Feasibility Study on Atmospheric Neutrino Oscillations at JUNO

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On behalf of JUNO Collaboration

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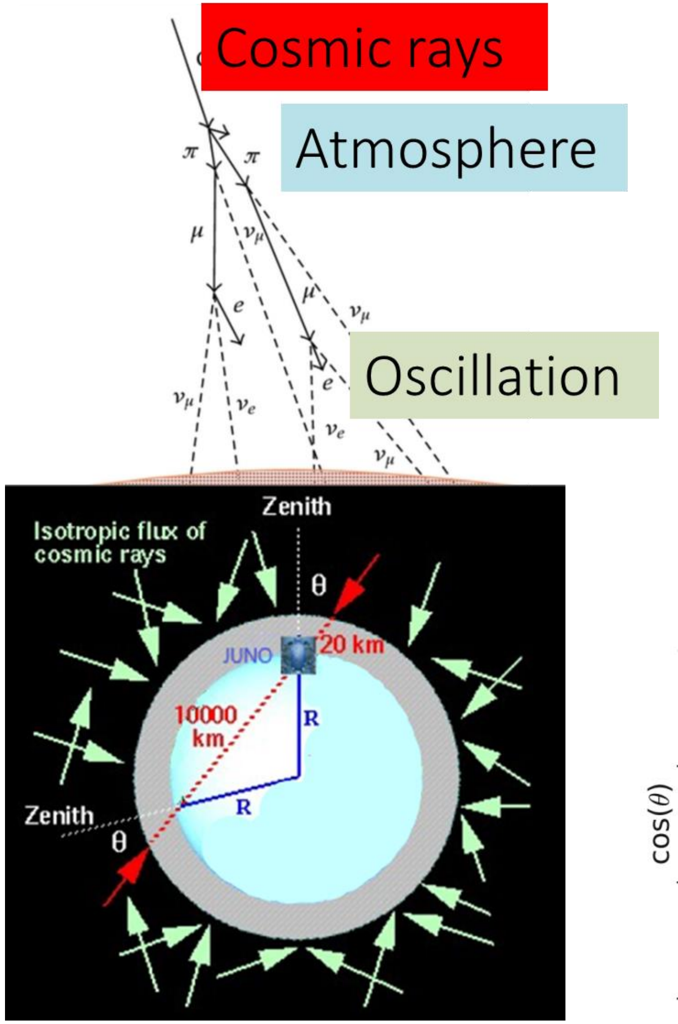
Atmospheric Neutrino Oscillations



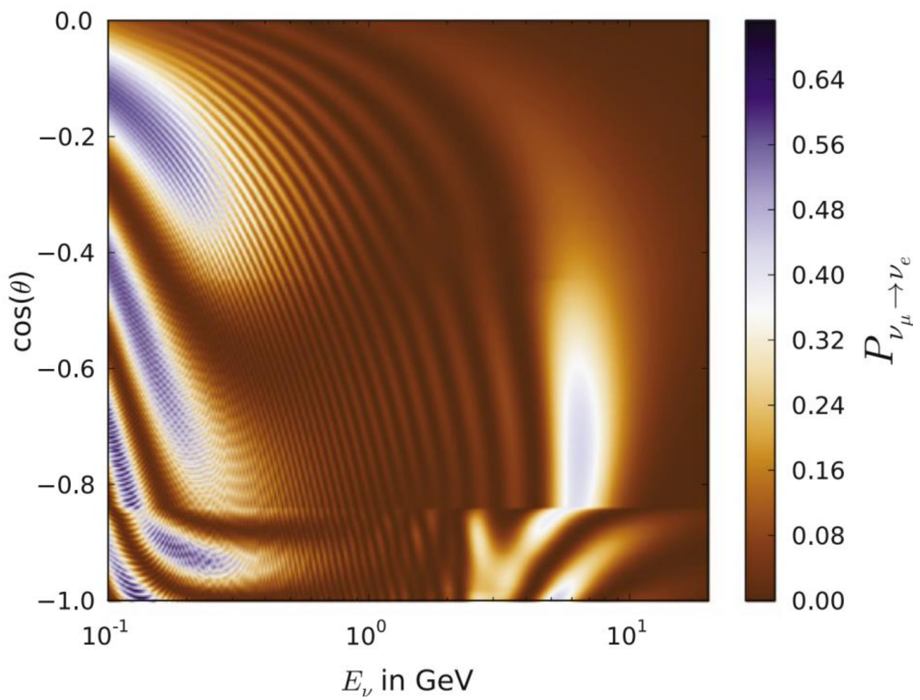
Major flavors: $\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$

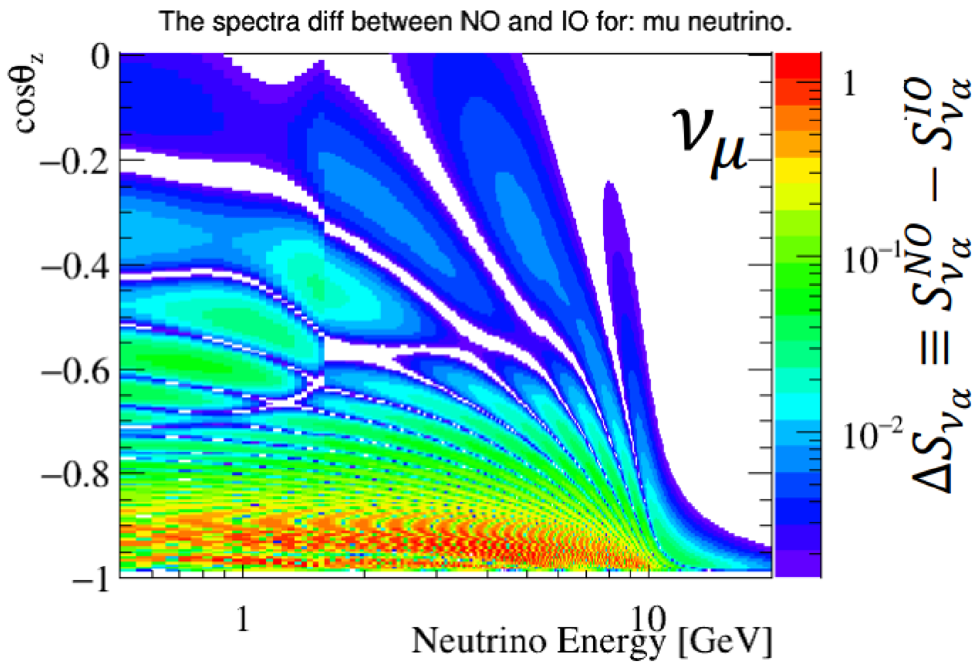
Source:

- Cosmic rays interact with the Earth's atmosphere, ν produced by the decay of secondary mesons

Propagation:

- Oscillation in matter is sensitive to neutrino mass ordering



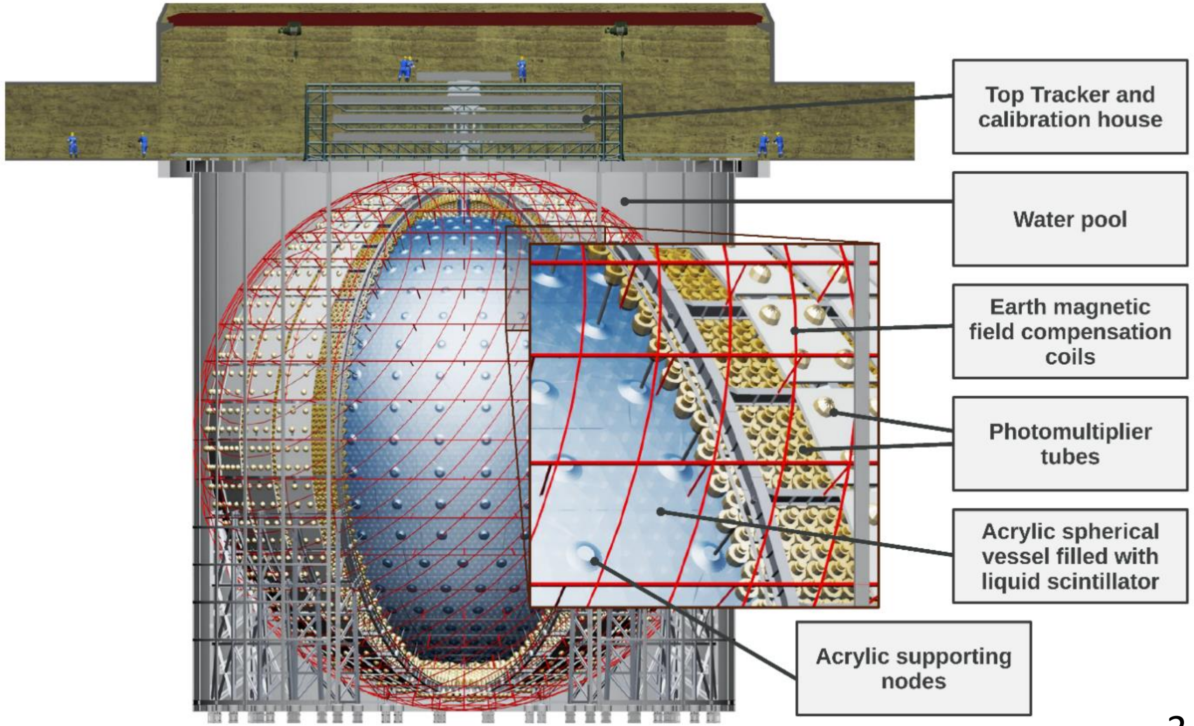


Detect Atmospheric Neutrino with JUNO

J. Phys. G 43, 030401 (2016)

The Jiangmen Underground Neutrino Observatory (JUNO):

- A multi-purpose detector with primary goal: determine the neutrino mass ordering (NMO)
- Target Mass: **20 kiloton liquid scintillator (LS)**
- Optical Coverage: $\sim$**78 %**
  - **17,612 20-inch large PMTs** and **25,600 3-inch small PMTs** instrumented in the **C**entral **D**etector (**CD**)
- Rock Overburden: $\sim$**650 m**



