Probing Nucleon GPDs at CLAS12: Neutron DVCS and Λ Transverse Polarization

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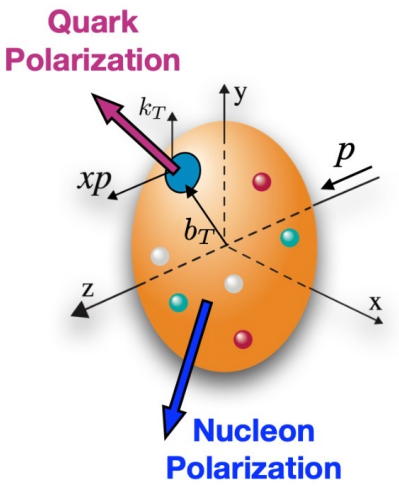
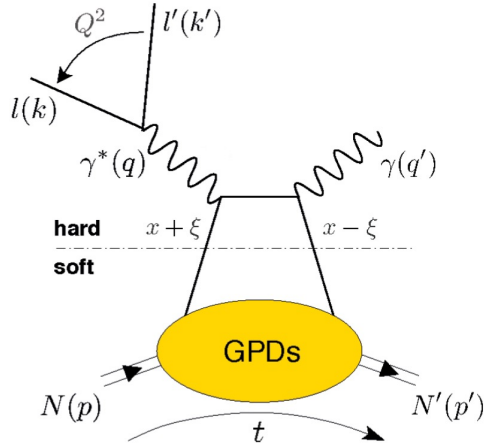
Outline

- Generalized Parton Distribution (GPD)
- Experimental Facility: CLAS12 detector
- Neutron DVCS cross-section extraction
  - Motivation: Probe chiral-even GPD
  - Analysis strategy
  - Preliminary results
- Study of Λ polarization in $K^+\Lambda$ electroproduction
  - Motivation: Probe chiral-odd GPD & Λ polarization mechanism
  - Analysis status
- Summary and outlook

Generalized Parton Distribution (GPD)

- Understanding the internal structure of nucleons remains one of the important challenges in hadronic physics
- The formalism of Generalized Parton Distributions (GPDs) provides a universal description of the partonic structure of the nucleon
  - Relate transverse position of partons to their longitudinal momentum
  - Give access to the angular momentum of quarks and gluons, the missing ingredient for understanding the nucleon spin composition
- 4 chiral-even GPDs (quark-helicity conservation) for each flavor at leading twist
  - Unpolarized GPDs H, E and polarized GPDs $\widetilde{H}, \widetilde{E}$
  - H and $\widetilde{H}$: nucleon-spin conservation; E and $\widetilde{E}$: nucleon-spin flip
  - The Deeply Virtual Compton Scattering (DVCS) is one of the cleanest channels to access chiral-even GPDs
- 4 chiral-odd GPDs (quark-helicity flip) for each flavor at leading twist
  - Difficult to access (helicity flip processes are suppressed)
  - Exclusive meson electroproduction (e.g. $ep \to eK^+\Lambda$) exhibits sensitivity to chiral-odd GPDs

