Reconstruction of atmospheric neutrinos and muons using Machine Learning-based methods in JUNO

Wing Yan Ma[1], Fanrui Zeng[1], Jiaxi Liu[2], Xinhai He[2], Zhen Liu[2], Wuming Luo[2], Hongye Duyang[1], Teng Li[1]

[1] Shandong University

[2] Institute of High Energy Physics, CAS

ACAT 2024

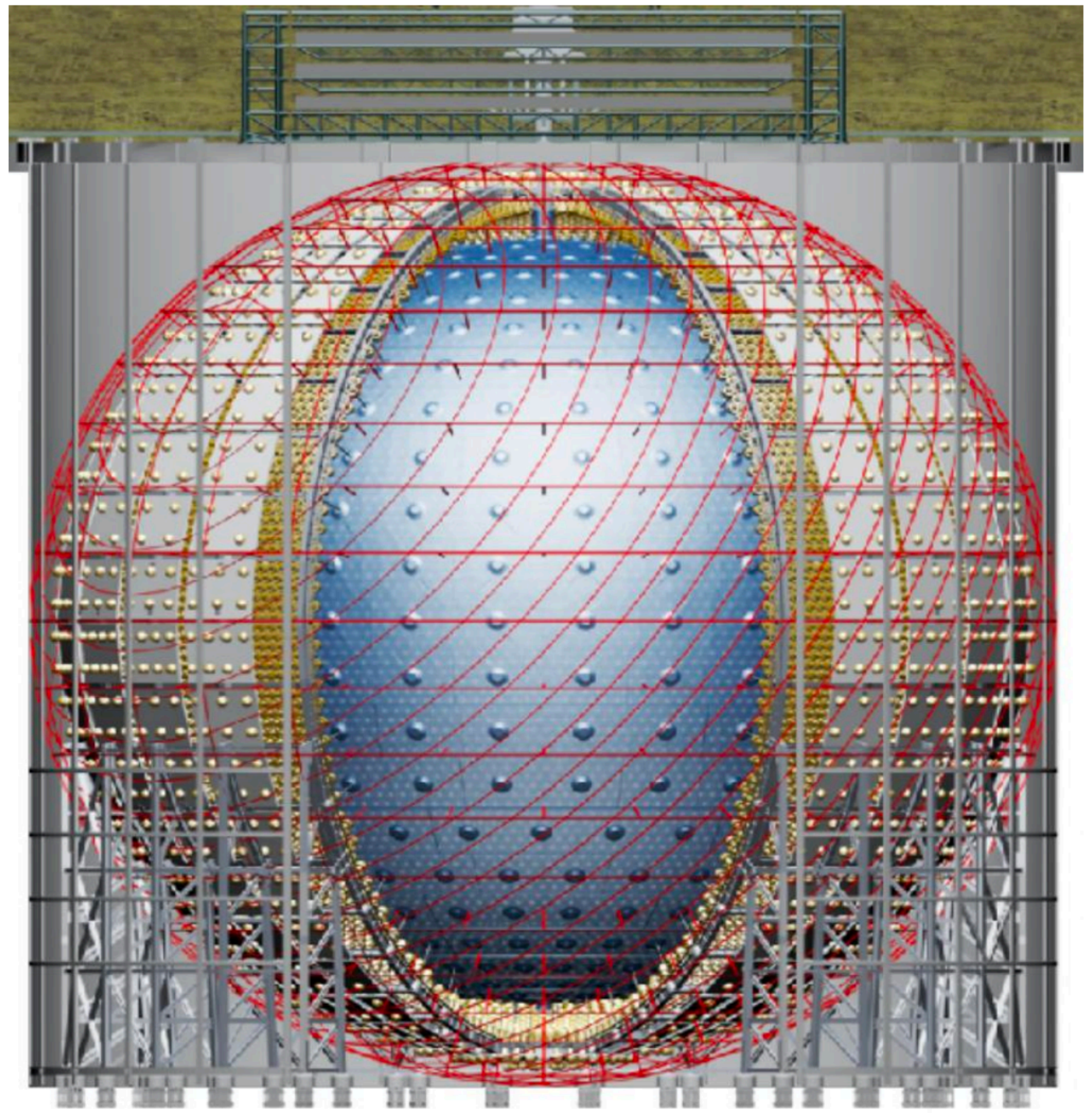
2024/03/11

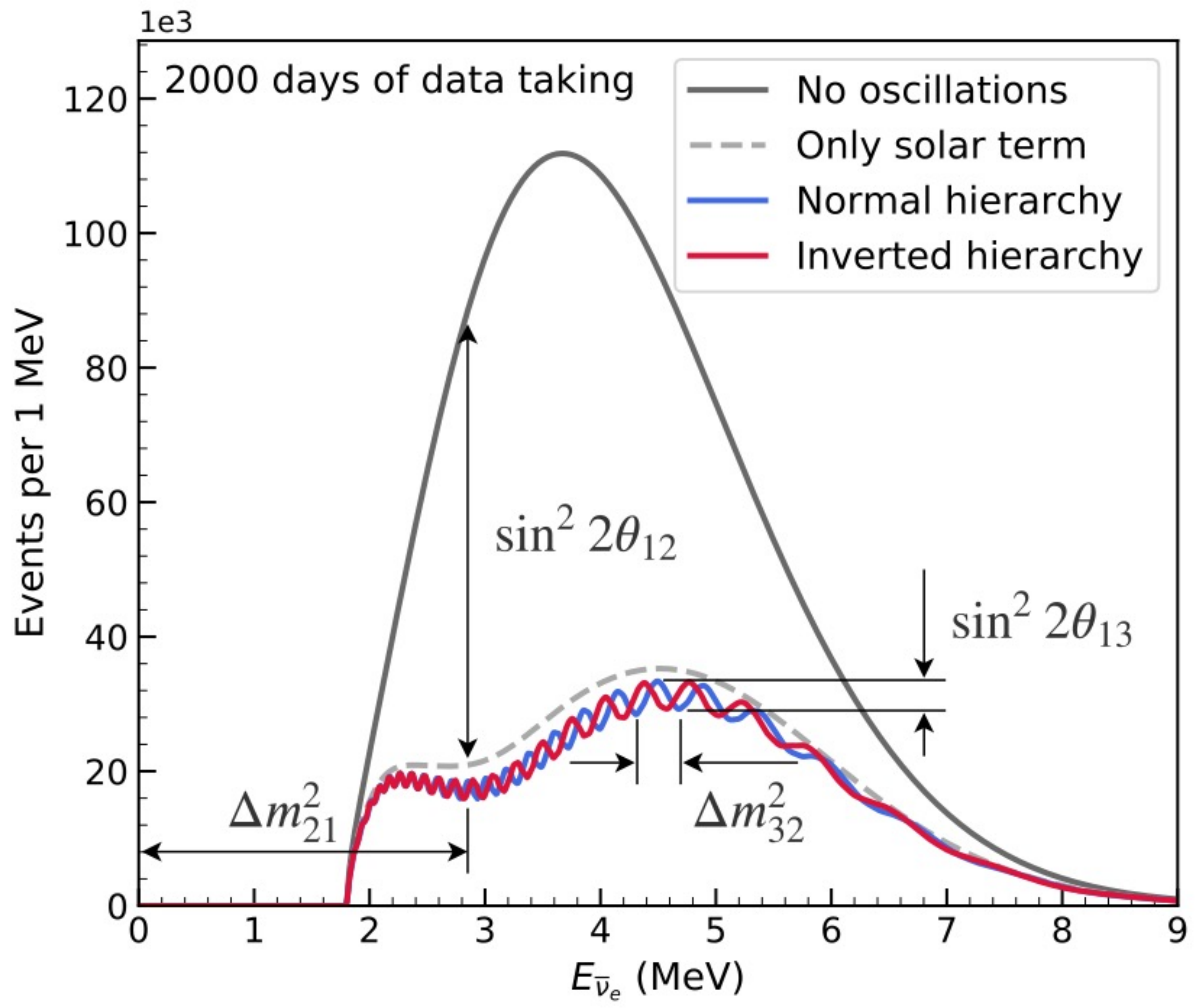
Outline

- Introduction: **JUNO**, **atmospheric neutrinos**
- Motivation and Strategy
- ML models considered
- Reconstruction performances
  - Atmospheric neutrinos' **direction/energy**
  - Cosmic muons
- Summary

The JUNO Experiment

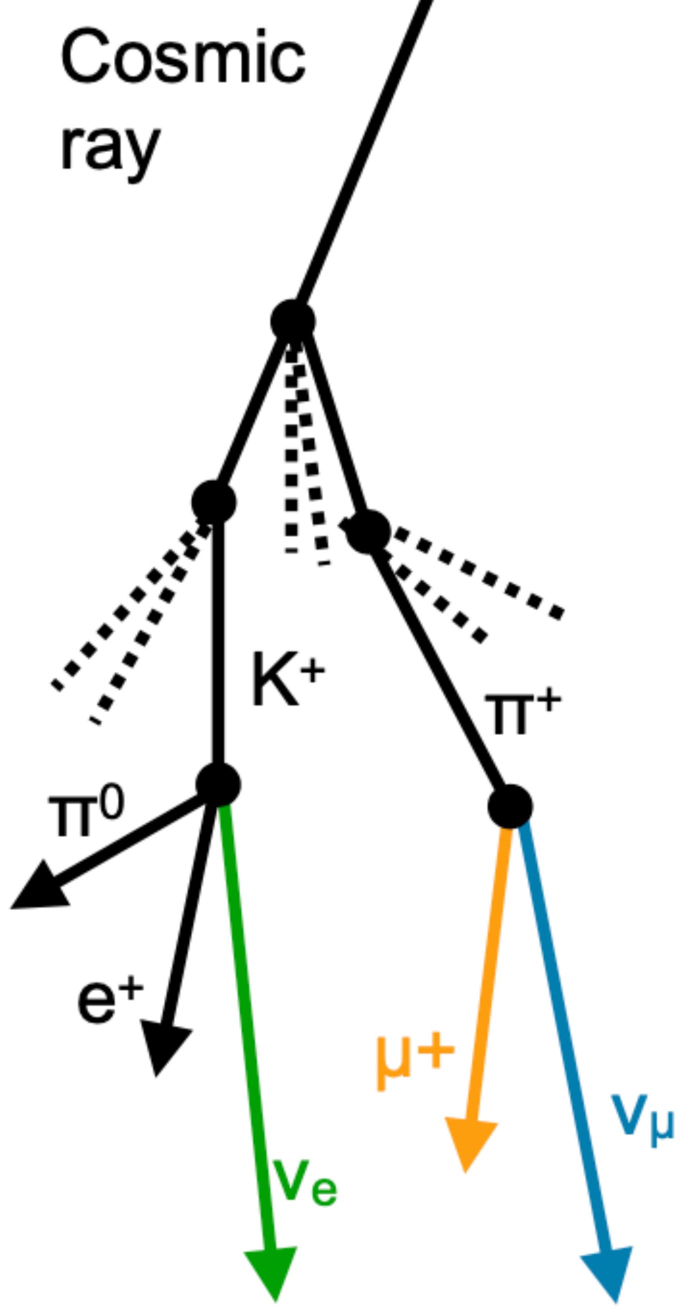
- The **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO) is a multi-purpose experiment currently under construction in southern China
  - 20 kton liquid scintillator in a spherical vessel surrounded by ~17k 20” + ~25k 3” PMTs
- Primary goal is to measure **neutrino mass ordering (NMO)**
  - Main sensitivity from **reactor neutrinos**
  - Pure source of electron anti-neutrino ($\bar{\nu}_e$) of **~1-10 MeV**
  - Measure deficit in $\bar{\nu}_e$

