Exclusive π^0 Production in ep Collisions (DVπ^0P)

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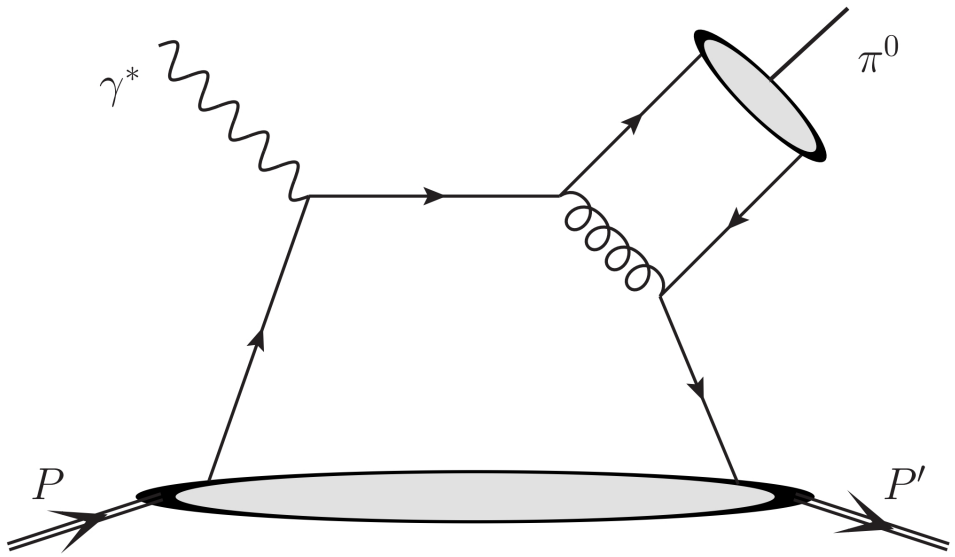
ePIC Physics Forum

Physics Motivation

Exclusive π^0 production



Phys. Rev. Lett. 133, 051901 (2024), arXiv:2312.01309

Hard exclusive production of π^0 mesons

- Provides access to the **3D nucleon structure** via **GPDs**.
- **Complementary to DVCS**, offering sensitivity to **polarized** and **transversity** GPDs.
- Previously studied in **fixed-target experiments** at JLab, and COMPASS.
- **Collider mode (never done before!)** at the EIC enables:
  - High proton polarization.
  - Broad kinematic coverage, reaching **lower x** and **higher Q^2**.
- Represents a **unique opportunity** to probe **quark orbital angular momentum (OAM)** → within **spin program**.
- DVMP π^0 **production** may serve as a **potential background** to DVCS.

Physics Goals

Generalized Parton Distributions (GPDs)

- Extract the **t-distribution** to obtain the **quark spatial distribution**

Quark Orbital Angular Momentum (OAM)

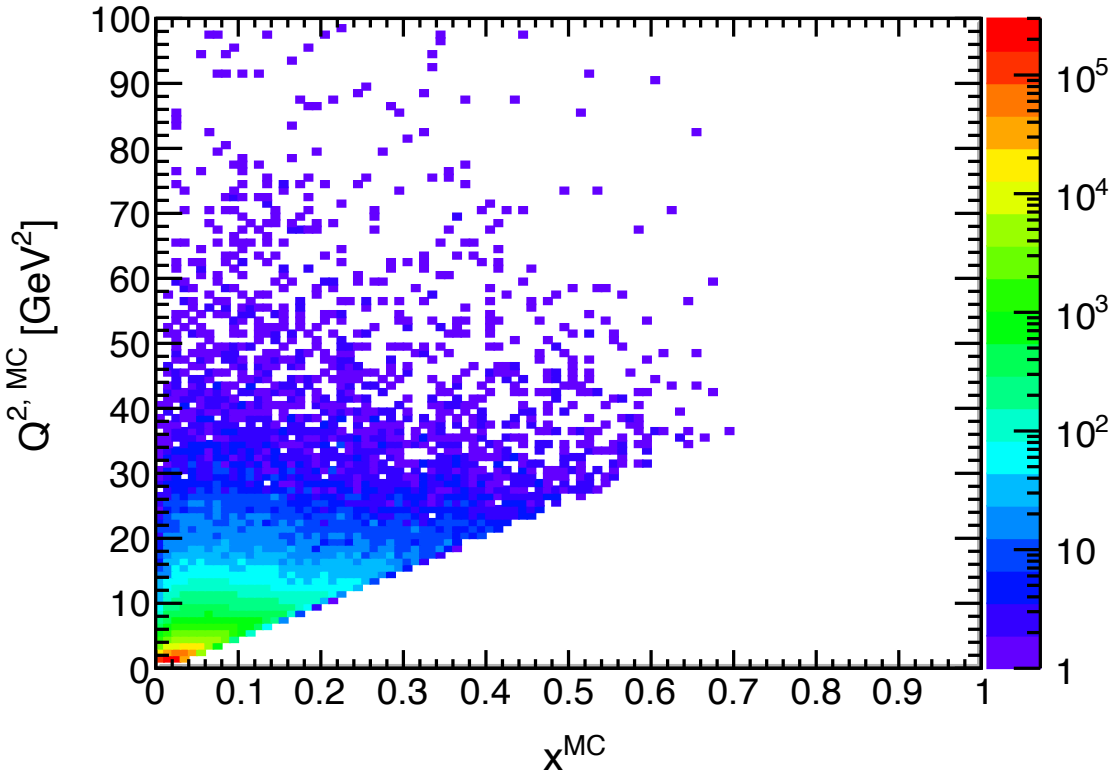
- Conduct a feasibility study of the **longitudinal single-target spin asymmetry**.
- Theory proposal[1]: Single-target spin asymmetry is sensitive to Quark OAM, yet **no experimental measurement** exists to date

Physics Background to DVCS

- Estimate rate of single-photon mis-identification[2], which can **mimic the DVCS signal**

[1]Phys. Rev. Lett. 133, 051901 (2024), arXiv:2312.01309
[2]Phys. Rev. D 112, 036010 (2025), arXiv:2503.05908

Simulation Sample



EpIC Monte Carlo Generator

Generation ranges:

- $1 < Q^2 < 1000$
- $10^{-5} < x_B < 0.95$
- $0.01 < t < 1.6$
- $0.01 < y < 0.85$

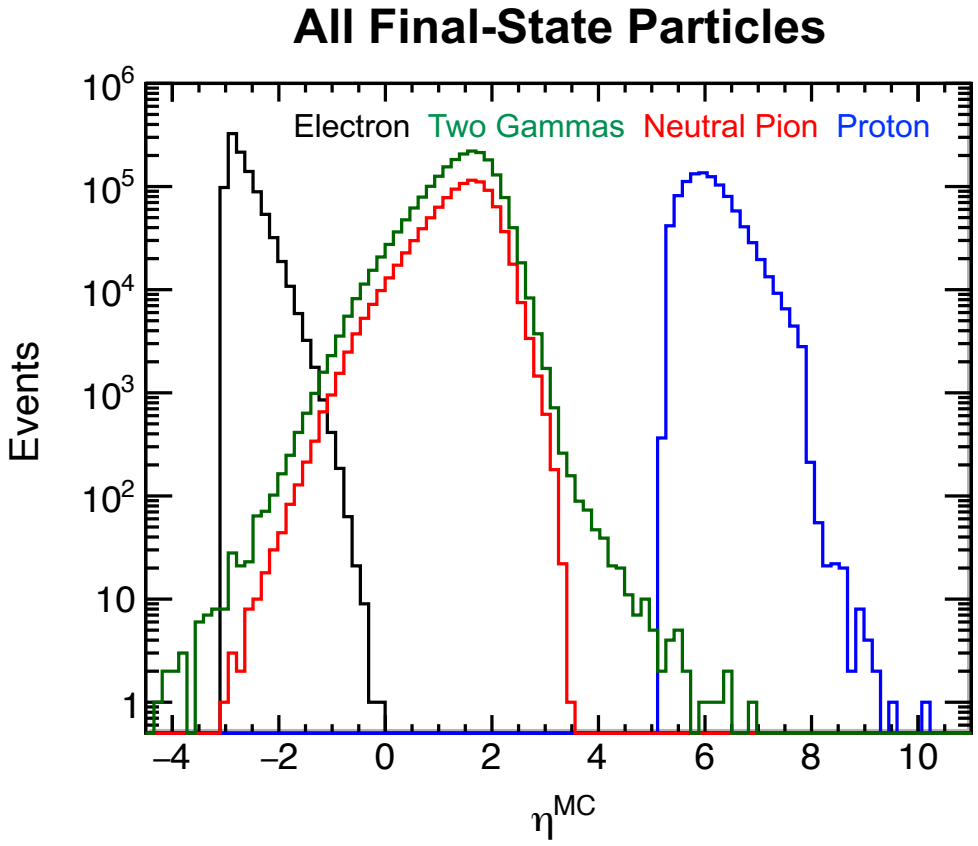
Simulation Setup:

All results are based on

ePIC October Simulation Campaign

25.10.2 (10×130 GeV²) + 25.10.3 (5×41 GeV²)

DVπ^0P Kinematics



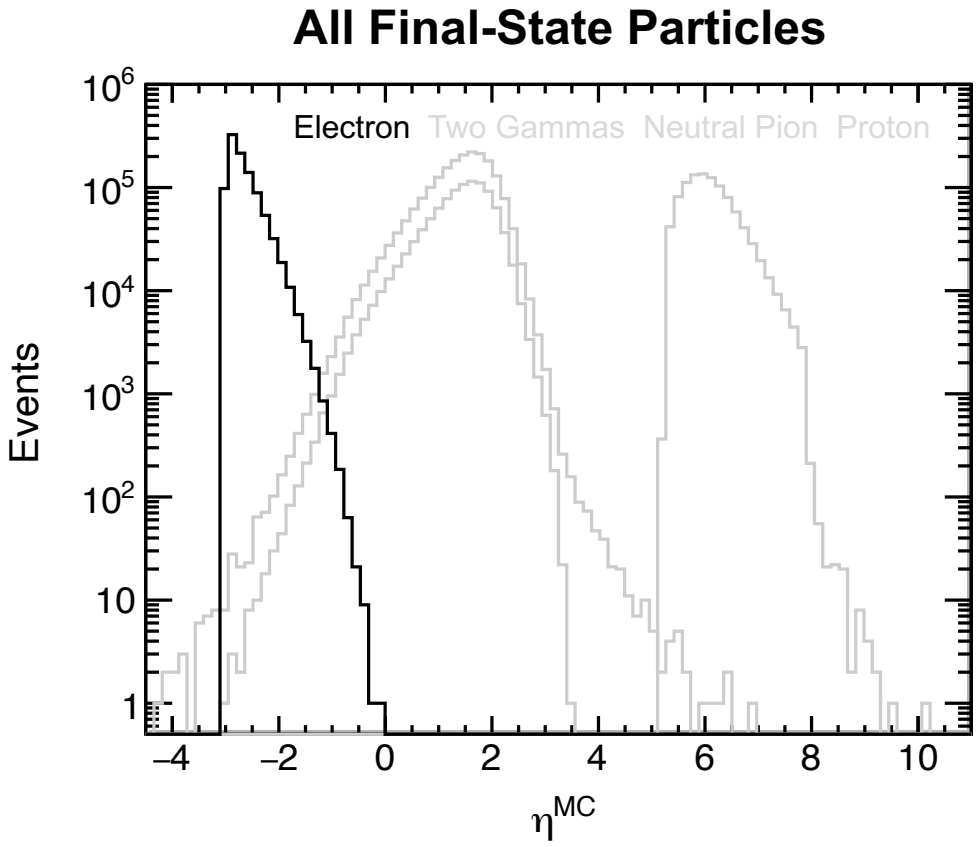
Relatively clean kinematics

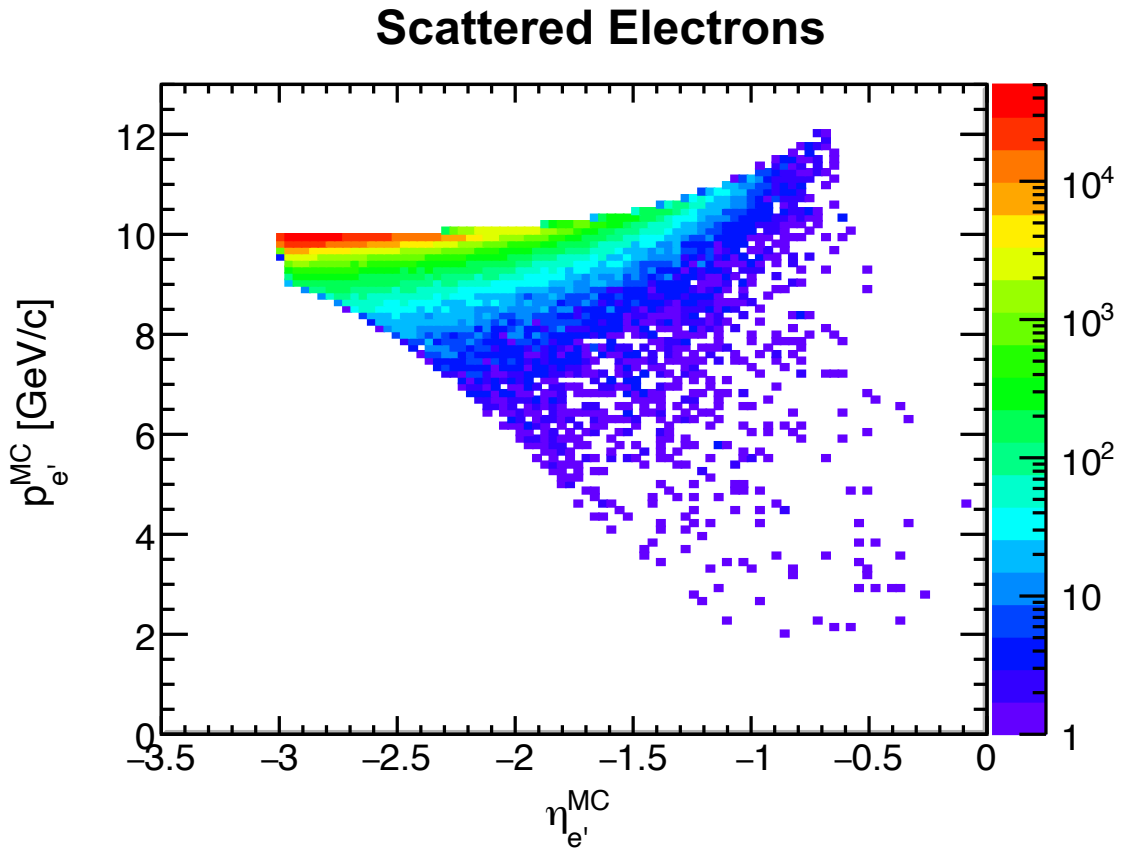
Minimal overlap between final-state particles

Detector Signatures

- Scattered electron:
  - Detected in backward region (Tracker + Calorimeter)
- Neutral pion ($\pi^0 \rightarrow \gamma\gamma$):
  - Detected in mid-rapidity and forward calorimeters
- Scattered proton:
  - Detected in Far-Forward tracker

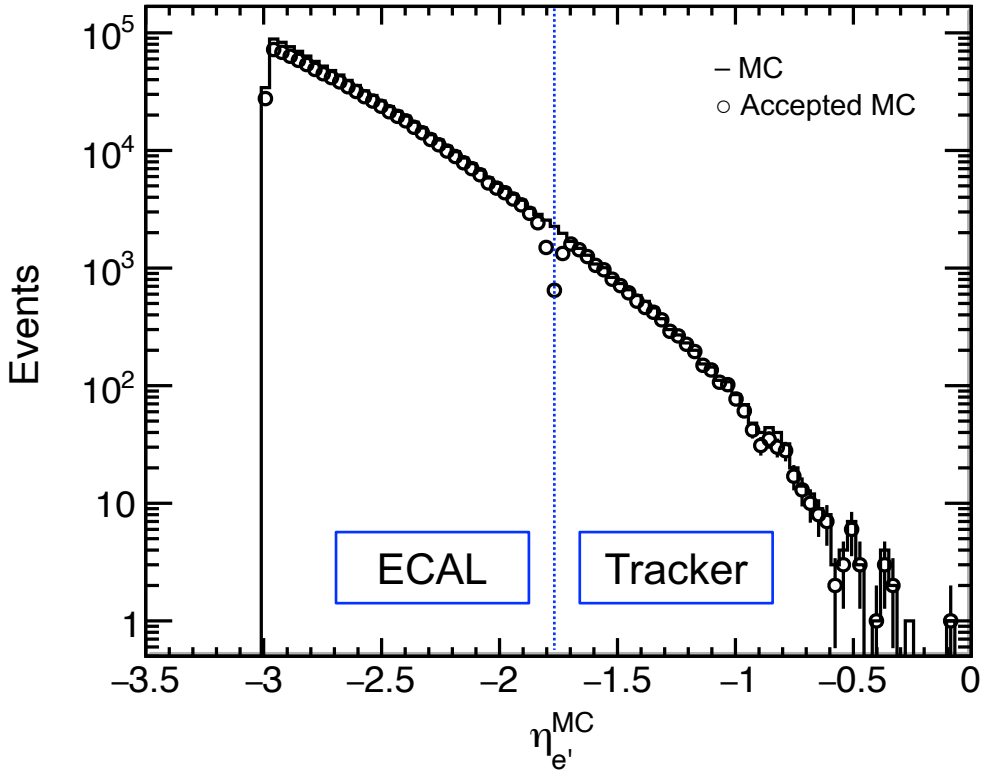
DVπ^0P Kinematics – Scattered Electron





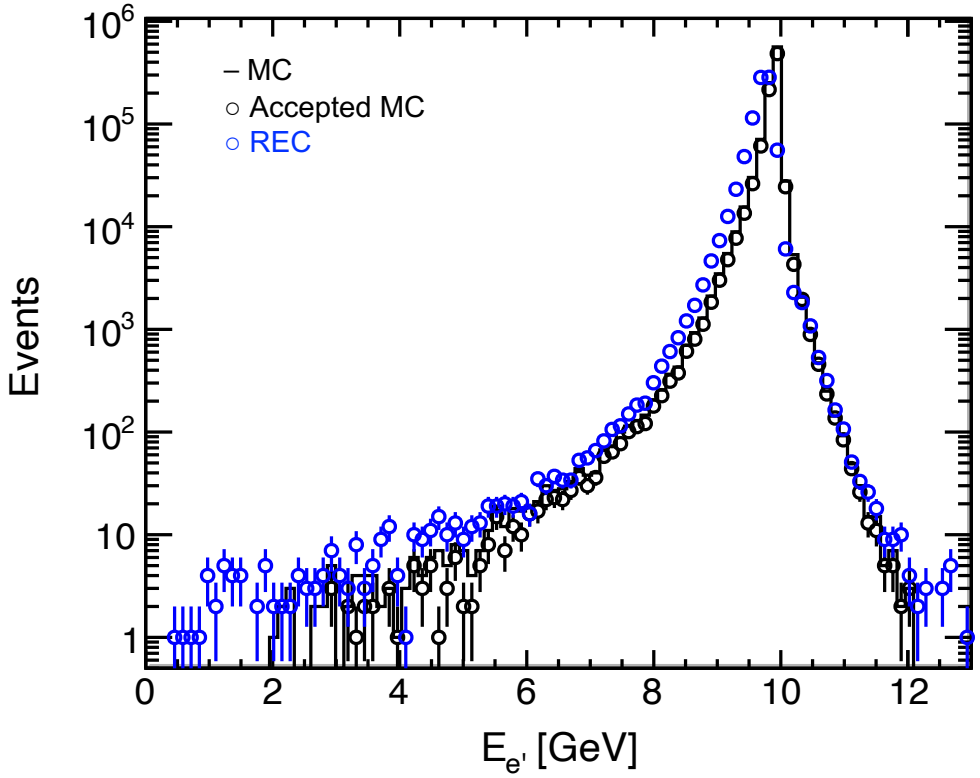
Relatively clean kinematics, with **minimal overlap** between all final-state particles.
Scattered electron momentum remains **very close to the incoming beam energy**.

