Neutron DVCS Cross-Section Extraction at the CLAS12 Experiment

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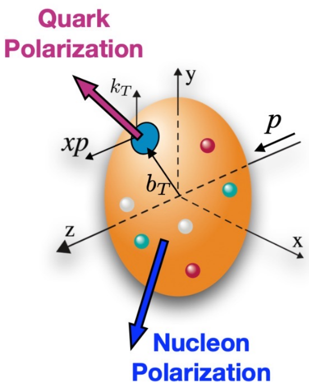
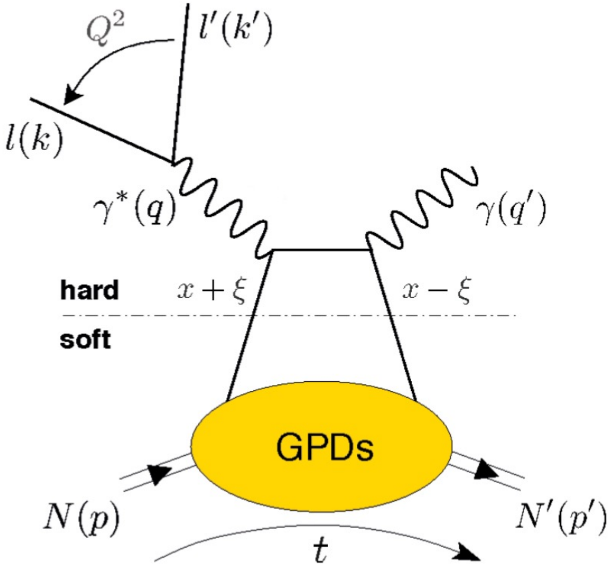
Outline

- Motivation
- CLAS12 experiment
- Event selection
- Backgournd subtraction
- Cross-section extraction
- Preliminary results
- Summary

Motivation

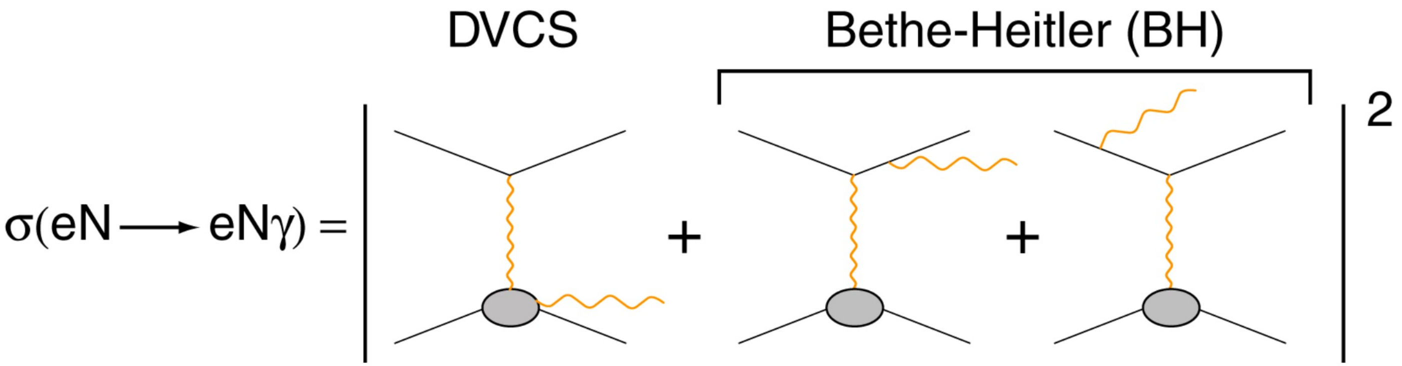
- Understanding the internal structure of nucleons remains one of the important challenges in hadronic physics
- The formalism of Generalized Parton Distributions (GPDs) provides a universal description of the partonic structure of the nucleon
  - Relate transverse position of partons to their longitudinal momentum
  - Give access to the angular momentum of quarks and gluons, the missing ingredient for understanding the nucleon spin composition
- The Deeply Virtual Compton Scattering (DVCS) is one of the cleanest channels to access GPDs
- For quark-helicity-conserving processes, the soft structure of the nucleon is parametrized by 4 GPDs for each quark flavor
  - Unpolarized GPDs H, E and polarized GPDs $\widetilde{H}, \widetilde{E}$
  - H and $\widetilde{H}$ conserve the spin of the nucleon
  - E and $\widetilde{E}$ correspond to a nucleon-spin flip