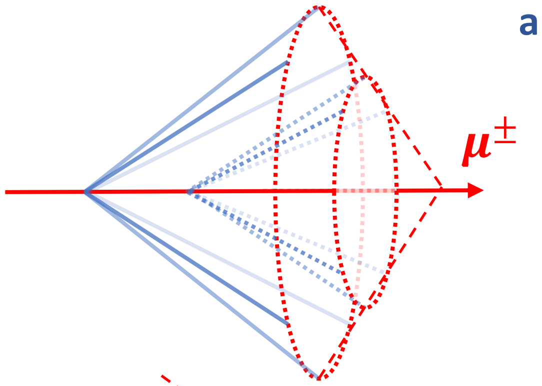
Detect Atmospheric Neutrino with JUNO

Water Cherenkov Detector:

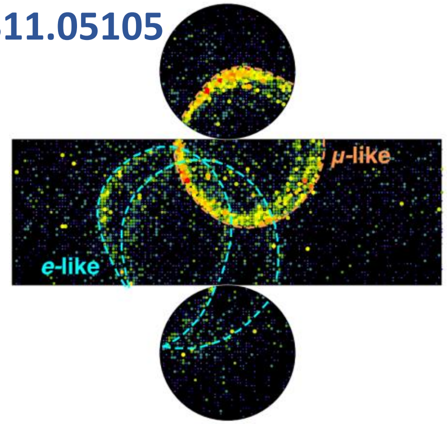
- Cherenkov ring
- High energy threshold

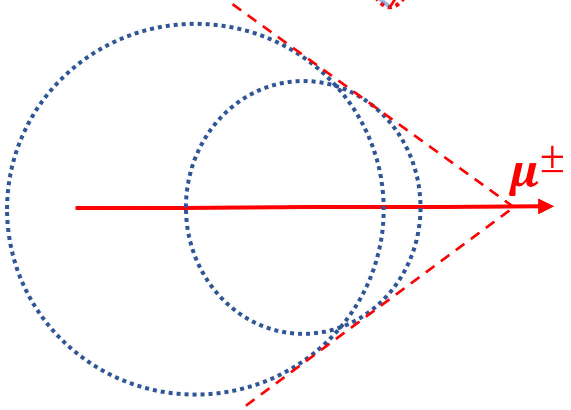
Liquid Scintillator Detector:

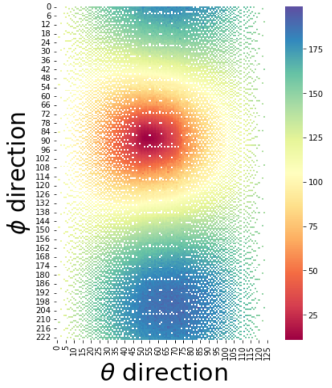
- Isotropic scintillation light
- Low energy threshold
  - ✓ Hadrons detection
  - ✓ Neutron tagging



arxiv: 2311.05105

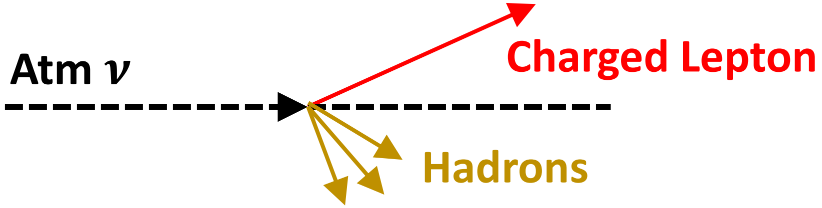






Key Information of Atm ν:

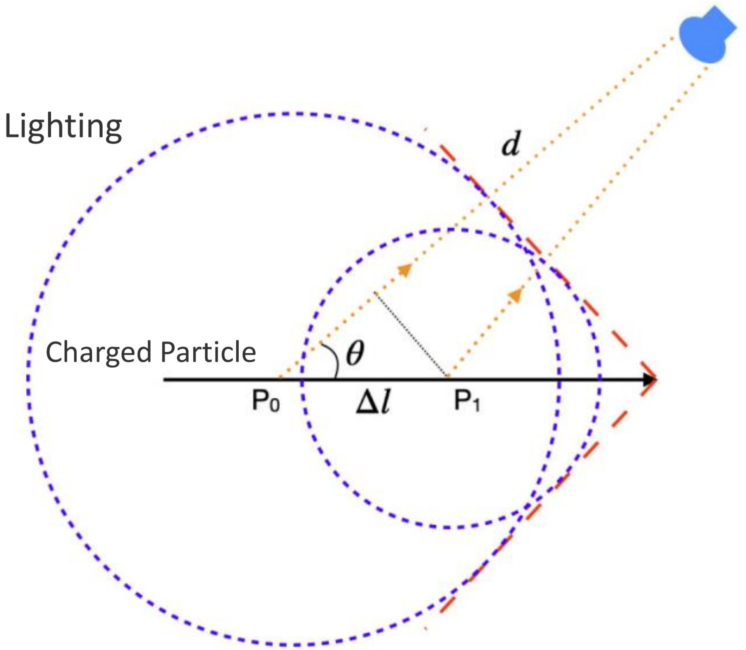
✓ Energy ● **Direction** ● **Flavor/Type**



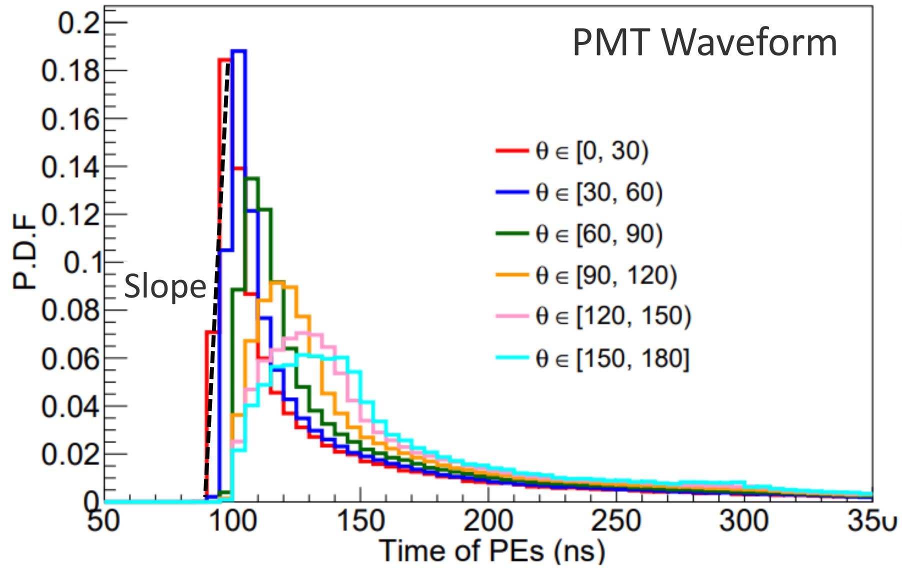
Challenges:

- Isotropic scintillation light from charged particles in LS
- Complicated final-state components from multi-GeV atmospheric neutrino

Directionality of Atmospheric Neutrino

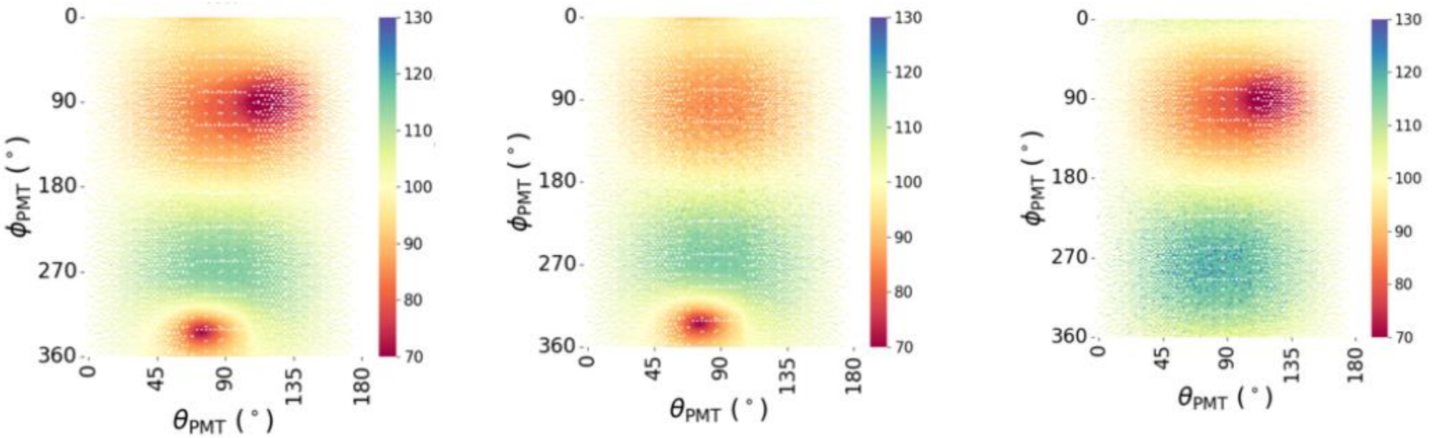


- **Directionality** of charged particle is reflected in the **PMT waveforms**
- **Final-state charged hadrons** provide extra constrain on directionality reconstruction for atmospheric neutrinos



FHT

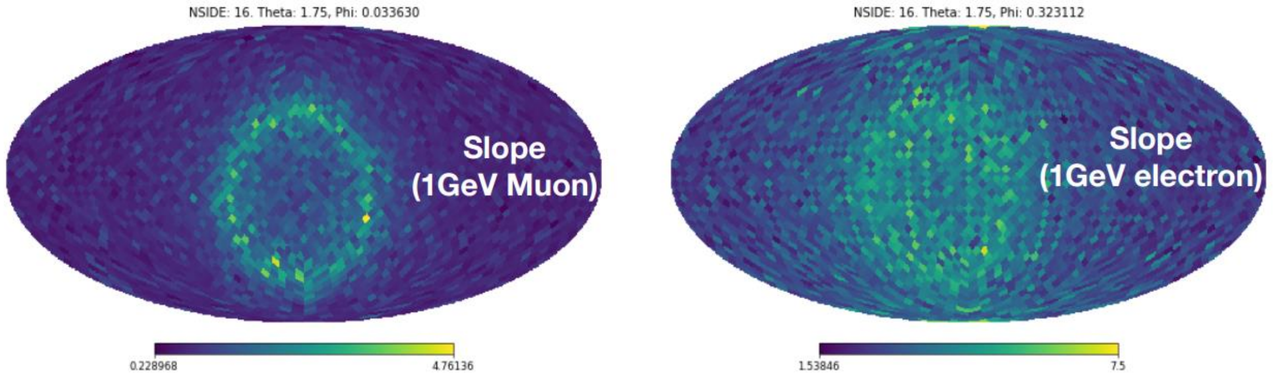
Atm ν CC Interaction exemplar: $^{12}\mathrm{C} + \nu_e \rightarrow {}^{11}\mathrm{C} + e^- + p^+$



