Through the Looking Glass:

Reconstruction and Optical Studies for DUNE Liquid Argon Detectors

Through the Looking Glass, and What Alice Found There

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Content

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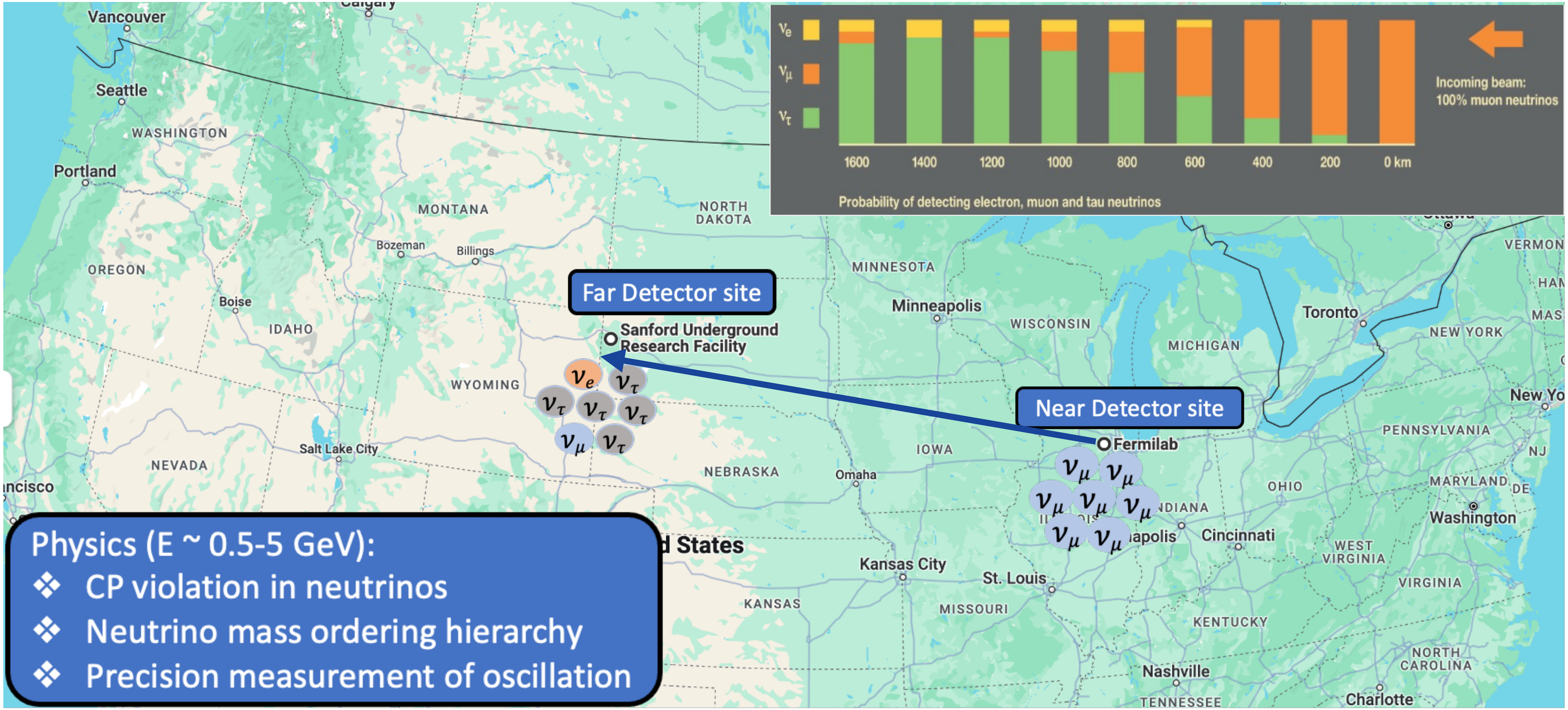
2. My thesis work

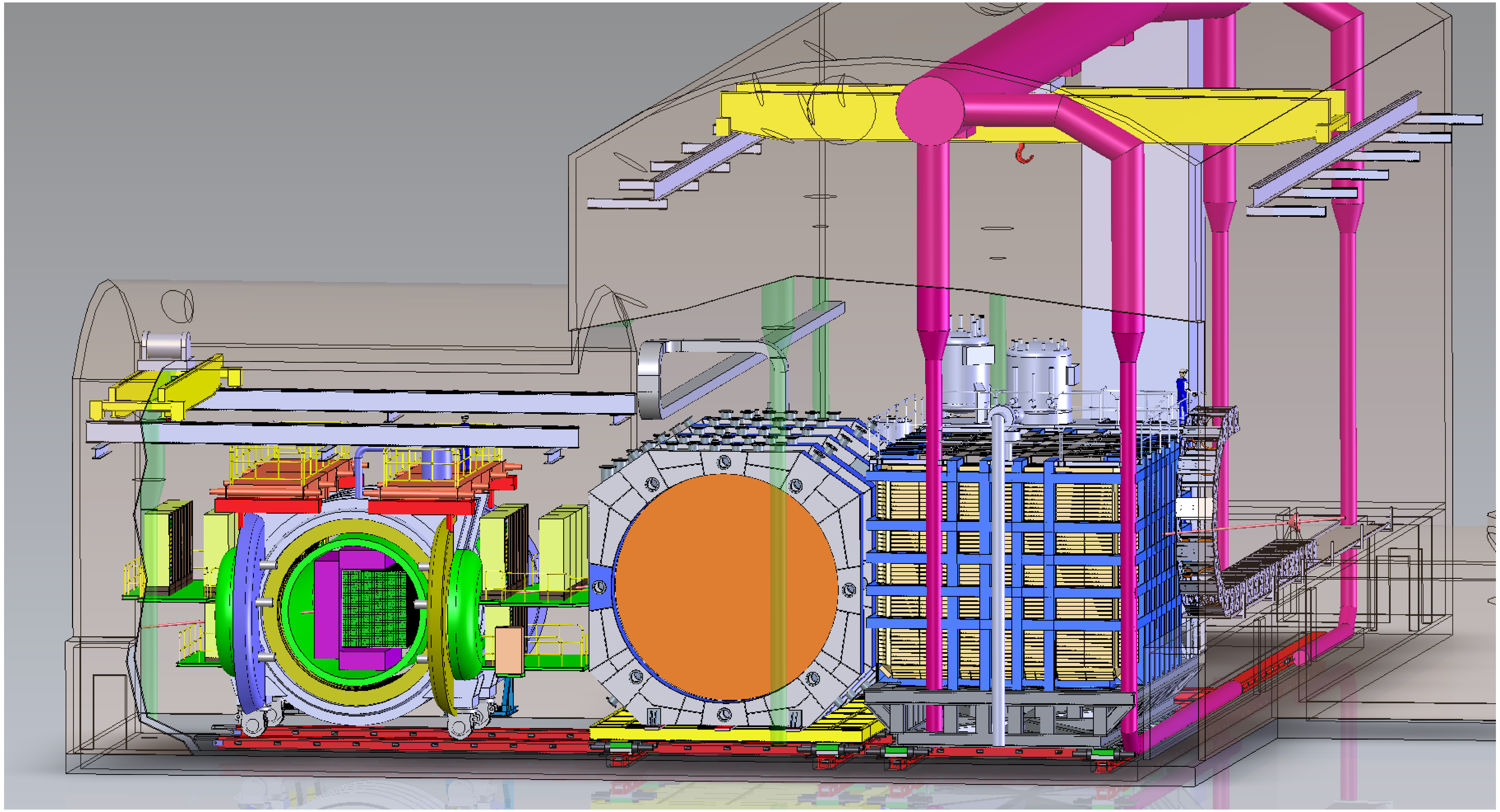
Introduction to DUNE

Deep Underground Neutrino Experiment (DUNE): measuring ν_μ -> ν_e oscillations with a 1300 km baseline



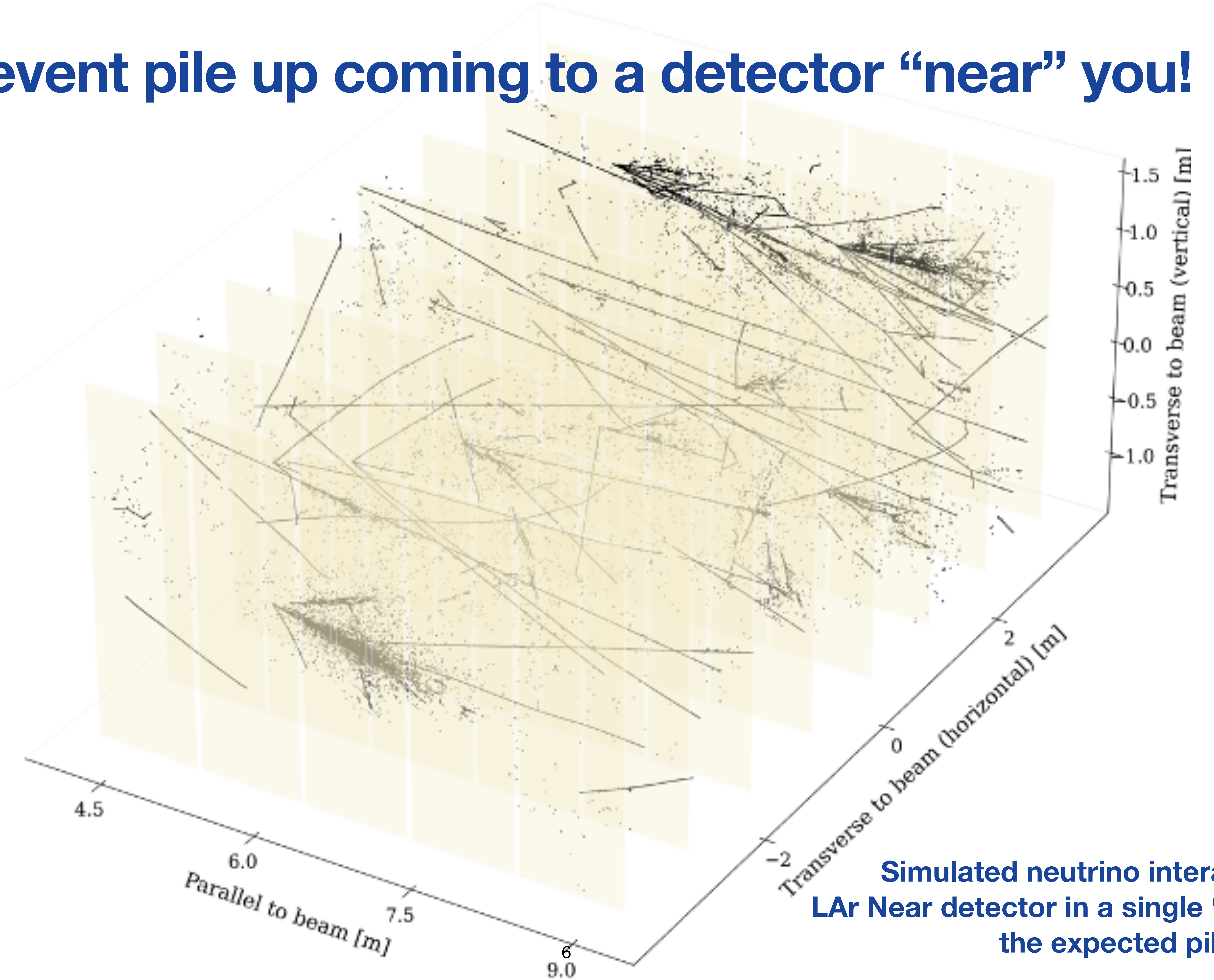
Physics (E ~ 0.5-5 GeV):
- CP violation in neutrinos
- Neutrino mass ordering hierarchy
- Precision measurement of oscillation

Near Detector: multi-detector design to characterise the intense neutrino beam at Fermilab and constrain systematic effects



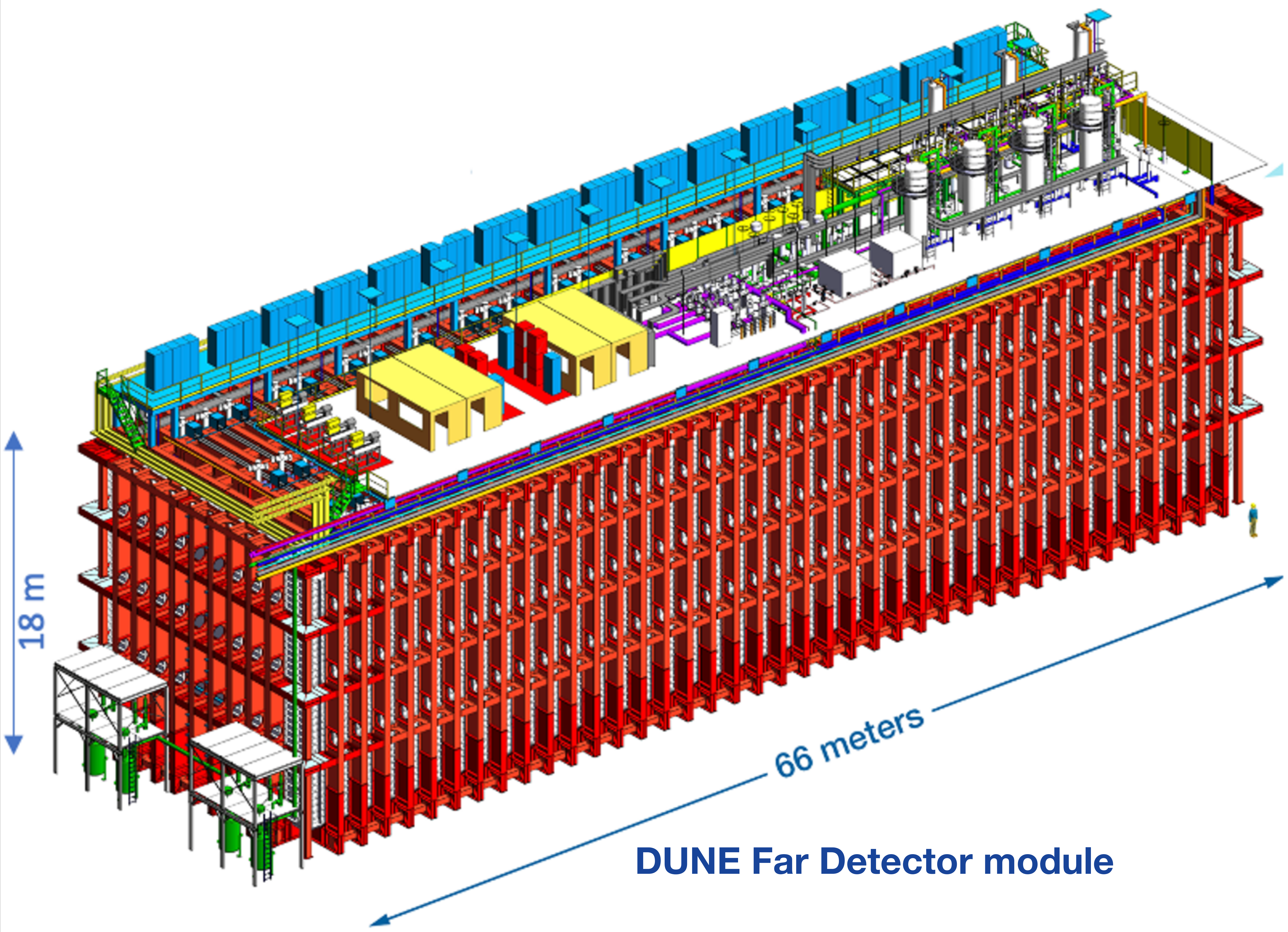
On-axis detector using straw tube tracker   Gaseous argon detector   Liquid argon detector

Neutrino event pile up coming to a detector "near" you!

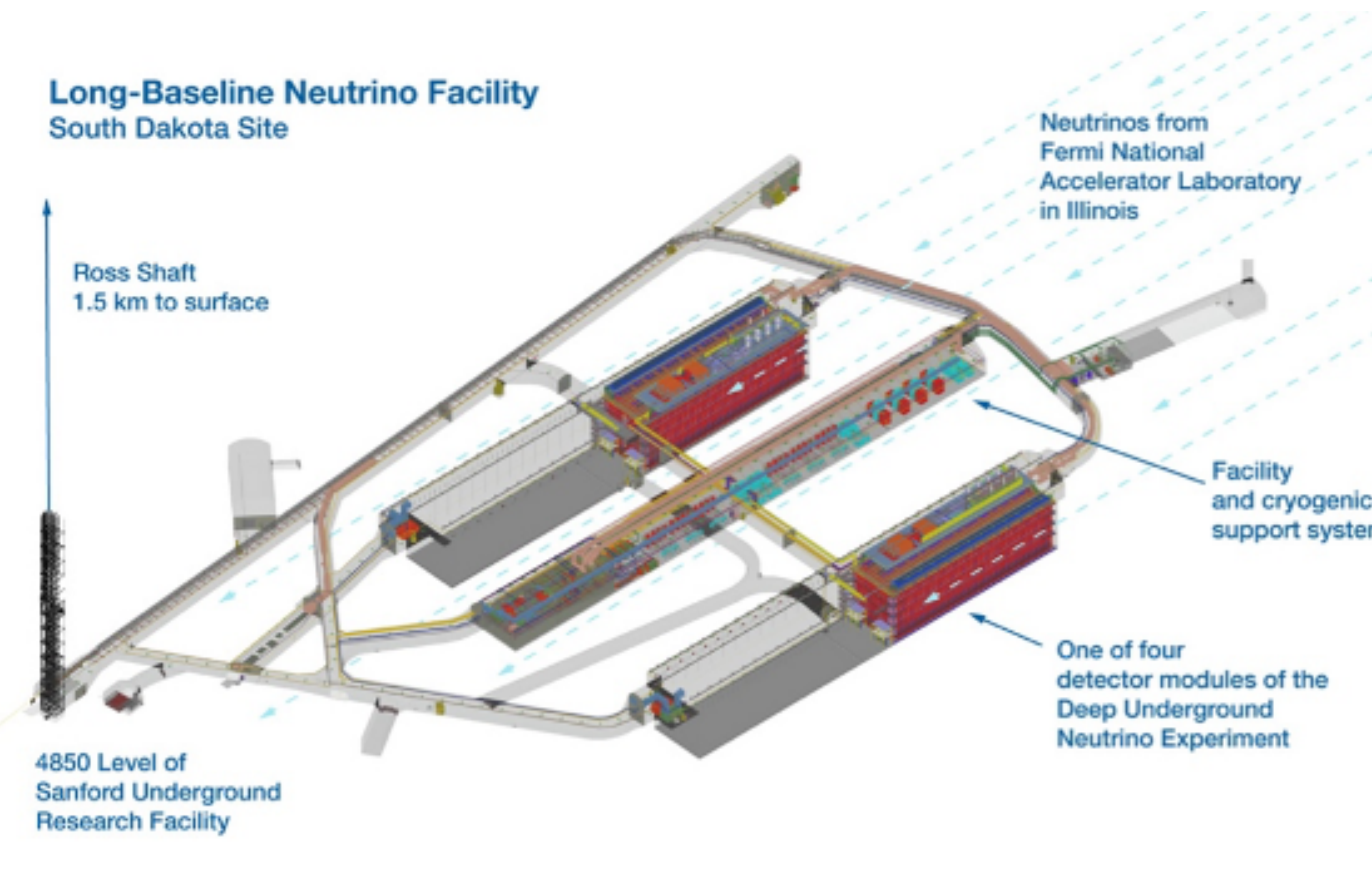


Simulated neutrino interactions in the LAr Near detector in a single "spill" showcasing the expected pile up

DUNE Far Detector: four 17 kt Liquid Argon Time Projection Chamber (LArTPC) kept 1.5 km underground to measure the oscillated neutrino flux

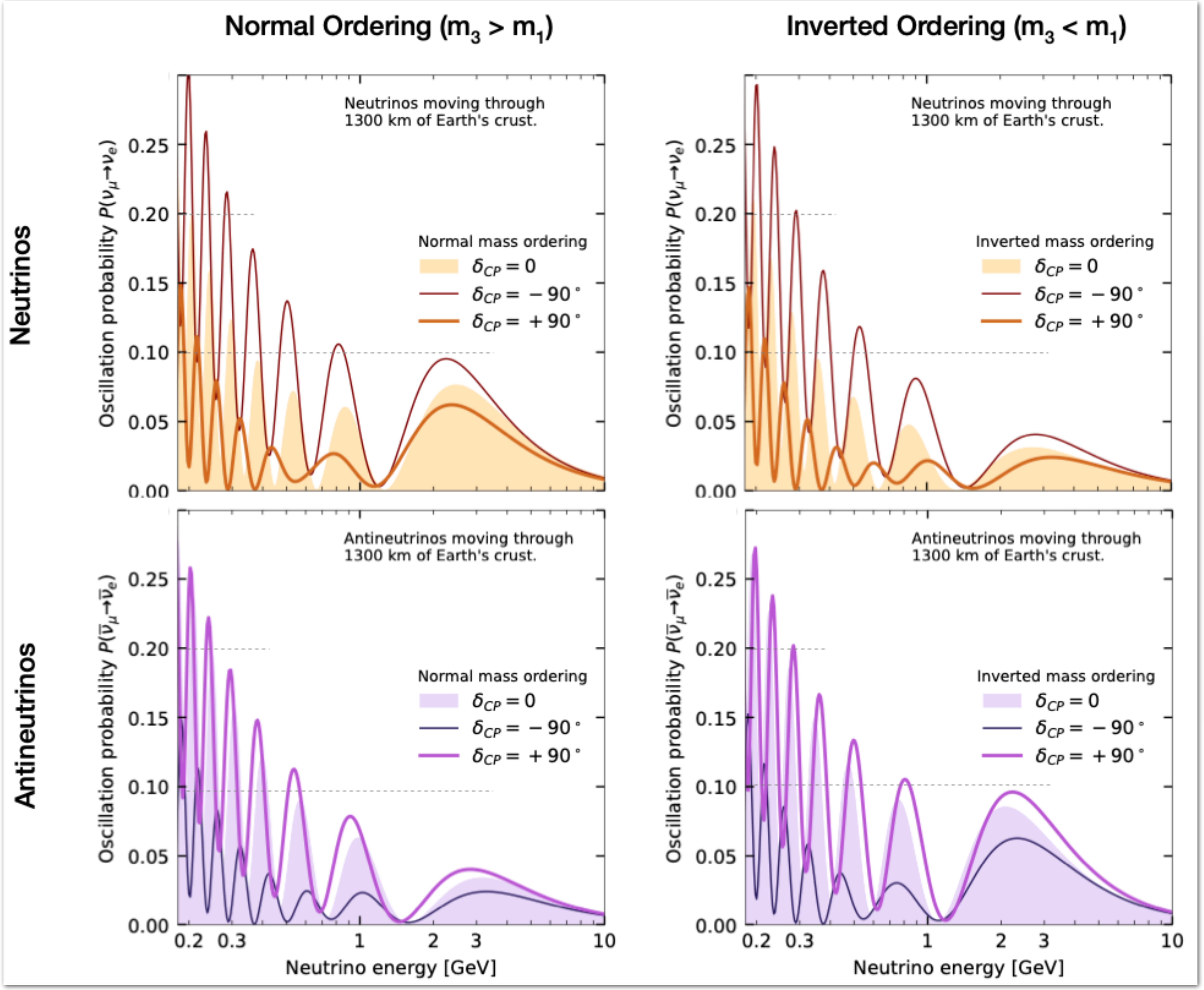


DUNE Far Detector module



The Far Detector site

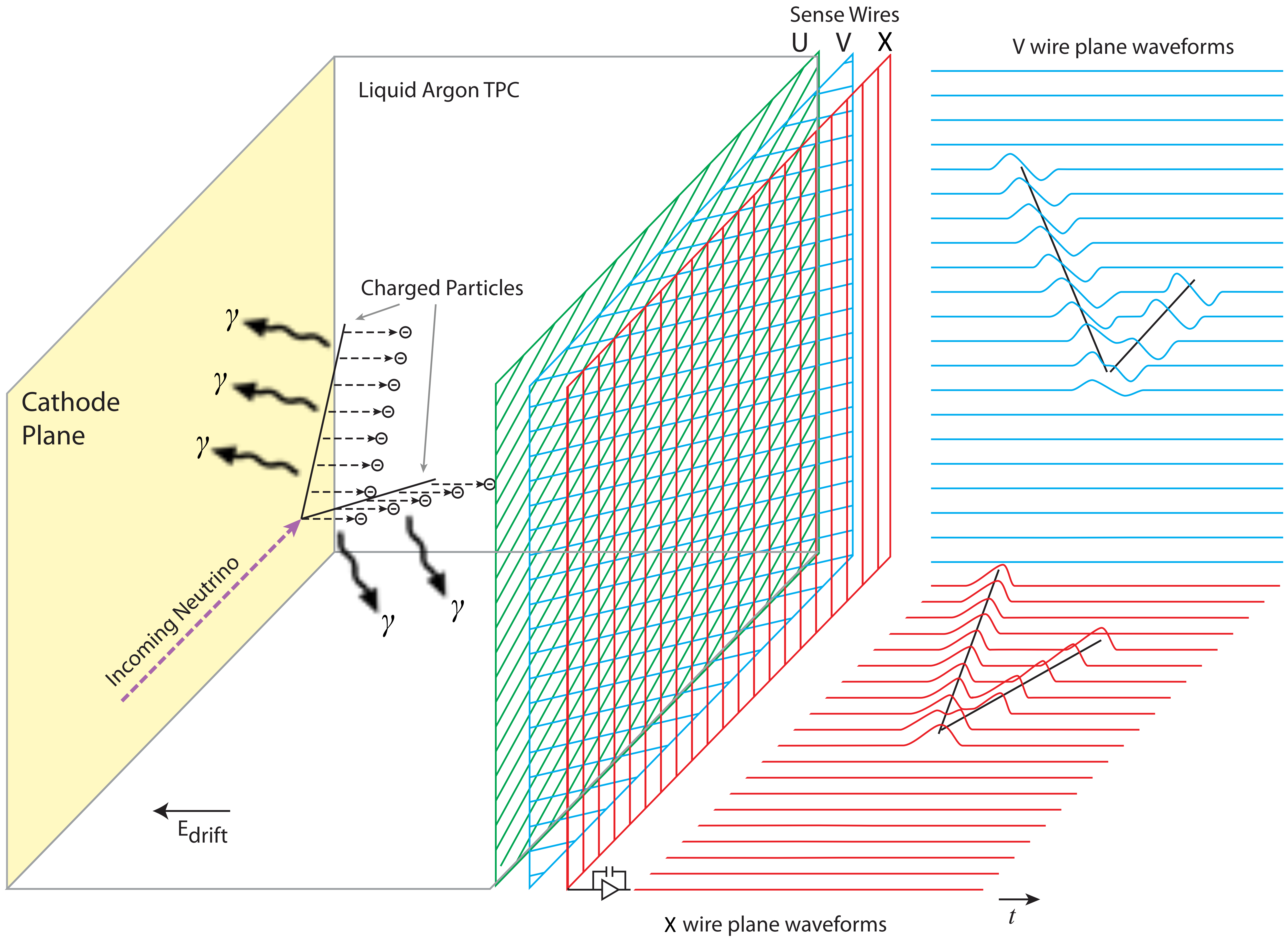
CP violation and mass ordering affect the oscillation pattern differently and the effects are disentangled by accurately estimating the neutrino energy



The mass ordering strongly affects the first oscillation maxima around 2—3 GeV while the effect of CP violation dominates at energies of 1 GeV and below for DUNE

Liquid Argon Time Projection Chamber (LArTPC)

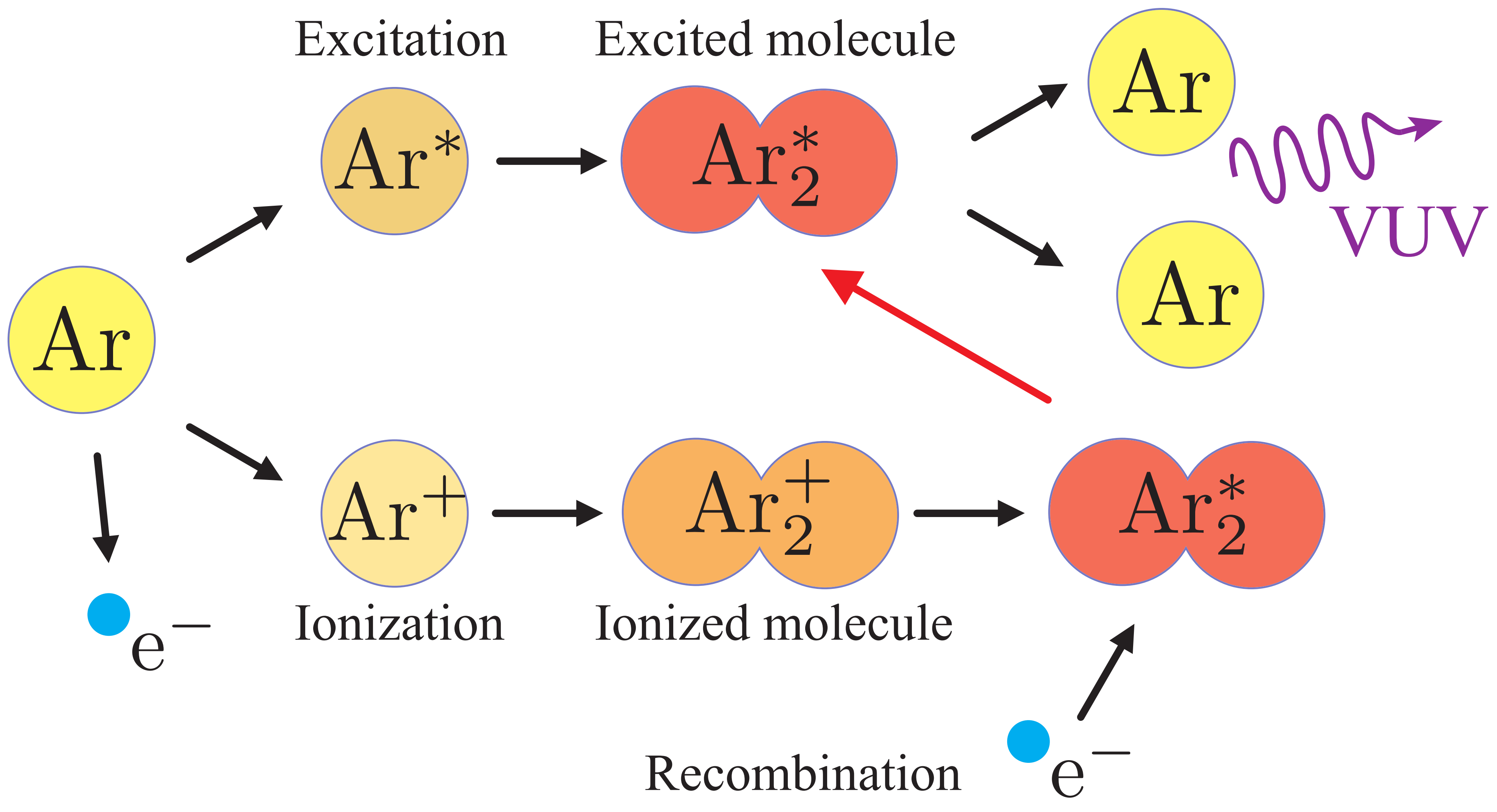
- Charged particles create ionization electrons and scintillation photons as they travel in liquid argon.
- A strong electric field (~500 V/cm) drifts the electrons to the anode -> high-resolution 2D image with sub-cm resolution and calorimetric information (dE/dx).
- The interaction depth in the detector is estimated from the electron drift time, measured relative to the event time (t_0) determined from scintillation light.

