Beam Single Spin Asymmetries in Semi-Inclusive Deep-Inelastic Charged Kaon Electroproduction off Protons in the Valence Region

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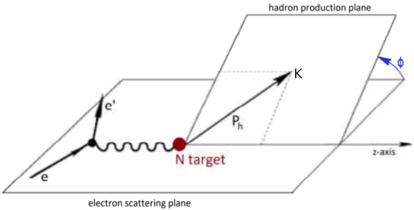
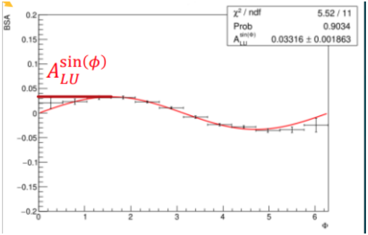
Introduction

- This talk is based on:
  - A. Kripko, S. Diehl, K. Joo et al. Phys. Rev. C 112, 055202 (2025).
  - DOI: `https://doi.org/10.1103/2m4z-htrp`
- Most of the visible mass consists of nucleons
- Their mass and spin emerge from the strong interactions of their constituents
- The most general objects describing the internal structure are the Wigner functions
- TMDs, PDFs, FFs and GPDs are all related to the Wigner functions
- SIDIS is a well established tool to measure these functions

Physics motivation

- Kaon SIDIS: $ep \to e'K^+X$
- Polarized electron beam interacting with an unpolarized target:
- $d\sigma = d\sigma_0(1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos 2\phi}\cos 2\phi + \lambda_e A_{LU}^{\sin\phi}\sin\phi)$
- $BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{A_{LU}^{\sin\phi}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos 2\phi}\cos 2\phi}$
- Main focus on structure function: $\frac{F_{LU}^{\sin\phi}}{F_{UU}} = \frac{A_{LU}^{\sin\phi}}{\sqrt{2\epsilon(1-\epsilon)}}$



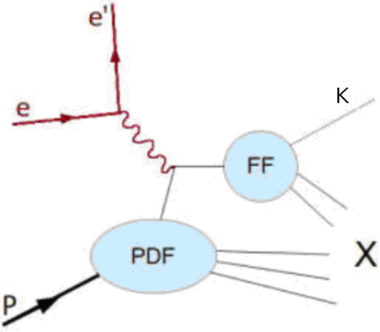


Physics motivation

- If factorization is valid (kinematic range):

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

- Convolution of TMDs and FFs (either one is always twist-3)
- Twist-3: suppressed by 1/Q



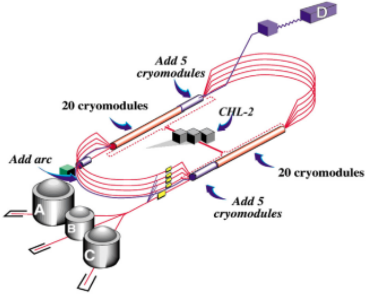
Physics motivation

- Sizable SSAs for charged hadrons have been observed in earlier SIDIS experiments:
  - COMPASS measured large SSAs for charged hadrons.
  - CLAS and CLAS12 measured multidimensional SSAs for charged pions.
  - HERMES measured SSAs for pions and kaons, but with lower statistics.
- By measuring the SIDIS structure functions, one can determine the TMDs and GPDs more precisely and obtain a deeper understanding of the origin of the proton spin
- Measuring kaons in the valence region and comparing them to pions allows the creation of a more complete picture of the proton's internal structure

C. Adolph et al. (COMPASS), Nucl. Phys. B 886, 1046 (2014).
W. Gohn et al. (CLAS), Phys. Rev. D 89, 072011 (2014).
A. Airapetian et al. (HERMES), Phys. Lett. B 797, 134886 (2019).
S. Diehl et al. (CLAS12), Phys. Rev. Lett. 128, 062005 (2022).

CEBAF

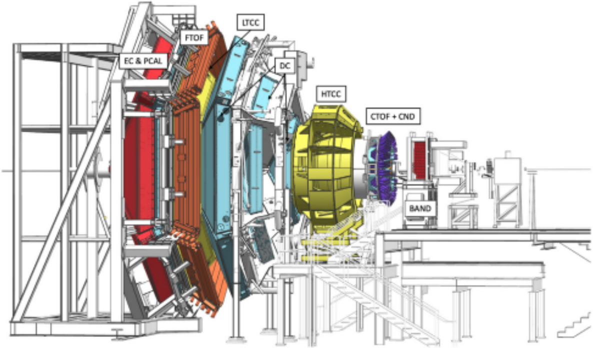
- Continuous Electron Beam Accelerator Facility
- Located at Jefferson Lab, Newport News, USA
- Composed of a pair of linear accelerators and 9 recirculating arcs arranged in a racetrack shape
- Capable of providing 11 GeV approx. 80% polarized electron beams