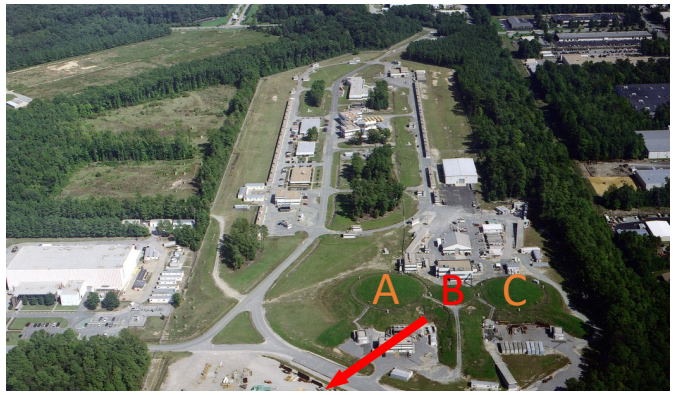




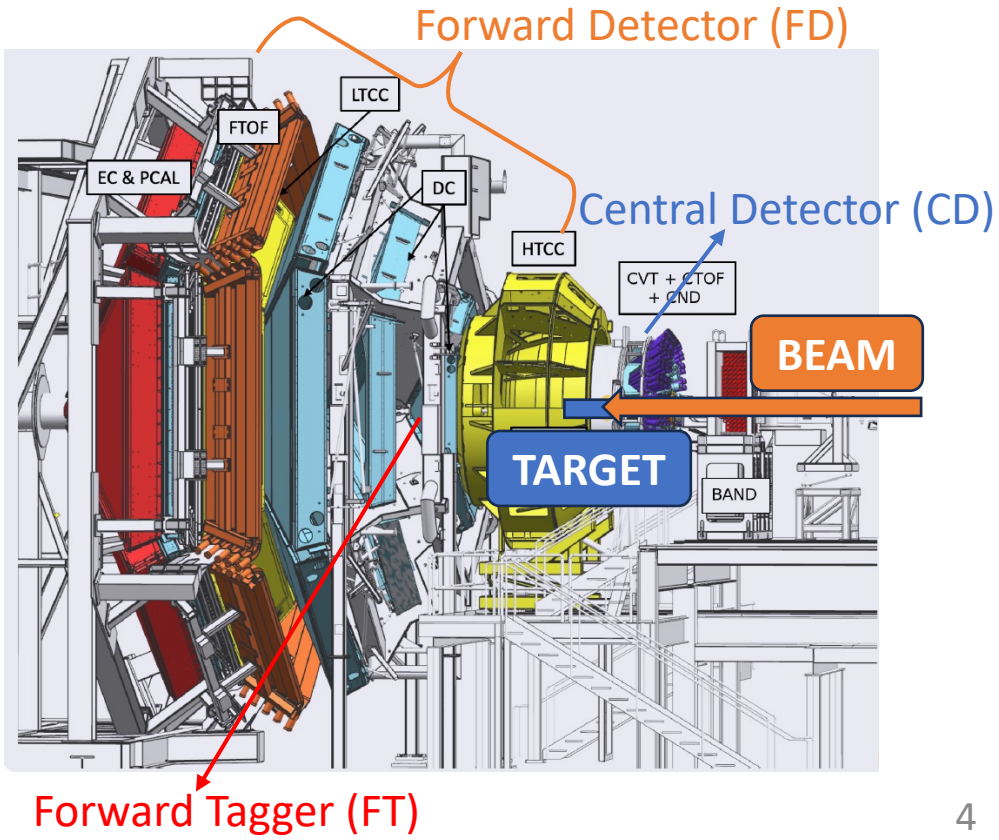
DVCS process

CEBAF and CLAS12 detector

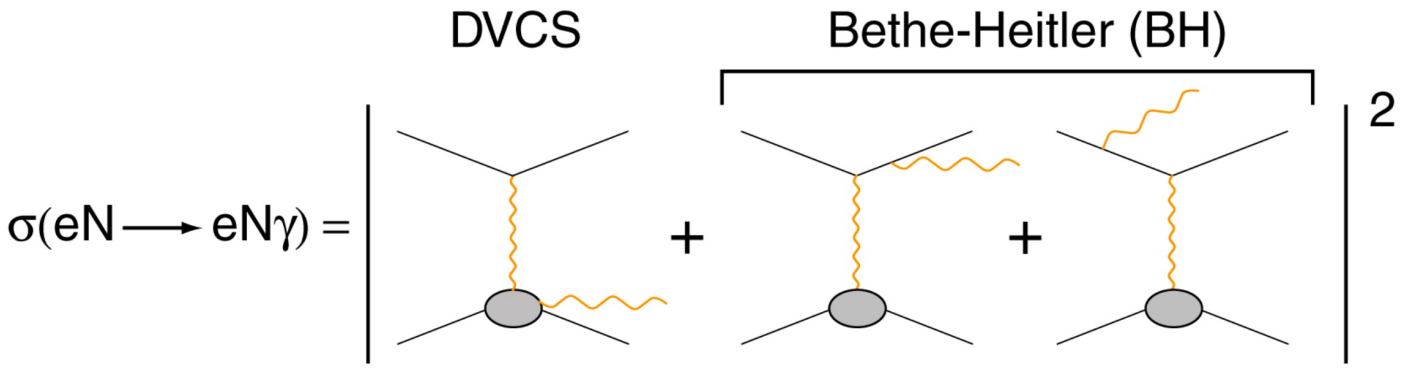
- Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab
  - Up to 12 GeV electrons
- Hall B: CLAS12 detector
  - Forward Detector (FD)
    - Full coverage in polar angle $5° < \theta < 35°$
  - Forward Tagger (FT)
    - Detect electrons and photons at $2° < \theta < 5°$
  - Central Detector (CD)
    - Central Vertex Tracker (CVT)
    - Central Time-of-Flight (CTOF) Detector
    - Central Neutron Detector (CND)
  - Ideal platform to study GPDs in the valence quark region



Hall B: CLAS12 detector



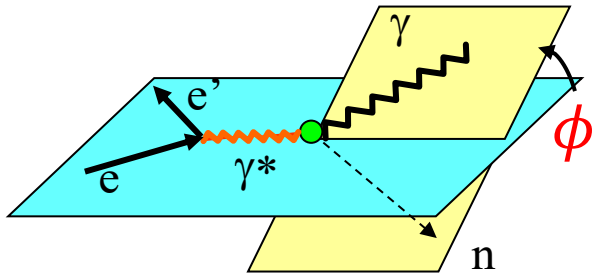
Probe GPDs via DVCS



- DVCS shares the same final state with the Bethe-Heitler (BH) process
  - BH process: a real photon is emitted by either the incoming or the scattered electron
- DVCS information can be extracted from the DVCS/BH interference term
- DVCS observables are linked to GPDs via the complex-valued functions: Compton Form Factors (CFFs)
  - CFFs $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \tilde{\mathcal{E}}$ correspond to GPDs $H, E, \widetilde{H}, \tilde{E}$
- The measurement of DVCS cross section from the neutron (nDVCS) can provide unique information on GPDs
  - GPD E is largely unknown so far
  - The unpolarized cross section of nDVCS is sensitive mainly to the real CFF of E
  - The polarized cross-section difference of nDVCS is sensitive to the imaginary CFF of E

