

Charged kaon SIDIS with CLAS12

Multidimensional measurements of beam single-spin asymmetries

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(CLAS Collaboration)

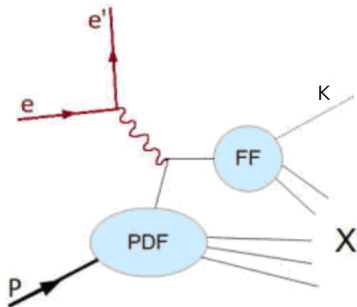
University of Connecticut

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Based on Á. Kripkó, S. Diehl, K. Joo et al. (CLAS Collaboration), Phys. Rev. C 112, 055202 (2025).

Why kaons and why twist-3?

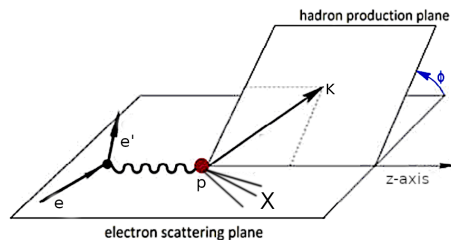


- ▶ Twist-3 observables probe dynamics beyond a leading-twist, single-parton picture
- ▶ $F_{LU}^{\sin \phi}$ is suppressed by $\mathcal{O}(M/Q)$
- ▶ Kaons change the flavor and fragmentation weighting relative to pions
- ▶ The multidimensional dependence constrains quark–gluon correlations

Question

Can K^+ data reveal kinematic structure hidden by one-dimensional projections?

The measured observable



$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$
$$= \frac{A_{LU}^{\sin \phi} \sin \phi}{1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos 2\phi} \cos 2\phi}$$

$$\frac{F_{LU}^{\sin \phi}}{F_{UU}} = \frac{A_{LU}^{\sin \phi}}{\sqrt{2\epsilon(1 - \epsilon)}}$$

Experimental handle

Reverse the beam helicity and extract the $\sin \phi$ modulation.

Twist-3 mechanisms

Convolution of TMDs and FFs:

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

Distribution-side twist-3

$$e H_1^\perp$$

$$g^\perp D_1$$

Fragmentation-side twist-3

$$f_1 \tilde{G}^\perp / z$$

$$h_1^\perp \tilde{E} / z$$

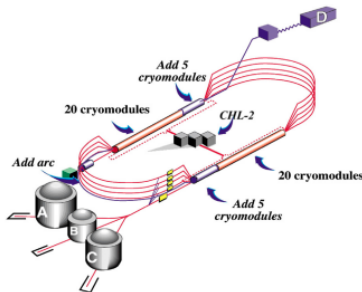
The published models retain $e H_1^\perp$ and $g^\perp D_1$.

Factorization is assumed for the interpretation and is most credible at low P_T .

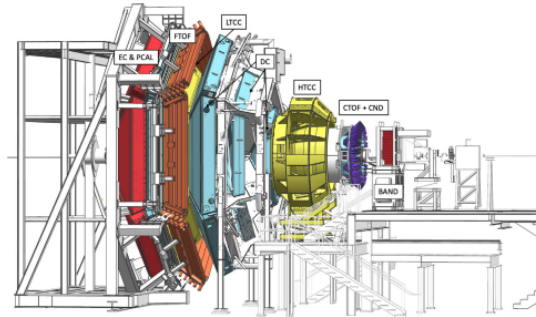
A. Bacchetta et al., JHEP 02, 093 (2007)

CEBAF

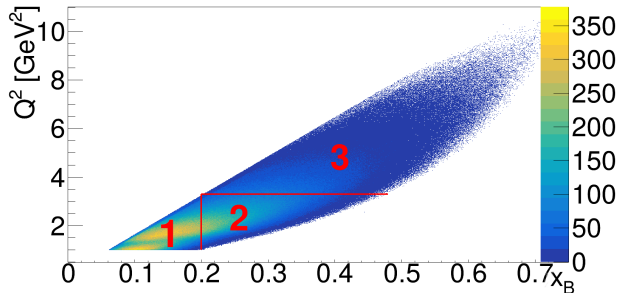
- ▶ Continuous Electron Beam Accelerator Facility
- ▶ Located at Jefferson Lab, Newport News, USA
- ▶ Composed of a pair of linear accelerators and recirculating arcs arranged in a racetrack shape
- ▶ Capable of providing 11 GeV approx. 80% polarized electron beams



