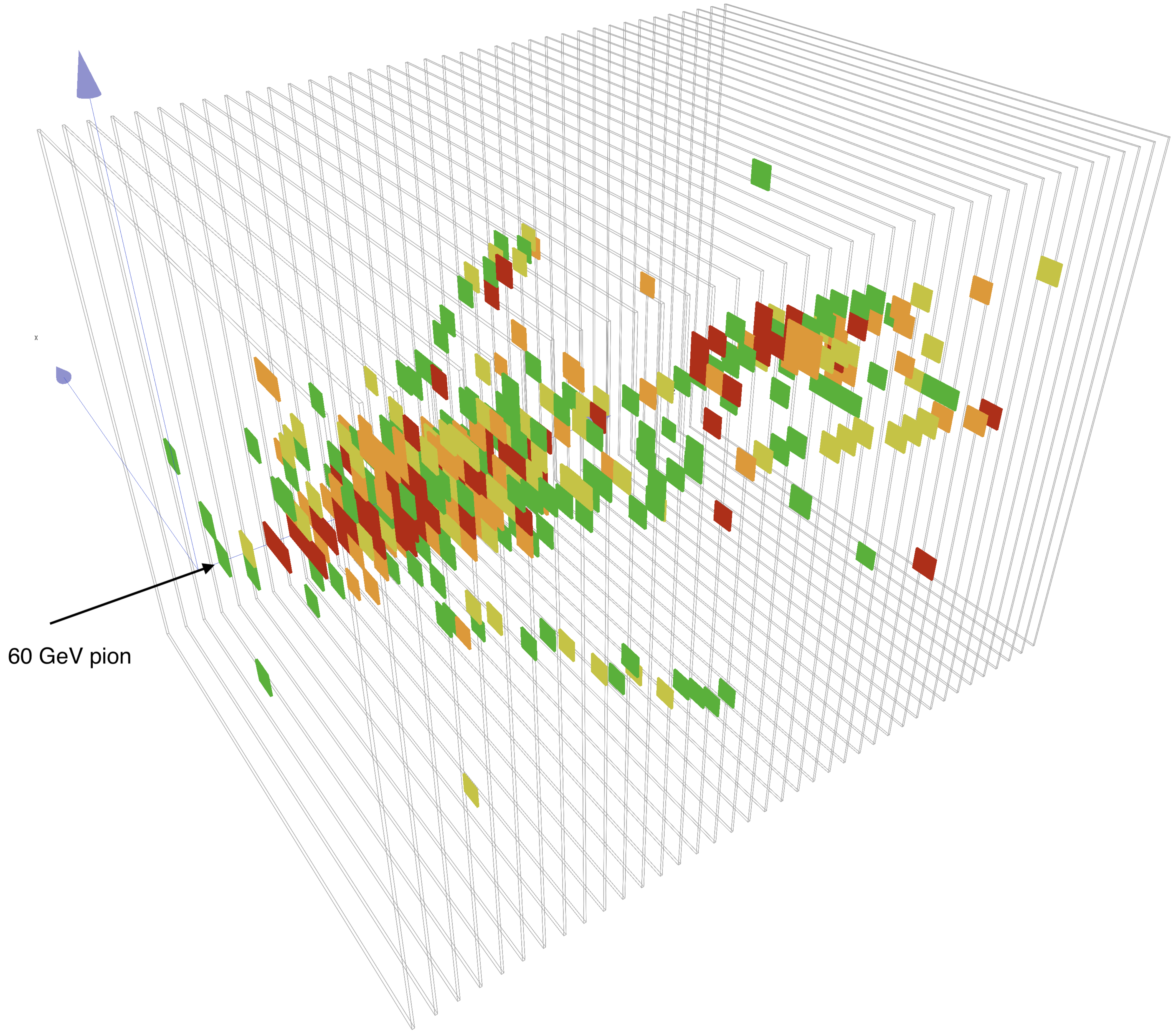
Timing with the CALICE AHCAL & SiPM-on-Tile Technology



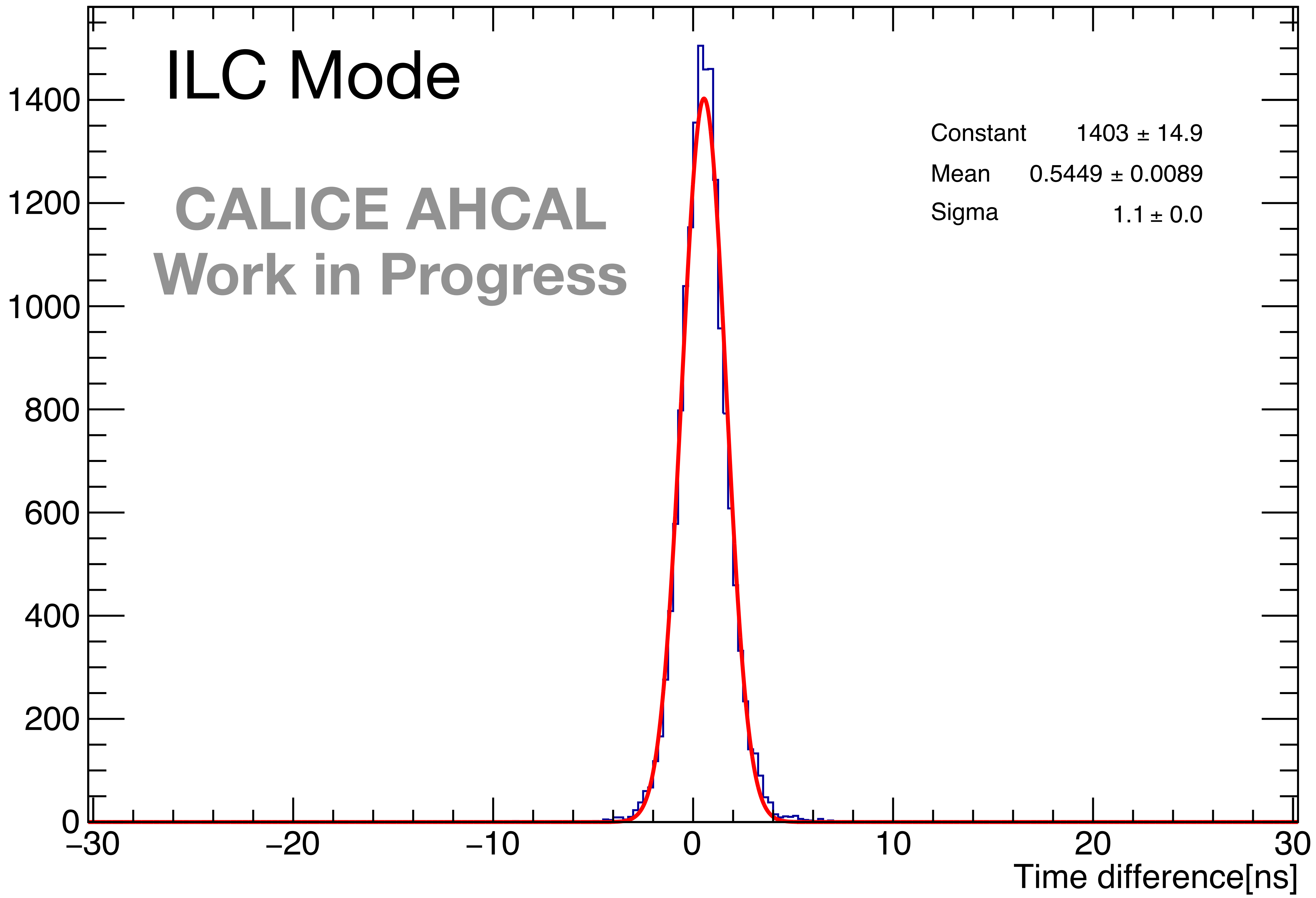
Lorenz Emberger, Fabian Hummer, Frank Simon
BMBF Scintillator R&D general meeting

MAX-PLANCK-INSTITUT FÜR PHYSIK

Scintillator Timing Setup

Motivation: Understand contribution of front end and SiPM-on-Tile on time resolution of the AHCAL

AHCAL large technological prototype



Single channel resolution: $1.1/\sqrt{2} = 0.78$ns

Strategy: Measure the time resolution of the SiPM-on-Tile technology:

- Independent of the AHCAL electronics and DAQ
- In a simple but modular setup
- Without involved calibration and reconstruction procedures
- With high particle rate and controlled energies

Beam Test Setup

Stack of 4 Tiles:

- BC408 or Polystyrene (AHCAL)
- Hamamatsu S13360-1325PE

↓ Ethernet Cat 7

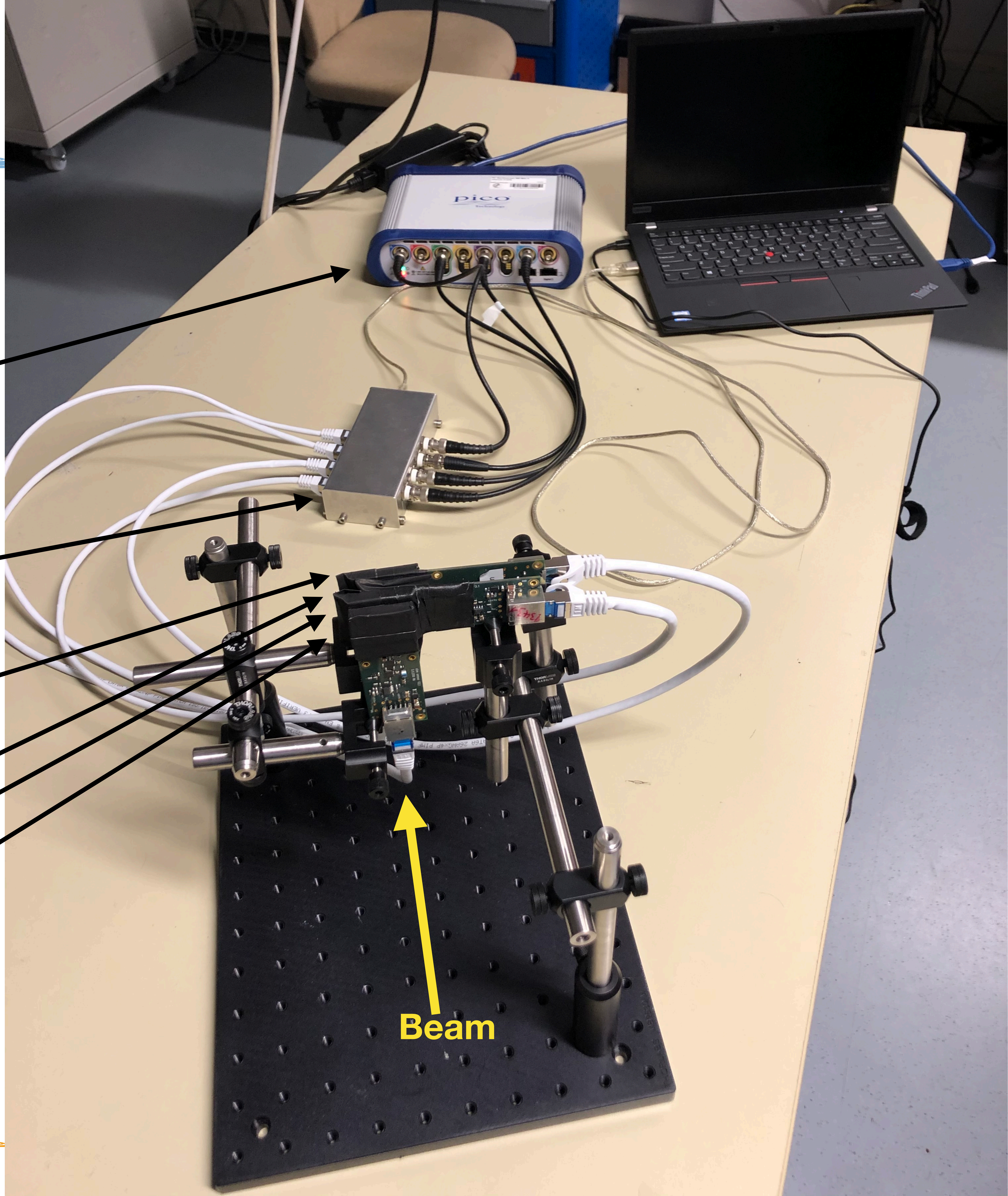
Receiver Box:

- USB controlled power supply
- Split signal and power lines

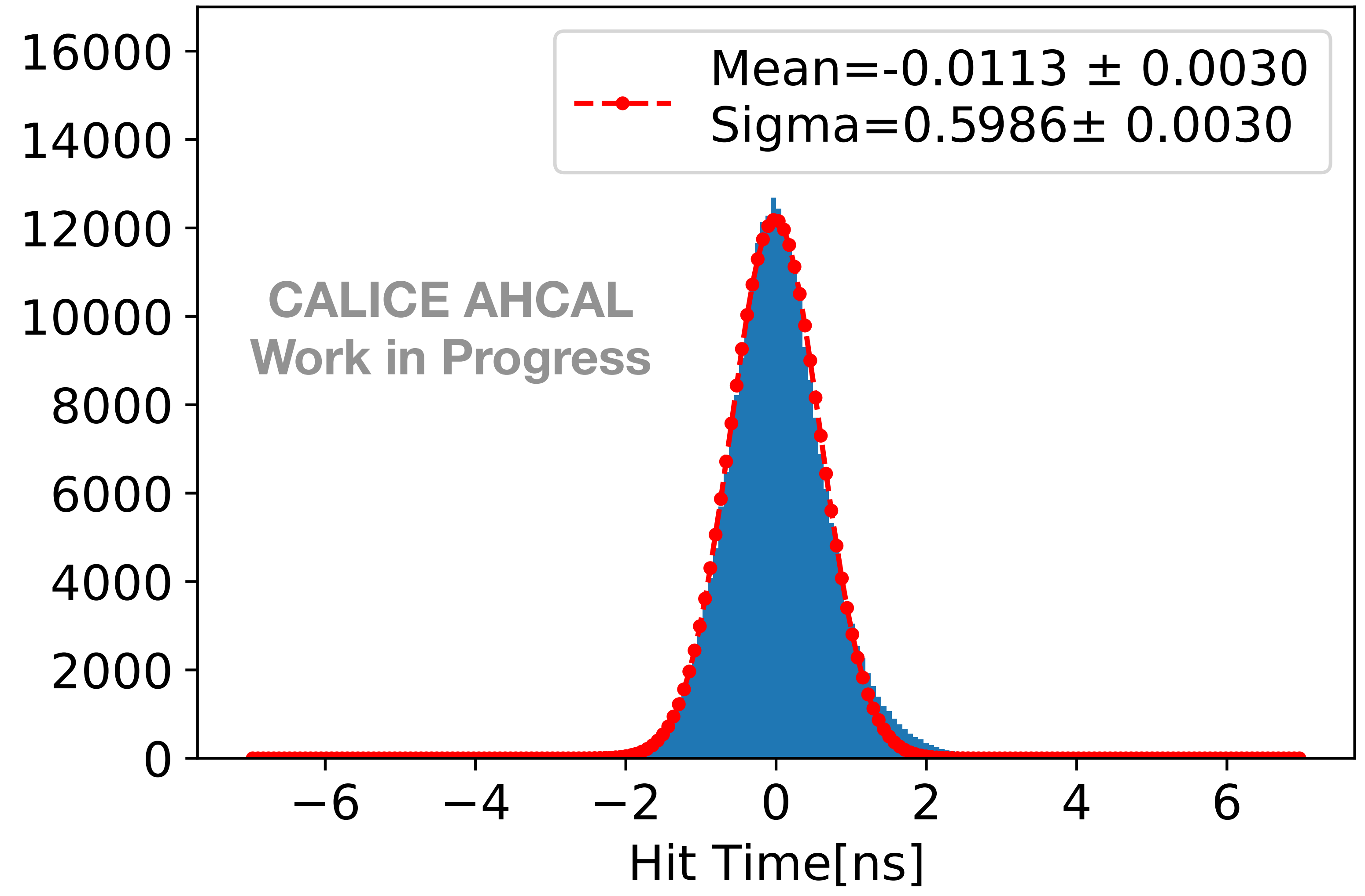
↓ BNC

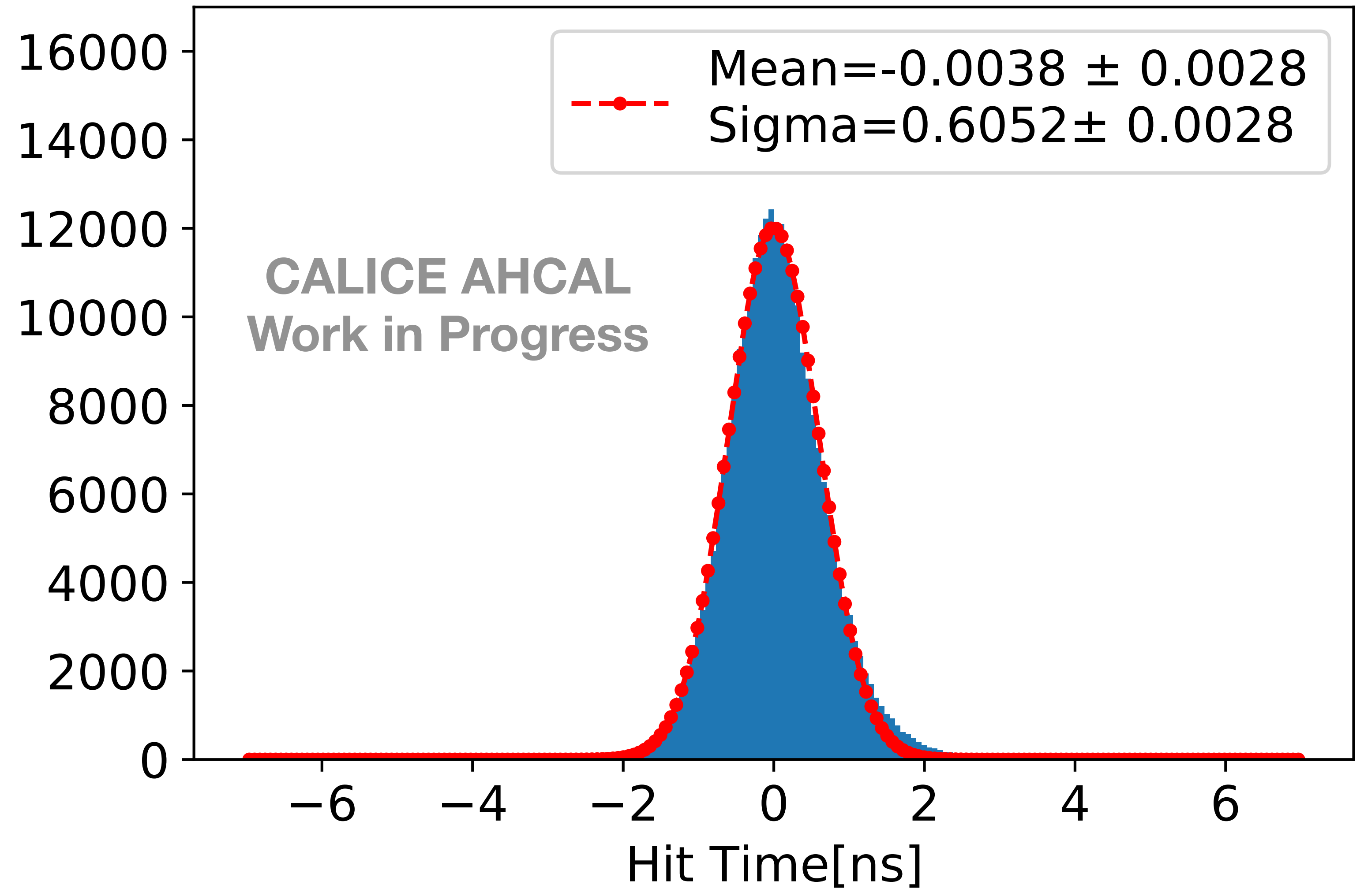
Picoscope:

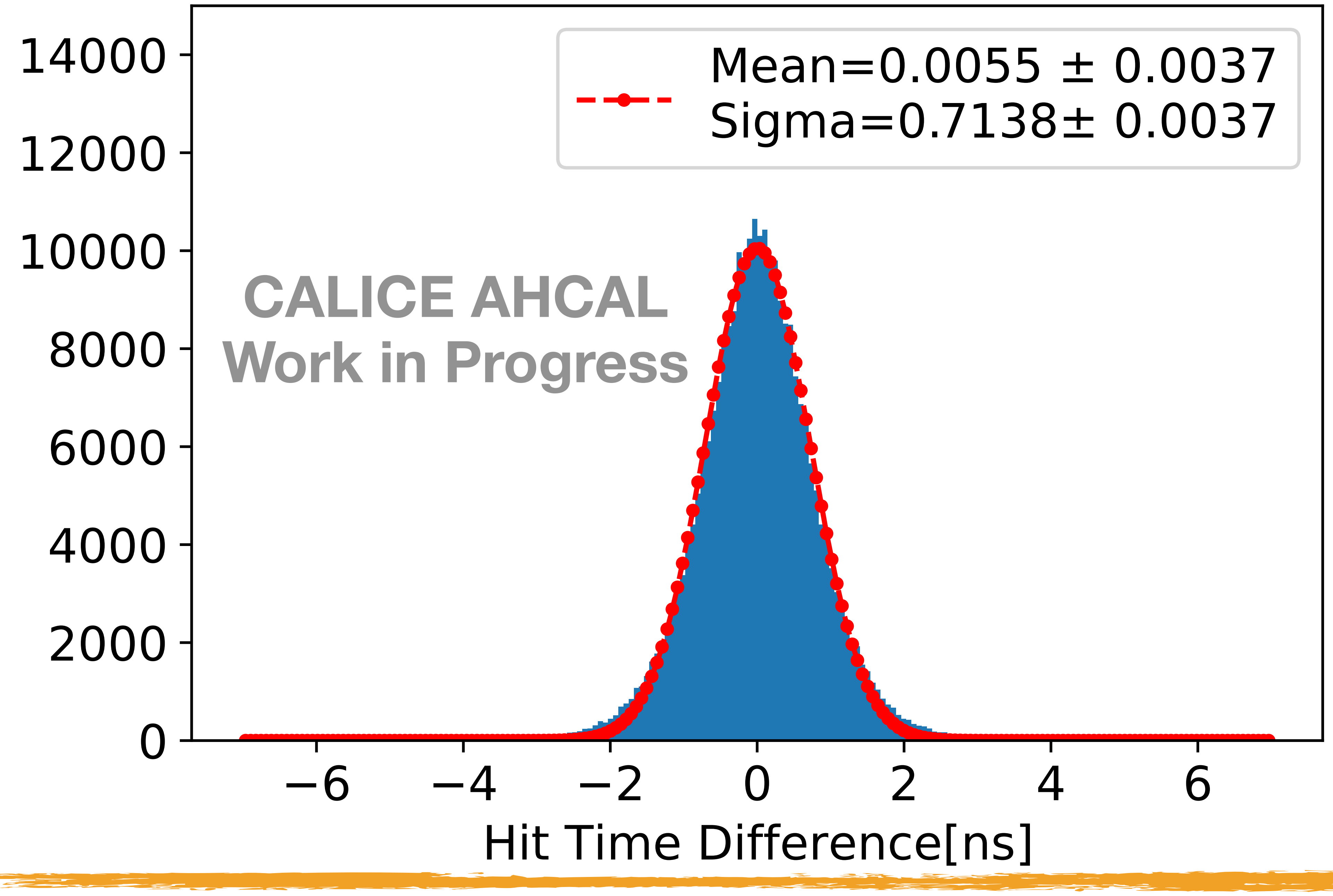
- Up to 2.5GHz sampling rate on 4 channels
- 300kHz peak trigger rate
- Save complete analog waveform



MIP Time Resolution - AHCAL Scintillator







Time resolution=0.718/sqrt(2)=0.507ns

- Interpret as intrinsic time resolution of SiPM-on-Tile

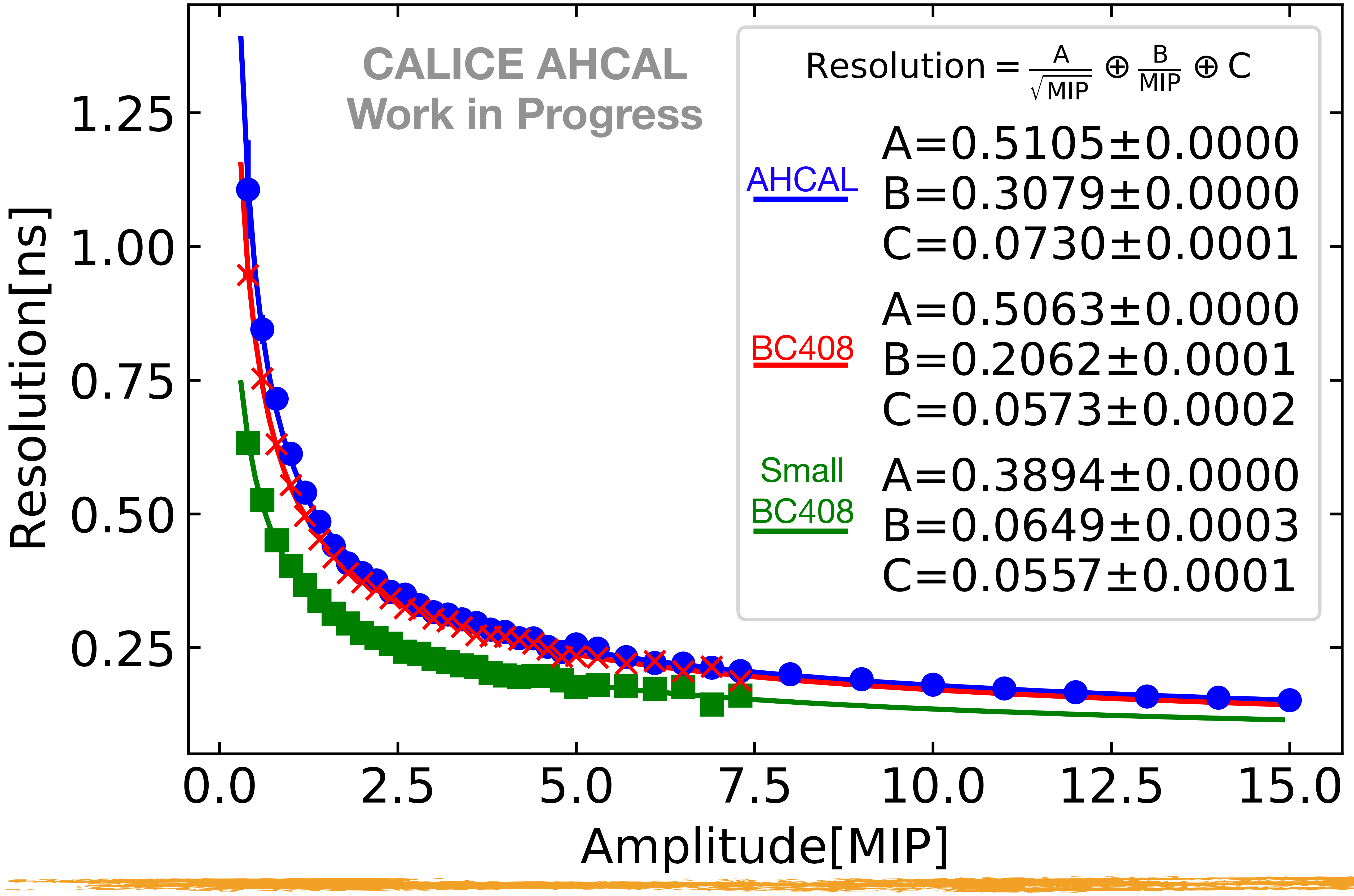
Compared to 0.780ns of the AHCAL:

- AHCAL front-end contributes at least 0.6ns

Energy Binned Time Resolution

Studied Scenarios:

- AHCAL Scintillator 30mm x 30mm x 3mm
- BC408 30mm x 30mm x3mm and 20mm x 20mm x 3mm



Poissonian statistics well reproduced:

- Material and size dependent

Noise contribution to be understood

Sub 100ps for very high signals

Ongoing Development

Optical GEANT4 Simulation + GOSSiP SiPM simulation:

- Reproduce analog signal waveforms
- Understand electronic effects of the setup
- Understand size dependence of the time resolution

Preparations for next beam test:

- Study fast Bicron scintillators
- Study different tile dimensions
- Establish scaling of the time resolution with respect to the tile size

Muon/Pion Separation with the DUNE Gaseous Argon ND

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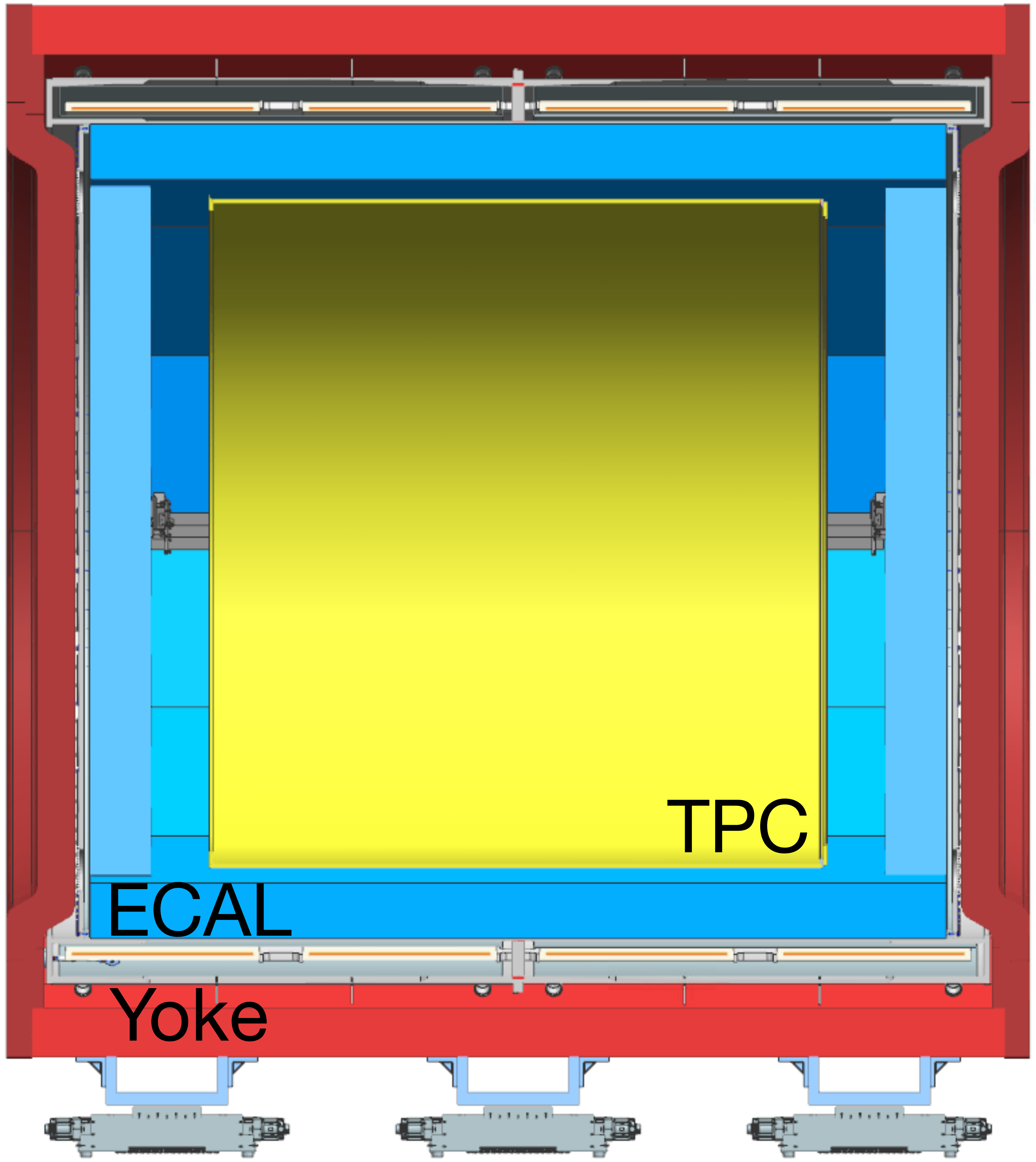
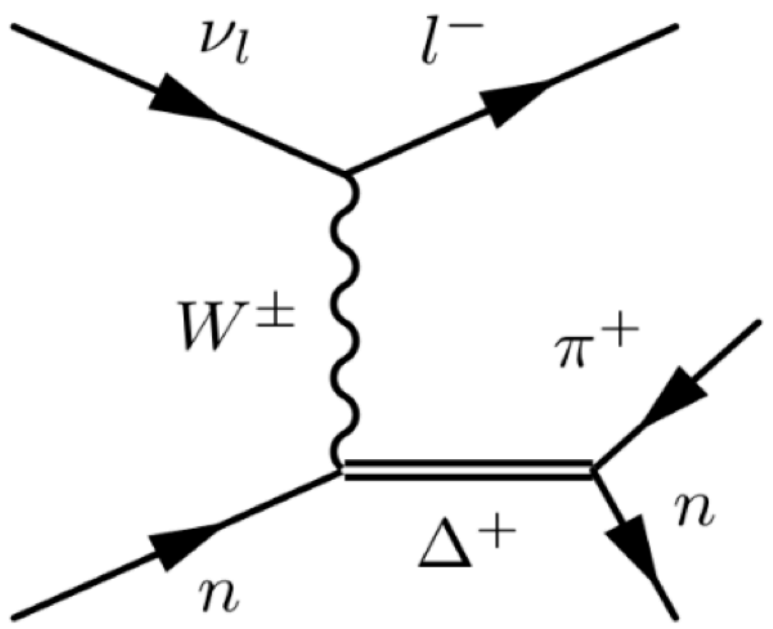
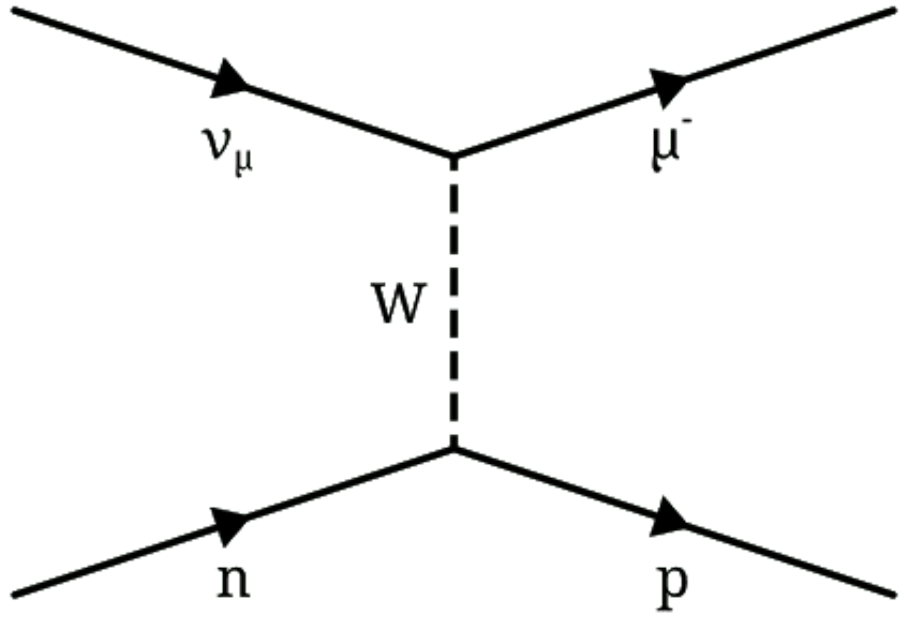
ND-GAr Design



Common interactions on argon target:





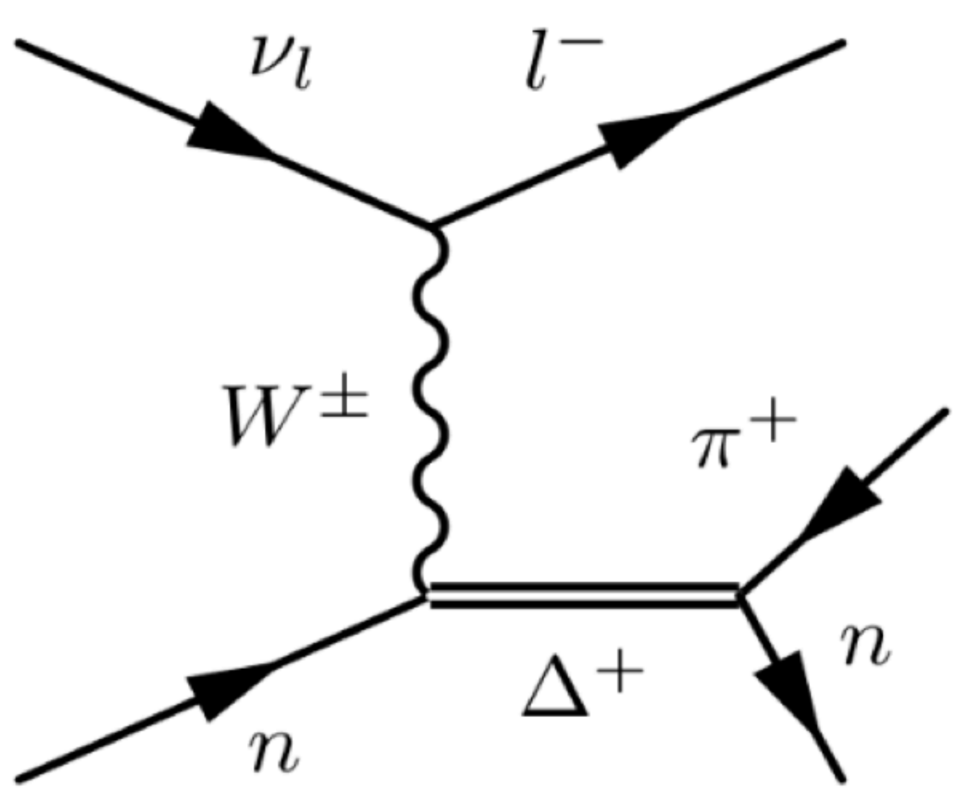
- Momentum and charge reconstruction of charged particles in TPC
- Reconstruction of photons and neutrons in highly granular scintillator ECAL
- 0.5T solenoid field
- Surrounded by a yoke and muon detector (technology tbd)

ECAL Design Drivers

Key roles of the ECAL:

1. Photon reconstruction
2. Neutron identification
3. Muon/Pion separation
   (with muon detector)

Pions and muons produced simultaneously:



- Charged pions and muons have almost same mass
- Similar energy loss per unit length
- Separation not possible in TPC at momentum > 250MeV

Misidentification of muon and pion will lead to wrong reconstruction of the energy and nature of the interaction→joint task of ECAL and muon detector

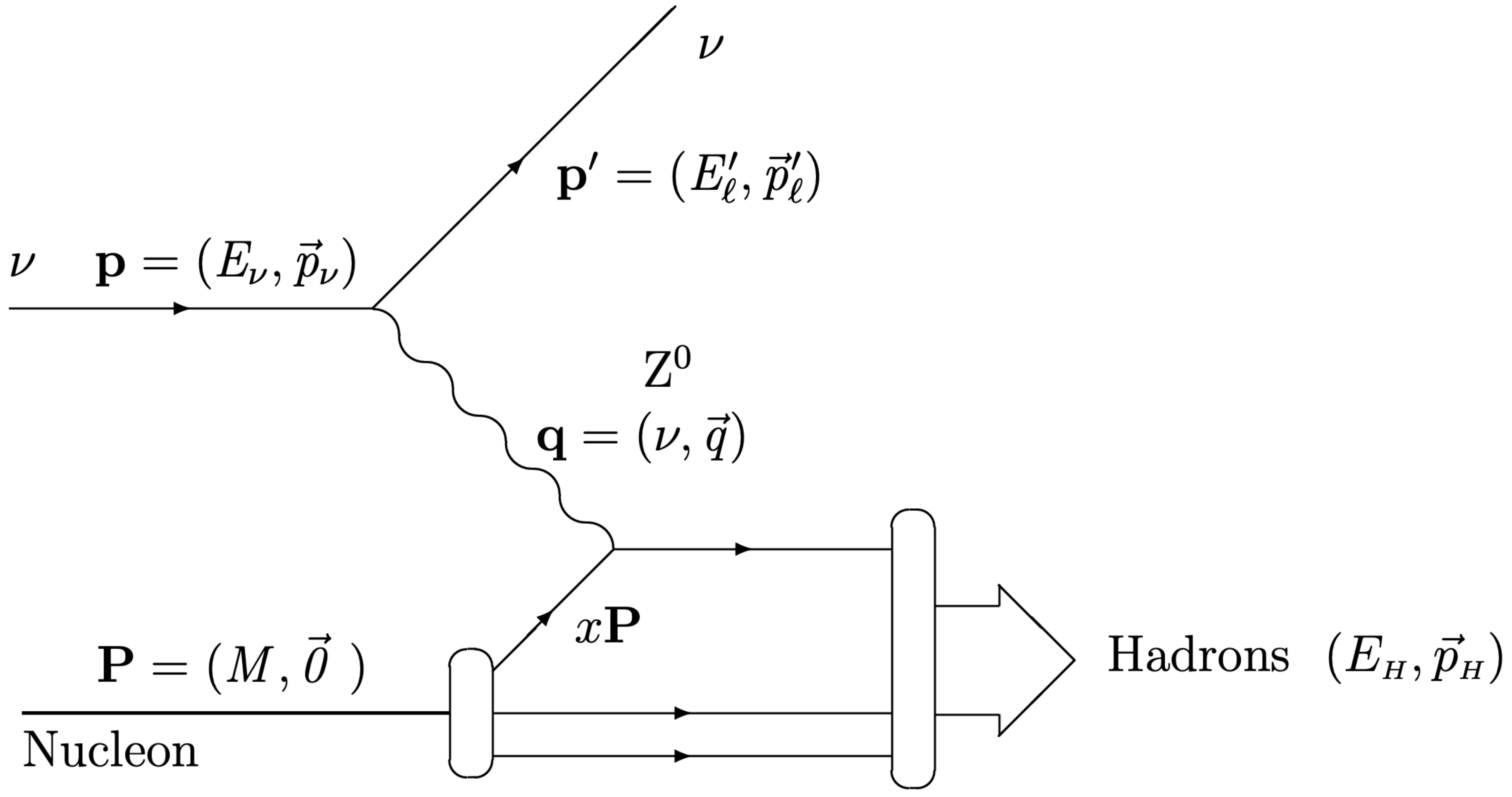
ECAL Design Drivers

Neutral current production of Δ baryons:

- $\Delta^+ \rightarrow \pi^+ + n$
- $\Delta^0 \rightarrow \pi^- + p$

Misidentification of $\pi^\pm$ leads to errors on cross-section

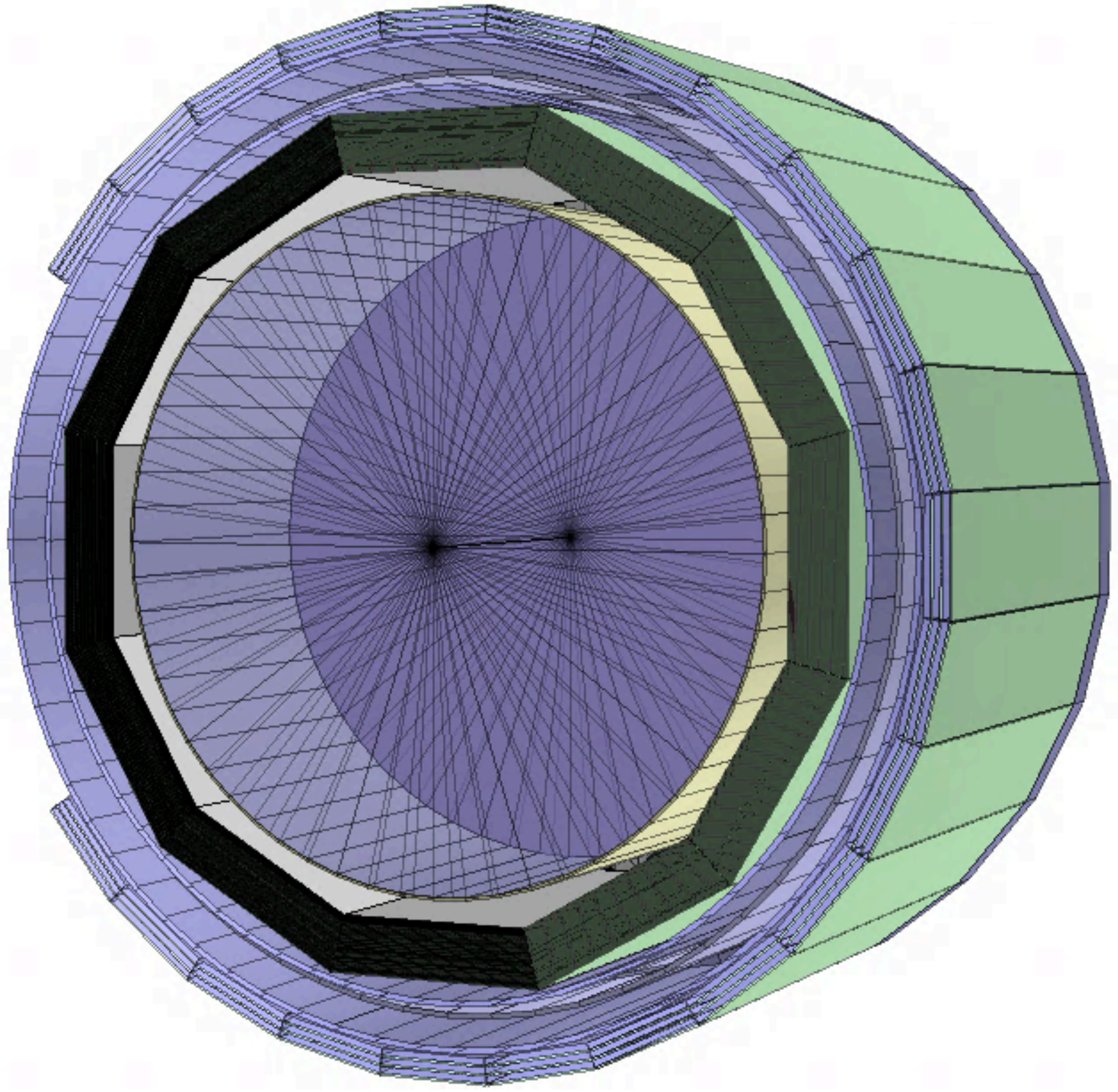
Deep-Inelastic neutral current scattering



Muon/Pion separation is also important for standalone measurements of ND-GAr

ECAL Concept

- 12-sided geometry, 42 Layers
- Key design features:
  - High granular layers based on CALICE R&D (AHCAL SiPM-on-tile design)
  - First 8 layers with 0.7 mm Lead / 5 mm plastic scintillator tiles of 2.5x2.5 cm^2
  - 34 layers with crossed strips in the back based on Mu2e with 1.4 mm Lead / 10 mm scintillator
  - 4 cm strip width spanning the full module width/ length (~few m)
- SiPM readout of ~1- 3M channels



Initial Considerations

Approximate Material budget:

Cryostat	9cm Steel ≙ 0.5λ
ECAL absorber	5.3cm Pb≙ 0.27λ
Magnet:	4cm Al ≙ 0.08λ
Return yoke	15cm Fe ≙ 0.75λ
Scintillator	38.5cm PS ≙ 0.4λ
Total	2.0λ

$P_{\mathrm{PunchThrough}} = \exp(-2.0)=0.135$

Simulated muon/pion ratio:

- 86% muons
- 14% pions

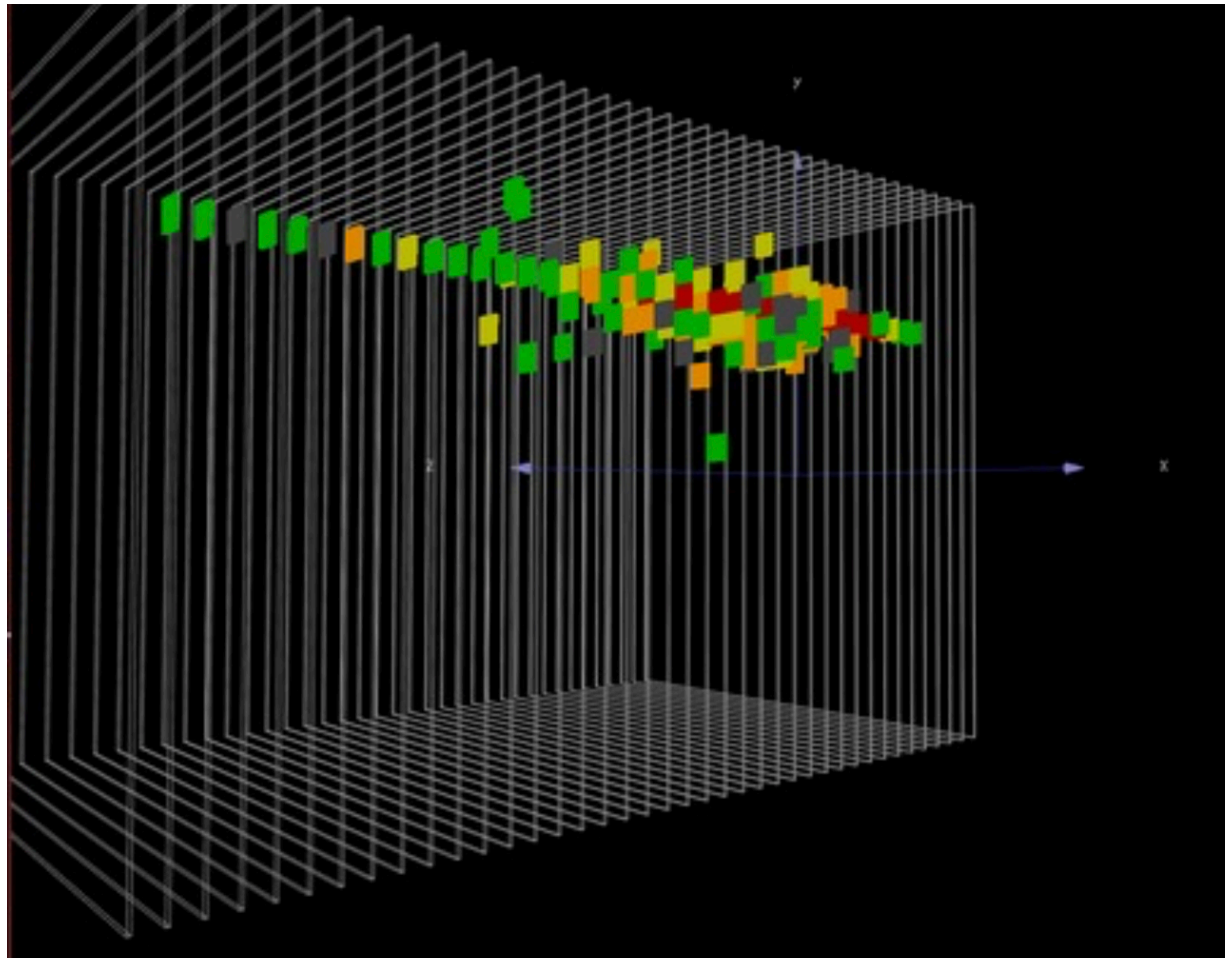
~2% fake muons from pions if:

- All muons are tagged correctly
- All inelastic pion interactions are resolved

Initial Considerations

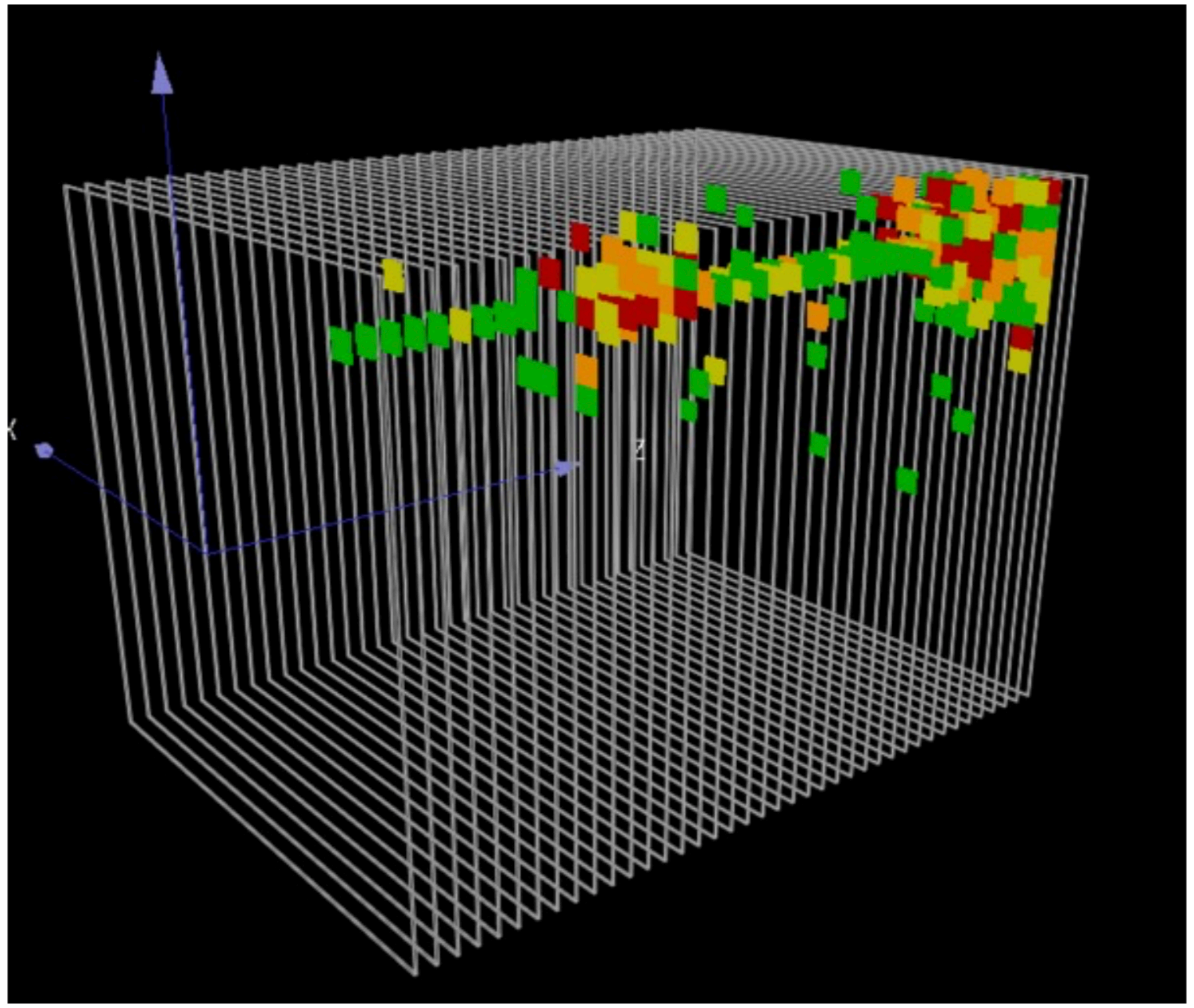
Actual data from CALICE AHCAL beam test

Showering muon, hard delta electron



Confusion with pion shower

Pion causing small shower



May look like a muon, if only a small shower develops in the detector

Muon/Pion Separation with BDT

Monte Carlo samples produced with GENIE event generator:

- Momentum cut at 250MeV, TPC can classify tracks of lower momentum
- Rejection of decaying particles:

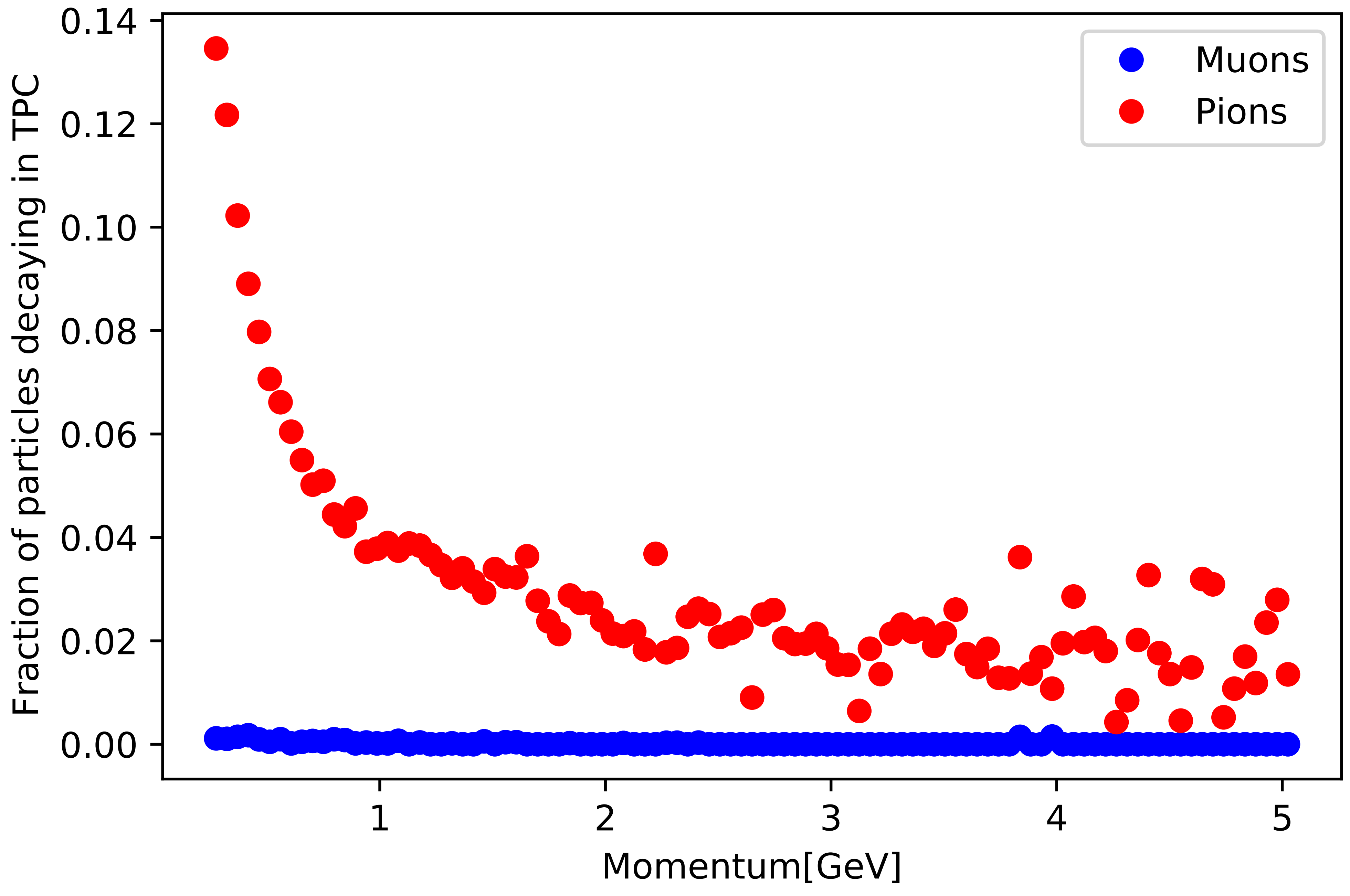
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$$

Rejection is based on mc truth:

Pions by looking for creation of muon neutrino in TPC volume

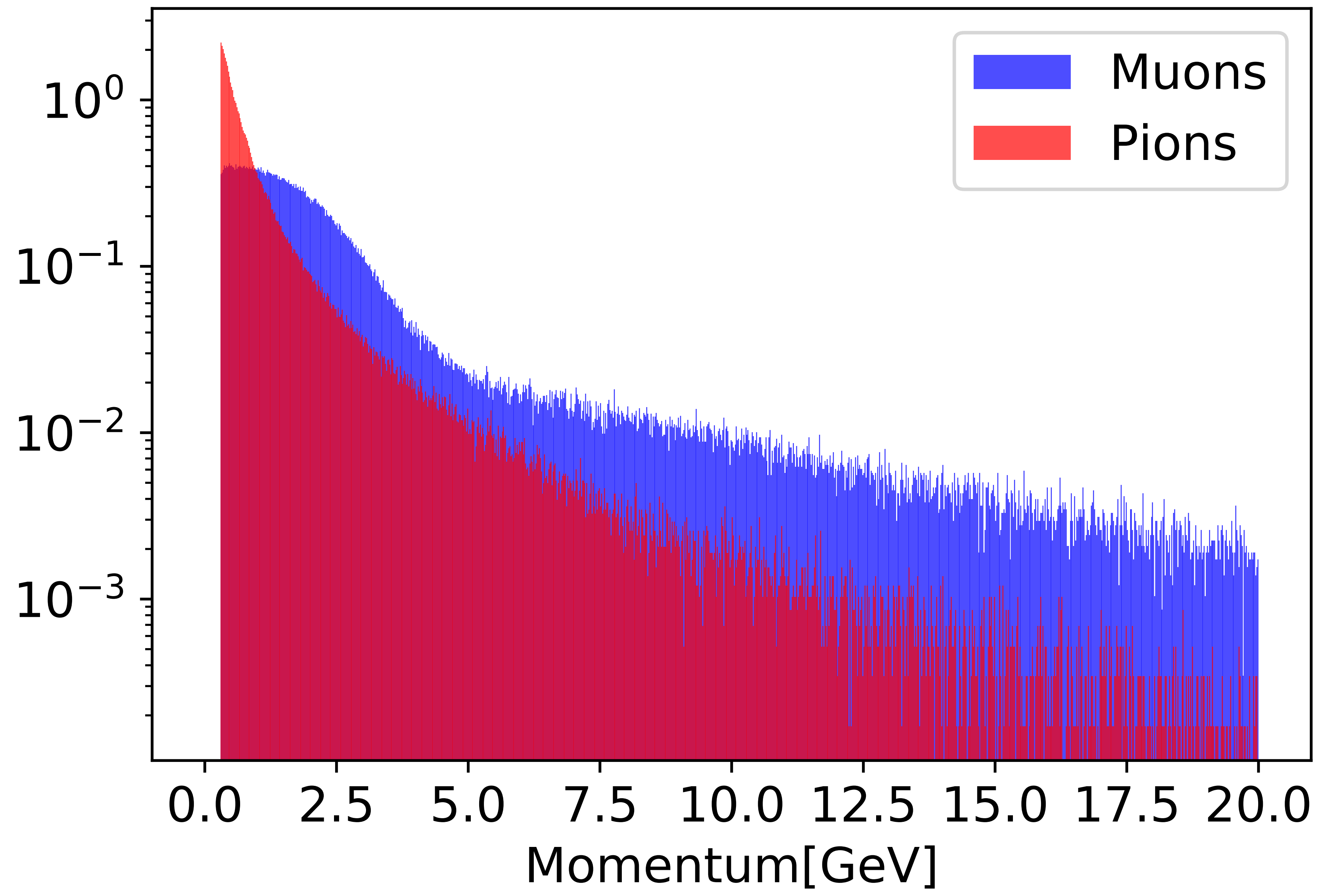
Muons by looking for creation of electron anti-neutrino in TPC volume

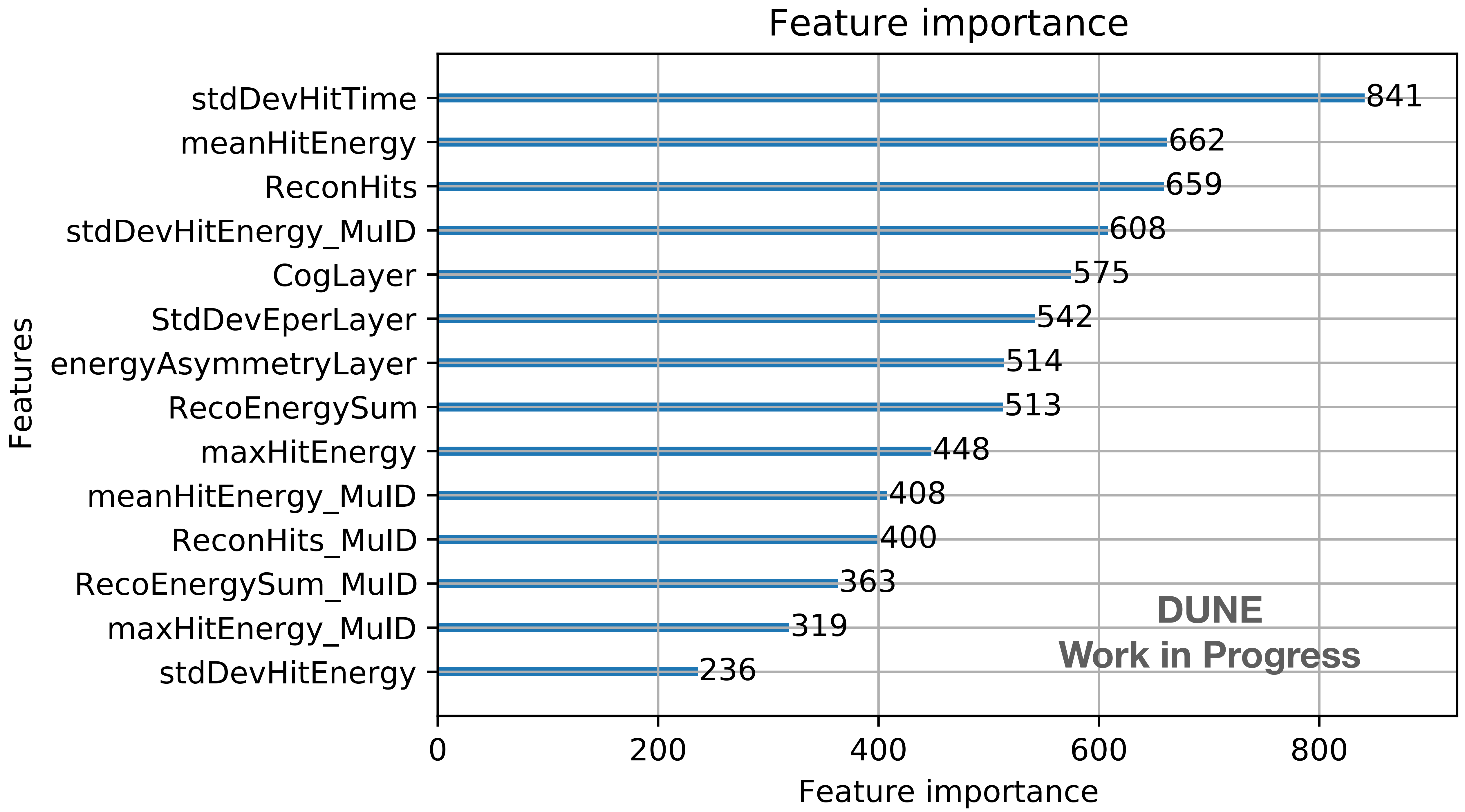


Muon/Pion Separation with BDT

Monte Carlo samples produced with GENIE event generator:

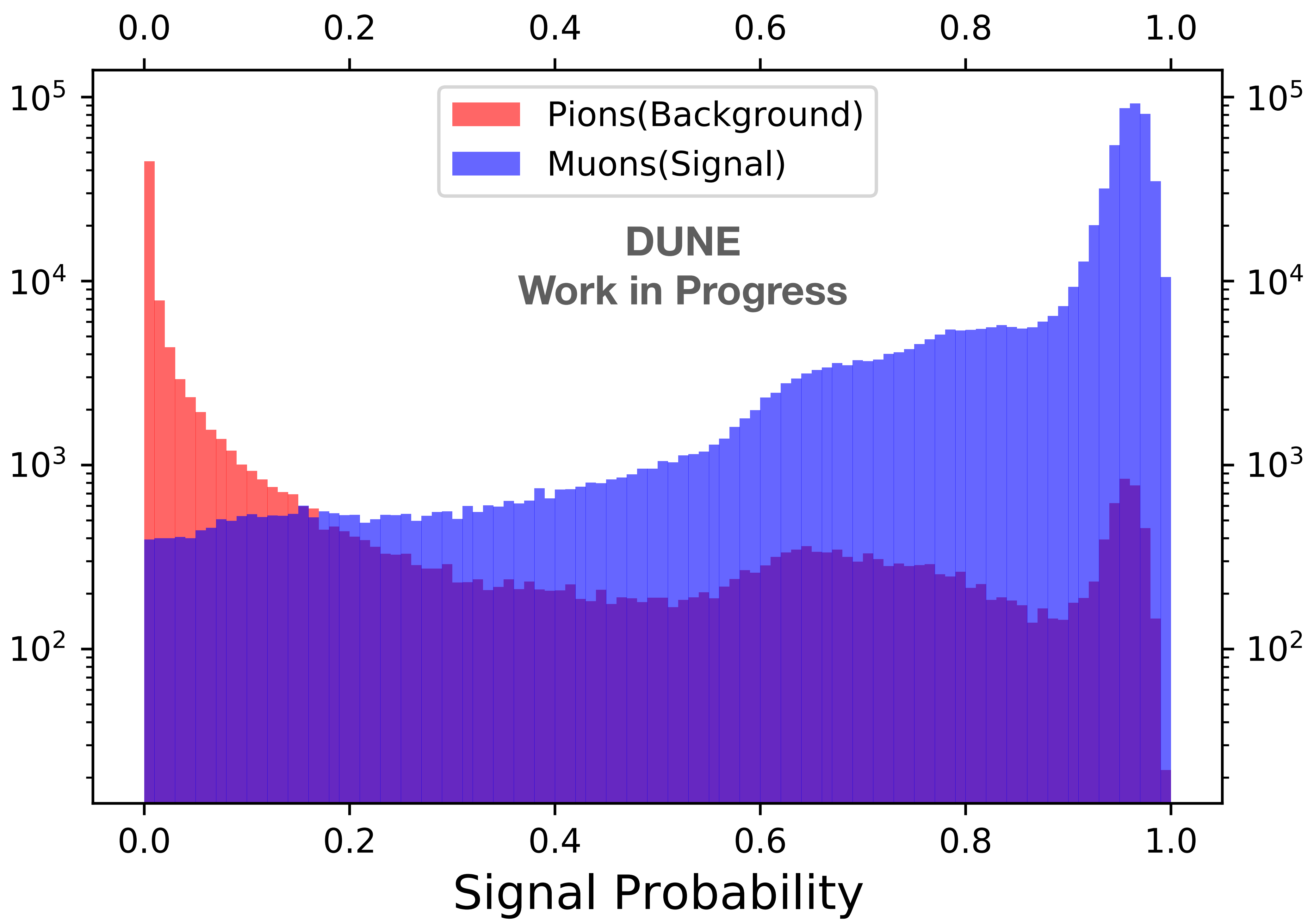
- Training with 50/50 ratio of muons and pions
- Testing with “realistic” muon/pion ratio of 86%/14% from GENIE

