Flavor Identification of Atmospheric Neutrinos in JUNO with Machine Learning

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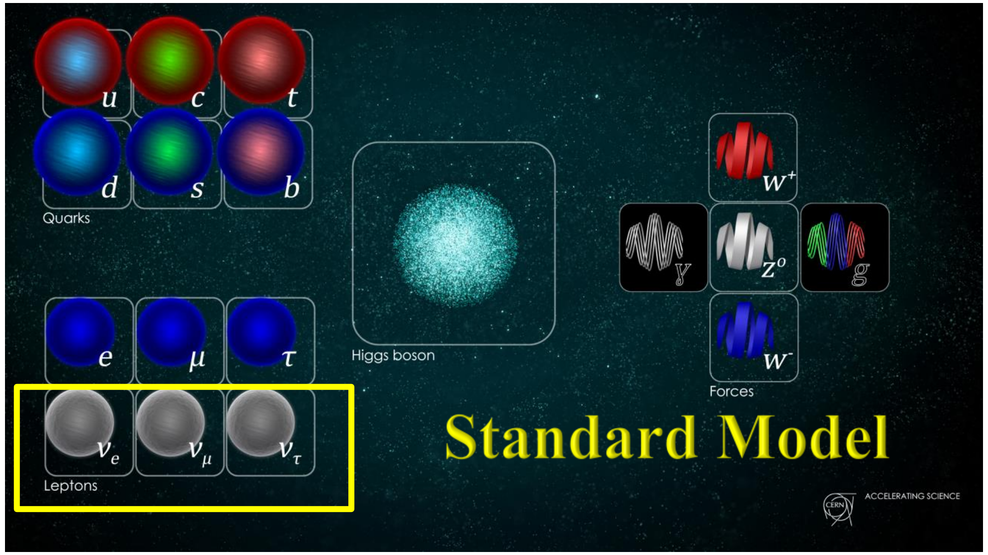
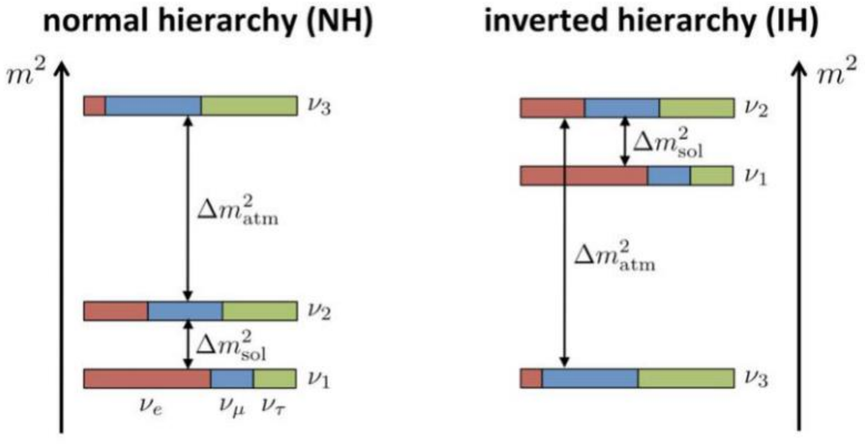
JUNO Physics

- In the Standard Model, neutrinos are assumed to be massless.
- Neutrino oscillation experiments have proven that neutrinos do have mass.
- This discovery goes beyond the Standard Model as the Standard Model can not account for neutrino masses.
- The specific ordering of neutrino masses (which type is lightest or heaviest) remains unknown.
- Solving this mystery is crucial for a deeper understanding of neutrino physics and cosmology



$$P(\overline{\nu}_\alpha \to \overline{\nu}_\alpha) = P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 1}|^2|U_{\alpha 2}|^2 \sin^2\left(1.27\frac{\Delta m^2_{21}}{E}L\right) - 4|U_{\alpha 1}|^2|U_{\alpha 3}|^2 \sin^2\left(1.27\frac{\Delta m^2_{31}}{E}L\right) - 4|U_{\alpha 2}|^2|U_{\alpha 3}|^2 \sin^2\left(1.27\frac{\Delta m^2_{32}}{E}L\right)$$

