Accessing TMD fracture functions in back-to-back hadron production at CLAS12

Timothy B. Hayward, Harut Avakian

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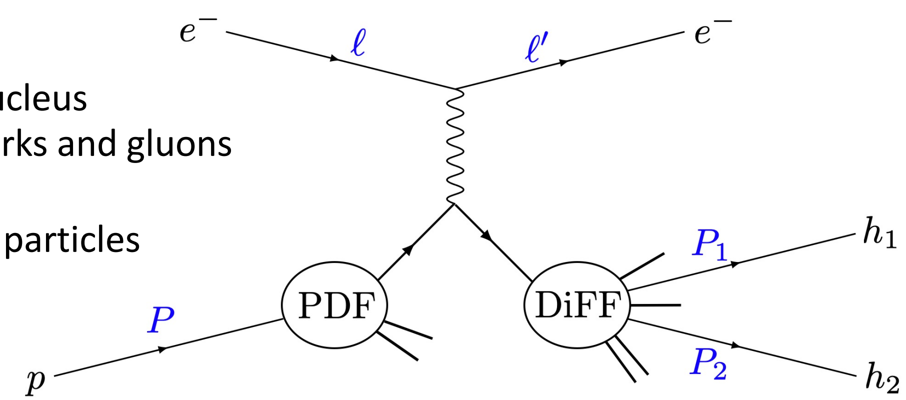
UCONN

Accessing 3D nucleonic structure

- Decades of study have led to detailed mappings of the momentum distribution of the nucleon in terms of 1-D parton distribution functions (PDFs).
- Theoretical advances have led to a framework in which information on the confined motion of the partons inside a nucleon are matched to 3-D transverse momentum dependent parton distribution functions (TMDs).

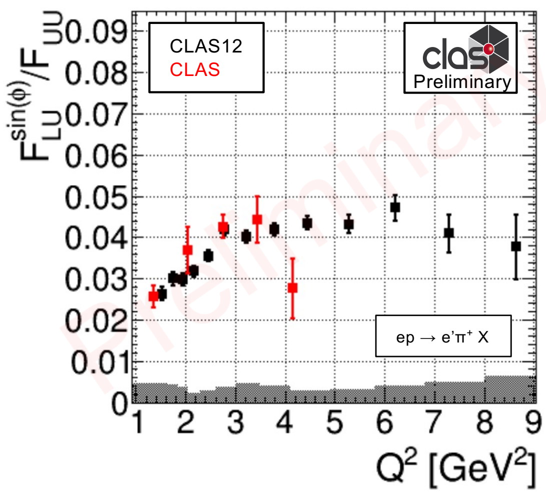
- TMDs/PDFs
  - Confined motion of quarks and gluons inside the nucleus
  - Orbital motion of quarks, correlations between quarks and gluons
- Fragmentation Functions
  - Probability for a quark to form particular final state particles
  - Insight into transverse momenta and polarization



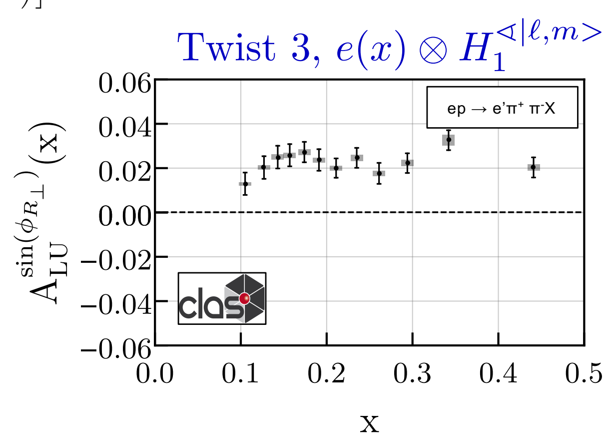
TMD-sensitive CLAS12 Measurements

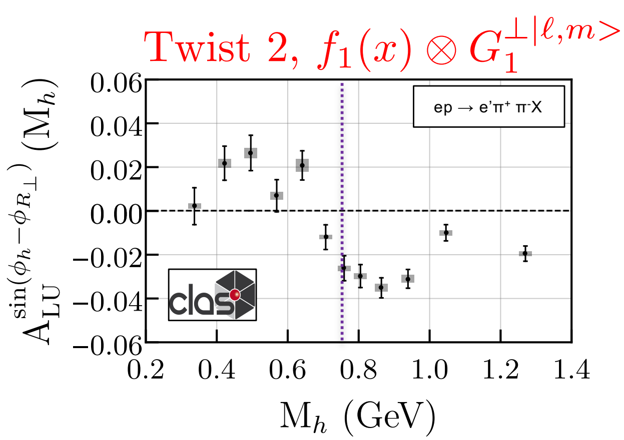
- CLAS12, with its high luminosity, wide acceptance and low Q^2 (for higher twist measurements) is an ideal place to study numerous physics observables which access these 3-D dependent quantities… Measurements traditionally focus on factorization theorems and assumption that hadrons are produced in current fragmentation.