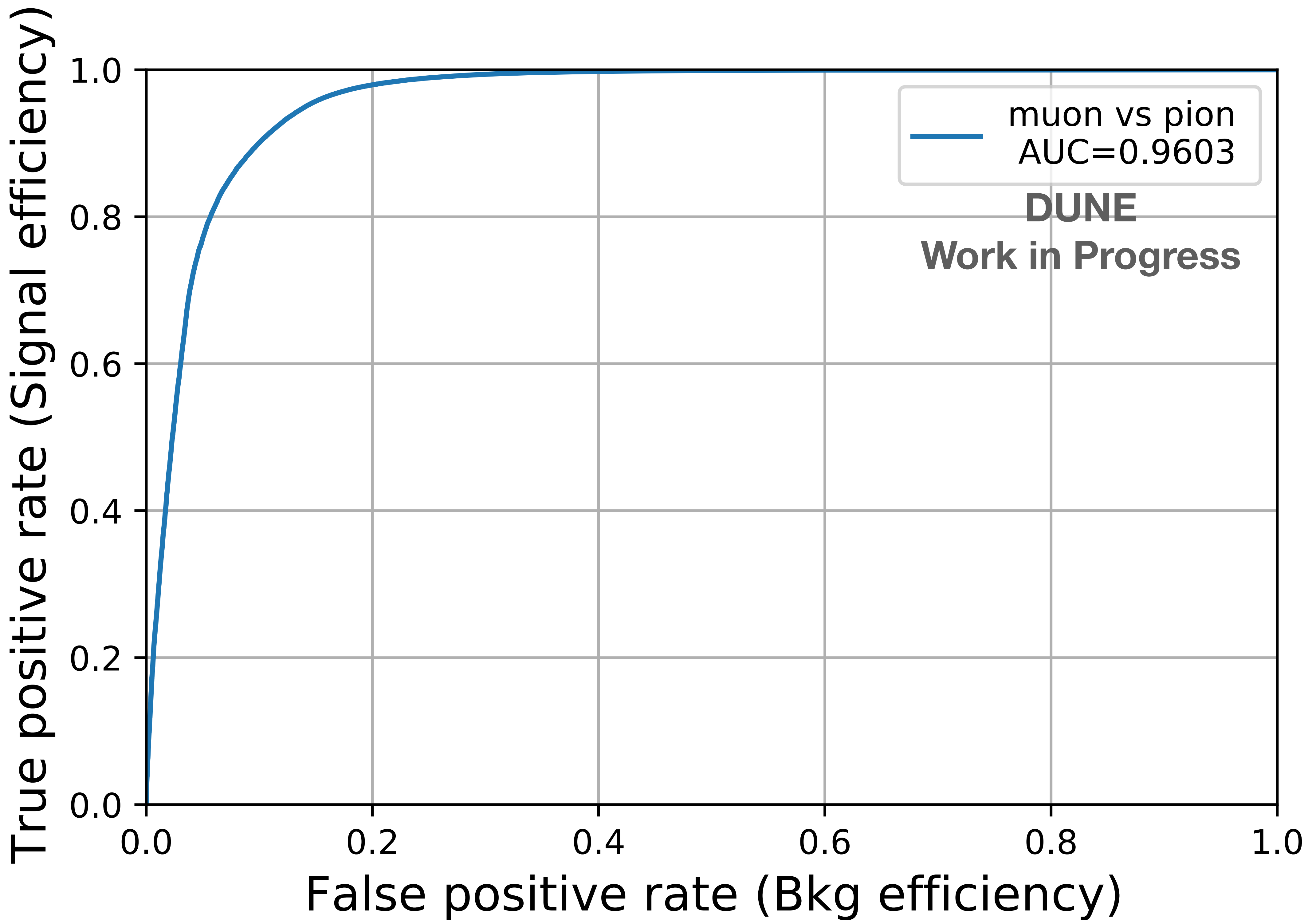




Performance with Full MuID

Results using GENIE momentum spectrum





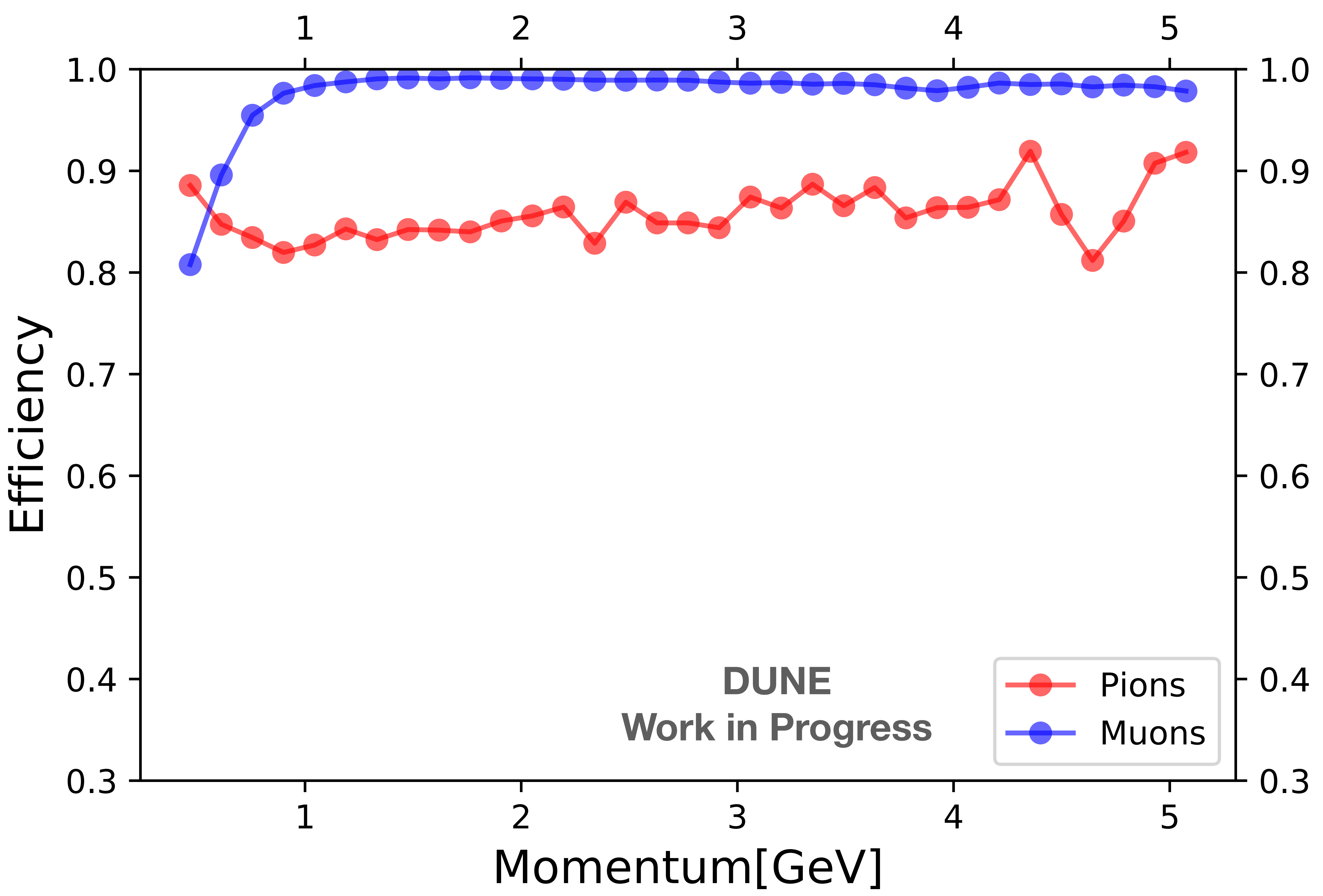
Detection threshold=0.5

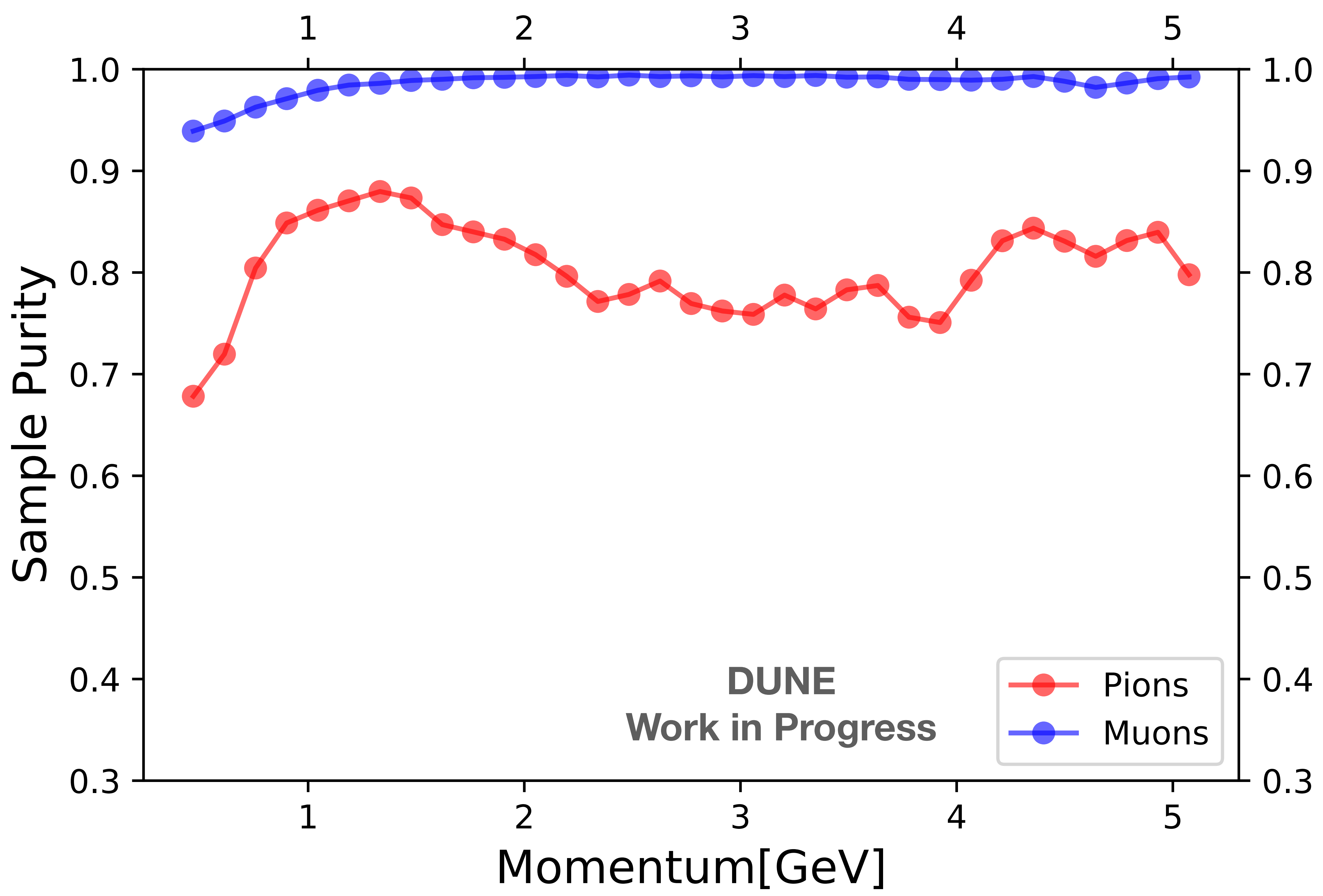
~14% of 81950 pions misidentified

~4.9% of 528316 muons misidentified

Performance with Full MuID

Results using GENIE momentum spectrum

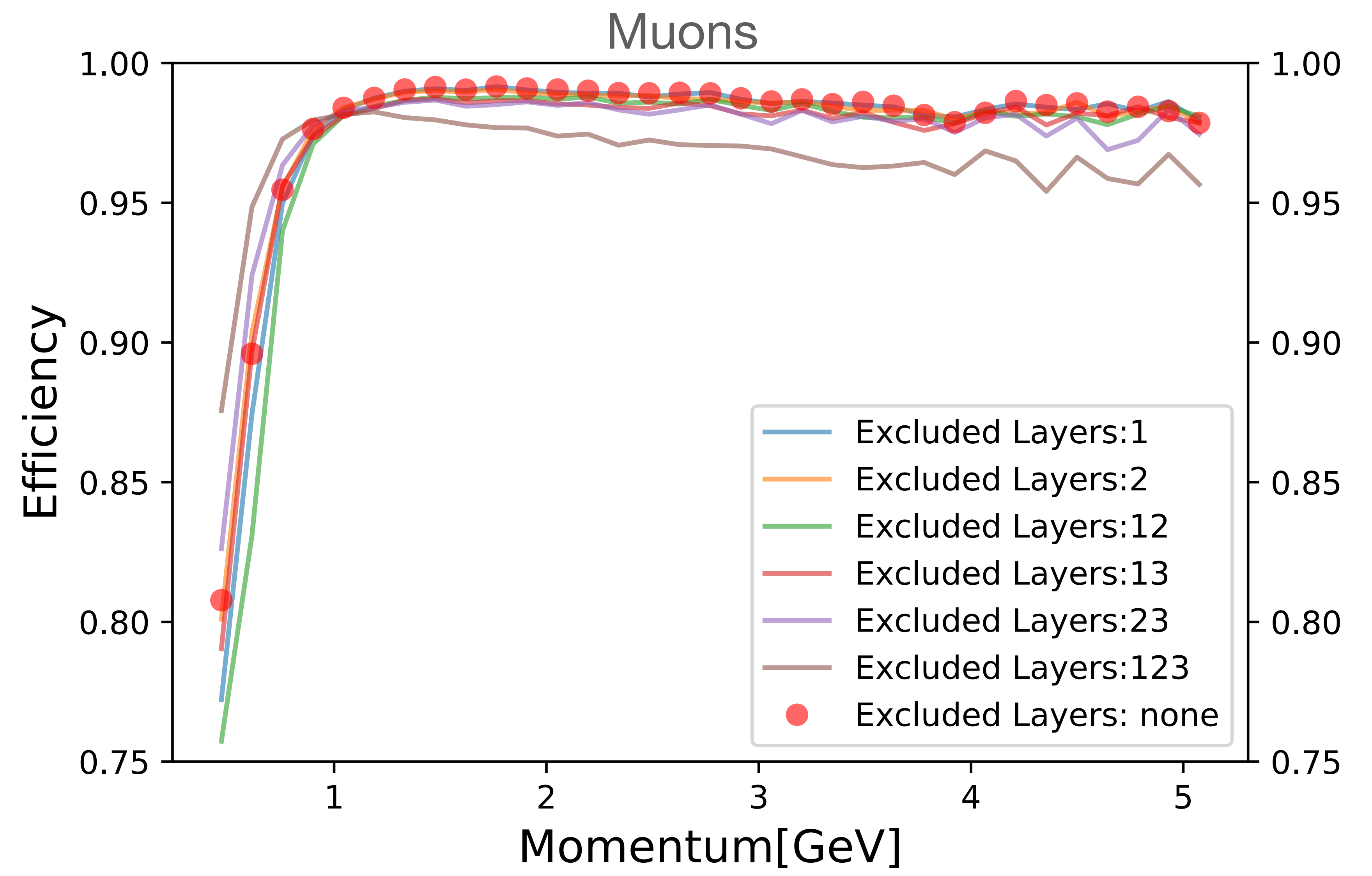


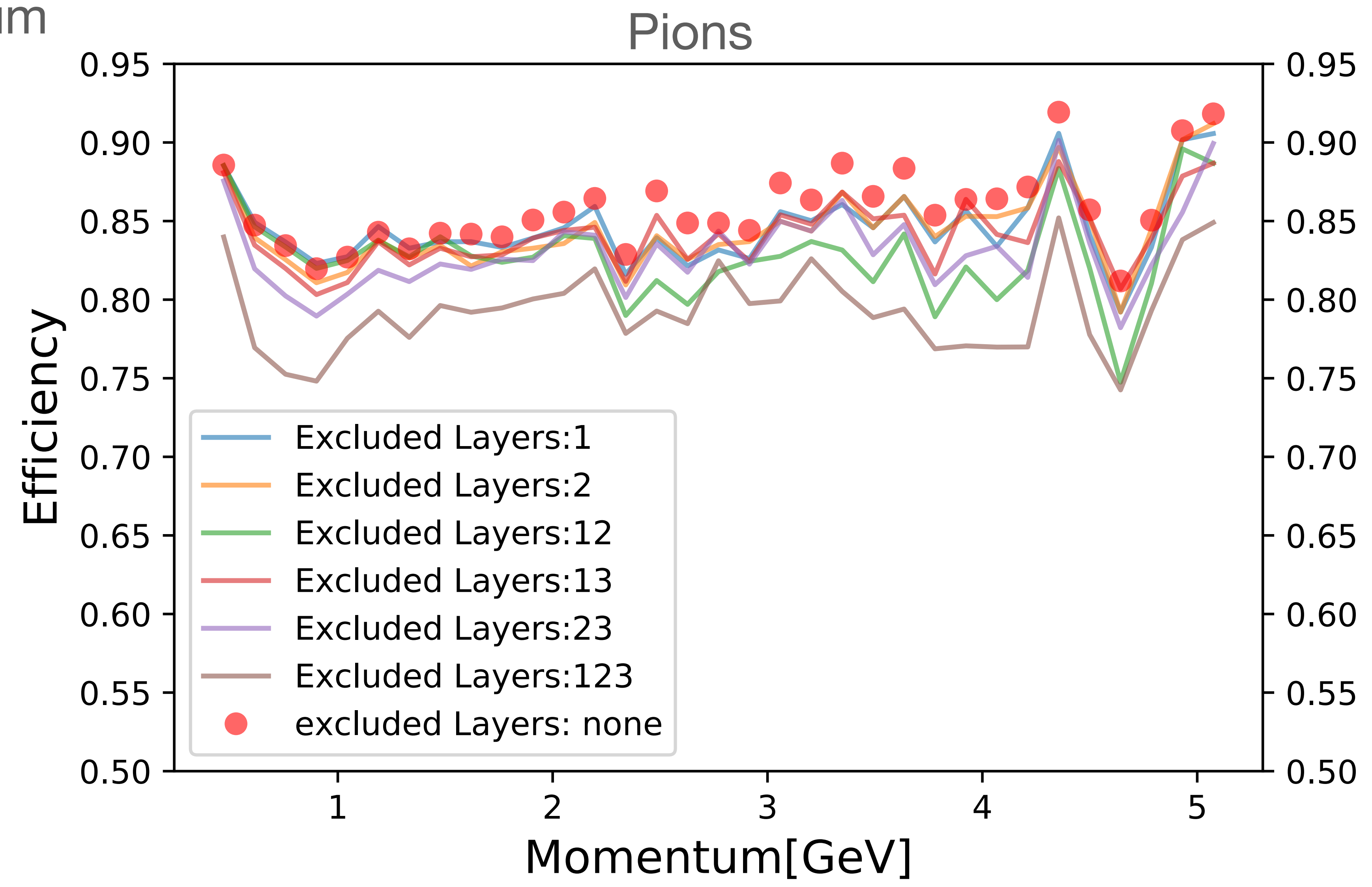


Baseline performance → investigate impact of MuID

Impact of the MuID

Results using GENIE momentum spectrum

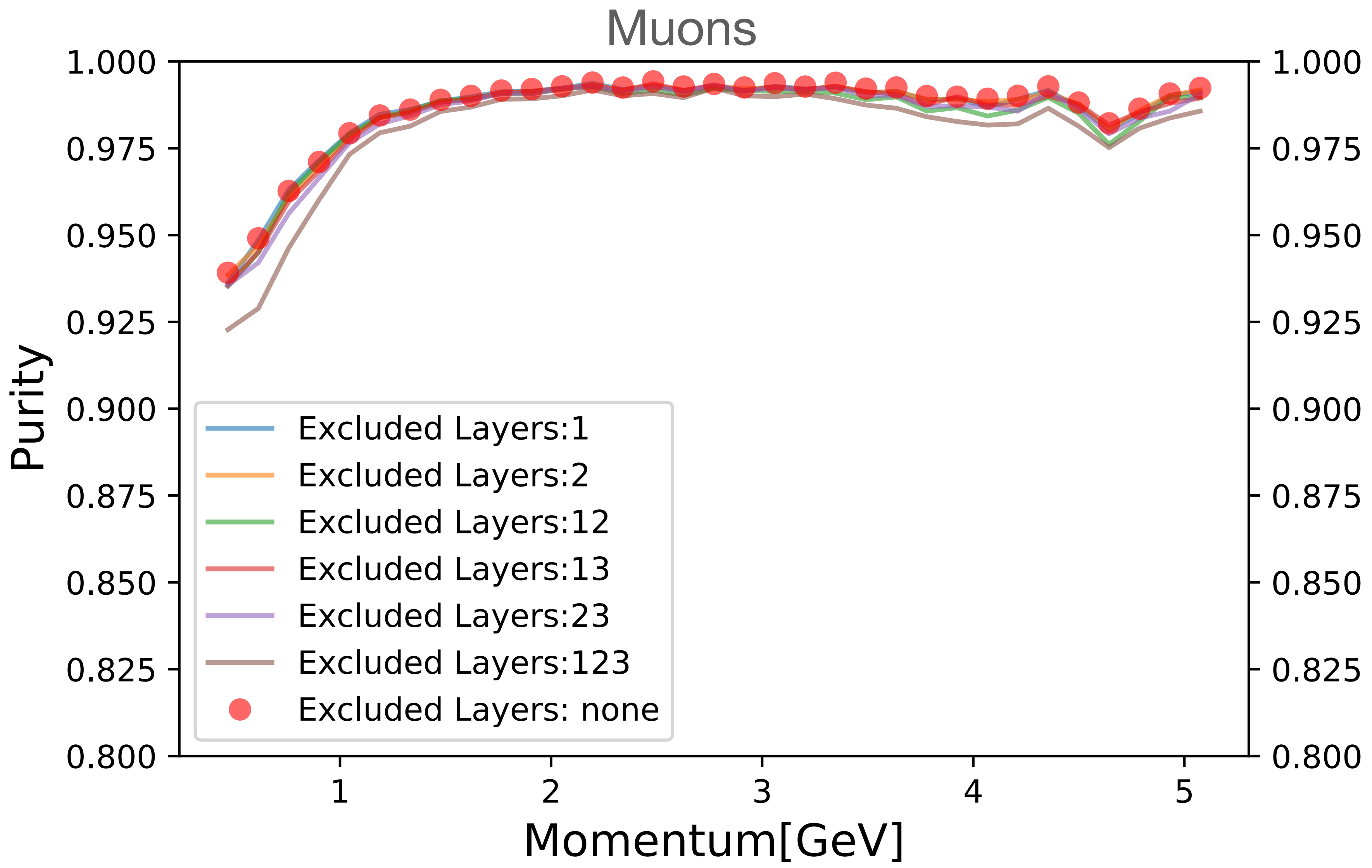