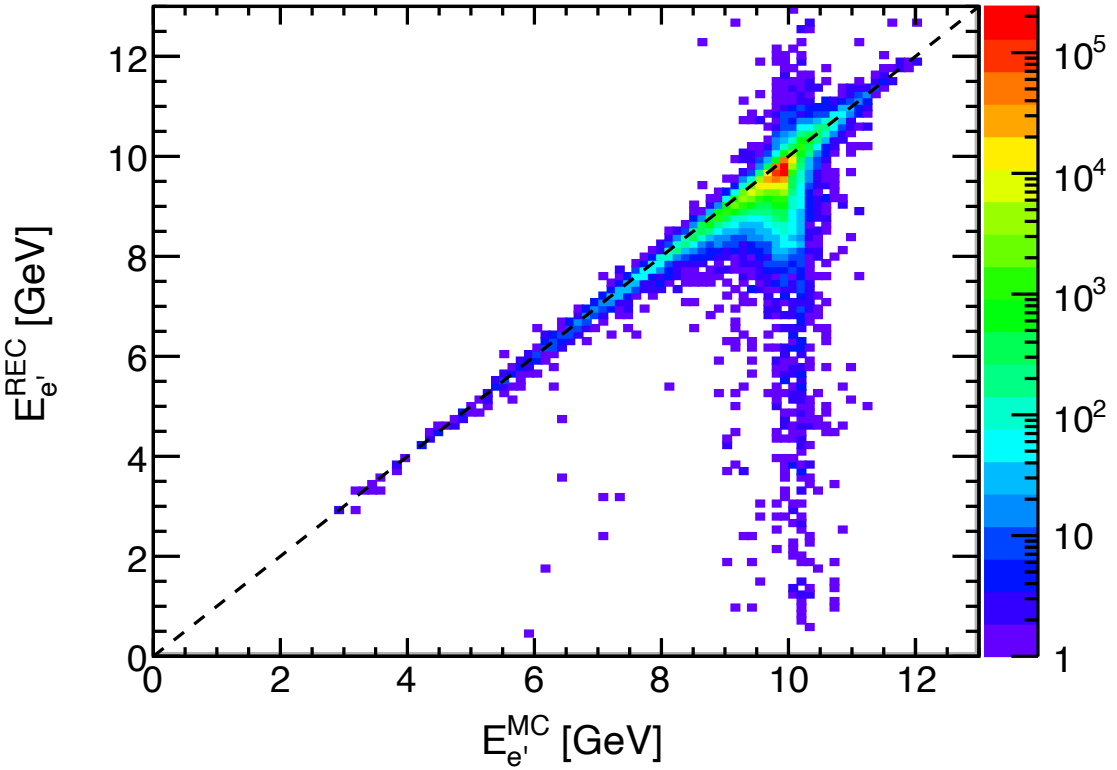
e'_{MC} Acceptance with E/p Cut



In this analysis, a **truth-associated** E/p **cut** is applied (when applicable). E/p cut: 0.9 < E/p < 1.2. If 10 < Q^2 <100, use 0.8 < E/p < 1.2. The **scattered electron acceptance** is approximately **85.7%**.

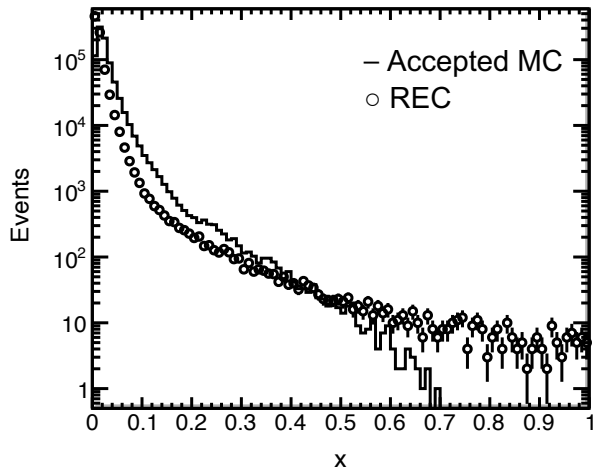
e'_{REC} with E/p Cut

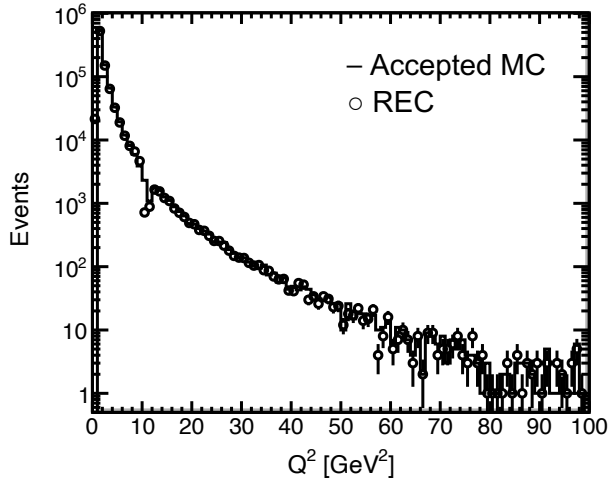


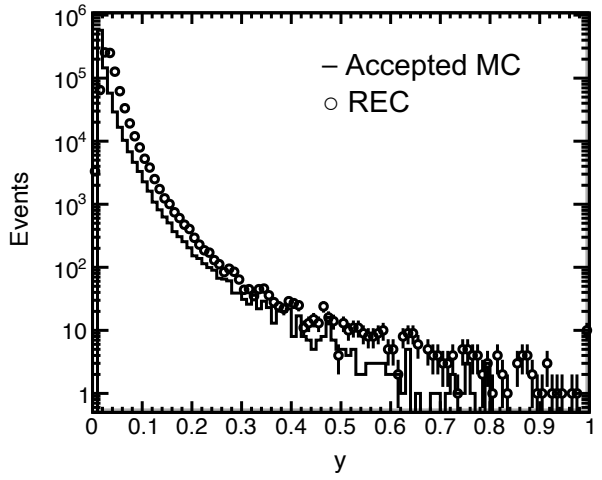


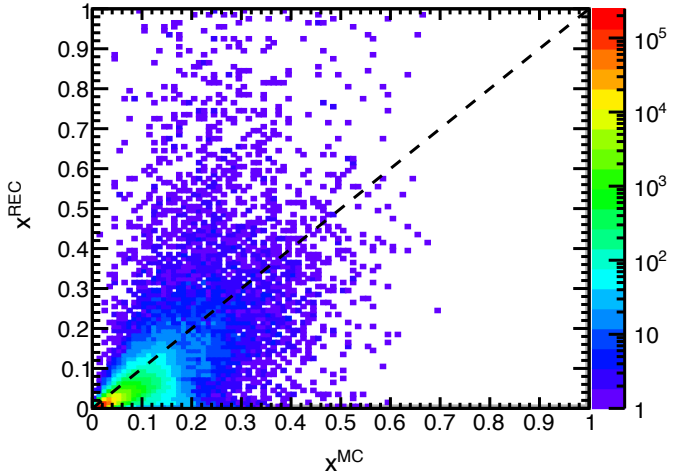
Potential to improve scattered-electron reconstruction and/or refine quality cuts.
Calorimetry calibration constant factor to adjust energy.

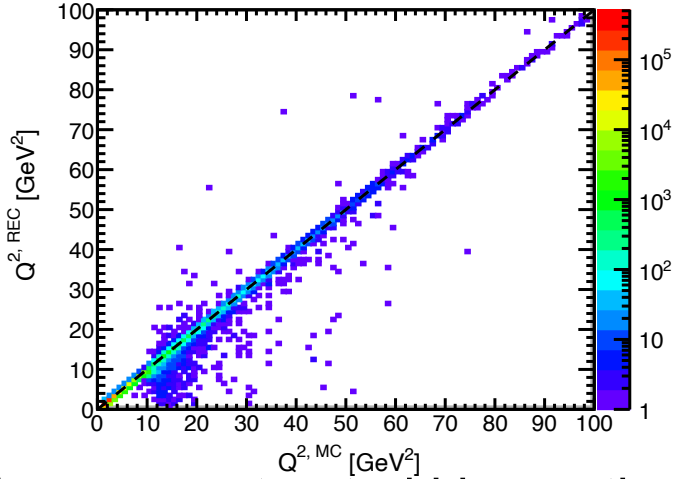
DIS Kinematics After Electron Selection

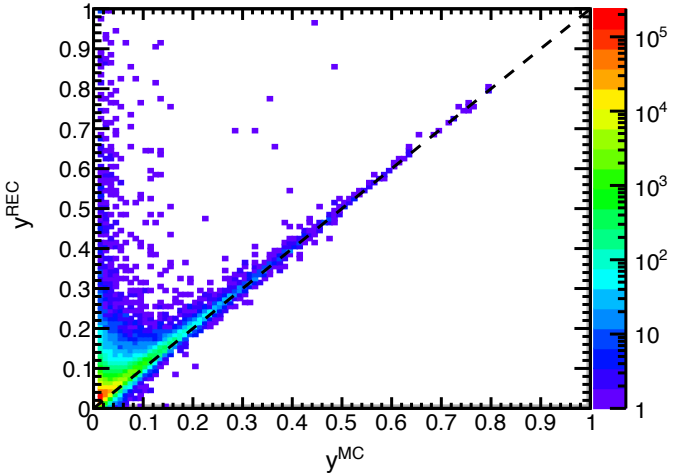






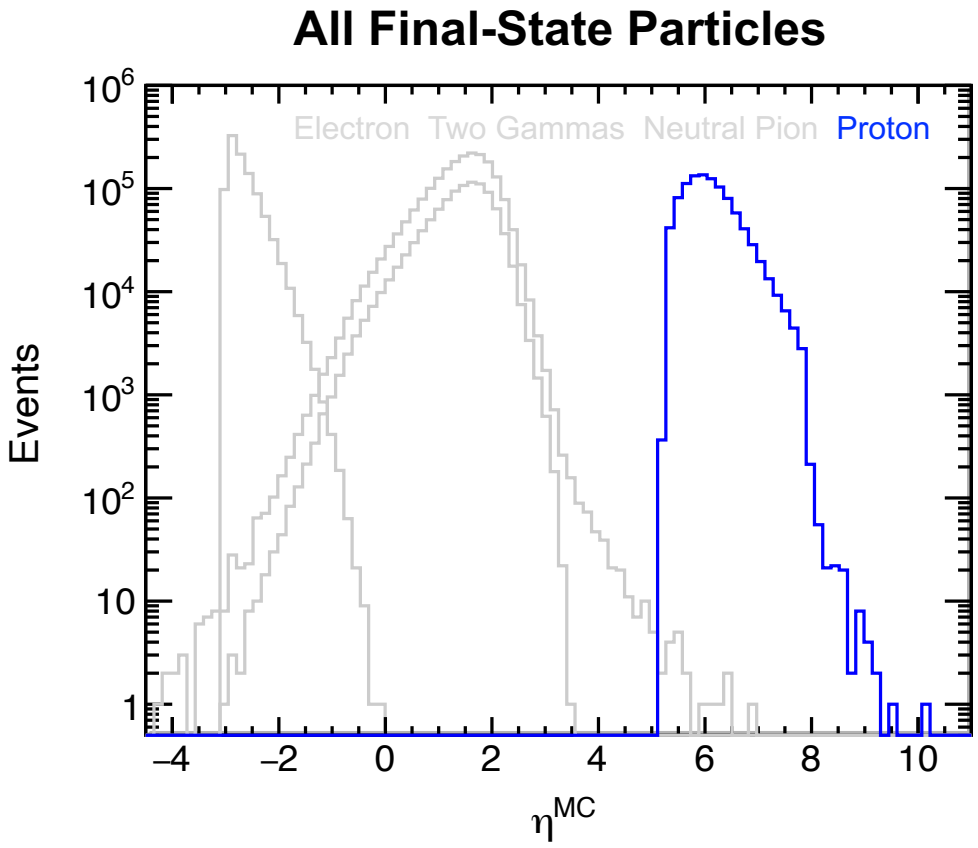


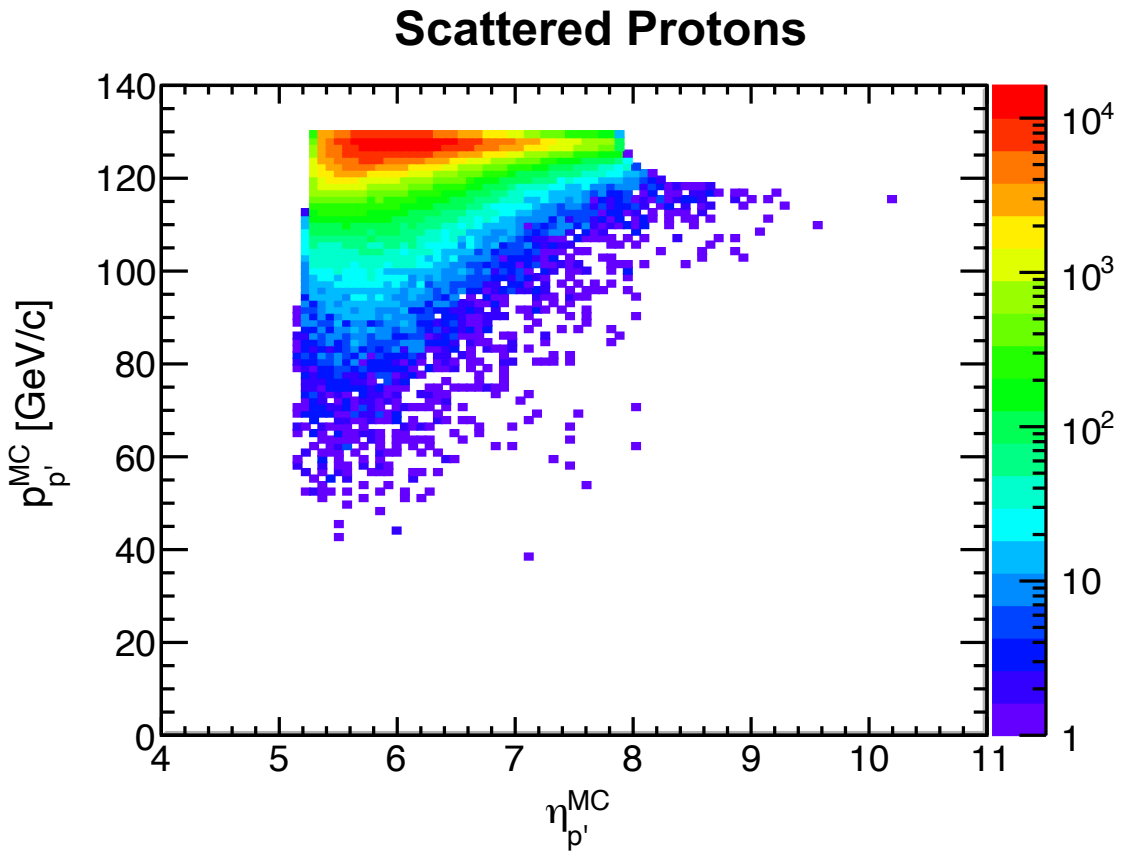




Using TREK + CAL information, reconstructed kinematics show fairly good agreement.

