Direction reconstruction of atmospheric neutrinos in JUNO with machine learning method

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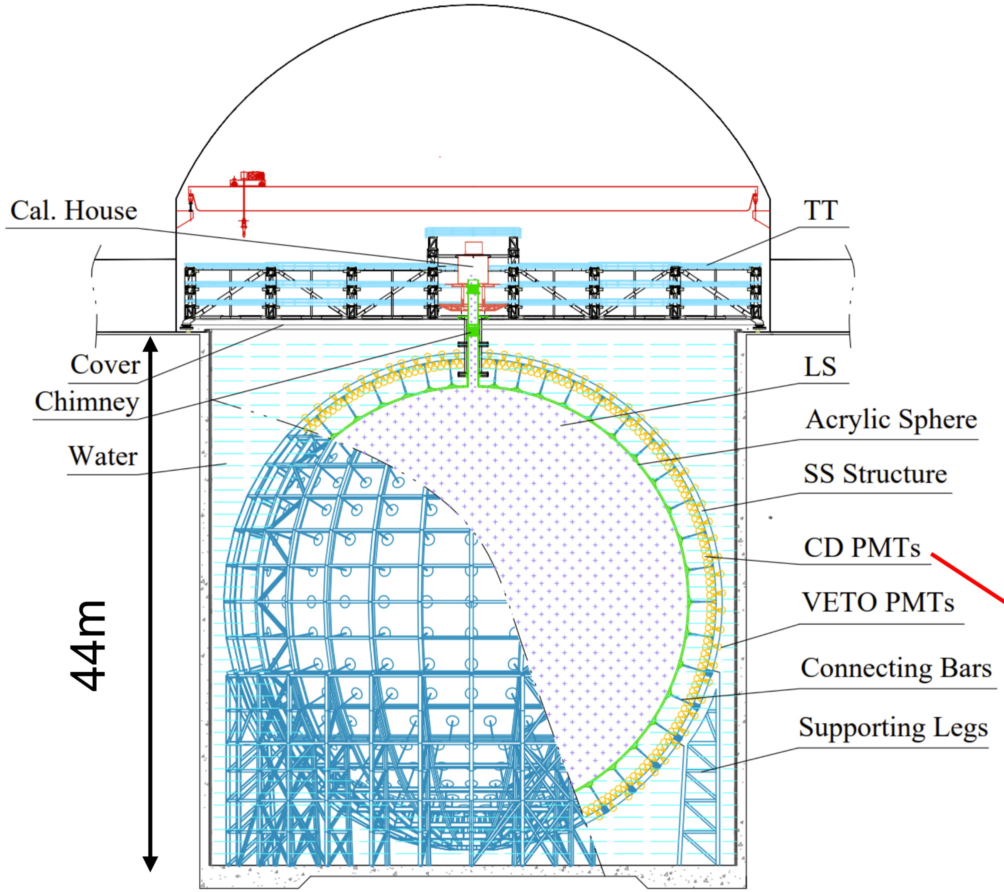
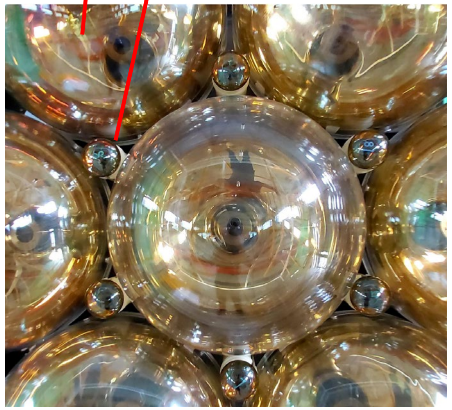
2022年6月30日

JUNO Experiment



- JUNO is a next-generation large liquid-scintillator neutrino detector
- The Central Detector (CD) is instrumented with
  - **17'612 20-inch Large-PMTs (LPMTs)**
  - **25'600 3-inch Small-PMTs (SPMTs)**



The PMT system acts like a "dual camera system", which is able to capture the temporal evolution signals originated from neutrino.

