Particle Identification and Reconstruction with DUNE ND-GAr

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MAX-PLANCK-INSTITUT FÜR PHYSIK

Long Baseline Neutrino Physics

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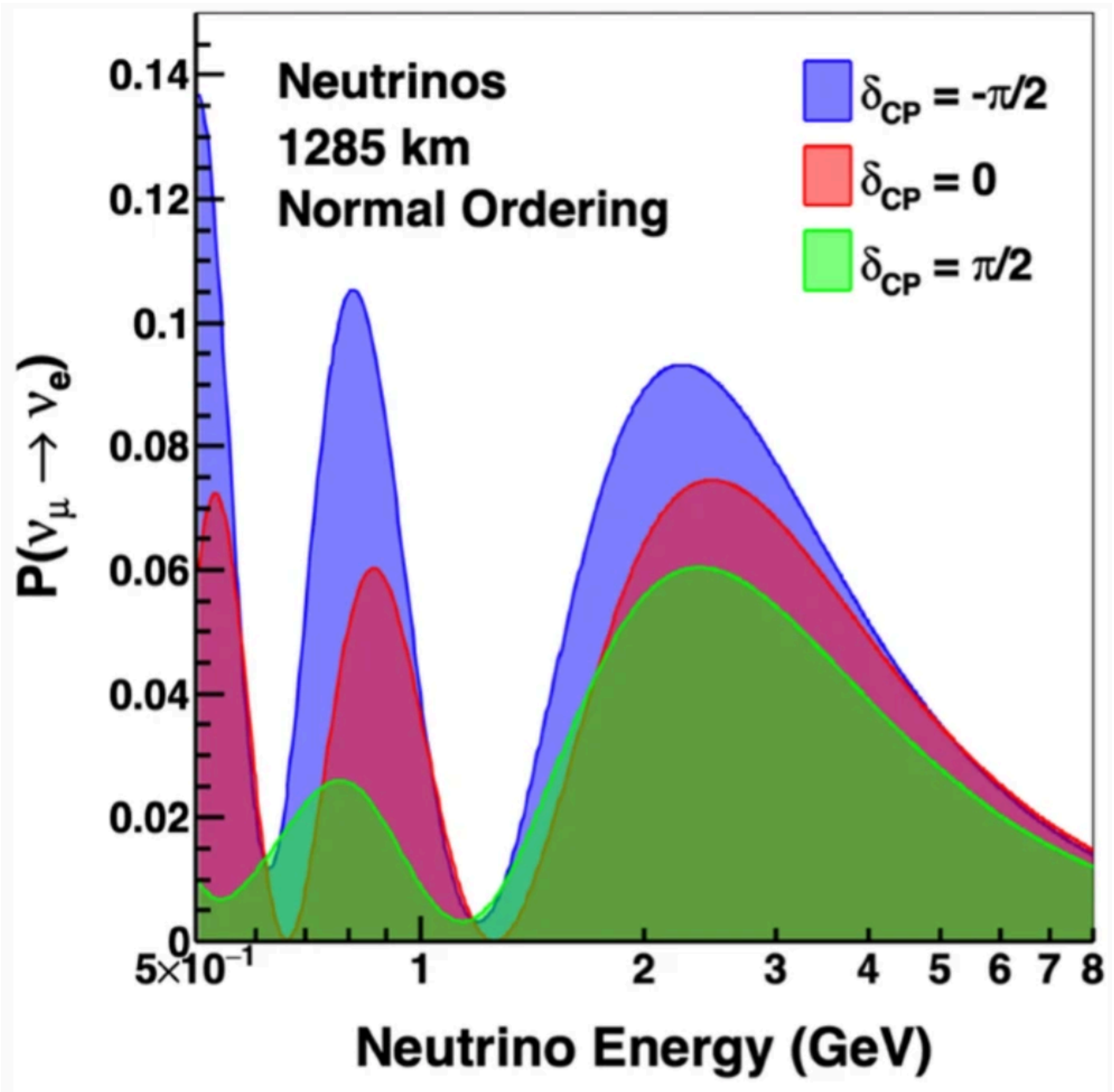
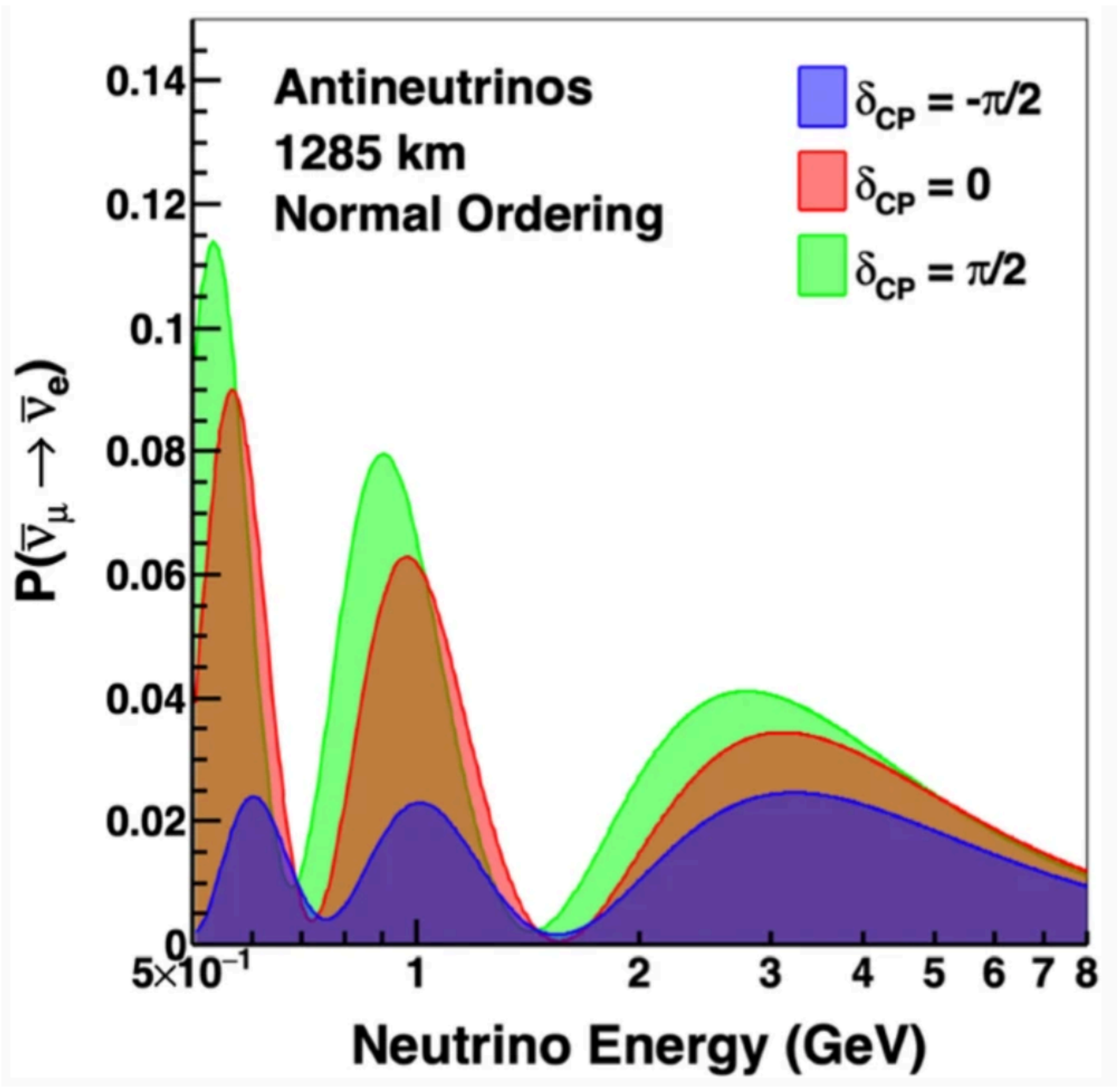
CP Violation in the neutrino sector

$$P\left(\nu_\mu(\overline{\nu_\mu}) \rightarrow \nu_e(\overline{\nu_e})\right) \simeq \sin^2(2\Theta_{13})\sin^2(\Theta_{23}) \cdot \frac{\sin^2\left[(1-x)\frac{\Delta m_{31}^2 L}{4E}\right]}{(1-x)^2} \pm P_1\left(\sin\delta_{CP}\right) \mp P_2\left(\cos\delta_{CP}\right)$$





Use subdominant oscillation to ν_e

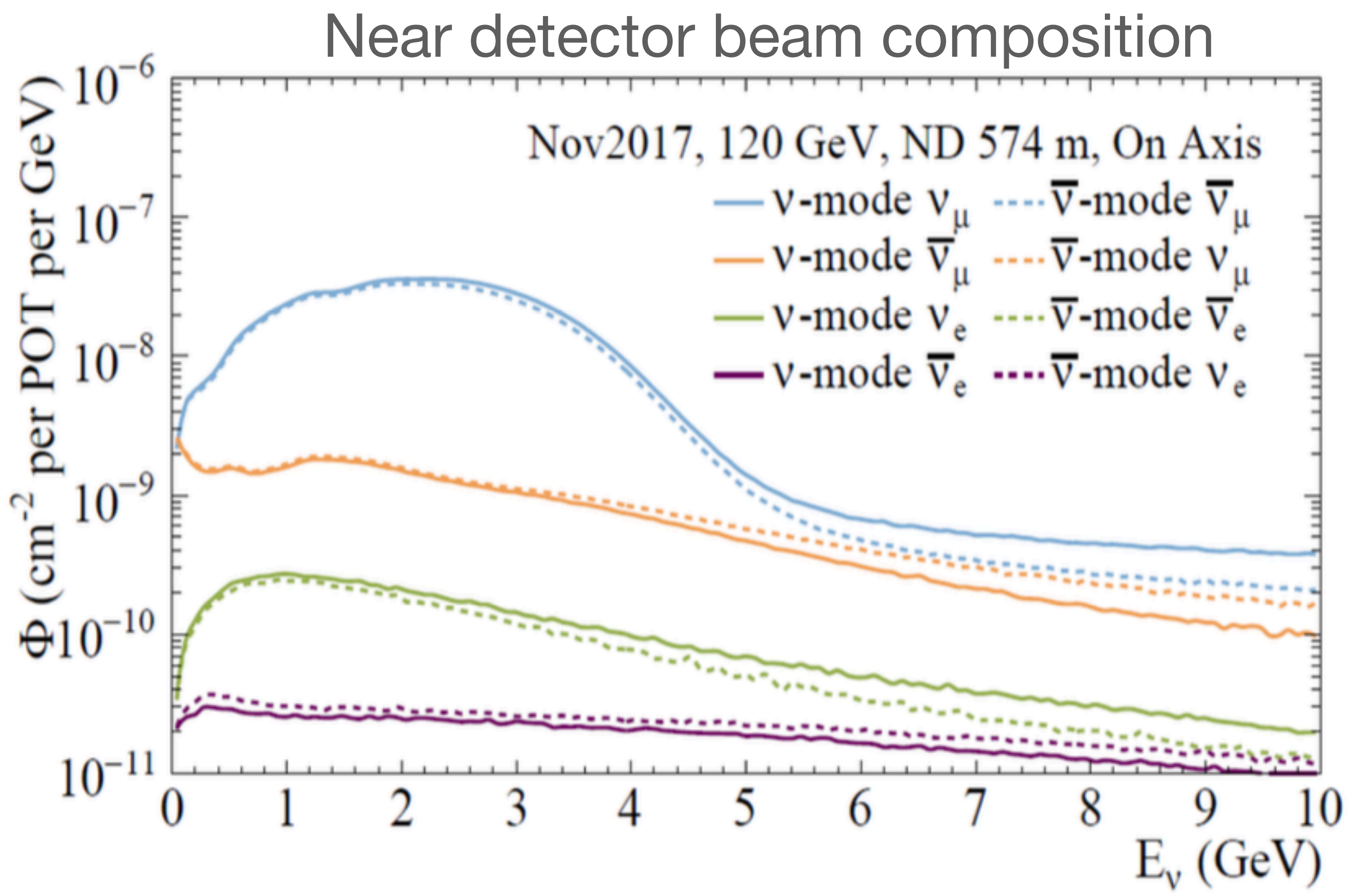
L fixed, E is in a wide range:

➡ Scan multiple oscillation maxima

ν_μ and anti-ν_μ mode:

➡ Investigate CP-Violation in δ_{CP}

The DUNE Setup

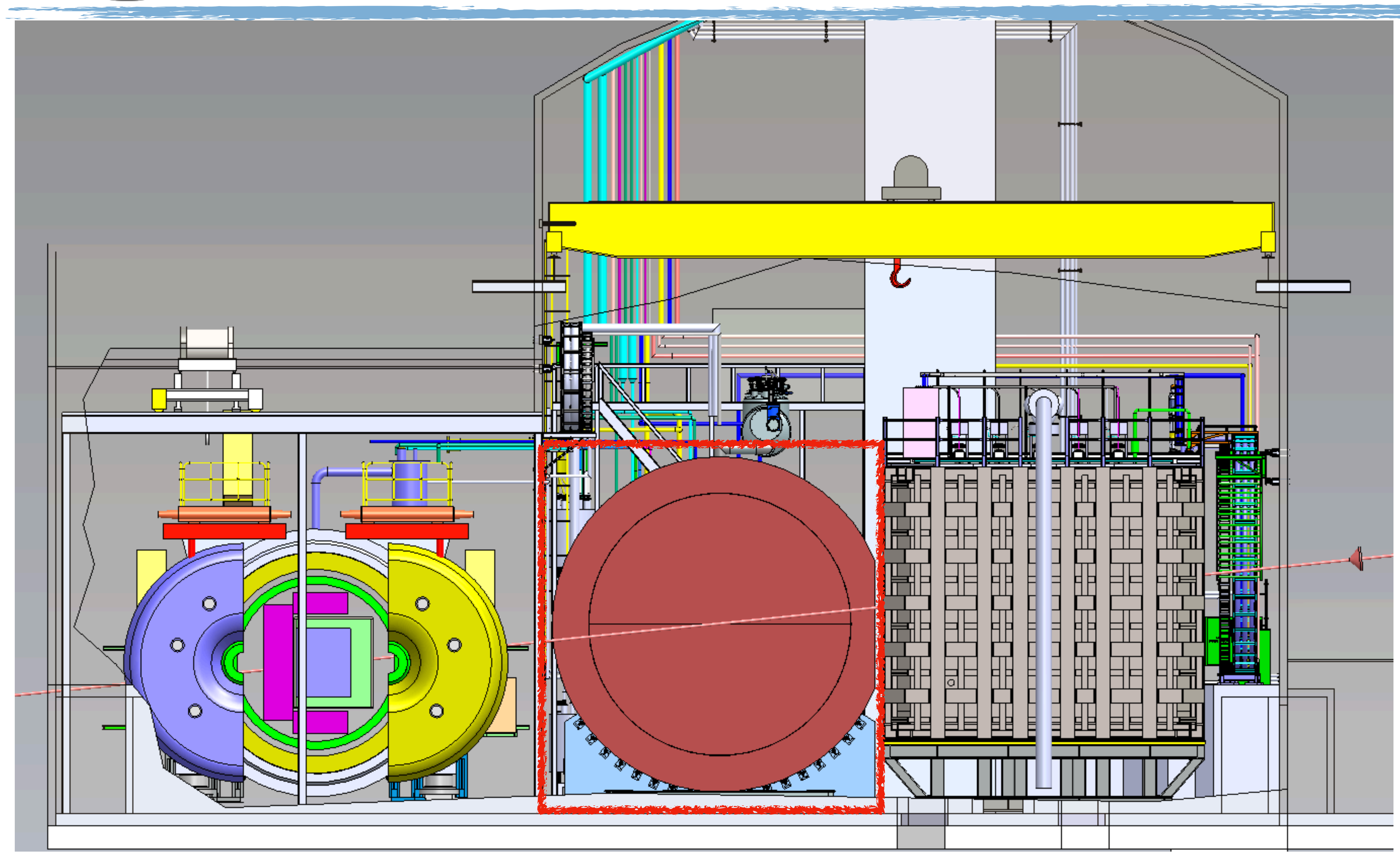


High energy, broadband, high rates → flexibility:

- Needs precise energy and flavour tagging
- Maximize oscillation probability:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\Theta)\sin^2\left(1.27\frac{\Delta m^2 \cdot L/km}{eV^2 \cdot E/GeV}\right), L = 1300km, < E > = 2.5GeV$$

The DUNE Near Site



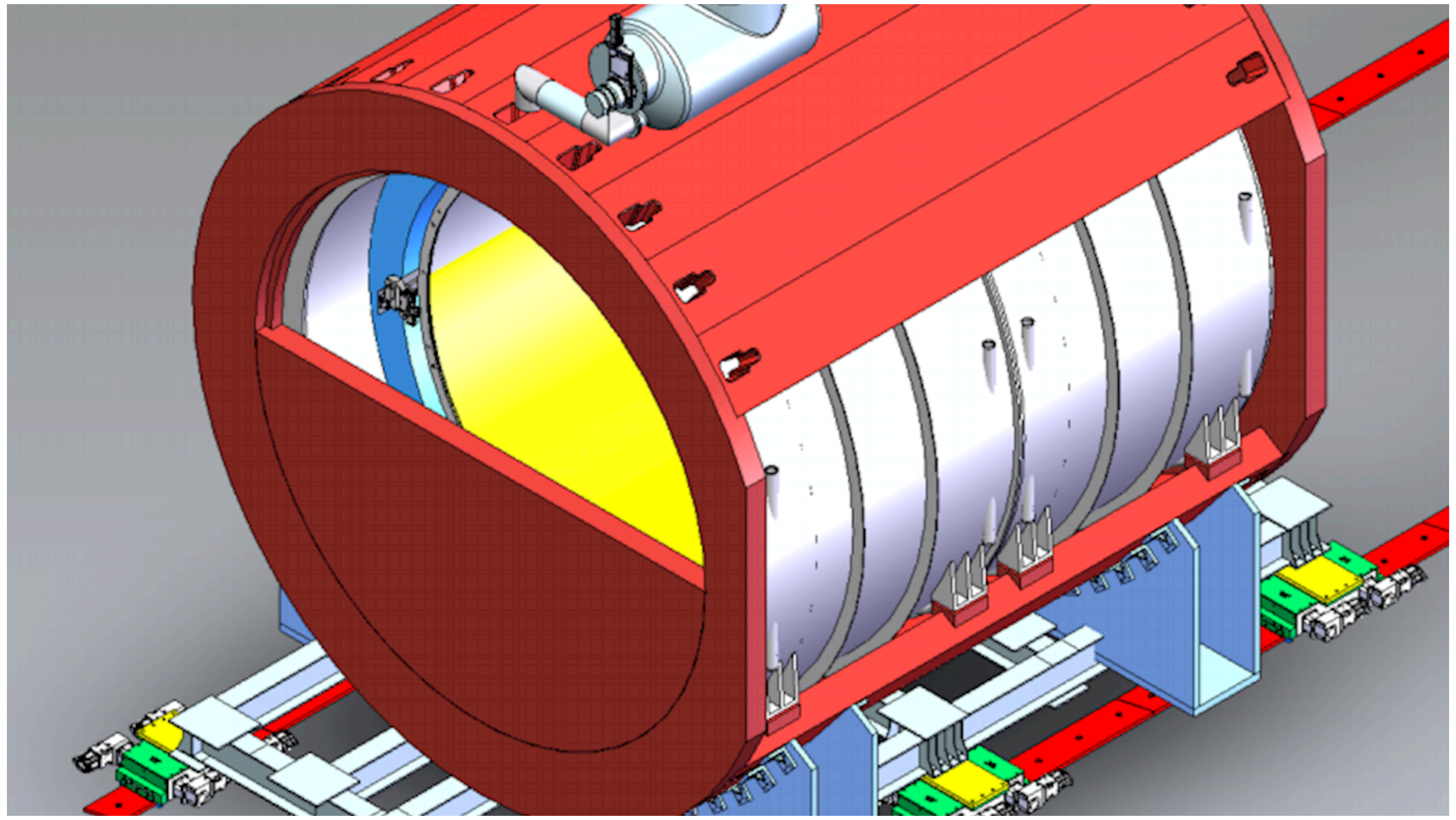
Near Detector Tasks:

- Charaterization of the neutrino beam
- Monitoring of the flux, background
- Constraining systematics
- Precision measurements on neutrino interaction cross sections

Gaseous Argon TPC:

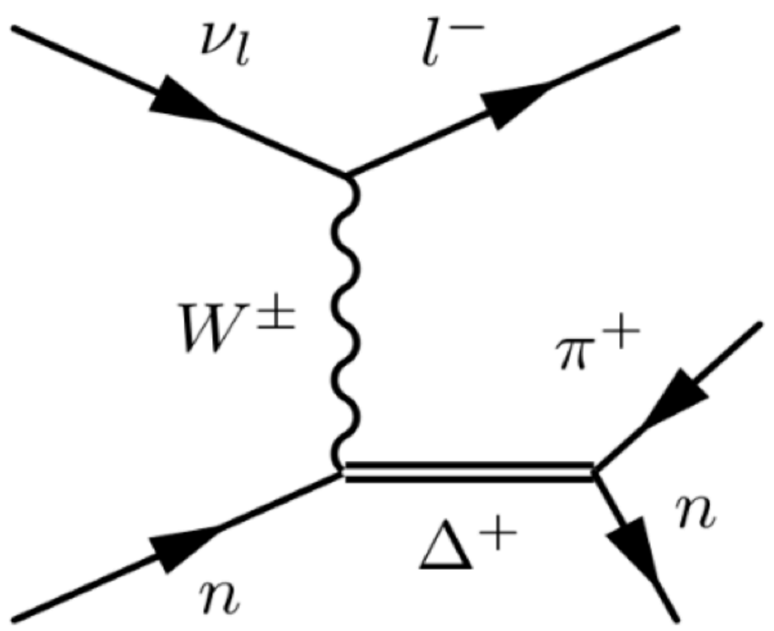
- Gaseous target, low detection threshold for charged particles
- ECAL and muon detector for complete reconstruction of final states
- Sensitivity to rare neutrino interactions

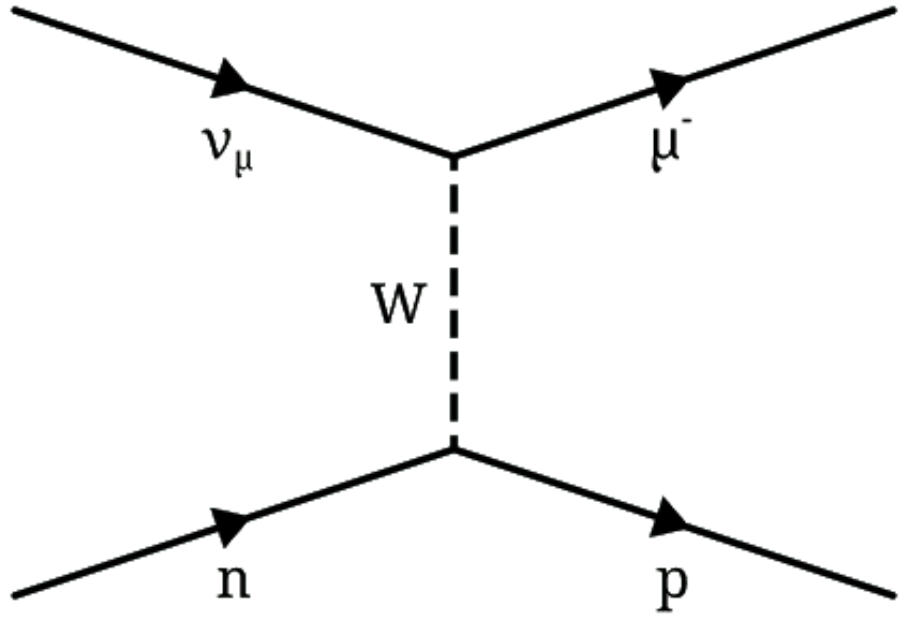
ND-GAr Design



- Central argon TPC, also serves as neutrino target
- Upstream window to capture particles escaping upstream detector