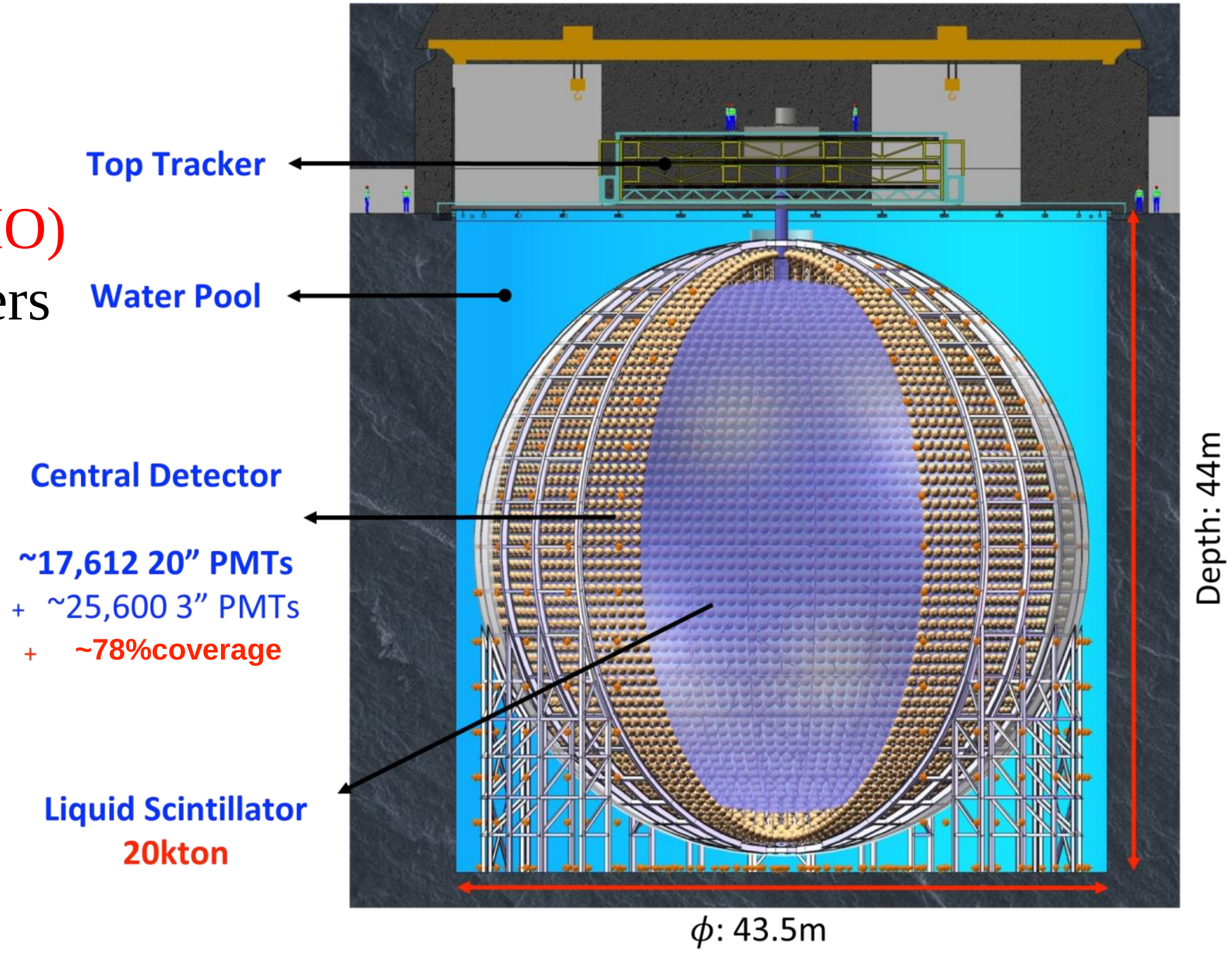


There are still two possibilities for neutrino mass order

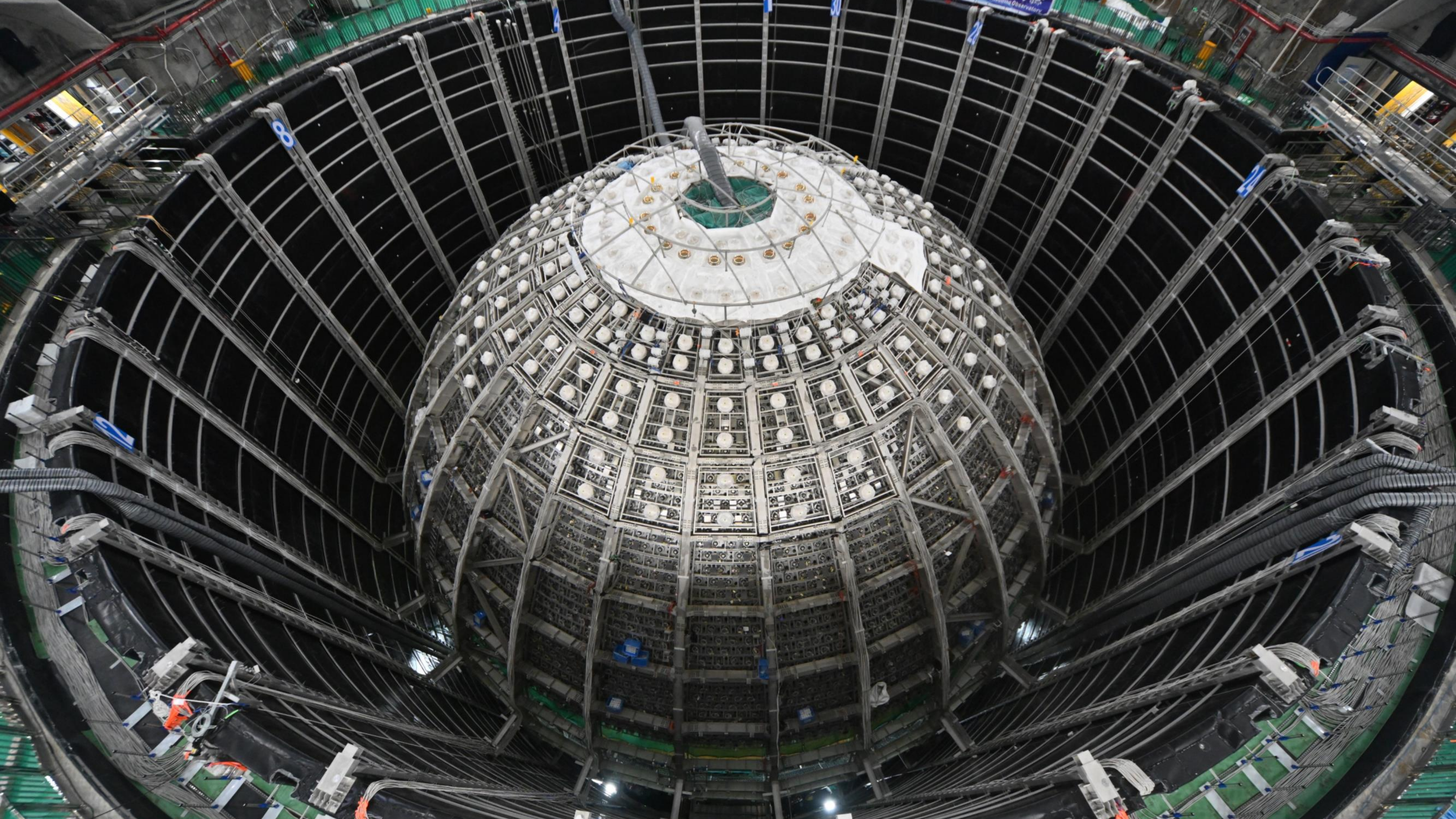
JUNO Detector

- Jiangmen Underground Neutrino Observatory (JUNO) :
  - Measure the neutrino mass order (NMO)
  - Measure neutrino oscillation parameters to sub-percent level

	DETECTOR TARGET MASS	ENERGY RESOLUTION
KamLAND	1000 t	6%@1MeV
D. Chooz	8+22 t	8%@1MeV
RENO	16 t	
Daya Bay	20 t	
Borexino	300 t	5%@1MeV
JUNO	**20000 t**	3%@1MeV

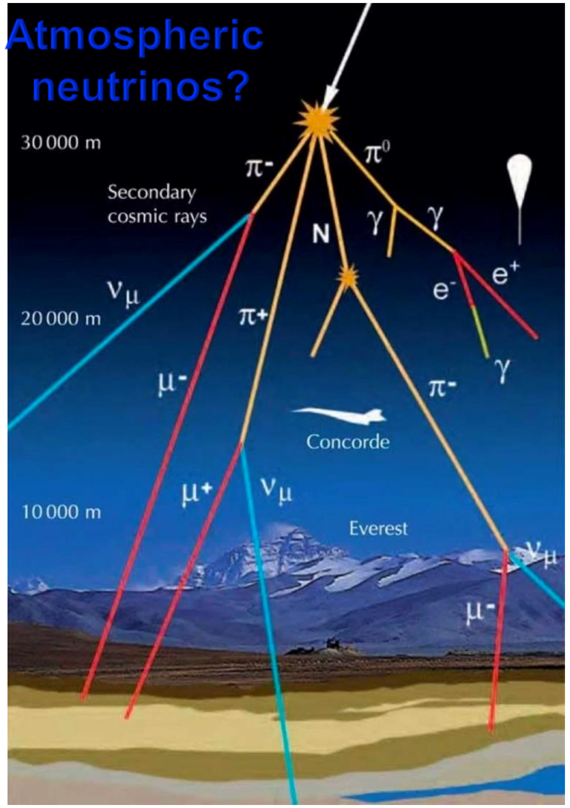


The largest liquid scintillator ever built.



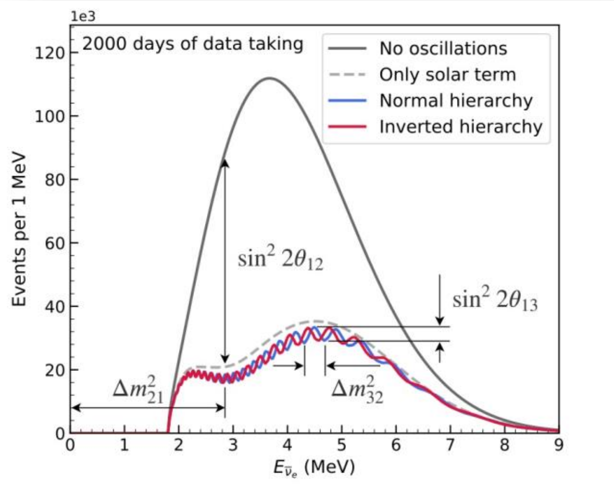
JUNO Physics

- Detect neutrinos from:
reactor, solar, atmosphere, supernova, geo.



- Combing reactor and atmospheric neutrino oscillations can enhance JUNO's overall sensitivity

- JUNO's NMO sensitivity mostly comes from reactor neutrinos

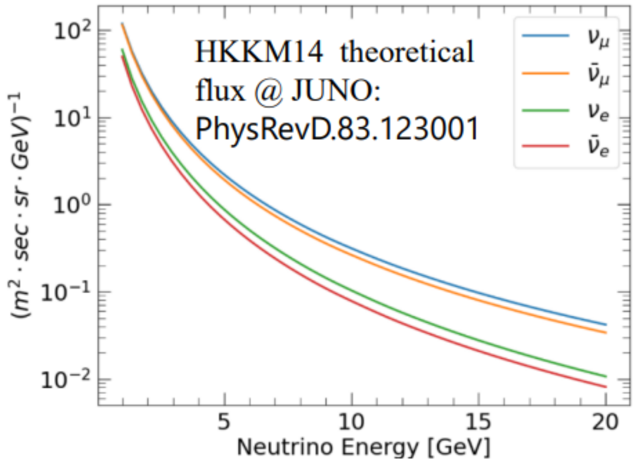


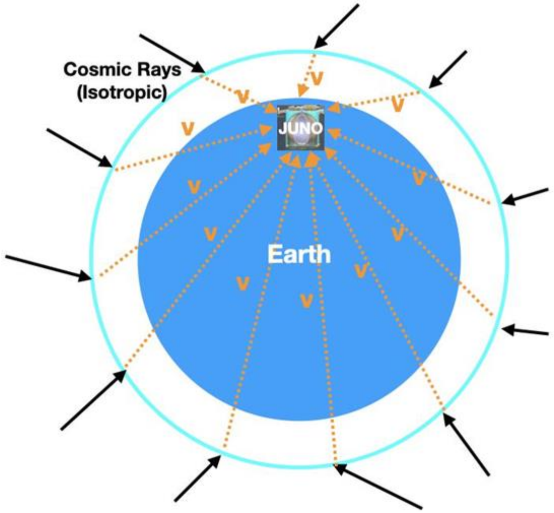
- Atmospheric neutrinos provide independent sensitivity to NMO via matter effects.