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xeH_1^{\perp}+\frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right)+\frac{\hat{h}\cdot p_T}{M}\left(xg^{\perp}D_1+\frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$



S. Diehl, A. Kim, G. Angelini, K. Joo et al., (2021) hep:ex/2101.03544.





T. B. Hayward, C. Dilks, A. Vossen, H. Avakian et al., *Phys. Rev. Lett.*, 126, 152501, (2021), hep:ex/2101.04842

Fracture Functions

- Information on the momentum distribution of quarks and gluons are encoded in TMDs that can be measured in inclusive processes such as SIDIS.
- TMDs have been extensively studied via azimuthal modulations of a final state hadron generated in the fragmentation of a struck quark (CFR).
- Final state hadrons can also form from the left-over target remnant (TFR) whose partonic structure is defined by "fracture functions": the probability to form a certain hadron given a particular ejected quark.

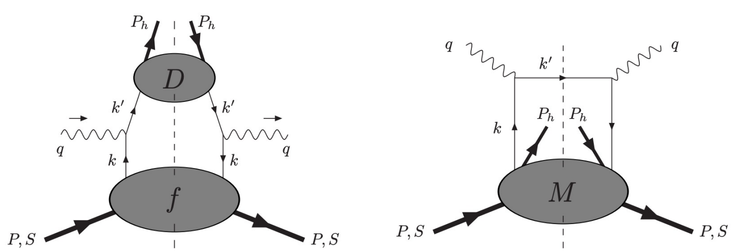


Figure 1: The handbag diagram for the SIDIS hadronic tensor in the current fragmentation region (left) and in the target fragmentation region (right).

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

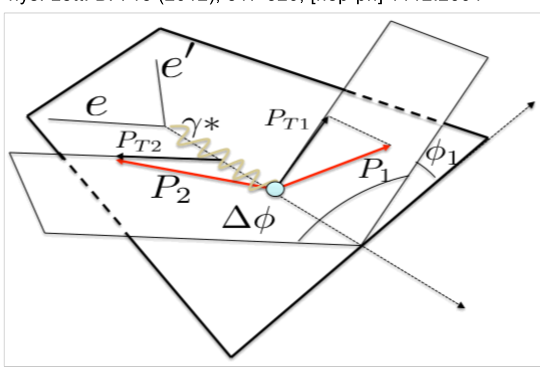
	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp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

Back-to-back Formalism

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2}\,\mathcal{C}\left[w_5\,\hat{l}_1^{\perp h} D_1\right],$$

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

Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604



- When two hadrons are produced "back-to-back" with one in the CFR and one in the TFR the structure function contains a convolution of a fracture function and a fragmentation function.

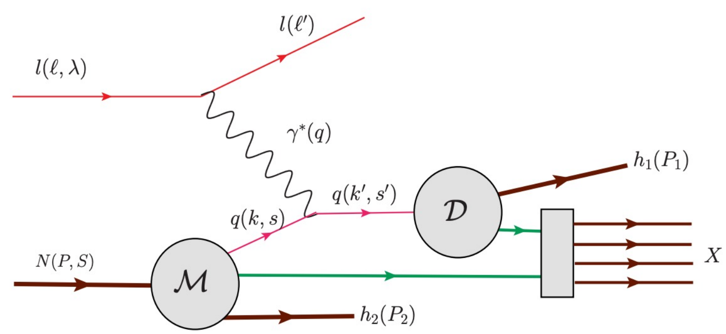


Figure 1: Lepto-production of two hadrons, one in the CFR and one in the TFR.

