Neutron DVCS Cross Section Extraction at the CLAS12 Experiment

Li XU

CLAS Collaboration Meeting

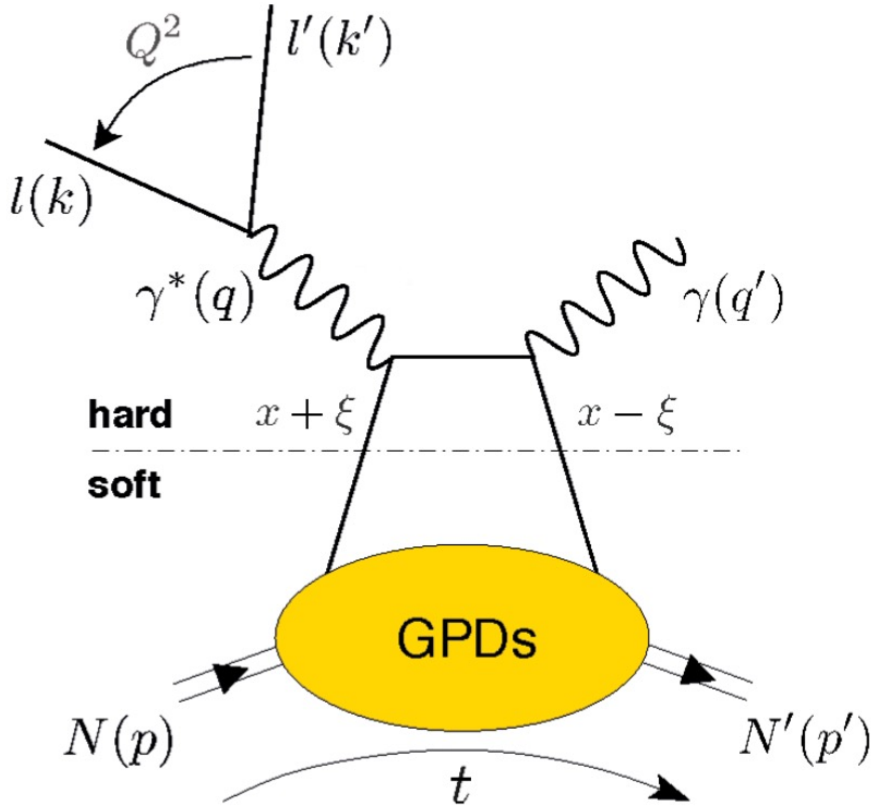
Jul 9, 2025

Outline

- Motivation
- Data and MC samples
- PID and fiducial cuts
- Neutron DVCS (nDVCS) selection
- Study of π^0 production contamination
- Acceptance and corrections
- Preliminary cross-section
- Summary and next to do

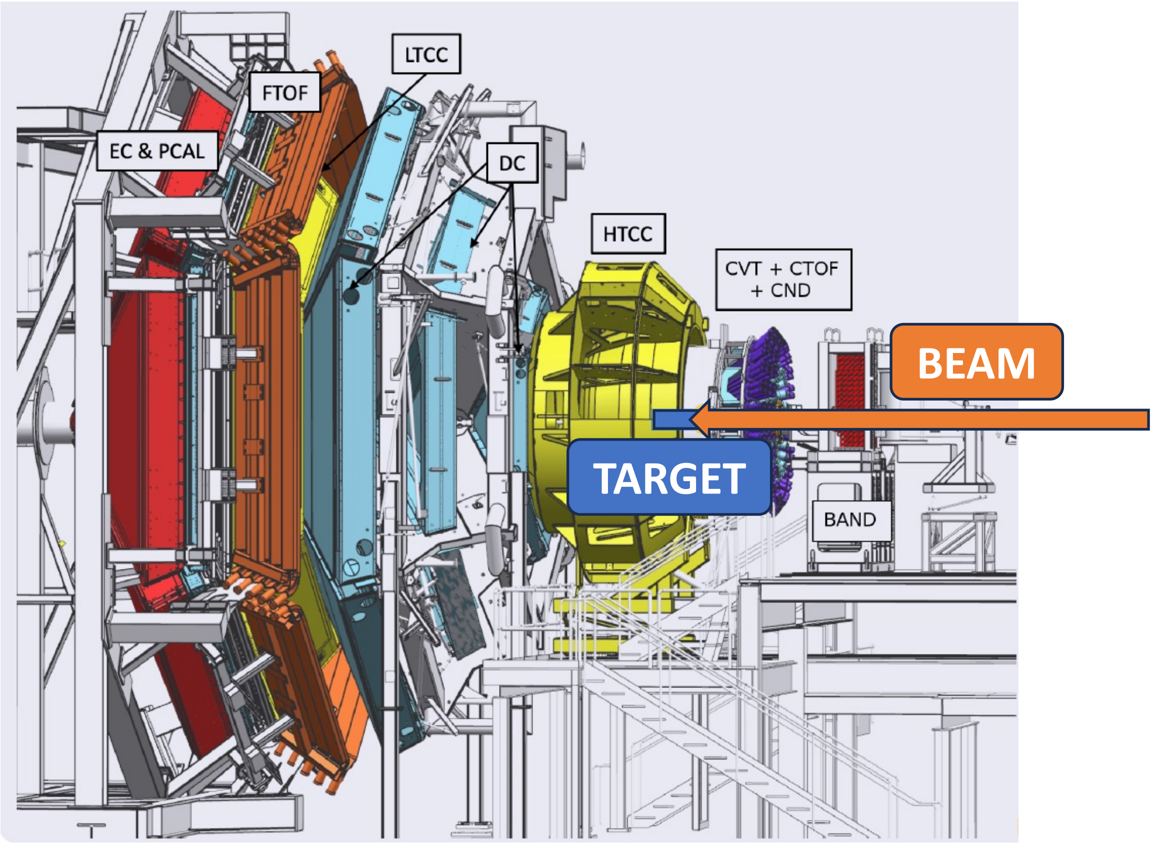
Motivation

- The study of multi-dimensional partonic structure of nucleons can provide important information to probe non-perturbative QCD
- Generalized Parton Distributions (GPDs) relate transverse position of partons to longitudinal momentum
- The Deeply Virtual Compton Scattering (DVCS) is one of the cleanest channels to access GPDs
- The measurement of DVCS cross-section from the neutron can provide unique information on GPDs

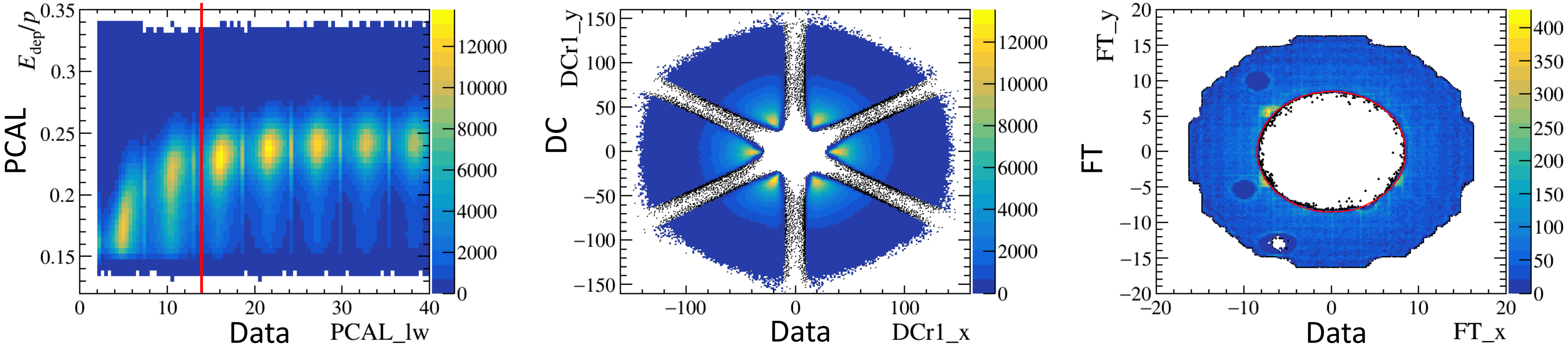


Data and MC samples

- Data
  - 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
- MC
  - Generator: genepi
  - 90M DVCS events
    - 30M for each beam energy
    - nDVCS: 21M events
    - pDVCS: 69M events



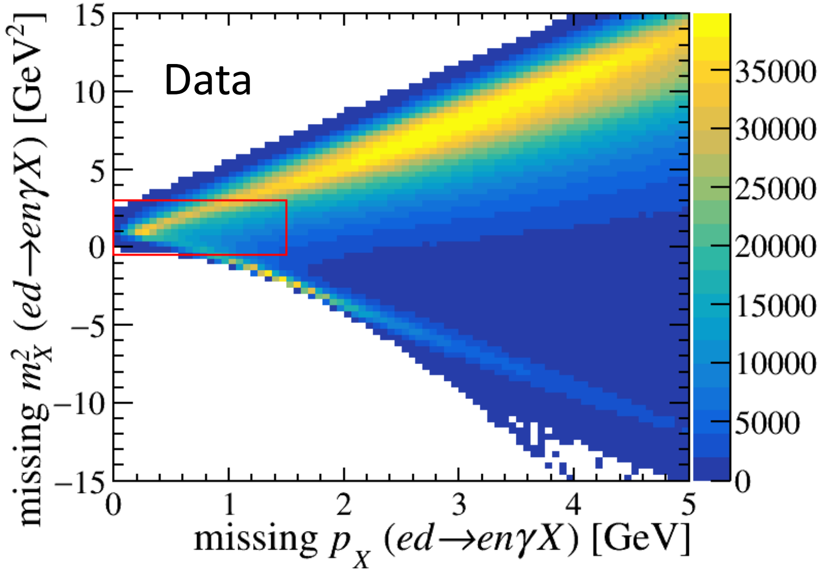
PID and fiducial cuts

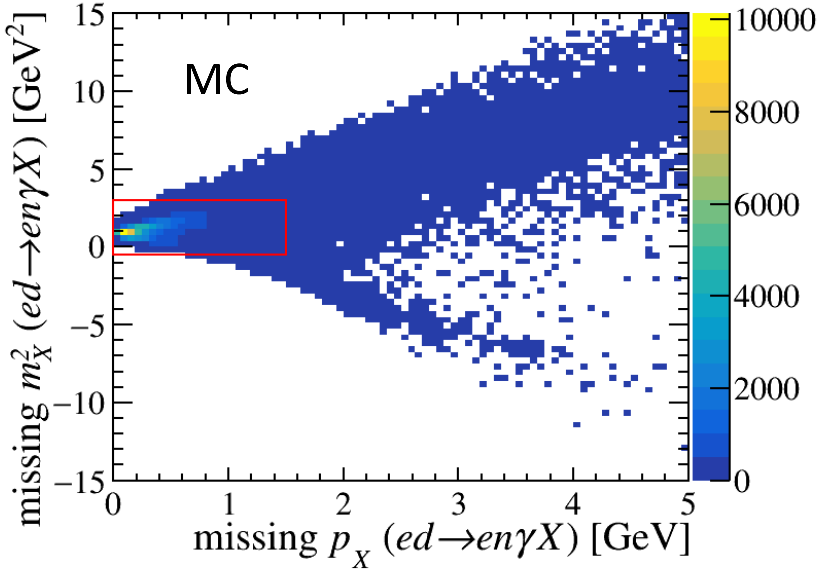


	Electron	Photon	Neutron
PID	11	22	2112
Momentum P	$>$ 1 GeV	$>$ 2 GeV	$>$ 0.35 GeV
Reconstructed in	FD	FD or FT	CD
Fiducial cuts	In FD: PCAL: lv(lw) $>$ 14 DC: edge $>$ 6	In FD: PCAL: lv(lw) $>$ 14 In FT: $x^2 + y^2 > 72$	In CD: $40° < \theta_n < 140°$

