

# Machine-Learning-Based Reconstruction of Atmospheric Neutrino Events in the JUNO Liquid Scintillator Detector

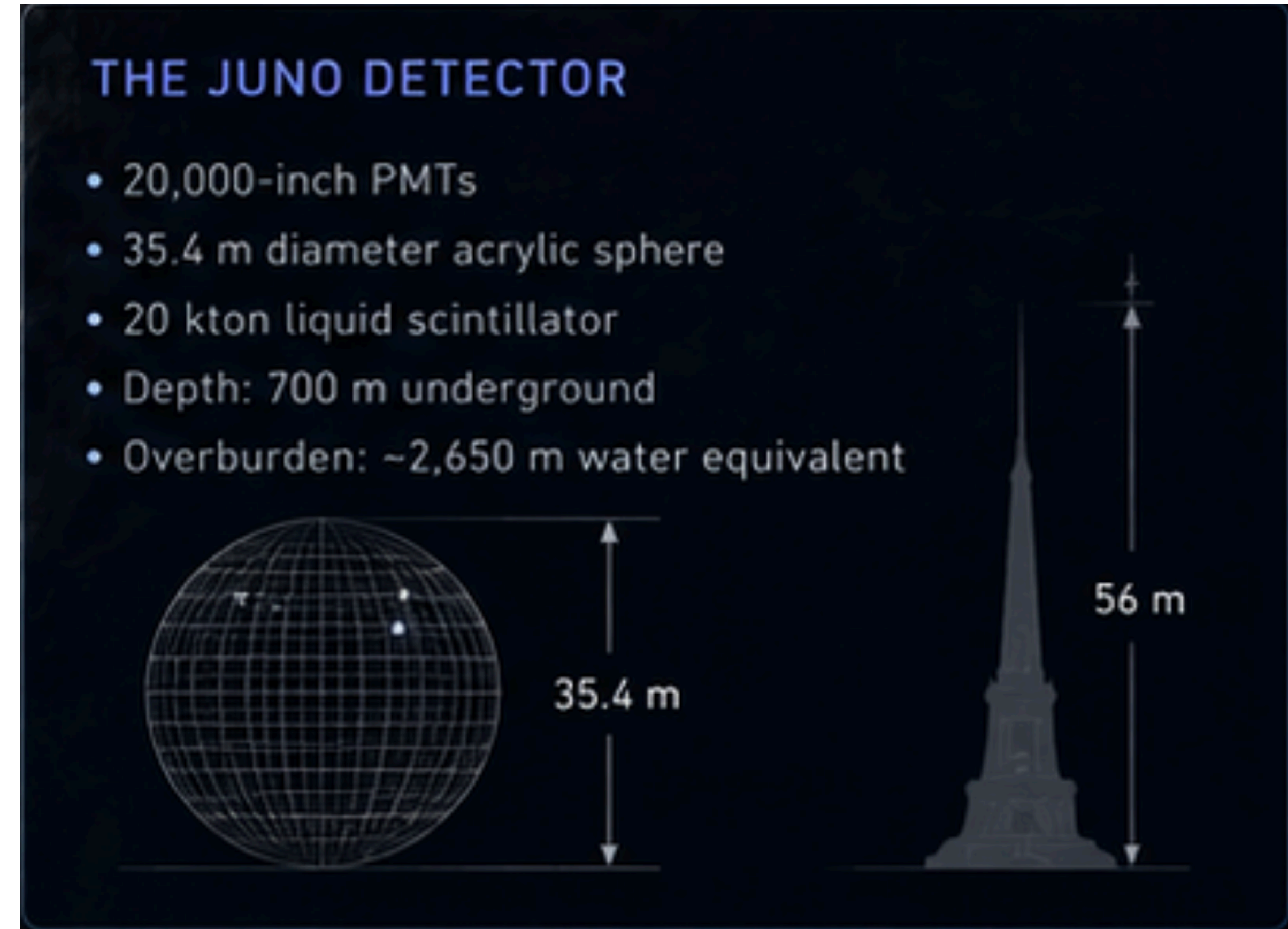
NPML 2026

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# The Jiangmen Underground Neutrino Observatory (JUNO)

## The Detector

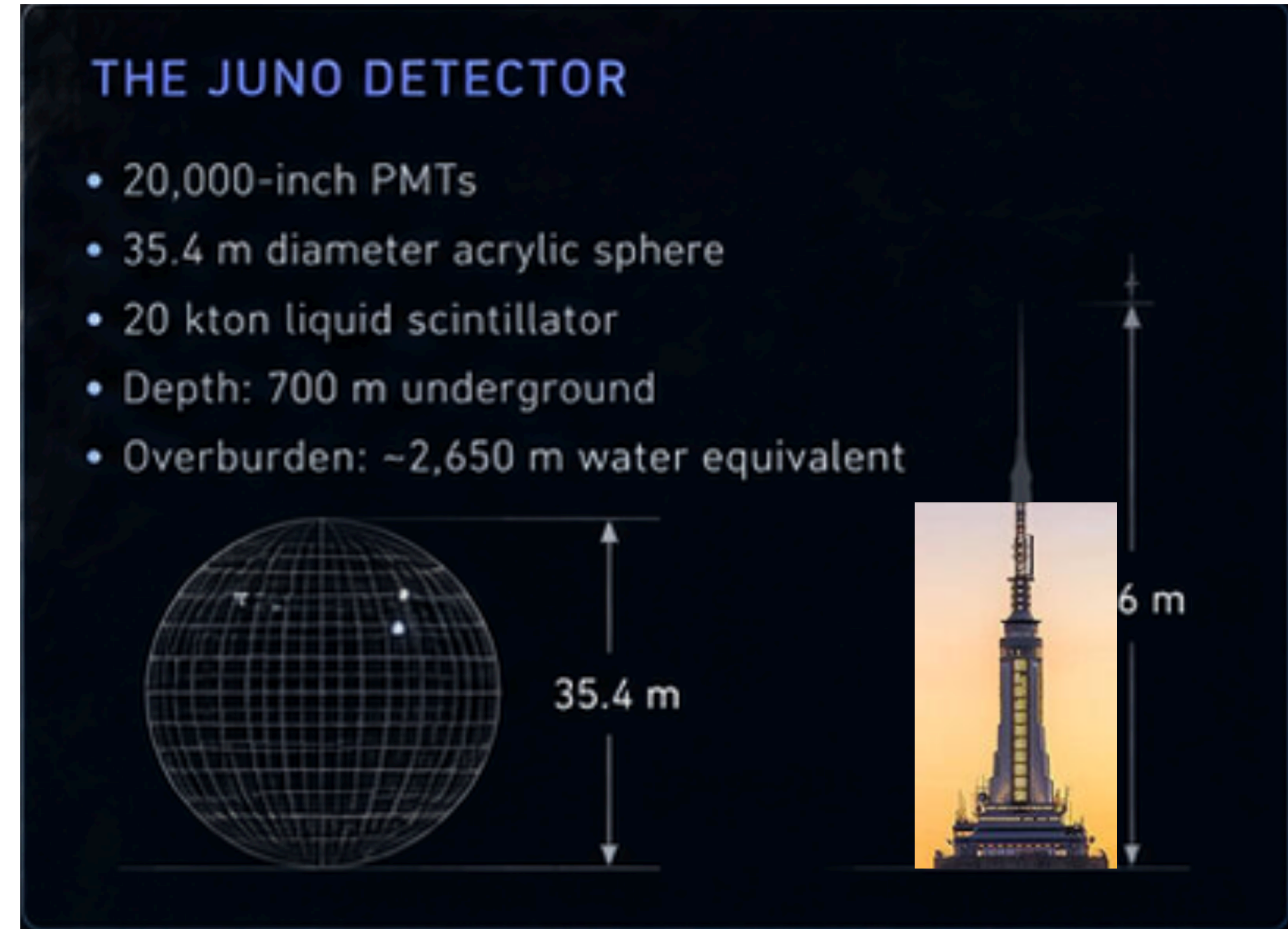
- 20 kt liquid scintillator detector
- ~18,000 large PMTs
- Main goal: measure Neutrino Mass Ordering (NMO) from reactor neutrinos
- Highly sensitive to reactor neutrinos, which have energy typically of  $O(1)$  MeV