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

Additional Modulations

$$\mathcal{F}_{LU} = \frac{|p_\pi^\perp||p_P^\perp|}{m_p m_\pi}\mathcal{C}\left[w_5 \hat{l}_1^{\perp h} D_1\right]$$

Phys. Lett. B. 713 (2012), 317-320, [hep-ph] 1112.2604

→ Structure functions carry a dependence on $|p_\pi^\perp||p_P^\perp|$ which introduces a dependence on $\cos\Delta\phi$.

If the correlations are assumed small, the fracture functions can be expanded in powers of $k^\perp \cdot p_P^\perp$.

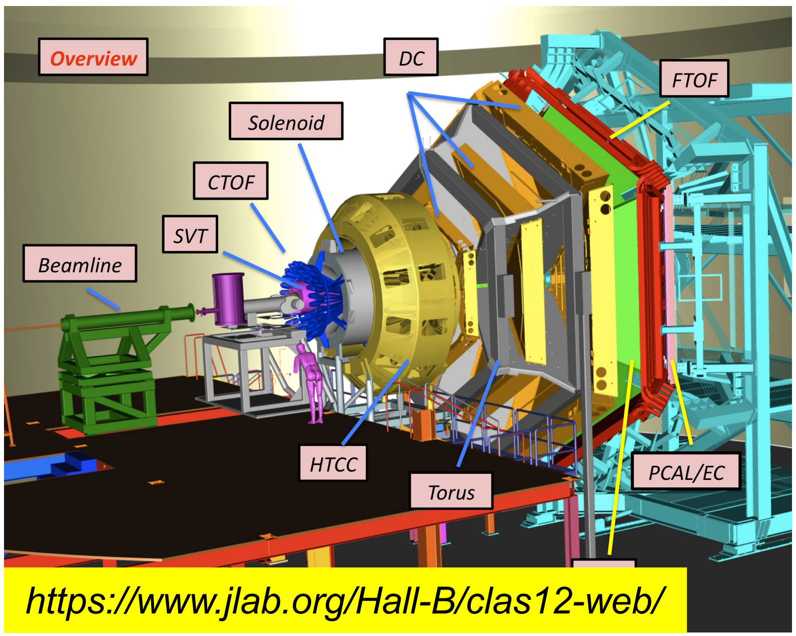
→

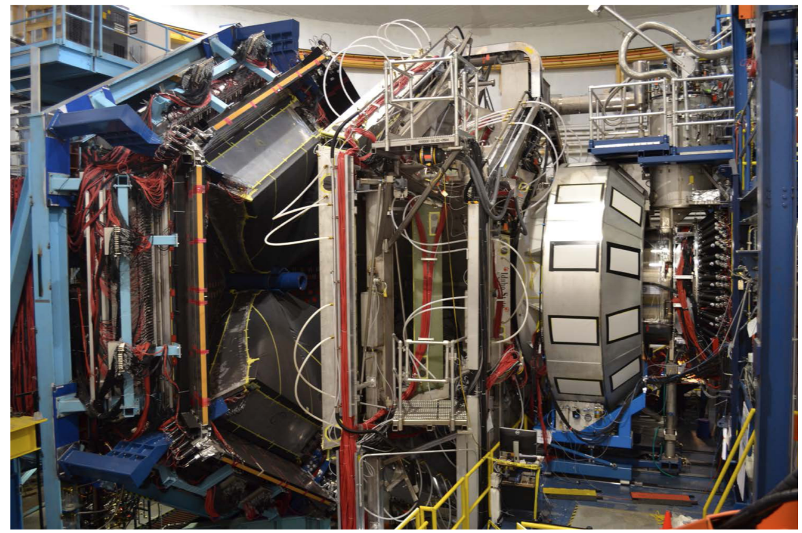
$$\hat{l}_1^{\perp h}(x,\zeta,\mathbf{k}^{\perp 2},\mathbf{p}_\mathbf{P}^{\perp 2},\mathbf{k}^\perp\cdot\mathbf{p}_\mathbf{P}^\perp) \approx a(x,\zeta,\mathbf{k}^{\perp 2},\mathbf{p}_\mathbf{P}^{\perp 2}) + b(x,\zeta,\mathbf{k}^{\perp 2},\mathbf{p}_\mathbf{P}^{\perp 2})\mathbf{k}^\perp\cdot\mathbf{p}_\mathbf{P}{}^\perp$$

The term linear in $k^\perp \cdot p_P^\perp$ yields a $\cos\Delta\phi$ which when combined with the already existing $\sin\Delta\phi$ term results in a $\sin 2\Delta\phi$.

