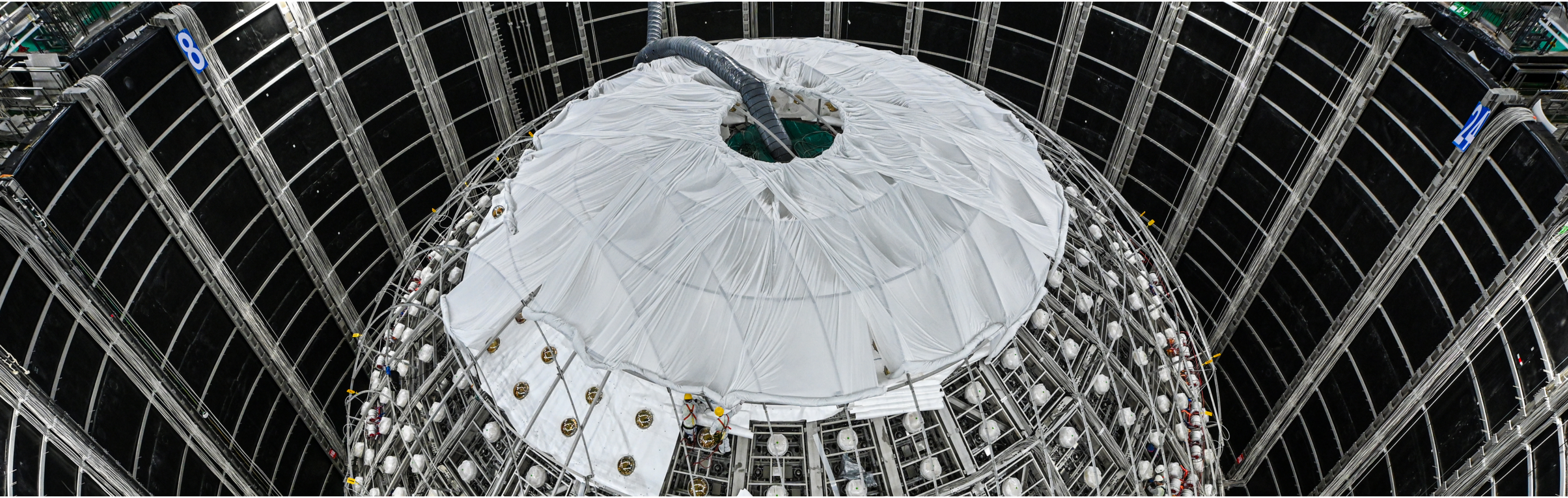


Flavor Identification of Atmospheric Neutrinos in JUNO

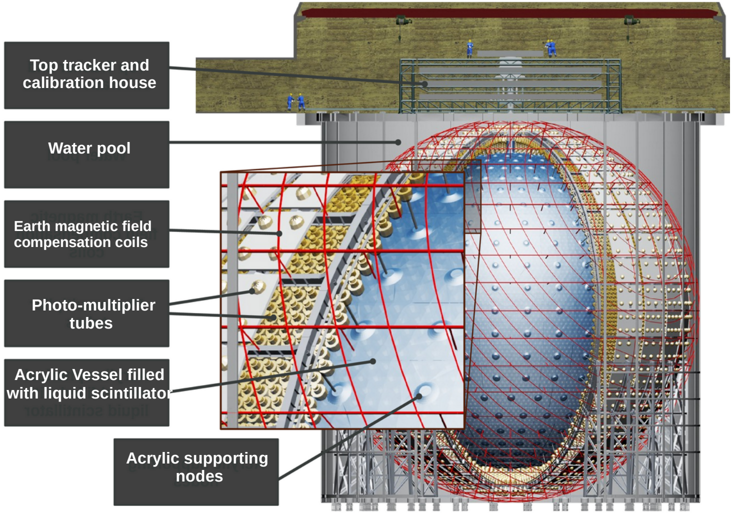
XX International Workshop on Neutrino Telescopes 2023

Rosmarie Wirth[1] for the JUNO collaboration

[1] Universität Hamburg, Germany

JUNO in a nutshell

- **J**iangmen **U**nderground **N**eutrino **O**bservatory
- Liquid scintillator with 20 kton Volume
  → largest of its kind
- Aiming to determine neutrino mass ordering (NMO) from reactor electron anti-neutrinos



Upcoming JUNO talks:

→ **Solar neutrinos** at 4.40pm by A.Singhal
→ **Supernova Neutrinos** at 10.25am by Y.Zhang
→ **Neutron decay** at 10.20 am by Y. Hu