Select nDVCS data

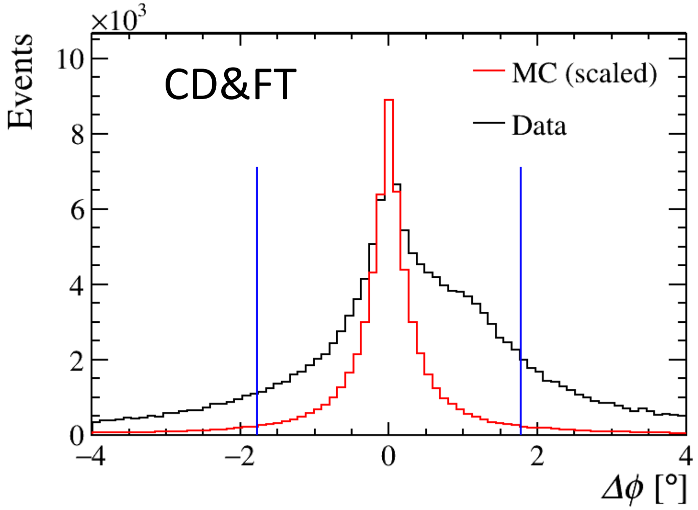
- Select events with at least one electron, one neutron and one photon
  - For cases with more than one combination, select the one with the smallest χ^2-like quantity (defined using exclusivity variables that peak at zero)
- Reaction kinematics: $Q^2 > 1\ \mathrm{GeV}^2$, $W > 2\ \mathrm{GeV}$
- Apply pre-selection on missing m_X^2 and p_X of $ed \rightarrow en\gamma X$
  - To reduce events from other channels mostly
  - Pre-selection: $-0.5 < m_X^2 < 3\ \mathrm{GeV}^2, 0 < p_X < 1.5\ \mathrm{GeV}$

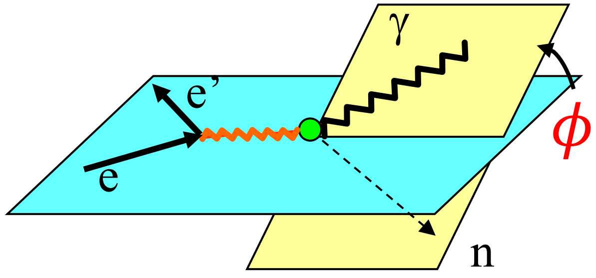


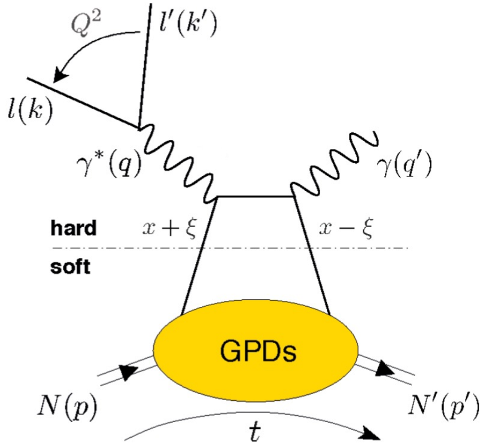


Exclusivity selection

- Criteria determined by comparing data and MC
  - $\sim 2\sigma$ of the MC distribution
- CD&FT (n in CD & γ in FT)







$|\Delta\phi| < 1.8°$

- $|\Delta\phi| < 1.8°$
- $-0.49 < \Delta t < 0.82$ GeV^2
- $-0.31 < m_X^2 < 0.16$ GeV^2 for $en \to en\gamma X$
- $-3.5 < m_X^2 < 3.1$ GeV^2 for $en \to enX$
- $\theta_{X\gamma} < 3.8°$ for $en \to enX$
- $0.1 < m_X^2 < 2.2$ GeV^2 for $ed \to en\gamma X$
- $p_X < 0.75$ GeV for $ed \to en\gamma X$

➢ The distributions for other variables and for CD&FD are presented in backup slides

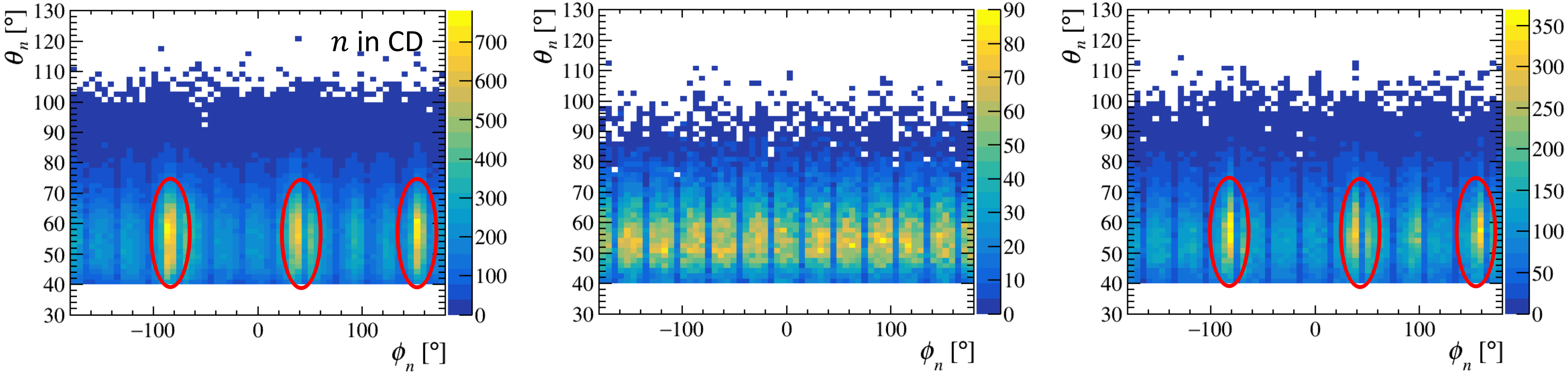
- After the exclusivity selection
  - $N = 2.92\times10^5$ for CD&FT
  - $N = 0.64\times10^5$ for CD&FD

- $\Delta\phi$: difference in ϕ between
  - hadronic plane formed by the neutron and the virtual photon
  - hadronic plane formed by the neutron and the outgoing photon
- Δt: difference in t between
  - t calculated by the neutron
  - t calculated by the photon
- $\theta_{X\gamma}$: cone angle formed by the missing photon X ($en \to enX$) and the outgoing photon γ

Proton misidentified as neutron in CD

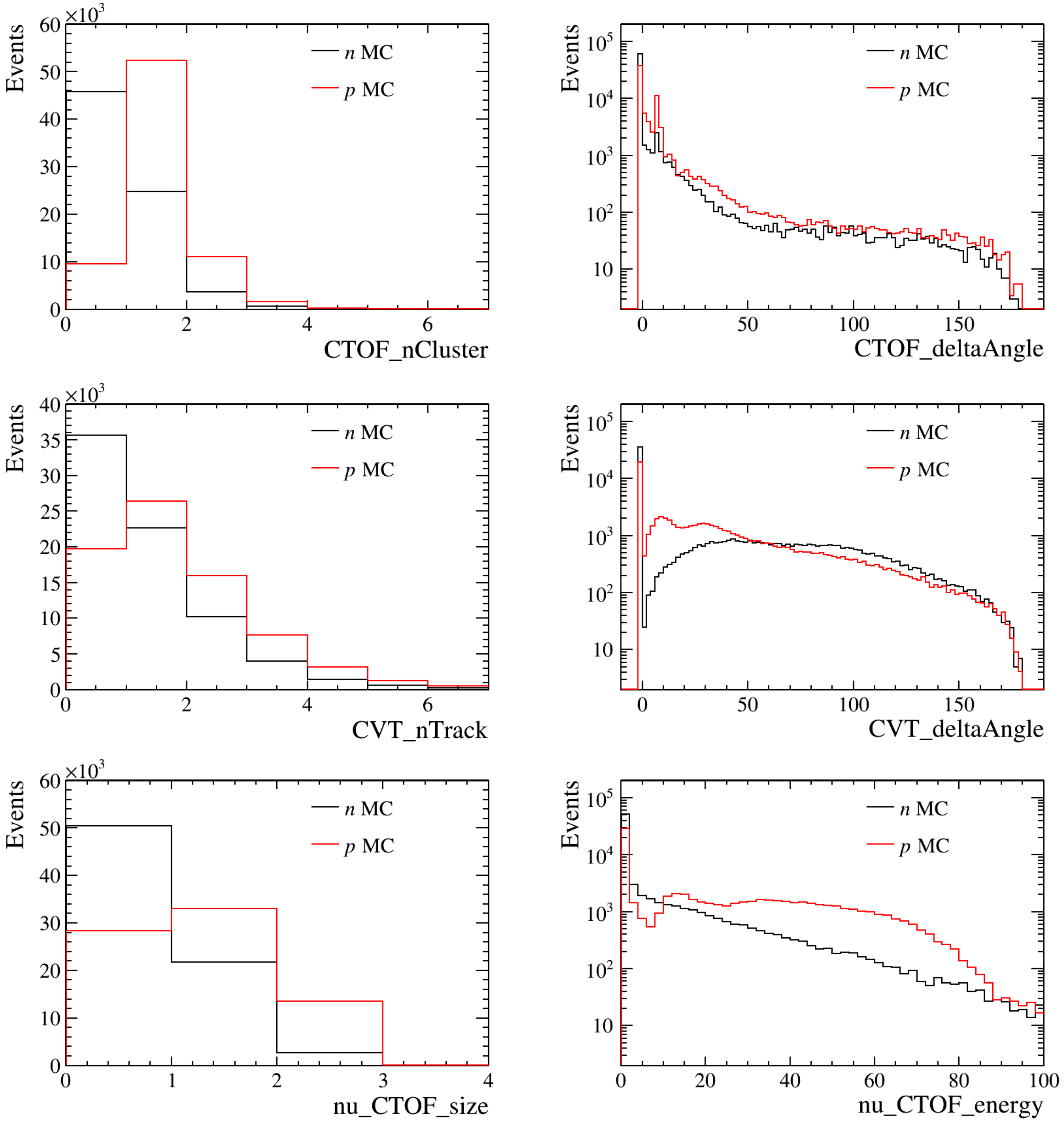
- The tracking system (CVT) in CD has dead or low-efficiency regions
- Protons: no tracks in CVT but hits in central neutron detector (CND)
  - ➢Misidentified as neutrons
- Reproduce distributions in MC mixing pDVCS and nDVCS (both reconstructed as nDVCS)

