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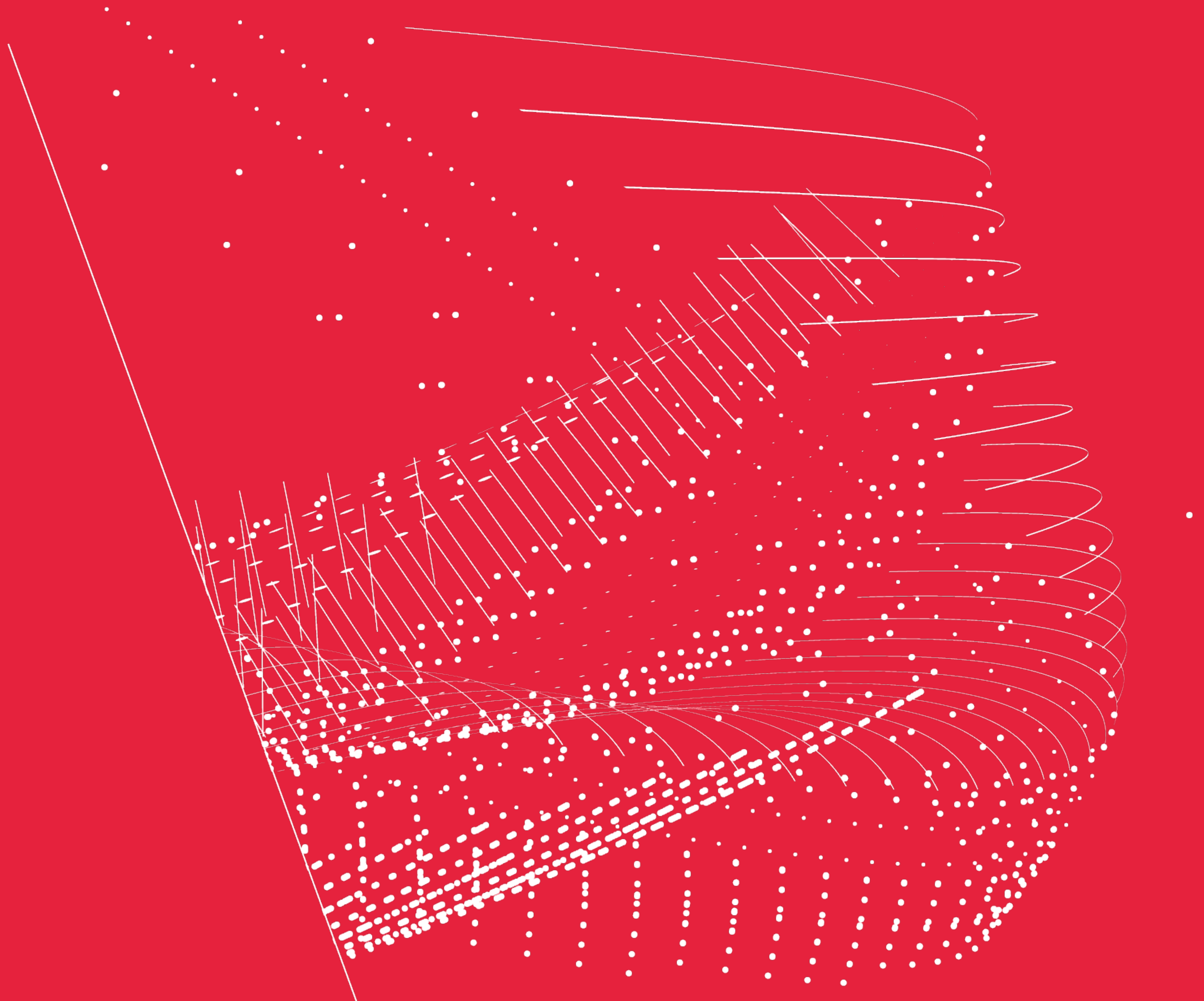
Π^0 STUDIES AT PROTODUNE-SP



Milo Vermeulen

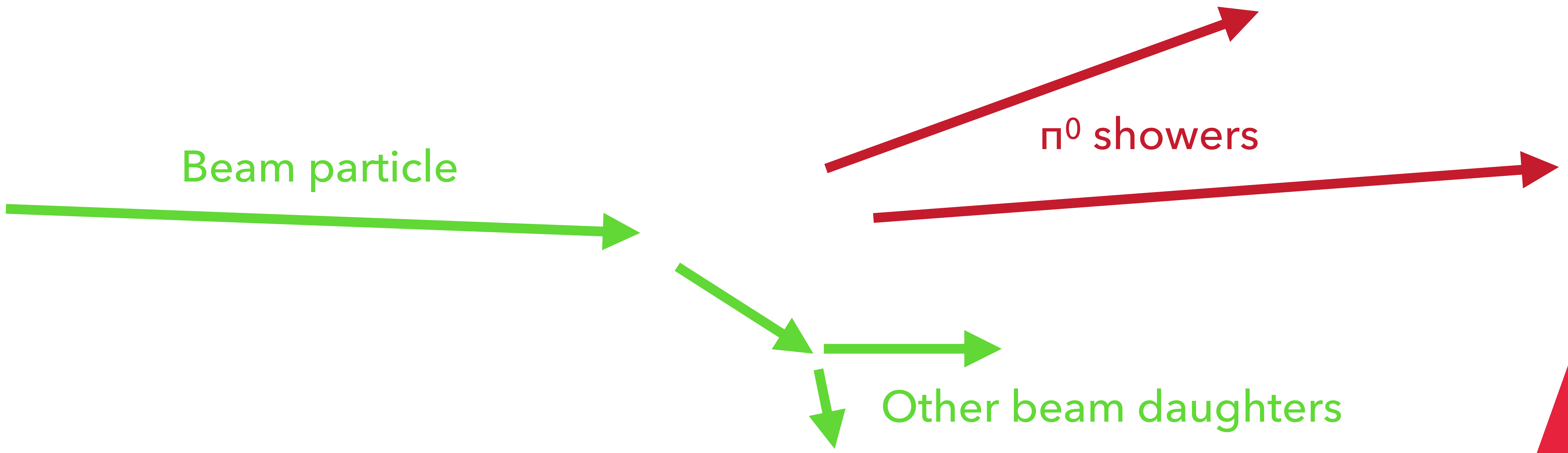
BACKGROUND

- π^0 are produced in hadronic interactions
- Decay almost immediately: $\pi^0 \rightarrow \gamma\gamma$

- Potential to mimic electron shower
  - Background to $\nu_e + n \rightarrow e^- + p$
- Can be used to calibrate shower energy reconstruction with known π^0 mass

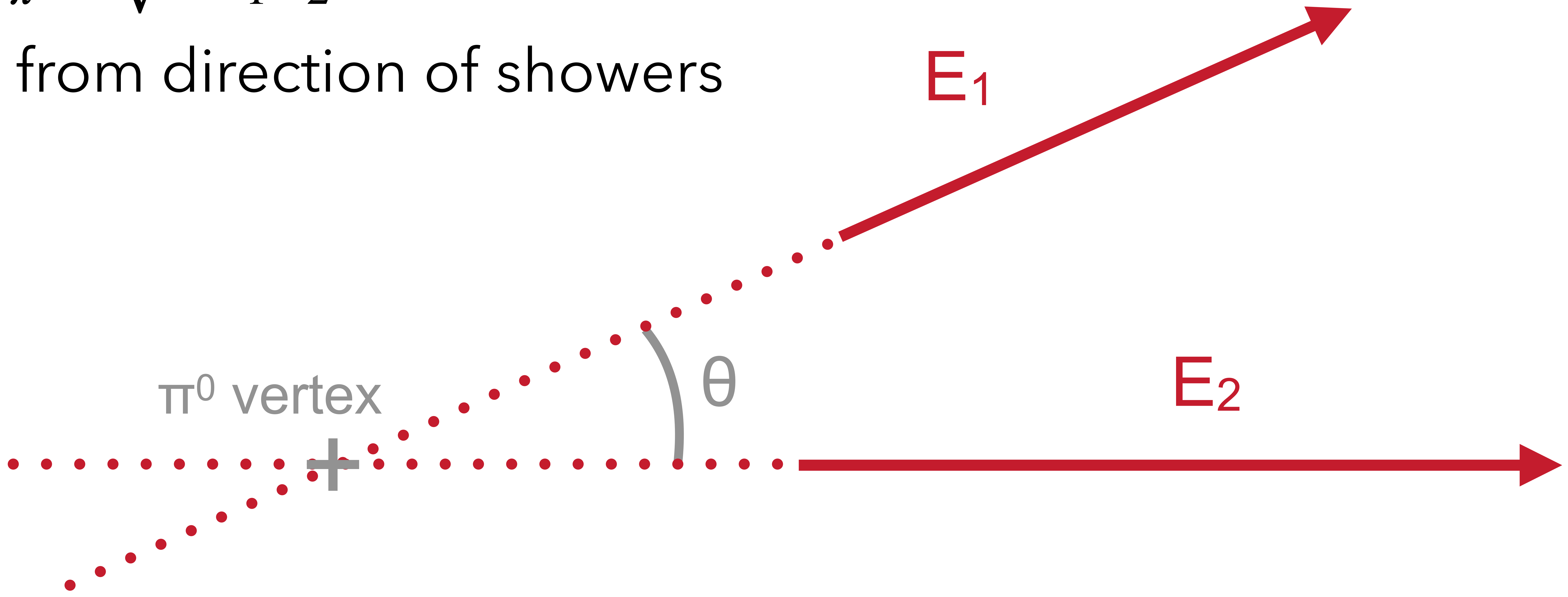
π^0 INVARIANT MASS

- Photons in ProtoDUNE-SP nearly all originate from π^0 particles
- Can reconstruct π^0 invariant mass from pure photon sample

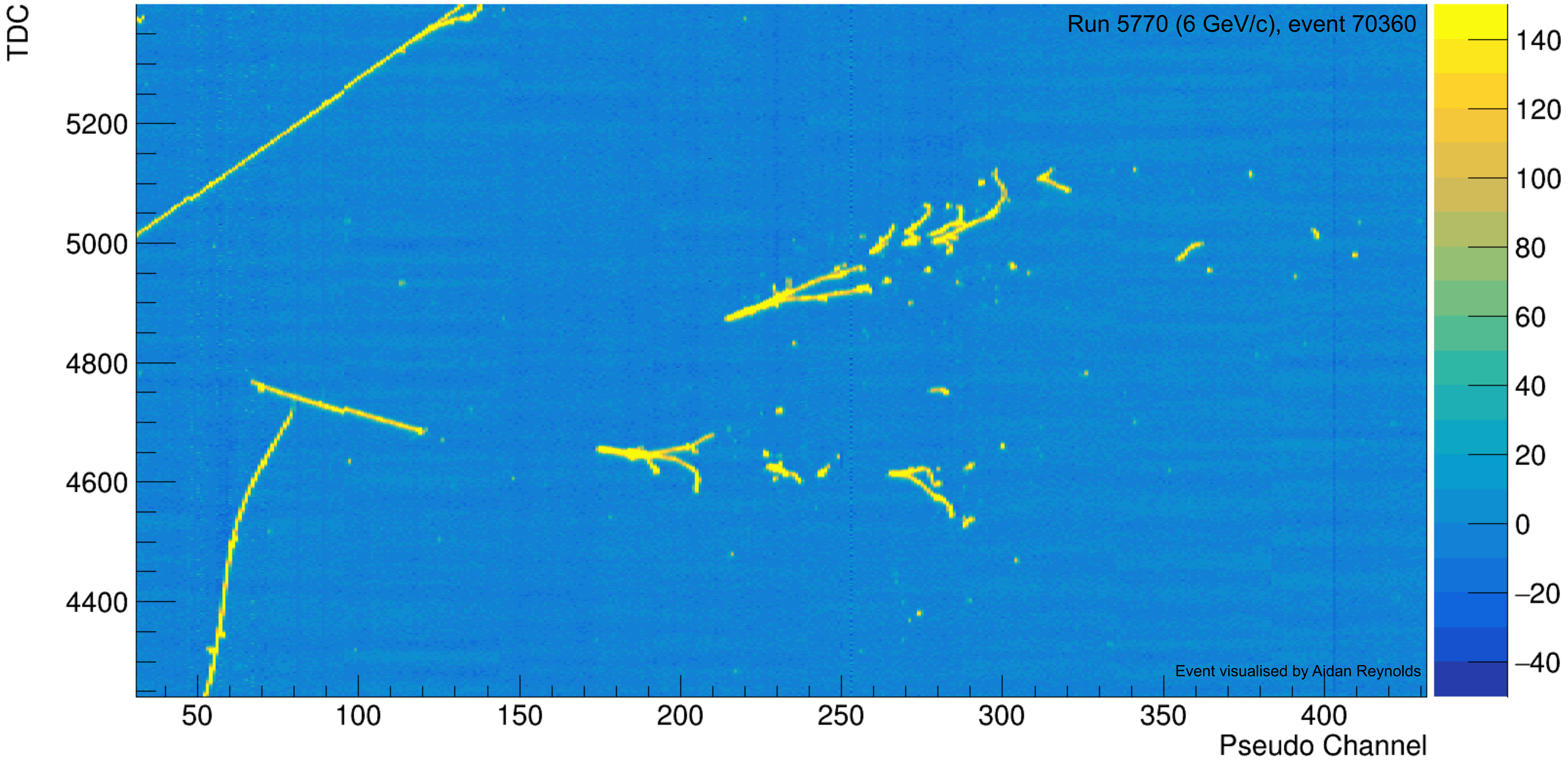


Π⁰ INVARIANT MASS

- π^0 invariant mass = 135 MeV/c^2
- $m_\pi = \sqrt{2E_1E_2(1-\cos\theta)}$
- θ from direction of showers



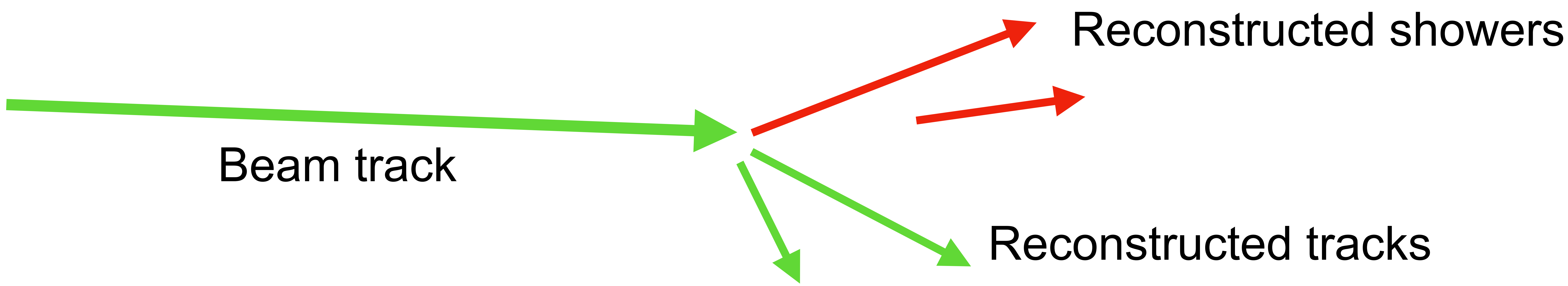
π⁰ INVARIANT MASS



SAMPLE

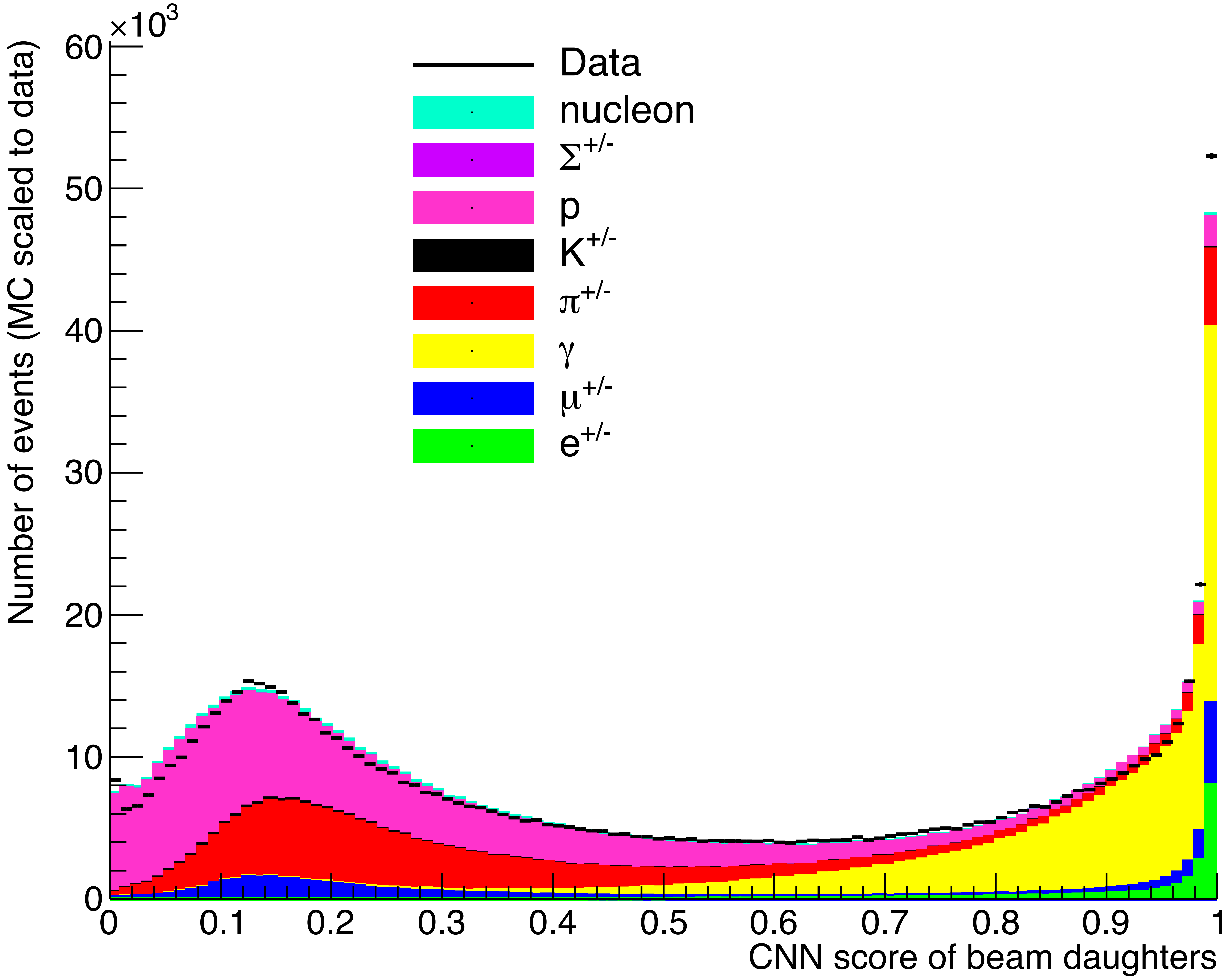
- Used most of the ProtoDUNE Production 2 runs
  - 1, 2, 3, 6, 7 GeV/c
- 340k MC events, 200k beam events
- Unless stated otherwise, all runs are combined in figures

- Consider only beam track and daughter particles



SHOWER SELECTION

- Pandora assigns track or shower status to reconstructed objects
- Complementary: track/em-like score from CNN by Aidan Reynolds



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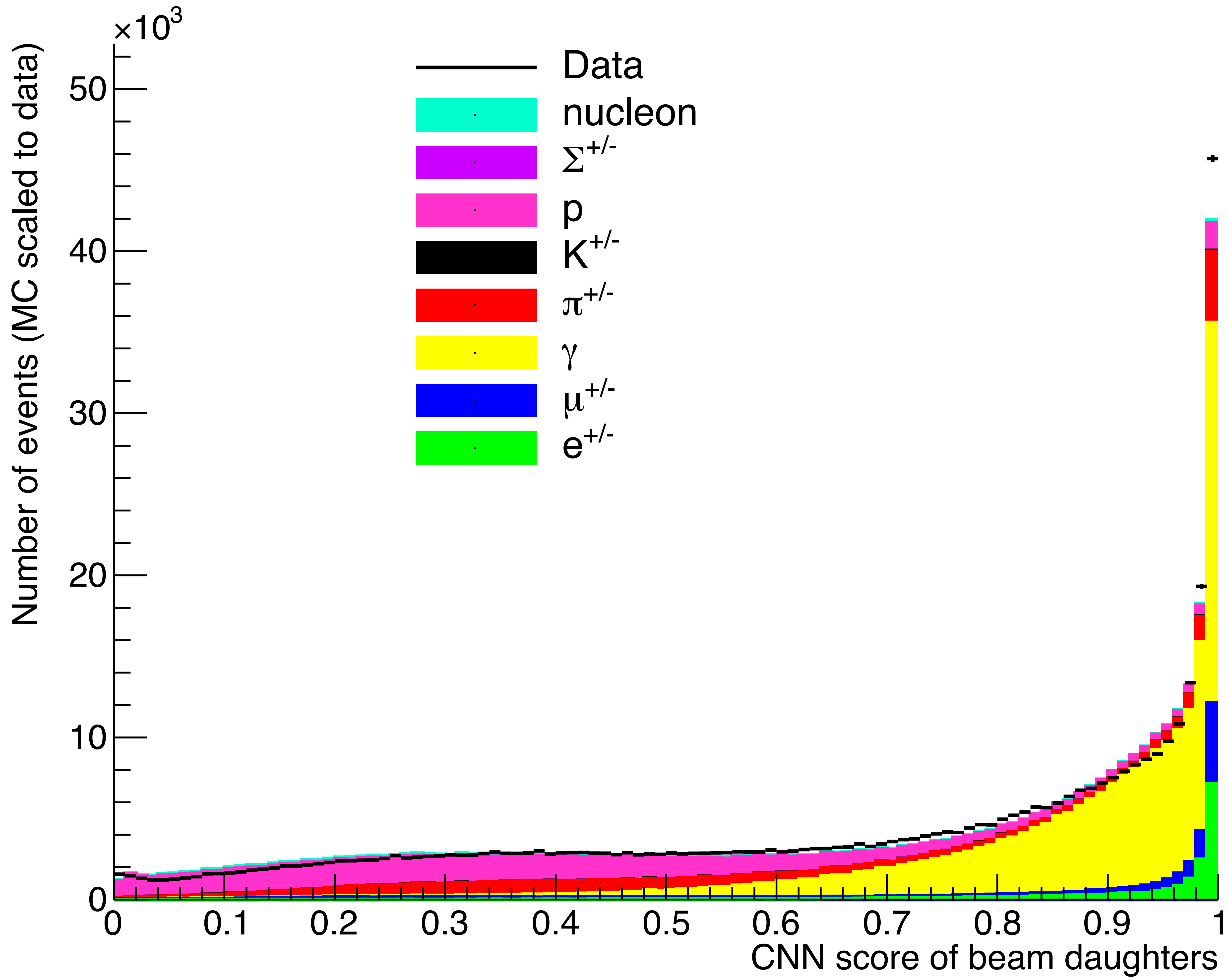
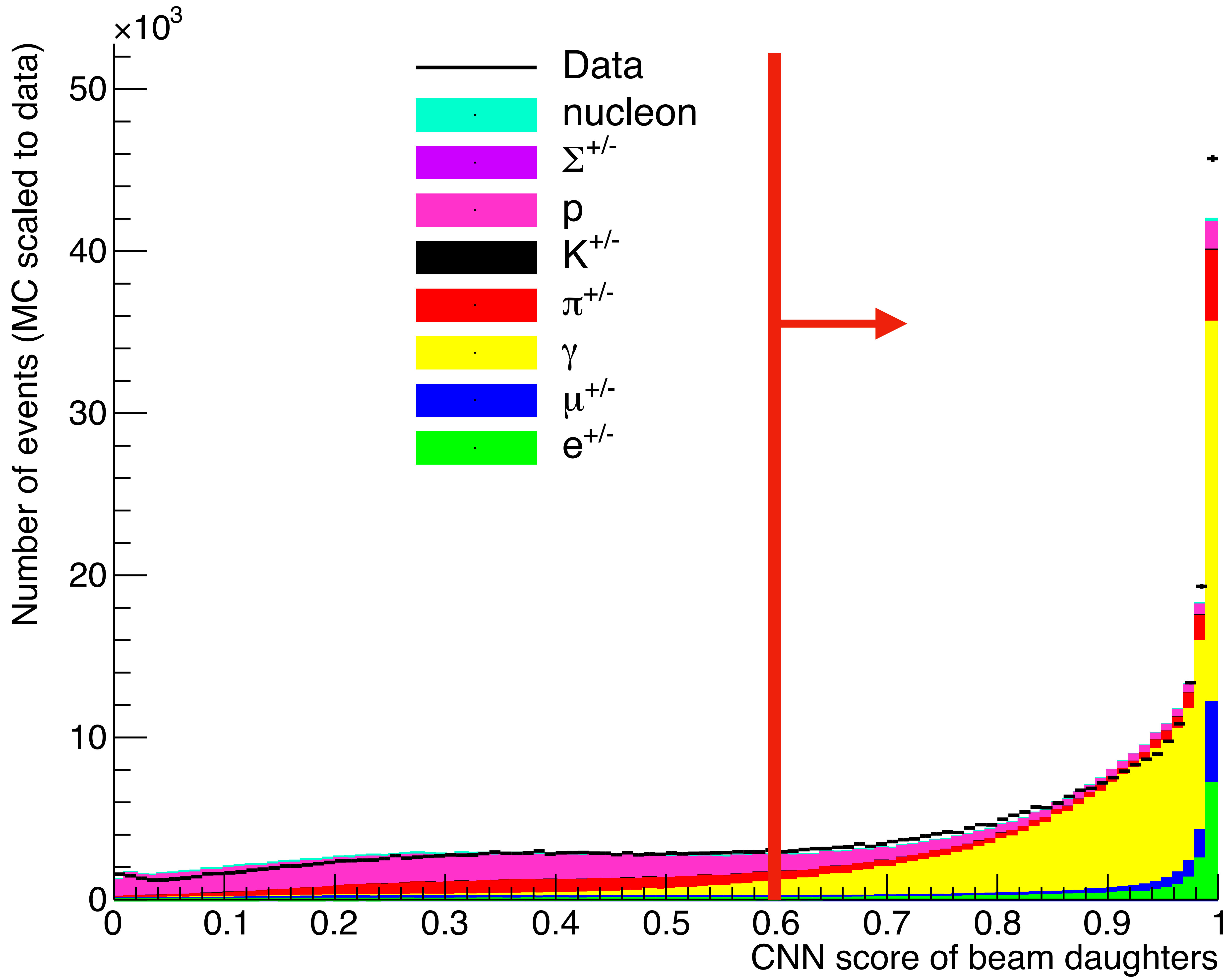