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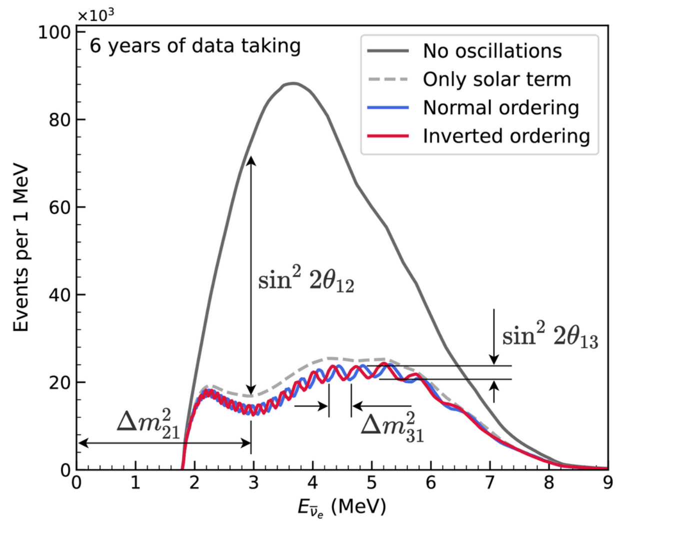
Determine NMO with reactor $\bar{\nu}_e$

- Baseline of ~ 52.5 km
- Double calorimetry system
- Optical overage of ~ 78 %
- Energy resolution of ~3 % at 1 MeV

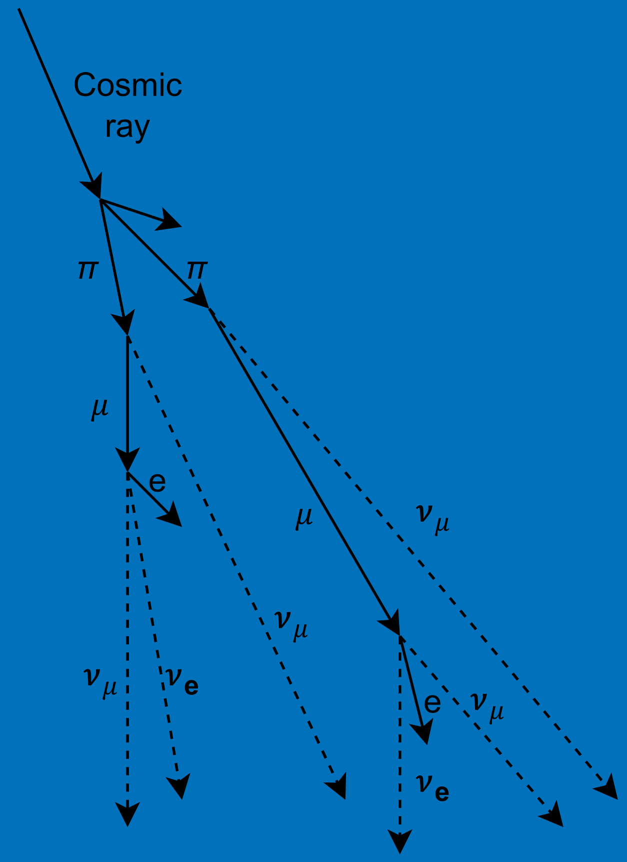


Expected oscillated spectrum for reactor anti-electron neutrinos with normal and inverted ordering at JUNO.

Atmospheric Neutrinos in JUNO

- Neutrinos produced by cosmic rays scattering with earth's atmosphere
  → producing $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$ with up to TeV Energies
- Reaching the detector from all directions, partially penetrating earth's core
  → Upcoming neutrinos experience matter effect
  → Resonance energy range $E_\nu \approx 3-10$ GeV
  → Significant differences for normal and inverted ordering
  → $P_{NO}(\nu_\alpha \rightarrow \nu_\beta) = P_{IO}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta), P_{IO}(\nu_\alpha \rightarrow \nu_\beta) = P_{NO}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$
- Provide independent neutrino mass ordering (NMO) sensitivity at GeV energies