Data **Only nDVCS MC** **Mix pDVCS and nDVCS MC**



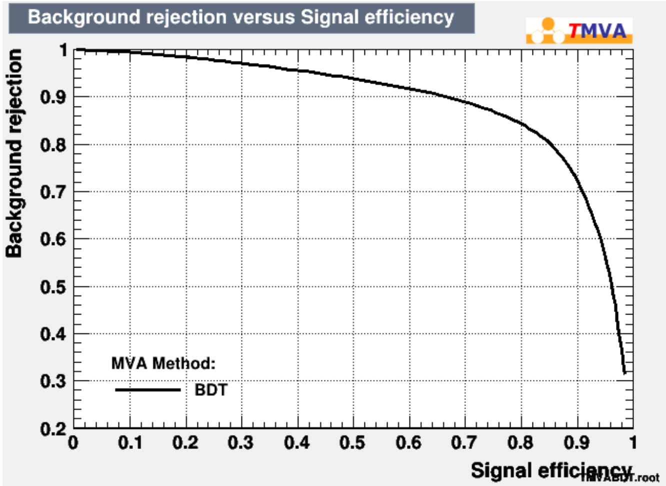
TMVA training

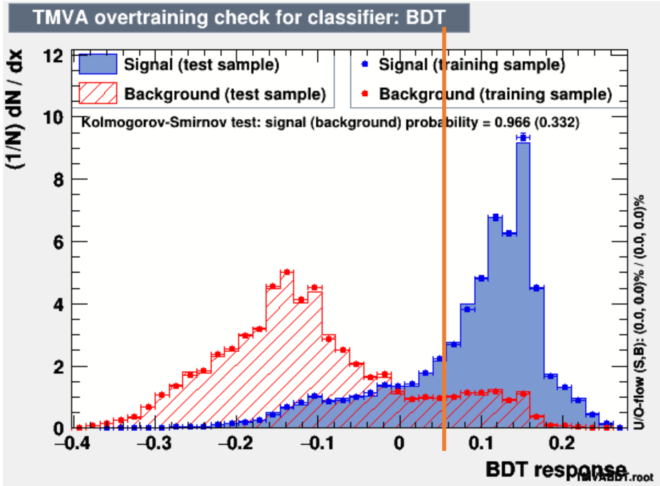
- Training and test sample:
  - MC with neutron target
  - MC with proton target
- Training variables (only use info at CTOF, CVT and CND)
  - Number of clusters at CTOF (most distinguishable)
  - Smallest cone angle between the CTOF cluster and $n(p)$ track
  - Number of tracks at CVT
  - Smallest cone angle between the CVT track and $n(p)$ track
  - Number of hits for the $n(p)$ cluster at CTOF and three layers of CND (in backup slides)
  - Deposit energy at CTOF and three layers of CND (in backup slides)

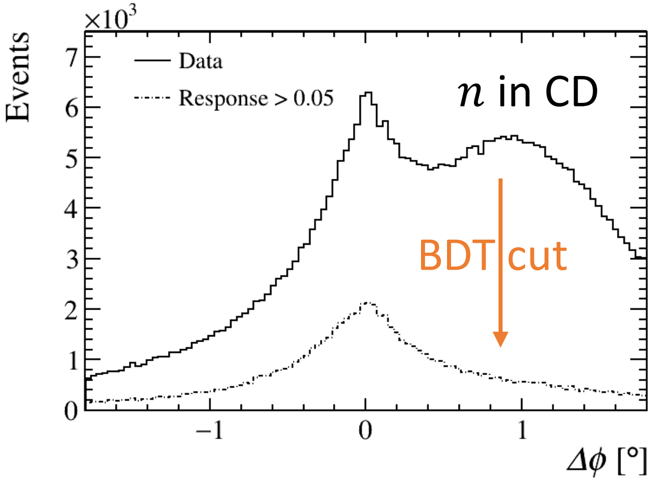


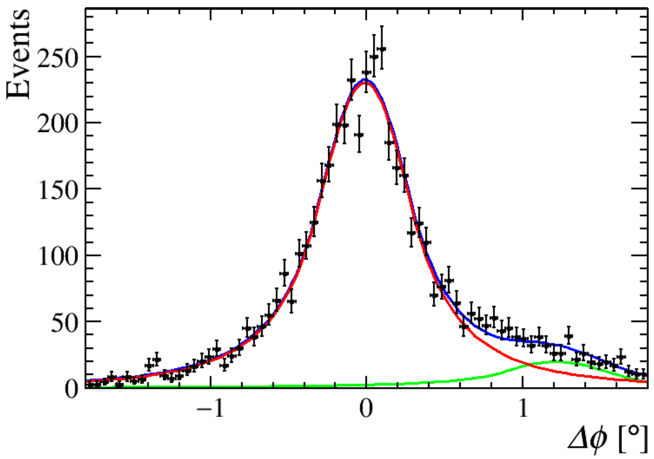
Boosted Decision Tree (BDT) classifier

- Selection:
    - BDT response > 0.05
- $N = 3.56\times10^5$ for n in CD (CD&FT + CD&FD)
- $N = 0.73\times10^5$ after the BDT response selection
- The remaining fake neutrons after the BDT cut is subtracted by the $\Delta\phi$ fit in kinematic bins