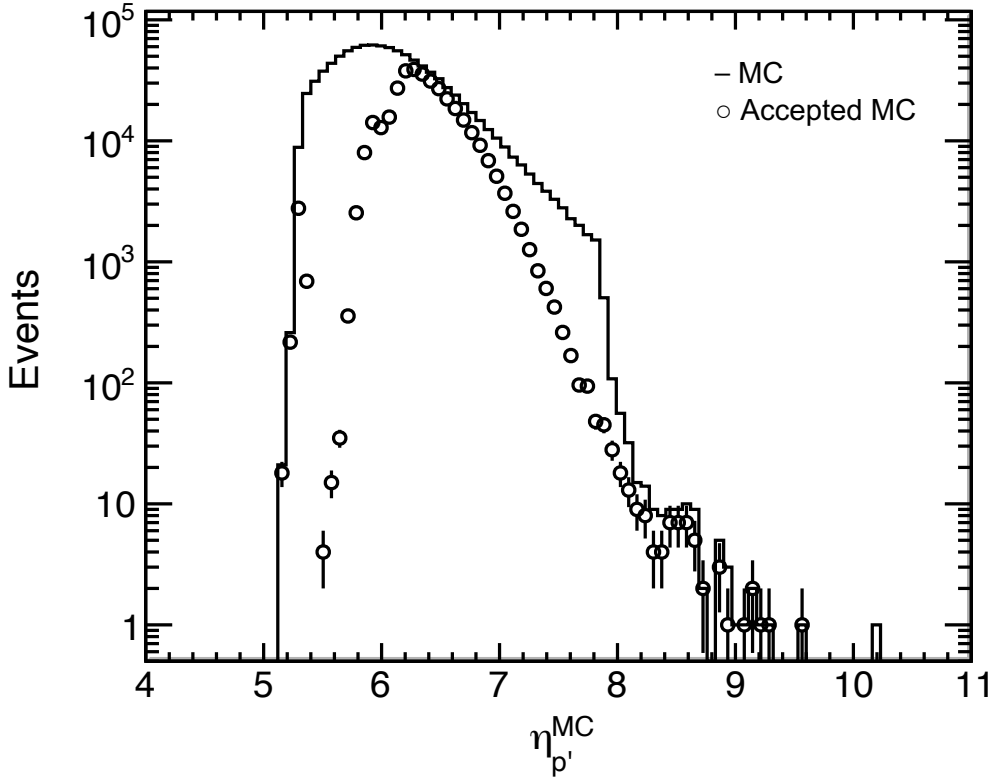
DVπ^0P Kinematics – Scattered Proton

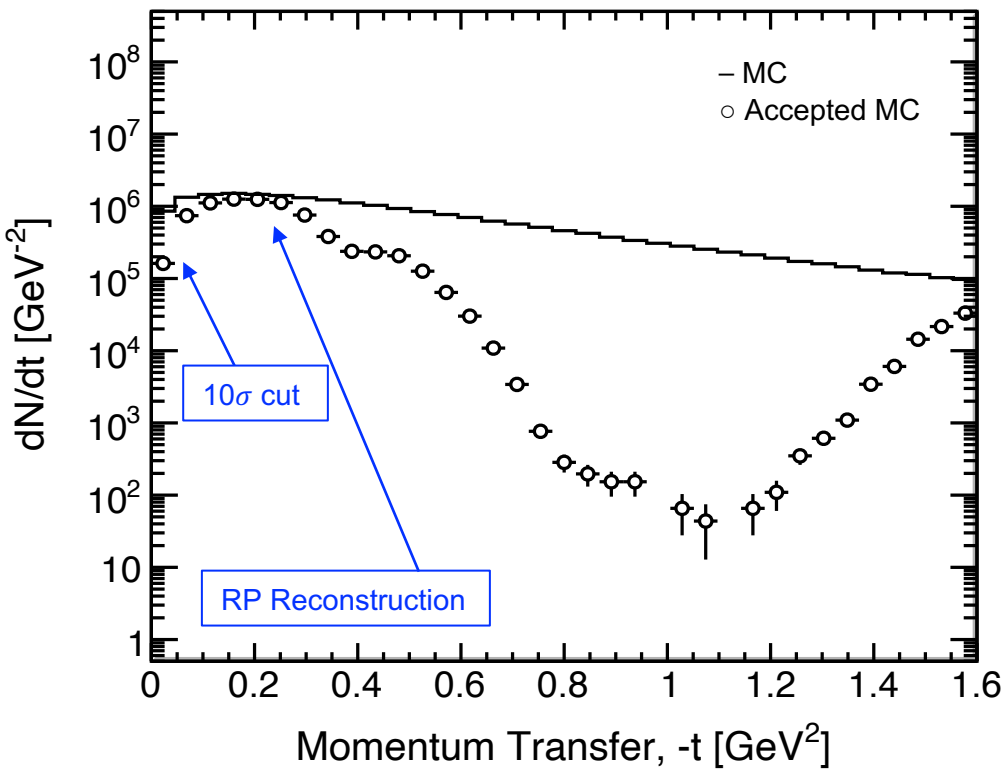




Relatively clean kinematics, with **minimal overlap** between all final-state particles.
Scattered protons travel to the **far-forward region**, detected by **B0 and Roman Pot detectors**.

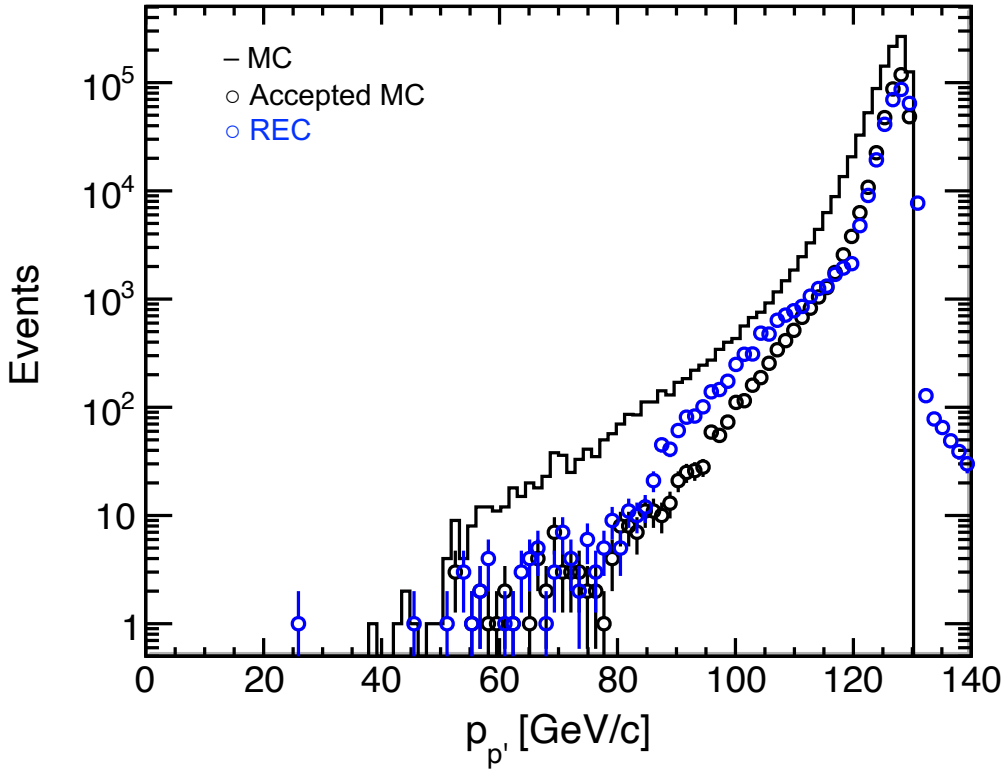
p'_{MC} and $t = (p - p')^2$ Acceptance

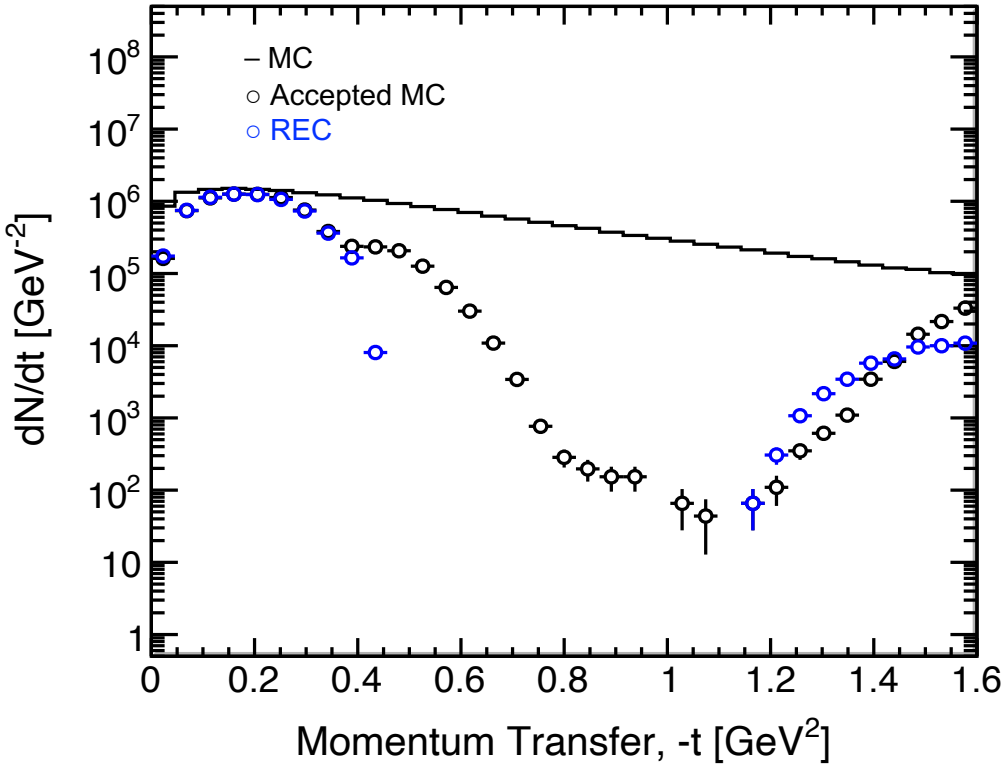




Scattered protons are mostly detected in the **Roman Pot**, not B0.
Rather larger acceptance gap between B0 and Roman Pot for p' comparing to 10×100 GeV².

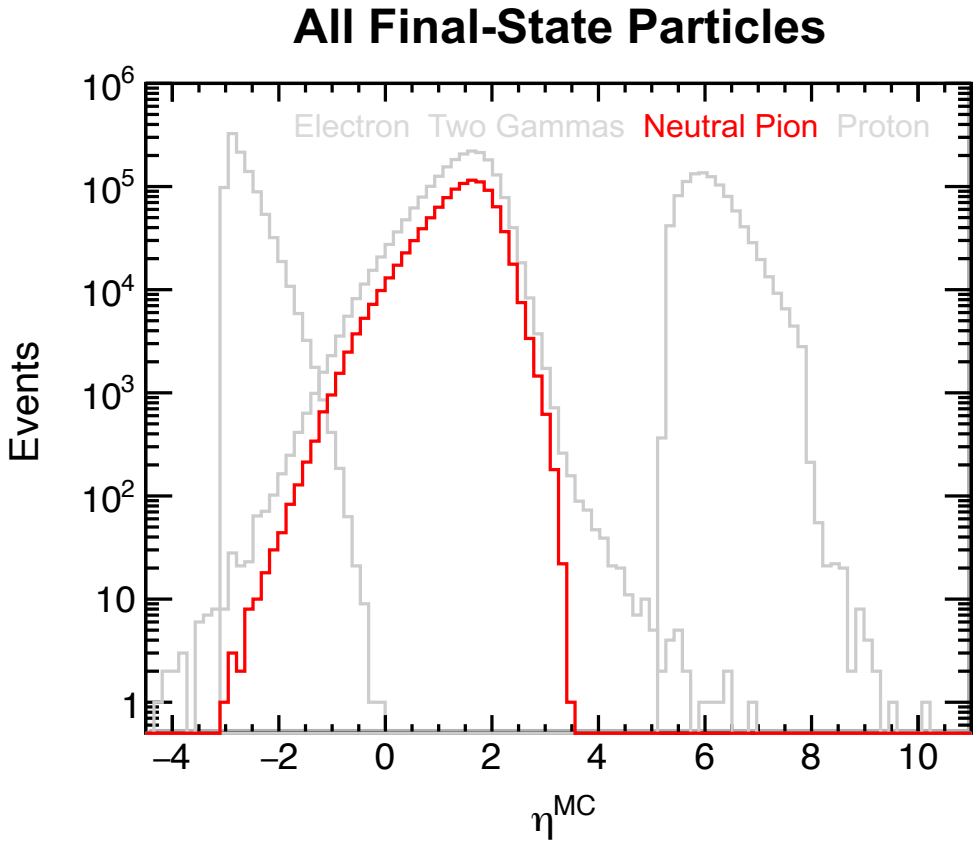
p'_{REC} and $t = (p - p')^2$ Reconstruction

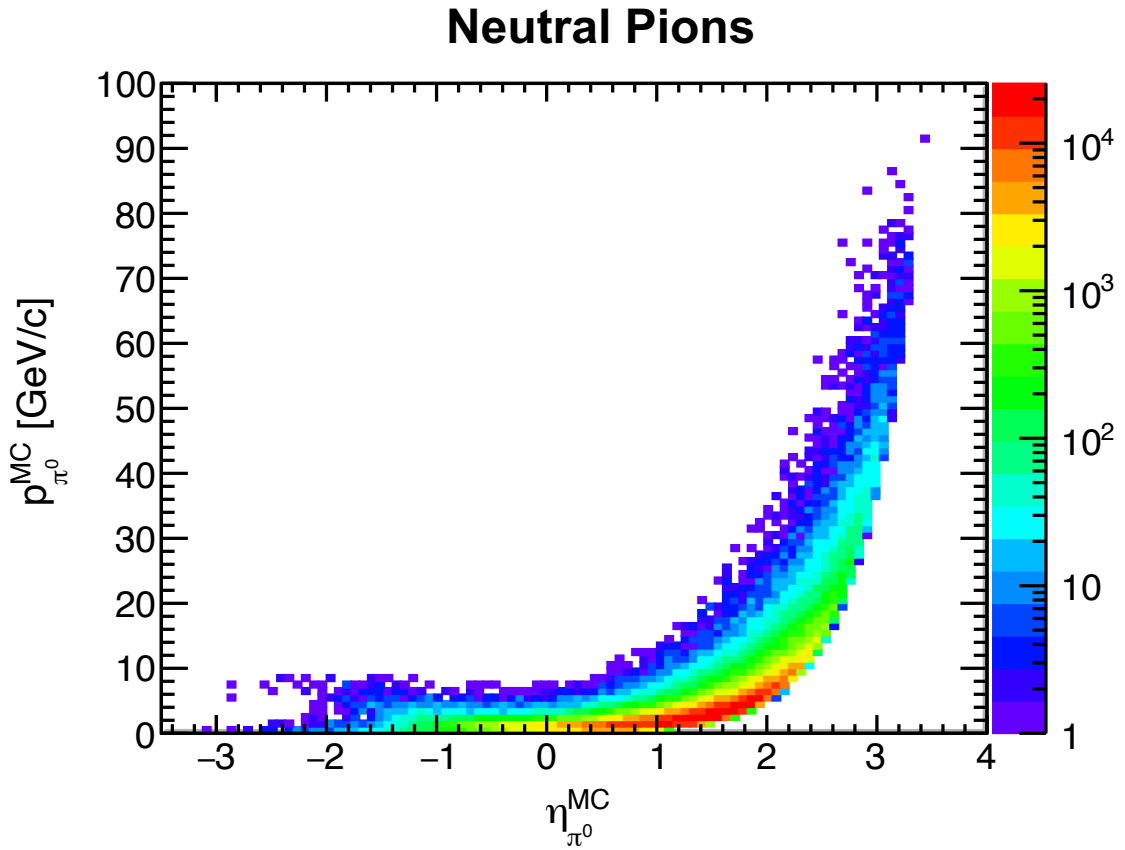




Improvements on p' reconstruction at Roman Pot, which leading better t-reconstruction with BABE.

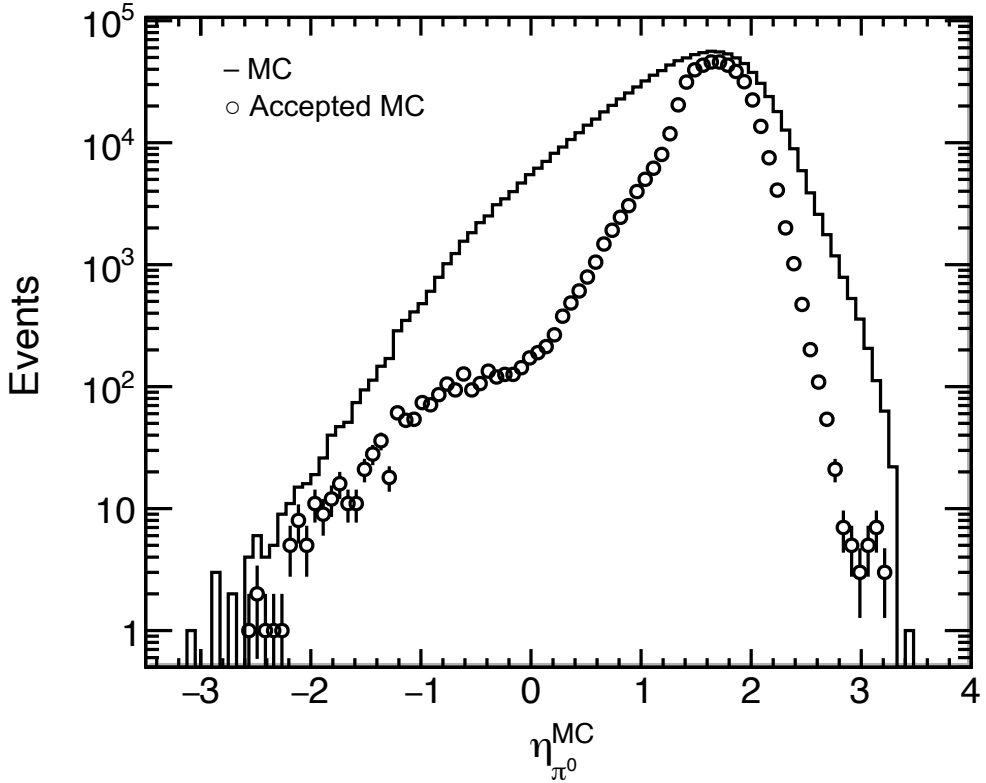
DVπ^0P Kinematics – Neutral Pion





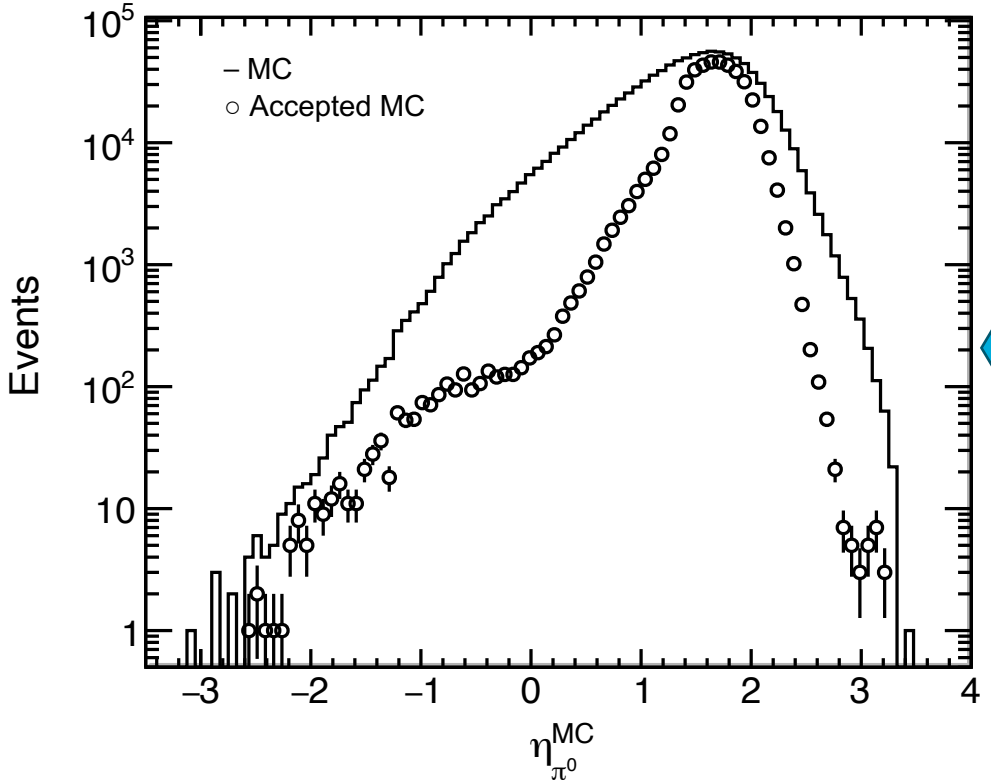
Relatively clean kinematics, with **minimal overlap** between all final-state particles.
Neutral pions are boosted into **forward** region.