Atmospheric neutrino production



Schematic atmospheric neutrino production

Atmospheric Neutrinos in JUNO

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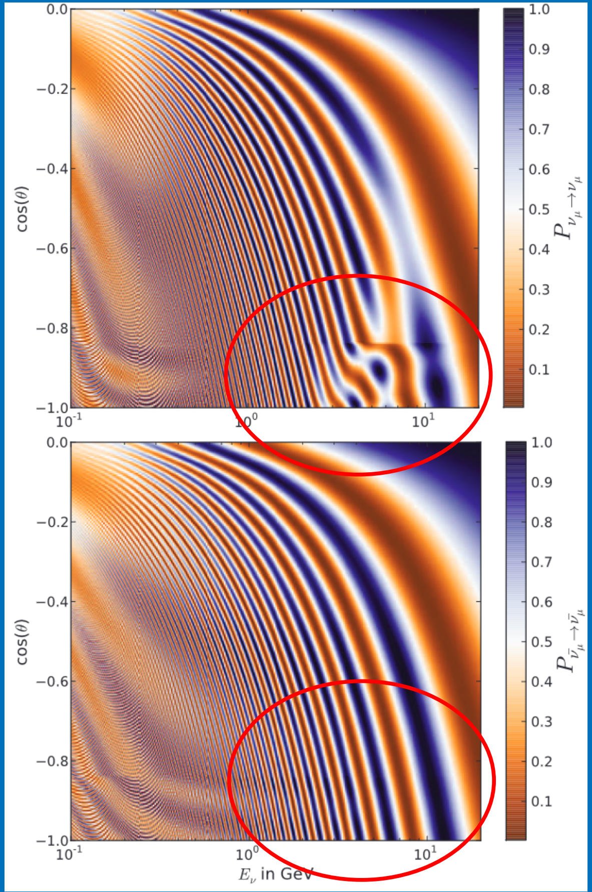
Atmospheric neutrino oscillograms



Oscillation probabilities for atmospheric neutrinos in normal hierarchy hypothesis. arXiv:1507.05613

Atmospheric Neutrinos in JUNO

Access the atmospheric neutrino channel for NMO analysis:

- Reconstruct neutrino direction
- Reconstruct neutrino energy
  - → Identify fully contained events
  - → Identify charged current events
- Identify incoming neutrino
  - → Identify charged current events
  - → Identify neutrino flavor

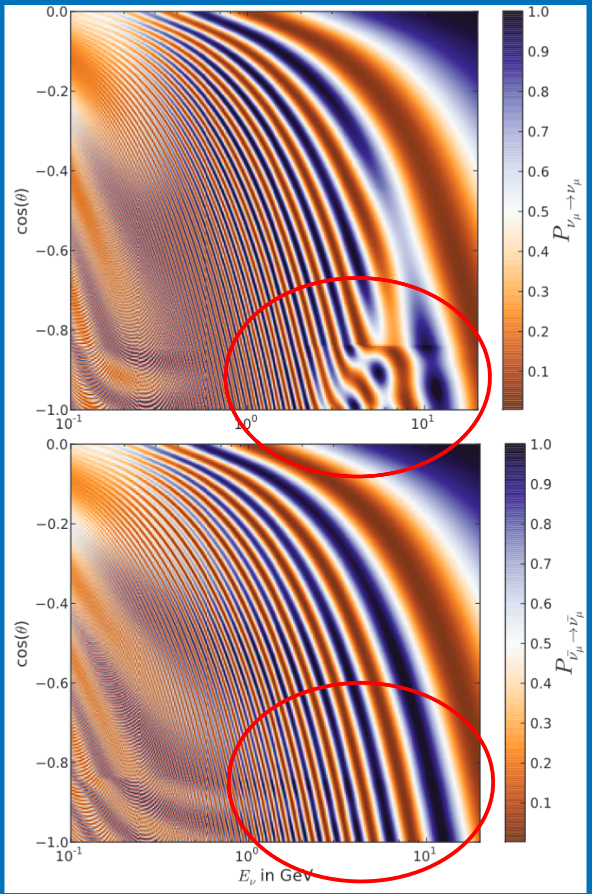
Upcoming talk by Z. Yang

Covered here

Atmospheric neutrino oscillations at JUNO

→ ***Covered by G. Li at 9.00 a.m.***

Atmospheric neutrino oscillograms



Oscillation probabilities for atmospheric neutrinos in normal hierarchy hypothesis. arXiv:1507.05613

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Atmospheric Neutrinos interactions

- **Neutral Current** (NC)**:**
  - Particle identification not accessible
  - Energy reconstruction problematic

    → Needs to be excluded for NMO analysis
- **Charged Current** (CC)**:**
  - Neutrino flavor information contained
  - Energy reconstruction promising

Identify 5 Classes: NC, CC: $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$