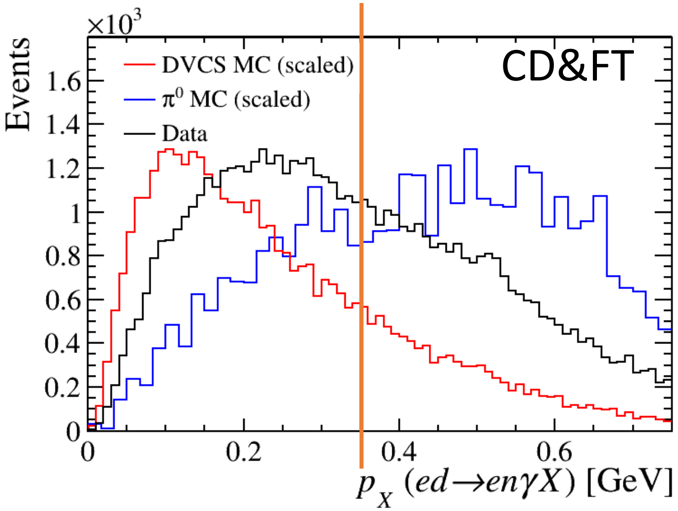


Distributions of nDVCS variables

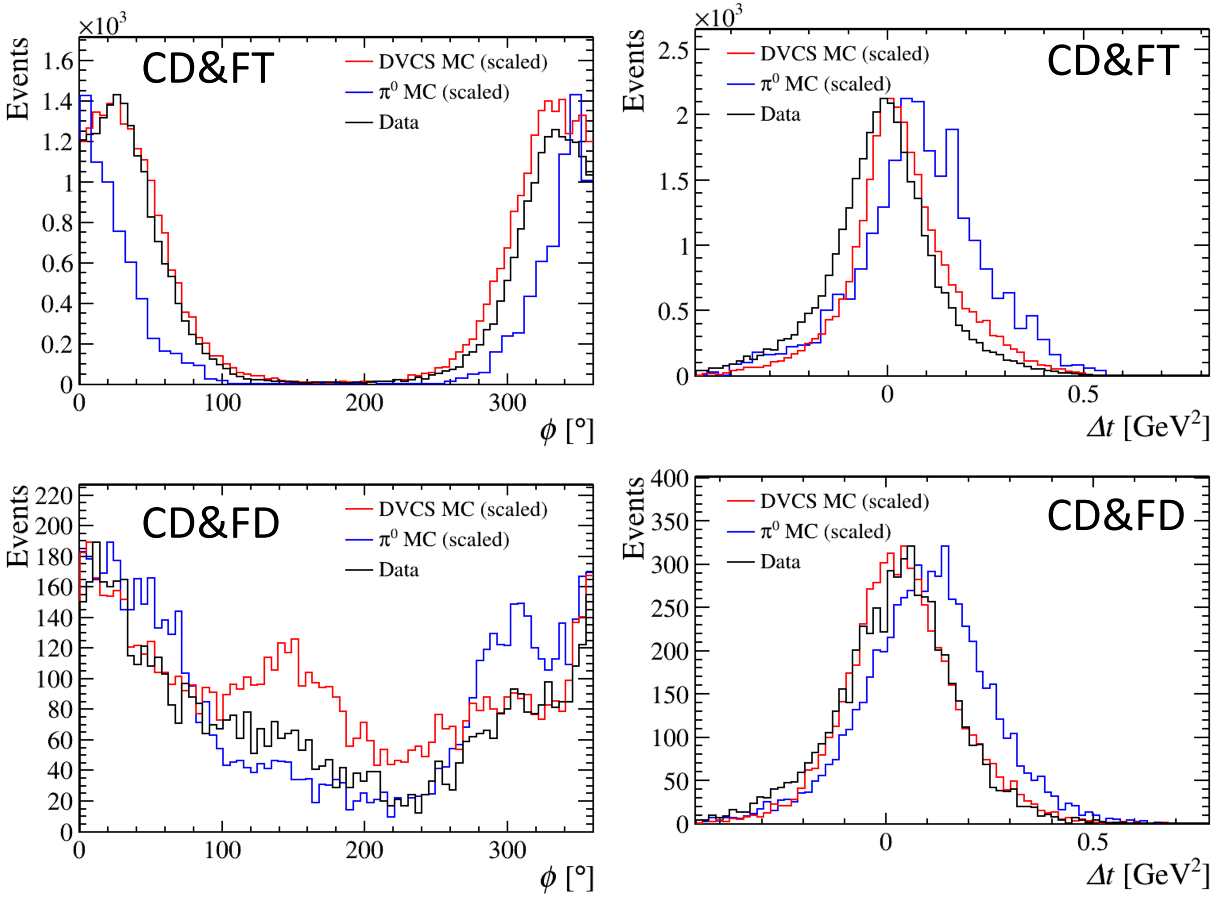
- Apply a further cut

  $p_X < 0.35$ GeV for $ed \to en\gamma X$

  - The spectator (p) has low momentum



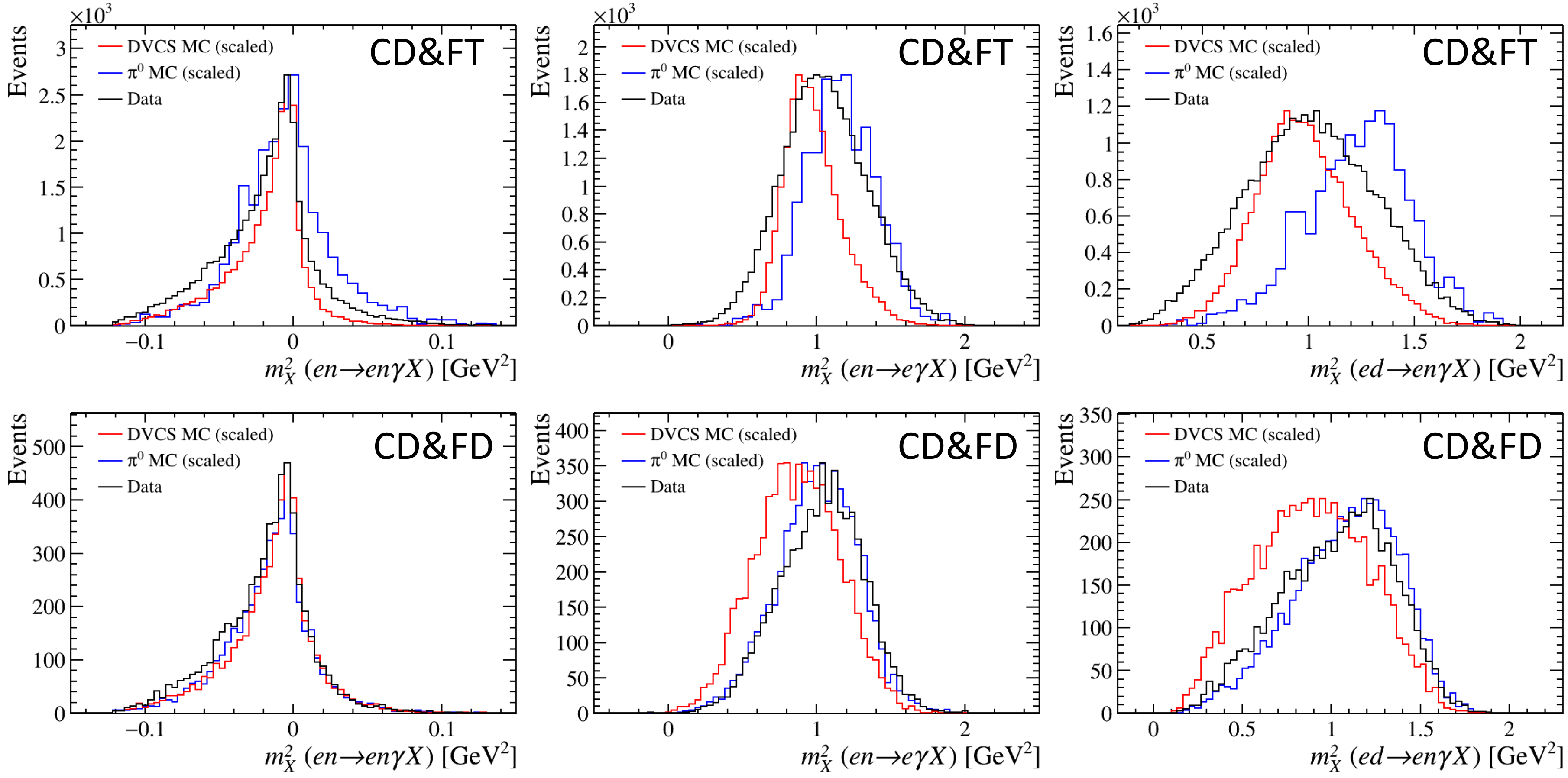
- π^0 production contamination:
  - $en \to en\pi^0(\to \gamma\gamma)$
  - π^0 MC: reconstructed as nDVCS



- After the cut $p_X < 0.35$ GeV for $ed \to en\gamma X$
- Distributions for data are consistent with nDVCS MC

Distributions of nDVCS variables

- π^0 production contamination:
  - $en \rightarrow en\pi^0(\rightarrow \gamma\gamma)$
  - π^0 MC: reconstructed as nDVCS



- π^0 contamination seems negligible for CD&FT, but still significant for CD&FD
- The difference between data and MC for nDVCS might be also due to their different resolution
- The momentum correction is under study

Study of π^0 production contamination

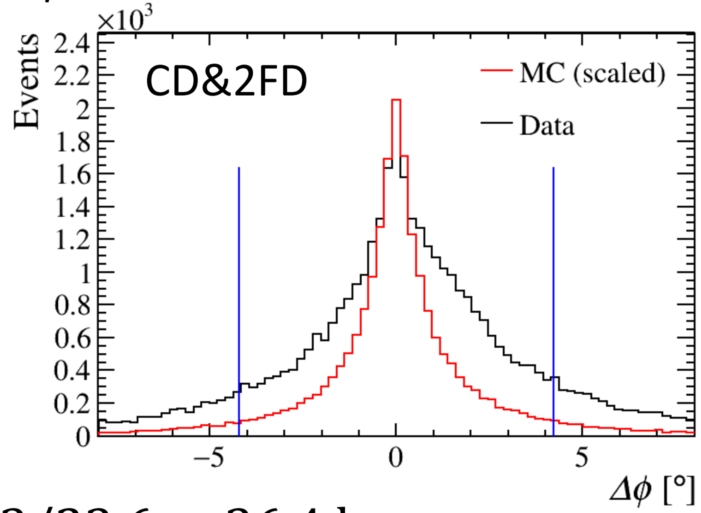
- $en \to en\pi^0(\to \gamma\gamma)$ background subtraction:
  - $N_{\mathrm{DVCS}} = N_{en\gamma} - N_{en\pi^0} \times f^{\mathrm{MC}} = N_{en\gamma} - N_{en\pi^0} \times \frac{N^{\mathrm{MC}}_{en\pi^0(1\gamma)}}{N^{\mathrm{MC}}_{en\pi^0(2\gamma)}}$

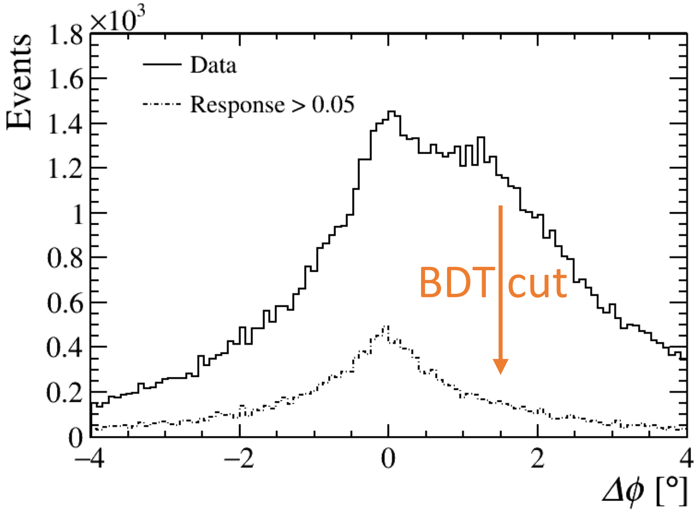
Partially reconstructed $en\pi^0(1\gamma)$ and passed DVCS selection

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

- Select π^0 production data
  - Select events with at least 1 e^-, 1 n and 2 γ
    - $p_e > 1$ GeV, $p_n > 0.35$ GeV, $p_\gamma > 0.6$ GeV
    - $0.10 < m_{\gamma\gamma} < 0.17$ GeV
  - Exclusivity cuts (in backup slides)
  - Use BDT to reduce misidentified protons

- CD&2FD: n in CD and 2 γ in FD





- Using events for n in CD to perform the subtraction
  - $N_{\mathrm{DVCS}} = 38.0\ \mathrm{k} - 4.6\ \mathrm{k} \times 8.3/23.6 = 36.4\ \mathrm{k}$
  - π^0 contamination: 4.3%

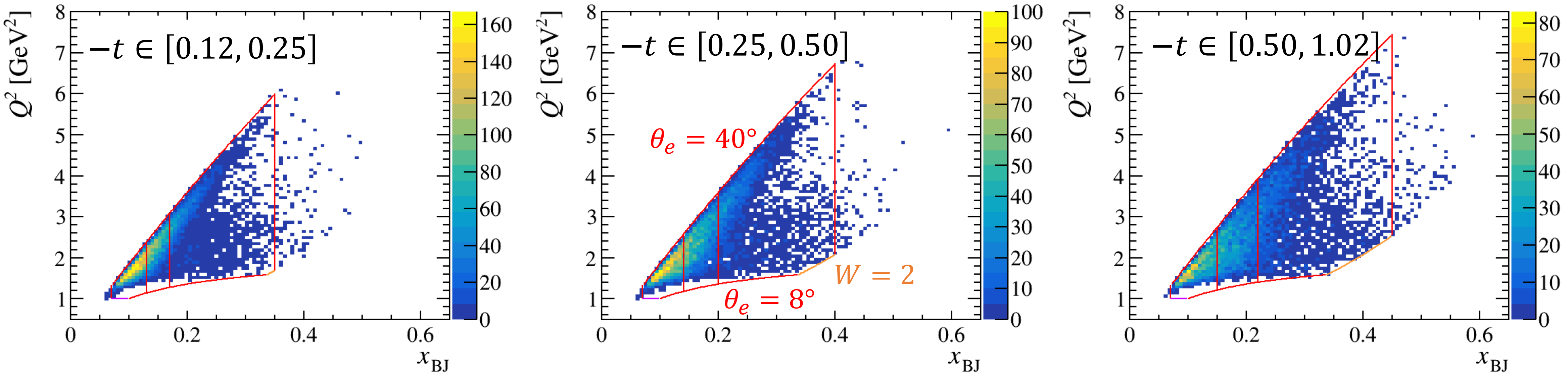
Binning scheme

- $-t \in [0.12, 0.25], [0.25, 0.50], [0.50, 1.02]$ GeV^2
- 3 bins in (Q^2, x_{BJ})
  - $Q^2 > 1\ \mathrm{GeV}^2, 8° < \theta_e < 40°$
  - x_{BJ} boundaries are adjusted according to $-t$

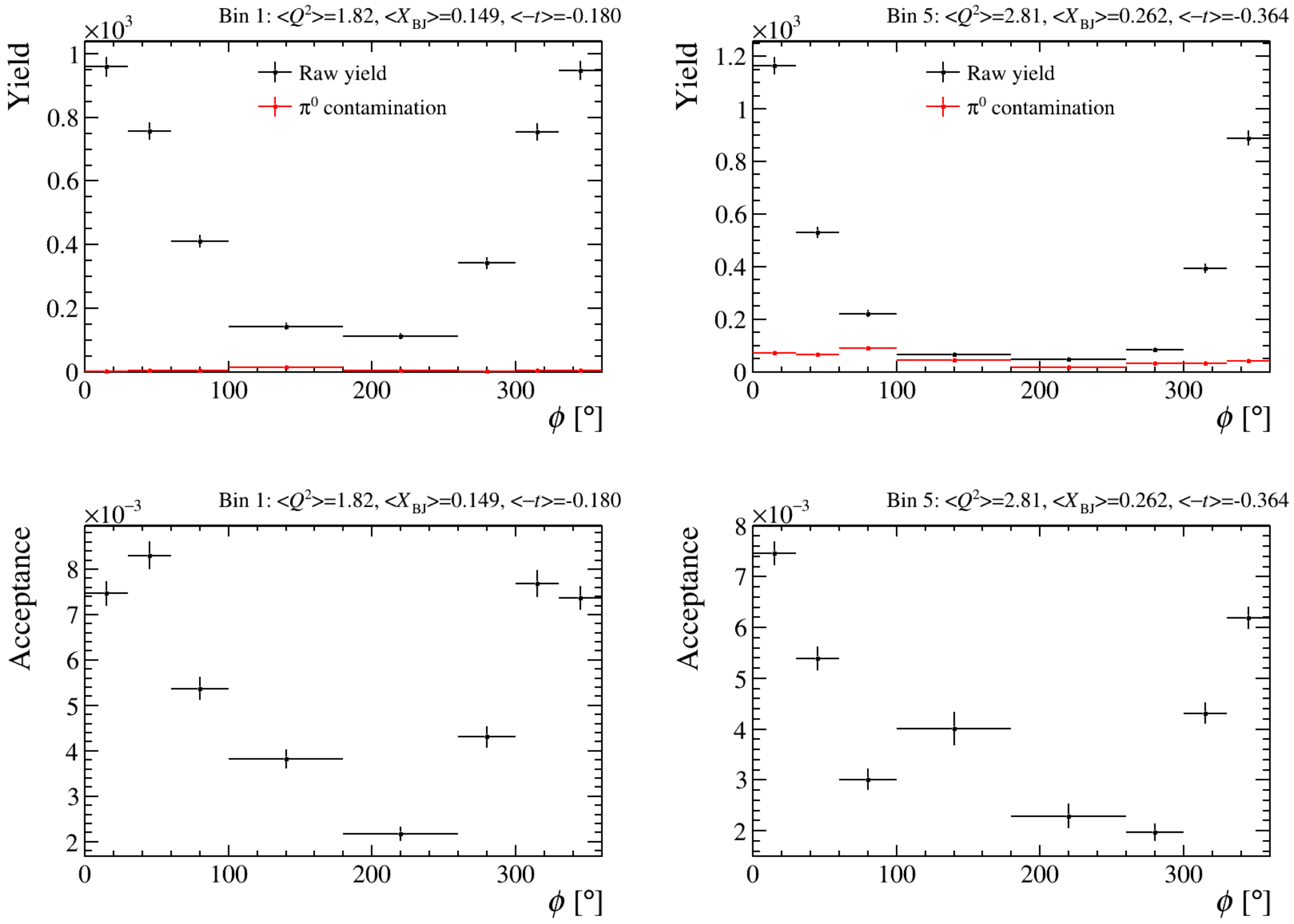
x_{BJ}: [0.07, 0.13, 0.17,0.35]

x_{BJ}: [0.07, 0.14, 0.20,0.40]

x_{BJ}: [0.07, 0.15, 0.25,0.45]