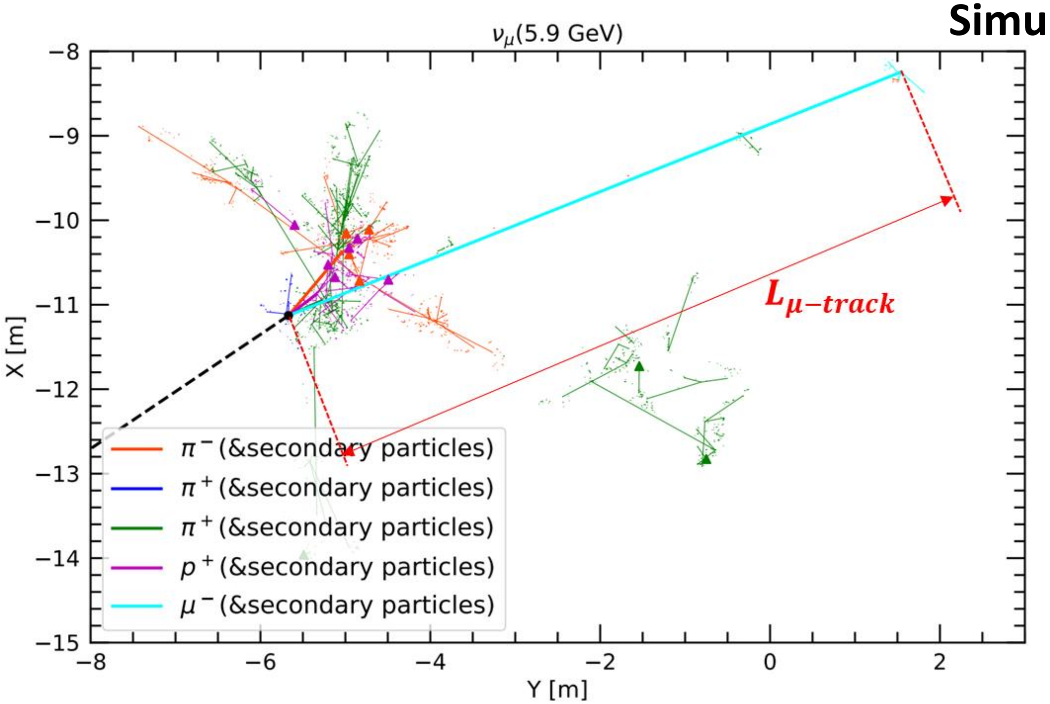
All particles | Without p | Without e^-

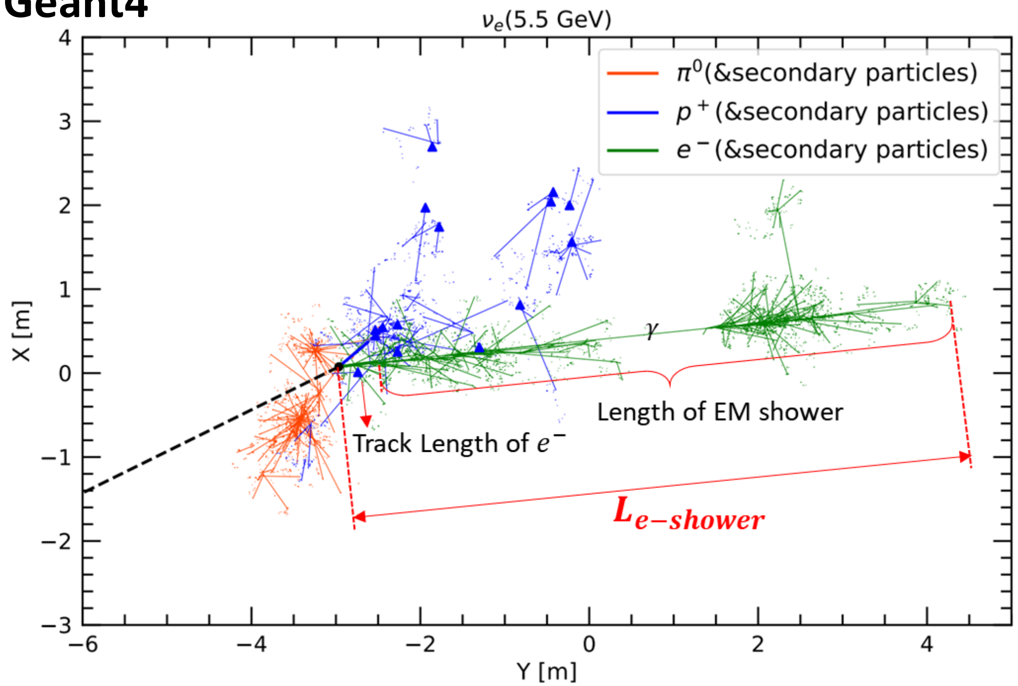
Atmospheric Neutrino Flavor Identification

- **Electron** induces EM shower to produce secondary electrons , while **muon** will directly deposit energy through ionization
- Electron and muon exhibit quite different topology of PMTs hitting pattern



Simulated by Geant4





Atmospheric $\nu/\bar{\nu}$ Discrimination

More energy transfer to hadrons for ν than $\bar{\nu}$

- More hadronic components: different quenching and timing with leptons

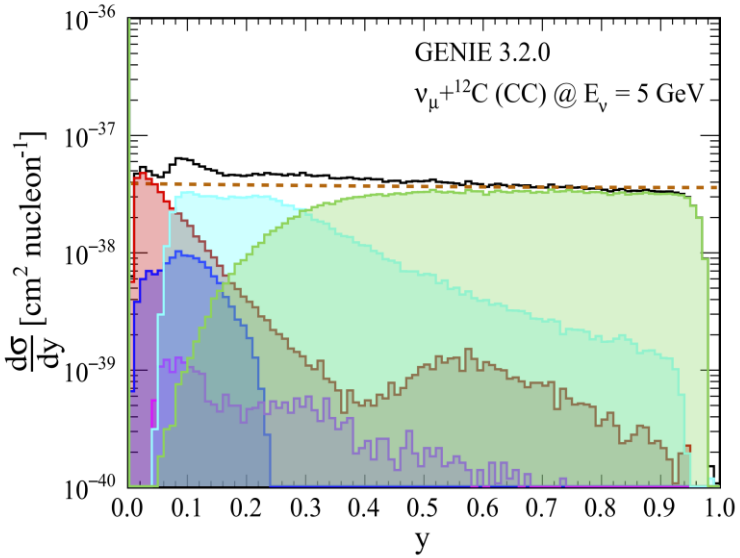
→ Prompt Signal Info.

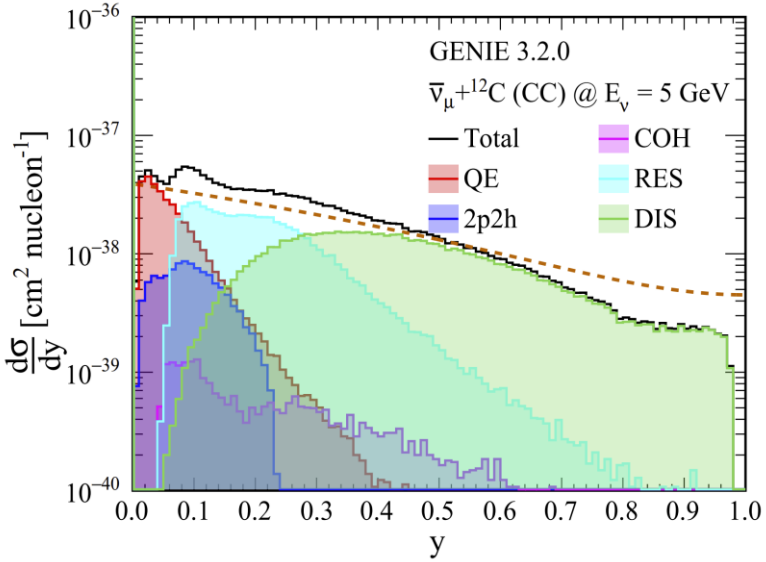
More primary neutrons from CC interaction of $\bar{\nu}$

- $\bar{\nu} + p^+ \rightarrow n + l^+$
- $\nu + n \rightarrow p^+ + l^-$

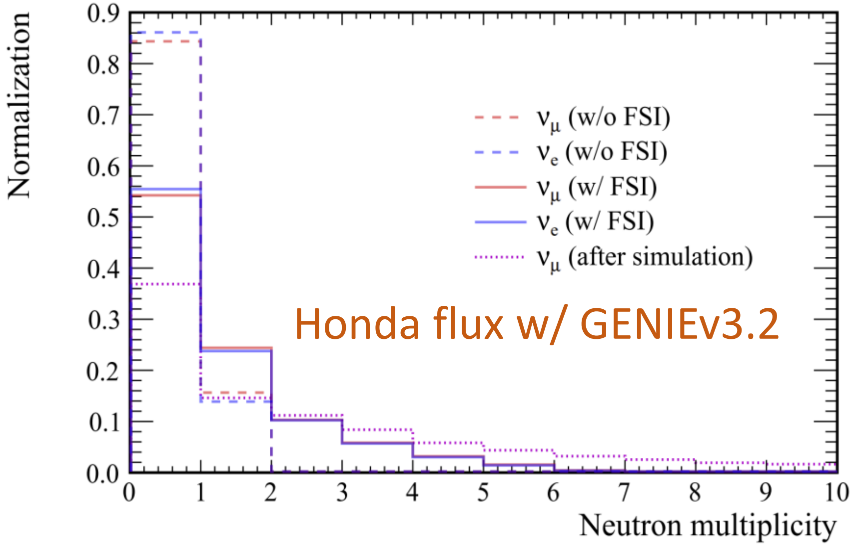
→ Secondary Signal Info.