DVCS process

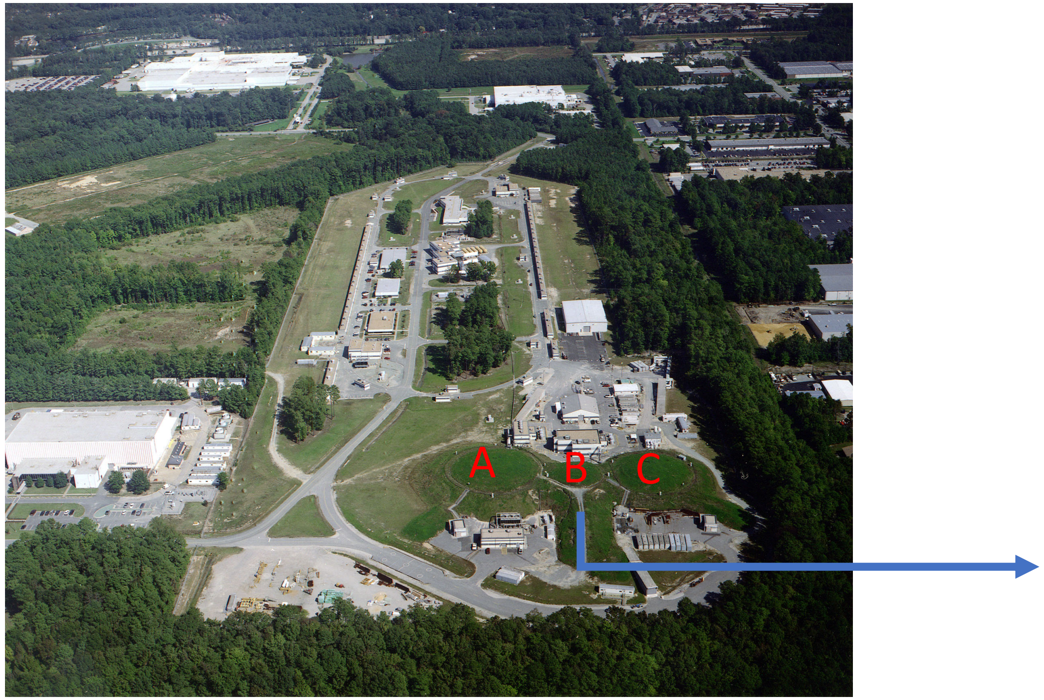
Motivation

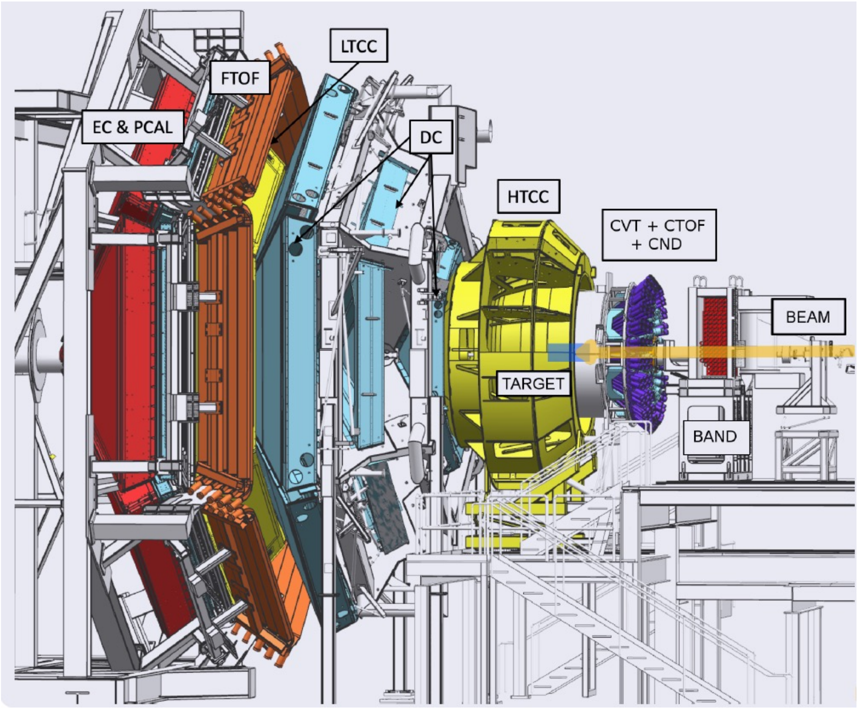


- DVCS shares the same final state with the Bethe-Heitler (BH) process
  - BH process: a real photon is emitted by either the incoming or the scattered electron
- DVCS information can be extracted from the DVCS/BH interference term
- DVCS observables are linked to GPDs via the complex-valued functions: 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

CEBAF and CLAS12 at Jefferson Laboratory

- Continuous Electron Beam Accelerator Facility (CEBAF)
  - Up to 12 GeV electrons
  - Hall B: CLAS12 detector
  - Ideal platform to study GPDs in the valence quark region

