Neutron DVCS Cross Section Extraction at the CLAS12 Experiment

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CLAS Collaboration Meeting

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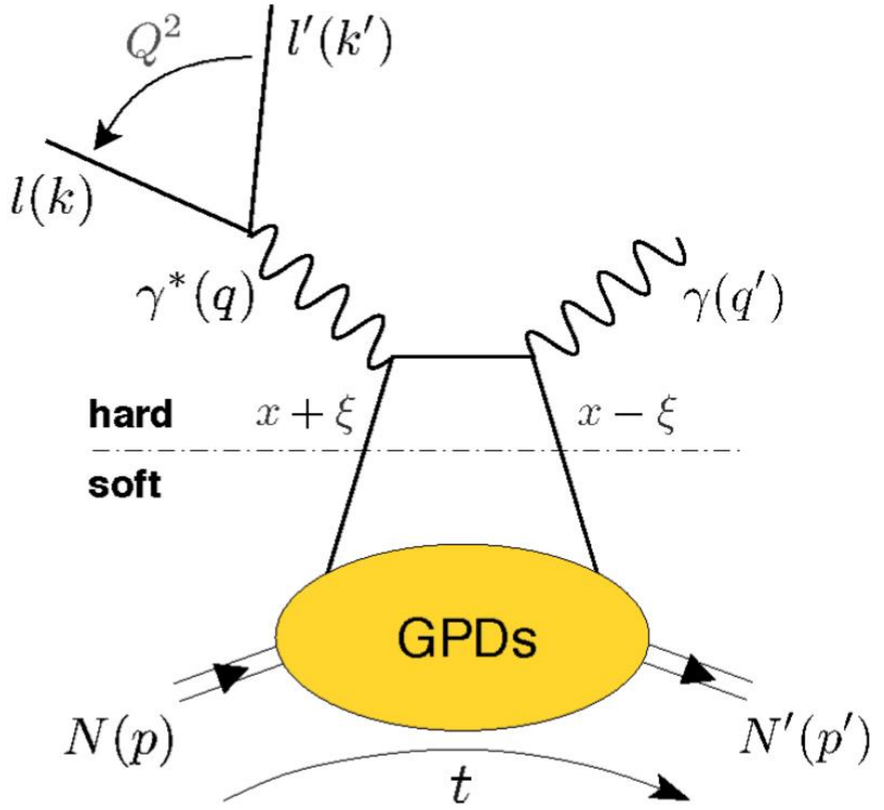
Outline

- Motivation
- Data and MC samples
- PID and fiducial cuts
- Select neutron DVCS (nDVCS) data
- Study of π^0 production contamination
- Beam-spin asymmetry as a check
- Acceptance-corrected yields
- Summary and next to do

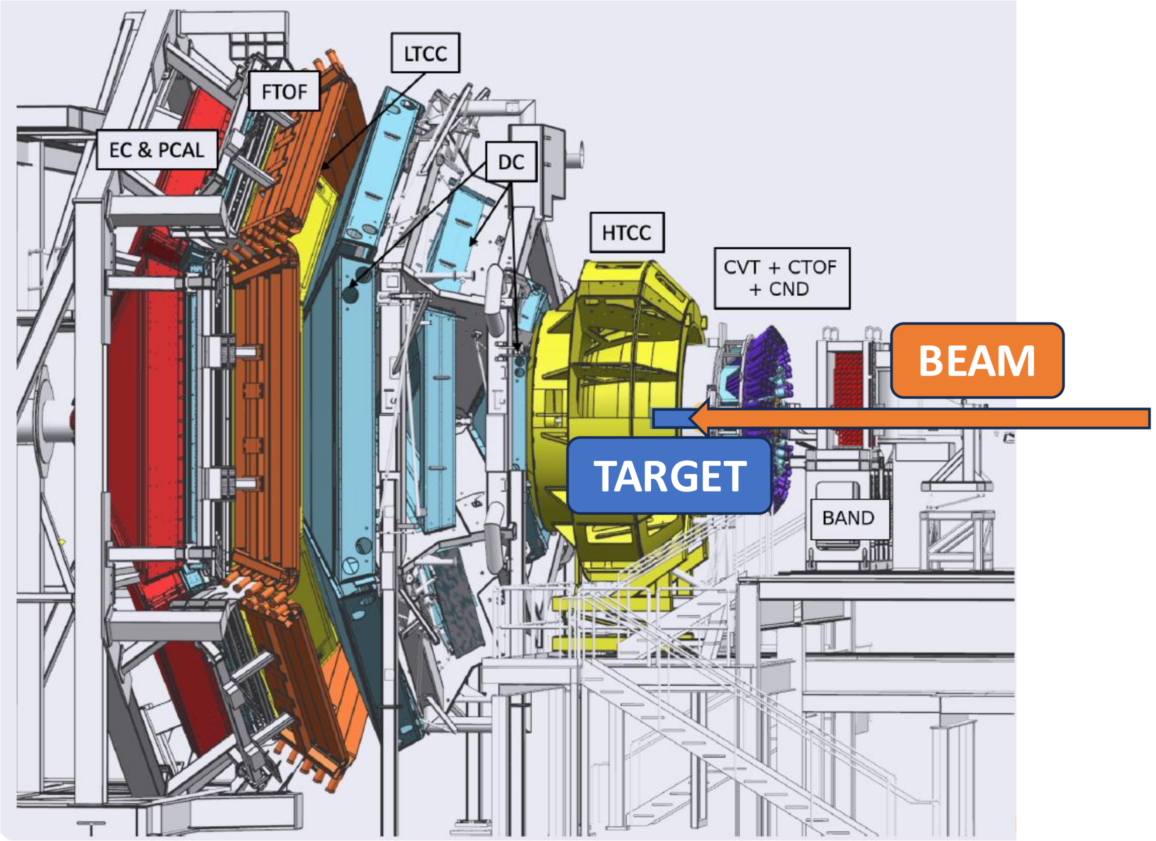
Motivation

- 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

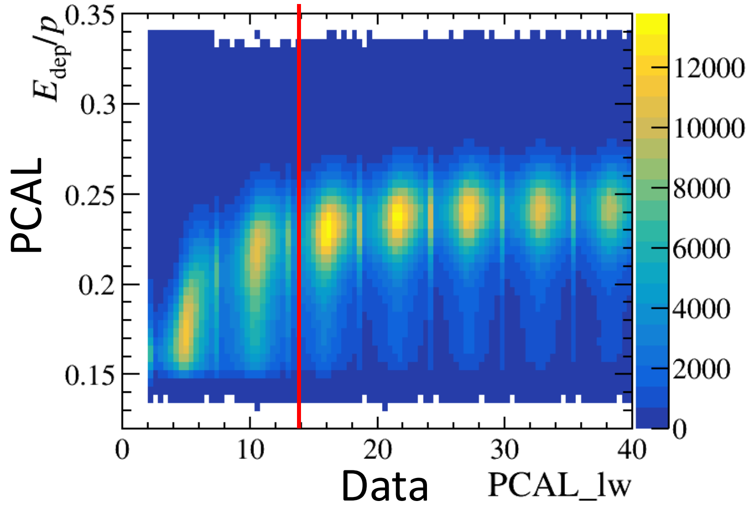


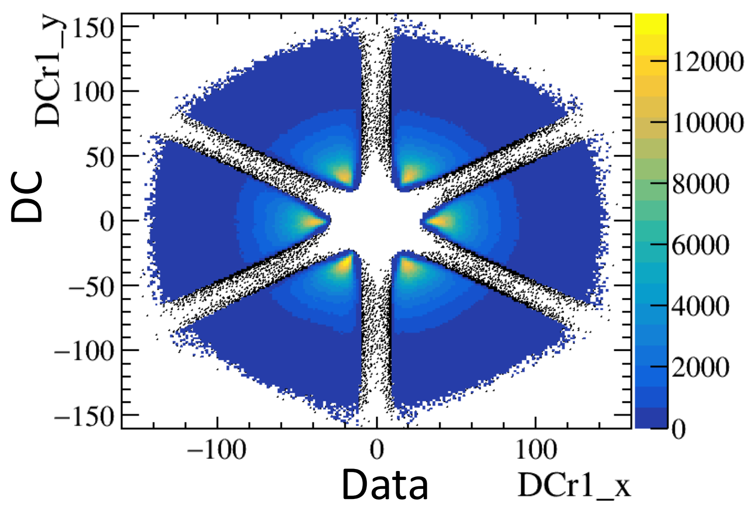
Data and MC samples

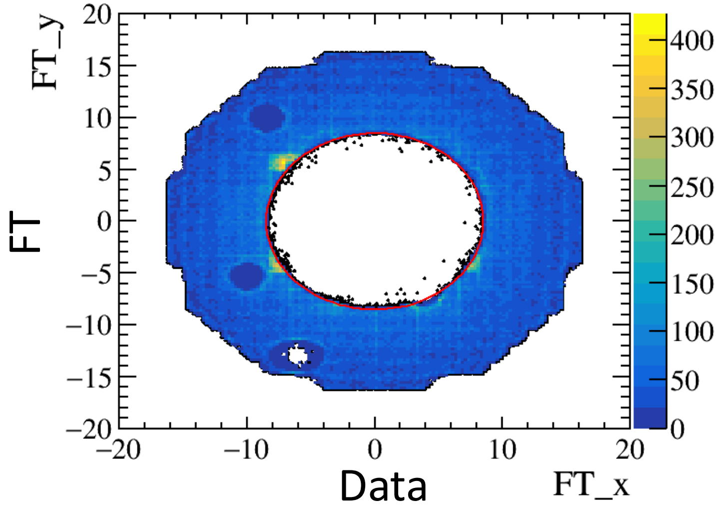
- Data
  - RGB data, collected in 2019 spring and 2020 spring (inbending)
  - 10.6/10.4/10.2 GeV electron beam
    - With an average polarization of 86%
    - Scattering off an unpolarized liquid deuterium target of 5 cm length
- MC
  - Generator: genepi
  - 90M DVCS events
    - 30M for each beam energy
    - nDVCS: 21M events
    - pDVCS: 69M events



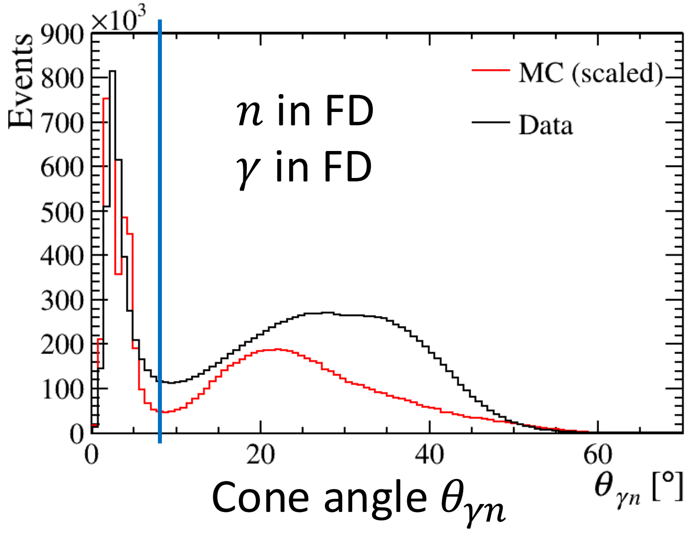
PID and fiducial cuts





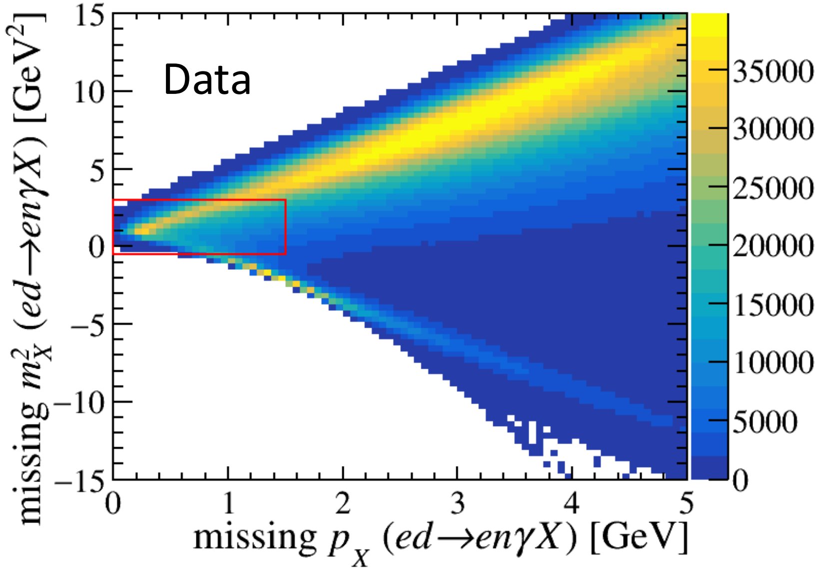


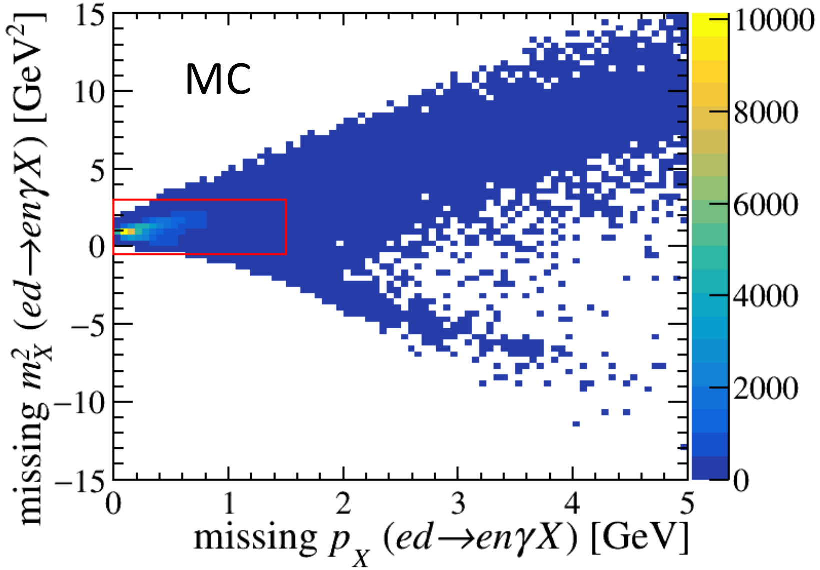
	Electron	Photon	Neutron
PID	11	22	2112
Momentum P	> 1 GeV	> 2 GeV	> 0.3 GeV
Reconstructed in	FD	FD or FT	FD or CD
Fiducial cuts	In FD: PCAL: lv(lw) > 14 DC: edge > 6	In FD: PCAL: lv(lw) > 14	In FD: $\theta_{en} > 12°$ and $\theta_{\gamma n} > 8°$ ECAL: lv(lw) > 14 and no hit in PCAL
		In FT: $x^2 + y^2 > 72$	In CD: $40° < \theta_n < 140°$