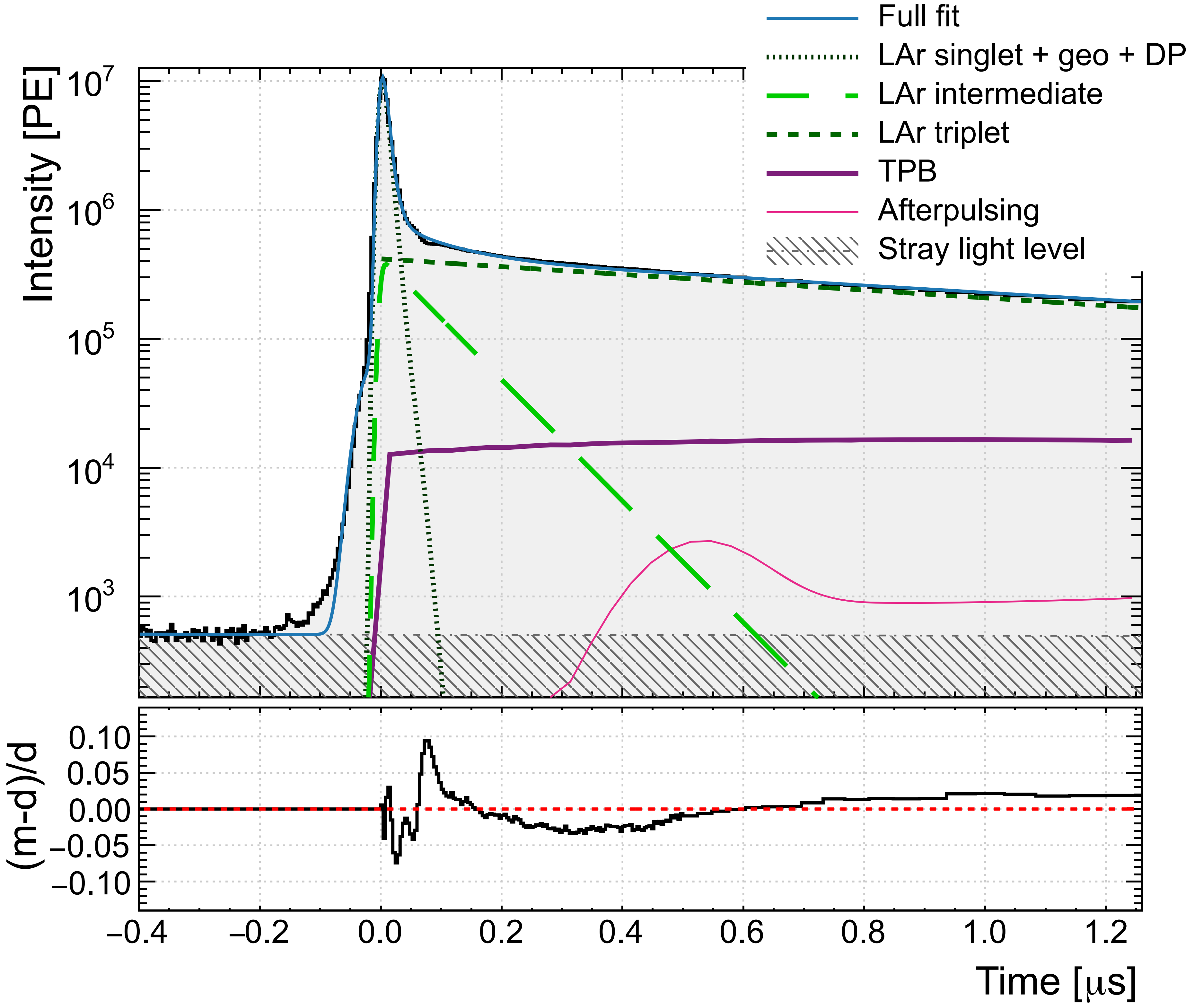


Imaging neutrino interaction in a LArTPC

Scintillation Light Production

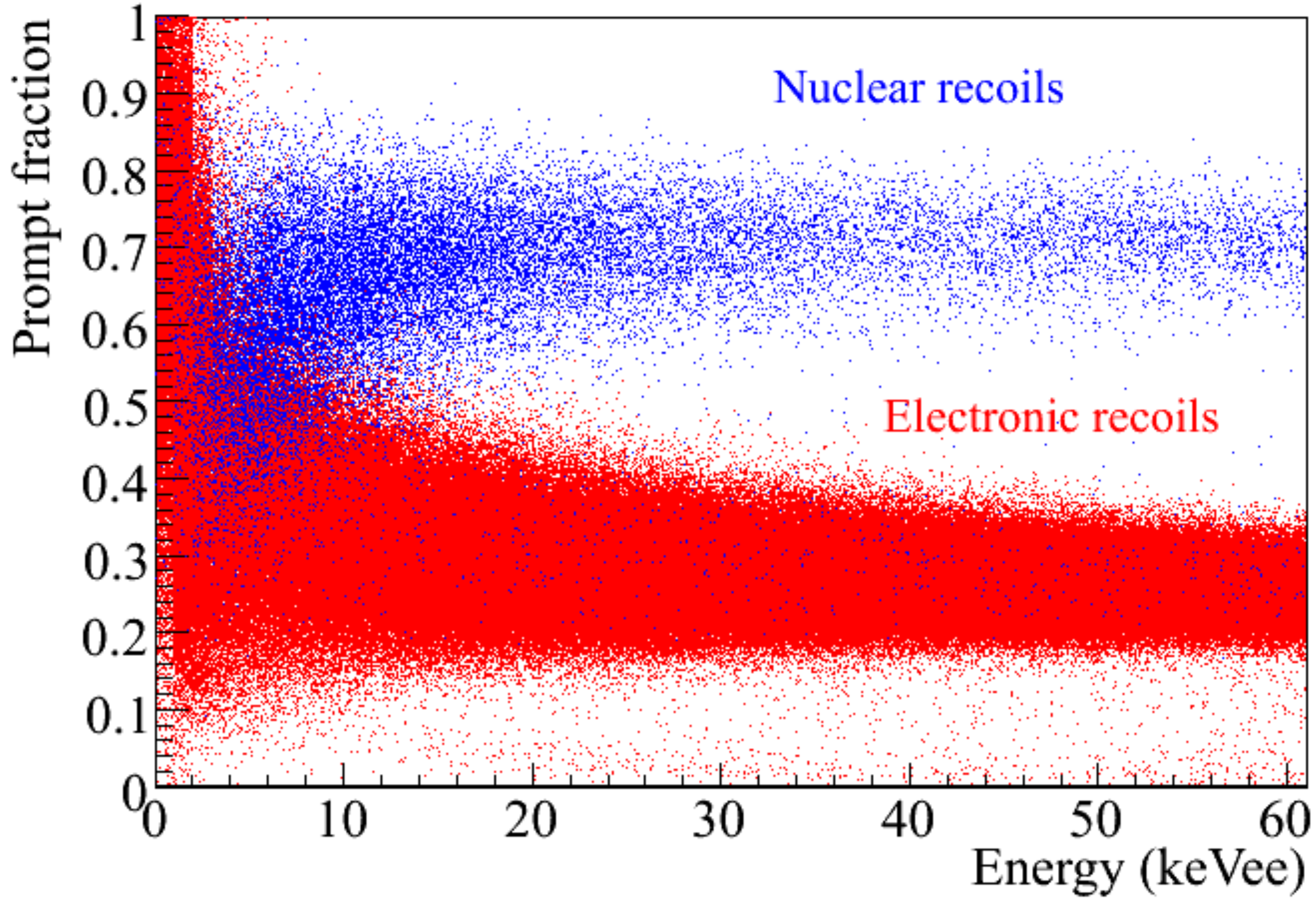
- Ar atoms are excited or ionized by the energy deposited by charged particles, which leads to formation of dimers
- The dimers decay with production of 128 nm photon which is wavelength shifted to visible light before detection.
- The dimers exist in single or triplet state (electronic spin configuration) and decay with lifetimes of 6 ns and 1.4 ms respectively.





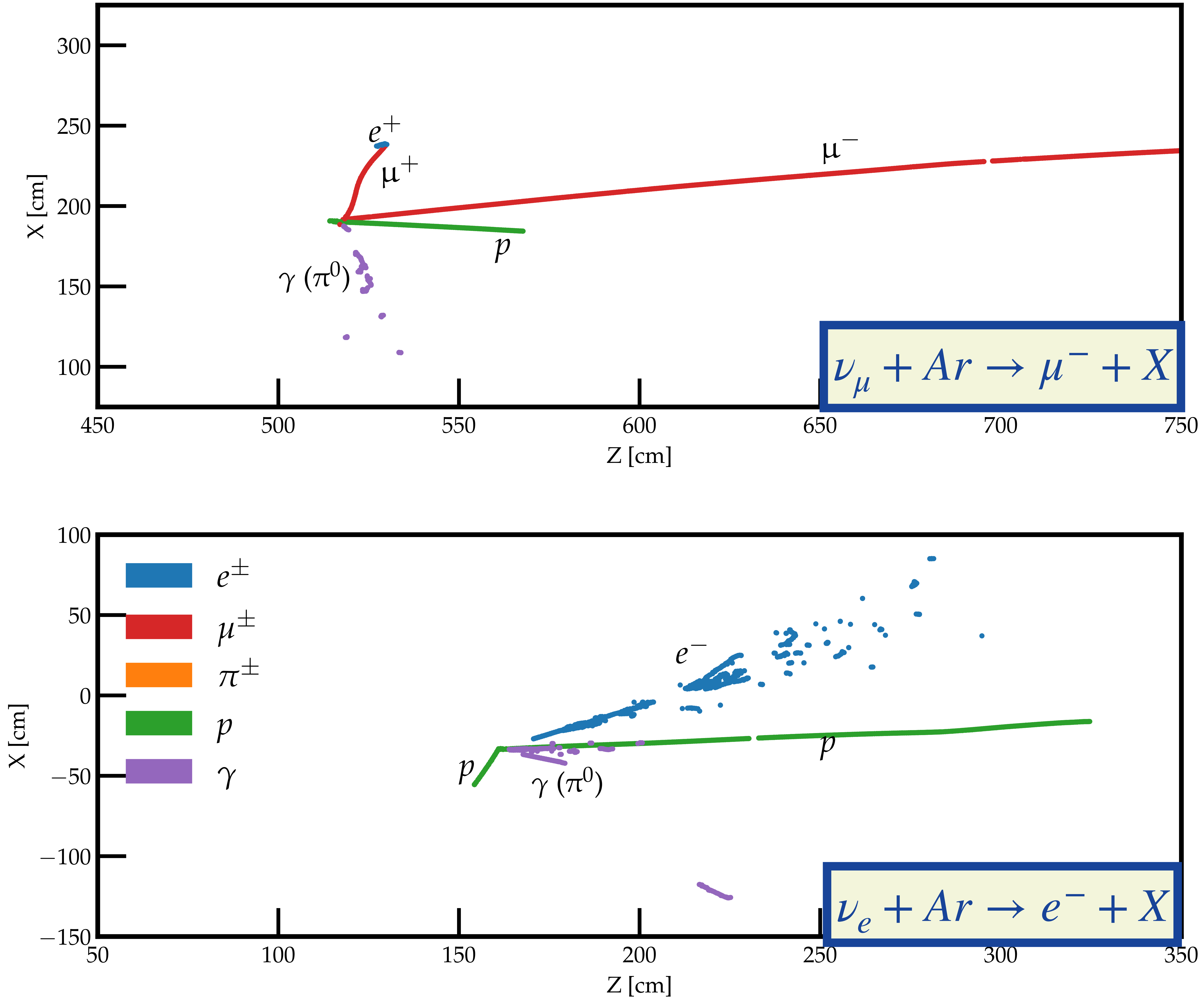
Pulse Shape Discrimination

- Ratio of singlet vs triplet dimers produced depends strongly on linear energy transfer (dE/dx).
- High discrimination power for nuclear vs electronic recoils at low energies (~MeV or below) by comparing light in a prompt vs total time window.
- Nuclear recoils have a prompt fraction of ~0.7 while electronic recoils have a value of ~0.3.



The neutrino beam flavor is inferred from charged-current (CC) interactions with argon

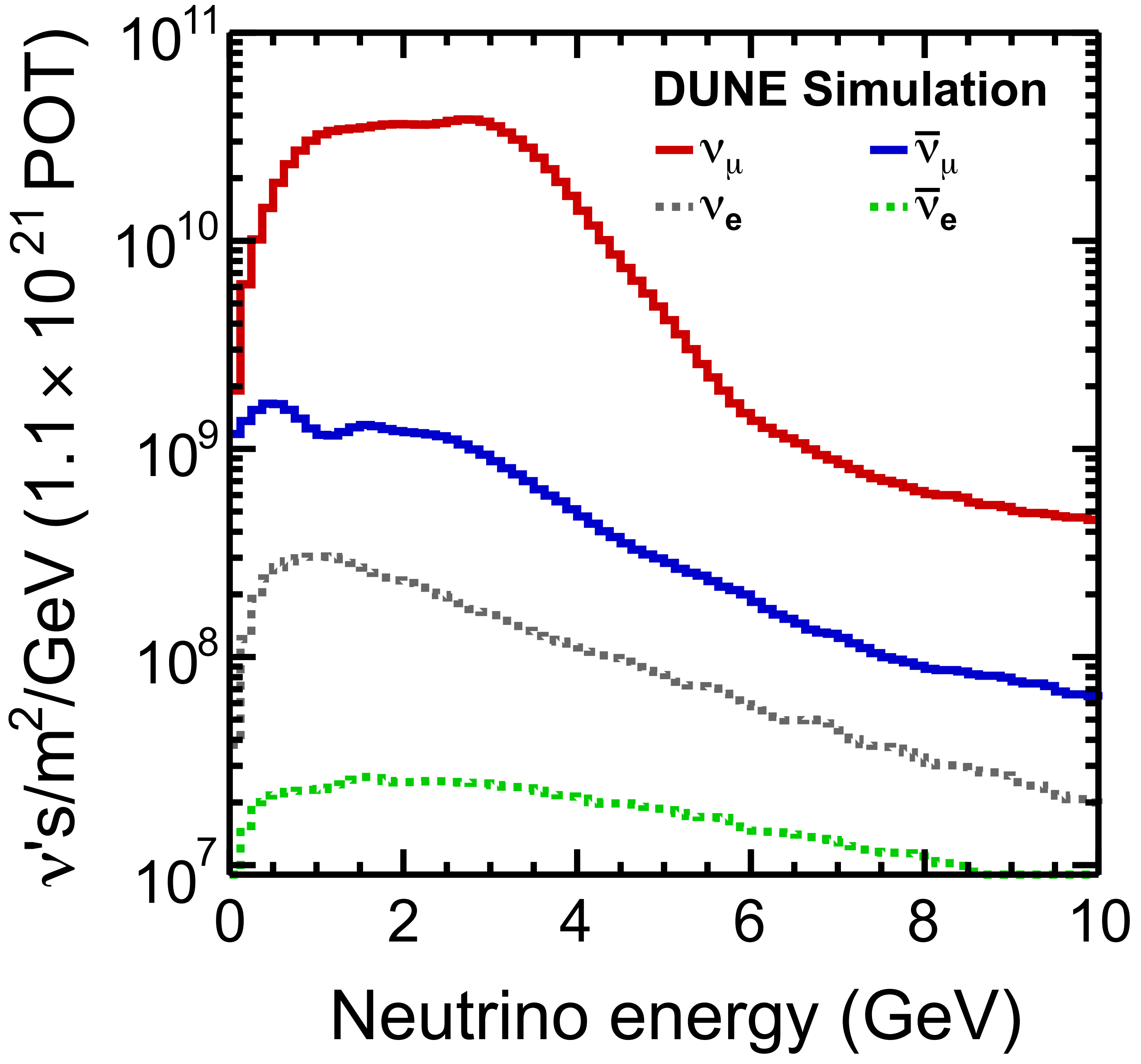
- Muons produce straight **track-like** topology while electrons generate compact **showers** pattern.



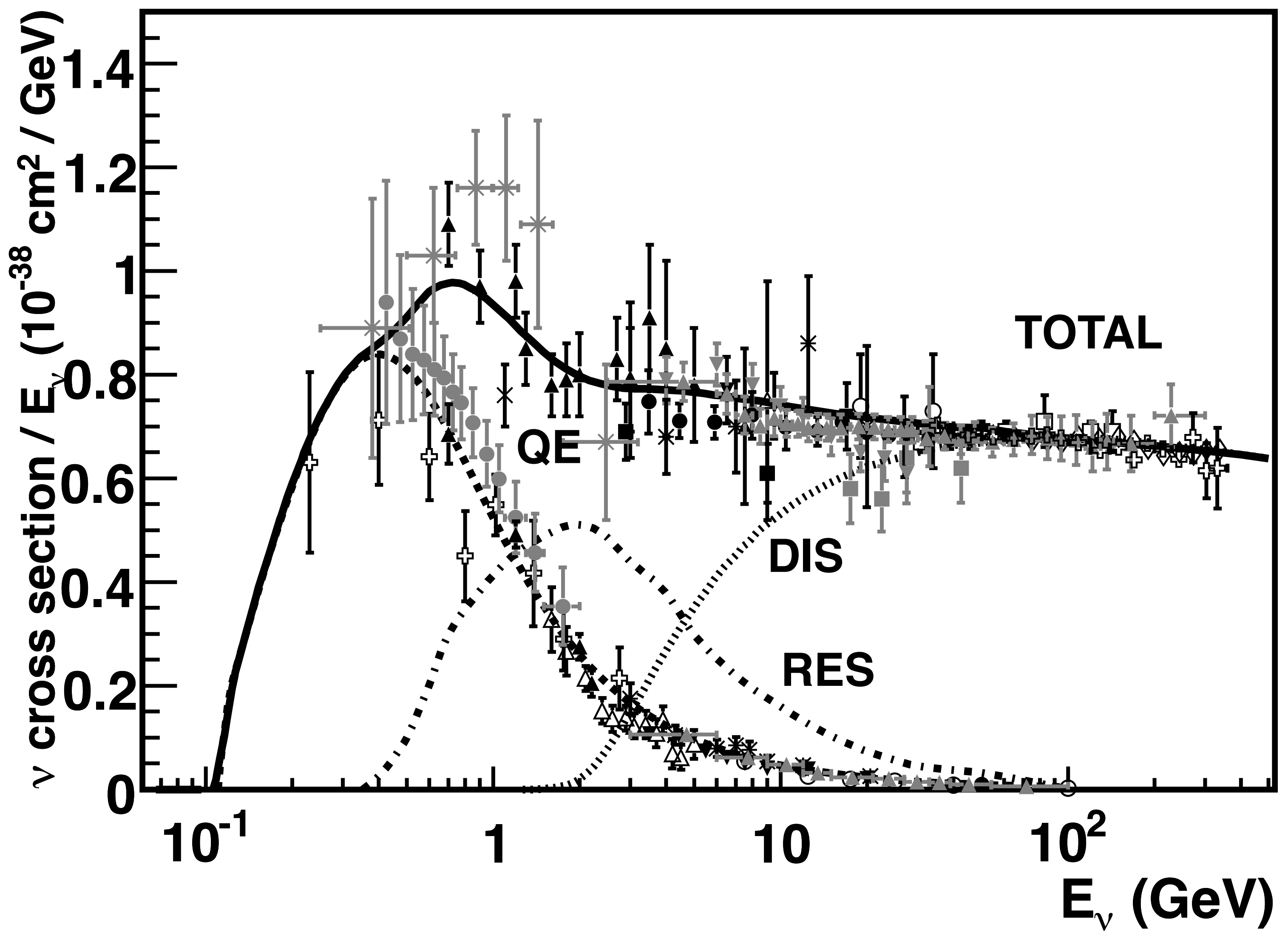
Simulated events from ~4 GeV neutrino interactions in DUNE Far Detector

The neutrino beam flavor is inferred from charged-current (CC) interactions with argon

- Muons produce straight **track-like** topology while electrons generate compact **showers** pattern.
- The neutrino beam energy will peak around 2—4 GeV in DUNE, where additional pions are produced via resonant pion production (RES).



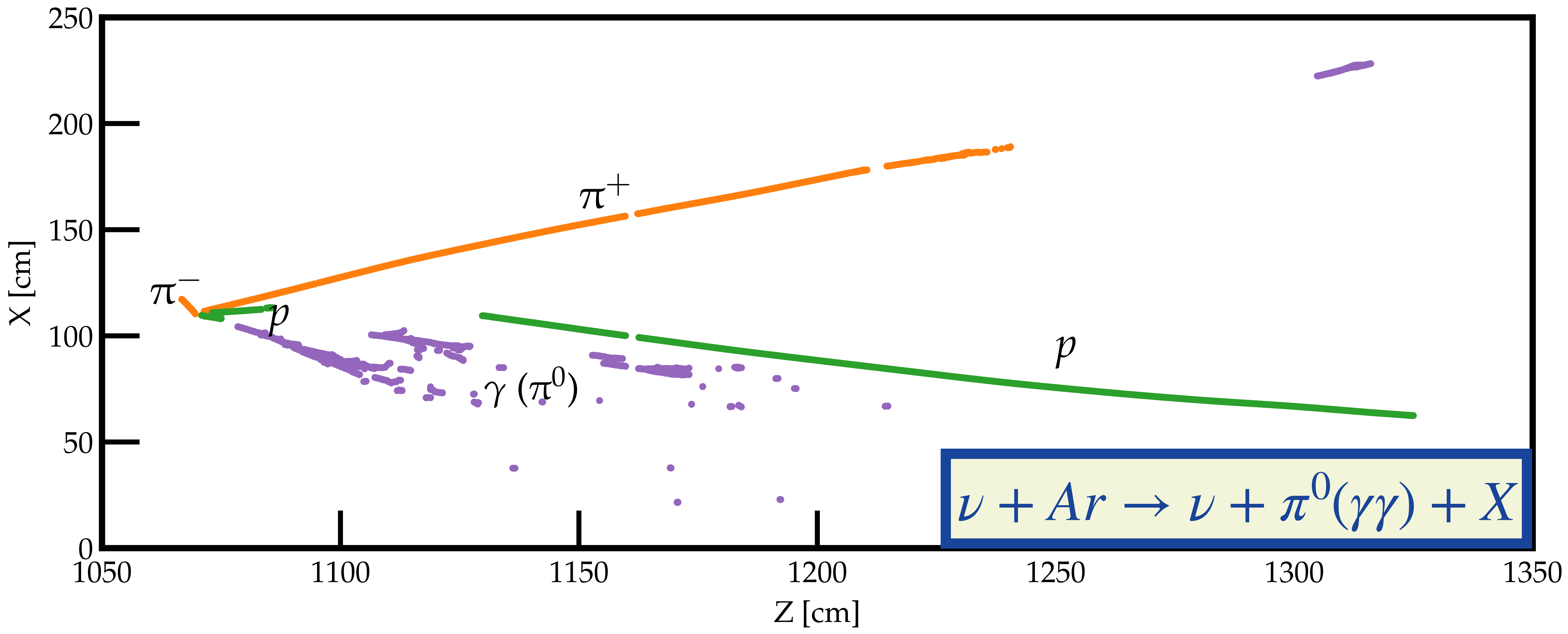
Neutrino beam energy profile in DUNE



Neutrino interaction cross-section as a function of energy

The neutrino beam flavor is inferred from charged-current (CC) interactions with argon

- Muons produce straight **track-like** topology while electrons generate compact **showers** pattern.
- The neutrino beam energy will peak around 2—4 GeV in DUNE, where additional pions are produced via resonant pion production (RES).
- π^0 produced in these interaction decay promptly to two photons, and are the primary source of **background** in beam flavor identification.



Simulated events from ~4 GeV neutrino interactions in DUNE Far Detector

Nuclear effects introduce additional complexity in identifying the flavor of the neutrino and accurately estimating its energy

- Fermi motion introduces energy smearing of O(200 MeV).
- Correlated nucleon pairs (mostly existing as n-p pairs) are knocked out together creating additional final states such as two-particle two-hole (2p2h).
- Hadron produced in the neutrino interactions can re-interact with argon nucleus further modifying the observed topology in the detector, also known as **Final State Interactions** (FSI).