$$\mathcal{A}_{LU}(x,\zeta,\mathbf{k}^{\perp 2},\mathbf{p}_\mathbf{P}^{\perp 2},\Delta\phi) = A(x,\zeta,\mathbf{k}^{\perp 2},\mathbf{p}_\mathbf{P}^{\perp 2})\sin\Delta\phi + B(x,\zeta,\mathbf{k}^{\perp 2},\mathbf{p}_\mathbf{P}^{\perp 2})\sin(2\Delta\phi)$$

CLAS12 Experimental Setup



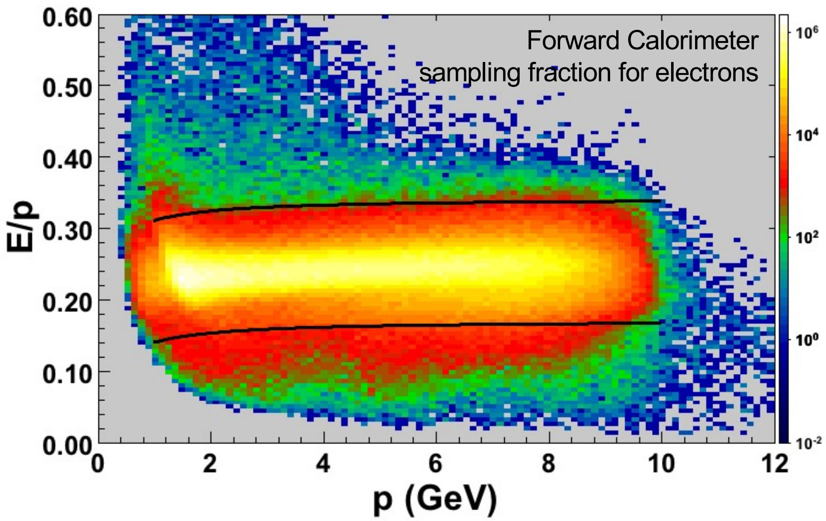


V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

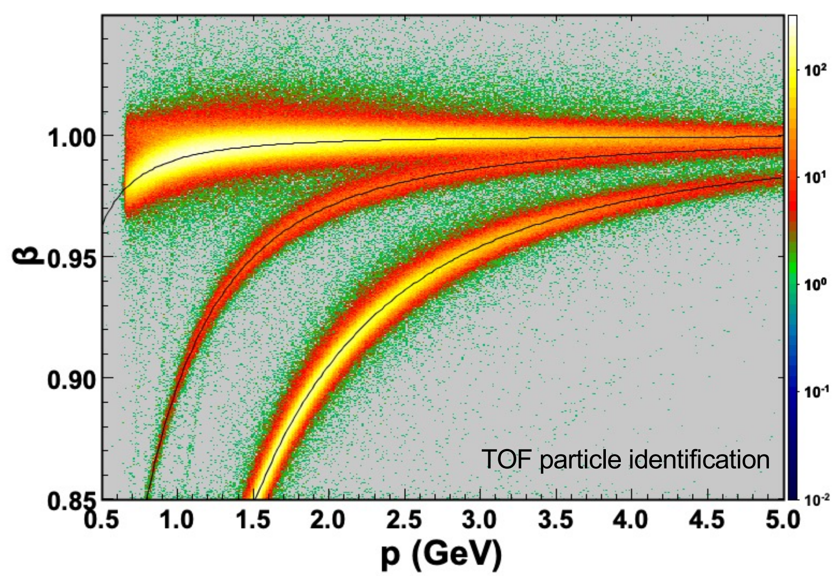
- Data taken during Fall 2018 and Spring 2019.
- 10.6 (2018) and 10.2 (2019) GeV longitudinally polarized electron beam with a H_2 target.
- Analyzed data is a small percentage of the total available data.

Particle ID

- Electron
  - Electromagnetic calorimeter.
  - Cherenkov detector.
  - Vertex and fiducial cuts.



- Hadron
  - β vs p comparison between vertex timing and event start time.
  - Vertex and fiducial cuts.



Selecting "back-to-back" events

- Formalism requires one hadron in the CFR and one hadron in the TFR.
- A natural choice for a first analysis are events with a pion (CFR biased) and proton (TFR biased).

PLOTS REMOVED ONLINE (DISTRIBUTIONS OF M_X AND X_F OF PROTON AND PION)

Monte Carlo

- 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.
- Excellent agreement between data and MC!