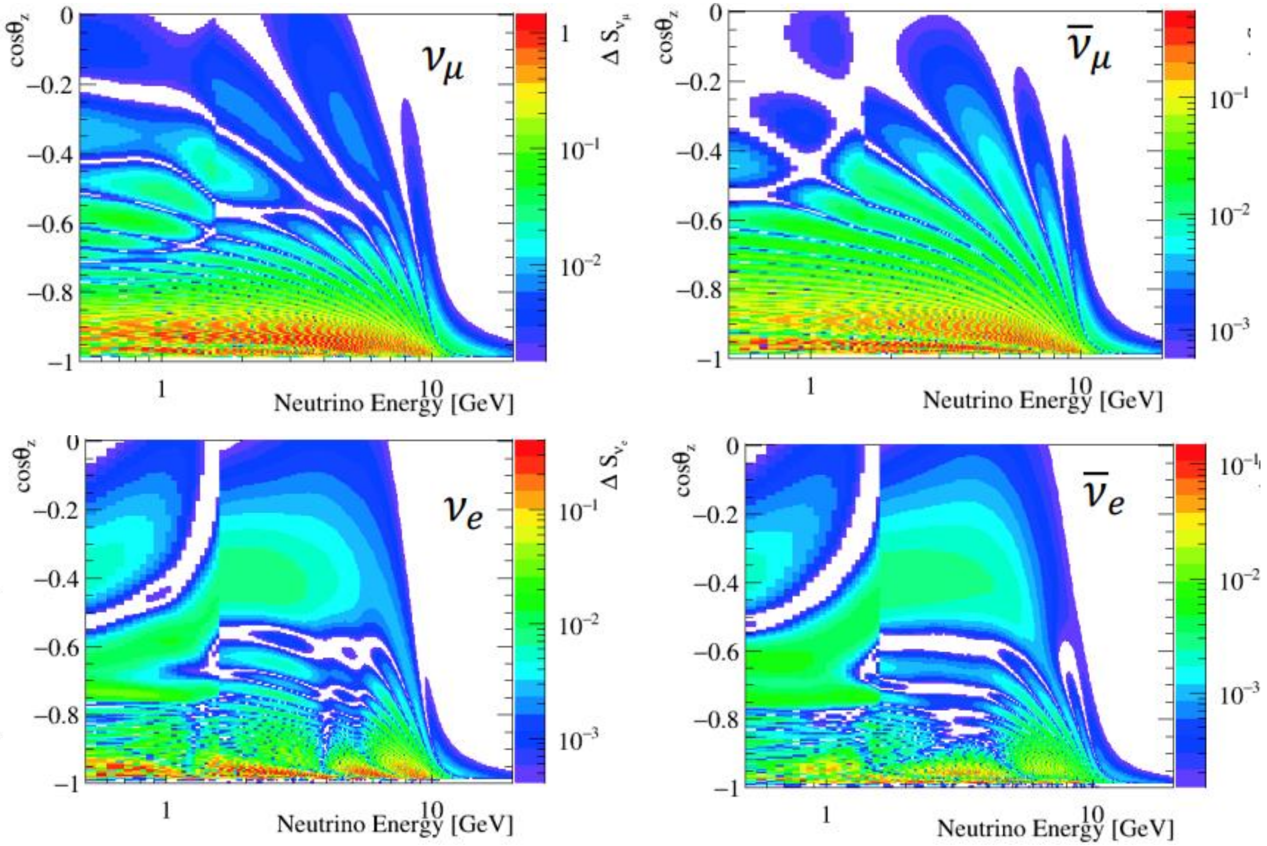
Why PID?

➢Measurements of atmospheric neutrinos require identification:

- Signal and Background： $\nu_\mu/\bar{\nu}_\mu \mathrm{CC}, \nu_e/\bar{\nu}_e \mathrm{CC}, \mathrm{NC}$







Differences between NO and IO in atmospheric neutrino oscillation spectrums

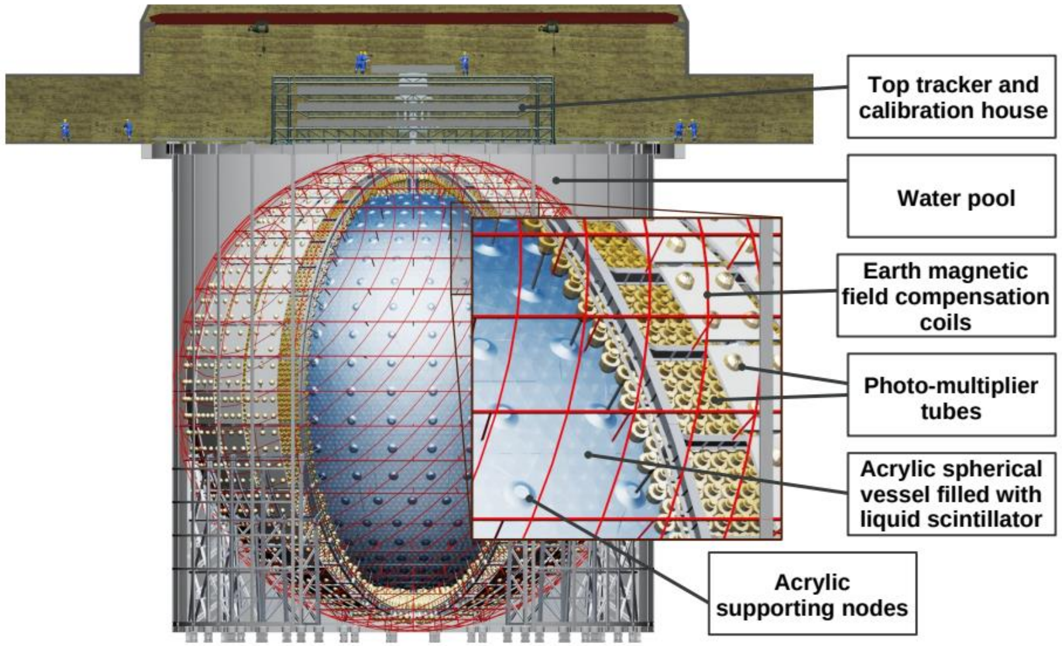
- **Flavor identification** is critical, including ν **vs** $\bar{\nu}$.

tips： CC:charged current NC: neutral current

JUNO Detector & PID?

- Liquid scintillator (LS) detectors play an important role in neutrino physics:
  - Offer low threshold and high-precision energy measurements
  - Ideal for low-energy topics such as reactor/solar neutrinos

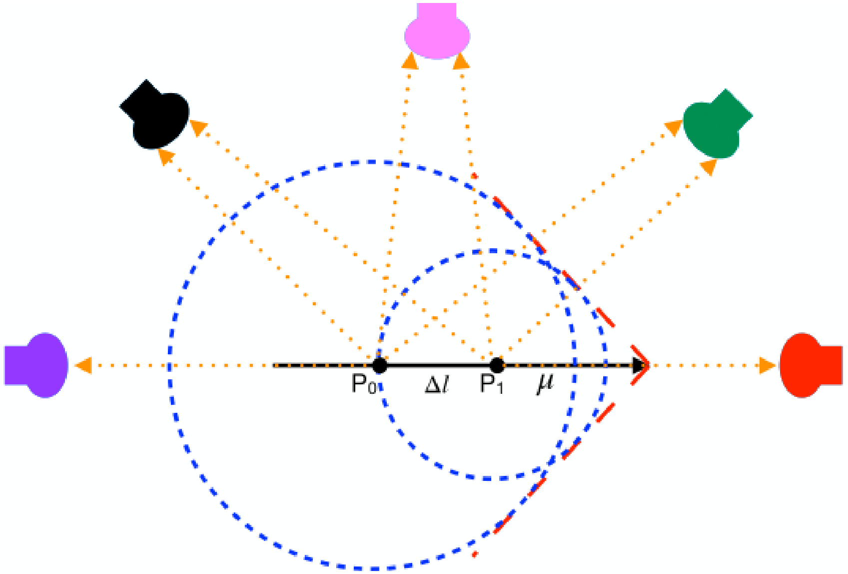
Advantages of JUNO for atmospheric neutrinos:
1.PMT coverage(78%);
2. excellent neutron tagging;
3. hadronic component visible in LS;
4. can measure distinctive isotopes

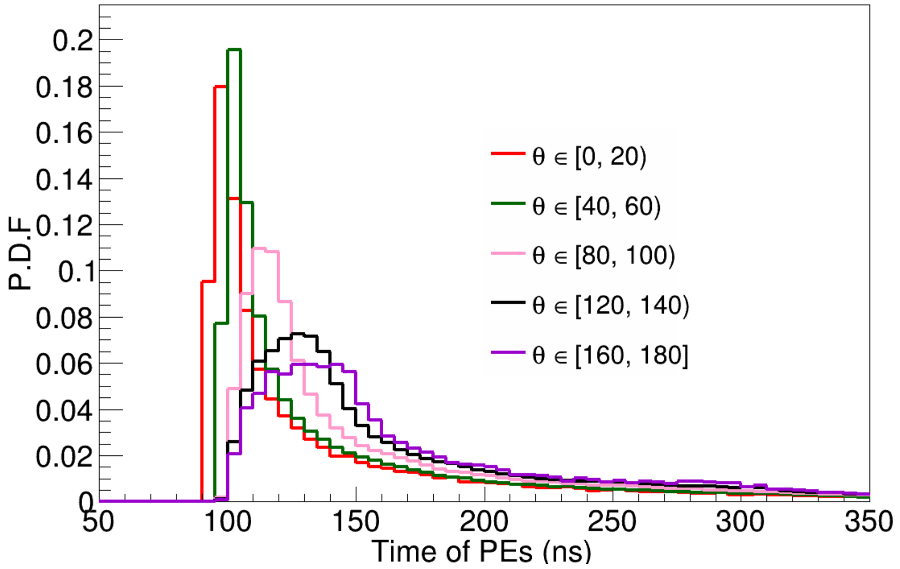


- However:
- LS detectors do not offer track information.
- Cherenkov light is only a few percent of scintillation light in JUNO

Can we do flavor identification for JUNO?

