Atmospheric Neutrino Oscillations at JUNO

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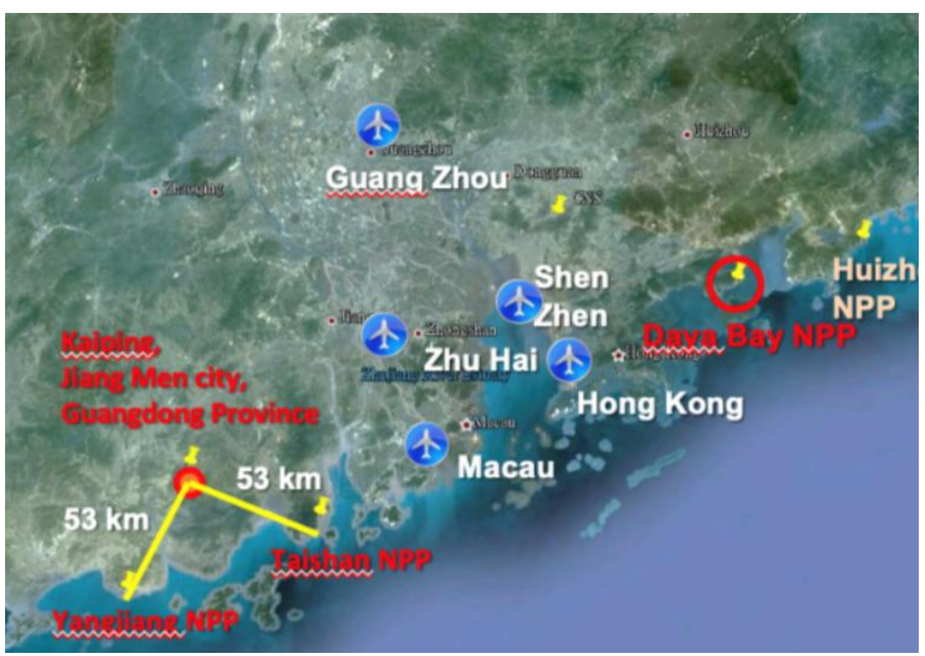
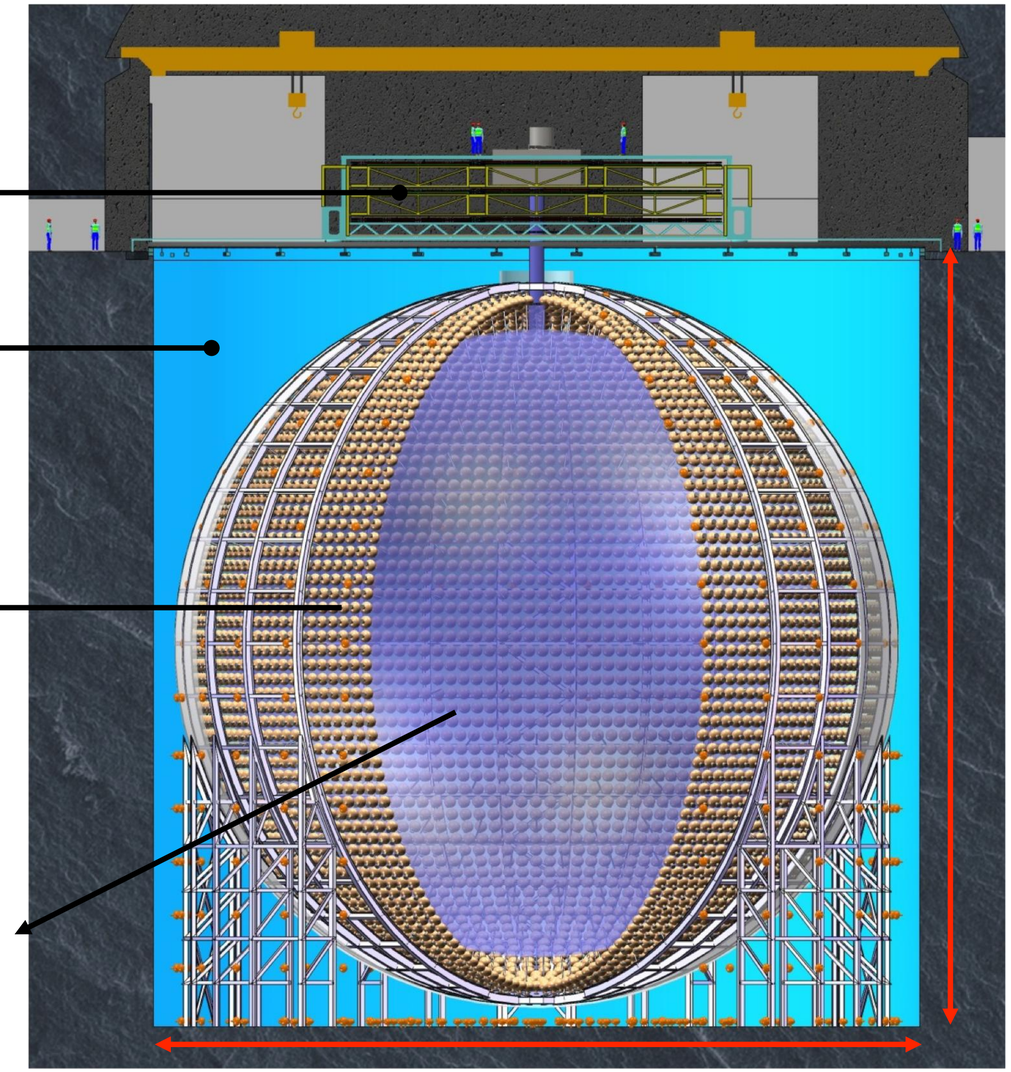
On behalf of the JUNO Collaboration