- ▶ CEBAF Large Acceptance Spectrometer
- ▶ The overall detector design consists of a forward detector with a torus magnet and 6 sectors and a central detector with a solenoid magnet



CLAS12 data set



► Optimal PID:

- $y < 0.75$ (minimal electron momentum of ~ 2.65 GeV)
- $1.25 \text{ GeV} < p_K < 3 \text{ GeV}$

► To select the deeply inelastic scattering region:

- $W > 2 \text{ GeV}$
- $Q^2 > 1 \text{ GeV}^2$

► To reject most of the kaons from the target fragmentation region:

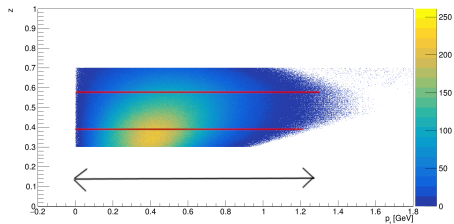
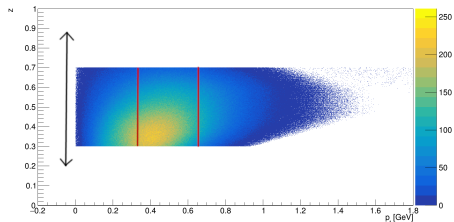
- $x_F > 0$
- $0.3 < z$

► To reduce the contamination from exclusive processes:

- $z < 0.7$
- $M_X > 1.6 \text{ GeV}$

► Event topology: at least one good electron and at least one good Kaon

Selection and four-dimensional binning



$$Q^2 > 1 \text{ GeV}^2, \quad W > 2 \text{ GeV}, \quad y < 0.75$$

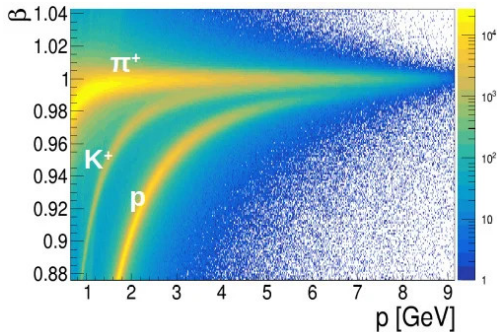
$$x_F > 0, \quad M_X > 1.6 \text{ GeV}$$

Binning

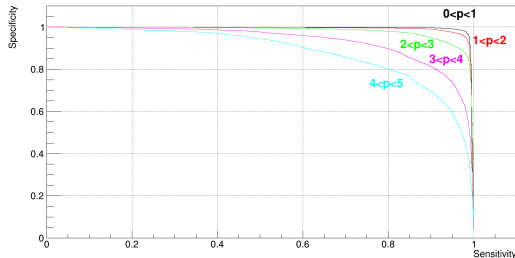
- ▶ 3 regions in the Q^2 – x_B plane
- ▶ 3 coarse bins in z or P_T
- ▶ Fine binning in the remaining variable

All four variables remain binned simultaneously.

Kaon identification is the experimental challenge

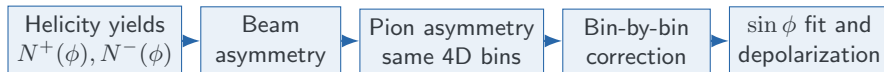


Standard TOF separation



- ▶ DNN combines timing and energy information from multiple detectors
- ▶ Simulated purity improves from 60–70% to 80–90%
- ▶ More than 50% of the kaon sample is retained
- ▶ Physics sample restricted to $p_K < 3$ GeV

Extraction and pion-contamination correction



$$A_{LU} = \frac{1}{P_e} \frac{N^+ - N^-}{N^+ + N^-}$$

$$A_{K,\text{corr}} \simeq \frac{A_{\text{selected}} - f_\pi A_\pi}{1 - f_\pi}$$

$P_e = 87.24\% \pm 2.42\%$, 30 Hz helicity reversal

Cross-checks and systematic studies

Alternative PID, denominator cosine terms, radiative effects, resonance backgrounds, acceptance, and bin migration. - from MC