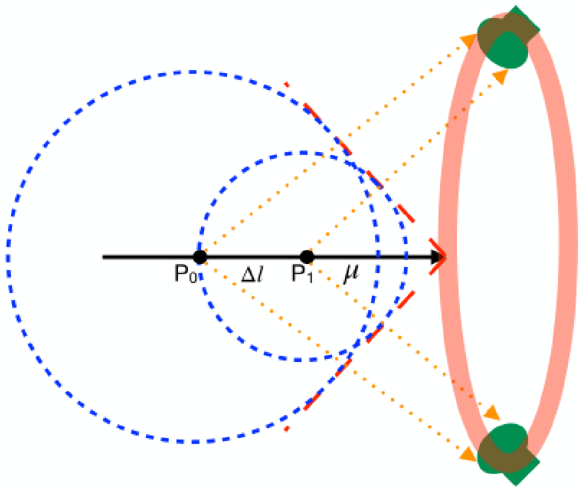
Event Topology in PMT Waveforms

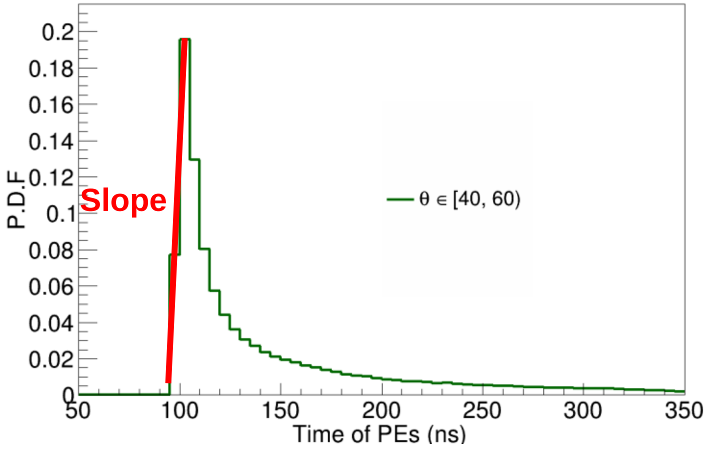


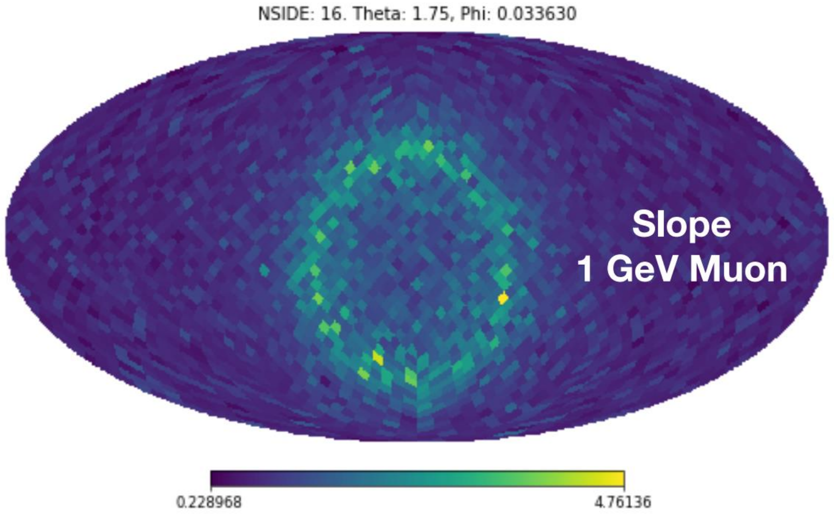


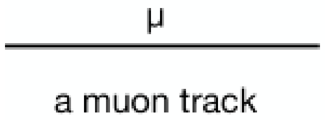
- In the LS detector, the light received by a PMT is the superposition of the scintillation light from points along the track.
- The time-dependent nPEs(t) is influenced by the incident particle's direction, interaction vertex, energy, and type (dE/dx).
- The characteristics of nPEs(t) reflect the event topology in the detector.

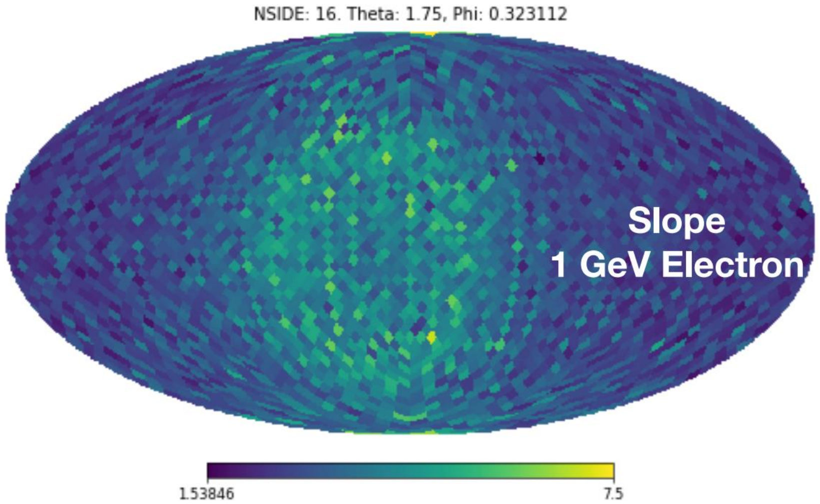
Event Topology in PMT Waveforms

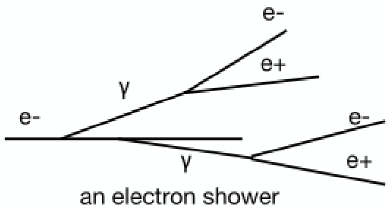






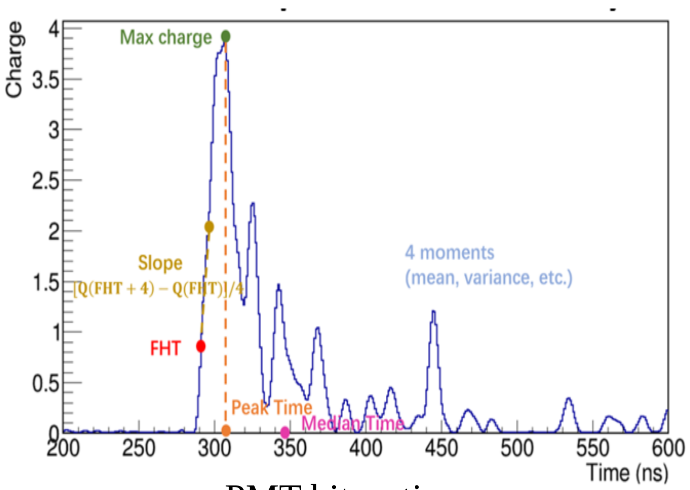




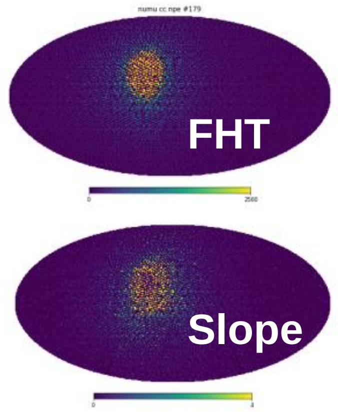


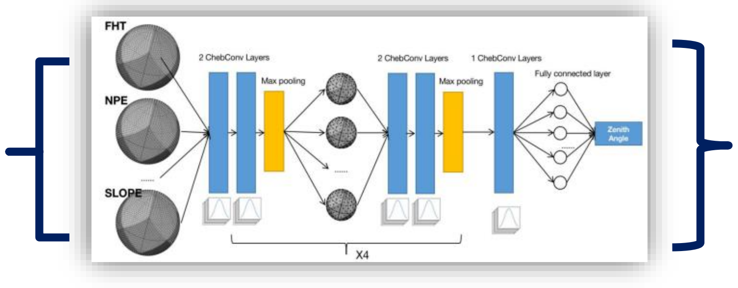
- Distribution of the slope of 1GeV muon /electron on the pmt sphere of JUNO

