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1 JUNO, motivation and reconstruction difficulty

The Detector

The JUNO central detector is a 20-kt liquid-scintillator detector with dense PMT coverage and full waveform readout. These data contain timing, charge and spatial information beyond total light yield.

The Motivation

Atmospheric neutrinos span a broad energy and baseline range. Upward-going events traverse the Earth, where matter effects can complement JUNO reactor-neutrino NMO studies.

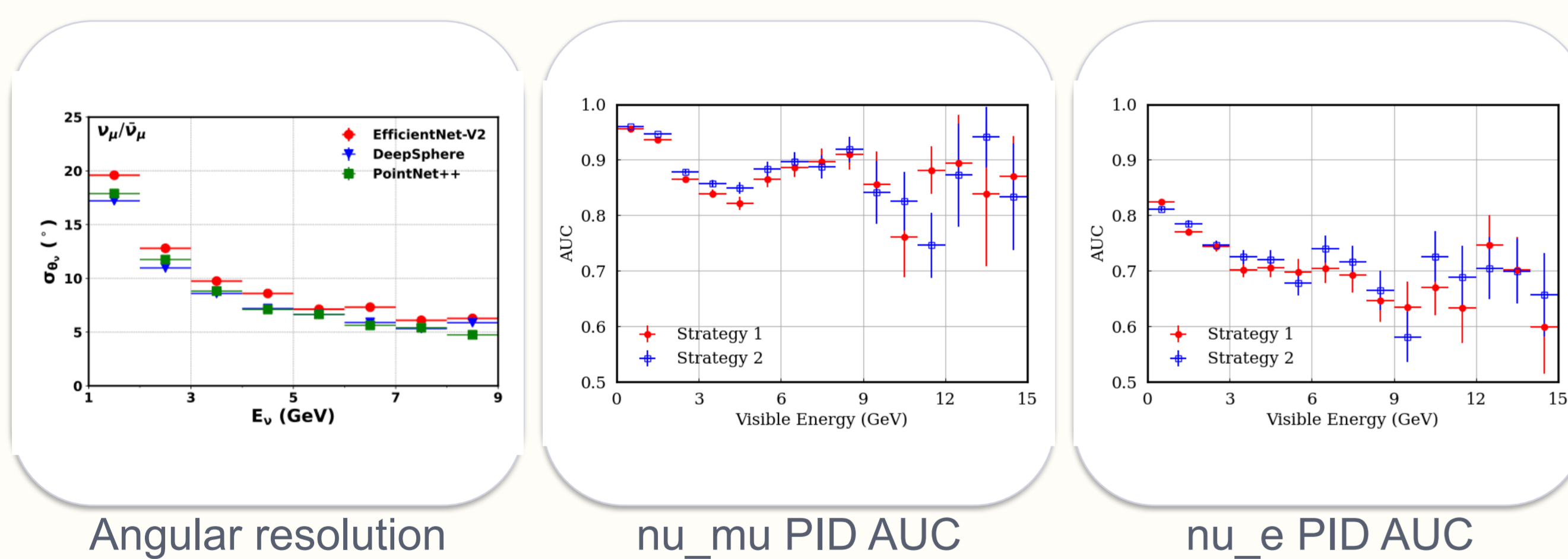
The Difficulty

Scintillation light is bright but nearly isotropic. Direction and flavor must be inferred from subtle timing, charge evolution and spatial correlations in PMT waveforms.