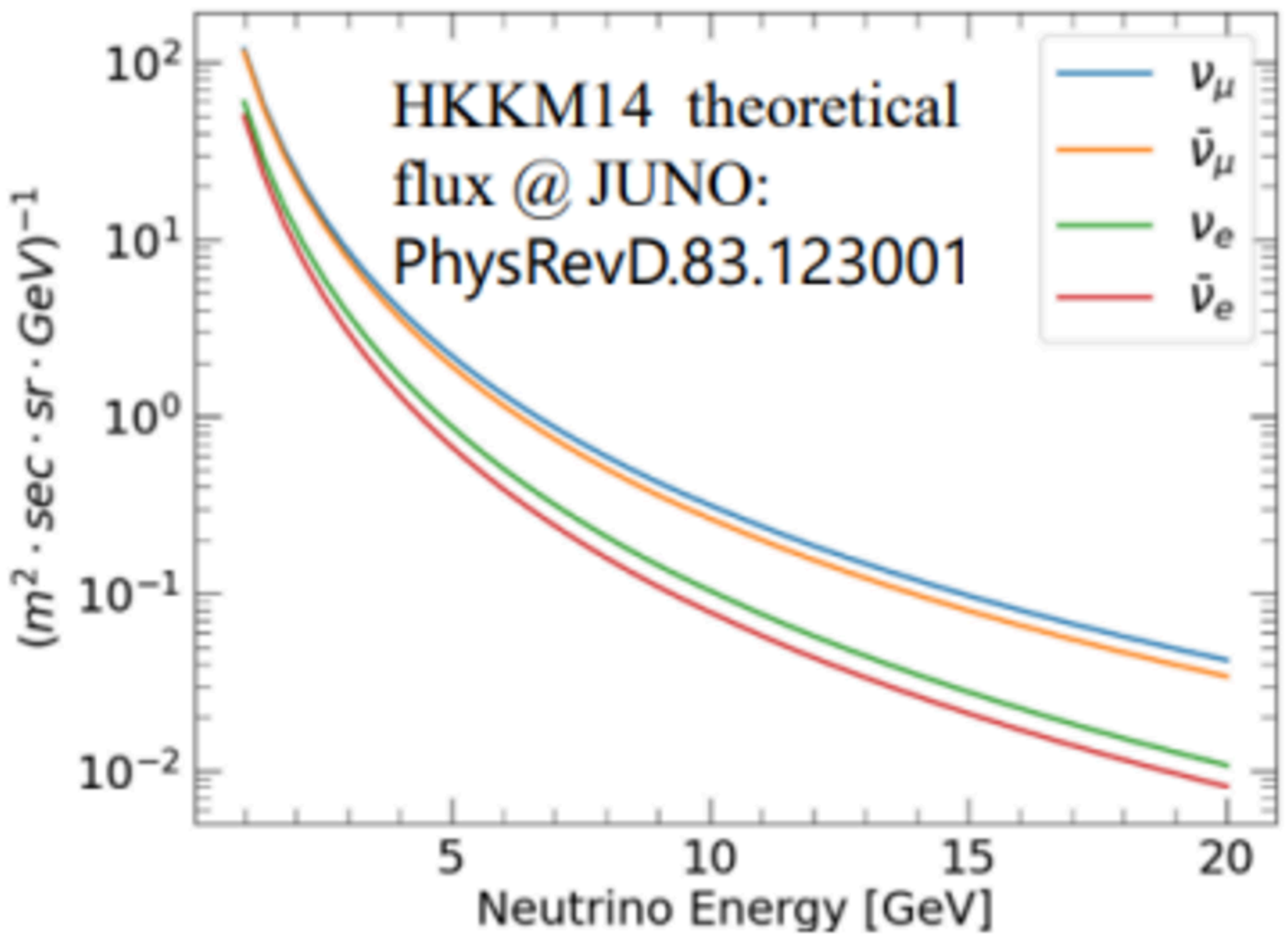


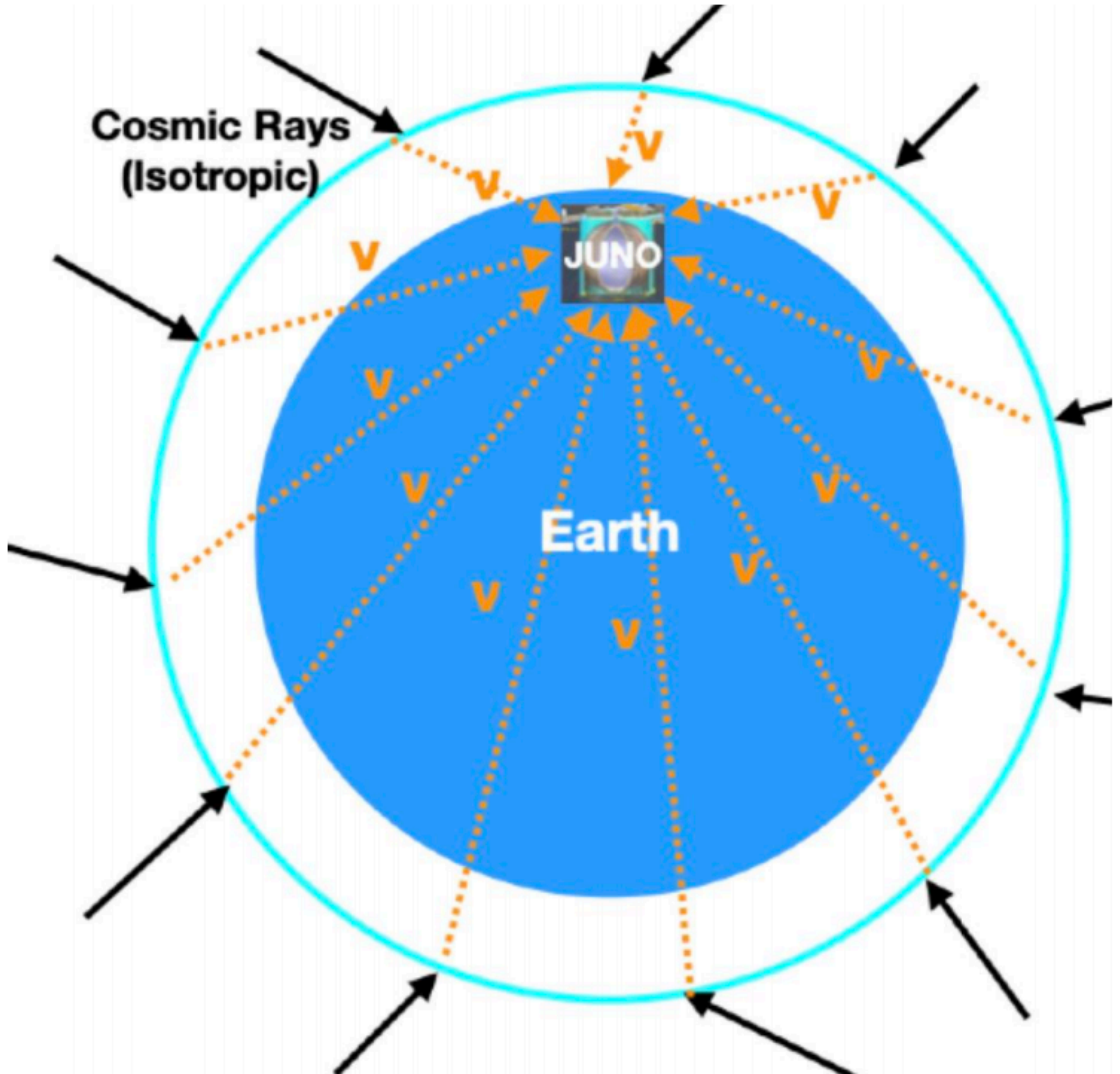


Atmospheric Neutrinos

- Large flux of atmospheric neutrinos (ν_{atm}) produced by cosmic ray interactions
- Isotropic with different baseline (L) and energy (E)
- Natural source of neutrinos in GeV region

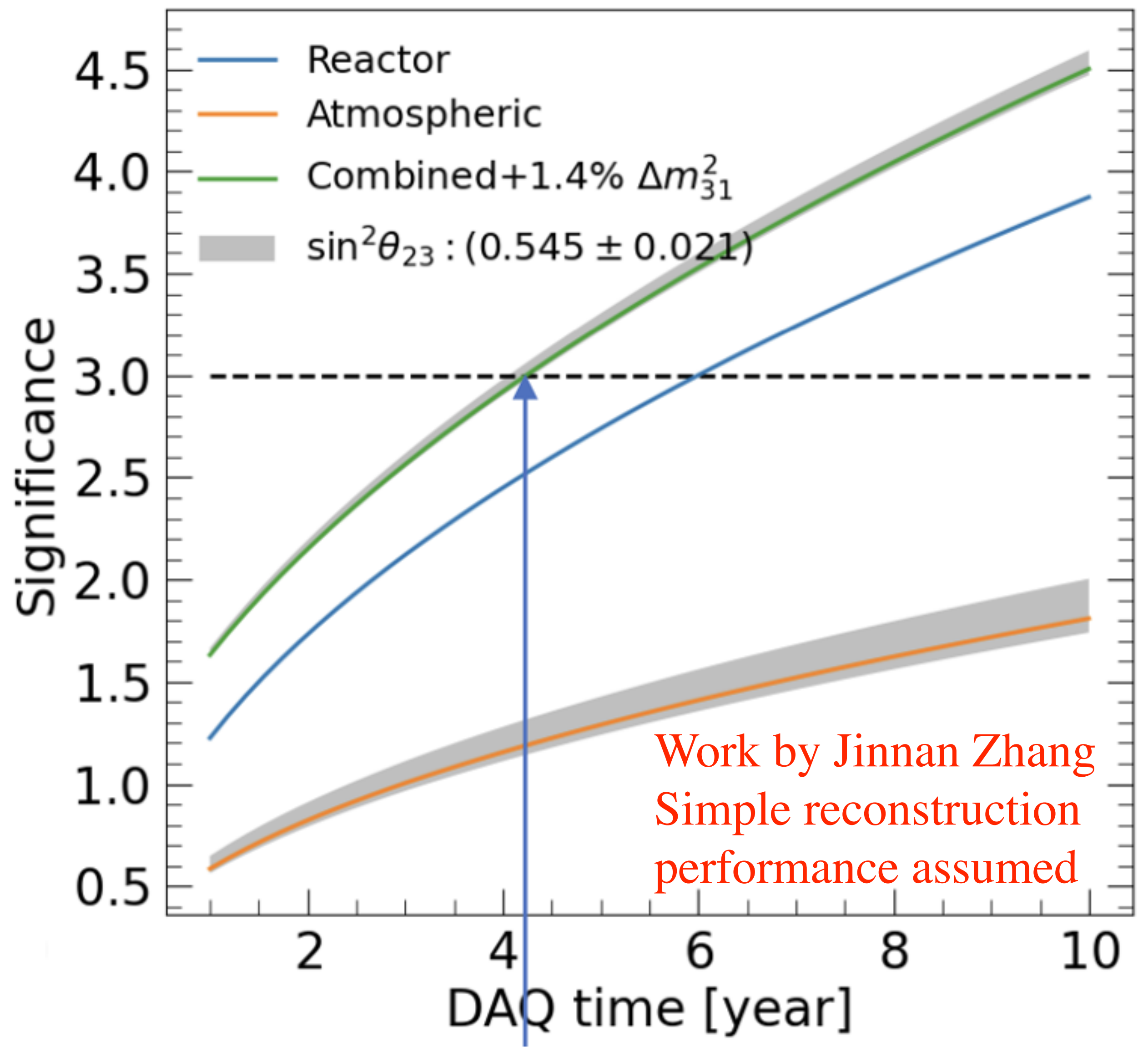


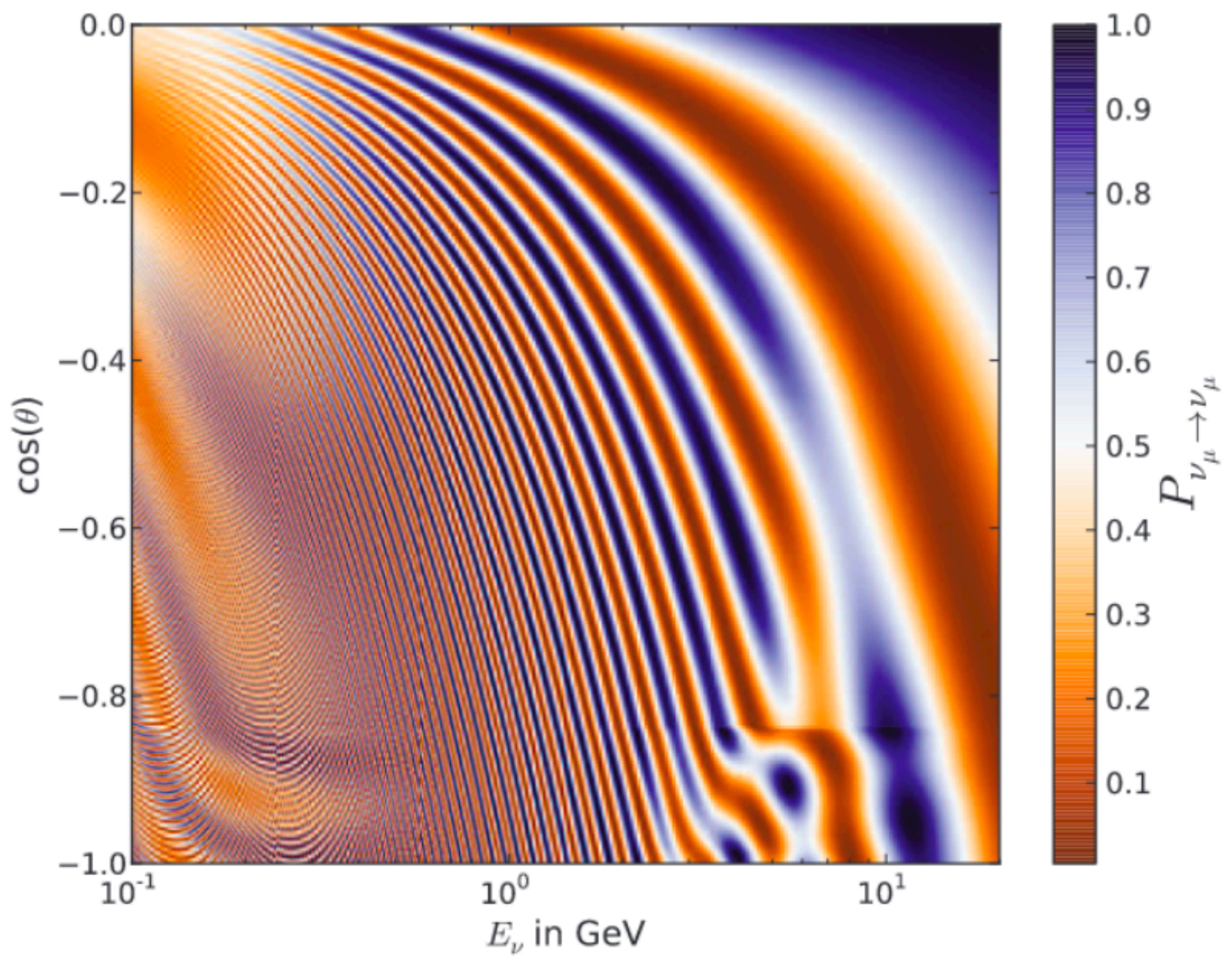




Motivation

- Oscillation sensitivities can be enhanced by studying ν_{atm} oscillations in GeV region
- To study ν_{atm} oscillations one needs to reconstruct neutrinos' **direction/energy/**flavor (particle type)
- Also important to reconstruct cosmic muons - background to main signal
    - A novel, **multi-purpose reconstruction method** based on Machine Learning