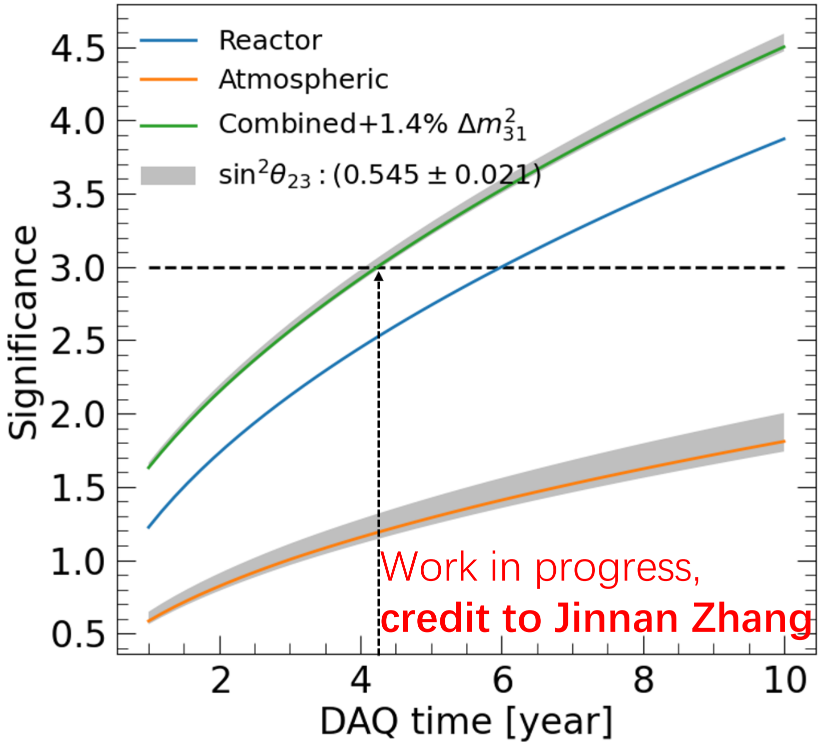
Motivation

JUNO's main physics goal is the determination of neutrino mass ordering.

To enhance its sensitivity to the mass ordering, JUNO will combine the measurements of

- reactor anti-neutrinos at low energies
- **atmospheric neutrinos at high energies (GeV level)**

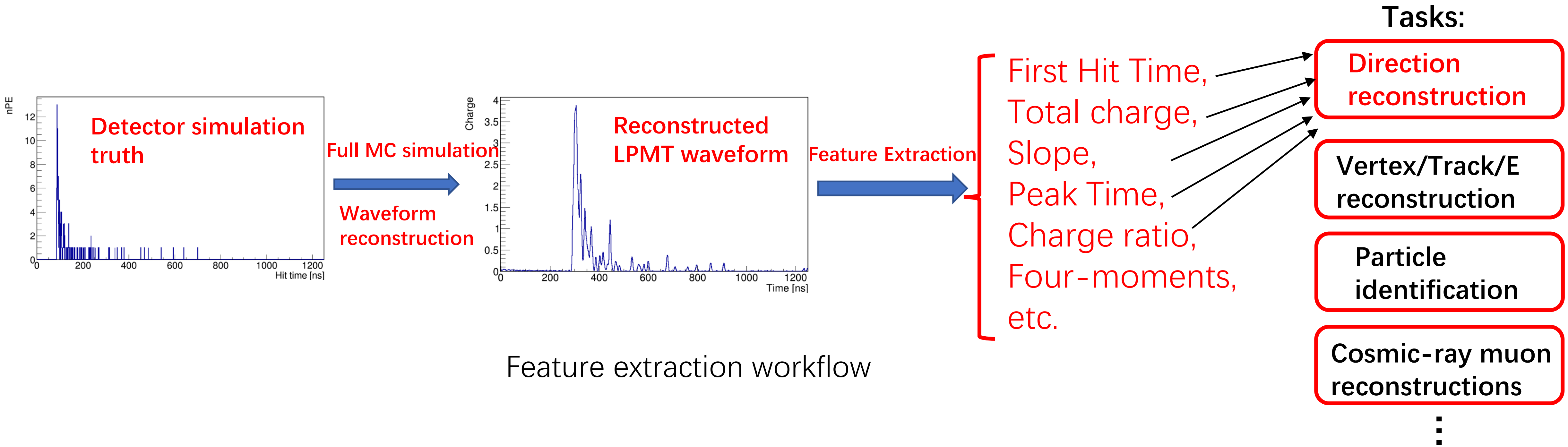
Its sensitivity significantly depends on the angular resolution of incident neutrino.