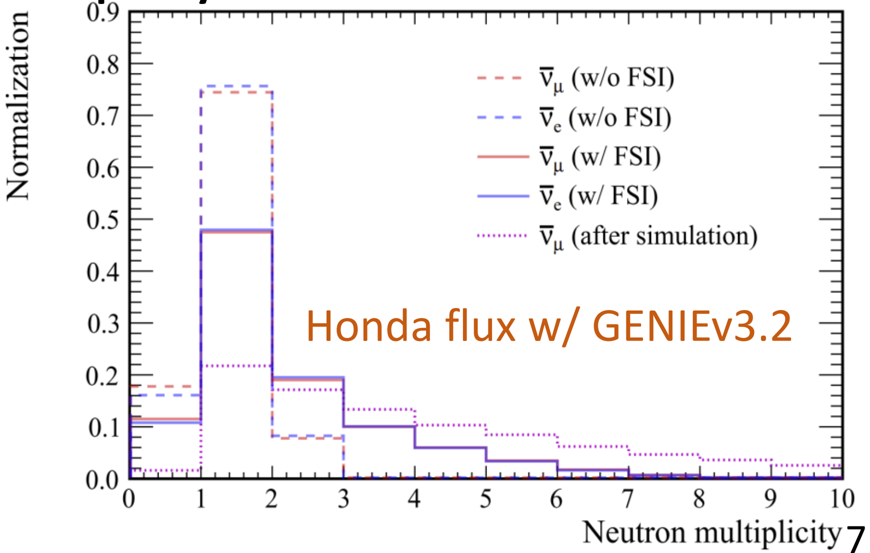
Inelasticity $y \equiv E_{hadron}/E_\nu$





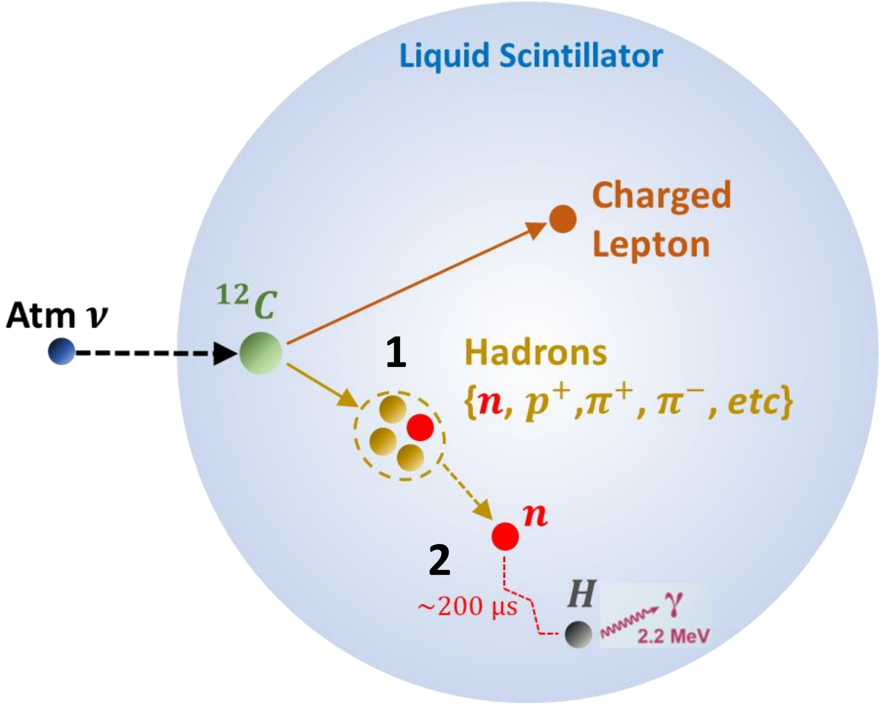
Neutron Multiplicity





Atmospheric $\nu/\bar{\nu}$ Discrimination

Characteristics of Captured Neutrons

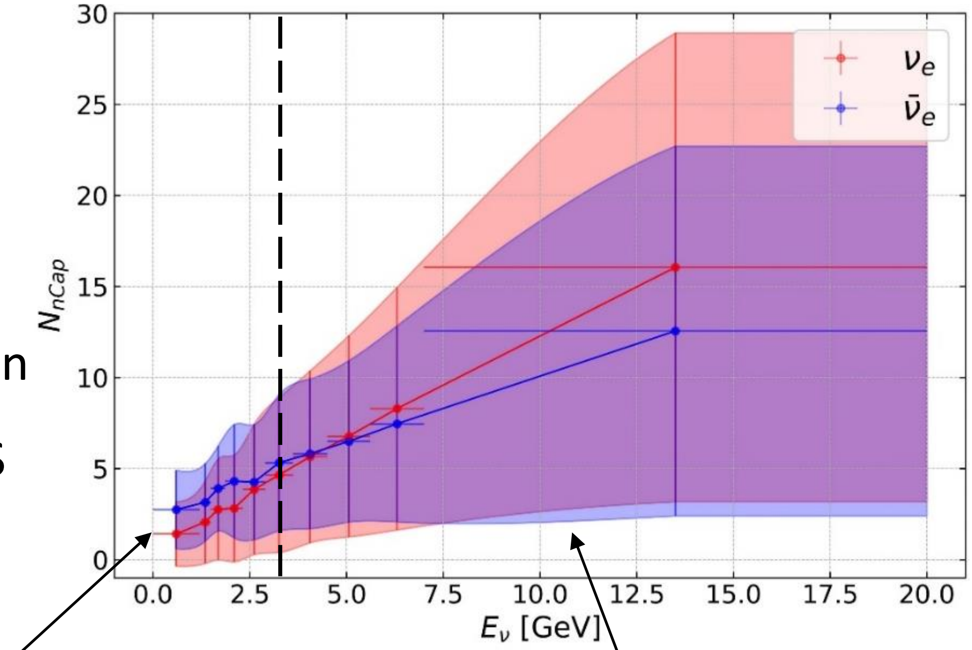


Neutron Production

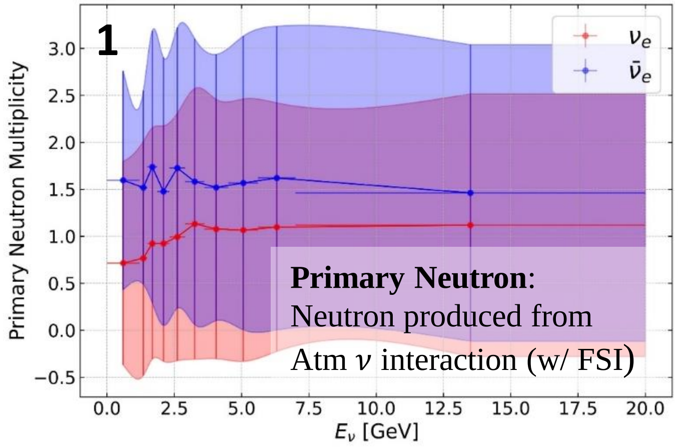
1. Charged-Current Interaction

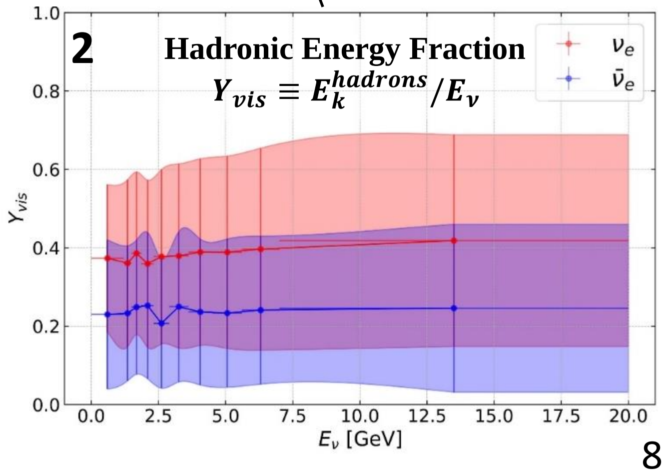
2. Secondary Interaction in LS

The E_ν-dependent multiplicity of captured neutron



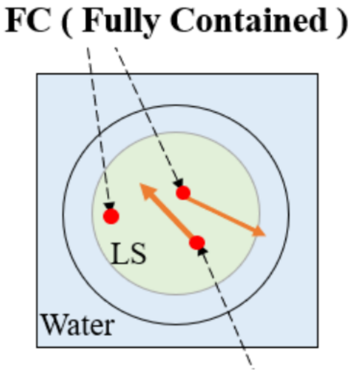
- Captured Neutron Multiplicity can be used to improve the performance of $\bar{\nu}/\nu$ discrimination with the information of both **Primary Neutron Multiplicity** and **Hadronic Energy Fraction**