ProtoDUNE program

- Neutrino platform at CERN for prototyping the next generation of neutrino experiments.
- Two ~800 ton LAr cryostat for testing, improving and validating the Far Detector design
- Charged particle beam for detector characterisation and hadron-argon cross section measurement:
  - PD-I took data in 2018-2020
  - PD-II took additional data in 2024-2025

The ProtoDUNE site with two cryostat shown in red

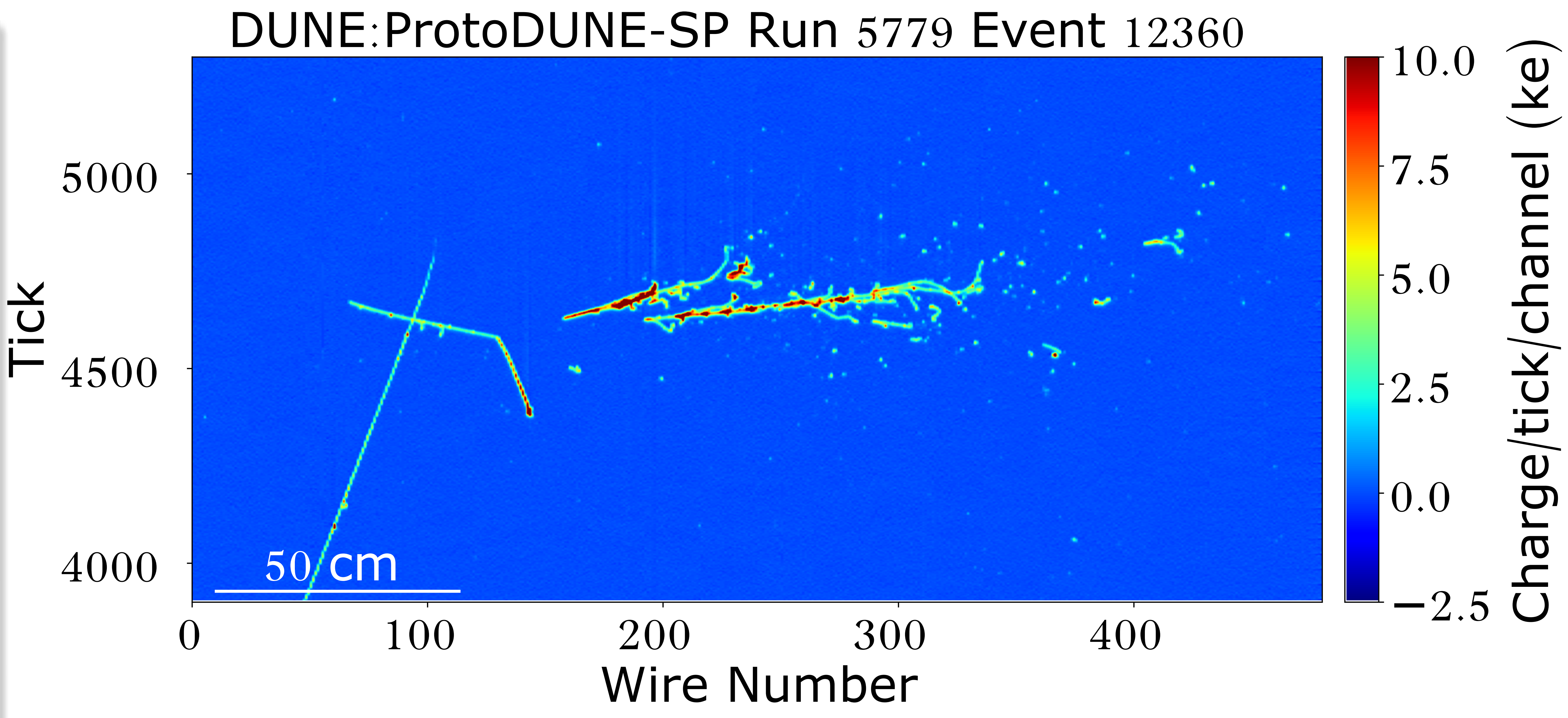
My thesis work

ProtoDUNE reconstruction studies using 1 GeV beam data

- **Shower energy scale calibration using π^0s produced in π^+—Ar interactions.**

❋ We can validate the shower energy reconstruction by comparing the invariant mass distribution of π^0 decay photon pairs to the known value.

❋ Understanding π^0 decay reconstruction performance is important to correctly estimate the background in oscillation analysis.



Example π^+—Ar interaction producing a π^0 and a proton. The π^0 decays promptly to two photons.

ProtoDUNE reconstruction studies using 1 GeV beam data

- **Shower energy scale calibration using π^0s produced in π^+—Ar interactions.**

TABLE 3.3: Summary of key photon shower reconstruction metrics in the 1 GeV MC sample for shower energy above 200 MeV.

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Energy Bias	-10% to -20%
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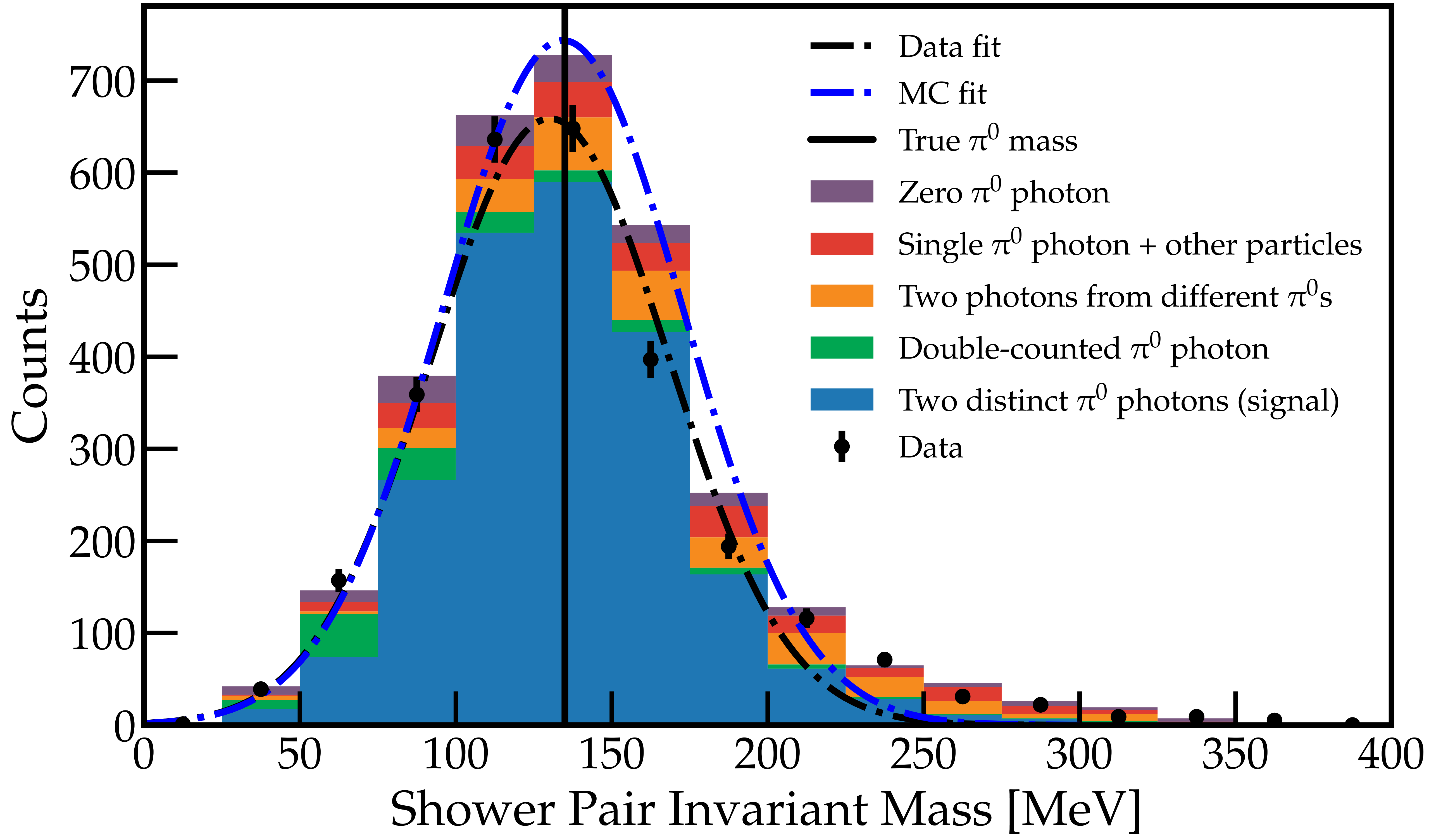
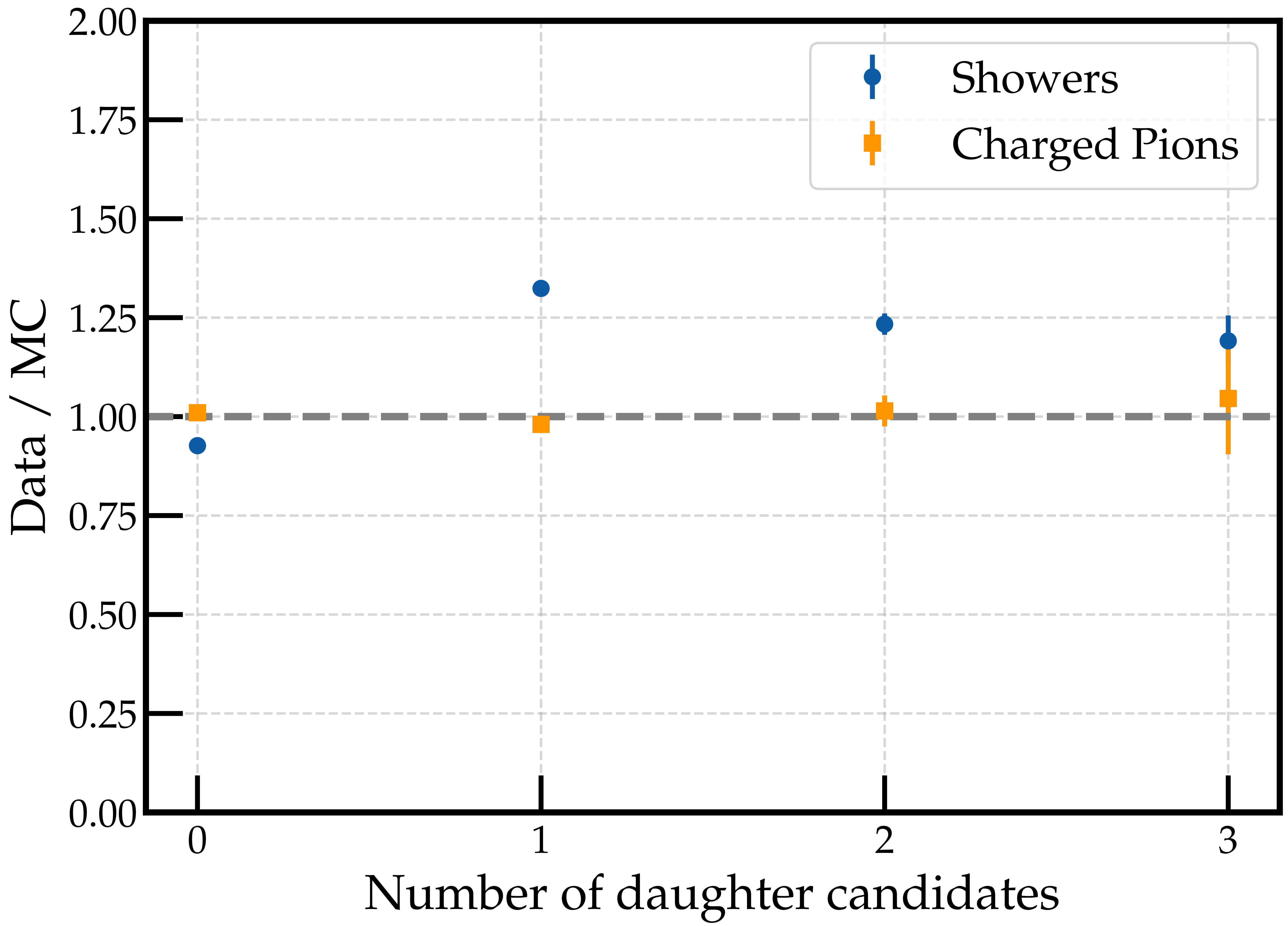


ProtoDUNE reconstruction studies using 1 GeV beam data

- **Cross-section of π^+—Ar interactions for the exclusive channel with more than one daughter pions, referred to as pion production (input for FSI modelling with no existing benchmark)**

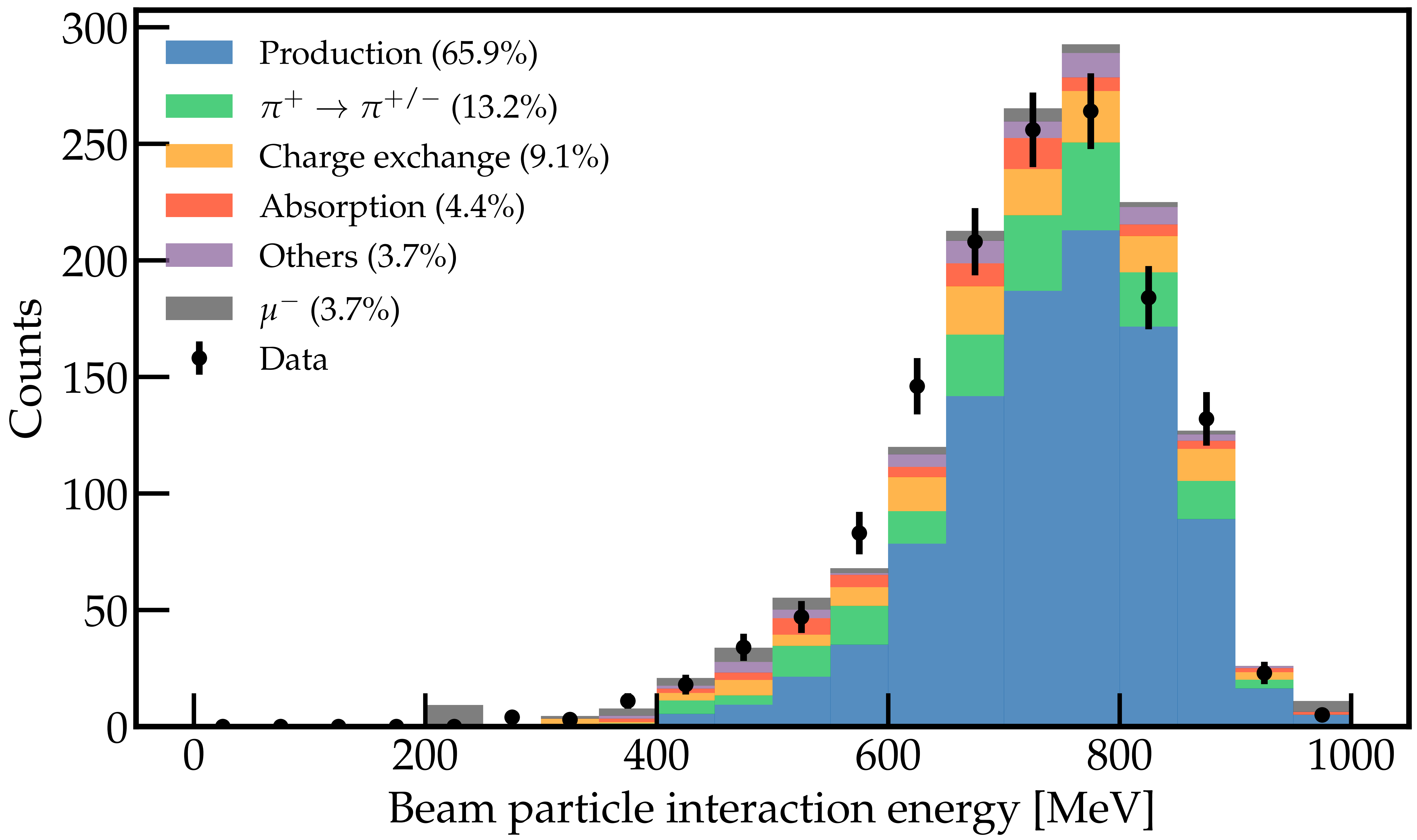
- Shower and charged pion candidates are identified from reconstructed daughters to tag pion production events.
- MC shows mismatch with data for number of shower candidates but excellent agreement for $\pi^{\pm}$.



ProtoDUNE reconstruction studies using 1 GeV beam data

- **Cross-section of π^+—Ar interactions for the exclusive channel with more than one daughter pions, referred to as pion production (input for FSI modelling with no existing benchmark)**

- Events are considered to be from pion production channel if:
  - **2 $\pi^\pm$ topology**: Two or more daughter charged pion candidates are required, with at least one pair separated by less than 6 cm.
  - **$\pi^\pm$ + π^0 topology:** One charged pion candidate and one or more shower candidates.
  - **2 π^0 topology**: not considered due to large contamination from charge exchange (1 **π^0** events).



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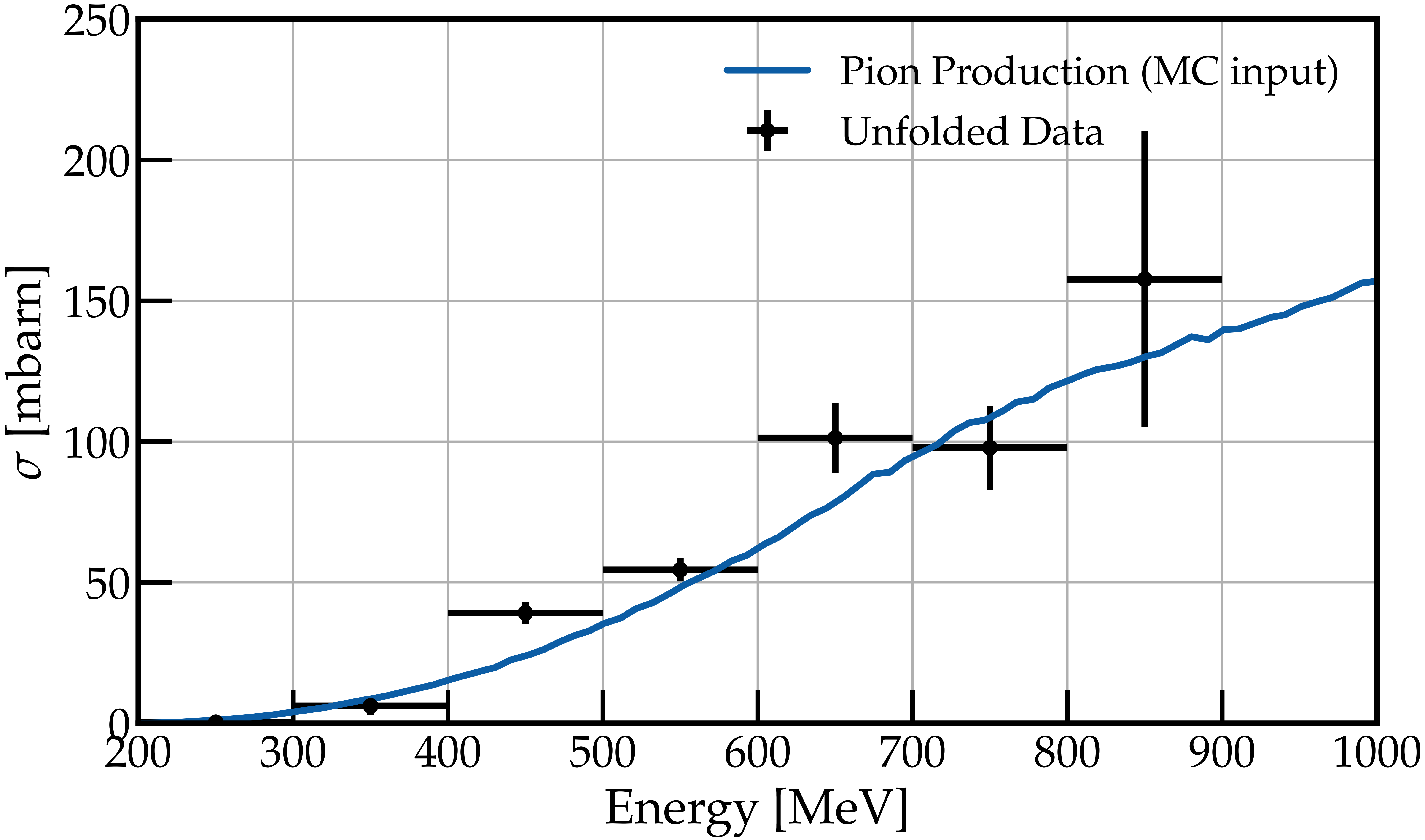
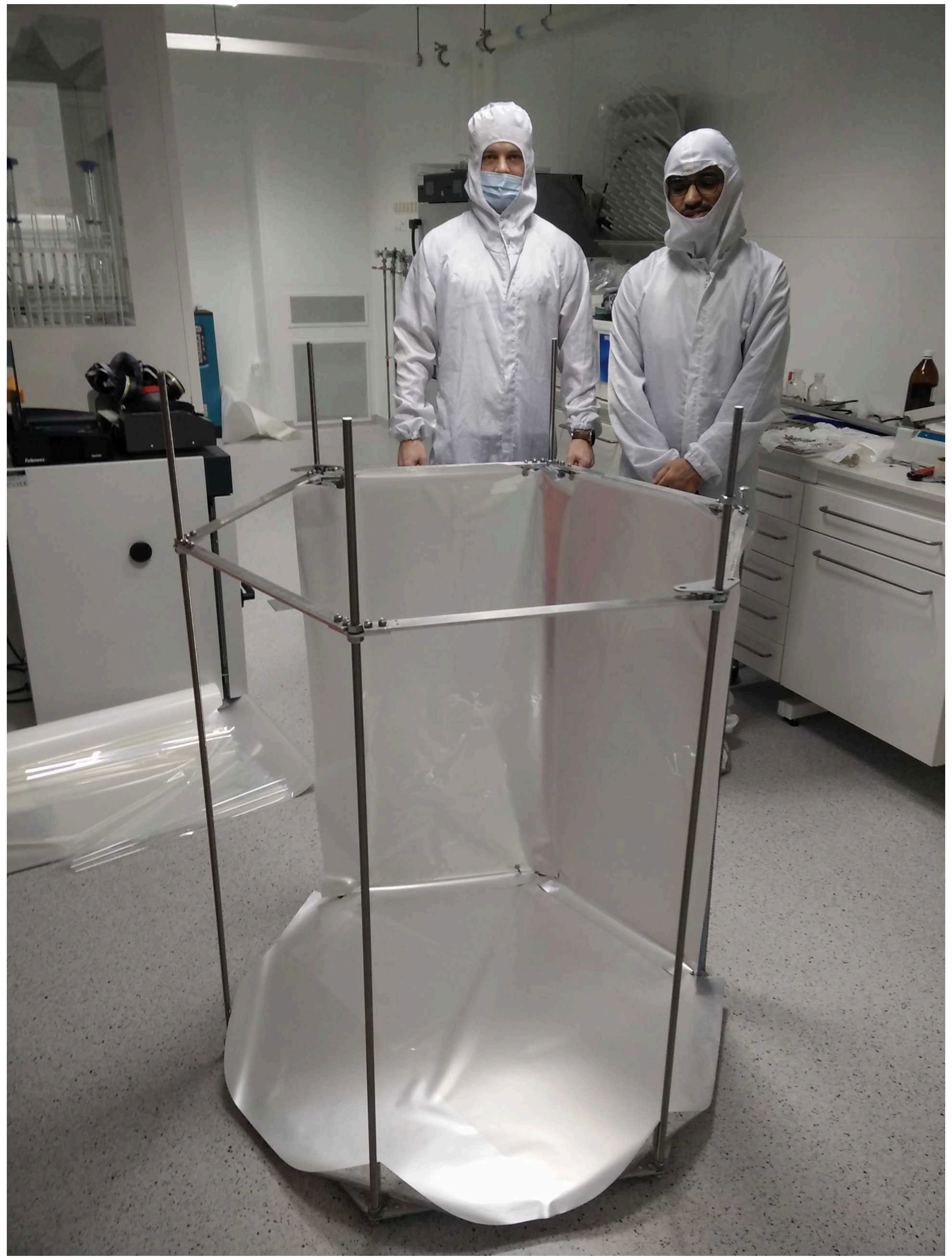
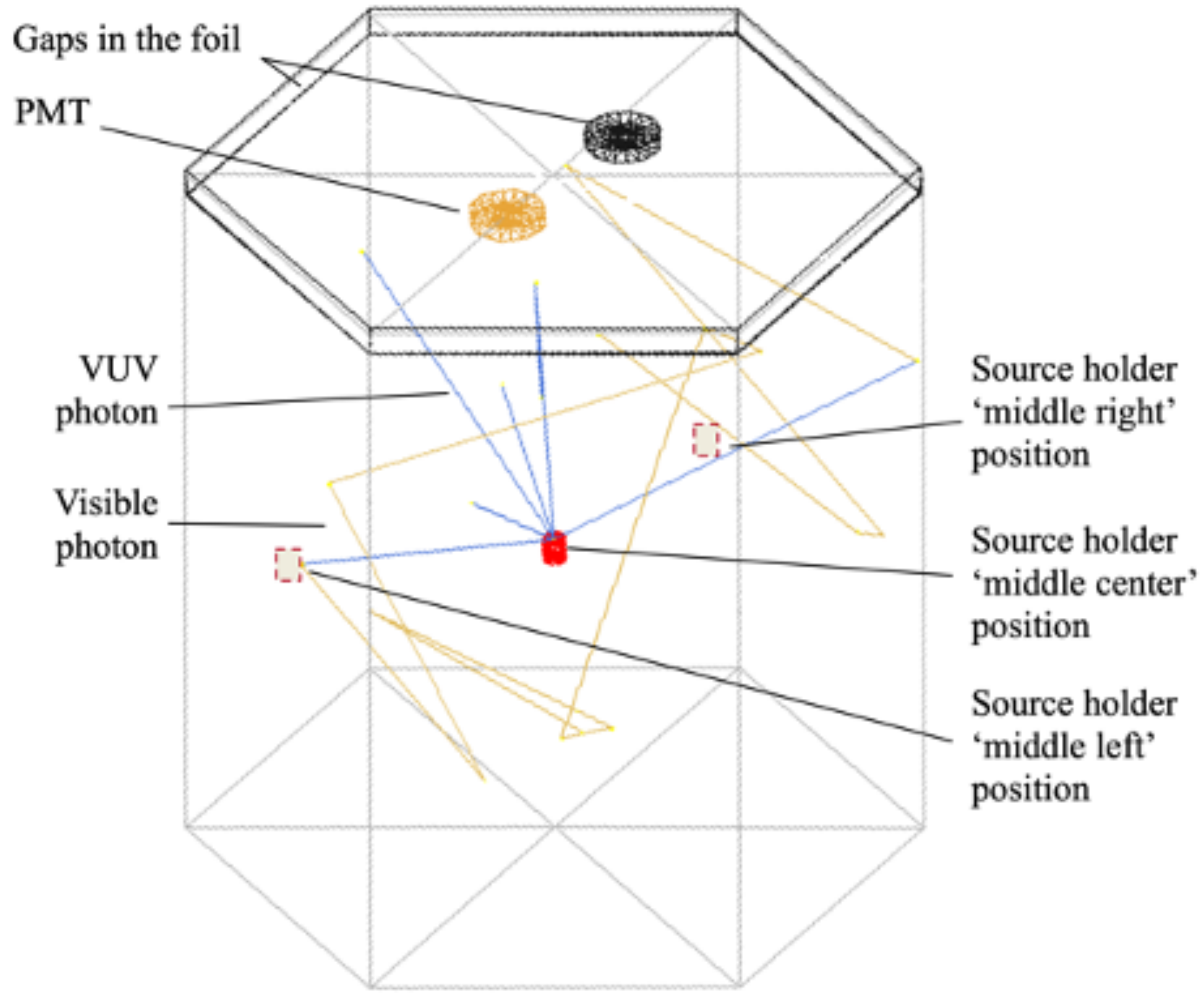


Only statistical error bars in this plot

Scintillation light studies

- **Large scale test of a novel polymer wavelength shifter material known as polyethylene naphthalate (PEN) for future LAr detectors**





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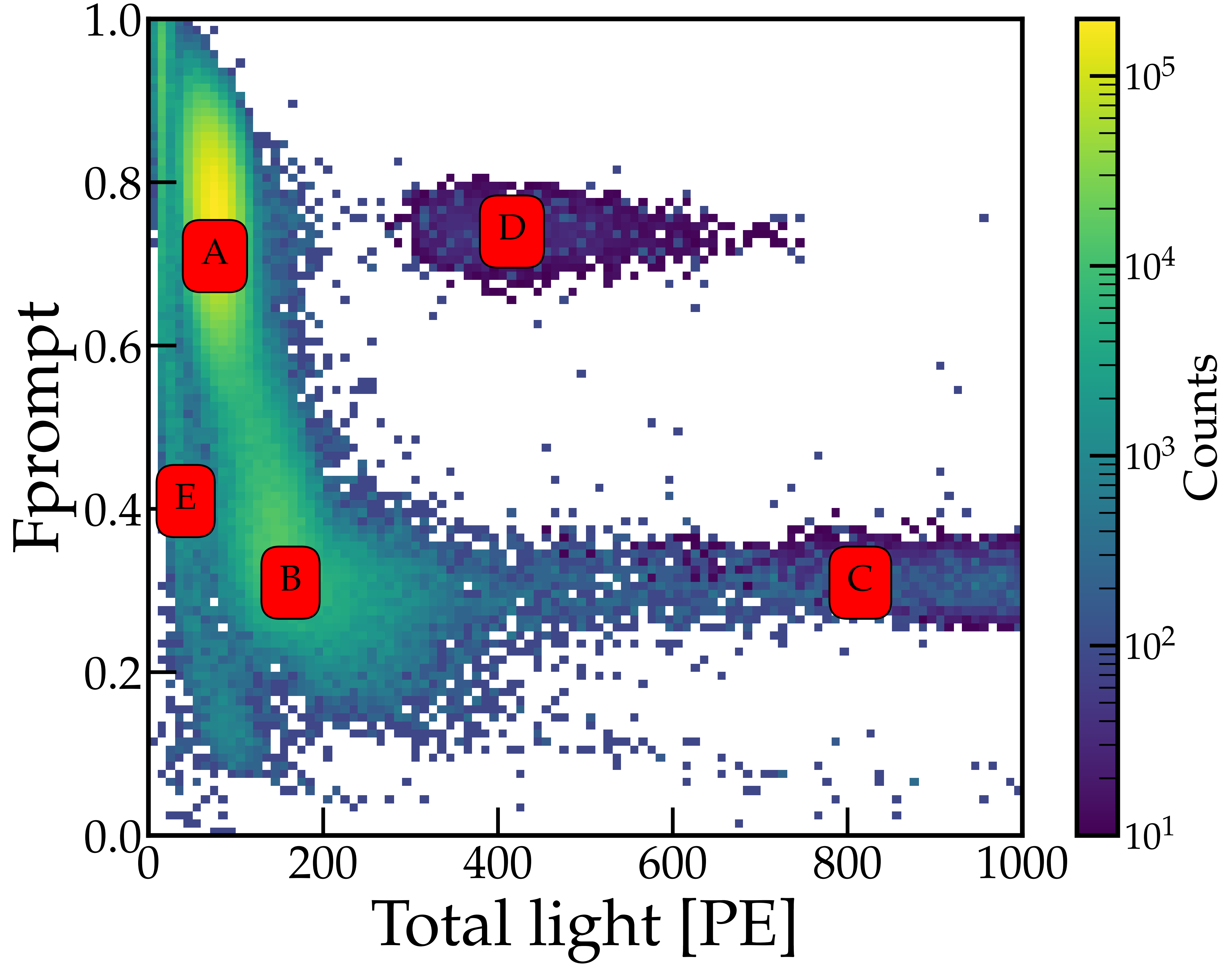

A. ^{241}Am α's

B. α-pileup

C. Cosmic ray muons

D. Likely candidate are protons from inelastic interaction of cosmic ray muons & neutrons

E. Short burst of light. Possible sources are Cherenkov light produced in the PMT cathode glass, PMT afterpulsing, interaction of radiation in PEN.

