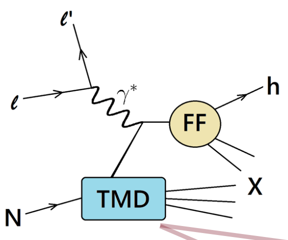
Summary

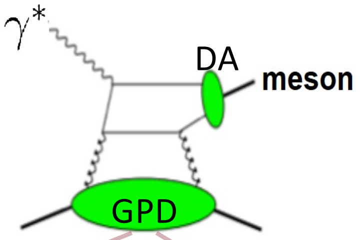
- The detection of target fragment baryons opens new avenues for studying the partonic structure of nucleons by introducing new observables, strengthening the understanding of a providing complimentary ways to measure previous observables and by aiding in the separation of VM contributions.
- Contributions from non-SIDIS vector mesons challenge the factorized picture of SIDIS. Moving towards a “p-free SIDIS” might help address these challenges in phenomenology and will be crucial for the interpretation of higher energy data, from JLab22 to EIC.
- A JLab22 would benefit from significantly higher statistics at the lowest and highest x_F values allowing for a complete picture over the full range in x_F for TFR SIDIS studies or VM studies at very low -t (in addition to benefiting SIDIS in the more common ways: increased P_T, extension of Q^2 studies, etc.)

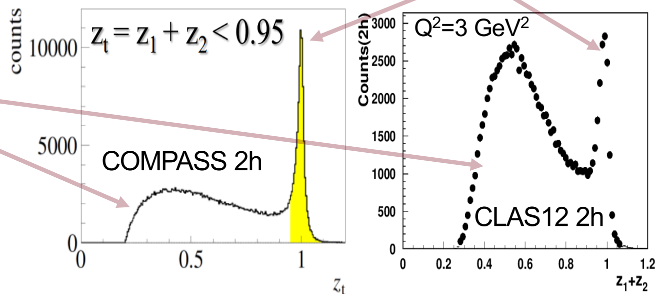
Backup

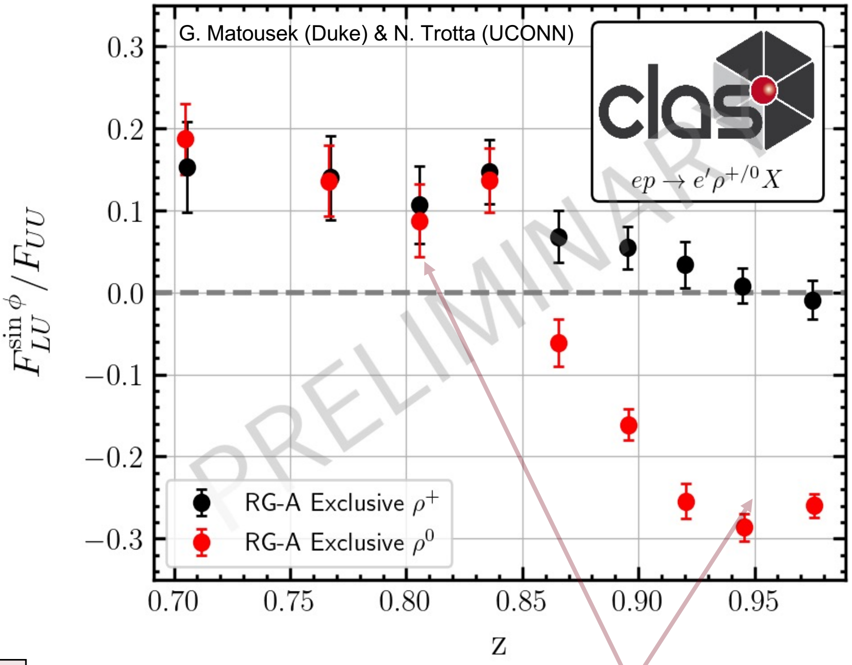
Quark-gluon correlations; Impact of VMs

- A TMD based description is valid *only* for pions from current fragmentation **BUT** the $e\pi X$ sample also contains pions from exclusive processes.