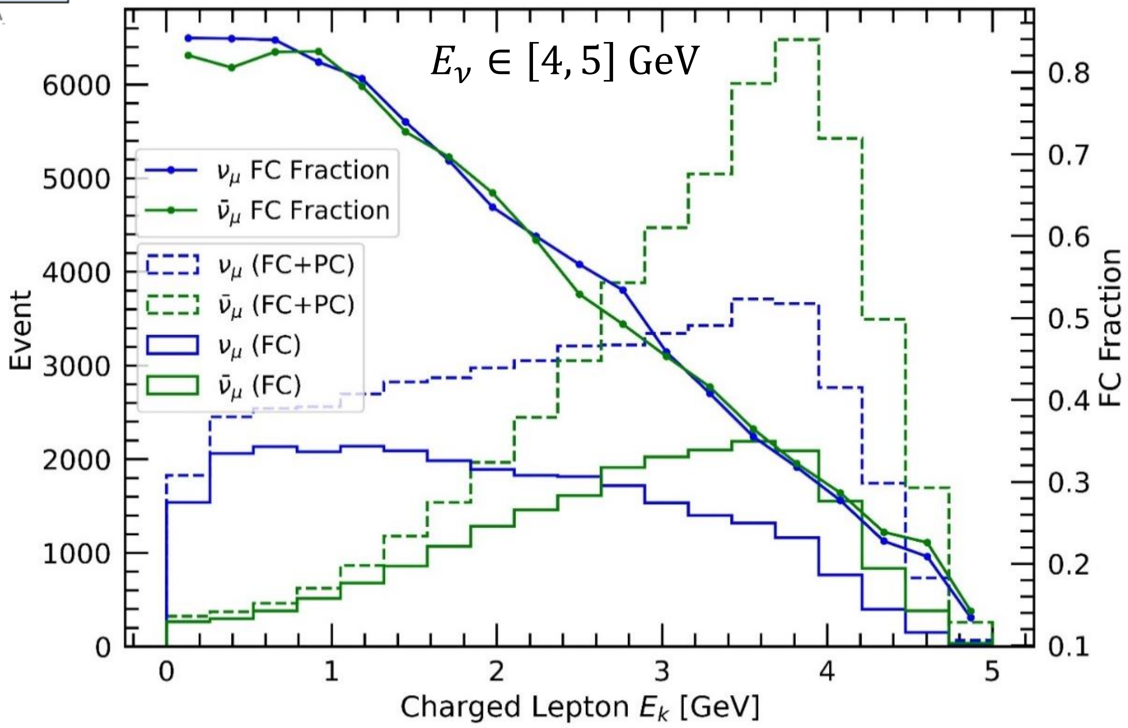


Detector Geometry Effect at JUNO

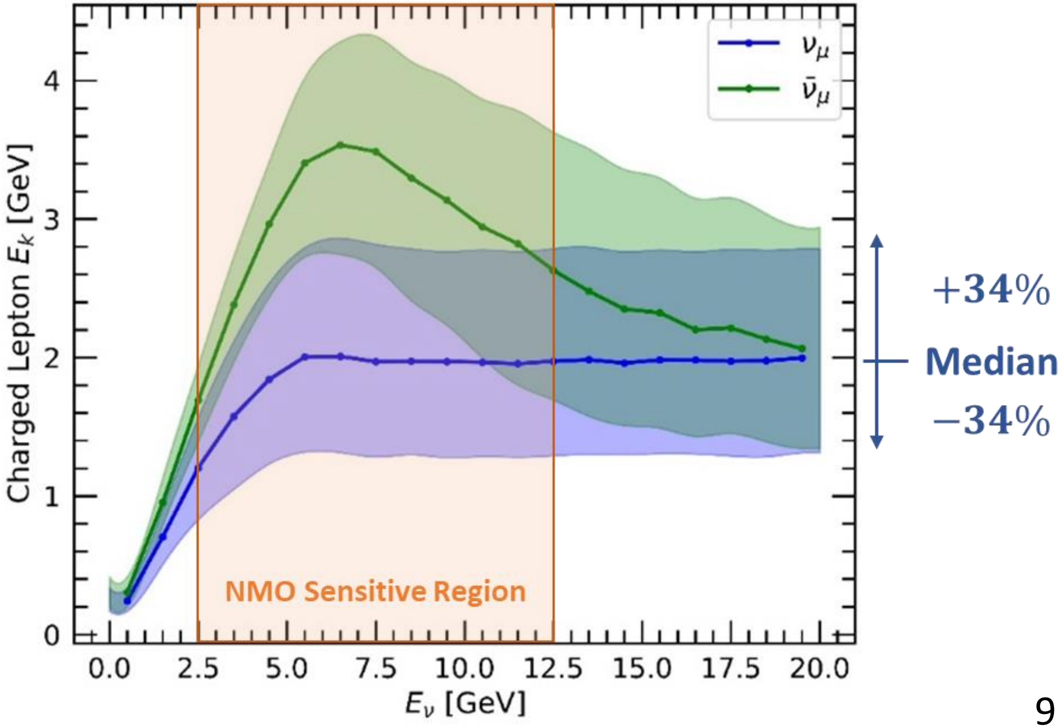
Detector Geometry Effect on Fully-Contained Events



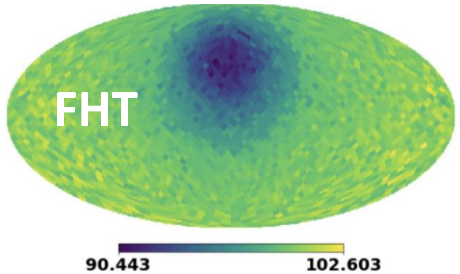
- The final-state muon tends to attain higher energy from $\bar{\nu}_\mu$-CC than ν_μ-CC

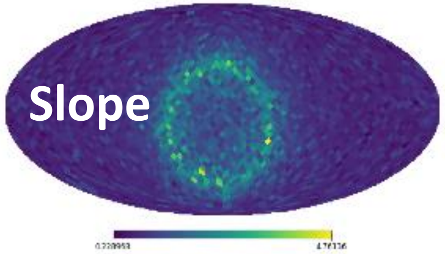


- Thanks to the large detector size (R_{CD}~20 m), kinematic difference can be remained between $\bar{\nu}_\mu$-CC and ν_μ-CC under the geometry effect

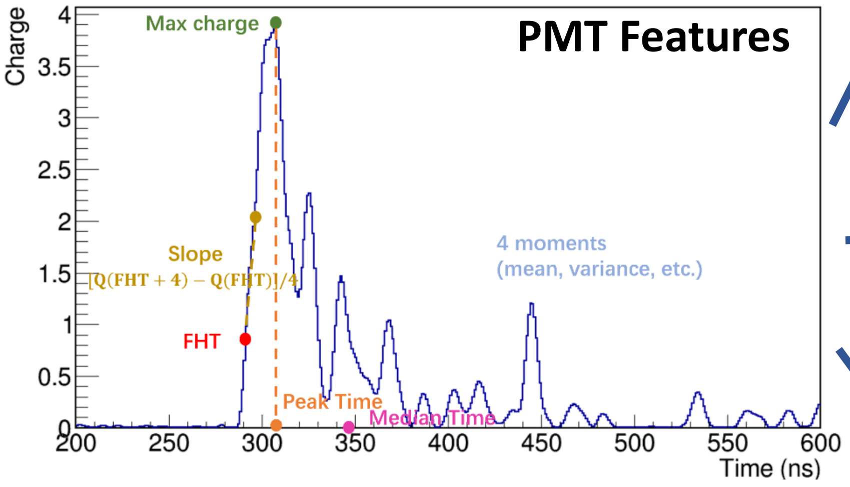


A Multi-purpose Machine Learning Approach

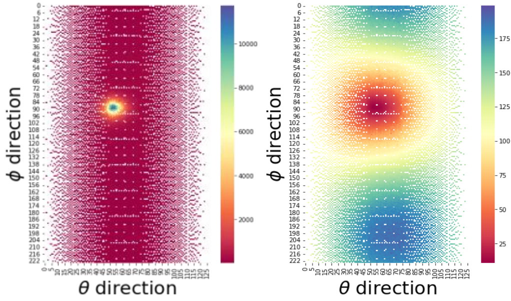




- **Step 1: Features extraction from PMT waveforms**
- **Step 2: Features projection**
- **Step 3: Model training**
- **Step 4: Validation**

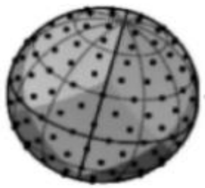


Planar projection



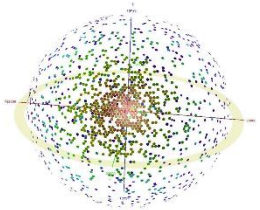
Planar model (EfficientNetV2)

Spherical projection



Spherical model (DeepSphere)

Point clouds



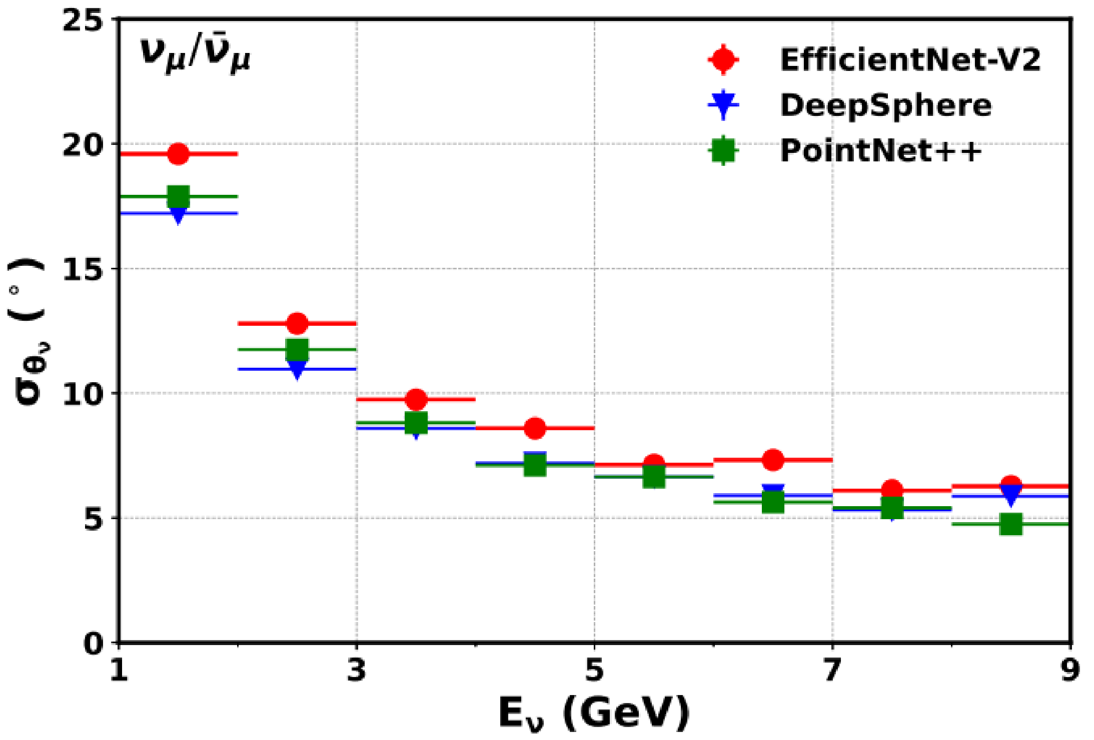
Point-cloud model (PointNet++)