PLOTS REMOVED ONLINE (Data/MC Comparisons of Q^2, $P^{\perp}$, X_F of pion and $\Delta\phi$)

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.

Extracting A_{LU}

- Select $ep \rightarrow e'P\,\pi^+ + X$.
- Consider all possible hadron pairs.
- Amplitudes are extracted simultaneously via maximizing a likelihood function.
- Unbinned maximum likelihood method:

$$\frac{N_\pm(\Delta\phi)}{N(\Delta\phi)} = \frac{1}{2}\frac{L_\pm a_\pm(\Delta\phi)\eta_\pm(\Delta\phi)}{La(\Delta\phi)\eta(\Delta\phi)}\left[1 \pm PA_{LU}(\Delta\phi)\right]$$

- Use MINUIT to minimize the -log likelihood.
- Include relevant beam polarization (~85% at JLab).

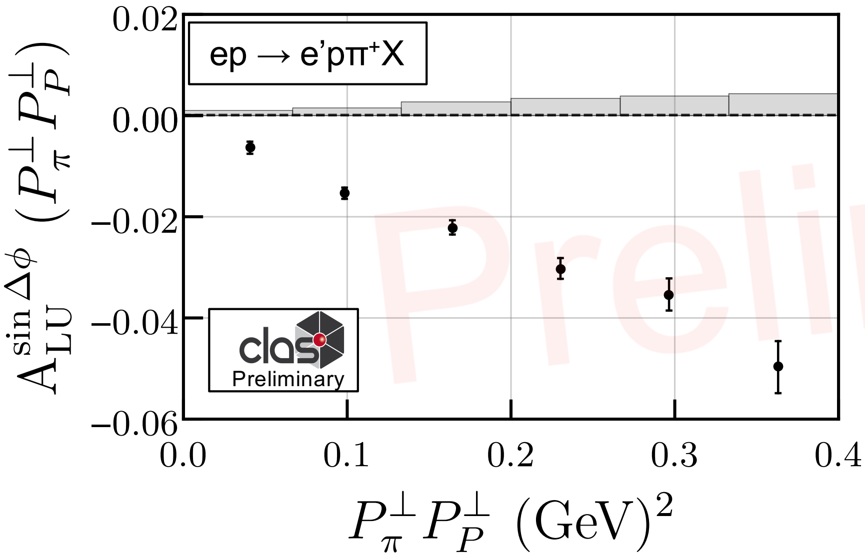
Channel selection

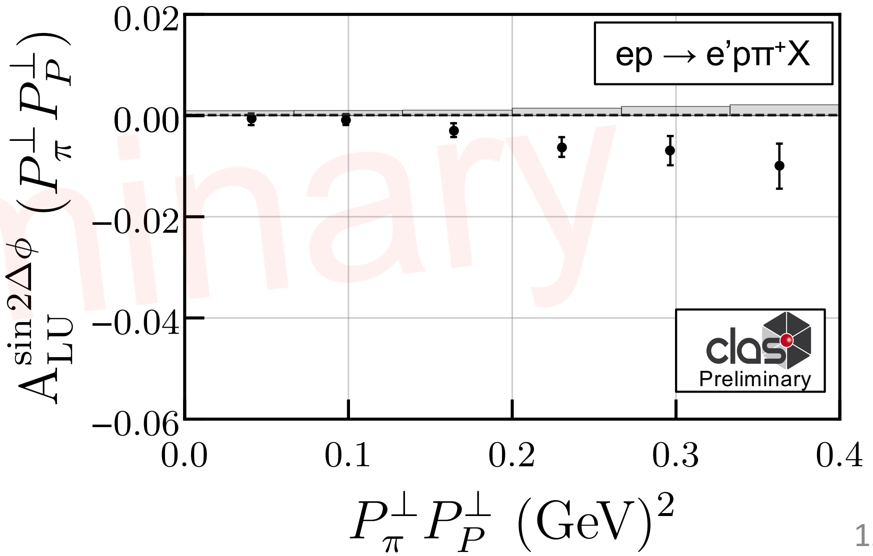
- $Q^2>1.0$ GeV^2
- $W>2.0$ GeV
- $M_{miss}>0.85$ GeV
- $y<0.75$
- $x_{F\pi} > 0$
- $x_{FP} < 0$
- $z_\pi > 0.2$