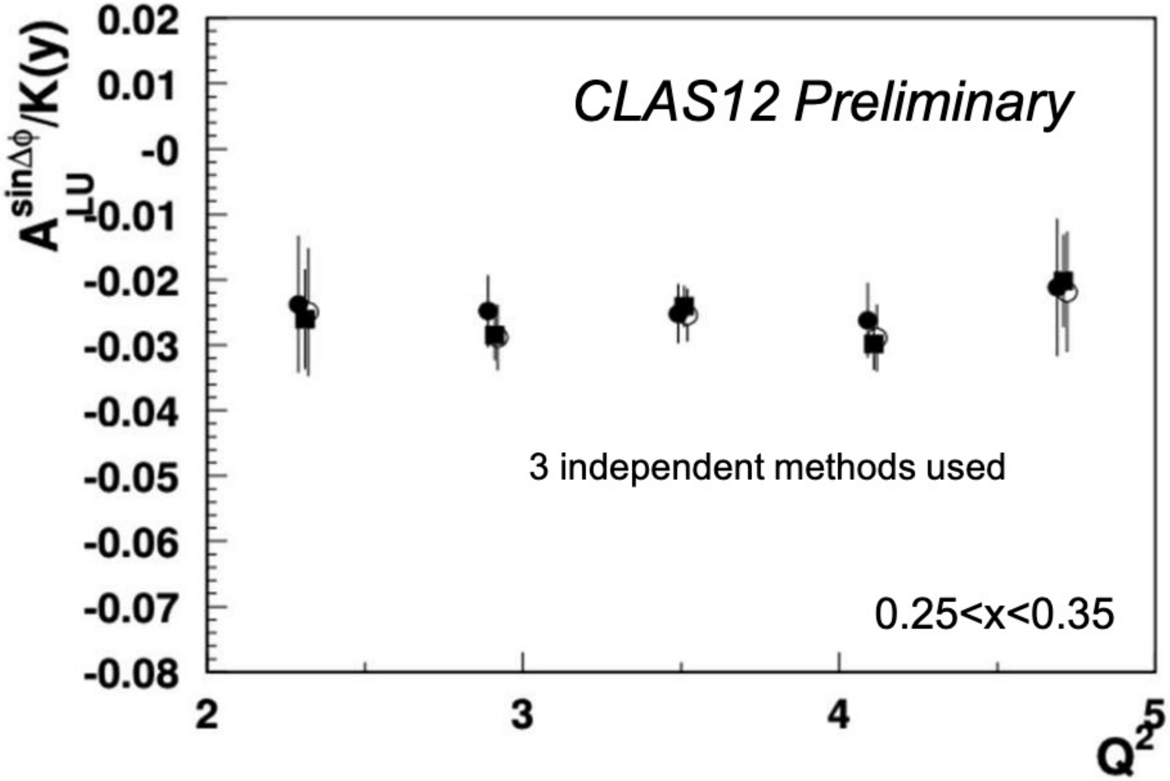




- Understanding of the SSAs of VMs is critical for interpretation of pion SIDIS.
- The fraction of diffractive mesons increases with energy.
- At large x the diffractive processes are suppressed by the minimum t.
- Fully evaluating the effect diffractive mesons have on the extraction of TMDs will be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

Q^2 dependence of dSIDIS proton-π^+



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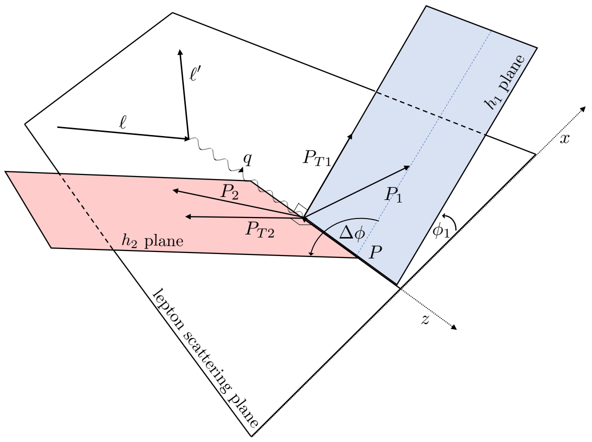