π^0_{MC} Acceptance



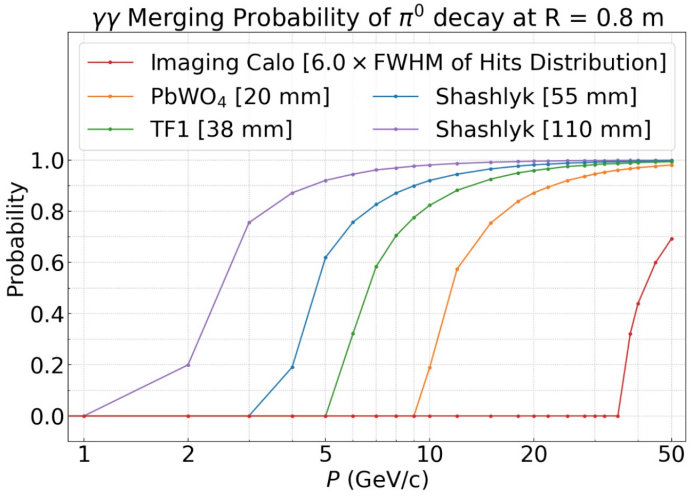
Acceptance loss observed in **mid-rapidity** and **forward regions.**
Caused by **non-optimized cluster splitting** in the current **EICrecon reconstruction pipeline**

π^0_{MC} Acceptance – Potential Improvement



Mid-rapidity

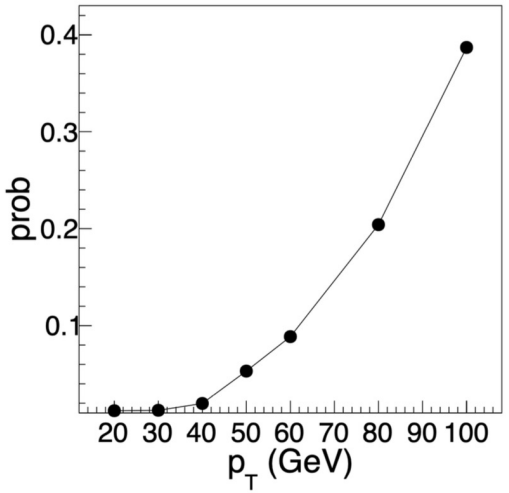
Taken from ePIC preTDR v2.2
(Figure 8.148 (b) on page 230)



Upper limit of $\gamma\gamma$ merging probability at η = 0, up to p_{π^0} **~ 35 GeV** can be separable

Forward

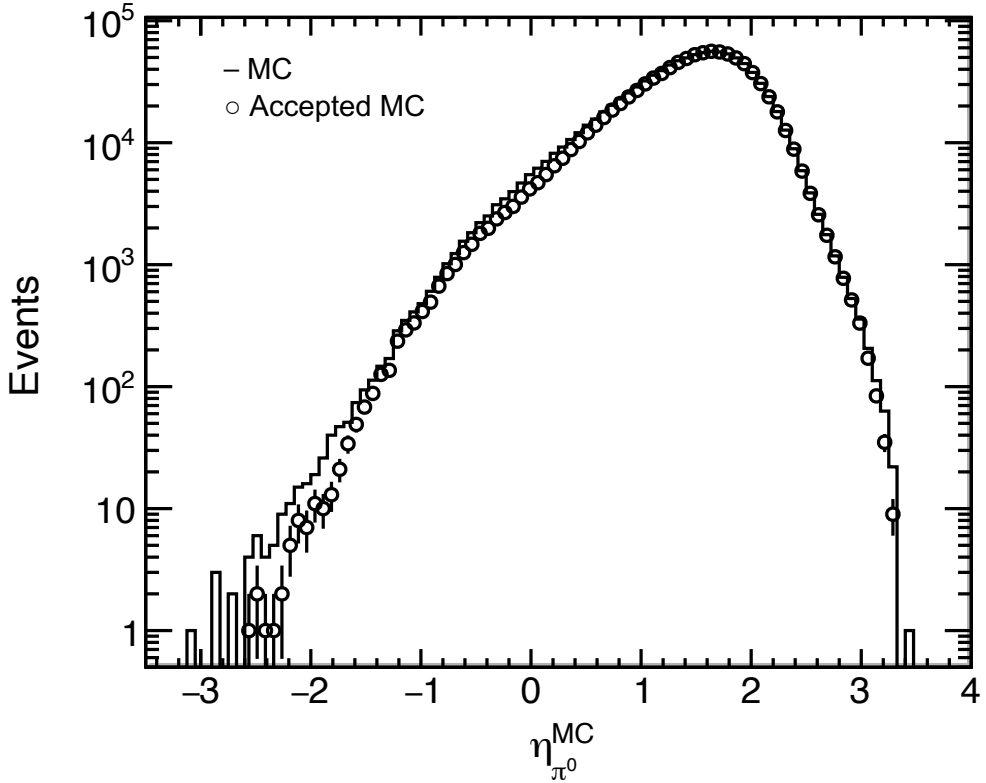
Taken from ePIC preTDR v2.2
(Figure 8.162 on page 253)



W/SciFi 2.5×2.5 at z = **3.3 m**
Misidentification rate **at 60 GeV** is approximately **10 %**

Standalone ML studies in preTDR as a **potential improvement** for future reconstruction.
Targeting **mid-rapidity** and **forward regions**.

π^0_{MC} Acceptance – Potential Improvement



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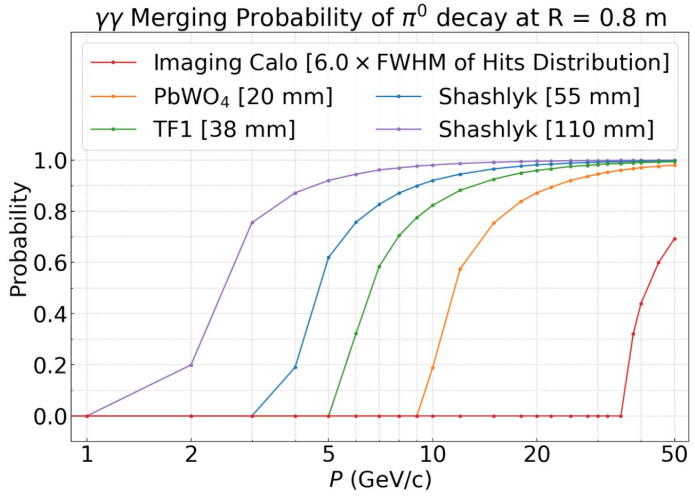

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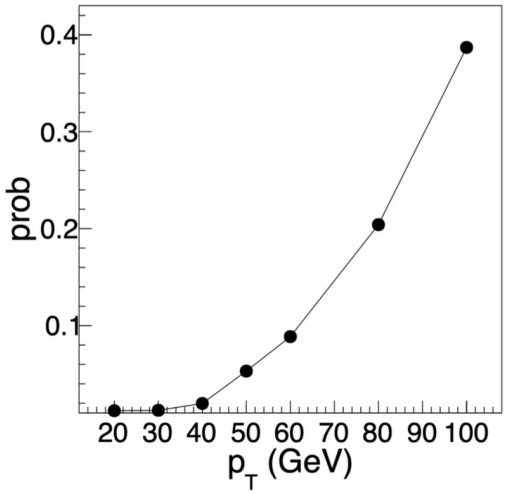
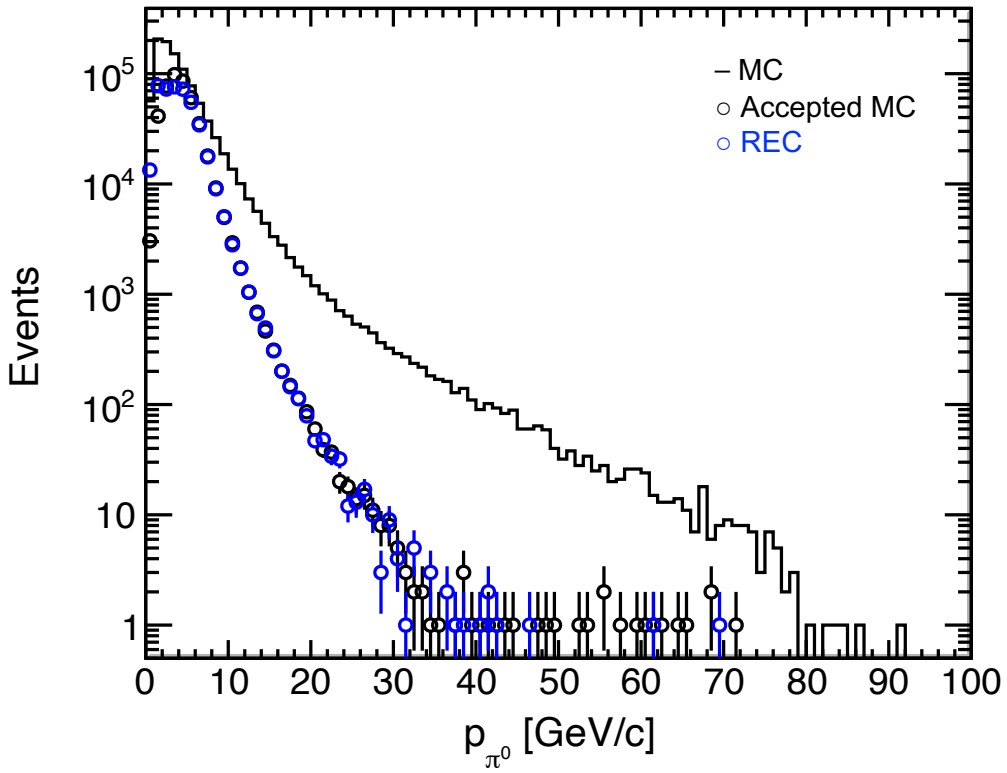
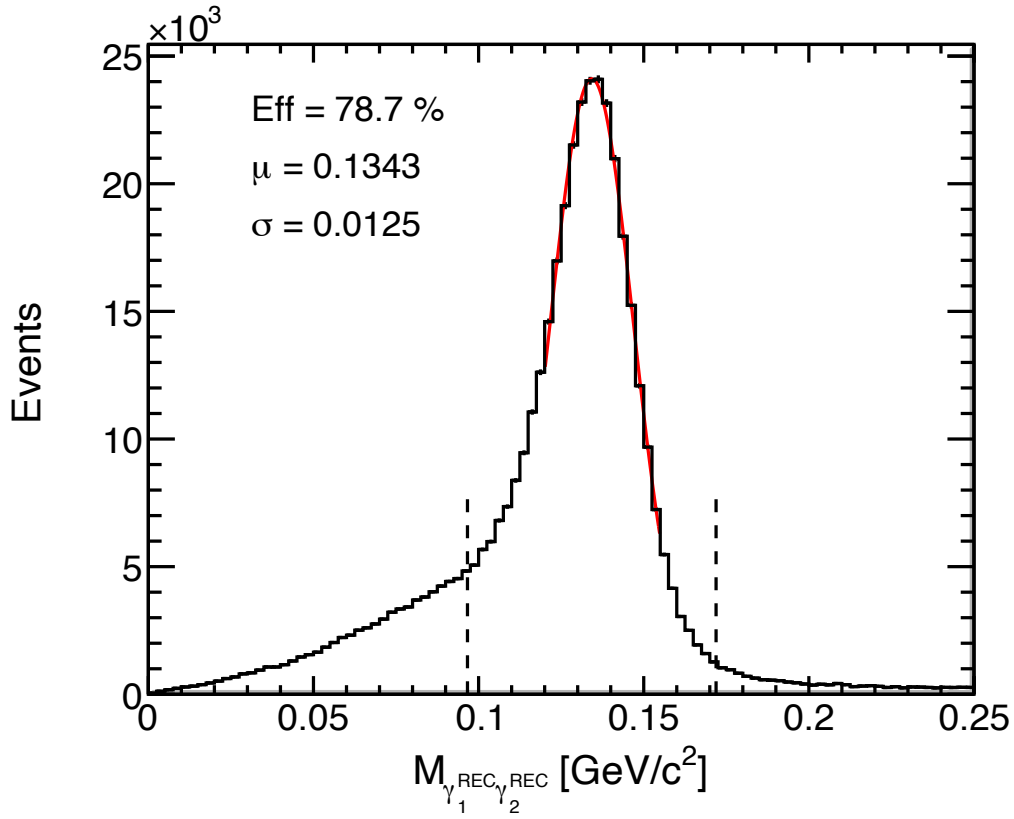


W/SciFi 2.5×2.5 at z = **3.3 m**
Misidentification rate **at 60 GeV** is approximately **10 %**

Standalone ML studies implemented as a **potential improvement** for future reconstruction.
Targeting **mid-rapidity** and **forward regions**. Acceptance increased from 45 % to 95 %.

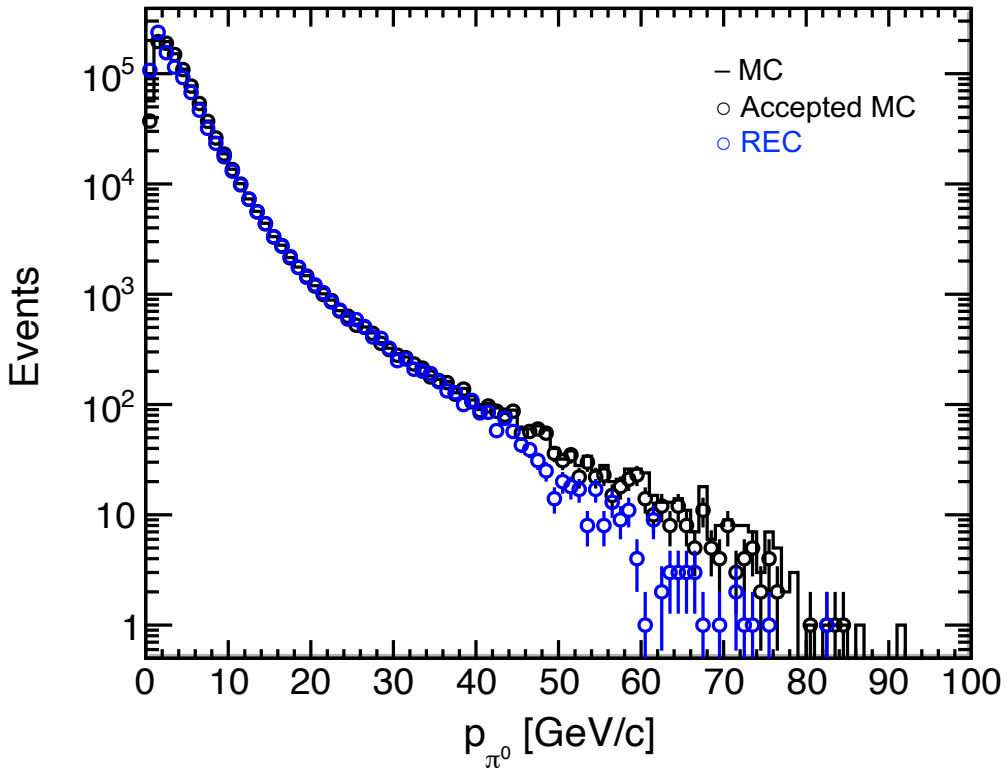
π^0_{REC} Reconstruction and Invariant Mass

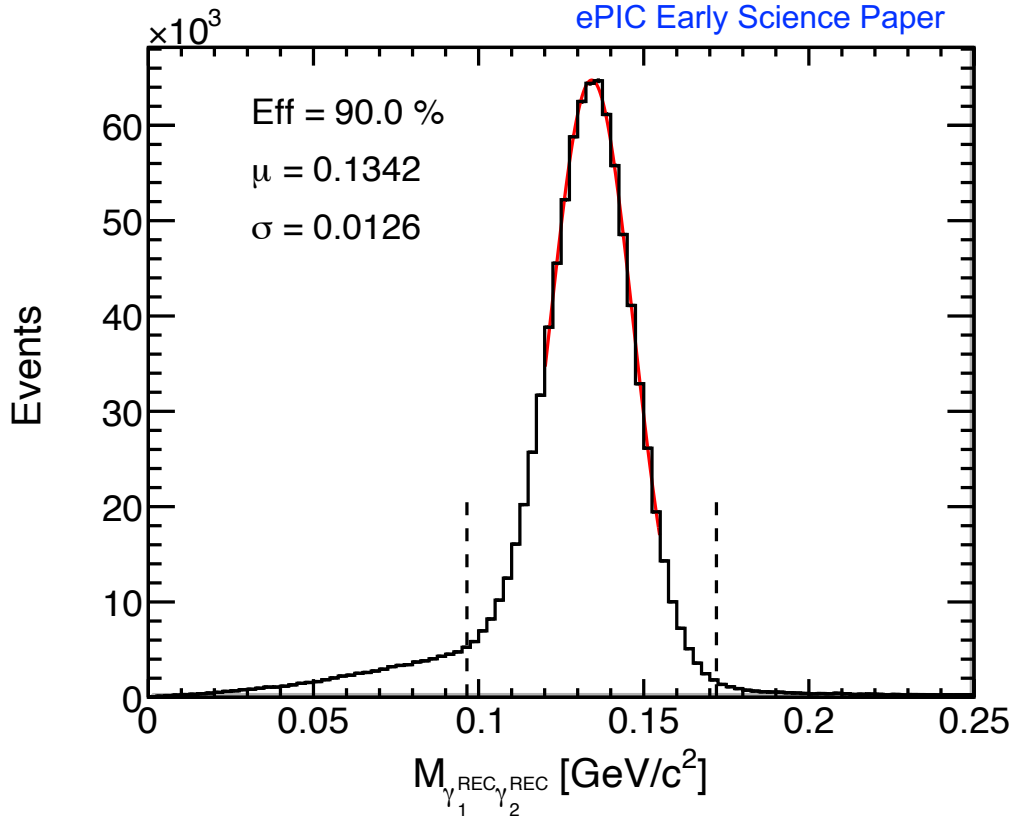




Acceptance loss observed in Low- or high-momentum neutral pions.
"Good" reconstructed neutral pions defined as those within $\pm$ 3σ **of the mean.**