Select nDVCS data

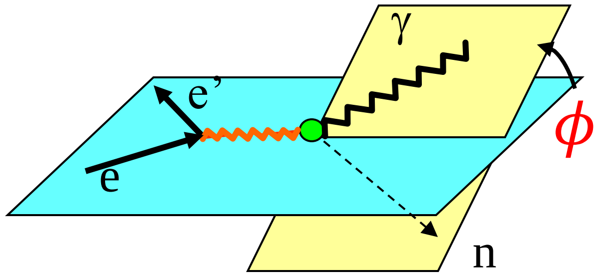
- Select events with at least one electron, one neutron and one photon
  - For cases with more than one combination, select the one with the smallest χ^2-like quantity (defined using exclusivity variables that peak at zero)
- Reaction kinematics: $Q^2 > 1\ \mathrm{GeV}^2$, $W > 2\ \mathrm{GeV}$, $t > -1.9\ \mathrm{GeV}^2$
- Apply pre-selection on missing m_X^2 and p_X of $ed \to en\gamma X$
  - To reduce events from other channels mostly
  - Pre-selection: $-0.5 < m_X^2 < 3\ \mathrm{GeV}^2$, $0 < p_X < 1.5\ \mathrm{GeV}$

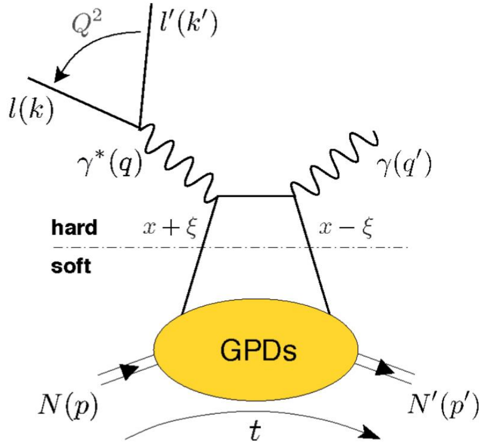


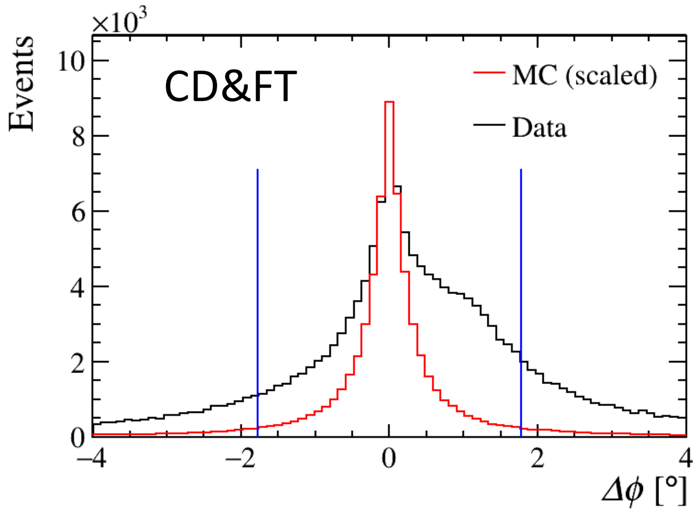


Exclusivity selection

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







$|\Delta\phi| < 1.8°$

- $|\Delta\phi| < 1.8°$
- $-0.5 < \Delta t < 0.8$ GeV^2
- $-0.31 < m_X^2 < 0.16$ GeV^2 for $en \to en\gamma X$
- $-3.7 < m_X^2 < 3.1$ GeV^2 for $en \to enX$
- $\theta_{X\gamma} < 3.7°$ for $en \to enX$
- $0.1 < m_X^2 < 2.2$ GeV^2 for $ed \to en\gamma X$
- $p_X < 0.8$ GeV for $ed \to en\gamma X$

- $\Delta\phi$: 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

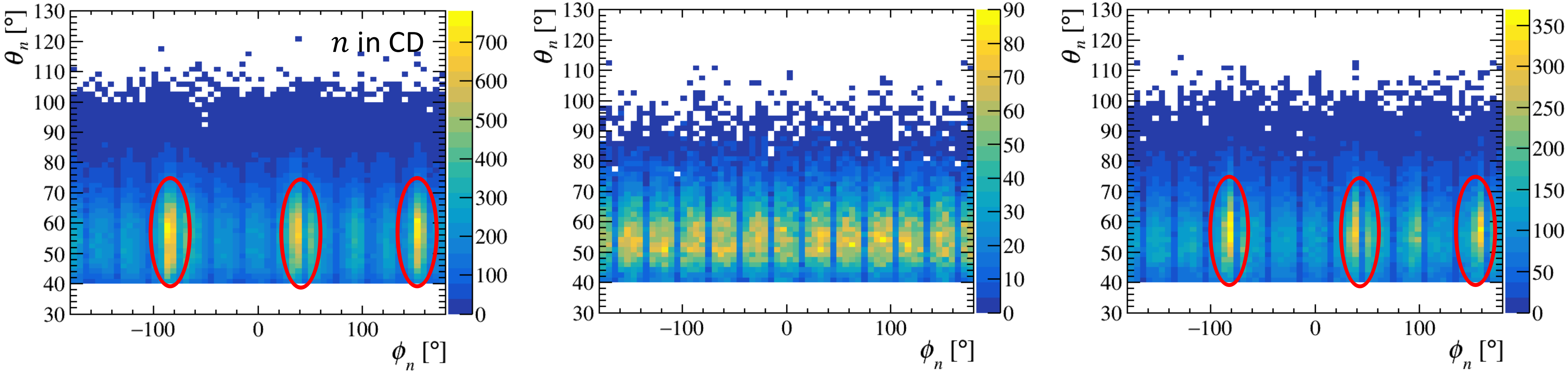
- After the exclusivity selection
  - $N = 3.52 \times 10^5$ for CD&FT
  - $N = 0.74 \times 10^5$ for CD&FD

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

Proton misidentified as neutron in CD

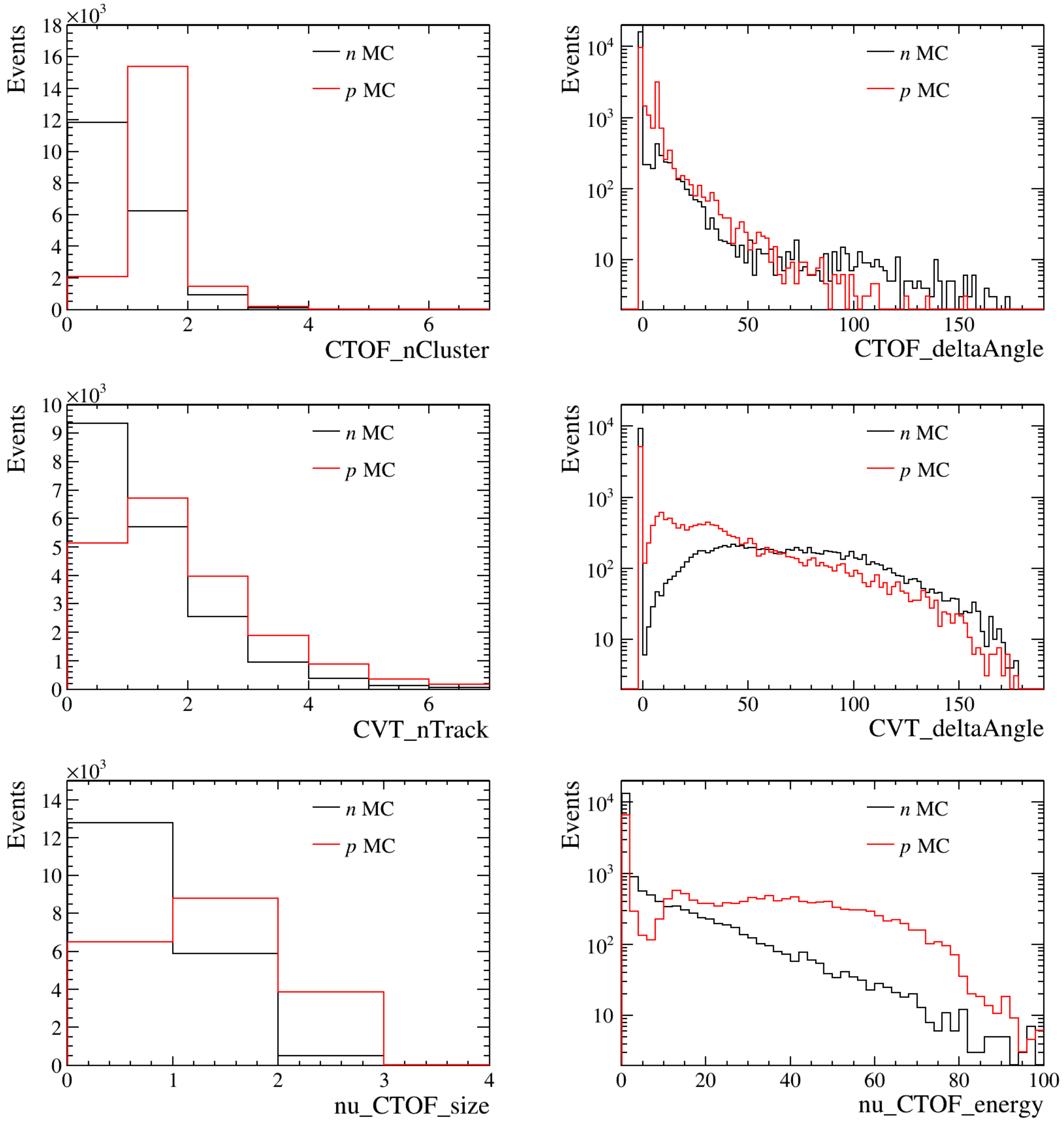
- The tracking system (CVT) in CD has dead or low-efficiency regions
- Protons: no tracks in CVT but hits in central neutron detector (CND)
    - ➢ Misidentified as neutrons
- Reproduce distributions in MC mixing pDVCS and nDVCS (both reconstructed as nDVCS)

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



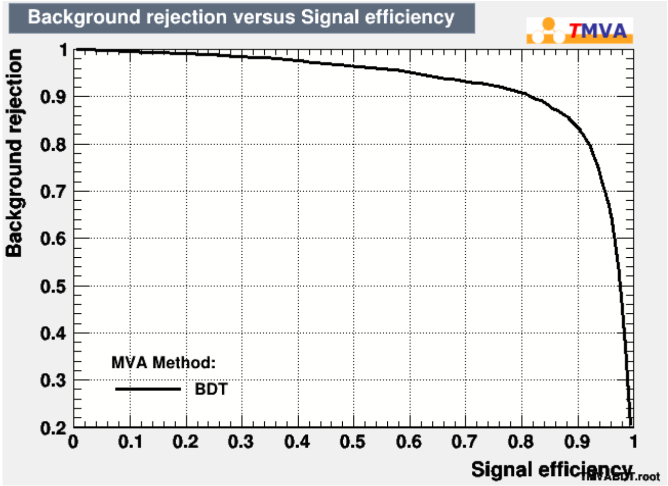
TMVA training

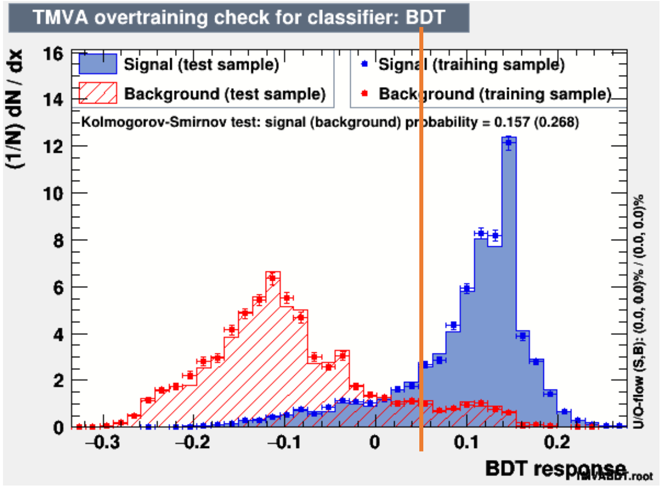
- Training and test sample:
  - MC with pure neutron target
  - MC with pure proton target
- Training variables (only use info at CTOF, CVT and CND)
  - Number of clusters at CTOF (most distinguishable)
  - Smallest cone angle between the CTOF cluster and $n(p)$ track
  - Number of tracks at CVT
  - 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)

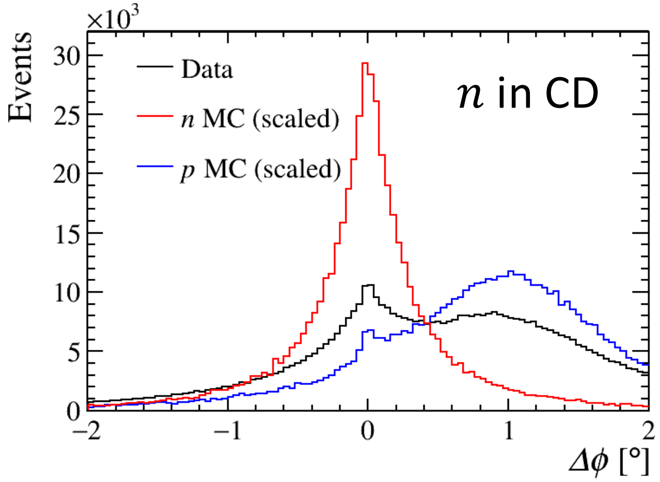


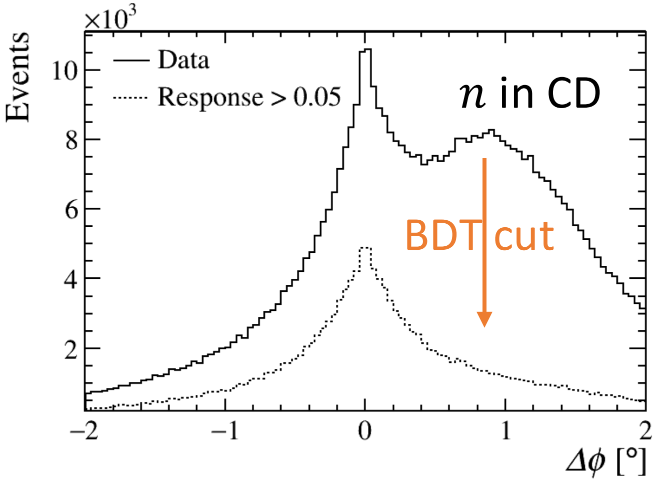
Boosted Decision Tree (BDT) classifier

- Selection:
  - BDT response > 0.05 (to be tuned)
- $N = 4.26 \times 10^5$ for n in CD (CD&FT + CD&FD)
- $N = 1.21 \times 10^5$ after the BDT response selection