V.D. Burkert et al. (CLAS collab.), NIM A, 959, 163419 (2020)

CLAS12

- 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



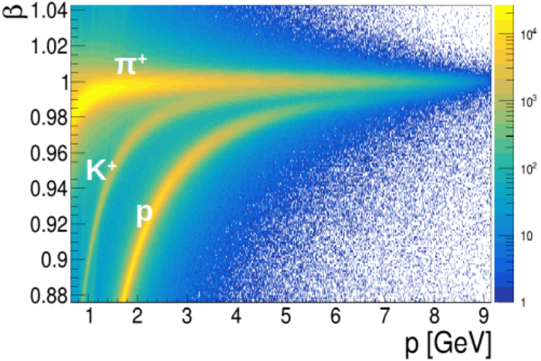
V.D. Burkert et al. (CLAS collab.), NIM A, 959, 163419 (2020)

Kinematic cuts

- Event topology: at least one good electron and at least one good Kaon
- Optimal PID:
  - y < 0.75 (minimal electron momentum of $\sim$2.65 GeV)
  - 1.25 GeV $< p_K <$ 3 GeV
- Only use forward detector:
  - $5^\circ < \theta < 35^\circ$
- To select the deeply inelastic scattering region:
  - W $>$ 2 GeV
  - $Q^2 > 1$ 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
  - $M_X > 1.6$ GeV
- RG-A 2018 and 2019 - in- and outbending

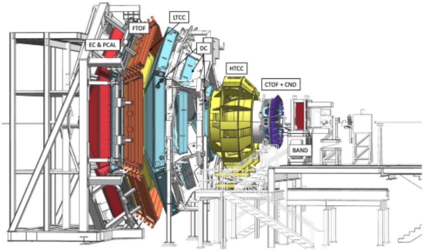
Particle ID

- CLAS12 Eventbuilder PID as a basis - TOF based, reliable up to 3 GeV
- Use machine learning to improve kaon ID
- RICH is available in 1 sector - good for validation



Machine learning

- Use most of the available detector information
- Main improvement is the combination of all timing information (calorimeters, DC, TOF layers) and HTCC
- Significantly reduces the pion contamination
- The results were cross-checked with other MC samples and with the RICH

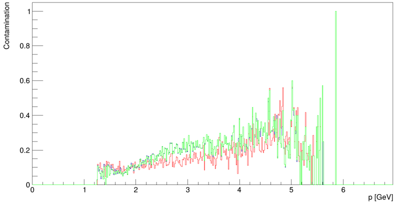


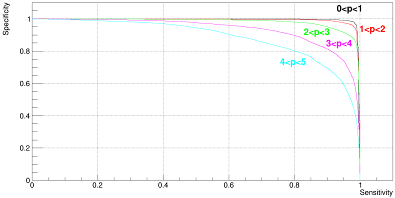
Algorithm

- ROOT TMVA
- Deep neural network
  - 3 hidden layers with 128 neurons per layer
  - Fully connected
  - tanh activation function, linear for the last neuron
- Training
  - Crossentropy loss function
  - Xavier weight initialisation
  - Optimizer: ADAM
  - Batch size: 30
  - Learning rate: 10^{-5}
  - The input variables are normalised, invalid events skipped
  - The same amount of π-s and K-s are used during the training

Machine learning, pion subtraction

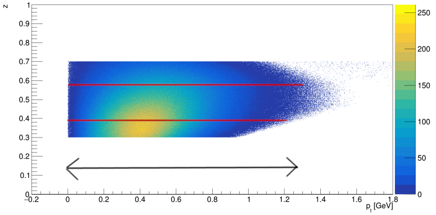
- The DNN effectively reduces the pion contamination
- The pion BSA is also extracted in the same kinematic binning as the kaons
- The pion contamination is subtracted bin by bin based in MC
- Different DNN cut settings give different contamination - validation of both MC and DNN
- A cut at 0.96 keeps the contamination below 20%

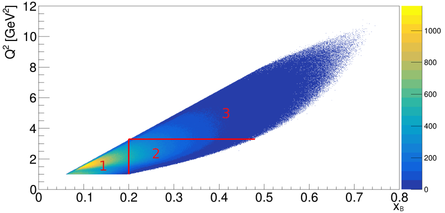


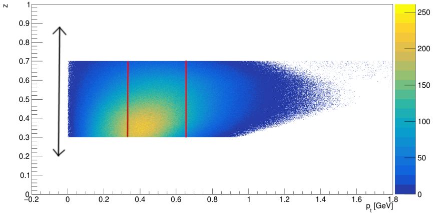


Multidimensional binning

- Data taken in 2018 and 2019
- Binning in x_B, Q^2, z, P_T:
- 3 bins in the x_B-Q^2-plane
- 3 bins in z or P_T
- 10 bins in the last dimension