Goal: PID and Direction Reconstruction

4 Model performance on MC

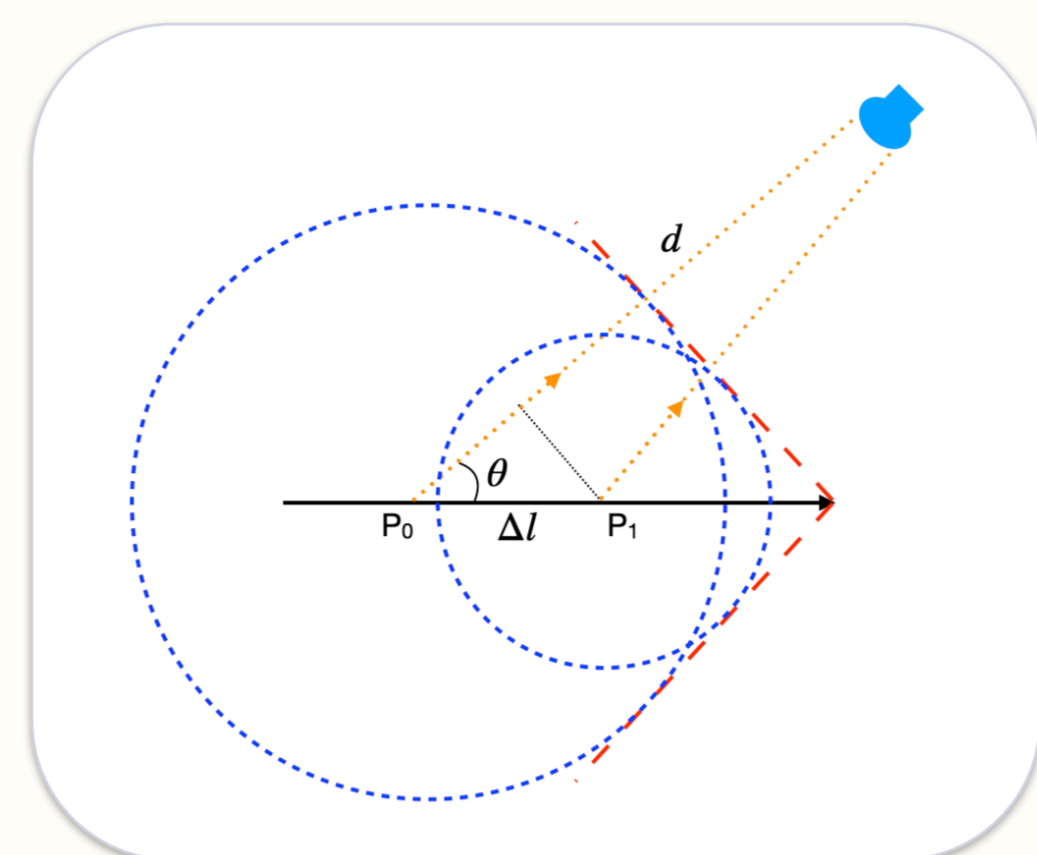
DeepSphere and PointNet++ are trained on waveform features to reconstruct atmospheric-neutrino direction and flavor ID. Performance is summarized versus visible energy.