Common interactions on argon target:





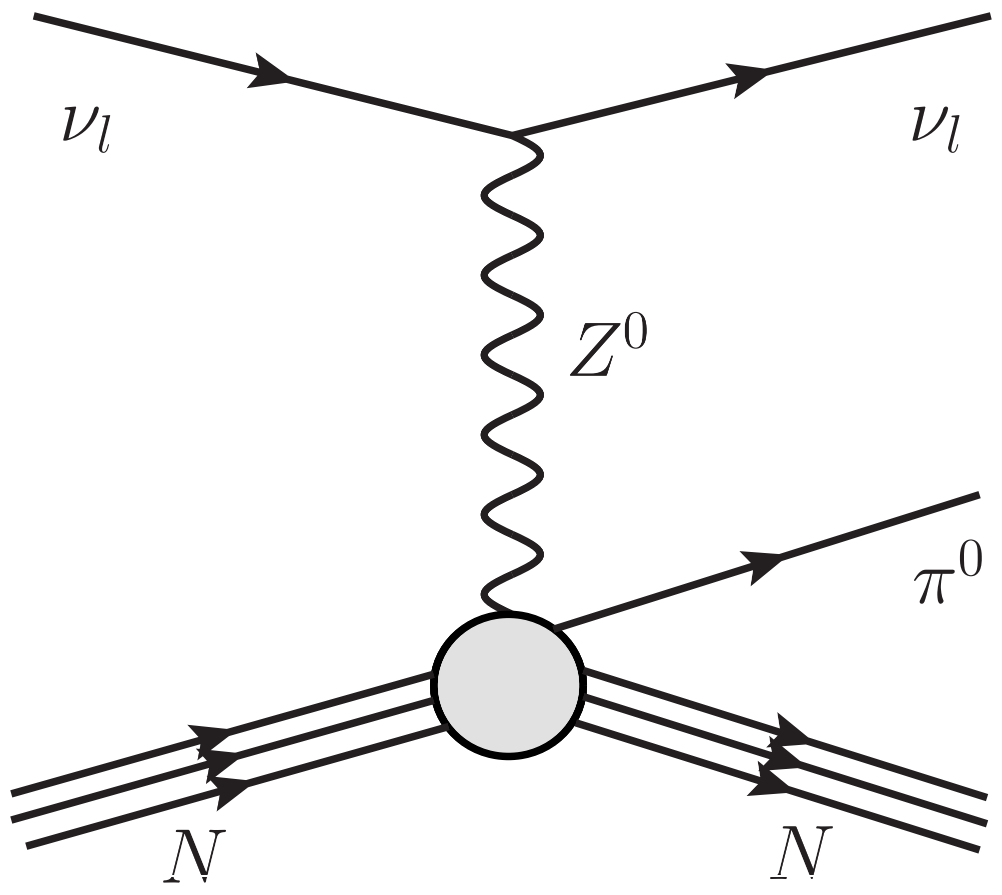
- Momentum and charge reconstruction of charged particles in TPC
- Reconstruction of photons and neutrons in highly granular scintillator ECAL
- 0.5T solenoid field
- Surrounded by a yoke and muon detector (technology tbd)

ECAL Design Drivers

Key roles of the ECAL:

1. Photon reconstruction

NC/CC neutral pion production:



- Low momentum transfer
- $\pi^0 \rightarrow \gamma\gamma$
- Two photons as final state
- No signal in TPC
- Very hard to find the vertex and reconstruct the event

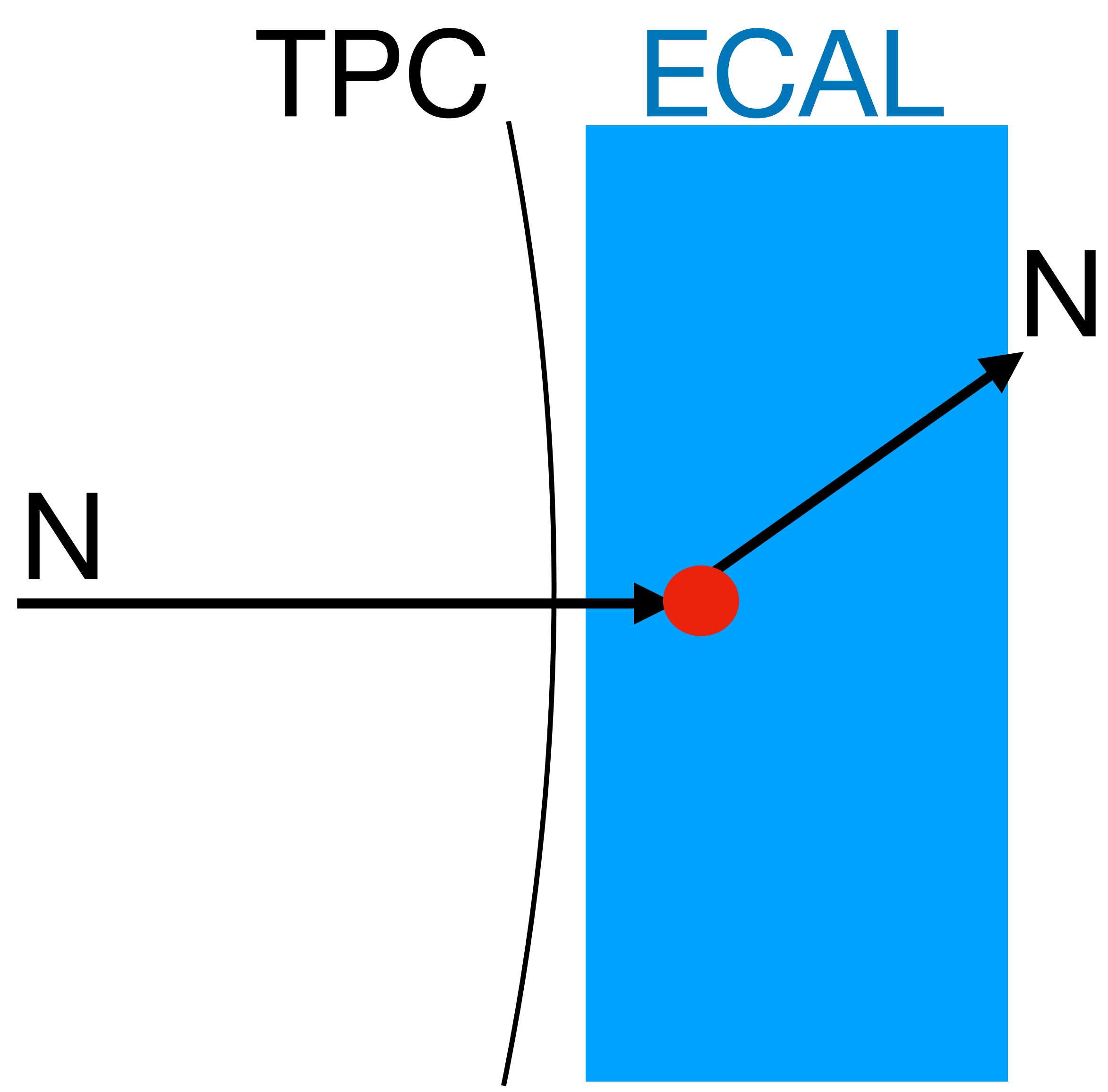
Electron neutrino appearance signal in an electron!

Electron/Photon separation challenging in the far detector
→understand rates of neutral pion production in near detector

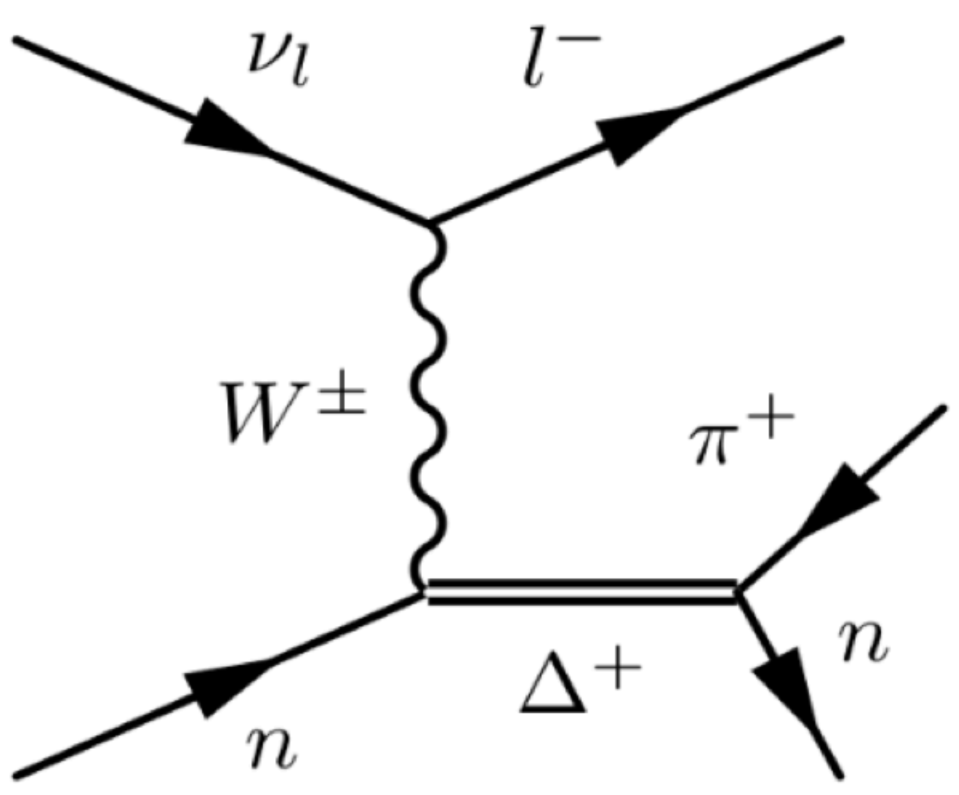
ECAL Design Drivers

Key roles of the ECAL:

1. Photon reconstruction
2. Neutron identification



NC/CC neutron production:



- Neutrons have momentum O(1MeV) to O(1GeV)
- Neutral particle, no TPC signal
- Interact primarily in scintillator of the ECAL
- Deposited energy is typically small and isolated

Challenging identification of neutron hits

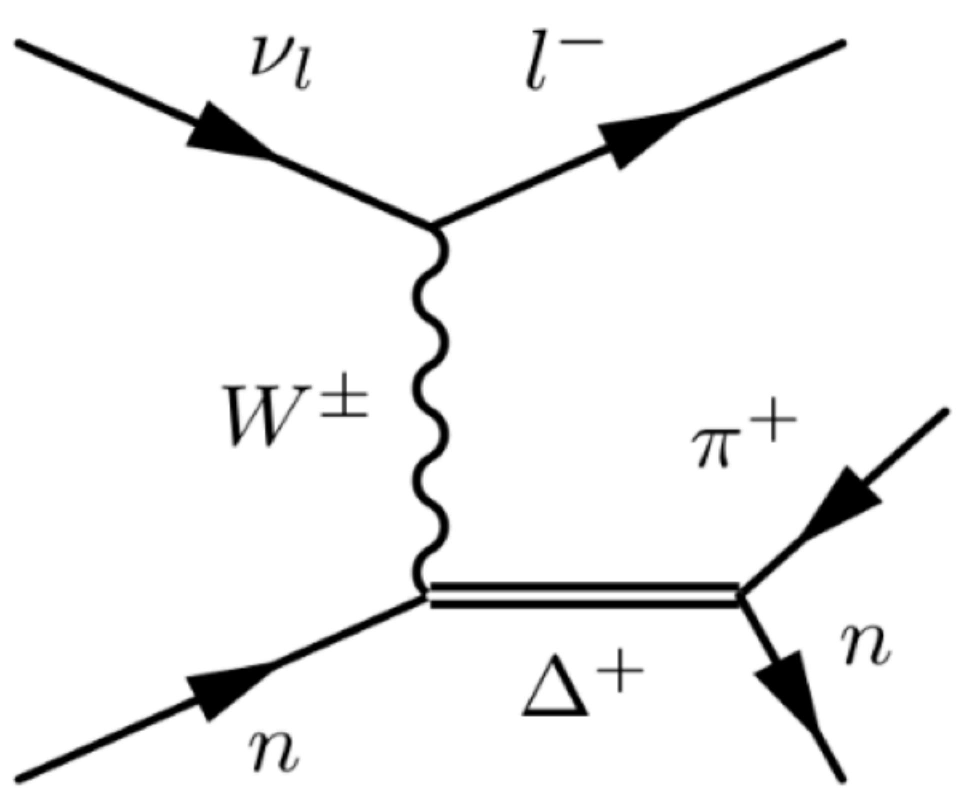
→ Important to reconstruct the energy of the neutrino