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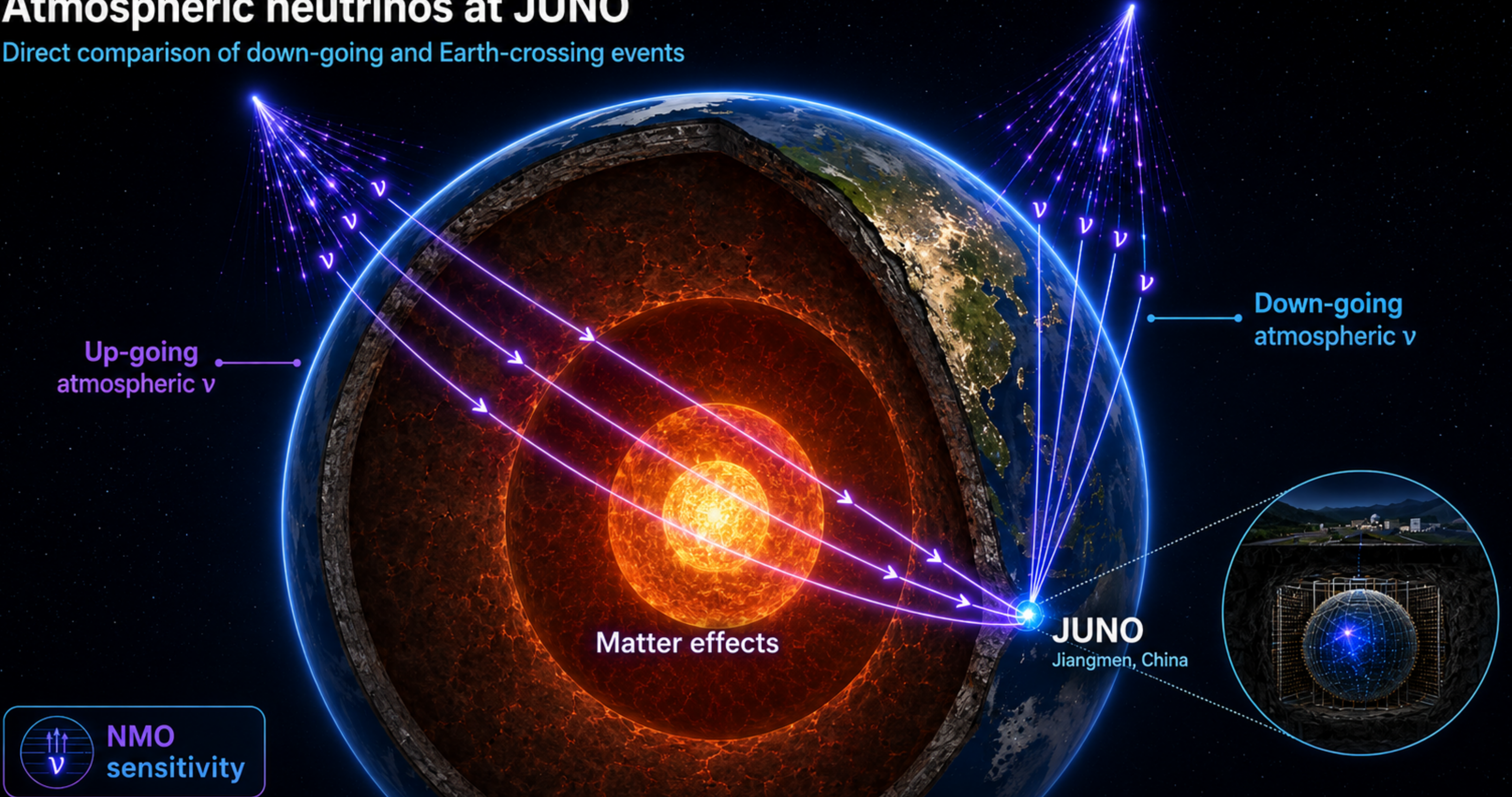
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AI-generated

# Atmospheric neutrinos at JUNO

Direct comparison of down-going and Earth-crossing events



# Atmospheric neutrinos

## The opportunity and the challenge

- Upward-coming atmospheric neutrinos travel through the entire Earth,
- potential to contribute to NMO sensitivity from accumulating matter effect.
- Atmospheric neutrinos are typically  $O(100)$  MeV  $\sim$   $O(10)$  GeV
  - drastically different from the  $O(1)$  MeV reactor neutrinos
- No obvious track or direction information.
- No control samples.