Select nDVCS data

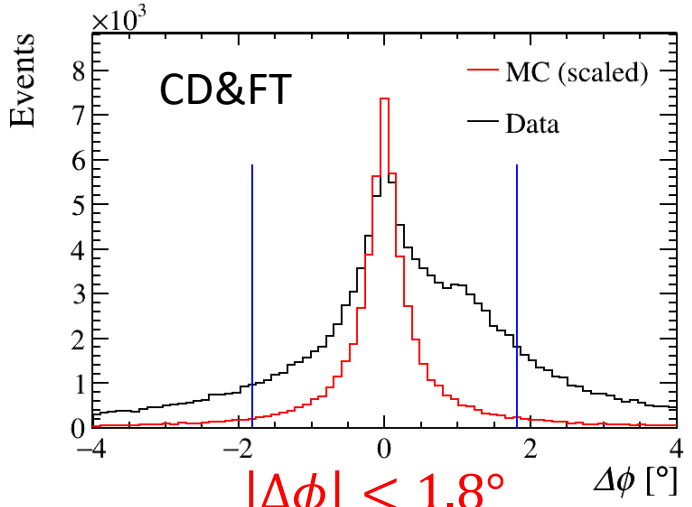
- Run Group B (RGB) Data
  - Collected in 2019 spring and 2020 spring
  - Beam: 10.6/10.4/10.2 GeV electron beam with an average polarization of 86%
  - Target: Unpolarized liquid deuterium target of 5 cm length
- Select $en\gamma$ final states
  - $p_e > 1$ GeV, $p_n > 0.35$ GeV, $p_\gamma > 2$ GeV
  - Reaction kinematics: $Q^2 > 1$ GeV^2, $W > 2$ GeV
  - Exclusivity selections
    - Variables: $\Delta\phi$, missing m_X^2 of $en \to en\gamma X$, m_X^2 and p_X of $ed \to en\gamma X$, etc.
    - Criteria are determined from MC, separately for CD&FT (n in CD & γ in FT) and CD&FD (n in CD & γ in FD)
- Remaining backgrounds
  - Fake neutrons and π^0 contamination



ϕ: angle between leptonic plane and hadronic plane

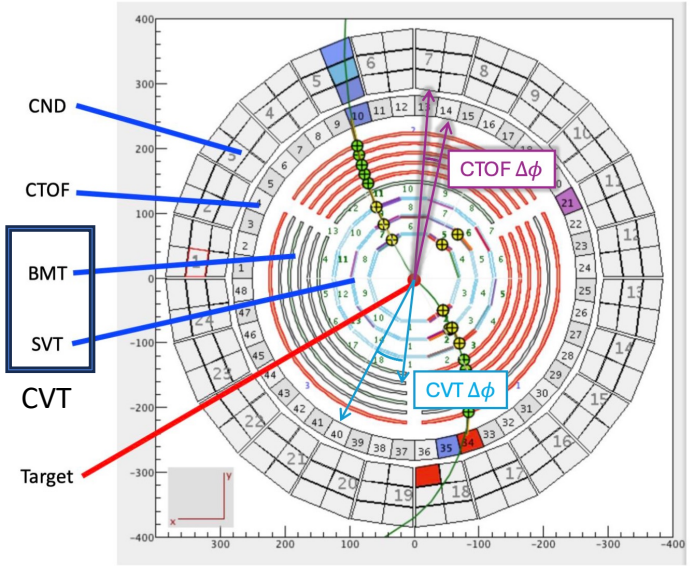
$\Delta\phi$: difference in ϕ between

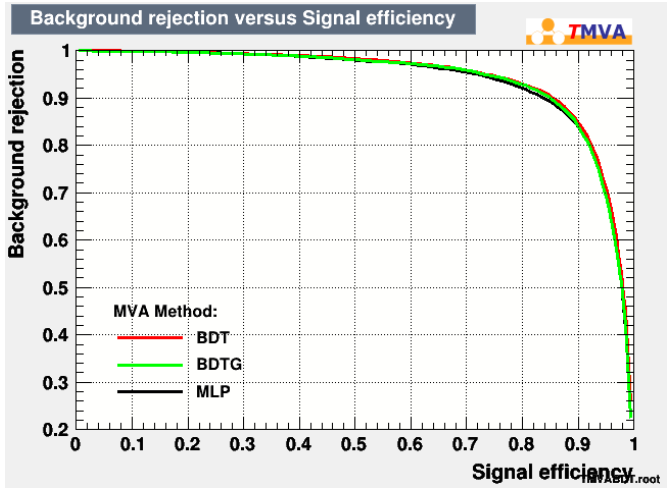
- hadronic plane formed by n and virtual γ^*
- hadronic plane formed by n and outgoing γ

