DVCS Background Study – Using Exclusive π^0

Jihee Kim (jkim11@bnl.gov) and Alex Jentsch

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Introduction

- Hard exclusive production of π^0 mesons
  - Provide information for polarized quark GPDs
  - It has been studied at fixed target mode at JLab for example
  - Collider mode (never done yet) offers high proton polarization and coverage for much lower-x and higher Q^2
  - DVMP π^0 may become a background to DVCS
- **(Quick) Estimate single photon contamination (background)** from exclusive **π^0 sample** comparing to DVCS at the most updated ePIC simulation
  - Where one of gammas from π^0 is mis-identified as DVCS photon
  - Geometrical acceptance, energy thresholds, and granularity

Sample

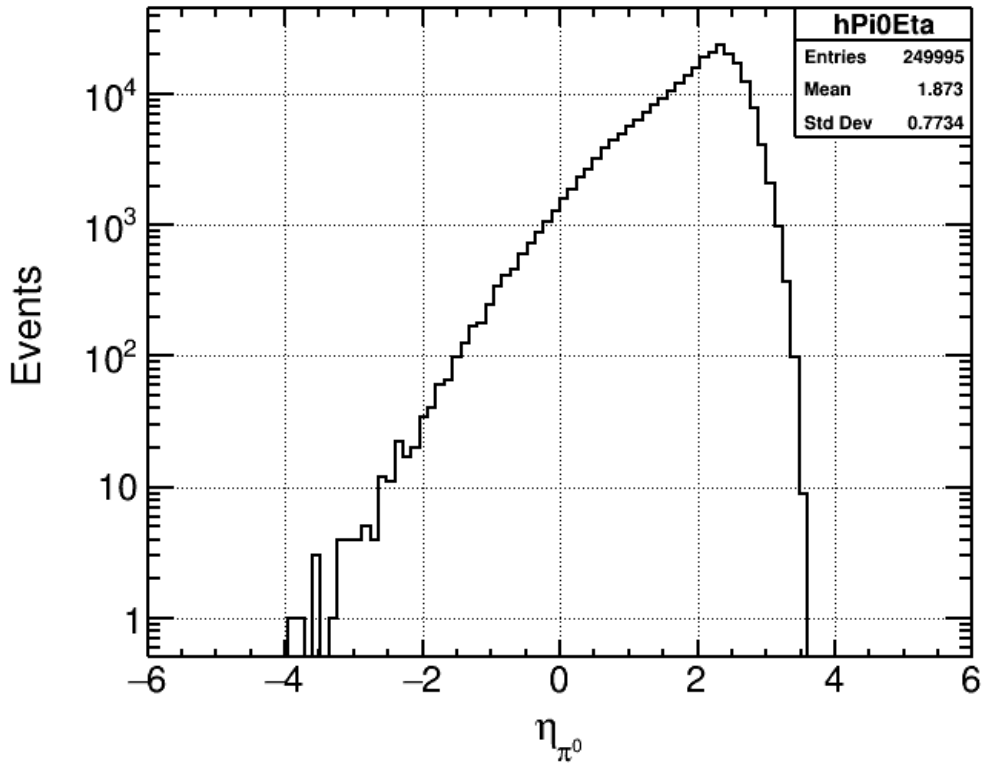
- Exclusive π^0 samples from EpIC generator
  - Total ~250,000 events each beam configuration
  - Beam configuration: 5×41, 10×100, and 18×275 GeV^2

- Run ePIC simulation (craterlake version)
  - Calorimeter information: EcalEndcapN / EcalBarrel / EcalEndcapP
  - Truth ID used to exclude scattered electron
  - Work with remaining clusters in calorimeters

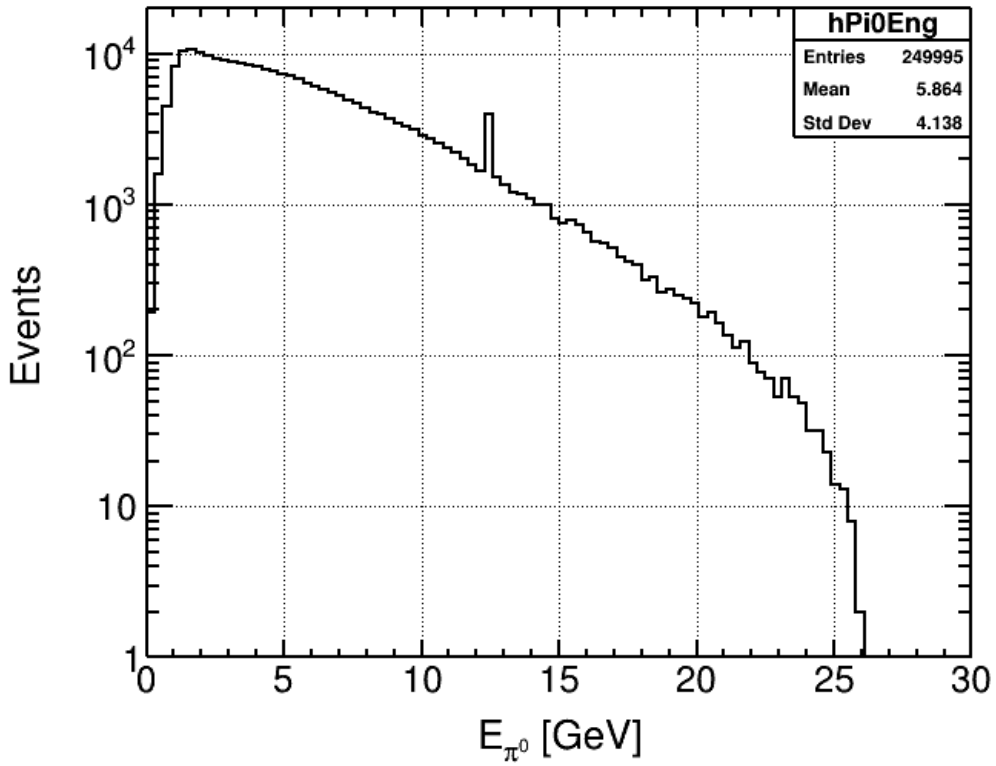
5×41 GeV^2

π^0 Kinematics

Neutral Pion Pseudo-rapidity



Neutral Pion Energy



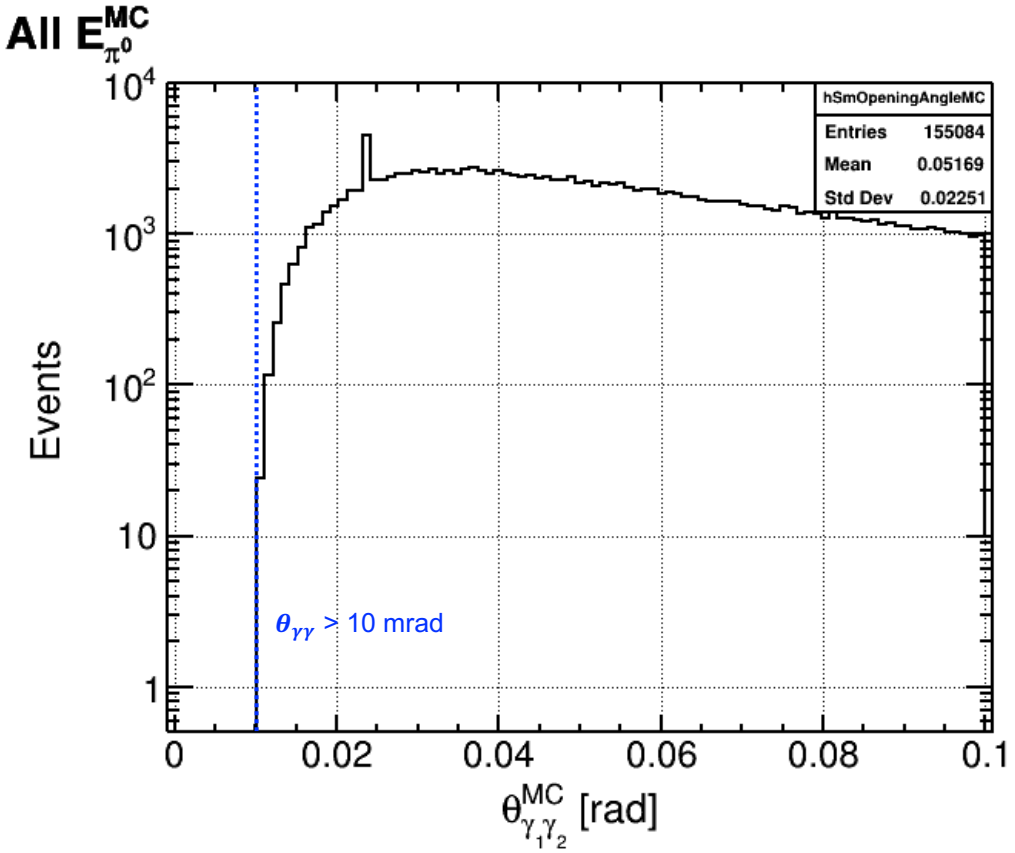
Most of π^0s are going forward and their energy can be up to 25 GeV

Spike – unphysical values put in to account for “nan” values in the MC sample

5×41 GeV²

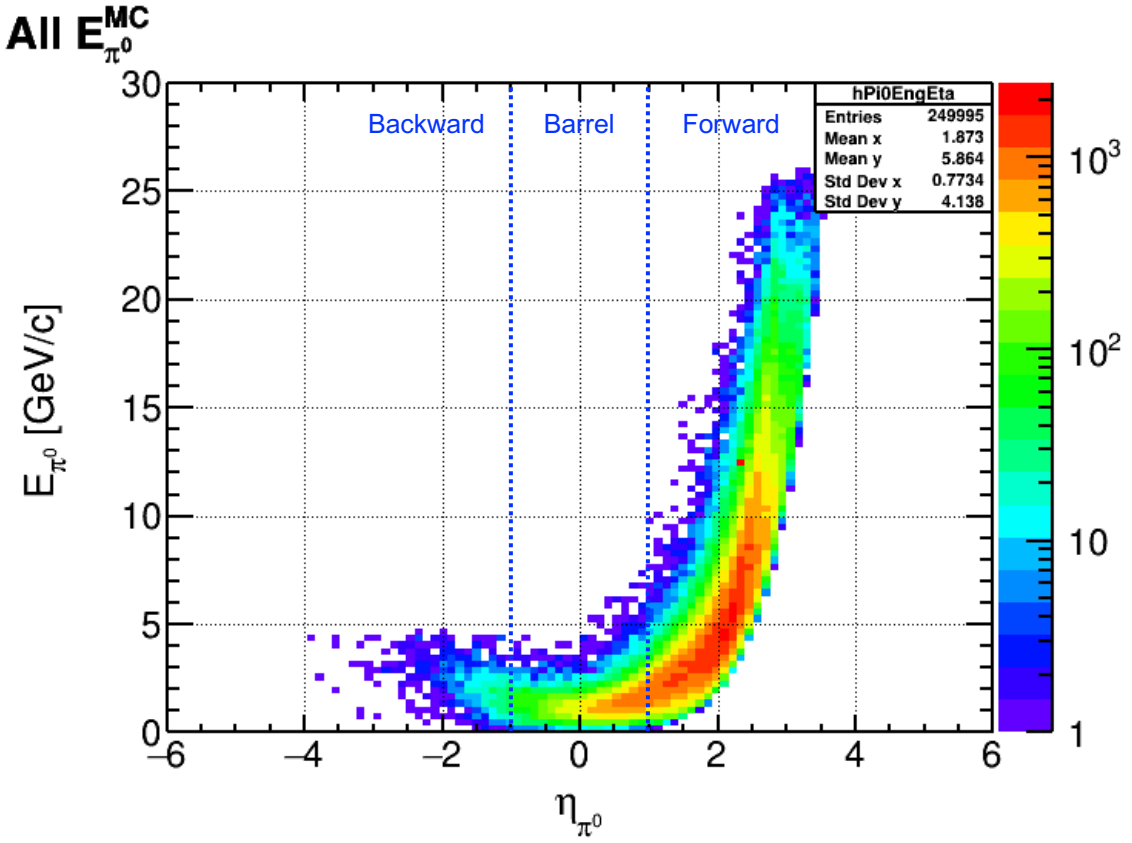
π^0 Kinematics

Opening Angle of Two Photons < 100 mrad



Reference: $\theta_{\gamma\gamma\ \min}|_{10\ \mathrm{GeV}} \sim \frac{2m_{\pi 0}}{p_{\pi 0}} \sim 1.55° \sim 27\ \mathrm{mrad}$