NuFACT2025
Liverpool, UK

Introduction to JUNO

- Jiangmen Underground Neutrino Observatory (JUNO):
  - Determine the neutrino mass ordering (NMO)
  - Measure neutrino oscillation parameters to sub-percent level
  - SuperNova, Solar, Geo., **Atm.**, etc.
- Construction done, **full-LS data taking has started since 26 Aug**



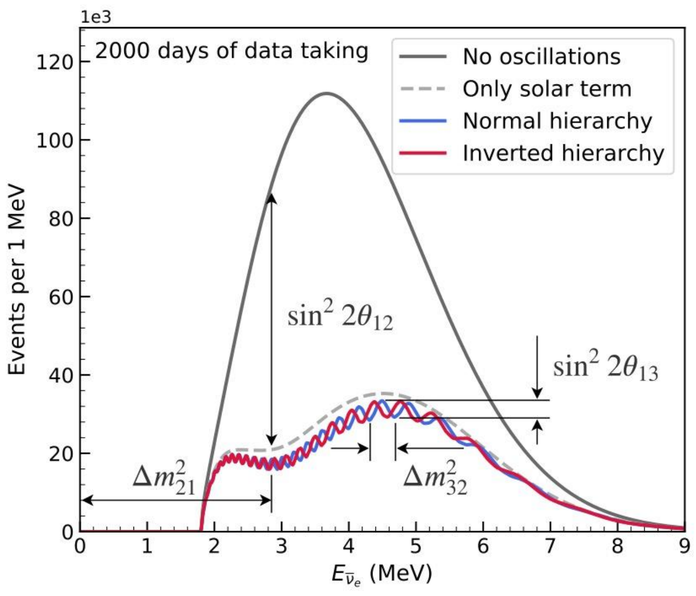


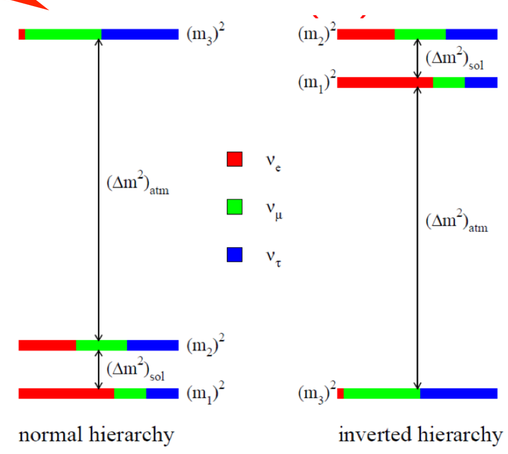
The largest liquid scintillator detector ever built.