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:

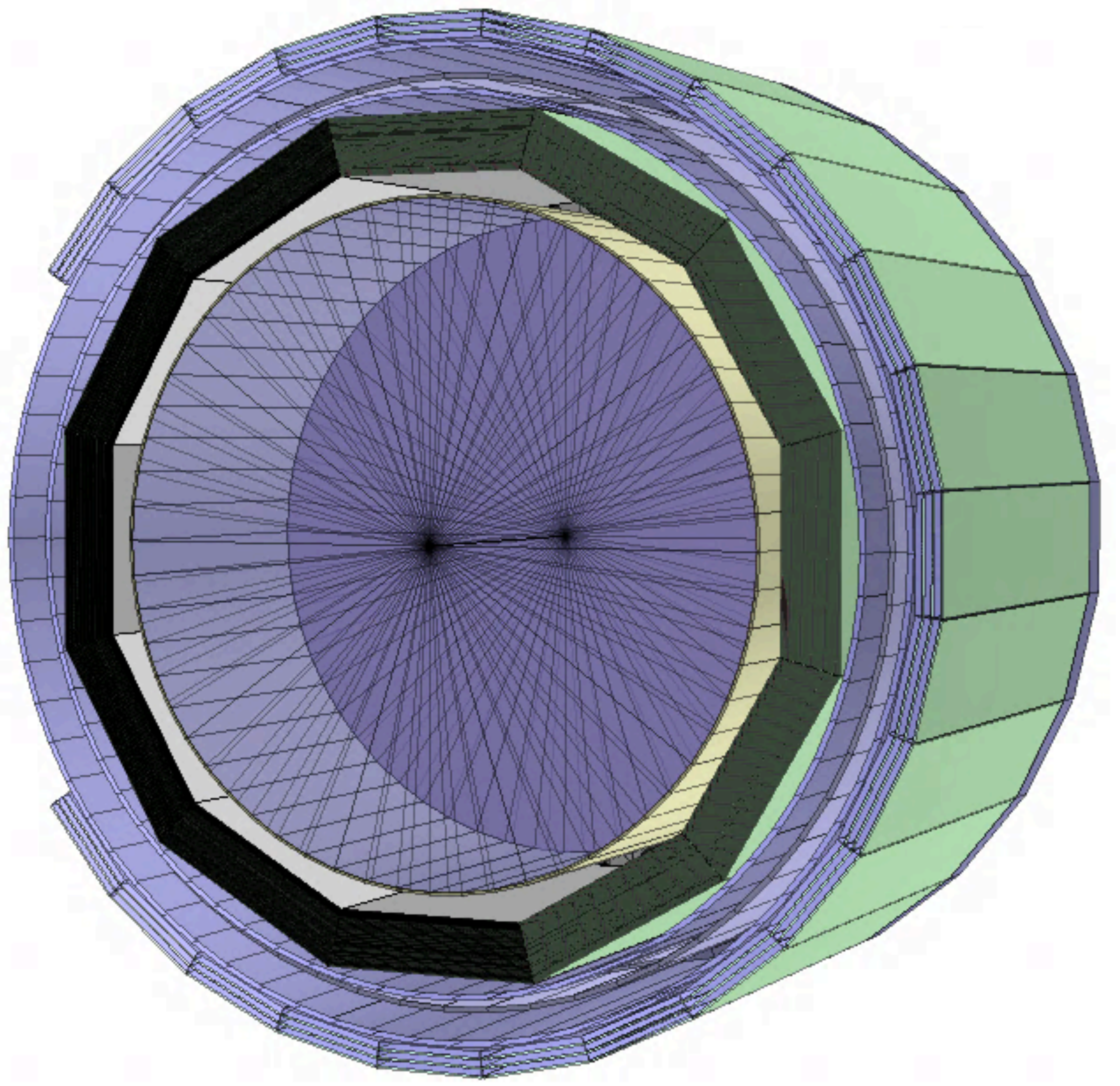


- Charged pions and muons have almost same mass
- Similar energy loss per unit length
- Separation not possible in TPC at momentum > ~250MeV

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 Concept

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



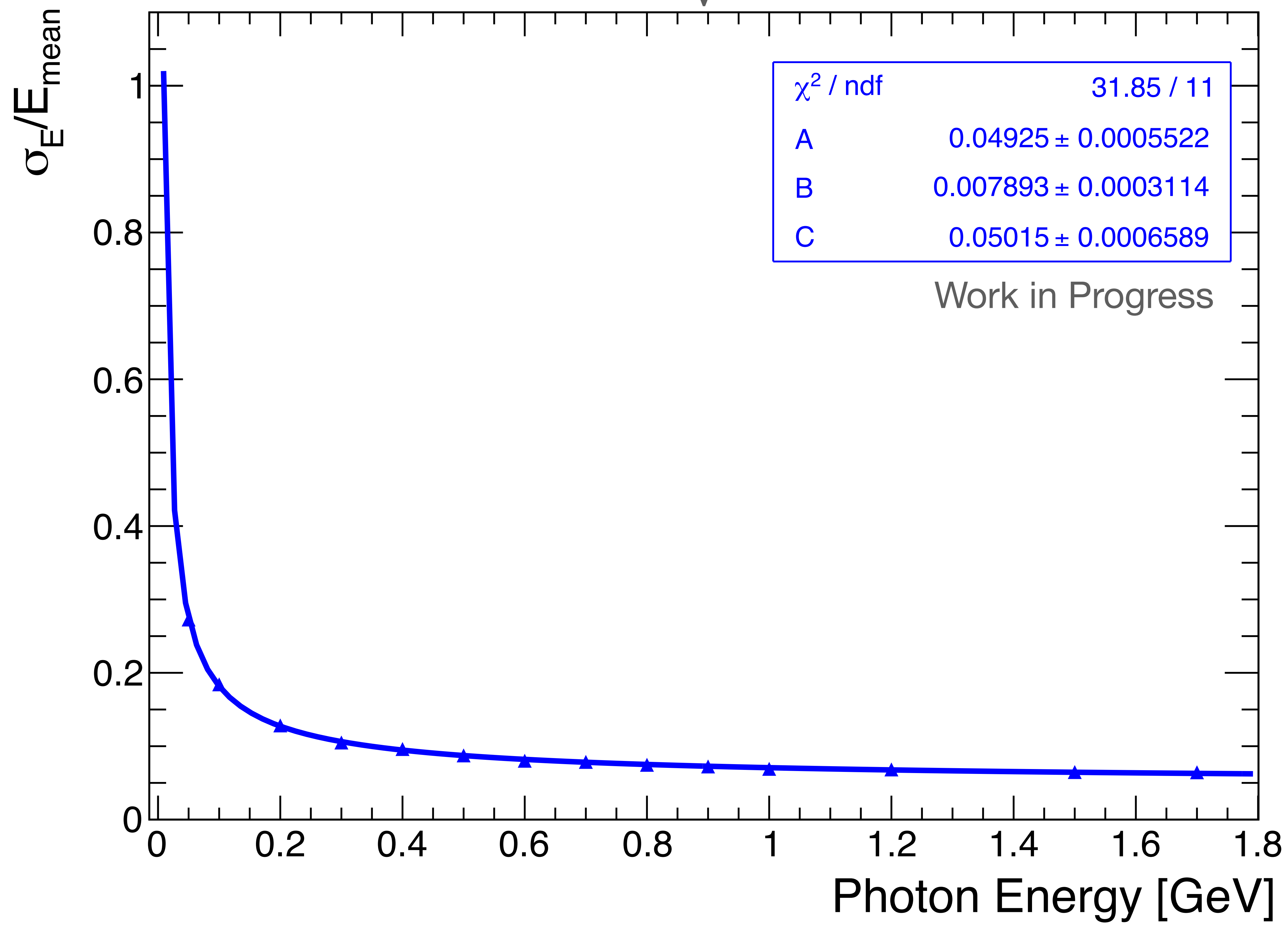
Next talk: Mechanical design details presented by Sebastian Ritter