# Machine learning

## But how?

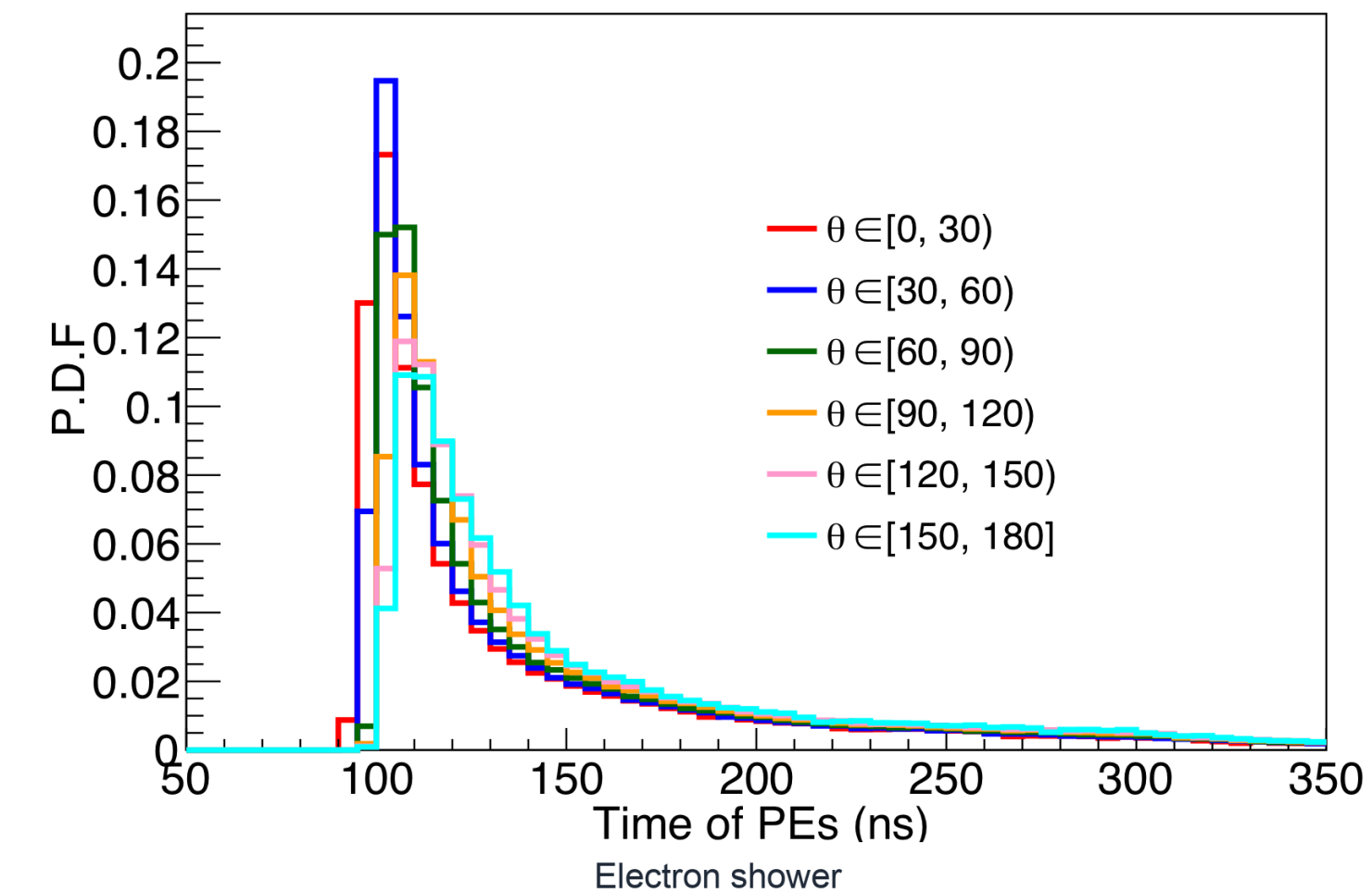
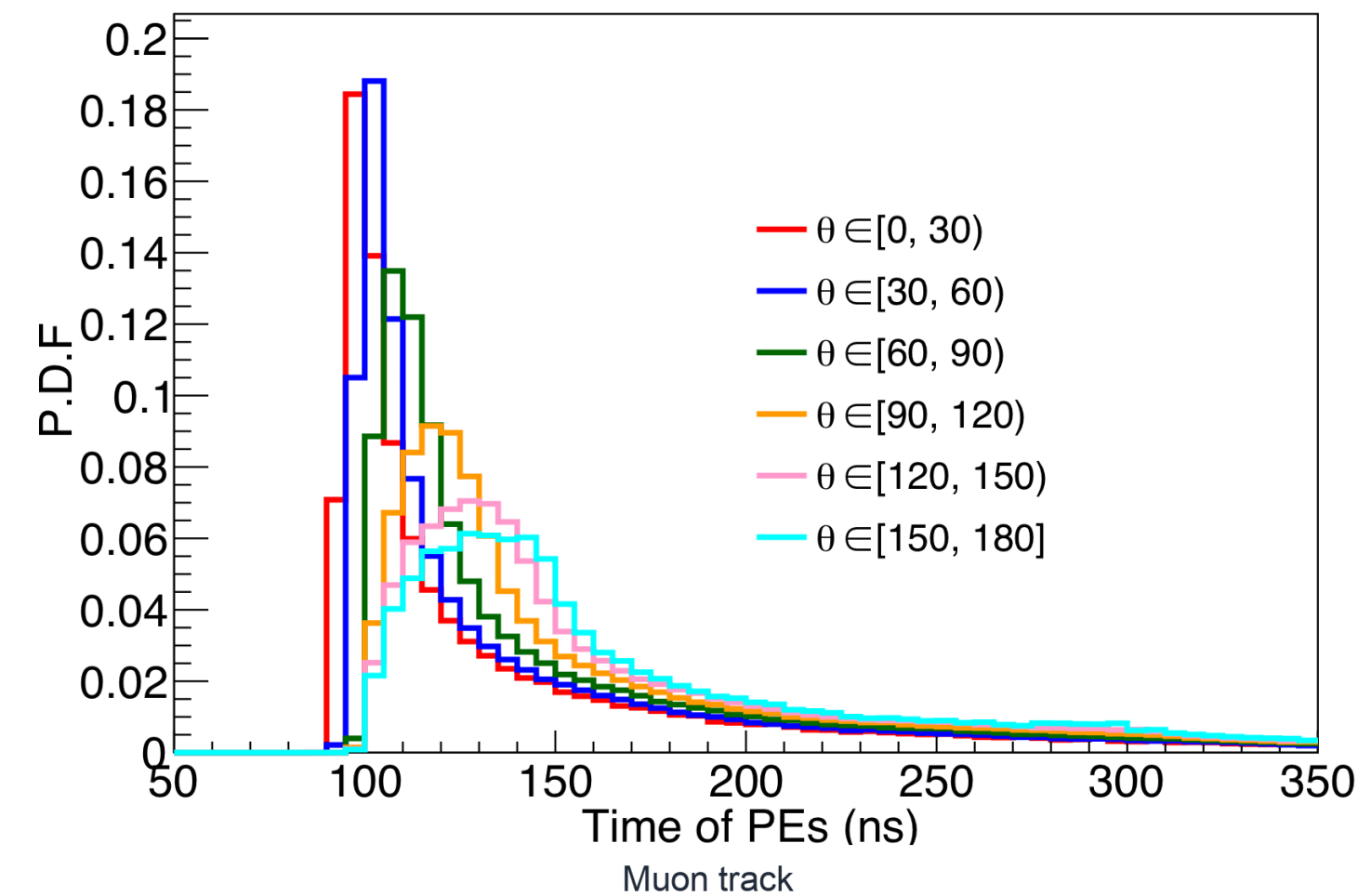
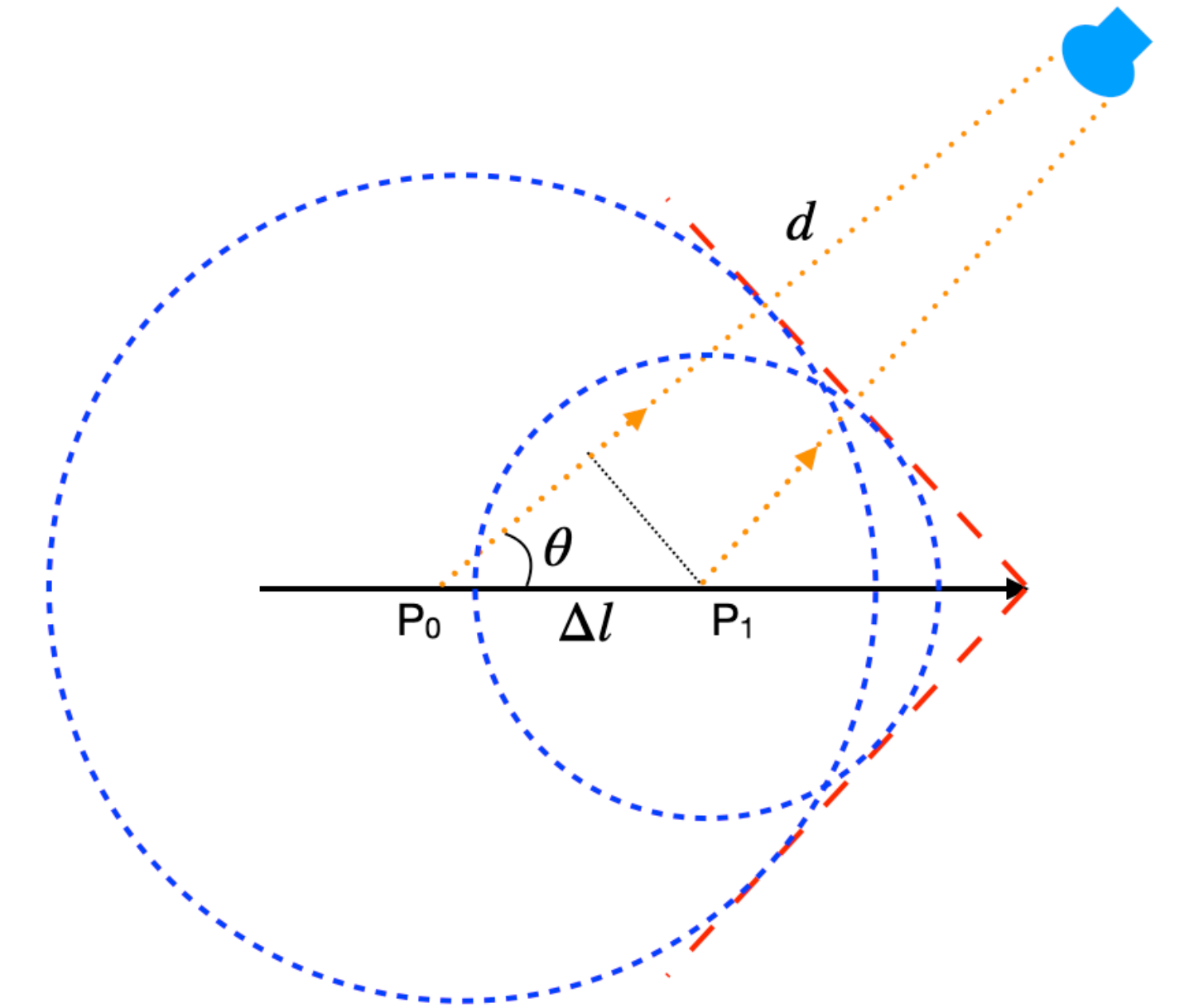
- Due to the Cherenkov effect, PMTs located at the Cherenkov angles have photons both before and after the specific location arriving at nearly the same time -> sharply rising edge