Neutral Pion Energy vs Pseudorapidity

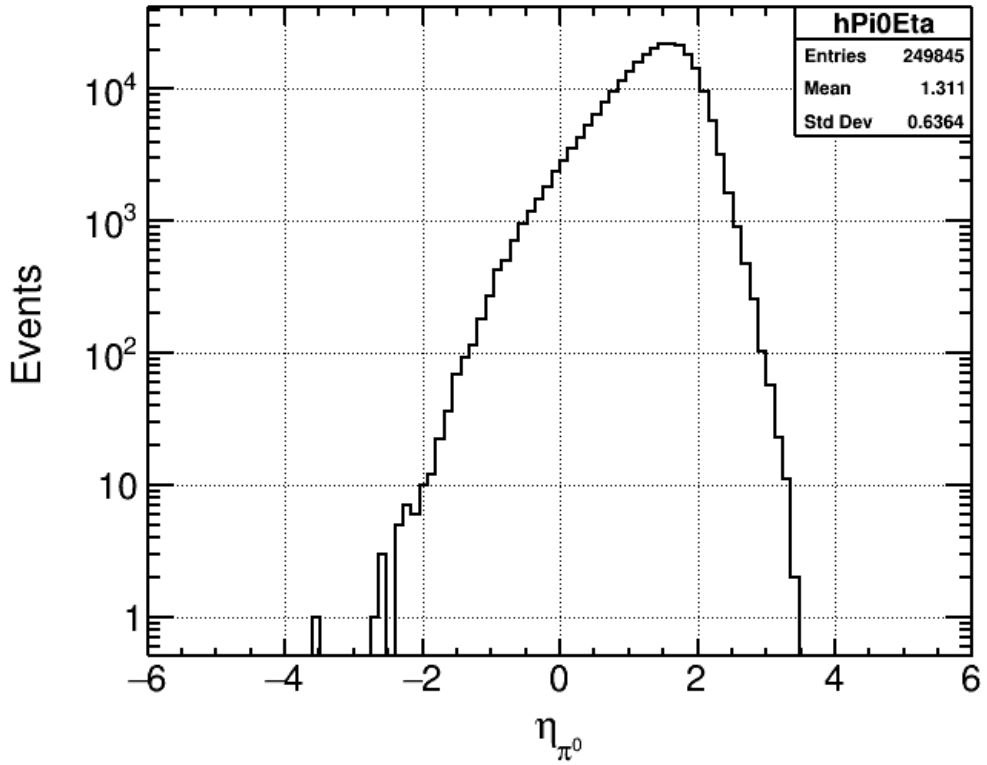


Minimum opening angle of two γs is 10 mrad

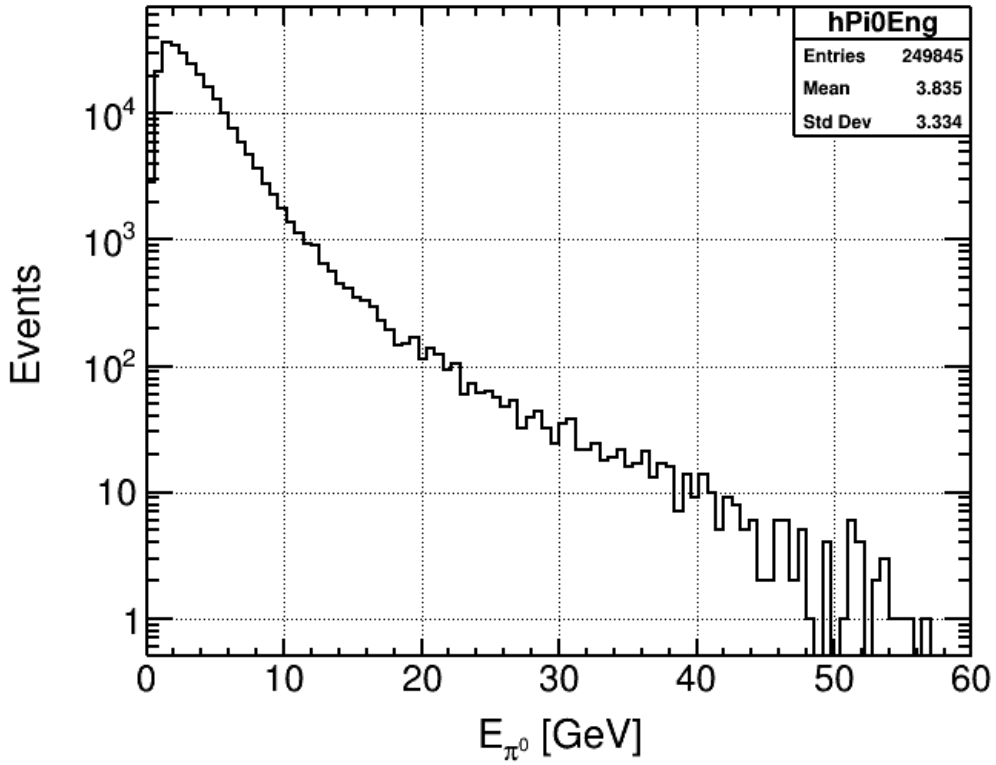
10×100 GeV^2

π^0 Kinematics

Neutral Pion Pseudo-rapidity



Neutral Pion Energy

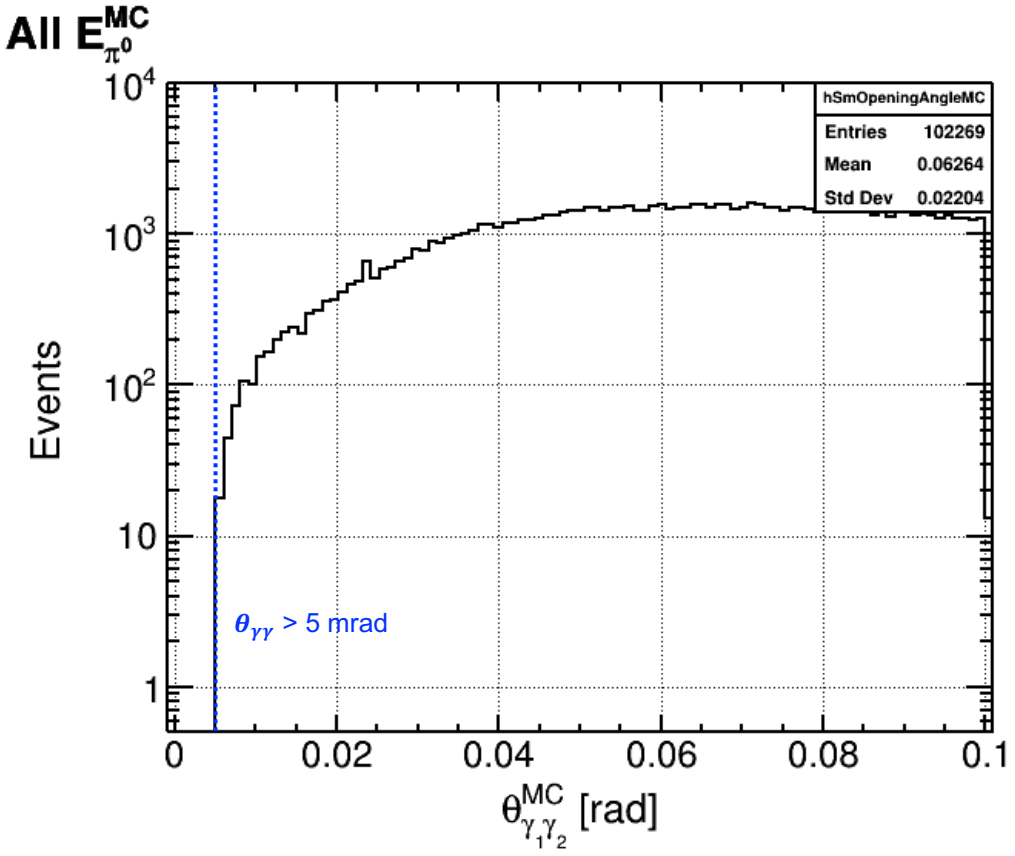


π^0s are starting to move toward central and their energy can be up to 60 GeV

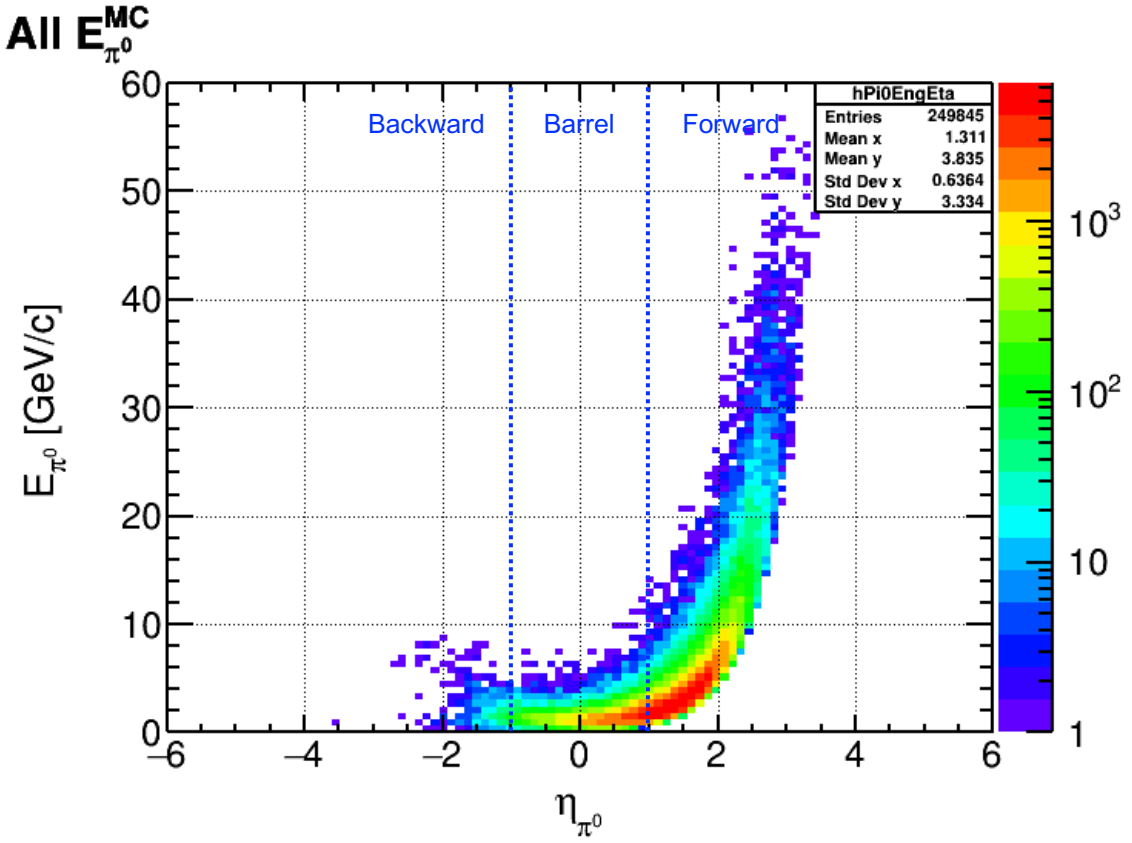
10×100 GeV^2

π^0 Kinematics

Opening Angle of Two Photons < 100 mrad



Neutral Pion Energy vs Pseudorapidity

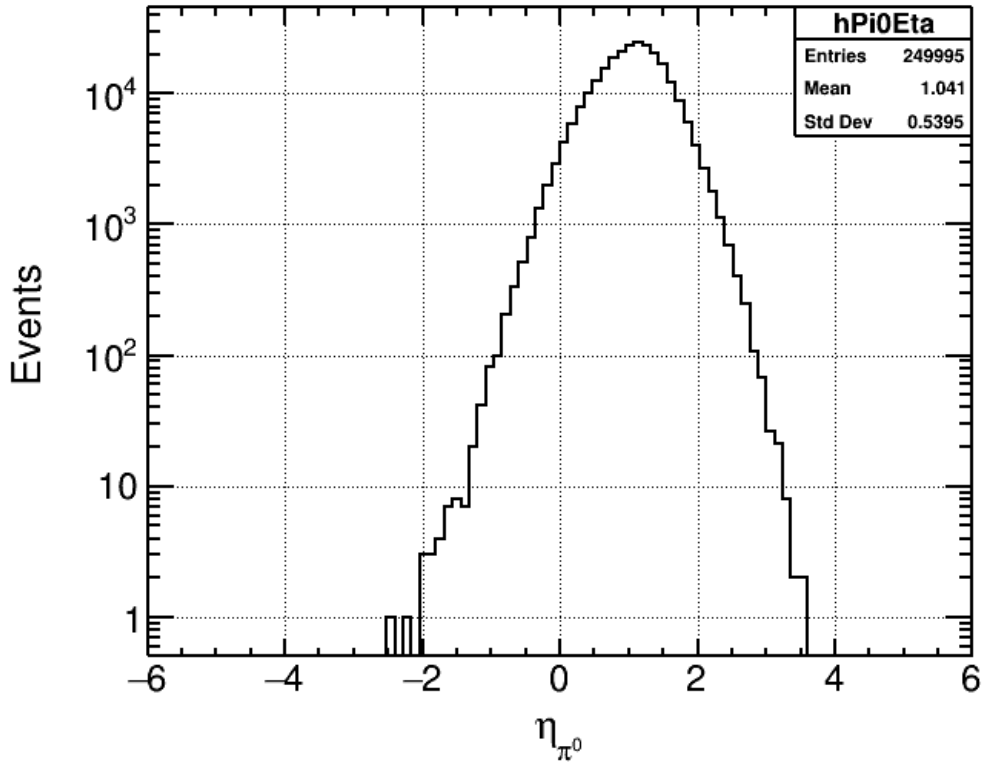


Minimum opening angle of two γs is 5 mrad

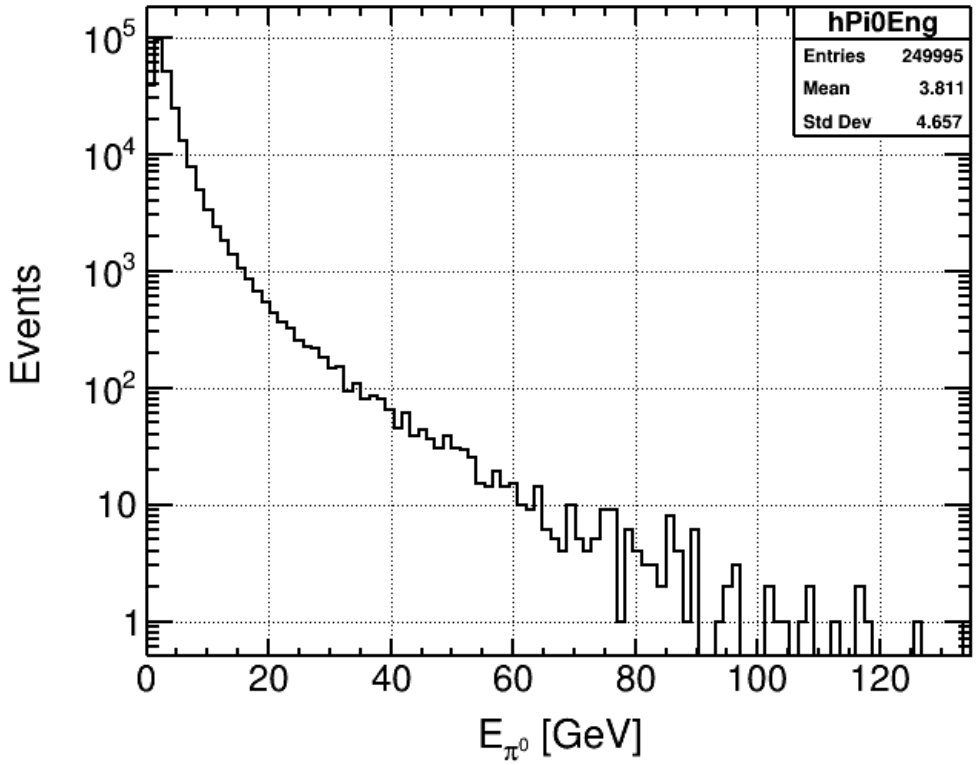
18×275 GeV^2

π^0 Kinematics

Neutral Pion Pseudo-rapidity



Neutral Pion Energy

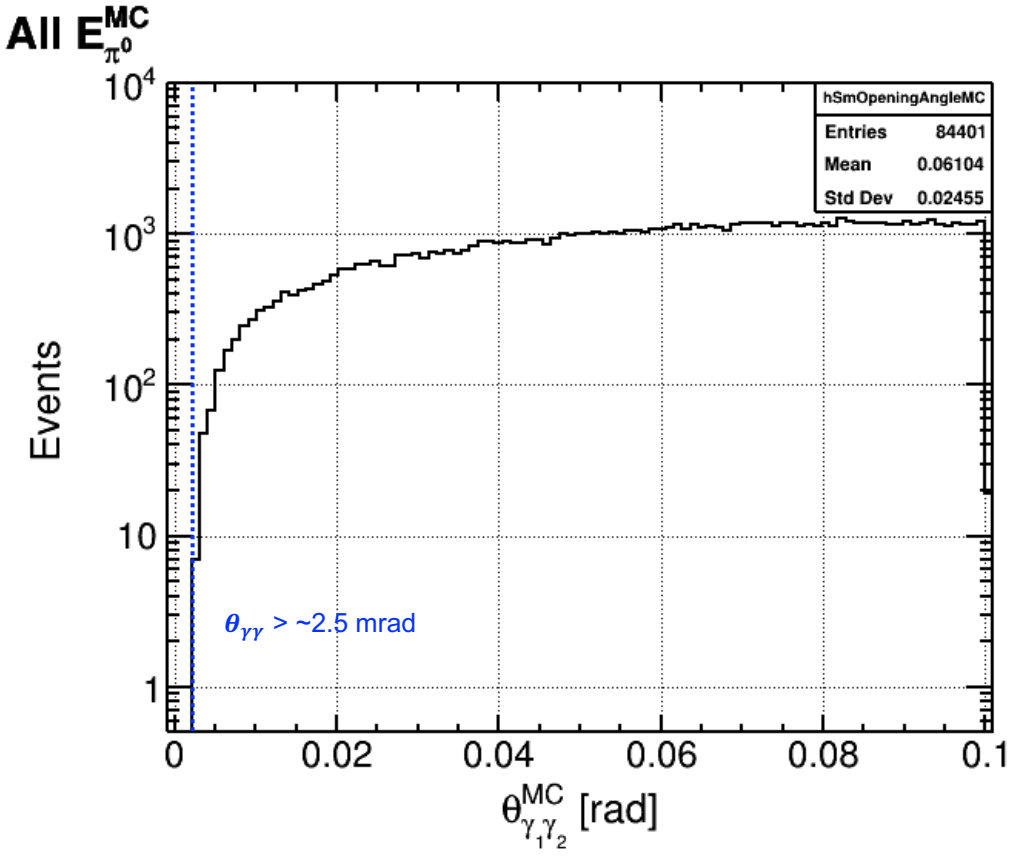