ECAL Resolution

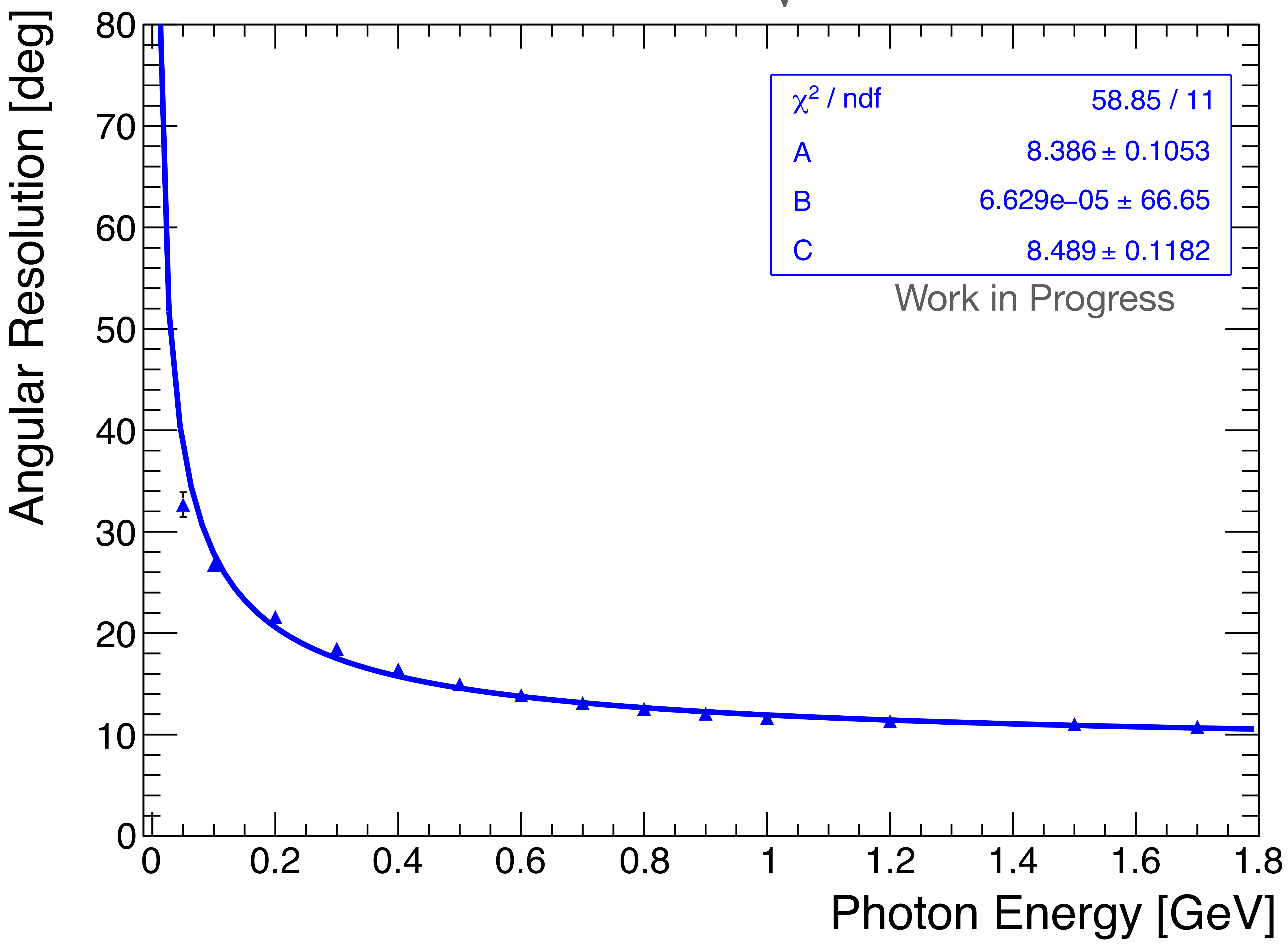
By Eldwan Brianne

Obtained with simulated electromagnetic showers from photons

$$\frac{\sigma_E}{E_{mean}} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

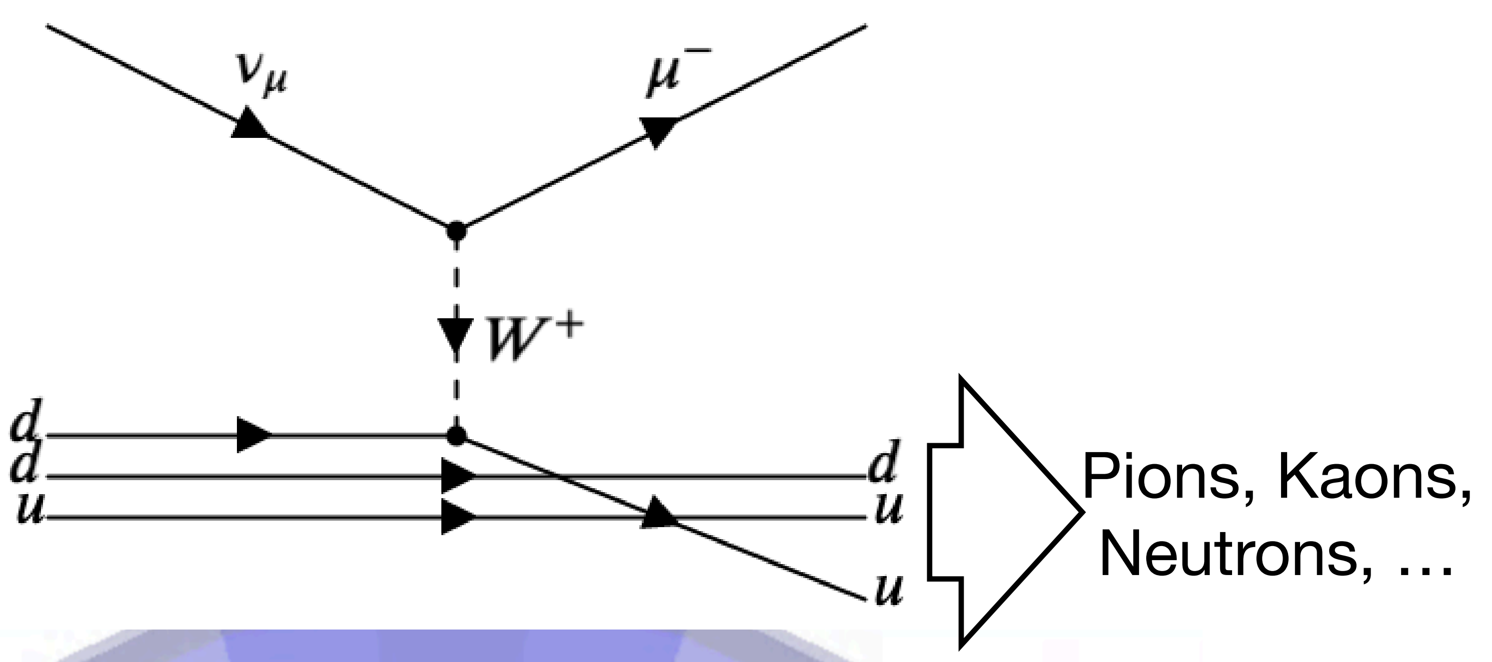


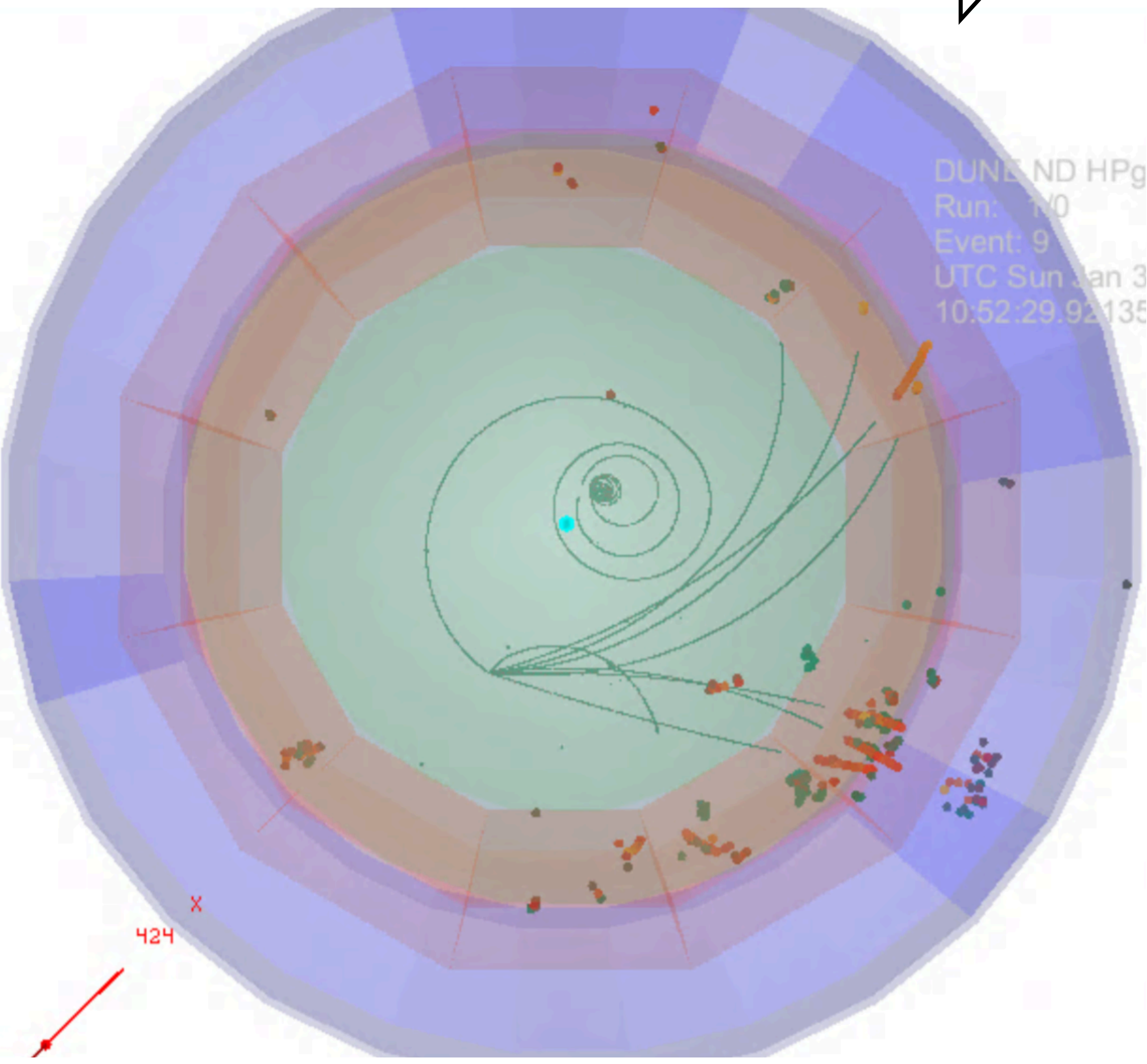
$$AngularResolution = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