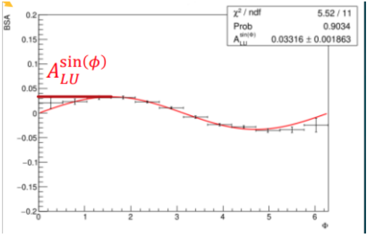


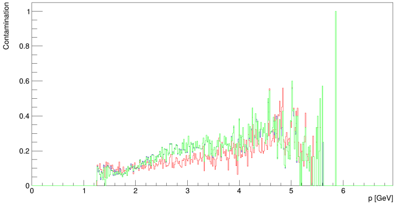




Extraction of the modulation

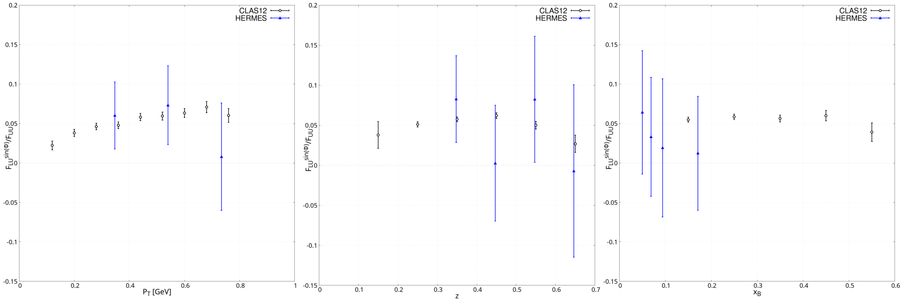
- In all kinematic bins, the BSA is extracted in 12 Φ bins
- Both for Kaons and for pions the $A_{LU}^{\sin(\Phi)}$ is extracted
- The contamination is estimated from MC for the kinematic bins and subtracted





Comparison with other experiments

- One dimensional binning
- More statistics over large kinematics



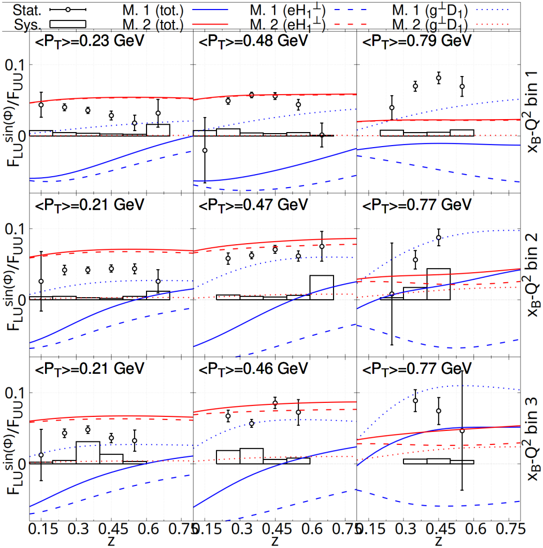
A. Airapetian et al. (HERMES), Phys. Lett. B 797, 134886 (2019).

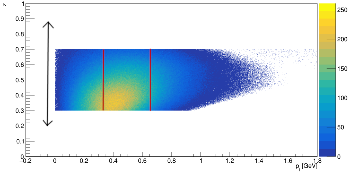
Comparison with existing models

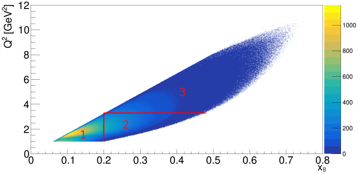
- As the first fully multidimensional analysis in this region it can distinguish between existing models
- Comparison with models from Nanjing University
- Describe the proton as an active quark and a spectator diquark
- They include the $eH_1^\perp$ and the $g^\perp D_1$ terms

W. Mao and Z. Lu EPJ C 73, 2557 (2013) and 74, 3910 (2014)

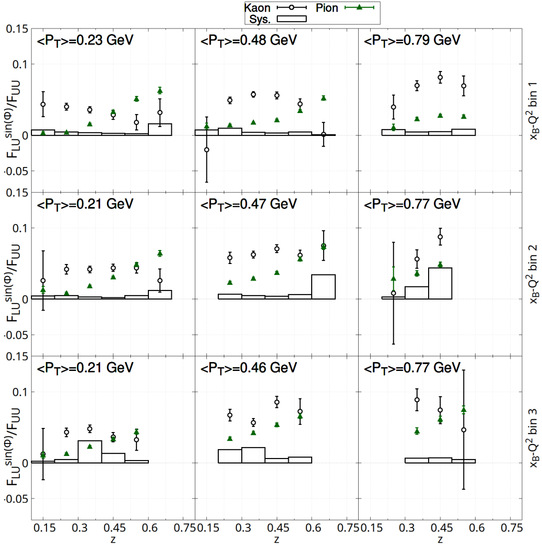
4D results theory comparison - K^+ z-dependence