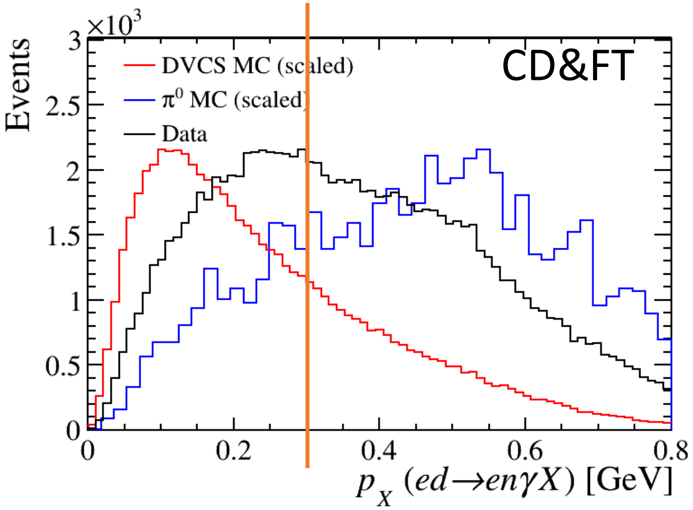


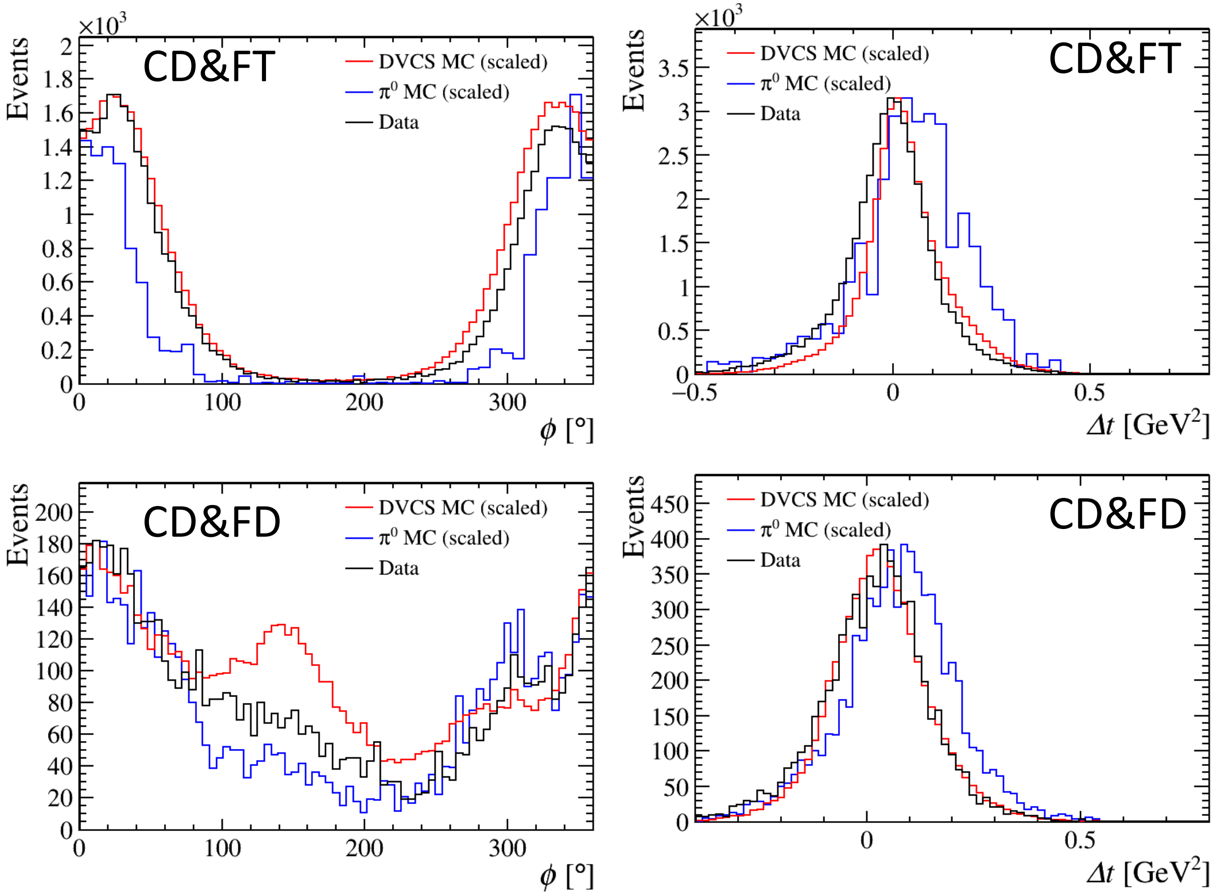
Distributions of nDVCS variables

- Apply a further cut

$$p_X < 0.3 \text{ GeV for } ed \rightarrow en\gamma X$$

- For nDVCS, the spectator has low momentum



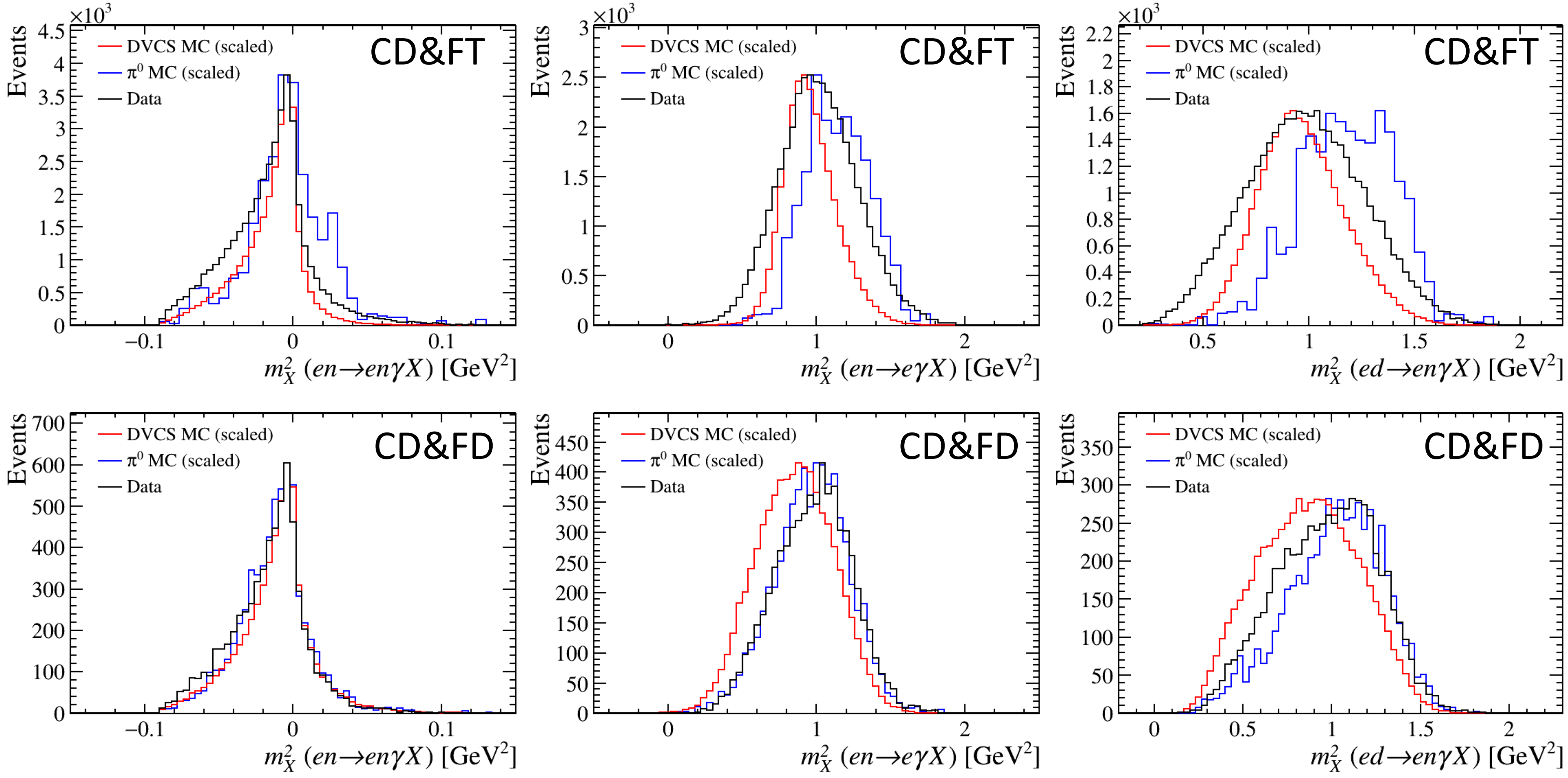


- π^0 production contamination:
  - $en \rightarrow en\pi^0(\rightarrow \gamma\gamma)$
  - π^0 MC: reconstructed as nDVCS

- 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



- After the cut $p_X < 0.3$ GeV for $ed \rightarrow en\gamma X$
- 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

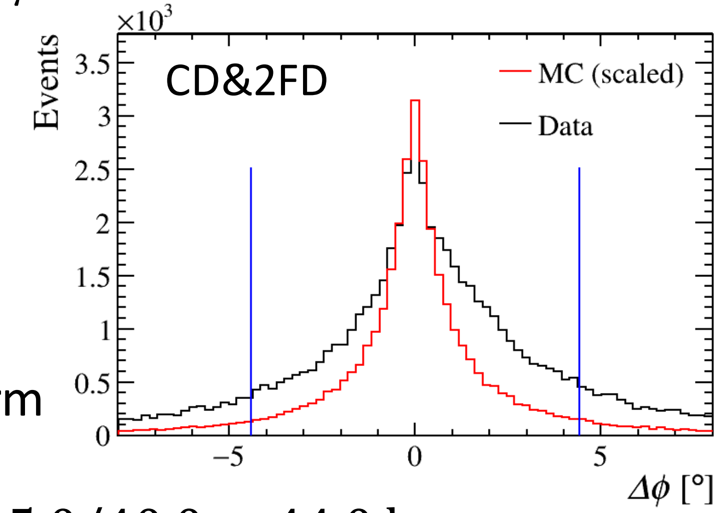
- $en \rightarrow en\pi^0(\rightarrow \gamma\gamma)$ background subtraction:
  - $N_{\mathrm{DVCS}} = N_{en\gamma} - N_{en\pi^0} \times f^{\mathrm{MC}} = N_{en\gamma} - N_{en\pi^0} \times \frac{N^{\mathrm{MC}}_{en\pi^0(1\gamma)}}{N^{\mathrm{MC}}_{en\pi^0(2\gamma)}}$

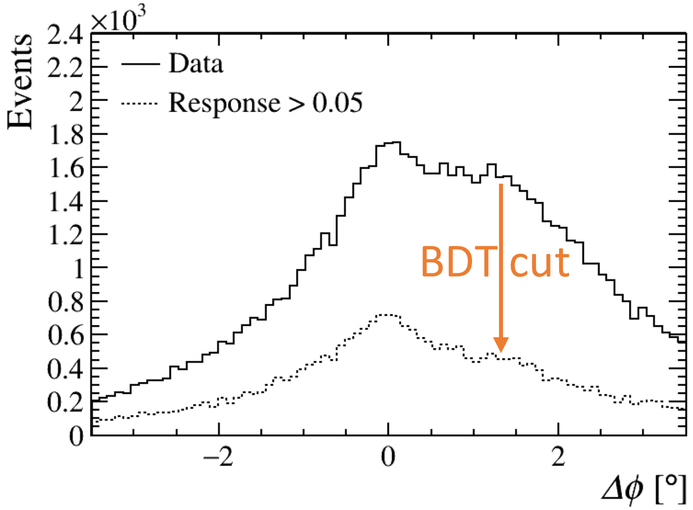
Partially reconstructed $en\pi^0(1\gamma)$ and passed DVCS selection

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, $p_n > 0.3$ GeV, $p_\gamma > 0.3$ GeV
    - $0.10 < m_{\gamma\gamma} < 0.17$ GeV
  - Exclusivity cuts (in backup slides)
  - BDT response cut to reduce misidentified protons

- CD&2FD: n in CD and 2 γ in FD



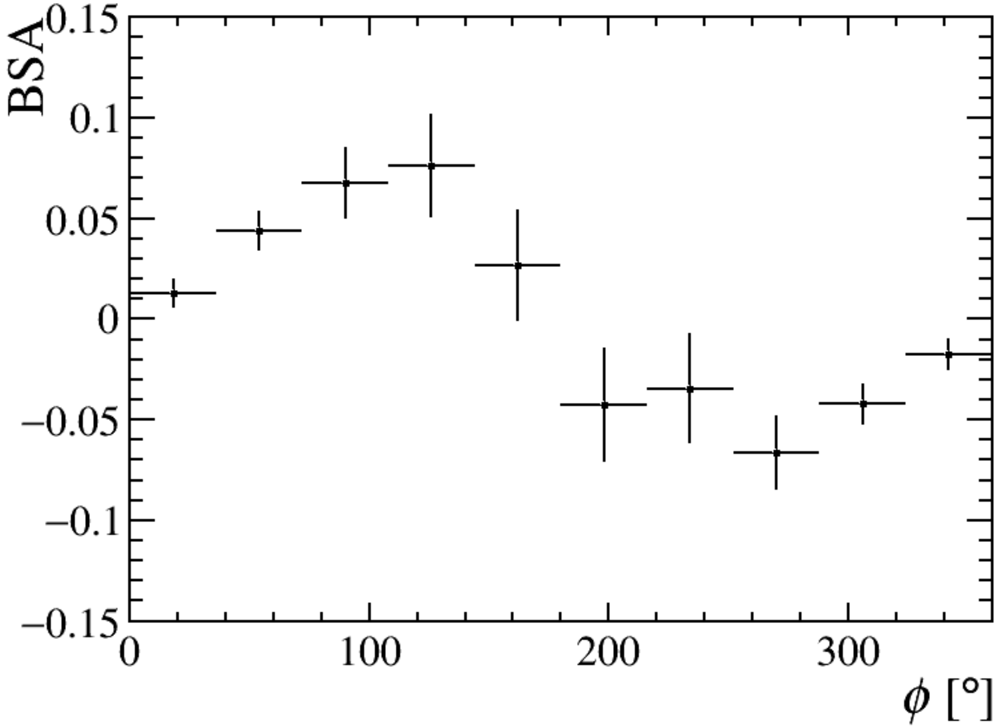


➢ Using events for n in CD to perform the subtraction
  ➢ $N_{\mathrm{DVCS}} = 46.6\text{ k} - 20.4\text{ k} \times 5.0/40.0 = 44.0\text{ k}$
  ➢ π^0 contamination: 5.5%