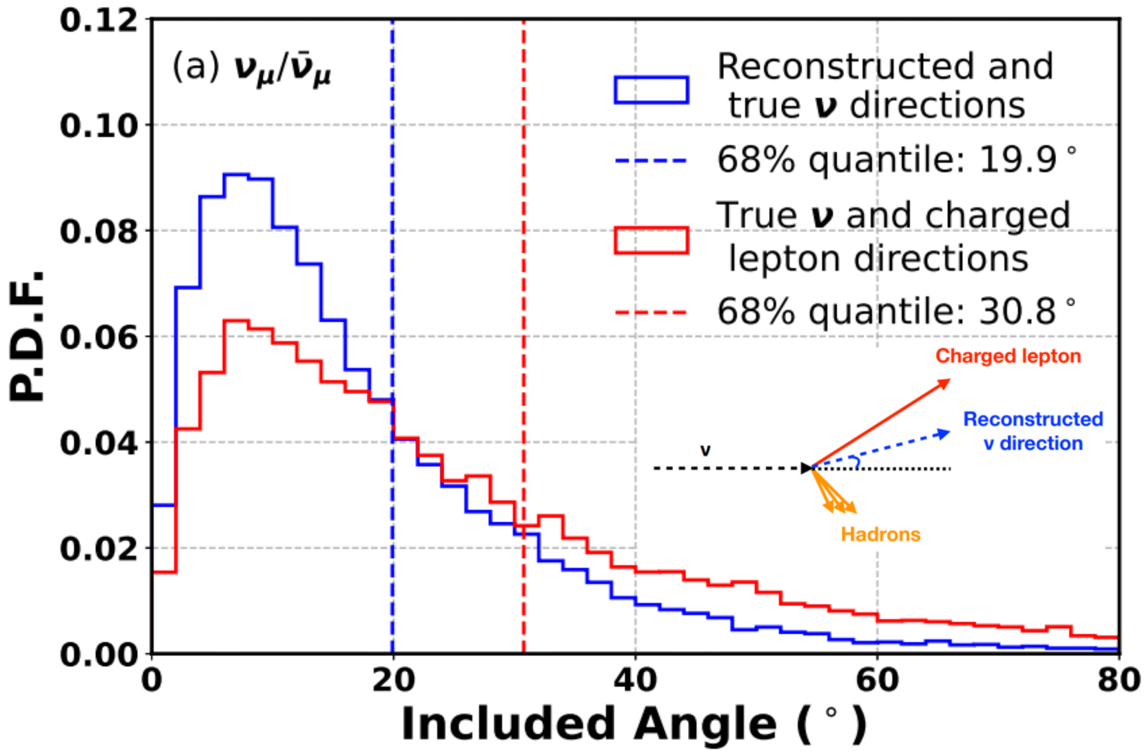
Tasks
Direction Reconstruction
Flavor/Type Identification
Energy Reconstruction
Cosmic-ray Muon Reconstruction

Direction Reconstruction

Phys. Rev. D 109, 052005 (2024)

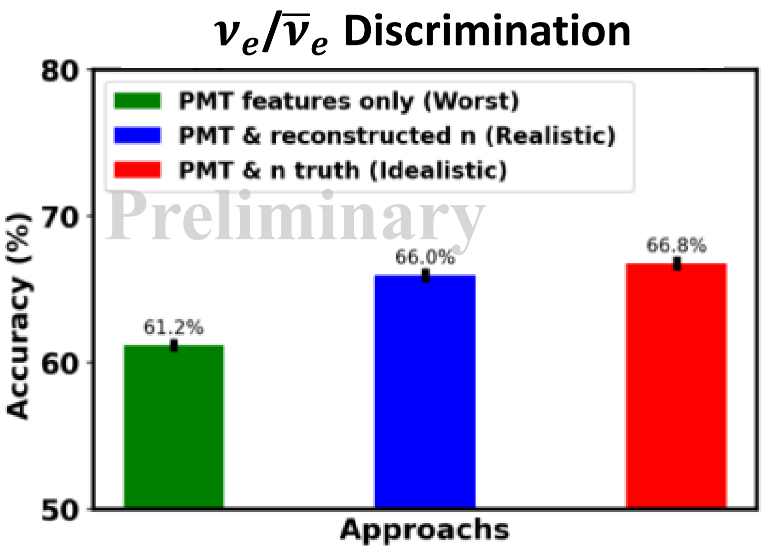
- Better than 10° zenith angle resolution for neutrino with $E_\nu > 3$ GeV
- This resolution is smaller than the average angle between the directions of neutrino and charged lepton:
  - ➢ Both lepton and hadrons information has been used in direction reconstruction
  - ➢ Low energy threshold of LS detectors allows more precise detection for hadrons

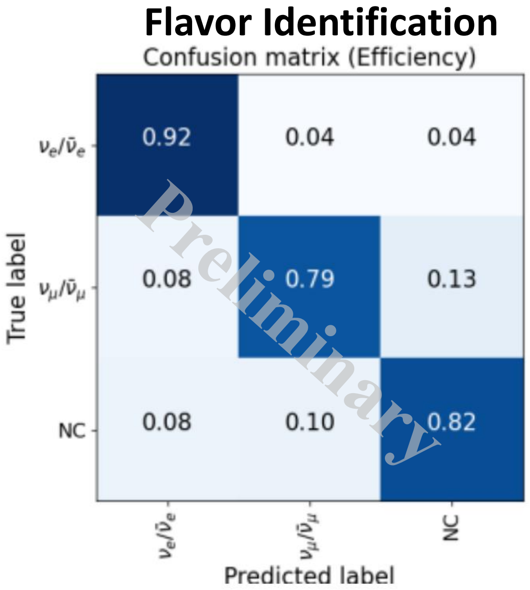


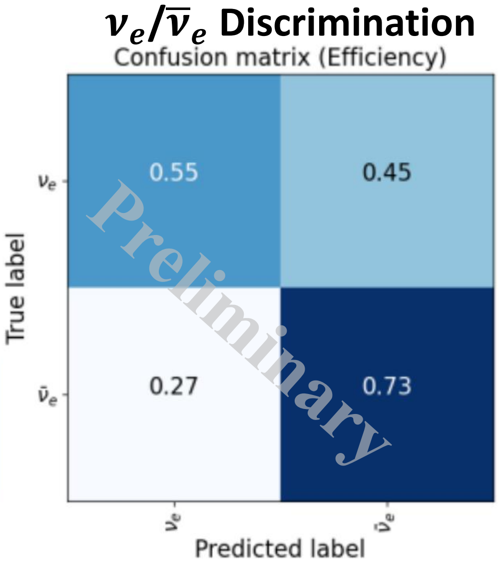


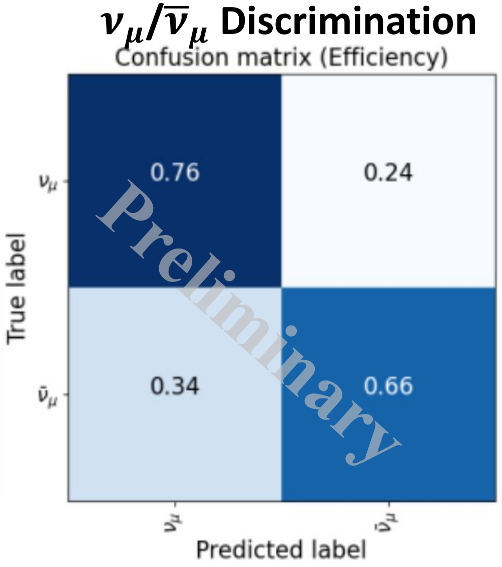
Type Identification

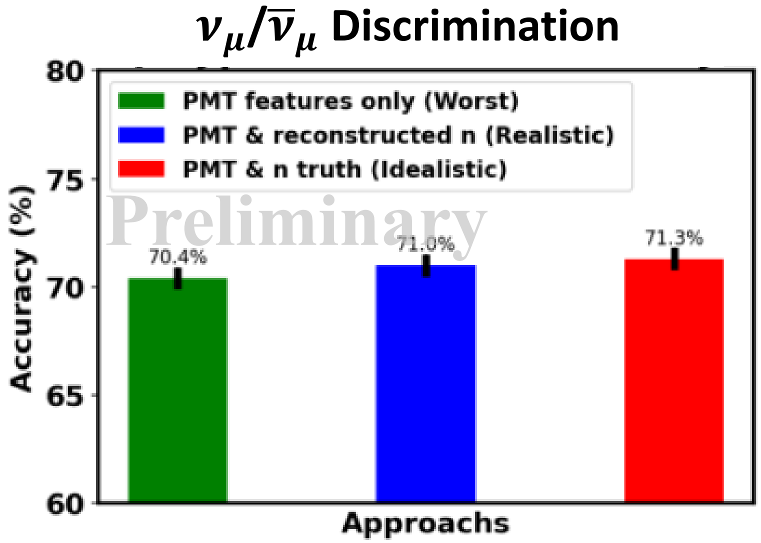
- Better performance for $\nu_\mu/\bar{\nu}_\mu$ discrimination with PMT features only:
  - ➢ It is more easy to divide hadronic and leptonic part for muon neutrino than electron neutrino
- **Capture neutrons information** improves the performance of $\nu_e/\bar{\nu}_e$ **discrimination**, while less effective for $\nu_\mu/\bar{\nu}_\mu$











Summary

- **Atmospheric neutrino oscillations** with matter effect can enhance the NMO sensitivity at JUNO
- Challenges: Directionality reco. and PID
  - Directionality of charged particle is reflected in the PMT waveforms
  - Electron and muon show different topology
  - Hadrons and captured neutron provide great potential for $\nu/\bar{\nu}$ discrimination
- A Multi-purpose machine learning approach has been developed for GeV atm. ν reconstruction