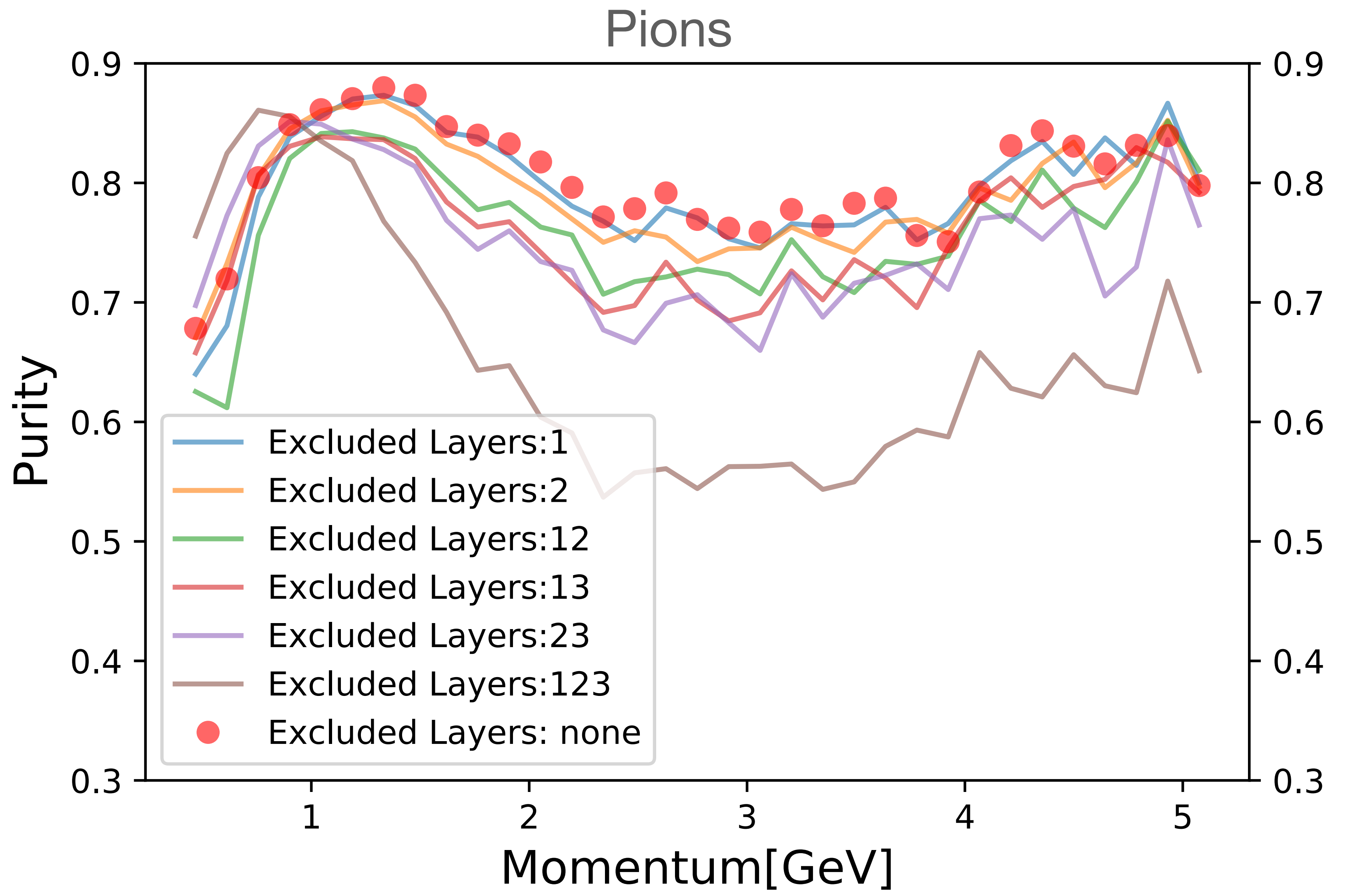


1: inner layer

2: middle layer

3: outer layer





Conclusion

Muon/Pion separation is important for neutrino energy measurement and to reconstruct the nature of the interaction

Full MuID performance:

- ~98% to 99% efficiency/purity for muons above 1GeV
- ~80% to 85% efficiency/purity for pions above 1GeV

MuID significantly increases the performance by:

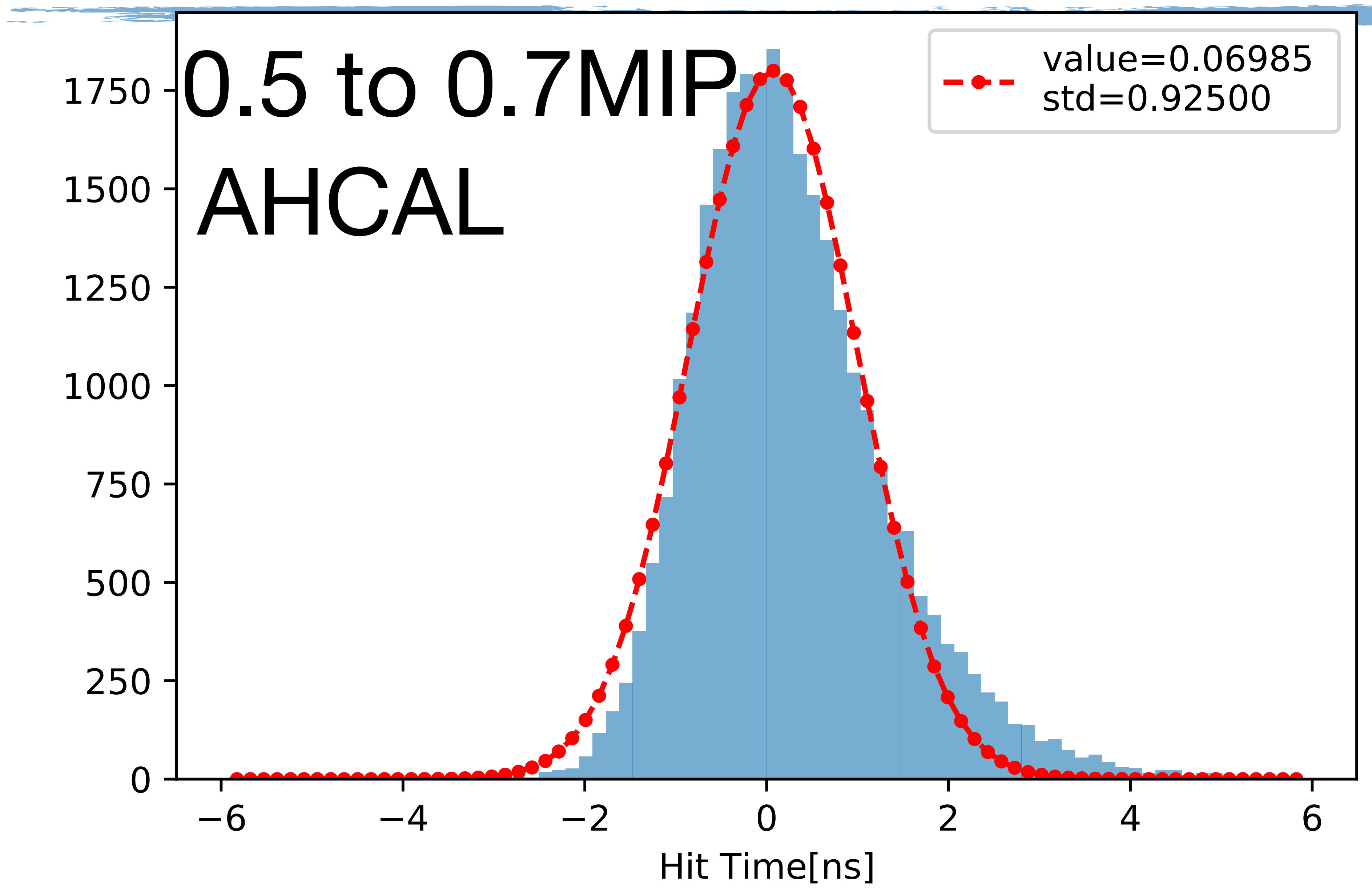
- up to 25% for pion purity
- ~5% to 8% for pion efficiency

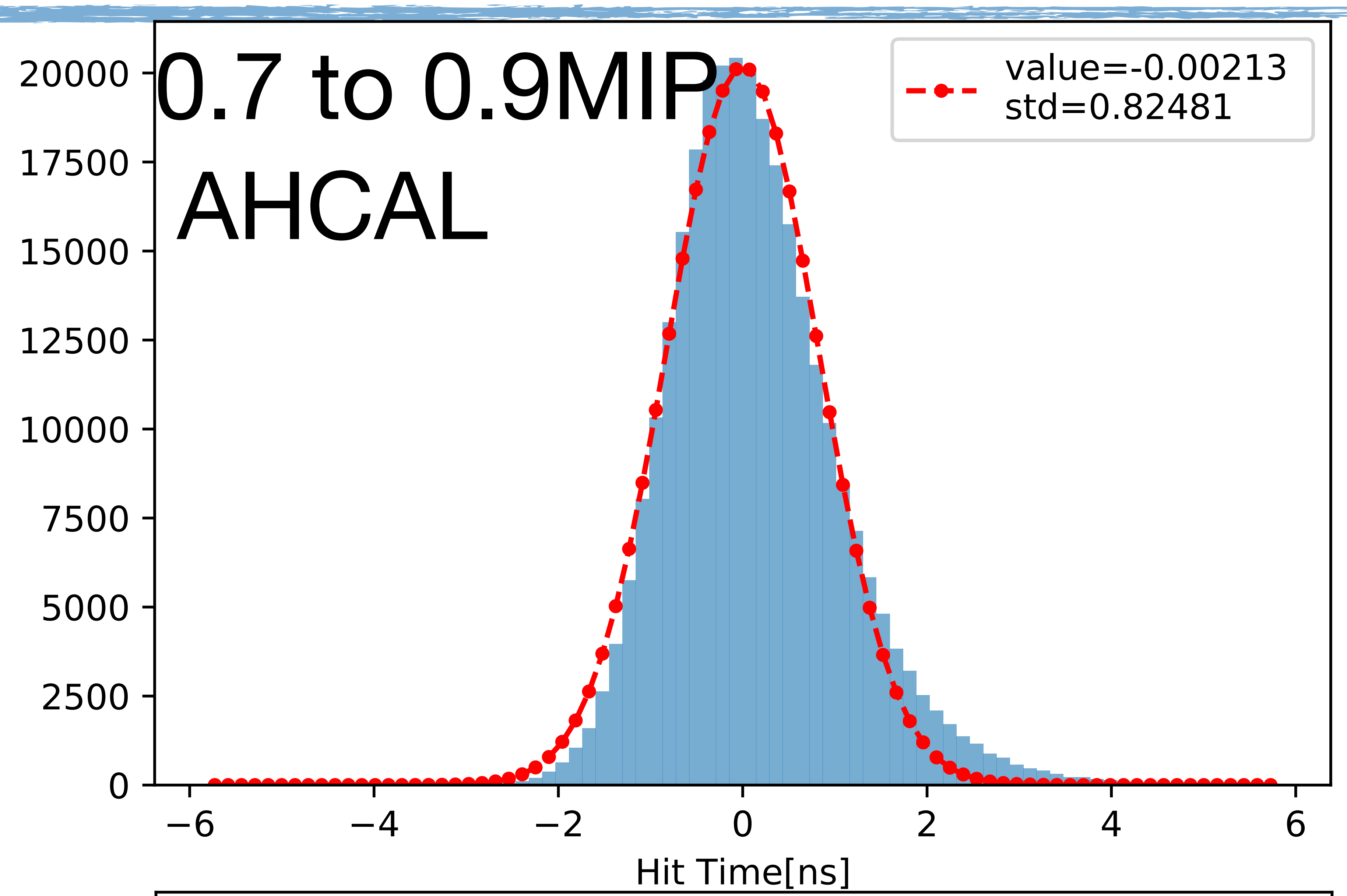
No dramatic loss of performance when excluding the inner MuID layer