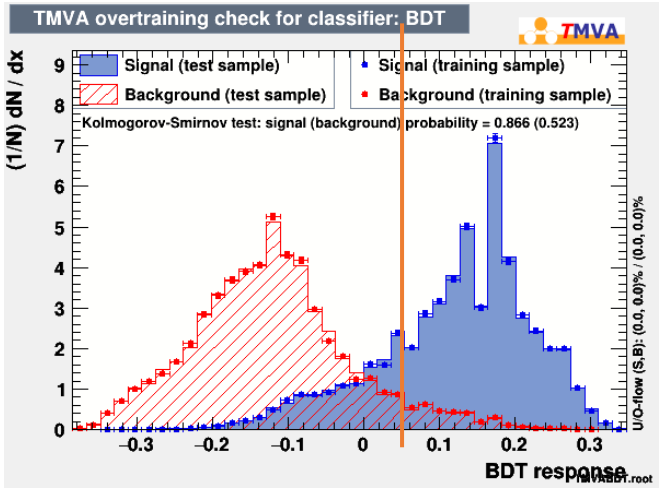


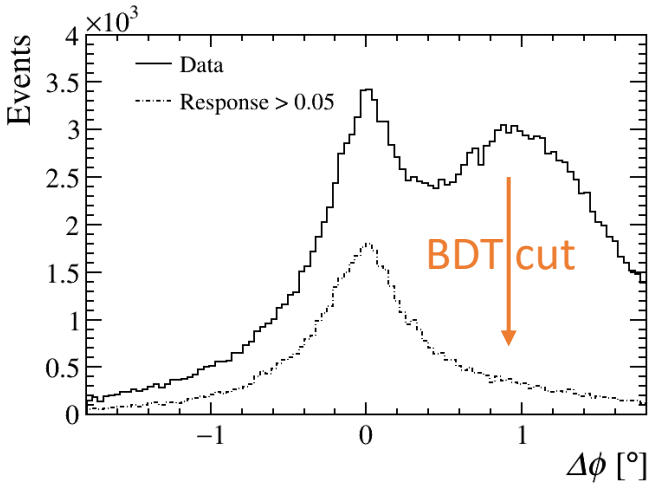
Use BDT to reduce fake neutrons

- The selection of neutron is a challenge in this analysis
  - The tracking system (CVT) in CD has dead or low-efficiency regions
  - Protons having no tracks in the CVT but having hits in CND will be misidentified as neutrons
- Boosted Decision Tree (BDT) classifier
  - Training sample: MC with neutron target and proton target
  - Training variables: Info at CTOF, CVT and CND
    - Number of clusters (tracks) at CTOF (CVT), deposit energy at CTOF and three layers of CND, etc.









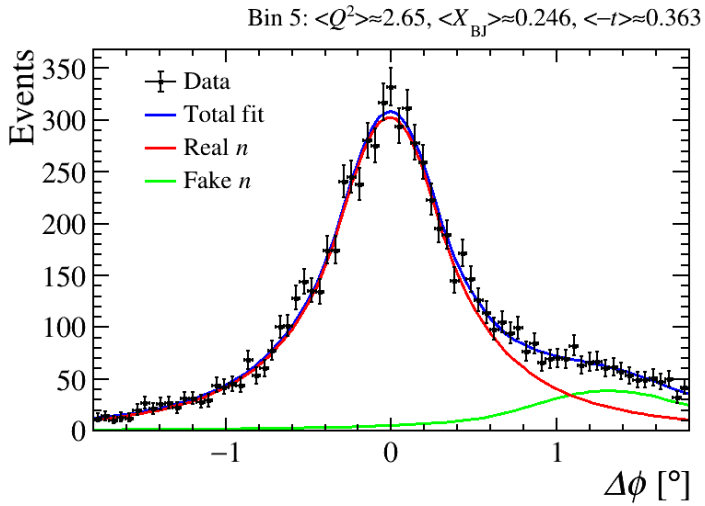
Selection: BDT response > 0.05

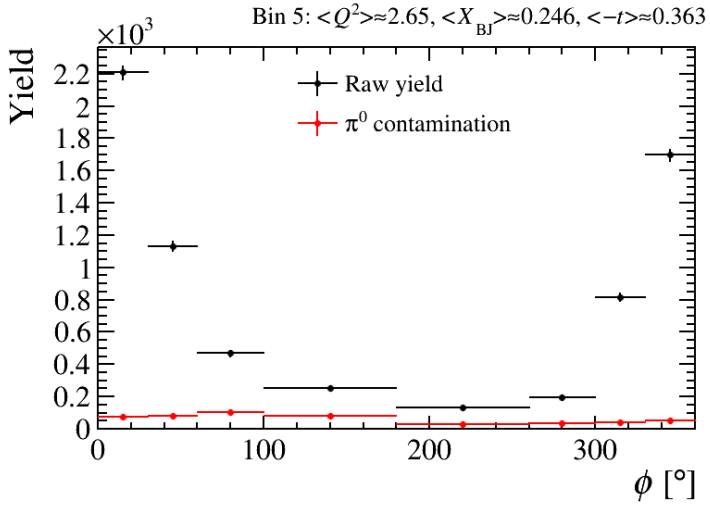
Background subtraction

- Remaining fake neutrons after the BDT cut
  - Perform the $\Delta\phi$ fit in each kinematic bin
  - Fake neutrons: 7.2%-23.0% across different bins
- π^0 production contamination $en \rightarrow en\pi^0(\rightarrow \gamma\gamma)$
  - $N_{\mathrm{DVCS}} = N_{\mathrm{en}\gamma}^{\mathrm{raw}} - N_{en\pi^0} \times f^{\mathrm{MC}} = N_{\mathrm{en}\gamma} - N_{en\pi^0} \times \frac{N_{en\pi^0(1\gamma)}^{\mathrm{MC}}}{N_{en\pi^0(2\gamma)}^{\mathrm{MC}}}$
    - $N_{en\pi^0}$ is the yield of selected π^0 events in RGB data
    - $f^{\mathrm{MC}} = \frac{N_{en\pi^0(1\gamma)}^{\mathrm{MC}}}{N_{en\pi^0(2\gamma)}^{\mathrm{MC}}}$

      Partially reconstructed $en\pi^0(1\gamma)$ passing DVCS selection

      Fully reconstructed $en\pi^0(2\gamma)$ passing π^0 production selection
  - Overall π^0 contamination: 3.7%
    - It is still significant in some kinematic bins
    - 0.0%-48.8% across different bins





Extraction of nDVCS cross section

- Unpolarized cross section

$$\frac{d^4\sigma_{en\to en\gamma}}{dQ^2 dx_{\mathrm{BJ}} dt d\phi} = \frac{N_{en\to en\gamma}}{L \cdot \varepsilon_{acc} \cdot V}$$