$$
\begin{aligned}
\sigma_{UT} = & -\frac{P_{T1}}{m_N} F_{k1}^{\hat{u}_{1T}^{\perp}\cdot D_1}\sin(\phi_1-\phi_S) - \left(\frac{P_{T2}}{m_2} F_0^{\hat{u}_{1T}^{h}\cdot D_1} + \frac{P_{T2}}{m_N} F_{k2}^{\hat{u}_{1T}^{\perp}\cdot D_1}\right)\sin(\phi_2-\phi_S) \\
& + D_{nn}(y)\Bigg[\left(\frac{P_{T1}}{m_1} F_{p1}^{\hat{t}_{1T}\cdot H_1} + \frac{P_{T1}P_{T2}^2}{2m_1m_2^2} F_{p1}^{\hat{t}_{1T}^{hh}\cdot H_1} - \frac{P_{T1}P_{T2}^2}{2m_1m_2m_N} F_{kp3}^{\hat{t}_{1T}^{\perp h}\cdot H_1} \right. \\
& \qquad \left. + \frac{P_{T1}^3}{2m_1m_N^2} F_{kkp1}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1} + \frac{P_{T1}P_{T2}^2}{2m_1m_N^2} F_{kkp4}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1} + \frac{P_{T1}}{m_1m_N^2} F_{kkp5}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1} \right)\sin(\phi_1+\phi_S) \\
& \qquad + \left(\frac{P_{T2}}{m_1} F_{p2}^{\hat{t}_{1T}\cdot H_1} + \frac{P_{T2}^3}{2m_1m_2^2} F_{p2}^{\hat{t}_{1T}^{hh}\cdot H_1} + \frac{P_{T1}^2P_{T2}}{2m_1m_2m_N} F_{kp1}^{\hat{t}_{1T}^{\perp h}\cdot H_1} + \frac{P_{T2}}{m_1m_2m_N} F_{kp4}^{\hat{t}_{1T}^{\perp h}\cdot H_1} \right. \\
& \qquad \left. + \frac{P_{T1}^2P_{T2}}{2m_1m_N^2} F_{kkp2}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1} + \frac{P_{T2}^3}{2m_1m_N^2} F_{kkp3}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1} + \frac{P_{T2}}{m_1m_N^2} F_{kkp6}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1} \right)\sin(\phi_2+\phi_S) \\
& \qquad + \frac{P_{T1}^3}{2m_1m_N^2} F_{kkp1}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1}\sin(3\phi_1-\phi_S) \\
& \qquad + \left(\frac{P_{T2}^3}{2m_1m_2^2} F_{p2}^{\hat{t}_{1T}^{hh}\cdot H_1} + \frac{P_{T2}^3}{2m_1m_N^2} F_{kkp3}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1} \right)\sin(3\phi_2-\phi_S) \\
& \qquad + \left(\frac{P_{T1}P_{T2}^2}{2m_1m_2^2} F_{p1}^{\hat{t}_{1T}^{hh}\cdot H_1} + \frac{P_{T1}P_{T2}^2}{2m_1m_N^2} F_{kkp4}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1} \right)\sin(\phi_1+2\phi_2-\phi_S) \\
& \qquad - \frac{P_{T1}^2P_{T2}}{2m_1m_2m_N} F_{kp1}^{\hat{t}_{1T}^{\perp h}\cdot H_1}\sin(2\phi_1-\phi_2+\phi_S) \\
& \qquad - \frac{P_{T1}P_{T2}^2}{2m_1m_2m_N} F_{kp3}^{\hat{t}_{1T}^{\perp h}\cdot H_1}\sin(\phi_1-2\phi_2-\phi_S) \\
& \qquad + \frac{P_{T1}^2P_{T2}}{2m_1m_N^2} F_{kkp2}^{\hat{t}_{1T}^{\perp\perp}\cdot H_1}\sin(2\phi_1+\phi_2-\phi_S) \Bigg]
\end{aligned}
$$