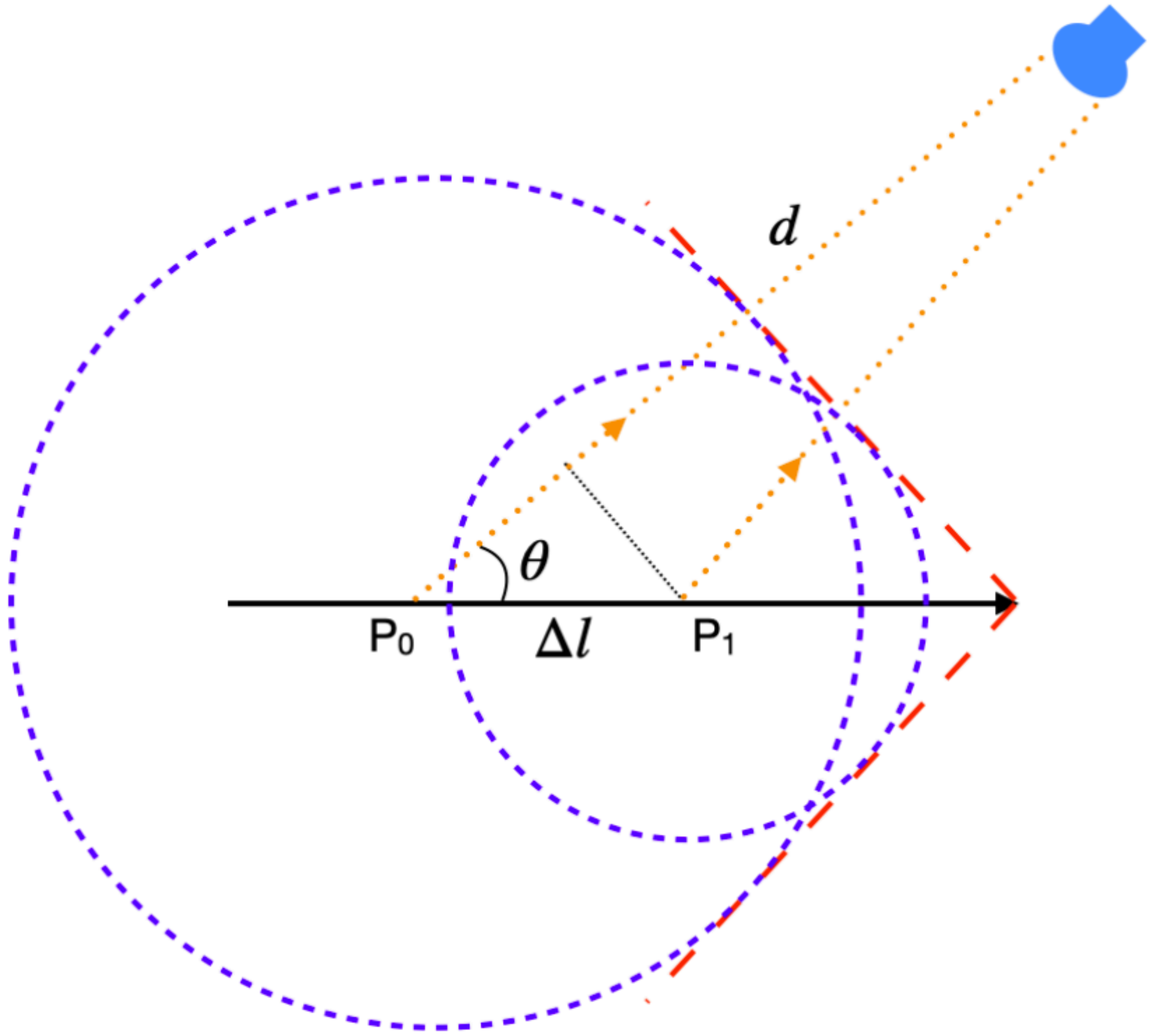


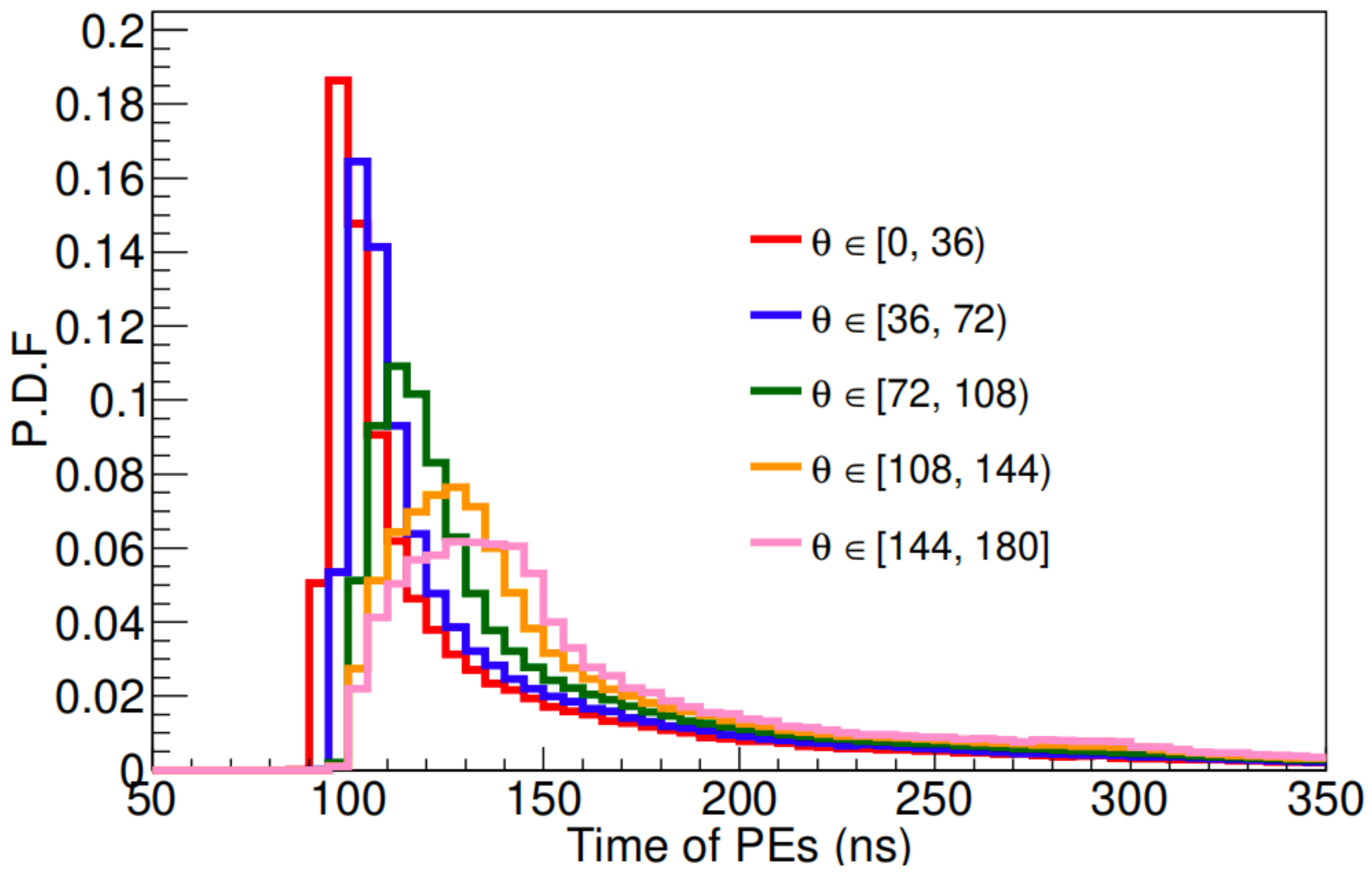


$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^4(\theta_{13})\sin^2(2\theta_{23})\sin^2\left(1.267\Delta m^2_{32}(\text{eV}^2)\frac{L(\text{km})}{E(\text{GeV})}\right)$$

Scintillation light at the detector

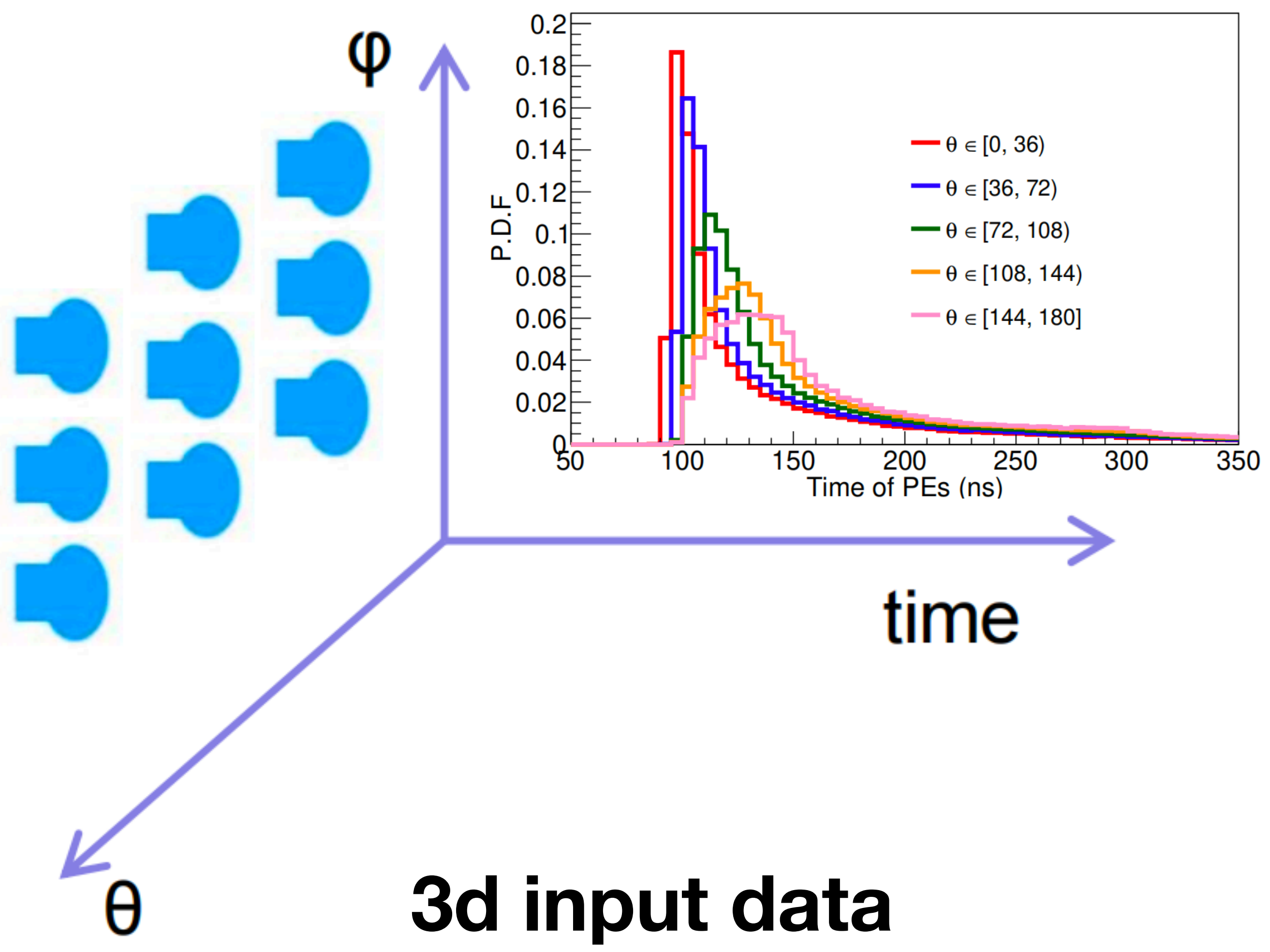
- Light seen by PMTs of an LS detector is a superposition of light generated from many points along the track
- Shape of light curve received by each PMT depends on :
    - Angle w.r.t. track direction θ
    - Track starting and stopping position
    - Particle type - different dE/dx
- Typical LS detectors are designed for low-energy neutrinos - ν_{atm} **oscillations measurements using LS detectors has never been performed**



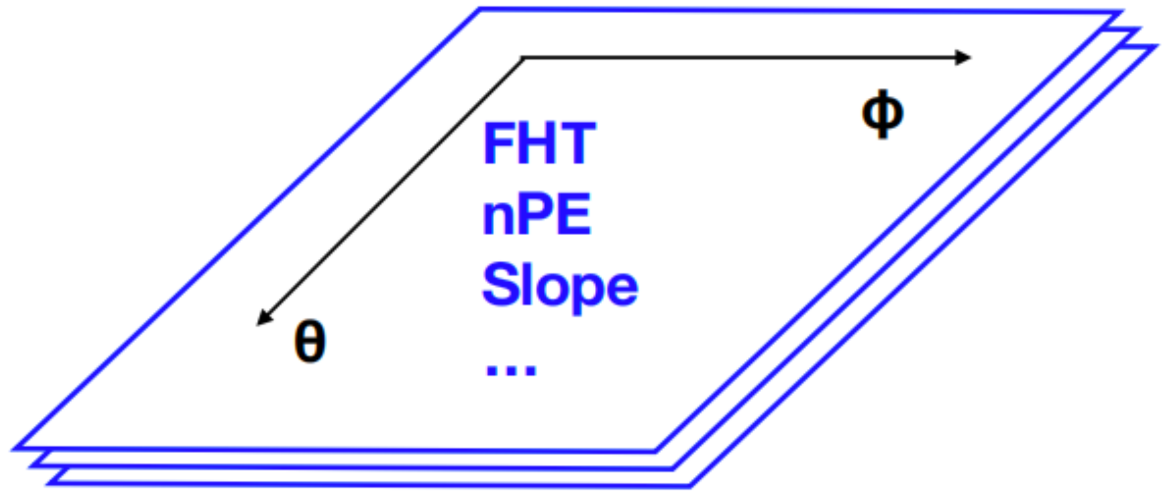


Methodology

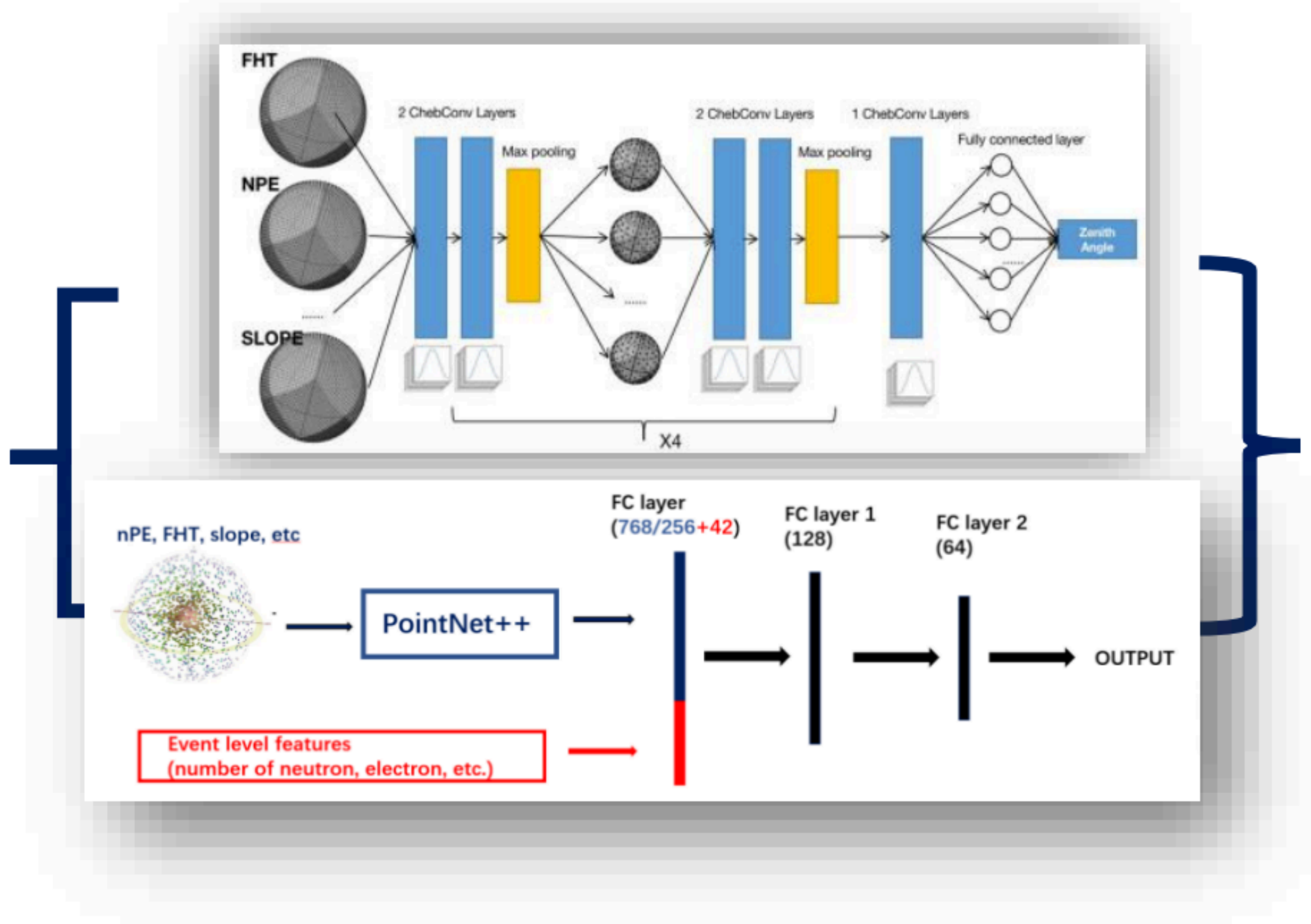
- Due to large number of PMTs in the JUNO detector, directly feeding full waveform from all PMTs are computationally expensive
- Features that reflects the waveforms are extracted to reduce the data volume