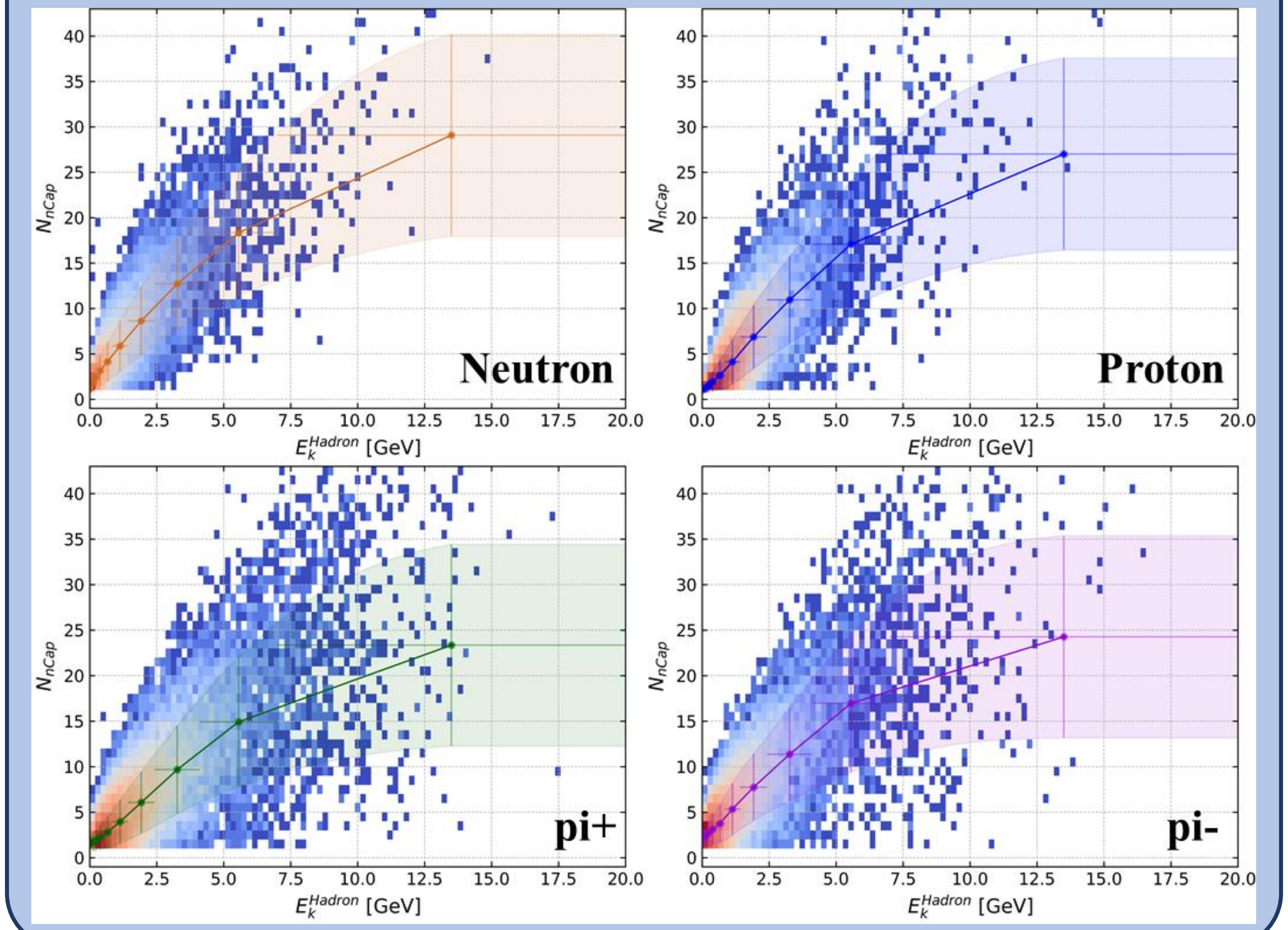
Thank you!

	Recent Developments
Event Selection $\nu_e/\bar{\nu}_e$	$E_{vis} > 1$ GeV
Directionality	$\sigma_{\theta_\nu} < 10^\circ$ ($E_\nu > 3$ GeV)
Classification	**CC-e/CC-μ/NC: 80%~95% eff.**
	ν vs $\bar{\nu}$: 50%~80% eff.
Energy	σ_{E_ν} (To be updated)

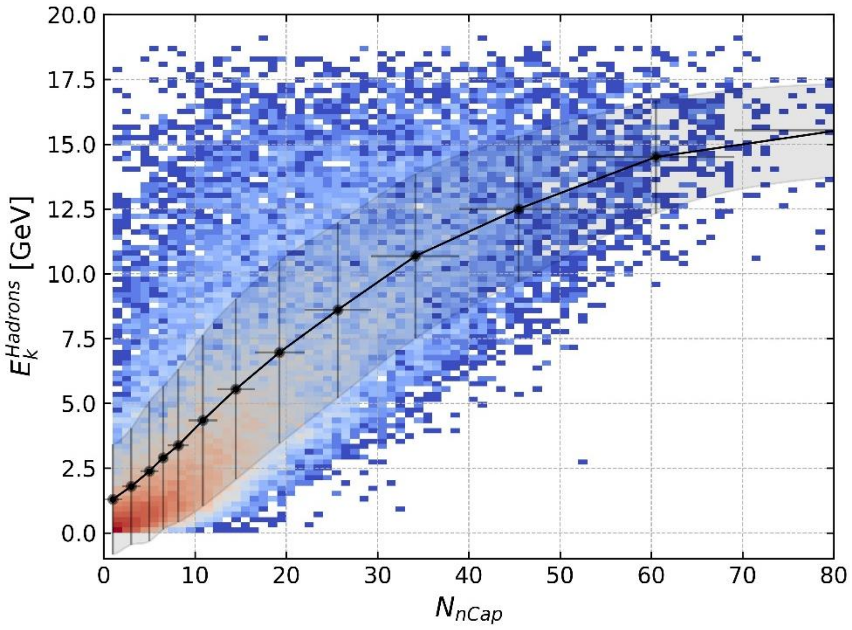
Backup: Atmospheric $\nu/\bar{\nu}$ Discrimination

Characteristics of Captured Neutrons

N_{nCap} vs E_k of each final-state hadrons



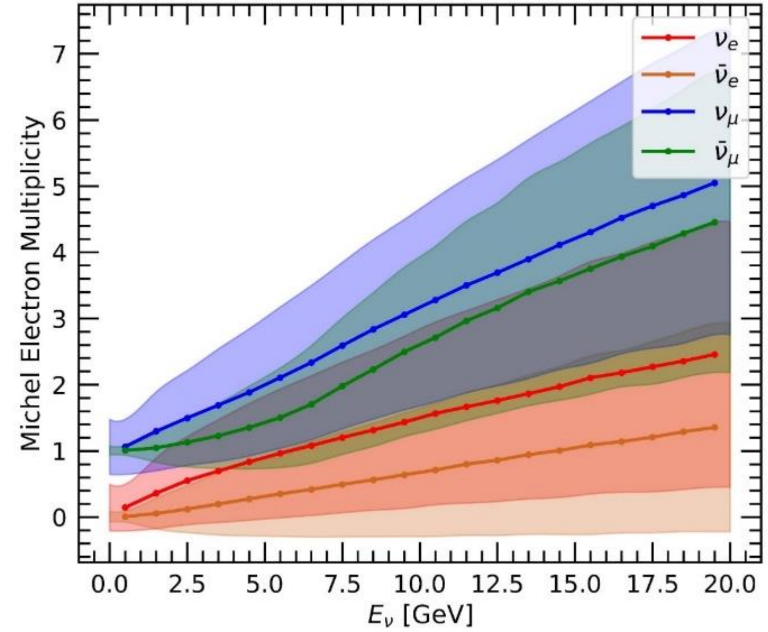
- Captured neutrons are mainly produced by secondary interaction of final-state hadrons, such as $\{n, p^+, \pi^+, \pi^-\}$
- The multiplicity of captured neutrons (N_{nCap}) will carry the energy information of hadrons