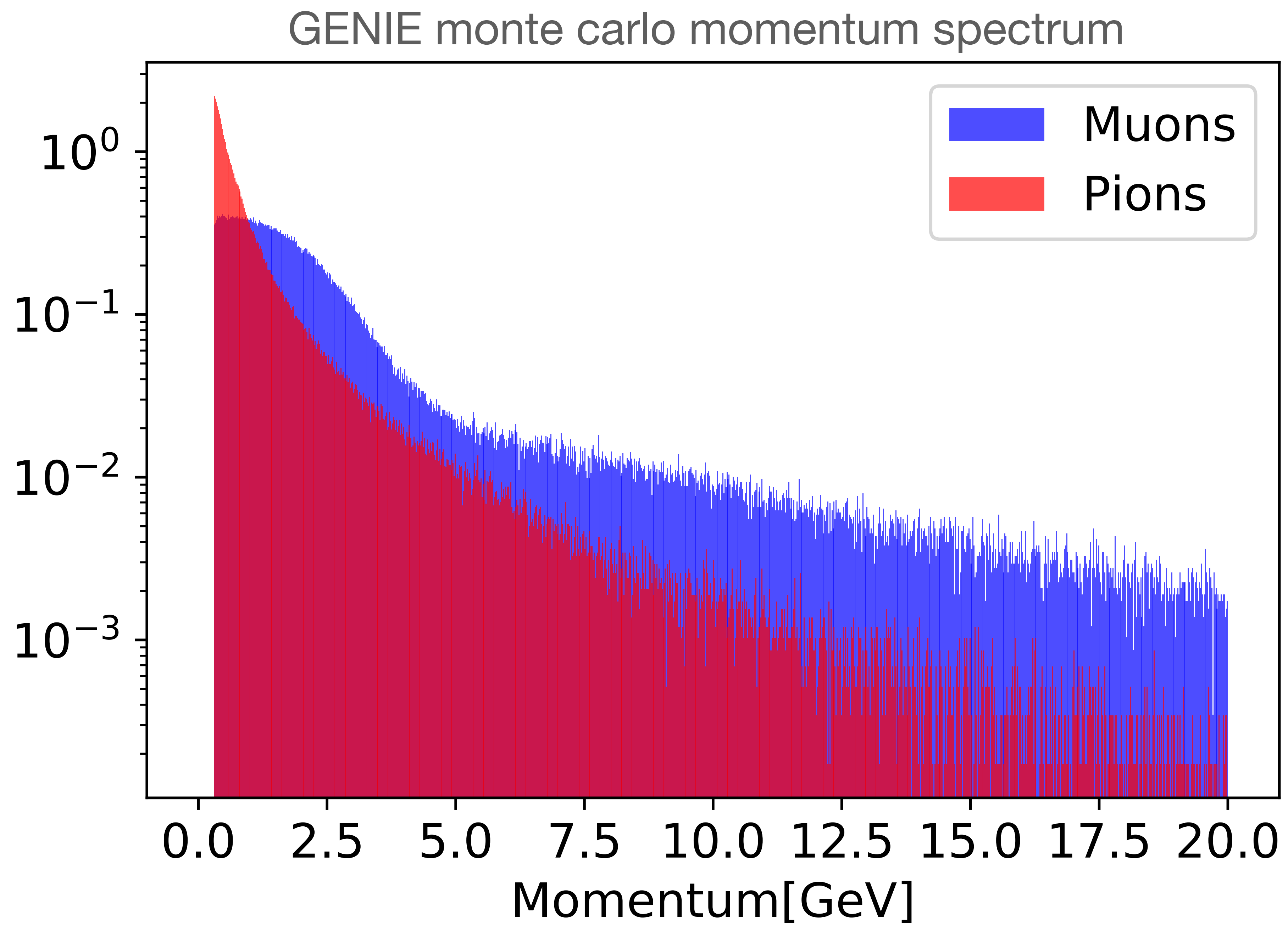


Muon Pion Separation

Simulated deep-inelastic scattering event





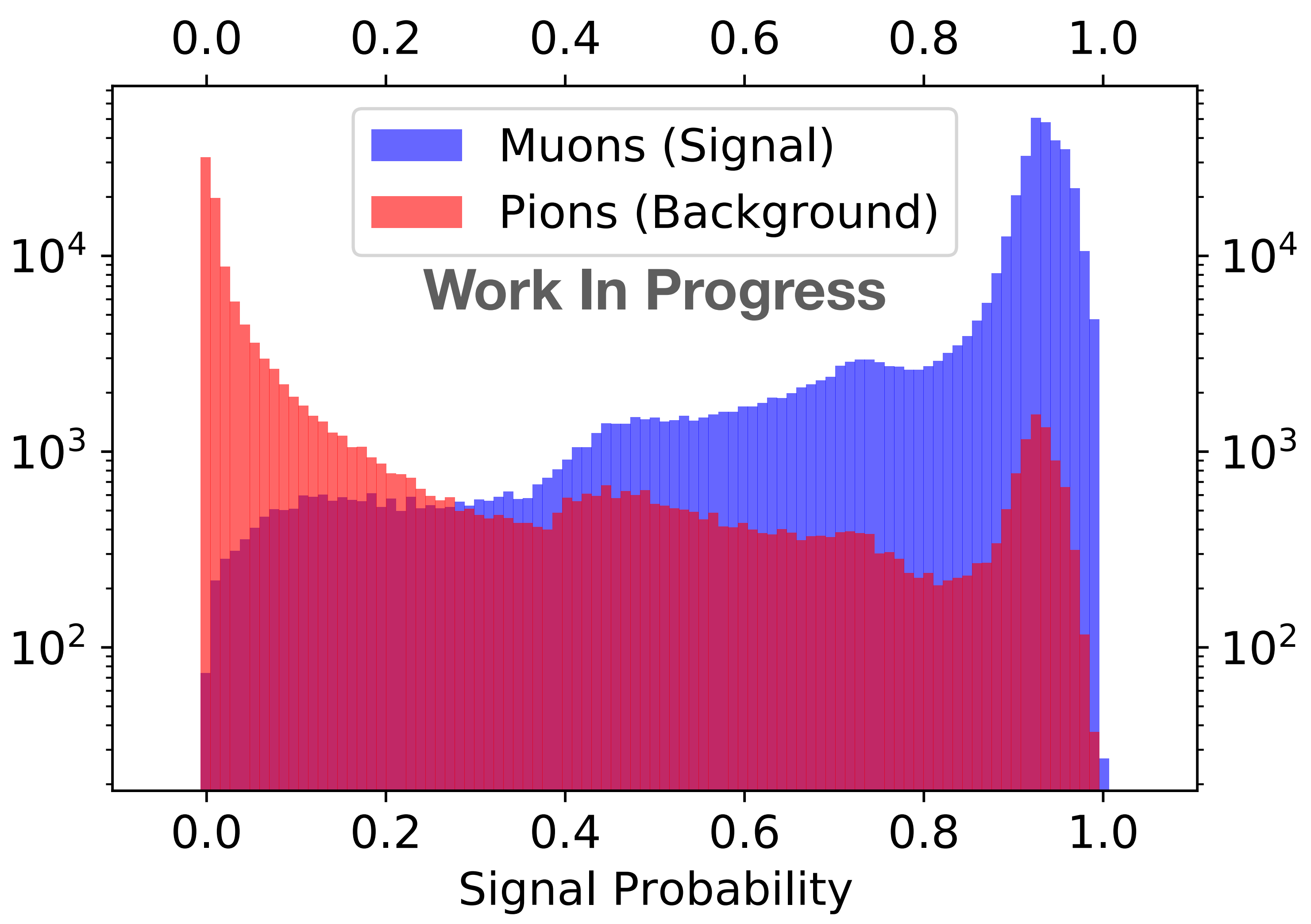


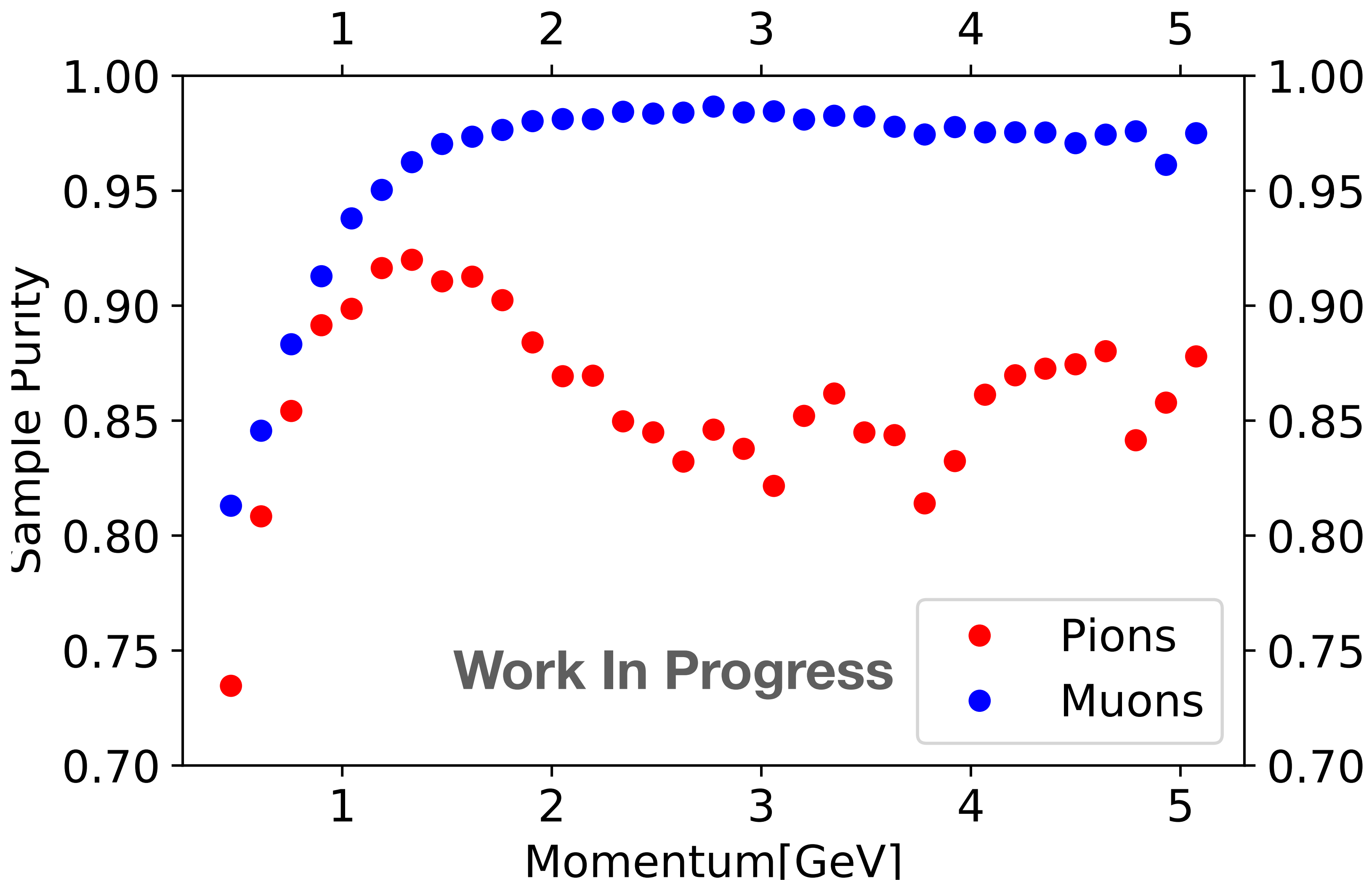
Muon mainly ionizes the detector and leaves a track

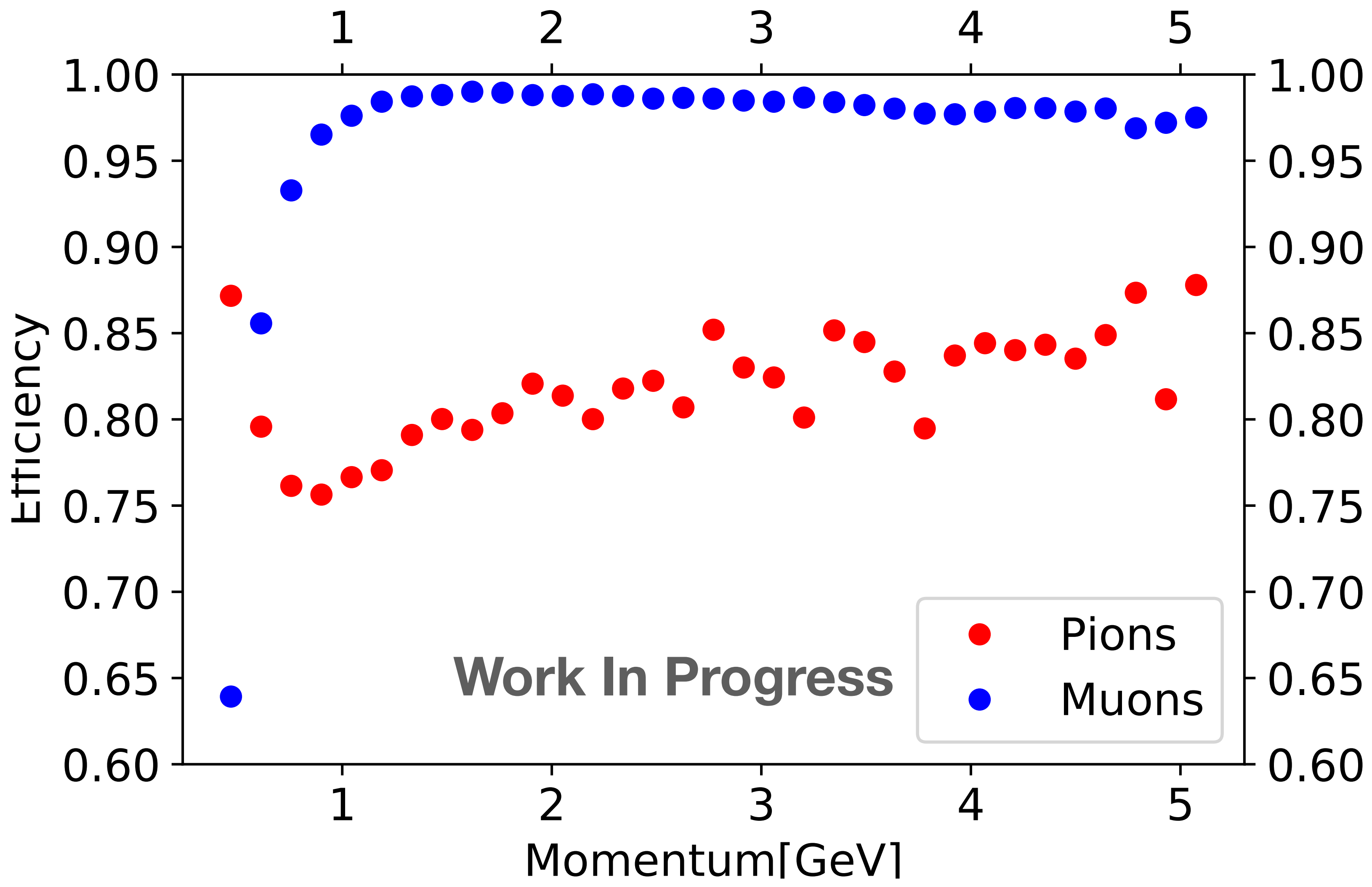
Pions have access to hadronic interactions and more diverse signatures used to identify them