Beam-spin asymmetry as a check

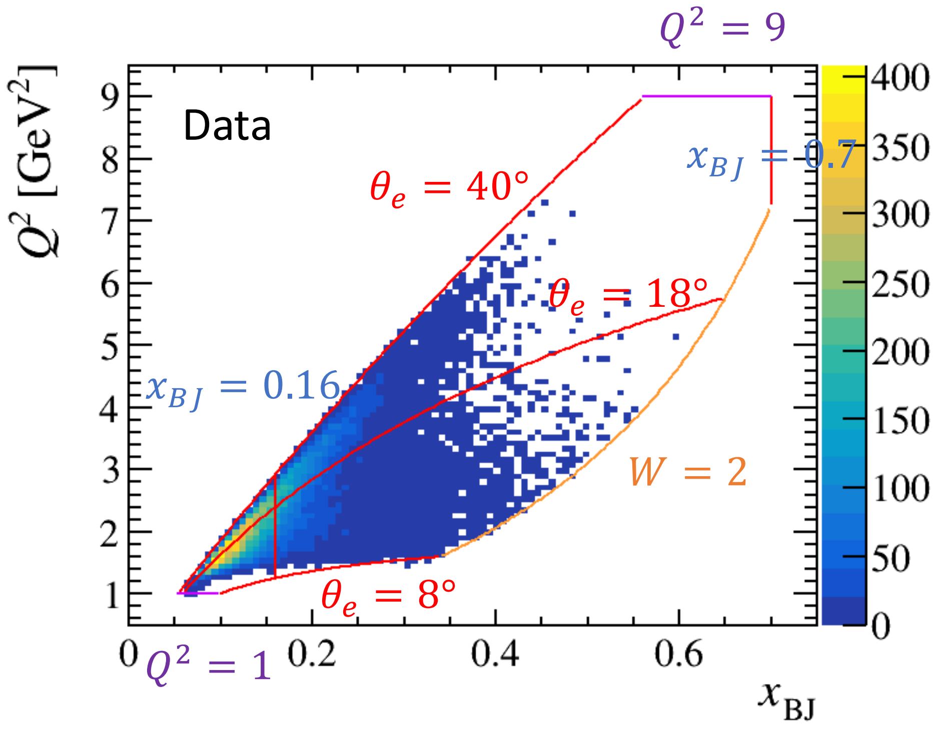
$$BSA = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}$$

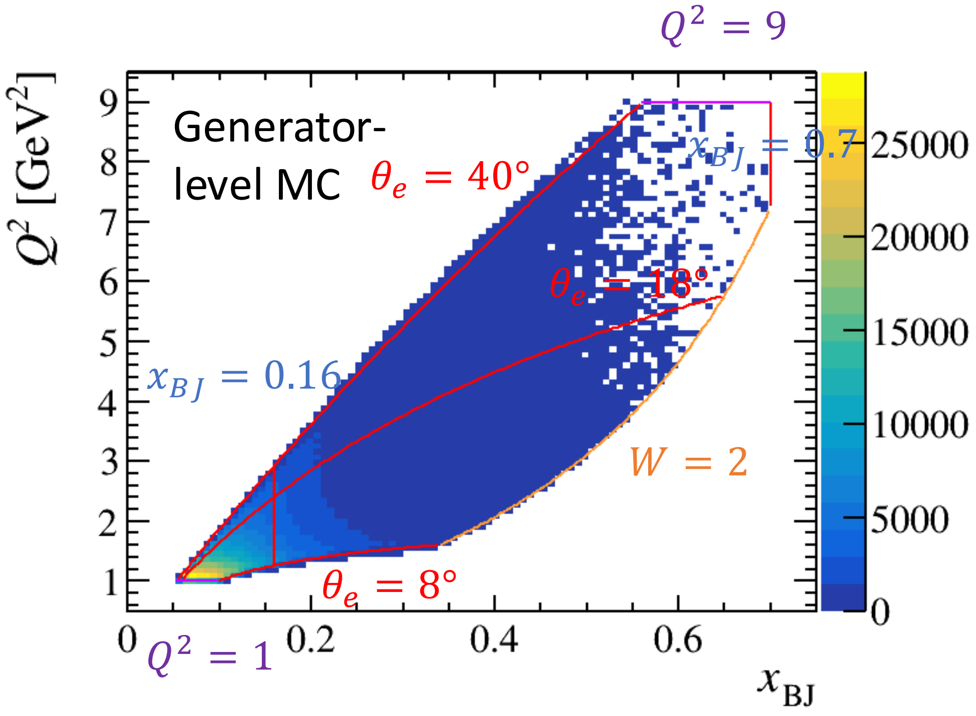
- P is the average beam polarization
- N^+ is the nDVCS yield for positive helicity
- N^- is the nDVCS yield for negative helicity
- Extract BSA using nDVCS events
  - only for n in CD
  - after the BDT response selection
  - subtract π^0 production contamination in each ϕ bin
- The BSA has the expected sinusoidal shape, and its amplitude is on the order of a few percent
  - consistent with the recent CLAS12 measurement [A. Hobart, S. Niccolai et al (CLAS), arXiv:2406.15539]



Binning scheme

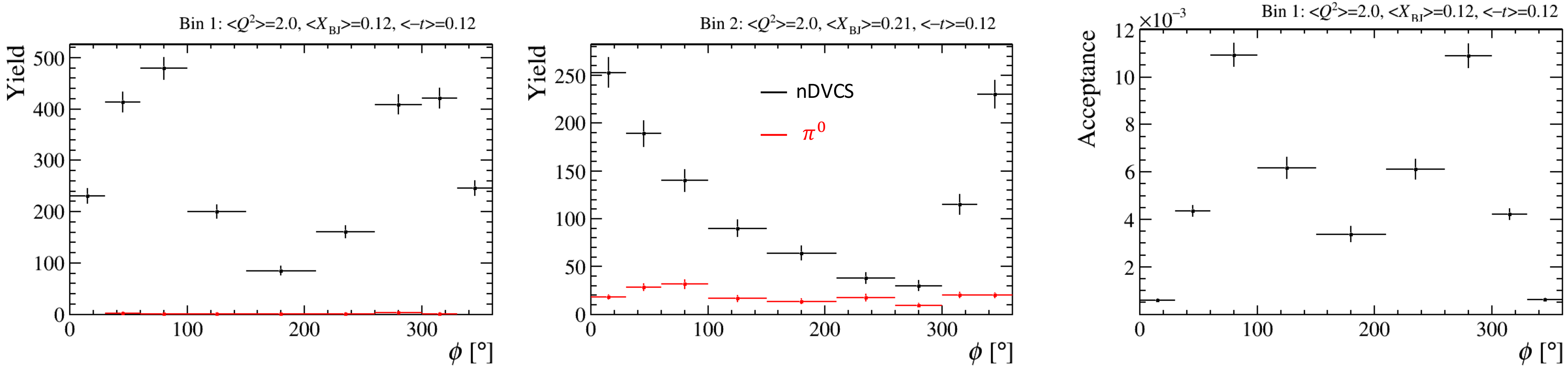
- 4 bins in (Q^2, x_{BJ})
  - Use θ_e to define bins in order to follow the shape of the acceptance
- $-t \in [0.08, 0.15], [0.15, 0.3], [0.3, 0.6], [0.6, 1.2]\ \mathrm{GeV}^2$





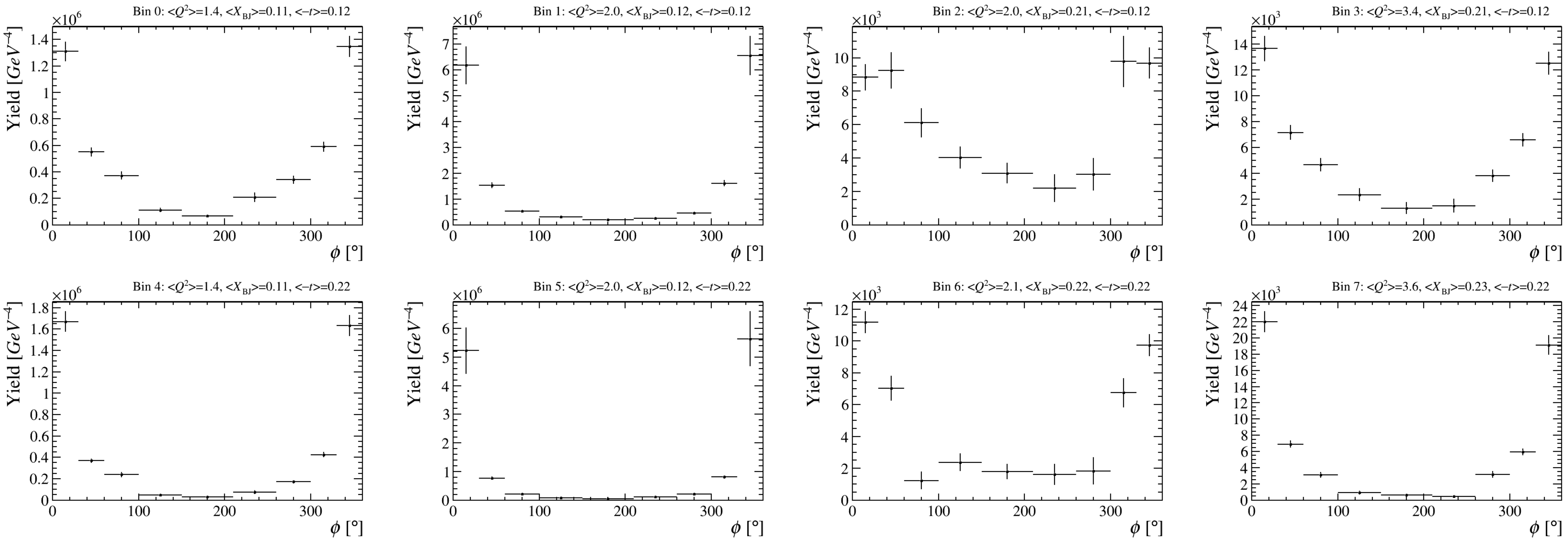
Yield and acceptance

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



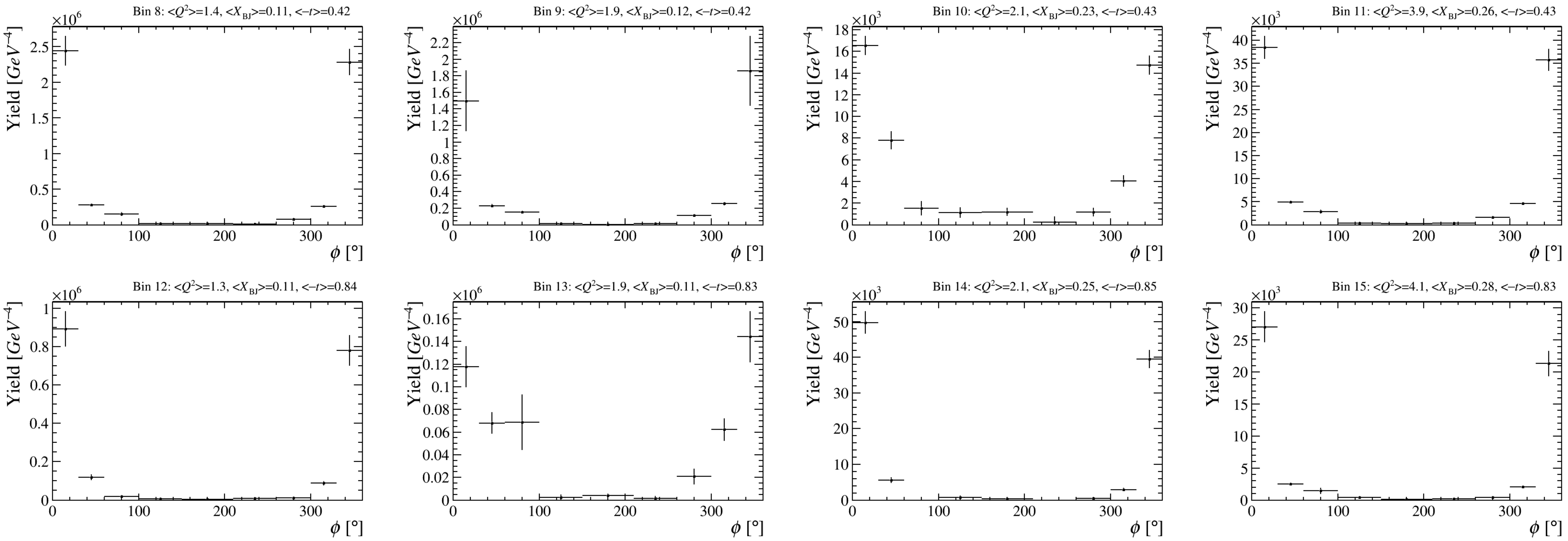
- π^0 contribution is negligible in some bins, while it is still significant in some other bins
- $N^{\mathrm{corr}} = (N_{\mathrm{nDVCS}} - N_{\pi^0})/\varepsilon_{\mathrm{Acc}}$

Acceptance-corrected yield



- The acceptance-corrected yield peaks at $\phi = 0$ or $360°$
- The bin-volume correction is under study

Acceptance-corrected yield



- The acceptance-corrected yield peaks at $\phi = 0$ or $360°$
- The bin-volume correction is under study

Summary

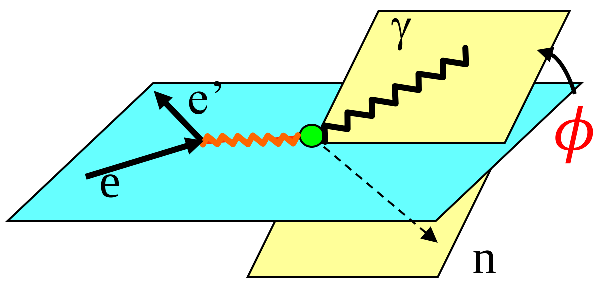
- nDVCS events are selected and compared with MC
- Beam-spin asymmetry is consistent with the recent CLAS12 measurement
- Acceptance-corrected yields are extracted in $(Q^2, x_{\mathrm{BJ}}, t, \phi)$ bins
- Next to do
  - Study other topologies (FD&FT, FD&FD) for nDVCS
  - Study the momentum corrections
  - Study the neutron efficiency correction and bin-volume correction
  - Extract the integrated luminosity and obtain the cross-sections
  - Estimate the systematic uncertainties

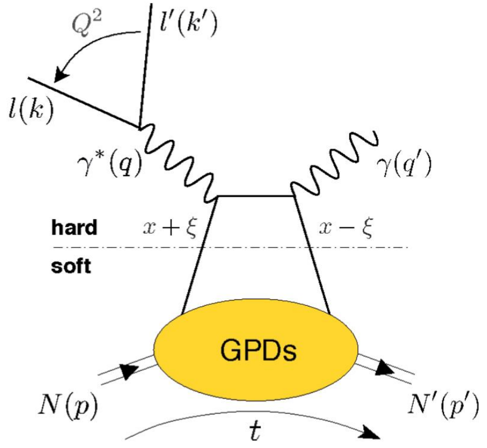
Thank you!