  - $N_{en\to en\gamma}$ is the yield obtained after the background subtraction in each $(Q^2, x_{\mathrm{BJ}}, -t, \phi)$ bin
  - Luminosity $L = 134.1\ \mathrm{fb}^{-1}$
  - Acceptance ε_{acc} determined from MC
    - Neutron detection efficiency is corrected using the RGB $ep \to en\pi^+$ data
    - BDT cut efficiency is corrected by data (performing the $\Delta\phi$ fit)
  - V is the bin volume

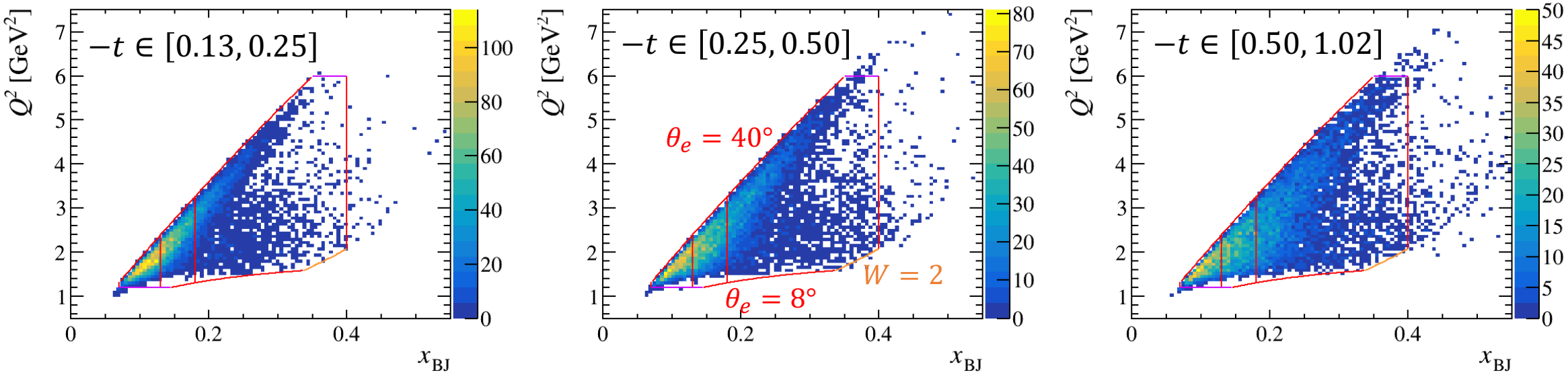
- Polarized cross-section difference

$$\frac{d^4\vec{\sigma}_{en\to en\gamma}}{dQ^2 dx_{\mathrm{BJ}} dt d\phi} - \frac{d^4\overleftarrow{\sigma}_{en\to en\gamma}}{dQ^2 dx_{\mathrm{BJ}} dt d\phi} = \frac{N_+ - N_-}{L_{+(-)} \cdot P \cdot \varepsilon_{acc} \cdot V}$$

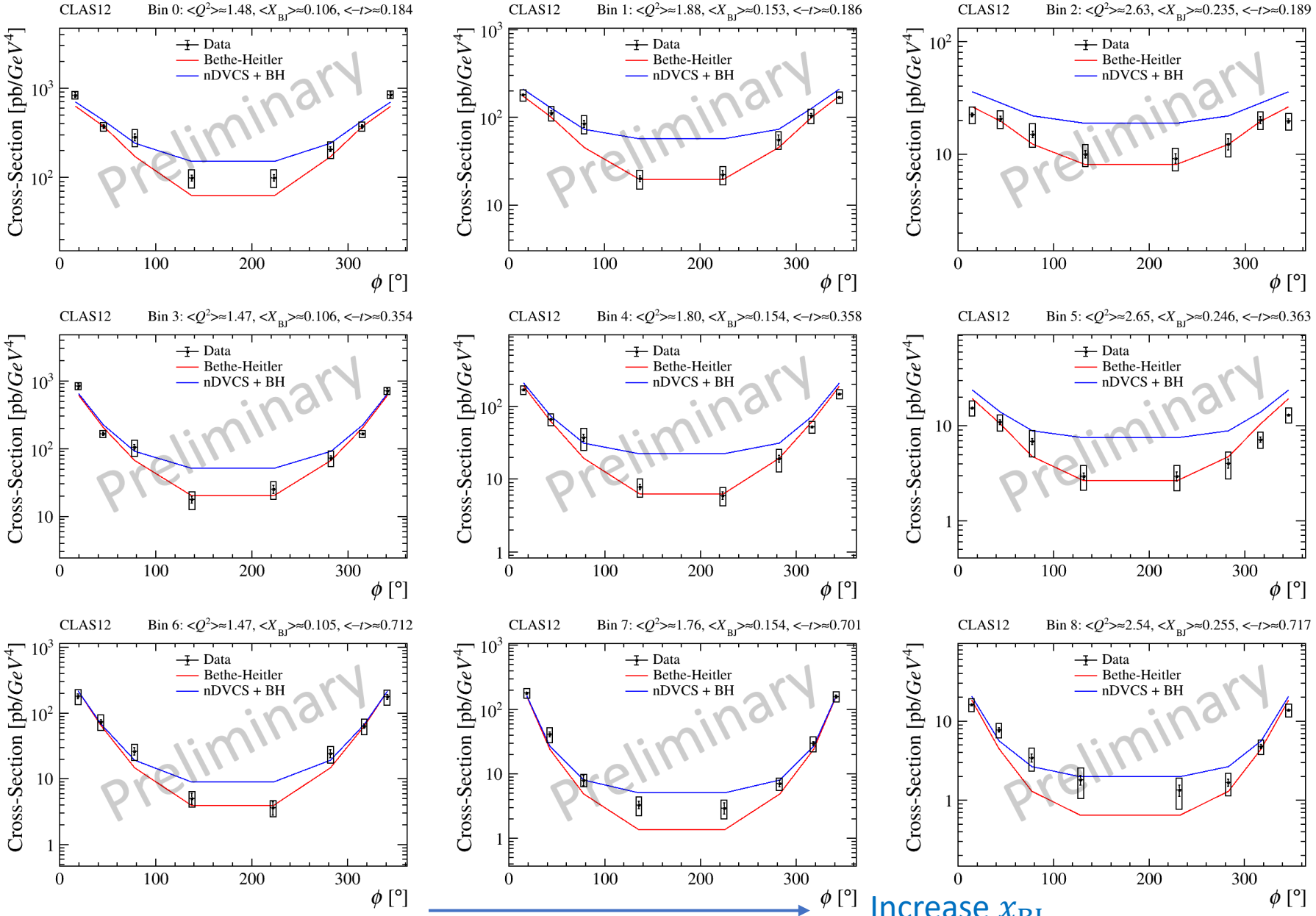
  - N_+ is the yield for positive beam helicity
  - N_- is the yield for negative beam helicity
  - Luminosity $L_{+(-)} = 64.5\ \mathrm{fb}^{-1}$
  - Beam polarization $P = 86\%$