Pandora classification shower

SHOWER SELECTION

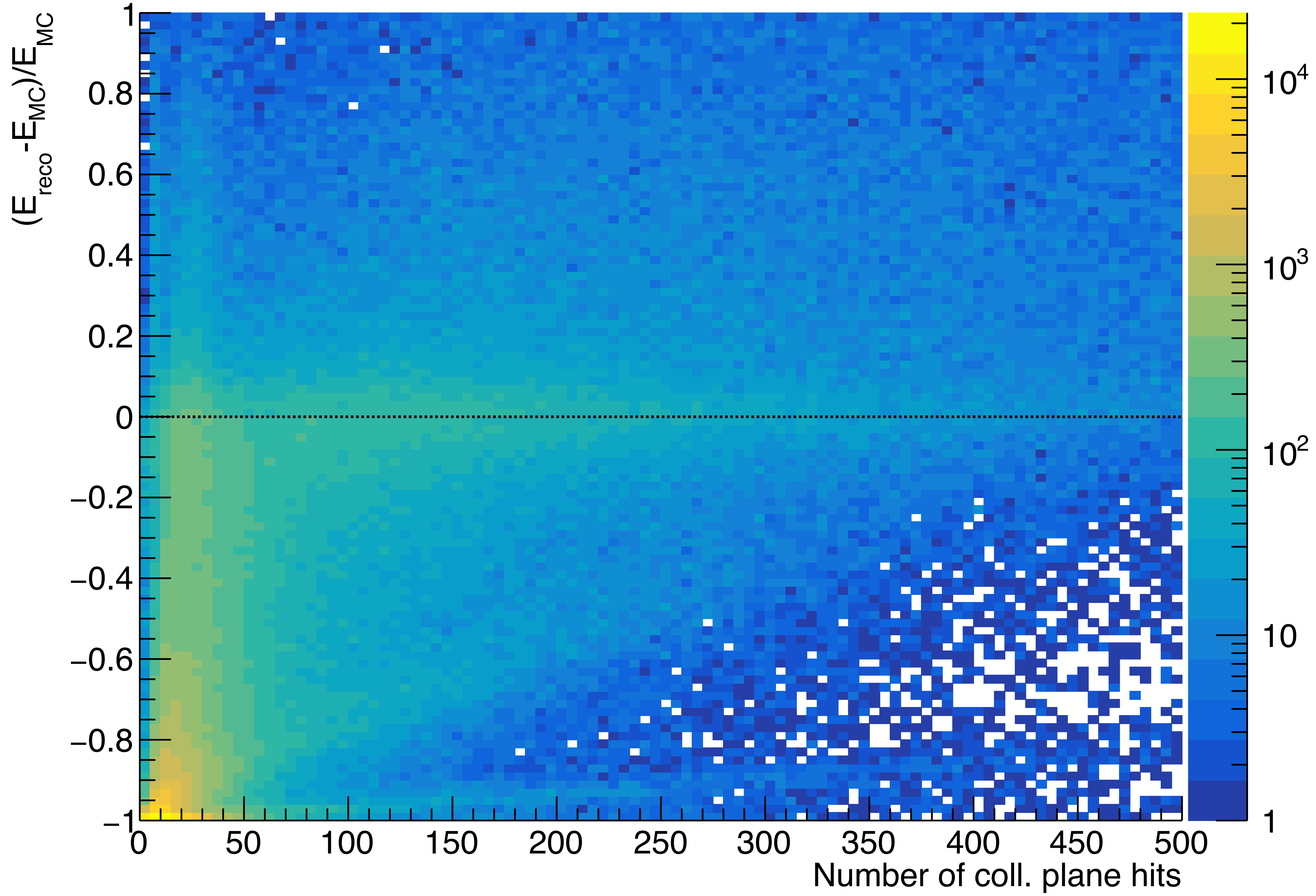
- Pandora assigns track or shower status to reconstructed objects
- Complementary: track/em-like score from CNN by Aidan Reynolds



Pandora classification shower

SHOWER SELECTION – NUMBER OF HITS

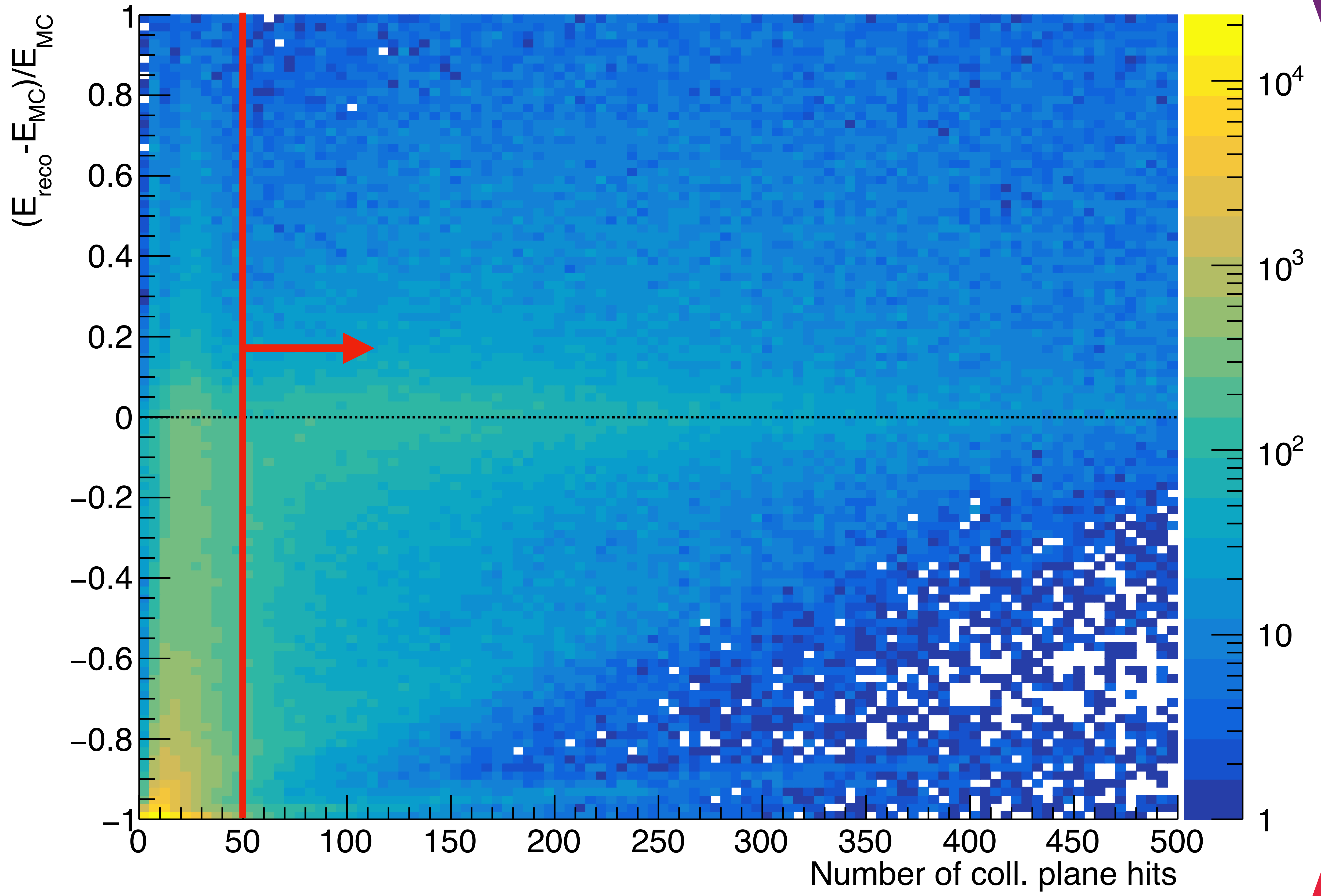
- Relative energy difference vs shower size
- Central peak lined up with 0 by hand
  - Multiplicative factor to capture charge loss, clustering inefficiencies, etc.



Pandora classification	shower
Particle CNN score	> 0.6

SHOWER SELECTION – NUMBER OF HITS

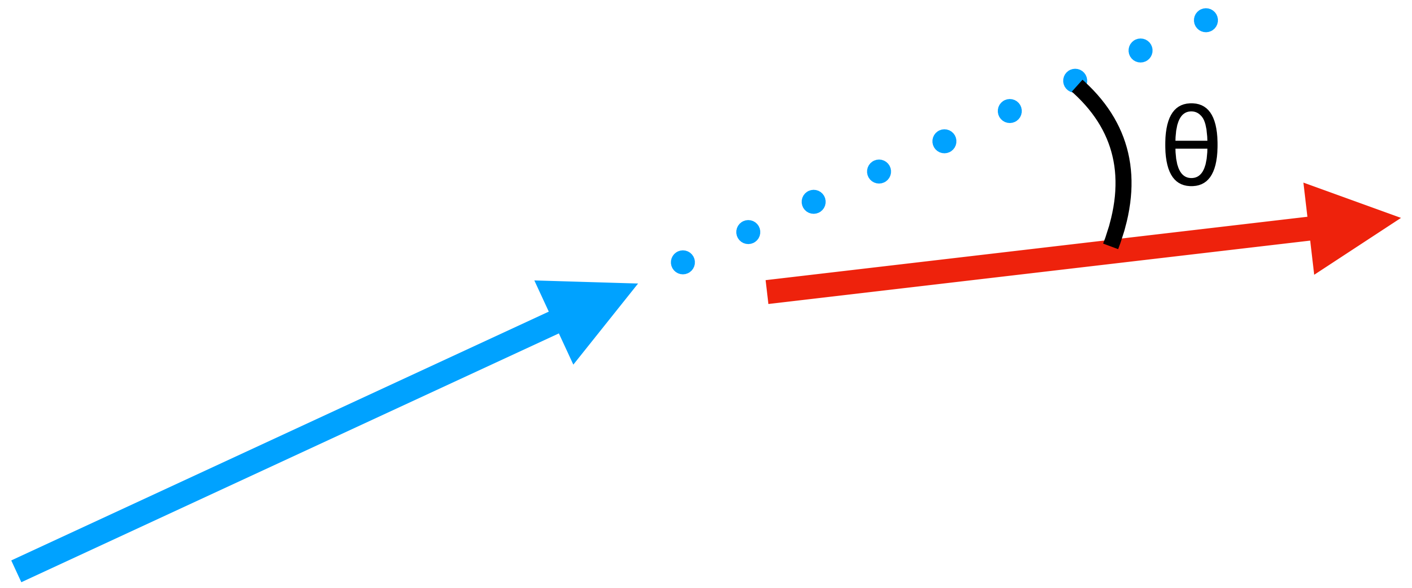
- Number of hits is a good indicator for reconstruction quality
- Energy reconstruction improves > 50 hits

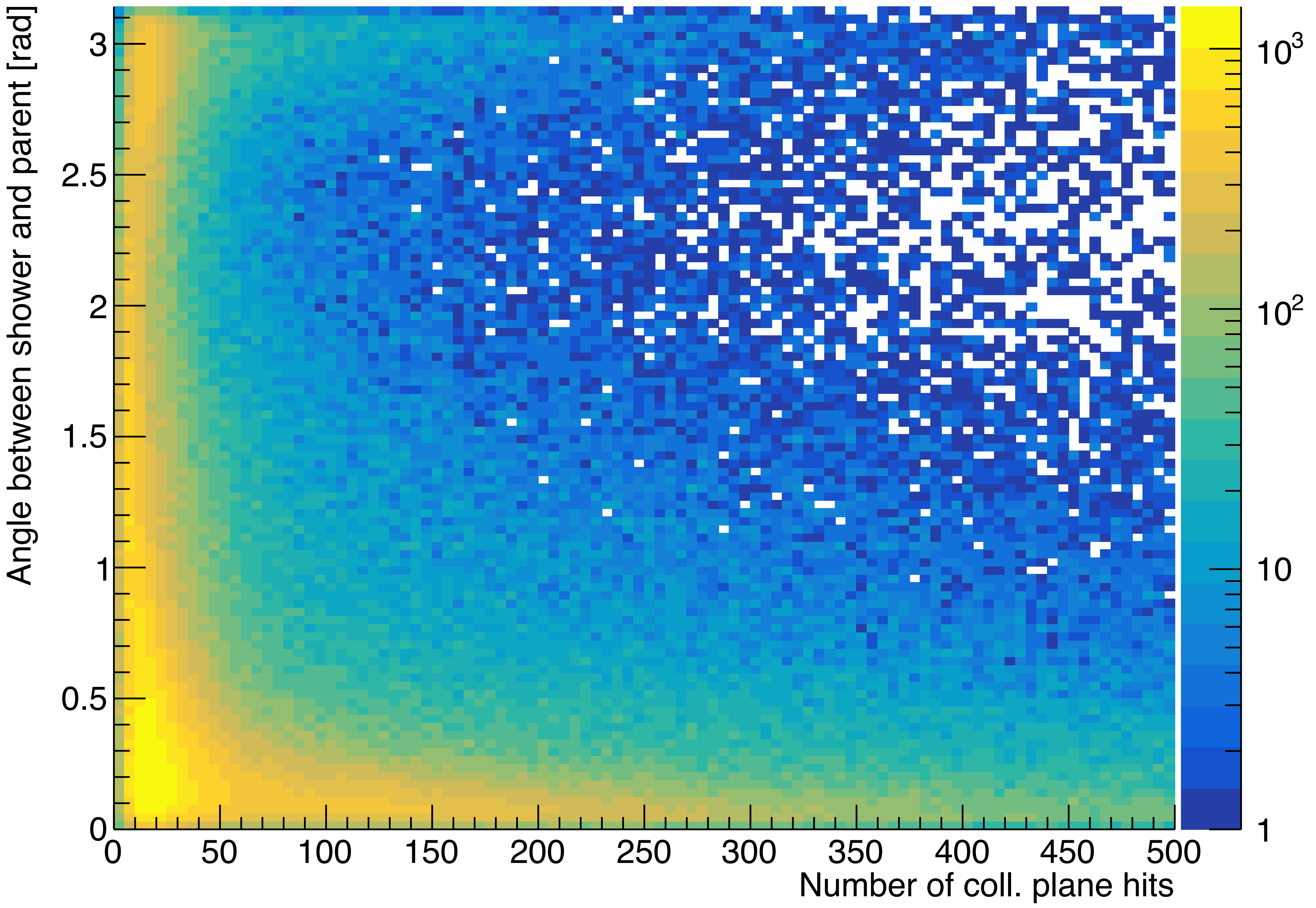


Pandora classification	shower
Particle CNN score	> 0.6

SHOWER SELECTION – NUMBER OF HITS

- Number of hits is a good indicator for reconstruction quality
- Angular reconstruction improves > 50 hits





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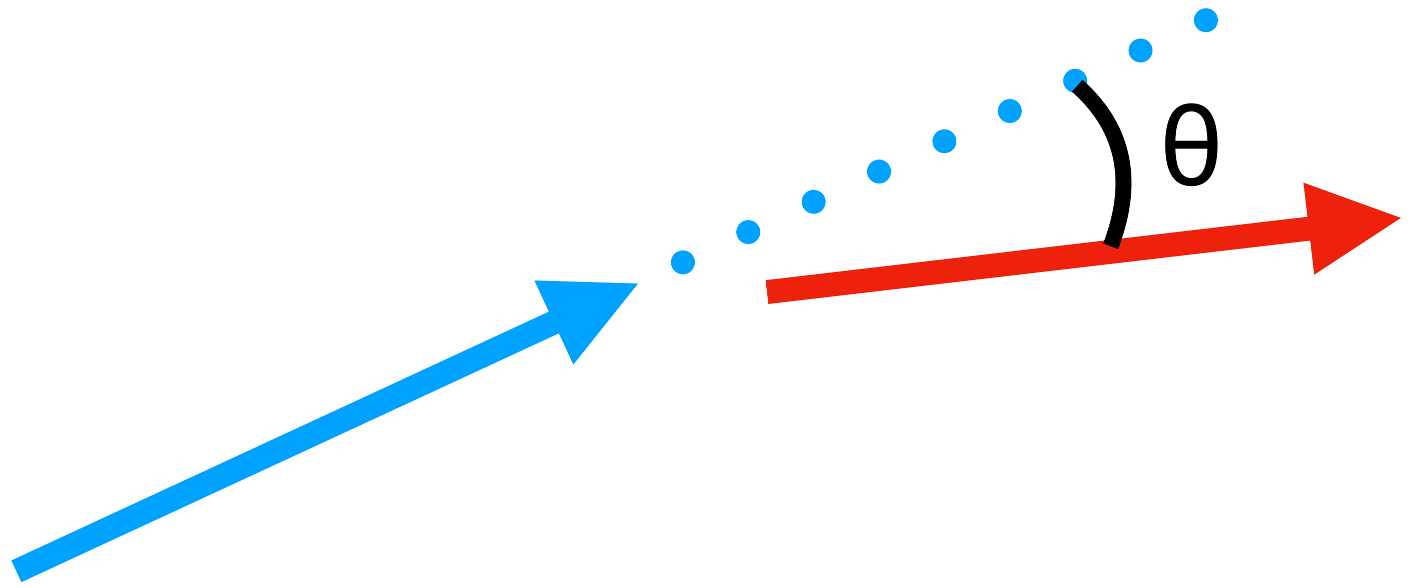
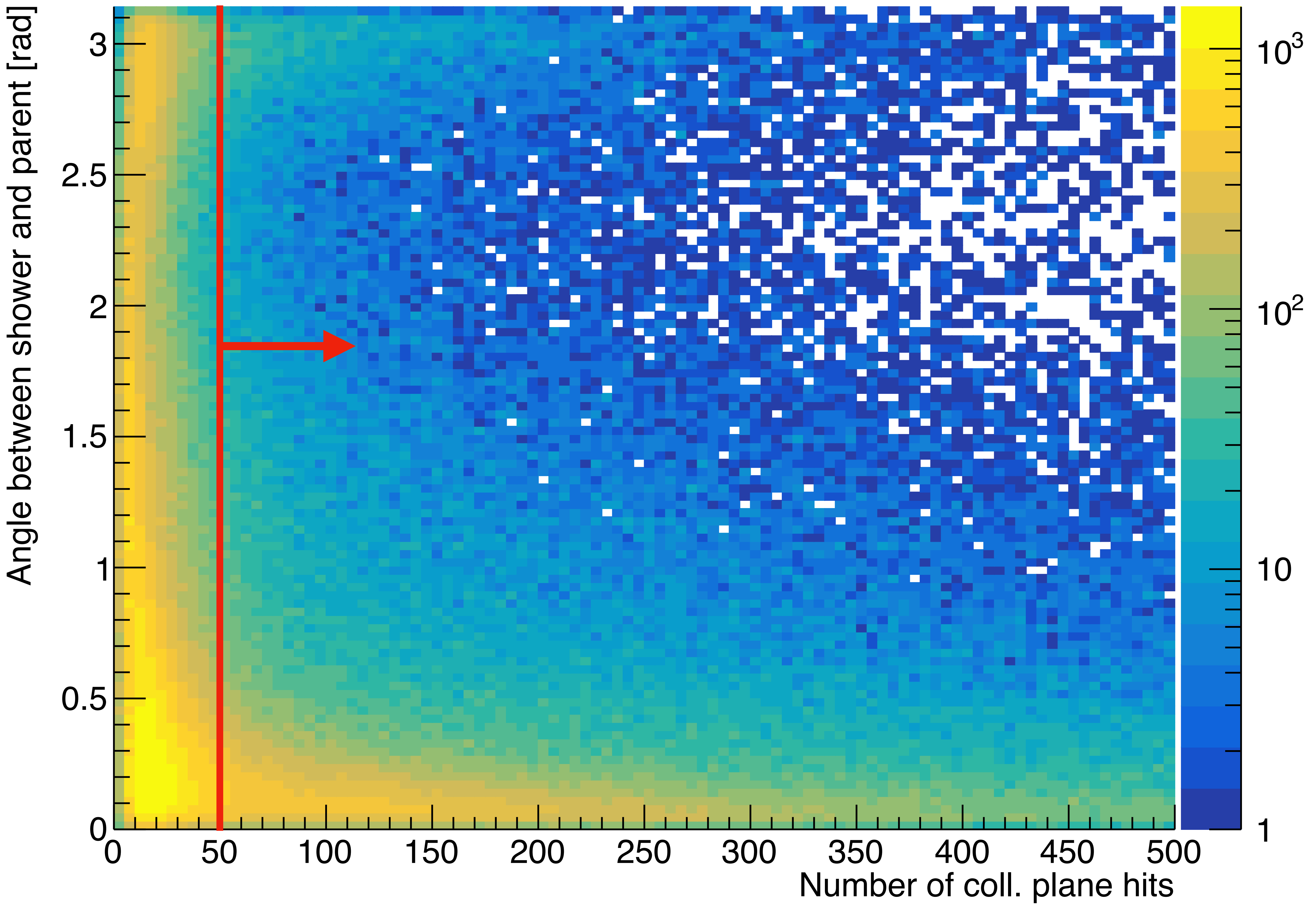


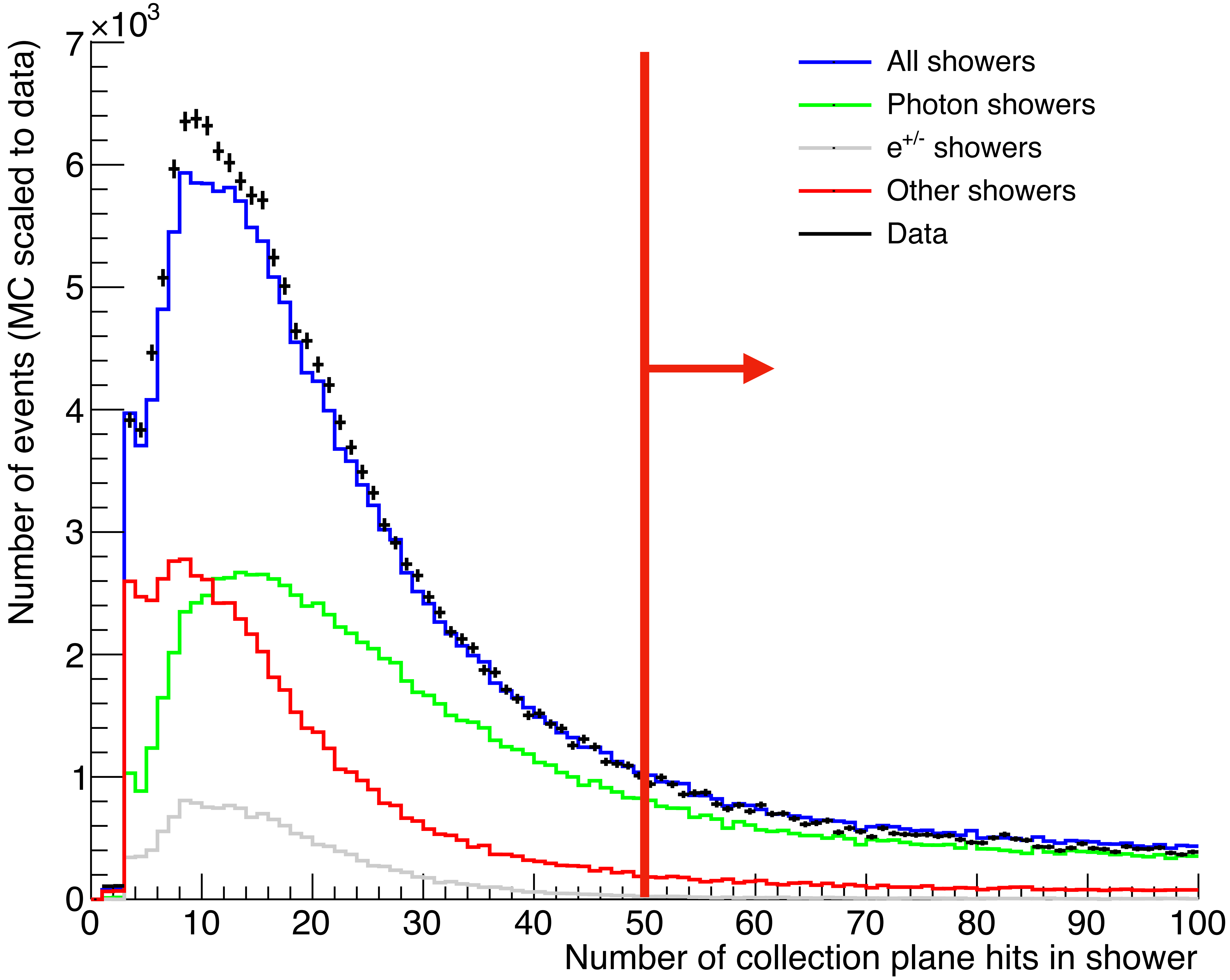


Pandora classification	shower
Particle CNN score	> 0.6

SHOWER SELECTION – NUMBER OF HITS

- Number of hits also very useful for cutting out leftover electrons, protons, pions
- Result: quite pure photon sample
- Cut efficiency: 46%