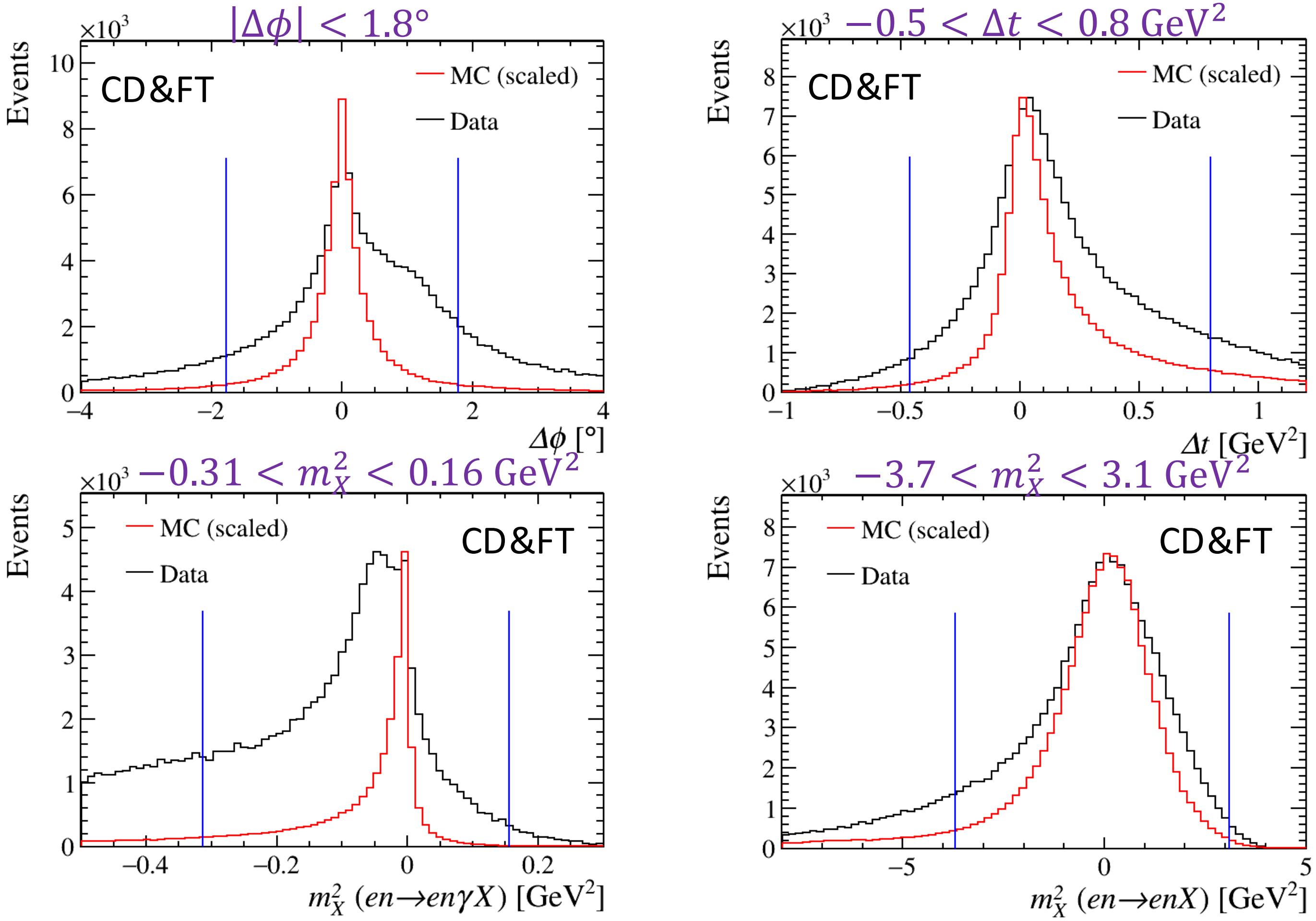
Backup slides

Exclusivity selection

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







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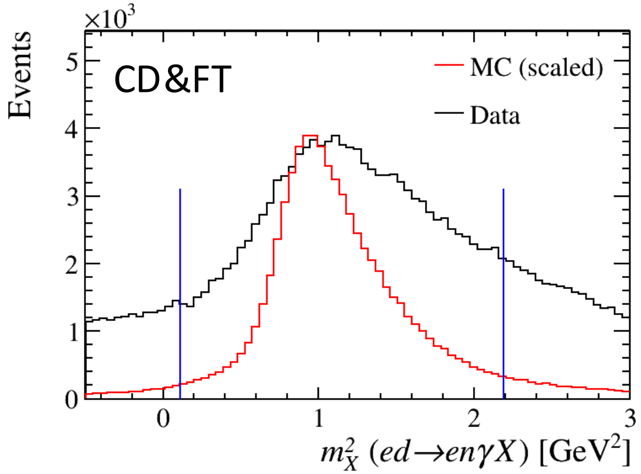
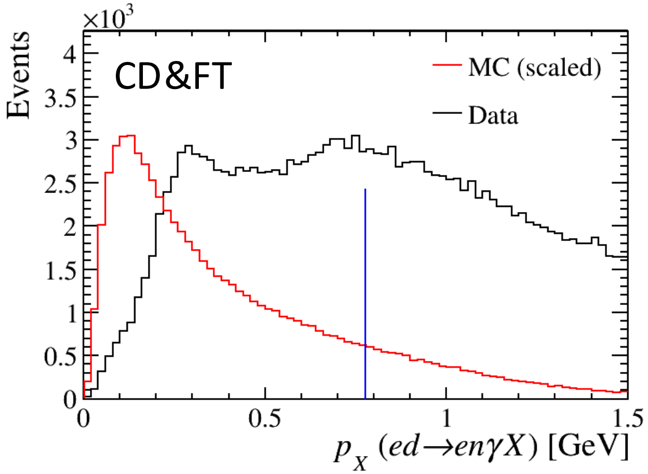
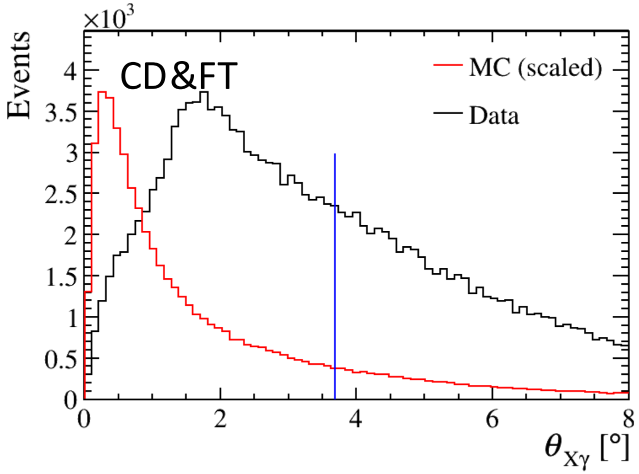
- $\theta_{X\gamma}$: cone angle formed by the missing photon X ($en \to enX$) and the outgoing photon γ



$0.1 < m_X^2 < 2.2\ \mathrm{GeV}^2$



$p_X < 0.8\ \mathrm{GeV}$



$\theta_{X\gamma} < 3.7°$

- 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

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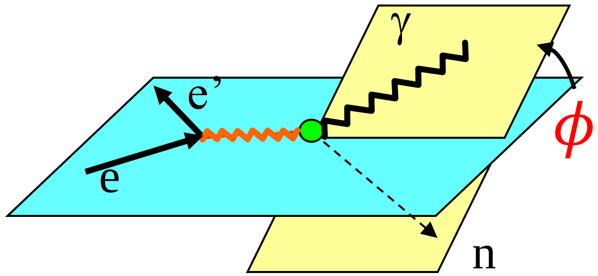
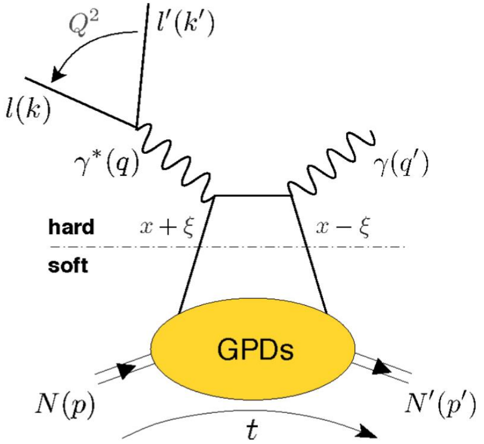
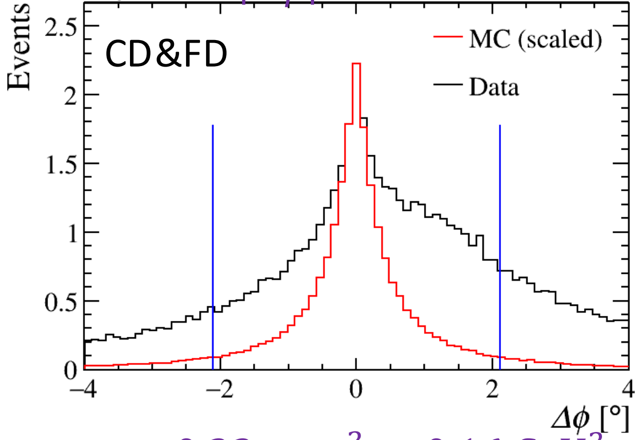
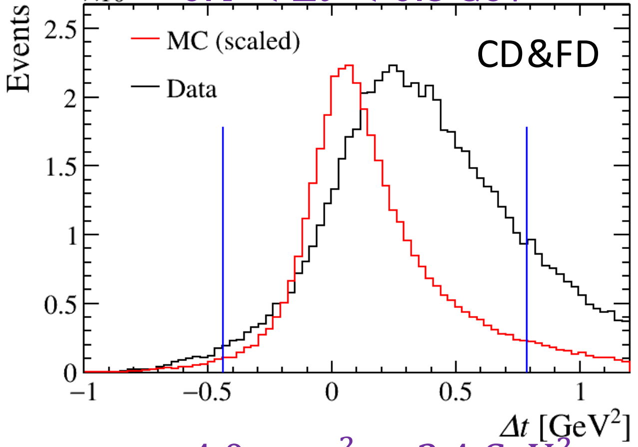




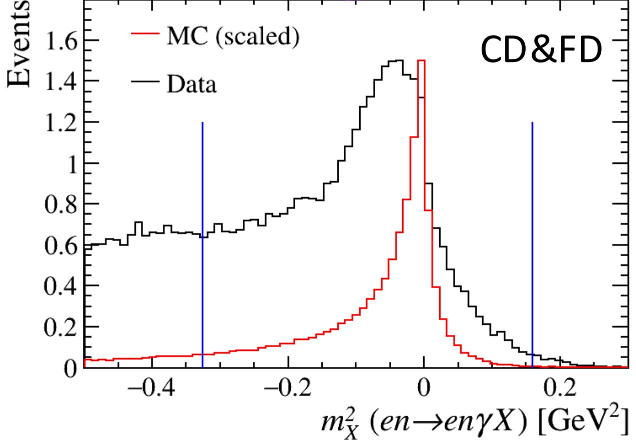
$|\Delta\phi| < 2.1°$



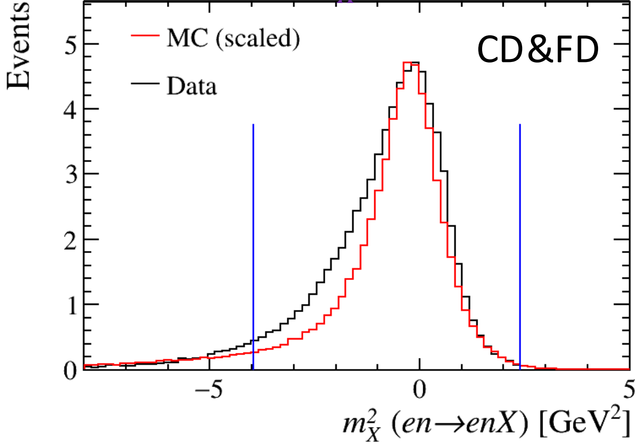
$-0.4 < \Delta t < 0.8\ \mathrm{GeV}^2$



$-0.33 < m_X^2 < 0.16\ \mathrm{GeV}^2$



$-4.0 < m_X^2 < 2.4\ \mathrm{GeV}^2$



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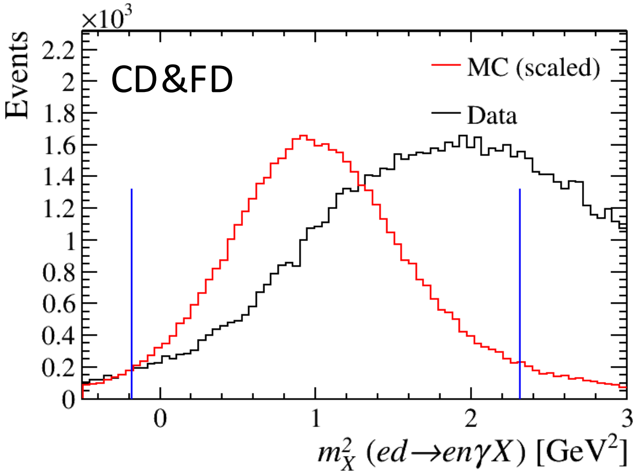

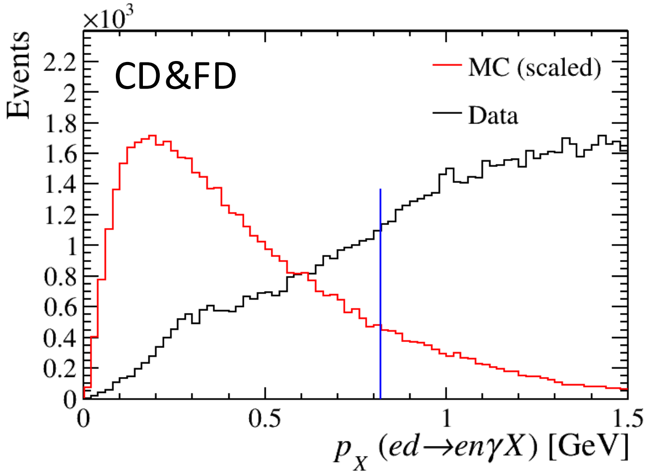

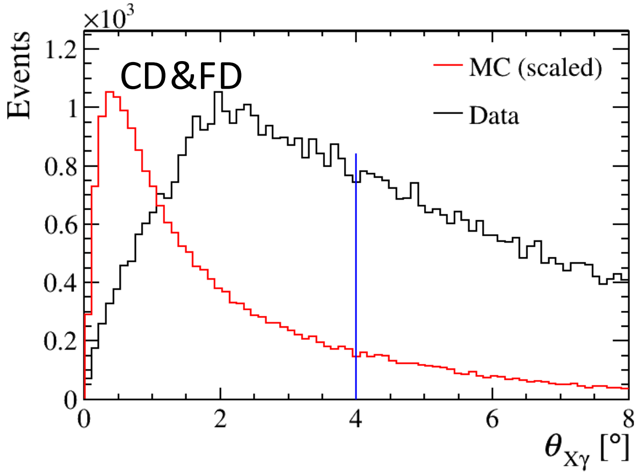

$-0.2 < m_X^2 < 2.3\ \text{GeV}^2$ $\quad$ $p_X < 0.8\ \text{GeV}$ $\quad$ $\theta_{X\gamma} < 4.0°$