- Direction sensitivity

- Electrons triggering shower are less affected

- PID Potential

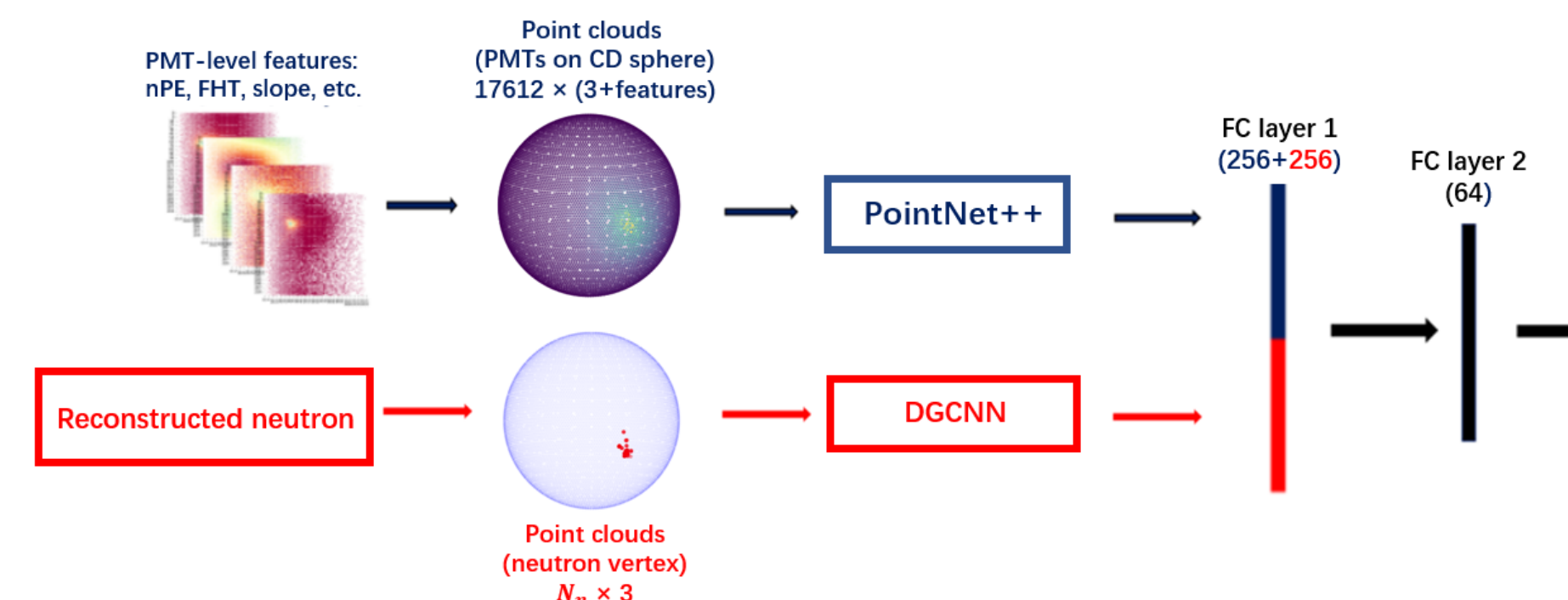
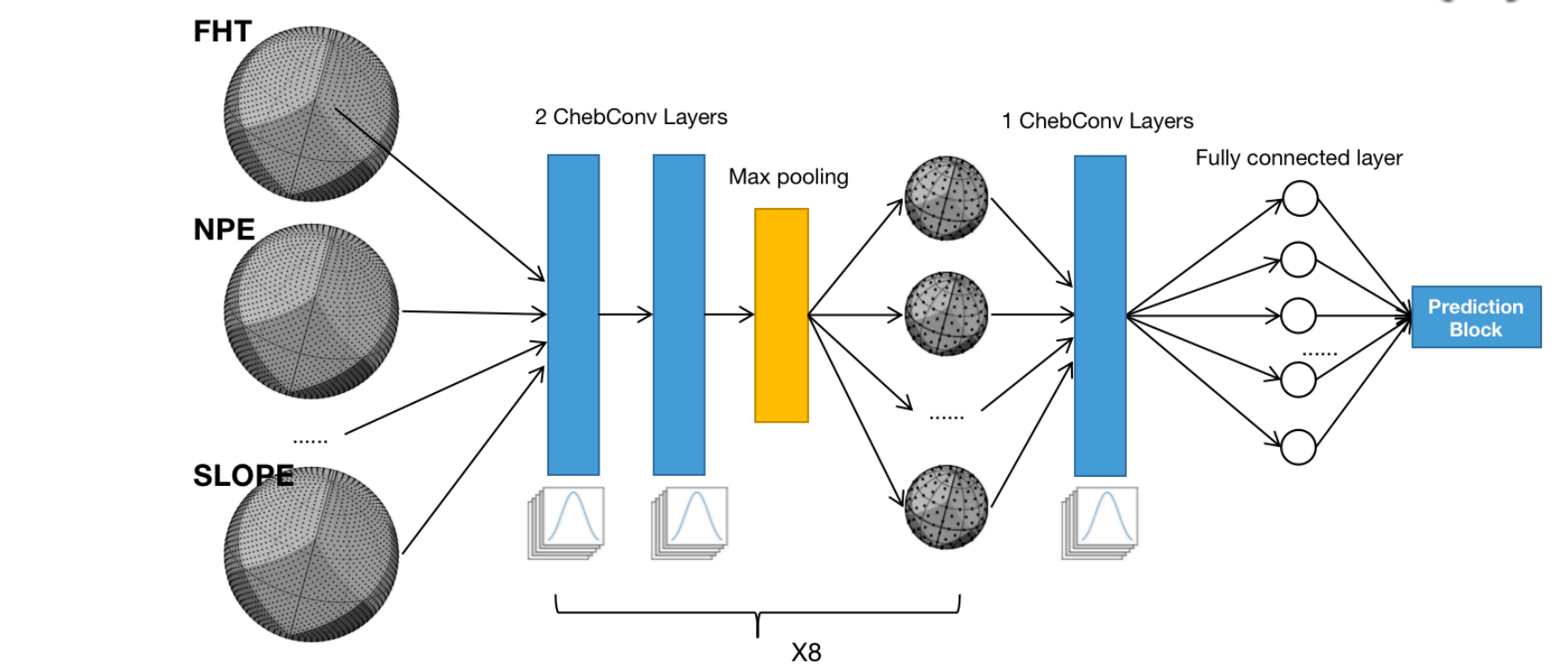
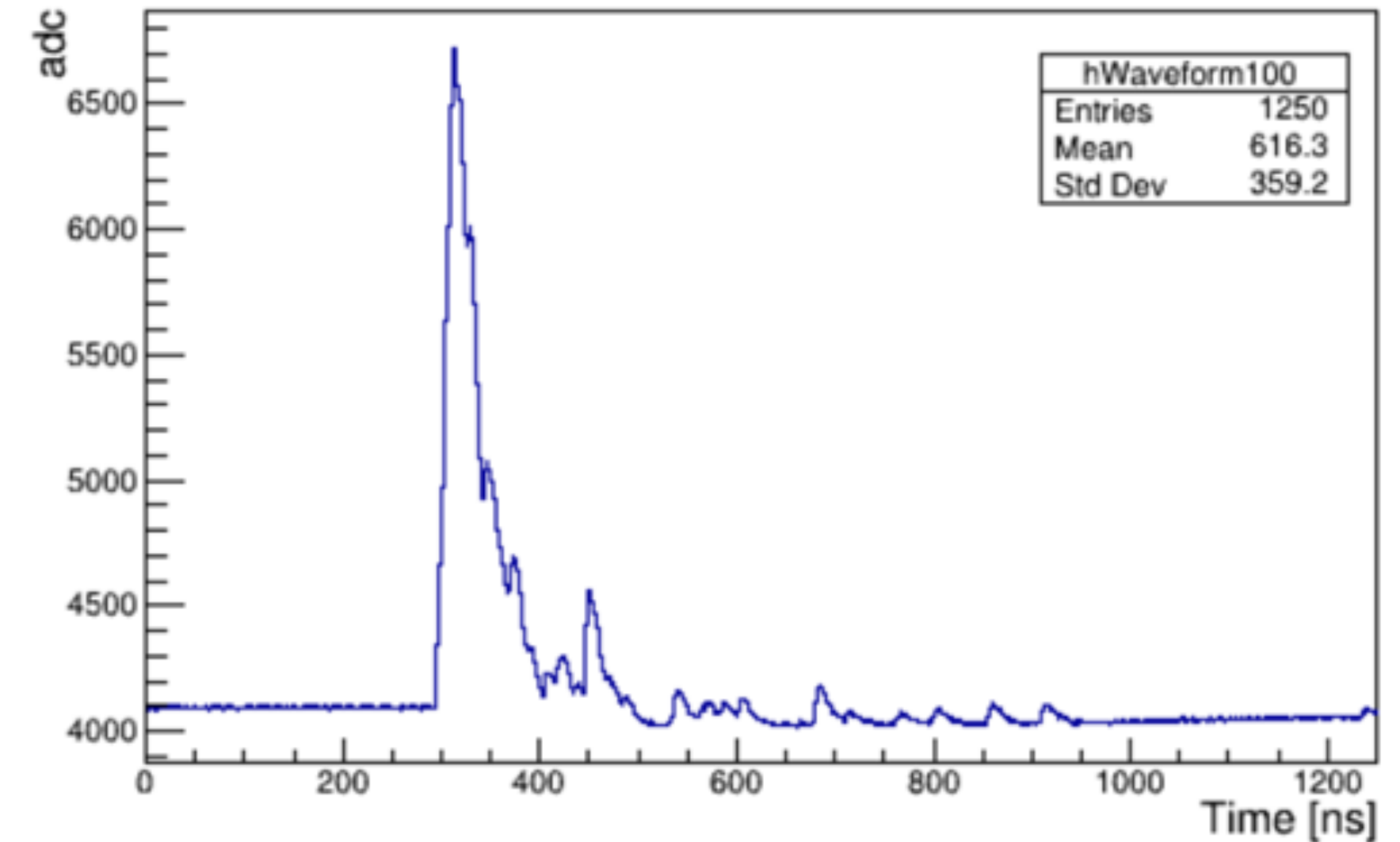
- Waveform shapes carry physics information