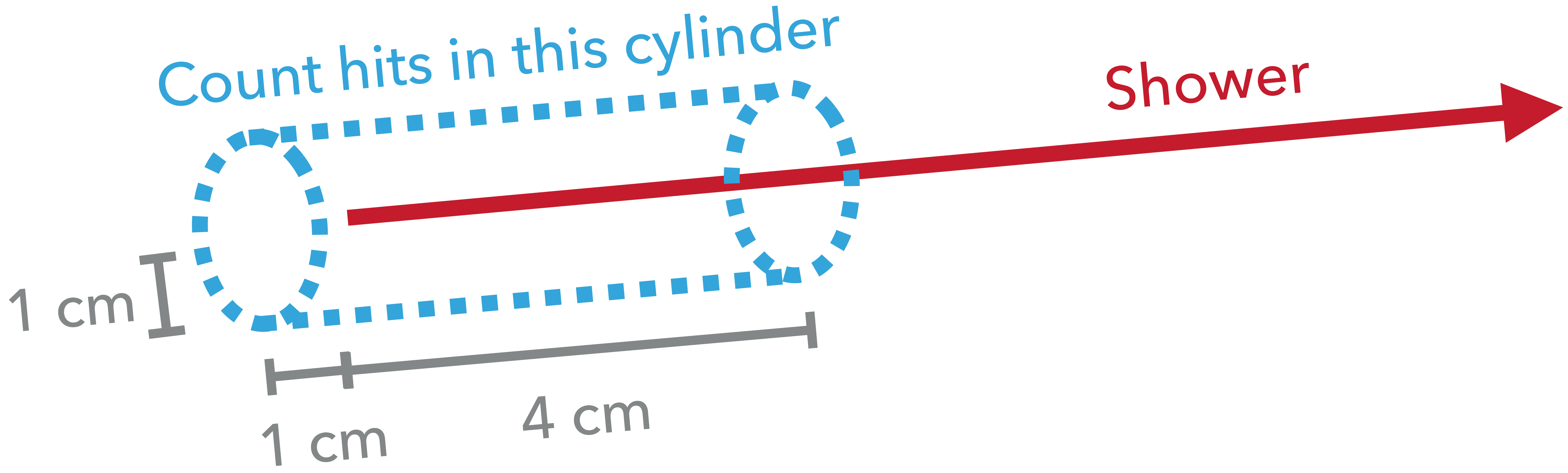
  Purity: 72% → 91%



Pandora classification	shower
Particle CNN score	> 0.6

SHOWER SELECTION – HITS AT START

- Convenient metric: number of hits at start of shower
  - "Start" defined as cylinder around initial part of shower object
- More hits generally means shower start is in the right place
  - More cylinder hits = better reconstruction



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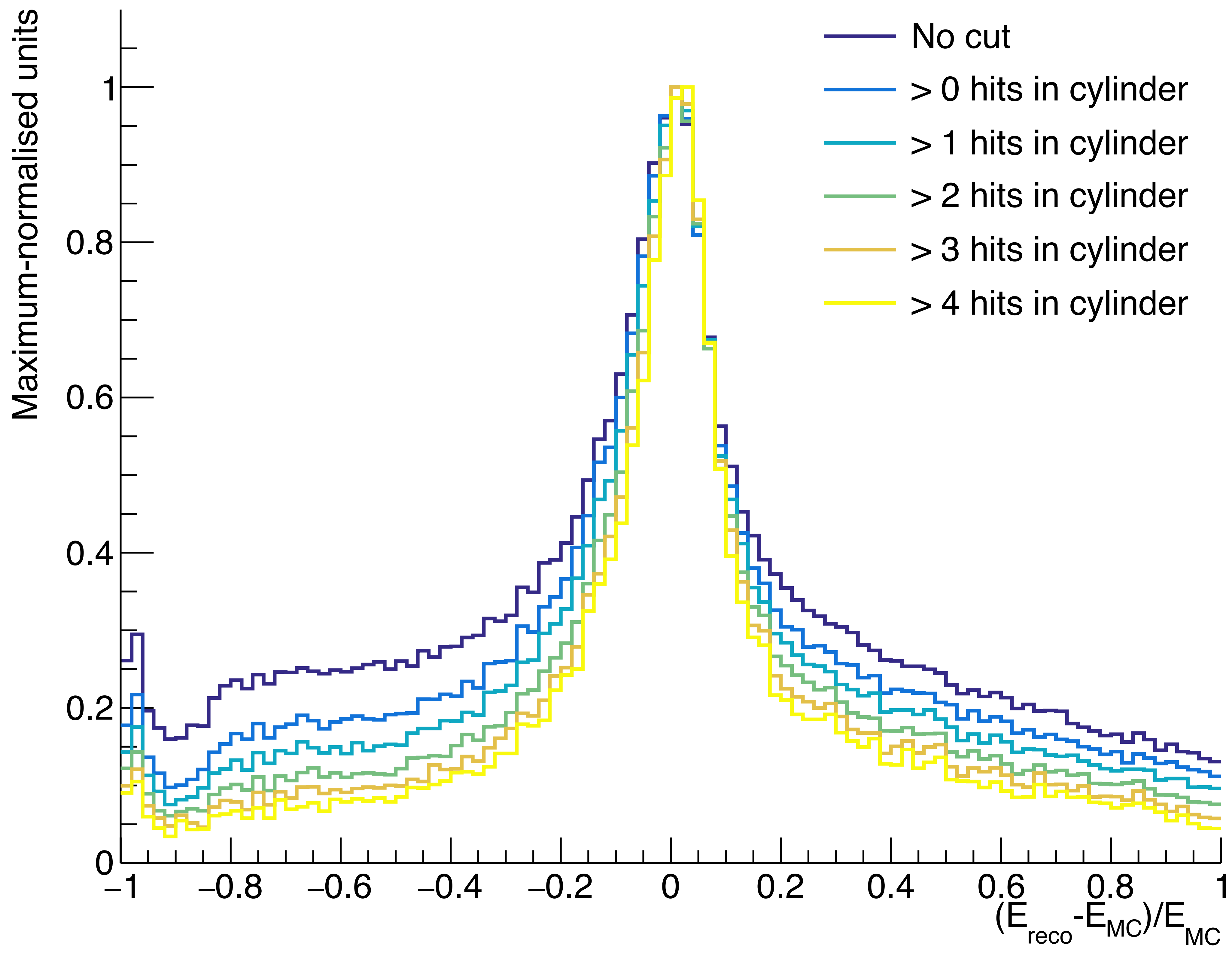
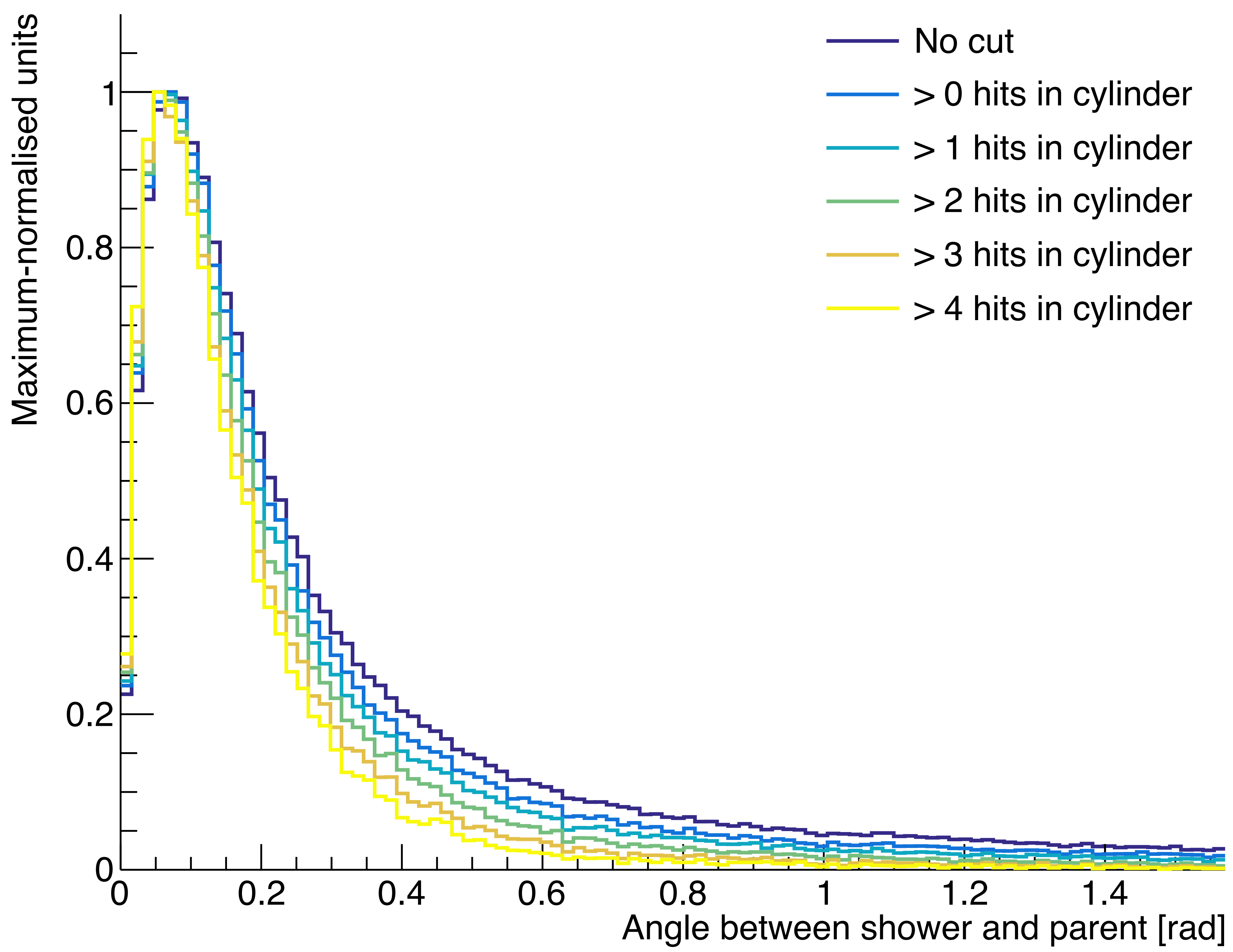
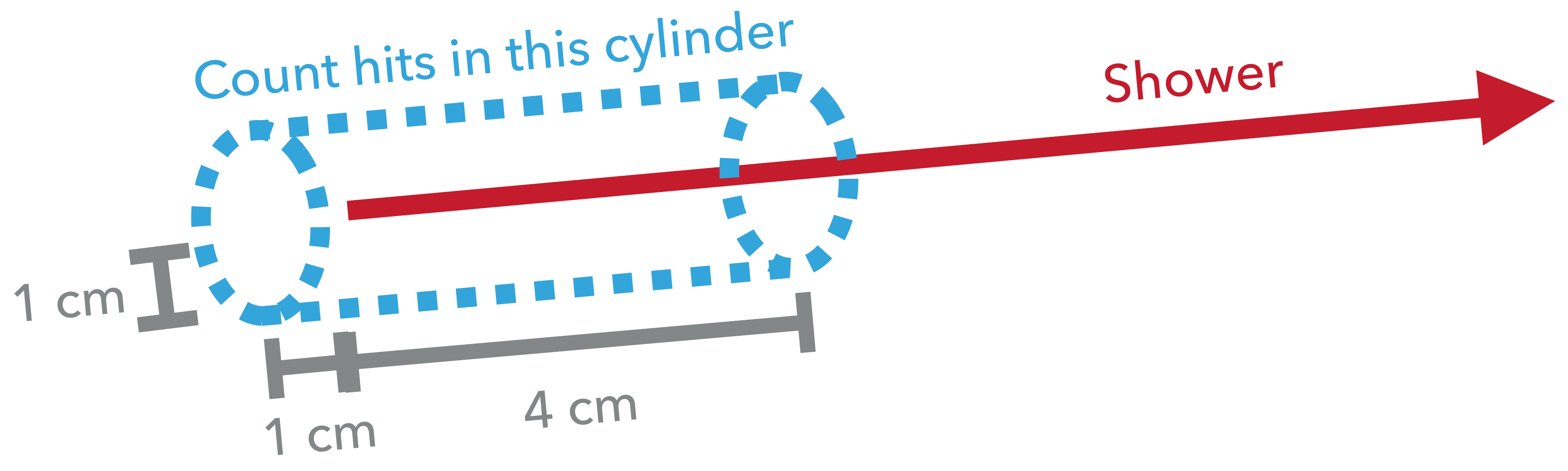
SHOWER SELECTION – HITS AT START





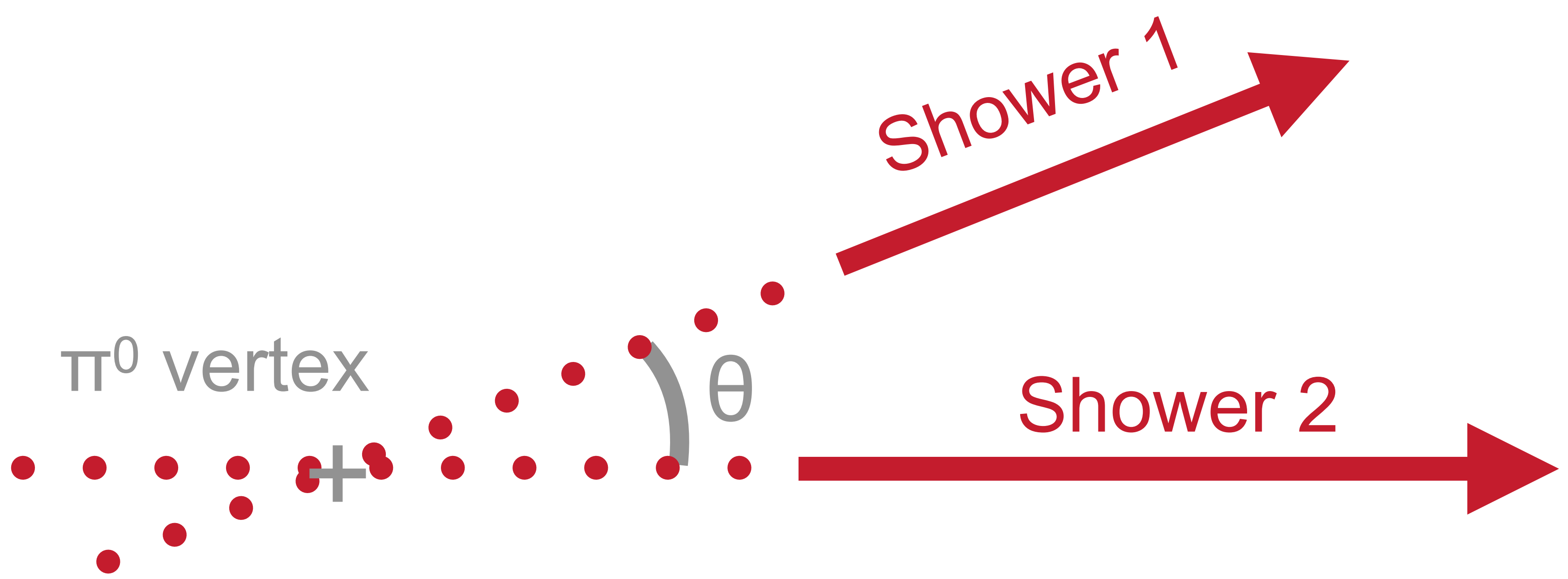


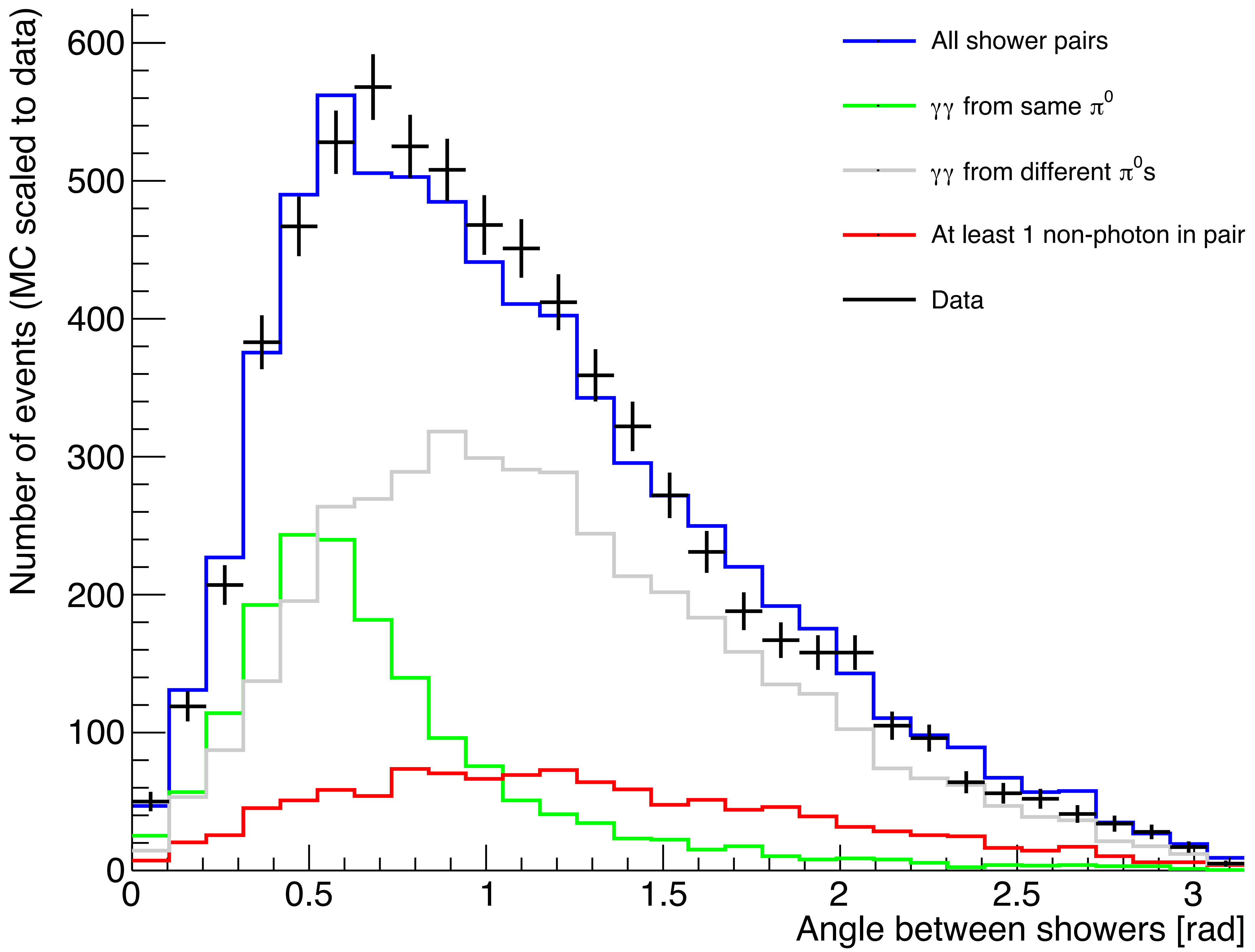
Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50

SHOWER PAIR ANGLE

Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50
Number of cylinder hits	> 1

- Unrelated photon shower pairs often have bigger opening angle than related photon shower pairs





SHOWER PAIR ANGLE

Pandora classification	shower
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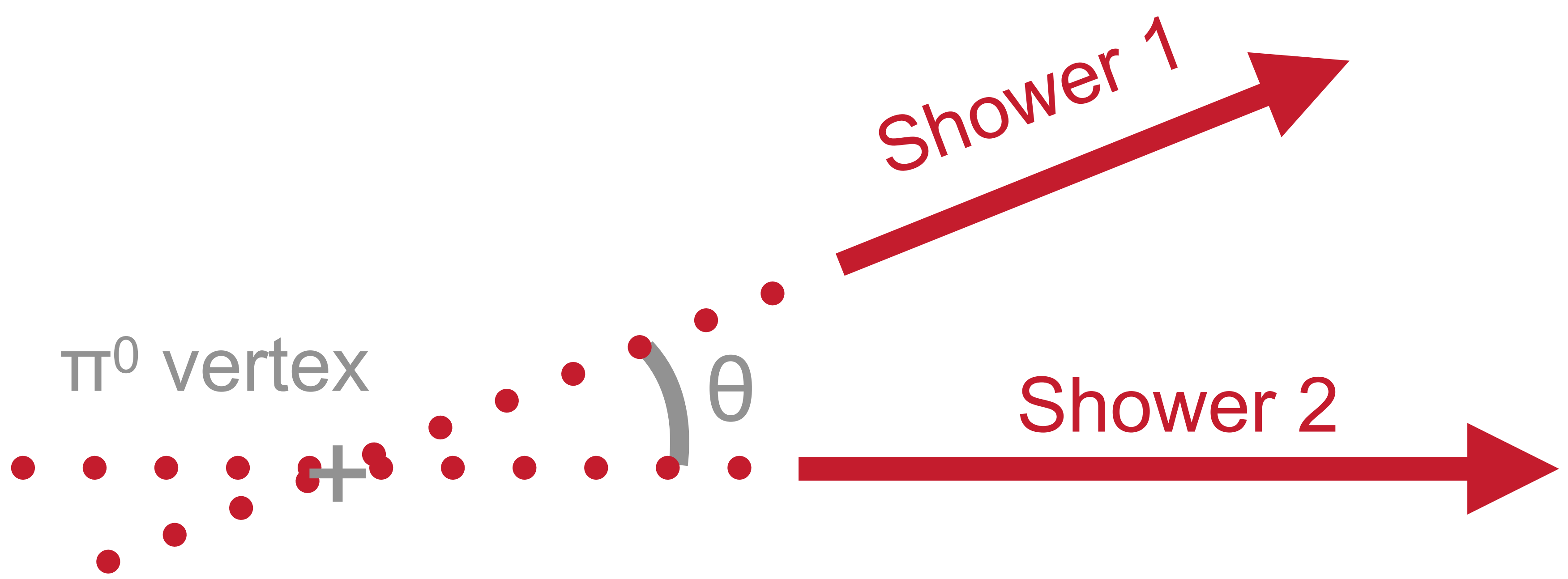