For more details see talk by Zhiyuan Chen (Friday)

Why Atmospheric Neutrinos in JUNO?

Reactor neutrinos: Sensitivity to NMO via oscillation in vacuum

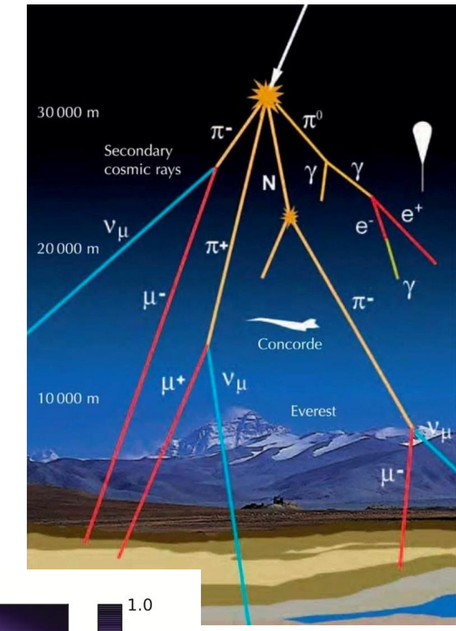


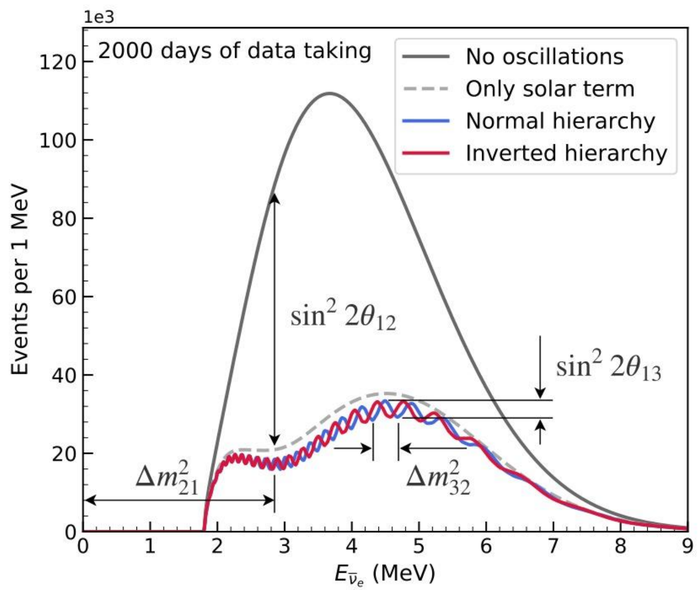


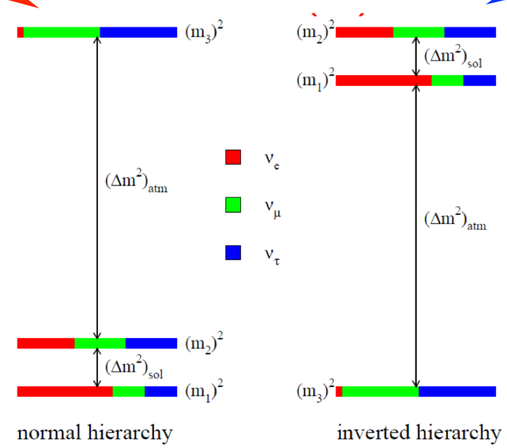
Why Atmospheric Neutrinos in JUNO?