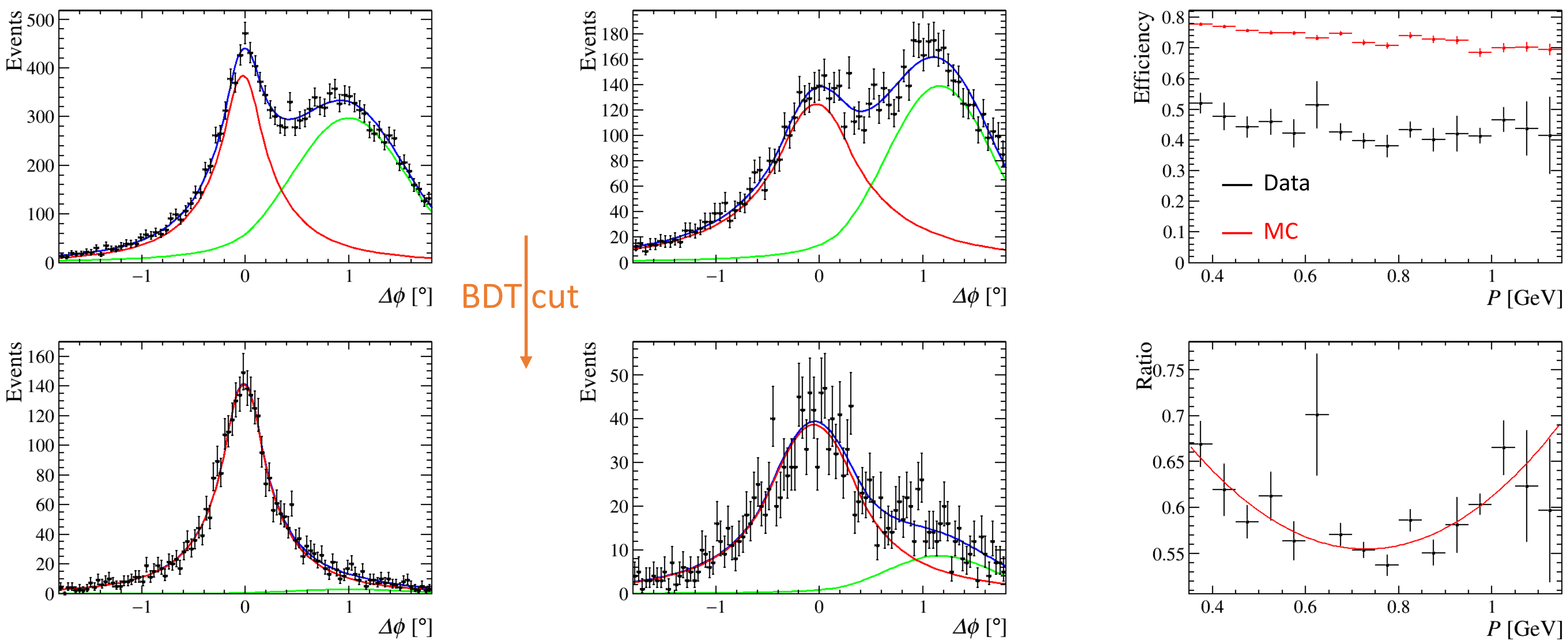
Yield and acceptance



- π^0 contribution is negligible in some bins, while it is still significant in some other bins
- BDT cut efficiency correction and neutron detection efficiency correction are applied to the ε_{acc} determination
- $N^{\text{corr}} = (N_{\text{nDVCS}} - N_{\pi^0})/\varepsilon_{\text{acc}}$

- $\varepsilon_{\text{acc}} = \dfrac{\text{Number of events for reconstructed MC passed all the nDVCS selections}}{\text{Number of events for generator–level MC inside the defined bin}}$

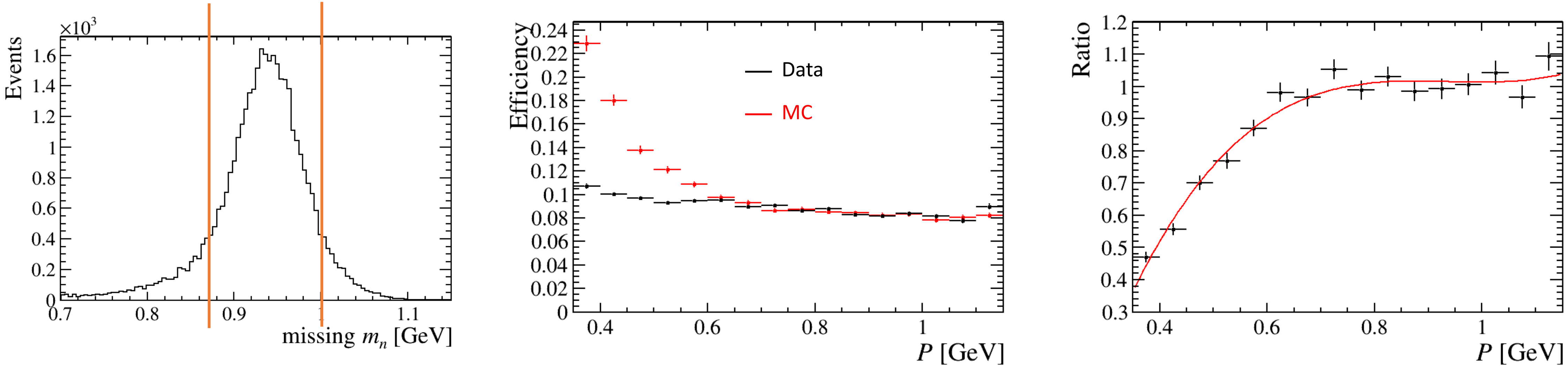
BDT cut efficiency correction



- Determine the efficiency vs. neutron momentum both in data (by fit) and MC
- The ratio of efficiency between data and MC is taken as the correction

Neutron detection efficiency correction

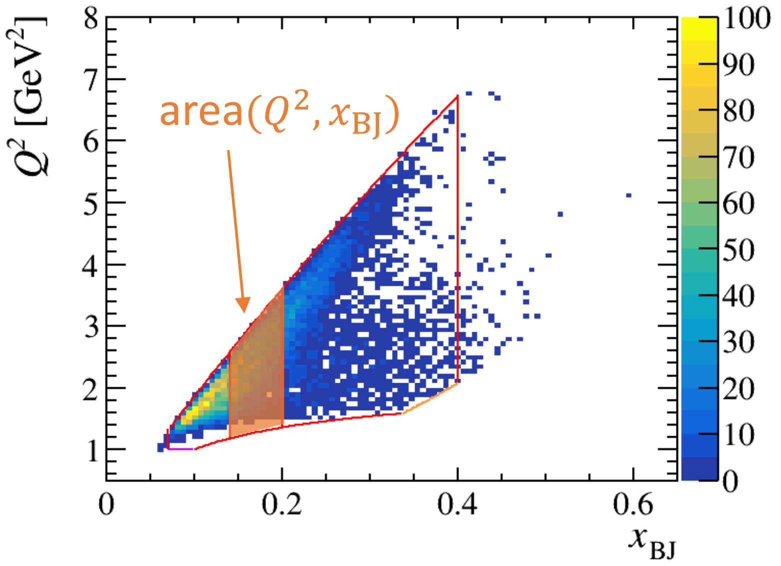
- RGA $ep \rightarrow en\pi^+$ data
- $\varepsilon_\mathrm{n} = \dfrac{\text{Number of events with } n \text{ reconstructed in CD passed all the nDVCS selections (without BDT cut)}}{\text{Number of events without } n \text{ reconstructed } (\theta_n > 40°)}$
- Determine the efficiency vs. neutron momentum both in data and MC
- The ratio of efficiency between data and MC is taken as the correction

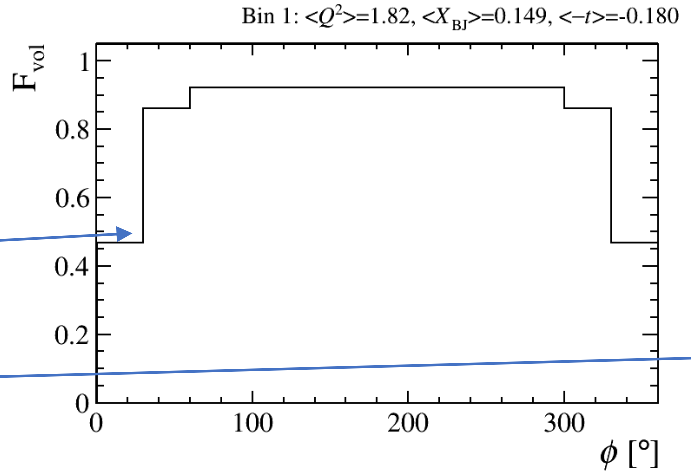


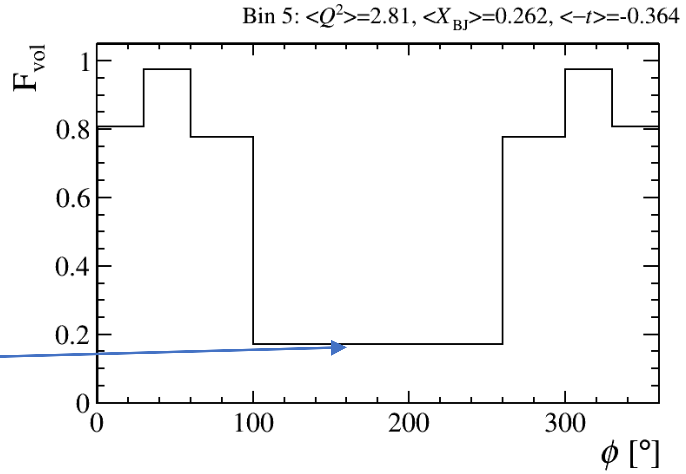
- MC overestimates the neutron detection efficiency at low-momentum