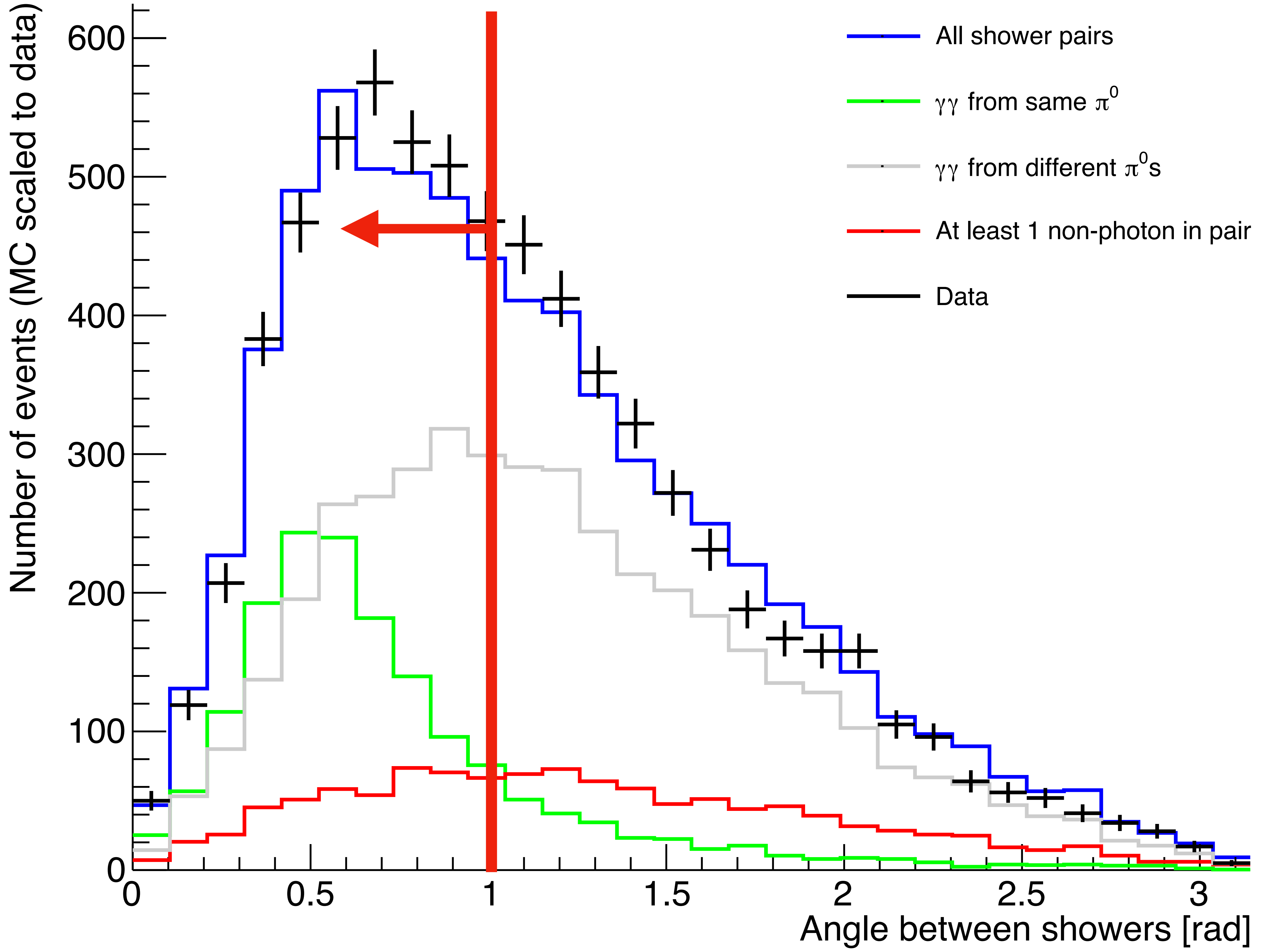

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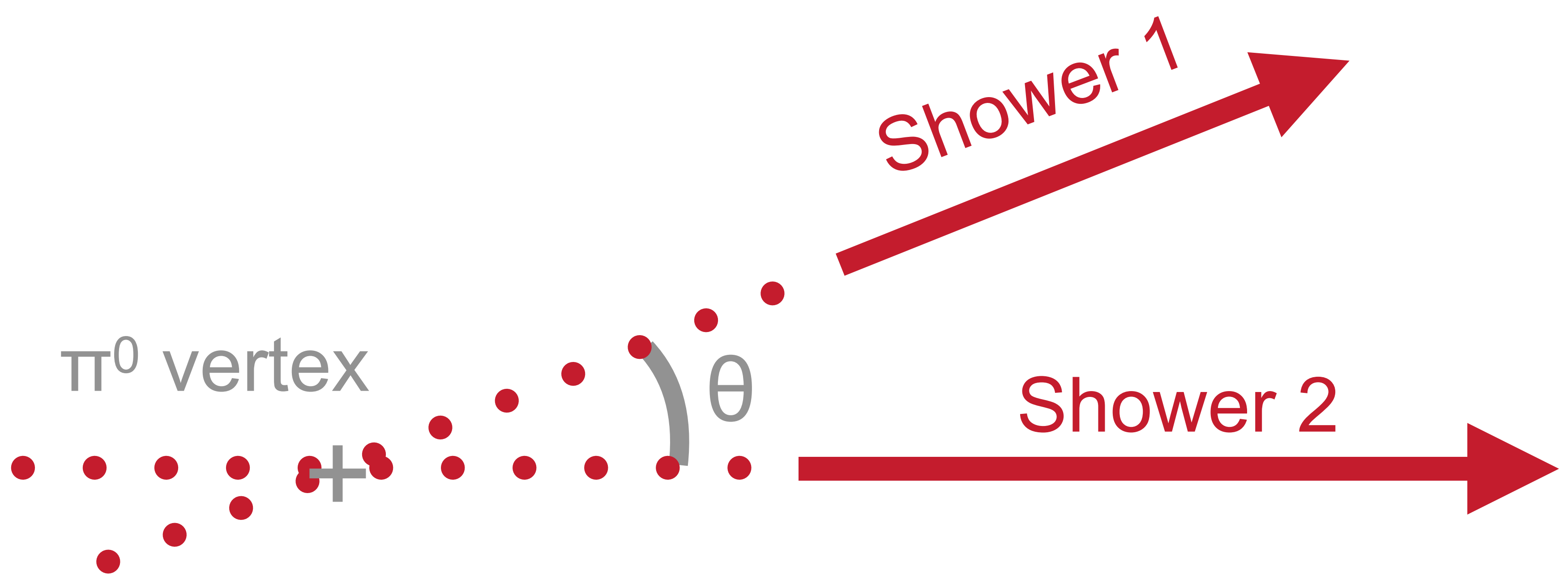
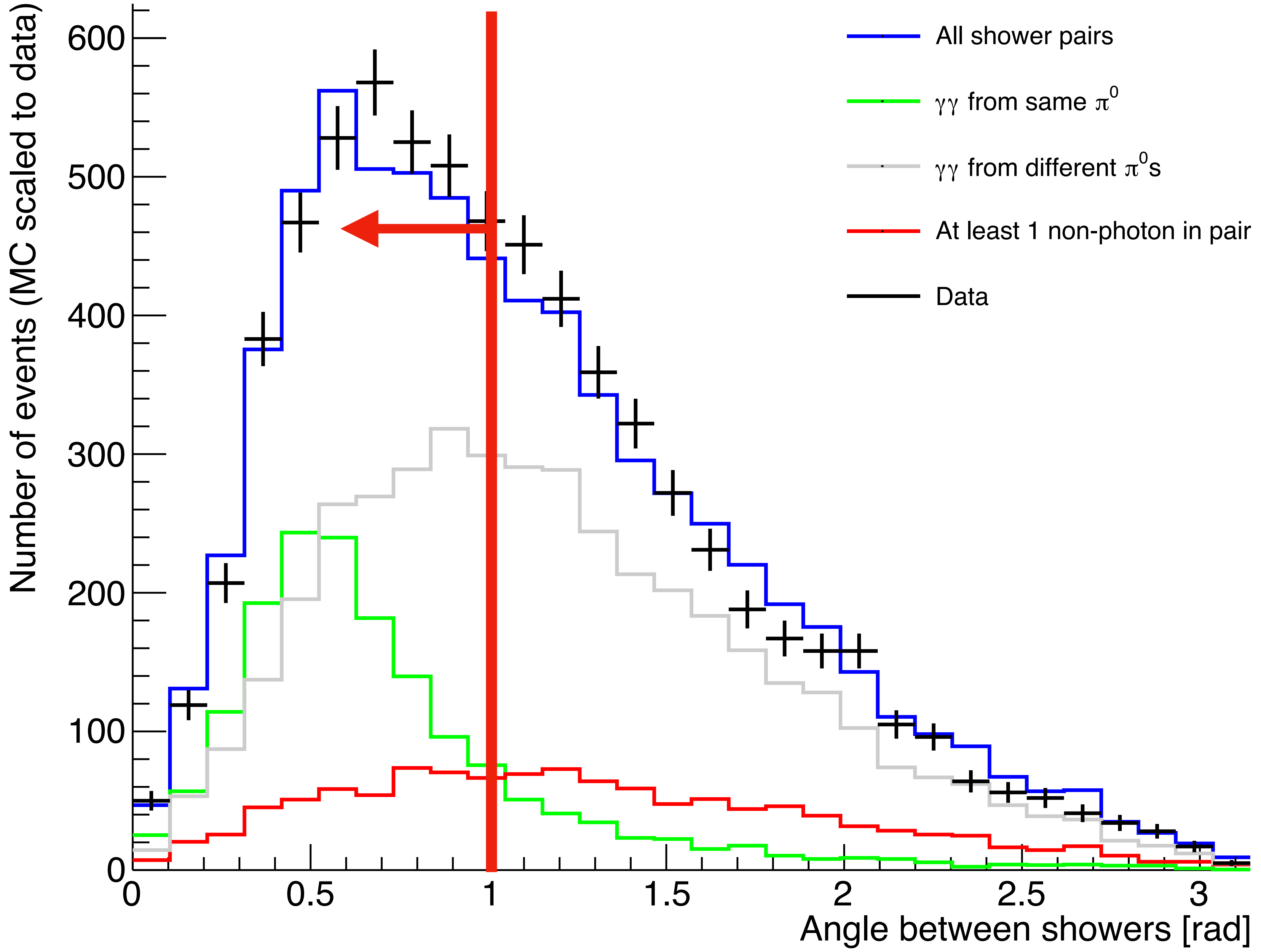
SHOWER PAIR ANGLE

Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50
Number of cylinder hits	> 1

- Unrelated photon shower pairs often have bigger opening angle than related photon shower pairs
- Also require exactly 1 shower pair that passes the cuts per event

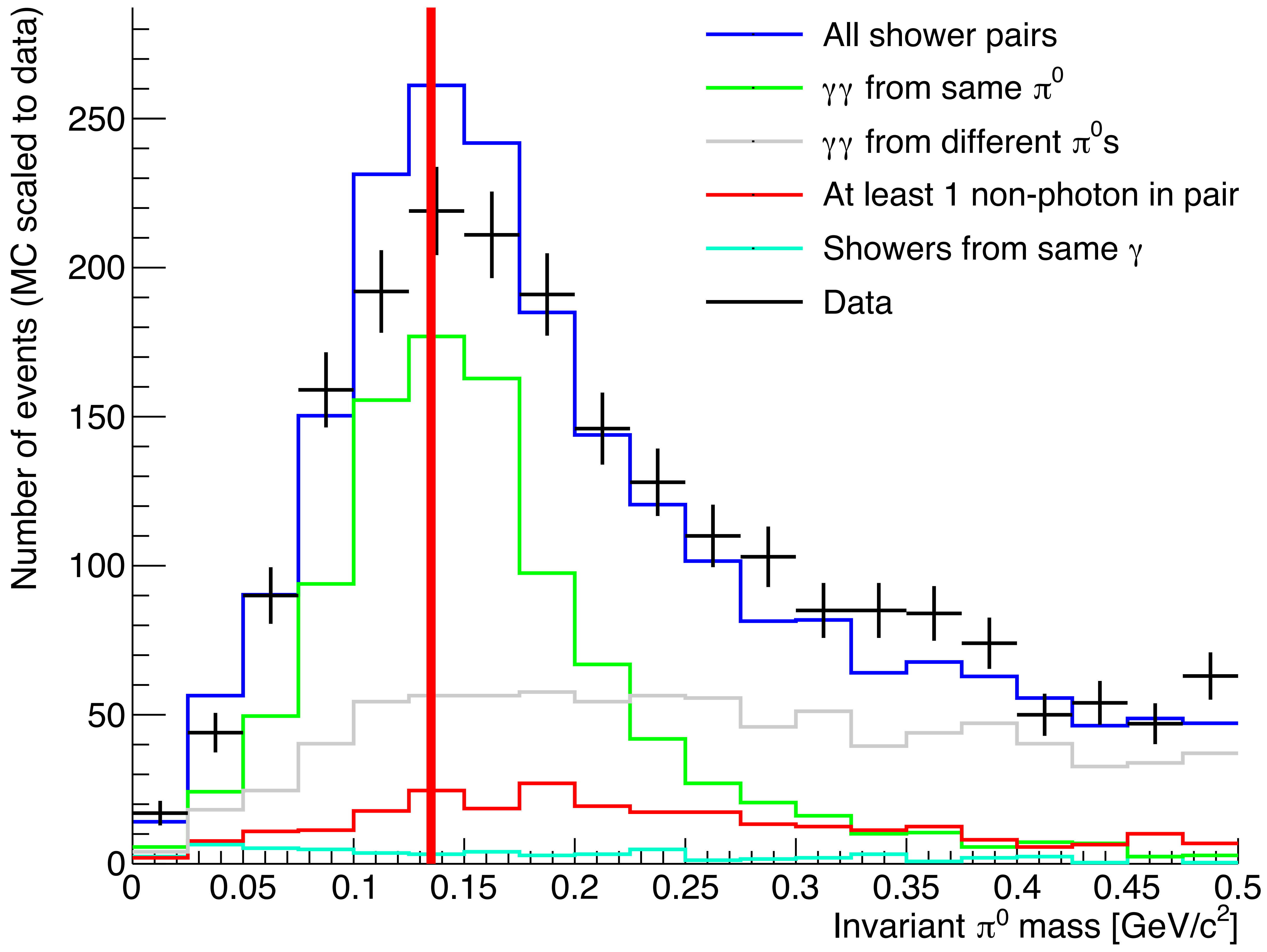




π⁰ INVARIANT MASS – RESULTS

Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50
Number of cylinder hits	> 1
Angle between showers	< 1 rad

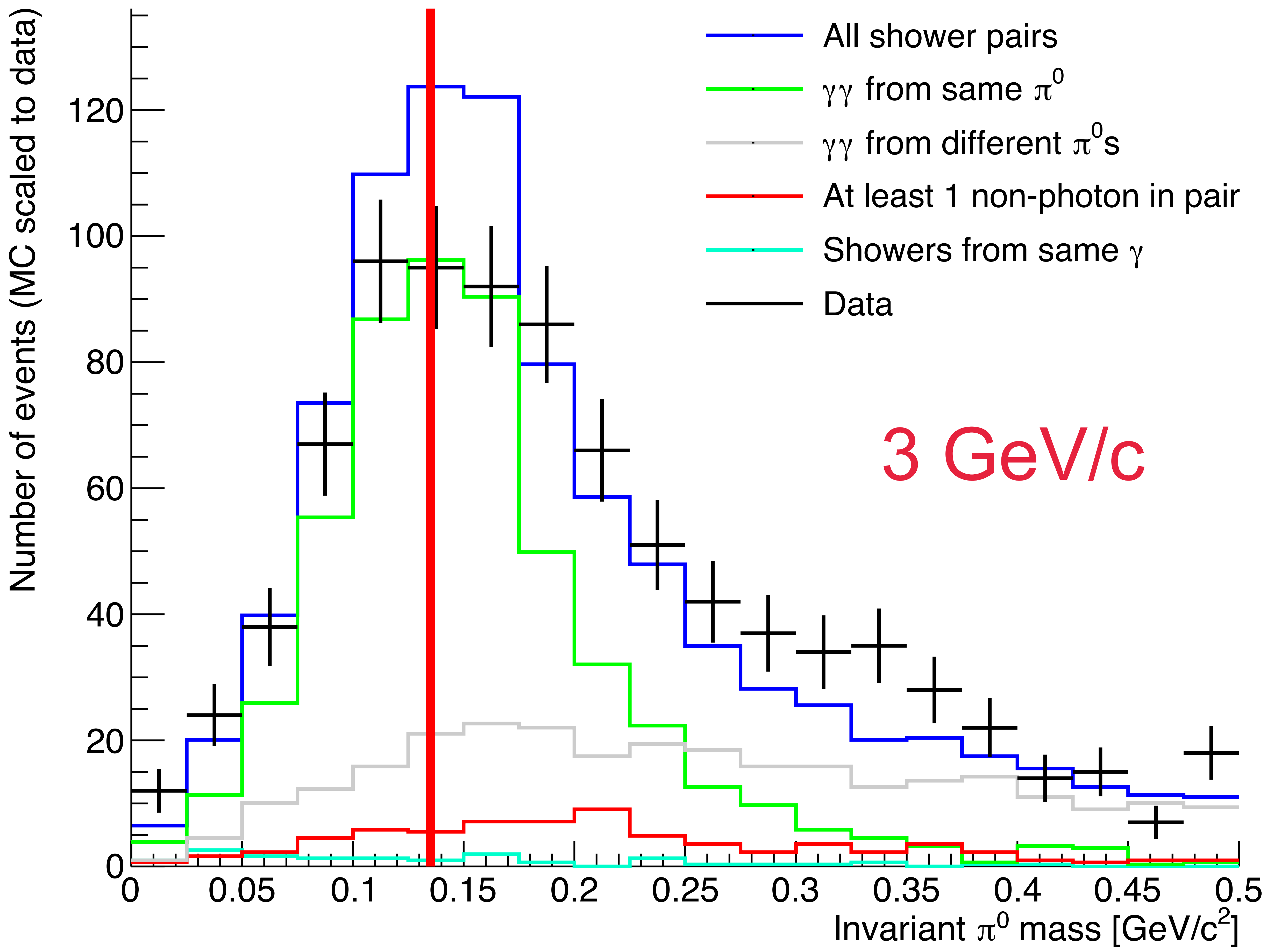
- Very clear peak around 135 MeV/c^2
- Width of signal peak from energy / angle reconstruction
- Main background from multiple π^0 events



Π⁰ INVARIANT MASS – RESULTS

Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50
Number of cylinder hits	> 1
Angle between showers	< 1 rad

- Easiest solution: look at lower energy events
- Fewer π^0 produced at once
- Great purity, lower statistics



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π⁰ INVARIANT MASS – CALIBRATION

Pandora classification	shower
Particle CNN score	> 0.6
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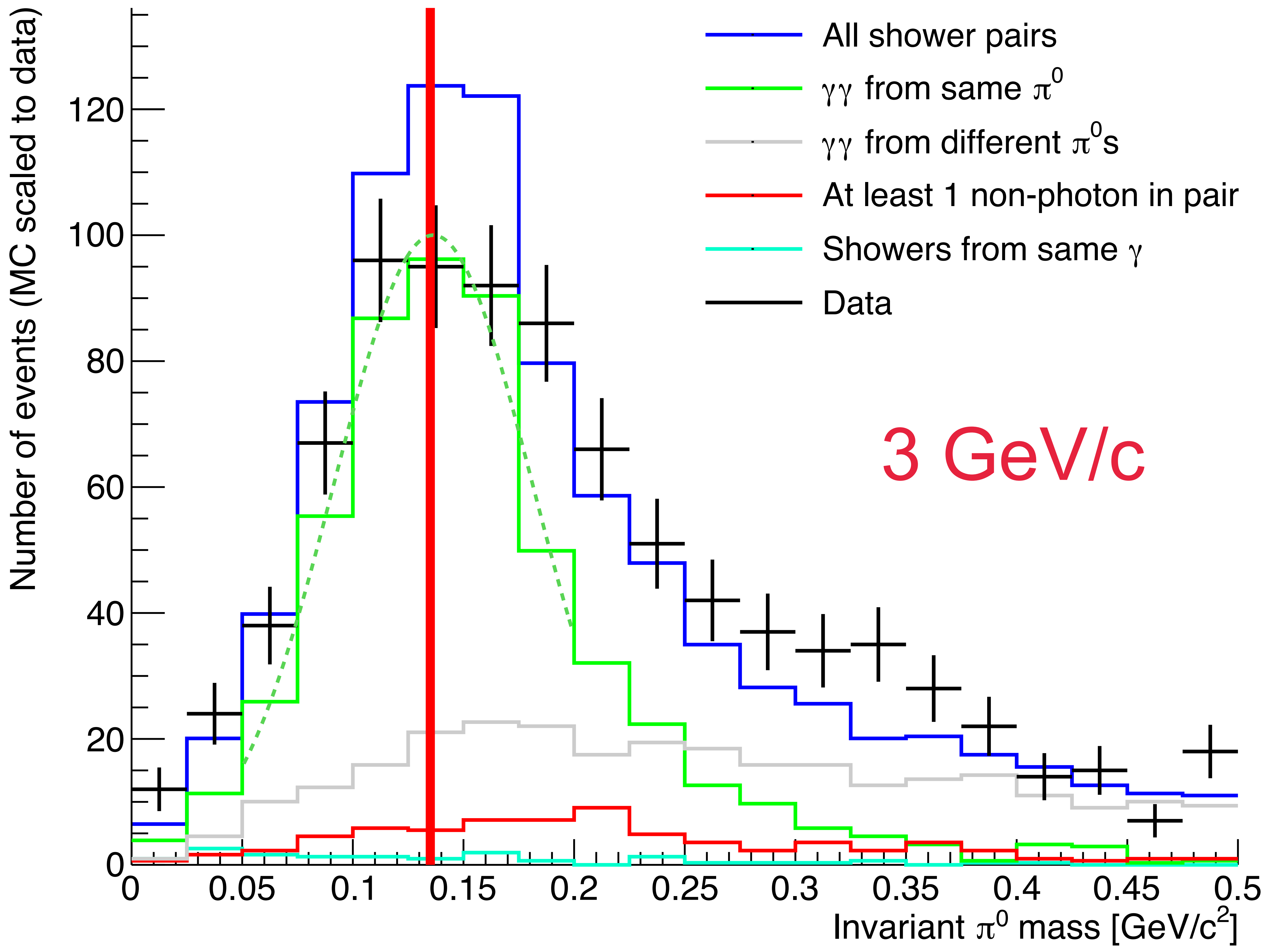
- Step 1: find correction in MC from good shower pairs
  - Align peak with exact π^0 mass
  - After aligning shower energy by hand, only 1% offset remained



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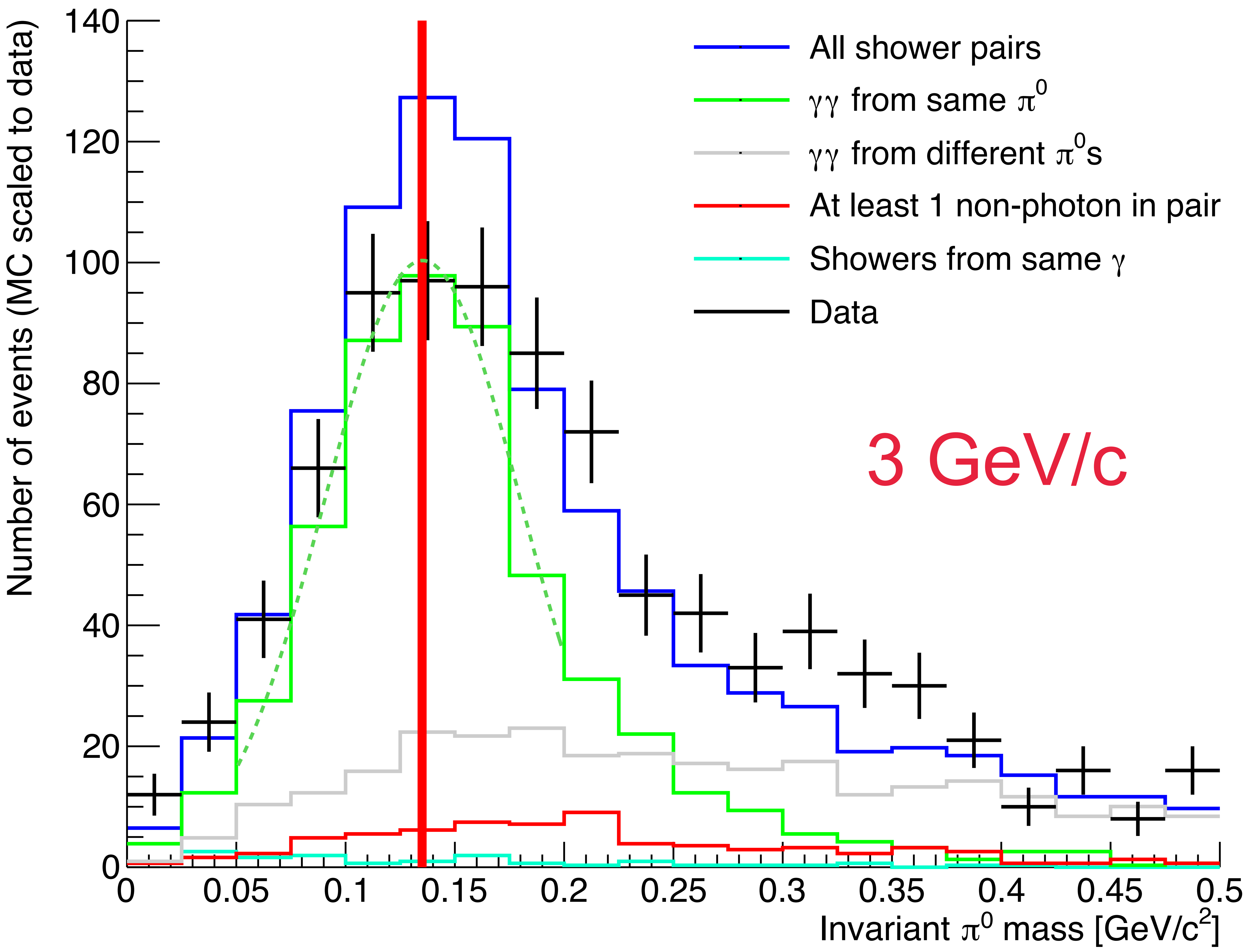

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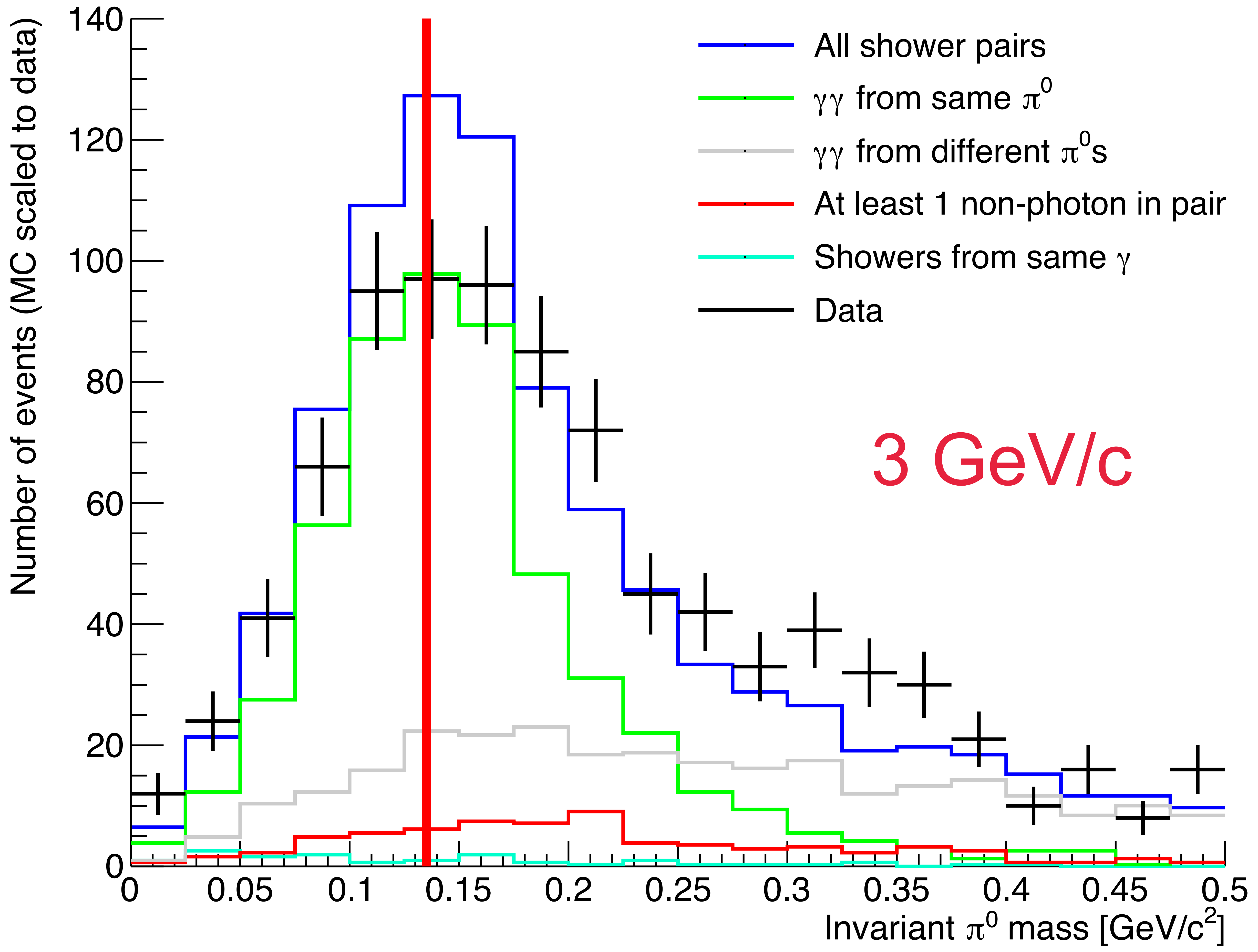
π⁰ INVARIANT MASS – CALIBRATION

Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50
Number of cylinder hits	> 1
Angle between showers	< 1 rad

- Step 2: fit data to MC (blue histogram)
  - Perform χ^2 test between data and MC for a range of biases



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π⁰ INVARIANT MASS – CALIBRATION