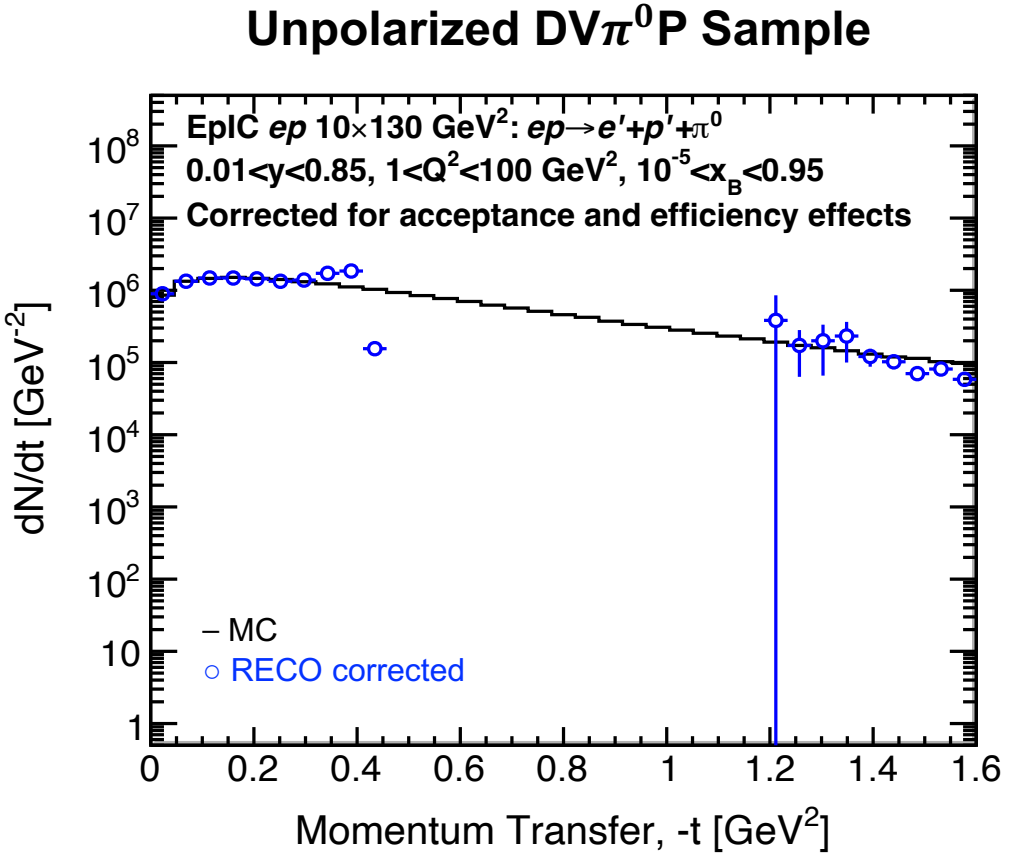
π^0_{REC} Reconstruction and Invariant Mass





Standalone ML studies implemented as a **potential improvement** for future reconstruction.
"Good" reconstructed neutral pions defined as those within $\pm 3\sigma$ **of the mean.**

Results – t-distribution $t_{\mathrm{BABE}} = (p - p')^2$



This is t-distribution integrated over x, and Q^2

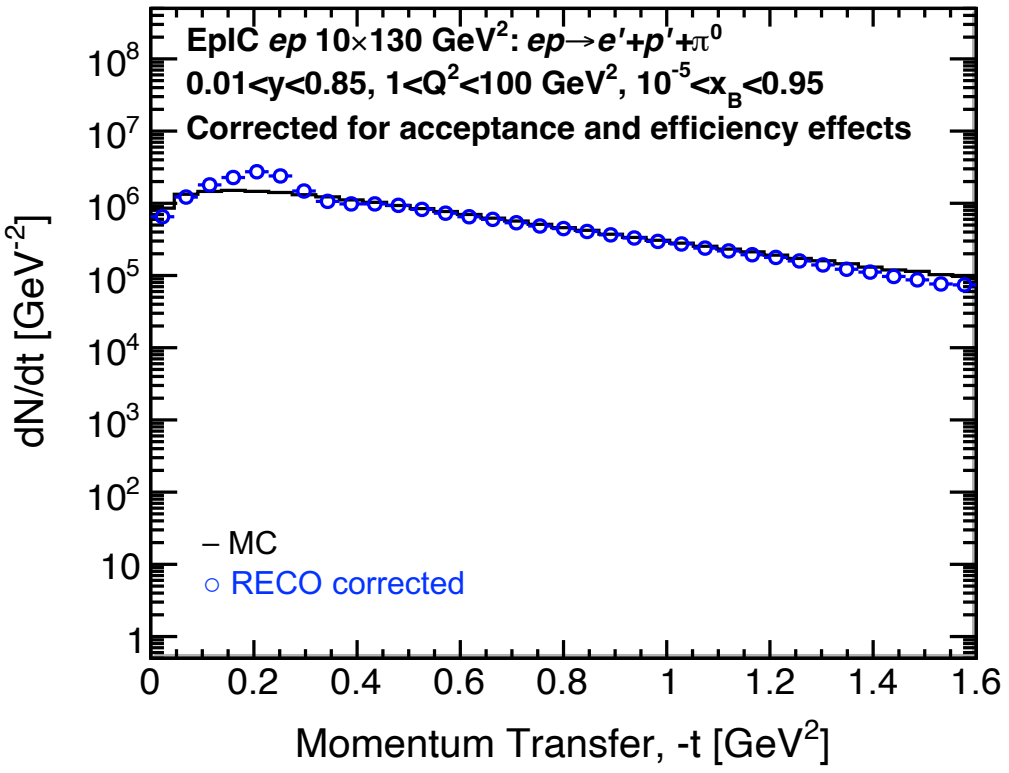
- Good **Proton** Selection:
  - ✓ is reconstructed in B0 or Roman Pot
  - ✓ **Within angular acceptance** in B0 or Roman Pot

$$5.5 \text{ mrad} < \theta^{\mathrm{REC}}_{\mathrm{p\ in\ B0}} < 20 \text{ mrad}$$

$$0 \text{ mrad} < \theta^{\mathrm{REC}}_{\mathrm{p\ in\ RP}} < 5 \text{ mrad}$$

- Good **Electron** Selection:
  - ✓ With truth-association E/p cut ($0.9 < E/p < 1.2$)
- Good **Neutral Pion** Selection:
  - ✓ Within ± 0.04 GeV of M_{π^0} ($0.096 < M_{\gamma\gamma} < 0.172$)
- Suppress photo production + radiative corrections
  - ✓ $\boldsymbol{E - p_z}$ cut ($15 < E/p < 25$)
- **Exclusivity** Cut
  - ✓ All final-state particles are reconstructed
- **Missing Mass** Cut:
  - ✓ With $|\boldsymbol{M^2_{Missing}}| < 1$ GeV²

Results – t-distribution $t_{\mathrm{eXBE}} = (p - p'_{corr})^2$



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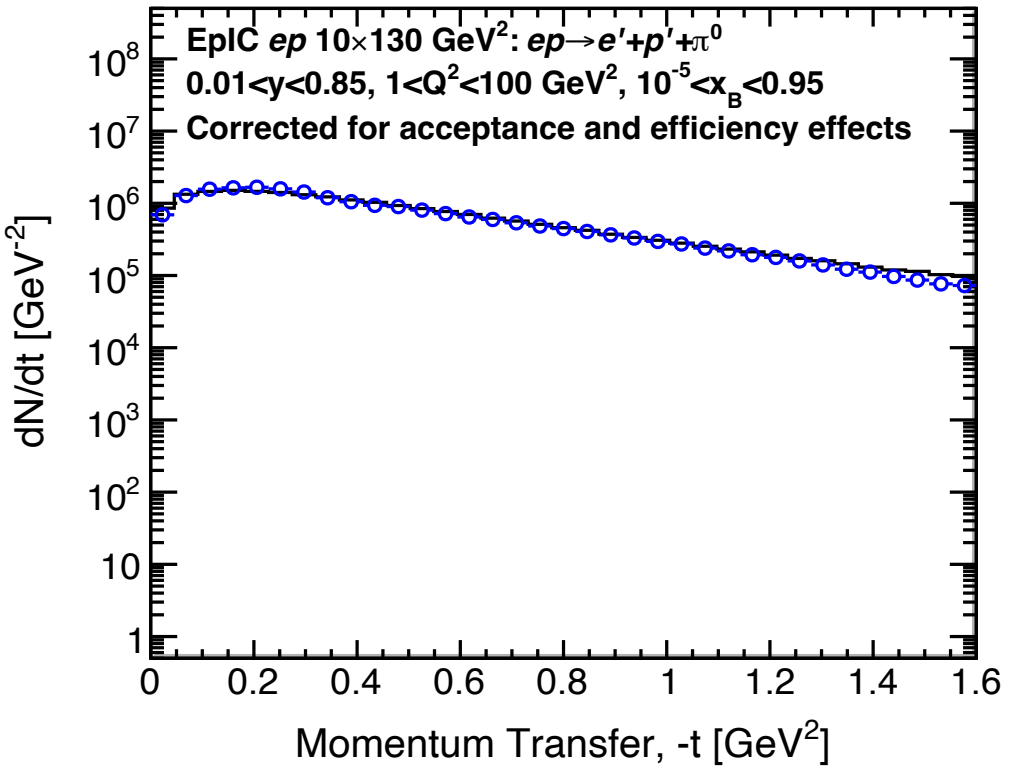
Results – t-distribution $t_{\text{total}} = t_{\text{BABE}} + t_{\text{eXBE}}$



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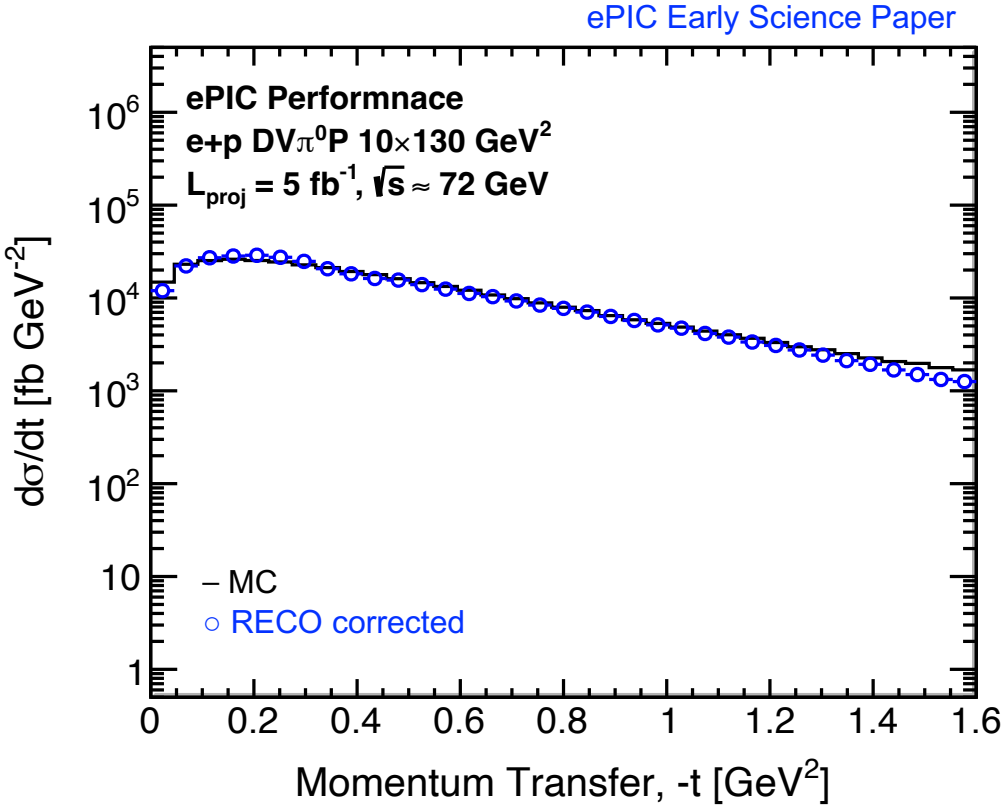
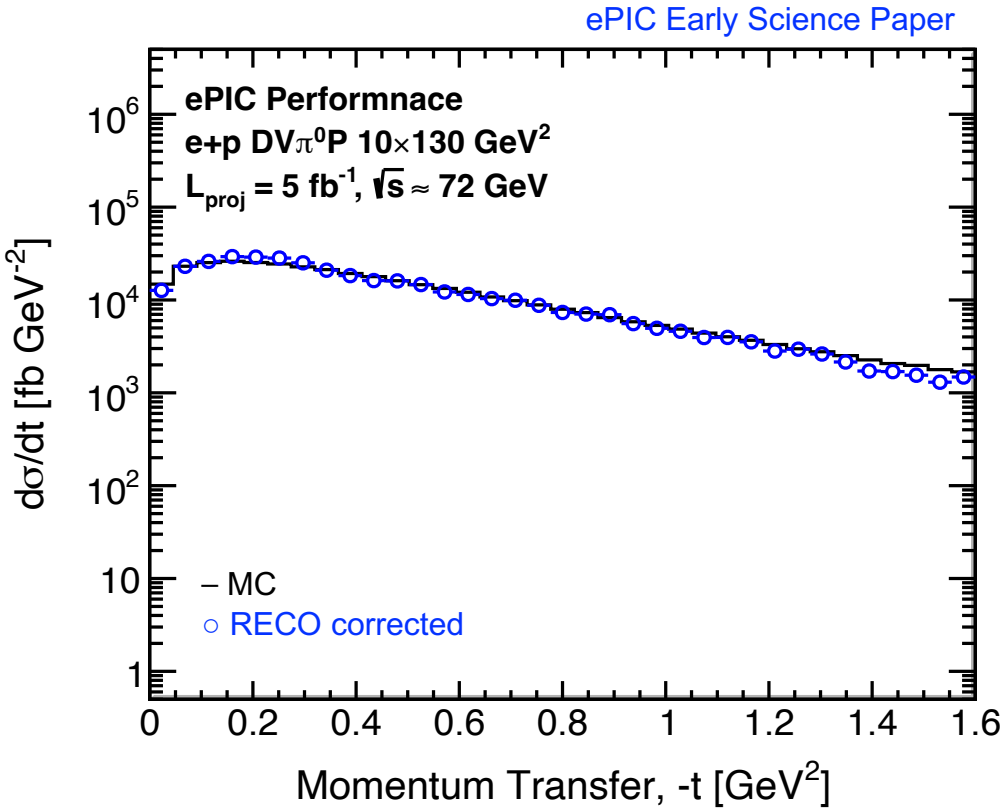
Results – Final t-distribution

ePIC Early Science Paper



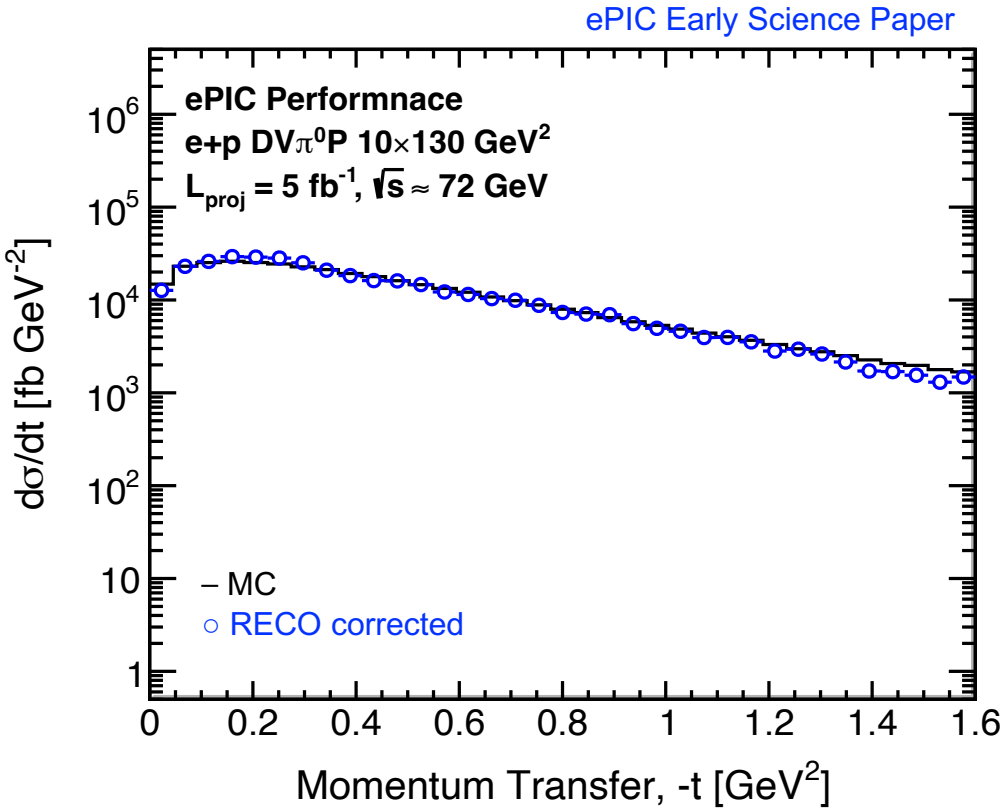
$\frac{d\sigma}{dt}$ distribution and 5 fb^{-1} projection

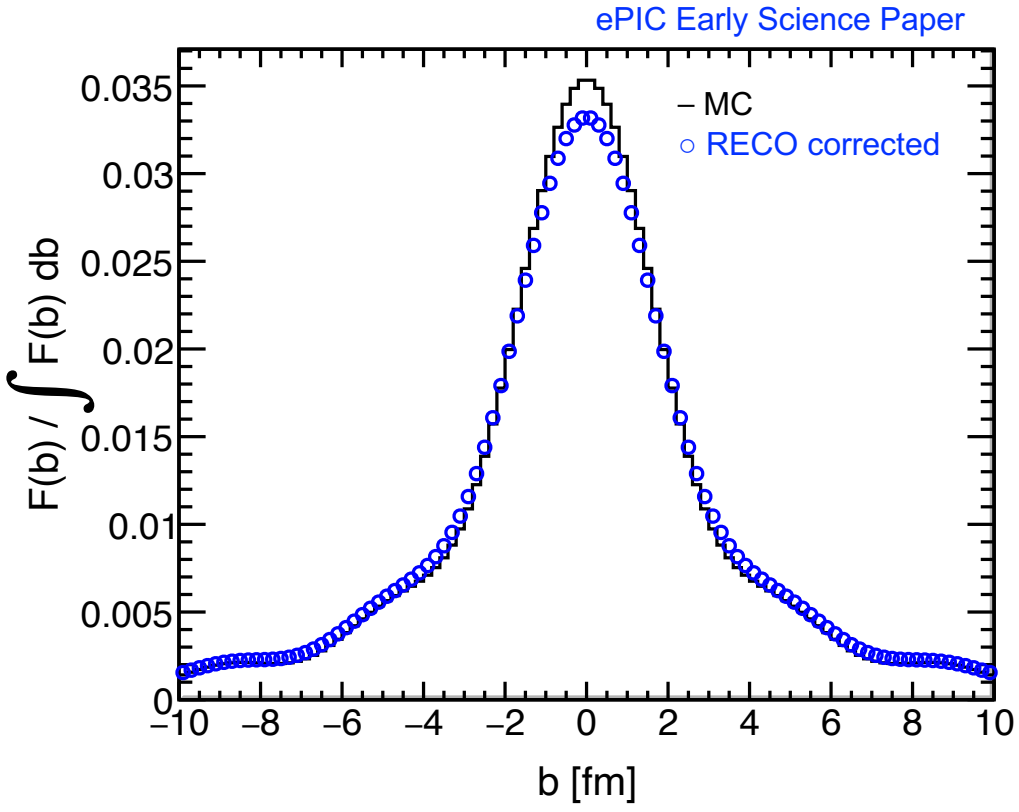
Results – Final t-distribution



$\frac{d\sigma}{dt}$ distribution → Added realistic fluctuations based on Gaussian(mean, error).