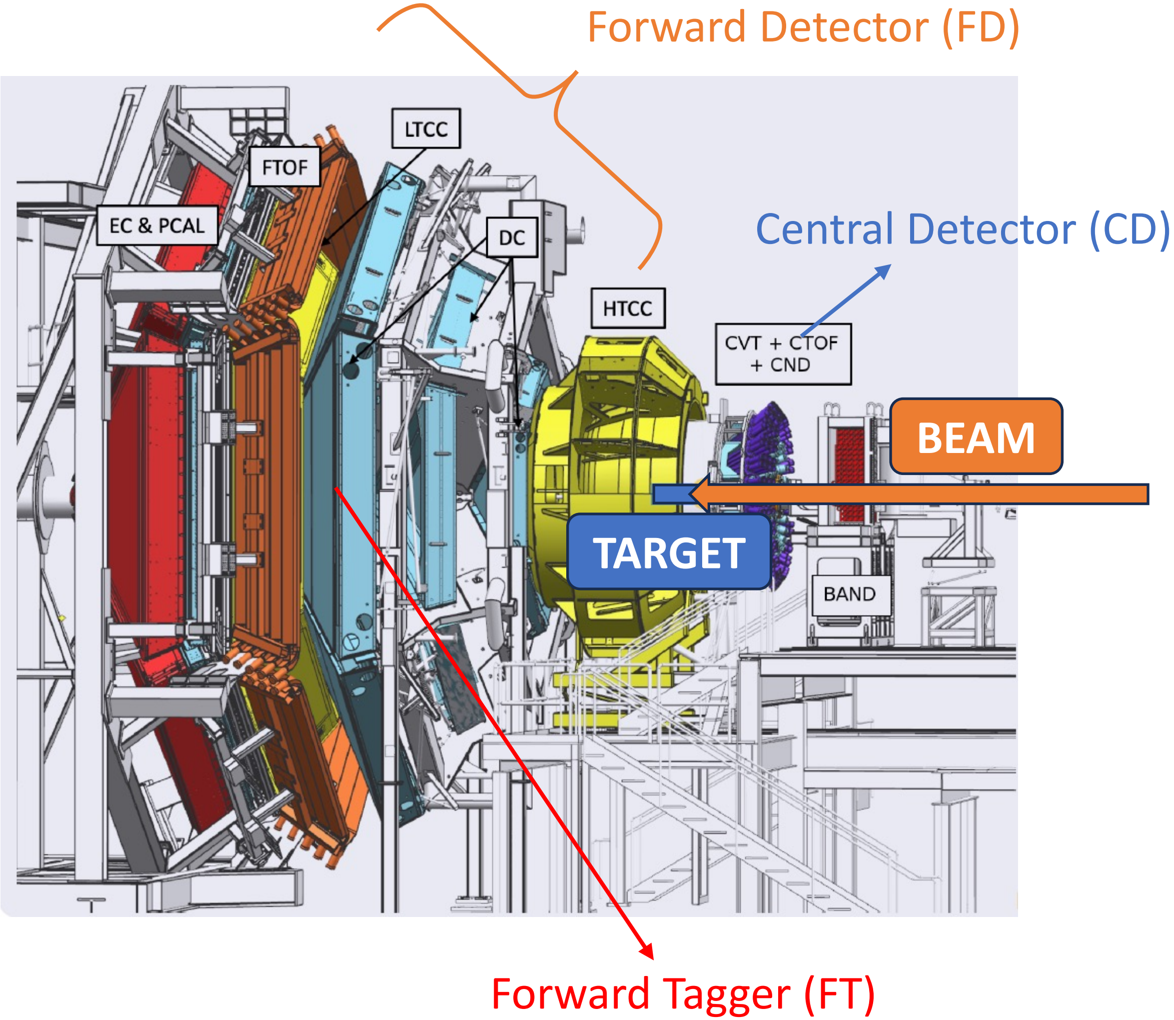




Hall B: CLAS12 detector

CLAS12 detector and Data sample

- 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)
- Run Group B (RGB) Data
  - Collected in 2019 spring and 2020 spring (inbending)
  - 10.6/10.4/10.2 GeV electron beam
    - With an average polarization of 86%
    - Scattering off an unpolarized liquid deuterium target of 5 cm length

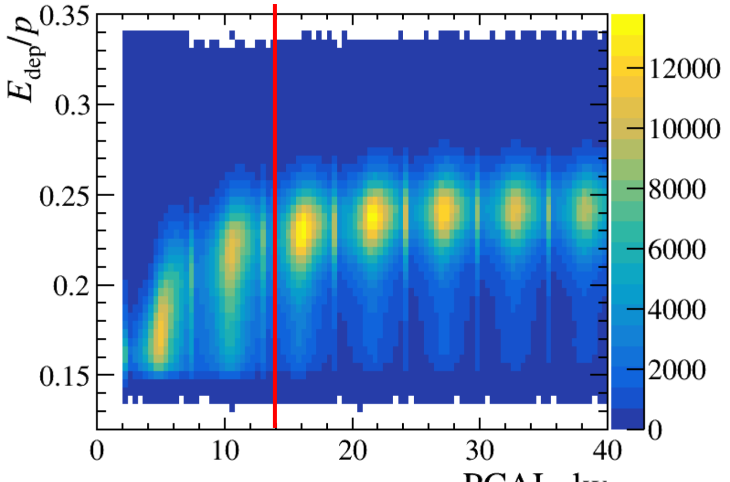


Select nDVCS data

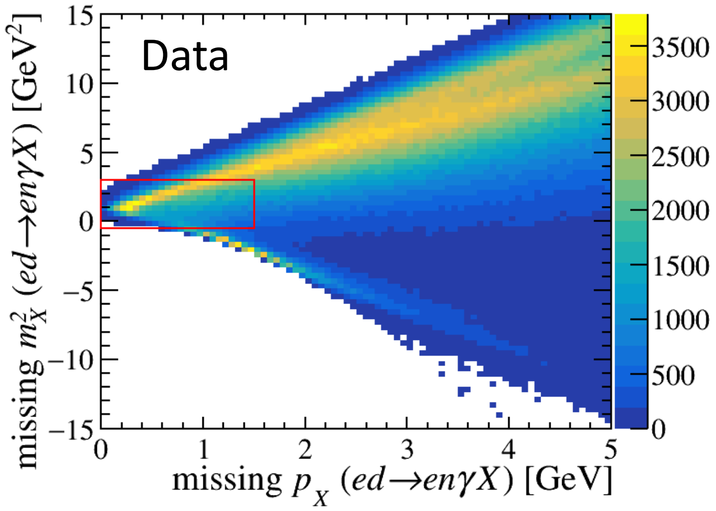
- Select $en\gamma$ final states
  - $p_e > 1$ GeV, $p_n > 0.35$ GeV, $p_\gamma > 2$ GeV
  - Fiducial cuts: exclude particles at the detector's edge where MC doesn't accurately reproduce data
- Reaction kinematics: $Q^2 > 1\ \mathrm{GeV}^2$, $W > 2$ GeV
- Pre-selection on missing m_X^2 and p_X of $ed \to en\gamma X$
  - Reduce events from other channels