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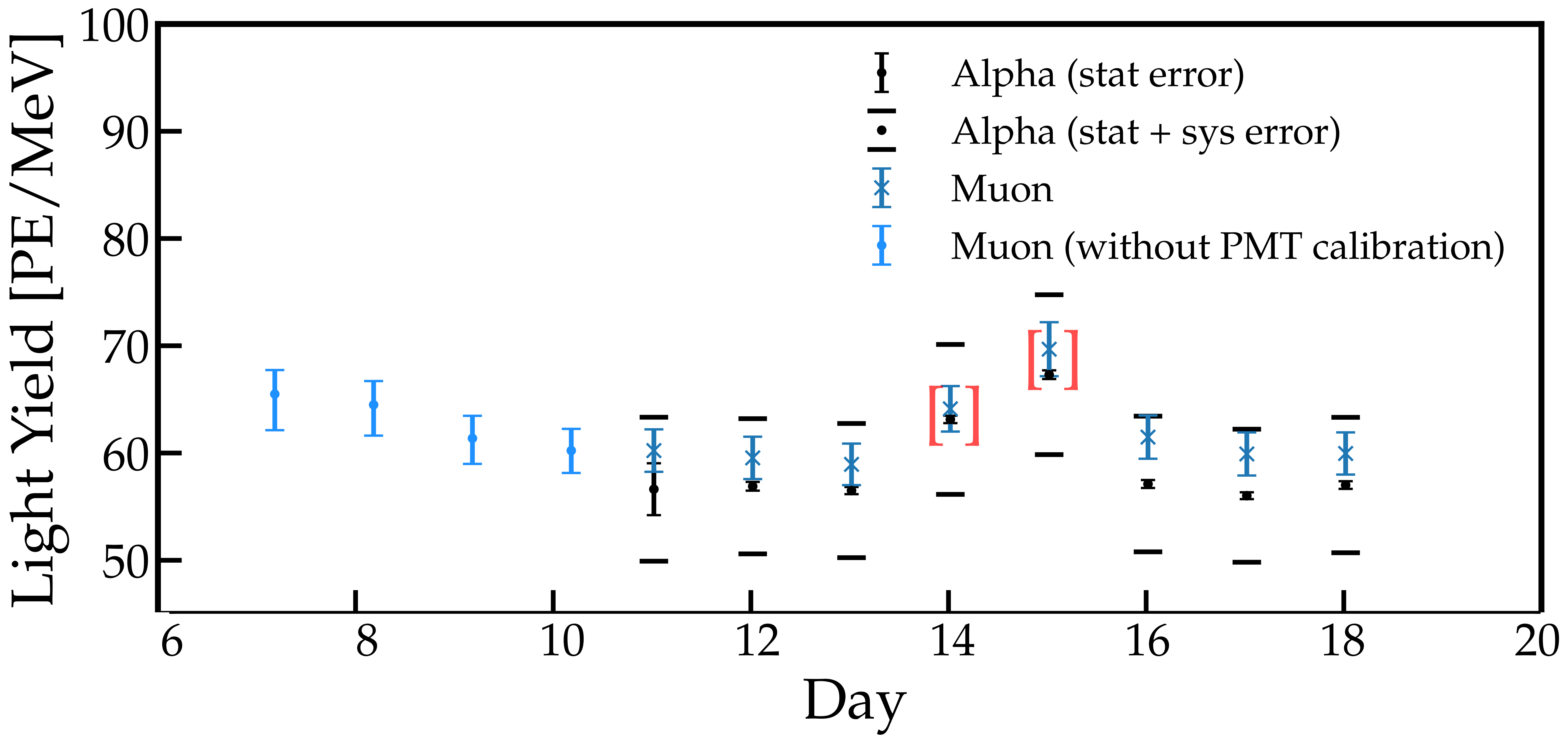
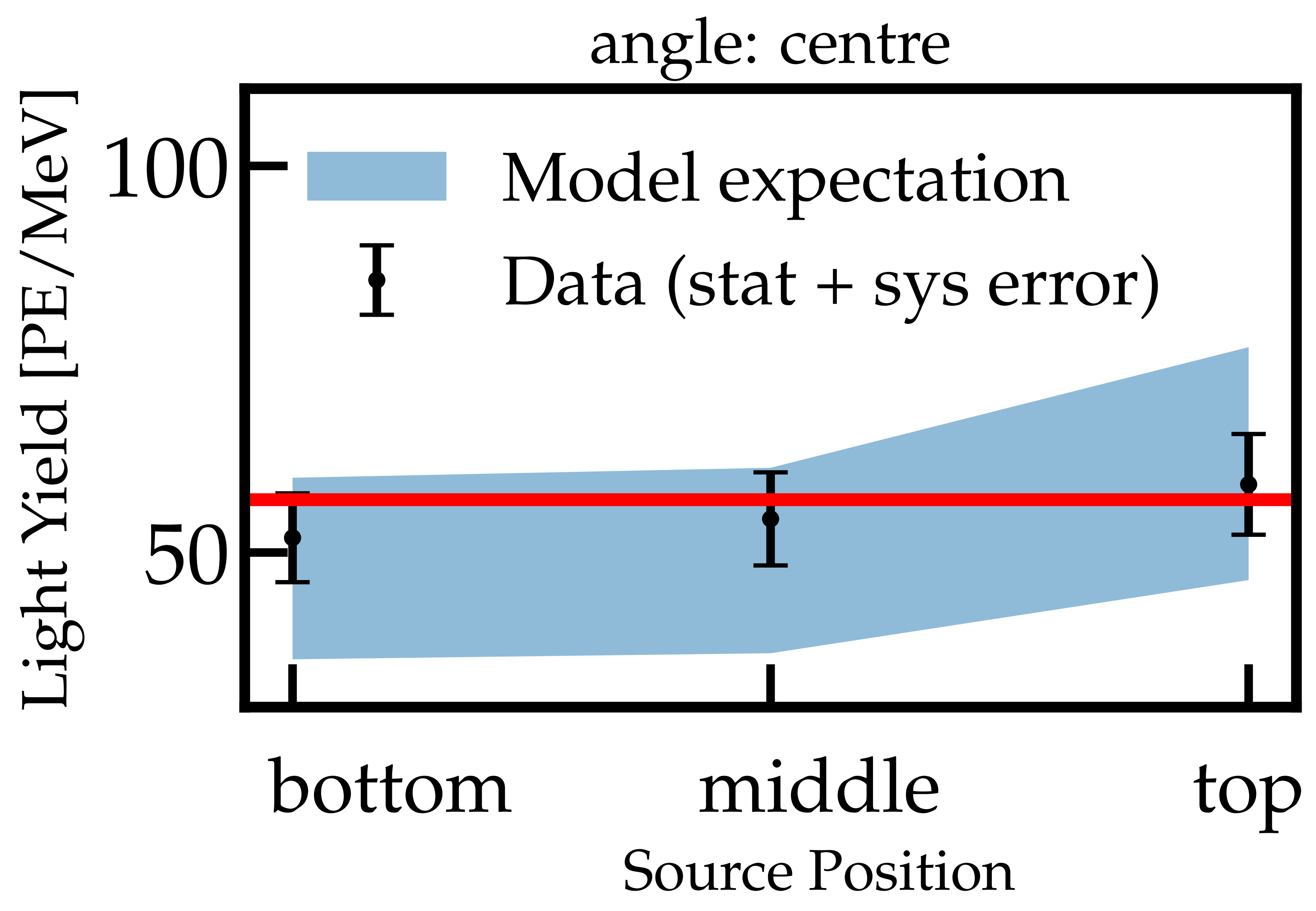
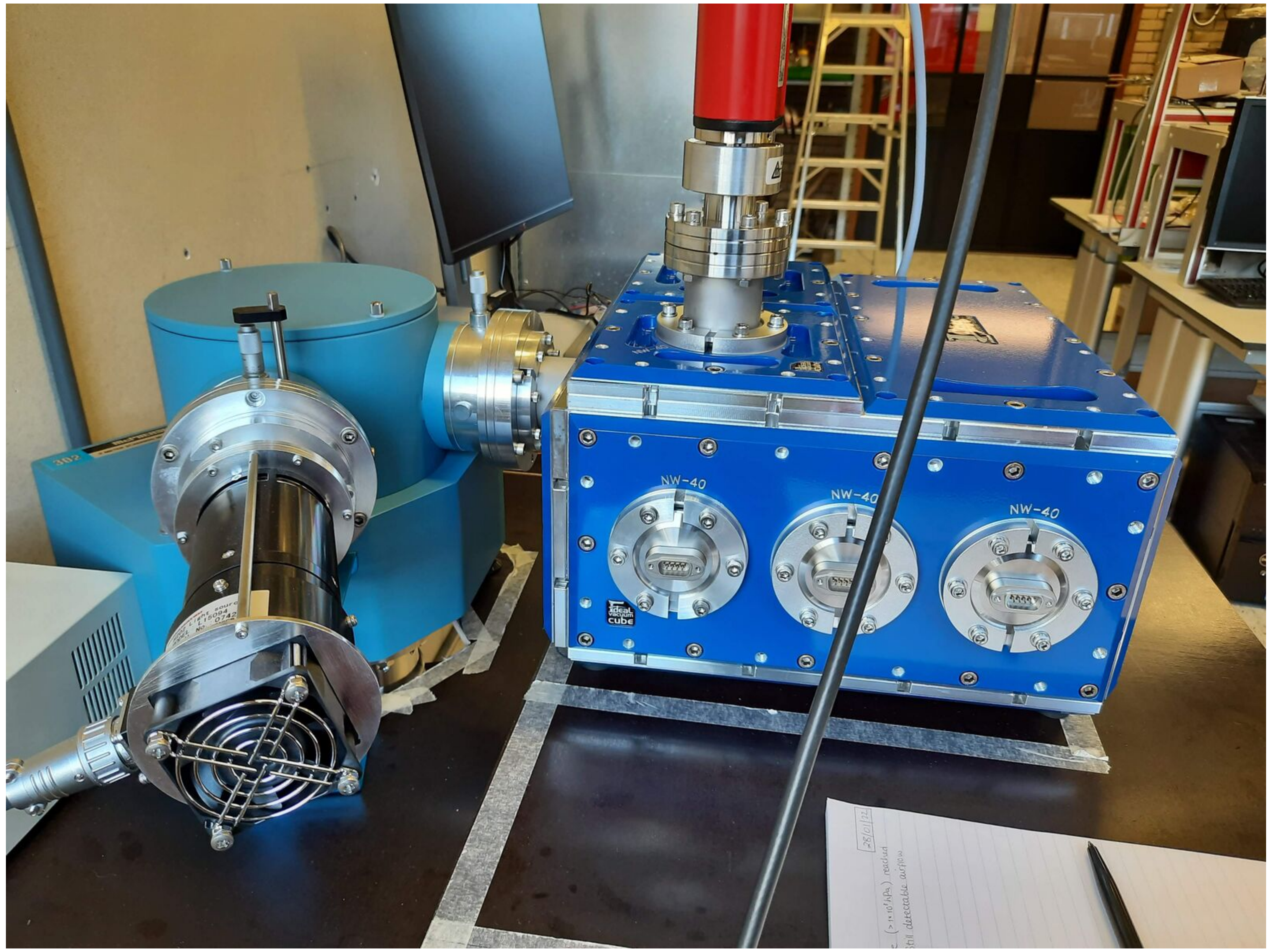
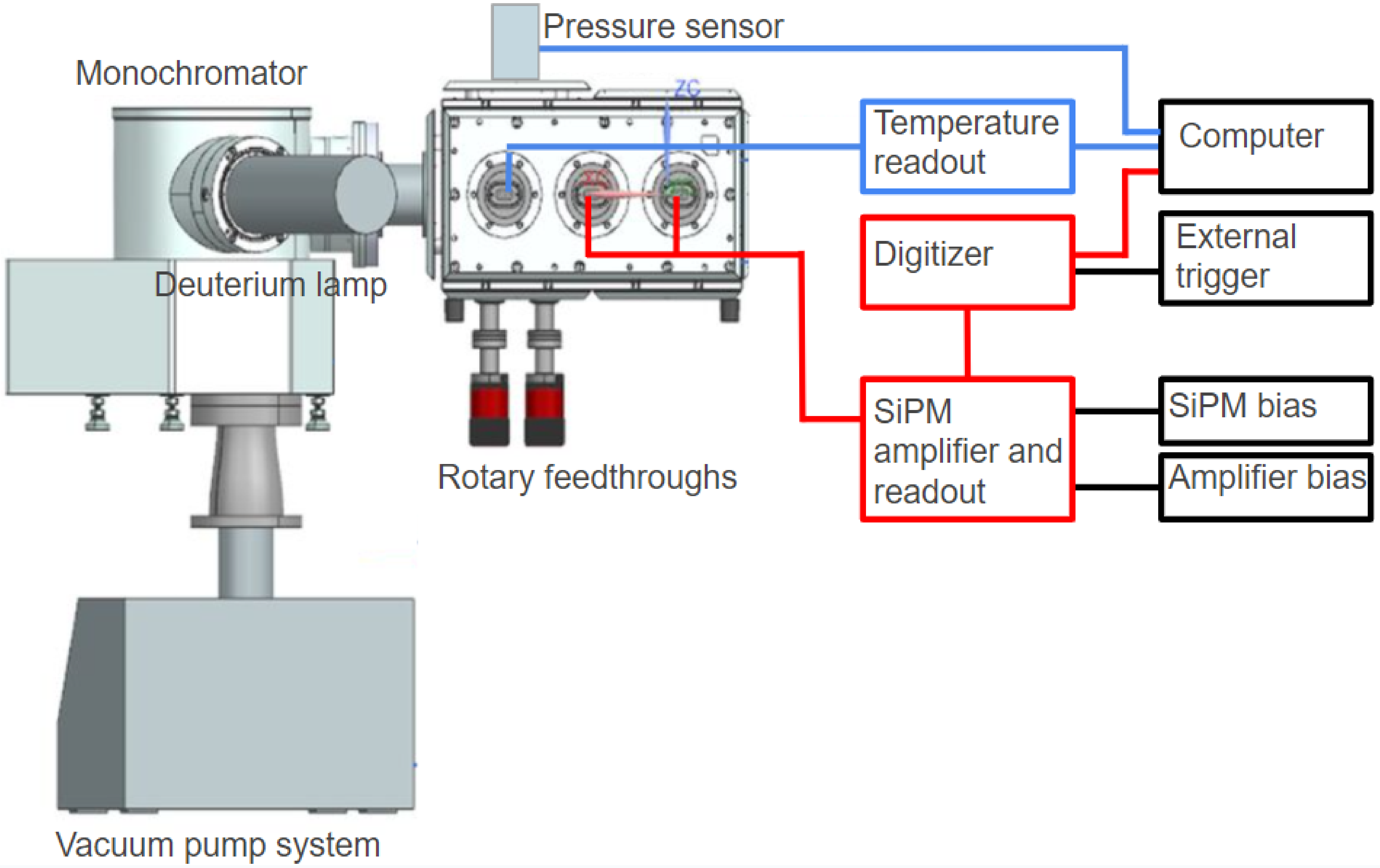




Scintillation light studies

- **Optical characterisation setup for liquid noble gas detectors**





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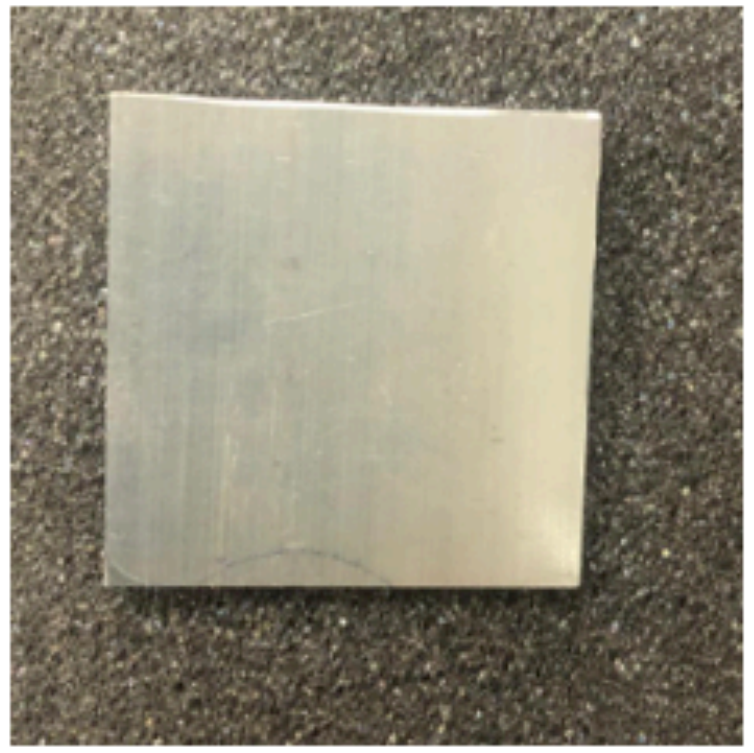
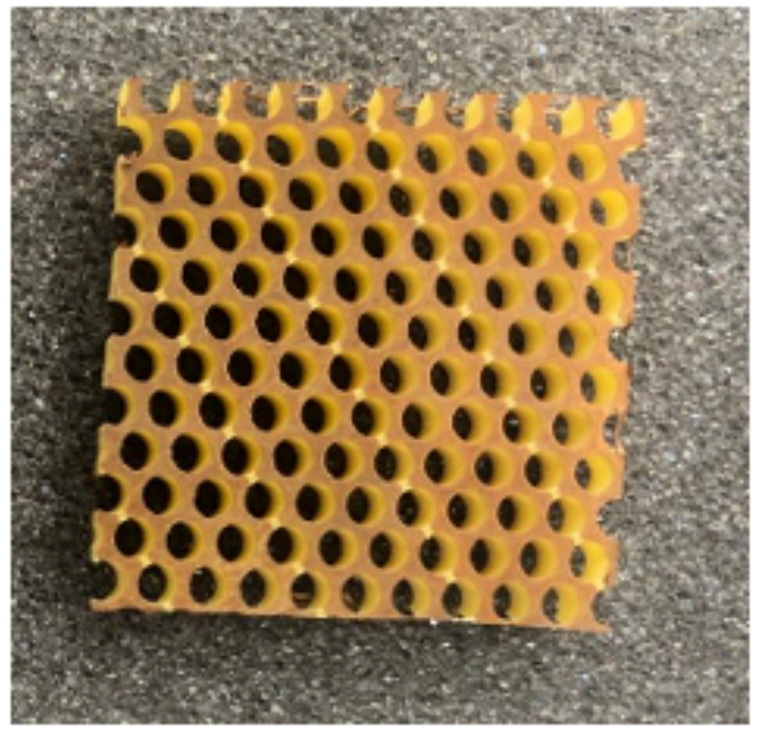
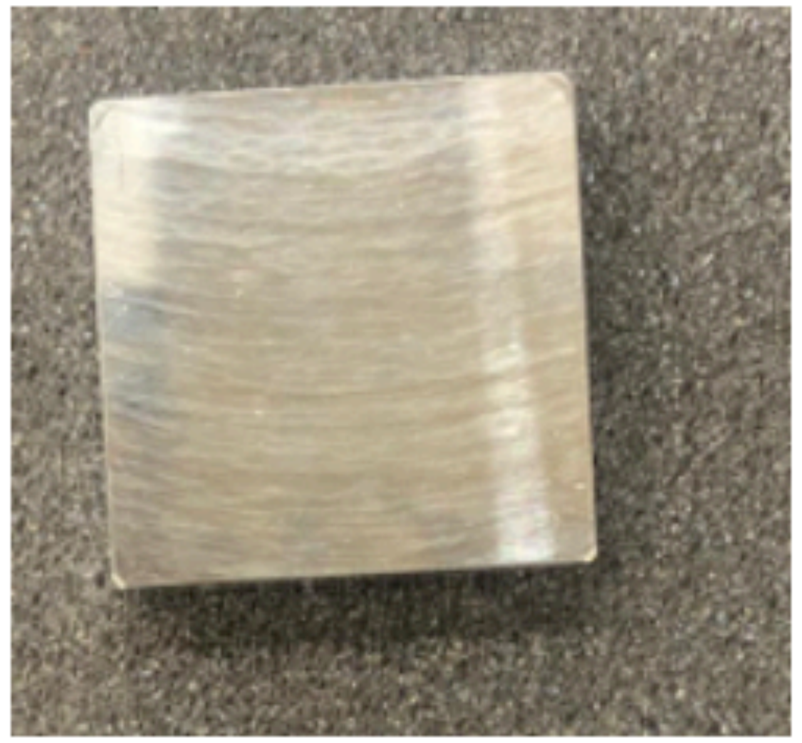
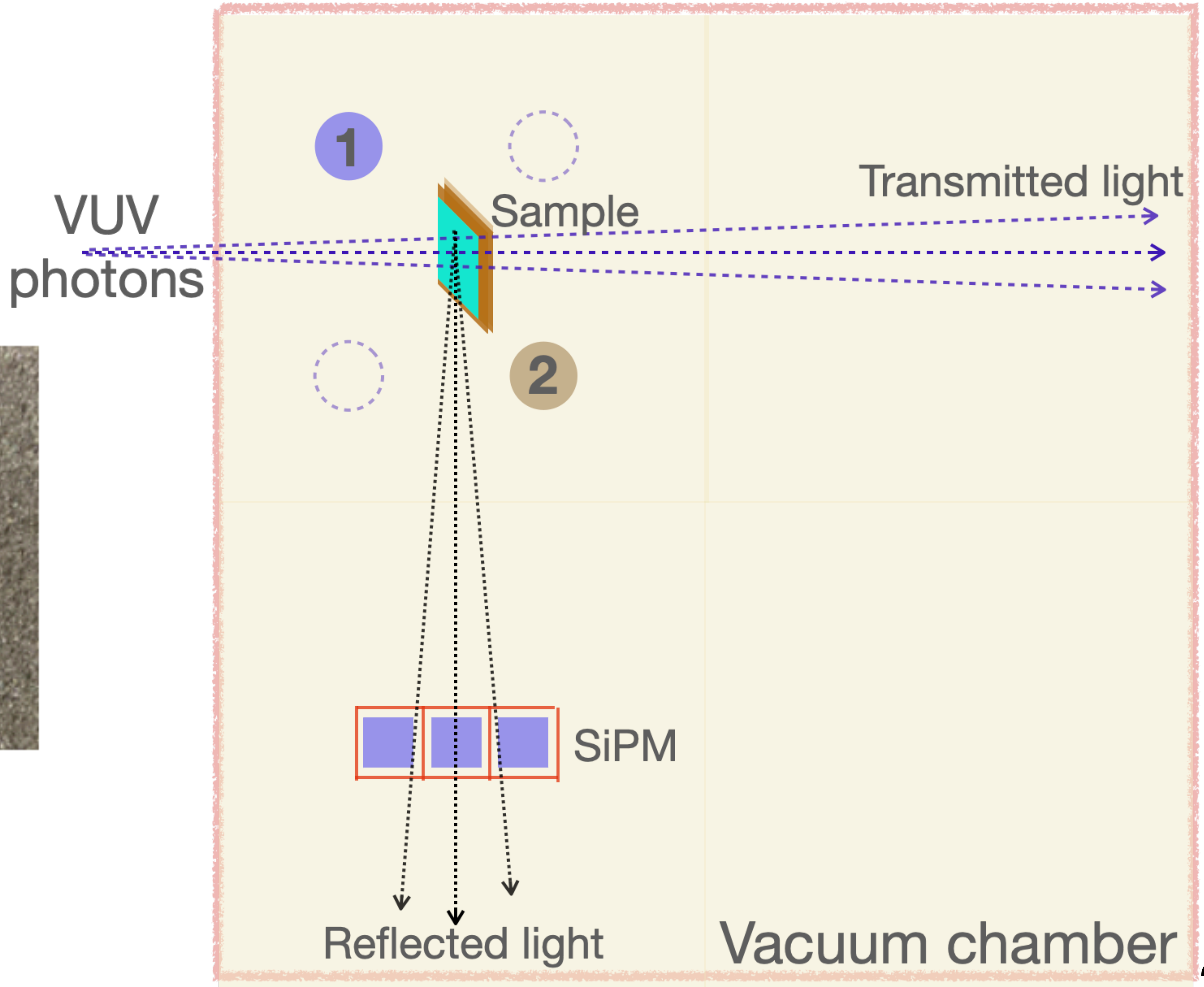