Many π^0s are going to central region and their energy can be up to 120 GeV

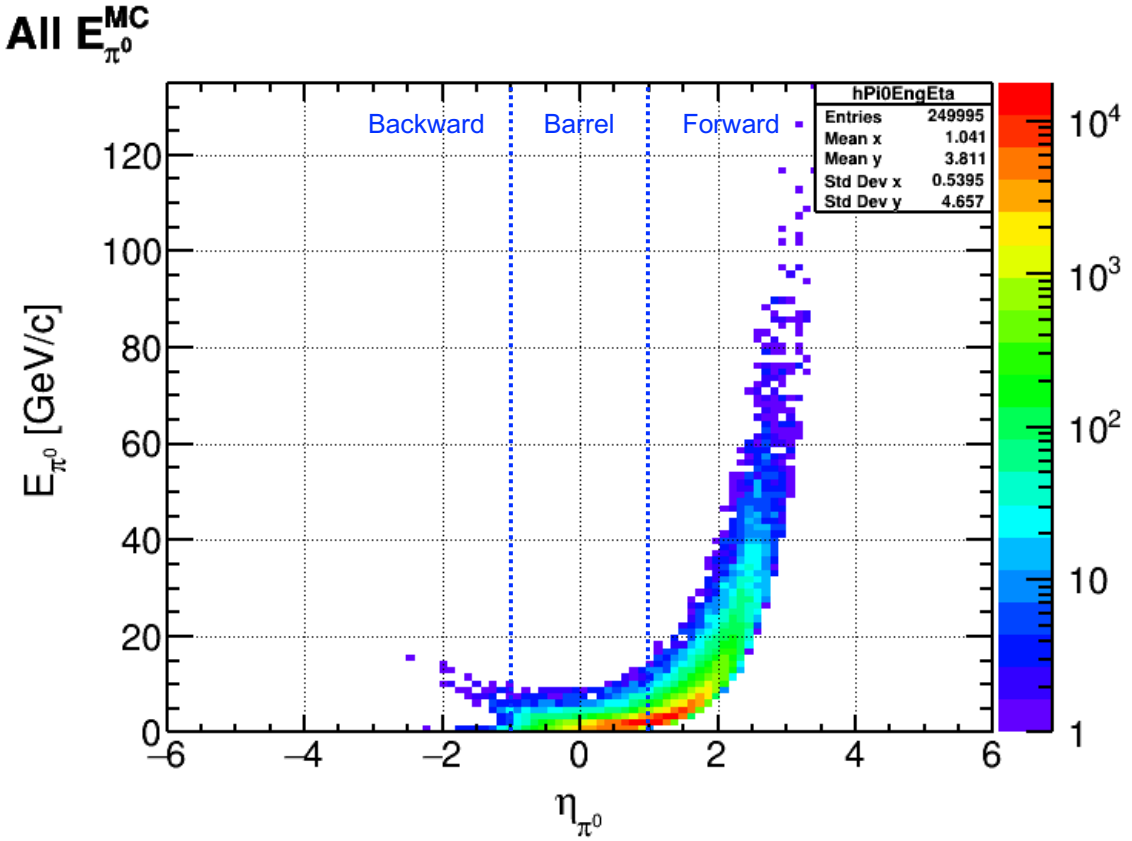
18×275 GeV^2

π^0 Kinematics

Opening Angle of Two Photons < 100 mrad



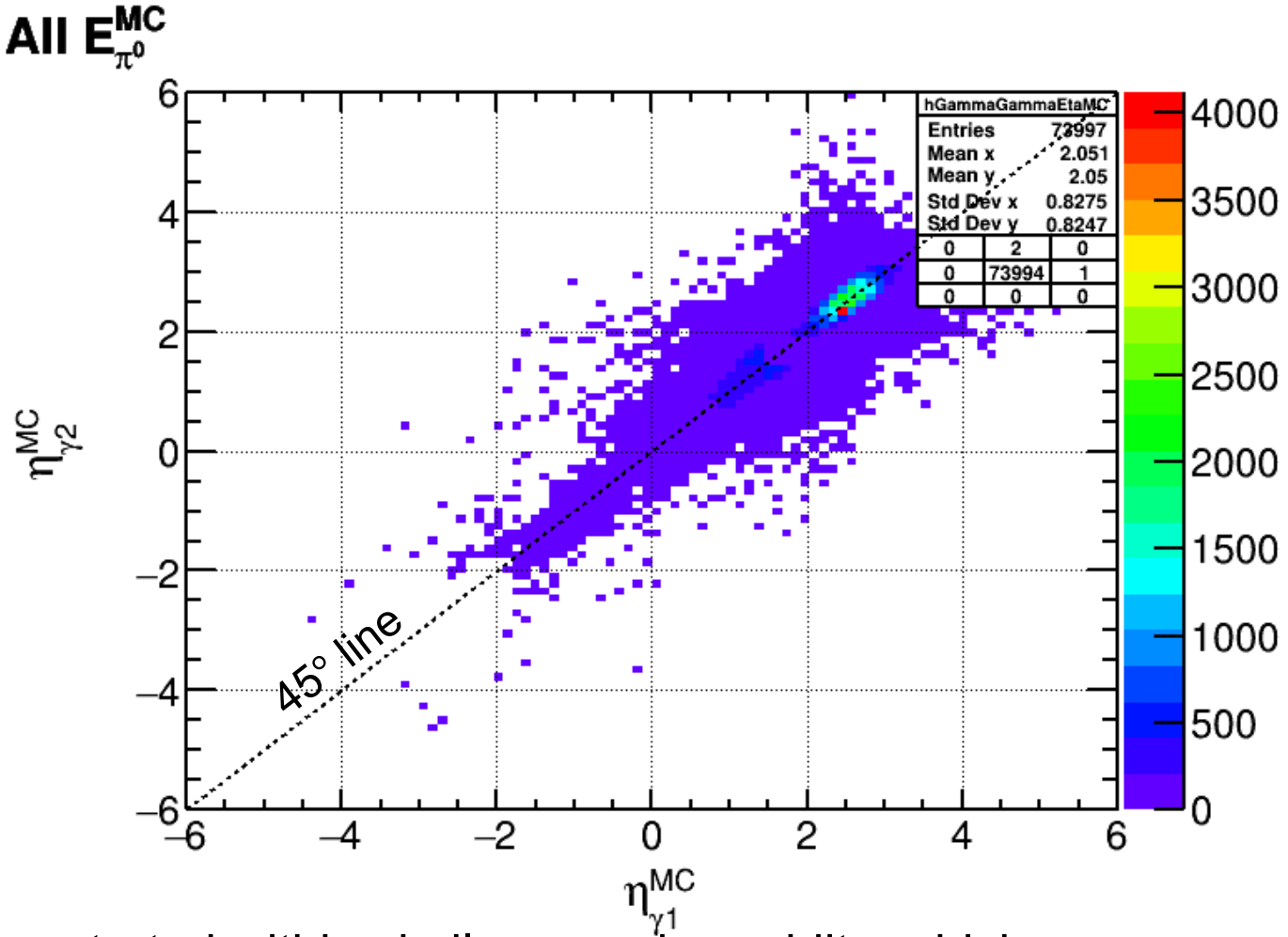
Neutral Pion Energy vs Pseudorapidity



Minimum opening angle of two γs is 2.5 mrad

5×41 GeV²

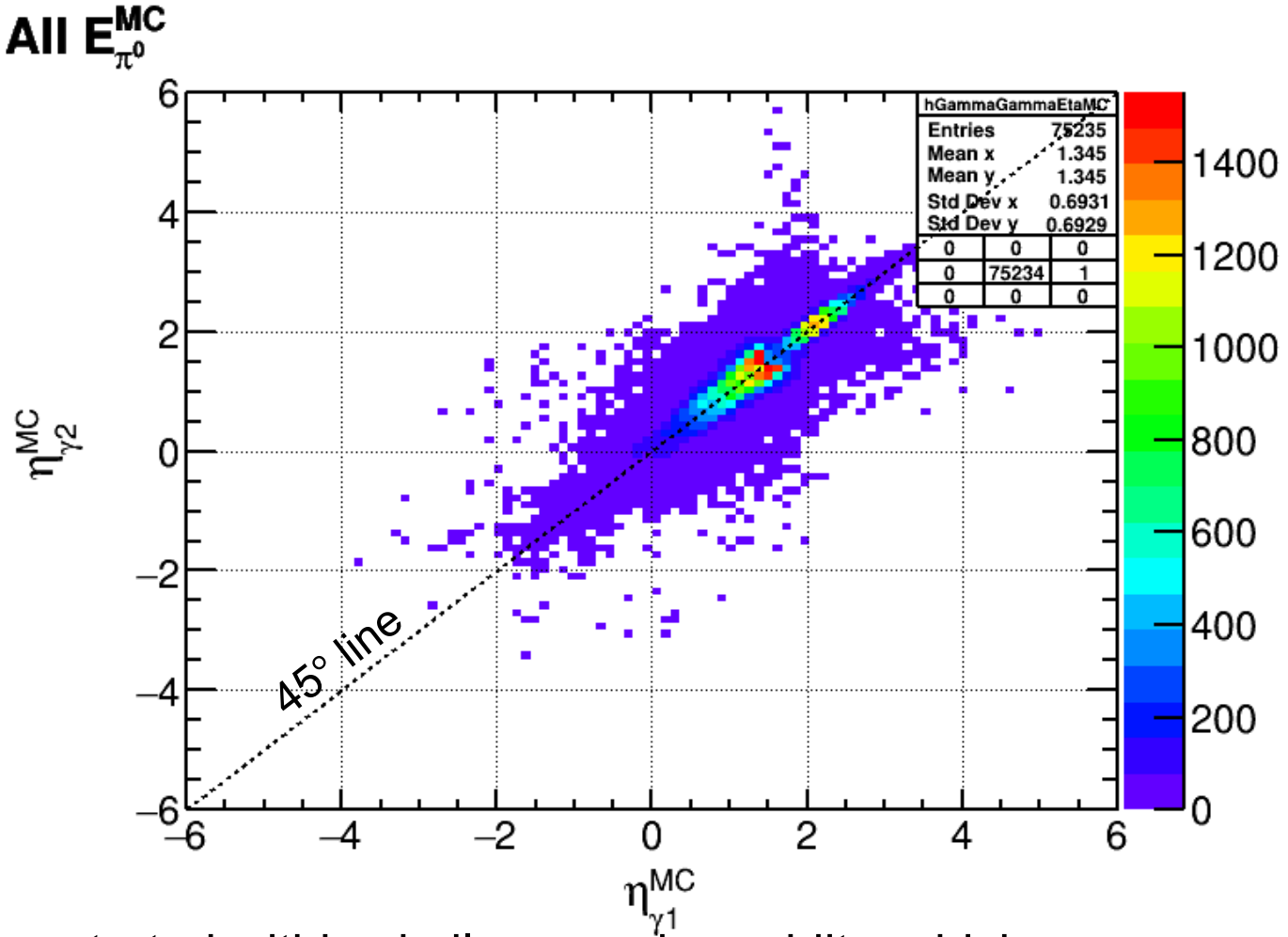
γ Kinematics – Pseudo-Rapidity



Mostly two γs are concentrated within similar pseudo-rapidity, which means very few events where we simply lose a photon by geometric acceptance

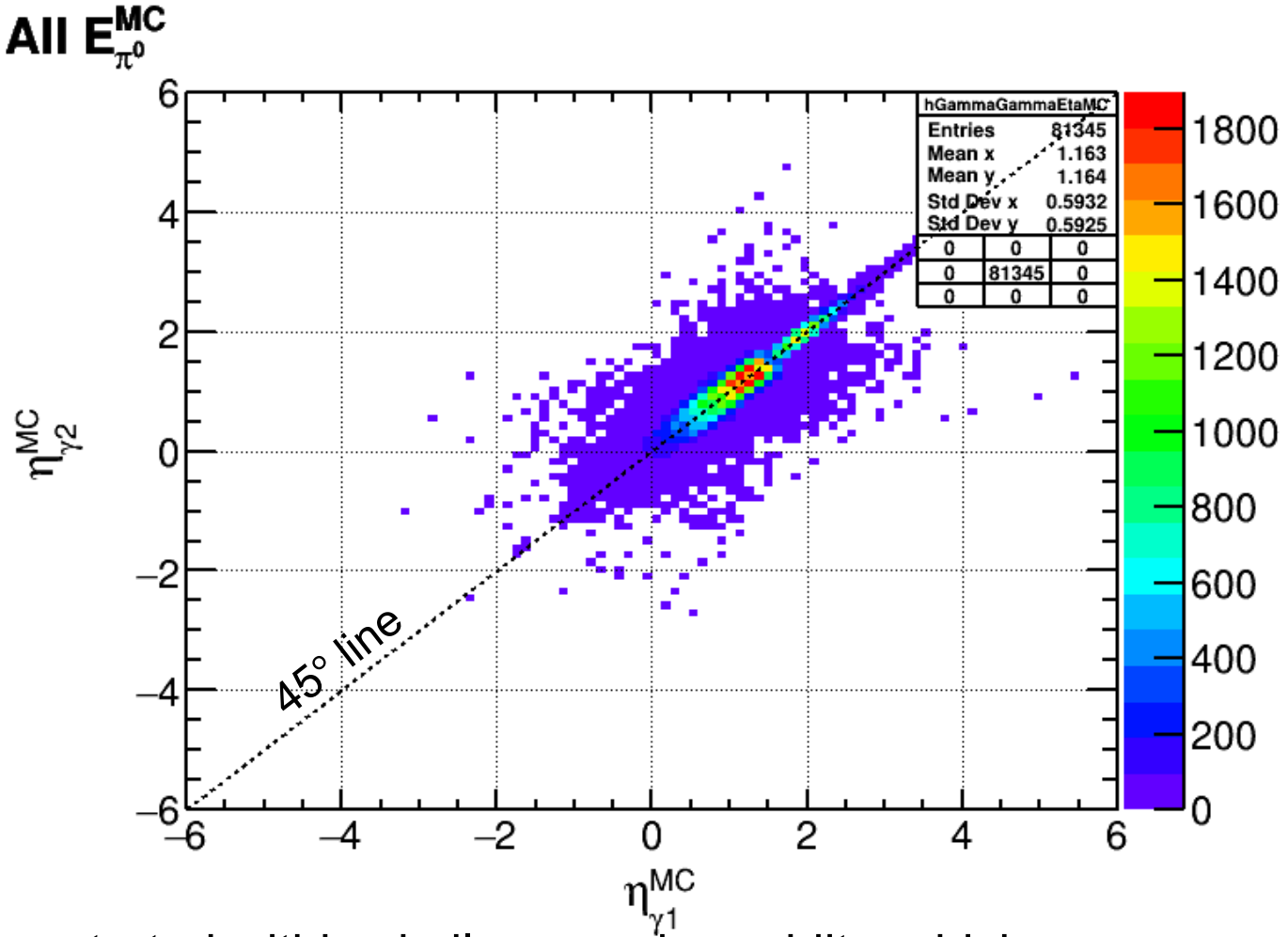
10×100 GeV^2

γ Kinematics – Pseudo-Rapidity



Mostly two γs are concentrated within similar pseudo-rapidity, which means very few events where we simply lose a photon by geometric acceptance