A Multipurpose Machine Learning Solution



PMT hit vs time





- Direction
- Energy
- **Flavor**
- Track
- Vertex

PMT Waveforms (After deconvolution and noise-removing) → **Pictures of PMT Features** → **Machine Learning Models** → **Outputs**

- **FHT**: First Hit Time
- **Slope**: Describes the average slope in the first 4ns.
- **Peak charge and peak time**: the charge and time of the peak of the waveform
- **Charge**: The total number of PEs

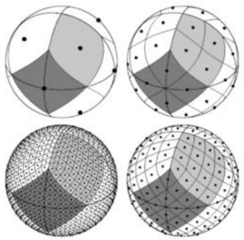
- Due to the large PMT number distributed on the sphere, directly feeding models with all waveforms is hard
- Features are extracted from each PMT to mathematically describe the waveform, which reflects **event topology** in the detector

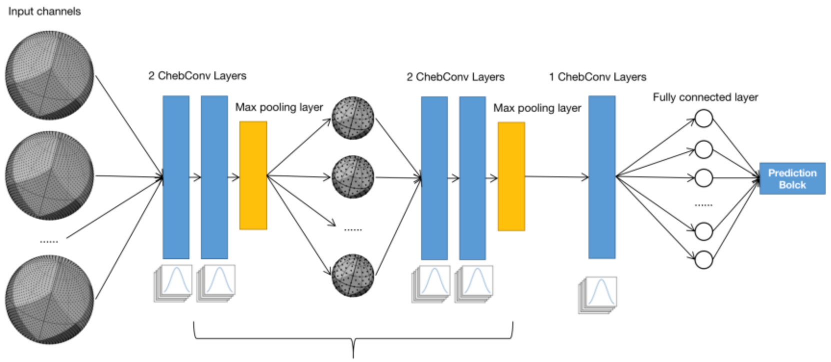
Models are trained with a large number of PMT feature pictures and learn to find direction/energy/ flavor/vertex etc. from the feature patterns

Machine Learning Models

DeepSphere

- DeepSphere: a popular tool processing spherical data originally developed for cosmology studies.
- Maintain rotation covariance;
- Avoid distortions caused by projection to a planar surface.
  - $N_{side} = 32$
  - Pixels=$12 \times N_{side}^2 = 12288$
  - If more than one PMTs are grouped into one pixel, information is merged:
  - First hit time: the earliest;Totoal charge: the sum;Slope and others: the average.

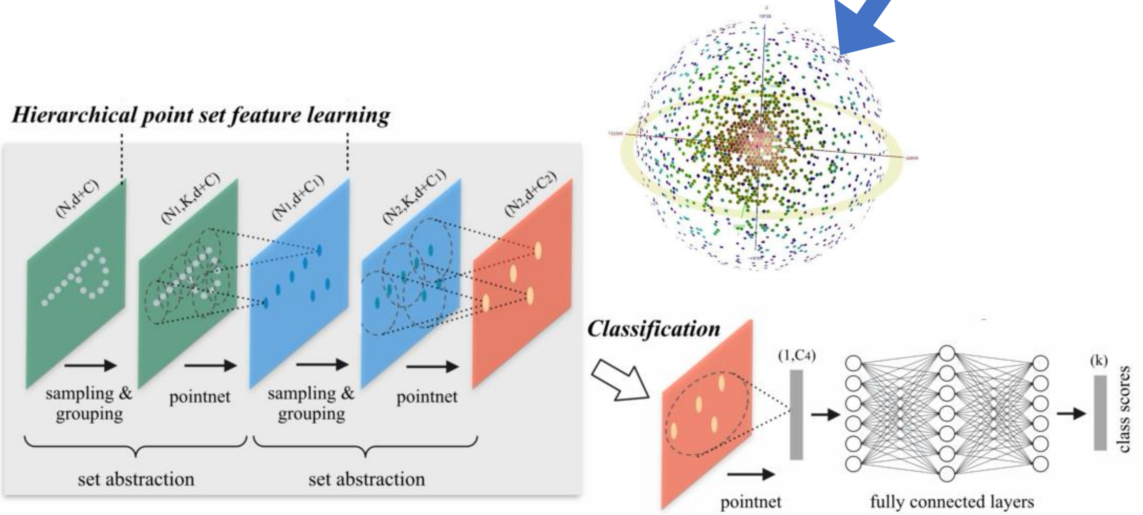




- 4 sets of convolution blocks, followed by one Chebyshev convolution layer, a fully connected layer and lastly a prediction block.

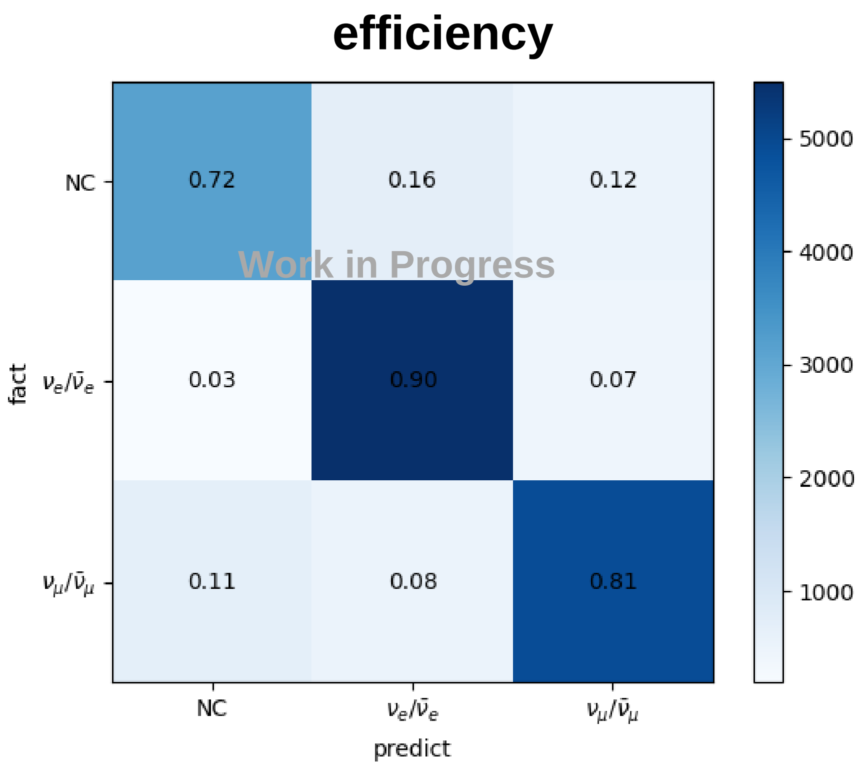
PointNet++

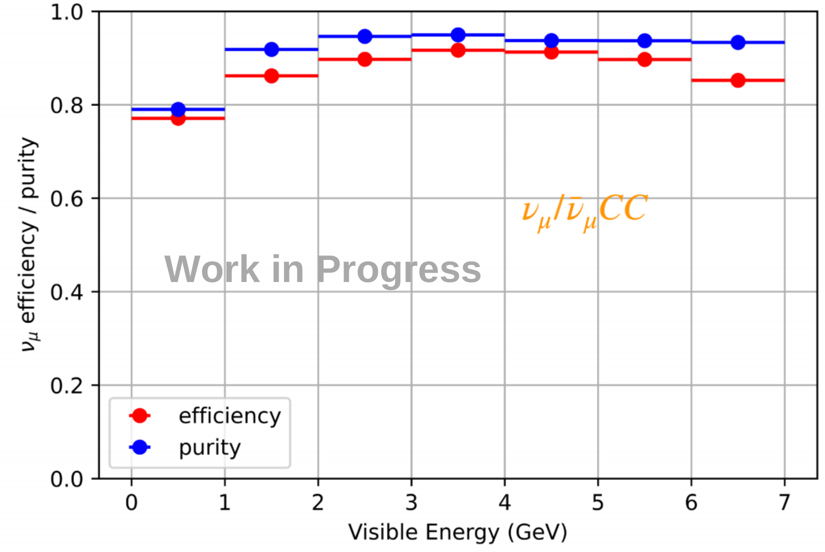
- Directly taking 3D point clouds as input → JUNO signal more resembles point clouds.