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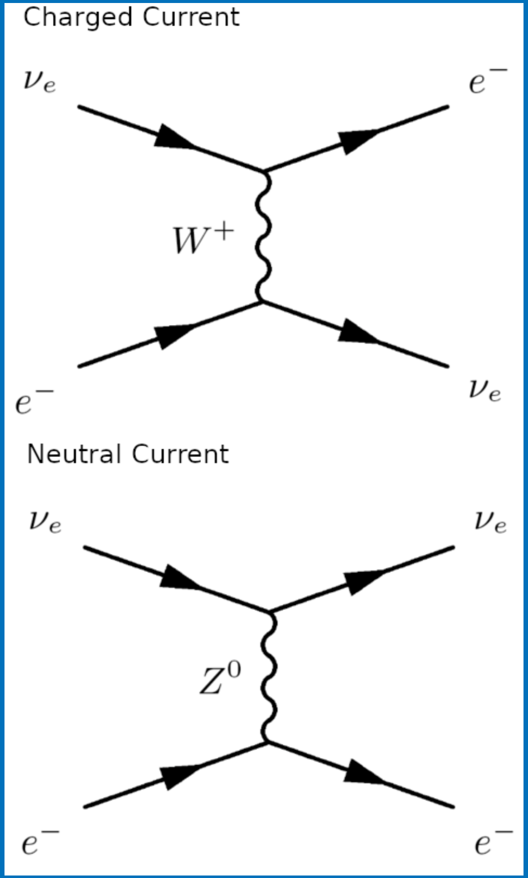
Neutrino interactions



Charged and neutral current neutrino interactions.

Atmospheric Neutrino CC interactions

- **Flavor identification:**
  - Secondary lepton differentiates
  - Electrons more point like, muons track like
    → secondary lepton track length
  - Michel electron could identify secondary muons
- **Neutrino / anti-neutrino discrimination:**
  - Statistically more Neurons in anti-neutrino events
  - Neutron capture information needed, from following trigger windows
    → Depending on the Neutron tagging efficiency

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Neutrons in CC neutrino interactions

	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	$\nu_\mu + N \rightarrow \mu^- + X$	$\bar{\nu}_\mu + N \rightarrow \mu^+ + X$

Table of CC interaction types for $\nu_\mu, \bar{\nu}_\mu$.

- Neutron appears more often in CC anti-neutrino channel
- Neutron capture, releasing a 2.2 MeV ɣ

→ **Statistical discrimination of $\nu, \overline{\nu}$ from neutron capture information possible.**

Reconstruction Approaches in JUNO

- Investigation on different inputs:
  - **PMT level data:** FHT, total charge, slope, total charge over time ...
  - **Event level data:** neutron multiplicity, ...
    → Dependent on reconstruction quality
- Several reconstruction approaches developed
  - Using mainly Machine Learning methods
  - Promising results with Point Clouds and Graph Networks

→ Using fully contained events, in GeV region.

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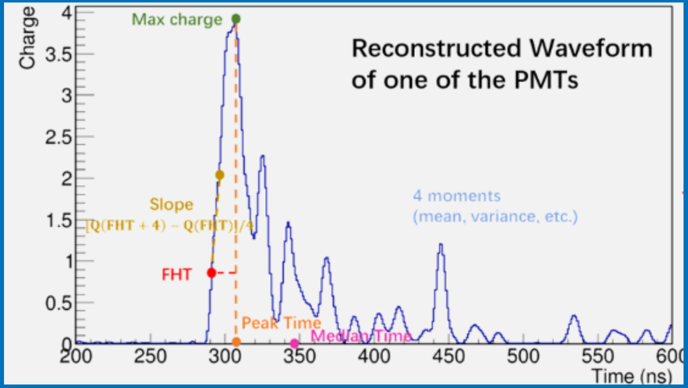
Input features PMT level:

Waveform shapes reflect the event characteristics



First waveform signal from one PMT, with waveform reconstruction and noise removing.