γ Kinematics – Pseudo-Rapidity

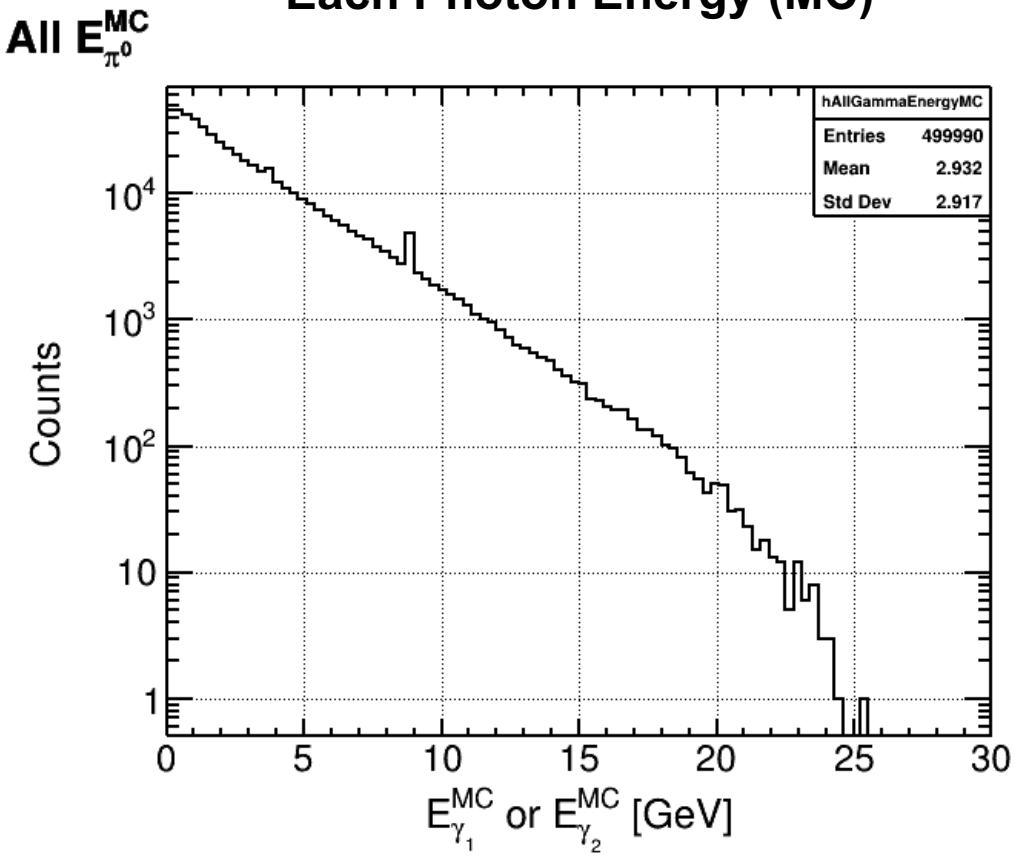


Mostly two γs are concentrated within similar pseudo-rapidity, which means very few events where we simply lose a photon by geometric acceptance

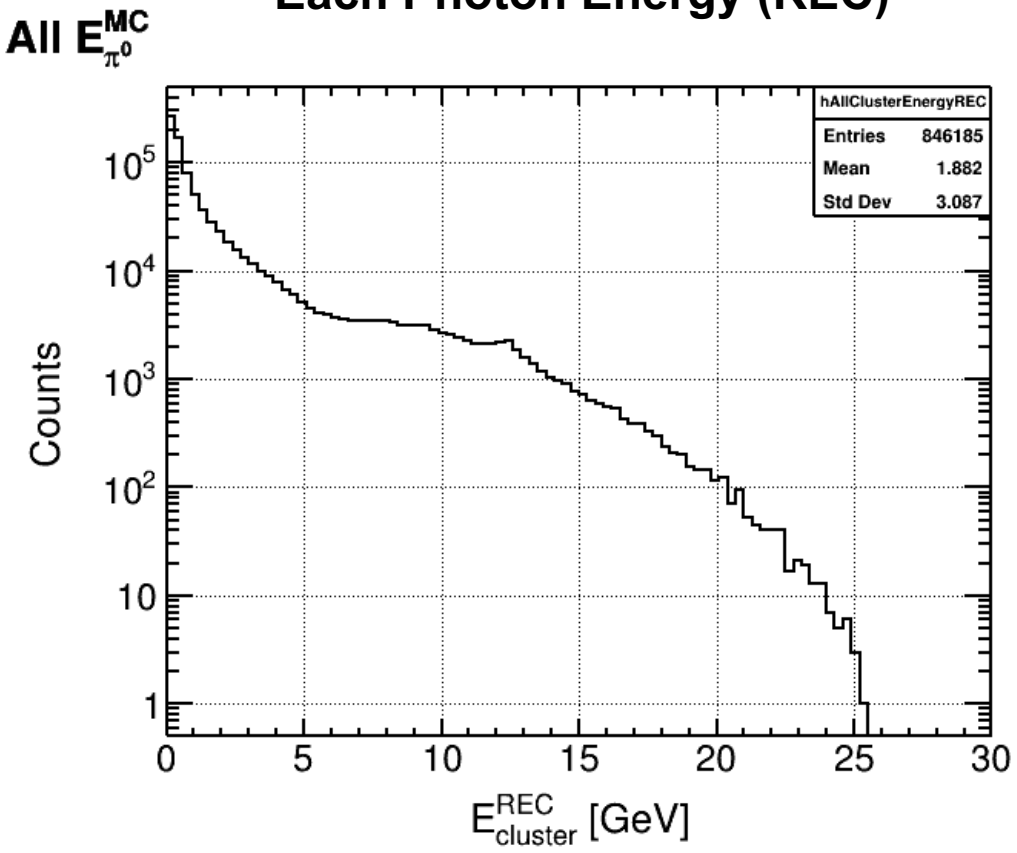
5×41 GeV²

Truth VS. Reconstructed: E_γ

Each Photon Energy (MC)



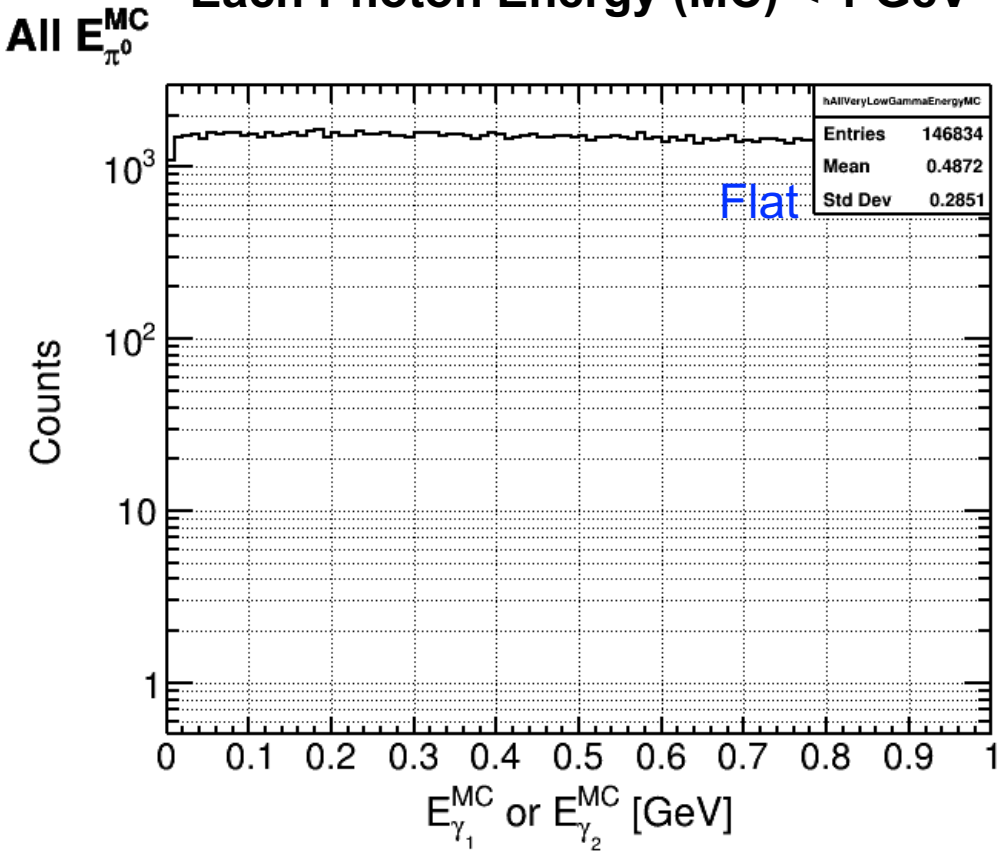
Each Photon Energy (REC)



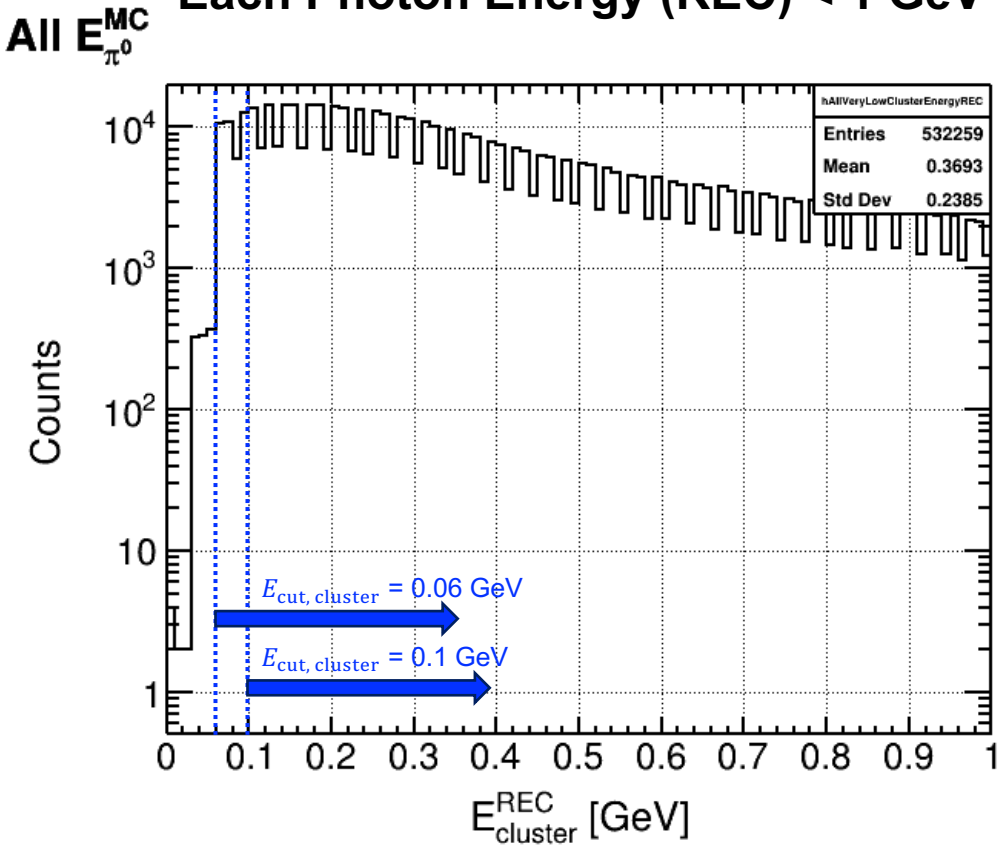
Note that all reconstructed clusters are considered as photon candidates at the moment