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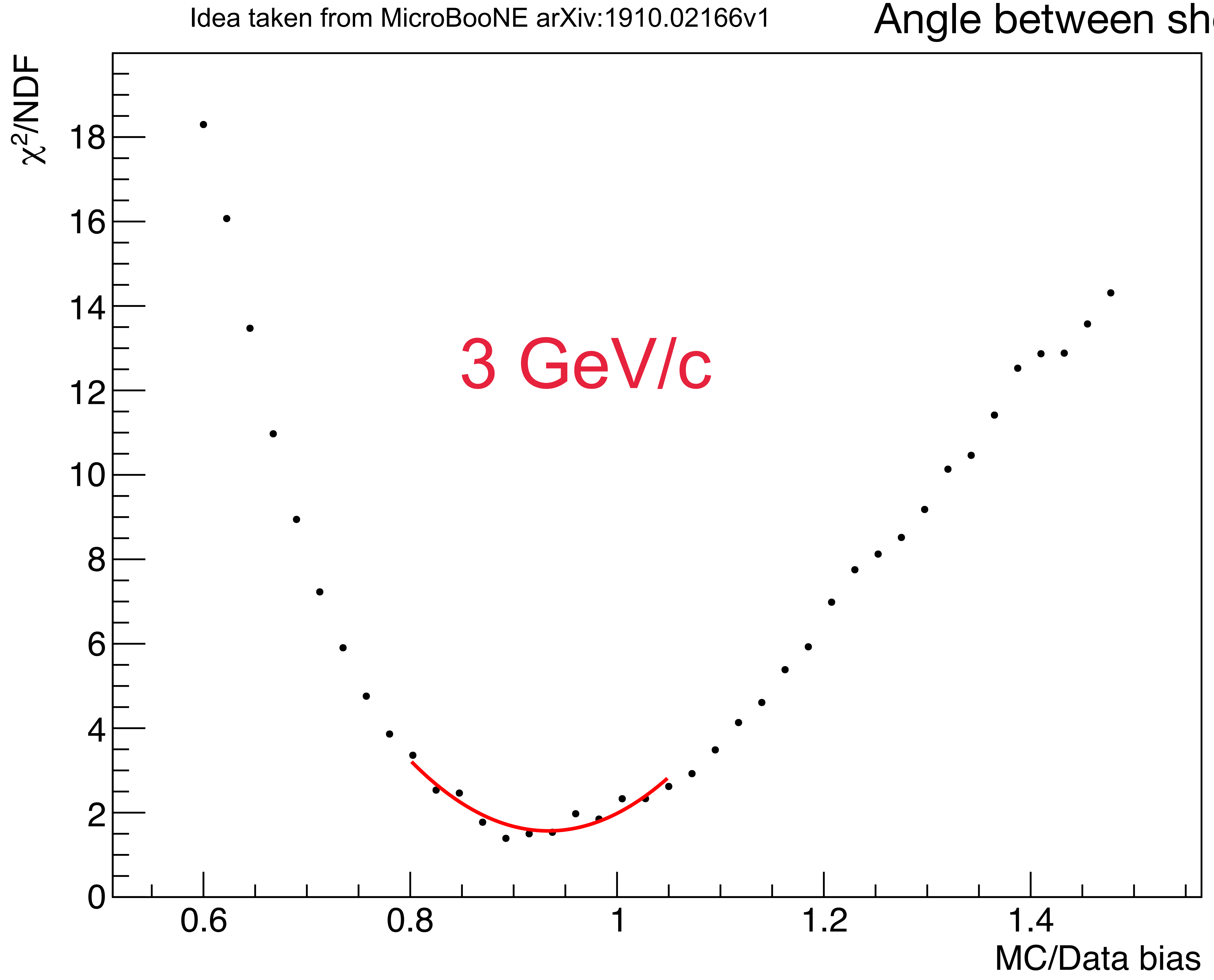
  - Dip approximated with parabola: central value of ~94%



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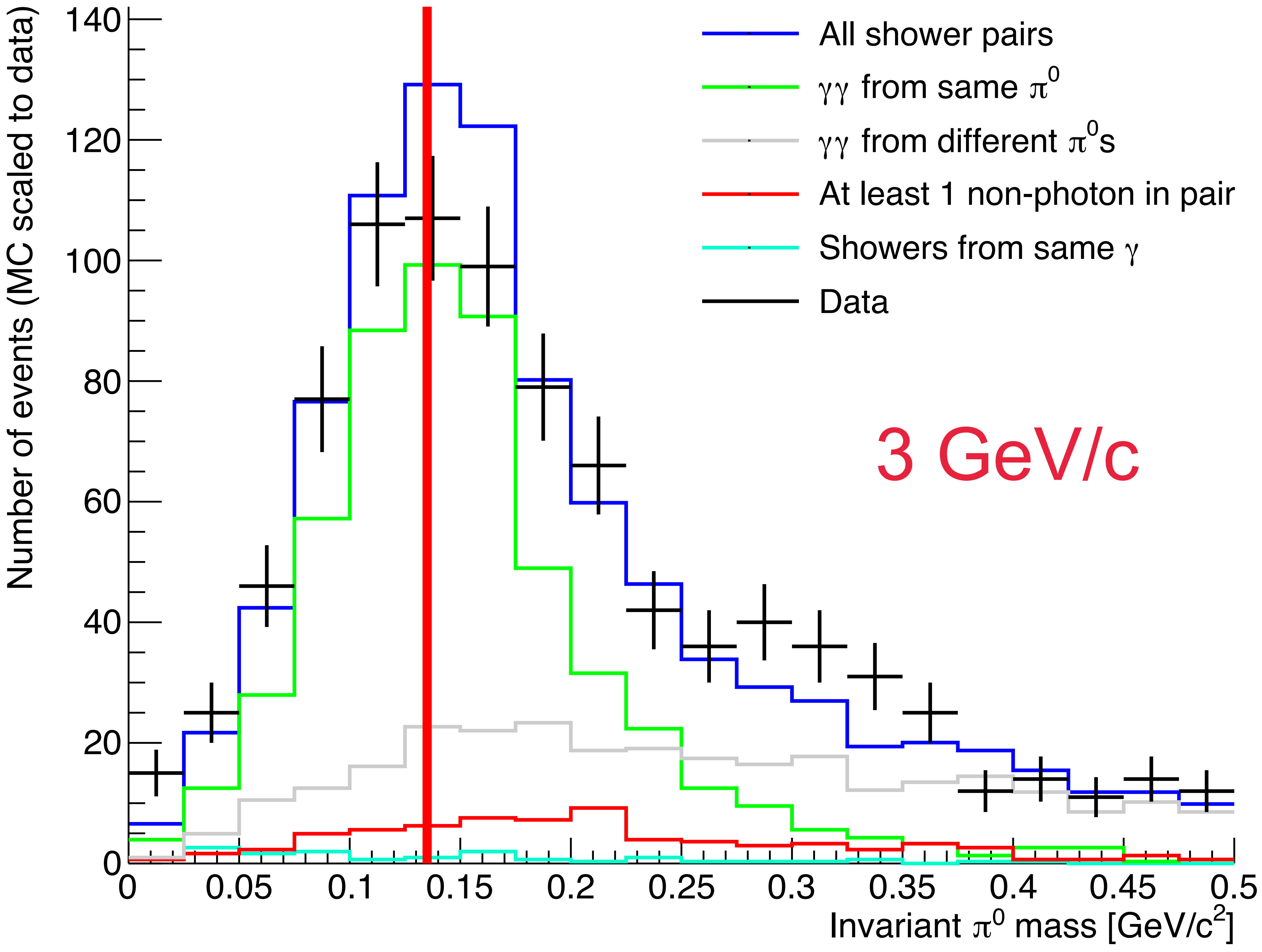

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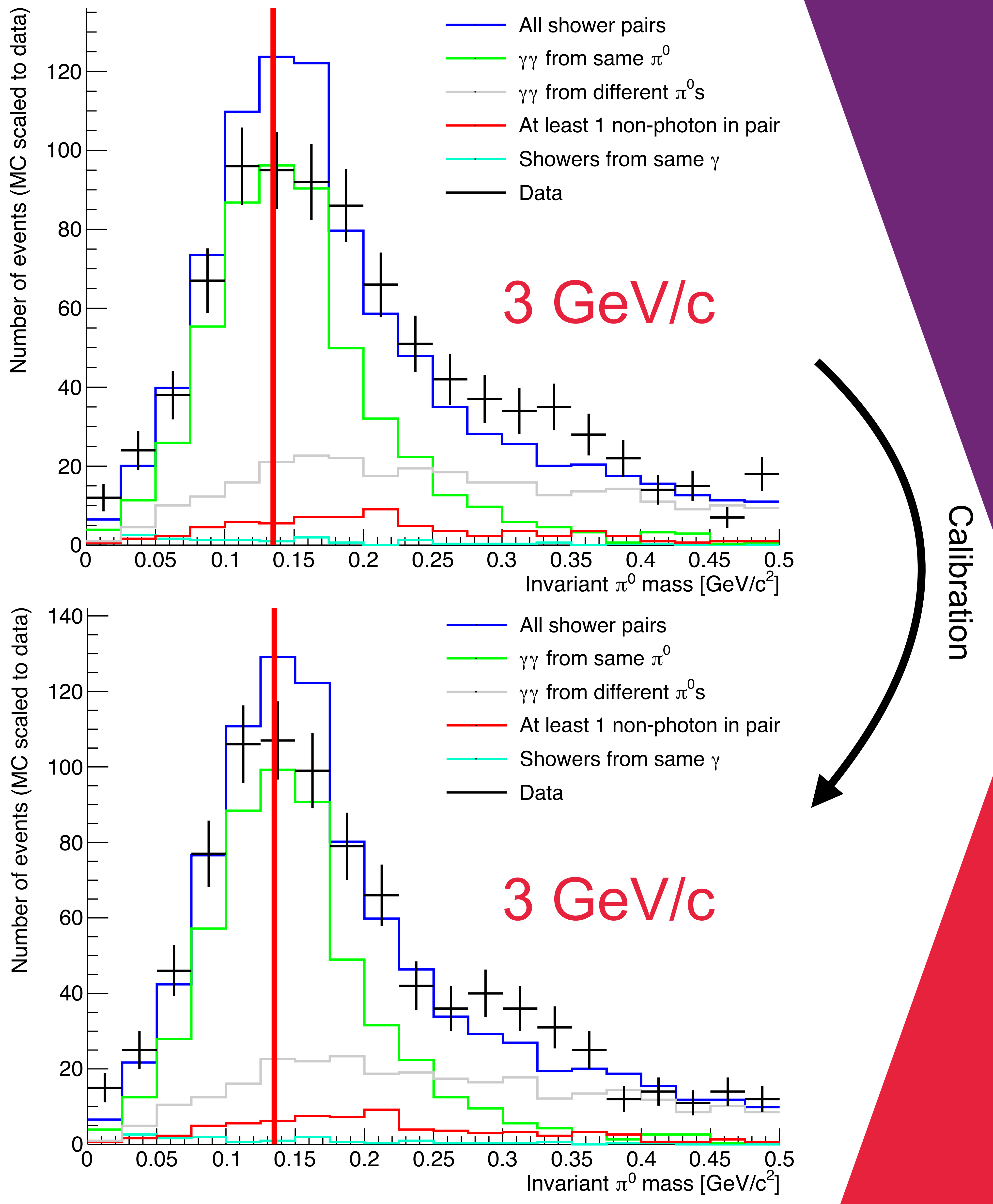
CONCLUSIONS

- Clear π^0 invariant mass peak
- Much to improve upon in terms of shower energy and direction reconstruction
- Energy bias between MC and data for this sample seems to be ~ 6 ± 0.5%
  - Likely partly due to other bias (angle, shower shape, …)



BACKUP

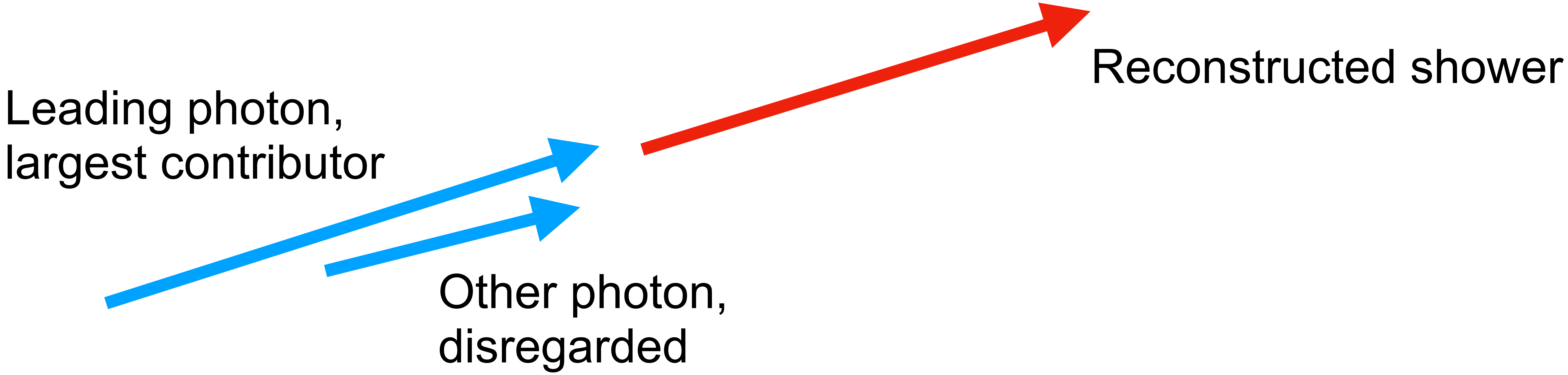
SAMPLE

- Used most of production 2 datasets

Beam momentum [GeV/c]	MC definition	Data definition
1	PDSPProd2_MC_1GeV_reco_sce_datadriven	protodune-sp_runset_5387_reco_v08_27_XX_v0
2	PDSPProd2_MC_2GeV_reco_sce_datadriven	protodune-sp_runset_5432_reco_v08_27_XX_v0
3	PDSPProd2_MC_3GeV_reco_sce_datadriven	protodune-sp_runset_5786_reco_v08_27_XX_v0
6	PDSPProd2_MC_6GeV_reco_sce_datadriven	protodune-sp_runset_5770_reco_v08_27_XX_v0
7	PDSPProd2_MC_7GeV_reco_sce_datadriven	protodune-sp_runset_5204_reco_v08_27_XX_v0

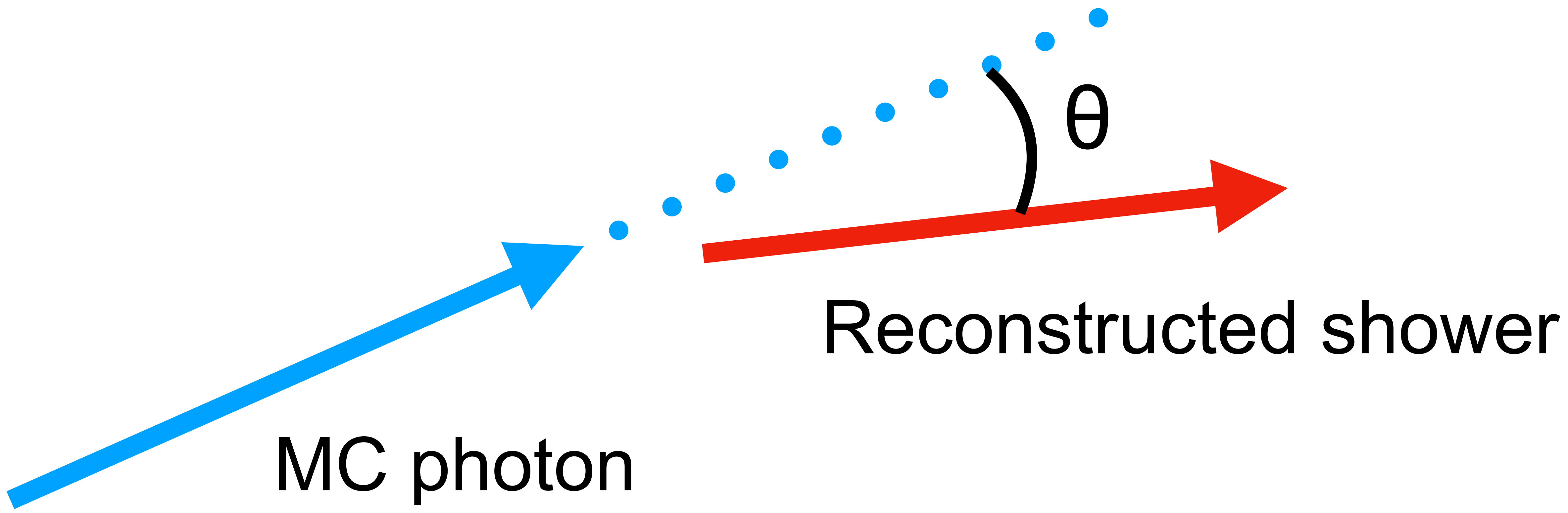
MC-RECO MATCHING

- Each reconstructed object is assigned one main MC contributor
- Based on highest number of hits contributed
- Origin of hits found through BackTracker

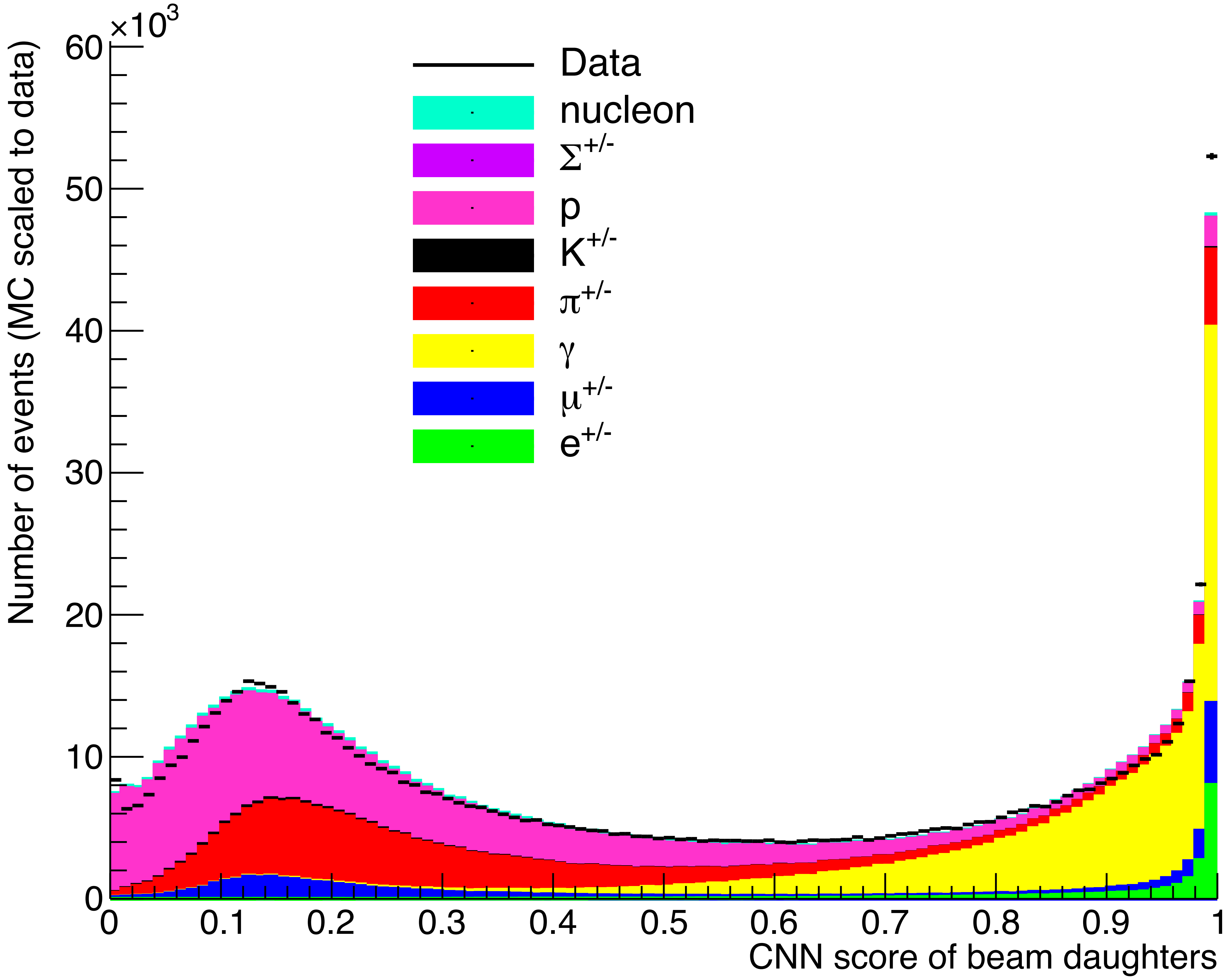


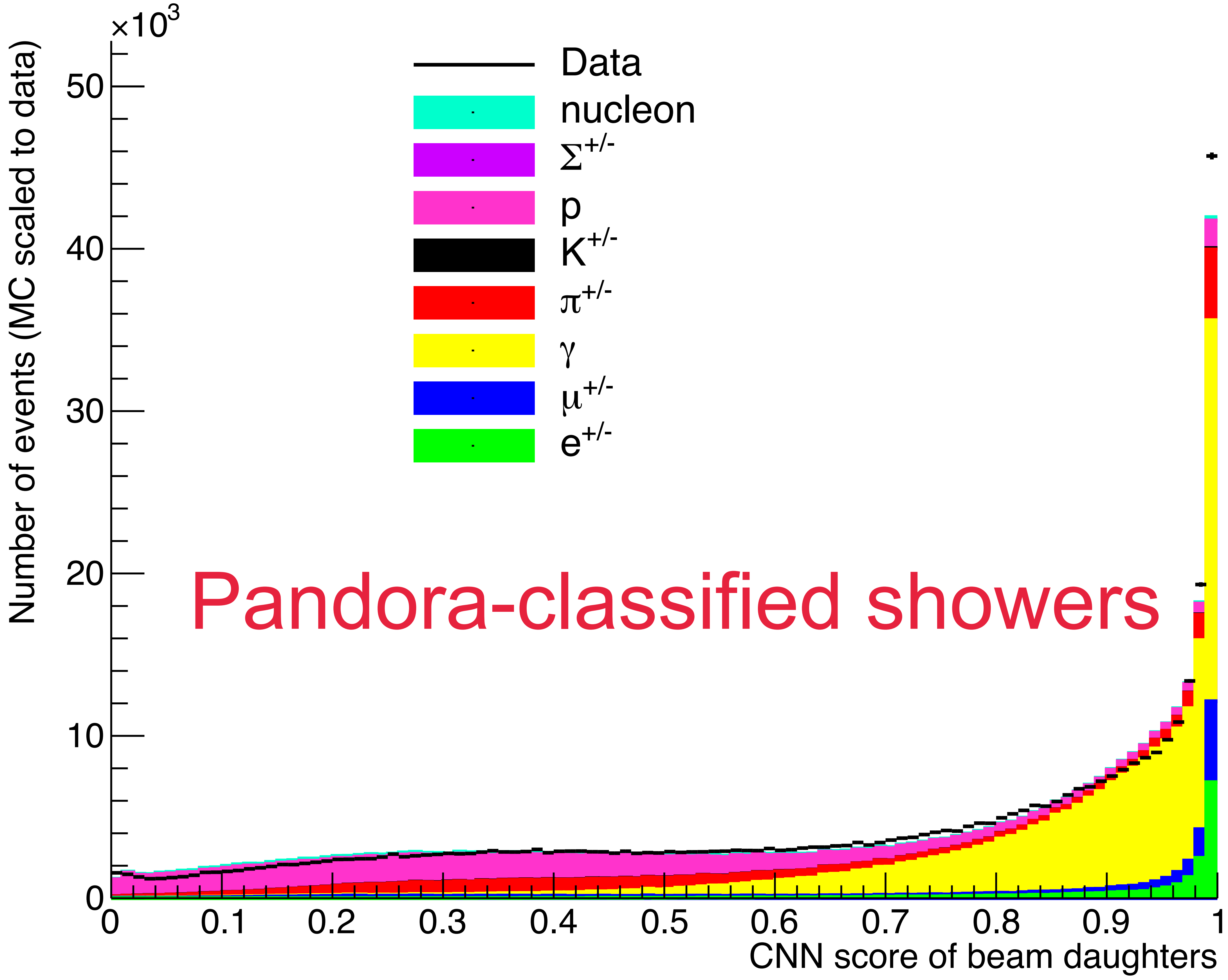
MC-RECO MATCHING

- Many useful properties from comparing reconstructed object to parent MCParticle
- Completeness, purity
- Relative energy difference $$\frac{E_{reco} - E_{MC}}{E_{MC}}$$
- Angle between MC and reconstructed particle