At least two MuID layers are desirable

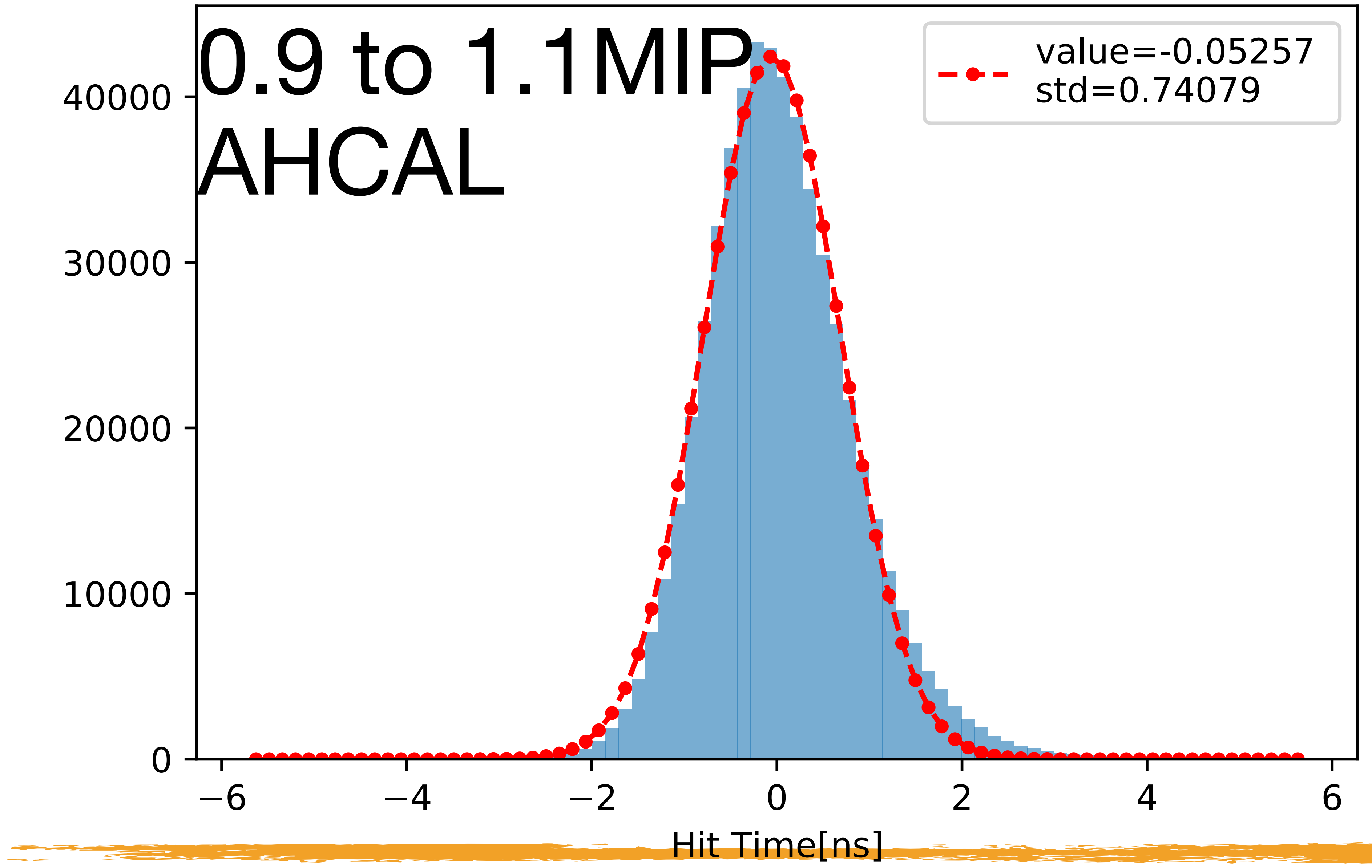
Backup

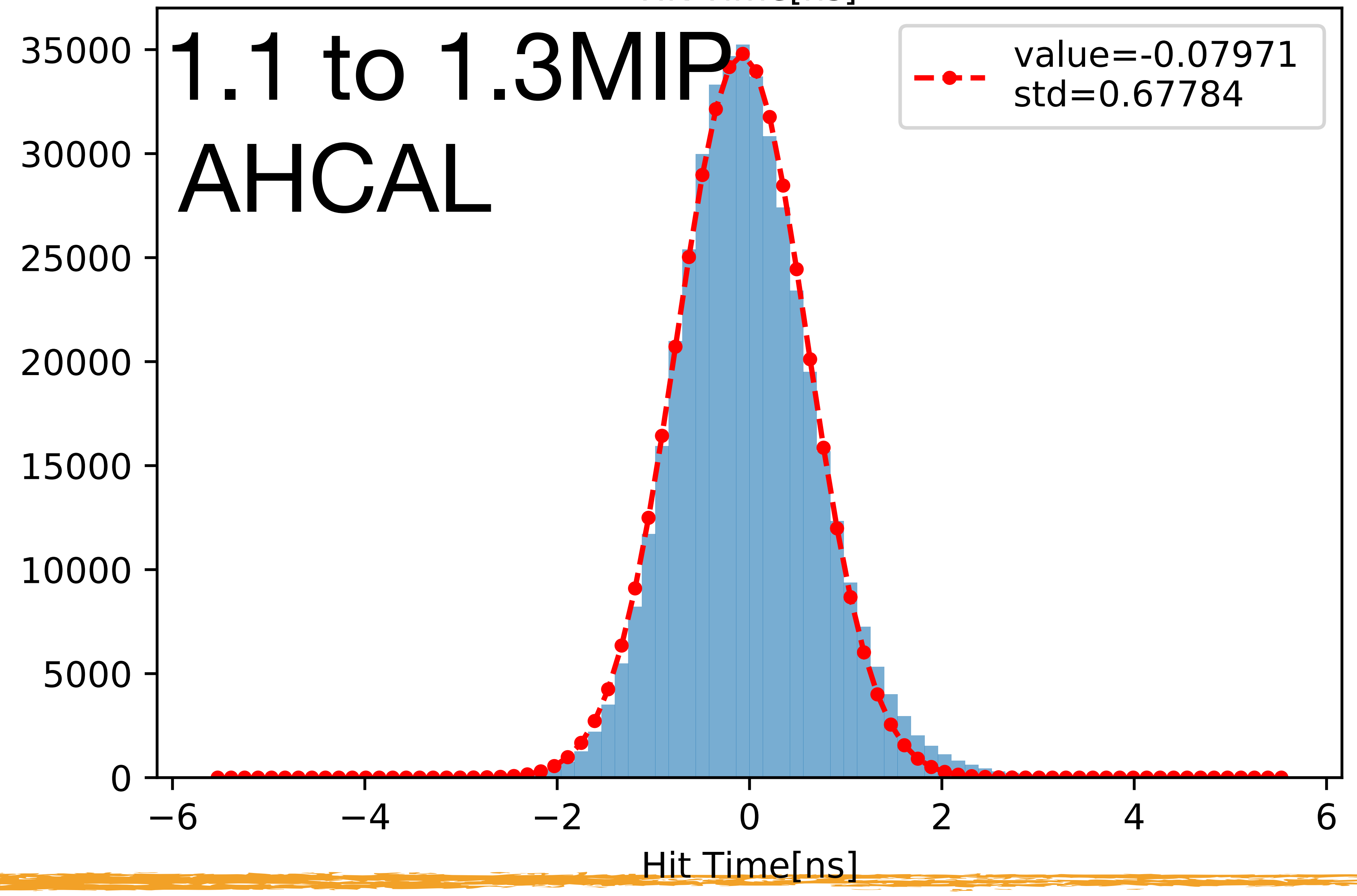
Energy Binned Time Resolution



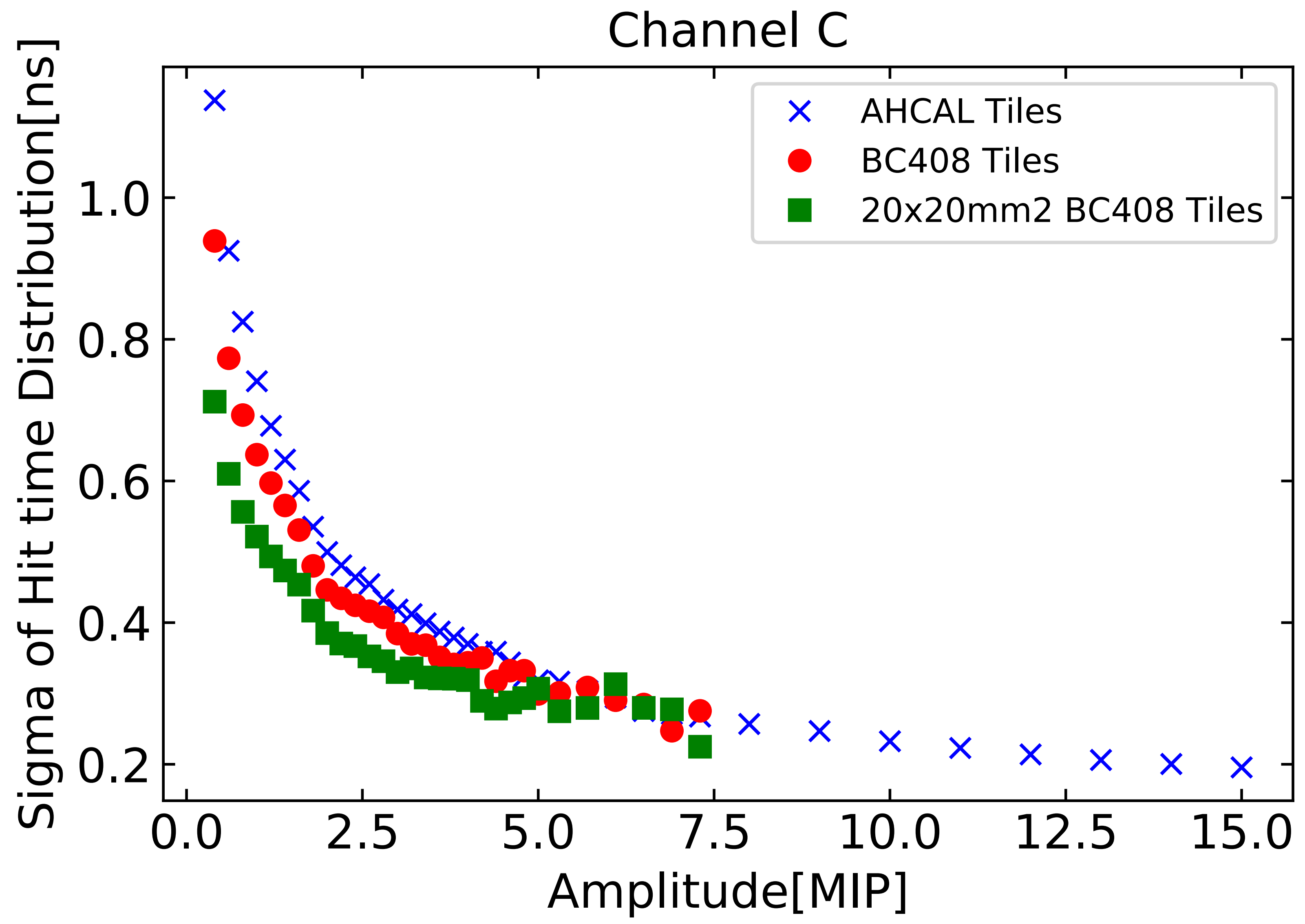


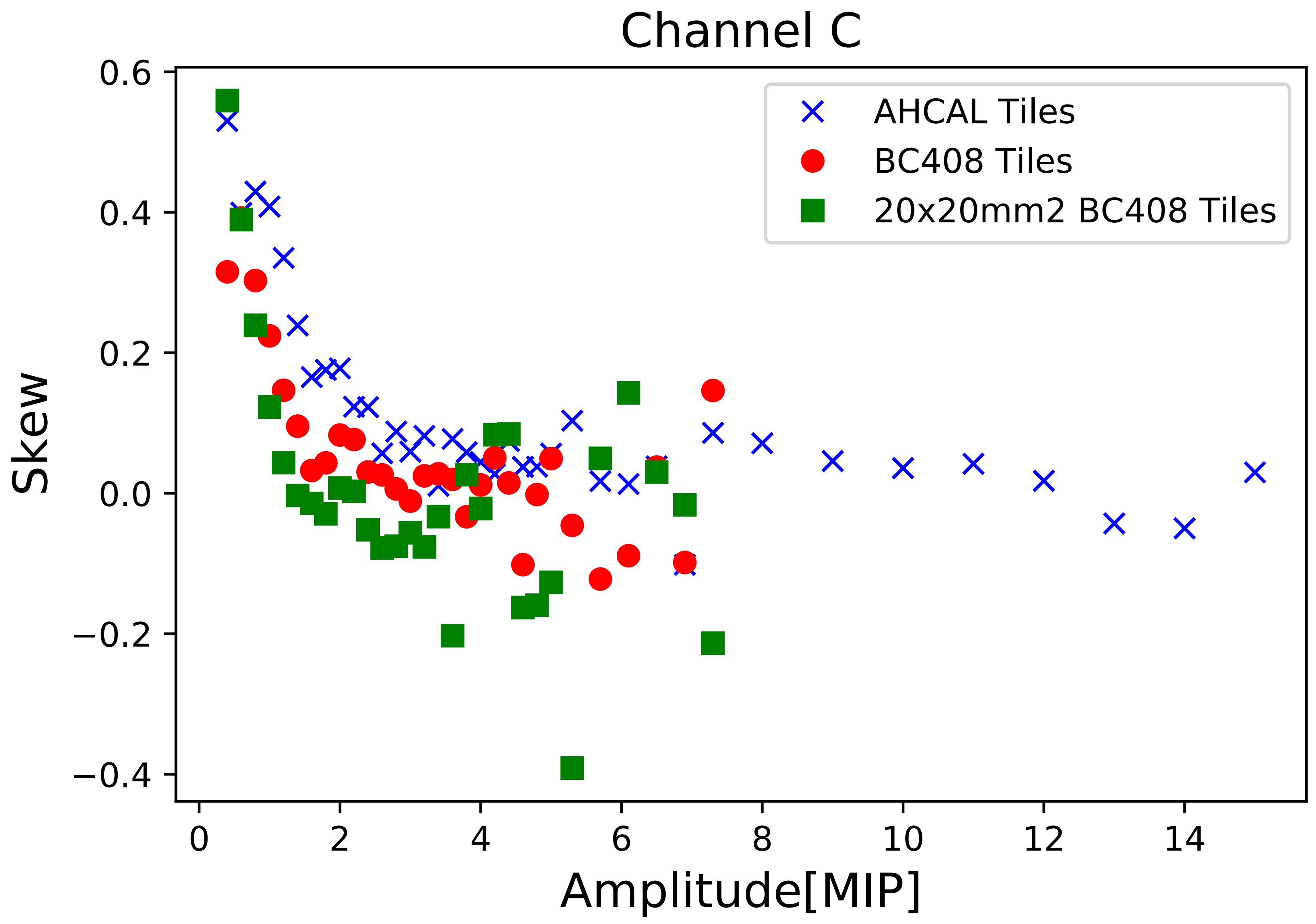
Distributions get narrow and more gaussian like