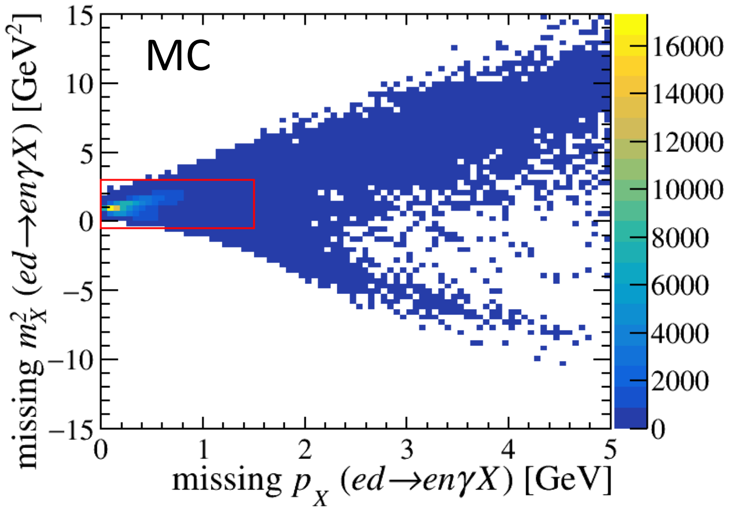
Electron	Photon	Neutron
In FD: PCAL: lv(lw) > 14 DC: edge > 6	In FD: PCAL: lv(lw) > 14	In CD: $40° < \theta_n < 140°$
	In FT: $x^2 + y^2 > 72$	

Pre-selection	$-0.5 < m_X^2 < 3\ \mathrm{GeV}^2$ $0 < p_X < 1.5$ GeV



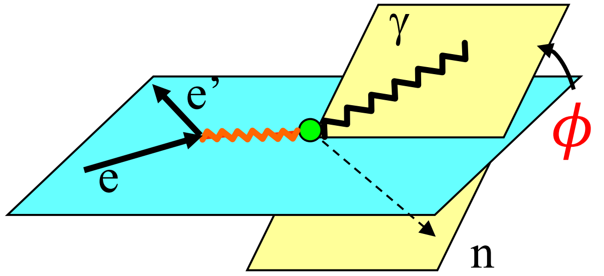
e^- in PCAL



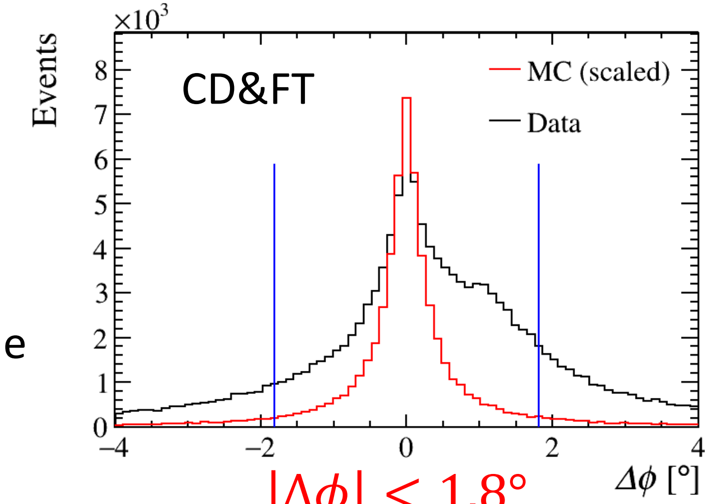


Exclusivity selection

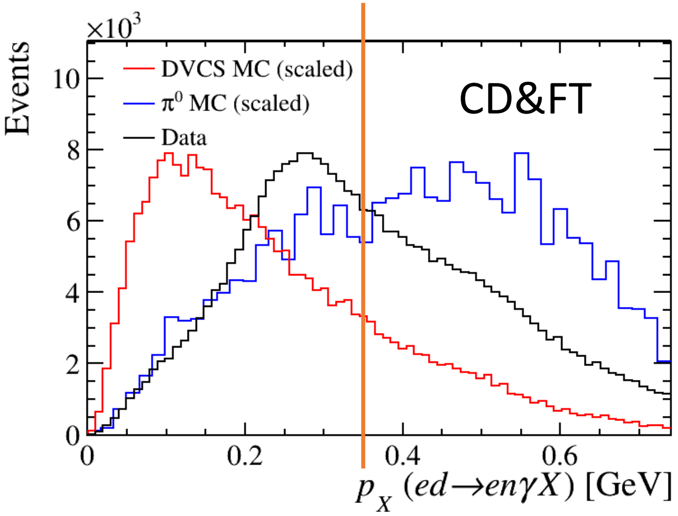
- Exclusivity variables
  - $\Delta\phi$, missing m_X^2 of $en \to en\gamma X$, m_X^2 and p_X of $ed \to en\gamma X$, etc.
- Selection criteria determined from MC
  - Separately for CD&FT (n in CD & γ in FT) and CD&FD (n in CD & γ in FD)



ϕ: angle between leptonic plane and hadronic plane



$|\Delta\phi| < 1.8°$



- $\Delta\phi$: difference in ϕ between
  - hadronic plane formed by the neutron and the virtual photon
  - hadronic plane formed by the neutron and the outgoing photon

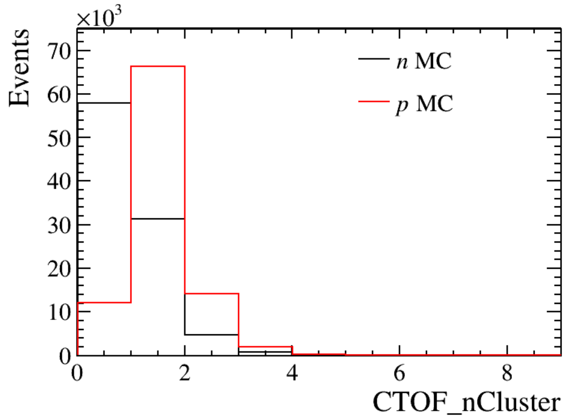
- $p_X < 0.35$ GeV for $ed \to en\gamma X$
  - The π^0 background $ed \to en\pi^0(\to \gamma\gamma)$ contributes to larger p_X