Aram Kotzinian
APCTP, Pohang, Korea. Jul 18 – 23, 2022

similar access to transversity

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

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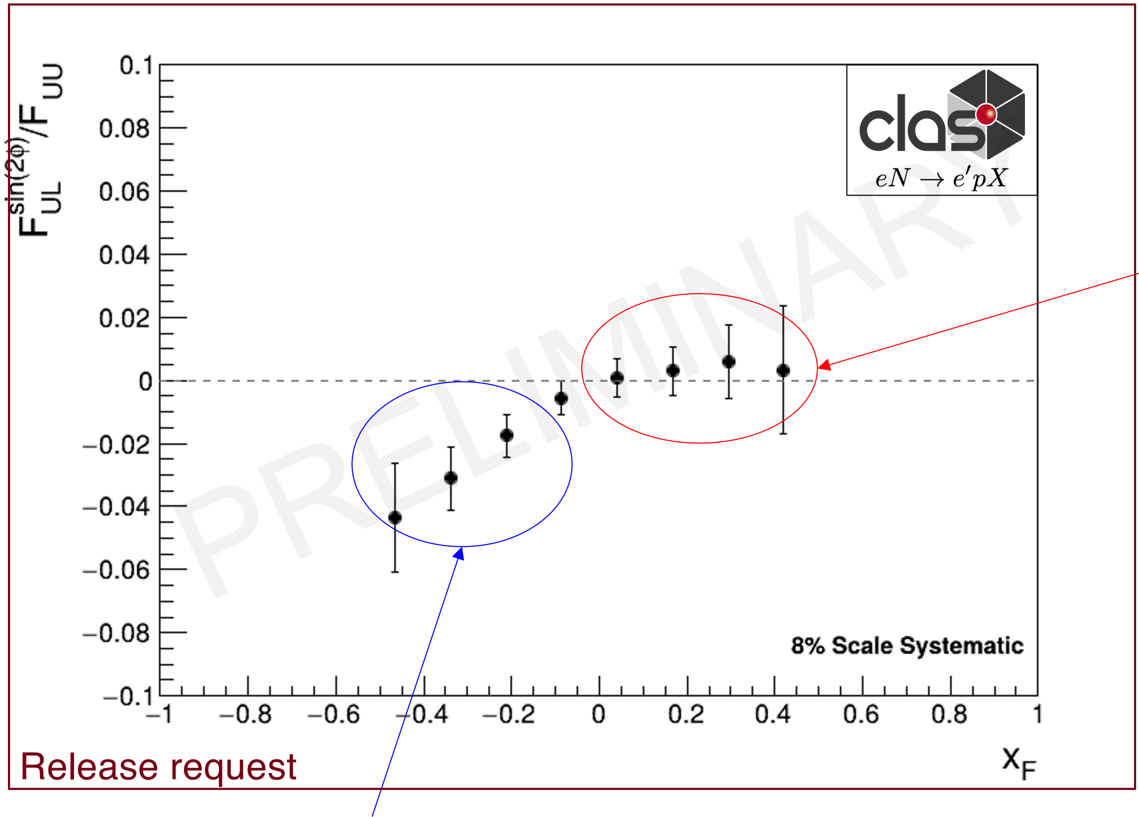
2. M. Anselmino et al., Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604

Kotzinian-Mulders



Release request

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1L}^{\perp} H_1^{\perp}\right]$$

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

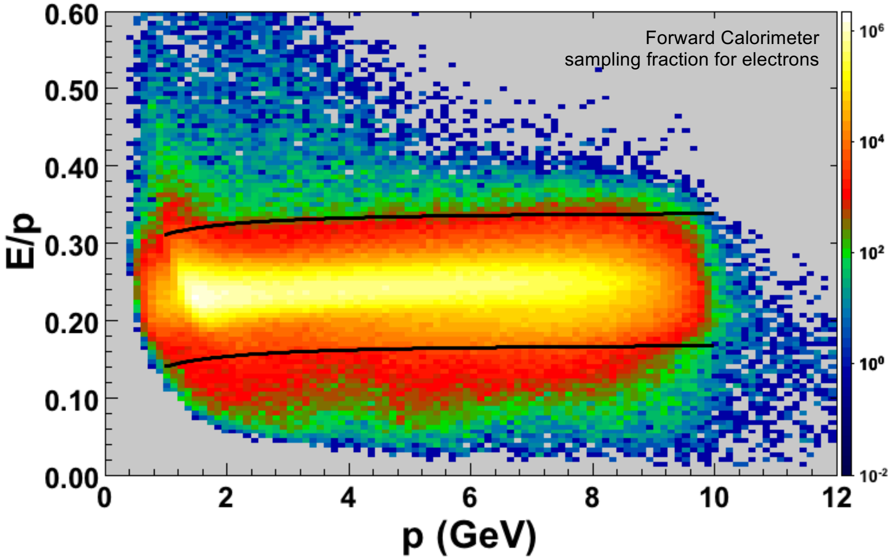
- The $F_{UL}^{\sin 2\varphi}$ asymmetry is theoretically purely generated by the Collins mechanism – whereby a transversely polarized quark flips orientation during hadronization and produces an asymmetric distribution in the transverse plane.
- Hadronization in the TFR is more isotropic – there is no additional chiral-odd quantity like the Collins function to pair with the Kotzinian-Mulders TMD because factorization into separate soft and hard scale processes does not hold.