Binning scheme

- nDVCS cross section is extracted as a function of ϕ in $(Q^2, x_{\mathrm{BJ}}, -t)$ bins
- 3 bins for $-t$: $[0.13, 0.25], [0.25, 0.50], [0.50, 1.02]$ GeV^2
- 3 bins for (Q^2, x_{BJ})
  - $1.2 < Q^2 < 6.0\ \mathrm{GeV}^2,\ 8° < \theta_e < 40°,\ W > 2\ \mathrm{GeV}$
  - x_{BJ} bins: $[0.07, 0.13], [0.13, 0.18], [0.18, 0.40]$

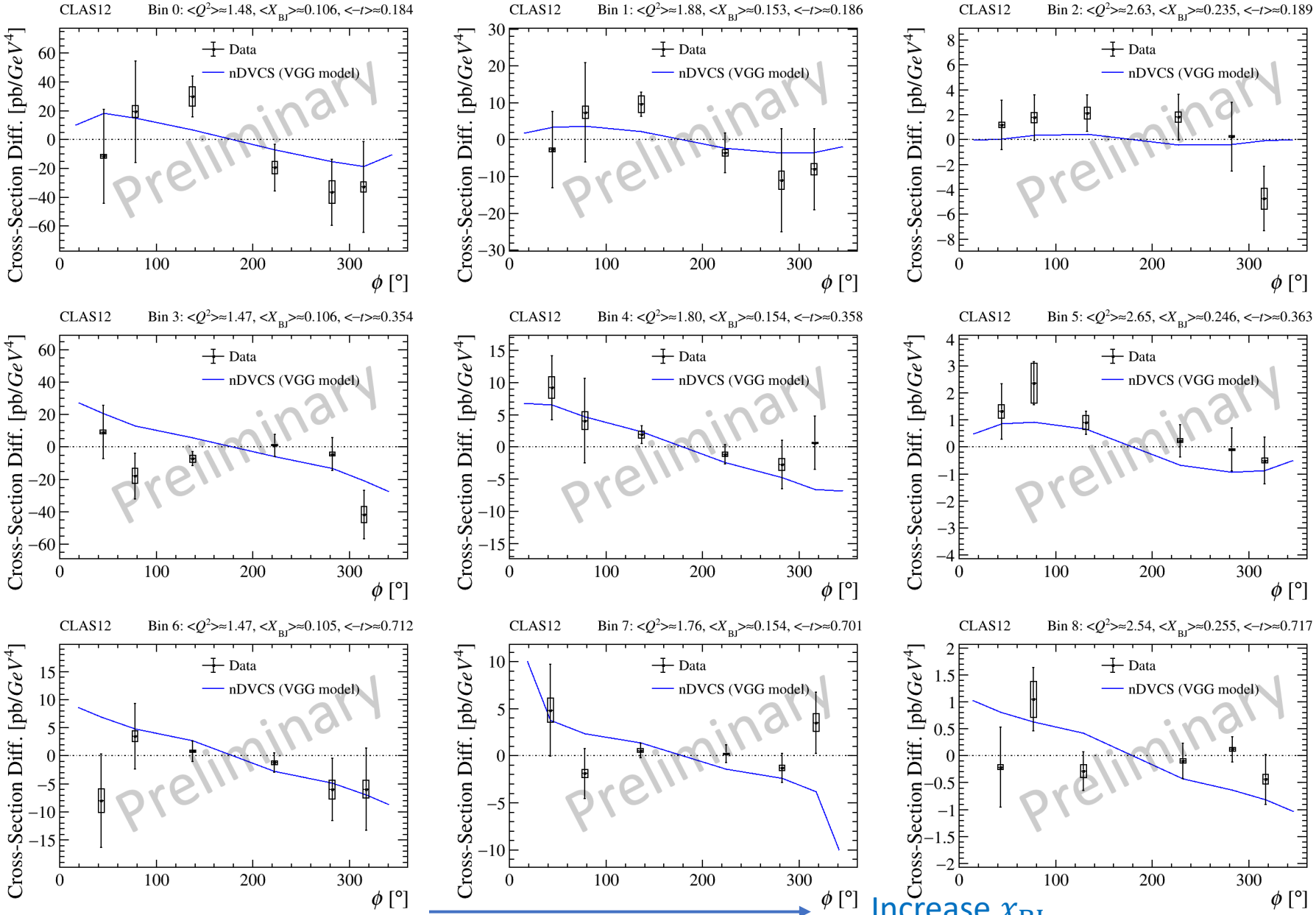


Unpolarized cross section



- Linked mainly to the real CFF of GPD E
- Error bars: statistical
  Boxes: systematic
- The data are compatible with the BH calculations at ϕ edges
- nDVCS+BH predictions: VGG model with $J_u = 0.3$ and $J_d = 0.1$
- Predictions overshoot the data in the central-ϕ region, indicating the real CFF of E is not correctly parametrized in the VGG model

Polarized cross-section difference

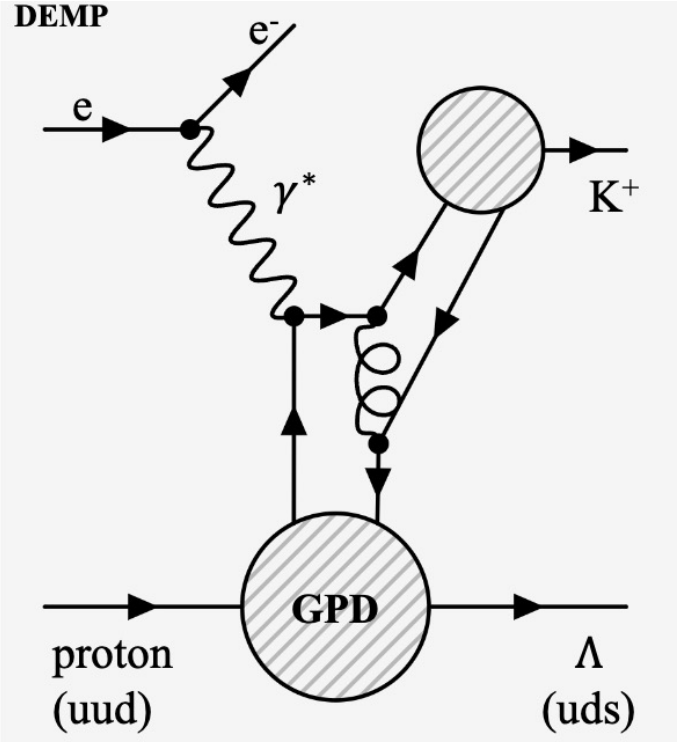


$$\Delta\sigma = \frac{N_+ - N_-}{L_{+(-)} \cdot P \cdot \varepsilon_{\text{acc}} \cdot V}$$

- Linked to the imaginary CFF of GPD E