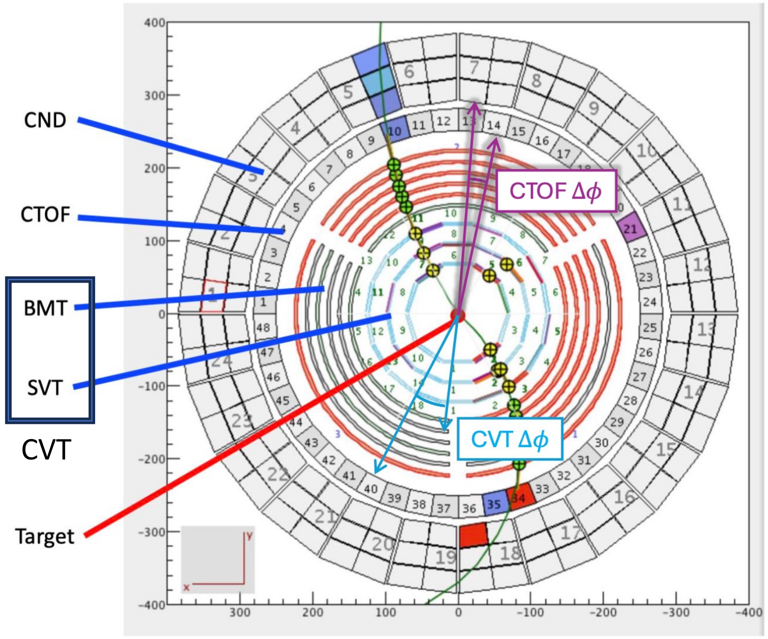
➢ The data and MC distributions are different at this stage

➢ Mainly due to backgrounds in data: fake neutrons and π^0 contamination

TMVA training to reduce fake neutrons

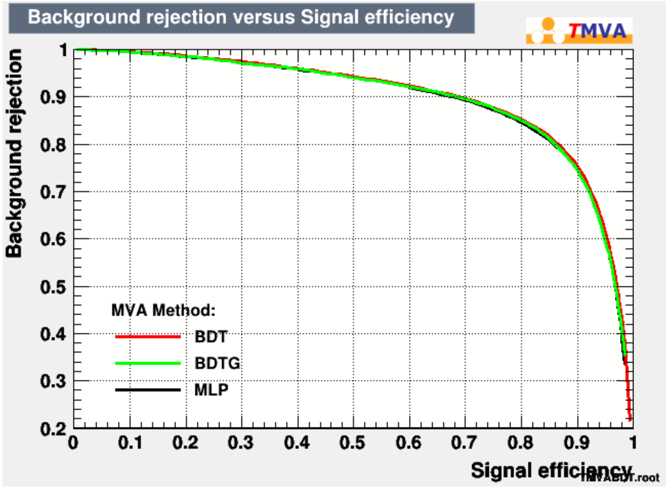
- The selection of neutron is a challenge in this analysis
  - The tracking system (CVT) in CD has dead or low-efficiency regions
  - Protons having no tracks in the tracking system but hits in CND will be misidentified as neutrons
- The TMVA training is used to reduce these fake neutrons
  - Training sample
    - MC with neutron target and proton target
  - Training variables (only info at CTOF, CVT and CND)
    - Number of clusters at CTOF (most distinguishable)
    - Smallest $\Delta\theta_{\mathrm{CTOF}}$ and $\Delta\phi_{\mathrm{CTOF}}$ between CTOF clusters and reconstructed neutron or proton $n(p)$
    - Number of tracks at CVT
    - Smallest $\Delta\theta_{\mathrm{CVT}}$ and $\Delta\phi_{\mathrm{CVT}}$ between CVT tracks and $n(p)$
    - Number of hits for the $n(p)$ cluster at CTOF and three layers of CND
    - Deposit energy at CTOF and three layers of CND