Classifier implemented as Boosted Decision Tree

Muon Pion Separation - BDT







Hadronic pion interactions clearly resolved

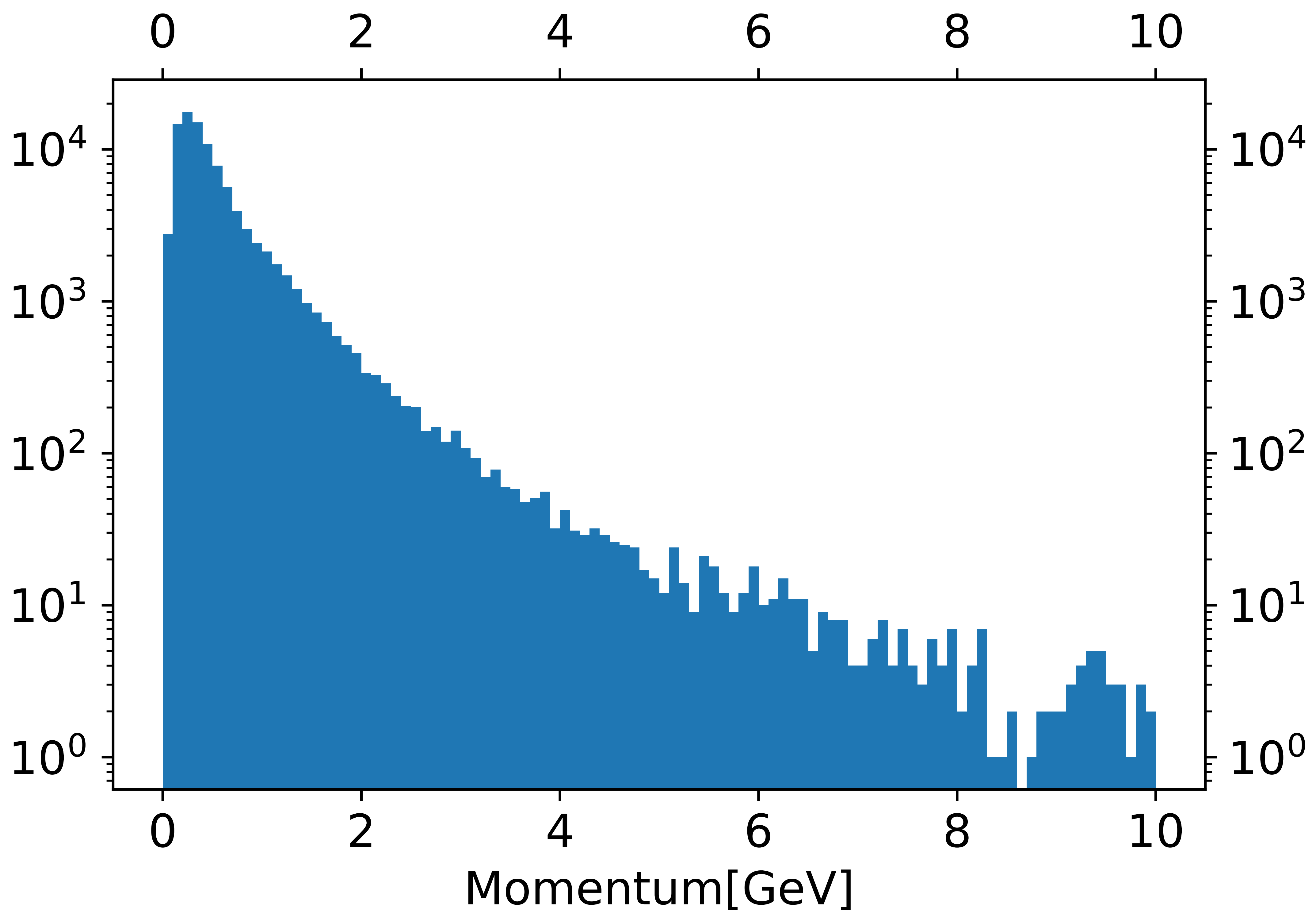
At momenta below ~1 GeV particles look more similar:

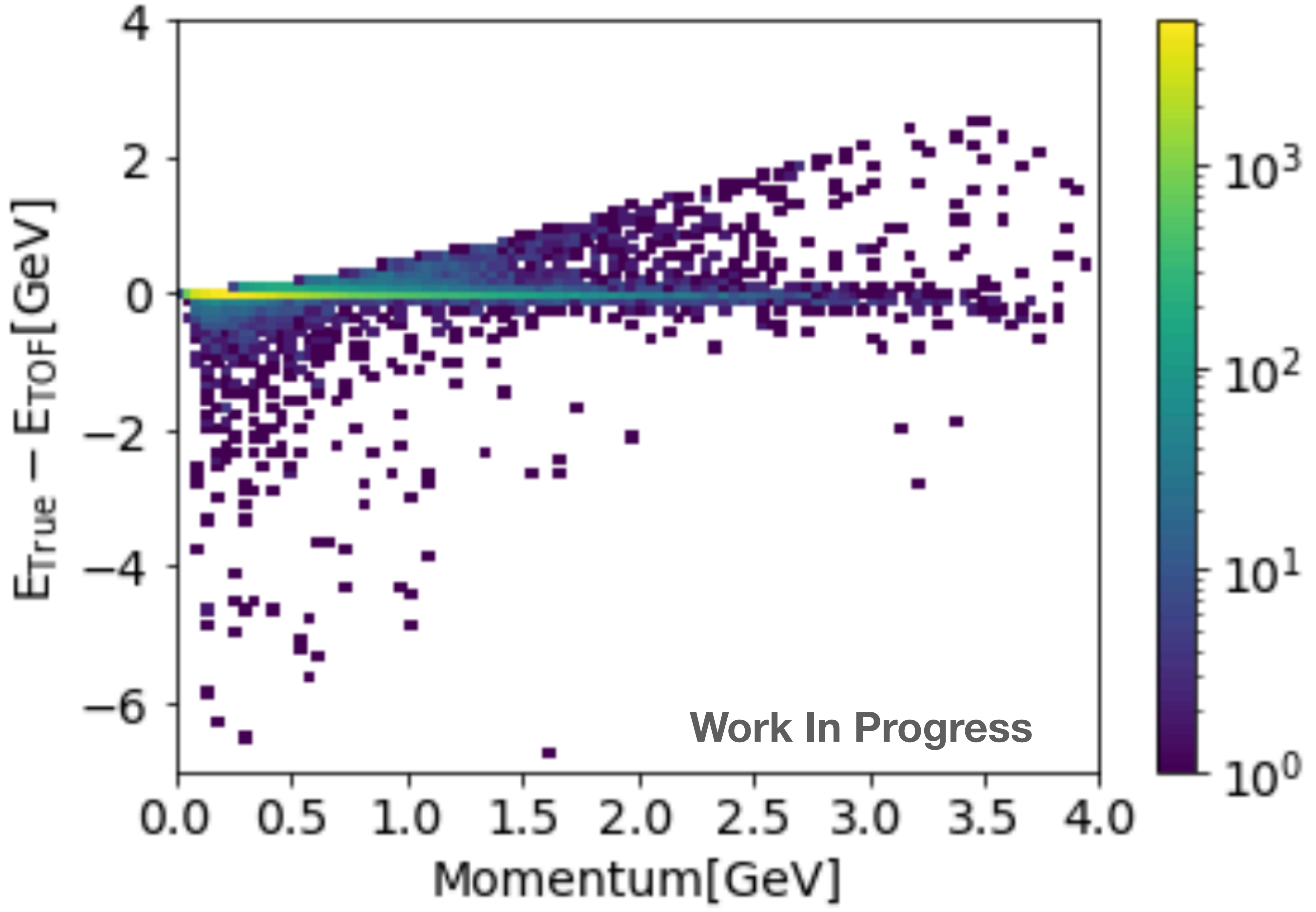
- Muon/Pion capture and decay are hard to separate in dense detectors
- Affects mostly the purity

Neutron TOF

Inelastic neutrino interactions also produce neutrons:

- Invisible to the TPC
- Use time-of-flight from vertex to ECAL signature for kinetic energy measurement





Conclusion

The ECAL in the ND-GAr has serval tasks:

- Photon reconstruction for neutral Pion identification
- Neutron reconstruction
- Muon/Pion separation

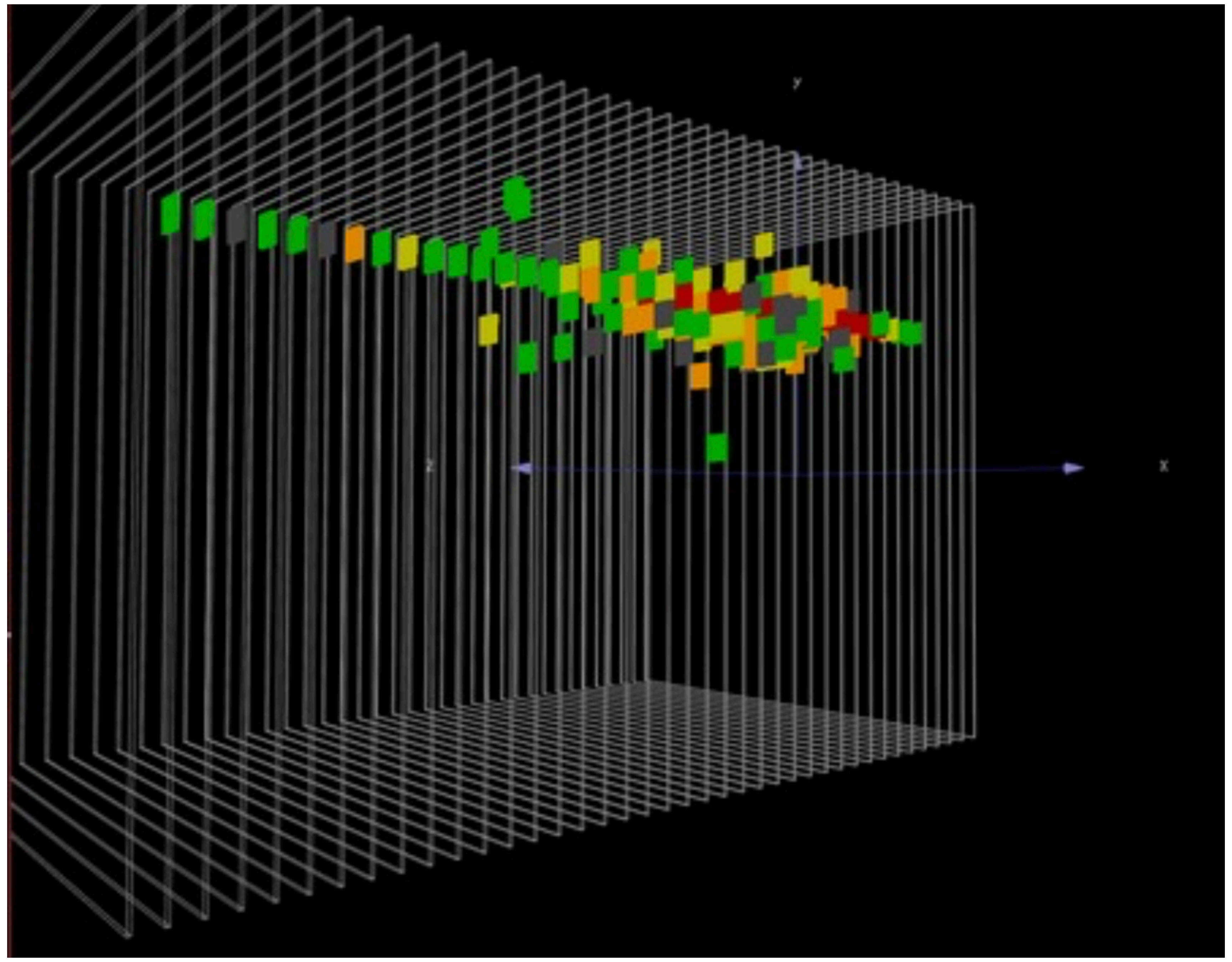
Simulation results:

- Stochastic energy resolution of ~6%/sqrt(E), angular resolution of ~8.3%/sqrt(E)
- Muon sample purity of ~ 85% to 98% (signal detection threshold of $p_{BDT}>0.5$)
- Pion sample purity of ~75% to 90% (background detection threshold of $p_{BDT}<0.5$)
- Time-of-flight measurement of neutron kinetic energy