3d input data

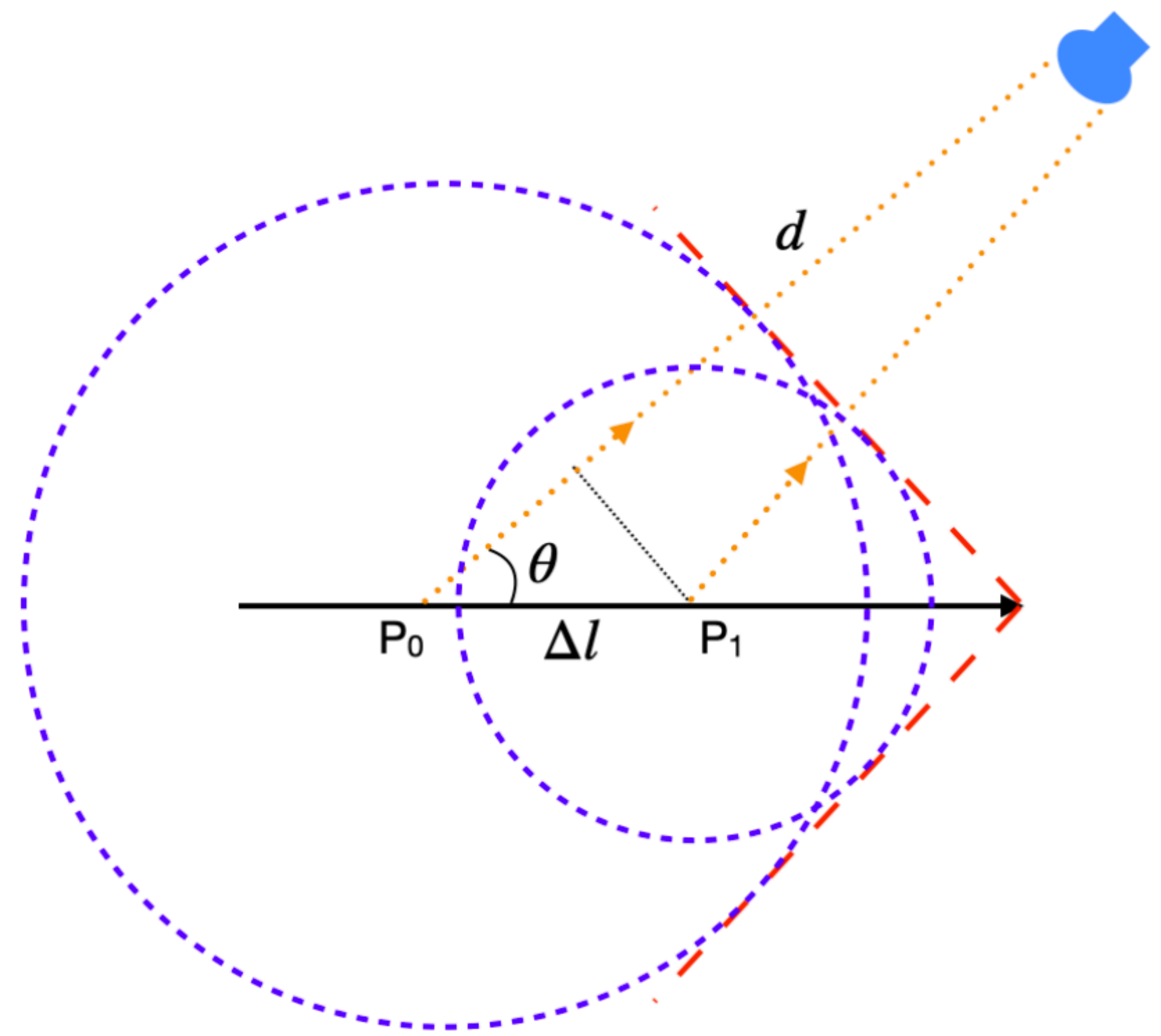


Multiple feature maps



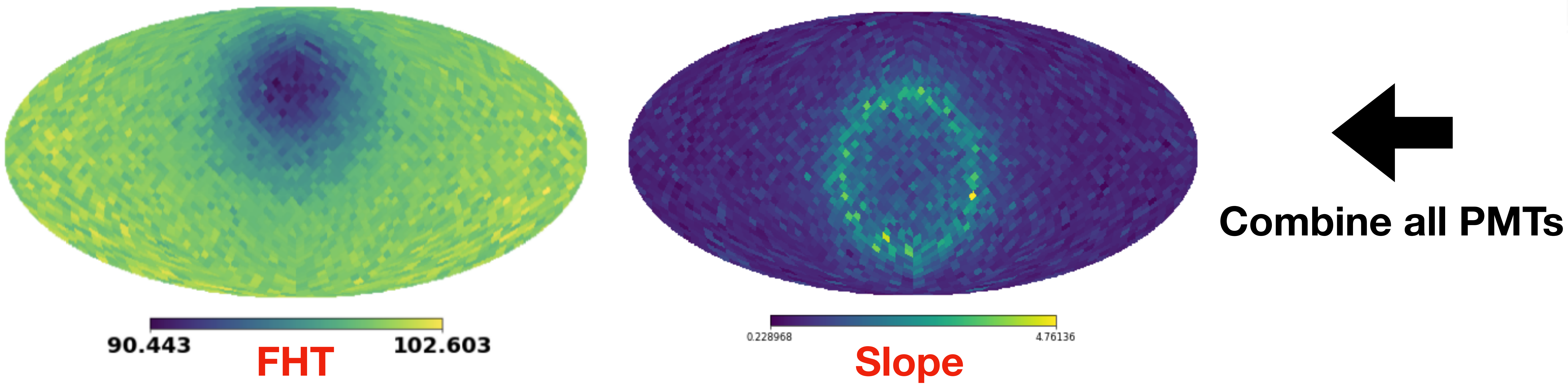
ML models

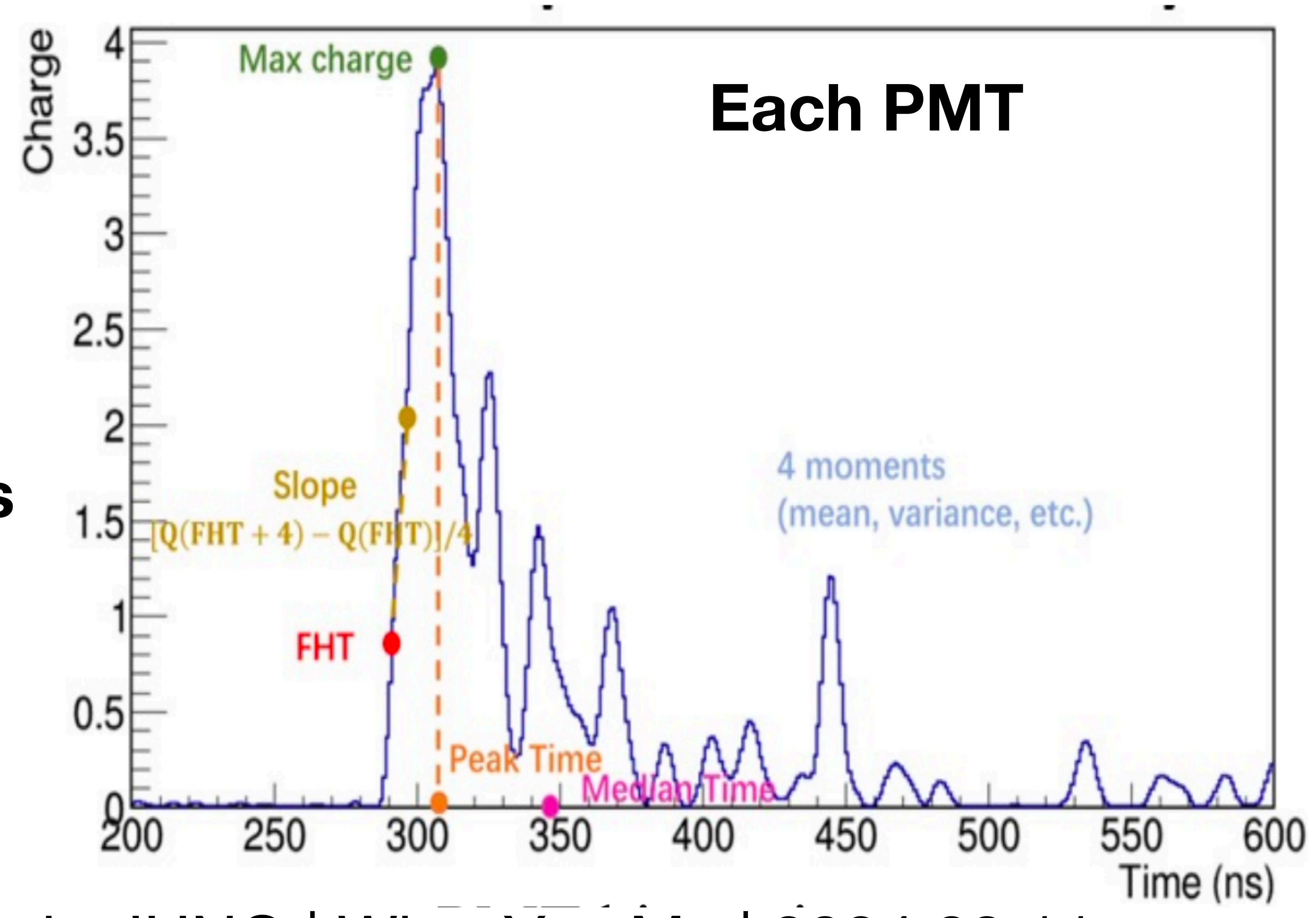
Feature Extraction



Select characteristic information from waveforms:

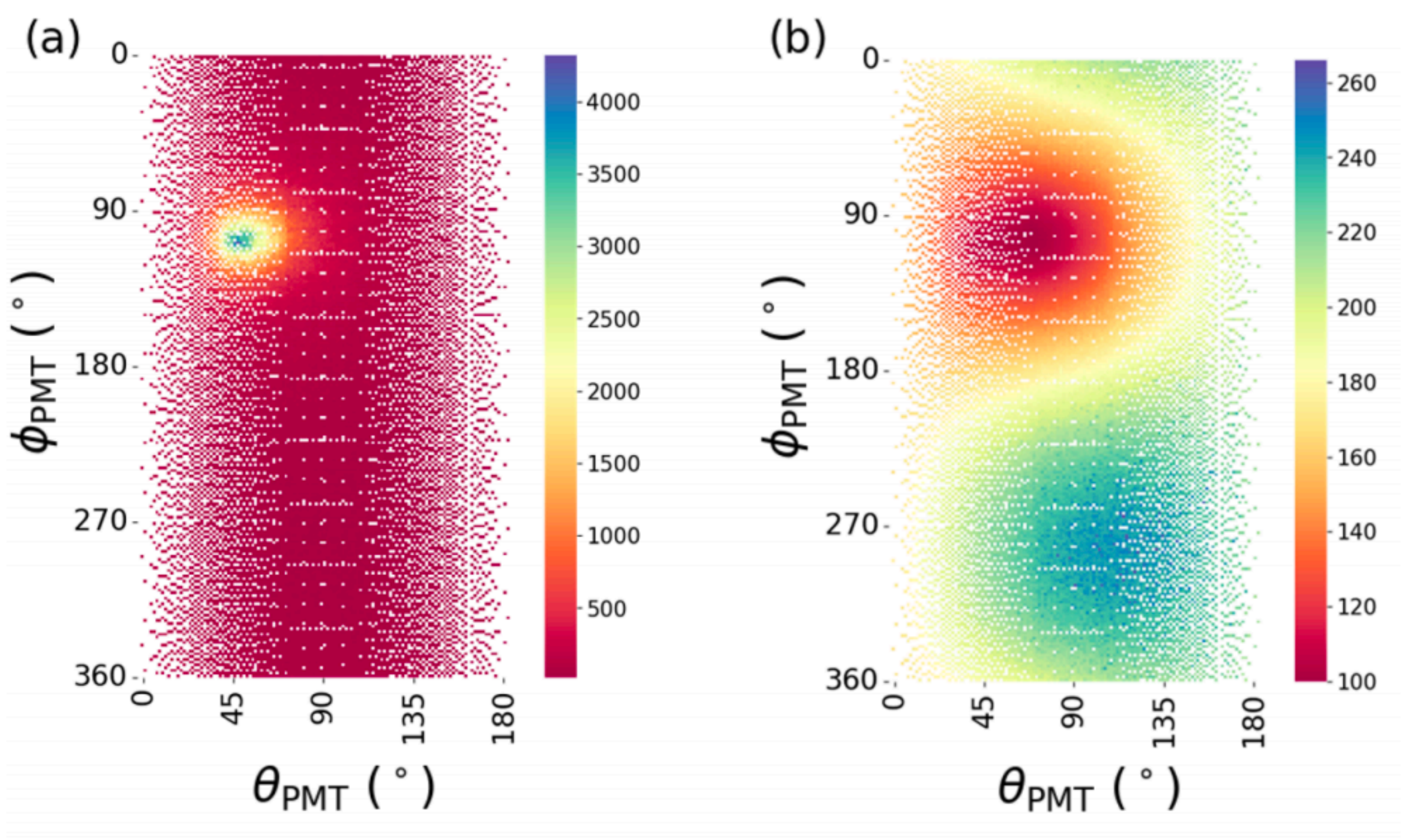
- **FHT**: time of first photon arriving at a PMT
- **Slope**: average slope of curve at the first 4 ns
- **Peak time**, **peak charge**, **total charge** etc.
- Checked feature importance to select the relevant features to models

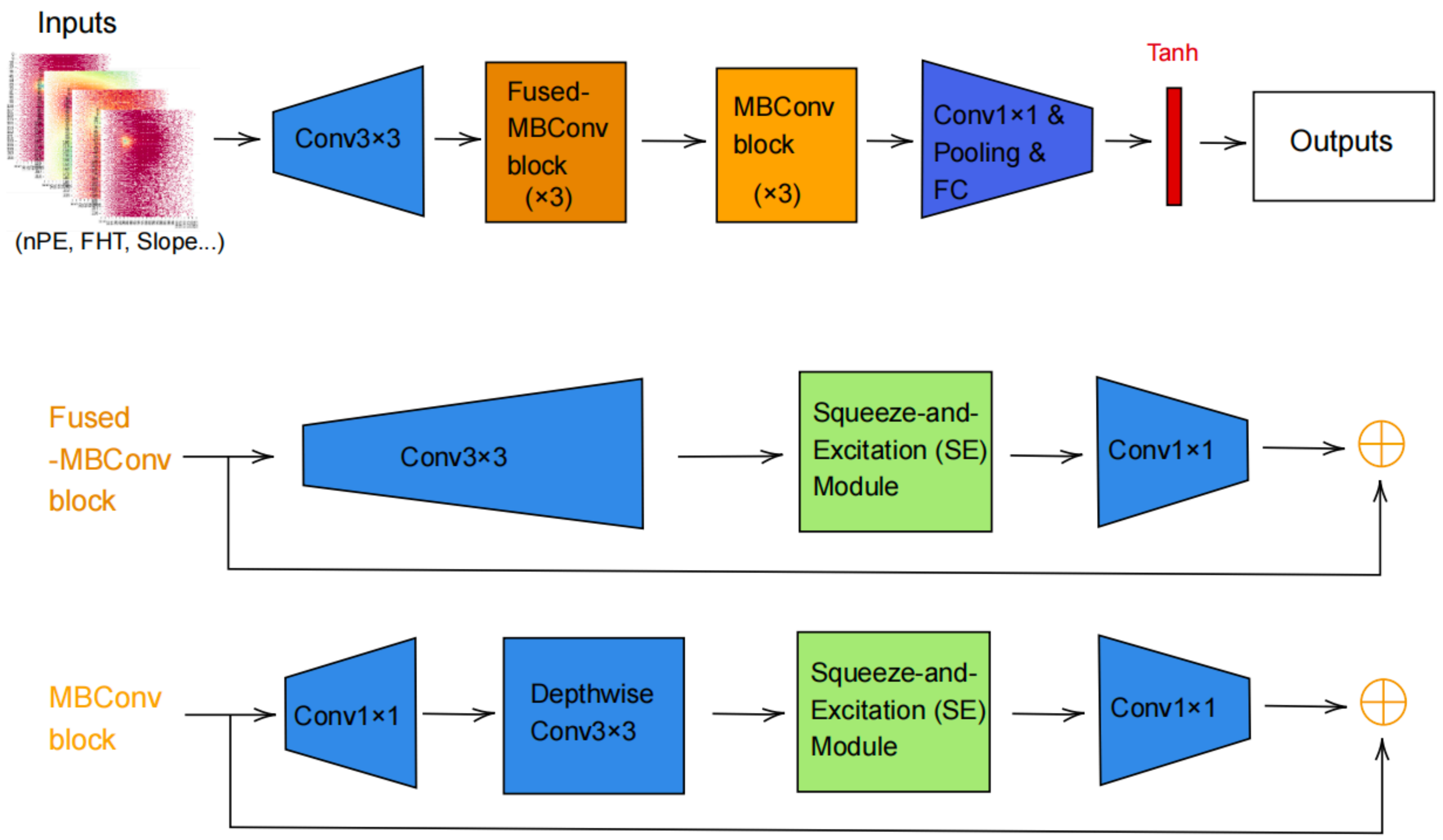




Planar Model: EfficientNetV2

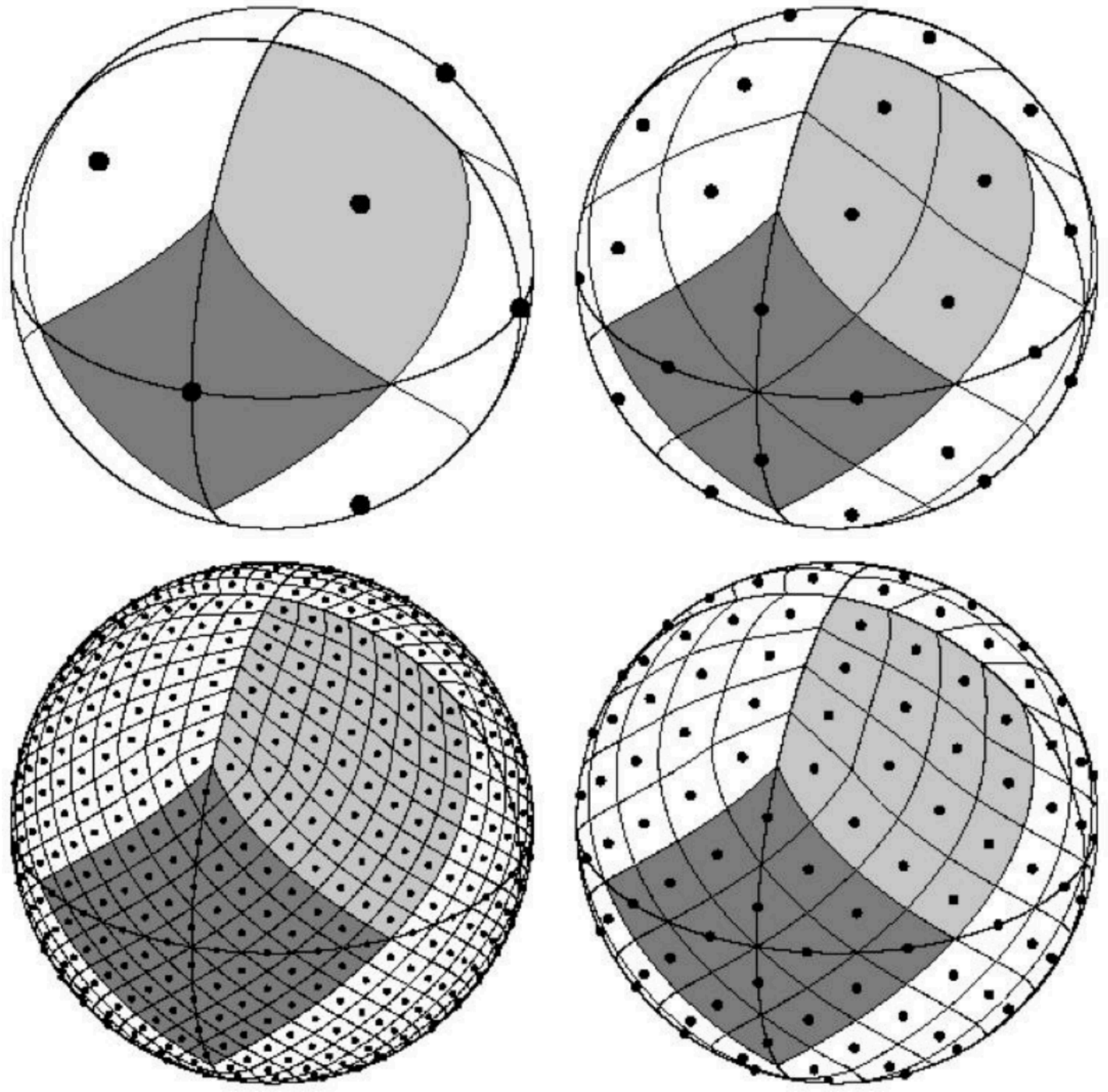
- PMTs are seen as pixels, with each feature projected from the sphere to the planar surface
- EfficientNetV2: superior performance and shorter training time compared to other popular CNNs
- E.g. projected total charge and FHT to $\theta_{PMT} - \phi_{PMT}$ plane