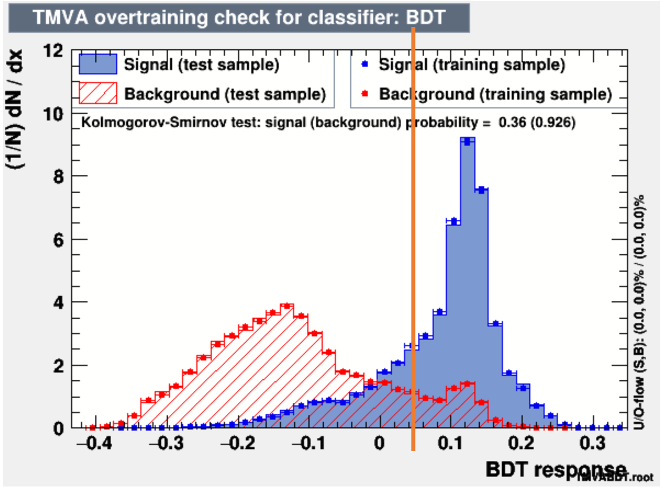


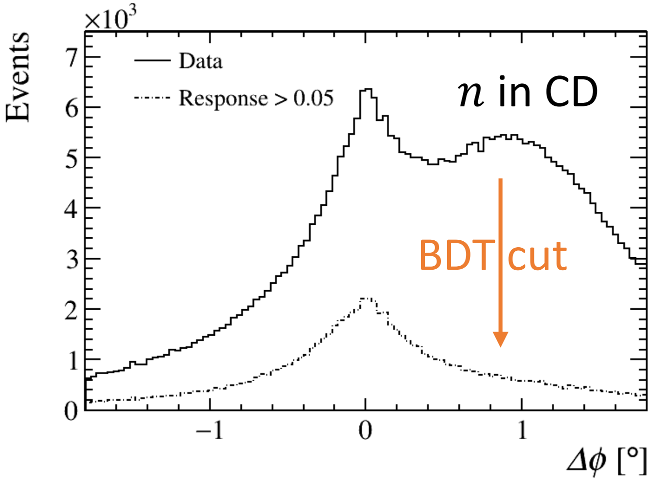


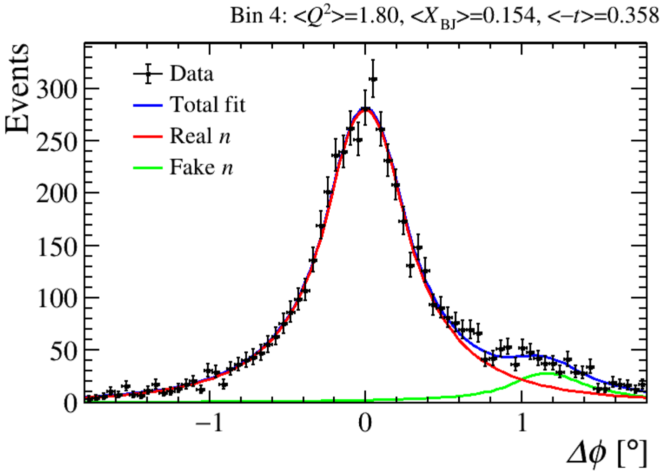
Boosted Decision Tree (BDT) classifier

- Multilayer perceptron (MLP), adaptive and gradient BDT have been trained
- The adaptive BDT is chosen because its performance is slightly better
- Selection:
    - BDT response > 0.05
- $N = 3.61{\times}10^5$ for n in CD
- $N = 0.77{\times}10^5$ after the BDT response selection
- The remaining fake neutrons after the BDT cut are subtracted by the $\Delta\phi$ fit in kinematic bins









Study of π^0 production contamination

- $en \to en\pi^0(\to \gamma\gamma)$ background subtraction:
  - $N_{\text{DVCS}} = N_{en\gamma} - N_{en\pi^0} \times f^{\text{MC}} = N_{en\gamma} - N_{en\pi^0} \times \frac{N^{\text{MC}}_{en\pi^0(1\gamma)}}{N^{\text{MC}}_{en\pi^0(2\gamma)}}$

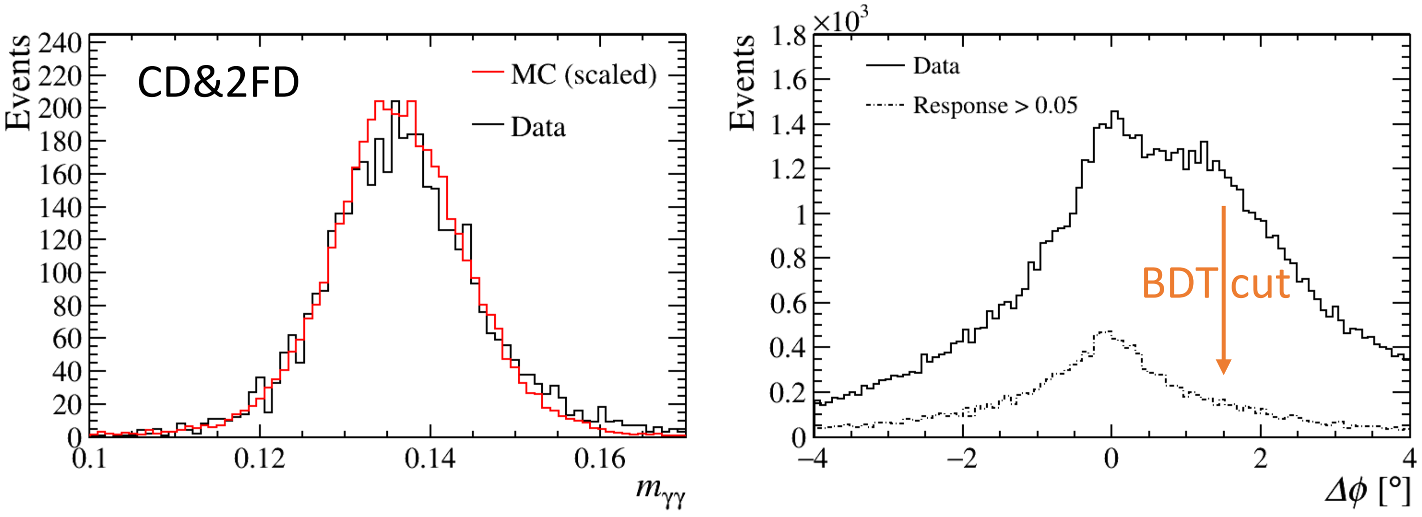
Partially reconstructed $en\pi^0(1\gamma)$ passing DVCS selection

Fully reconstructed $en\pi^0(2\gamma)$ passing π^0 production selection

- Select π^0 production data
  - Select $en\gamma\gamma$ final states
    - $p_e > 1$ GeV, $p_n > 0.35$ GeV, $p_\gamma > 0.6$ GeV
    - $0.10 < m_{\gamma\gamma} < 0.17$ GeV
  - Apply fiducial cuts and exclusivity cuts
  - Use BDT to reduce fake neutrons

➢ Using events for n in CD to perform the subtraction
  ➢ π^0 contamination: 4.4%

- CD&2FD: n in CD and 2 γ in FD



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 $L = 134.1\times 10^3\ \mathrm{pb}^{-1}$
  - 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