Systematic uncertainties

Source	Average absolute uncertainty
Statistical	0.020
Pion contamination	0.005
MC contamination	0.001
Beam polarization	0.001
Fiducial cuts	0.004
Radiative effects	0.002
Acceptance	0.002
Cosine terms	0.002
Total systematic	0.010

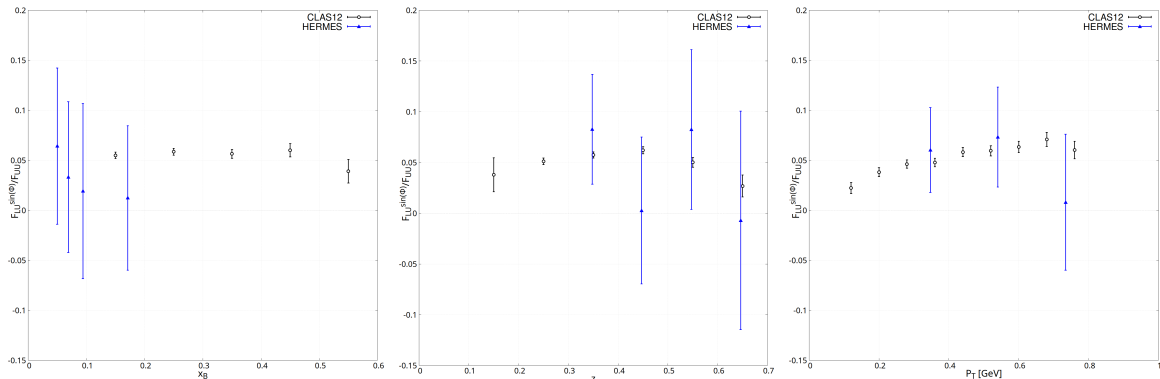
Relative scale

Point-to-point systematic: $\sim 22\%$

Average statistical: $\sim 29\%$

- ▶ Largest systematic: pion contamination
- ▶ Most bins remain statistics dominated
- ▶ Acceptance and migration are comparatively small

Comparison with HERMES



Consistent with HERMES, with narrower bins and smaller uncertainties.

HERMES data: A. Airapetian et al., Phys. Lett. B 797, 134886 (2019).

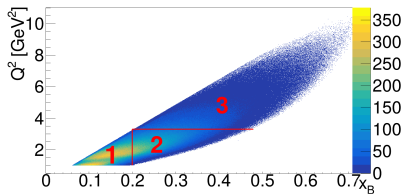
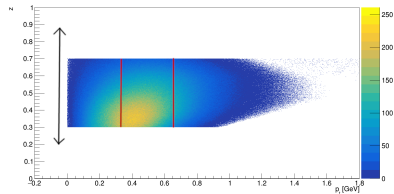
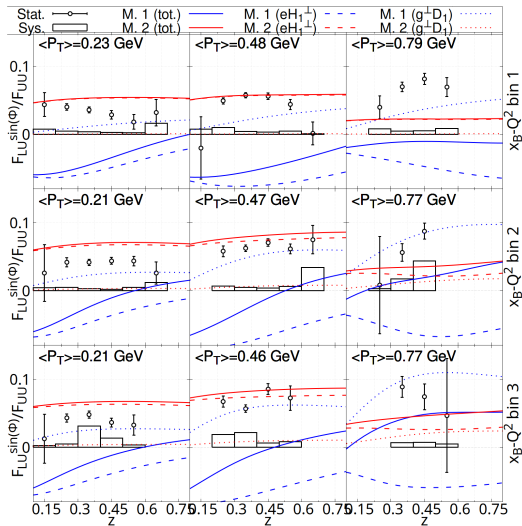
Comparison with existing models

- ▶ As the first fully multidimensional analysis in this region it can distinguish between existing models
- ▶ Comparison with models
- ▶ Describe the proton as an active quark and a spectator diquark
- ▶ They include the $eH_1^\perp$ and the $g^\perp D_1$ terms
- ▶ The models were recalculated for the exactly measured kinematics