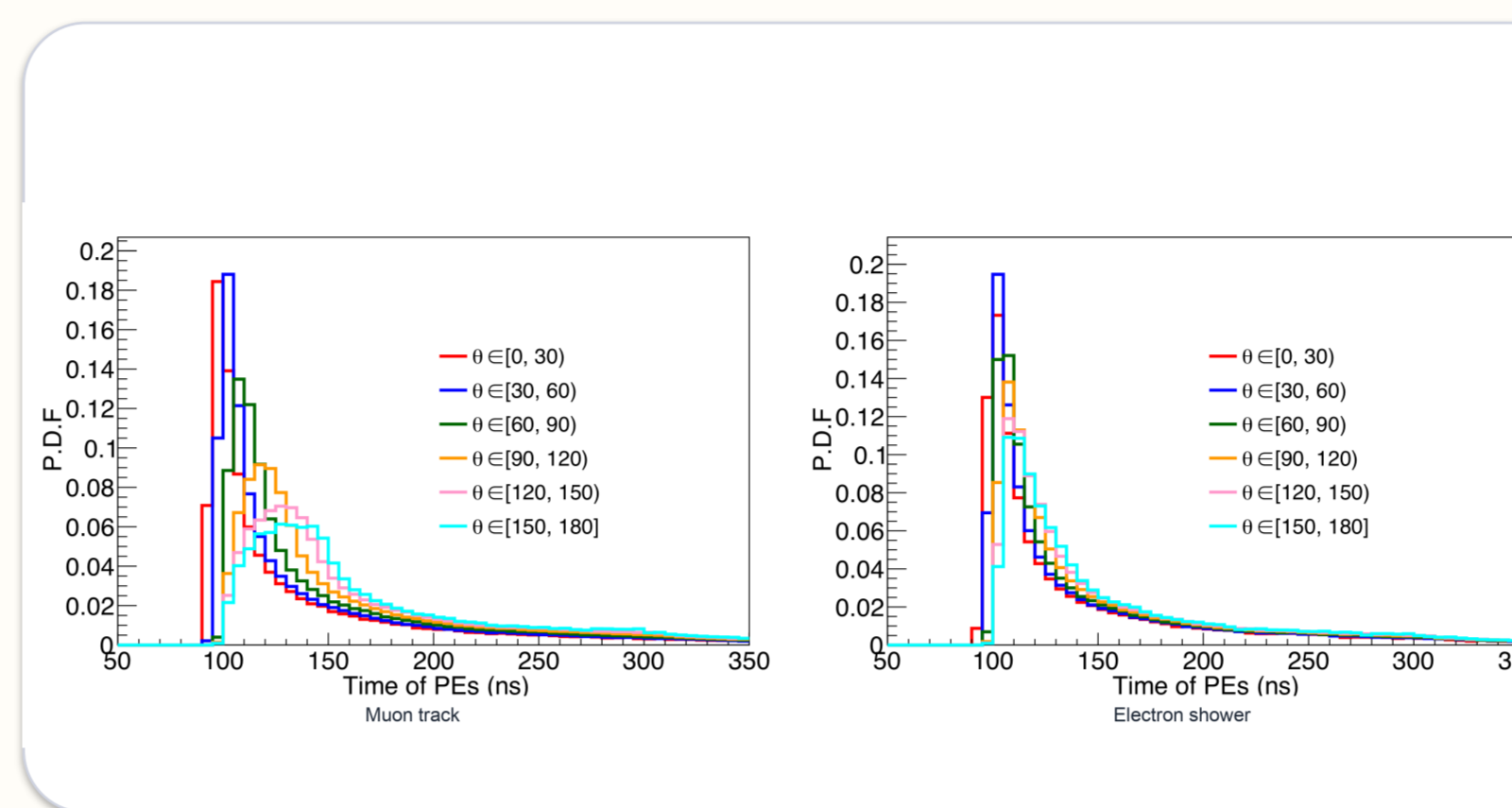
- Comparable performance between DeepSphere and PointNet++
- Good angular resolution
- Promising PID potential

Core message: waveform topology enables event-level PID and direction reconstruction in JUNO.