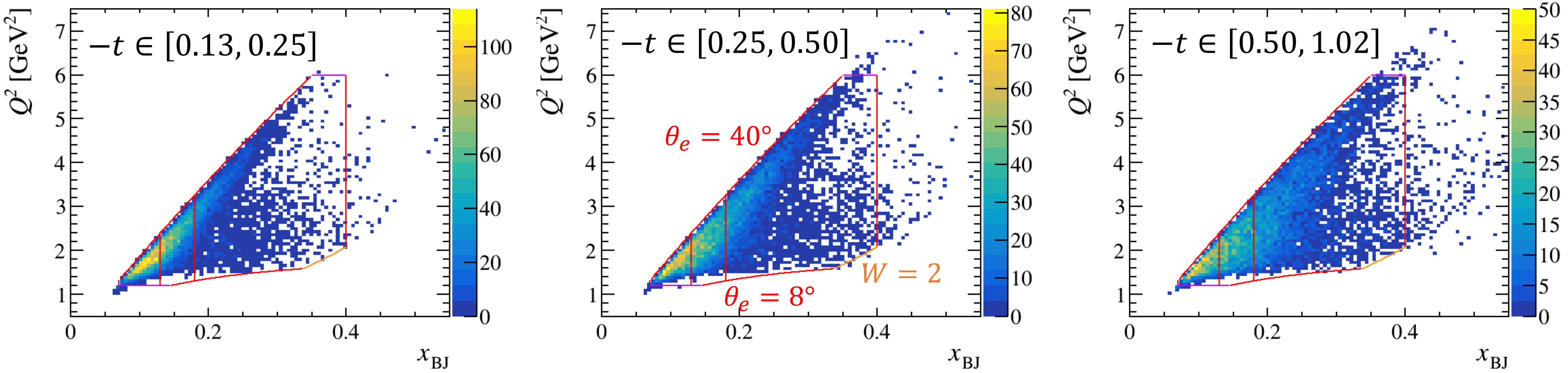
- Polarized cross-section difference

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

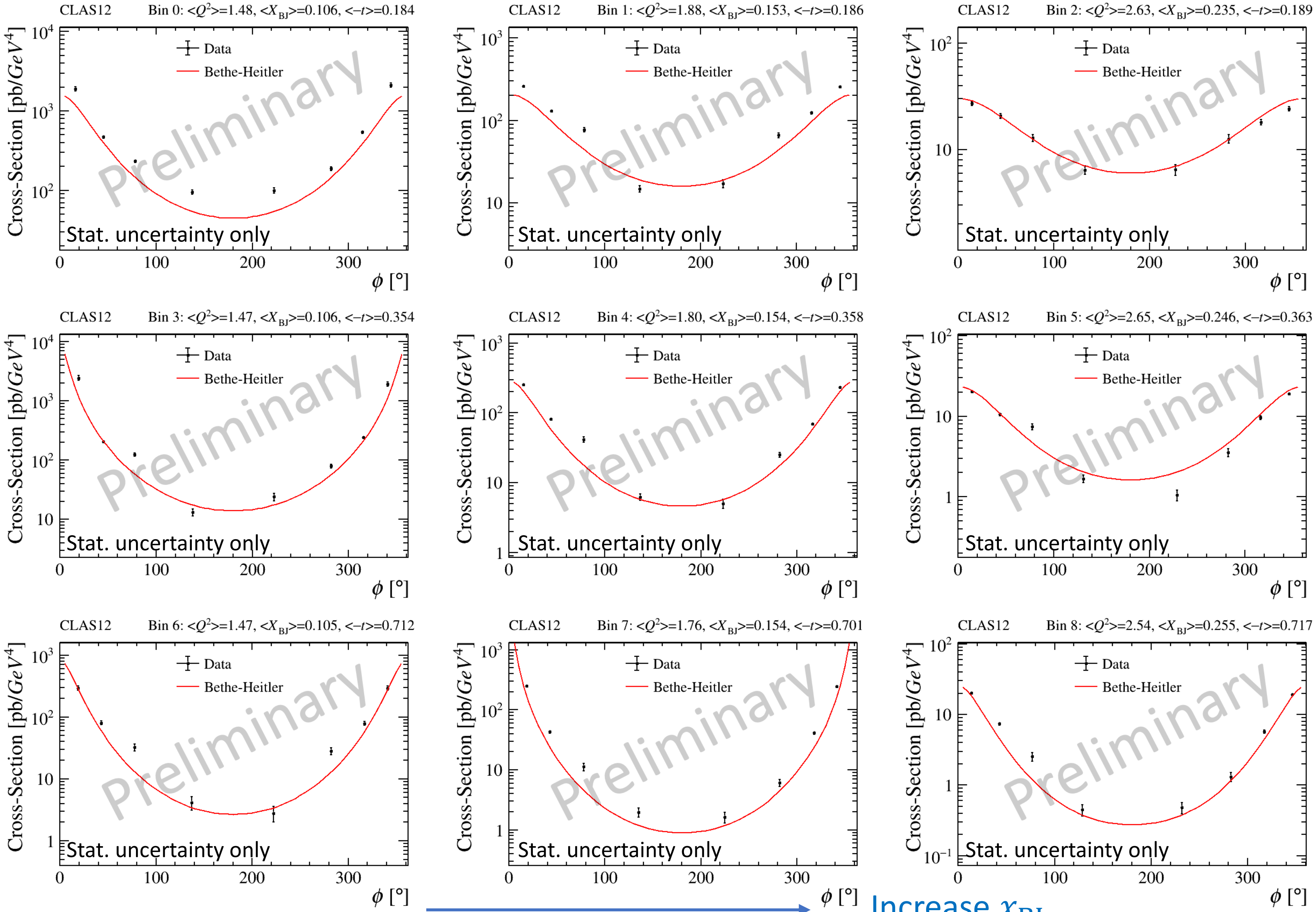
  - N_+ is the yield for positive beam helicity
  - N_- is the yield for negative beam helicity
  - Luminosity $L_{+(-)} = 64.5\times 10^3\ \mathrm{pb}^{-1}$
  - Beam polarization $P = 86\%$