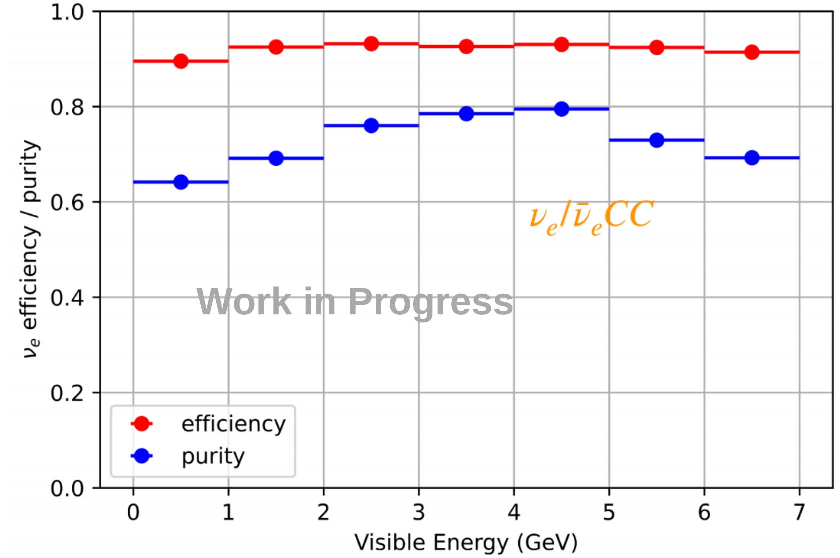
- (N.B. PointNet++ input format: for each event, N(PMT)*[x, y, z, features, ..])

3-Label Classfication

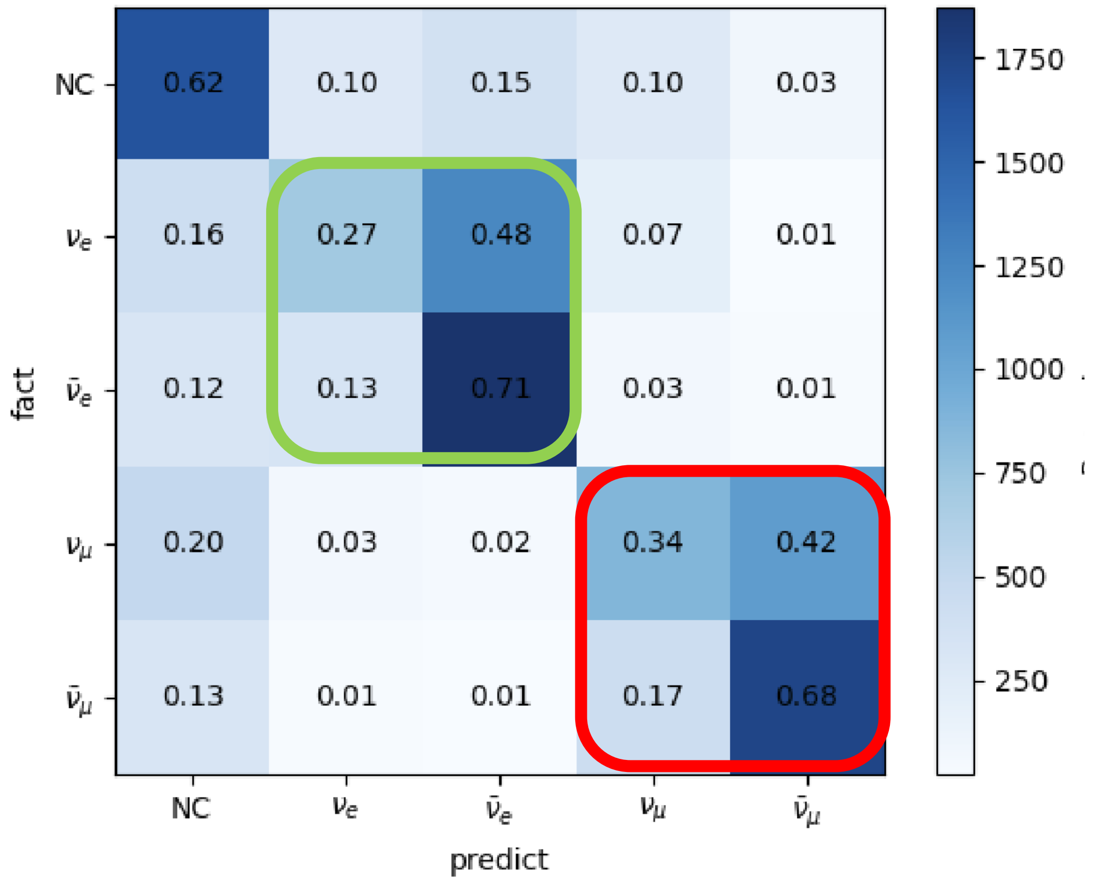




Efficiency/purity as functions of visible energy



5-Label Classfication



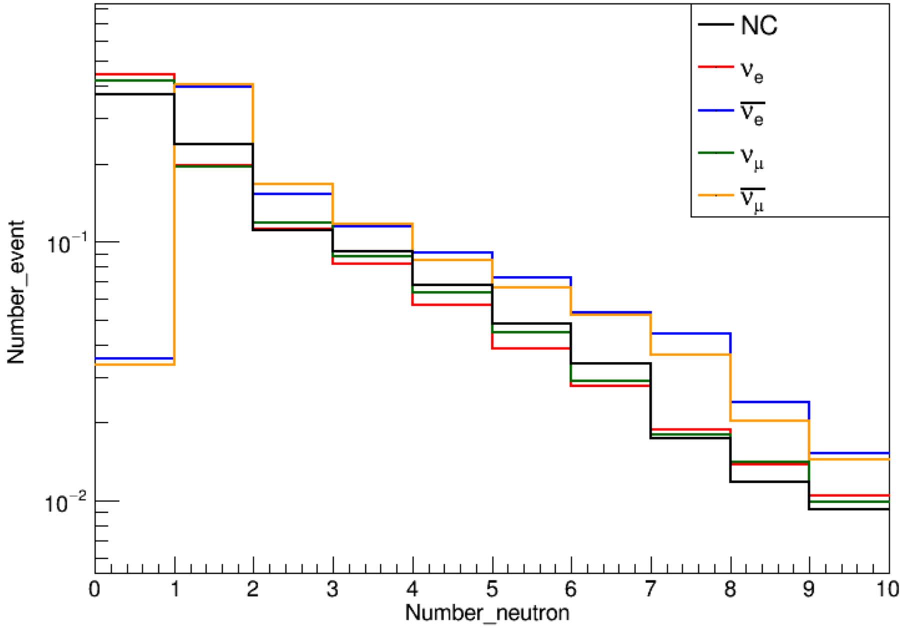
ν_e **or** $\overline{\nu}_e$?

ν_μ **or** $\overline{\nu}_\mu$?

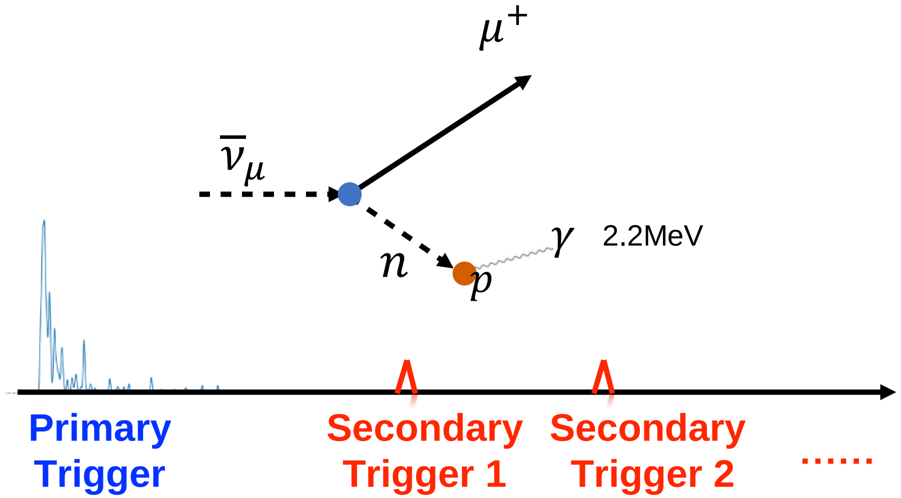
Atm ν ***and*** $\overline{\nu}$ **are hard to identify**

Neutron vs Neutrino

	ν_μ-CC	$\bar{\nu}_\mu$-CC
QE	$\nu_\mu + n \rightarrow \mu^- + p$	$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
RES	$\nu_\mu + p \rightarrow \mu^- + p + \pi^+$	$\bar{\nu}_\mu + p \rightarrow \mu^+ + p + \pi^-$
	$\nu_\mu + n \rightarrow \mu^- + p + \pi^0$	$\bar{\nu}_\mu + p \rightarrow \mu^+ + n + \pi^0$
	$\nu_\mu + n \rightarrow \mu^- + n + \pi^+$	$\bar{\nu}_\mu + n \rightarrow \mu^+ + n + \pi^-$
DIS	$\nu_\mu + N \rightarrow \mu^- + X$	$\bar{\nu}_\mu + N \rightarrow \mu^+ + X$