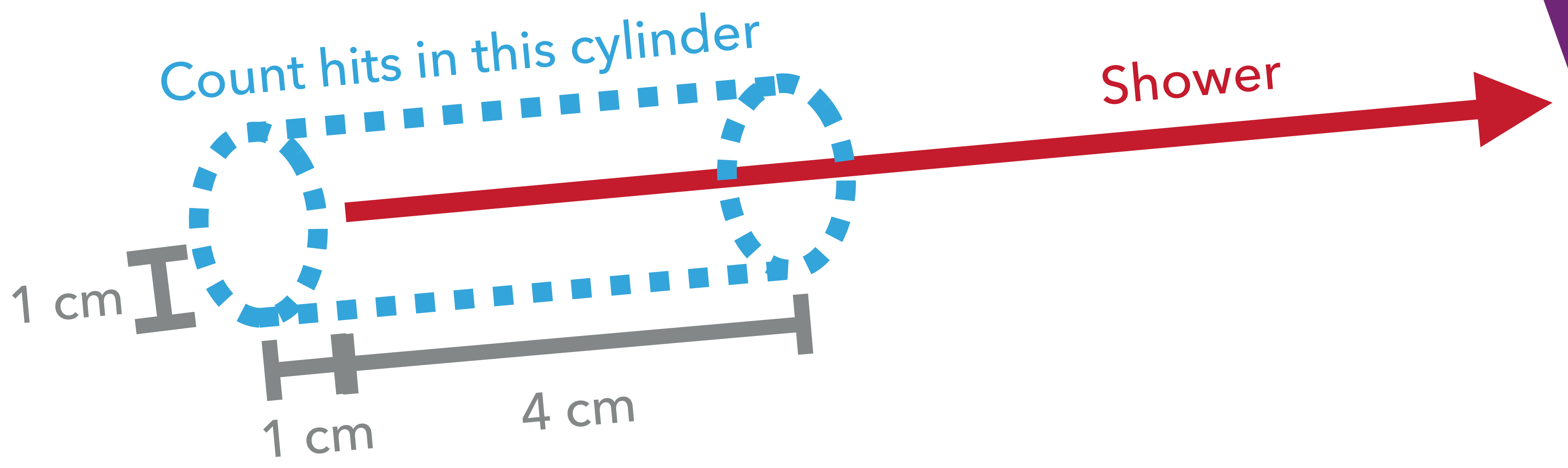
SHOWER CNN SCORE

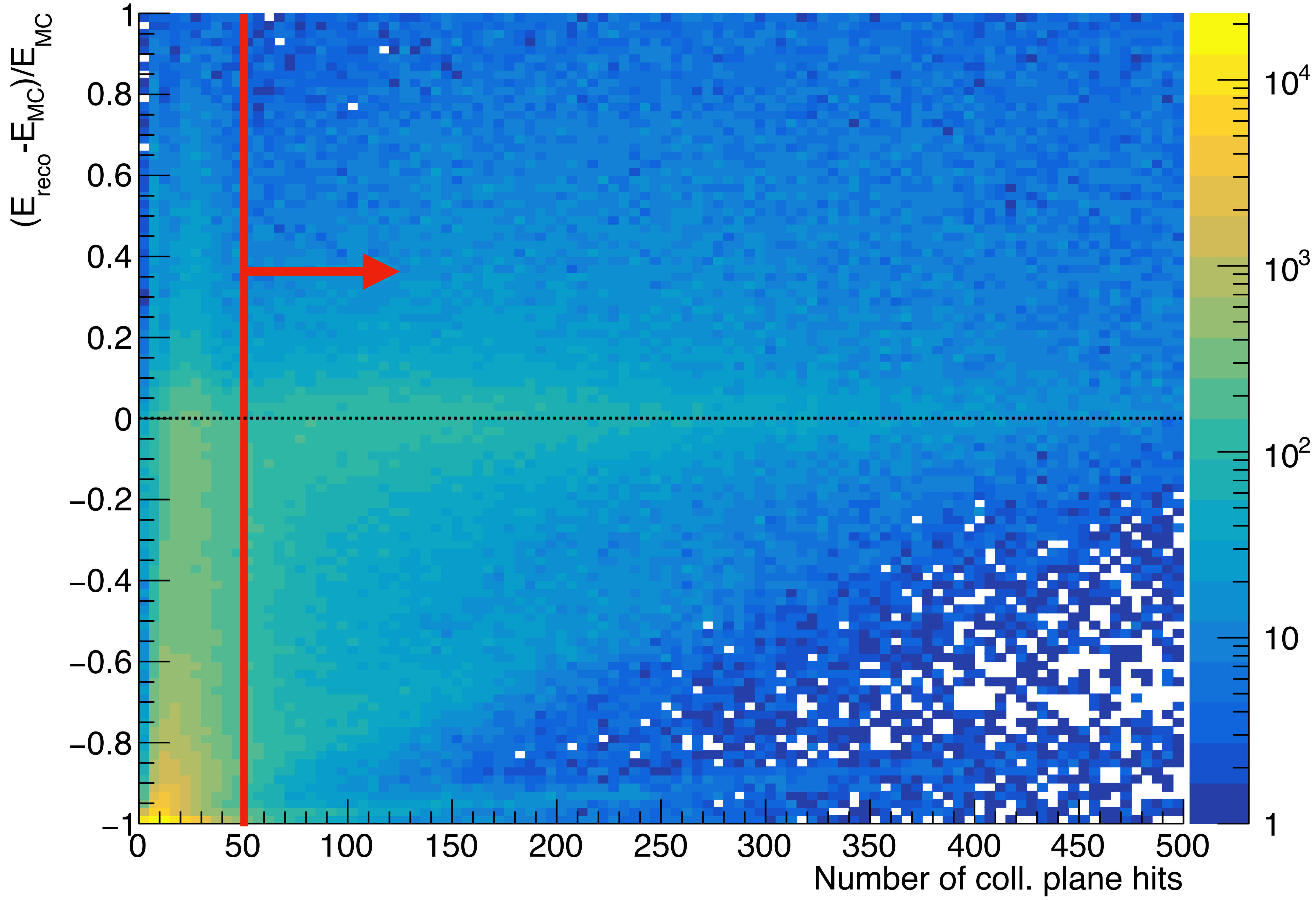


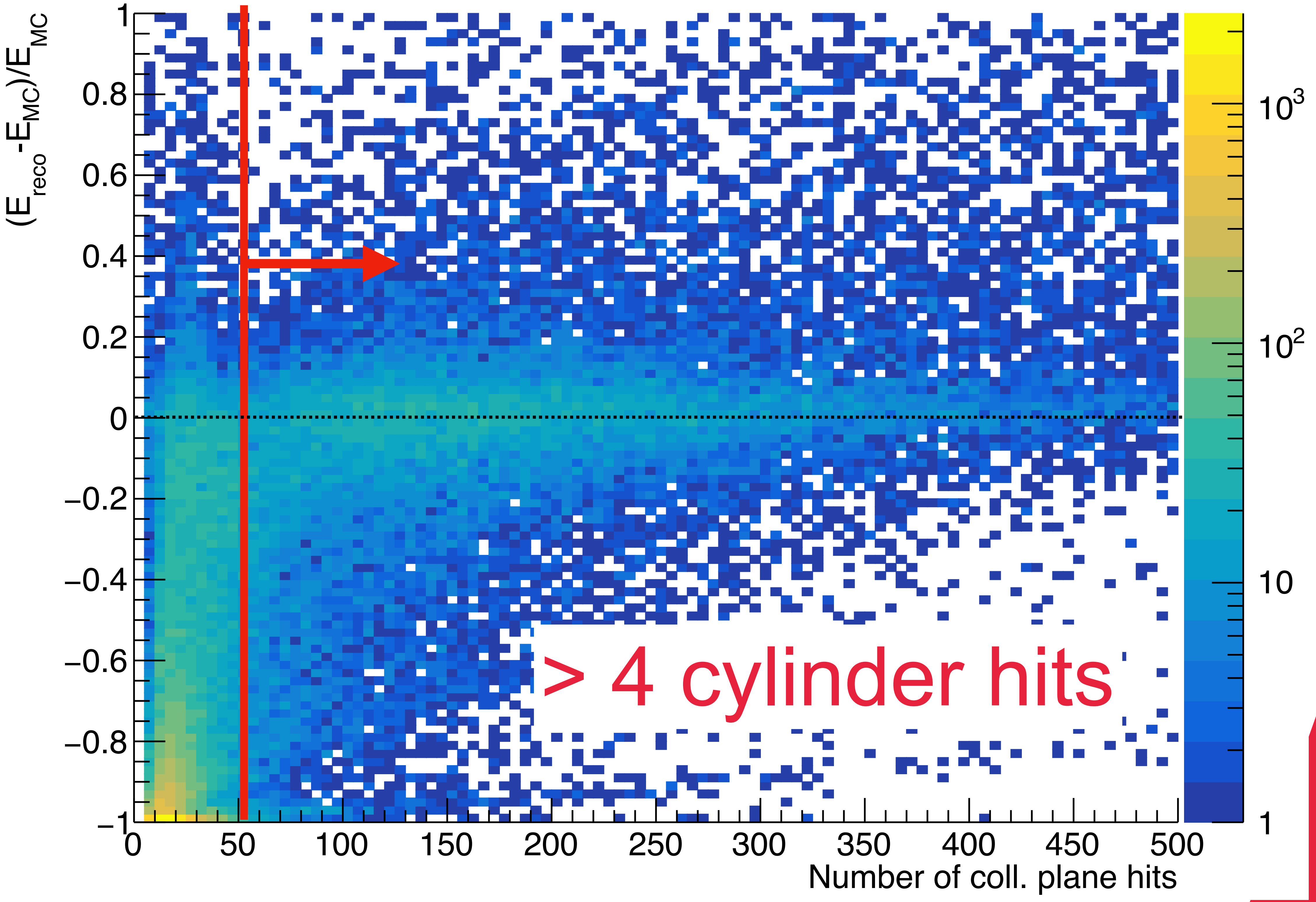


SHOWER ENERGY RECO QUALITY

- Requiring hits near start of shower improves quality of sample



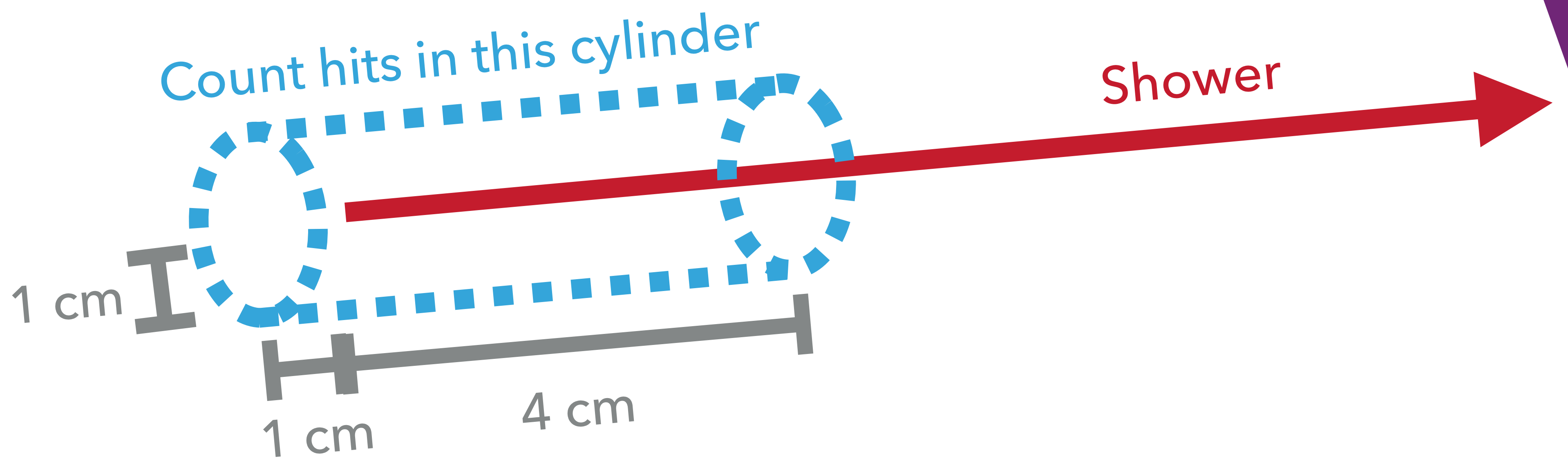


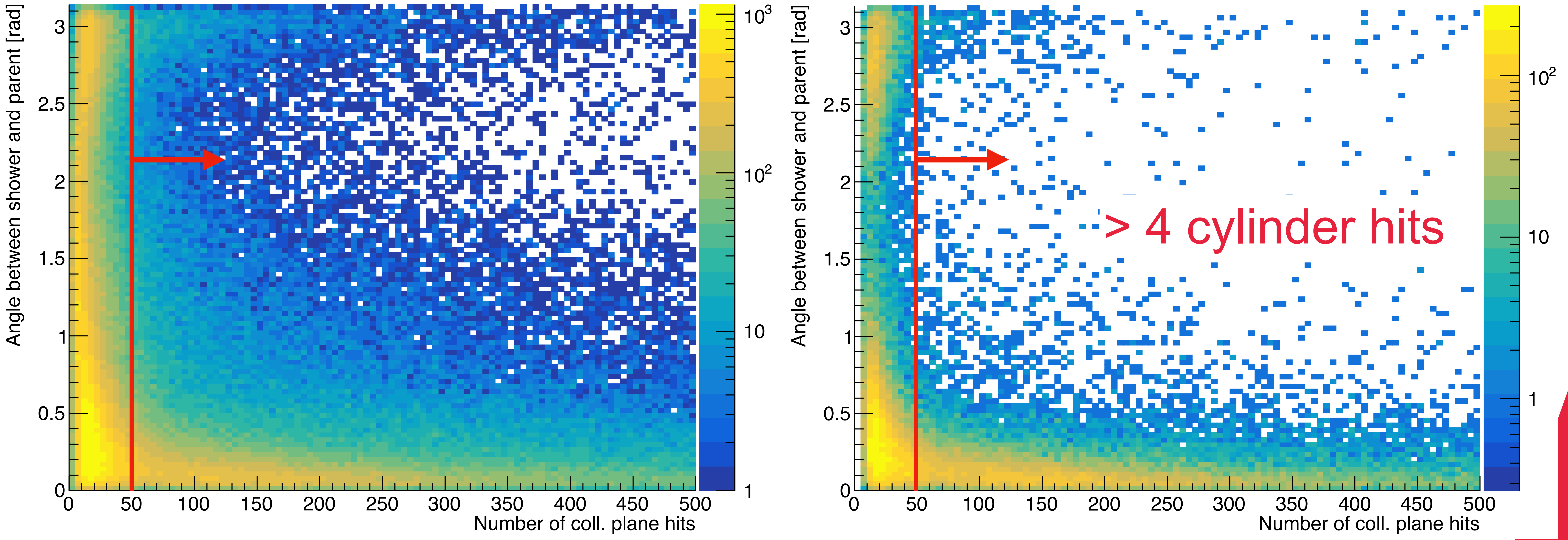


Pandora classification	shower
Particle CNN score	> 0.6

SHOWER DIRECTION RECO QUALITY

- Requiring hits near start of shower improves quality of sample





Pandora classification	shower
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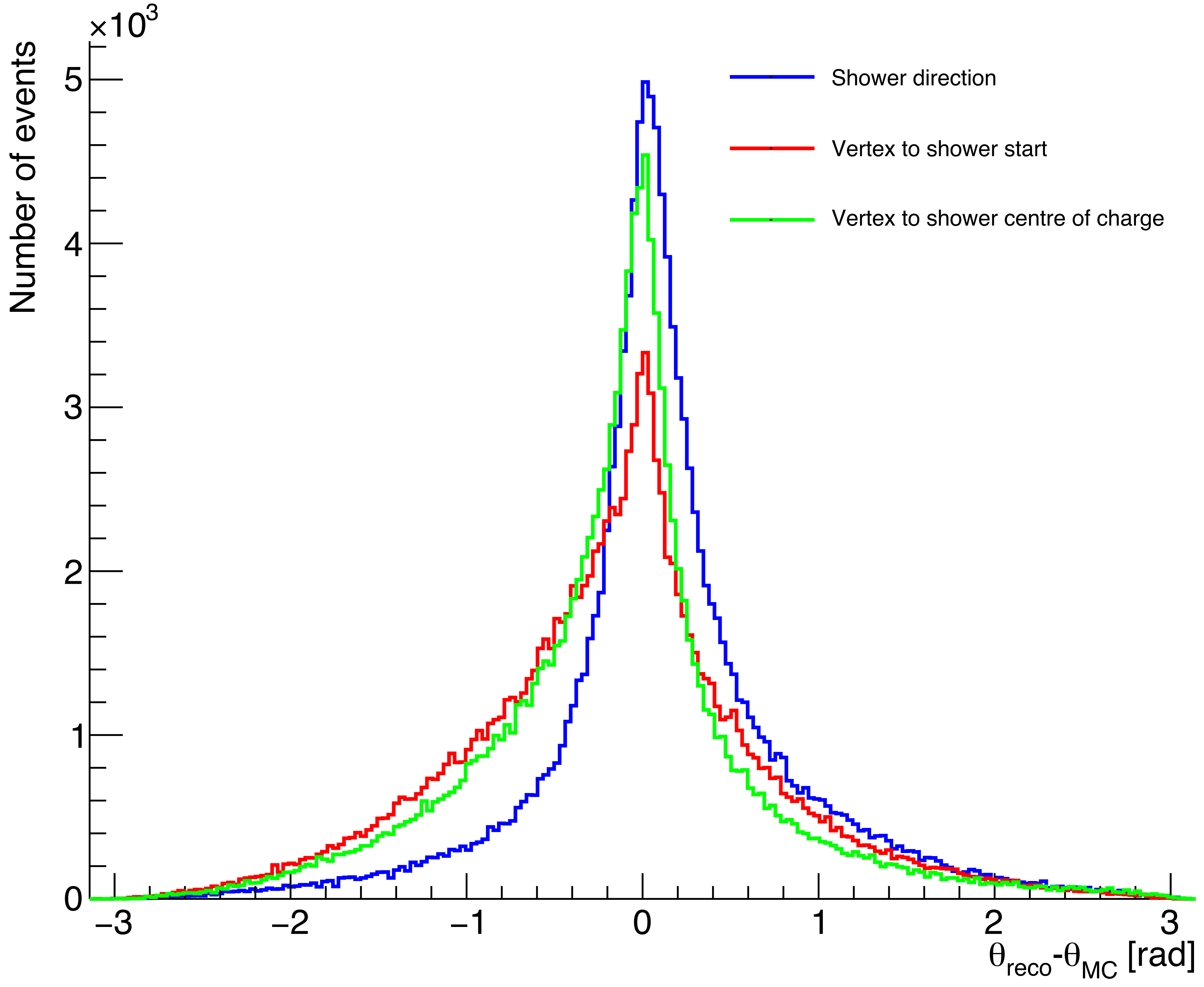
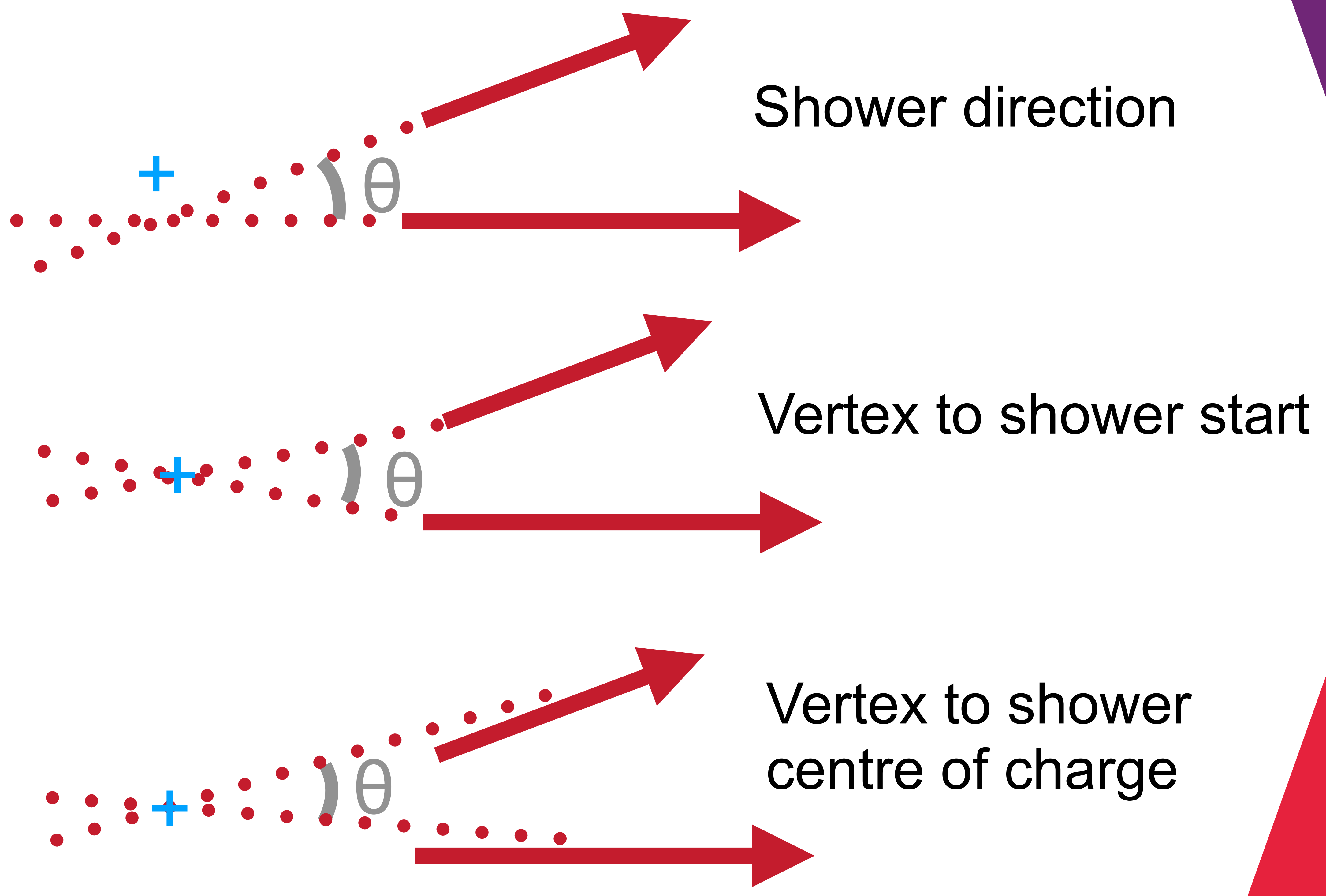
OPENING ANGLE RECO QUALITY

- Various ways to determine photon opening angle





+ = MC π^0 vertex

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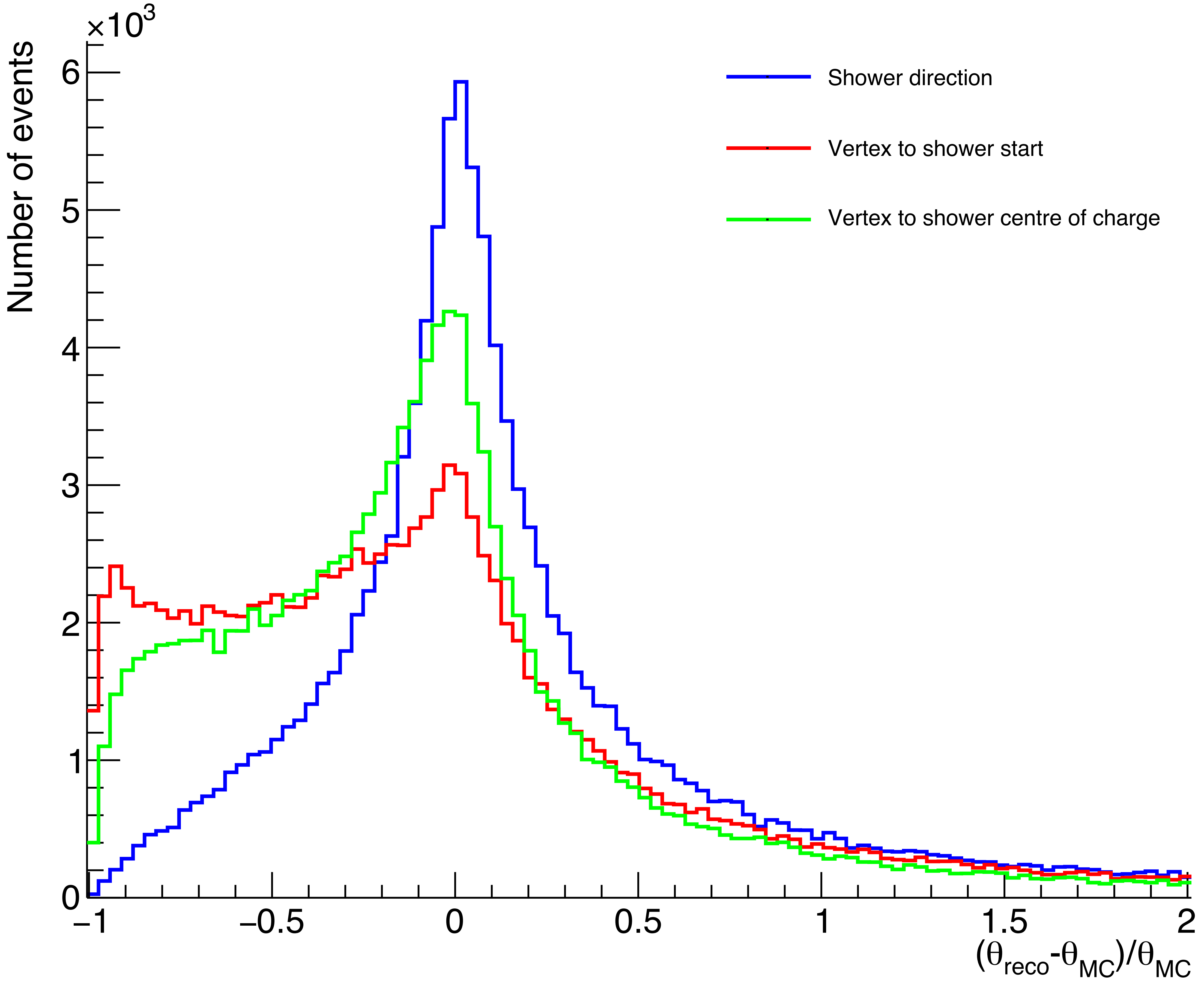
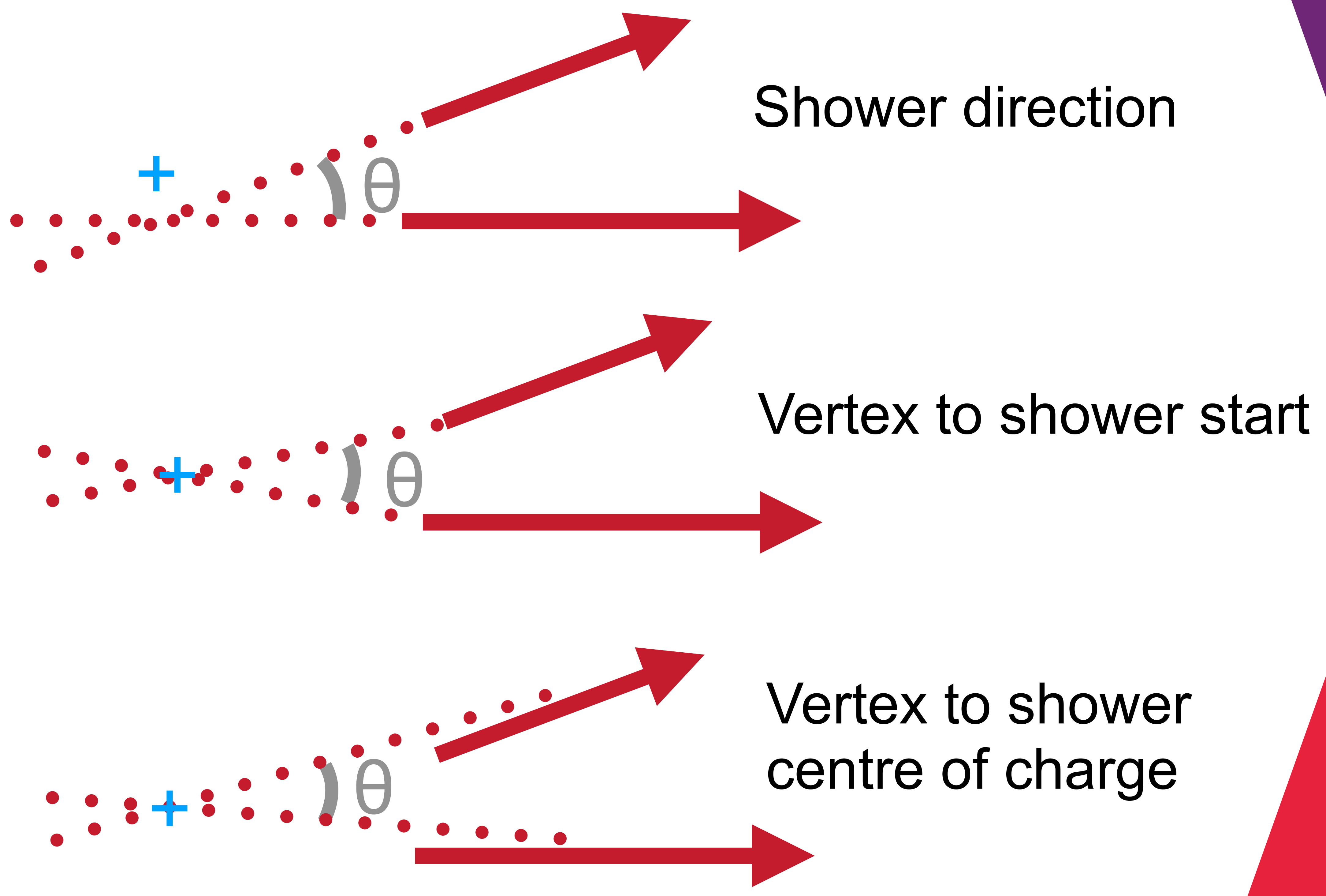
OPENING ANGLE RECO QUALITY