Direction reconstruction is a challenging work for JUNO.

Feature Extraction for machine learning inputs

- PMT waveforms reflect the event topology in the JUNO Central Detector
- Features extracted from PMT waveforms not only reduce the input data volume, but also preserve the characteristic of each PMT signal
- Properly selected features can be the inputs of multiple machine learning tasks



Feature extraction workflow

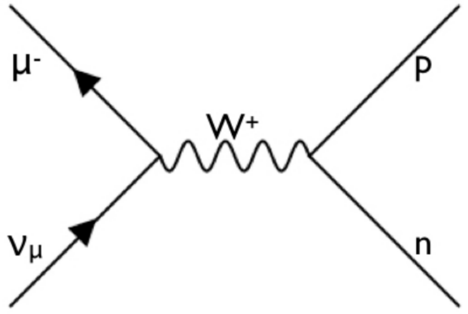
Atmospheric neutrino sample

500k atmospheric υ samples with

- detector simulation
- **full MC simulation**

Selection:

- **υ_μ**
- charged current events
- energy above 1GeV



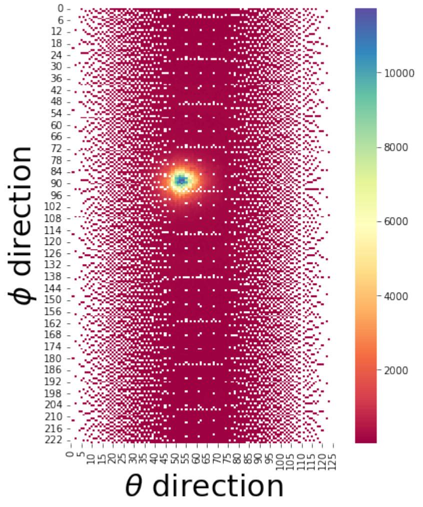
υ_μ charged current event

~135K υ_μ events were selected, with 80% for machine learning trainning and 20% for validation

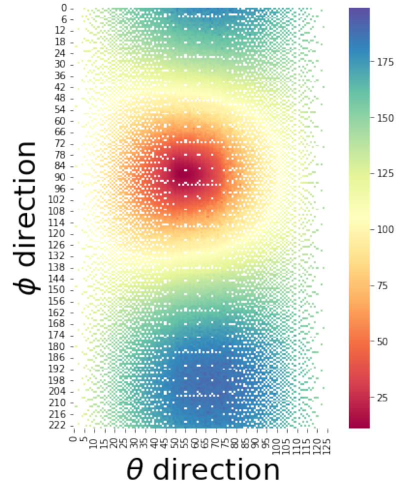
Machine learning method

- Serval state-of-the-art CNN networks (Efficient, LSTM, ResNet-RS, EfficientV2) have been tried, best performance obtained with **EfficientV2**
- Model architecture: EfficientnetV2-S + 2FC + Sigmoid
- LPMT and SPMT features
- **Input images are obtained by planar projection**
- Reconstructed zenith(θ) and azimuth(ϕ) simultaneously from $(cos\theta, sin\phi, cos\phi)$