Spherical CNN: DeepSphere

- Graph-CNN: developed for processing spherical data originally developed for cosmology studies
- Maintain rotation covariance
- Avoid distortions caused by projection to a planar surface



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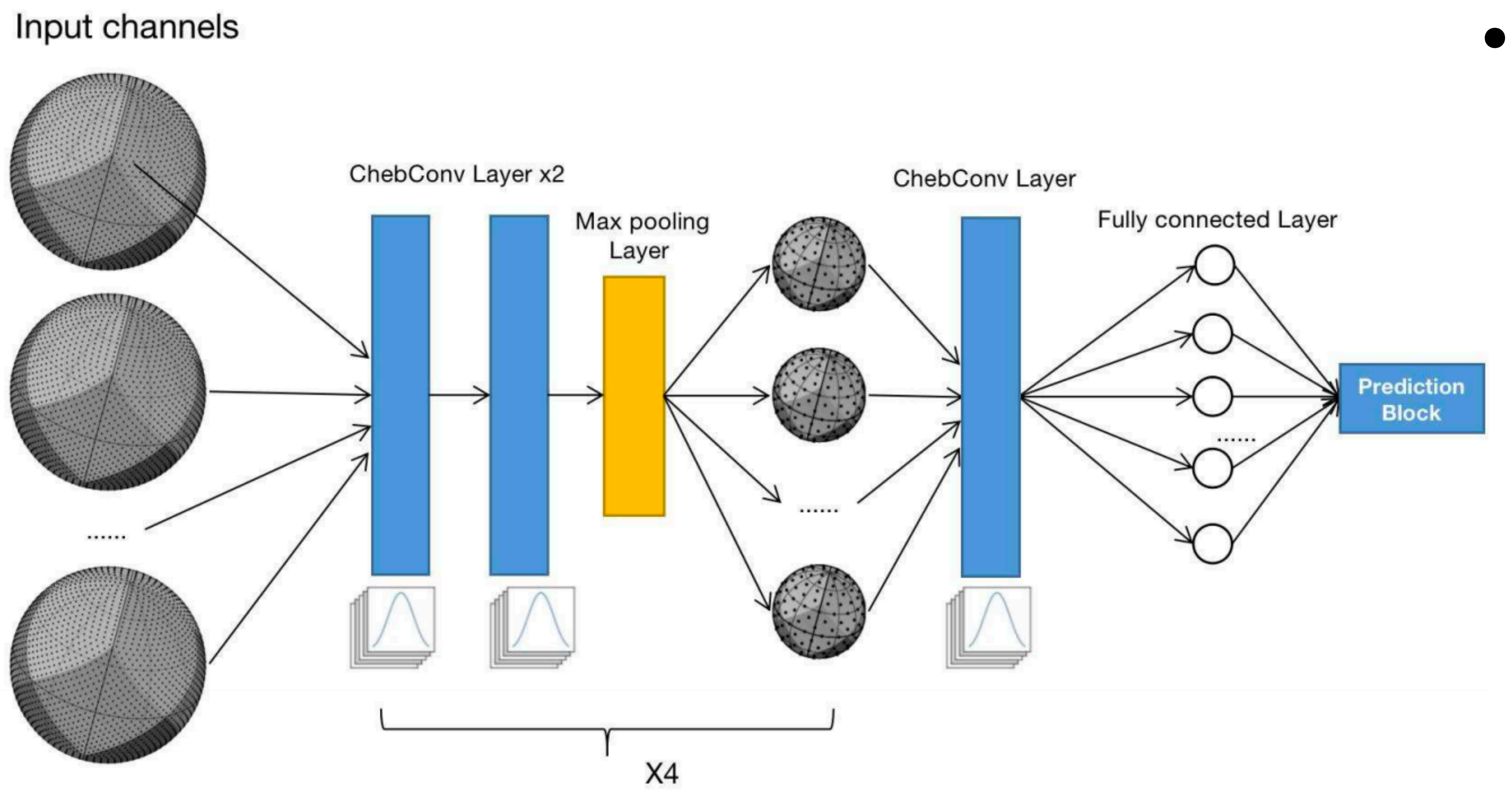
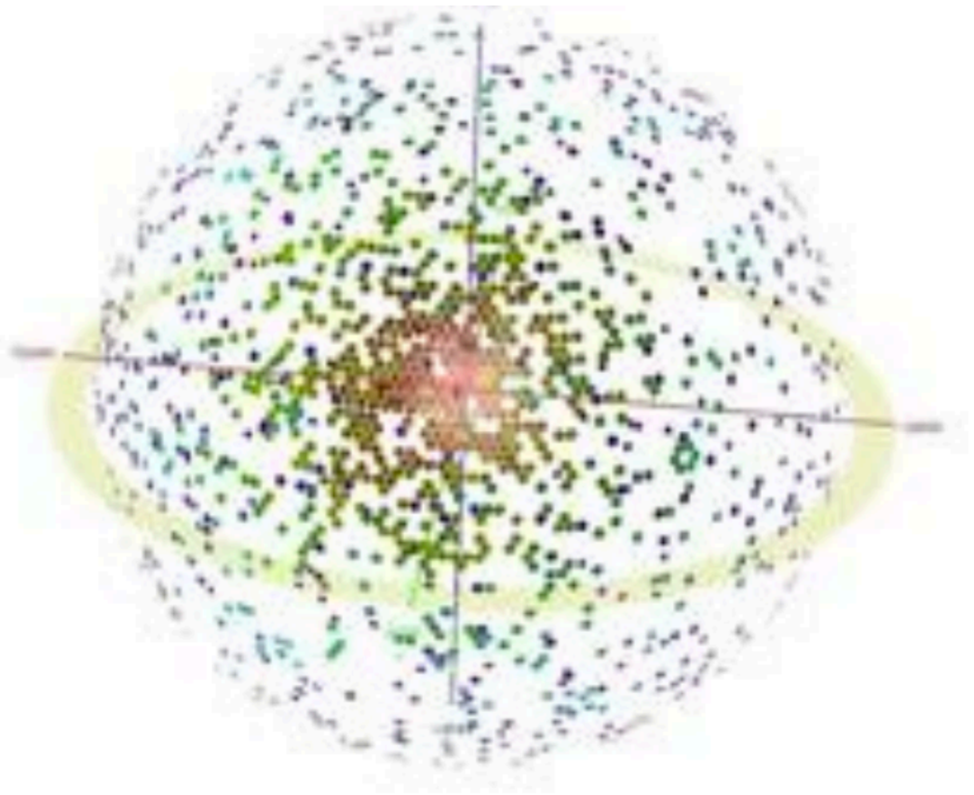
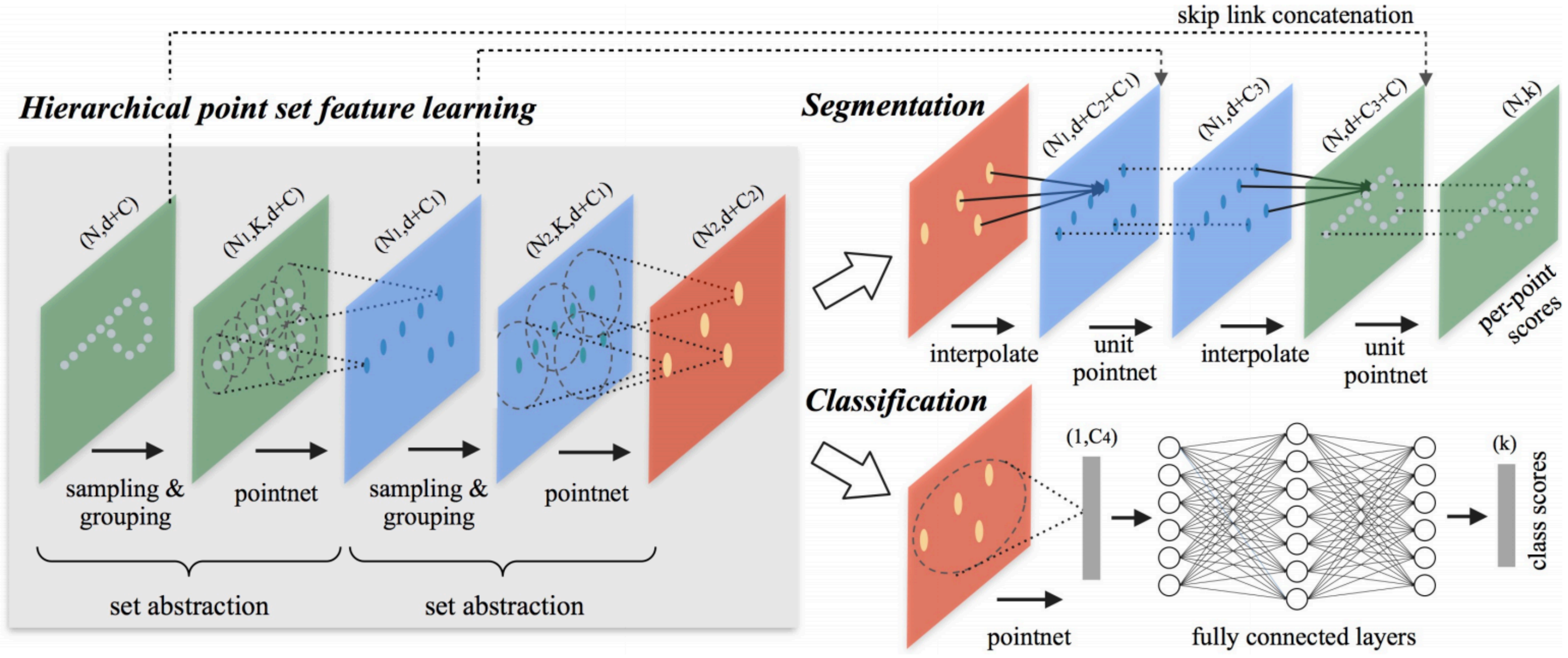


- Use Healpix sampling to define vertices
  - Equally divide the sphere into 12 parts
  - Further divide each part into N_{side} parts ($N_{side} = 2^n$)
  - Total number of pixels is 12×2^n
  - **If more than one PMTs are in one pixel, info is merged**

3D point-cloud: PointNet++

- Directly taking 3D point clouds ($N(PMT) \times$ [x, y, z, features...]) as inputs
- Detector signal more resemble **point clouds**
  - Minimise information loss during projection