Scintillation light studies

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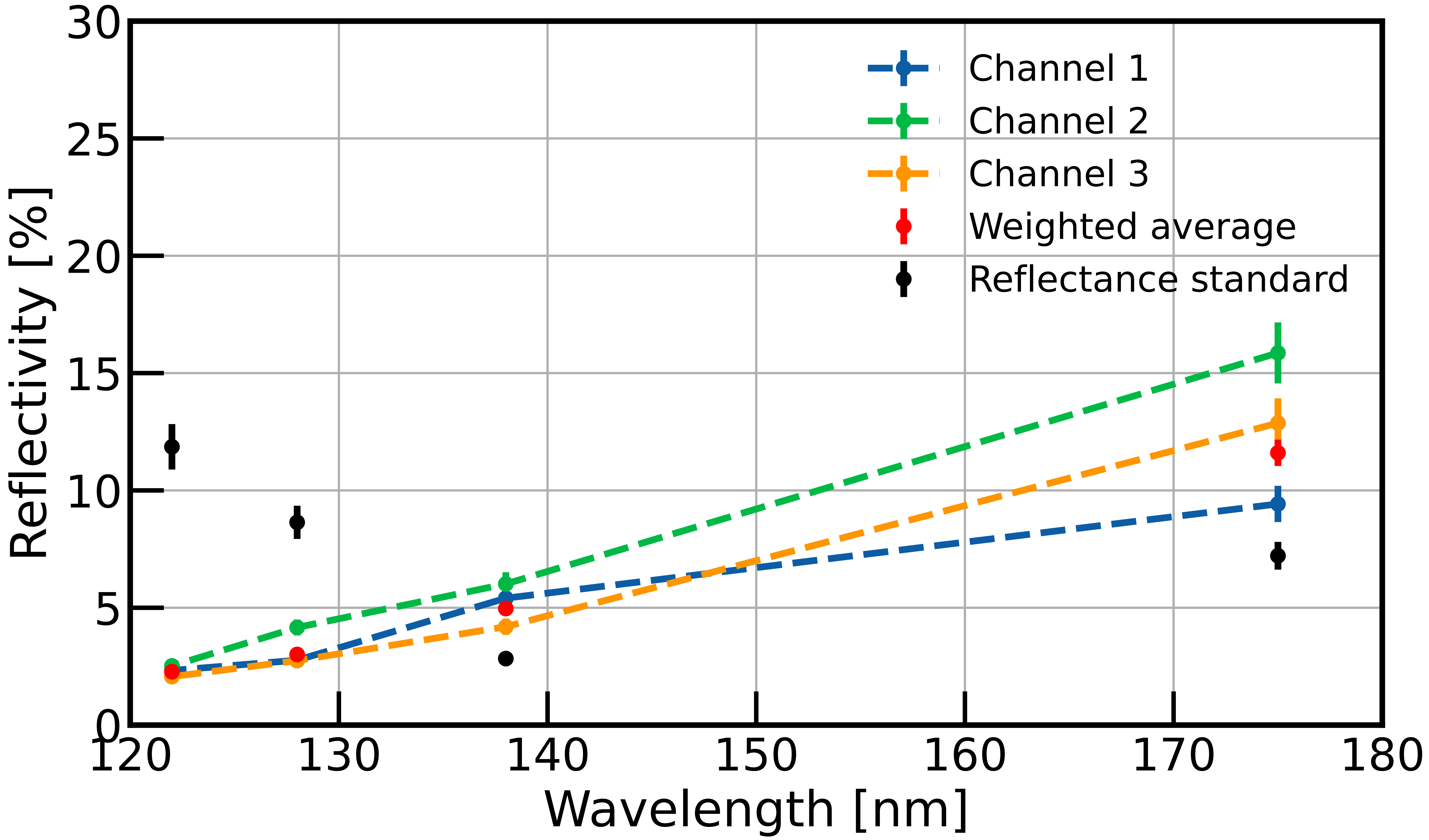
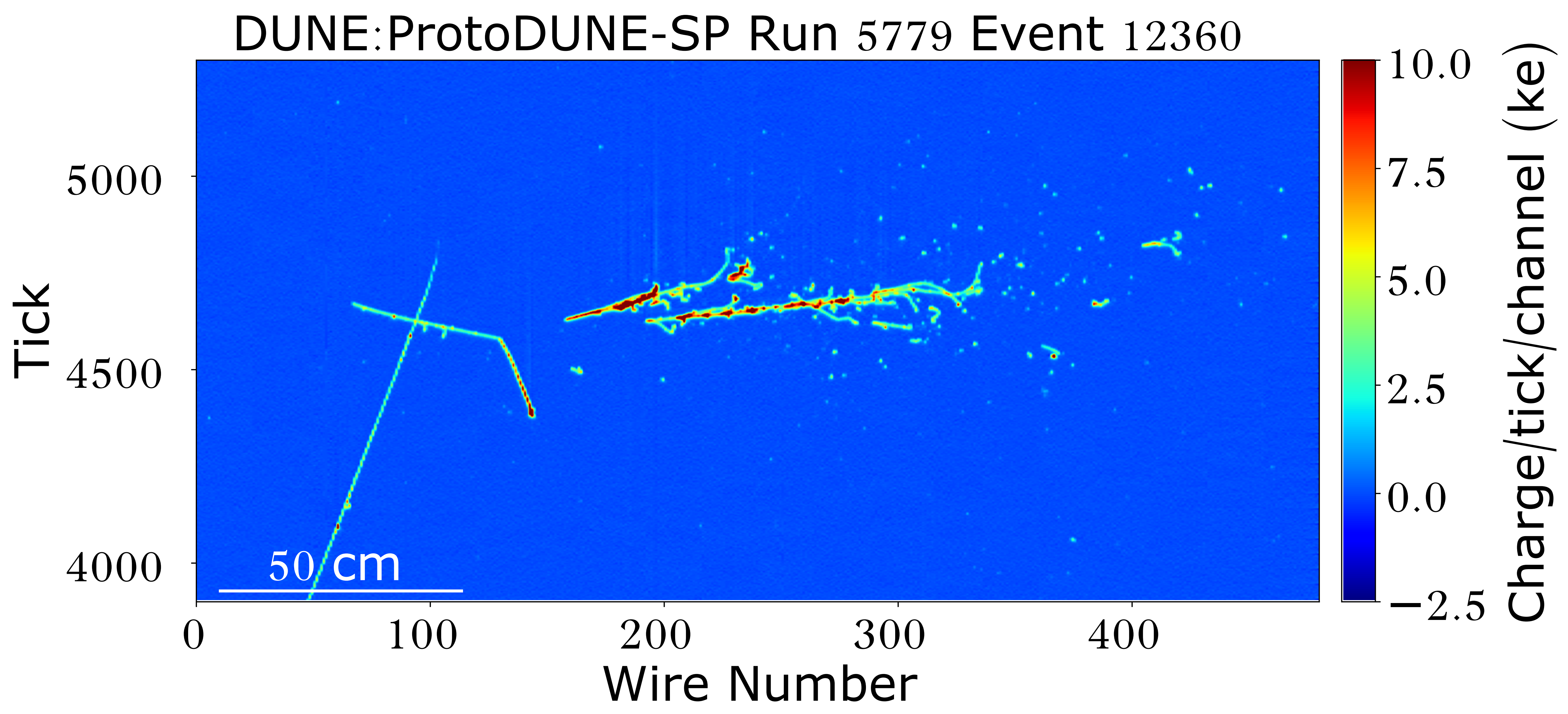


Backup

Shower energy scale calibration: MC performance

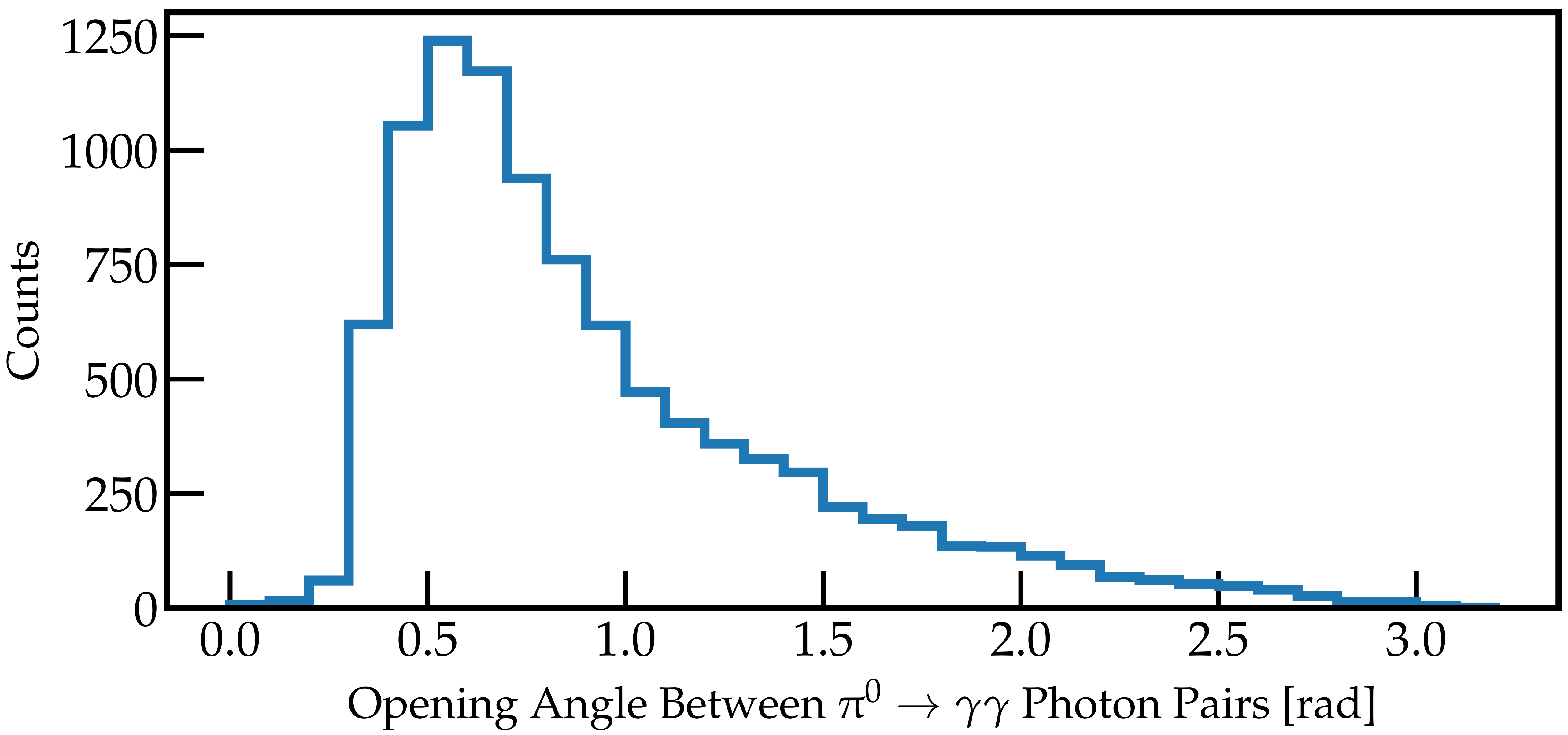
π^0 reconstruction is important for shower energy scale calibration and background mitigation in DUNE

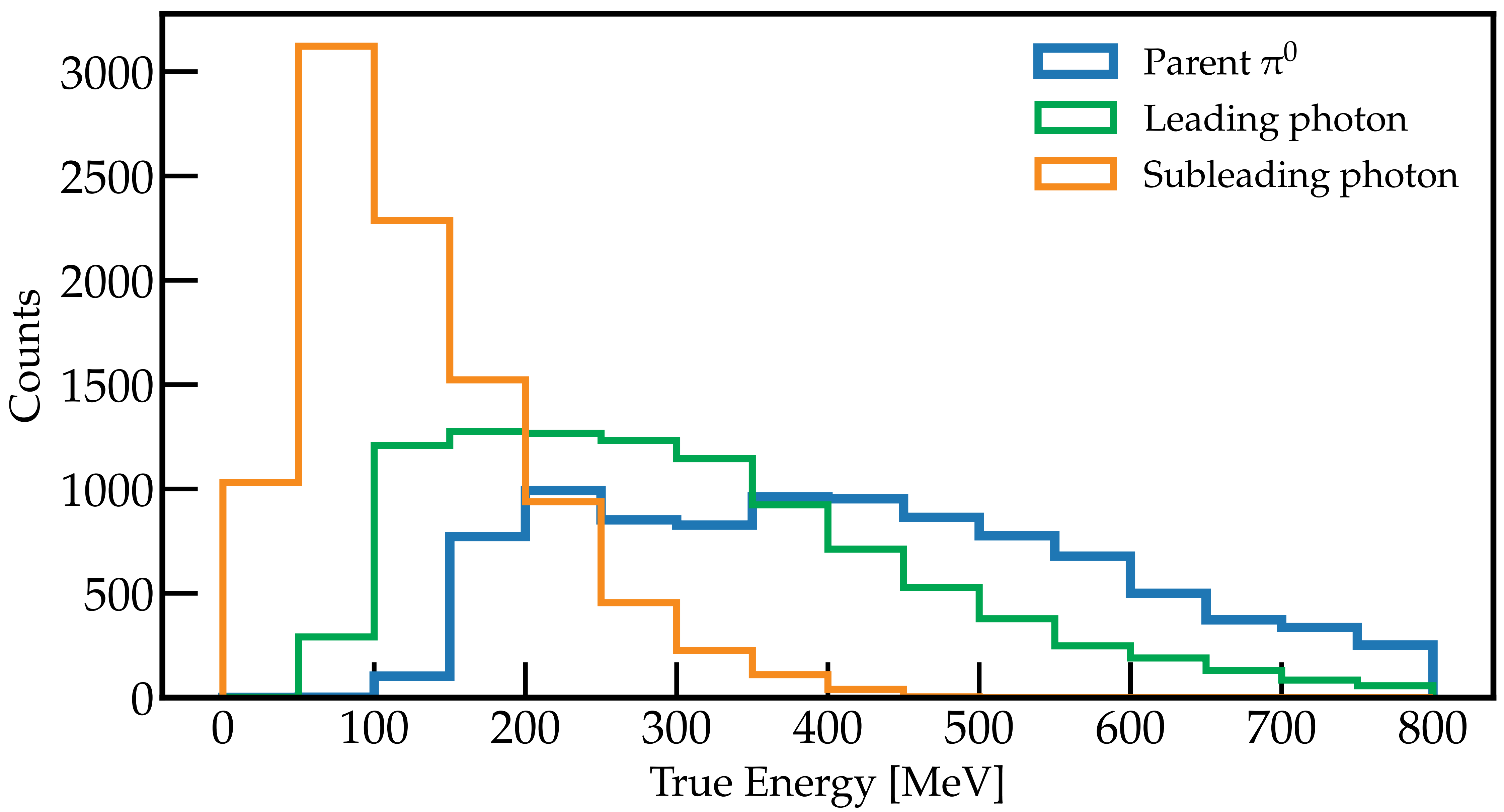
- We can validate the shower energy reconstruction by comparing the invariant mass distribution of **π^0** decay photon pairs to the known value.
- Understanding **π^0** decay reconstruction performance is important to correctly estimate the background in oscillation analysis.



Example π^+—Ar interaction producing a π^0 and a proton. The π^0 decays promptly to two photons.

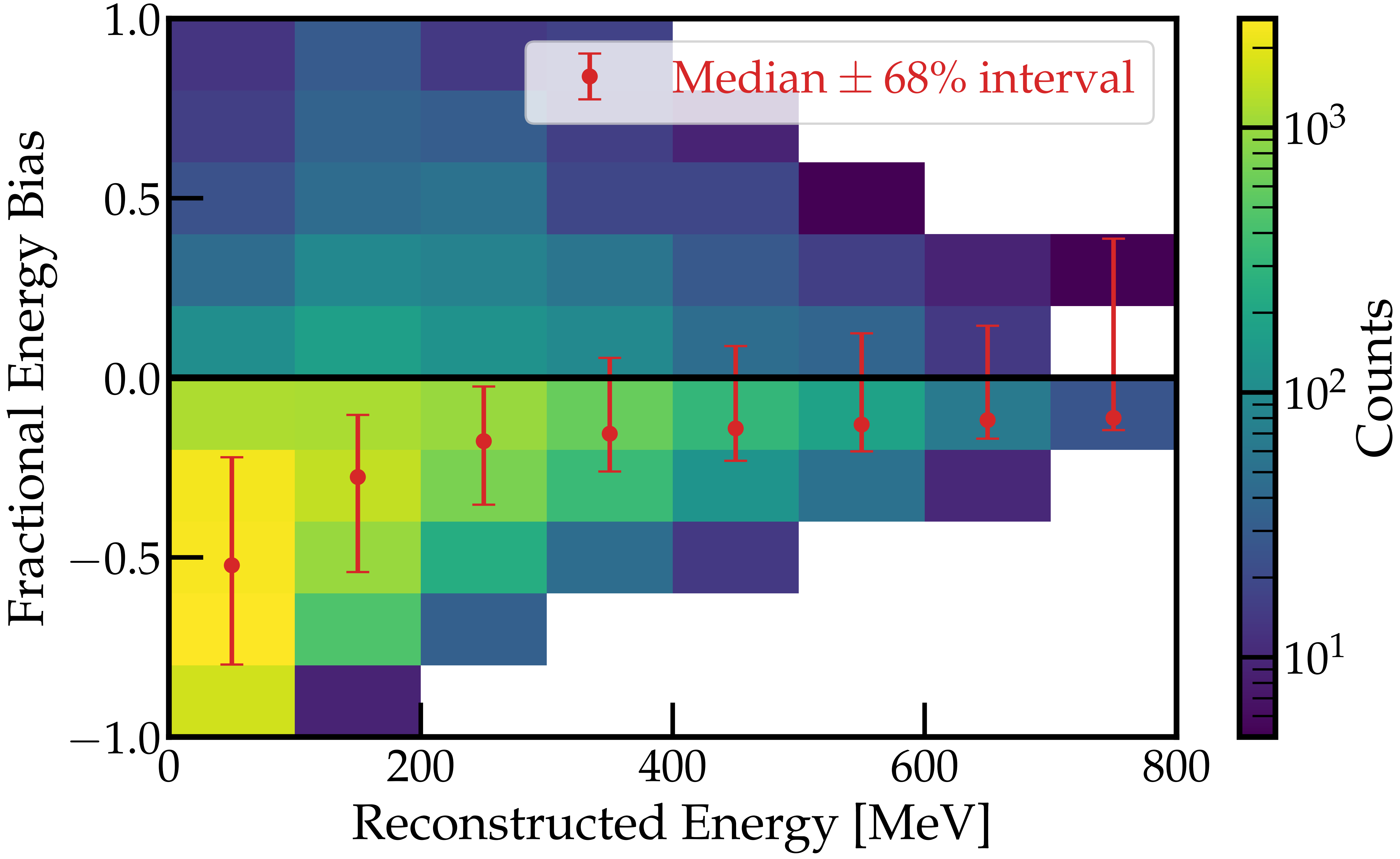
True energy and opening angle distribution for π^0 photon pair in the 1 GeV MC sample*

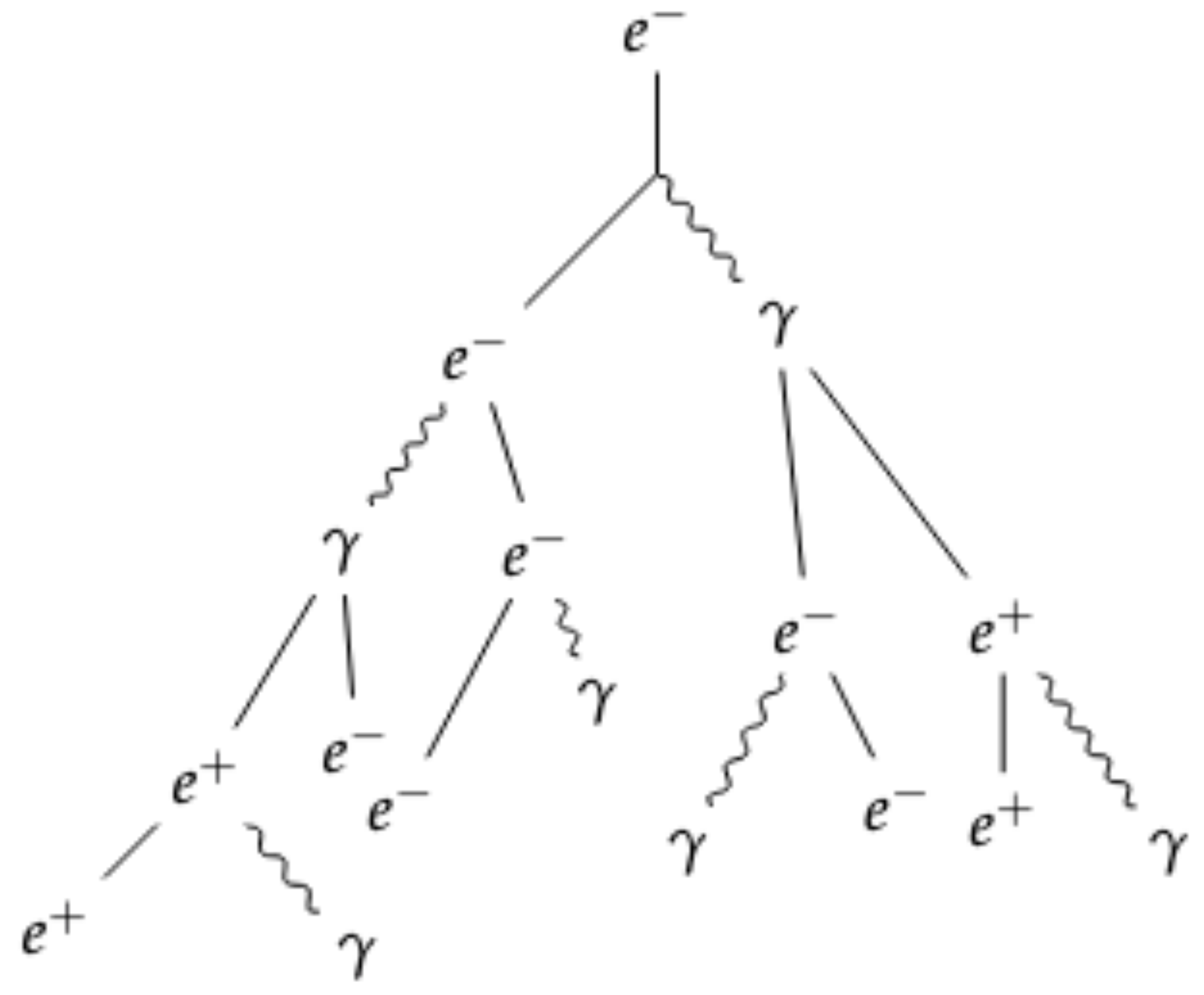




*Restricted to decay where both photons were reconstructed

Shower energy reconstruction suffers from large bias for low energy showers





EM cascade development with the production of many secondary electrons and photons

Shower direction reconstruction generally performance well

Key shower reconstruction performance metrics show room for improvement

TABLE 3.3: Summary of key photon shower reconstruction metrics in the 1 GeV MC sample for shower energy above 200 MeV.

Observable	**Estimate**
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Energy Bias	-10% to -20%
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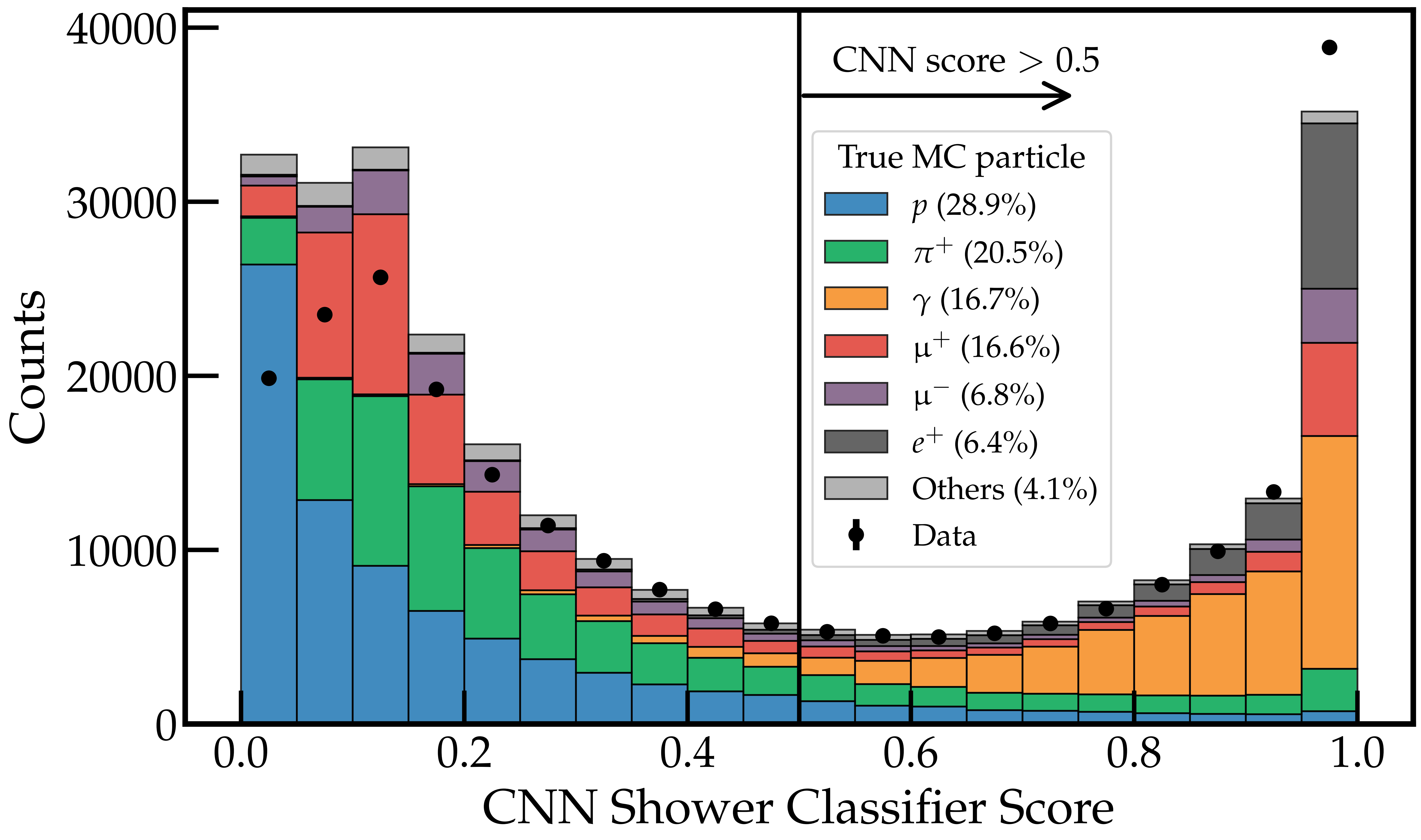
Photon Fragmentation Rate	16%
π^0 Reconstruction	
Photon Pair Opening Angle Bias	<0.1 rad
Reconstruction Efficiency for π^0 decay Photon Pair	35%