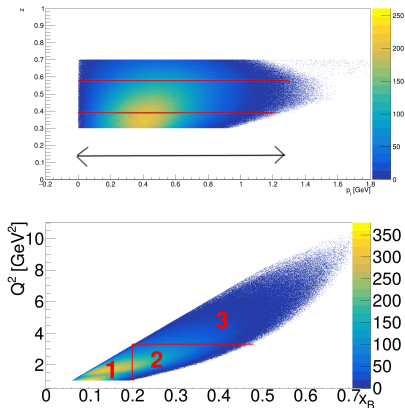
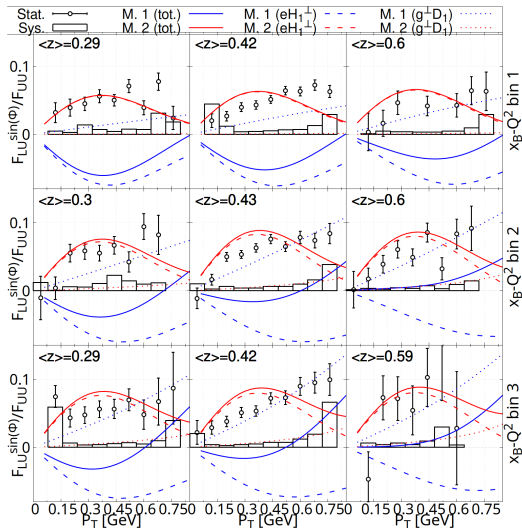
FF inputs: $D_1^{q \rightarrow h}$ from the LO DSS parametrization [D. de Florian, R. Sassot, and M. Stratmann, PRD 75, 114010 (2007)]; $H_1^{\perp q \rightarrow \pi}$ from M. Anselmino et al., Nucl. Phys. Proc. Suppl. 191, 98 (2009). For kaons, the pion favored/unfavored Collins analyzing powers $H_1^\perp/D_1$ are assumed.

W. Mao and Z. Lu EPJ C 73, 2557 (2013) and 74, 2910 (2014)

4D result: z dependence and theory comparison



4D result: P_T dependence and theory comparison



Interpretation of the model comparison

Model 1

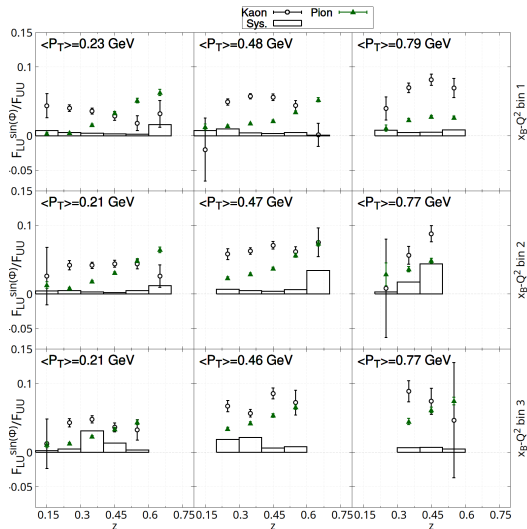
- ▶ $eH_1^\perp$ and $g^\perp D_1$ have opposite signs
- ▶ Negative $eH_1^\perp$ drives the total below zero
- ▶ The observed positive signal is not reproduced

Model 2

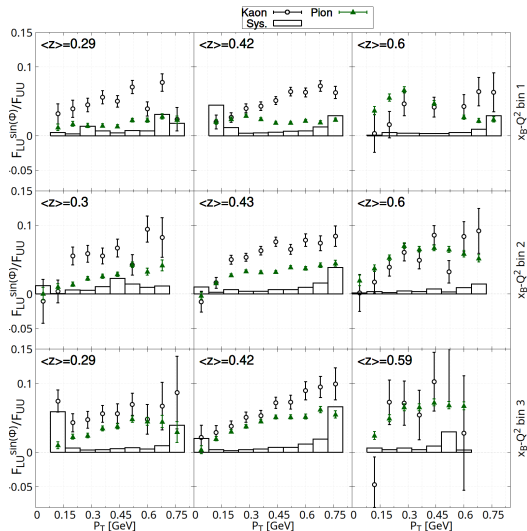
- ▶ The retained terms have the same sign
- ▶ The sign and many z and P_T tendencies are reproduced
- ▶ A turnover is predicted at higher P_T

High- P_T tension may indicate improved TMD/FF parametrizations, additional terms, higher twist, or limits of factorization.