- After the exclusivity selection
  - $N = 3.62 \times 10^5$ for CD&FT
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➢ The data and MC distributions are very different

  ➢ mainly due to the protons that are misidentified as neutrons, discussed in the later slides

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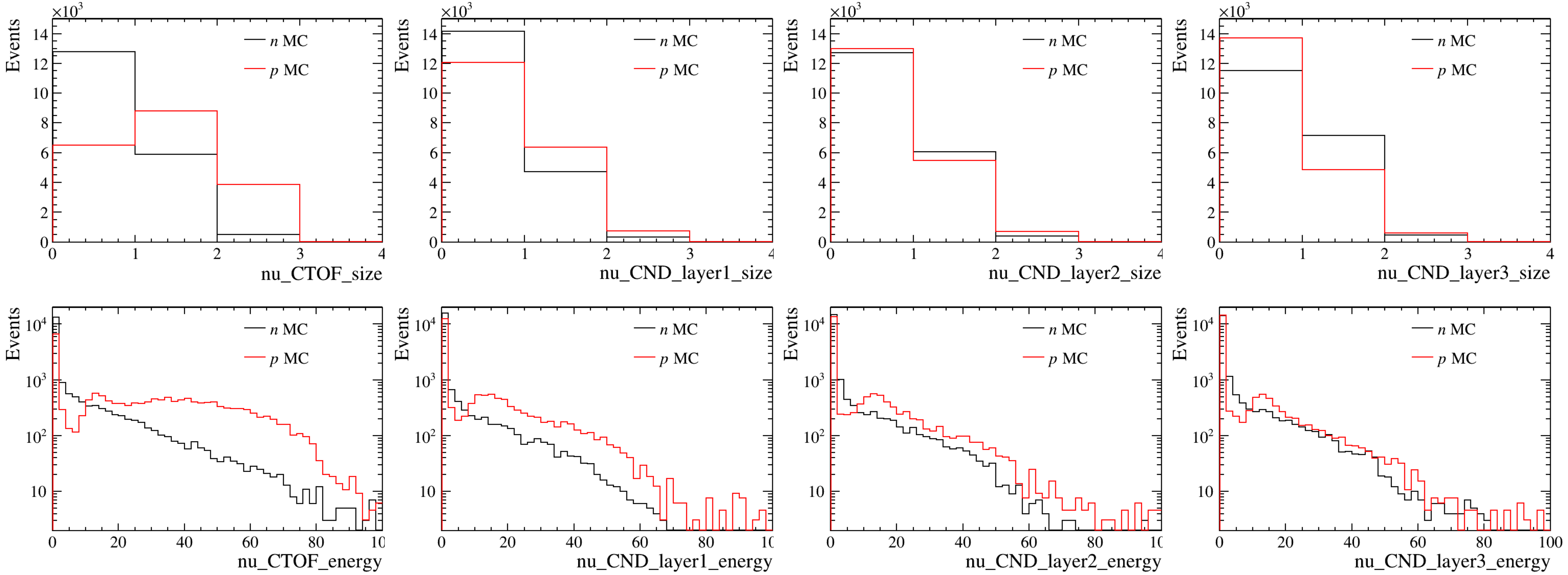
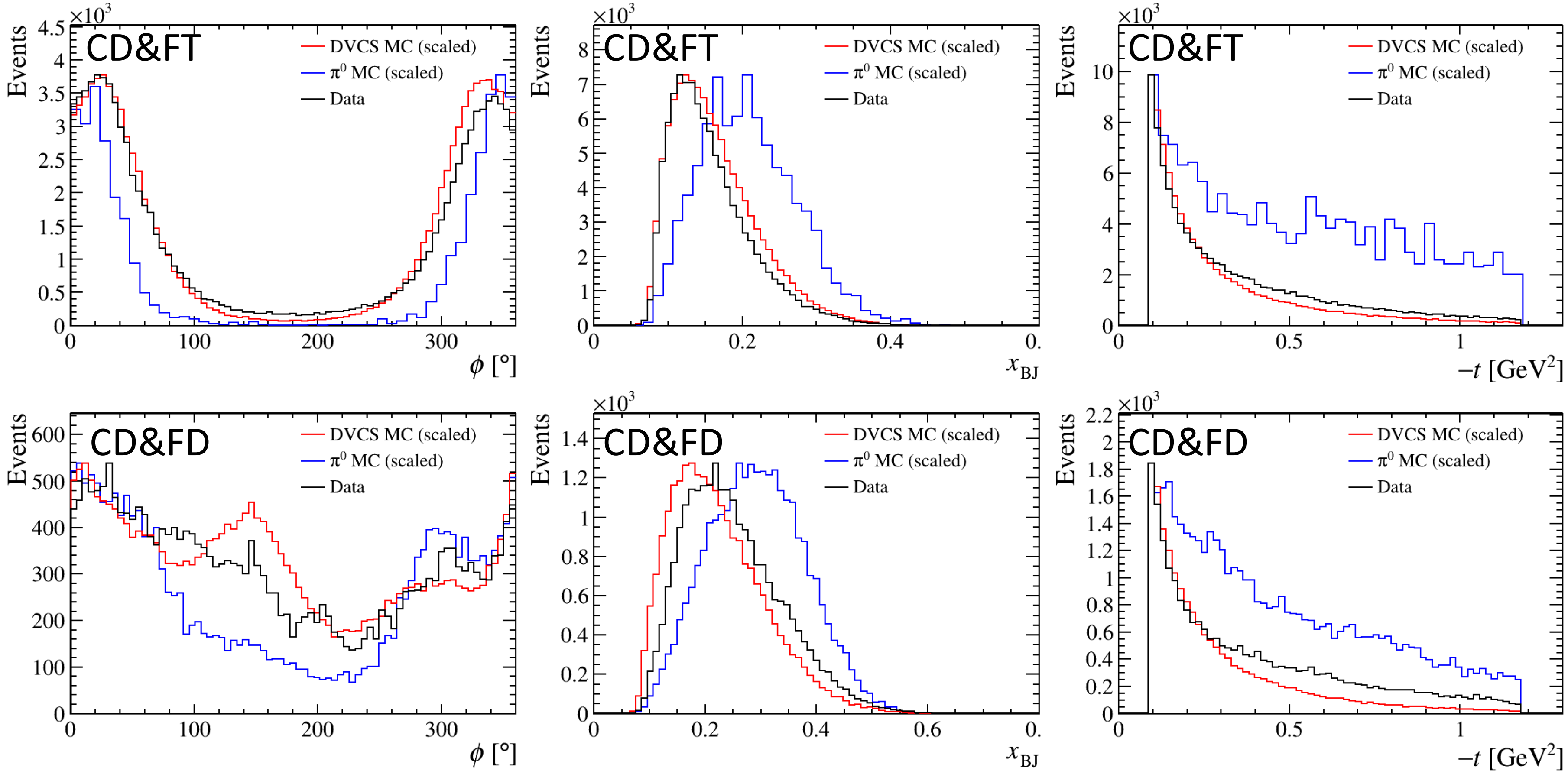


Distributions of nDVCS variables

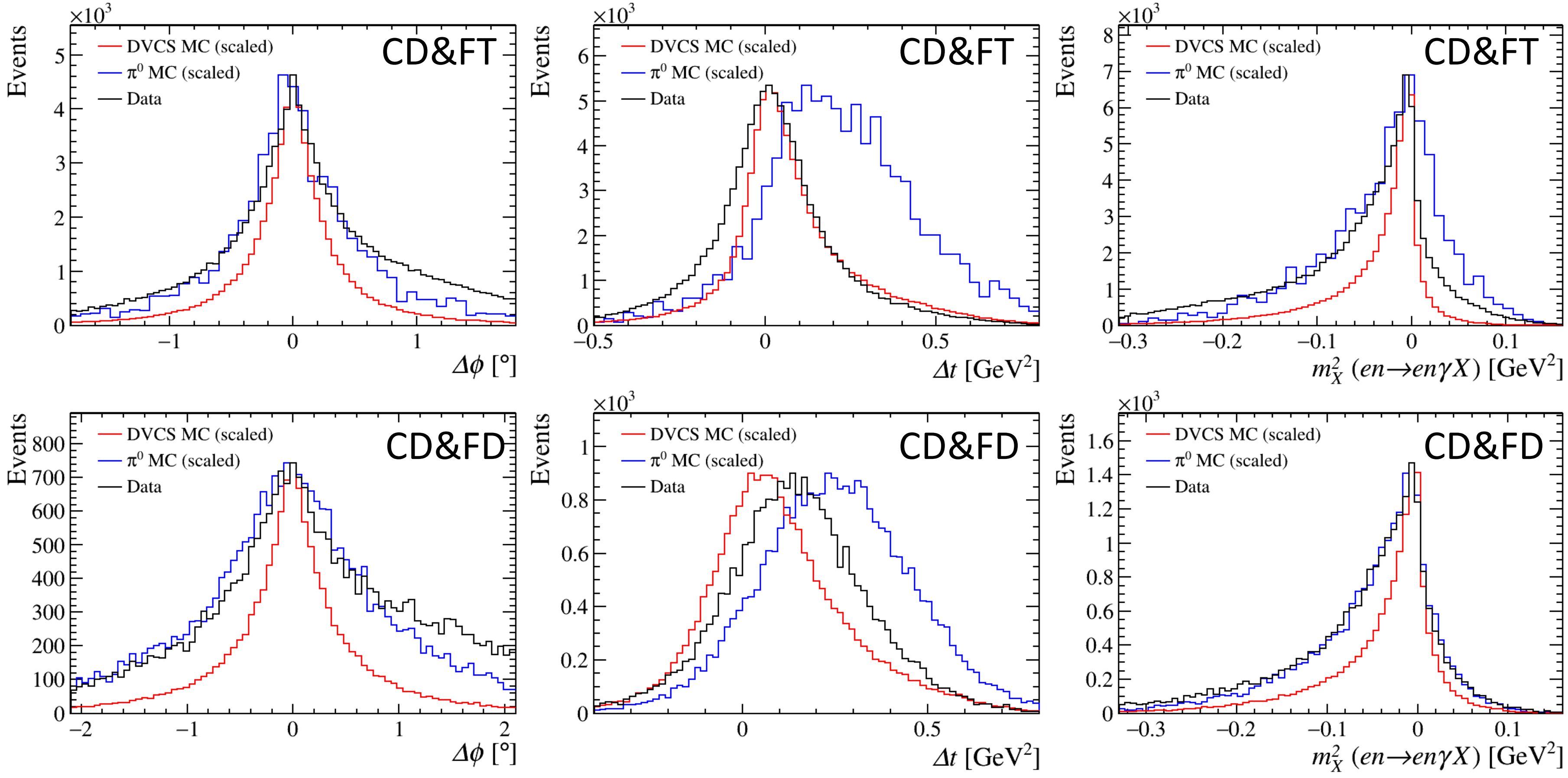
- π^0 production contamination:
  - $en \rightarrow en\pi^0(\rightarrow \gamma\gamma)$
  - π^0 MC: reconstructed as nDVCS



- CD&FT:
  - Distributions for data are consistent with nDVCS MC, inconsistent with π^0 MC
  - nDVCS dominated
- CD&FD:
  - Significant π^0 production contamination

Distributions of nDVCS variables

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



- CD&FT: nDVCS dominated
- CD&FD: significant π^0 production contamination
- The difference between data and MC for nDVCS might be also due to their different resolution
- Maybe need momentum correction

Distributions of nDVCS variables

- π^0 production contamination:
  - $en \to en\pi^0(\to \gamma\gamma)$
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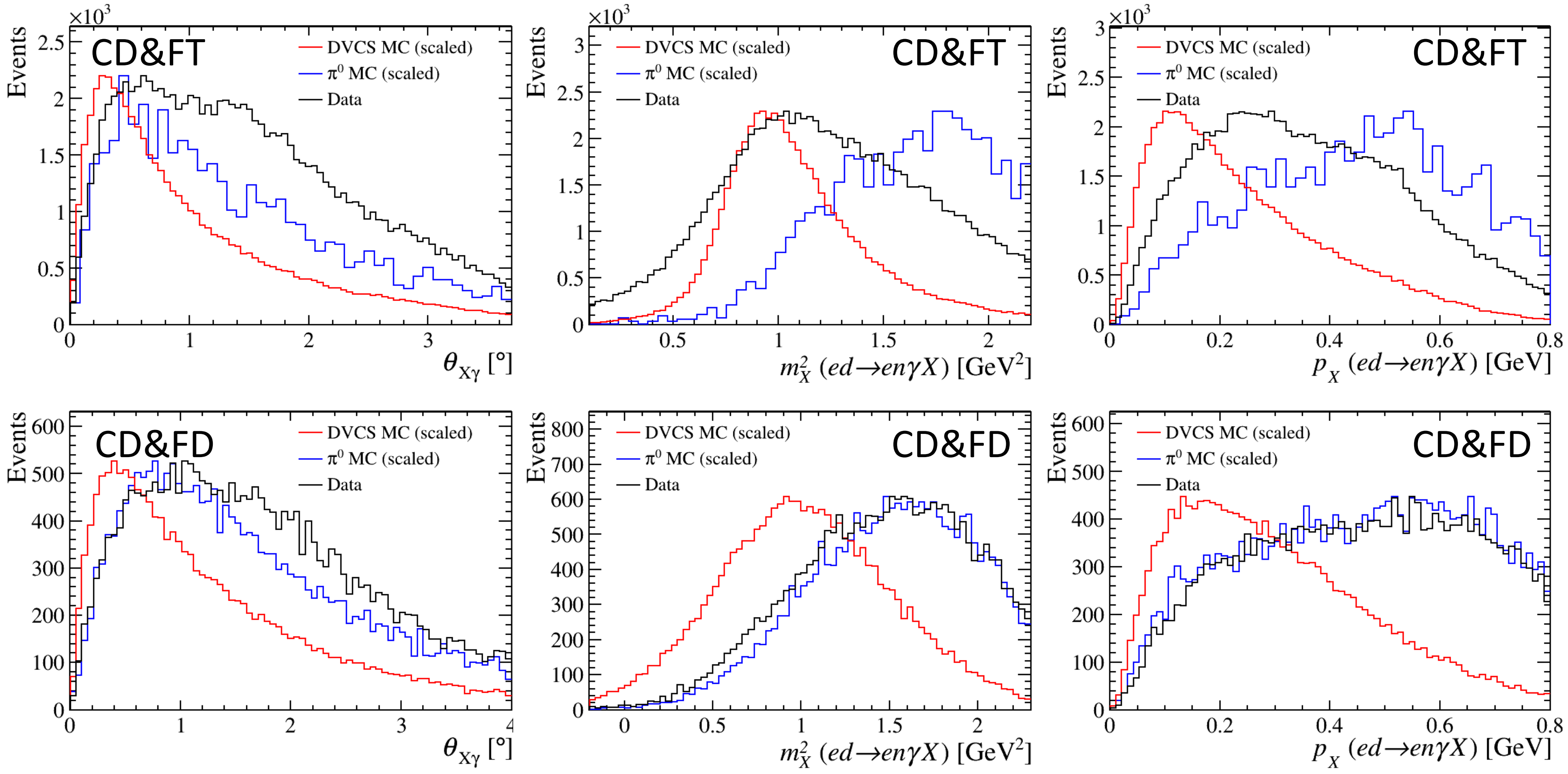