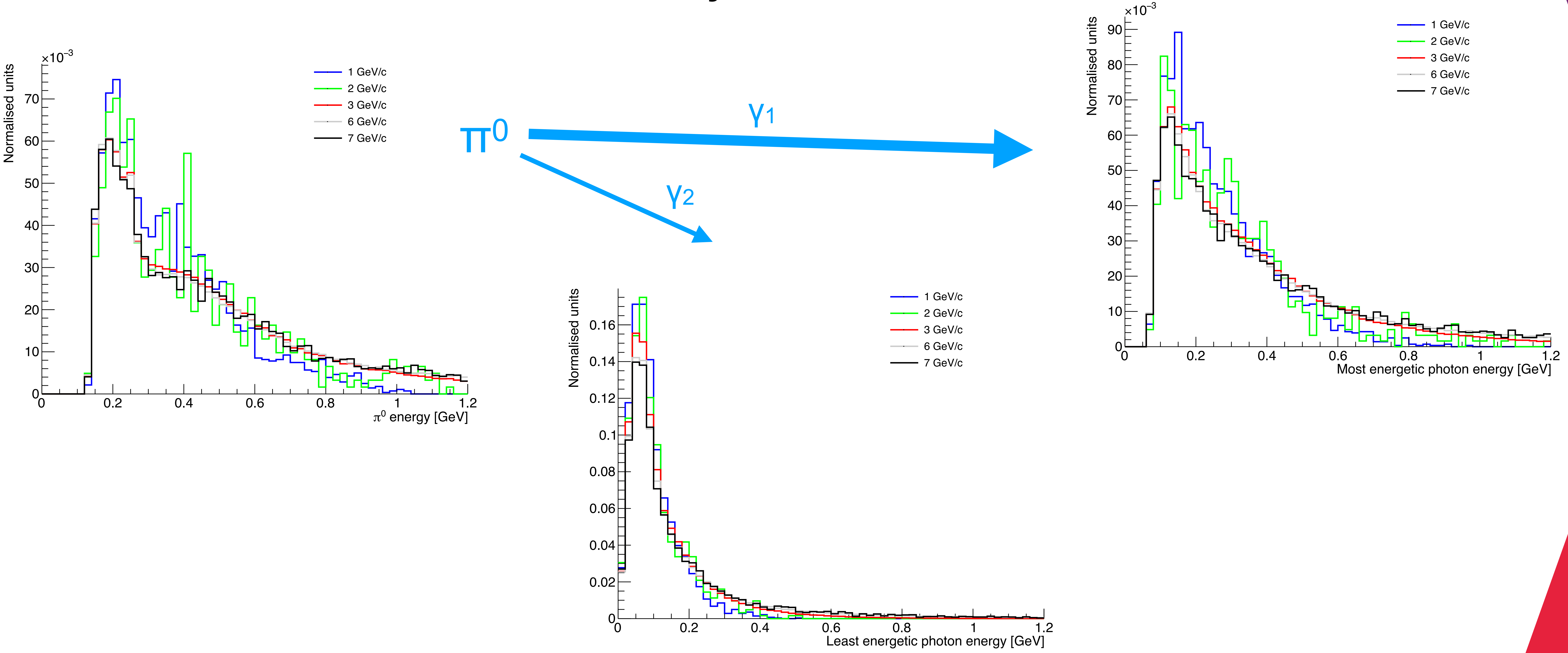
- Various ways to determine photon opening angle





RUN COMPARISONS (FROM MC)

- π^0 events between runs very similar



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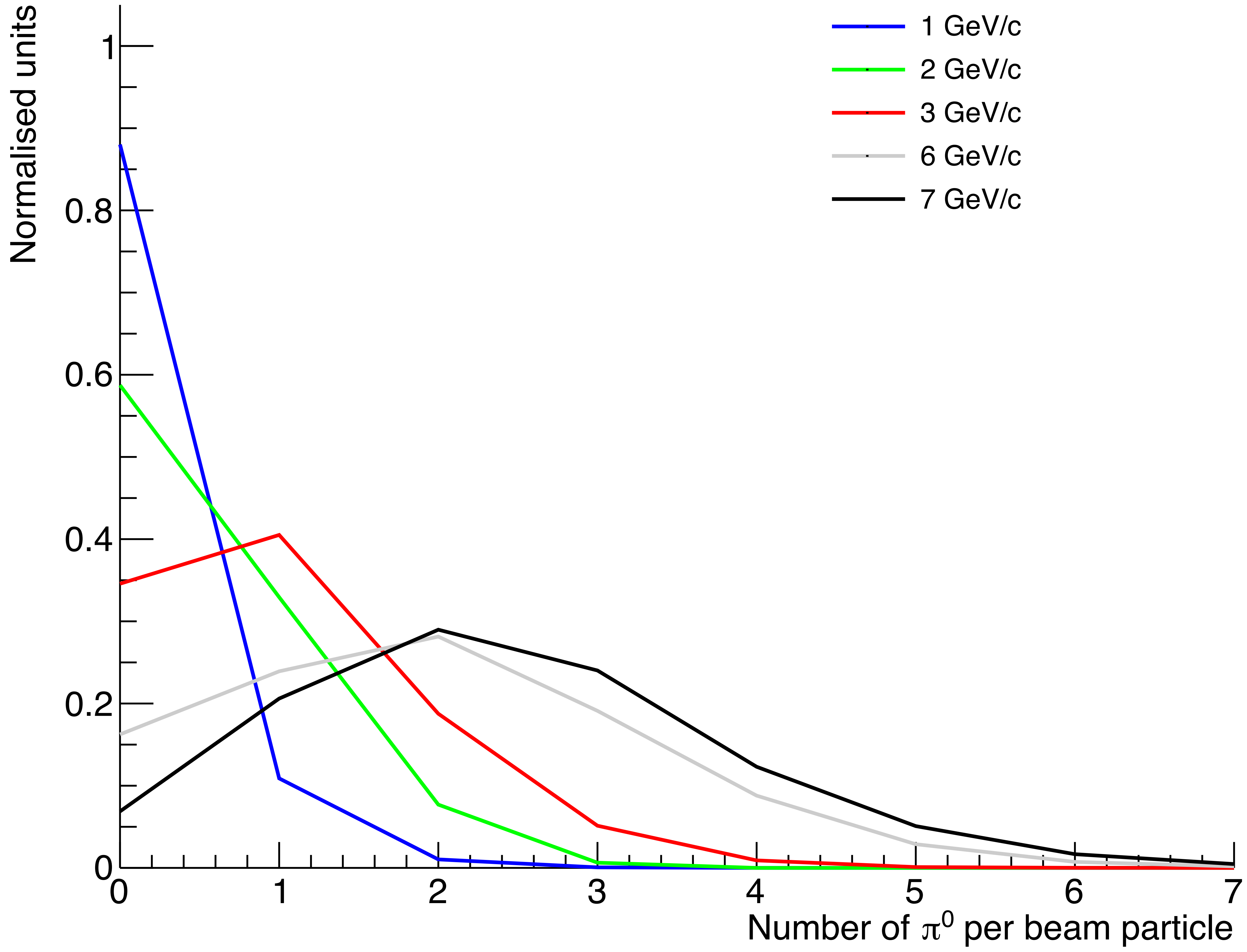
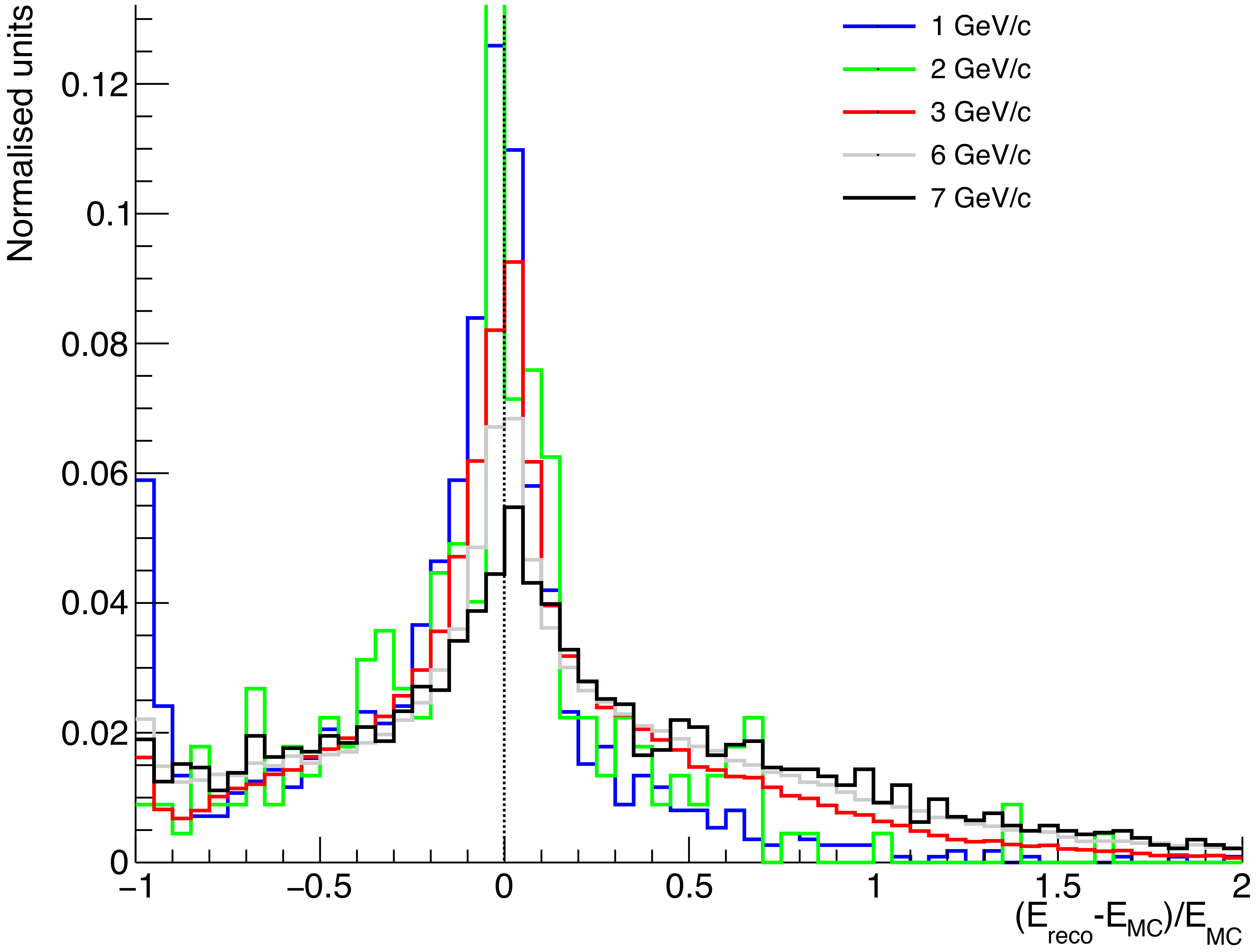
RUN COMPARISONS (FROM MC)

- Number of π^0s per event differs a lot
- Clear increase in π^0 production at higher beam momenta

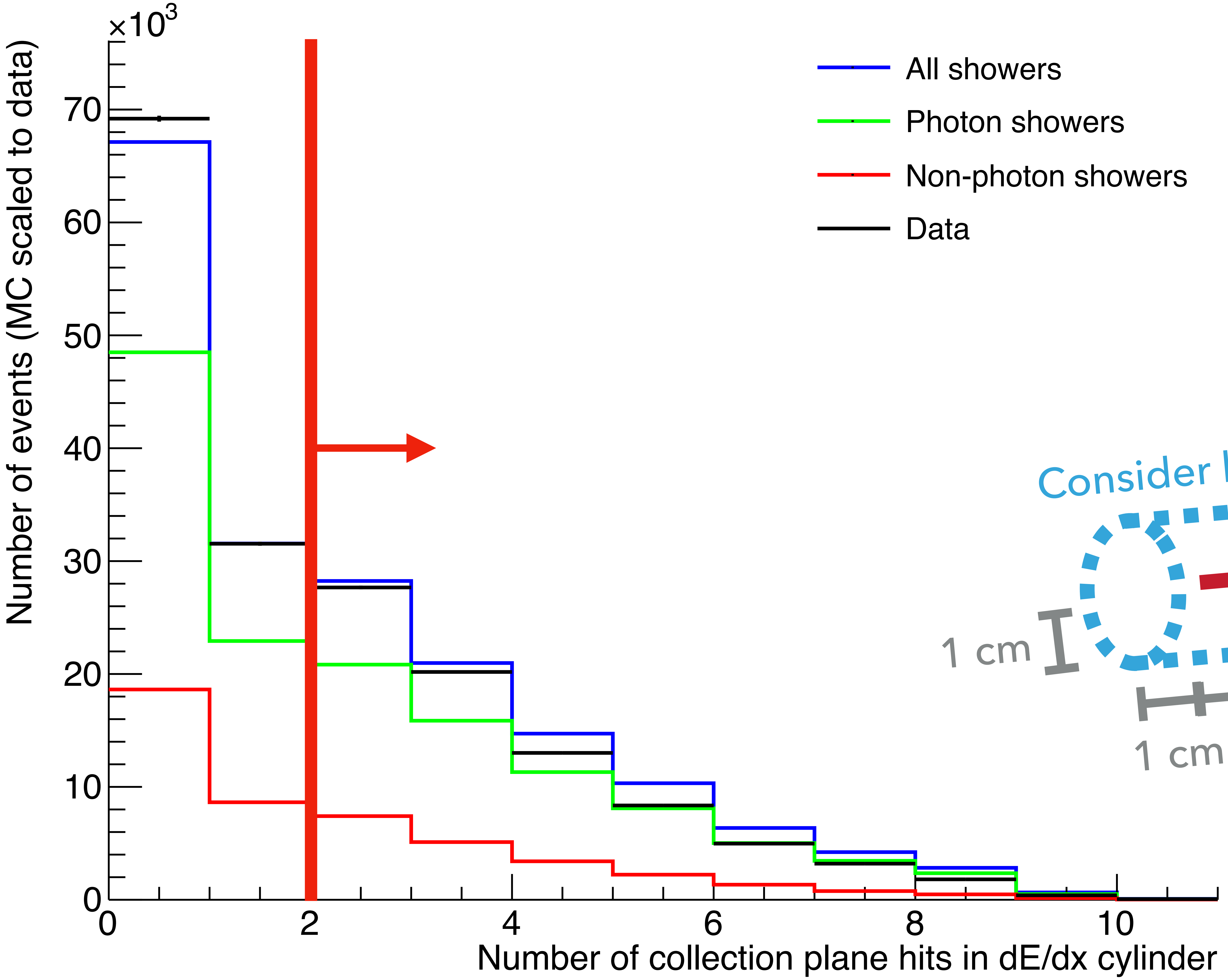


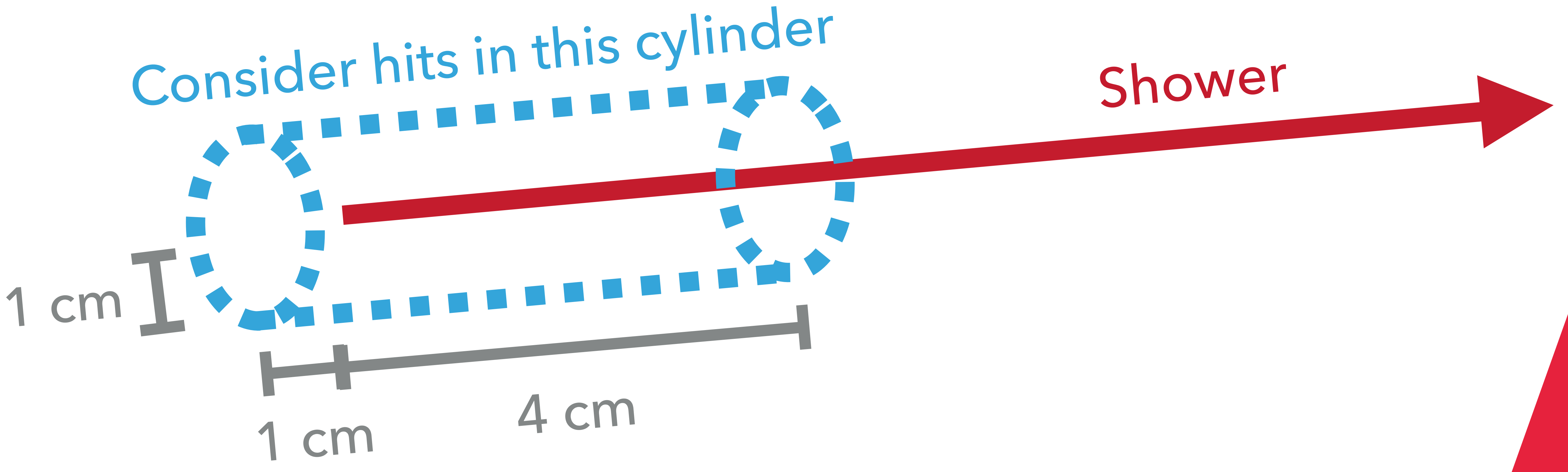
RUN COMPARISONS (FROM MC)

- Energy reconstruction according to modified box model
- Method described in DocDB 18355
- Energy losses of ~15% taken into account

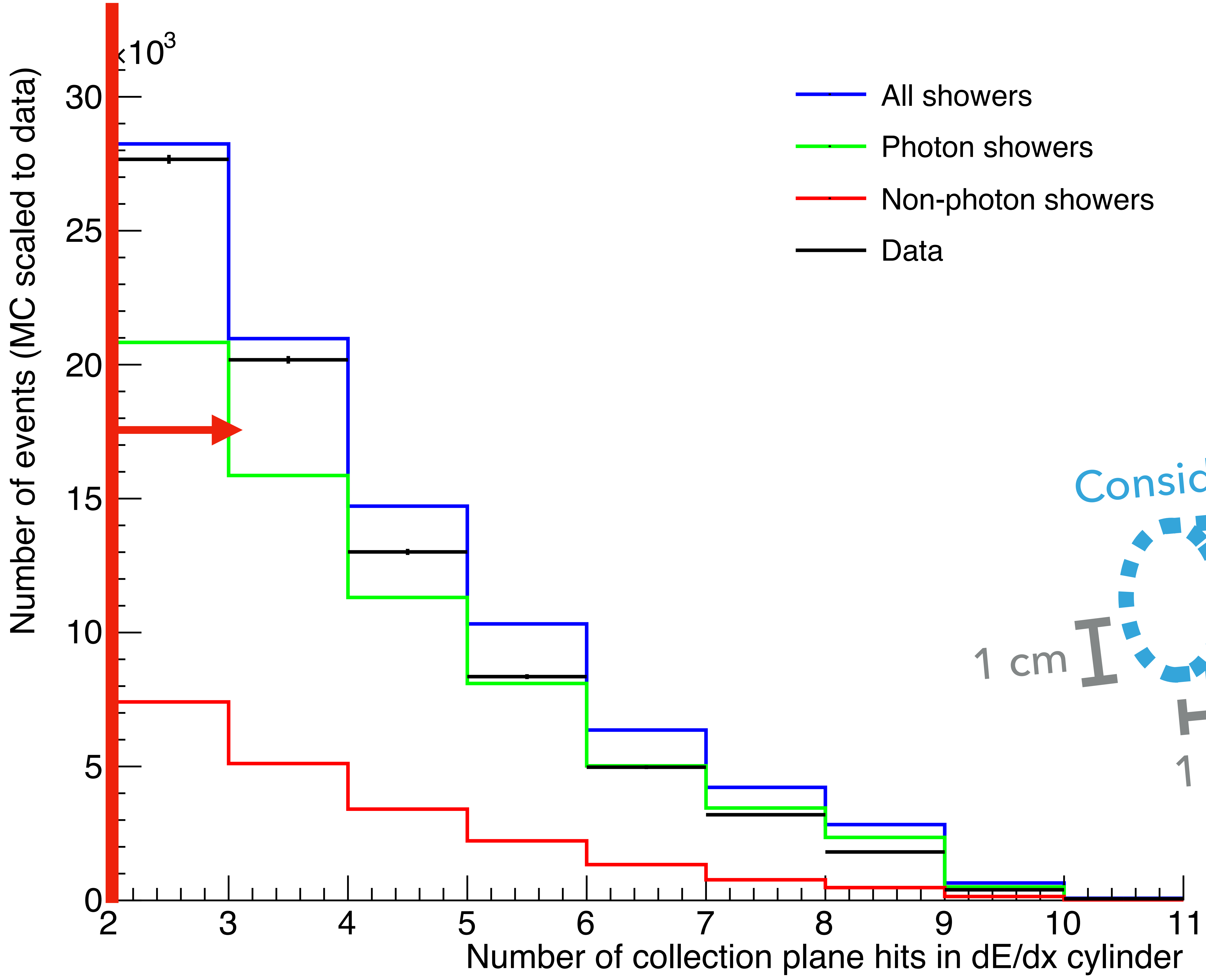


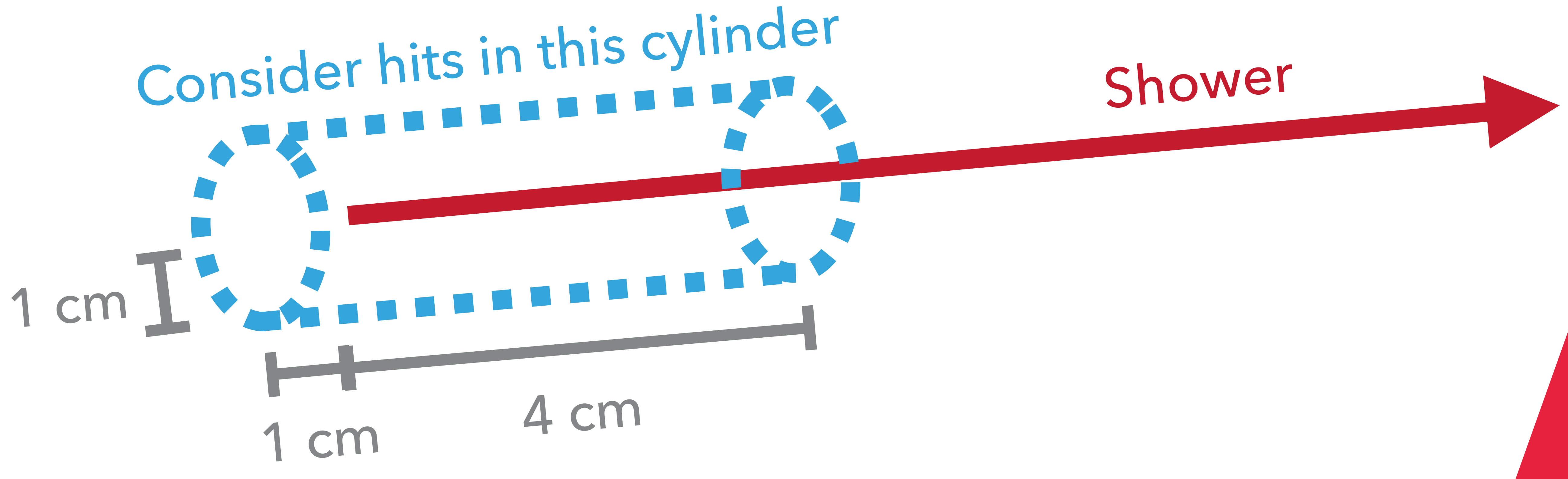
SHOWER SELECTION – CYLINDER HITS





SHOWER SELECTION – CYLINDER HITS

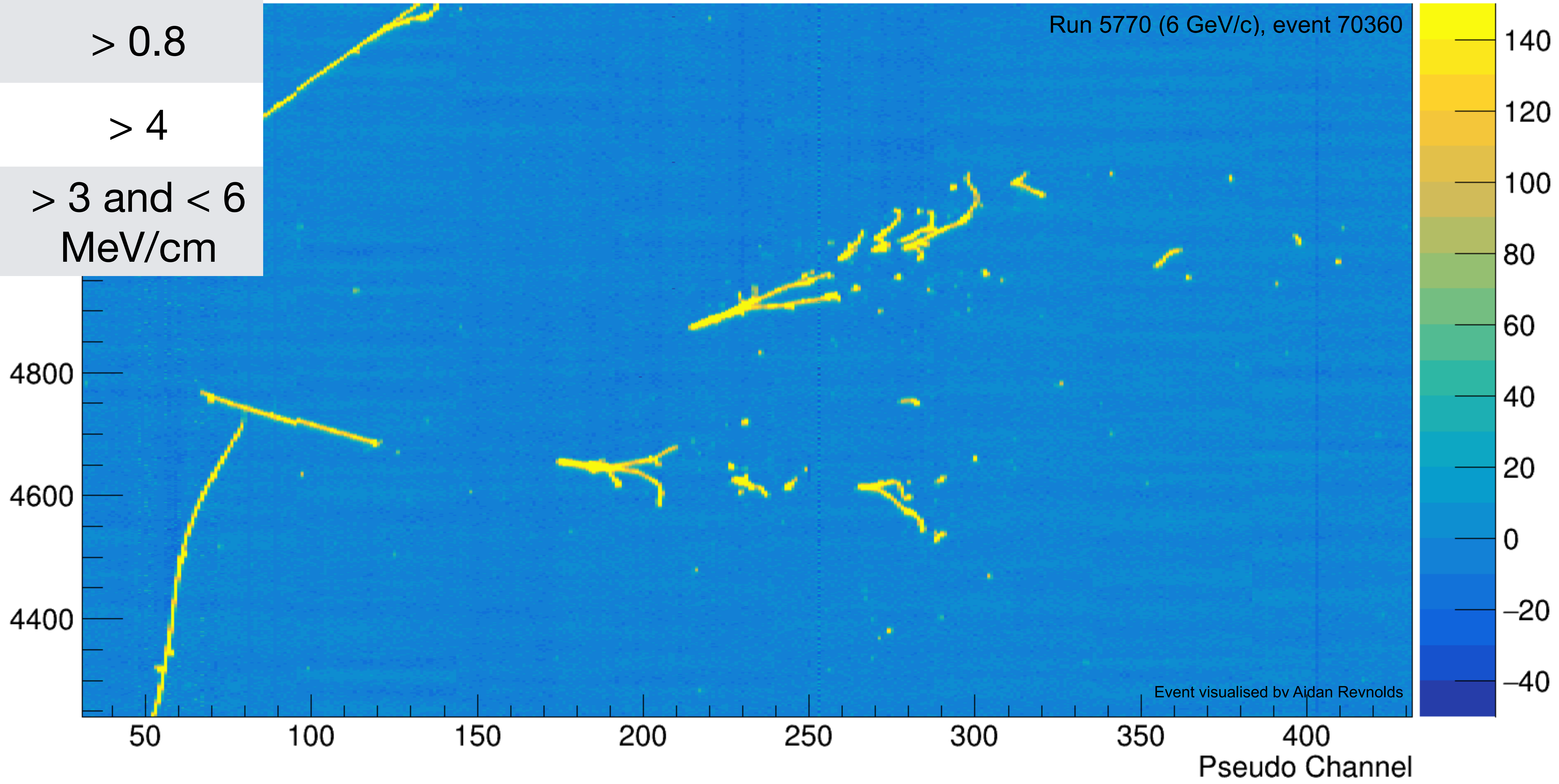




π^0 INVARIANT MASS – CUTS

Used extra tough cuts to select this nice event:

Number of shower hits	> 50
Shower CNN score	> 0.8
Hits included in cylinder	> 4
Median dE/dx	> 3 and < 6 MeV/cm



Nikhef

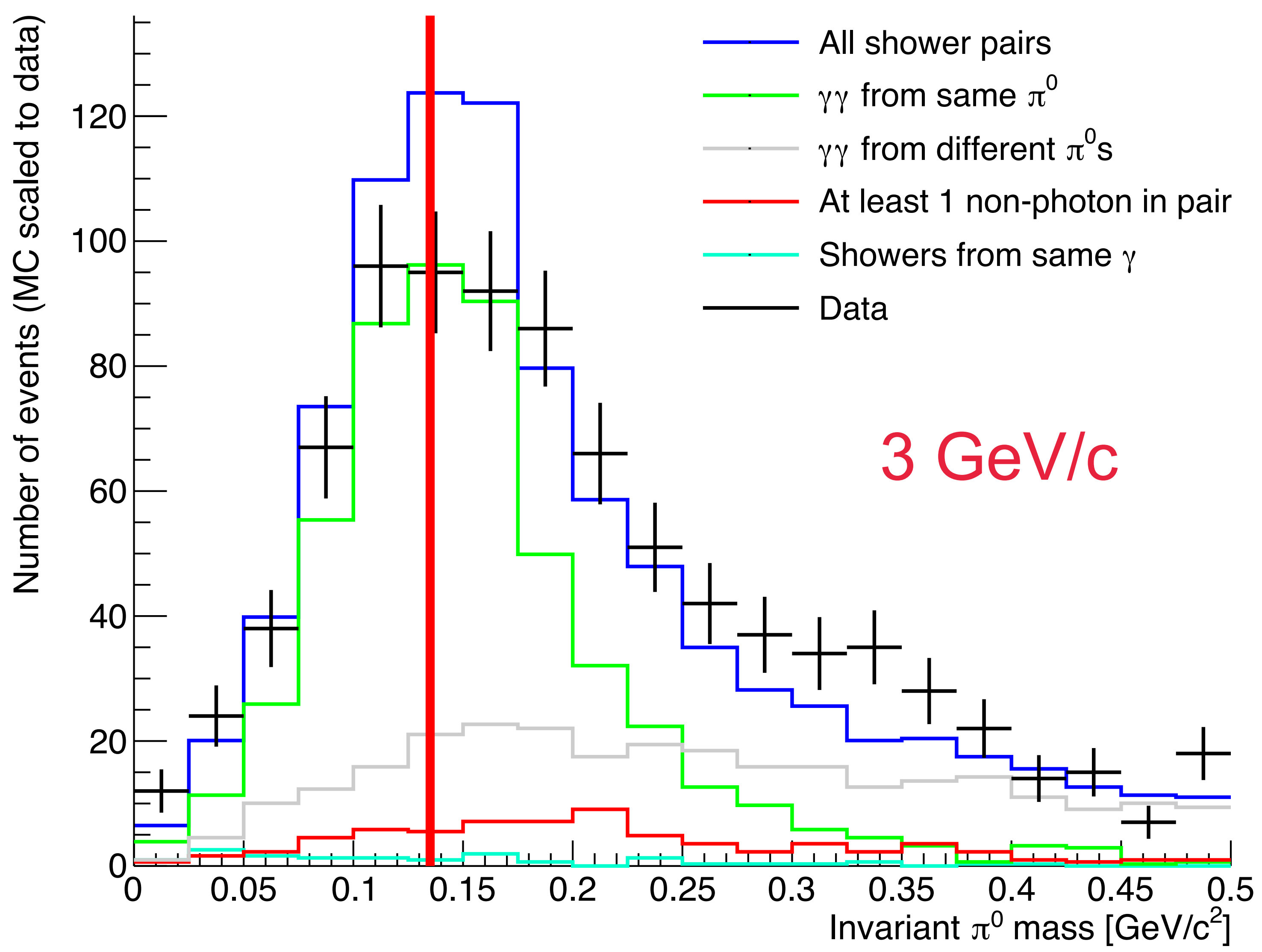
CUT SUMMARY

Shower cuts

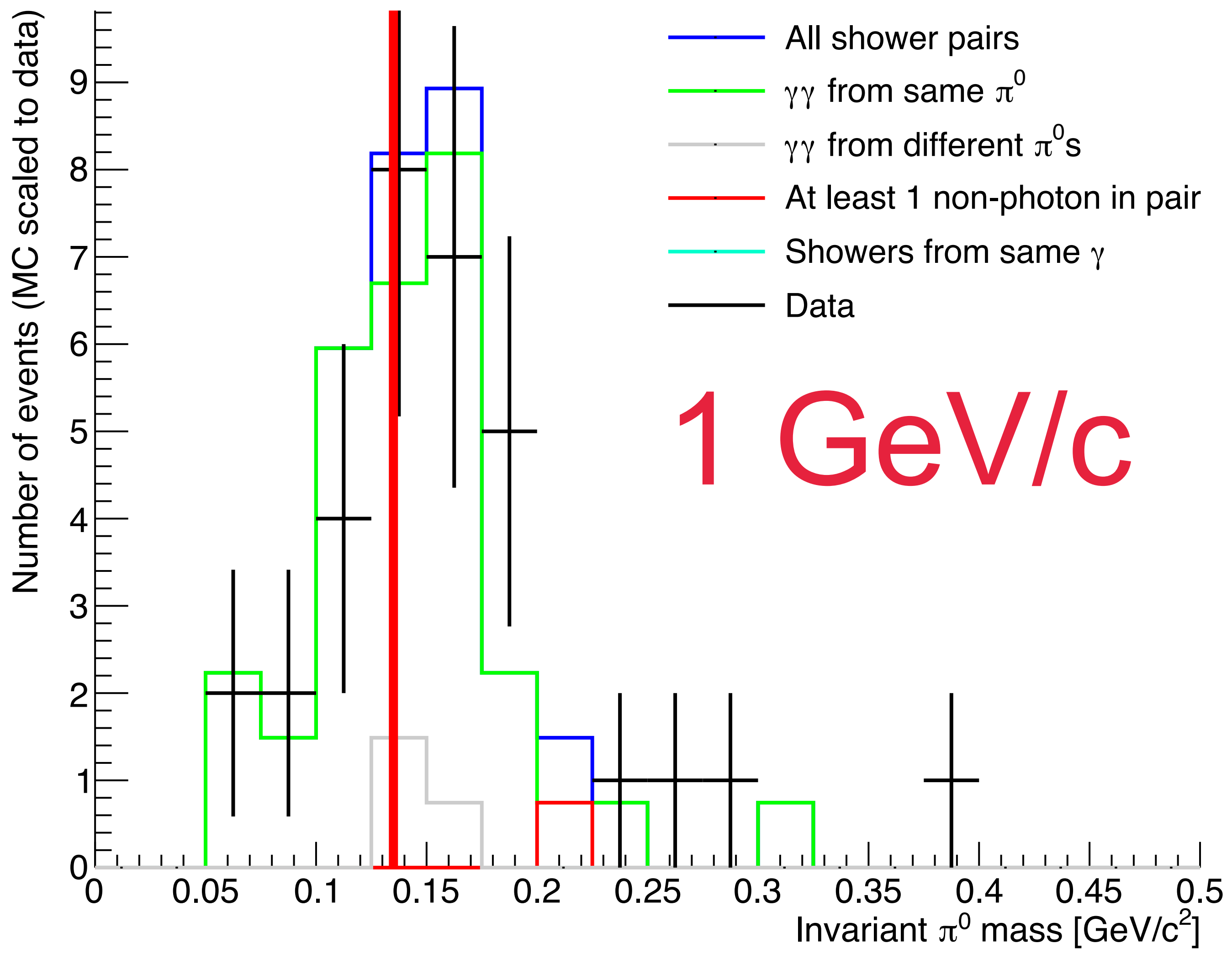
Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50
Number of cylinder hits	> 1

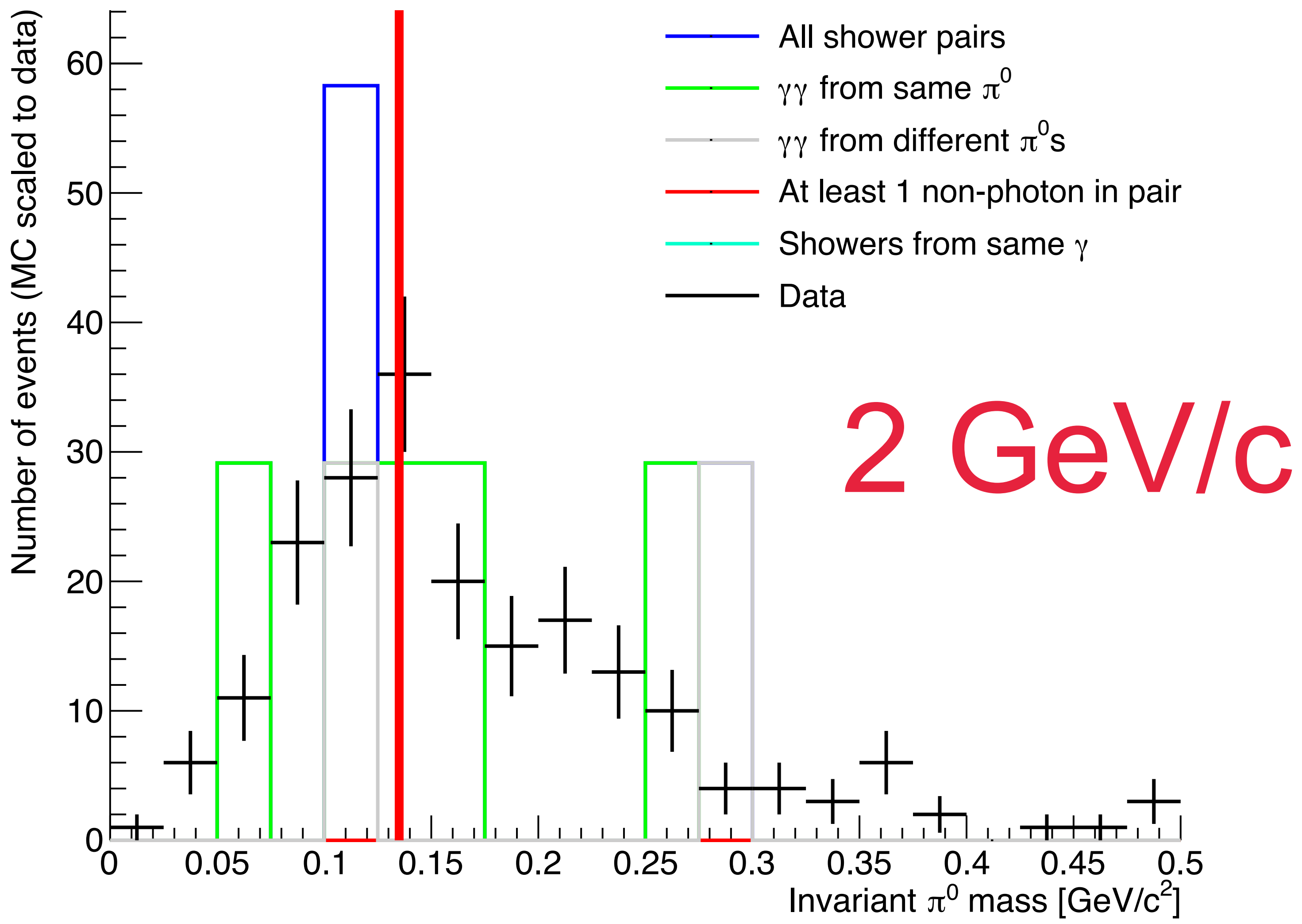
Event cuts

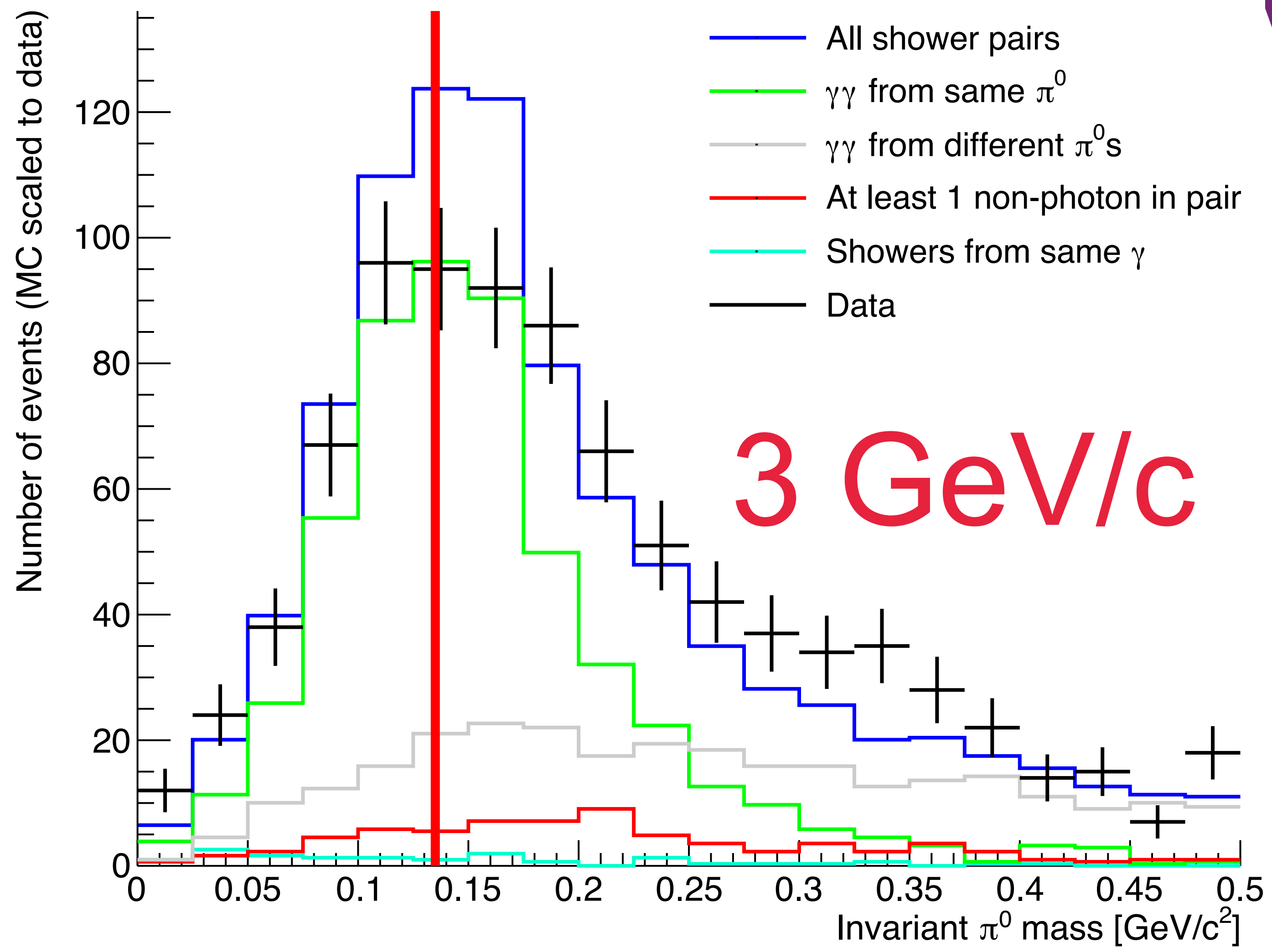
Beam particle Pandora classification	track
Number of cut-passing showers per event	2
Angle between showers	< 1 rad



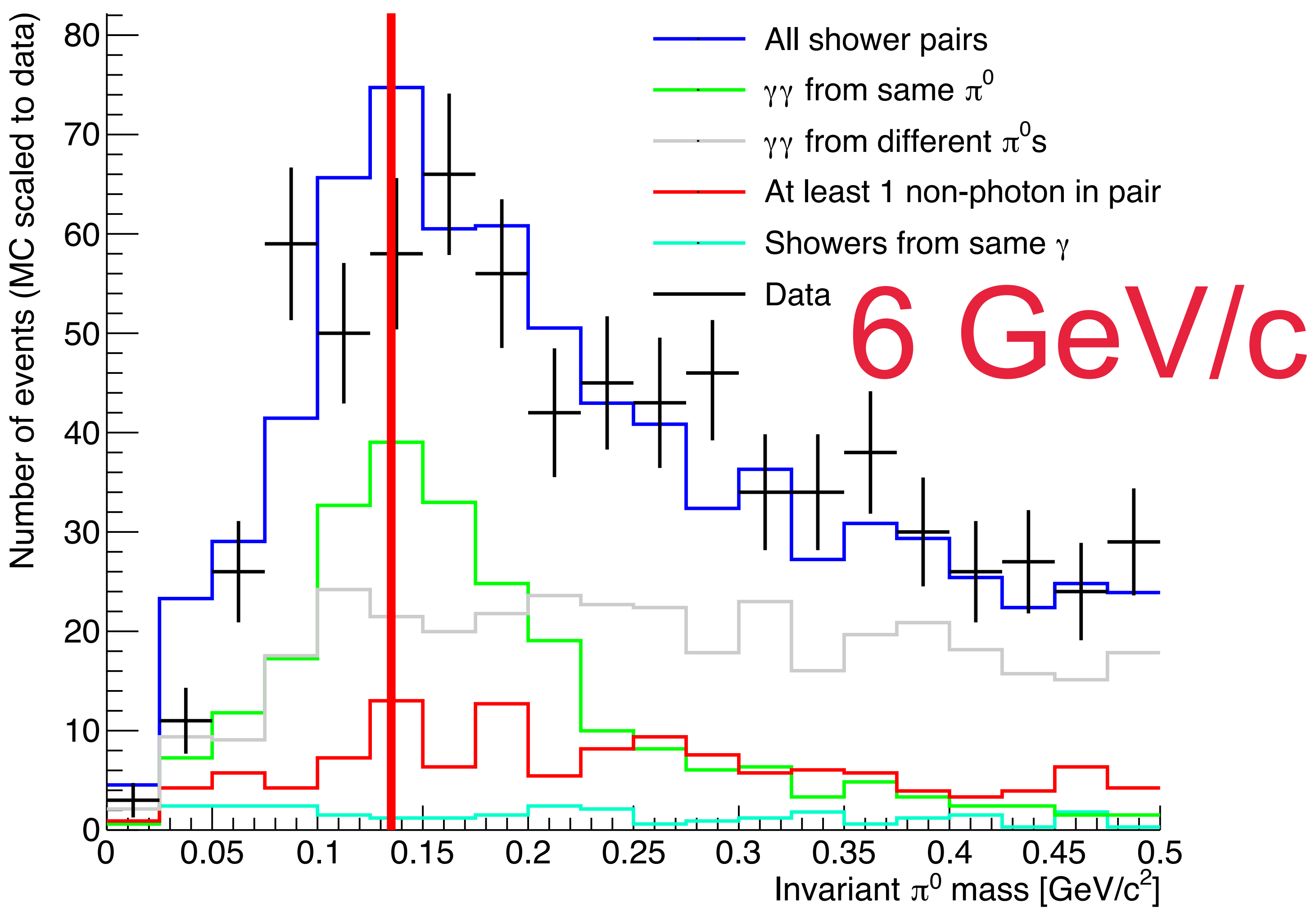
Π⁰ INVARIANT MASS – COMPARISON

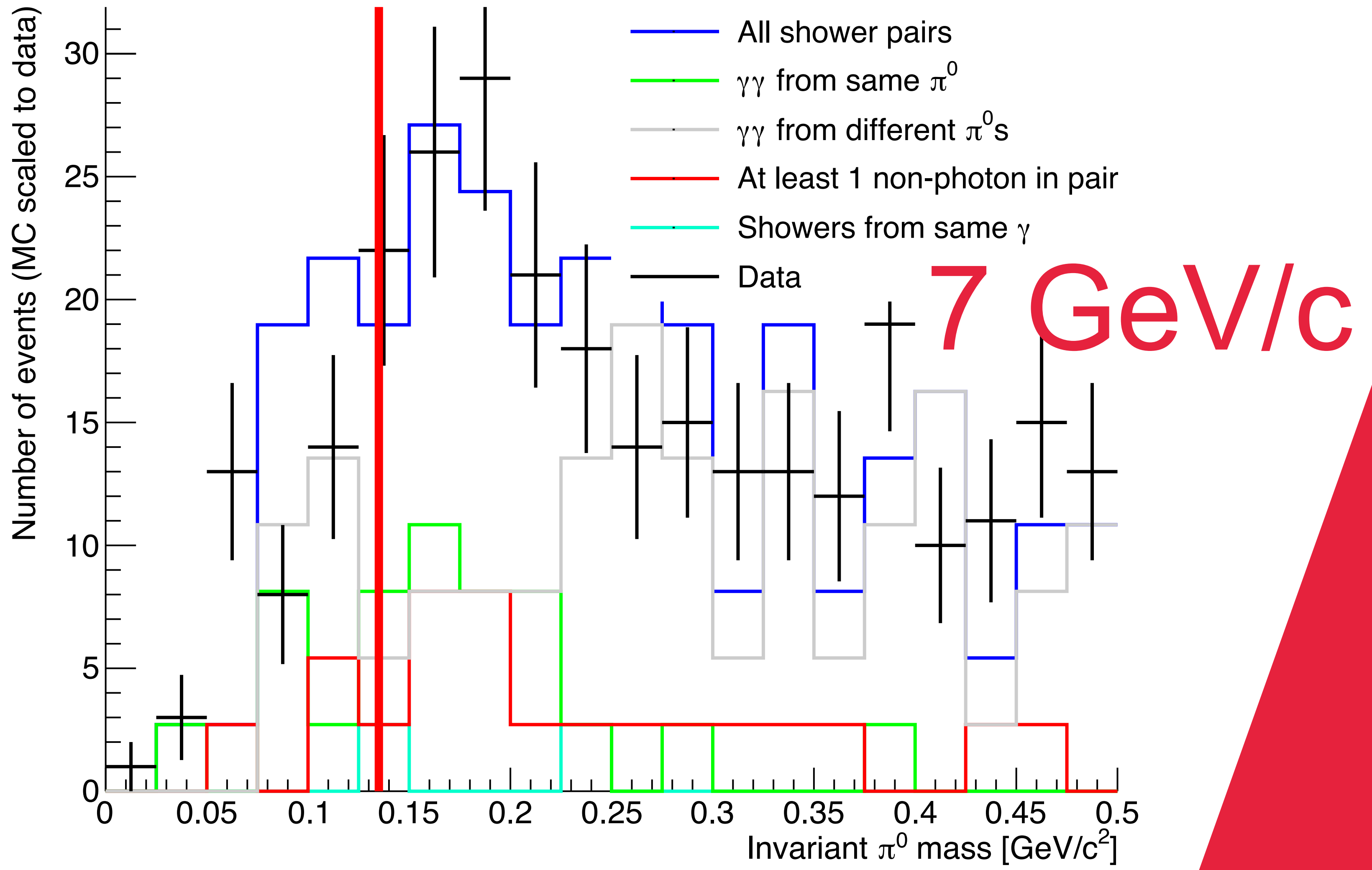






Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50
Number of cylinder hits	> 1
Angle between showers	< 1 rad





π⁰ INVARIANT MASS – EFFICIENCY

Pandora classification	shower
Particle CNN score	> 0.6
Number of coll. hits	> 50
Number of cylinder hits	> 1
Angle between showers	< 1 rad

- Efficiency of π^0 reconstruction is predictably low
- Shape of efficiency partially explained by photon efficiency