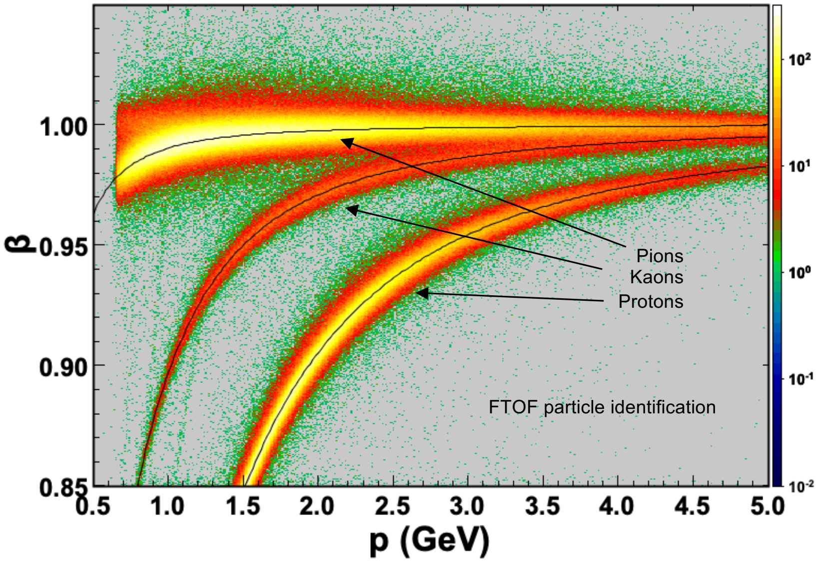
- No Collins mechanism in the TFR so $F_{UL}^{\sin 2\varphi}$ (and $F_{UU}^{\cos 2\varphi}$) are >= twist-4. We would expect small magnitude at $-x_F$…. and yet.

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)





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.

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unpolarized quarks in a longitudinally polarized proton

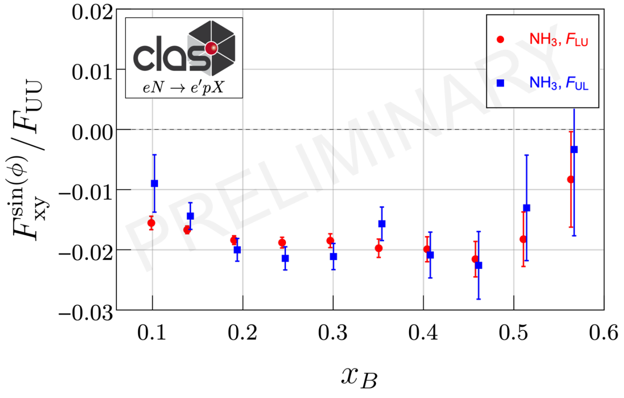
$$F_{LU}^{\sin\phi_h} = \frac{2|\vec{P}_{h\perp}|}{Q} x_B^2 l^h$$

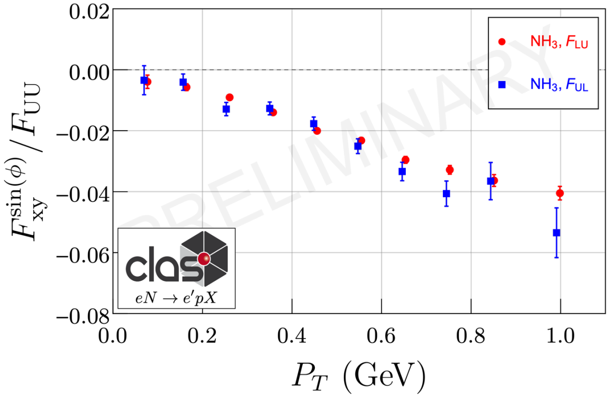
longitudinally polarized quarks in an unpolarized proton

Quark polarization

Nucleon polarization	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





For more theory details on higher-twist FrFs see talk Tuesday by X. B. Tong

Situation in CFR more complicated

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

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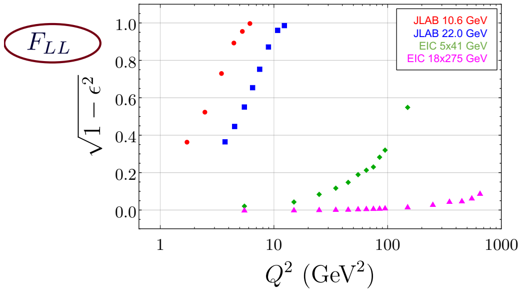
A. Bacchetta et al., *JHEP 0702,* 093 (2007).

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.

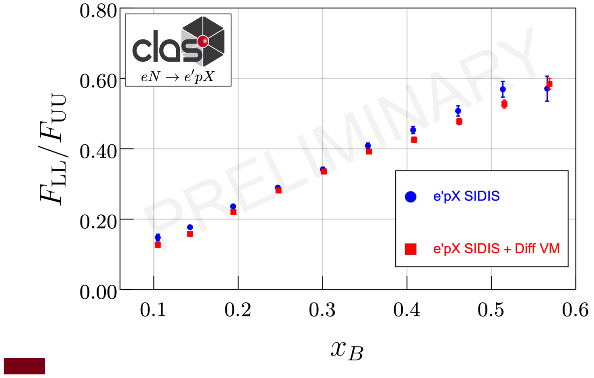
$$F_{LL} \propto g_1(x,k_T) \otimes D_1(z,p_T)$$