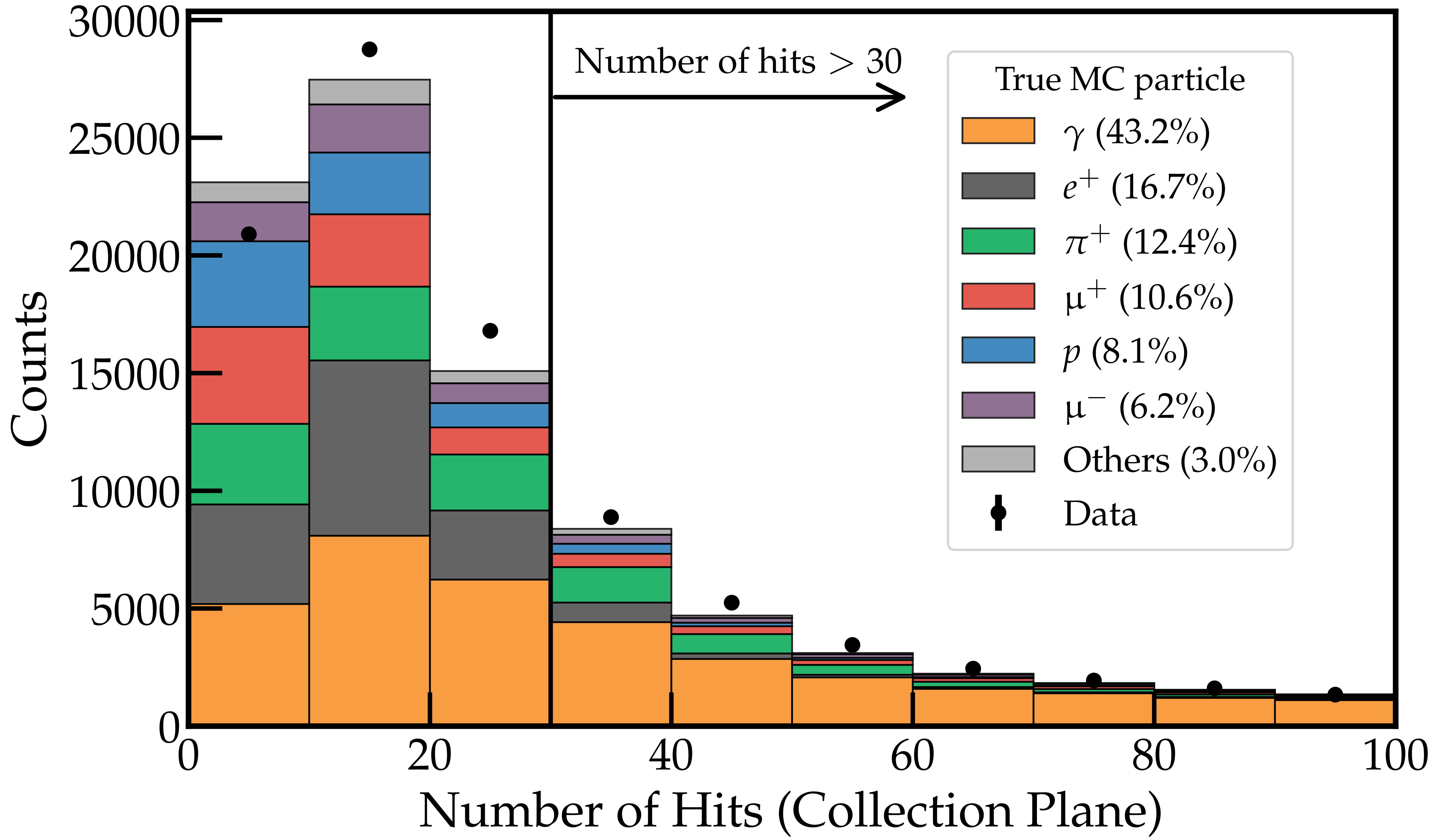
Shower energy scale calibration: comparison with data

Good shower vs track separation achieved using a Convolutional Neural Network classifier



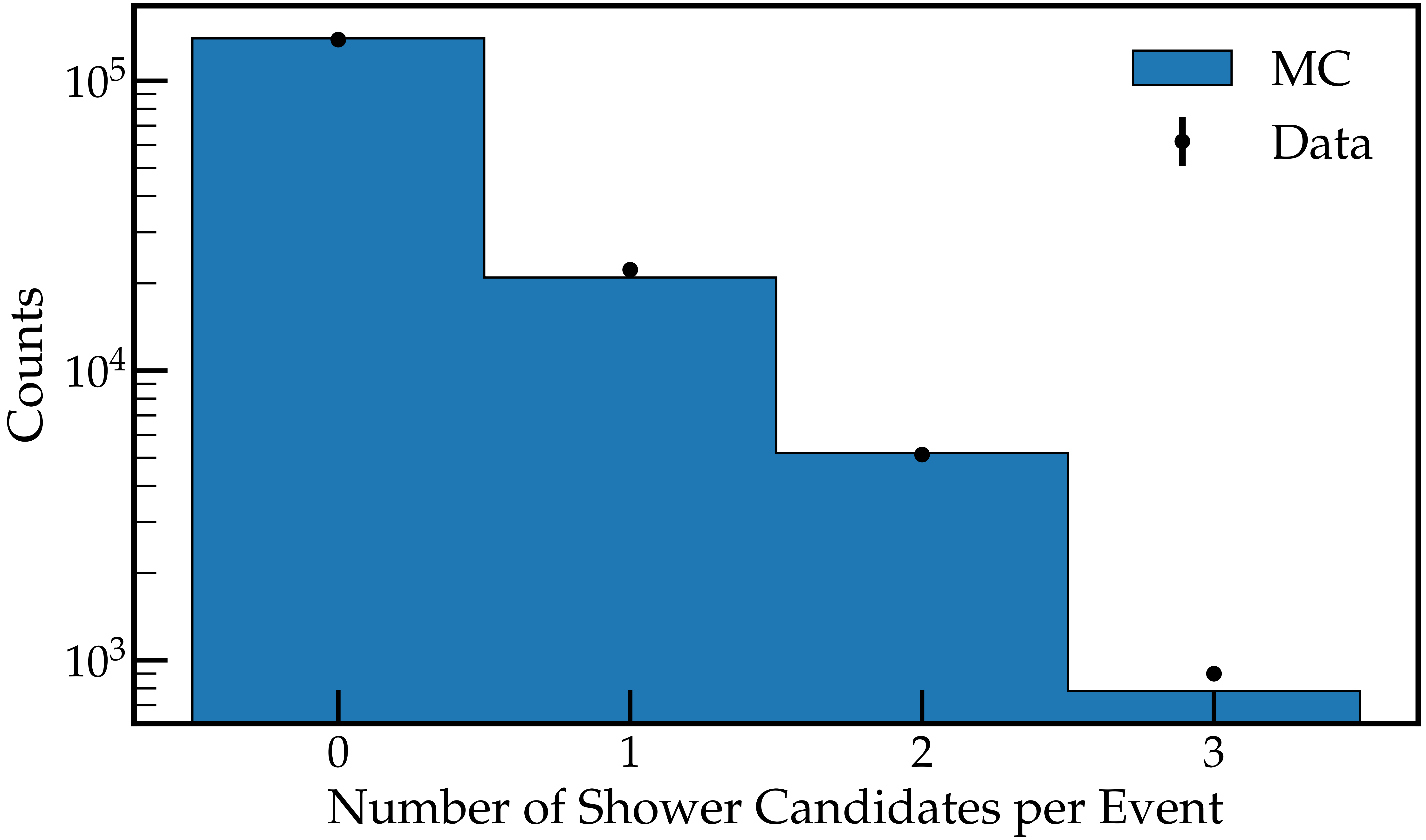
CNN score for reconstructed daughters in ProtoDUNE beam interaction

Low energy background is removed by requiring more than 30 hits associated with the reconstructed daughter

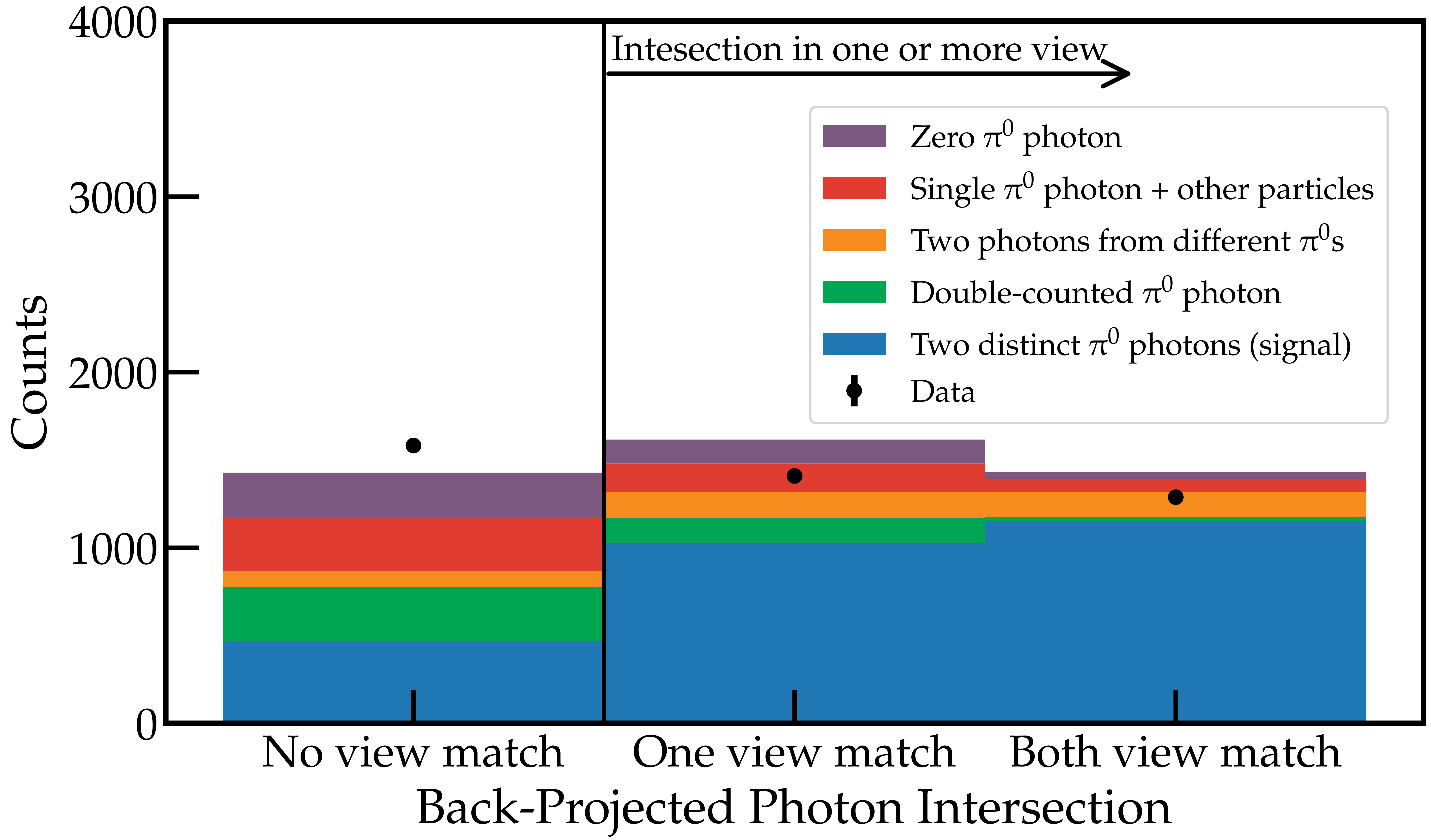


Distribution of number of hits for reconstructed shower like daughters

The two highest energy showers are selected as the π^0 photon candidates

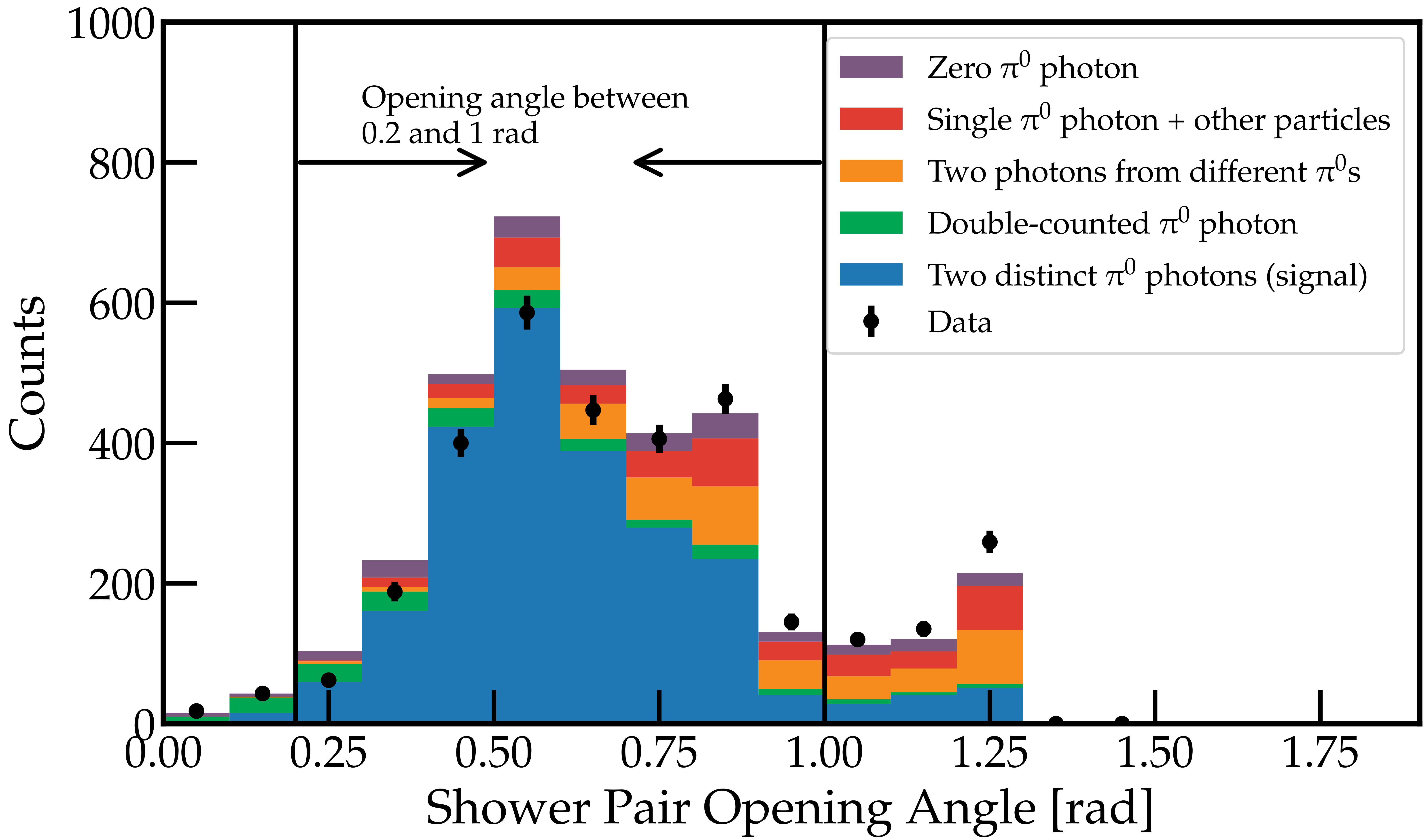


Background photon pairs are removed by looking at the agreement between the shower direction towards a common vertex

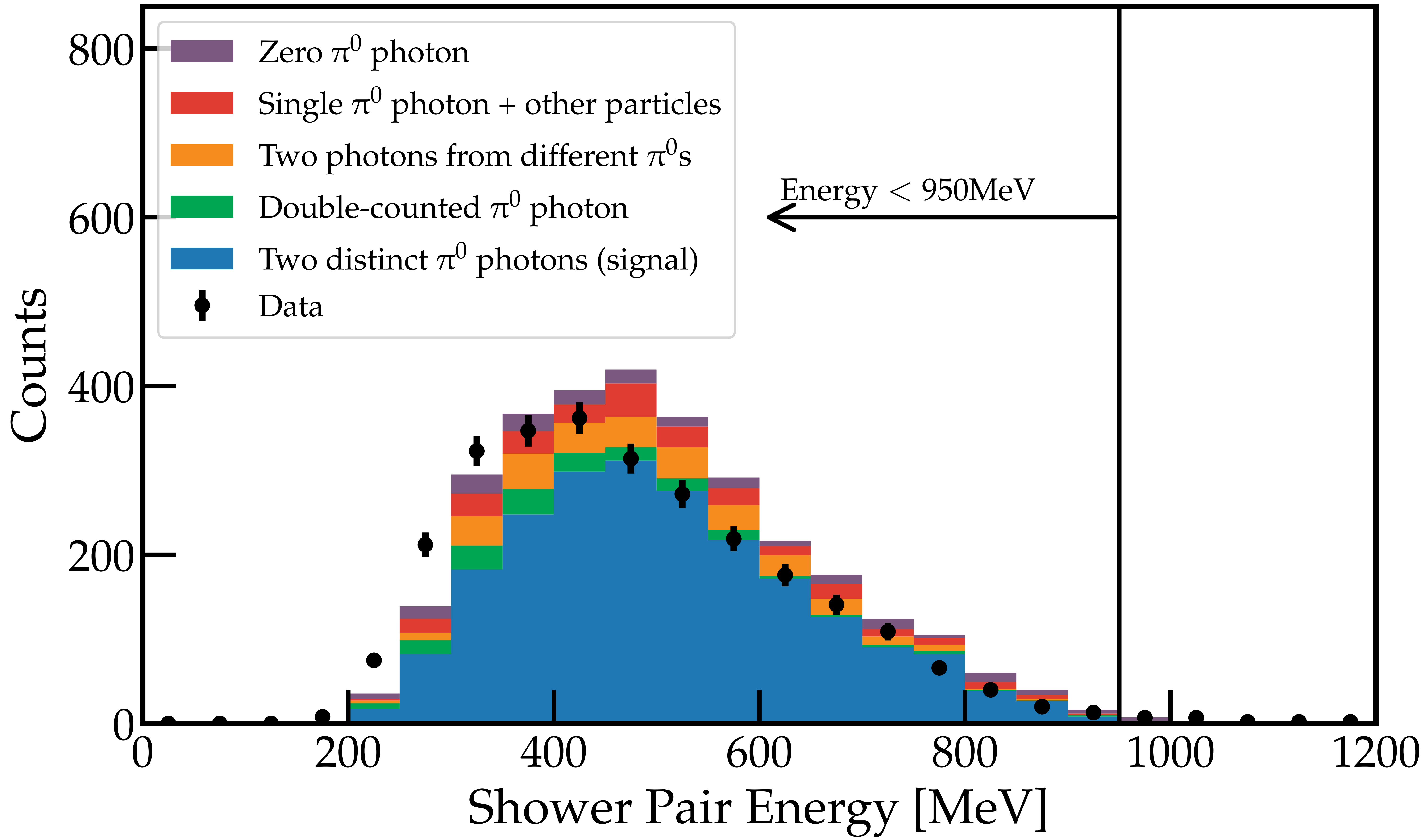


Intersection of backtracked photon direction vectors in the two 2D views (XZ,YZ)

Further background is removed by requiring the opening angle between the selected photon pairs within 0.2—1 rad.



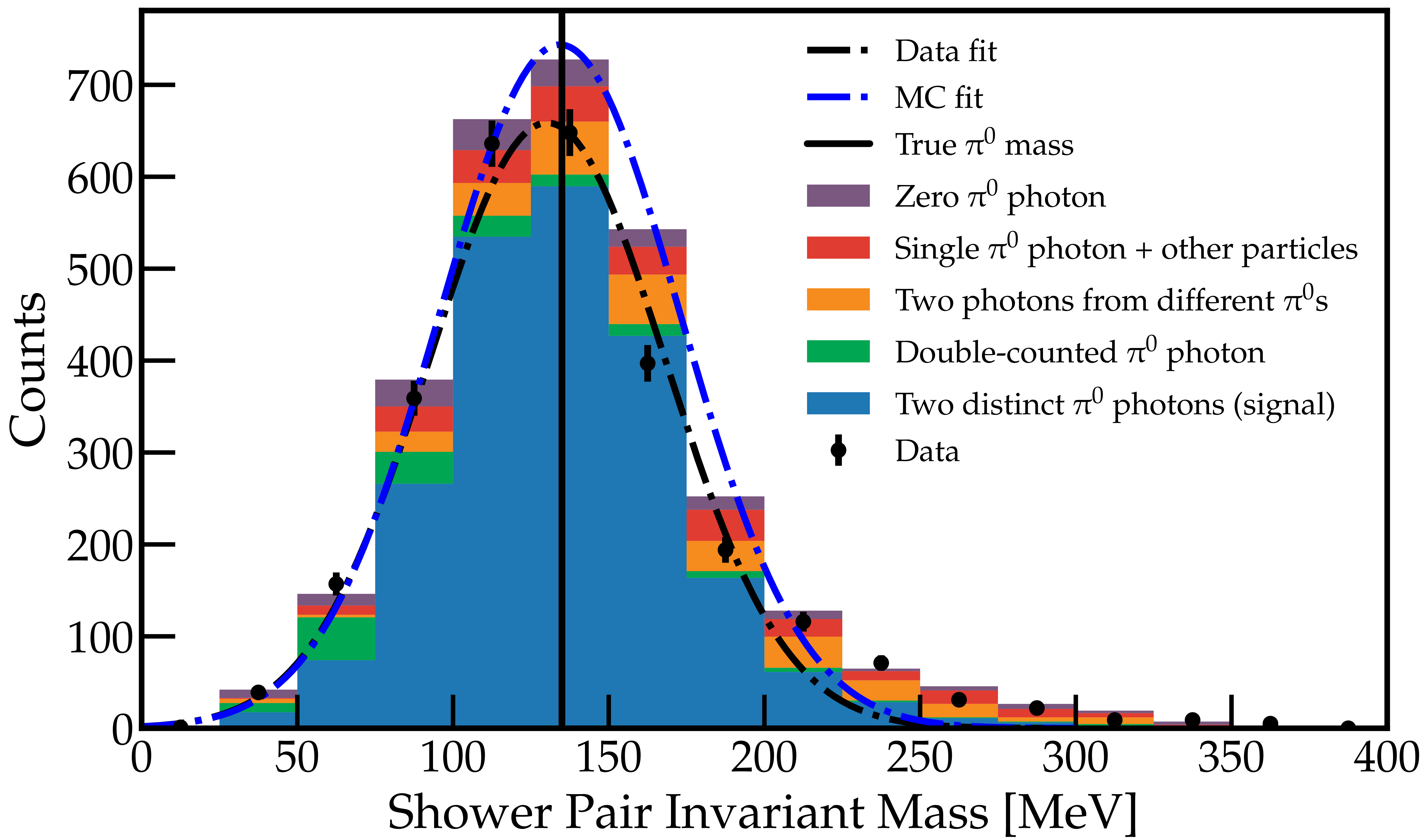
Final cut is applied on the shower pair energy to remove background



π^0 selection in numbers

Selection Step	Efficiency	Purity
Daughter shower selection		
CNN score > 0.5	93.3%	43.2%
Nhits > 30	50.4%	69.1%
π^0 shower pair selection		
Shower pairs	32.7%	52%
Topology cuts	24.4%	71.5%

Invariant mass distribution reveals underestimation of energy losses in shower



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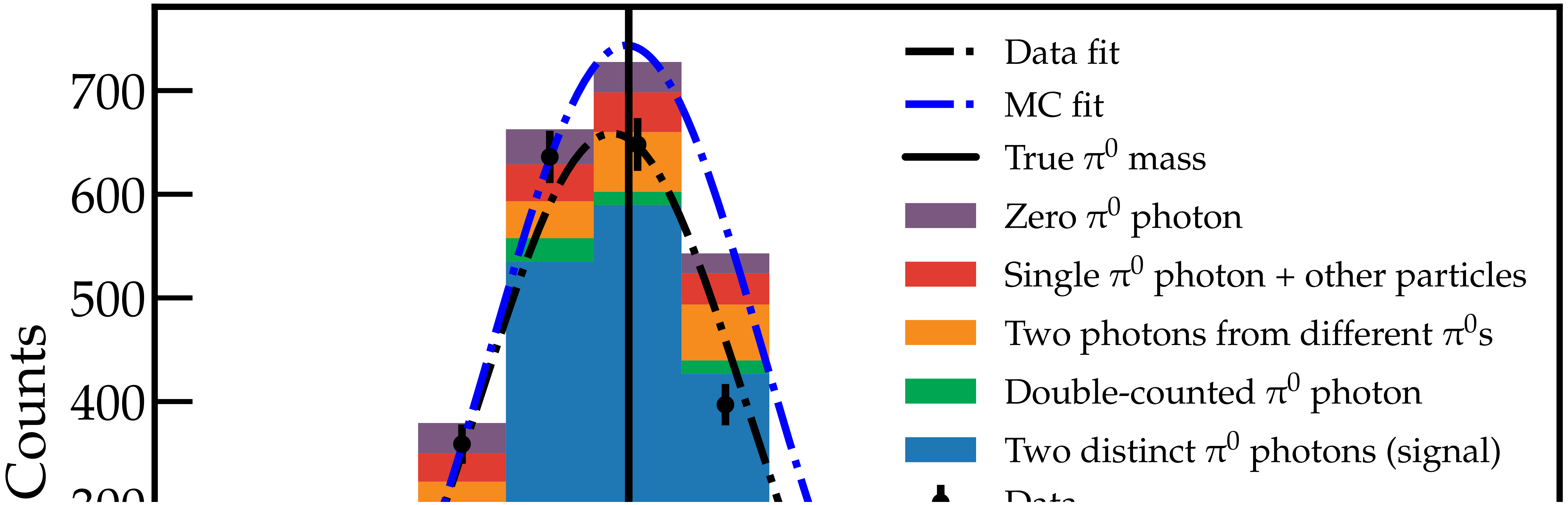


TABLE 3.5: Gaussian fit parameters for the invariant mass distribution of selected π^0 candidates in data and MC. Fit range restricted to 0-250 MeV to exclude high-mass tail.

Sample	Mass (MeV)	Width (MeV)
MC	134.31 ± 0.75	38.63 ± 0.50
Data	130.23 ± 0.79	38.00 ± 0.54

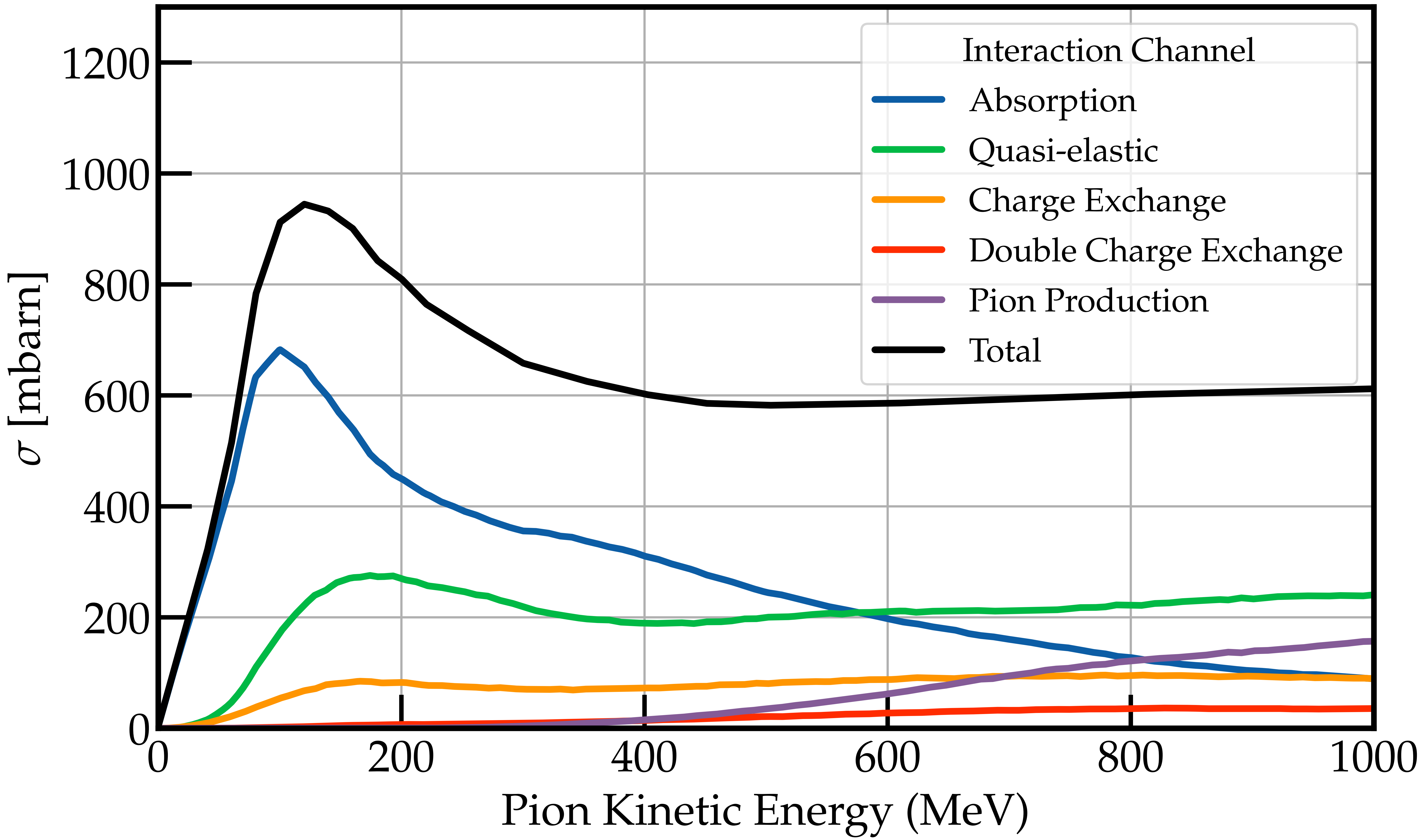
Cross-section of π^+—Ar interactions

Pion argon interactions

TABLE 3.2: Classification of $\pi^{\pm}$–Ar interactions according to the number and type of pions in the final state. X denotes all non-pion final-state particles, including the recoiling nucleus, nucleons, and other secondaries.