Truth VS. Reconstructed: E_γ < 1 GeV

Each Photon Energy (MC) < 1 GeV



Each Photon Energy (REC) < 1 GeV

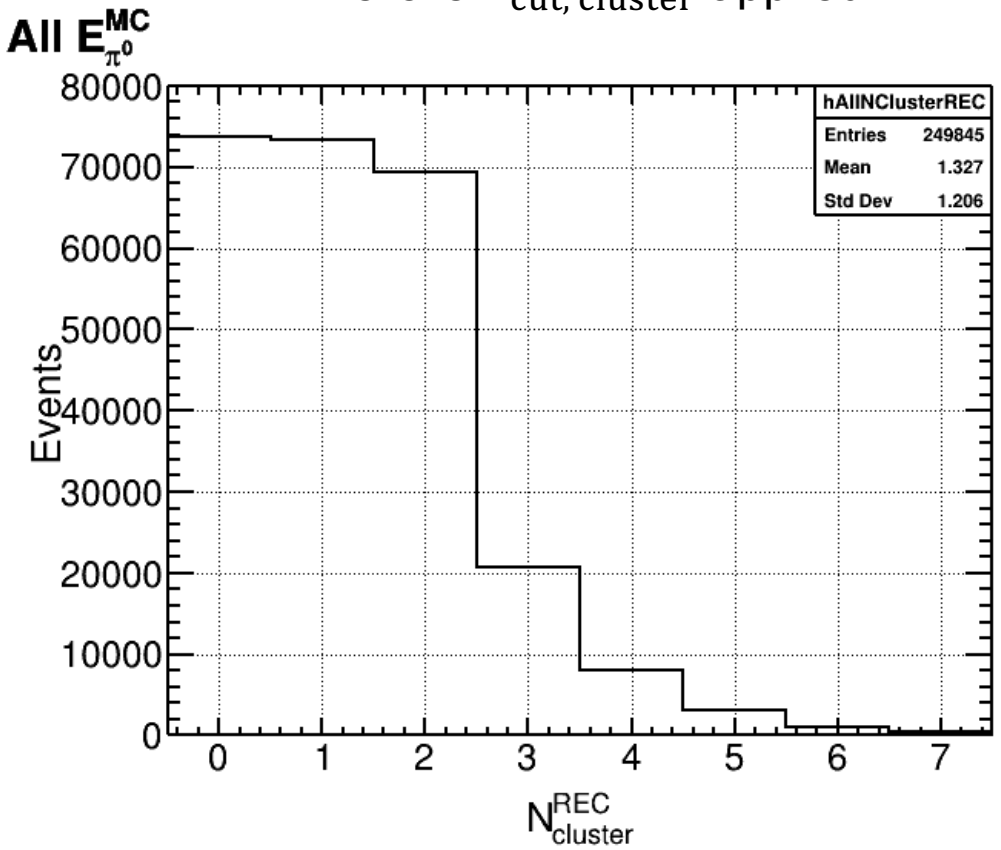


Minimum cluster energy cut for all reconstructed clusters is set to 100 MeV

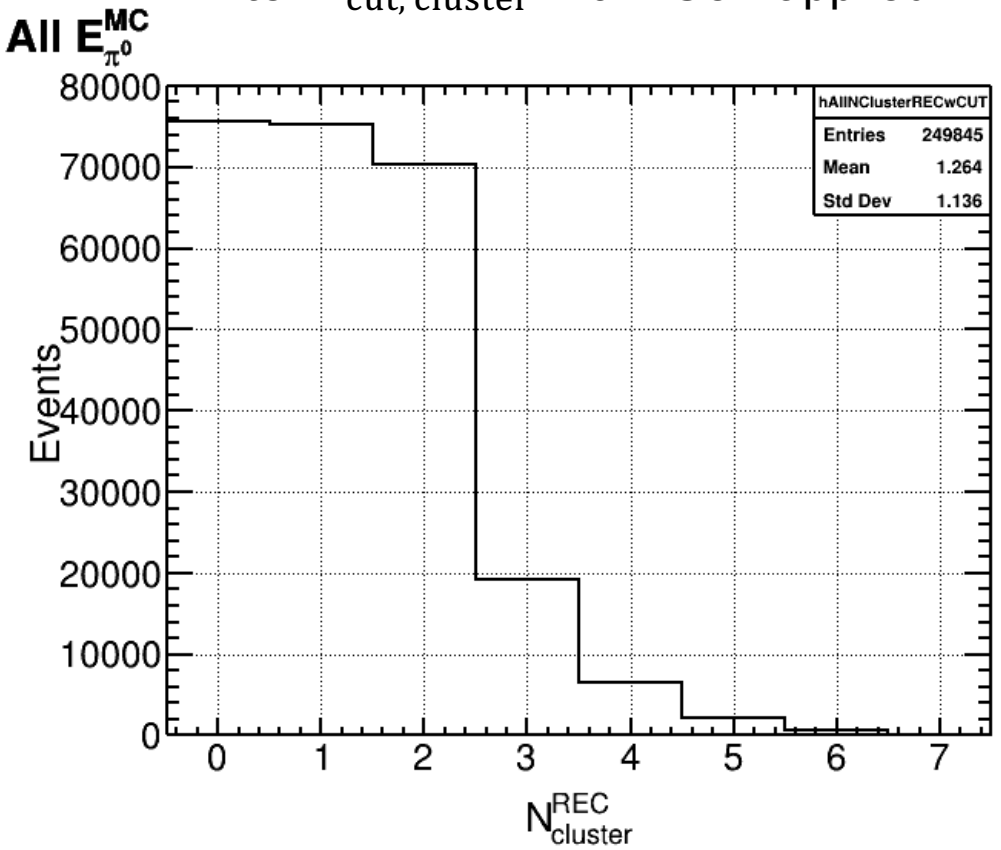
5×41 GeV^2

Number of Clusters: N_{Cluster}

Before $E_{\mathrm{cut,\,cluster}}$ applied



After $E_{\mathrm{cut,\,cluster}}$ = 0.1 GeV applied



Slight change in number of clusters, but not much difference was made

Results – First Pass

- When it uses current clustering algorithm in the EICrecon, **overall about 30 %** of exclusive π^0 appears to be contamination events to DVCS in three beam configuration: 5×41, 10×100, and 18×275 GeV^2

*Based on $E_{\text{cut, cluster}}$ = 0.06 GeV
**Based on $E_{\text{cut, cluster}}$ = 0.1 GeV

5×41 GeV² Energy [GeV]	# of Events with 1 cluster reconstructed*	Contamination* to DVCS	# of Events with 1 cluster reconstructed**	Contamination** to DVCS
All $E_{\pi^0}^{MC}$	72,621 / 249,995	**0.29049**	73,997 / 249,995	**0.295994**
10×100 GeV² Energy [GeV]	**# of Events with 1 cluster reconstructed***	**Contamination* to DVCS**	**# of Events with 1 cluster reconstructed****	**Contamination** to DVCS**
All $E_{\pi^0}^{MC}$	73,285 / 249,845	**0.293322**	75,235 / 249,845	**0.301127**
18×275 GeV² Energy [GeV]	**# of Events with 1 cluster reconstructed***	**Contamination* to DVCS**	**# of Events with 1 cluster reconstructed****	**Contamination** to DVCS**
All $E_{\pi^0}^{MC}$	80,142 / 249,995	**0.320574**	81,345 / 249,995	**0.325387**

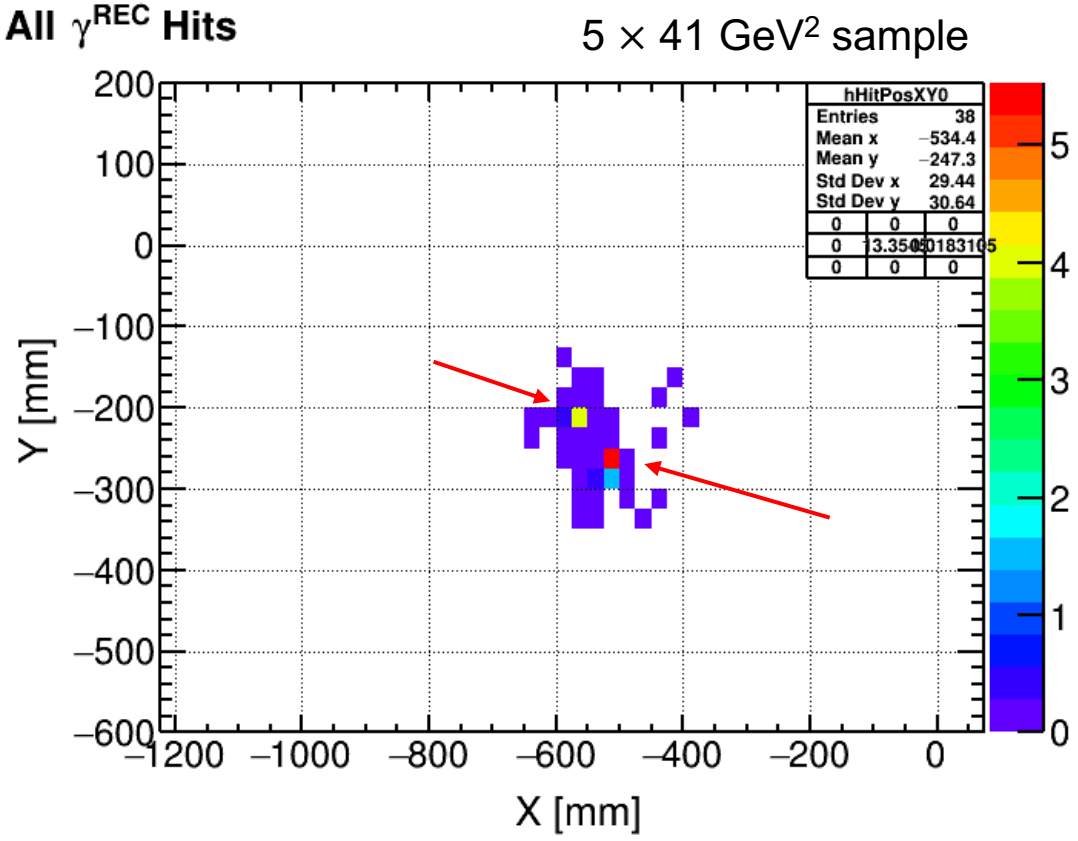
Results – First Pass

- **Among about 30 %** of exclusive π^0, look at events divided into three pseudo-rapidity per each beam energy configuration

Beam Configuration	Forward	Central	Backward	Total
5×41 GeV^2	25 %	5 %	< 0.1 %	~ 30 %
10×100 GeV^2	17 %	13 %	< 0.1 %	~ 30 %
18×275 GeV^2	12 %	20 %	< 0.1 %	~ 32 %

- **There might be room for improvement** 🤔
  - Depends on how to set optimal reconstruction parameters to form a cluster within algorithm for calorimeter
  - Based on granularity of Forward EMCAL and a distance from IP, it should be able to distinguish 7.5 mrad angle
  - Look at the other way for improvement in the Forward and Central region (on top of current clustering algorithm in the EICrecon)

Event Example 1



All reconstructed hits in forward EMCAL were drawn in position (X,Y) with energy (Z)

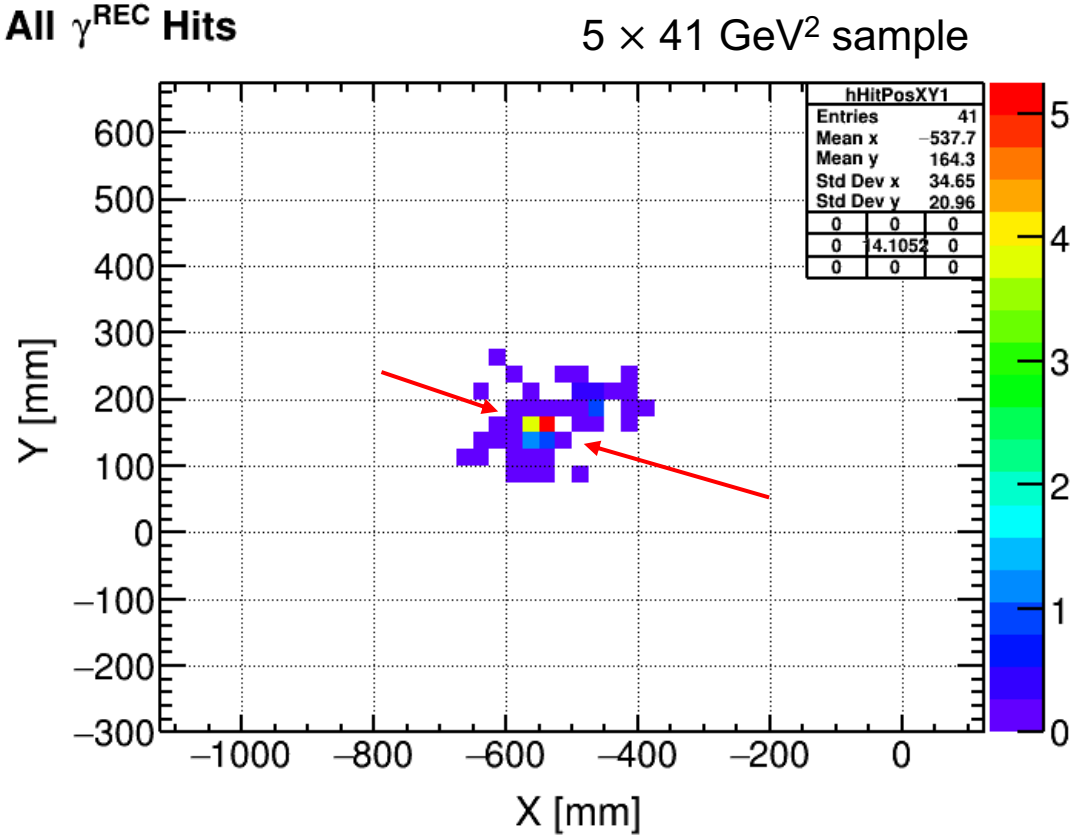
With clustering algorithm in the forward,
one cluster was formed. (ref. $\theta_{\gamma\gamma}^{MC}$ ~ 0.021 rad)

Calculated a distance between two highest energy hits
~ 70 mm (ref. transverse size of EMCAL = 25 mm)
Conclusion: this event can be identified as having **two** clusters (because larger than 2*transverse size of EMCAL tower)

Below list of reconstructed hits

	E	X	Y	Z
ievt: 1	**5.52979**	**-523.425**	**-271.15**	**3507**
ievt: 1	**3.93066**	**-573.275**	**-221.85**	**3507**
ievt: 1	1.45264	-523.425	-295.8	3507
ievt: 1	0.360107	-548.35	-295.8	3507
ievt: 1	0.354004	-598.2	-221.85	3507
ievt: 1	0.268555	-548.35	-271.15	3507
ievt: 1	0.256348	-573.275	-246.5	3507
ievt: 1	0.0976562	-548.35	-246.5	3507
ievt: 1	0.0915527	-573.275	-197.2	3507
ievt: 1	0.0854492	-623.125	-221.85	3507
ievt: 1	0.0793457	-498.5	-295.8	3507

Event Example 2



All reconstructed hits in forward EMCAL were drawn in position (X,Y) with energy (Z)

With clustering algorithm in the forward,
one cluster was formed. (ref. $\theta_{\gamma\gamma}^{MC}$ ~ 0.025 rad)

Calculated a distance between two highest energy hits
~ 25 mm (ref. transverse size of EMCAL = 25 mm)
Conclusion: this event can be identified as having **one** clusters (because smaller than 2*transverse size of EMCAL tower)

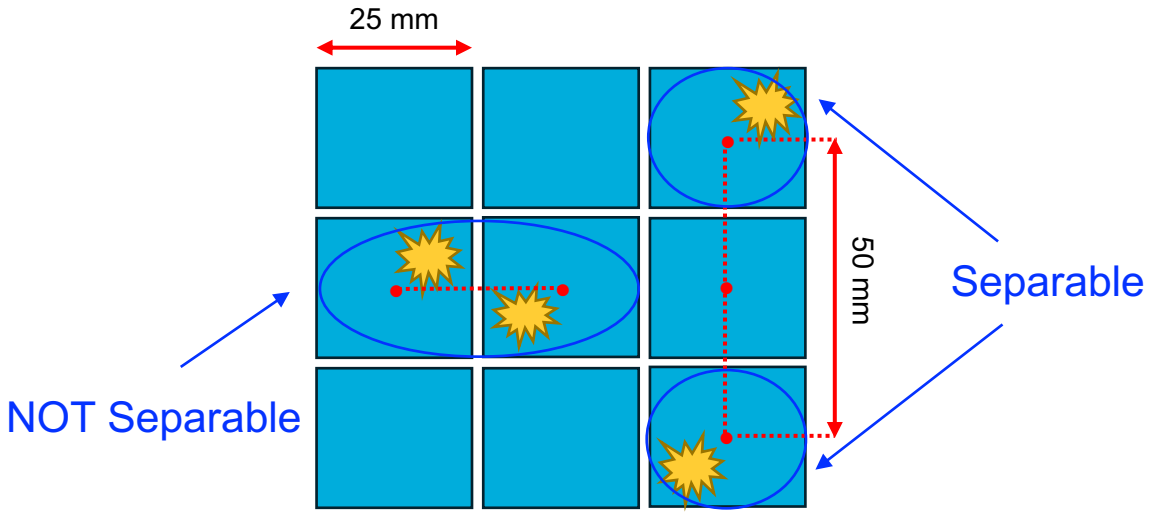
Below list of reconstructed hits

	E	X	Y	Z
ievt: 3	**5.24902**	**-548.35**	**172.55**	**3507**
ievt: 3	**3.75366**	**-573.275**	**172.55**	**3507**
ievt: 3	1.05591	-573.275	147.9	3507
ievt: 3	0.915527	-548.35	147.9	3507
ievt: 3	0.891113	-473.575	197.2	3507
ievt: 3	0.469971	-473.575	221.85	3507
ievt: 3	0.396729	-498.5	221.85	3507
ievt: 3	0.195312	-498.5	197.2	3507
ievt: 3	0.177002	-598.2	172.55	3507
ievt: 3	0.134277	-573.275	197.2	3507
ievt: 3	0.109863	-598.2	147.9	3507