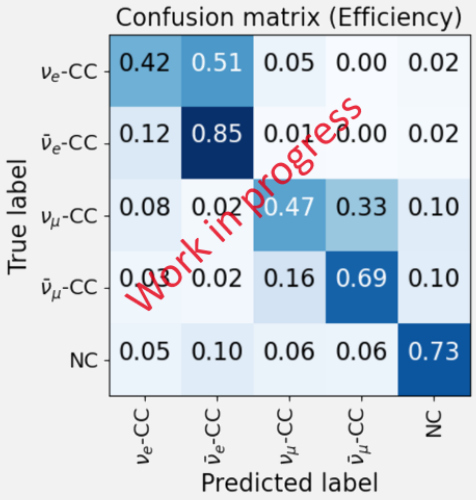
Extracted features:

- First hit time (FHT)
- Total charge
- Slope
- Charge ratio
- Max charge
- Peak time

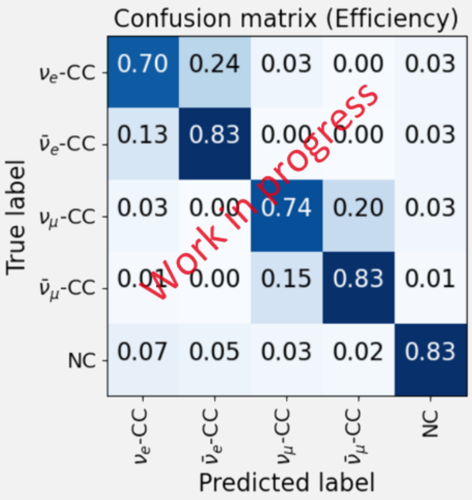
Flavor Identification Performance

Example results from current studies:

Using waveform features:



+ event level features:



→ **Results obtained without consideration of the electronic effect of the detector.**

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Used Architecture:

- Using PointNet++ PMT-wise on waveform features
- Additionally fully connected layers with decreasing size
- For event level case:
  - 42 features → very idealistic
  - added to fully connected layers

PointNet++[1] Architecture

- 3D Point Cloud based model
- Each point in cloud resembles features of one PMT
- Resembles 3D structure of the detector

1. Qi, C. R., et al. (2017) PointNet++: Deep Hierarchical Feature Learning on Point Sets in a Metric Space

Summary

- JUNO will be able to detect atmospheric neutrinos
- Secondary, independent channel for NMO analysis
- Flavor identification crucial to access this channel
- Many different methods under investigation, comparing different inputs and methods
- Current Classification approaches already promising
- **Works towards a more realistic approach ongoing** (electronics effects, neutron information)

Thanks, for your attention!

BACKUP

Example Method

- PointNet++ on PMT features
- Fully Connected layers including event level features

PointNet++[1] Architecture

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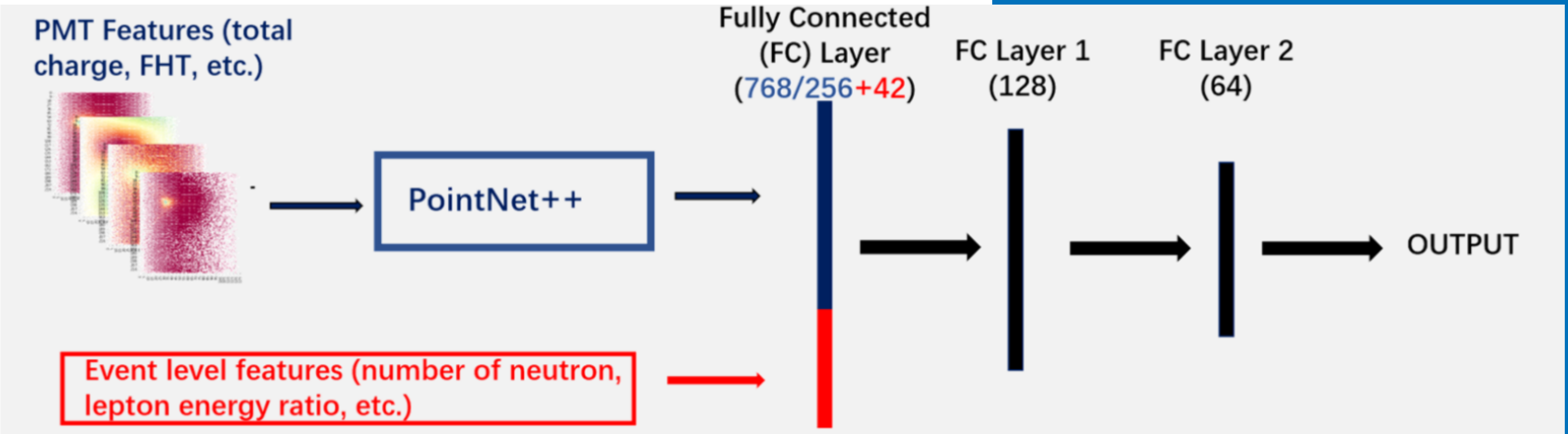

Schematic Network Architecture