Kaons and pions: multidimensional z dependence



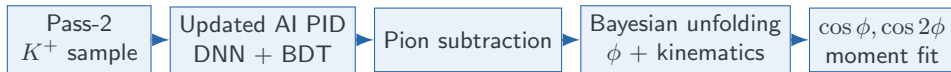
Kaons and pions: multidimensional P_T dependence



Outlook: $\cos \phi$ and $\cos 2\phi$ from the same data

- ▶ Polarized electron beam interacting with an unpolarized target:

- ▶ $d\sigma = d\sigma_0(1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos 2\phi} \cos 2\phi + \lambda_e A_{LU}^{\sin \phi} \sin \phi)$



Physics targets

Cahn effect, Boer–Mulders mechanism, and transverse-momentum dependence

Work in progress

Summary and acknowledgments

- ▶ First published multidimensional K^+ beam-spin result in the valence-quark region
- ▶ ML PID and bin-by-bin pion correction make the channel viable
- ▶ Updated AI and Bayesian unfolding extend the program to unpolarized cosine moments using the same data set with better calibration and acceptance control
- ▶ The kinematic coverage of CLAS12 will complement the future EIC program

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Thank you

CLAS Collaboration, Jefferson Lab staff, and all analysis contributors



Backup: exact multidimensional bin boundaries

Q^2 - x_B

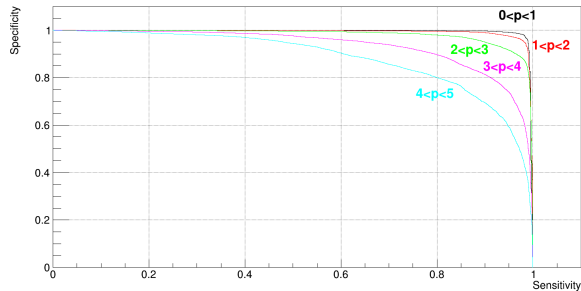
- 1: $x_B < 0.2$
- 2: $x_B > 0.2, Q^2 < 3.3 \text{ GeV}^2$
- 3: $x_B > 0.2, Q^2 > 3.3 \text{ GeV}^2$

Coarse bins

$P_T < 0.33, 0.33 < P_T < 0.66, P_T > 0.66 \text{ GeV}$
 $z < 0.34, 0.34 < z < 0.52, z > 0.52$

Backup: published DNN configuration

- ▶ ROOT TMVA
- ▶ 3 fully connected hidden layers
- ▶ 128 neurons per layer
- ▶ tanh activation
- ▶ Xavier initialization
- ▶ ADAM optimizer
- ▶ Cross-entropy loss
- ▶ Batch size 30
- ▶ Learning rate 10^{-5}



Comparison of the two spectator-model sets

	Model 1 / Set 1	Model 2 / Set 2
Axial-vector diquark propagator	Light-cone transverse polarization sum: $d_{\mu\nu} = -g_{\mu\nu} + \frac{P_{X\mu}n_{-\nu} + P_{X\nu}n_{-\mu}}{P_X \cdot n_-} - \frac{M_X^2 n_{-\mu}n_{-\nu}}{(P_X \cdot n_-)^2}$	Simpler prescription: $d_{\mu\nu} = -g_{\mu\nu}$
Flavor-diquark relation	Model-fitted weights: $f^u = c_s^2 f^s + c_a^2 f^a, \quad f^d = c_{a'}^2 f^{a'}$	SU(4) spin-flavor weights: $f^u = \frac{3}{2} f^s + \frac{1}{2} f^a, \quad f^d = f^{a'}$
Spectator parameters	Fitted scalar and axial-vector masses, cutoffs, and coefficients; strongly non-degenerate axial-vector spectators	Common cutoff and SU(4) coefficients; degenerate axial-vector spectator masses
Result for e^u	Predominantly negative in the relevant kinematics	Predominantly positive in the relevant kinematics
Contributions to K^+	$eH_1^\perp$ and $g^\perp D_1$ have opposite signs; the negative $eH_1^\perp$ term drives the total downward	$eH_1^\perp$ and $g^\perp D_1$ have the same sign; the positive $eH_1^\perp$ term generally dominates
Comparison with data	Usually predicts the wrong sign for the total asymmetry	Reproduces the positive sign and many z - and P_T -dependent trends