The Other Way to Find Separable Events

Forward EMCAL

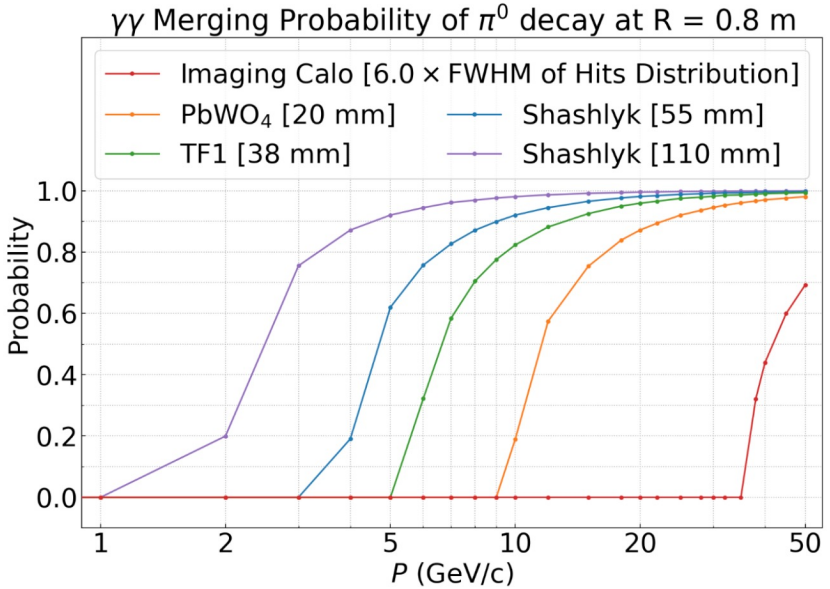
Note that transverse size of EMCAL tower = 25 mm



Based on tower size for hits,
Distance between two highest hits needs
at least twice tower size (50 mm)
to be separable

Barrel EMCAL

Taken from EIC PDR v0.1.3 (Figure 8.96 on page 173)



Based on the upper limit of the probability of merging two γs from a π^0 decay into one cluster at η = 0, **upto p_{π^0} ~ 35 GeV can be separable**

Results – Second Pass

- Below summaries estimated contamination from exclusive π^0 to DVCS
  - Using only clustering algorithm in EICrecon
  - + Potential improvement in finding separable hits (Hit-level) & Barrel ML

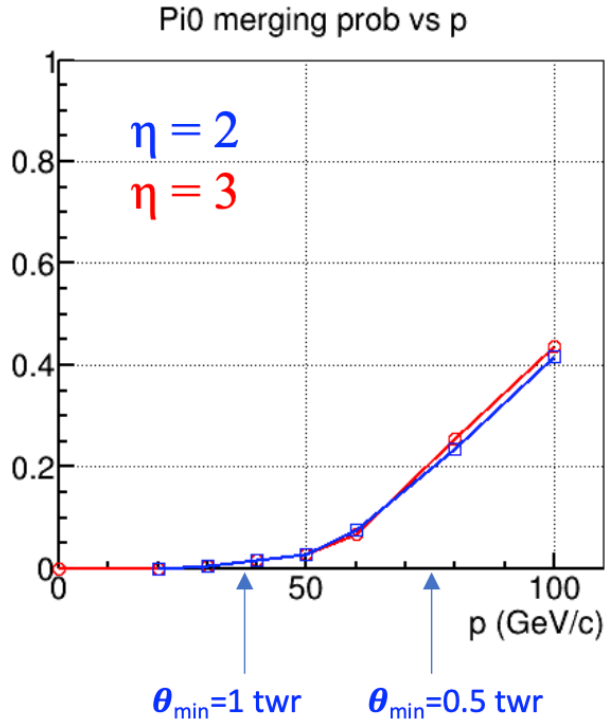
**Based on $E_{\text{cut, cluster}}$ = 0.1 GeV

5×41 GeV² Energy [GeV]	# of Events with 1 cluster reconstructed**	Contamination** to DVCS	# of Events with 1 cluster reconstructed**	Contamination** to DVCS
All $E_{\pi^0}^{MC}$	73,997 / 249,995	0.295994	26,282 / 249,995	0.10513
10×100 GeV² Energy [GeV]	**# of Events with 1 cluster reconstructed****	**Contamination** to DVCS**	**# of Events with 1 cluster reconstructed****	**Contamination** to DVCS**
All $E_{\pi^0}^{MC}$	75,235 / 249,845	0.301127	24,417 / 249,845	0.0977286
18×275 GeV² Energy [GeV]	**# of Events with 1 cluster reconstructed****	**Contamination** to DVCS**	**# of Events with 1 cluster reconstructed****	**Contamination** to DVCS**
All $E_{\pi^0}^{MC}$	81,345 / 249,995	0.325387	17,140 / 249,995	0.0685614

Even More Potential Improvement w/ ML

Forward EMCAL

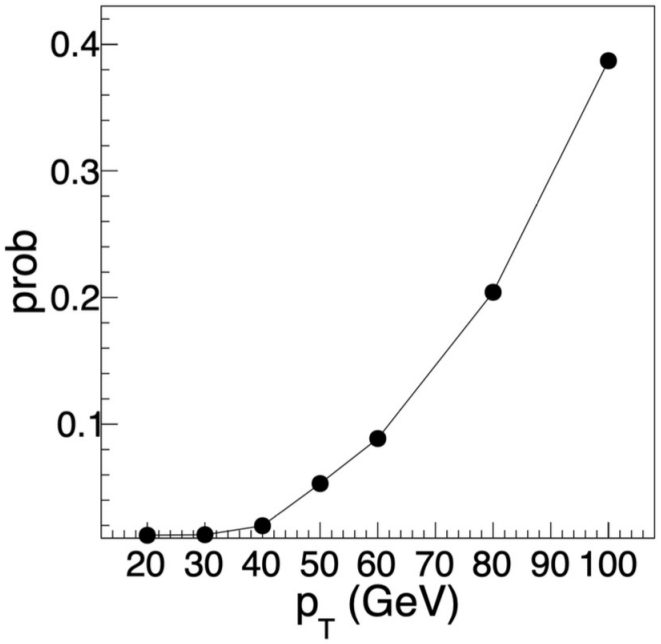
Taken from Sasha slide#8 from EEEMC Meeting on 2022/03/18



W/SciFi
2.5×2.5 at z = **3.5 m**

No rapidity dependence and can effectively discriminate γ/π^0 even when two γs are separated by 0.5 tower size

Taken from EIC PDR v0.1.3 (Figure 8.109 on page 194)



W/SciFi
2.5×2.5 at z = **3.3 m**

Misidentification rate at 60 GeV is approximately 10 %

Final Results – Contamination Estimation

- With potential improvements in discrimination γ/π^0 factor from hit-level, Forward EMCAL and Barrel EMCAL ML
  - Appear to be below 1 % contamination (drastically improves all cases)
  - Reality probably sits somewhere between 2nd col and 3rd col (likely close to 3rd col)

	Only Clustering Algorithm		+ Potential Improvement hits & Barrel ML		+ Potential Improvement w/ Forward ML	
5×41 GeV² Energy [GeV]	# of Events with 1 cluster reconstructed*	Contamination* to DVCS	# of Events with 1 cluster reconstructed*	Contamination* to DVCS	# of Events with 1 cluster reconstructed*	Contamination* to DVCS
All $E_{\pi^0}^{MC}$	73,997 / 249,995	0.295994	26,282 / 249,995	0.10513	279 / 249,995	0.00111602
10×100 GeV² Energy [GeV]	# of Events with 1 cluster reconstructed*	Contamination* to DVCS	# of Events with 1 cluster reconstructed*	Contamination* to DVCS	# of Events with 1 cluster reconstructed*	Contamination* to DVCS
All $E_{\pi^0}^{MC}$	75,235 / 249,845	0.301127	24,417 / 249,845	0.0977286	250 / 249,845	0.00100062
18×275 GeV² Energy [GeV]	# of Events with 1 cluster reconstructed*	Contamination* to DVCS	# of Events with 1 cluster reconstructed*	Contamination* to DVCS	# of Events with 1 cluster reconstructed*	Contamination* to DVCS
All $E_{\pi^0}^{MC}$	81,345 / 249,995	0.325387	17,140 / 249,995	0.0685614	193 / 249,995	0.000772015

Summary and Next Steps

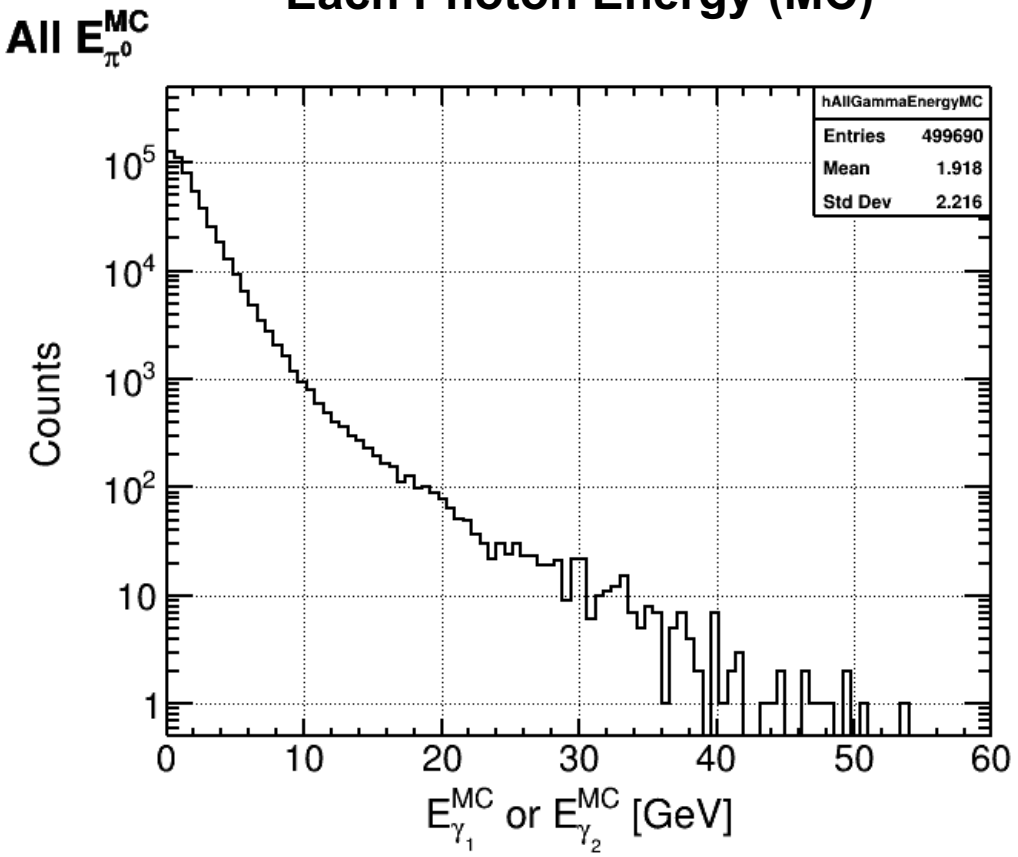
- Estimated single photon contamination using exclusive π^0 sample, which is the background to DVCS
  - With potential improvements in discrimination γ/π^0 factors within ePIC detector performance, it appears to be below 1 % contamination
- Ultimately, we would like to have estimated contamination from exclusive π^0 to DVCS in (x, Q^2) phase
  - Need more samples
- I am more interested in actual π^0 reconstruction to complete this analysis

BackUp Slides

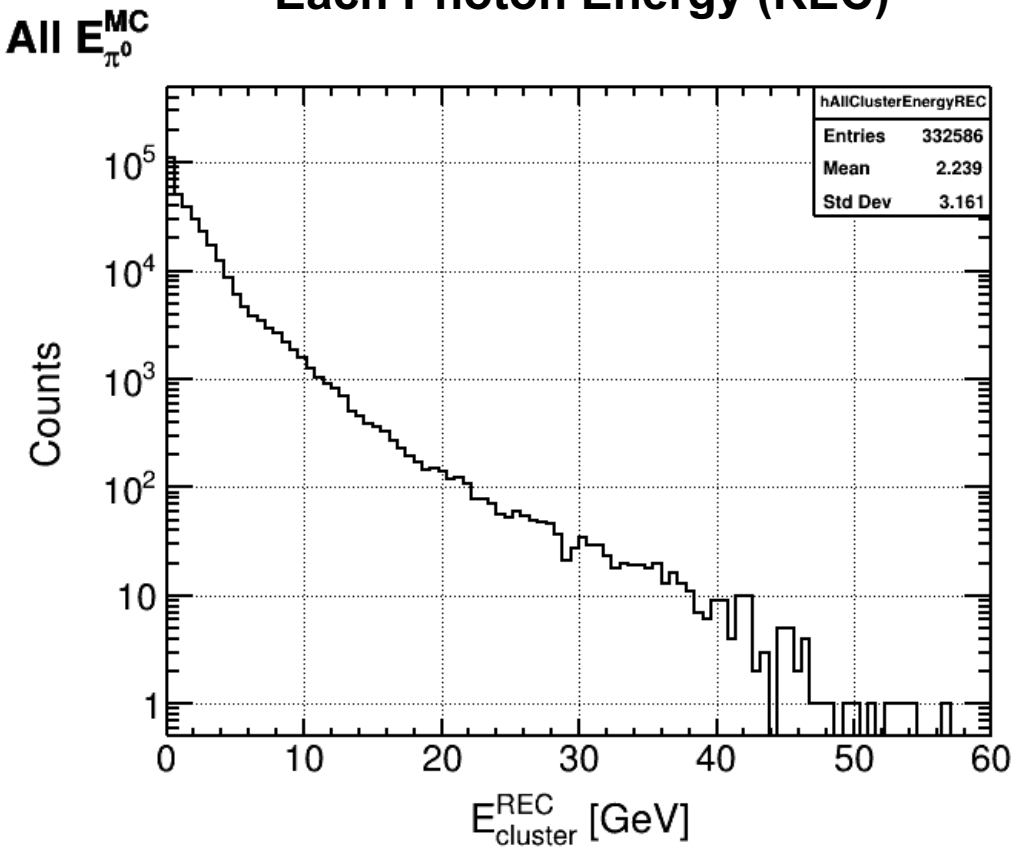
10×100 GeV^2

Truth VS. Reconstructed: E_γ

Each Photon Energy (MC)