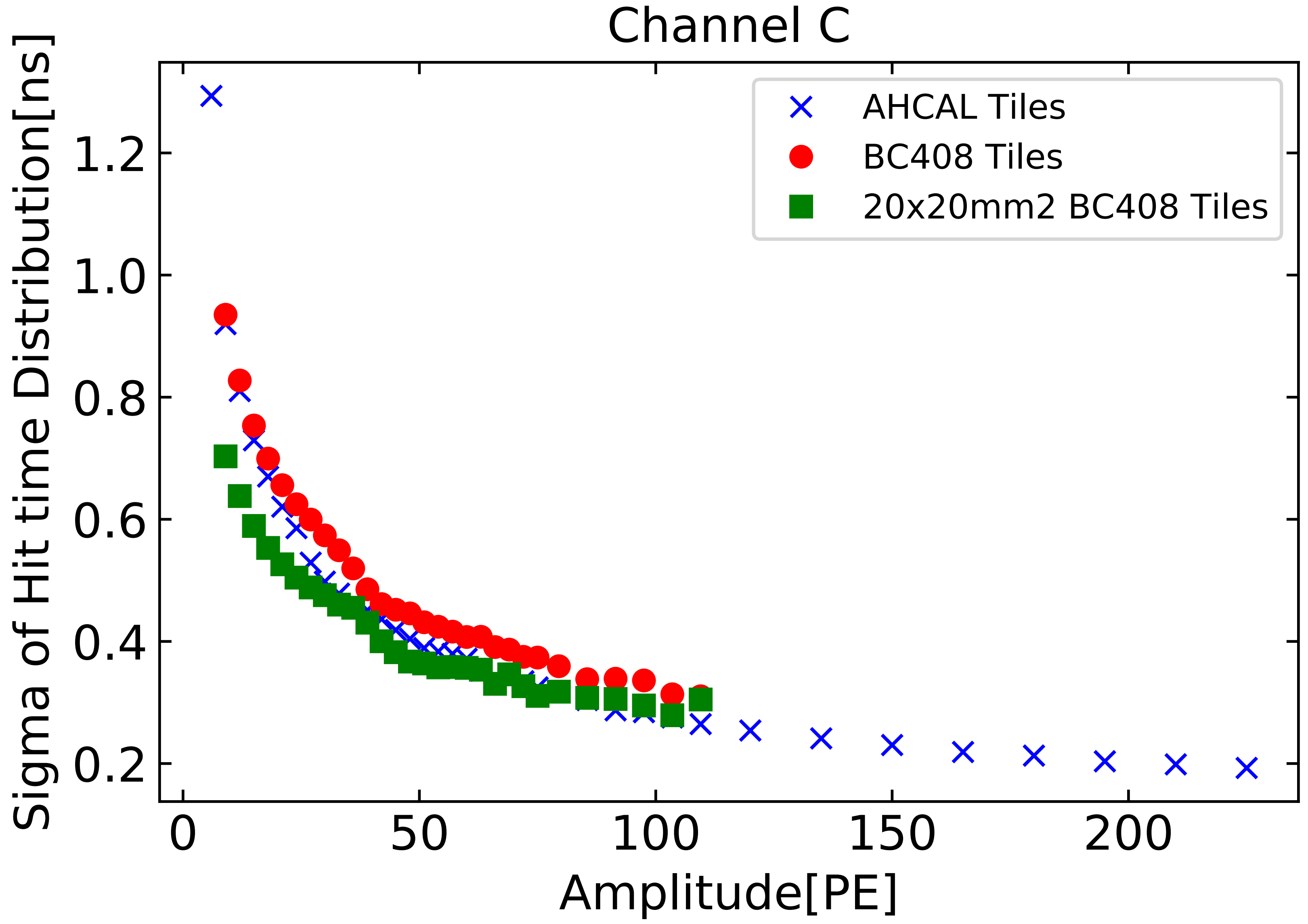


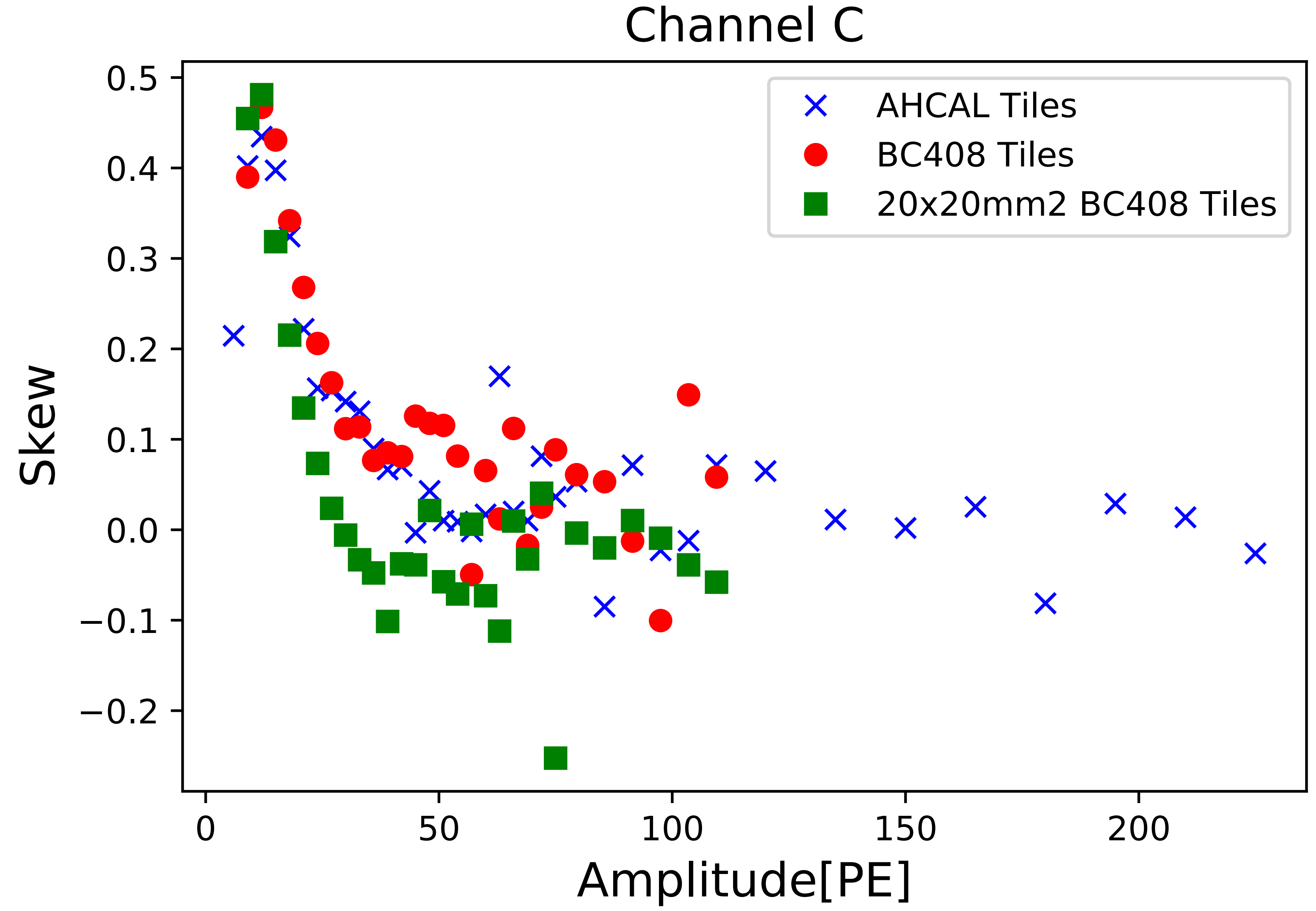
AHCAL vs. BC408 vs. small BC408



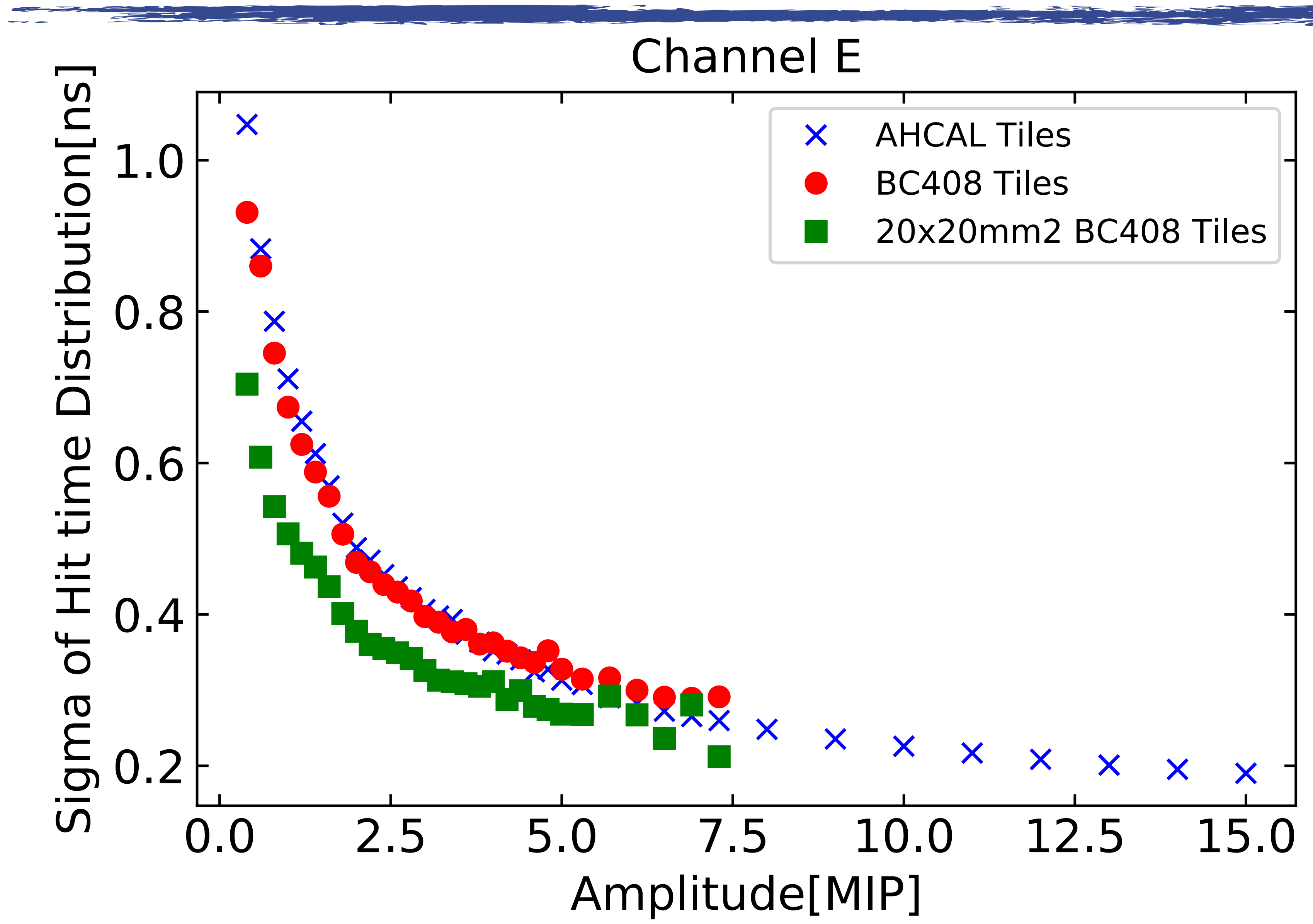


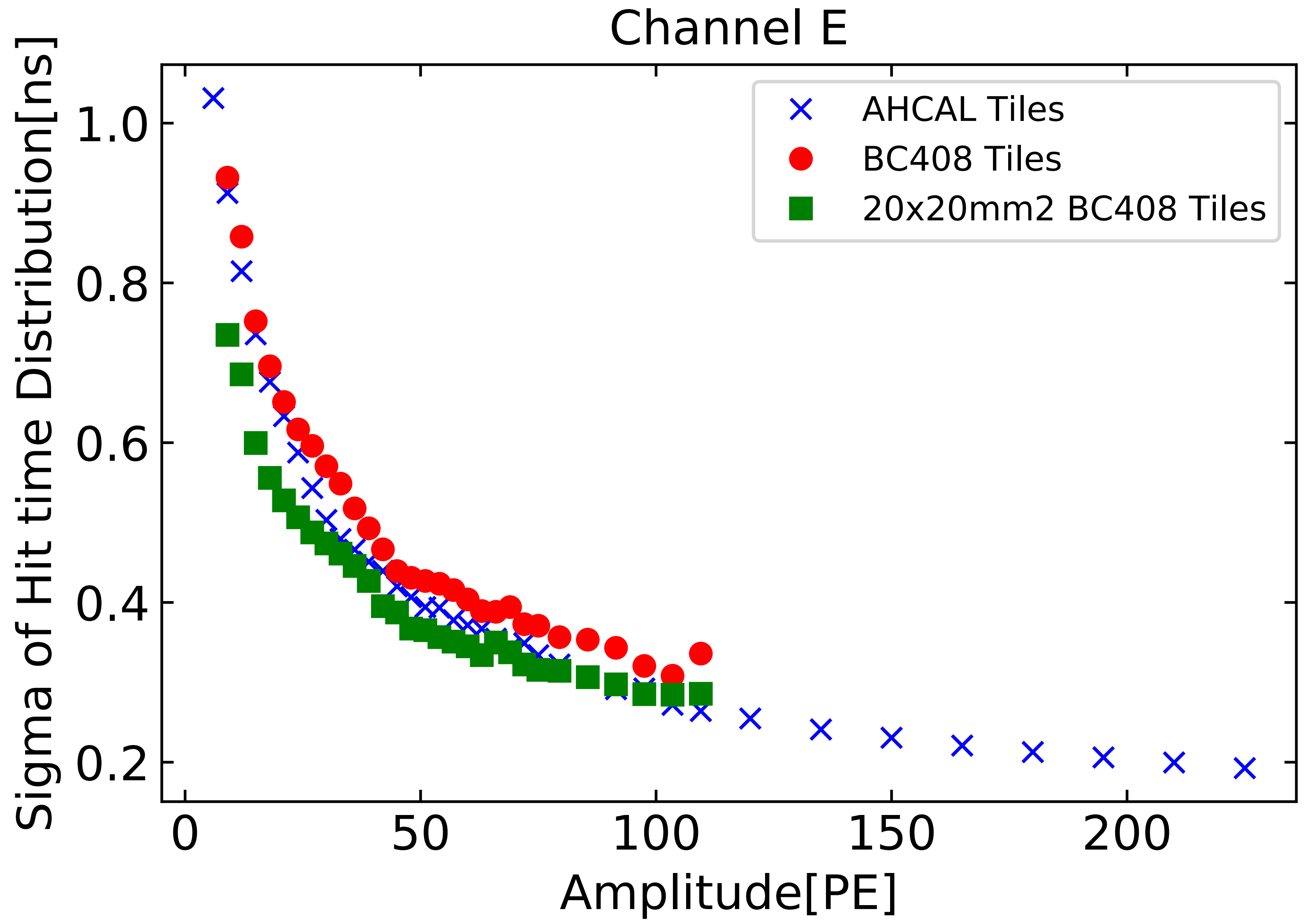
Channel C
AHCAL:14.3 pe/MIP
BC408: 22.87 pe/MIP
BC408small: 21.85 pe/MIP



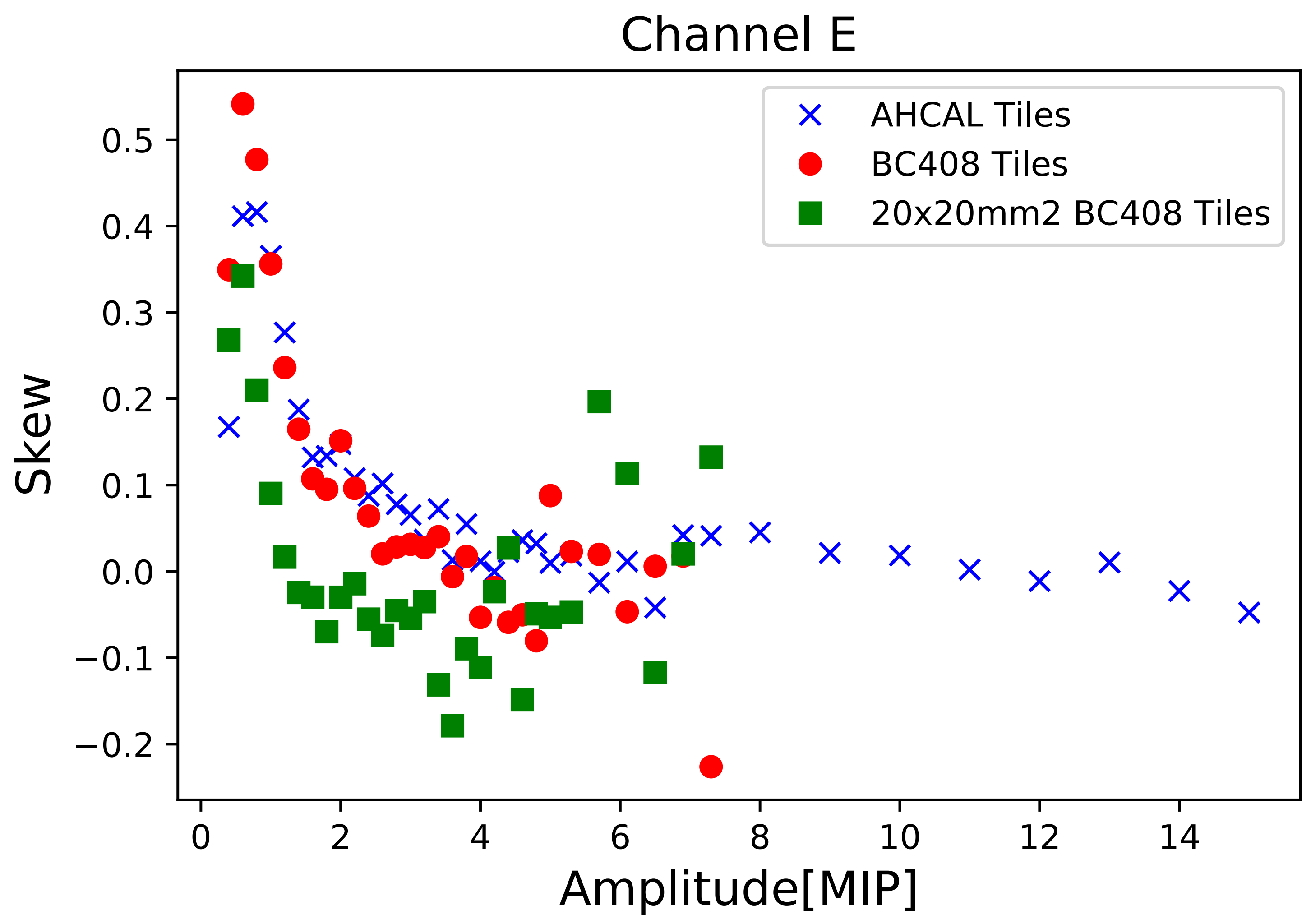


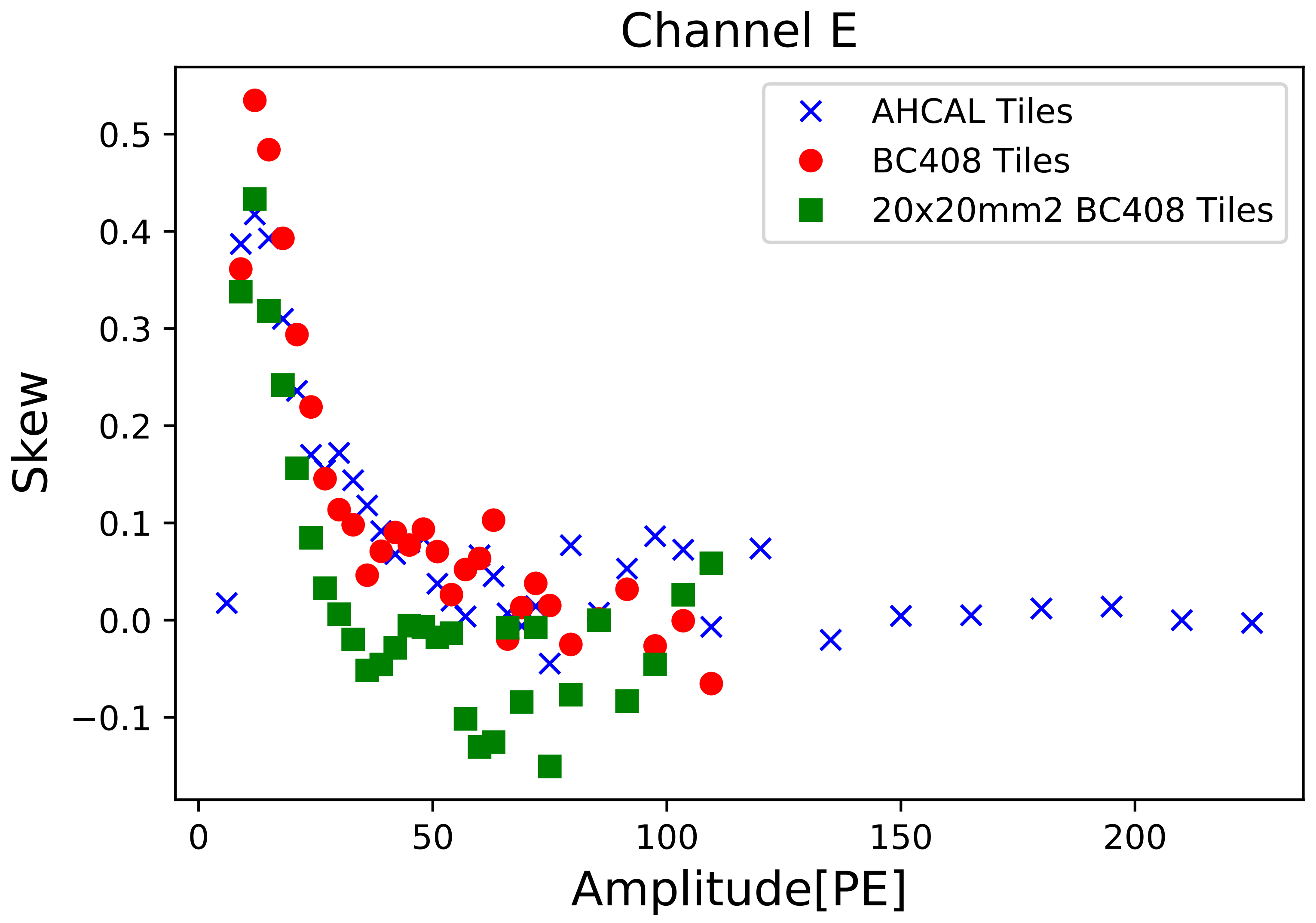
AHCAL vs. BC408 vs. small BC408



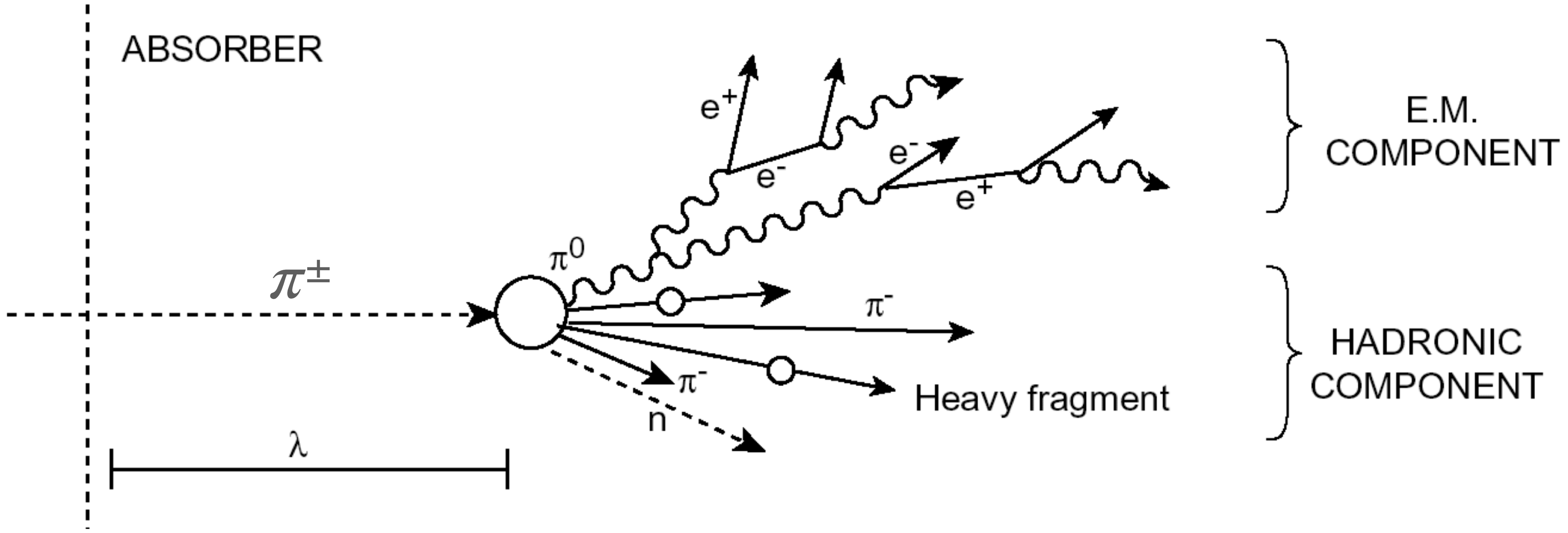


Channel E
AHCAL:16.4 pe/MIP
BC408: 19.3 pe/MIP
BC408small: 23.9 pe/MIP





Hadronic Interaction



Particle multiplication after inelastic interaction:

- Charged hadrons
- Neutral pions → electrons/positrons

Higher charged particle density leads to high energy calorimeter hits

Nuclear interaction length λ: Mean free path before inelastic interaction

- Typically several 10cm in metal, depends on element
- Depends on incoming hadron, e.g. Proton: λ_{Iron}=16.77cm, Pion: λ_{Iron}=20.42cm

Punch through probability: Probability of no inelastic interaction in the detector

$P_{\text{PunchThrough}} = \exp(-\lambda)$