Bin-volume correction

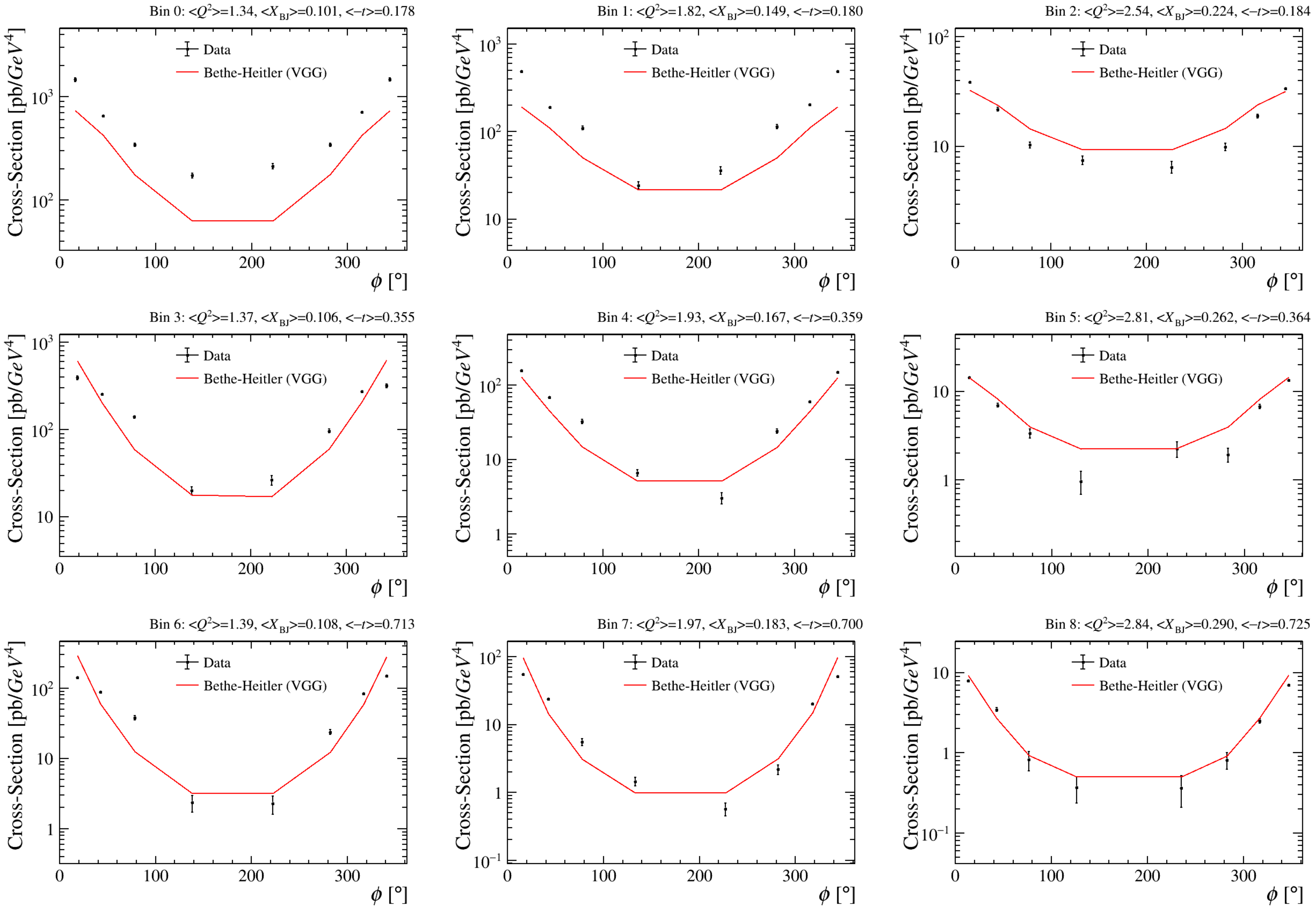
- Bin volume = area(Q^2, x_{BJ}) $\times$ t bin width $\times$ ϕ bin width
  - Some kinematic cuts make the real volume smaller
- Correction F_{vol}
  - Divide each $(Q^2, x_{\mathrm{BJ}}, -t, \phi)$ bin into 80×80×80×80 sub-volumes
  - Use the center value $(Q^2, x_{\mathrm{BJ}}, -t, \phi)$ of the sub-volume to calculate variables $p_{e,n,\gamma}$, $\theta_{e,n,\gamma}$, t_{min}
  - $F_{\mathrm{vol}} = \dfrac{\text{Number of sub−volumes within the bin inner limit}}{\text{Number of sub−volumes within the bin outer limit}}$
- Bin outer limit
  - $(Q^2, x_{\mathrm{BJ}}, -t, \phi)$ boundaries
- Bin inner limit
  - $p_e > 1$ GeV
  - $p_\gamma > 2$ GeV
  - $\theta_\gamma > 2.5°$
  - $p_n > 0.35$ GeV
  - $40° < \theta_n < 140°$
  - $-t > t_{\mathrm{min}}$







Preliminary cross-section



$$\sigma = \frac{N_{\mathrm{nDVCS}} - N_{\pi^0}}{\varepsilon_{\mathrm{acc}} \times L \times V \times F_{\mathrm{vol}}}$$

- The preliminary cross-sections are at the same level with the Bethe-Heitler predictions

larger $-t$

Summary

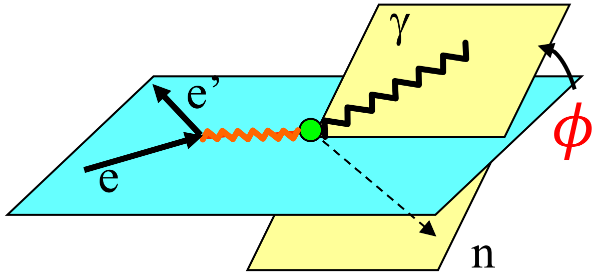
- nDVCS events are selected and compared with MC
- Fake neutron events are subtracted by TMVA and the $\Delta\phi$ fit
- π^0 production contamination is subtracted as well
- Preliminary cross-sections are extracted in $(Q^2, x_{\mathrm{BJ}}, t, \phi)$ bins
- Next to do
  - Study the momentum corrections and the efficiency corrections
  - Estimate the systematic uncertainties
  - Extract the beam-polarized cross section differences
    - The absolute cross-section is linked to a combination of real parts of CFF, while the beam-polarized cross-section difference is linked to imaginary part of GPD E

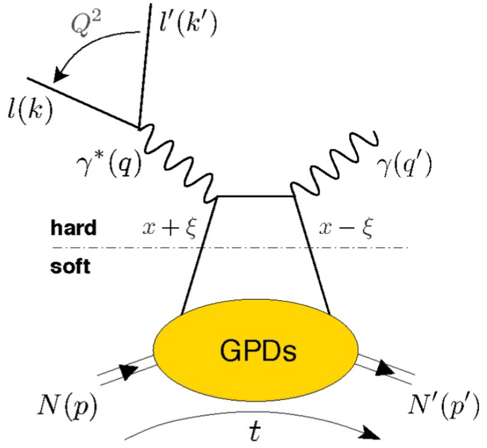
Thank you!

Backup slides

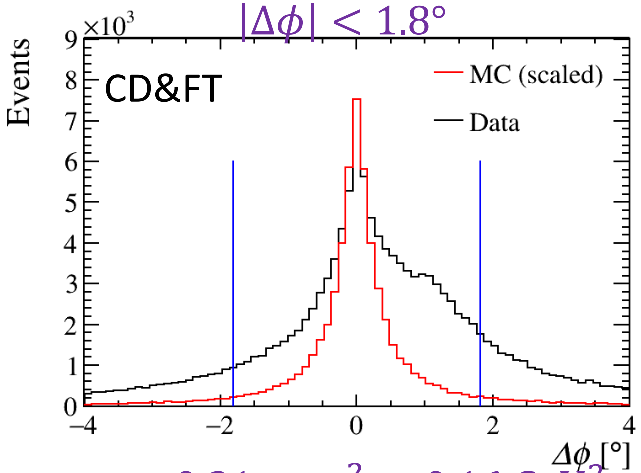
Exclusivity selection

- Criteria determined by comparing data and MC
  - $\sim 2\sigma$ of the MC distribution
- CD&FT (n in CD & γ in FT)

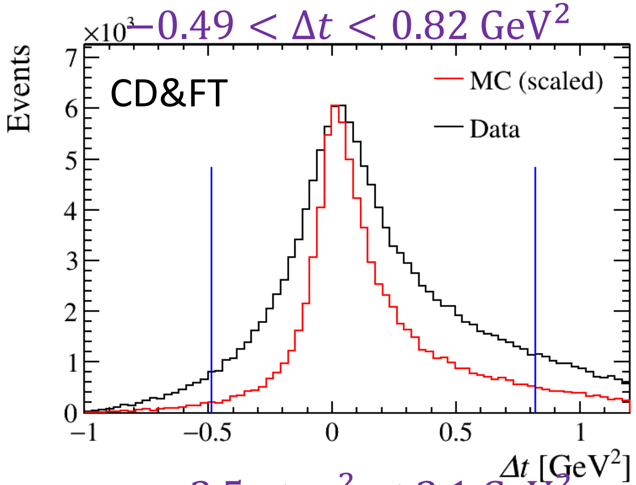




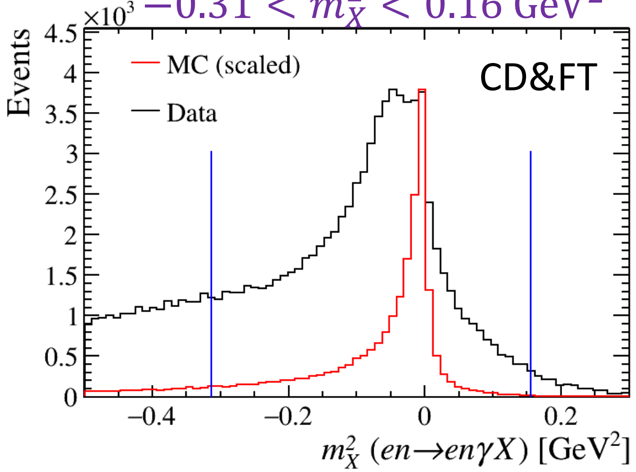
$|\Delta\phi| < 1.8°$



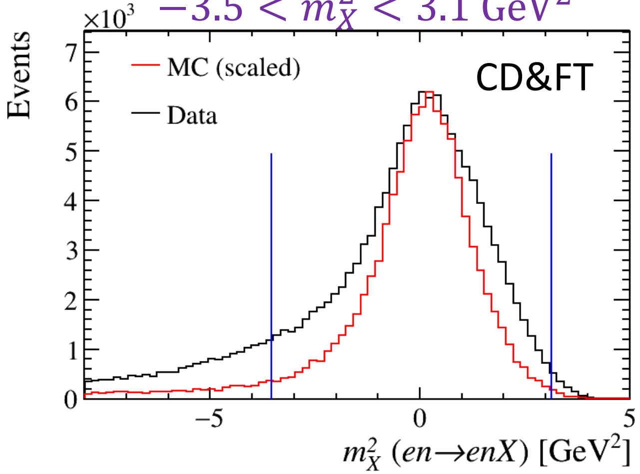
$-0.49 < \Delta t < 0.82\ \mathrm{GeV}^2$