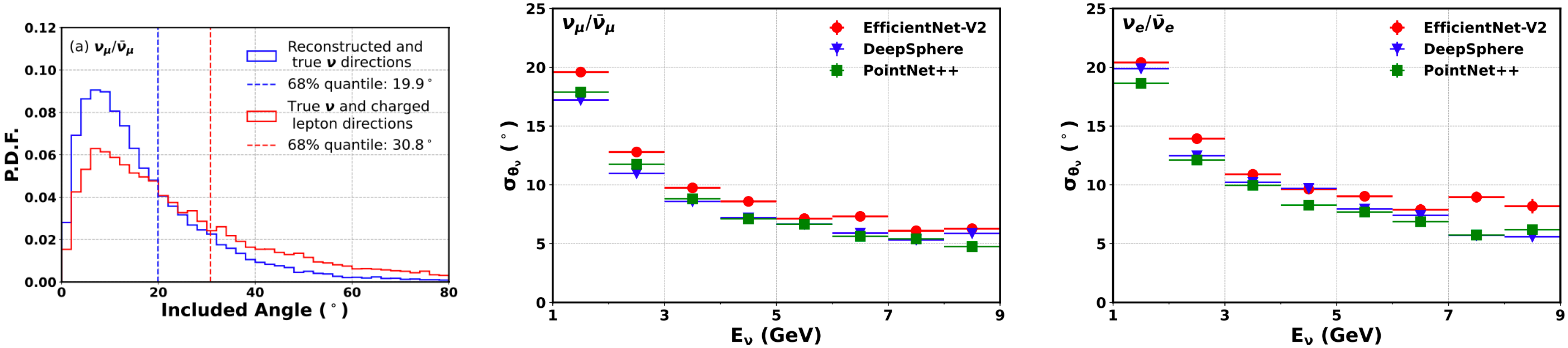




Directional reconstruction

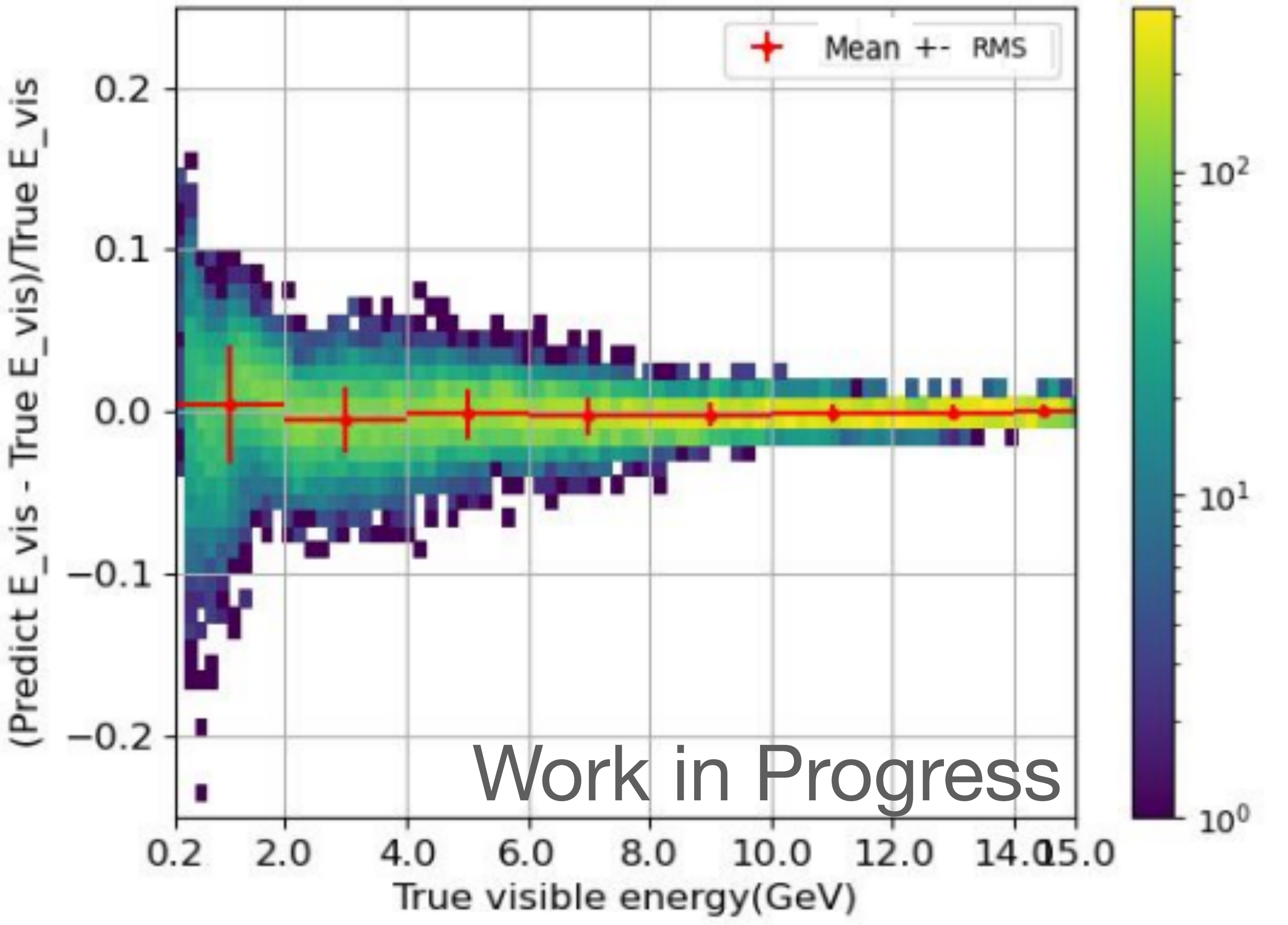
arxiv:2310.06281

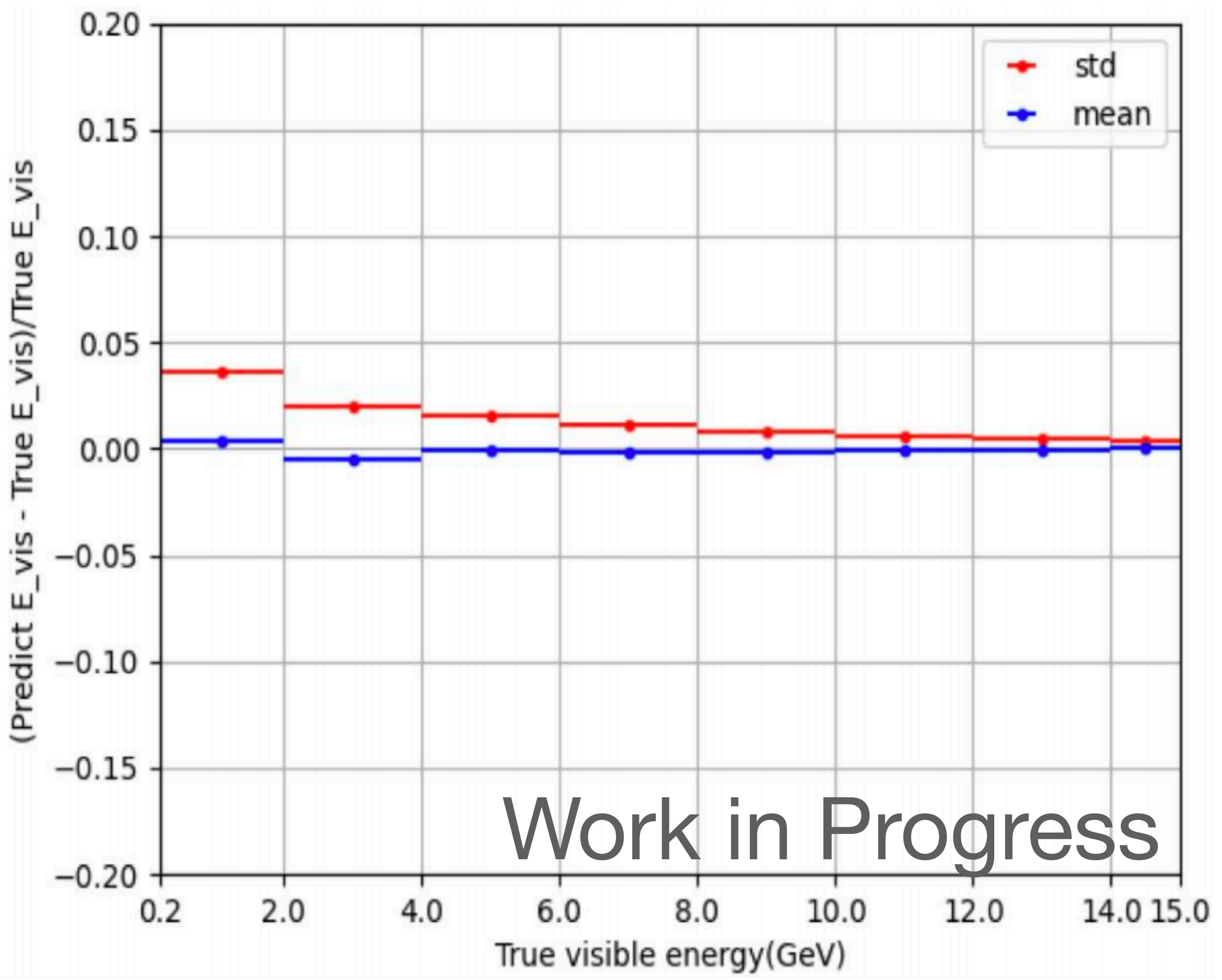
- Scintillation light from both leptons and hadrons are capable to directly reconstructing ν_{atm} direction
- Used JUNO Monte-Carlo sample: Data sample: 135k $\nu_\mu/\bar{\nu}_\mu$, 57k $\nu_e/\bar{\nu}_e$ Charged-Current events, 80% training
- Systematic effects from ν interaction models and electronic effects are studied
- Paper accepted, to be published in PRD
- **First demonstration in reconstructing ν_{atm} direction in a LS detector with MC**

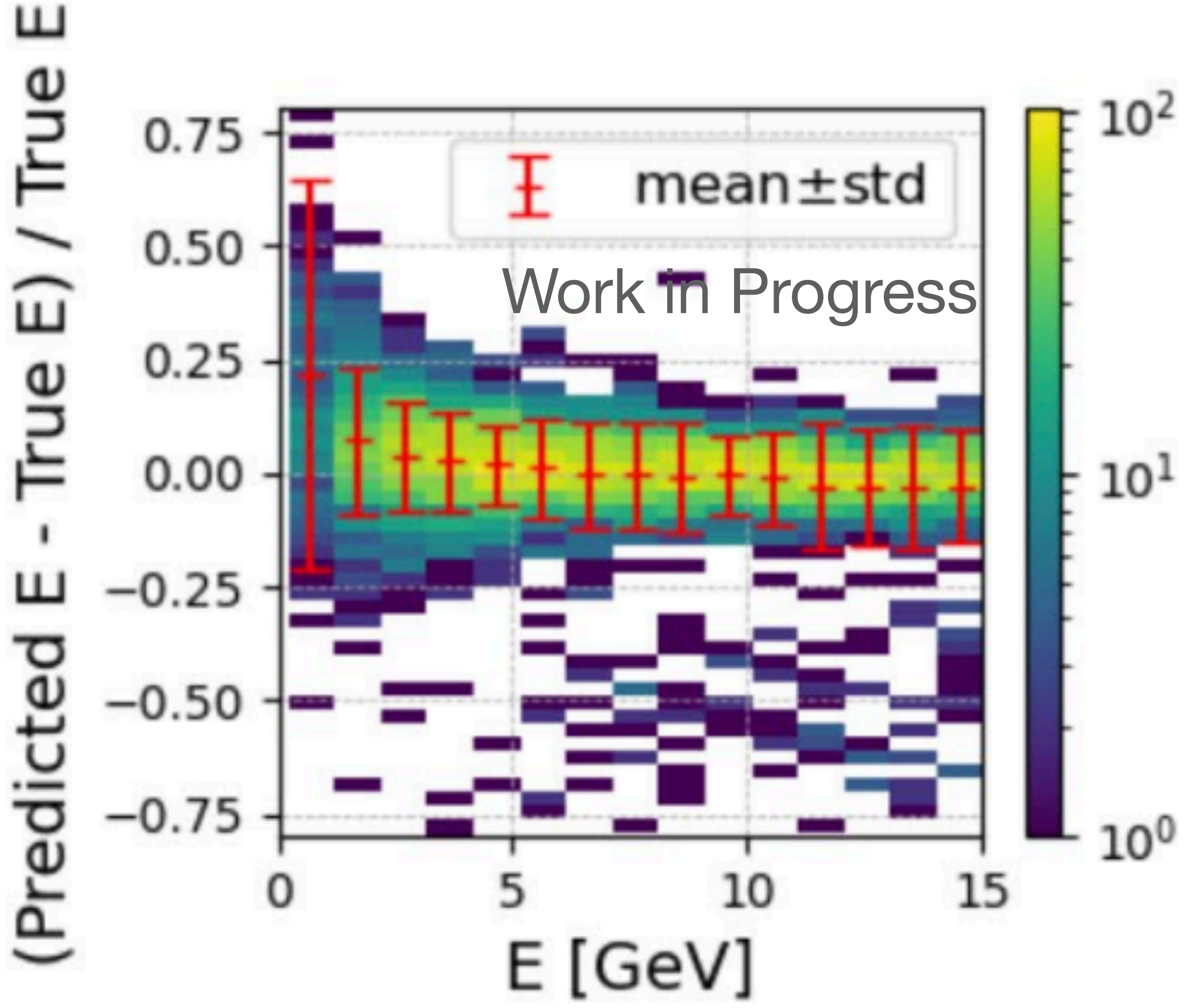


Energy reconstruction

- Energy reconstruction based on the **Spherical** and **Planar** models
- Same dataset is used as directional reconstruction
- Can reconstruct both E_{vis}/E_{ν} with good resolution