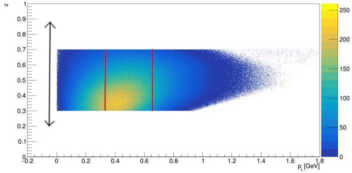


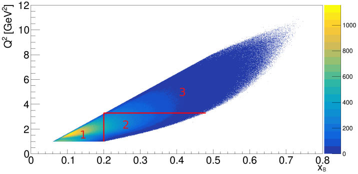




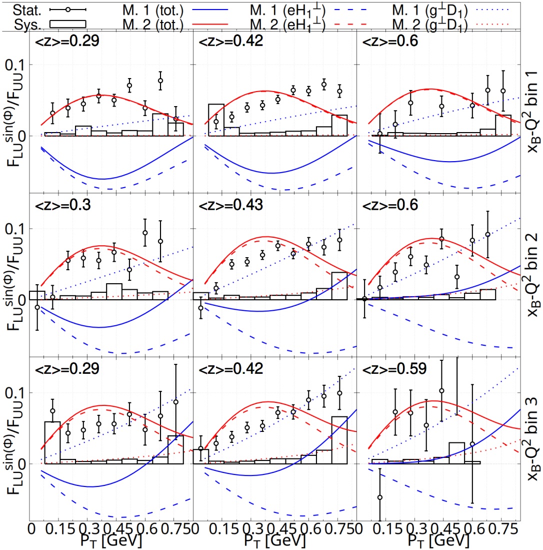
4D results pion comparison - K^+ z-dependence

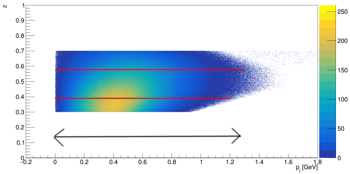


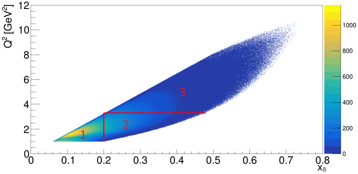




4D results theory comparison - K$^+$ P_T-dependence







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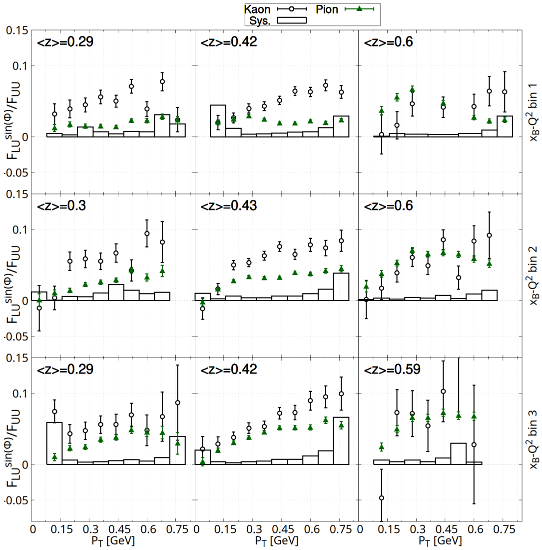

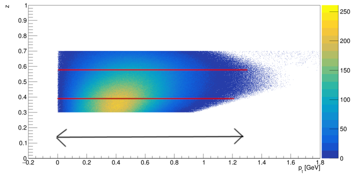

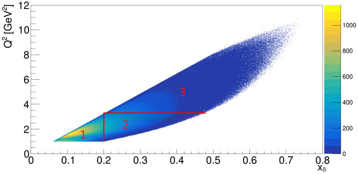

Systematic uncertainties

Source	Absolute uncertainty
Statistical uncertainty	0.02
Pion contamination	0.005
MC contamination	0.001
Beam polarization	0.001
Fiducial cuts	0.004
Pion bin migration	0.001
Radiative effects	0.002
Acceptance	0.002
Cos terms	0.002
Bin migration	0.001
Phi bin migration	0.0005
Charge-symmetric background	0.0001
Accidentals	0.0005
Total systematic uncertainty	0.01

Summary and outlook

- The kaon signals generally follow the pion signals, but they have larger values
- The high pion contamination can be dealt with by using ML PID and by subtraction based on MC
- The high statistics on an extended kinematic range, which is uniquely available with CLAS12, enables a fully differential analysis for the first time
- The data can distinguish between existing models

- Cross section measurement to extract the cosine modulations
- The DNN is being improved and fine tuned
- Acceptance corrections