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
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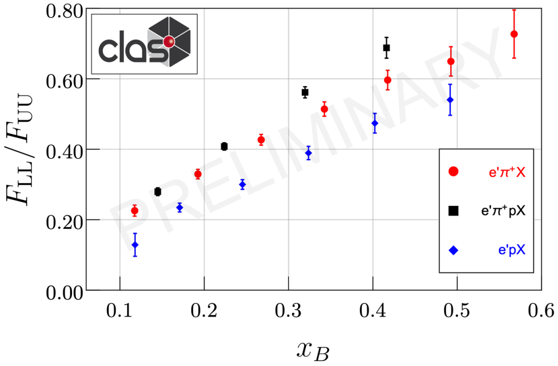
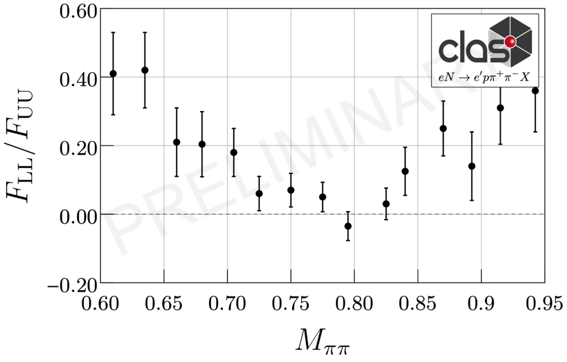


3. Exclusivity cuts, $z_{\pi\pi} > 0.9$



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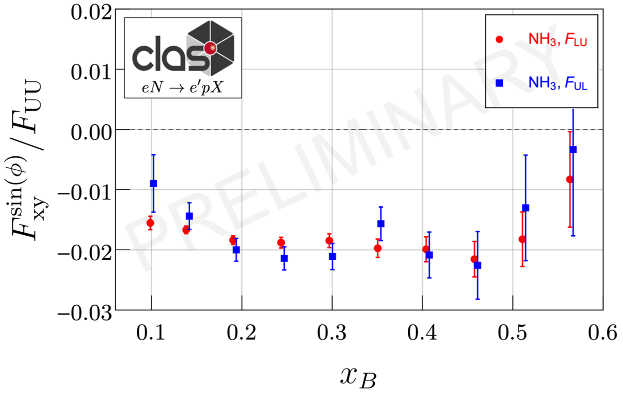