# Machine learning

## Implementation

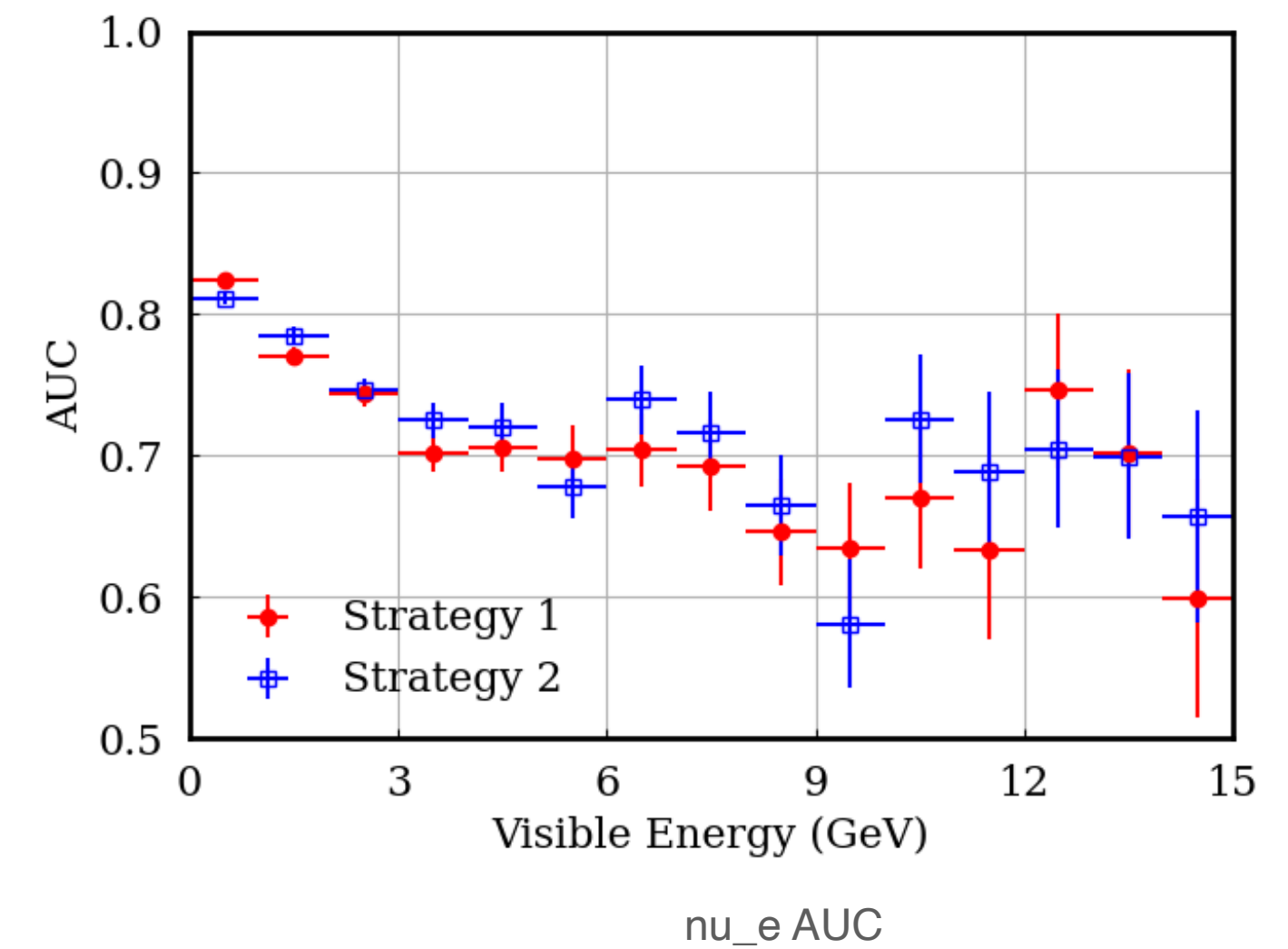
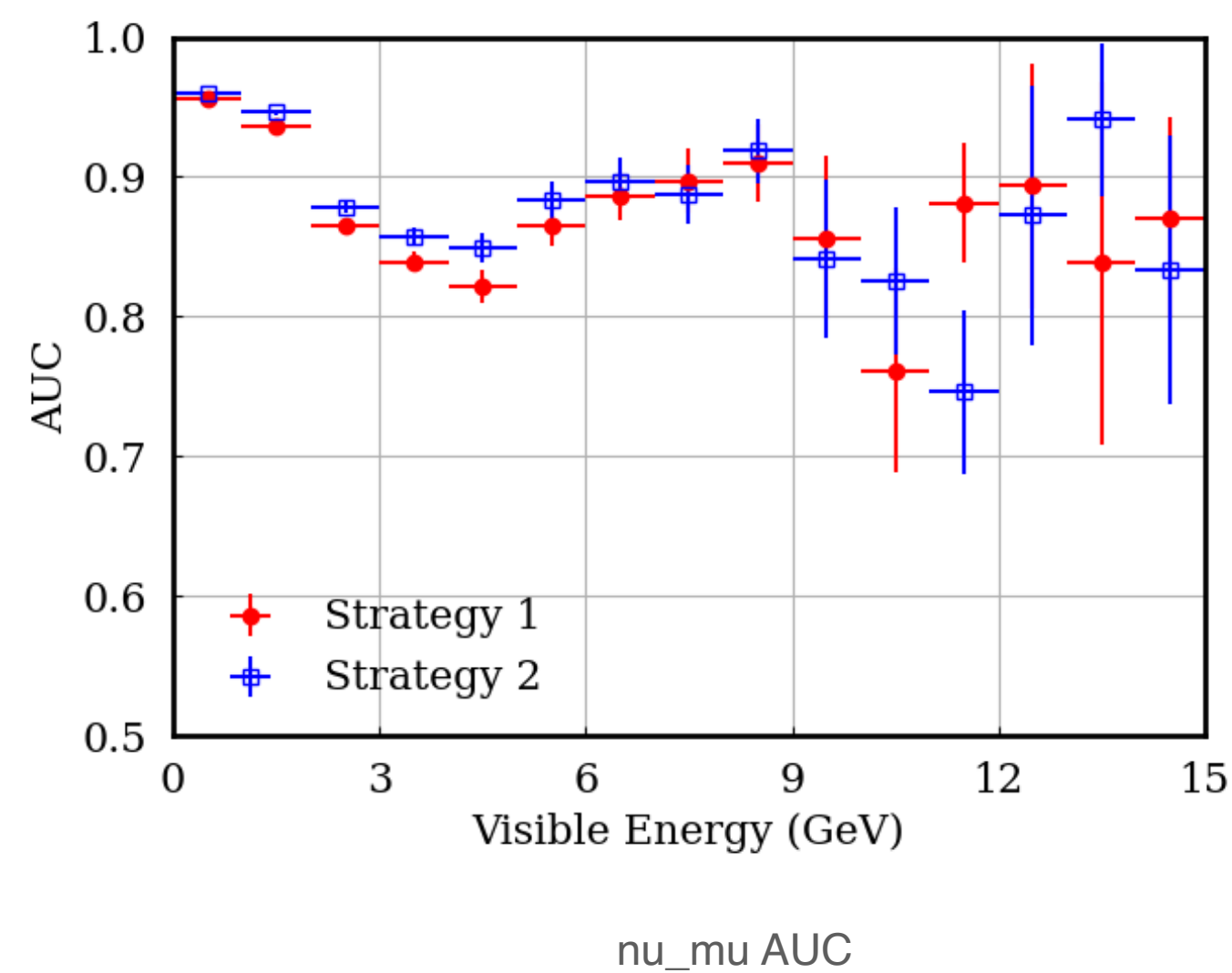
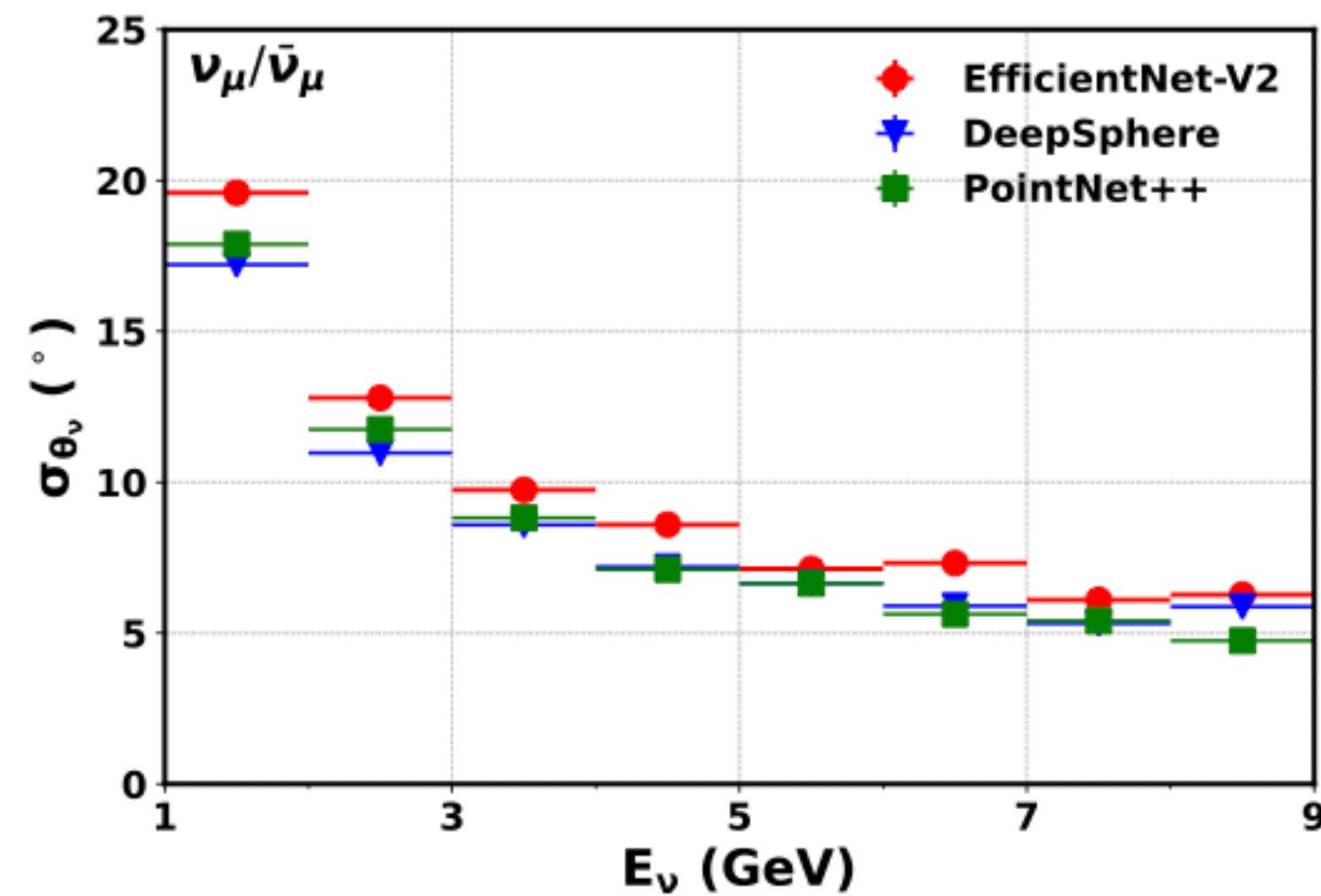
- Capture the waveform characteristics with multiple designed features:
  - Total charge (NPE) — Integral of waveform
  - First hit time (FHT) — Time at 20% amplitude of the first peak
  - Slope4 — Front-edge slope in first 4 ns after FHT
  - NPERatio4, Waveform Peak, Peak time, Waveform mean/median/std/skewness/kurtosis ...
- Use these waveform features to train ML models, DeepSphere & PointNet++, for PID and direction reconstruction