- CD&FT: nDVCS dominated
- CD&FD: significant π^0 production contamination
- The difference between data and MC for nDVCS might be also due to their different resolution
- Maybe need momentum correction

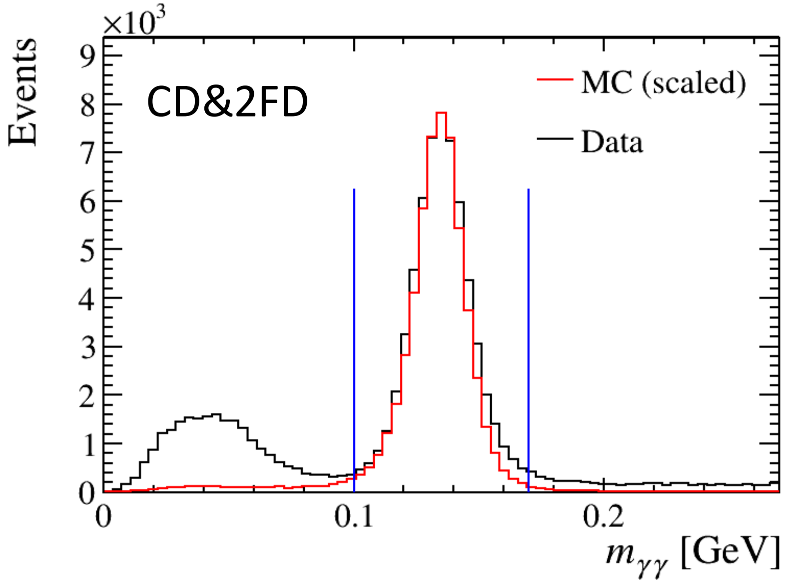
Study of π^0 production contamination

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

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

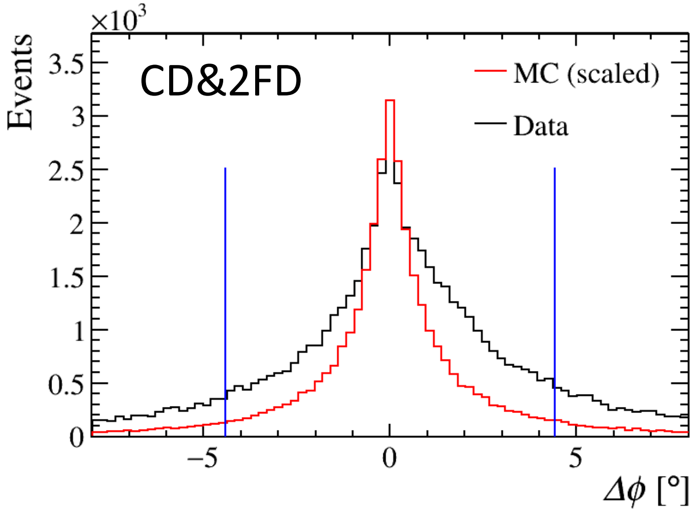
Fully reconstructed $en\pi^0(2\gamma)$ and passed π^0 production selection

- Select π^0 production data
  - PID and fiducial cuts:
    - $p_e > 1$ GeV, $p_n > 0.3$ GeV, $p_\gamma > 0.3$ GeV
    - Same fiducial cuts for the nDVCS selection
  - Select events with at least 1 e^-, 1 n and 2 γ
    - $0.10 < m_{\gamma\gamma} < 0.17$ GeV
    - 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:
    - $Q^2 > 1$ GeV^2 , $W > 2$ GeV, $t > -1.9$ GeV^2
  - Pre-selection before determining the exclusivity cuts:
    - $-0.5 < m_X^2 < 3$ GeV^2, $0 < p_X < 1.5$ GeV for $ed \to en\gamma\gamma X$



Exclusivity selection of π^0 production

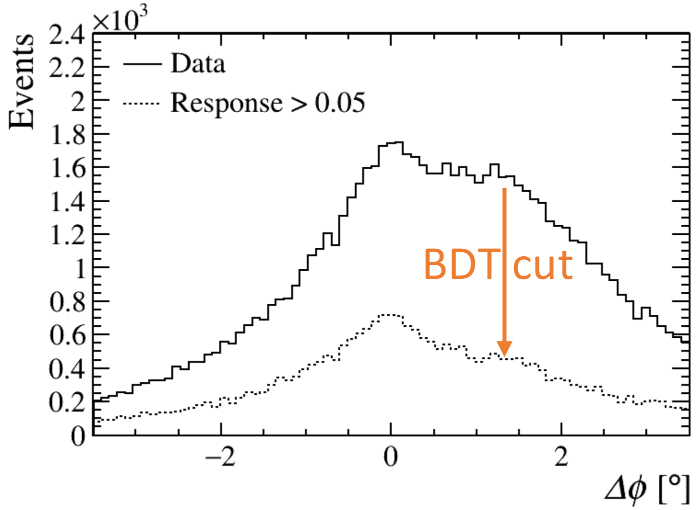
- Criteria determined by comparing data and MC
  - $\sim 2\sigma$ of the MC distribution
- CD&2FD: n in CD and 2 γ in FD



- $|\Delta\phi| < 4.4°$
- $-0.5 < \Delta t < 1.5\ \mathrm{GeV}^2$
- $-0.33 < m_X^2 < 0.13\ \mathrm{GeV}^2$ for $en \to en\gamma\gamma X$
- $-1.3 < m_X^2 < 1.5\ \mathrm{GeV}^2$ for $en \to en\gamma_1 X$
- $-2.4 < m_X^2 < 1.2\ \mathrm{GeV}^2$ for $en \to en\gamma_2 X$
- $\theta_{X\pi^0} < 8.4°$ for $en \to enX$
- $-0.1 < m_X^2 < 2.4\ \mathrm{GeV}^2$ for $ed \to en\gamma\gamma X$
- $p_X < 1.0$ GeV for $ed \to en\gamma X$

- After the exclusivity selection
  - $N = 8.39 \times 10^5$ for CD&2FD
  - $N = 0.88 \times 10^5$ for CD&2FT
  - $N = 0.52 \times 10^5$ for CD&1FT1FD

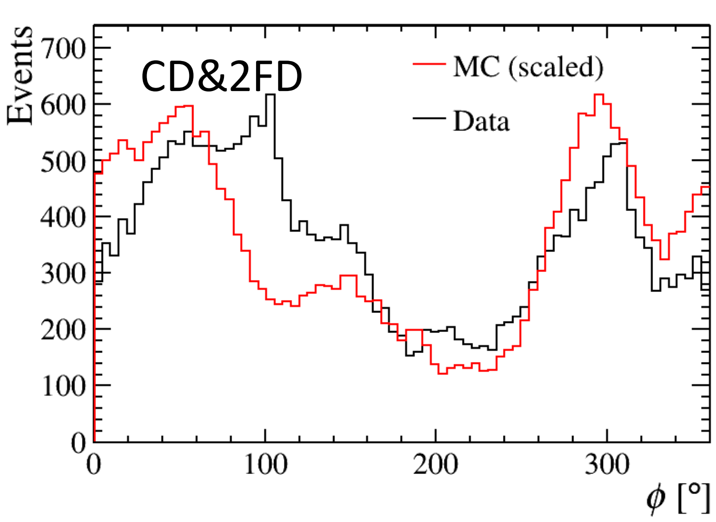
- Events for n in CD after the exclusivity selection
  - still have protons misidentified as neutrons
  - apply the BDT cut

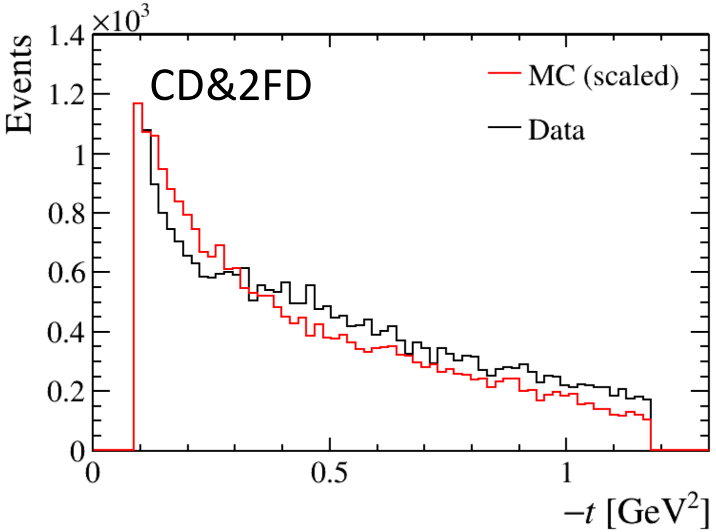


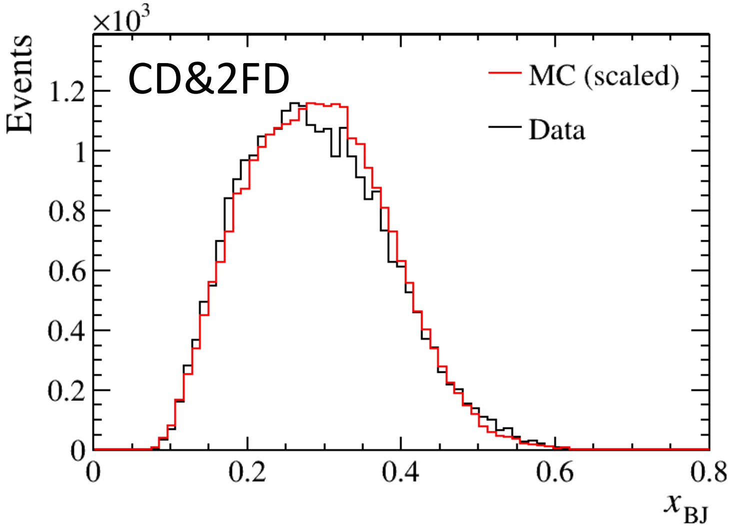
➢ The distributions for other variables and for CD&2FT and CD&1FT1FD are presented in backup slides

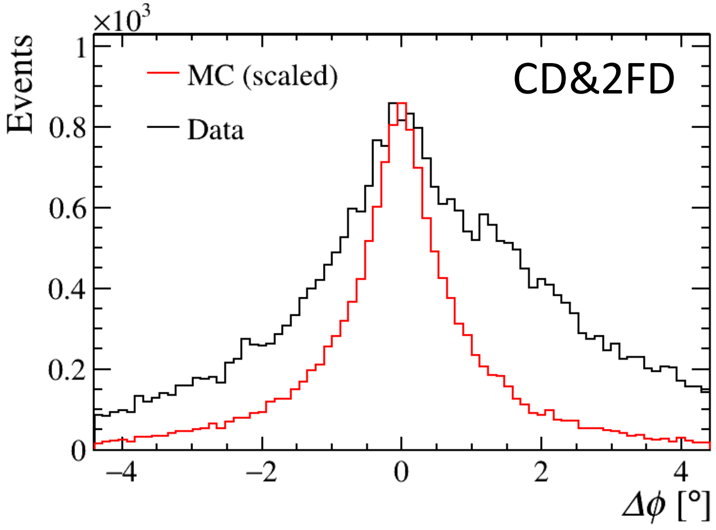
Distributions of π^0 production variables

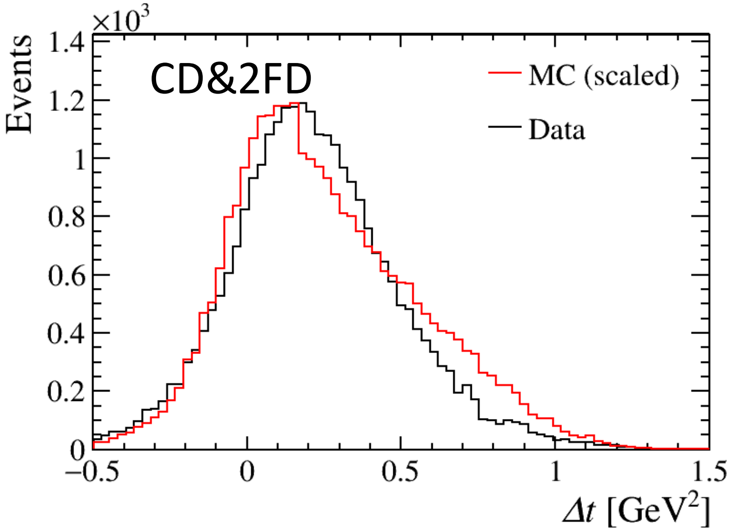
- CD&2FD: n in CD and 2 γ in FD
  - After the BDT cut
  - The difference between data and MC is maybe due to their different resolution