- Error bars: statistical
  Boxes: systematic
- nDVCS predictions: VGG model with $J_u = 0.3$ and $J_d = 0.1$
- The data are consistent with the predictions given the large statistical uncertainties

Λ polarization in $K^+\Lambda$ electroproduction

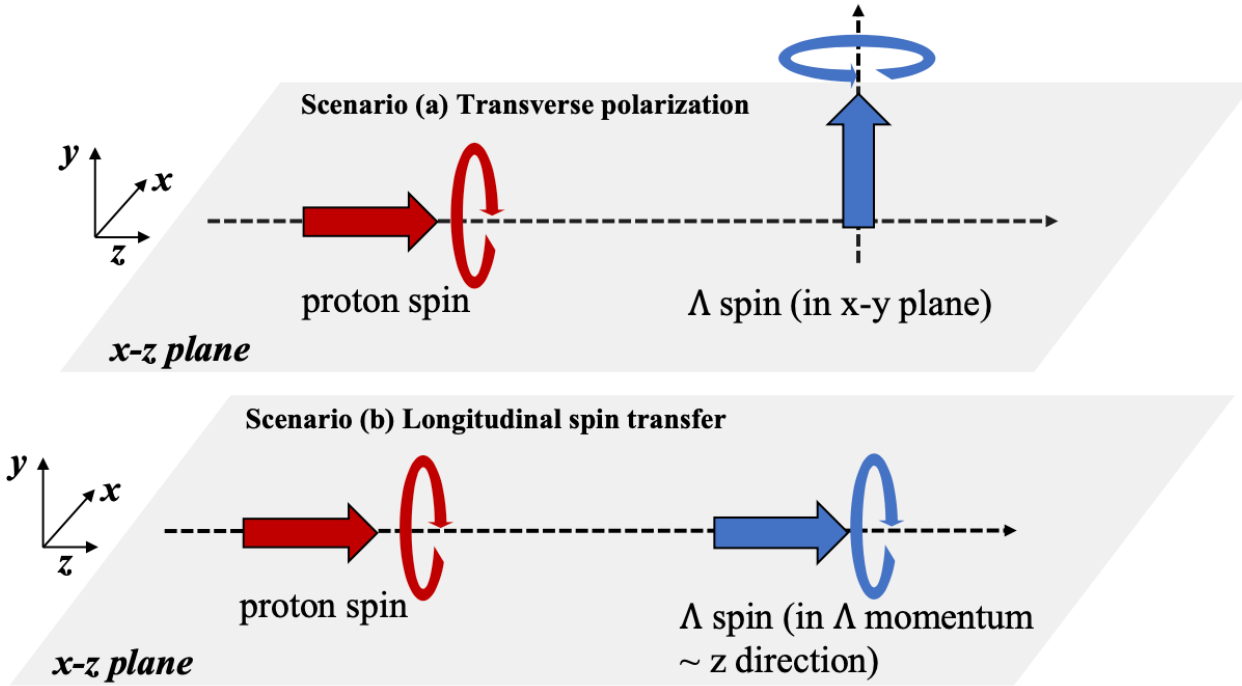
- Motivation
  - Probe chiral-odd GPD
    - Difficult to access (helicity flip processes are suppressed)
    - Λ polarization is a sensitive probe for the chiral-odd GPD
  - Probe the origin of Λ transverse polarization
    - Λ polarization puzzle: unexpected transverse Λ polarization in unpolarized collisions (pp, ep, etc.)
    - Key question: the underlying mechanism of Λ polarization
- Approach
  - $ep \rightarrow eK^+\Lambda$ with longitudinally polarized target
    - $\Lambda \rightarrow p\pi^-$: Self-analyzing weak decay
    - Exclusive process: Simplify the picture of Λ polarization
      - No fragmentation, no feed-down
    - Polarized target: Study the spin transfer from the target