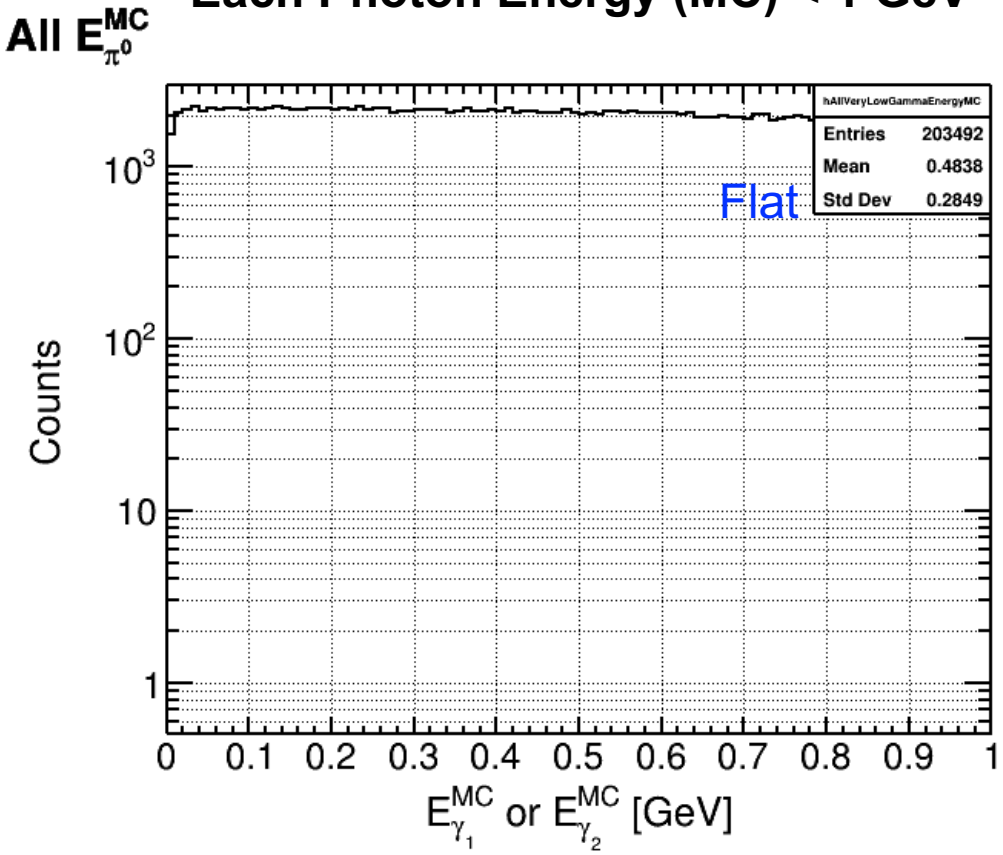
Each Photon Energy (REC)



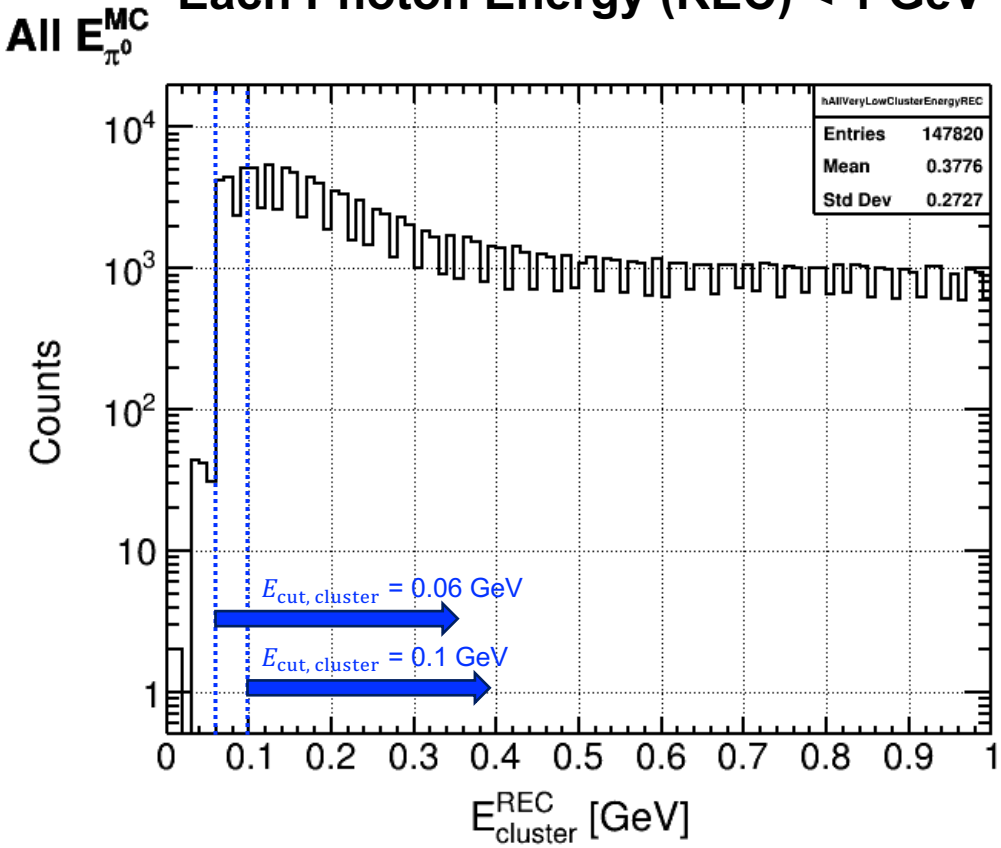
10×100 GeV^2

Truth VS. Reconstructed: E_γ < 1 GeV

Each Photon Energy (MC) < 1 GeV



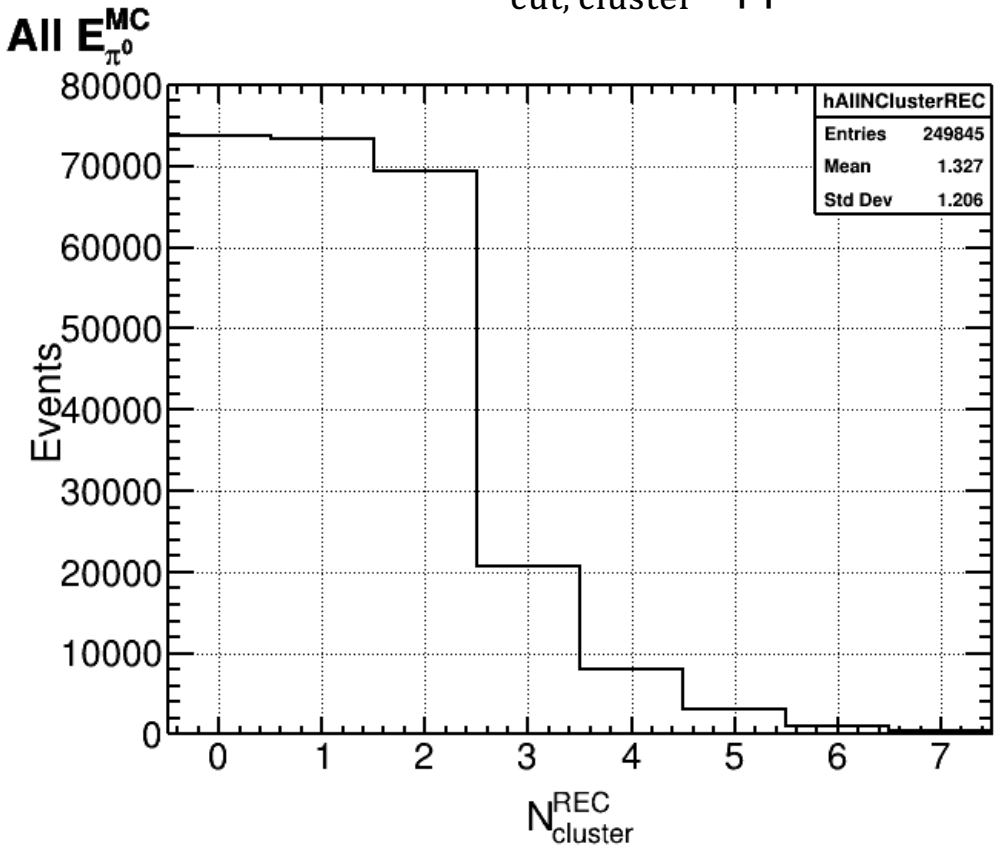
Each Photon Energy (REC) < 1 GeV



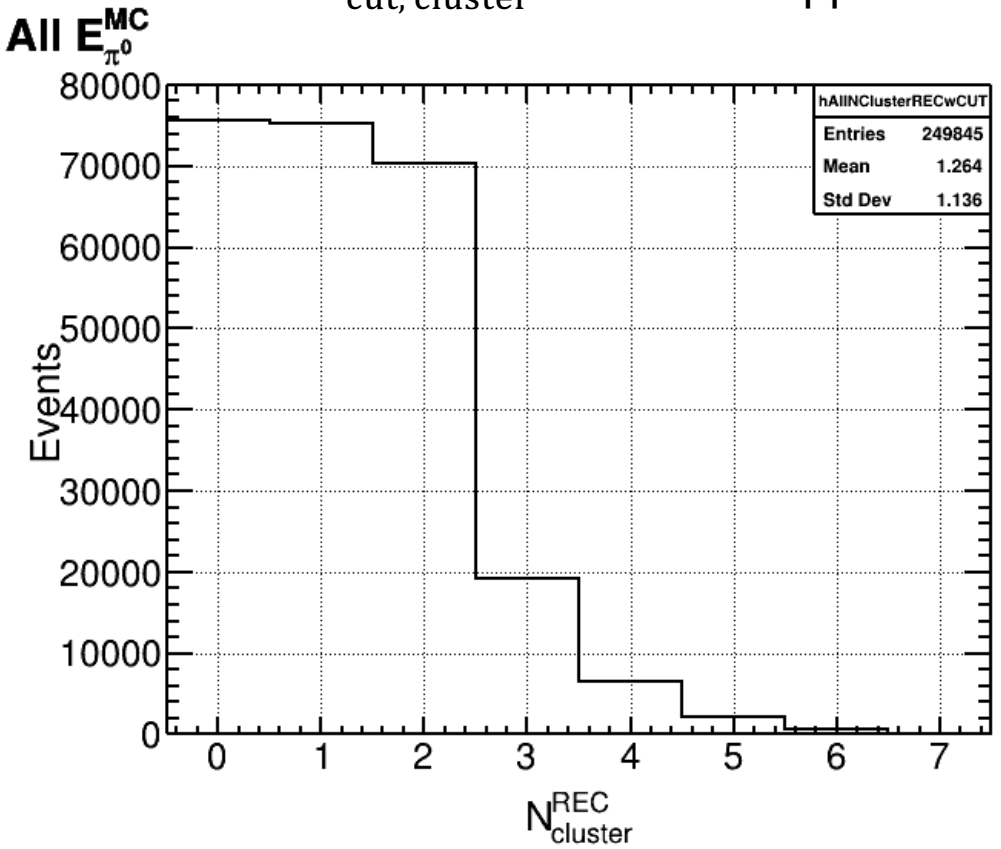
10×100 GeV^2

Number of Clusters: N_{Cluster}

Before $E_{\mathrm{cut,\,cluster}}$ applied



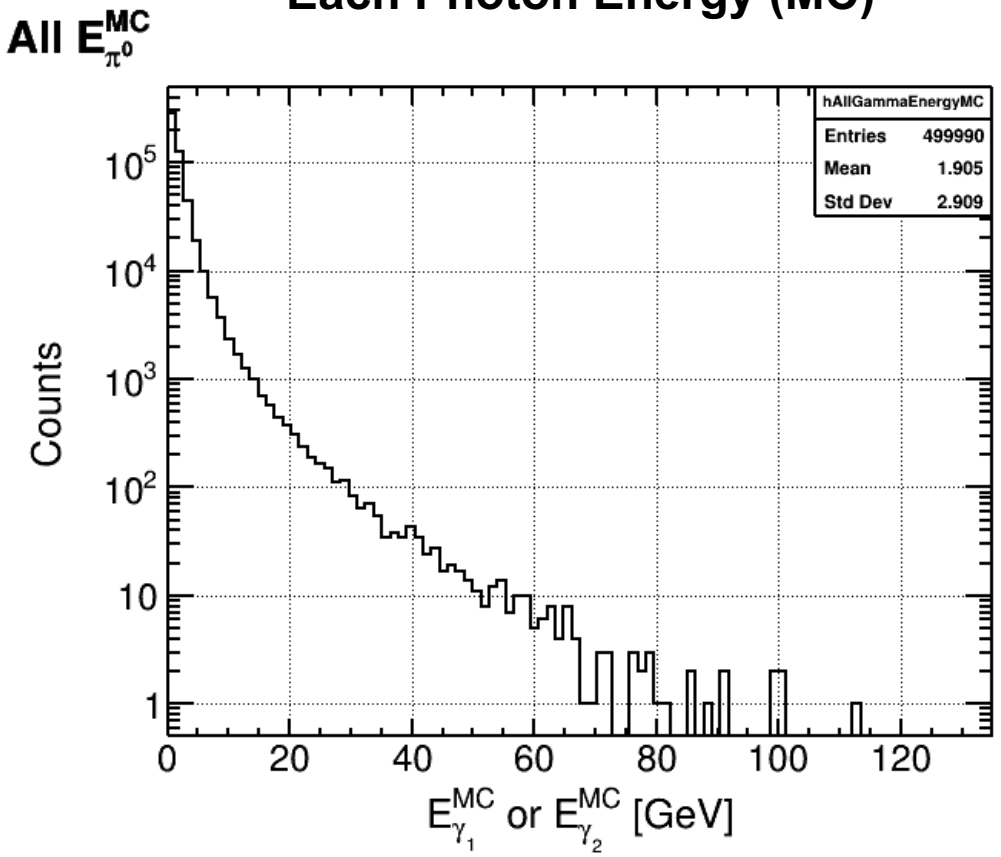
After $E_{\mathrm{cut,\,cluster}}$ = 0.1 GeV applied