2 Why PMT waveforms carry physics



Track-to-PMT timing geometry



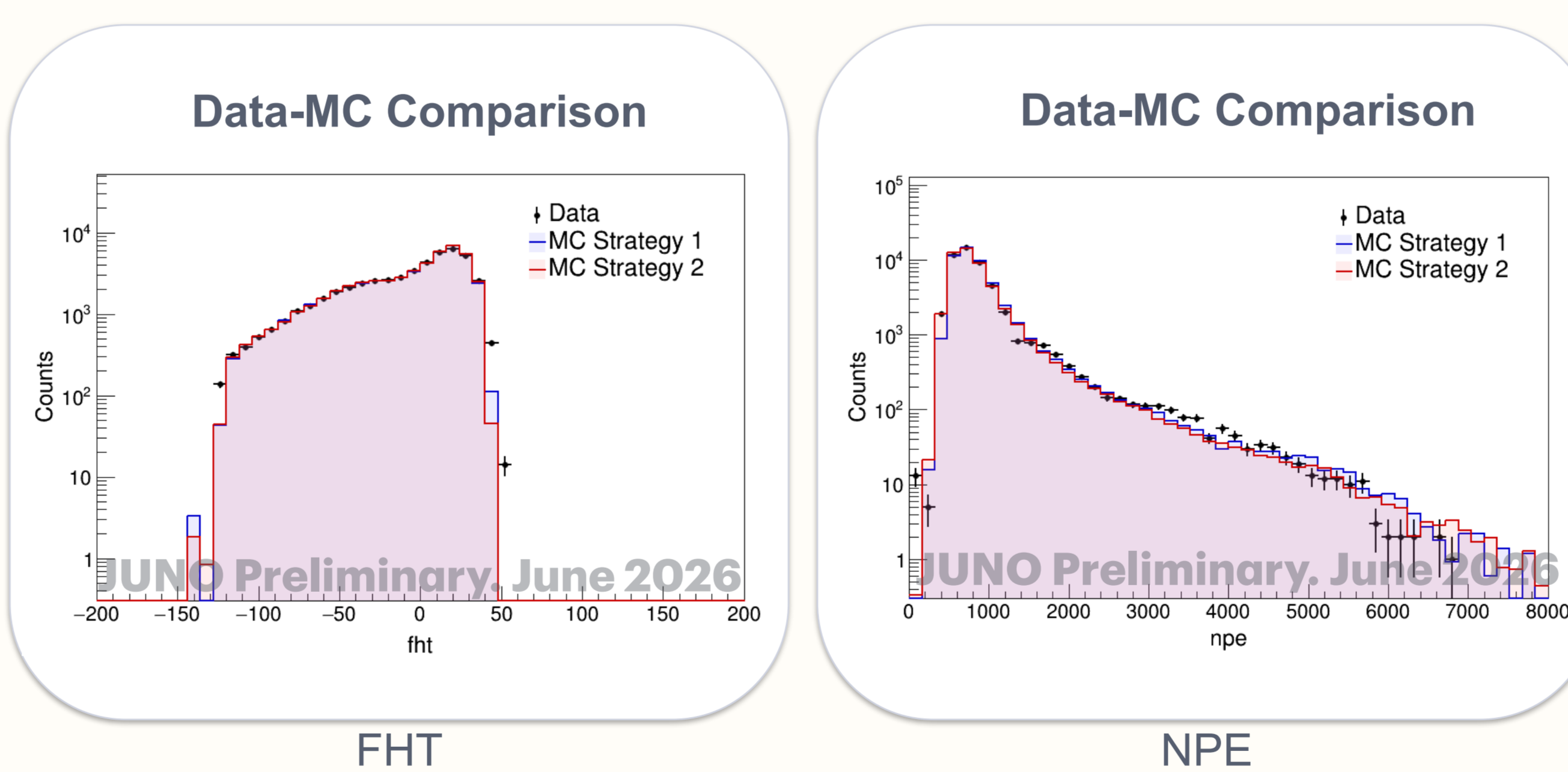
Waveform and timing-shape examples

- Cherenkov-angle PMTs can show a sharper rising edge than PMTs away from the emission geometry.
- Charge, first-hit time, front-edge slope and waveform moments encode direction and particle-ID information.
- The event becomes a high-dimensional pattern on the PMT sphere, rather than a single timing or charge number.

Core message: liquid scintillator is not directionless when PMT waveform patterns are used as topology observables.

5 Waveform-feature data-MC validation

Independent through-going-muon samples compare PMT-level waveform features in data and MC. Features with good agreement are promoted to reconstruction inputs and cross-checks.