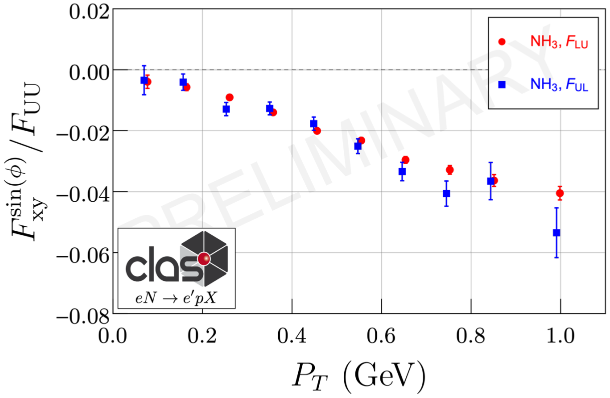

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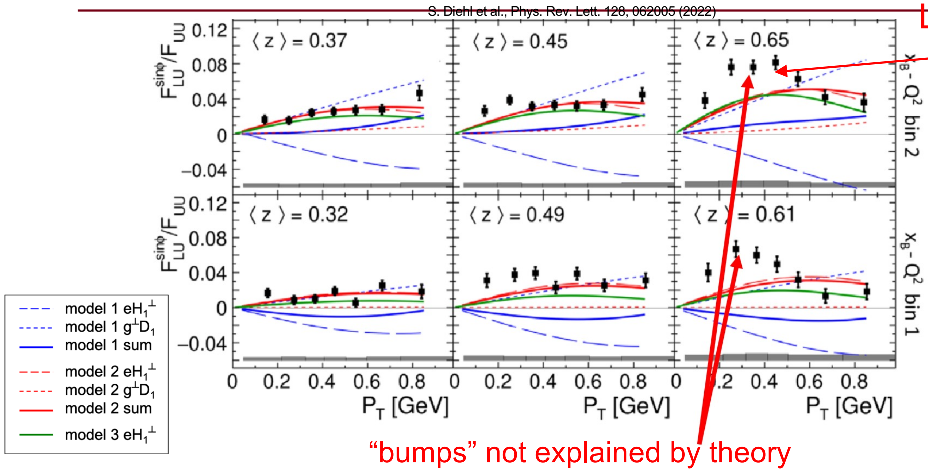
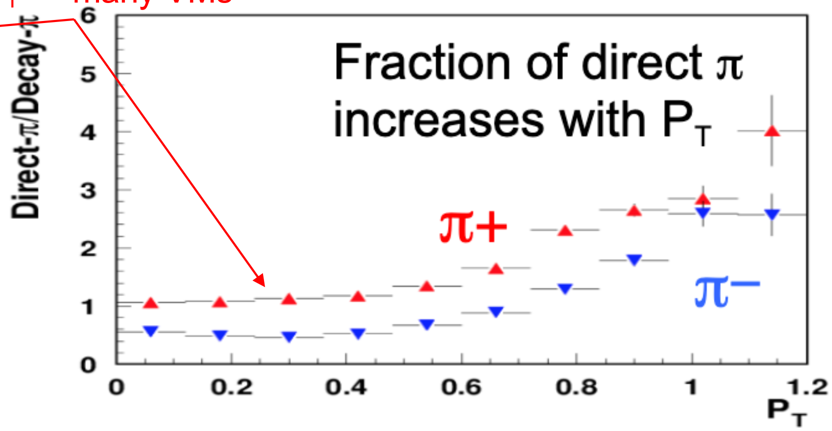
A. Bacchetta et al., *JHEP 0702,* 093 (2007).

Contributions of Vector Mesons

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

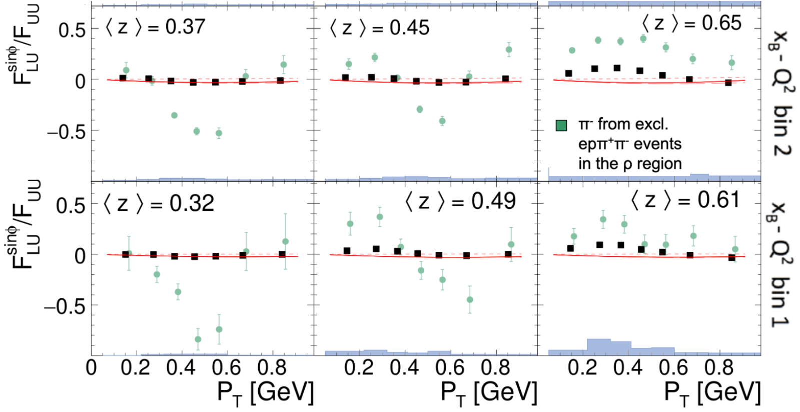
Low P_T → many VMs





Fraction of direct π increases with P_T

“bumps” not explained by theory



- Contributions from diffractive vector meson production represent an indistinguishable background when only a single CFR hadron is detected.
- Diffractive ρ^0 contamination is a large obstacle to phenomenological interpretation of analyses intending to measure TMDs.
- Detecting the target fragment enables the analyzer to avoid VMs with sufficient cuts on M_x.

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!

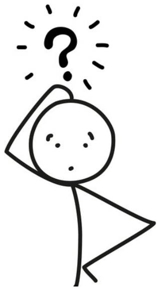
$$\left[F_{UT,T}^{\sin(\phi_h-\phi_S)}\right]_{\mathrm{TFR}} = -\sum_a e_a^2\, x_B\,\frac{|\boldsymbol{P}_{h\perp}|}{m_h}\,M_T^h(x_B,\zeta,\boldsymbol{P}_{h\perp}^2)$$

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

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

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

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

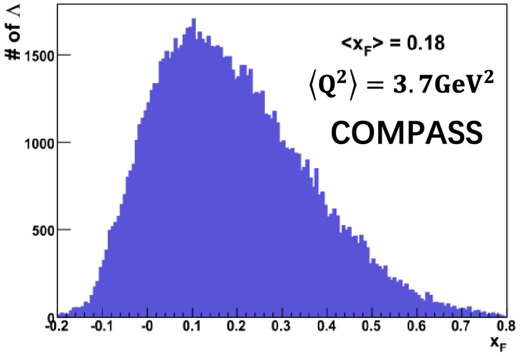


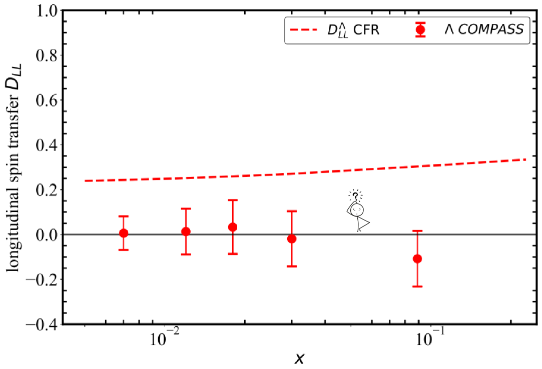
… while some asymmetries uniquely appear in a single kinematic region, strengthening their interpretation.