Total charge

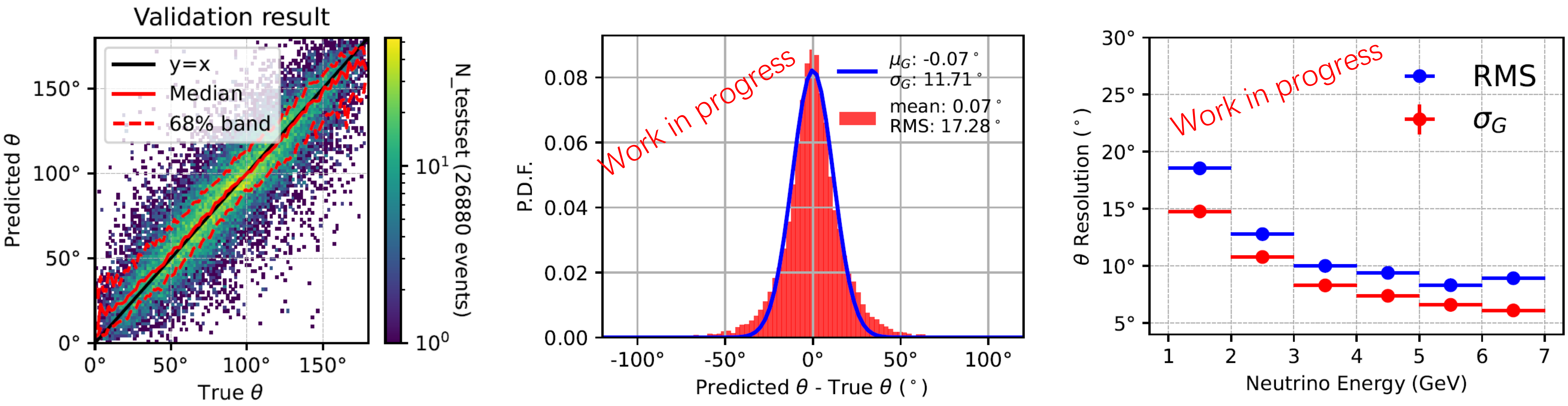


First hit time

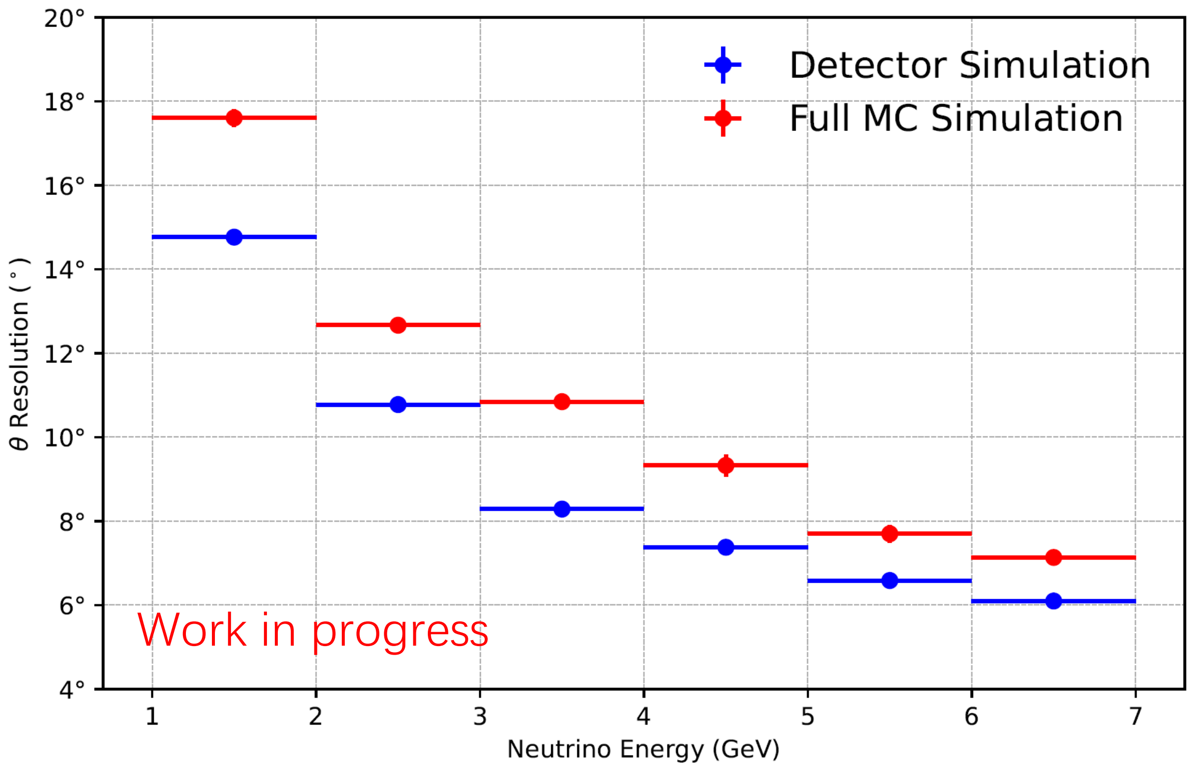


Reconstruction performance

Zenith (θ) direction reconstruction results based on 135k υ_μ full MC simulation sample



Reconstruction performance: comparison between detector simulation and full MC simulation results



- **An unprecedent zenith angular resolution has been obtained;**
- **detector simulation and full MC simulation results show similar energy dependence: resolution improves with increasing energies;**
- **Performance degenerated by ~2° with full MC simulation sample.**