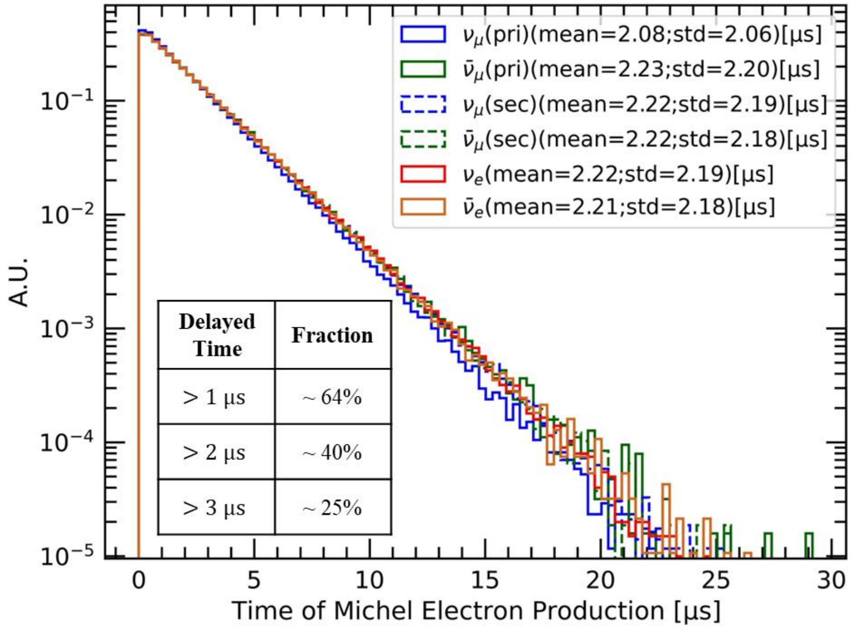


Backup: Atmospheric Neutrino Type Identification

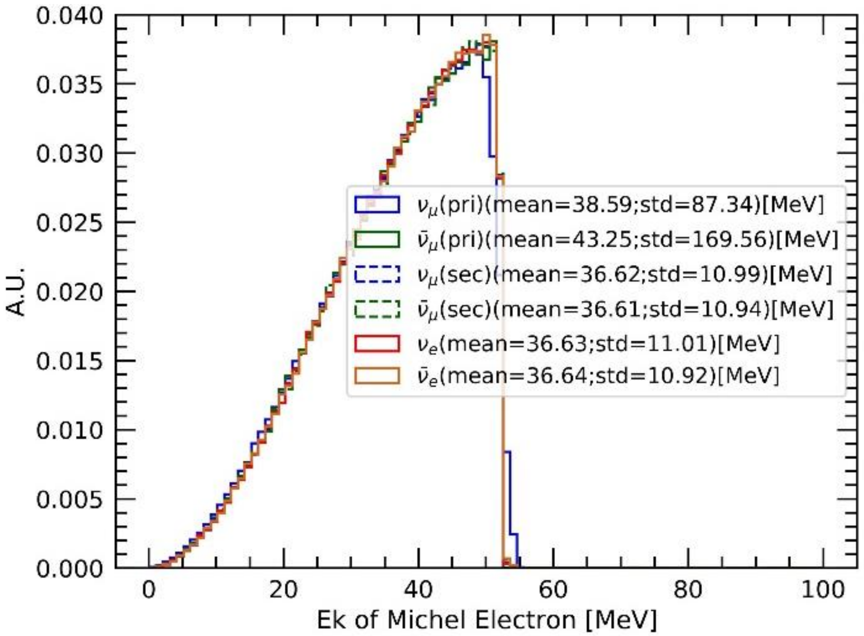
Characteristics of Michel Electron

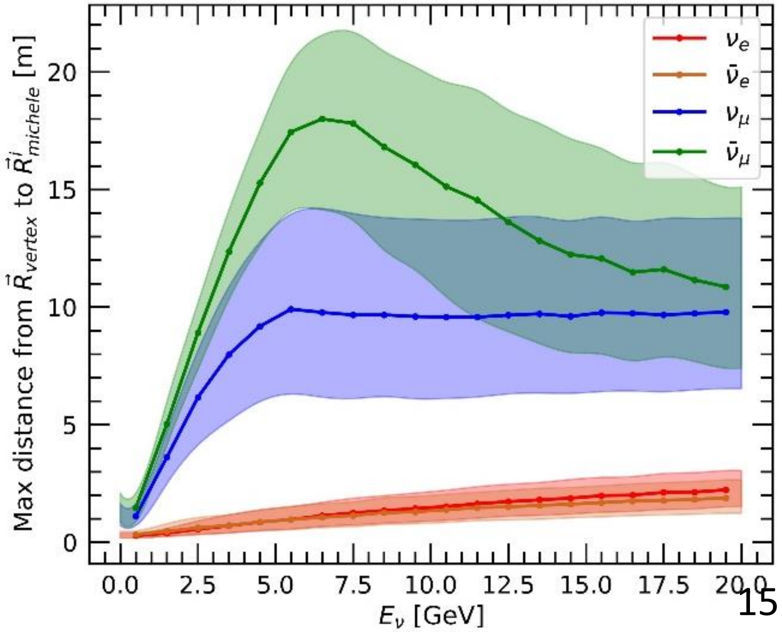
- Muon decay will produce Michel electron with few-tens MeV energy and ~2.2 μs delayed time
- The **distance between Michel electron and interaction vertex** can represent the **track length of final-state muon**, which can benefit the neutrino flavor identification



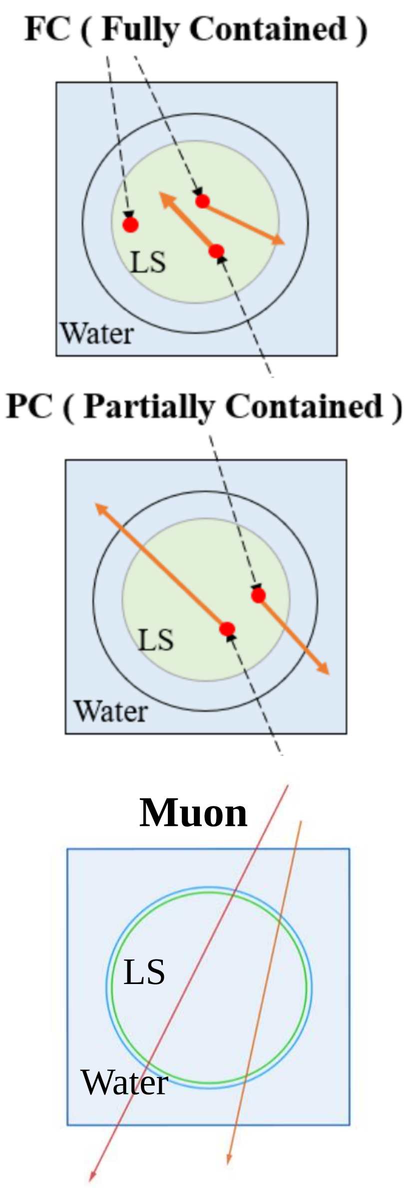


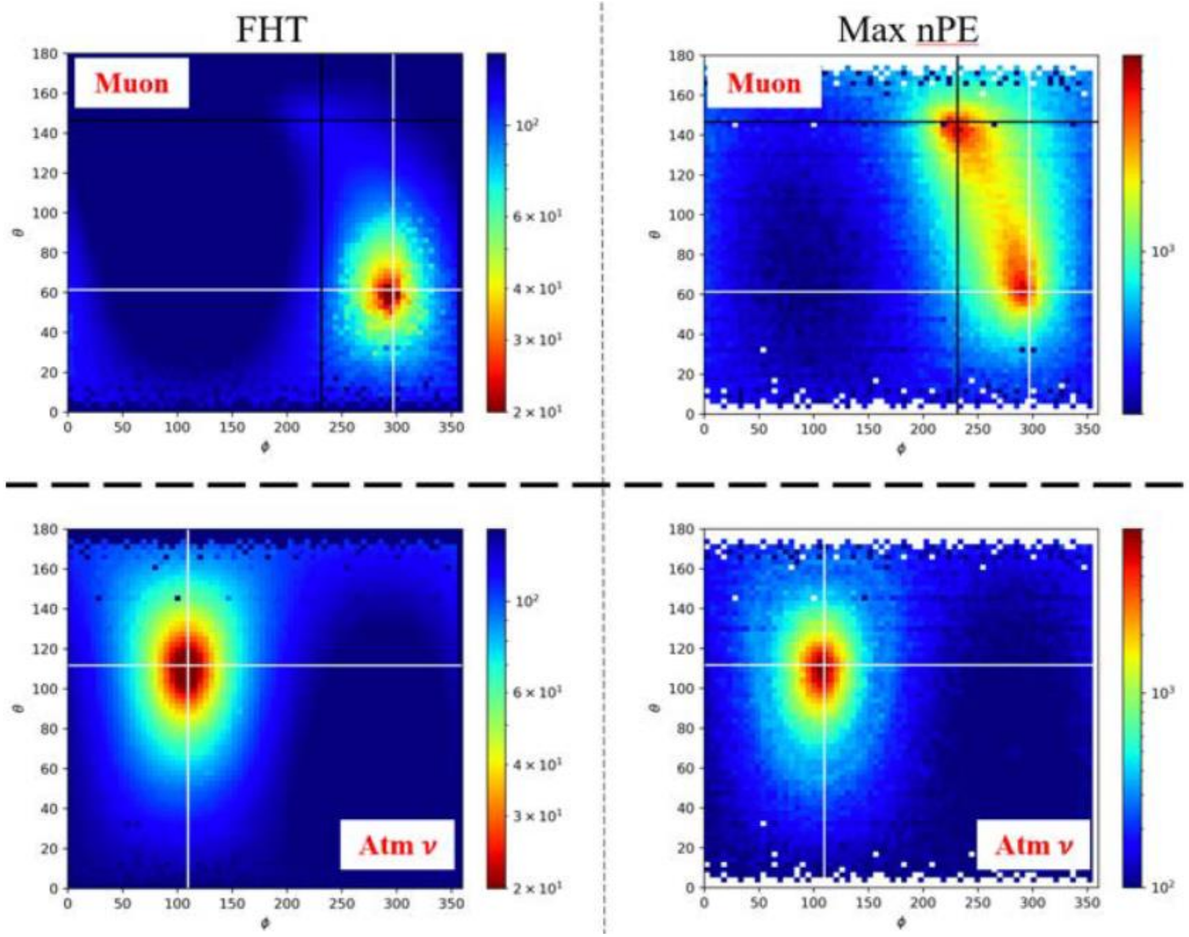
Delayed Time	Fraction
> 1 μs	~ 64%
> 2 μs	~ 40%
> 3 μs	~ 25%

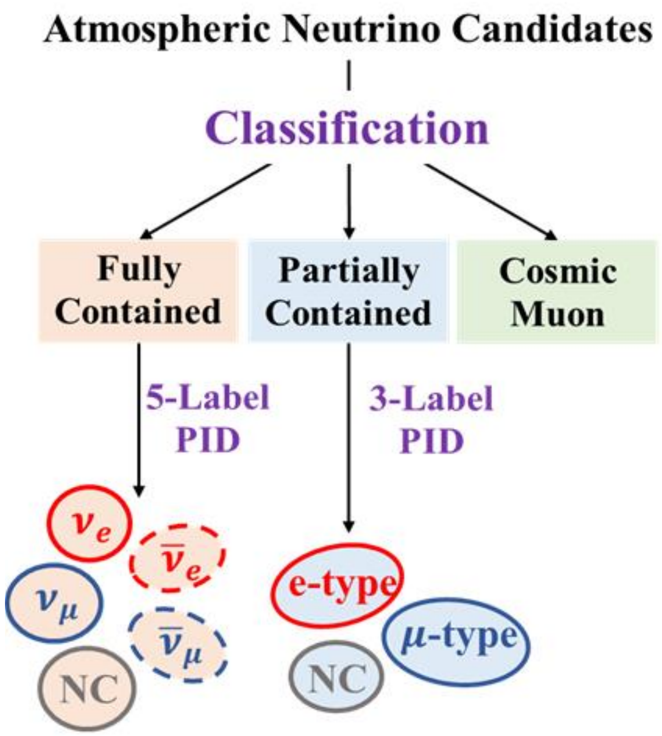




Backup: Cosmic-ray Muon Suppression







- Use Central Detector and Water Pool PMT features to classify FC/PC/Muon events
- Right plot: an exemplar event classification/selection strategy

Backup: Detector Geometry Effect