Back-to-back results

- Observed linear dependence on the product of transverse momenta is consistent with expectations.
- Non-zero asymmetries are the first experimental observation of possible spin-orbit correlations between hadrons produced simultaneously in the CFR and TFR.

$$\mathcal{F}_{LU} = \frac{|p^{\perp}_{\pi^+}||p^{\perp}_{P}|}{m_p m_\pi}\mathcal{C}\left[w_5 \hat{l}_1^{\perp h} D_1\right]$$



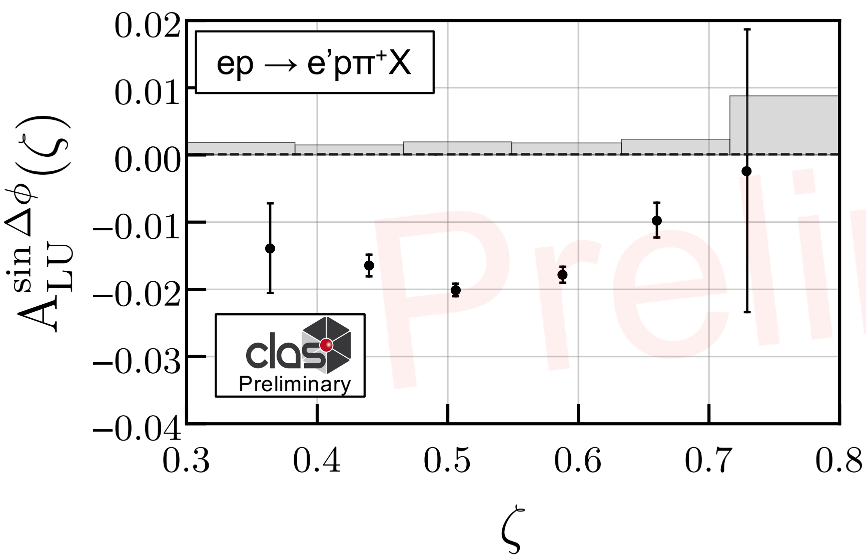


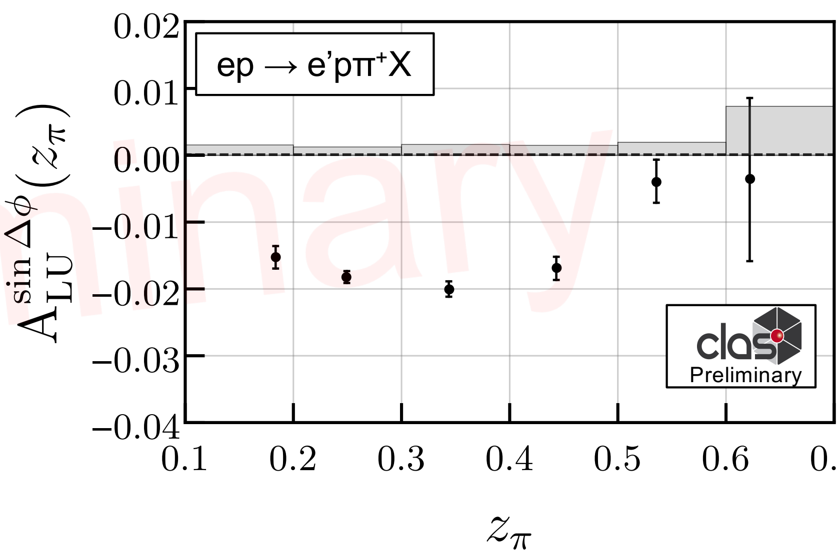
Access to unmeasured fracture function

- Fracture function $\hat{l}_1^{\perp h}$ depends on ζ.
- Fragmentation function D_1 depends on z_π.

$$\mathcal{F}_{LU}^{\sin(\Delta\phi)} = \frac{|p_{\pi^+}^{\perp}||p_P^{\perp}|}{m_P m_{\pi^+}} \mathcal{C}\left[w_5 \hat{l}_1^{\perp h} D_1\right]$$

$$\zeta = E_P/E \quad z_\pi = E_\pi/\nu$$





Conclusions

- Significant single-spin asymmetries have been observed **for the first time** in back-to-back proton-pion electroproduction.
- Beam-spin asymmetries amplitudes indicate that spin-orbit correlations may exist between hadrons produced simultaneously in the target and current fragmentation regions.
- Analysis in final collaboration review with the aim of submission for publication this year.