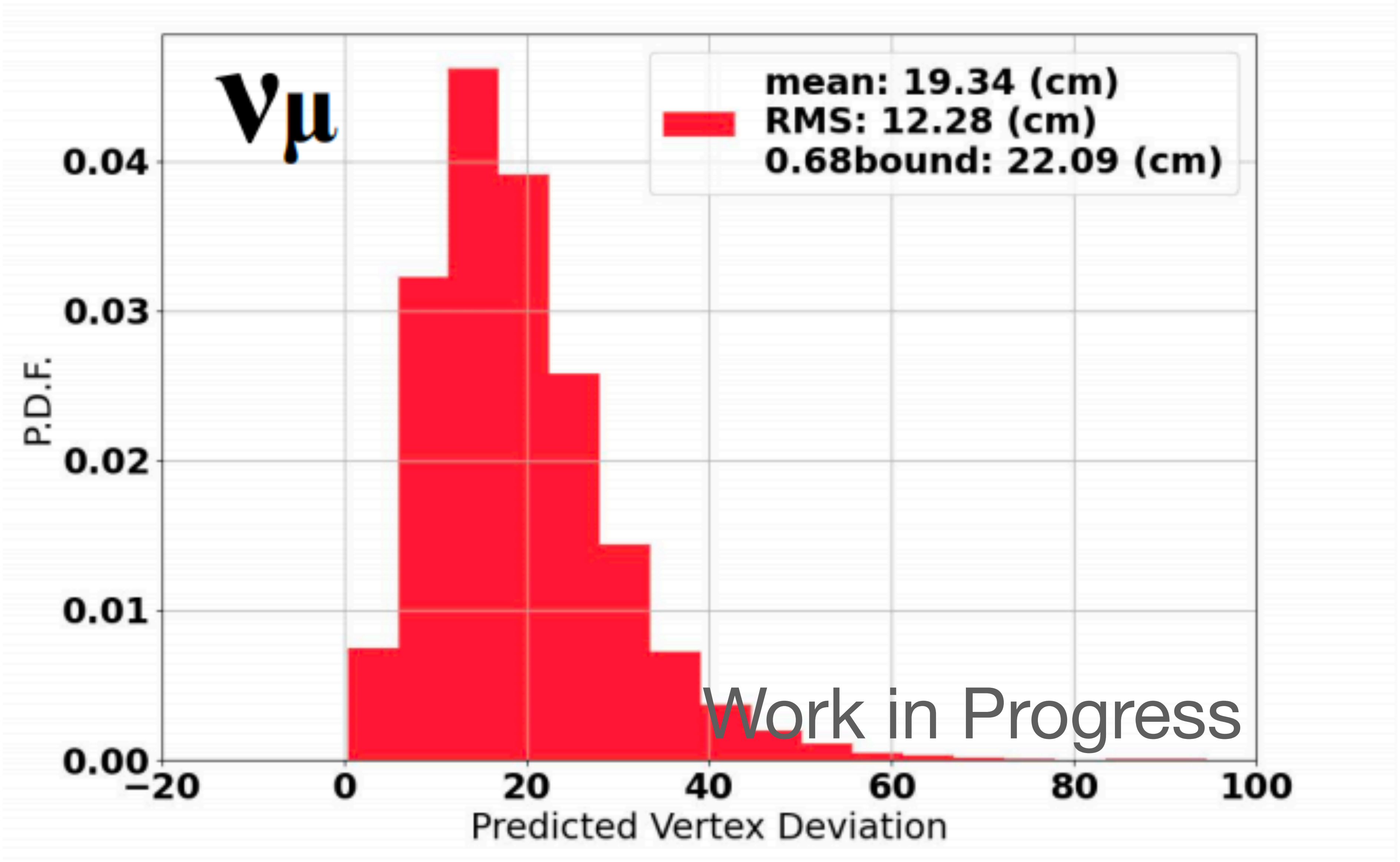


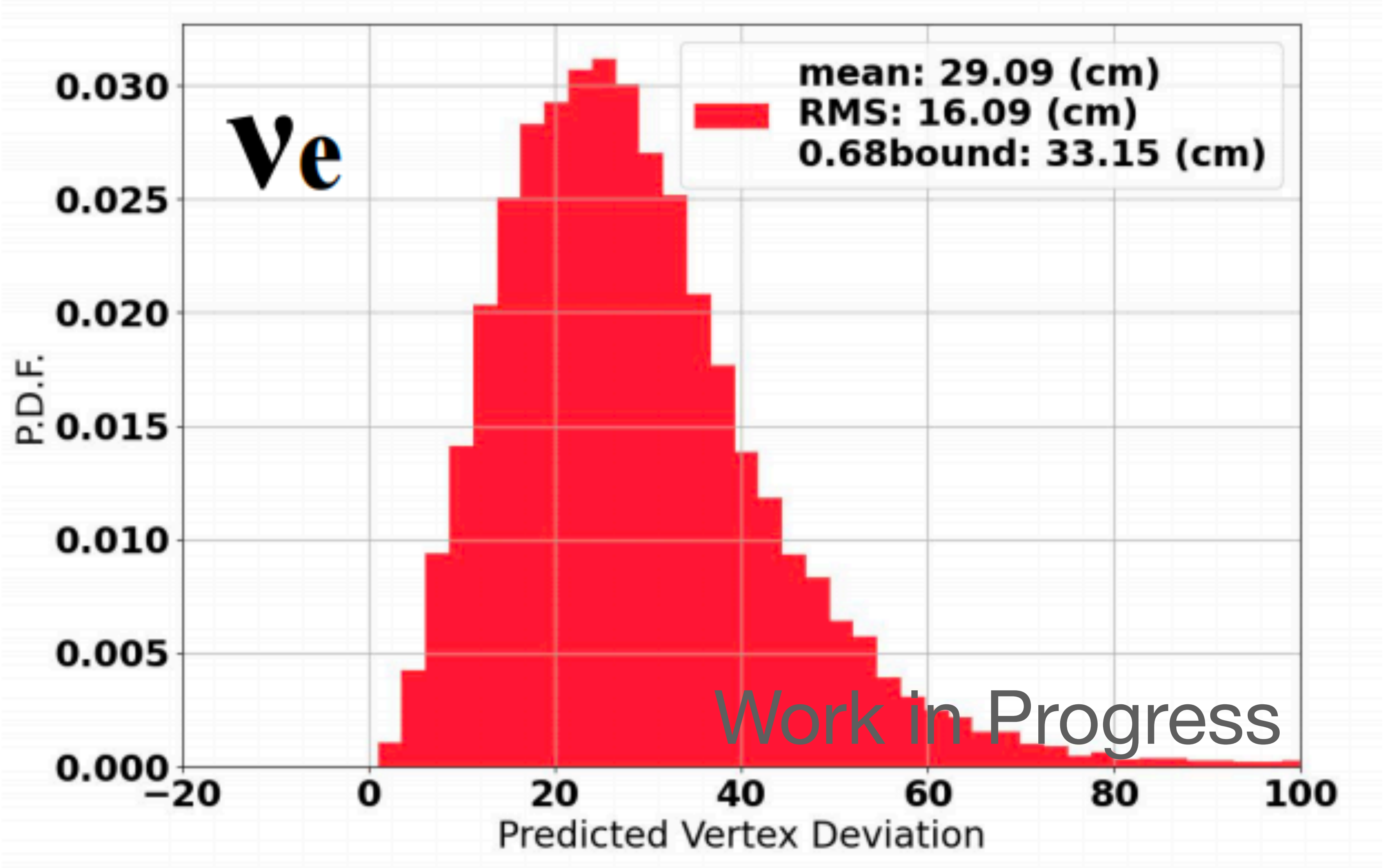




Vertex reconstruction

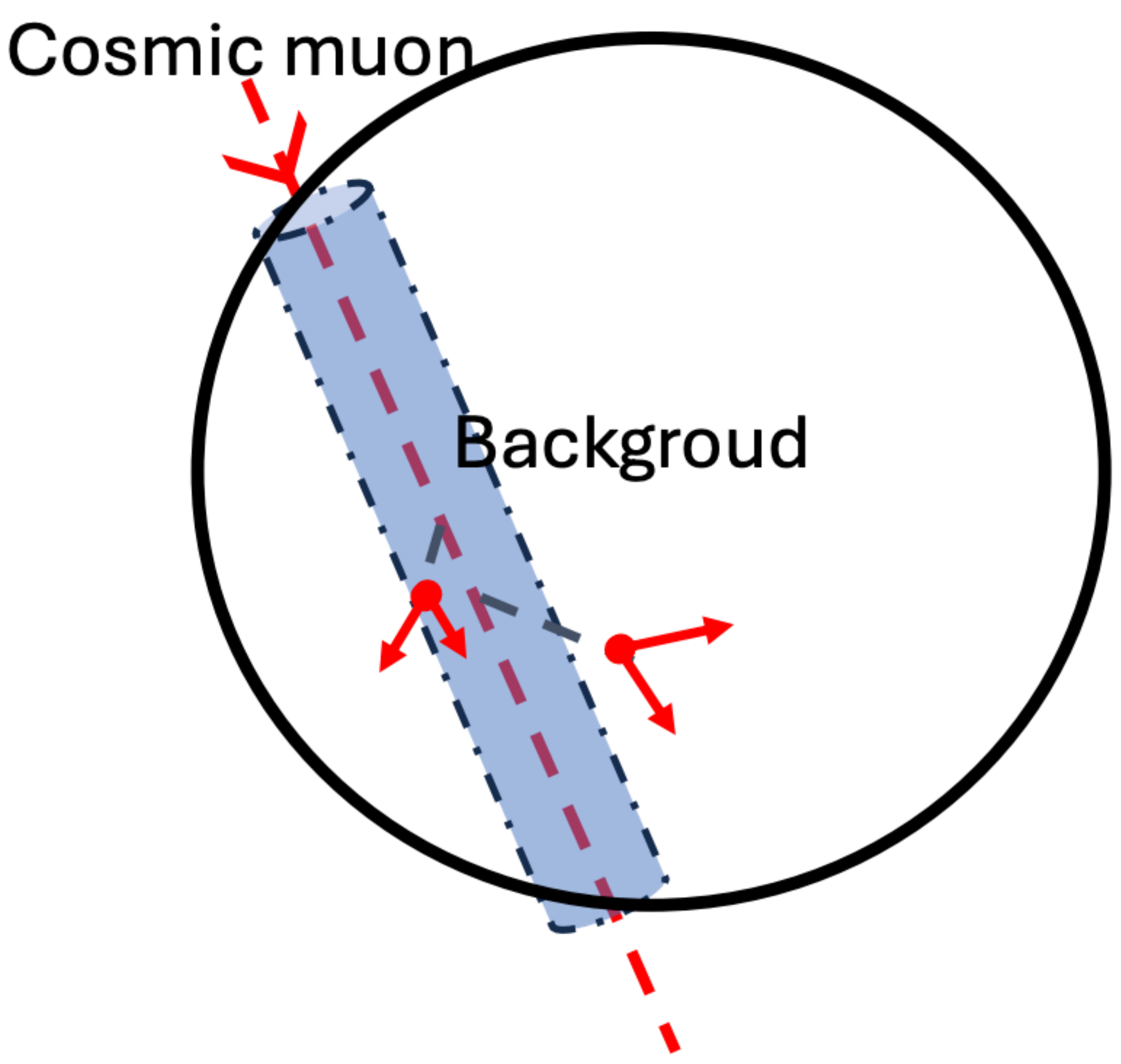
- Models output vertex position x, y, z
- Resolution defined by the 68% quantile of distance between true and reconstructed vertices
- Vertex resolution for ν_μ ~20 cm and ν_e ~30 cm, muon tracks are cleaner





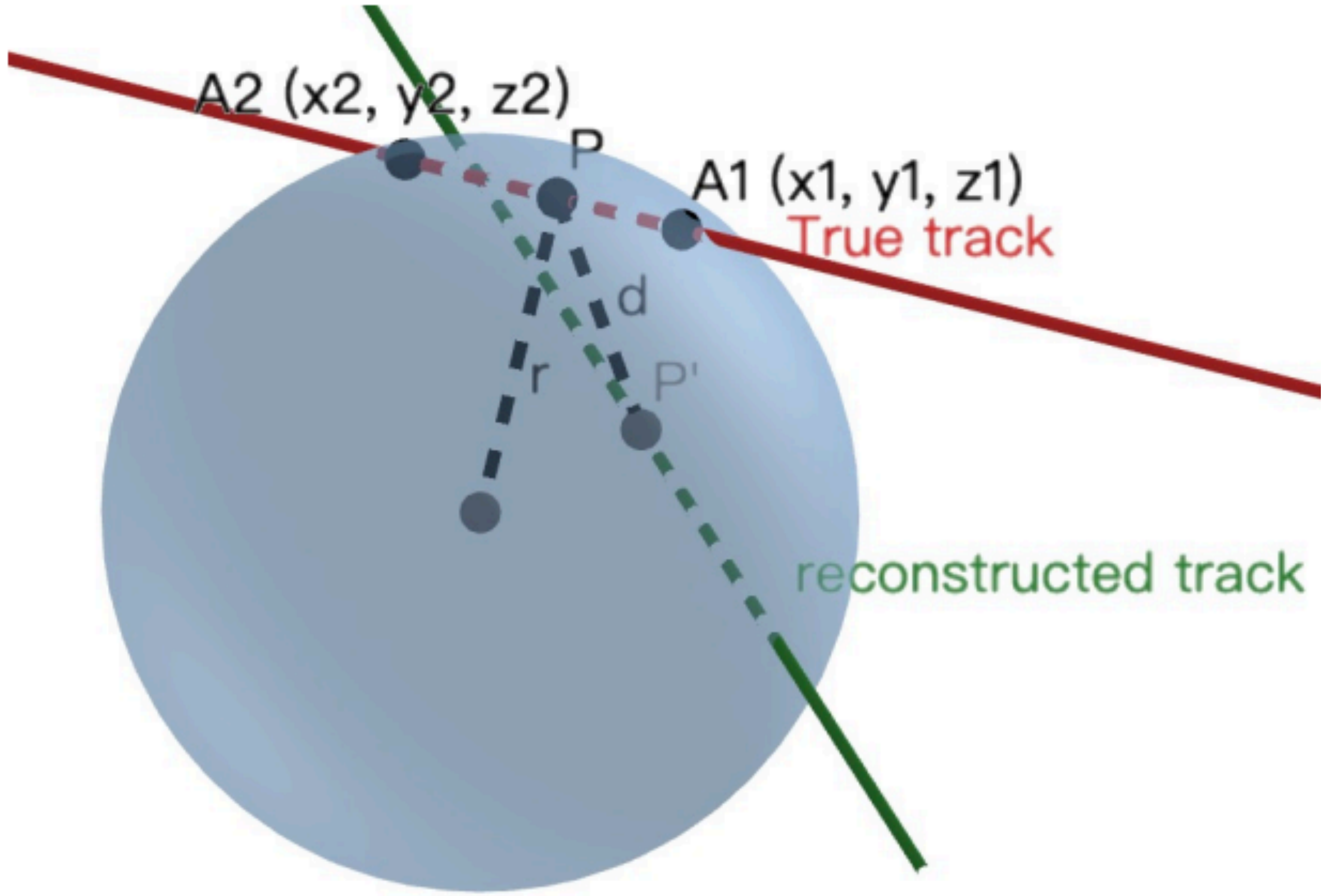
Reconstructing muon events

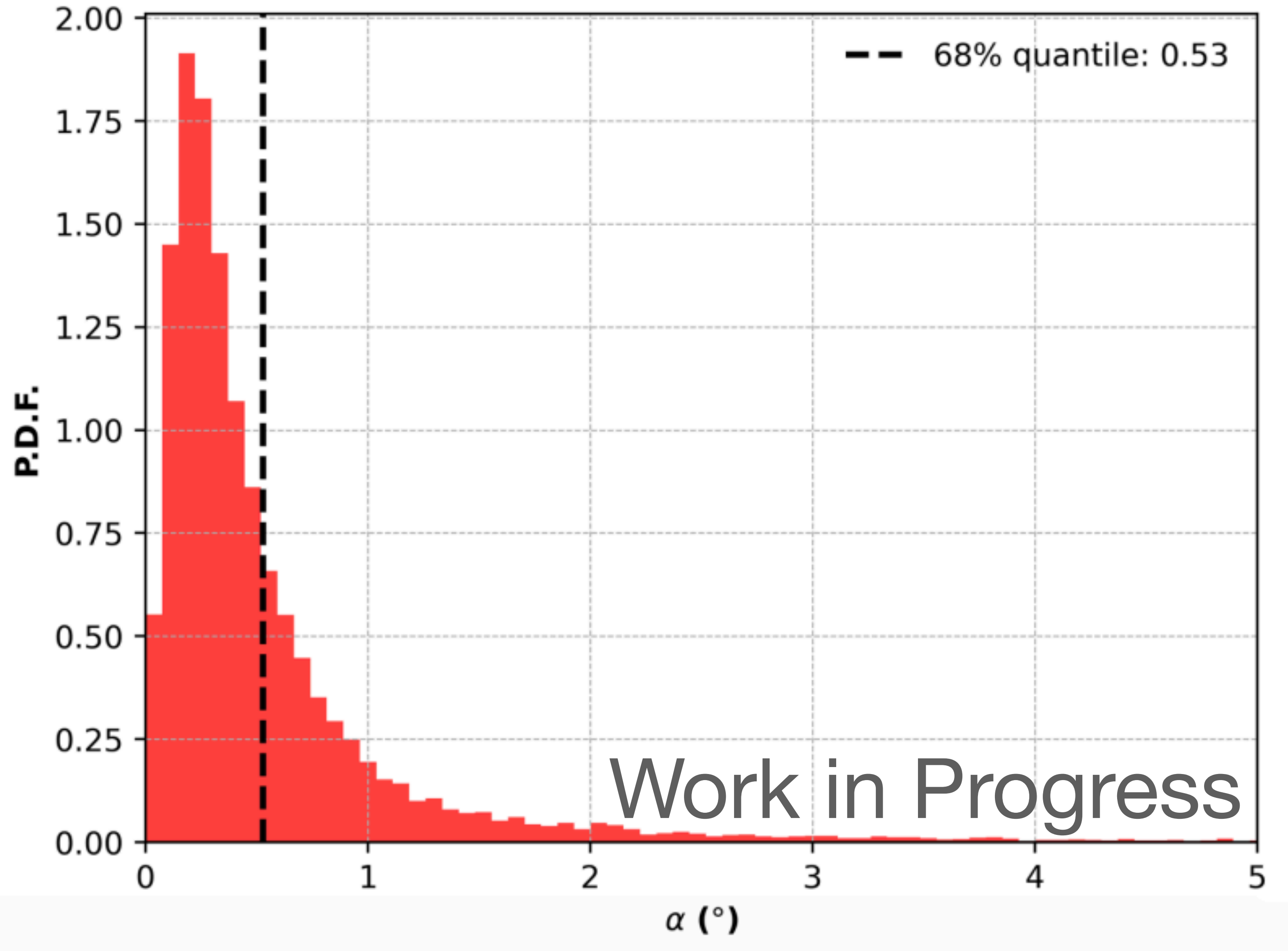
- Cosmic muons penetrate the detector and can interact
- Many isotopes (such as $^{8}He/^{9}Li$) are produced along their tracks
  - Main background of signal from reactor neutrinos
- Accurately identifying such events is key to physics analyses

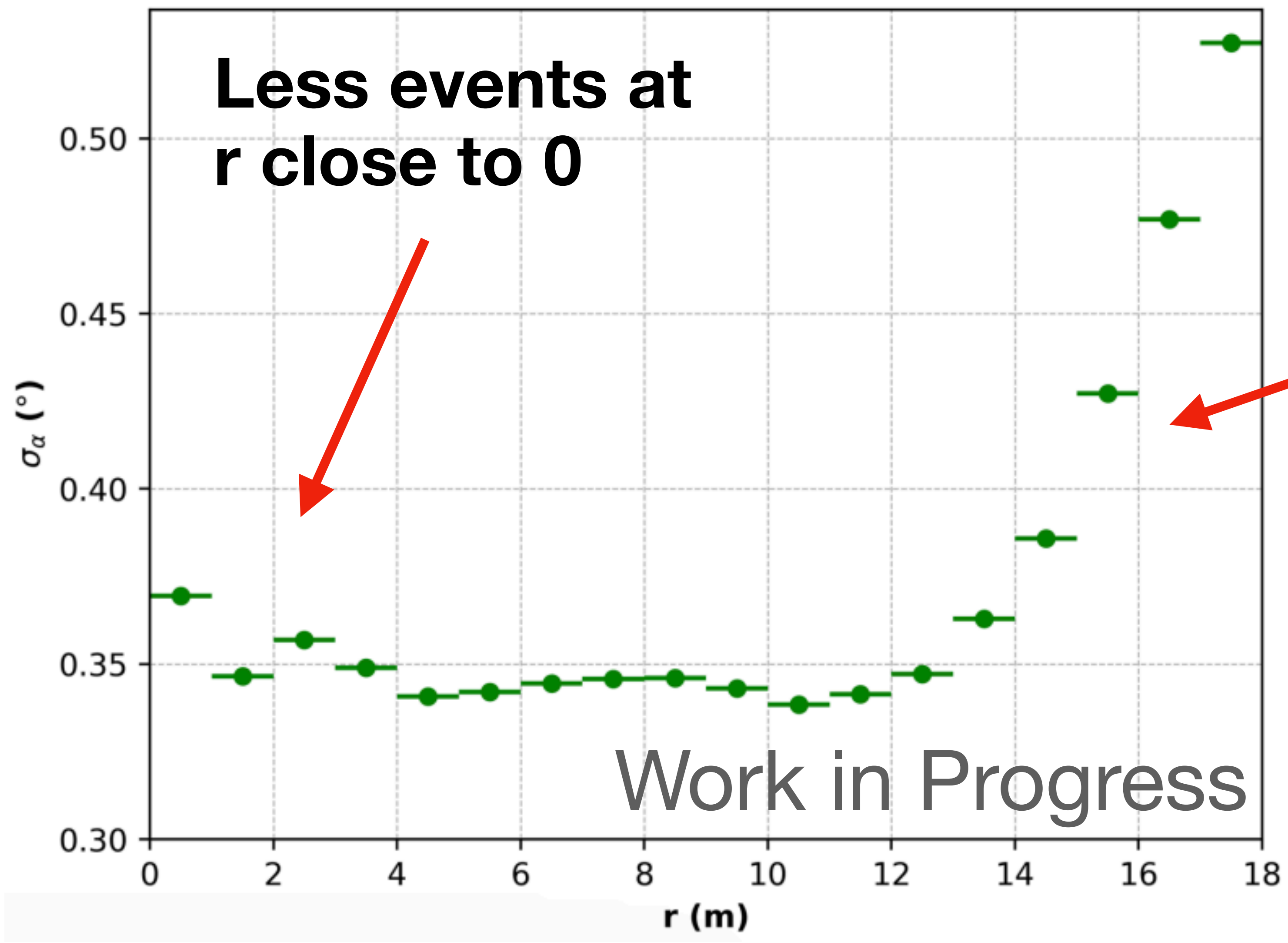


Reconstructing muon tracks

- Attempt to reconstruct A1, A2 and direction of true tracks for identifying cosmic muons
- Quantify directional reconstruction performance by α (angle between true and reconstructed track)