# Model Performance

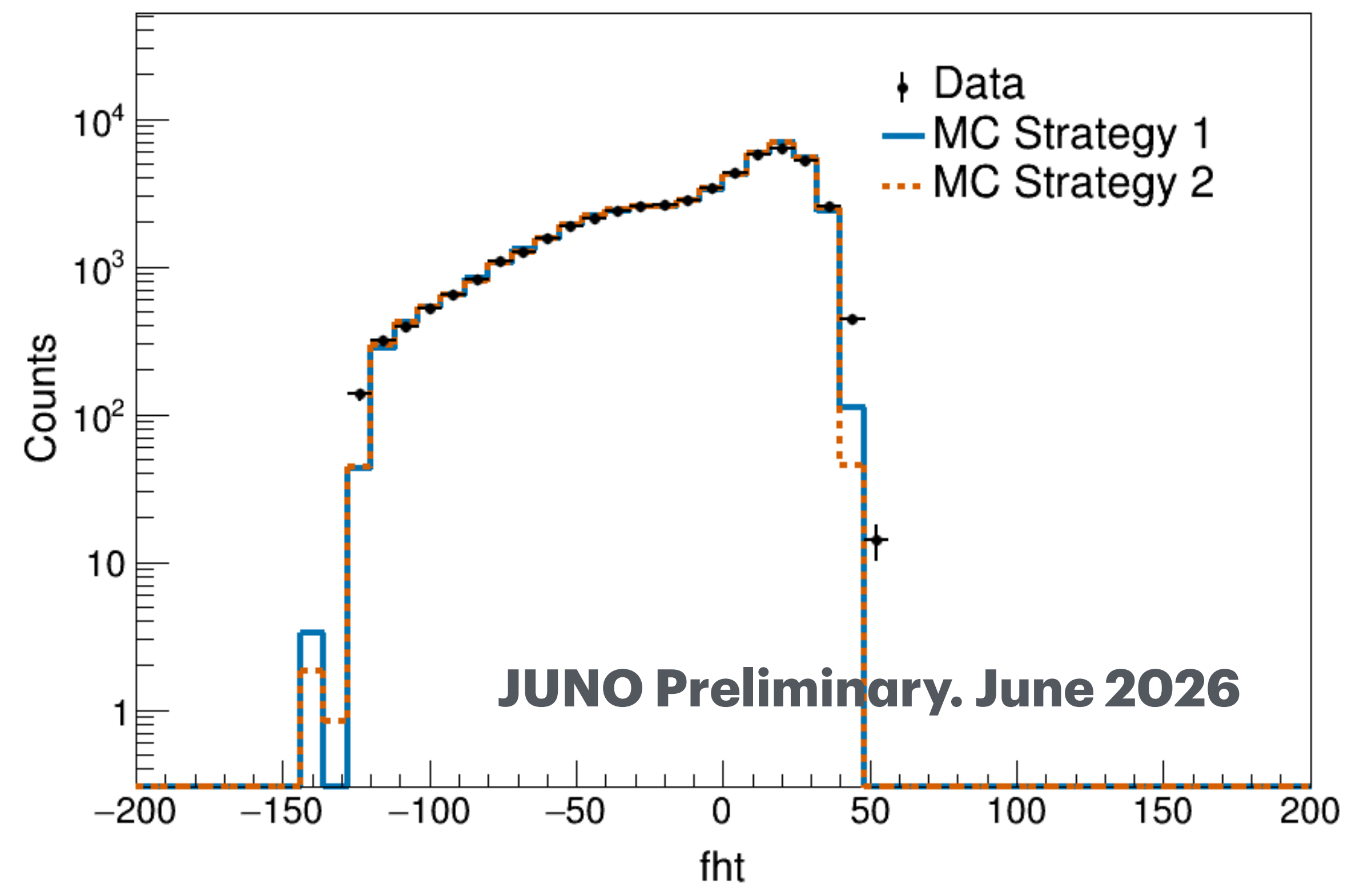
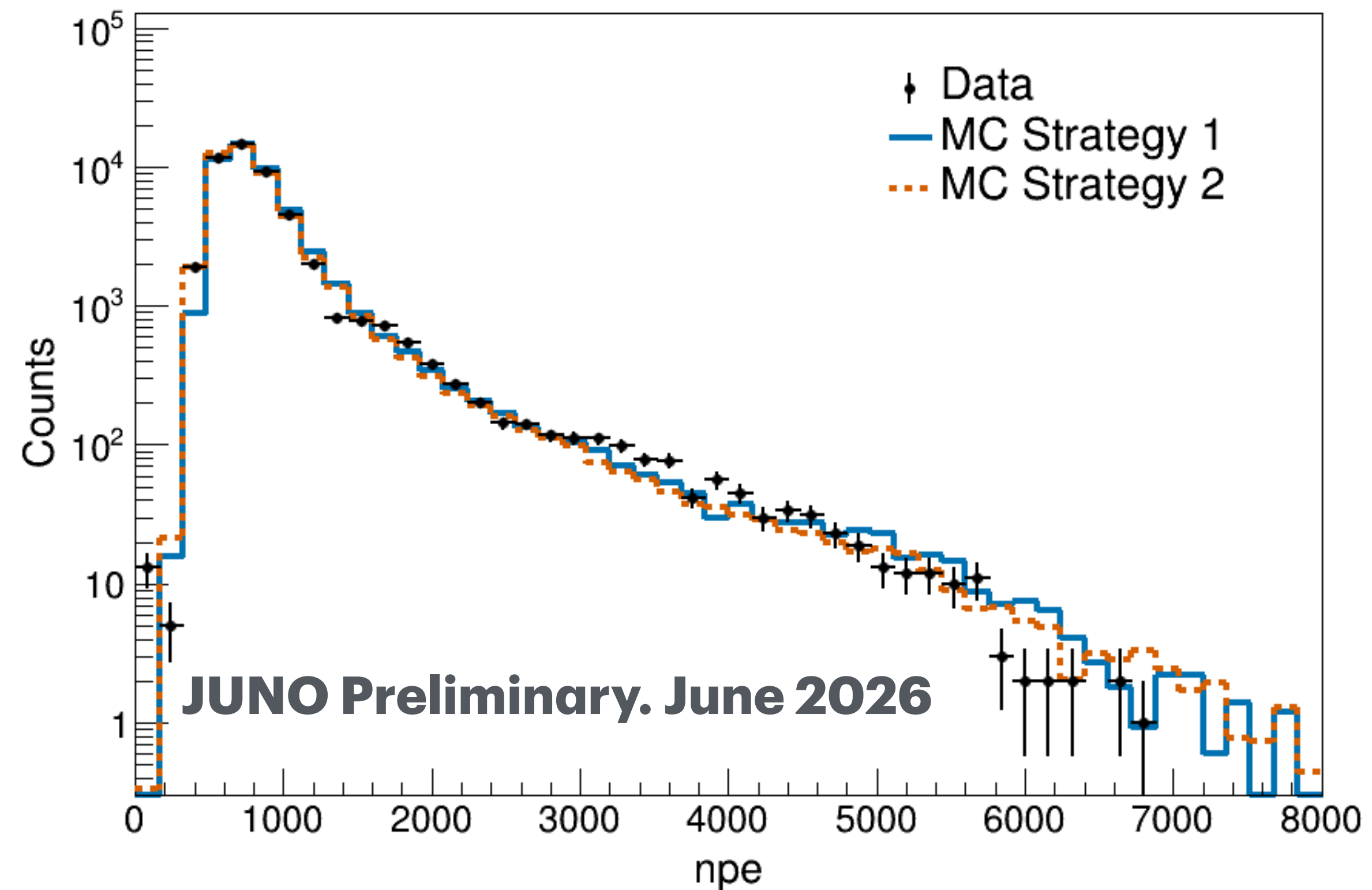
On MC