Initial Considerations

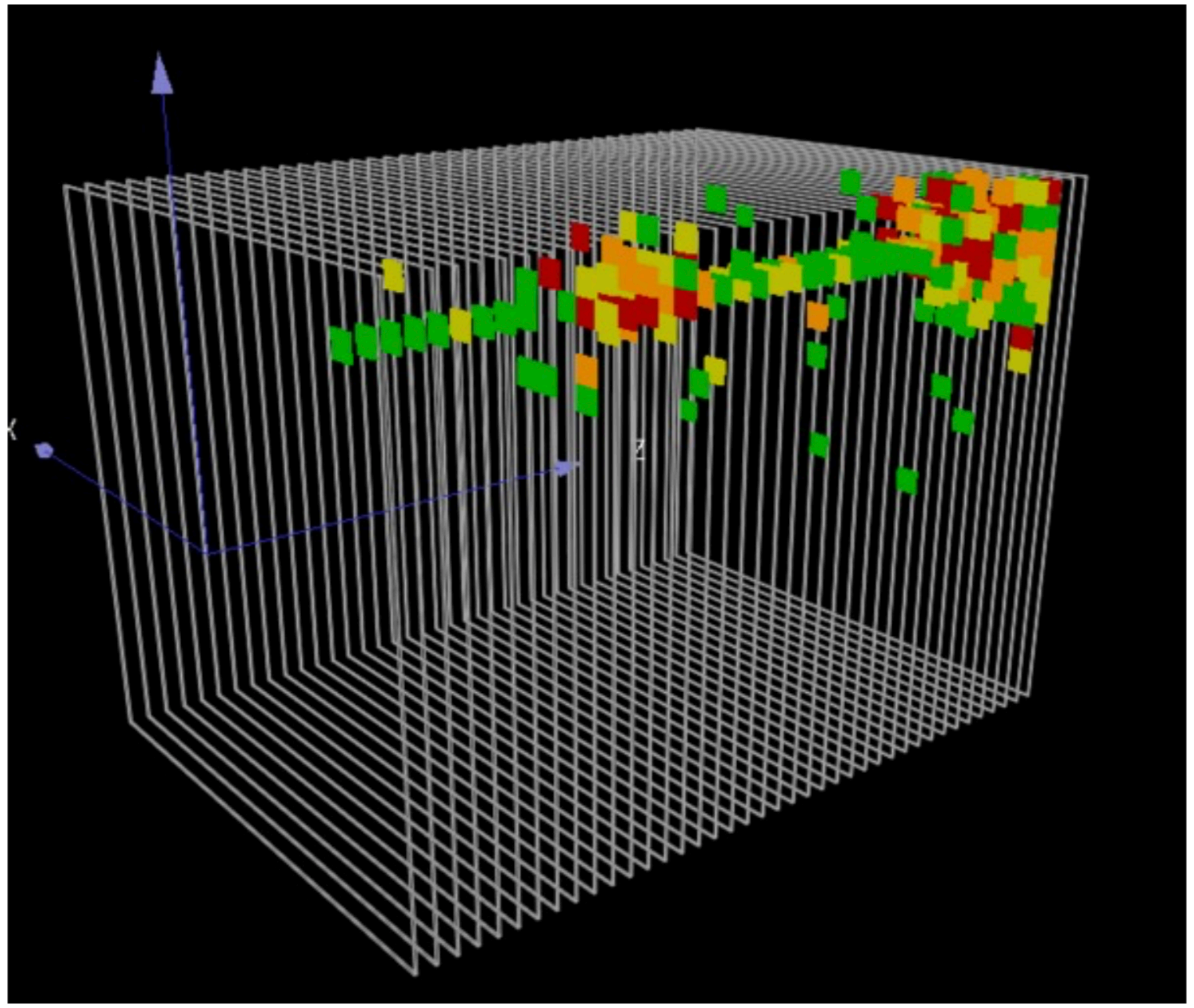
Actual data from CALICE AHCAL beam test

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

Initial Considerations

Material budget:

Pressure vessel	4.4cm Al ≙ 0.1λ
ECAL absorber	12cm Cu ≙ 0.65λ
Magnet:	10cm Al ≙ 0.2λ
Return yoke	15cm Fe ≙ 0.75λ
Scintillator	30cm PS ≙ 0.3λ
Total	2.0λ

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

Simulated muon/pion ratio:

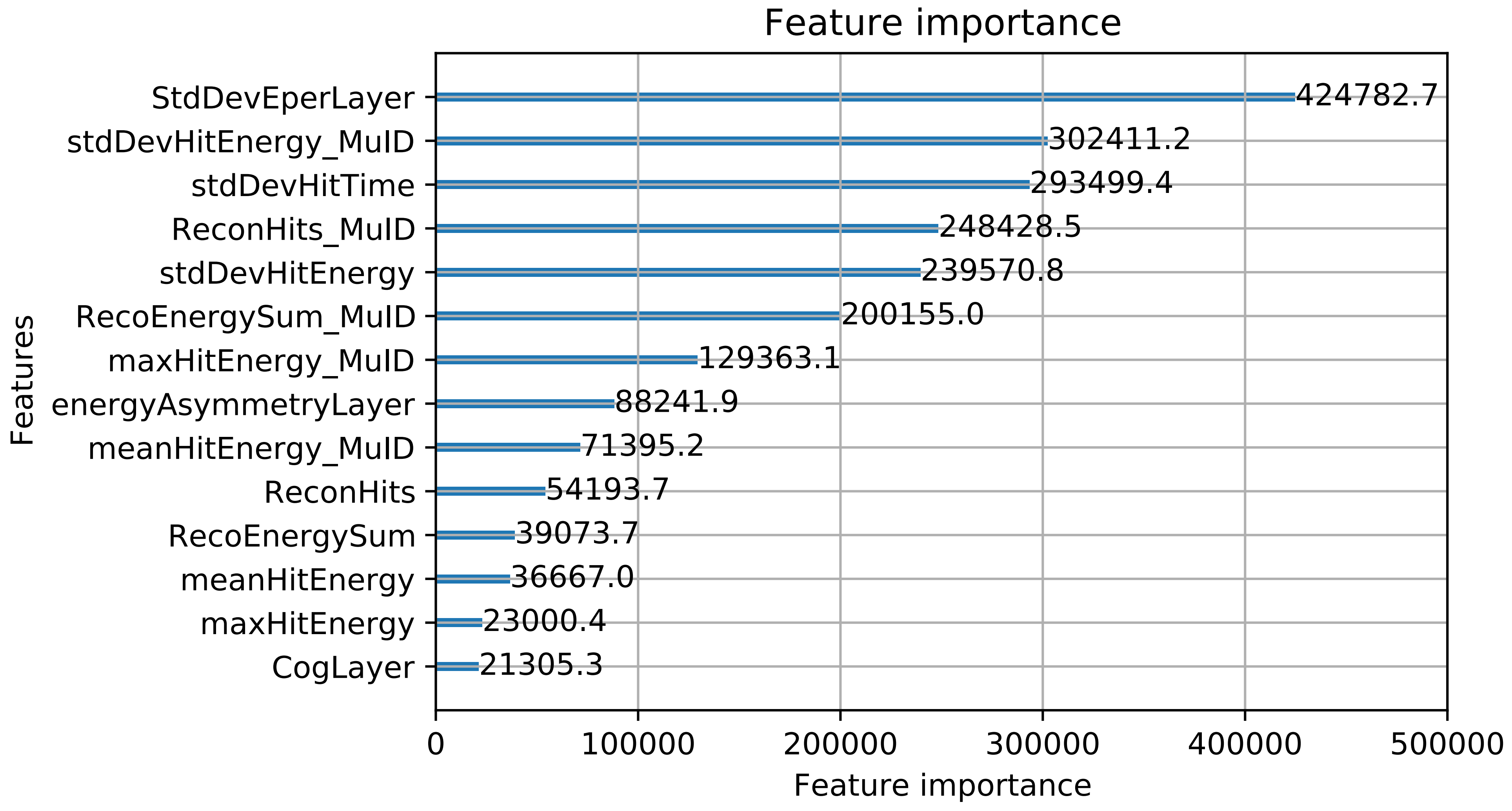
- 86% muons
- 14% pions

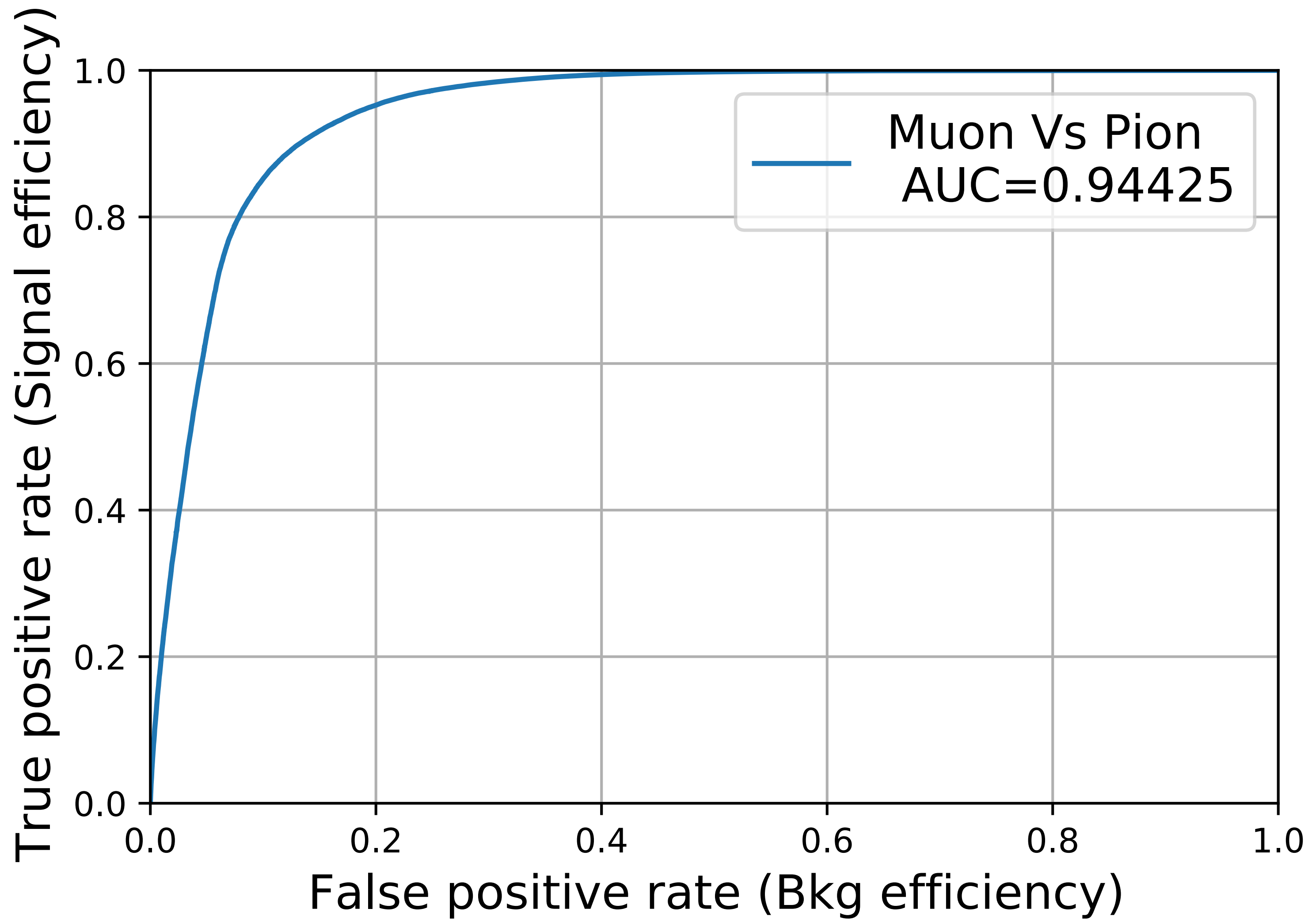
~2% fake muons from pions if:

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

Switching to lead absorber: $X0_{Lead}$ / $X0_{Copper}$=0.35 but $\lambda_{Lead}/\lambda_{Copper}$ =1.07

Backup


Feature importance
StdDevEperLayer
stdDevHitEnergy_MuID
stdDevHitTime
ReconHits_MuID
stdDevHitEnergy
RecoEnergySum_MuID
maxHitEnergy_MuID
energyAsymmetryLayer
meanHitEnergy_MuID
ReconHits
RecoEnergySum
meanHitEnergy
maxHitEnergy
CogLayer
424782.7
302411.2
293499.4
248428.5
239570.8
200155.0
129363.1
88241.9
71395.2
54193.7
39073.7
36667.0
23000.4
21305.3
Features
0
100000
200000
300000
400000
500000
Feature importance


Muon Vs Pion
AUC=0.94425
True positive rate (Signal efficiency)
False positive rate (Bkg efficiency)
0.0
0.2
0.4
0.6
0.8
1.0

Neutron Time-Of-Flight