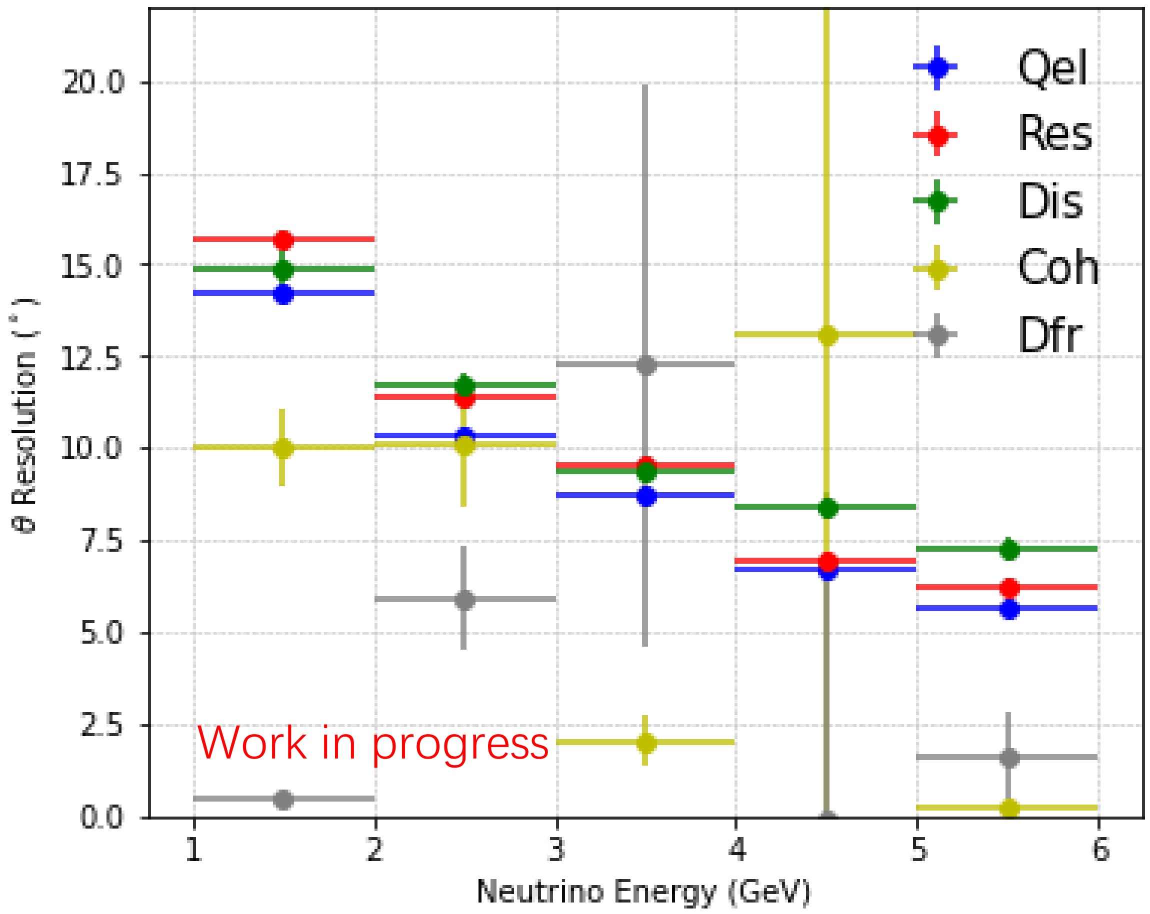
Conclusions

1. **A general approach of feature extraction from LPMT waveforms has been proposed**
2. **An unprecedent zenith angular resolution (~12° overall) has been obtained with machine learning method**
3. **Preliminary results show great potential for the high-precision reconstruction of the neutrino direction.**