$-0.31 < m_X^2 < 0.16\ \mathrm{GeV}^2$



$-3.5 < m_X^2 < 3.1\ \mathrm{GeV}^2$

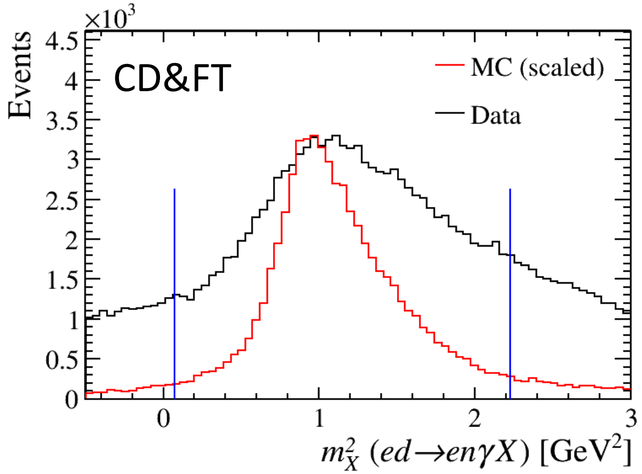


- $\Delta\phi$: difference in ϕ between
  - hadronic plane formed by the neutron and the virtual photon
  - hadronic plane formed by the neutron and the outgoing photon
- Δt: difference in t between
  - t calculated by the neutron
  - t calculated by the photon

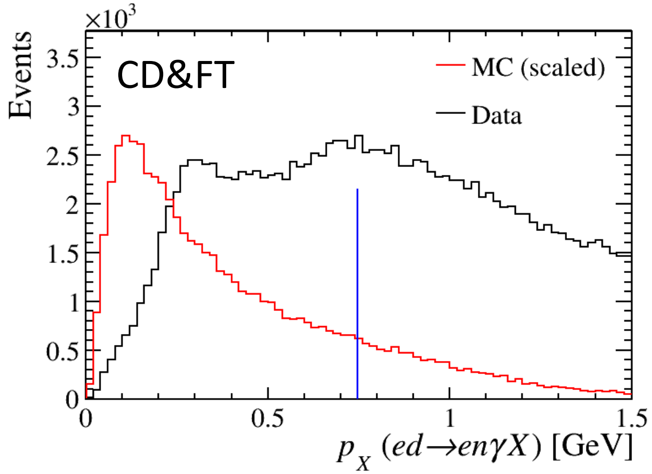
Exclusivity selection

- Criteria determined by comparing data and MC
  - $\sim 2\sigma$ of the MC distribution
- CD&FT (n in CD & γ in FT)

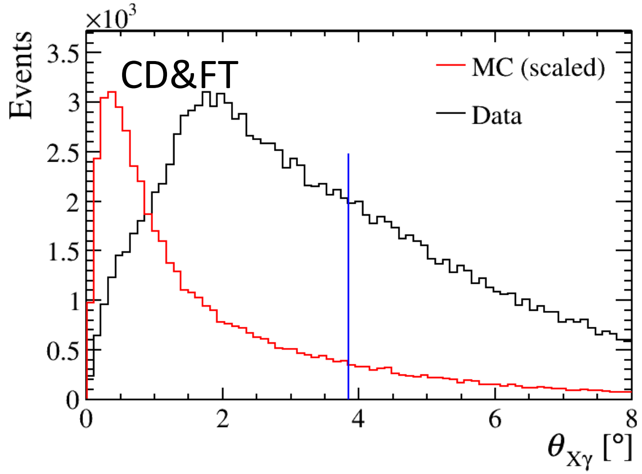
- $\theta_{X\gamma}$: cone angle formed by the missing photon X ($en \to enX$) and the outgoing photon γ



$0.1 < m_X^2 < 2.2$ GeV^2



$p_X < 0.75$ GeV



$\theta_{X\gamma} < 3.8°$

- After the exclusivity selection
  - $N = 3.62 \times 10^5$ for CD&FT
  - $N = 0.74 \times 10^5$ for CD&FD

➢ The data and MC distributions are very different
  ➢ mainly due to the protons that are misidentified as neutrons, discussed in the later slides

Exclusivity selection

- Criteria determined by comparing data and MC
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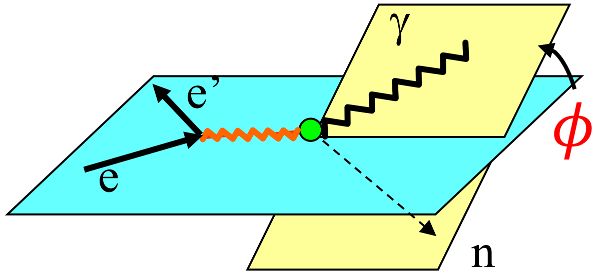
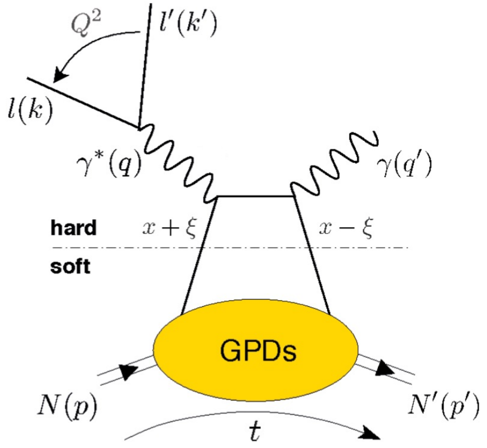
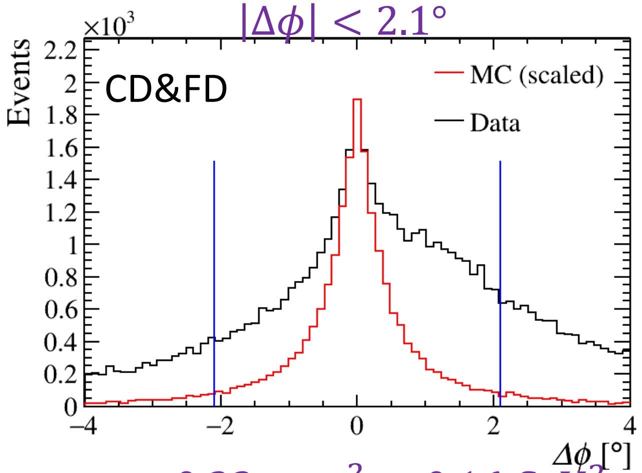
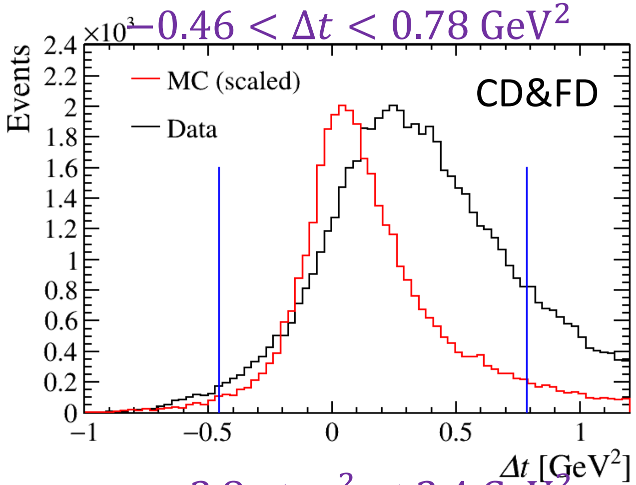




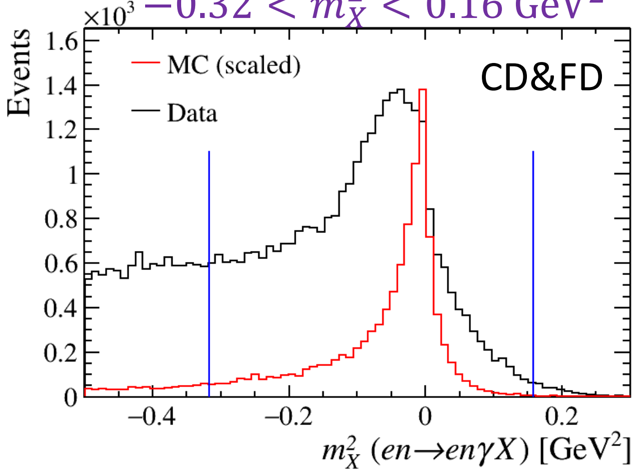
$|\Delta\phi| < 2.1°$



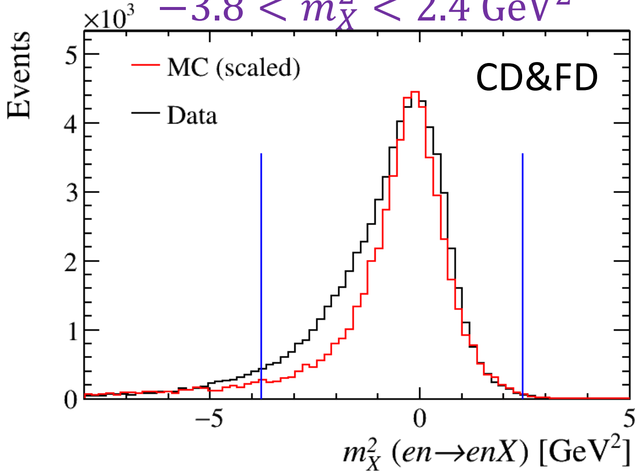
$-0.46 < \Delta t < 0.78$ GeV^2



$-0.32 < m_X^2 < 0.16$ GeV^2



$-3.8 < m_X^2 < 2.4$ GeV^2



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Exclusivity selection

- Criteria determined by comparing data and MC
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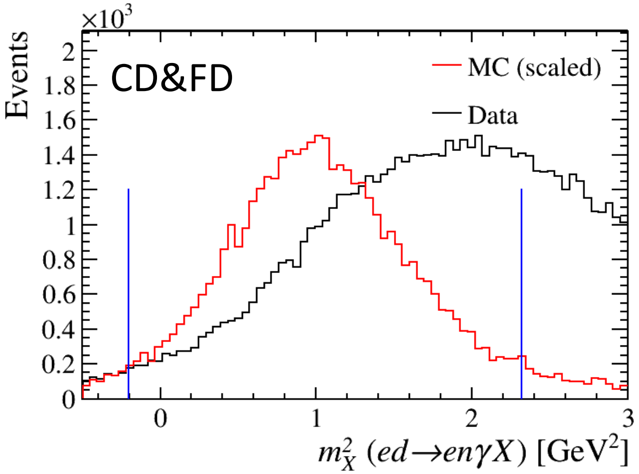
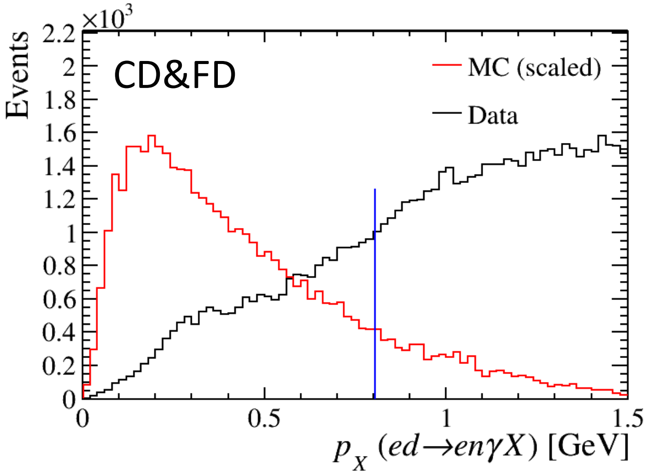
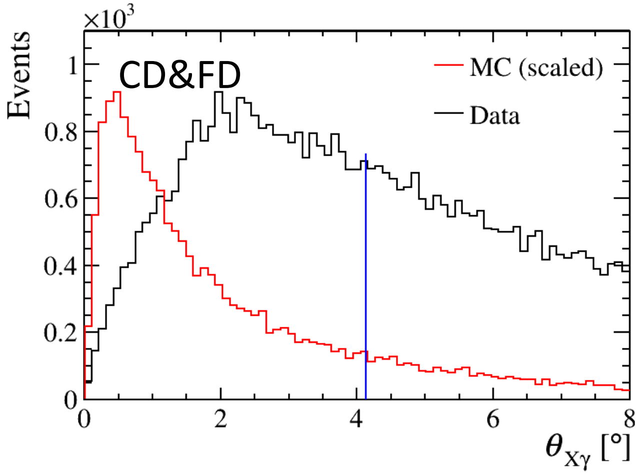
- $\theta_{X\gamma}$: cone angle formed by the missing photon X ($en \to enX$) and the outgoing photon γ