- To put things in perspective, water Cherenkov detectors have great angular resolution, but for the lepton only.



# Waveform features data-MC comparison

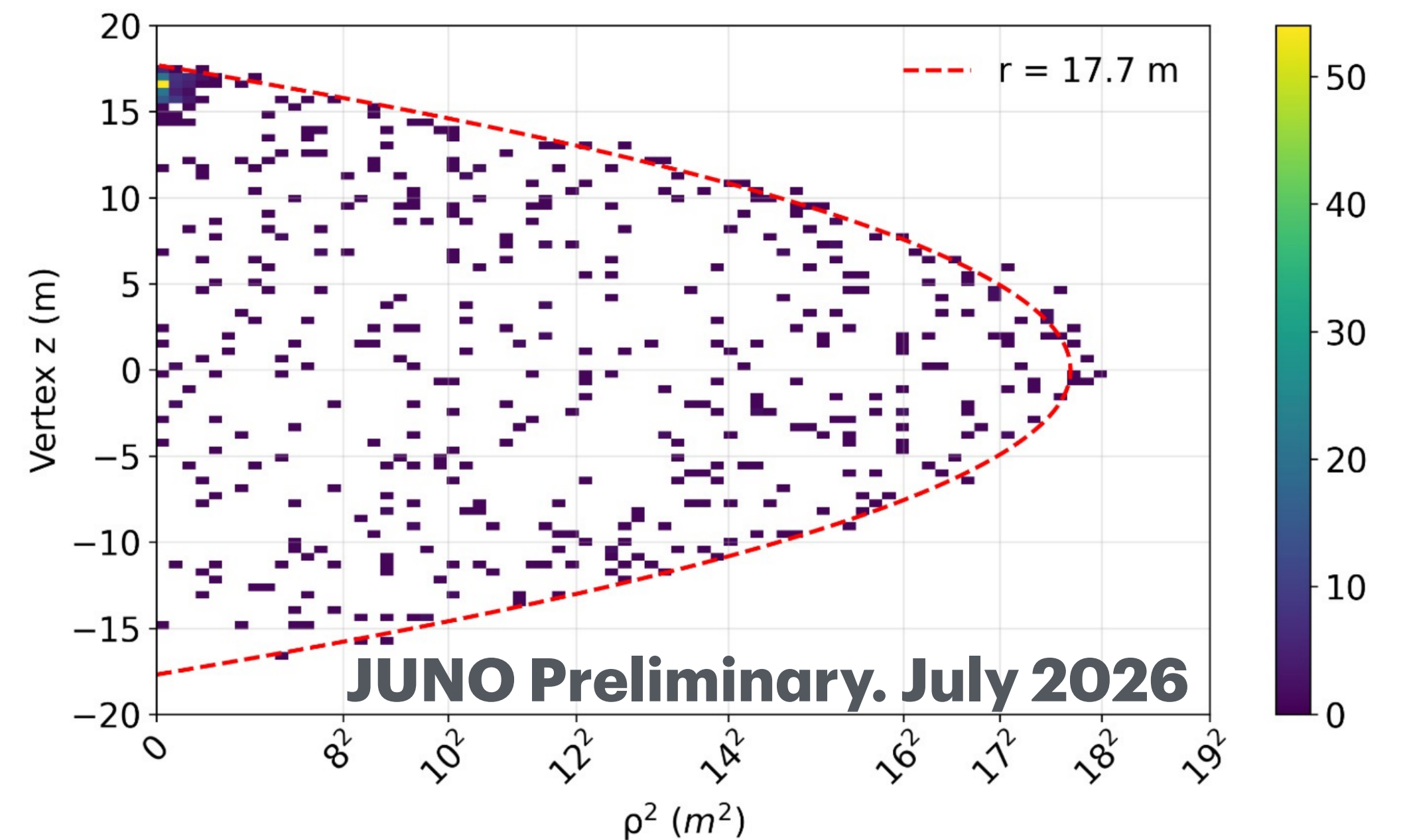
Some features match well ...



# Vertex reconstruction

as validation

- Using two of the features that match well to perform Vertex reconstruction
- Reconstructed vertices distribute relatively uniformly in the detector
- Chimney muons are also correctly reconstructed as a further confirmation
- Consistent between DeepSphere and PointNet++



# Summary

What next?

- Improve waveform feature data-MC comparison
- Deal with the MC-data domain shift — Domain-Adversarial Neural Networks
- Explore more advanced models, like transformer
- More physics-motivated development