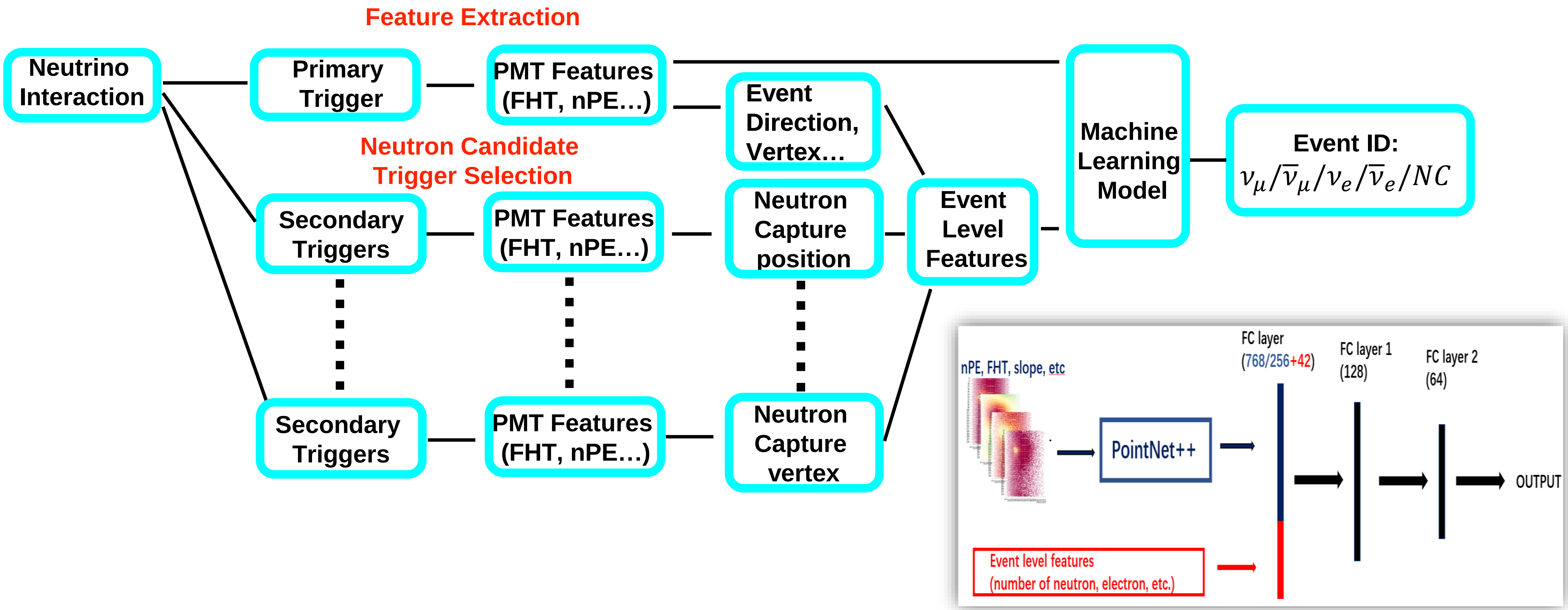
Number of neutrons in different type



- Using only the primary trigger is difficult to discriminate $\nu/\overline{\nu}$
- The Atmospheric ν and $\overline{\nu}$ events produce different numbers of neutrons
- Neutron capture emits a fixed-energy photon
- Neutrons create Atm $\nu/\overline{\nu}$ events' secondary triggers

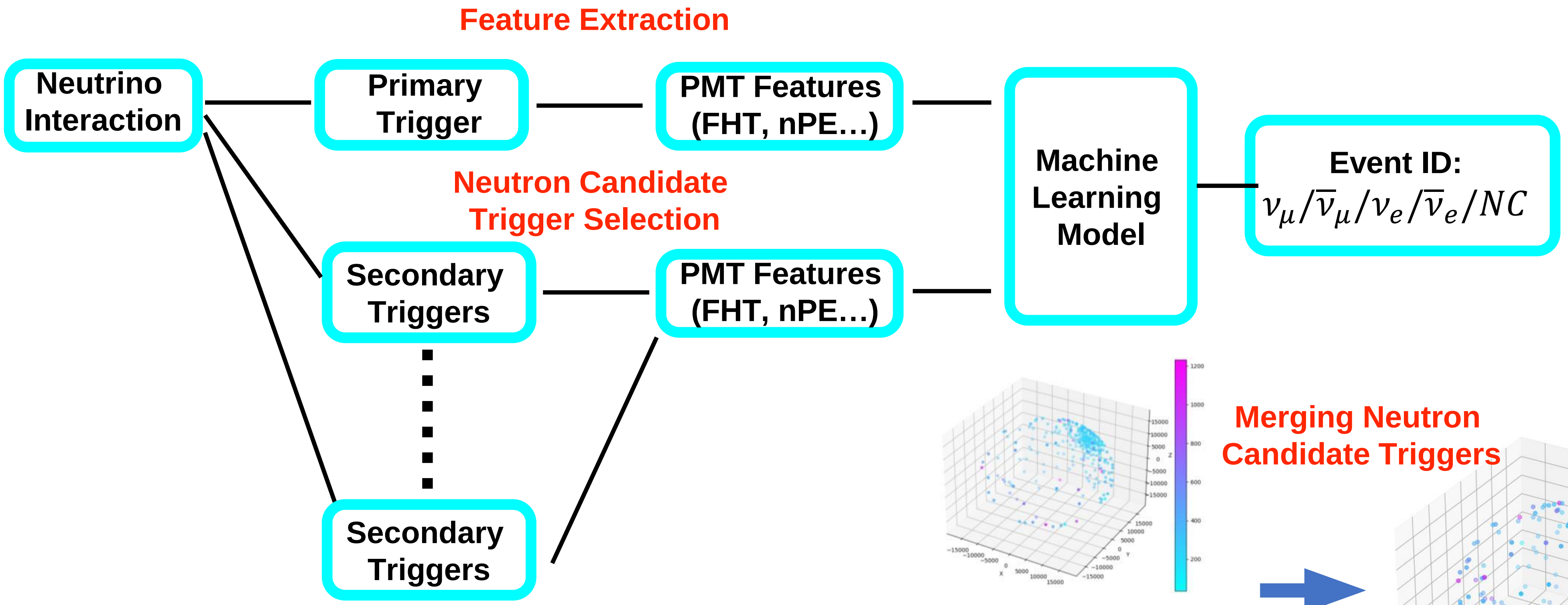
- It is possible to statistically separate ν and $\overline{\nu}$ with neutron informations.

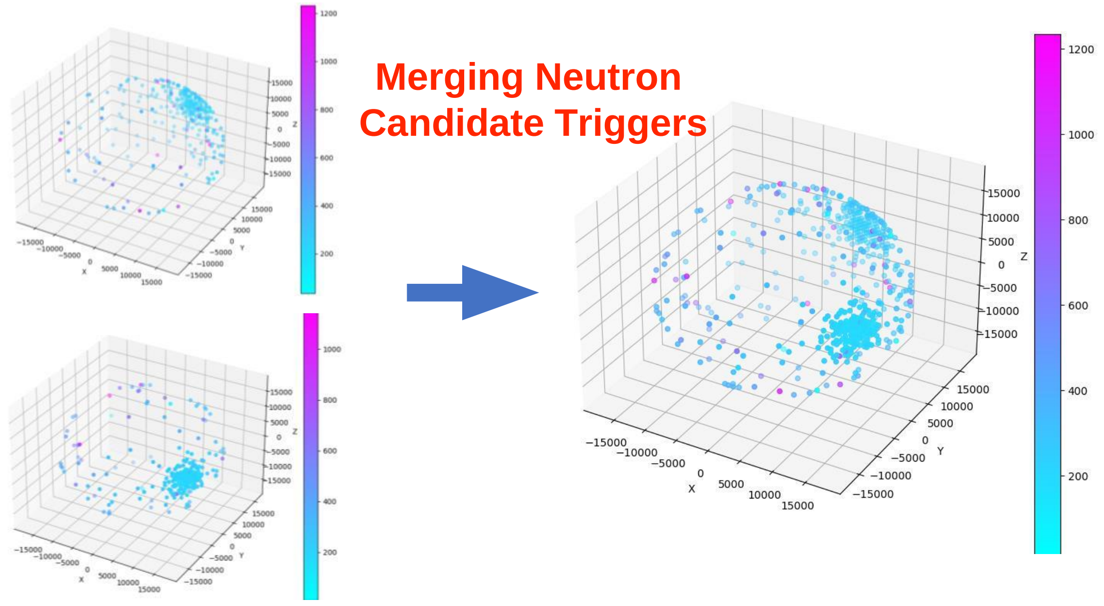
Flavor Identification Strategies



- **Strategies1**: Combine the PMT-level features with event-level features (neutron-multiplicity, relative positions of neutrons to event vertex/directions, etc.).