Binning scheme

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



Unpolarized cross section



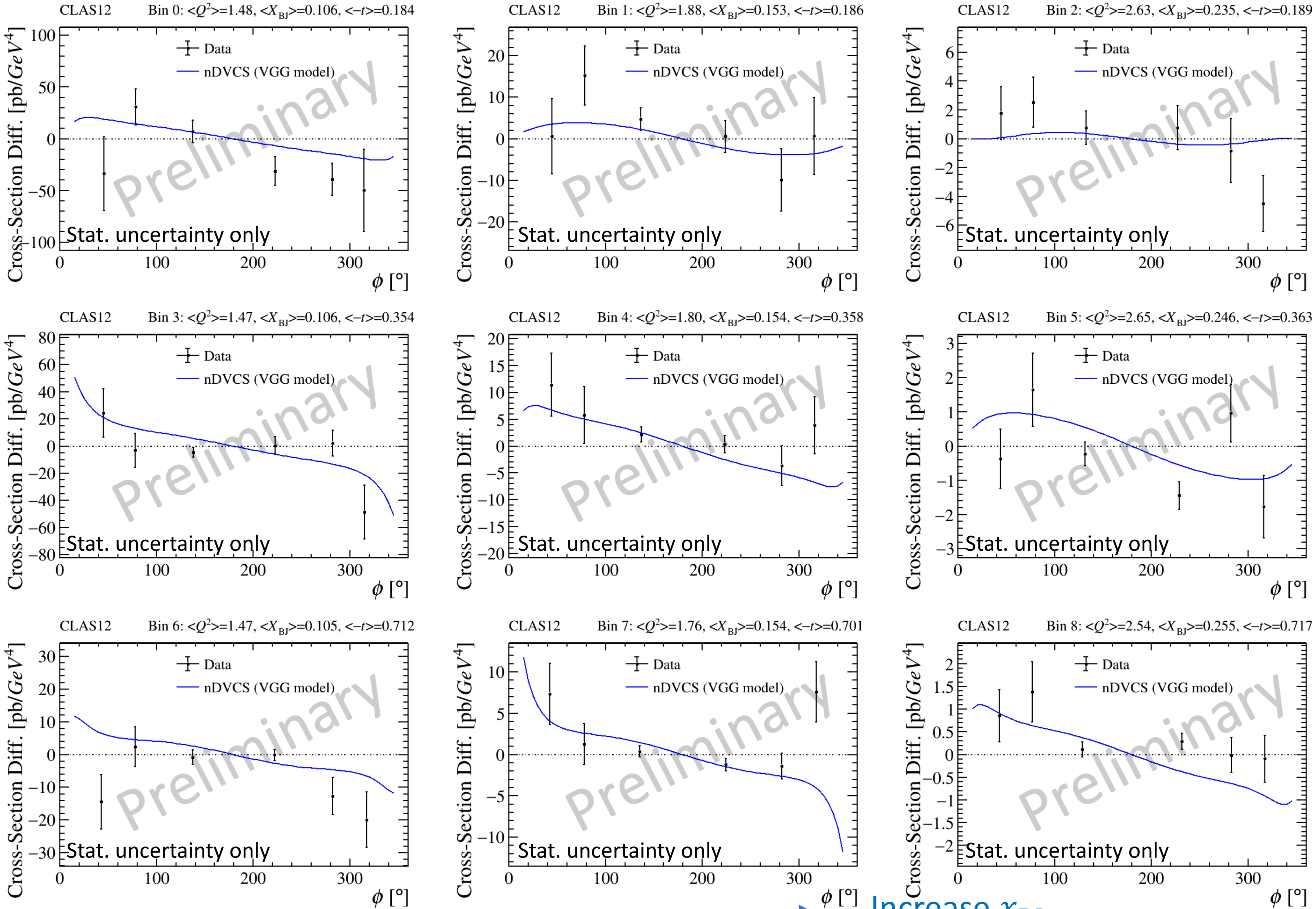
Increase $-t$

Increase x_{BJ}

$$\sigma = \frac{N_{en\to en\gamma}}{L \cdot \varepsilon_{\mathrm{acc}} \cdot V}$$

- Linked mainly to the real CFF of E
- Only the statistical uncertainty is presented
- The measured results are at the same level with the BH calculations

Polarized cross-section difference



Increase $-t$

Increase x_{BJ}

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

- Linked to the imaginary CFF of E
- Only the statistical uncertainty is presented
- nDVCS predictions: VGG model with particular parameters $J_u = 0.3$ and $J_d = 0.1$
- The measured results are consistent with the predictions given the large statistical uncertainties

Summary

- The measurement of nDVCS cross section can provide unique information on GPDs
- The nDVCS cross section is measured at the CLAS12 experiment, with a ∼10.4 GeV electron beam scattering off a liquid deuterium target
- Both unpolarized cross section and polarized cross-section difference are extracted
  - The measured unpolarized cross sections are compatible with the BH calculations
  - The polarized cross-section differences are consistent with the VGG model predictions given the large statistical uncertainties
- The systematic uncertainties are still under study, and the analysis will be completed soon

Thank you!