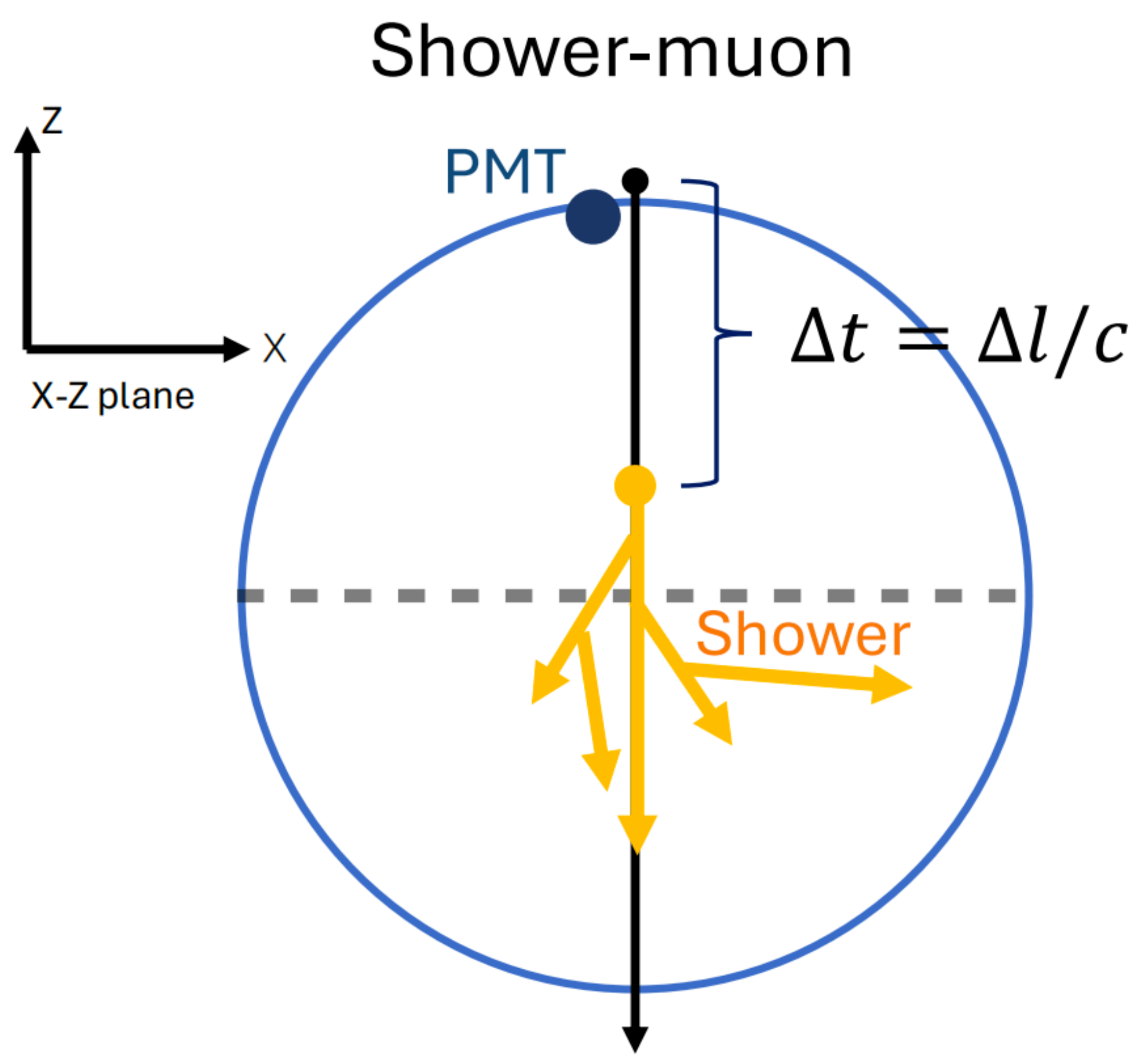


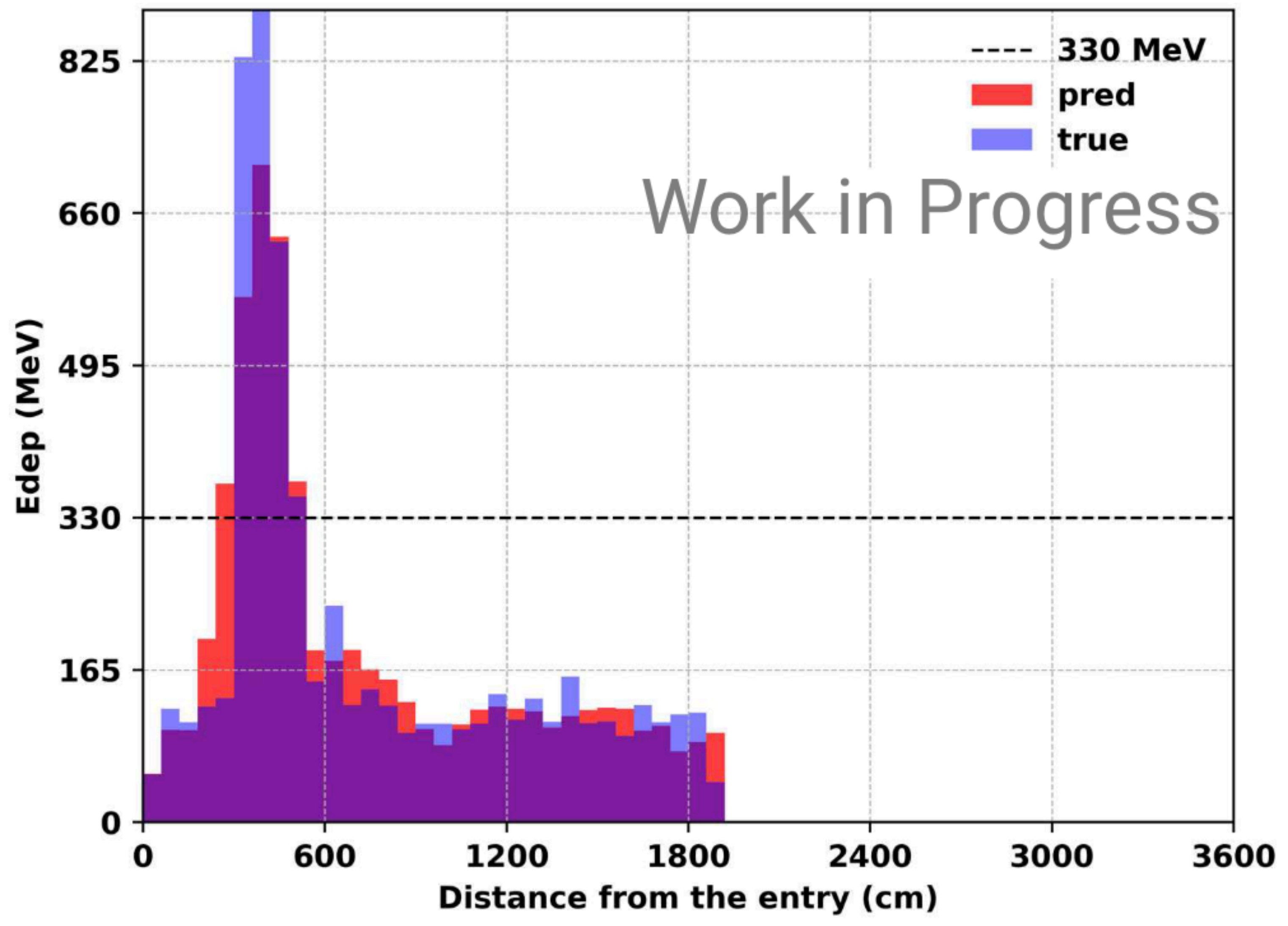


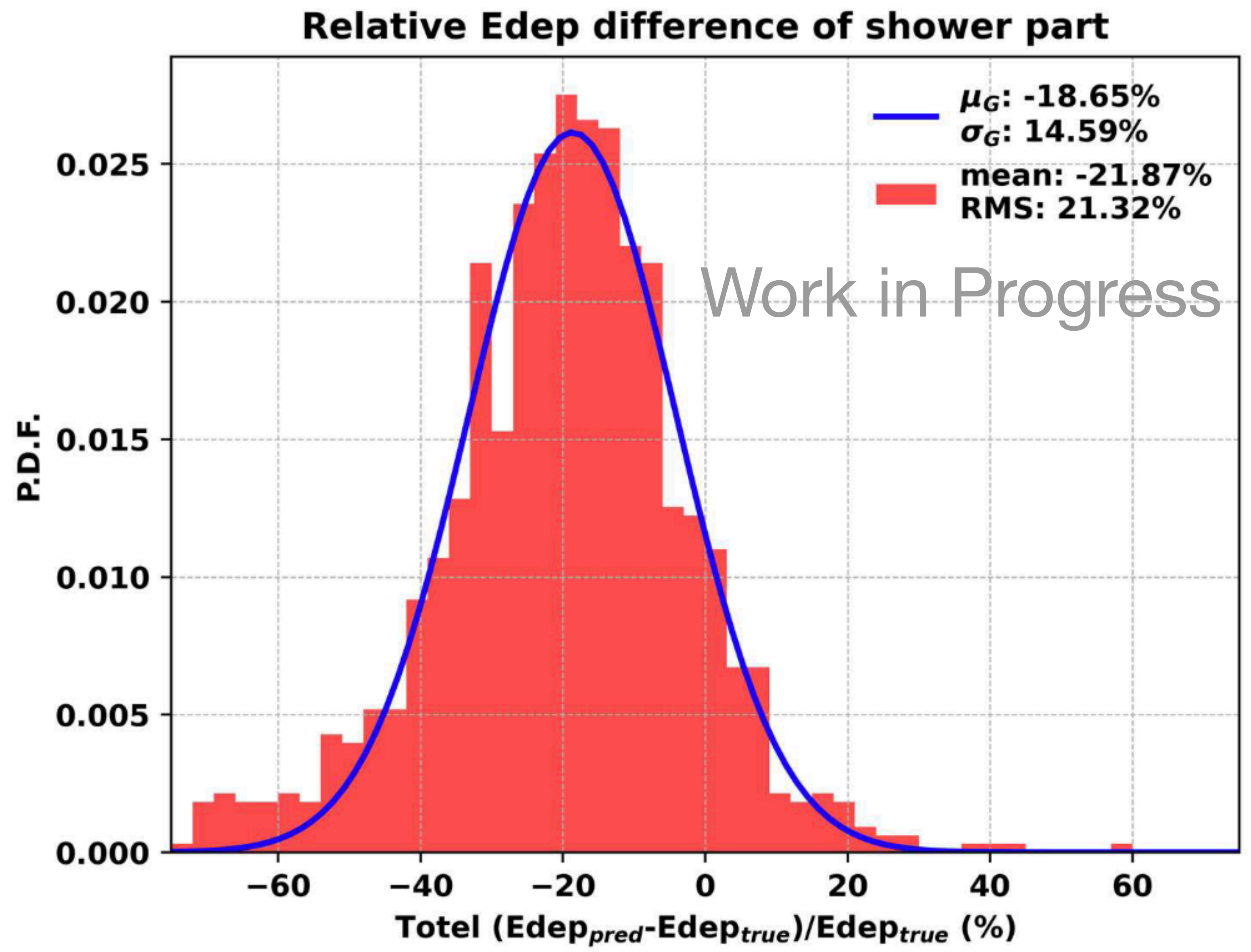
Track length shorten as r increase

Reconstructing muon showers

- Also need to know E_{dep} of showers to veto isotopes production - reconstruct dE/dx along muon track
- Can very well reconstruct the peak E_{dep} with RMS of 1 bin
- Total E_{dep} of shower reconstructed < true - possibly interfered by E_{dep} from the actual muon

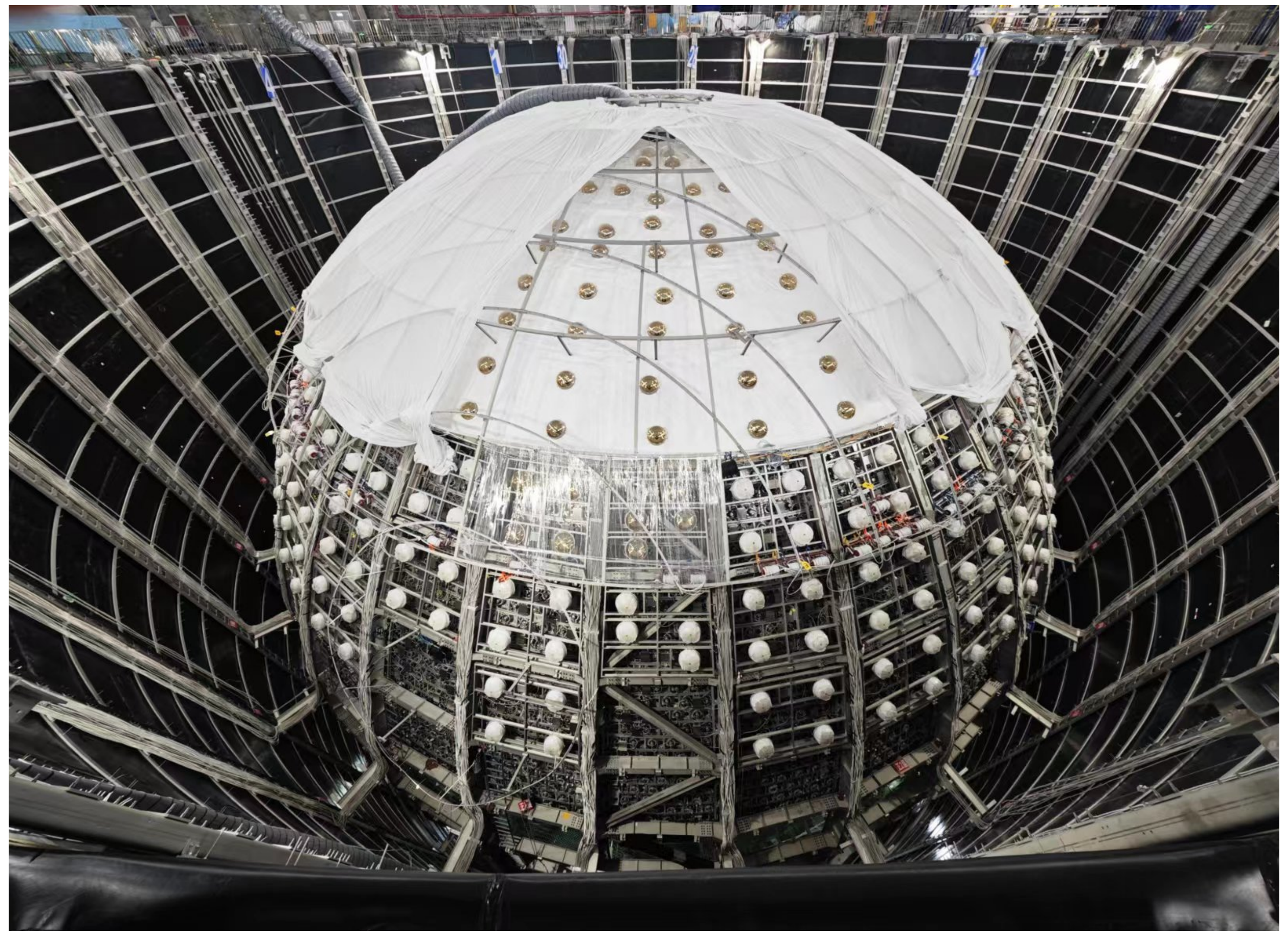






Summary

- A novel method of reconstructing events for LS detector is presented
- Multiple ML models are developed to validate the reconstruction method
- Using JUNO MC samples, different variables that are crucial to physics analyses such as **direction, energy** of atmospheric neutrinos can be reconstructed with good resolution
    - Learn about **particle identification** in an another talk on Wednesday!



Backup

JUNO Event Rates after selection