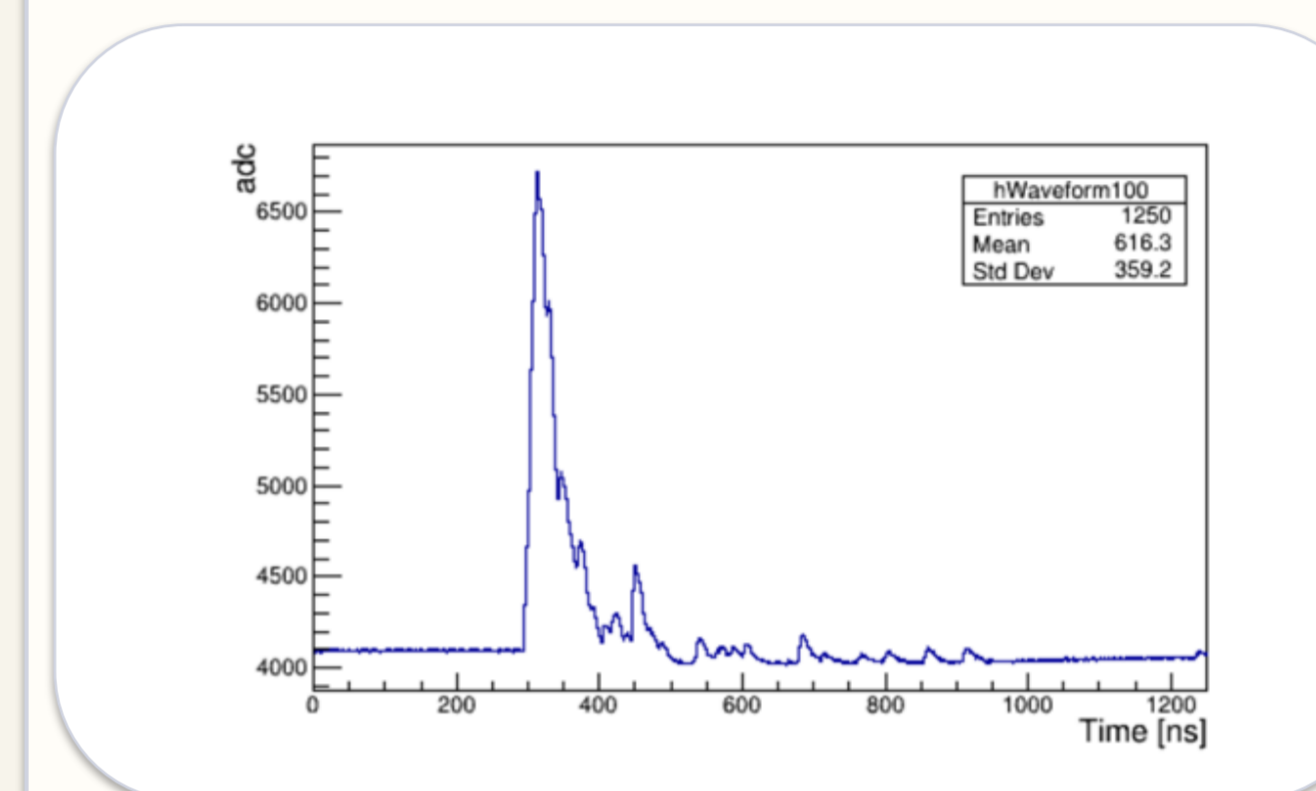
Core message: First-hit-time and charge agree considerably well on the PMT level.