Backups

Reconstruction performance

σ_G

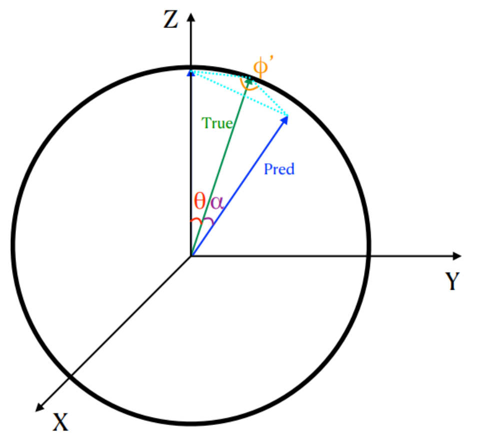


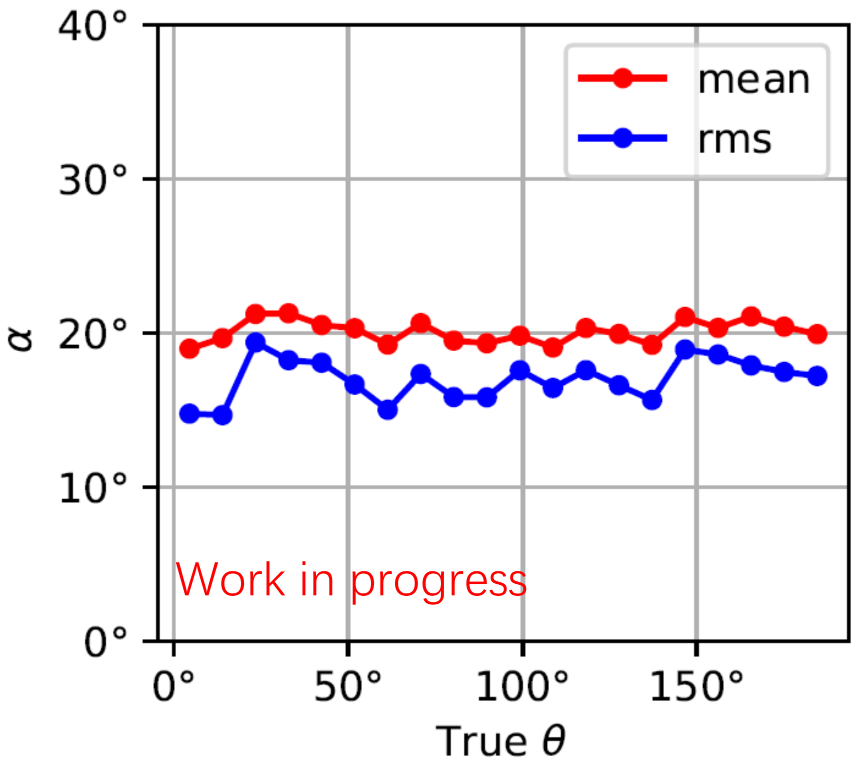
quasi-elastic scattering event
resonance neutrino-production event
deep-inelastic scattering event
coherent meson production event
diffractive meson production event

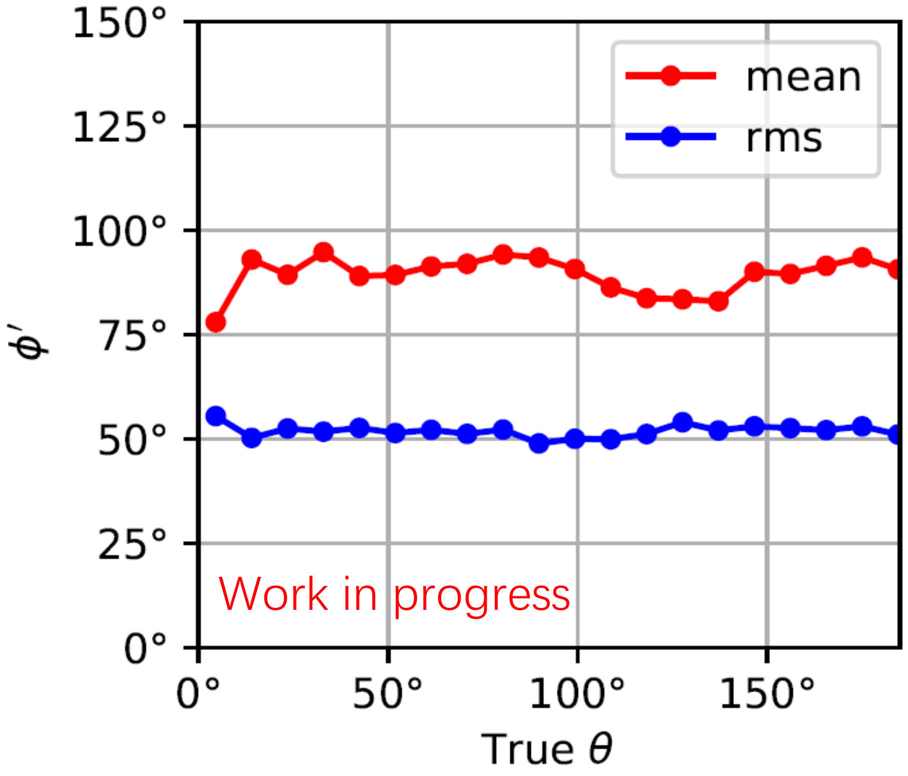
Reconstruction performance

Frame independent angles:

- α : the opening angle between predicted vector and true vector
- φ’: the rotation angle (predicted vector around the true vector)







nPE slope and nPE ratio

Taken from **Duyang Hongyue's talk** at Physics/Offline meeting 2022-01-19

Evolution of Light Received by PMTs

Idea inspired by Hu Yuxiang and Guo Wanlei

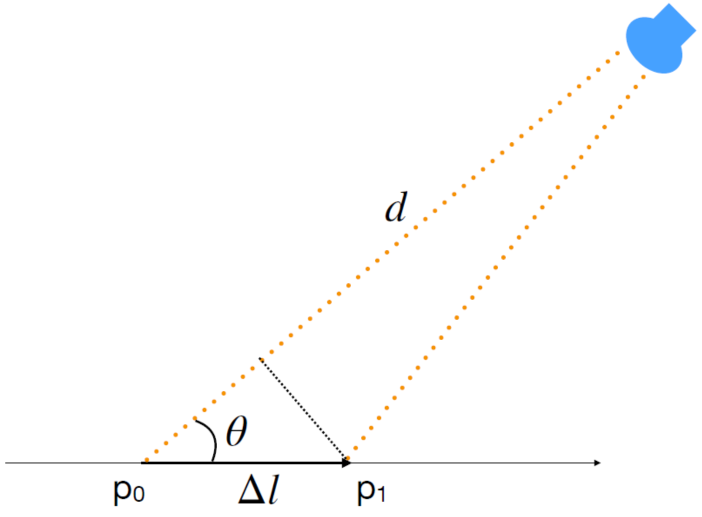
Time for scintillation light from points on a track to reach a PMT

$$t_0 = \frac{d}{c/n} \qquad t_1 = \frac{\Delta l}{v} + \frac{d - \Delta l cos\theta}{c/n}, (\Delta l << d)$$

$$\Delta t = |t_1 - t_0| = \Delta l |(\frac{1}{v} - \frac{cos\theta}{c/n})|$$

$$\frac{dl}{dt} = \frac{1}{|\frac{1}{v} - \frac{cos\theta}{c/n}|} = \frac{v}{|1 - n\beta cos\theta|}$$

(Length of the track visible to a PMT as a function of time)



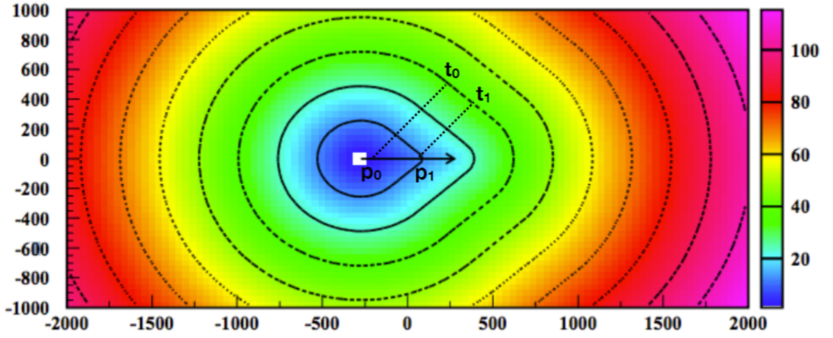
$\frac{dl}{dt}$ is a a function of θ, also depends on where the track starts and stops.

The amount of light emitted depends on l and particle type (dE/dx).

The amount of light received by a PMT evolves as a function of time according to the event topology in the detector.

Maximum light rising slope at $cos\theta = \frac{1}{n\beta}$ if $\beta > 1/n$

(the same angle as CKV)



Times of First Photon   Learned J G 2009 (arXiv:0902.4009)

the light wavefront propagate at a certain angle (same as the Cherenkov angle) wrt the particle direction