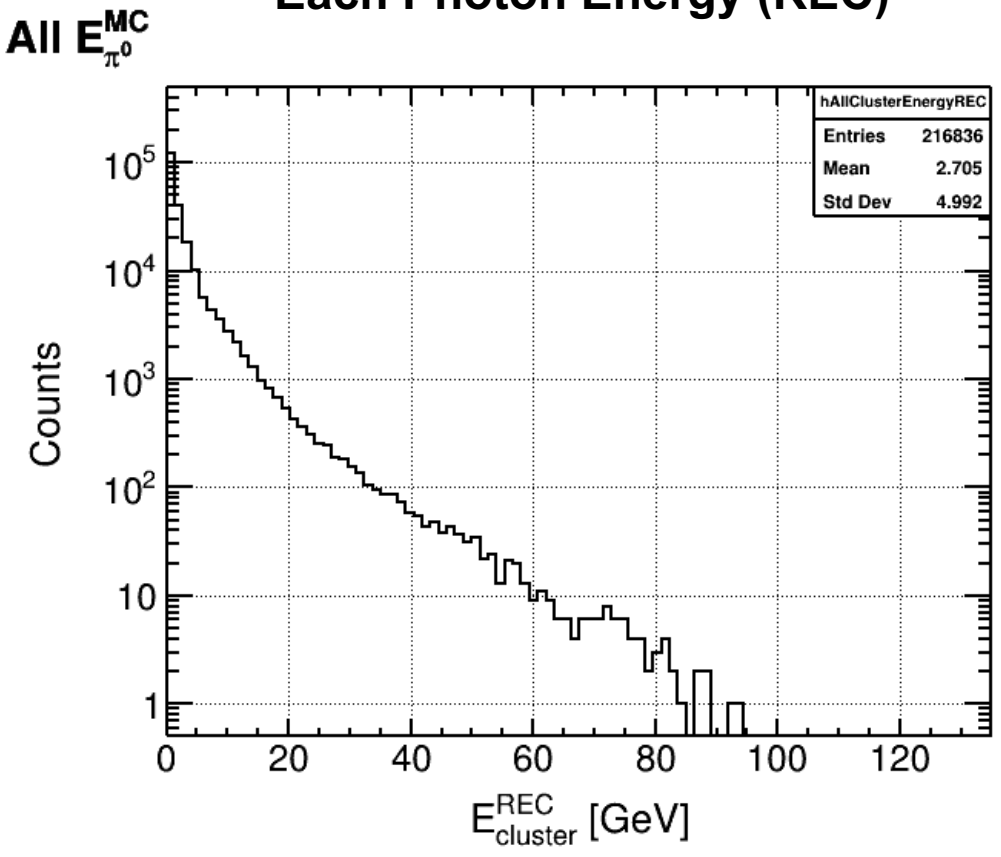
18×275 GeV^2

Truth VS. Reconstructed: E_γ

Each Photon Energy (MC)



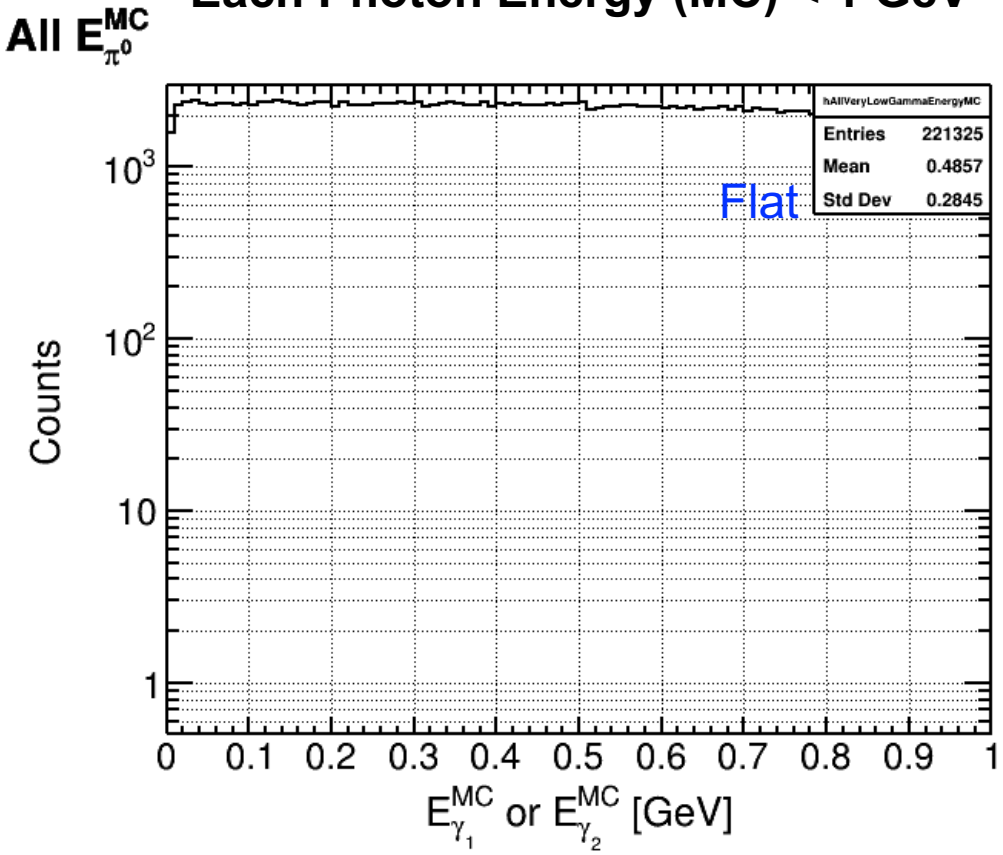
Each Photon Energy (REC)



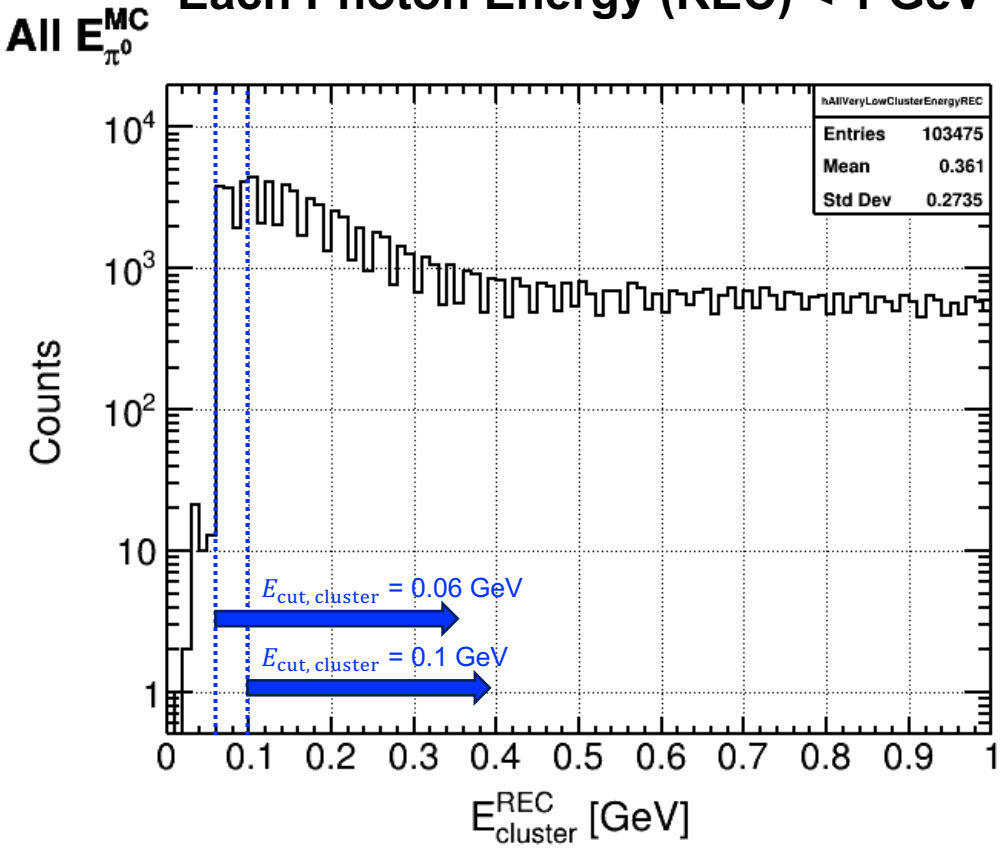
18×275 GeV^2

Truth VS. Reconstructed: E_γ < 1 GeV

Each Photon Energy (MC) < 1 GeV

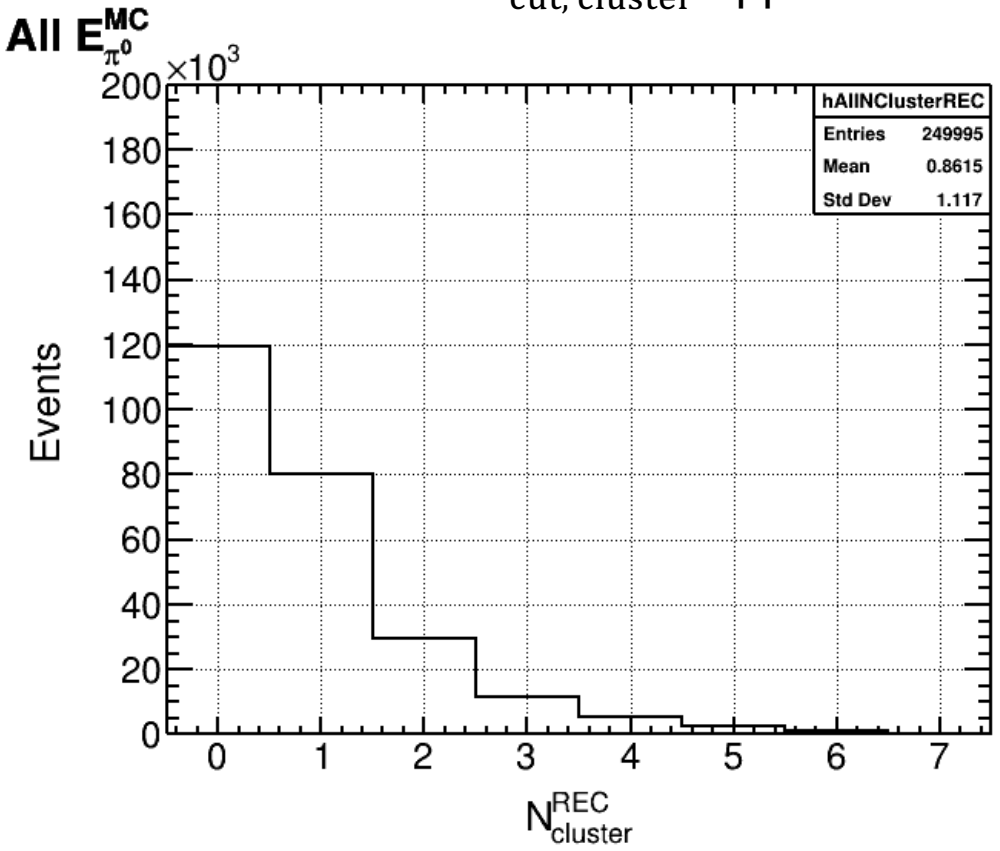


Each Photon Energy (REC) < 1 GeV

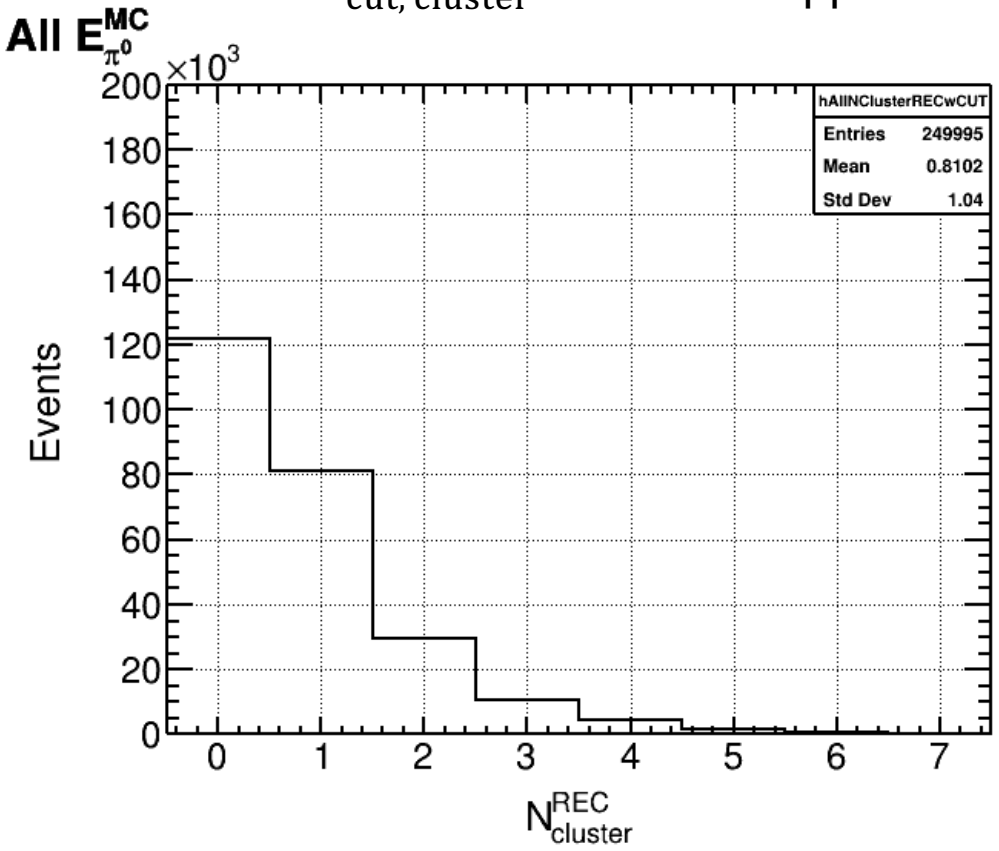


Number of Clusters: N_{Cluster}

Before $E_{\mathrm{cut,\,cluster}}$ applied



After $E_{\mathrm{cut,\,cluster}}$ = 0.1 GeV applied



“NAN” Value in MC Sample

```
if($1 == "P" && $2 == "2" && index($0, "nan") != 0){
    ISNAN=1

    EVENT="E "ID" 3 8"
    EVENT=EVENT"\n""U GEV MM"
    EVENT=EVENT"\n""W 1.0000000000000000000000e+00"
    EVENT=EVENT"\n""A 0 GenCrossSection 1.00000000e+00 0.00000000e+00 -1 -1"
    EVENT=EVENT"\n""P 1 0 11 0.0000000000000000e+00 0.0000000000000000e+00 -9.9999999869440064e+00 1.0000000000000000e+01 5.1099888971089147e-04 4"
    EVENT=EVENT"\n""P 2 1 11 -2.0144599441863438e+00 1.7659995293153501e+00 -9.6842206494475249e+00 1.0047931779748877e+01 5.0894824067755694e-04 1"
    EVENT=EVENT"\n""P 3 1 22 2.0144599441863438e+00 -1.7659995293153501e+00 -3.1577933747166753e-01 -4.7931779709084528e-02 -2.6970766282664735e+00 13"
    EVENT=EVENT"\n""P 4 0 2212 0.0000000000000000e+00 0.0000000000000000e+00 9.9995598131265865e+01 1.0000000000000001e+02 9.3827201300135255e-01 4"
    EVENT=EVENT"\n""V -2 0 [3,4]"
    EVENT=EVENT"\n""P 5 -2 111 2.1689254221735963e+00 -1.3613378062095911e+00 1.2220566114230678e+01 1.2486710253081359e+01 1.3497660003709563e-01 2"
    EVENT=EVENT"\n""P 6 -2 2212 -1.5446547798705895e-01 -4.0466172310571308e-01 8.7459252679405665e+01 8.7465357967051986e+01 9.3827201300135255e-01 1"
    EVENT=EVENT"\n""P 7 5 22 1.4962540349890630e+00 -8.9581517757774021e-01 8.5634296997597446e+00 8.7391984296231051e+00 -1.1920928955078125e-07 1"
    EVENT=EVENT"\n""P 8 5 22 6.7267138658766945e-01 -4.6552262825722612e-01 3.6571364111079729e+00 3.7475118200220527e+00 4.2146848510894035e-08 1"

}
```

Unphysical values put in to account for “NAN” values in the EpIC MC sample