Results – Spatial Distribution





Realistic $\frac{d\sigma}{dt}$ distribution → Fourier transformation to obtain spatial distribution.

Background Study – Inclusive DIS and Physics

Approach – Inclusive DIS Background

- **Goal**: **Estimate inclusive DIS background to DVπ^0P channel**
  - ep inclusive DIS sample provided by Stephen Maple
    /gpfs02/eic/maples/RECO_pythia6_ep_early_science/ on RCF @ BNL
  - Two samples of 10×130 GeV^2 with $1 < Q^2 < 10$ and $10 < Q^2 < 100$
  - **Objective**: Identify inclusive DIS events that mimic exclusive π^0 process

- **Selection Criteria**:
  - An event **has four final-state particles** (i.e. e', p', and 2γs)
    - ReconstructedParticles: three final-state particles (i.e. e' and 2γs)
    - ReconstructedTruthSeededChargedParticles / ForwardRomanPotRecParticles: (i.e. p')
  - An event **pass quality cuts**
    - Selections based on E/p for e', $M_{\gamma\gamma}$ for π^0, and $\theta_{p'}$ for p'

Results – ep Inclusive DIS Background

Check if

1) Central Detector:
   Exactly three reconstructed particles
   1-1) **One negative** and **two neutral charges**
2) Far-Forward Detector:
   One reconstructed **positive-charge particle**
   Passes **angular acceptance cut (θ_p^{REC})**
3) Electron Candidate:
   Passes **E/p cut**
4) Neutral Pion candidate:
   Passes **$M_{\gamma\gamma}$ (invariant mass) cut**

*Note that no luminosity information is taken into account

Selection	10×130 GeV² 1 < Q² < 10	10×130 GeV² 10 < Q² < 100
1)	11.3232 % (56,616/500,000)	3.3658 % (16,829/500,000)
1-1)	2.1324 % (10,662/500,000)	0.486 % (2,430/500,000)
2)	0.5494 % (2,747/500,000)	0.1132 % (566/500,000)
3)	0.479 % (2,395/500,000)	0.0838 % (419/500,000)
4)	**0.14 %*** (700/500,000)	**0.0114 %*** (57/500,000)

π^0s can be produced via multiple processes – this is expected.

Results – ep Inclusive DIS Background

$1 < Q^2 < 10$ for 500k events

- DVπ^0P

  $\sigma_{\text{integrated}} \approx 0.017$ nb

- DIS

  $\sigma_{\text{integrated}} \approx 0.64\ \mu$b

  Scaling factor: **37,647.059**

$10 < Q^2 < 100$ for 500k events

- DVπ^0P

  $\sigma_{\text{integrated}} \approx 3.4\times10^{-4}$ nb

- DIS

  $\sigma_{\text{integrated}} \approx 0.047\ \mu$b

  Scaling factor: **138,235.29**

*Note that no luminosity information is taken into account

Selection	10×130 GeV^2 $1 < Q^2 < 10$	10×130 GeV^2 $10 < Q^2 < 100$
1)	11.3232 % (56,616/500,000)	3.3658 % (16,829/500,000)
1-1)	2.1324 % (10,662/500,000)	0.486 % (2,430/500,000)
2)	0.5494 % (2,747/500,000)	0.1132 % (566/500,000)
3)	0.479 % (2,395/500,000)	0.0838 % (419/500,000)
4)	**0.14 %*** (700/500,000)	**0.0114 %*** (57/500,000)
	5270.6 %	**1575.9 %**

Additional selection cut required to reduce DIS background

Additional Cuts

Missing mass ($M^2_{Missing}$)

- Incoming beams are known
- Incoming beam particles (Truth) Final-state particles (Reconstructed)
  $P^2_{\text{Missing}} = \left((P_e + P_p) - (P_{e'} + P_{p'} + P_{\pi^0})\right)^2 = M^2_{\text{Missing}}$
- If exclusive π^0 event, $\boldsymbol{P^2_{\text{Missing}}}$ should be close to **0**
- If not, P^2_{Missing} indicates other particles being produced
- Note: Detector resolution/smearing effects being included

Far-Forward Detector Veto

- Scattered proton can be detected at Roman Pot and B0 detectors (possibly Off-Momentum Detector?)
- No activities are expected at Zero Degree Calorimeter
- If there are hits, then it is not exclusive π^0 events

Results – ep Inclusive DIS Background

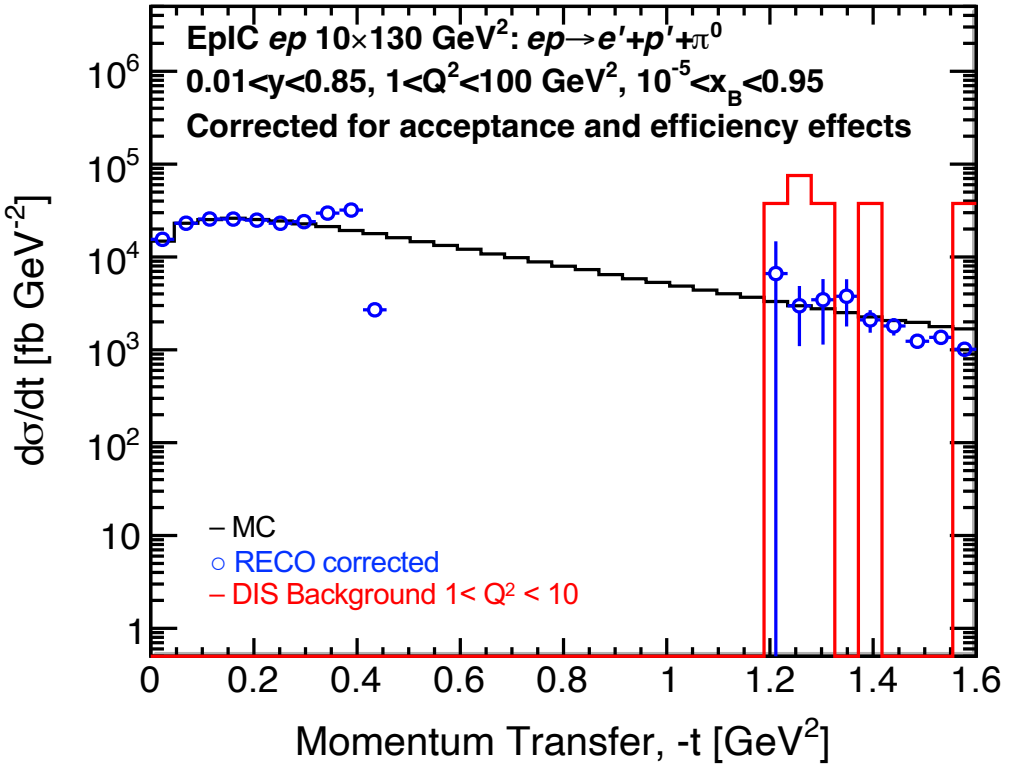
Check if

1) Central Detector:
   Exactly three reconstructed particles
   1-1) **One negative** and **two neutral charges**
2) Far-Forward Detector:
   One reconstructed **positive-charge particle**
   Passes **angular acceptance cut (θ_p^{REC})**
3) Electron Candidate:
   Passes **E/p cut**
4) Neutral Pion candidate:
   Passes **$M_{\gamma\gamma}$ (invariant mass) cut**
5) Missing Mass: ref. $M_{\pi^0}^2 \sim 0.02$ GeV + $E - p_z$
   Passes $M_{Missing}^2$ cut ($|M_{Missing}^2| < 1$ GeV^2)
6) Far-Forward Detector Veto (ZDC)

*Note that no luminosity information is taken into account

Selection	10×130 GeV² 1 < Q² < 10	10×130 GeV² 10 < Q² < 100
1)	11.3232 % (56,616/500,000)	3.3658 % (16,829/500,000)
1-1)	2.1324 % (10,662/500,000)	0.486 % (2,430/500,000)
2)	0.5494 % (2,747/500,000)	0.1132 % (566/500,000)
3)	0.479 % (2,395/500,000)	0.0838 % (419/500,000)
4)	0.14 %* (700/500,000)	0.0114 %* (57/500,000)
5)	0.0032 %* (16/500,000)	0.0004 %* (2/500,000)
6)	0.002 **(0.0016) %*** (10(**8**)/500,000)	**0.0002 %*** (1/500,000)
	60.2 %	**27.6 %**

Results – t-distribution $t_{\mathrm{BABE}} = (p - p')^2$



This is t-distribution integrated over x, and Q^2

- Good **Proton** Selection:
  - ✓ is reconstructed in B0 or Roman Pot
  - ✓ **Within angular acceptance** in B0 or Roman Pot

$$5.5 \text{ mrad} < \theta^{\mathrm{REC}}_{\mathrm{p\ in\ B0}} < 20 \text{ mrad}$$

$$0 \text{ mrad} < \theta^{\mathrm{REC}}_{\mathrm{p\ in\ RP}} < 5 \text{ mrad}$$

- Good **Electron** Selection:
  - ✓ With truth-association E/p cut ($0.9 < E/p < 1.2$)
- Good **Neutral Pion** Selection:
  - ✓ Within ± 0.04 GeV of M_{π^0} ($0.096 < M_{\gamma\gamma} < 0.172$)
- Suppress photo production + radiative corrections
  - ✓ $\boldsymbol{E - p_z}$ cut ($15 < E/p < 25$)
- **Exclusivity** Cut
  - ✓ All final-state particles are reconstructed
- **Missing Mass** Cut:
  - ✓ With $|\boldsymbol{M^2_{Missing}}| < 1$ GeV²

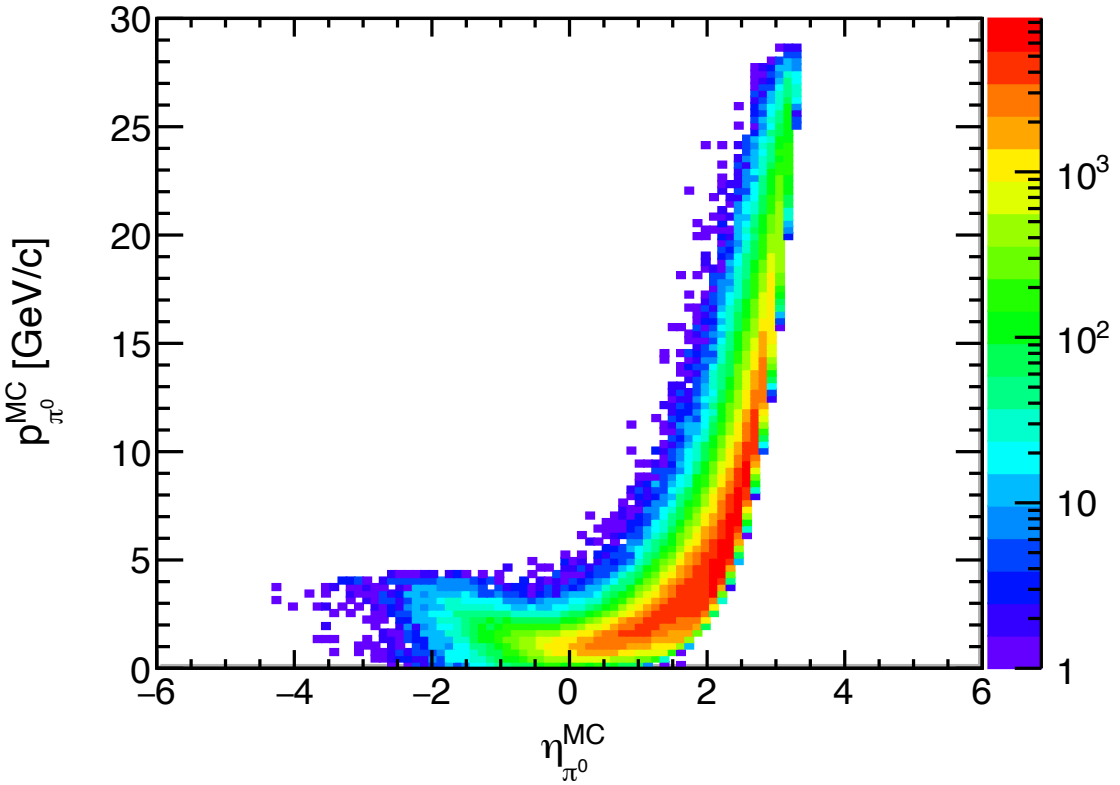
Approach – Physics Background to DVCS

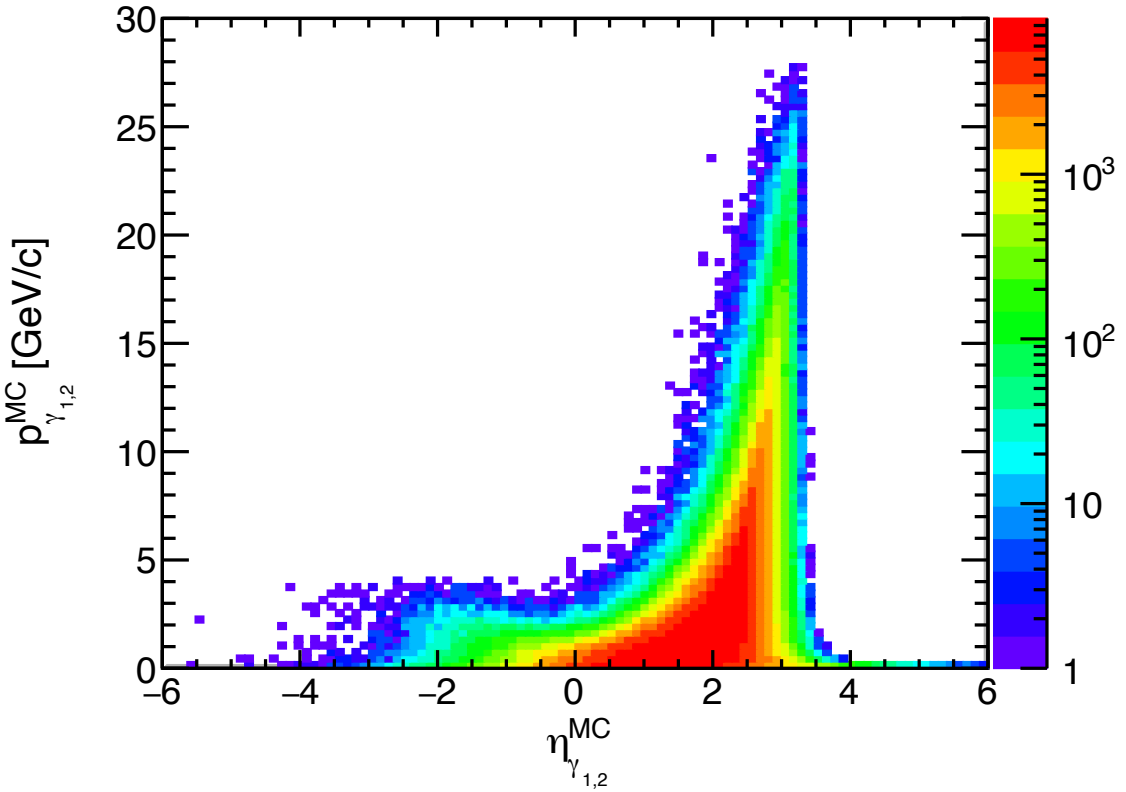
- Main goal: **Estimate single photon misidentification** from October Simulation Campaign 5×41 GeV^2 comparing to DVCS
  - Where one of gammas from π^0 is mis-identified as DVCS γ
  - Geometrical acceptance, energy thresholds, and granularity
- Method
  - MC-level phase space cuts

    Same cut on EIC DVCS paper
    $0.03 < -t < 1.5$, $0.01 < y < 0.85$, $1 < Q^2 < 100$, $0.00001 < x_B < 0.7$
  - EM Calorimeter information: EcalEndcapN / EcalBarrel / EcalEndcapP
  - Truth ID used to exclude scattered electron
  - Minimum cluster energy cut at 0.1 GeV
  - <u>Look for reconstructed events with 1 cluster formed</u>

References:
https://indico.bnl.gov/event/26526/contributions/103508/attachments/60126/103303/ePIC_exclusive_diffraction_tagging_mtg_JKIM_20250224.pdf
Phys. Rev. D 112, 036010 (2025) https://doi.org/10.1103/fy8y-bjc9