PhysRevC.109.055205

Analysis goal and data sample

- Find out which direction the Λ is polarized
  - Scenario (a): Measure transverse polarization P_n relative to the production plane
  - Scenario (b): Measure longitudinal spin transfer D_{LL} from the target
- Run Group C (RGC) Data
  - Collected in summer 2022, fall 2022 and spring 2023
  - Beam: 10.5 GeV highly polarized electron beam
  - Target: Longitudinally polarized NH3 + background targets



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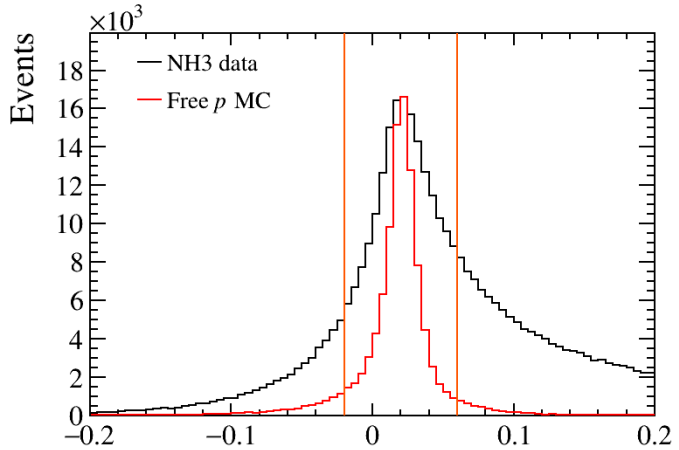
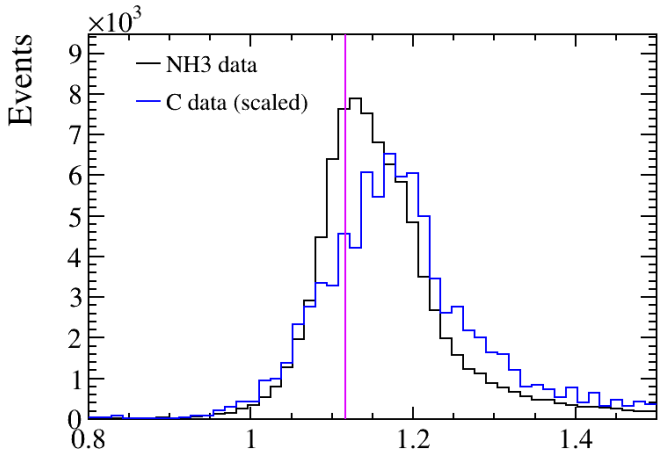
Analysis status

- Select $ep \to eK^+\Lambda(\to p\pi^-)$ data
  - Final states: eK^+p (π^- is not required)
    - Limited detection efficiency for low momentum π^-
  - $p_e > 1$ GeV, $p_{K^+} > 0.3$ GeV, $p_p > 0.3$ GeV
  - e, K^+, p are all reconstructed in FD ($5° < \theta < 35°$)
  - Exclusivity selections
    - $p_X < 0.5$ GeV and $-0.02 < m_X^2 < 0.06$ GeV^2 for $ep \to eK^+pX$, etc.
- Feasibility and performance
  - Clear Λ signal peak for missing mass m_X for $ep \to eK^+X$
  - Compared with area-normalized carbon background to validate the free proton signal
  - Need to study the contamination of $K^+\Sigma^0$ channel



m_X^2 for missing π^- $(ep \to eK^+pX)$ [GeV²]



m_X for missing Λ $(ep \to eK^+X)$ [GeV]

Summary and outlook

- The nDVCS cross section is measured at the CLAS12 experiment, with an electron beam of about 10.4 GeV scattering off a liquid deuterium target
  - Both unpolarized cross section and polarized cross-section difference are extracted
    - Provide essential constraints the vastly unknown neutron CFFs
    - Bring considerable progress toward the quark flavor-separation of GPD
- The Λ polarization measurement in $K^+\Lambda$ electroproduction with a longitudinally polarized NH3 target is ongoing
  - Promising process to probe chiral-odd GPD and Λ polarization mechanism

Thank you!