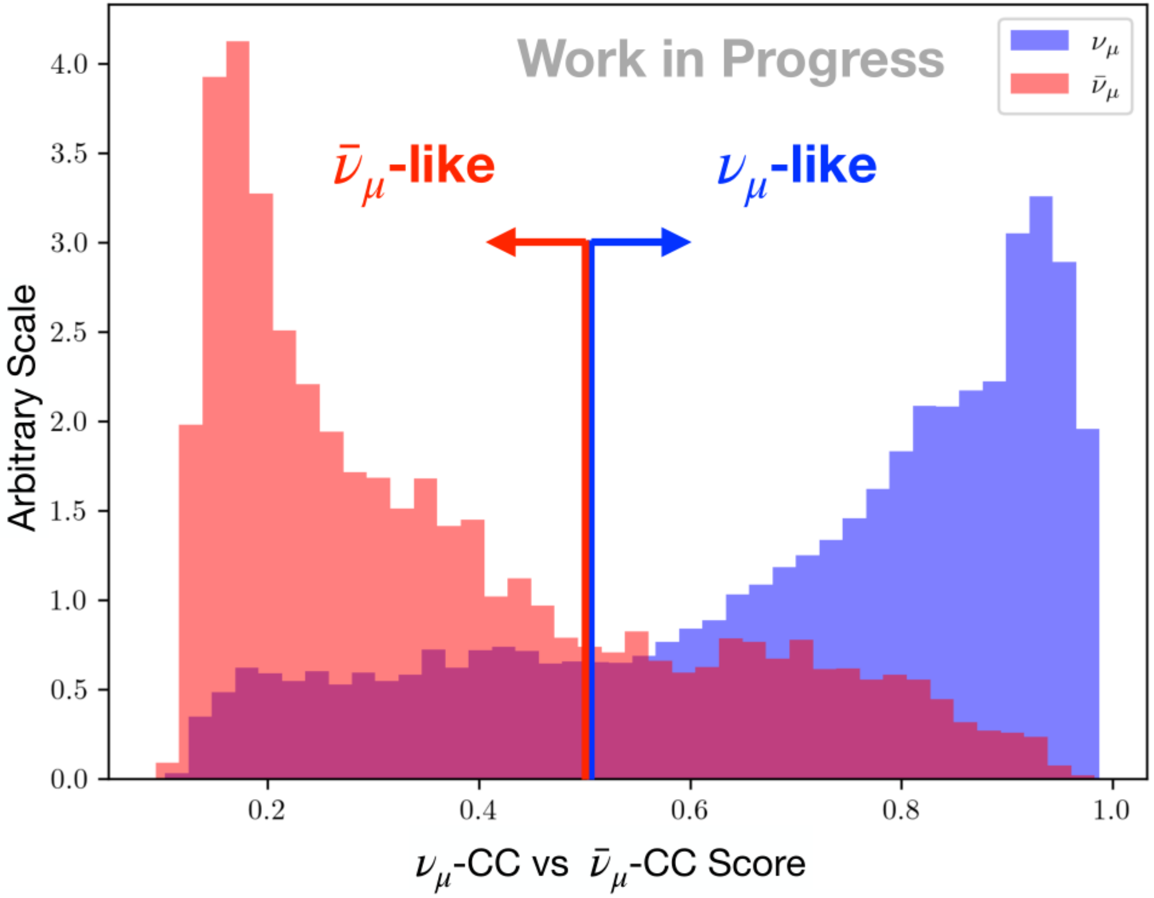
Flavor Identification Strategies





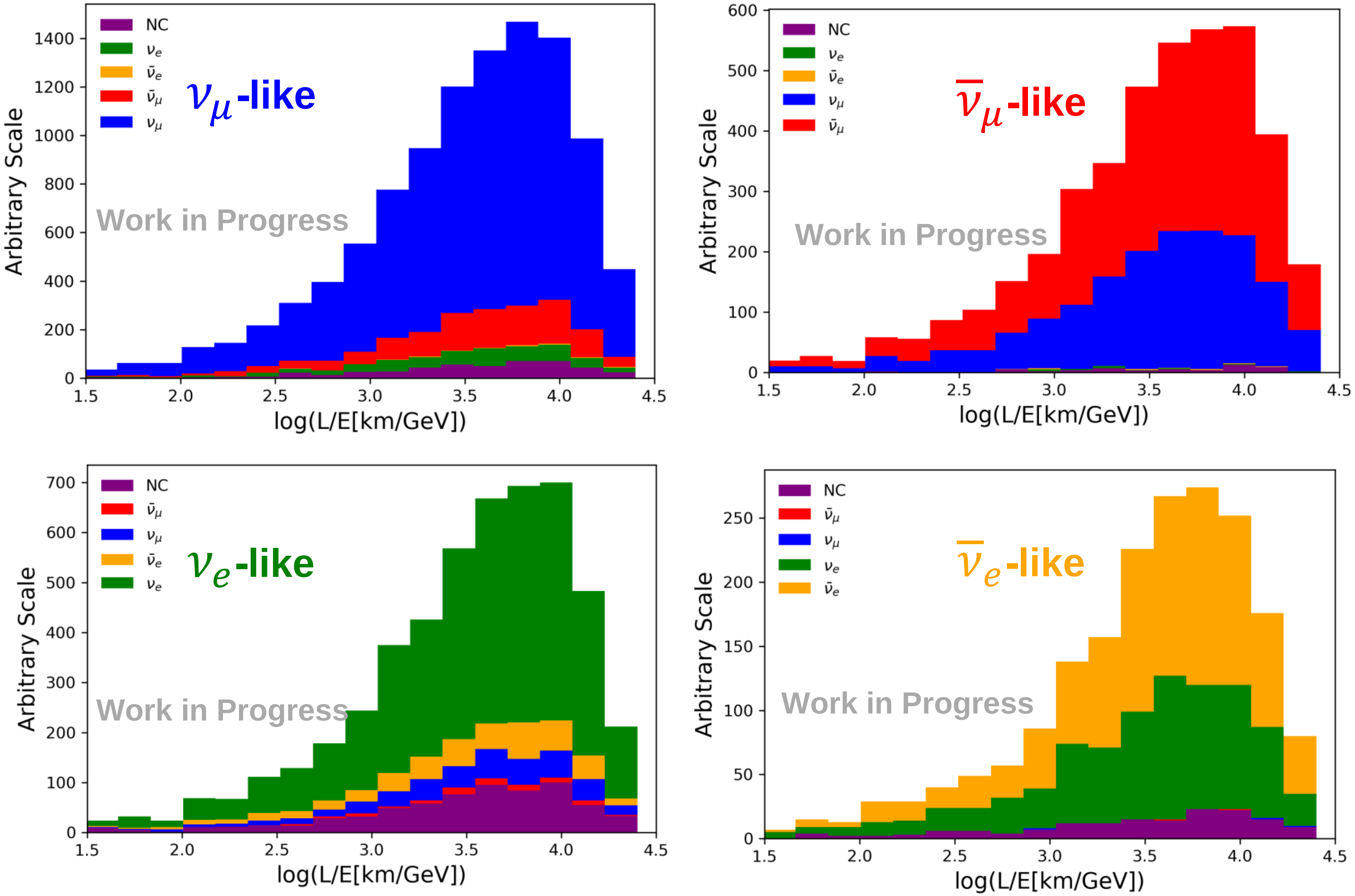
- **Strategies2**: Directly input PMT features from multiple triggers into ML.

Results



- Input features from both the prompt trigger and delayed triggers into ML.
- ν and $\bar{\nu}$ can be statistically separated with the help from neutron-capture informations.

Results



Upward-going events, $E_\nu > 0.5$GeV

Summary

- ✓ A machine learning approach for the identification of atmosphere neutrino events in JUNO was presented.
- ✓ Flavors of atmospheric neutrinos are identified with good efficiency and purity.
  - Especially neutrinos and anti-neutrinos can be identified.
- ✓ This method is applicable to other large homogeneous LS detectors as well, making them suitable candidates for future atmospheric neutrino oscillation measurements.
- ✓ We aim to perform the first atmospheric neutrino oscillation measurement in an LS detector in the world and increase JUNO's total sensitivity to NMO.

Thanks!

BACKUPS

Extension

- What we need from reconstruction for atmospheric neutrino oscillation analysis:
- Flavor ($\nu_\mu/\bar{\nu}_\mu$ vs $\nu_e/\bar{\nu}_e$vs NC);
- Energy;
- Directionality (oscillation baseline length):
- As this method is multi-purposed, these atmospheric neutrino reconstruction topics also be studied.