$-0.2 < m_X^2 < 2.3\ \mathrm{GeV}^2$

$p_X < 0.80\ \mathrm{GeV}$

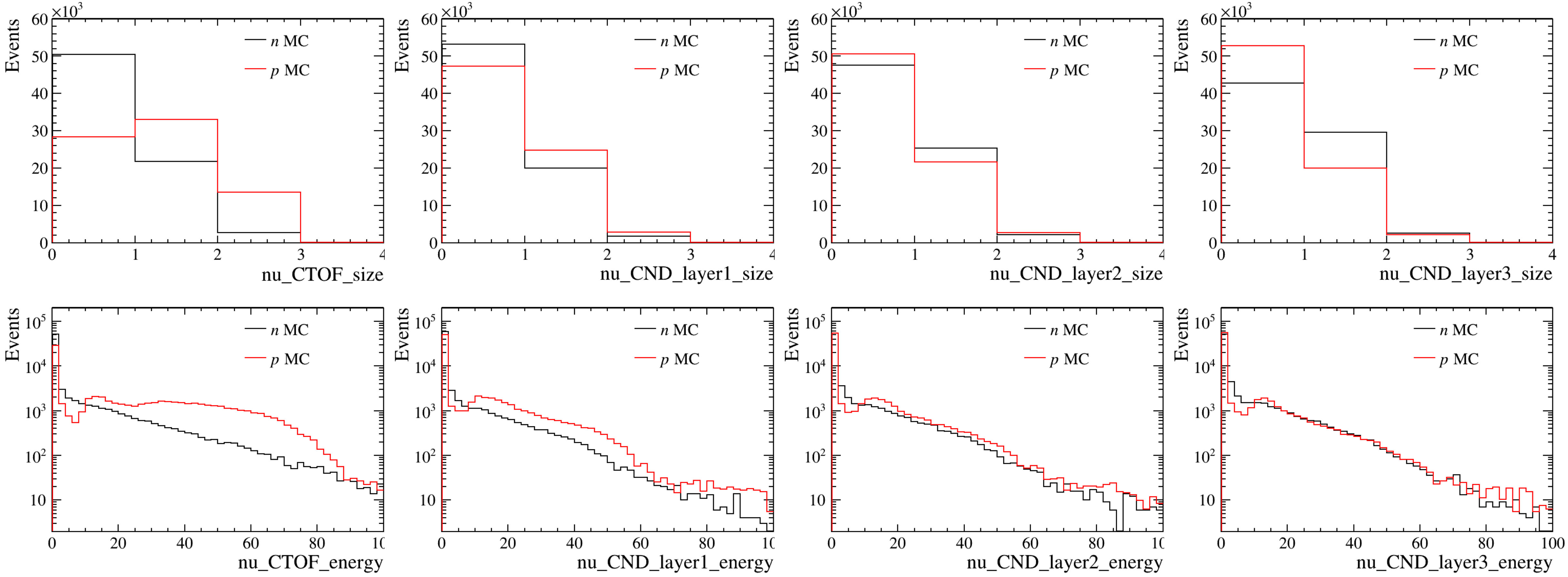
$\theta_{X\gamma} < 4.1°$

- After the exclusivity selection
  - $N = 2.92\times10^5$ for CD&FT
  - $N = 0.64\times10^5$ for CD&FD

➢ The data and MC distributions are very different
  ➢ mainly due to the protons that are misidentified as neutrons, discussed in the later slides

TMVA training

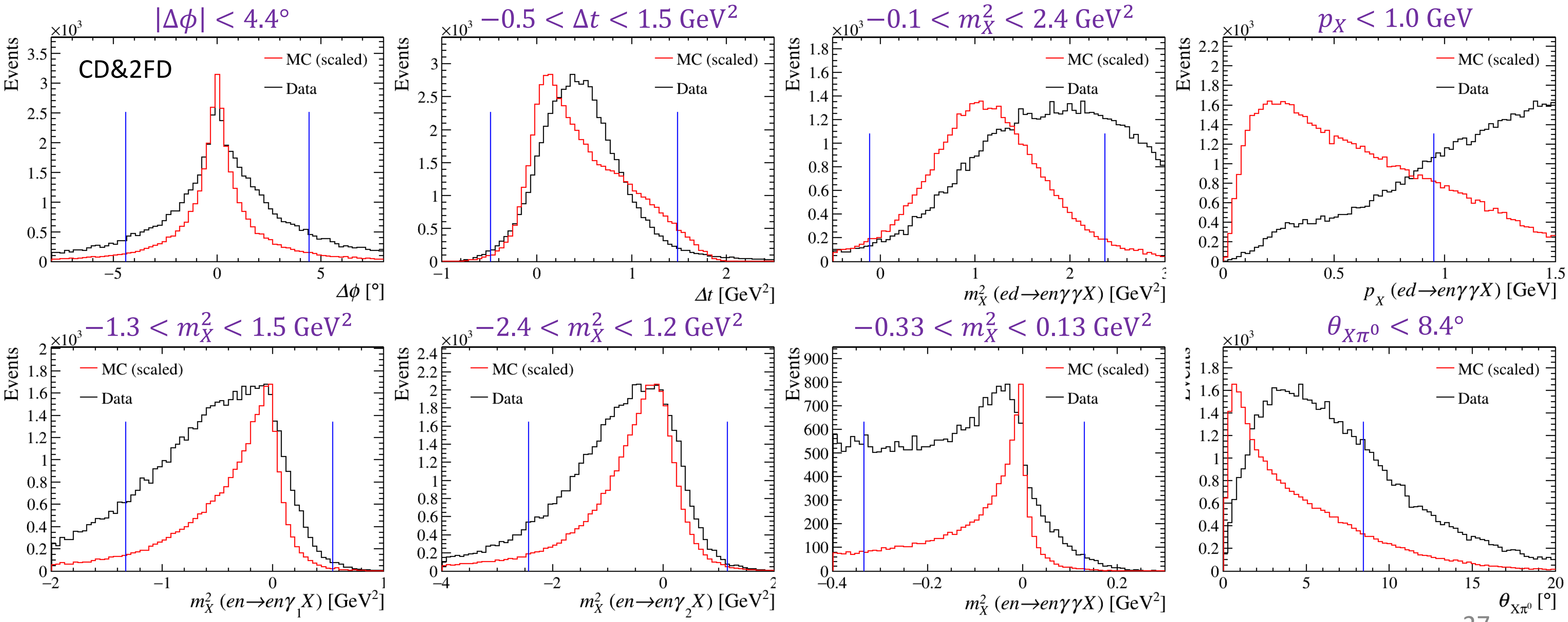
- Number of hits for the $n(p)$ cluster at CTOF and three layers of CND
- Deposit energy at CTOF and three layers of CND



Exclusivity selection of π^0 production

- Criteria determined by comparing data and MC
  - $\sim 2\sigma$ of the MC distribution

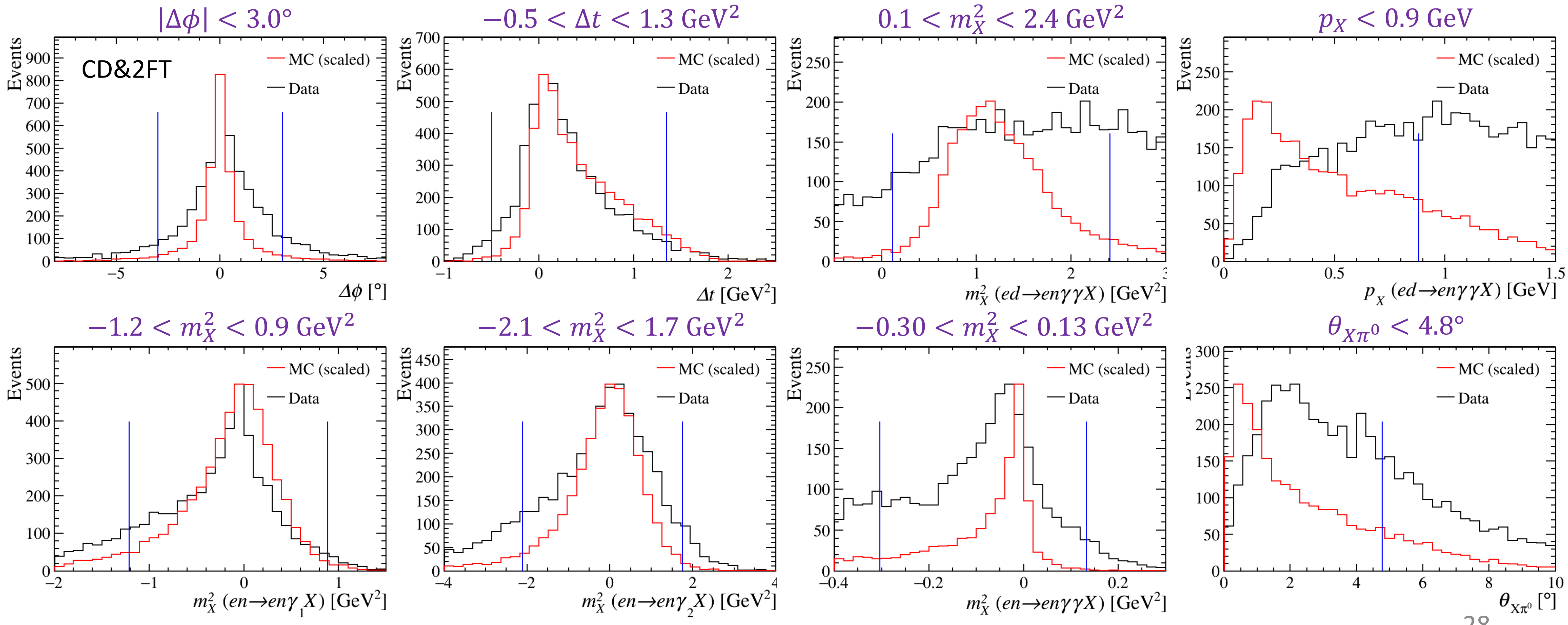
- CD&2FD: n in CD and 2 γ in FD
  - still have protons misidentified as neutrons



Exclusivity selection of π^0 production

- Criteria determined by comparing data and MC
  - $\sim 2\sigma$ of the MC distribution

- CD&2FT: n in CD and 2 γ in FT
  - still have protons misidentified as neutrons



Exclusivity selection of π^0 production

- Criteria determined by comparing data and MC
  - $\sim 2\sigma$ of the MC distribution

- CD&1FT1FD: n in CD and 1 γ in FT, 1 γ in FD
  - still have protons misidentified as neutrons