Final-State Reaction	**Interaction Type**
$\pi^{\pm} + \text{Ar} \rightarrow \pi^{\pm} + X$	Quasi-elastic
$\pi^{\pm} + \text{Ar} \rightarrow 0\pi + X$	Absorption
$\pi^{\pm} + \text{Ar} \rightarrow \pi^{0} + X$	Charge–Exchange
$\pi^{\pm} + \text{Ar} \rightarrow \pi^{\mp} + X$	Double Charge–Exchange
$\pi^{\pm} + \text{Ar} \rightarrow n\pi + X,\ n > 1$	Pion Production

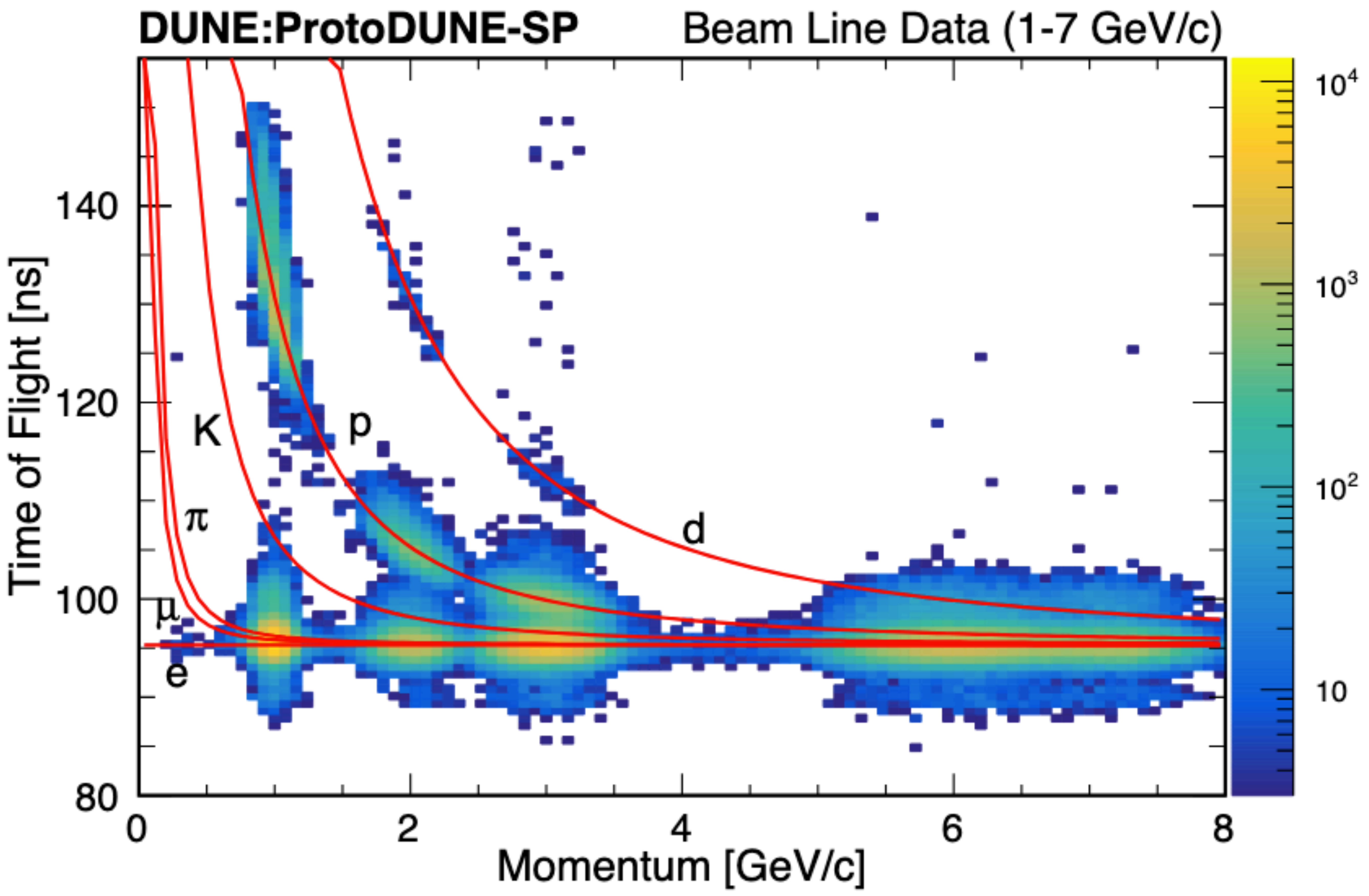
Pion argon interaction cross-section input in MC



Cross-section of π^+—Ar interactions: **Beam pion selection**

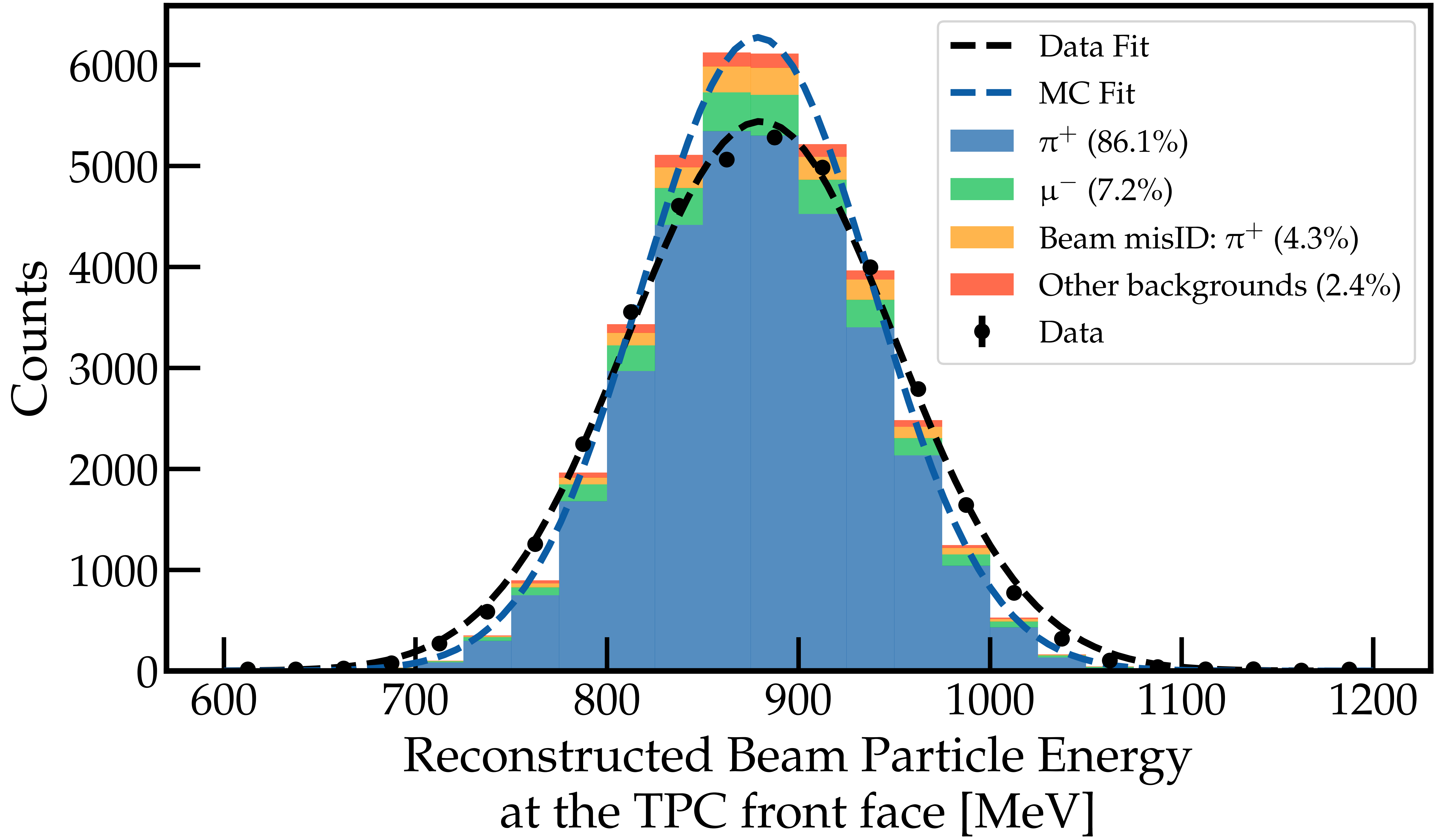
Beam Pion Selection

- Beam instrumentation separates different charge particles using Time of Flight information.
- Pions and muons are not separated using this cut.
- Reconstruction can also fail in identifying the correct beam pion track and is the dominating source of background events.

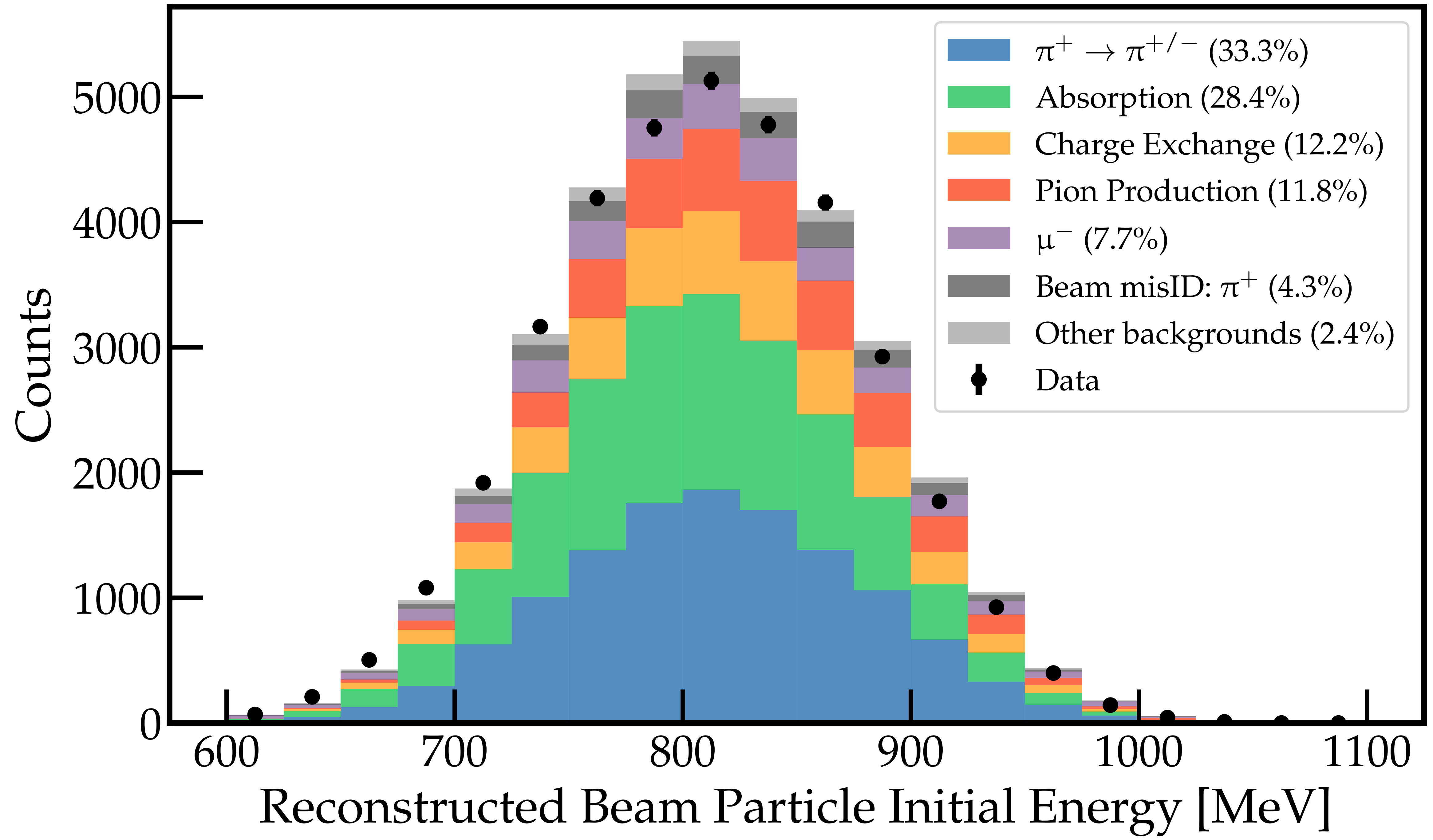


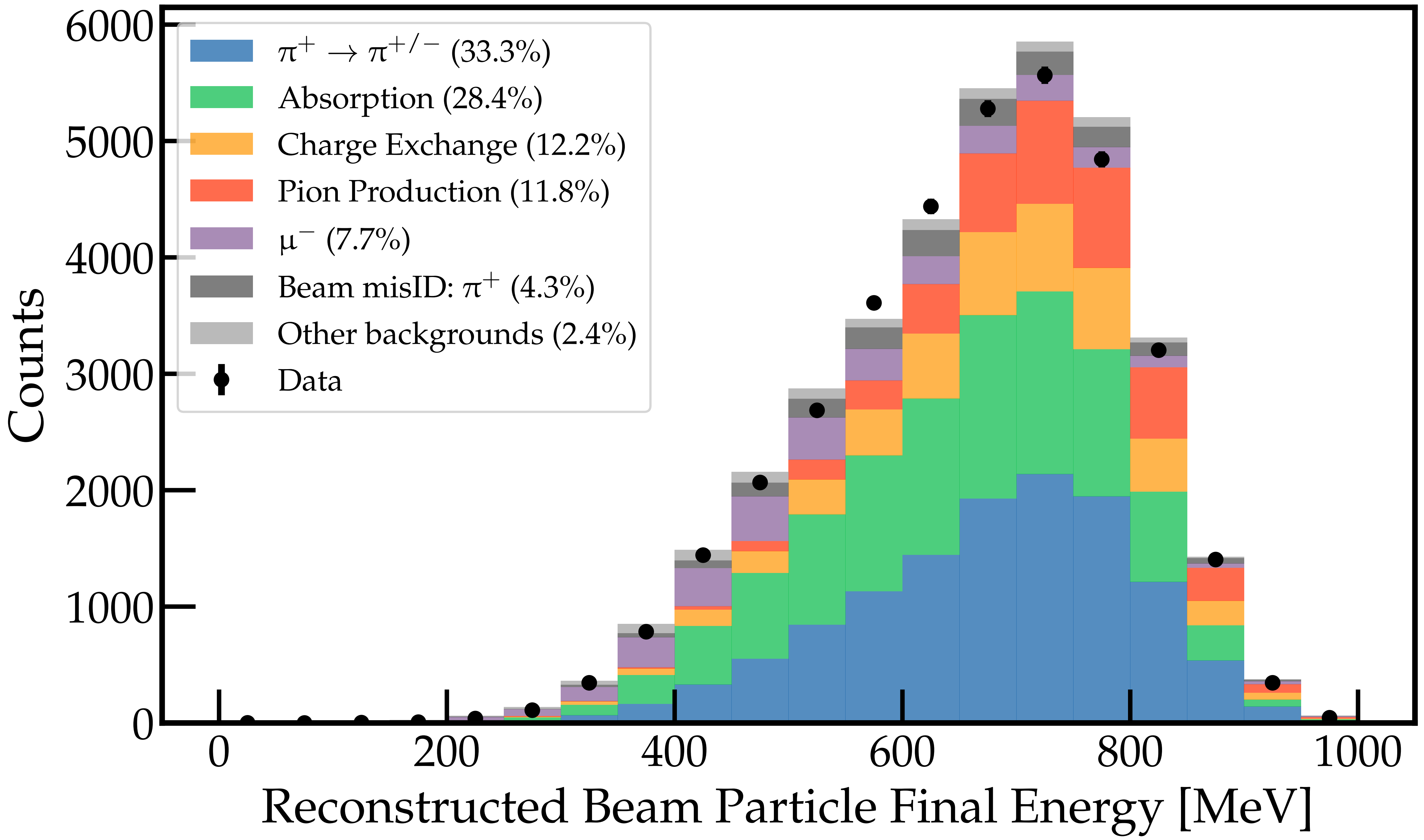
Beam Pion Selection

Selection Requirement	Efficiency	Purity
Beam Instrumentation	100%	58.1%
Misidentified Secondary Particle Background	93.3%	74.2%
Beam Muon Rescaling	93.3%	68%
Fiducial Volume Requirement	68.9%	80.6%
Beam Scrapper Events	63.8%	83.0%
Proton Veto	61.4%	84.4%
Muon Veto	61.1%	86.1%



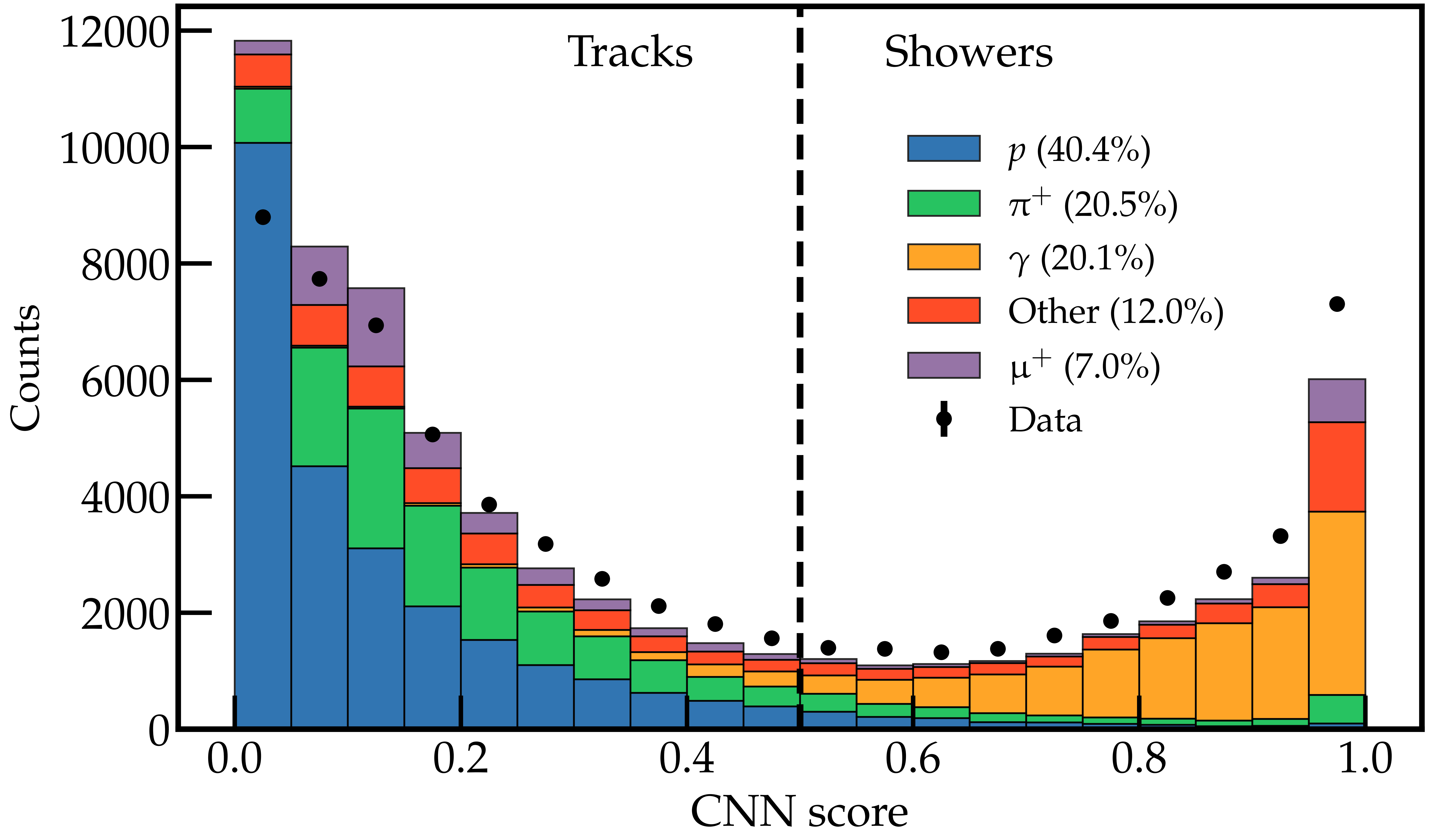
Reweighted MC energy distributions show good agreement with data for beam particle energy along its track