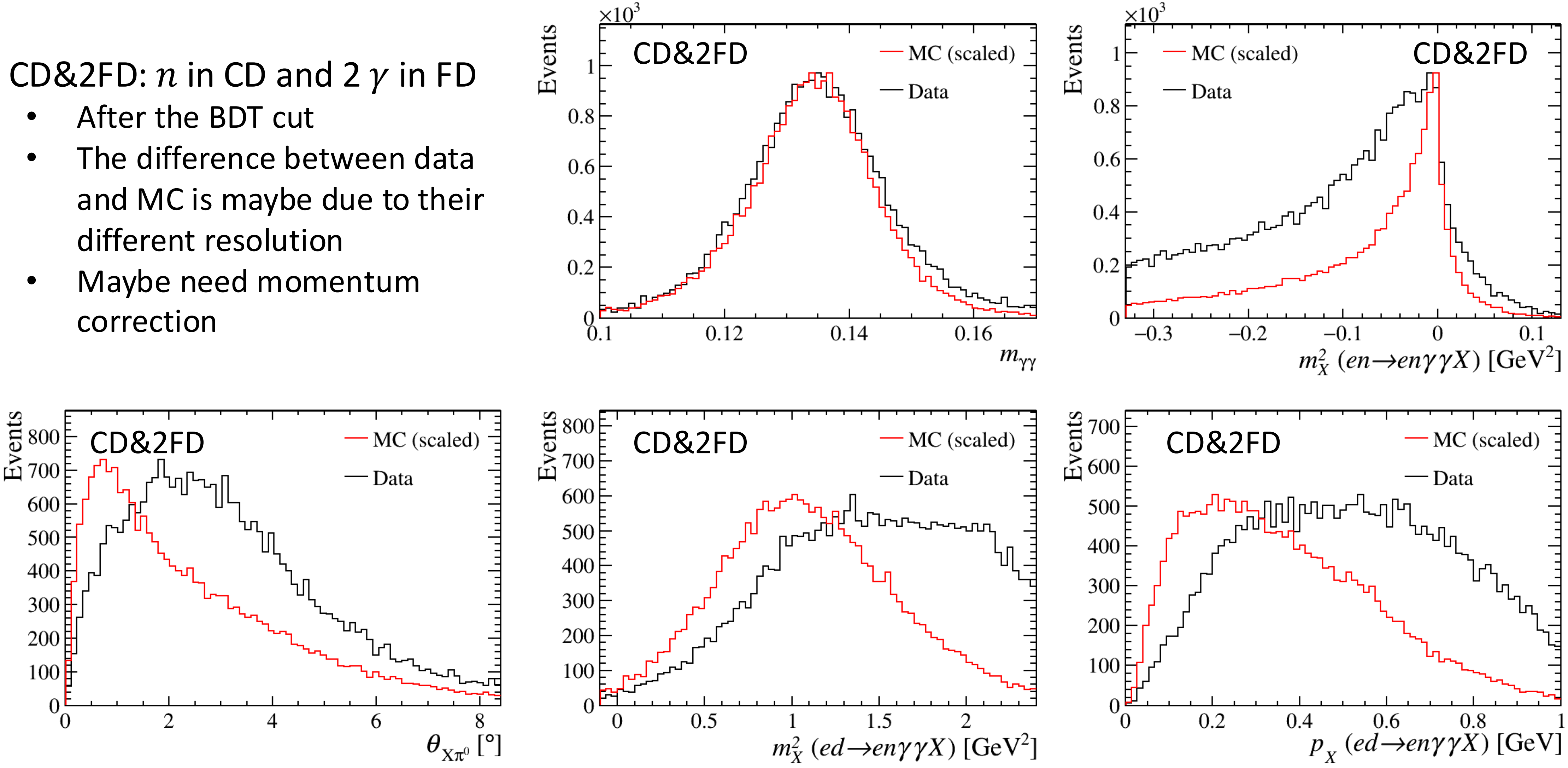






Distributions of π^0 production variables

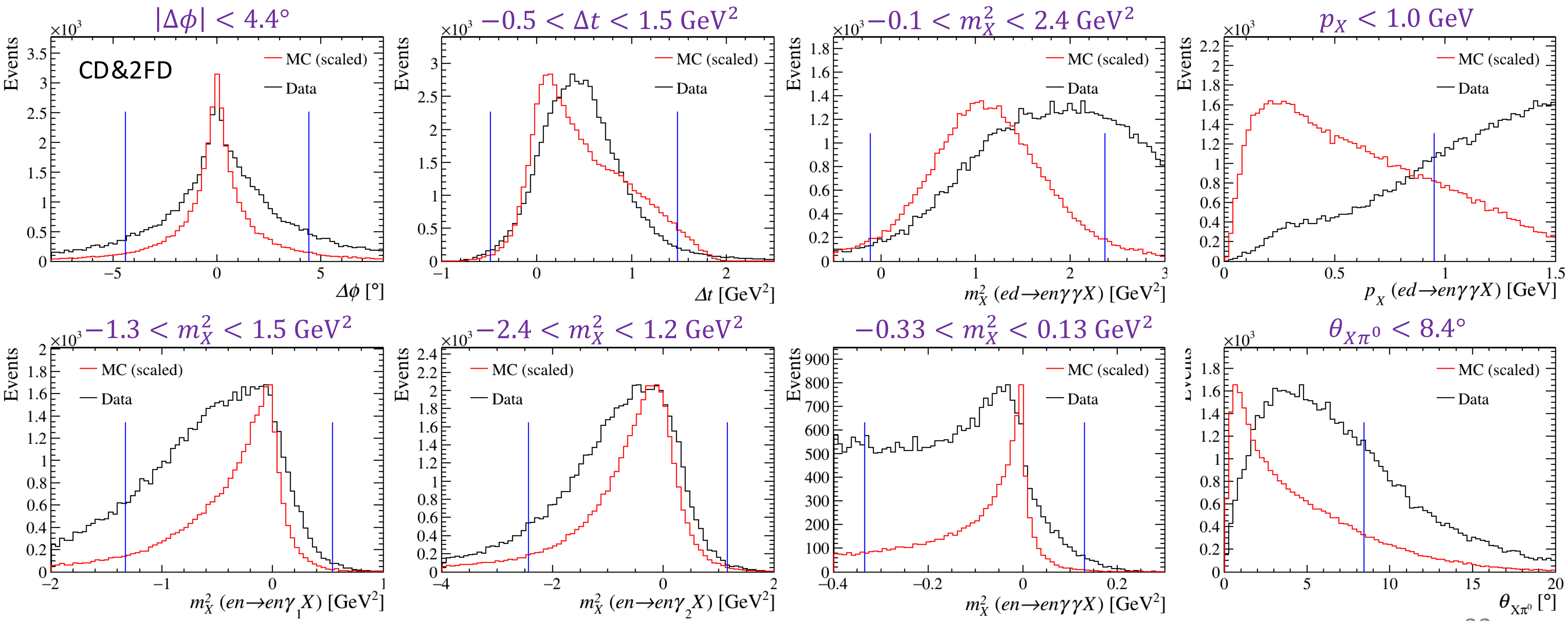
- CD&2FD: n in CD and 2 γ in FD
  - After the BDT cut
  - The difference between data and MC is maybe due to their different resolution
  - Maybe need momentum correction



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

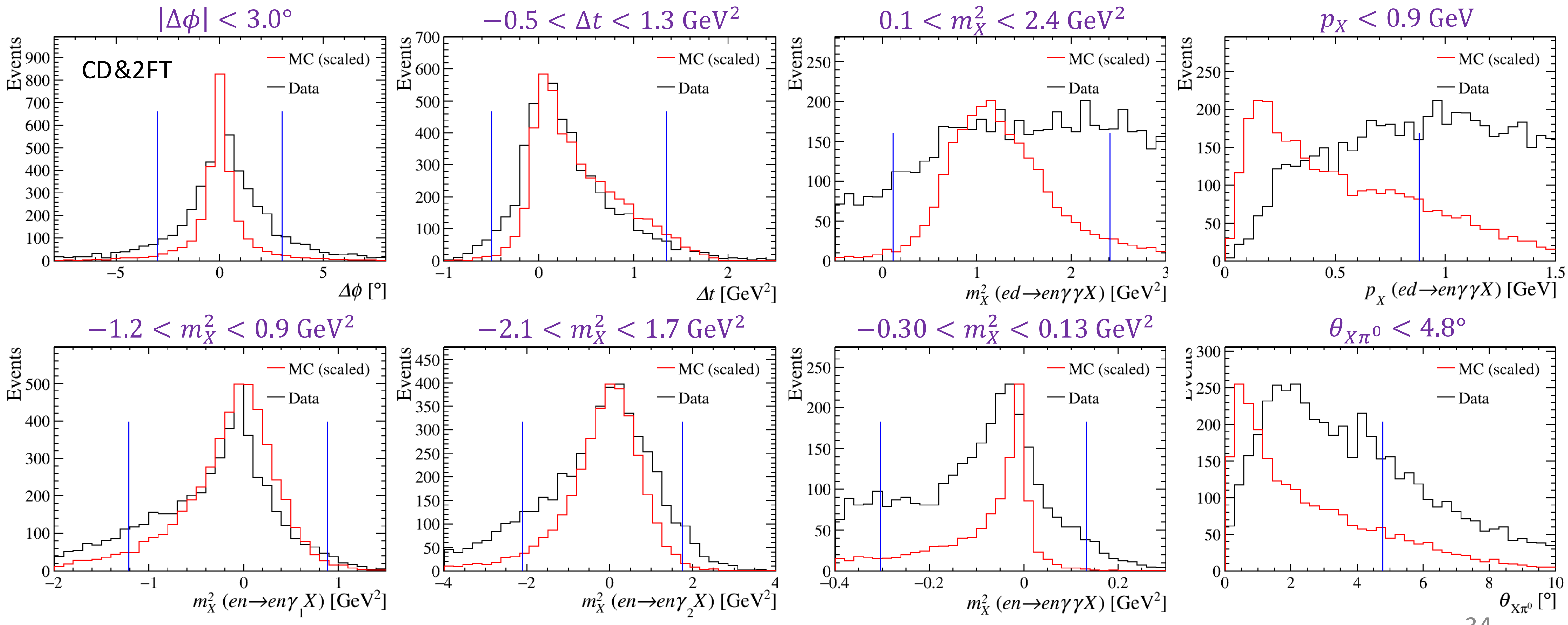


➢ The distributions for CD&2FT and CD&1FT1FD are presented in backup slides

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

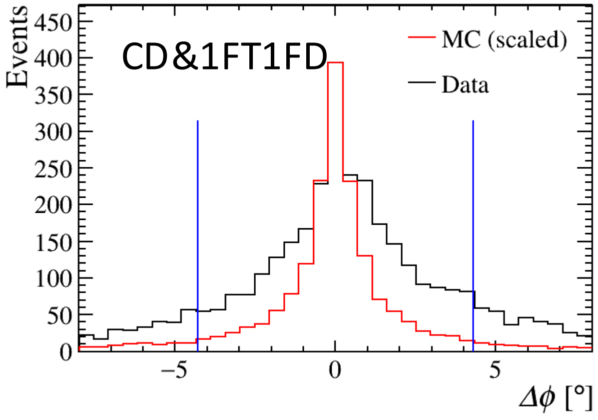


Exclusivity selection of π^0 production

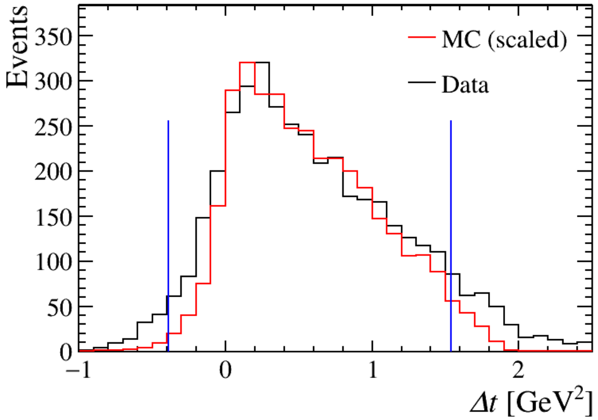
- Criteria determined by comparing data and MC
  - $\sim 2\sigma$ of the MC distribution

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

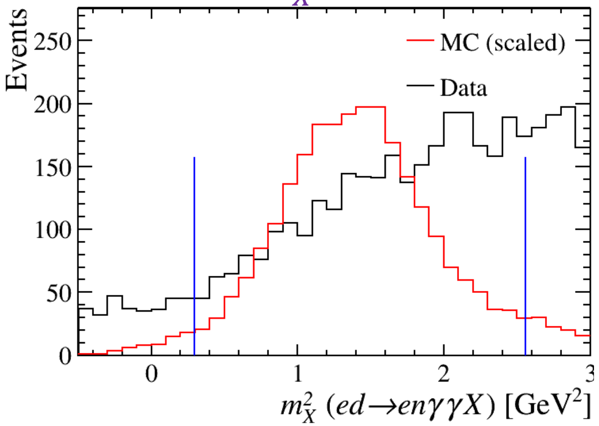
$|\Delta\phi| < 4.3°$



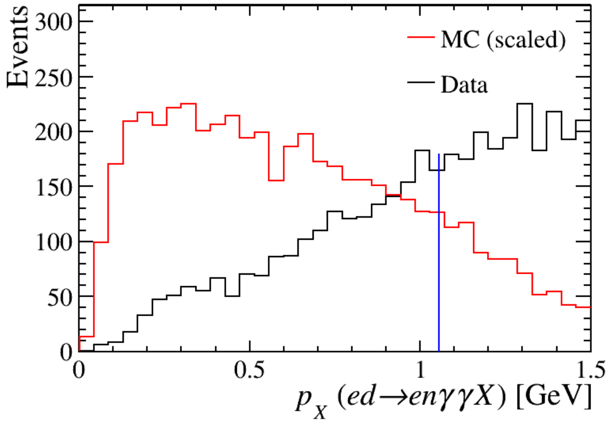
$-0.4 < \Delta t < 1.5$ GeV^2



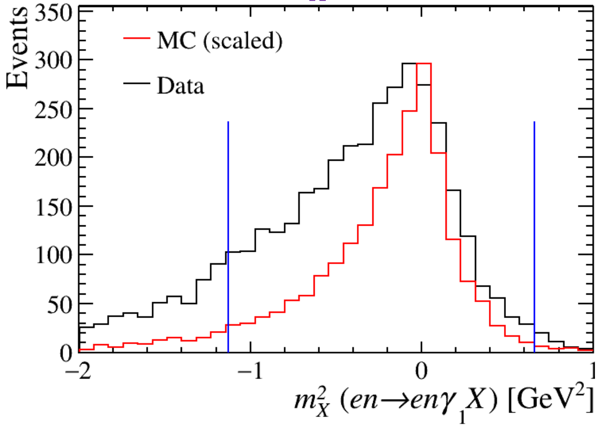
$0.3 < m_X^2 < 2.5$ GeV^2



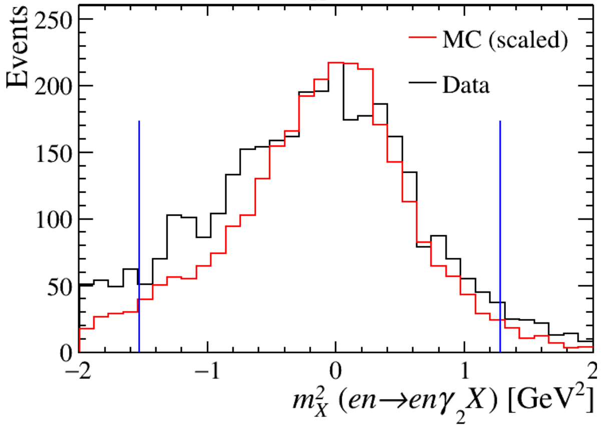
$p_X < 1.0$ GeV



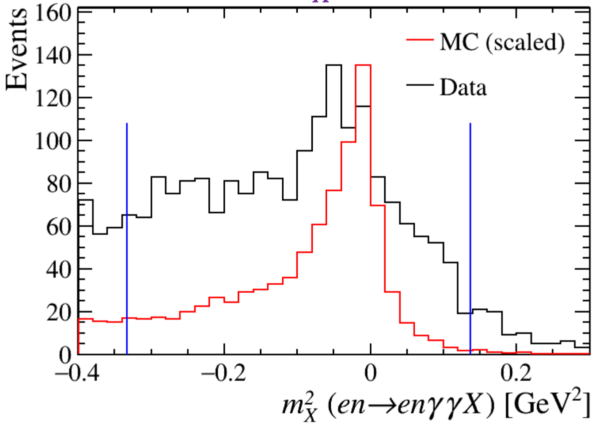
$-1.1 < m_X^2 < 0.7$ GeV^2



$-1.5 < m_X^2 < 1.3$ GeV^2



$-0.33 < m_X^2 < 0.14$ GeV^2



$\theta_{X\pi^0} < 8.5°$