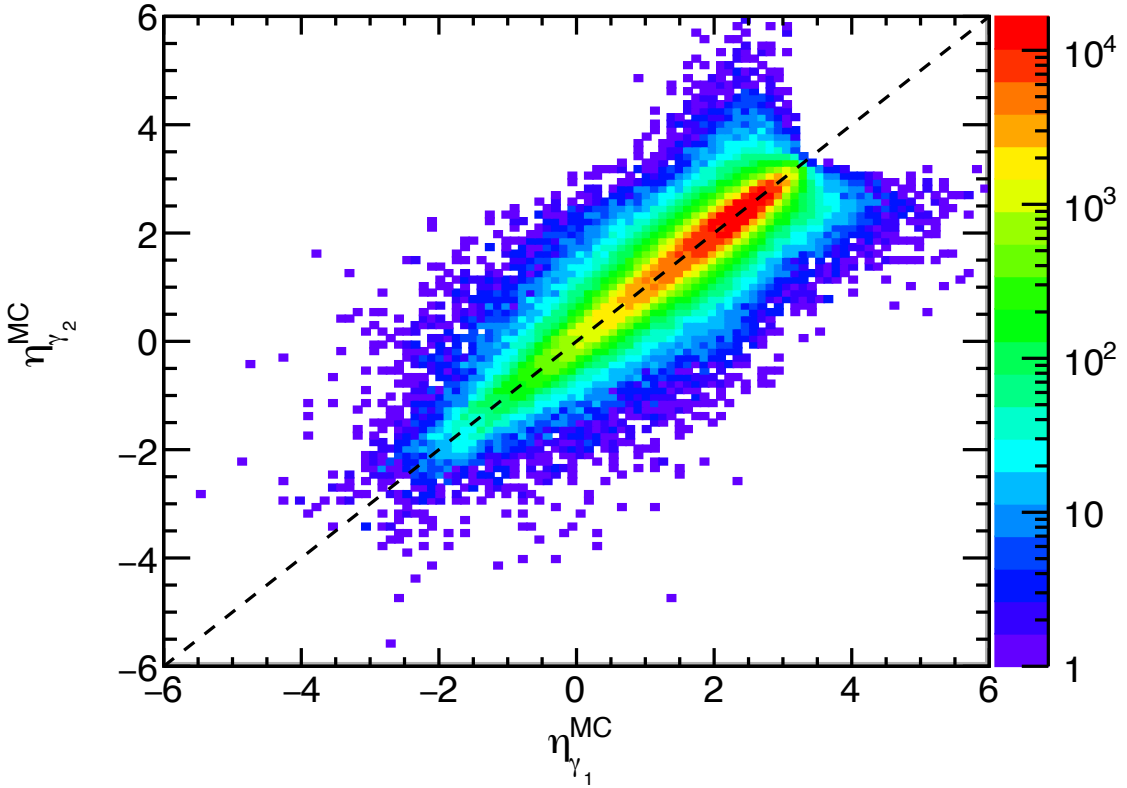
π^0 and 2γ Kinematics – p vs η

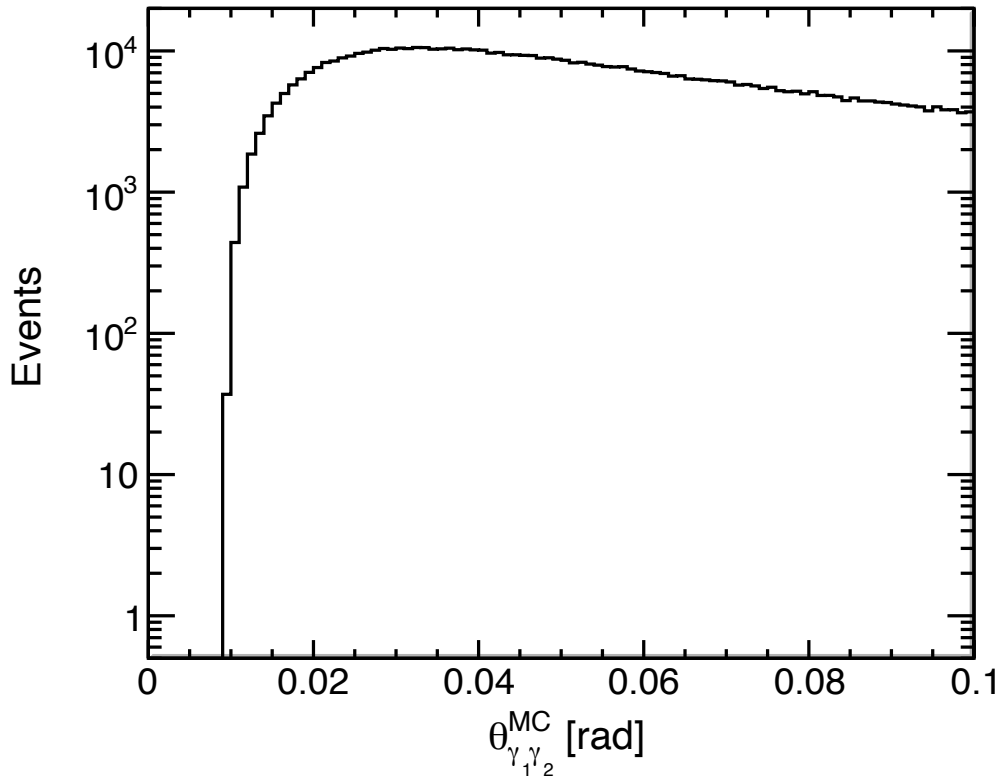




(Left) π^0 and (Right) decaying two γs
π^0 dominates in the forward

2γ Kinematics – η vs η and $\theta_{\gamma\gamma}$





$\gamma\gamma$ are concentrated **within similar pseudo-rapidity** and threshold of $\theta_{\gamma\gamma}$ is around 0.01 rad

Very few events where we simply lose a photon by geometric acceptance

Initial Results

5×41 GeV^2	# of Events	Misidentification
	327,621 / 975,885	**0.335717**

Above summary shows estimated misidentification ($\pi^0 \rightarrow$ DVCS)

- Current reconstruction pipeline in EICrecon

Initial Results

5×41 GeV^2	# of Events	Misidentification
	327,621 / 975,885	**0.335717**

Above summary shows estimated misidentification ($\pi^0 \rightarrow$ DVCS)

- Current reconstruction pipeline in EICrecon

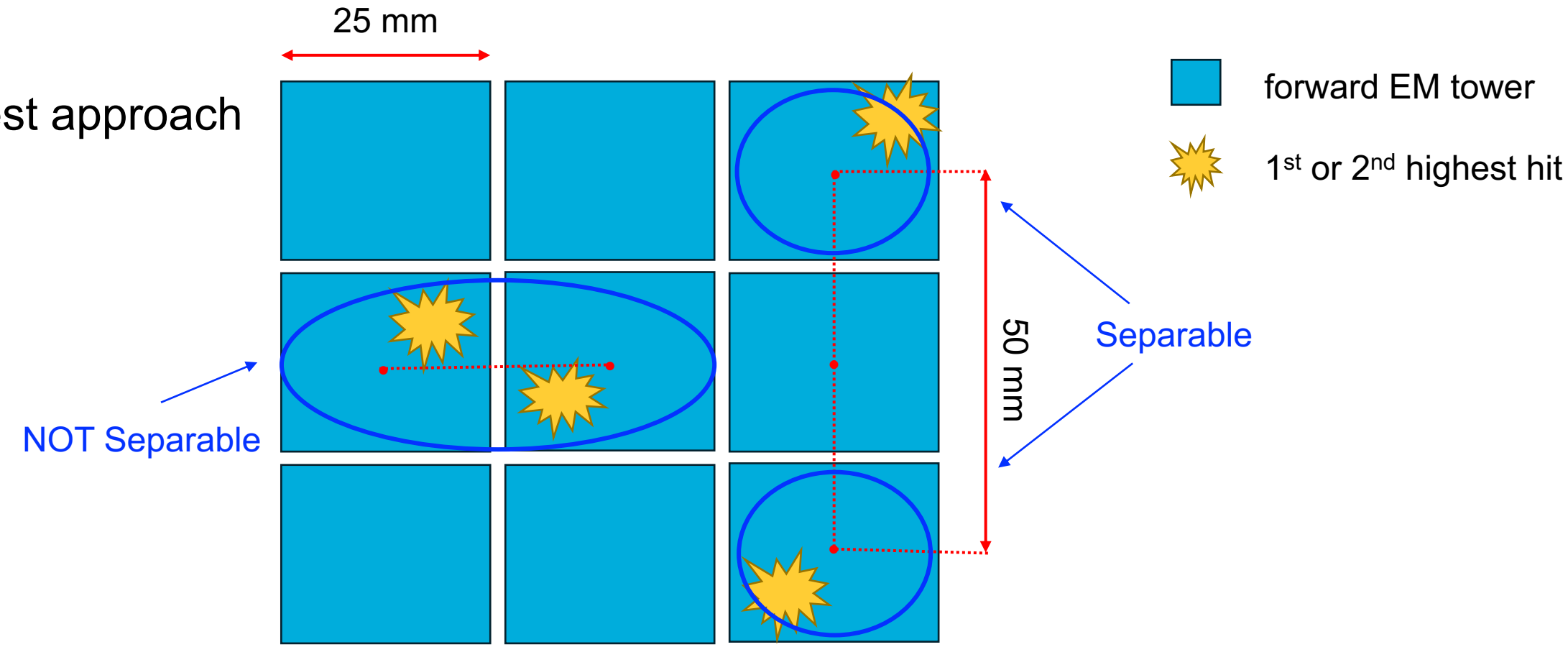
There is still room for improvement!

- Optimal reconstruction parameters (ex. cluster-splitting)
- Granularity of forward EMCAL ~ 0.015 rad (ex. tower size)

Forward EMCAL tower size: 25 mm and distance from IP: 3,290 mm

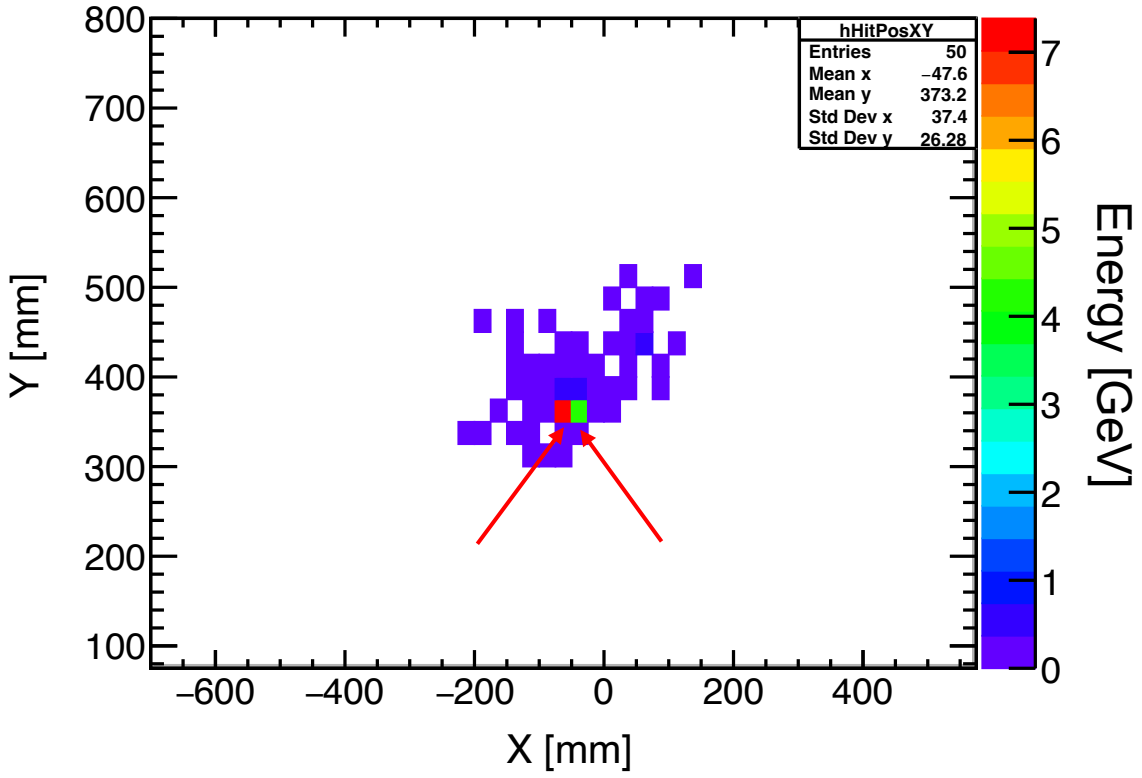
Look for Separable Events in Forward

Simplest approach



If distance between two highest hits is at least twice tower size (50 mm) to be separable

Example for 5 GeV × 41 GeV Event



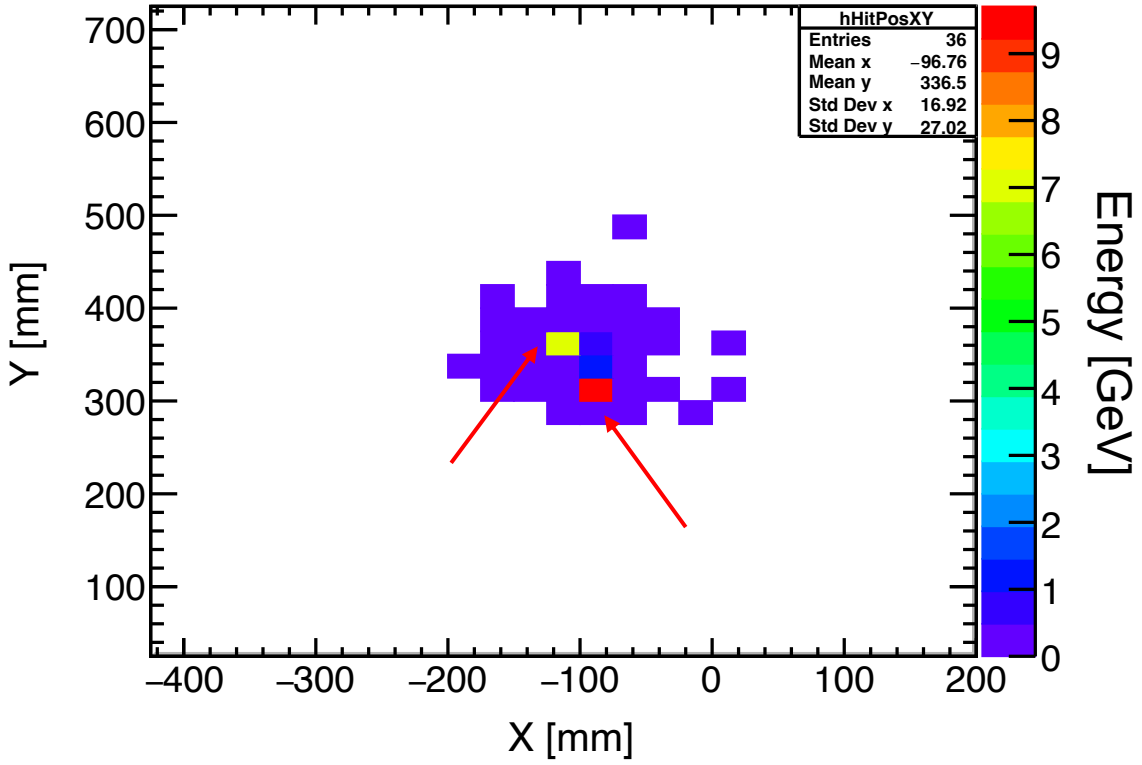
Using current reconstruction pipeline
→ 1 cluster reconstructed

MC information
→ $\theta_{\gamma\gamma}^{\mathrm{MC}}$ ~ 0.028 rad

Distance between two highest hit towers
→ ~ 25 mm

This event may NOT be identified as two clusters **at hit-level**.

Example for 5 GeV × 41 GeV Event



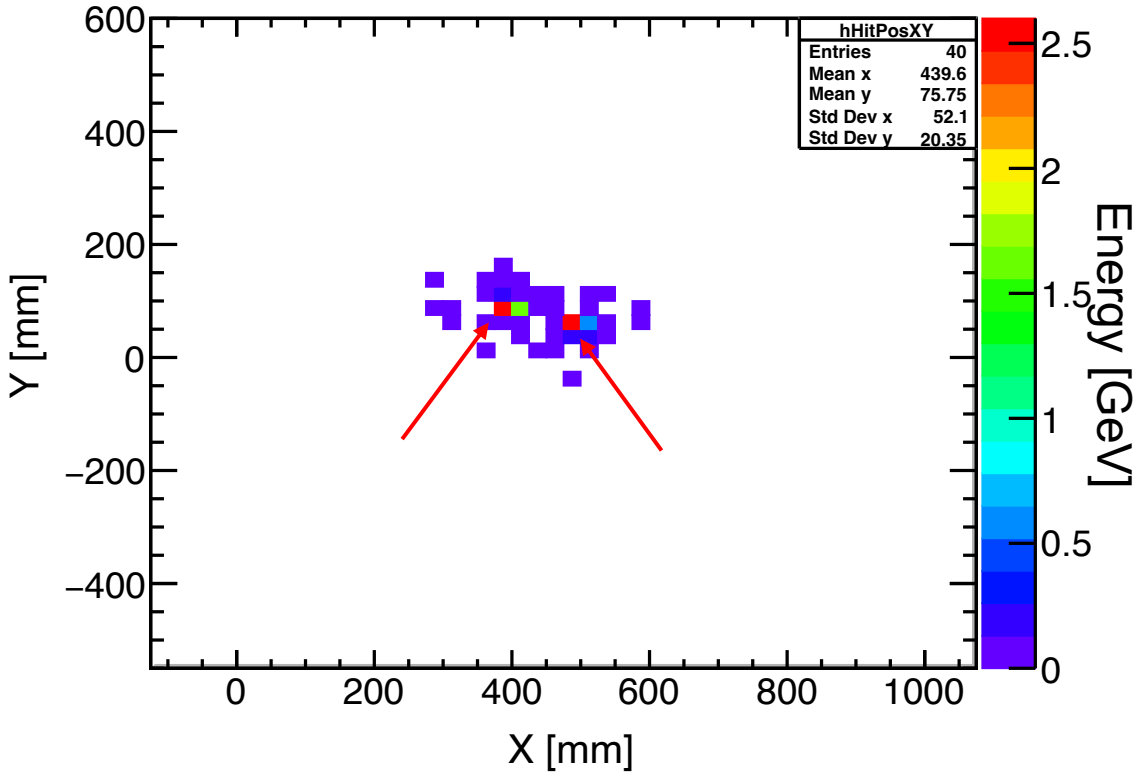
Using current reconstruction pipeline
→ 1 cluster reconstructed

MC information
→ $\theta_{\gamma\gamma}^{\mathrm{MC}}$ ~ 0.014 rad

Distance between two highest hit towers
→ ~ 50 mm

This event can be identified as two clusters **at hit-level**.