3 ML implementation: features to event labels

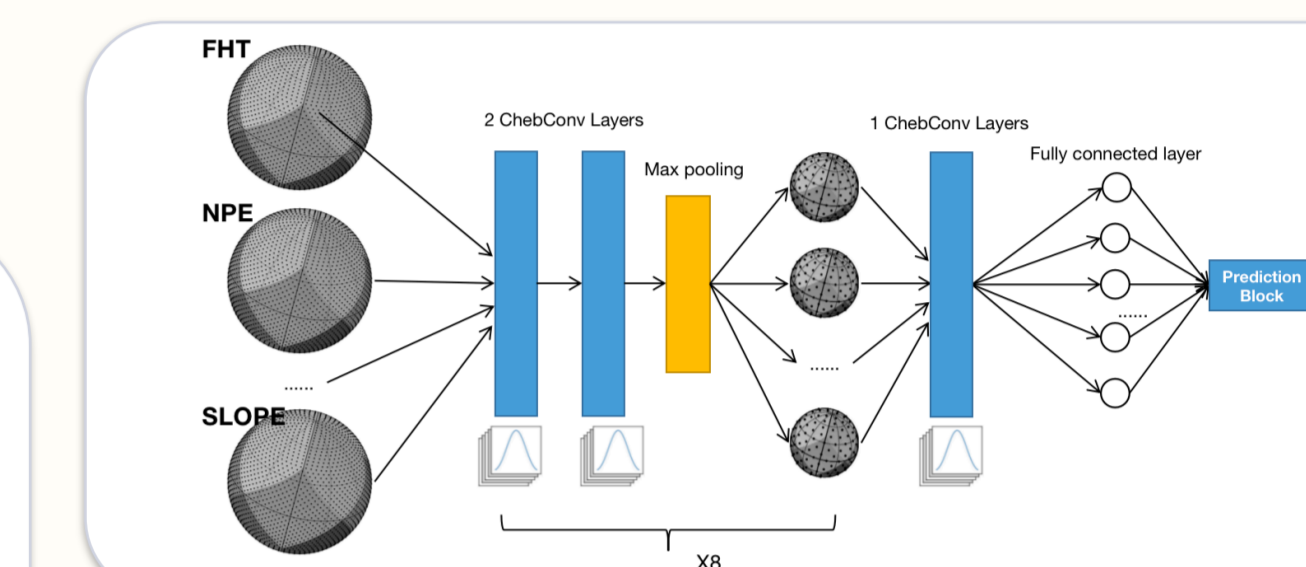


Features used to train the models:

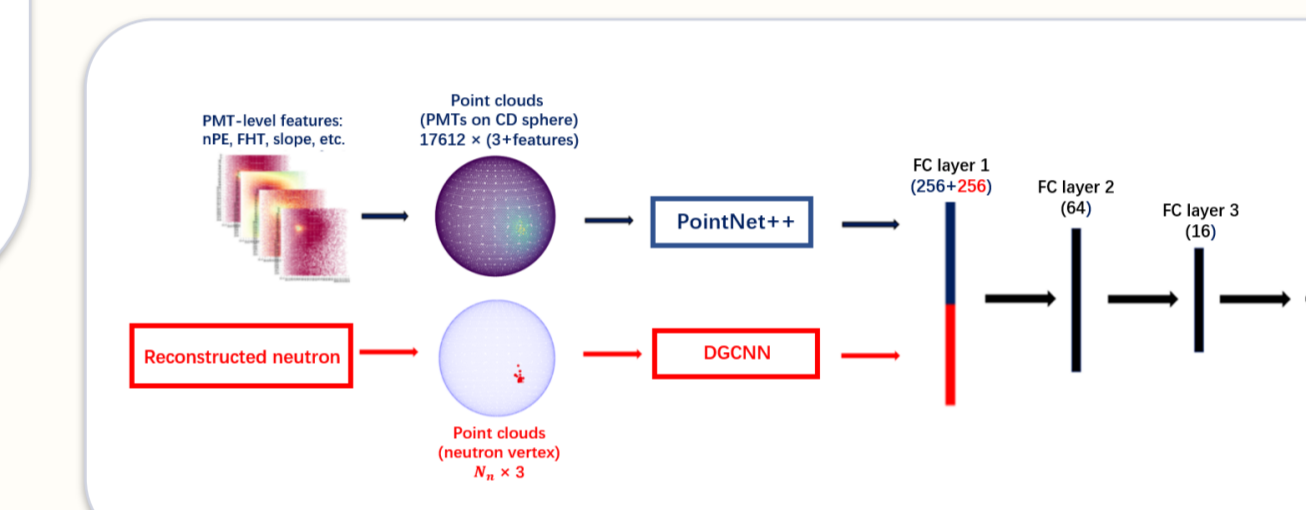
- Total charge (NPE) : waveform integral
- First hit time (FHT): time at 20% amplitude of first peak
- Slope4: front-edge slope in first 4 ns after FHT
- and more ...