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.

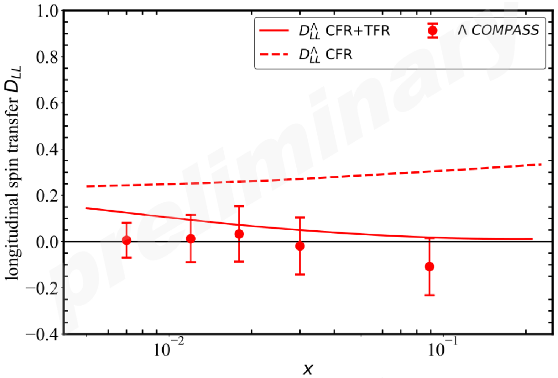
$$P_L(x, z, Q^2) = \frac{d\sigma_{\Downarrow} - d\sigma_{\Uparrow}}{d\sigma_{\Downarrow} + d\sigma_{\Uparrow}} = \frac{F_{UL}}{F_{UU}} = D(y) D_{LL'}$$





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

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



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

Target fragmentation contribution!

Effects of the Kinematic Factor JLab vs EIC

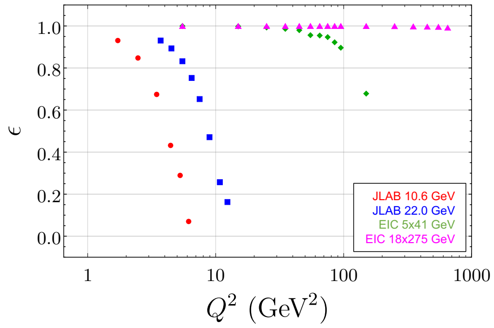
$F_{UU,L}$

$F_{UU}^{\cos 2\phi}$

$F_{UT}^{(3\phi-\phi_S)}$

$F_{UT,L}^{\sin(\phi-\phi_S)}$

etc

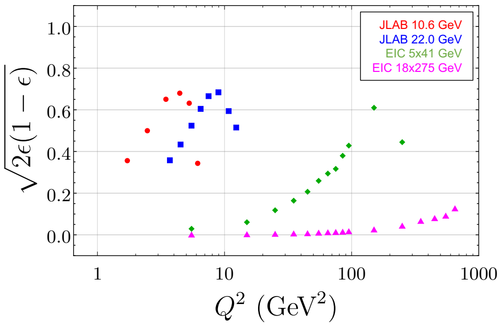


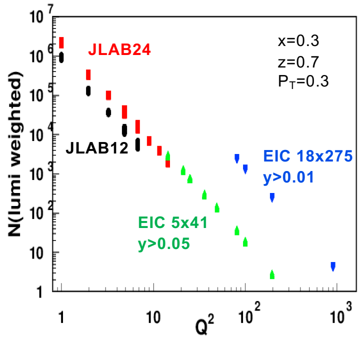
$F_{LU}^{\sin\phi}$

$F_{LU}^{\sin\phi_{R_\perp}}$

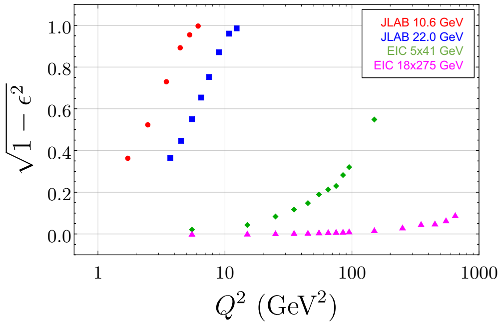
$F_{LL}^{\cos\phi}$

etc





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

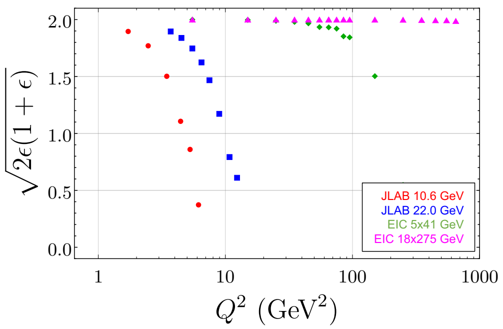


F_{LL}

$F_{LU}^{\sin\Delta\phi}$

$F_{LU}^{\sin(\phi_h-\phi_{R_\perp})}$

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.