Example for 5 GeV × 41 GeV Event



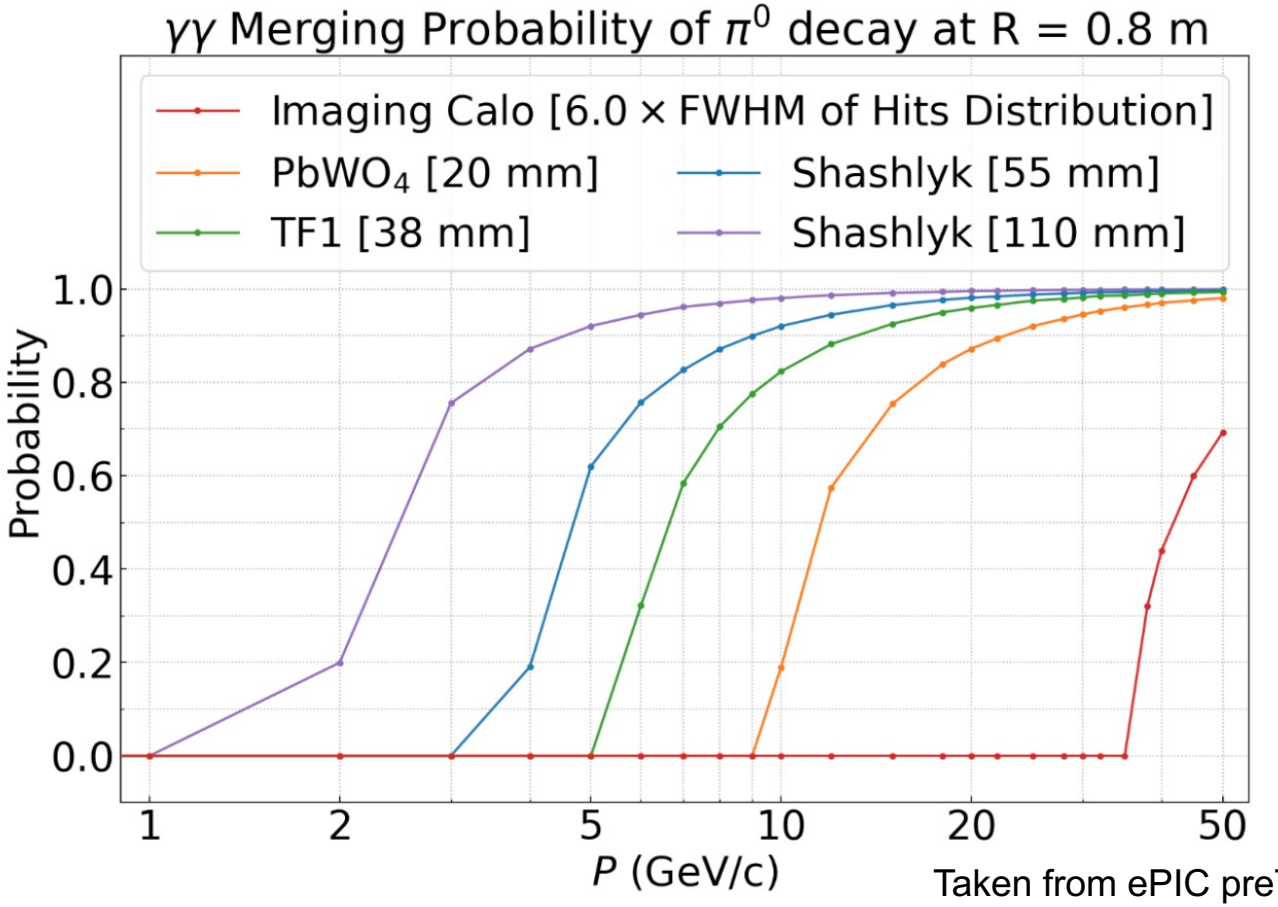
Using current reconstruction pipeline
→ 1 cluster reconstructed

MC information
→ $\theta_{\gamma\gamma}^{\mathrm{MC}}$ ~ 0.029 rad

Distance between two highest hit towers
→ ~ 100 mm

This event can be identified as two clusters **at hit-level**.

Look for Separable Events in Barrel



Taken from ePIC preTDR v2.2 (Figure 8.148 (b) on page 230)

Upper limit of $\gamma\gamma$ merging probability at η = 0, up to $\boldsymbol{p_{\pi^0}}$ **~ 35 GeV** can be separable

Intermediate Results

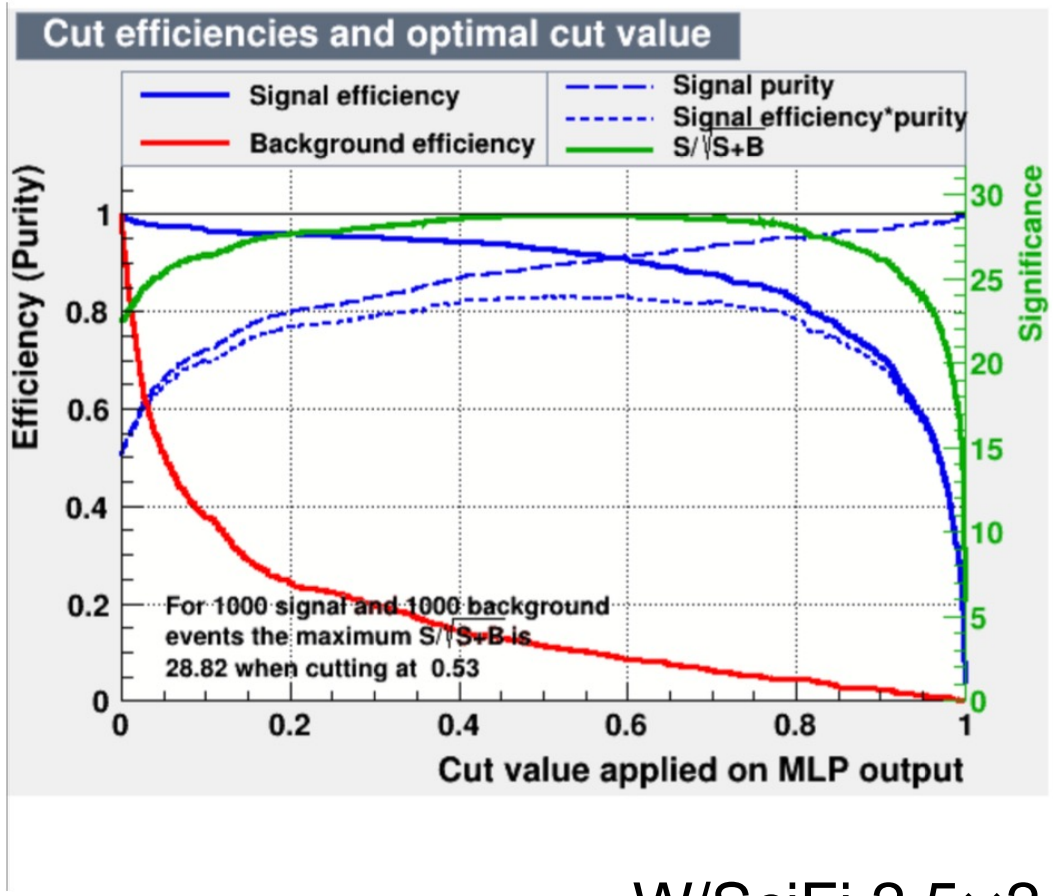
5×41 GeV^2	# of Events	Misidentification	# of Events	Misidentification
	327,621 / 975,885	**0.335717**	116,184 / 975,885	**0.119055**

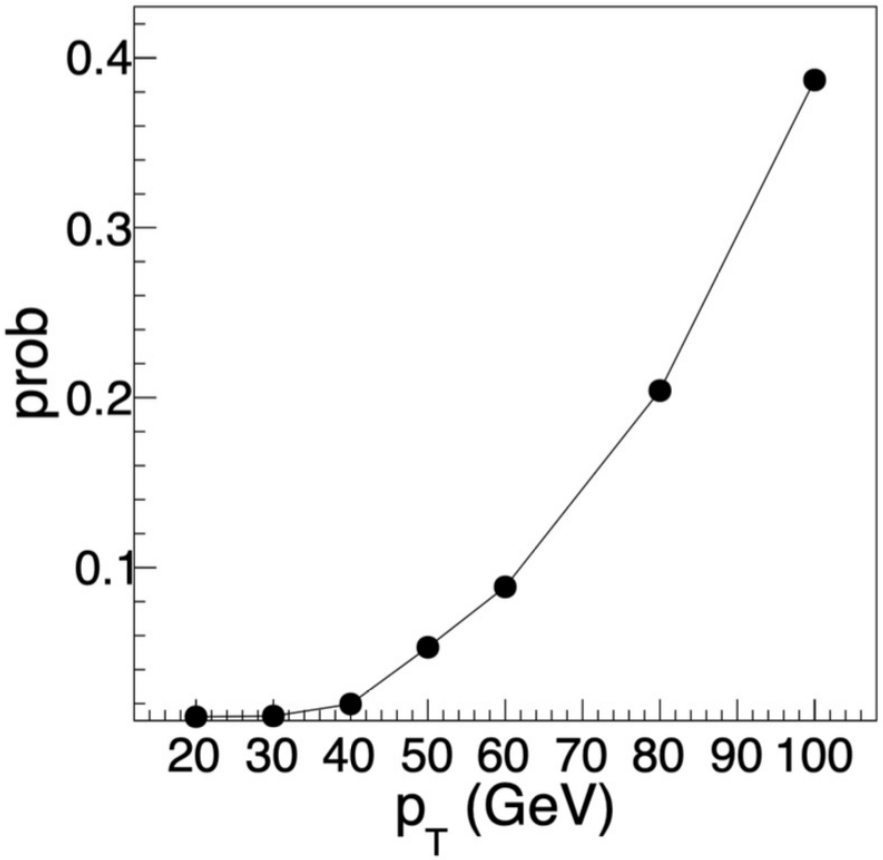
Above summary shows estimated misidentification ($\pi^0 \rightarrow$ DVCS)

- Current reconstruction pipeline in EICrecon
- Potential improvement in Forward (hit-level) & Barrel ML

Potential Improvement in Forward

Taken from ePIC preTDR v2.2 (Figure 8.162 on page 253)





W/SciFi 2.5×2.5 at z = **3.3 m**

Misidentification rate **at 60 GeV** is approximately **10 %**

Final Results

5×41 GeV^2	# of Events	Misidentification	# of Events	Misidentification	# of Events	Misidentification
	327,621 / 975,885	**0.335717**	116,184 / 975,885	**0.119055**	1,156 / 975,885	**0.00118457**

Above summary shows estimated misidentification ($\pi^0 \rightarrow$ DVCS)

- Current reconstruction pipeline in EICrecon
- Potential improvement in Forward (hit-level) & Barrel ML
- Potential improvement in Forward ML

Cross-section considerations:

Pure DVCS $\sigma_{\text{integrated}} \approx 0.47$ nb (All DVCS ~ 1.88 nb), and DVπ^0P $\sigma_{\text{integrated}} \approx 0.18$ nb.

Scaling factor: DVCS vs DVπ^0P ~ 1 : 0.096 ⇒ **1.14 %**.

Summary

Analysis Note: https://doi.org/10.5281/zenodo.17943008

- Studied exclusive π^0 production physics channel at EIC
  - Extracted t-distribution using $\boldsymbol{t_{\mathrm{BABE}}}$ and $\boldsymbol{t_{\mathrm{eXBE}}}$ methods.
  - Derived quark spatial distribution.
- Inclusive DIS Background
  - As this is expected, π^0s can be produced via multiple processes.
  - All remaining events has multiple π^0s already.
  - Even with cross-section scaling on sample, the background level is 60 % at low Q^2 region. But it has t-dependency and mostly in high-t region.
  - The background contains only one event, leading to a 100% statistical uncertainty. As a result, completely suppressing background is challenging.
- Physics Background to DVCS
  - Single-photon misidentification estimated at ~ 11.9% (conservative estimate).
  - Cross-section considerations:
    - Pure DVCS $\sigma_{\mathrm{integrated}} \approx 0.47$ nb (All DVCS ~ 1.88 nb), and DVπ^0P $\sigma_{\mathrm{integrated}} \approx 0.18$ nb.
    - Scaling factor: DVCS vs DVπ^0P ~ 1 : 0.096 ⇒ 1.14 % background contribution.
  - So far, results appear consistent with *EIC DVCS paper.

*Phys. Rev. D 112, 036010 (2025) https://doi.org/10.1103/fy8y-bjc9

Backup Slides

From Thomas Ullrich (BNL/Yale)

Method L

- How the method works
  - Calculate p of outgoing A': $p_{A'} = p_A - (p_V + p_{e'} - p_e)$
  - Express and correct the outgoing nucleus in light cone variables:
    - $p^+_{A'} = E_{A'} + p_{z,A'}$
    - $p^2_{T,A'} = p^2_{x,A'} + p^2_{y,A'}$
    - $p^-_{A'} = (M^2_A + p^2_{T,A'})/p^+_{A'}$ where $p^-_{A'}$ is now modified by using the true mass M^2_A.
  - The corrected 4-momentum of the outgoing nuclei is now

$$p^{\text{corr}}_{A'} = \left[p_{x,A'},\ p_{y,A'},\ (p^+_{A'} - p^-_{A'})/2,\ (p^+_{A'} + p^-_{A'})/2\right]$$

  - In short, you are using the true invariant mass of the nucleus to compensate the smearing in the larger component of the electron 4-momentum by modifying $E_{A'}$ and $p_{z,A'}$ simultaneously.
  - Now simply: $t_{\text{corr}} = \left| p_A - p^{\text{corr}}_{A'} \right|^2$

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Experiment – COMPASS@CERN

Table 2
Summary of the estimated relative systematic uncertainties for the $|t|$ and ϕ-dependent cross sections and the integrated cross section. The values are given in percent. Note that the uni-directional uncertainty $\sigma_\uparrow$ is a positive number, and $\sigma_\downarrow$ is a negative number.

Source	$\sigma^t_\uparrow$	$-\sigma^t_\downarrow$	$\sigma^\phi_\uparrow$	$-\sigma^\phi_\downarrow$	$\sigma_\uparrow$	$-\sigma_\downarrow$
μ^+ flux	2	2	2	2	2	2
μ^- flux	2	2	2	2	2	2
ECAL threshold	5	5	5	5	5	5
acceptance	4	7	4	7	4	7
kinem. fit	0	7	0	7	0	7
ω background	0	1	0	1	0	1
rad. corr.	2	5	2	5	2	5
LEPTO norm.	5–28	3–11	5–51	3–21	8	3
yield mismatch	4–13	3–7	0–12	3–12	9	5
$\sum$	12–29	13–18	12–53	13–25	14	14

Phys. Lett. B805 (2020) 135454; arXiv:1903.12030

Table 2: Summary of the estimated relative systematic uncertainties on the measured $|t|$ and ϕ-dependent cross sections and on the extracted cross-section contributions $\frac{d\sigma_U}{dt} = \frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt}$ and $\frac{d\sigma_{TT}}{dt}$ in the full kinematic range. The values are given as a percentage. Note that the uni-directional uncertainty $\sigma_\uparrow$ ($\sigma_\downarrow$) has to be used with positive (negative) sign.

source	$\sigma^t_\uparrow$	$\sigma^t_\downarrow$	$\sigma^\phi_\uparrow$	$\sigma^\phi_\downarrow$	$\sigma_{U\uparrow}$	$\sigma_{U\downarrow}$	$\sigma_{TT\uparrow}$	$\sigma_{TT\downarrow}$
μ^+ flux	2	2	2	2	2	2	2	2
μ^- flux	2	2	2	2	2	2	2	2
acceptance	4	4	4	4	4	4	4	4
ECAL0 threshold	5 – 7	1	4 – 8	1	5	1	4	1
ECAL1 threshold	1 – 2	1	1 – 3	1	1	1	1	1
χ^2 of kinematic fit	3	5	2.0 – 5.6	4.0 – 8.8	3	5	3	4
LEPTO background	6 – 10	6 – 10	6 – 16	6 – 16	8.3	8.3	1	1
LEPTO normalisation	2 – 3	2 – 3	2 – 5	2 – 5	2.6	2.6	2	2
ω background	0	1.5 – 2.7	0	1.4 – 5.7	0	2.4	0	2.4
radiative corrections	6	3	6.3	3.6	6	3	2	2
Σ	12 – 16	10.1 – 13.1	11.6 – 22.4	9.6 – 20.1	13.3	11.7	7.7	7.1

Phys. Lett. B870 (2025) 139832; arXiv:2412.19923

Experiments – Hall A and CLAS@JLab

- Typical total systematic uncertainty:

  4 – 8 % 10 %

  (depends on kinematic setting)

Table 5.5: Systematic errors for exclusive π^0 cross-section. The DIS study error includes the systematic from radiative correction, electron identification, and spectrometer acceptance.

Systematic	Value (%)
Exclusivity Cuts	0.5
DIS study	3.5
Clustering threshold	0.5
Photon Energy cut	0.5
Total Quadratic (helicity-independent)	3.6
Beam polarization	1
Total Quadratic (helicity-dependent)	3.75

Phys. Rev. Lett. 127, 152301 (2021); arXiv:2011.11125

TABLE IV. Summary table of systematic uncertainties. B denotes bin-to-bin and O indicates overall uncertainties.

Source	Bin-to-bin or overall	Average uncertainty (%)
Proton ID	B	~2.5
Fiducial cut	B	~4.7
Cut on energy of photon detected in the EC	B	~1.6
Cut on missing mass of the $e'\gamma\gamma$	B	~2.5
Cut on invariant mass of 2 photons	B	~2.9
Cut on missing energy of the $ep'\gamma\gamma$	B	~3.2
Radiative corrections	B	~2.9
Total beam charge on target	O	<1
Target length	O	0.2
Absolute normalization	O	6.0

Phys. Rev. C90, 025205 (2014); arXiv:1405.0988