A typical Waveform



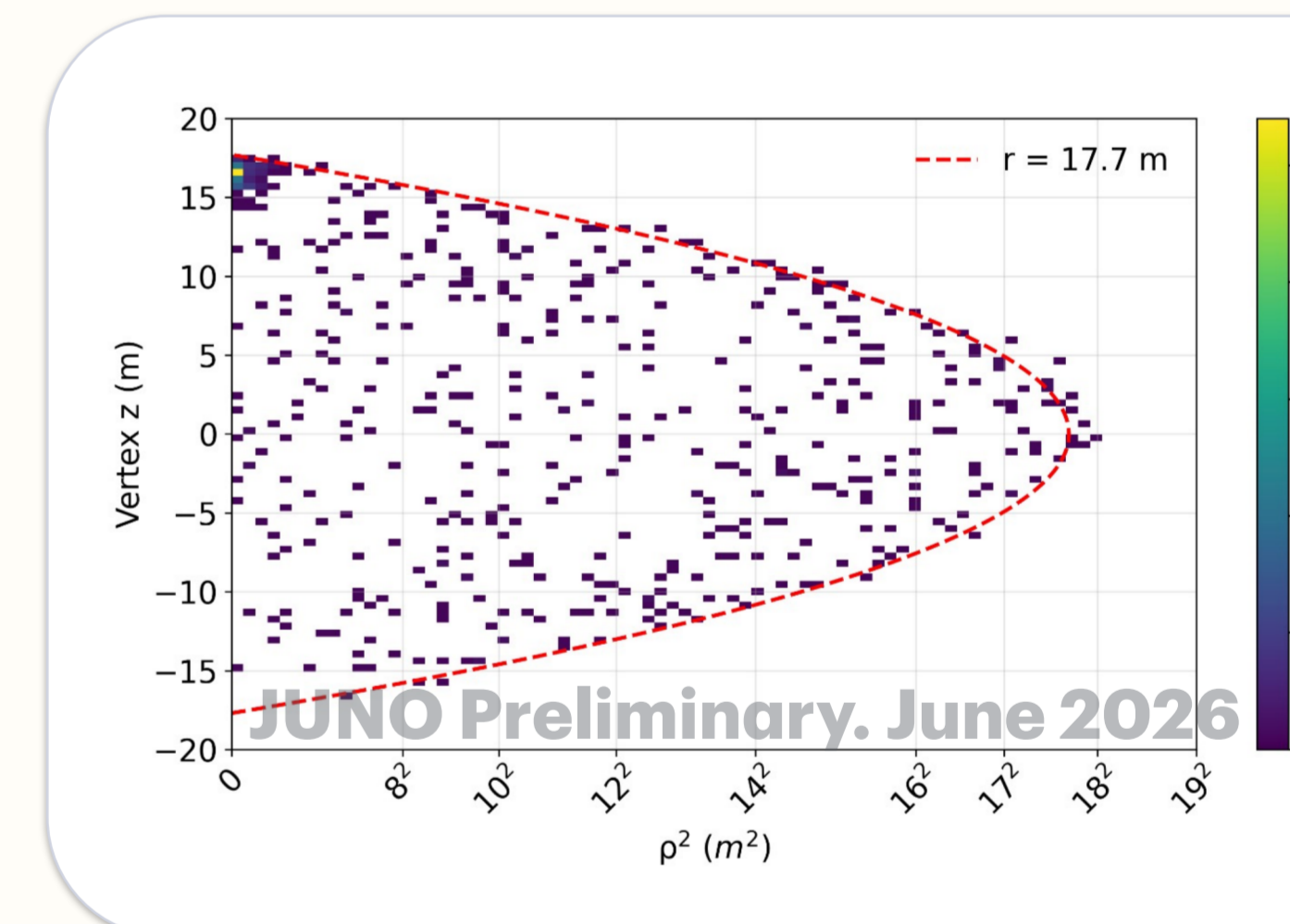
DeepSphere: spherical PMT feature maps



PointNet++: 3D PMT point clouds

6 Vertex reconstruction in atmospheric data

- Using FHT and NPE to train both DeepSphere and PointNet++ to reconstruct neutrino interaction vertices:
- Vertices are apparently uniform as expected.
 - Chimney muons are reconstructed correctly near the top of the detector.
 - Both models have consistent results.



Uniform FV behavior

Summary and next steps

Summary:

- Atmospheric neutrinos add an independent handle for JUNO.
- PMT waveforms encode timing, charge and topology.
- DeepSphere and PointNet++ reconstruct PID and direction.
- Validation uses feature agreement, vertex uniformity and muon samples.

Next steps:

- Improve data-MC agreement
- Implement DANN to tackle domain shift
- Explore more advanced models like Transformers