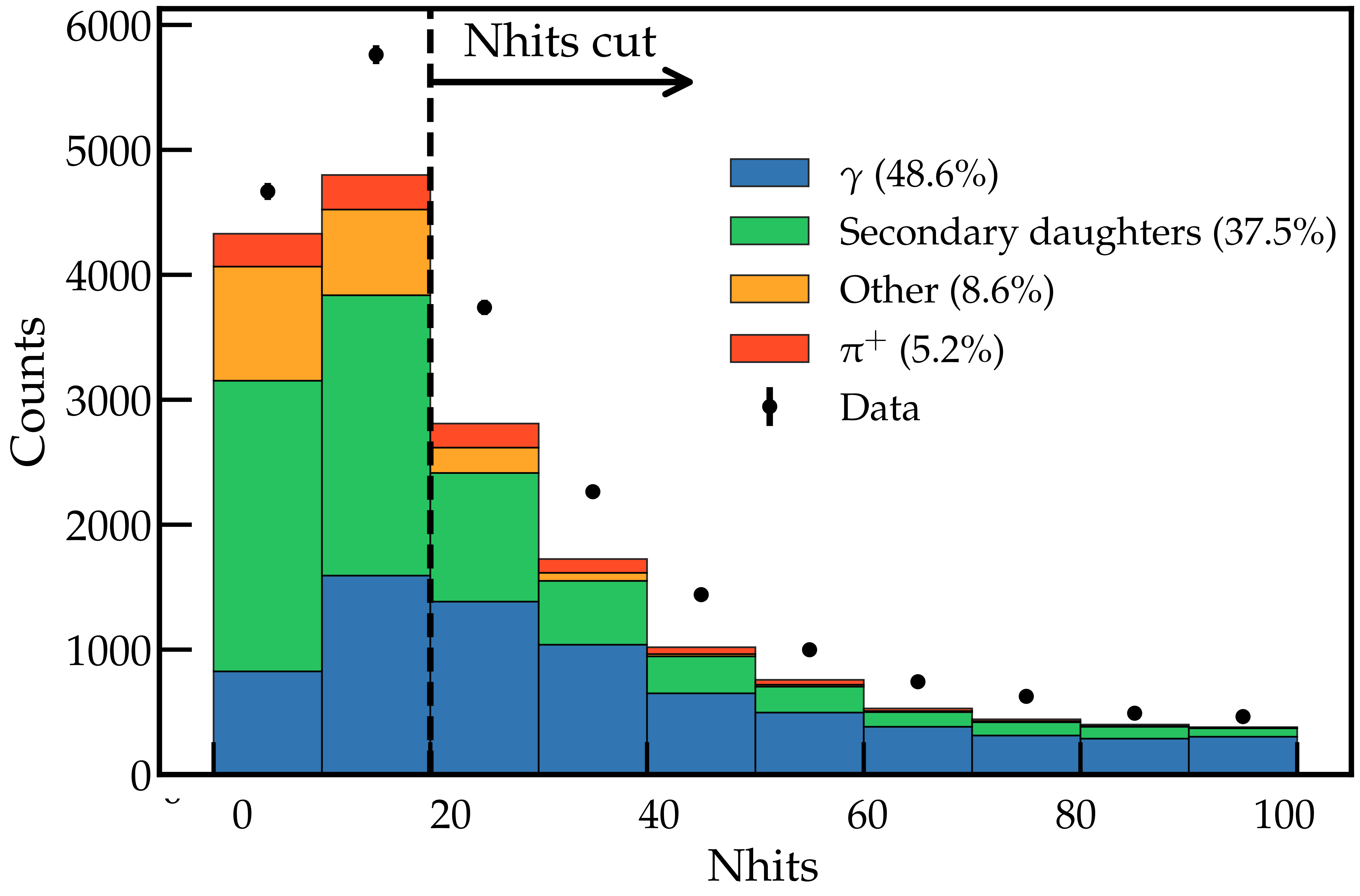


Cross-section of π^+—Ar interactions:
Pion production event selection

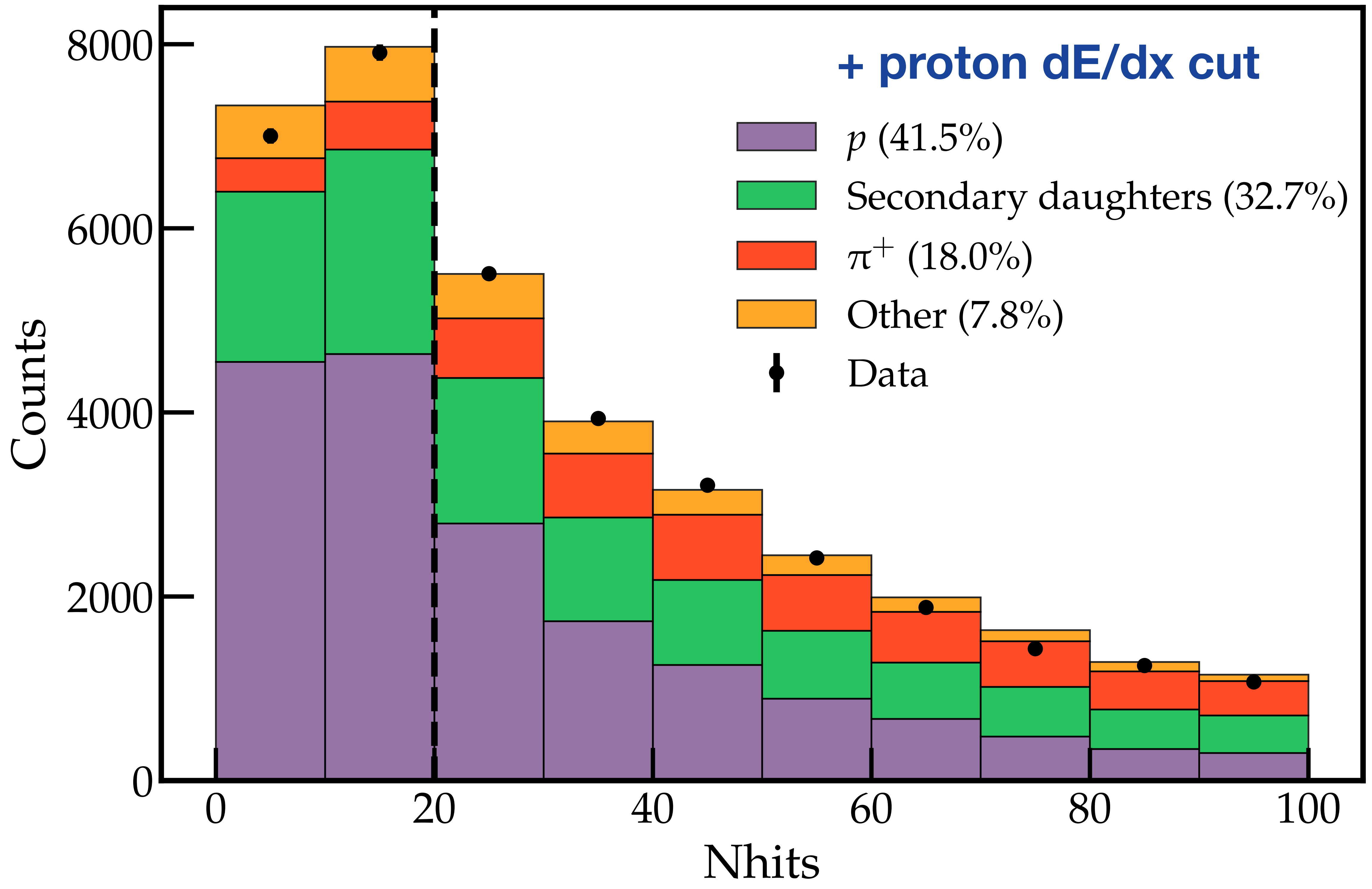
Pion production event selection



Pion production event selection

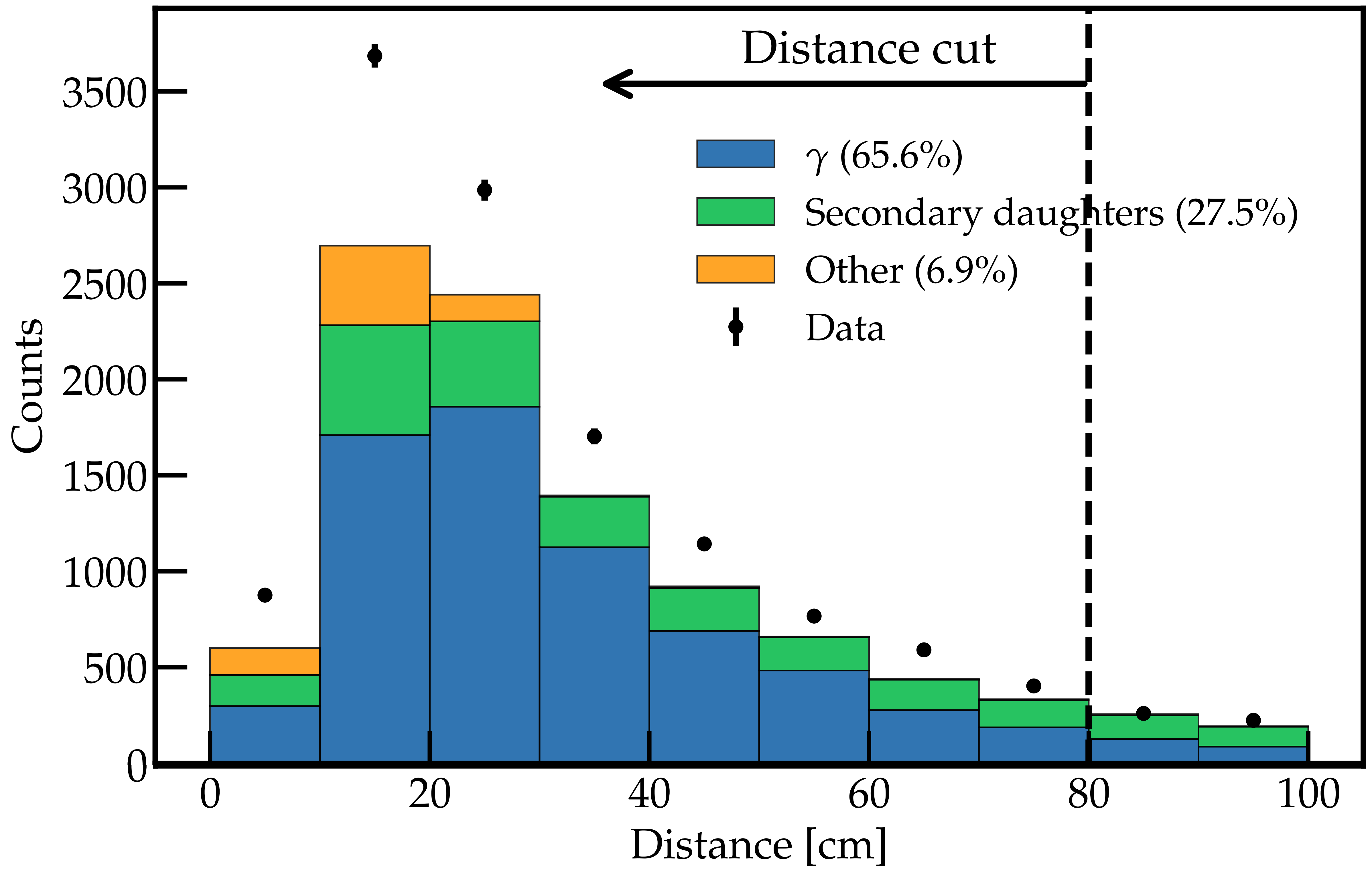


Shower candidates

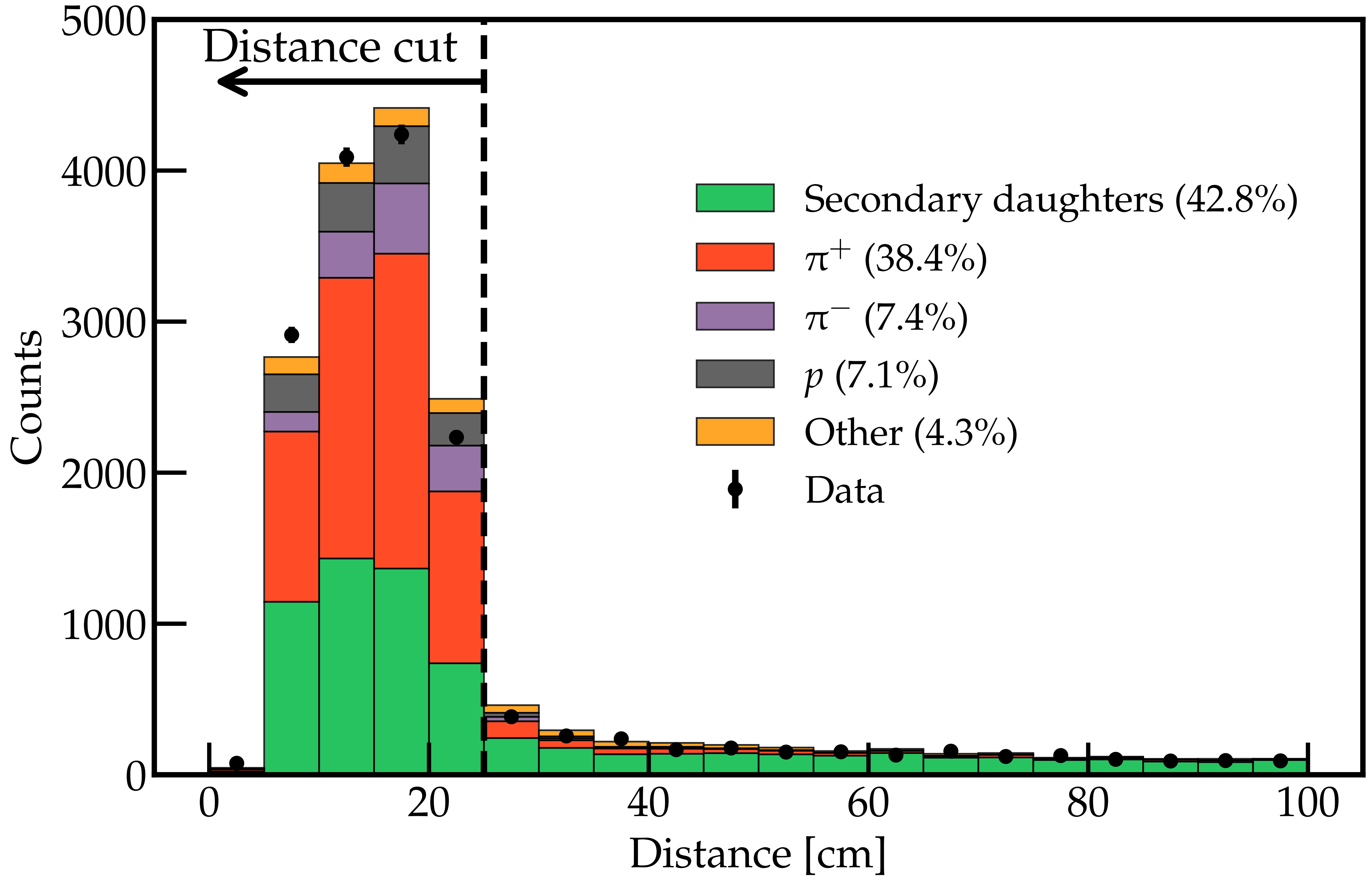


Track candidates

Pion production event selection



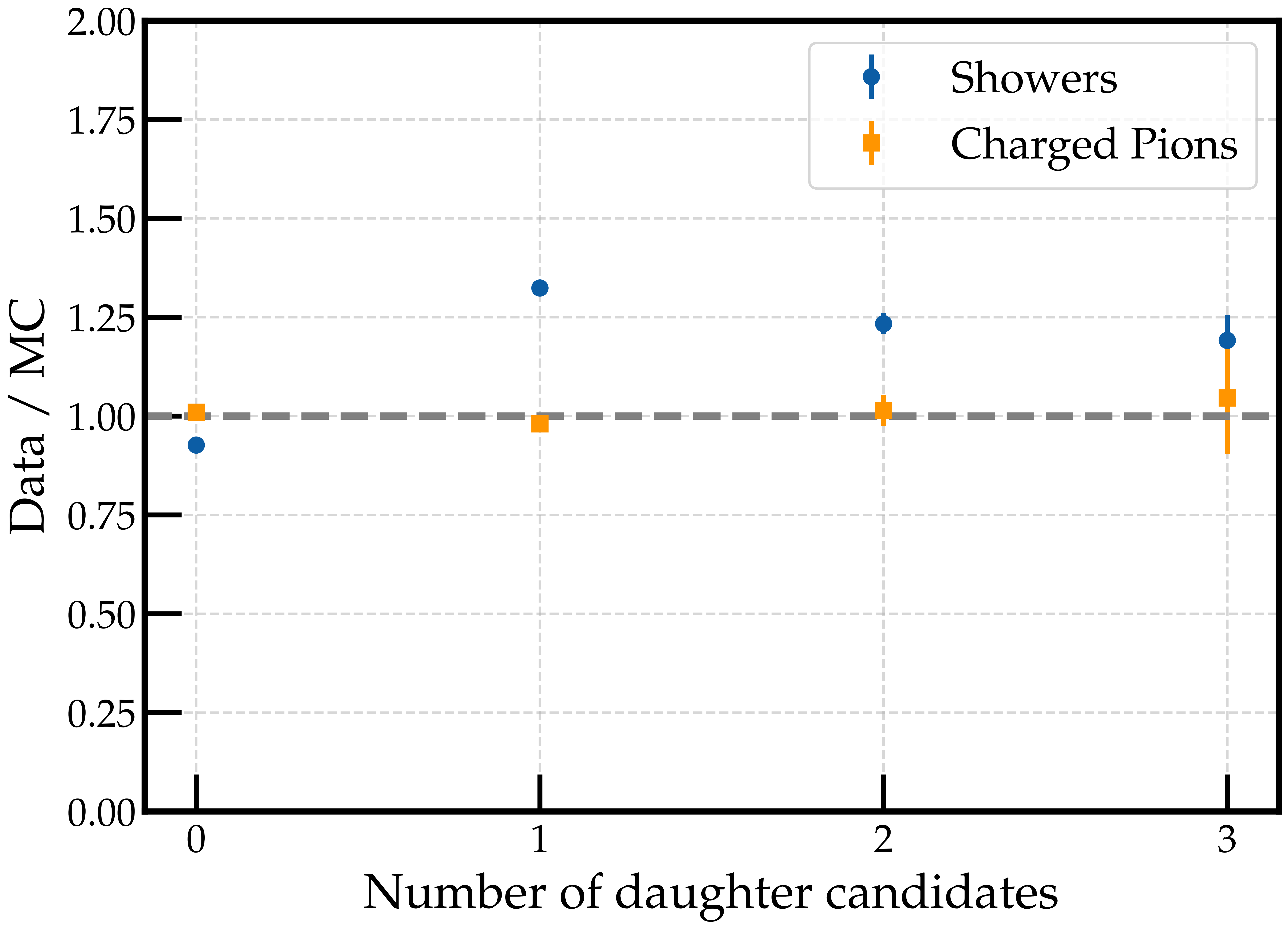
Shower candidates



Track candidates

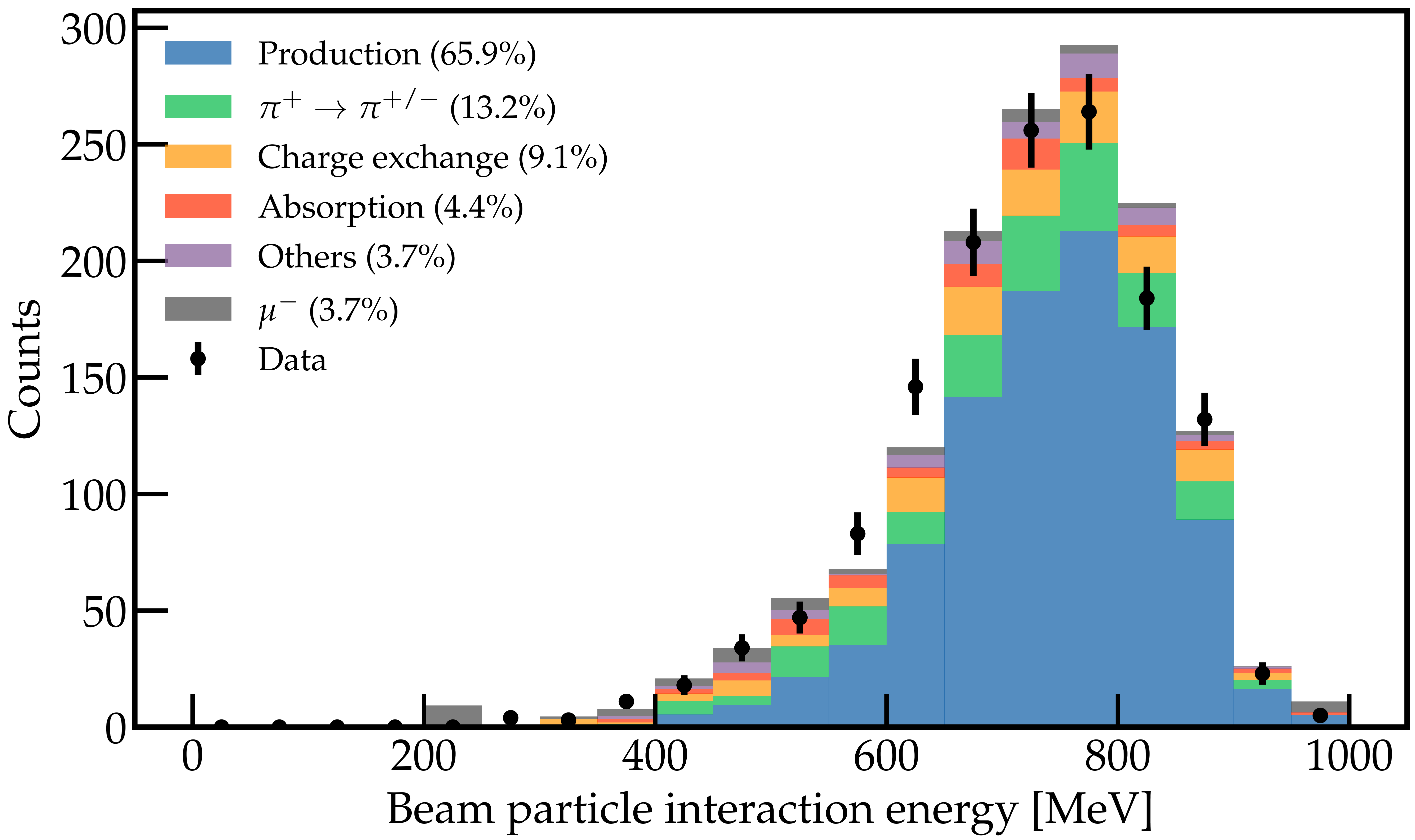
Pion production event selection

- Shower and charged pion candidates are identified from reconstructed daughters to tag pion production events.
- MC shows mismatch with data for number of shower candidates but excellent agreement for $\pi^{\pm}$.



Pion production event selection

- Events are considered to be from pion production channel if:
  - **2 $\pi^{\pm}$ topology**: Two or more daughter charged pion candidates are required, with at least one pair separated by less than 6 cm.
  - **$\pi^{\pm}$ + π^{0} topology:** One charged pion candidate and one or more shower candidates.
  - **2 π^{0} topology**: not considered due to large contamination from charge exchange events.



Pion production event selection

TABLE 4.4: Summary of pion production event selection in the 1 GeV MC sample.

Selection Step	Efficiency	Purity
Beam Daughter Charged Pions		
CNN score <= 0.5	88.1%	22.2%
Nhits > 20	75.5%	29.3%
Proton Veto	70.7%	45.8%
Distance to beam particle	65.9%	56.6%
Beam Daughter π^0 Photons		
CNN score > 0.5	92.8%	47.4%
Nhits > 20	69.3%	65.6%
Distance to beam particle	65.8%	70.3%
Pion Production Events		
Pion beam	100%	11.8%
Two charged pion with < 6 cm separation (Topology A)	7.2%	65.2%
One charged pion and one or more photon (Topology B)	3.5%	68.3%
Combined A+B	10.7%	66.2%
Beam interaction energy > 600 MeV	10%	70.7%

Cross-section of π^+—Ar interactions:
Unfolding measured distributions

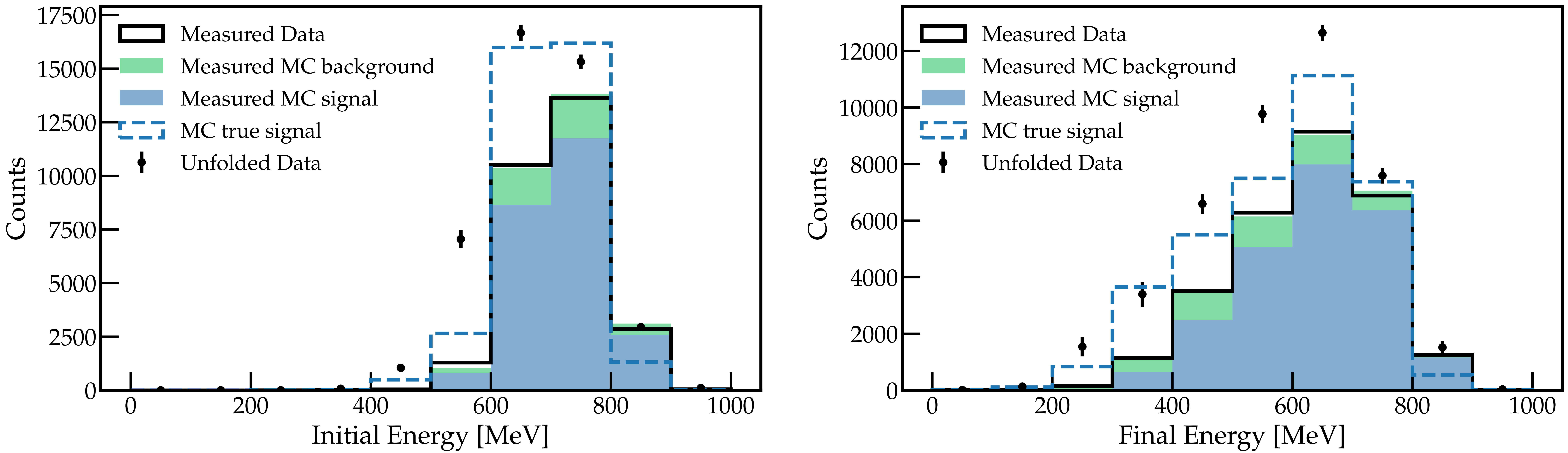
Unfolding

The unfolding process relies on the MC to model the relationship between true and reconstructed information in the detector:

- relation between the true and measured energy for the beam particle (Figure 4.17).
- subtraction of background events.
- efficiency correction for events missed during reconstruction and event selection.

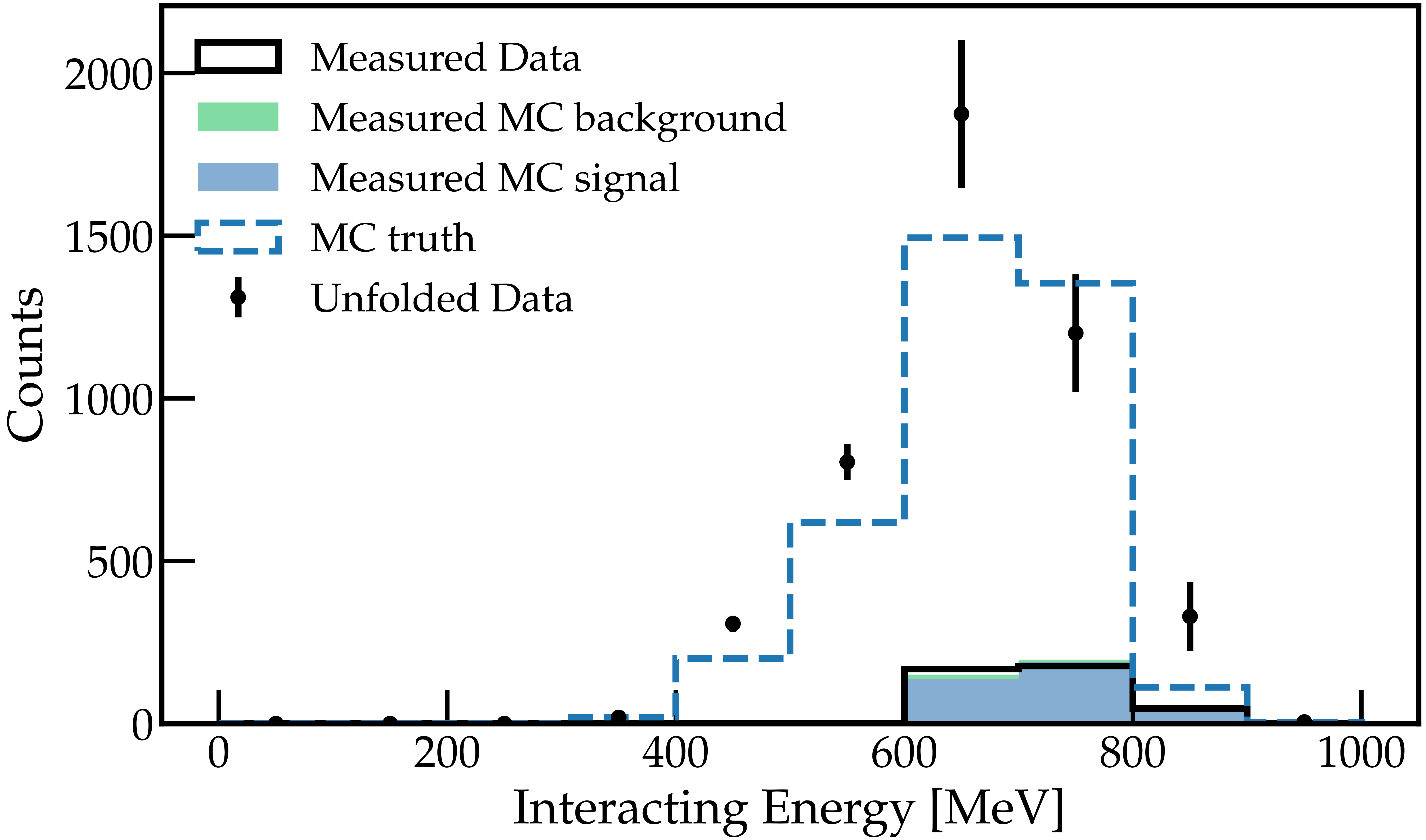
Unfolding is sensitive to statistical fluctuations in the measurement, and even small fluctuations can lead to significant bin-to-bin variance in the estimate. MC simulations are used to constrain the variance, while also introducing some bias in the results towards the MC expectation.

Unfolding



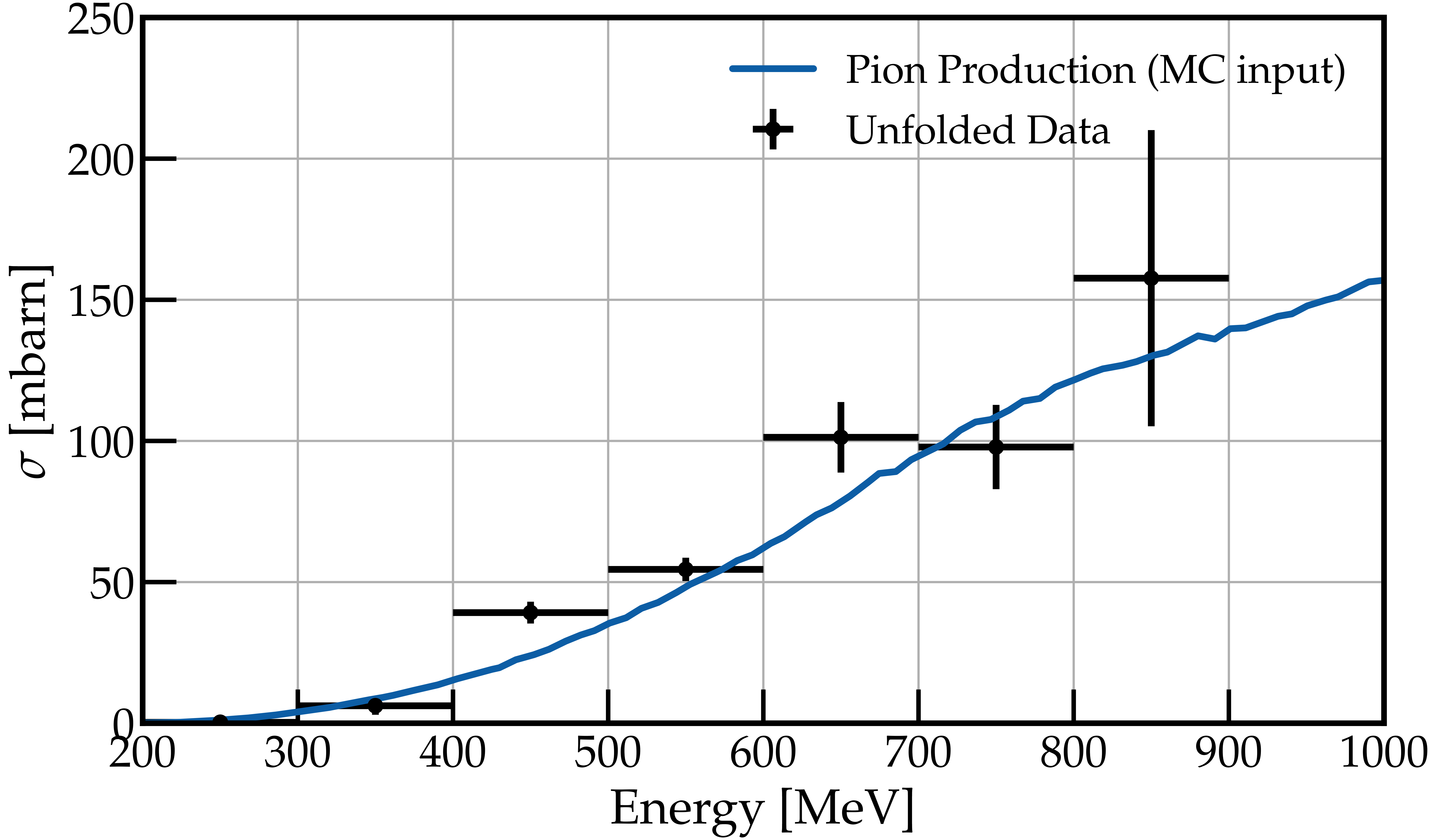
Measured Data
Measured MC background
Measured MC signal
MC true signal
Unfolded Data
Counts
17500
15000
12500
10000
7500
5000
2500
0
200
400
600
800
1000
Initial Energy [MeV]
Measured Data
Measured MC background
Measured MC signal
MC true signal
Unfolded Data
Counts
12000
10000
8000
6000
4000
2000
0
200
400
600
800
1000
Final Energy [MeV]

Unfolding



Measured Data
Measured MC background
Measured MC signal
MC truth
Unfolded Data
Counts
2000
1500
1000
500
0
0
200
400
600
800
1000
Interacting Energy [MeV]

Results


Pion Production (MC input)
Unfolded Data
σ [mbarn]
Energy [MeV]
0
50
100
150
200
250
200
300
400
500
600
700
800
900
1000