Reactor neutrinos: Sensitivity to NMO via oscillation in vacuum

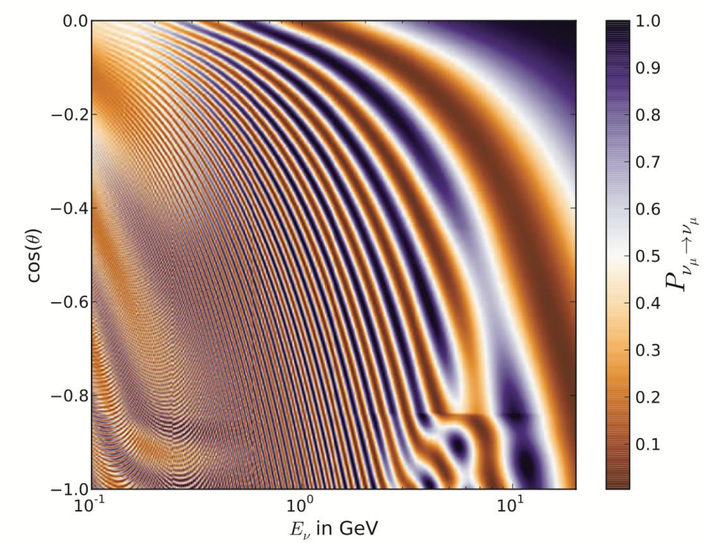
Atmospheric neutrinos: Sensitivity to NMO via matter effects





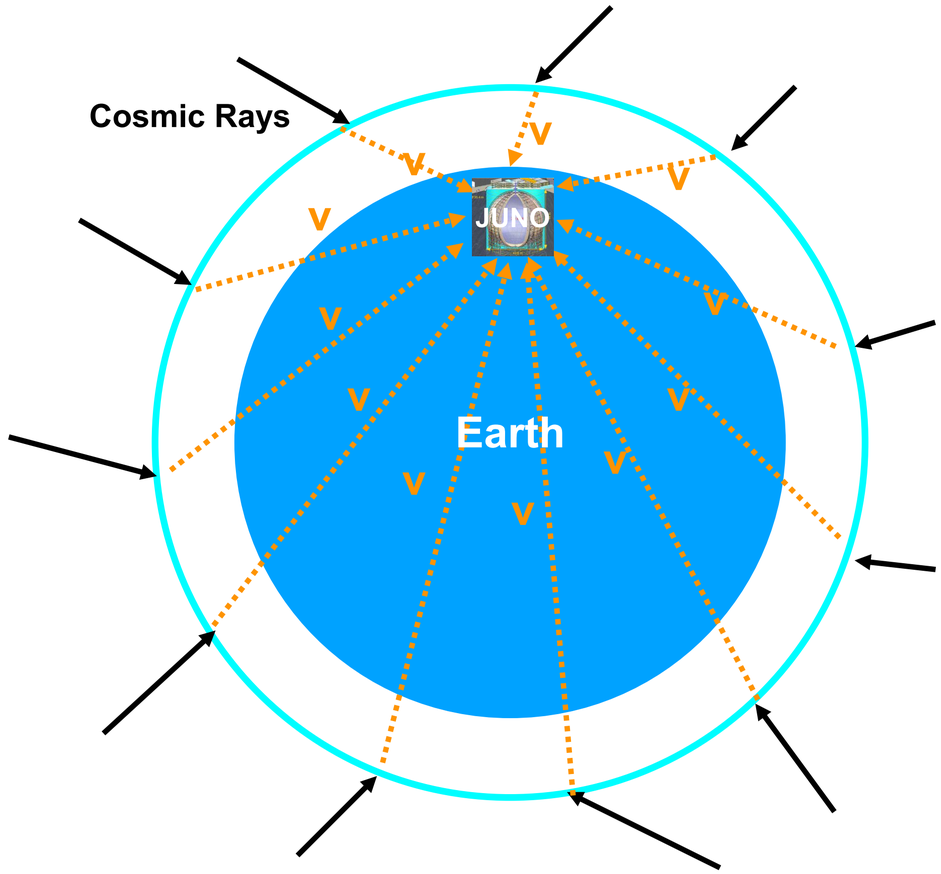


This talk



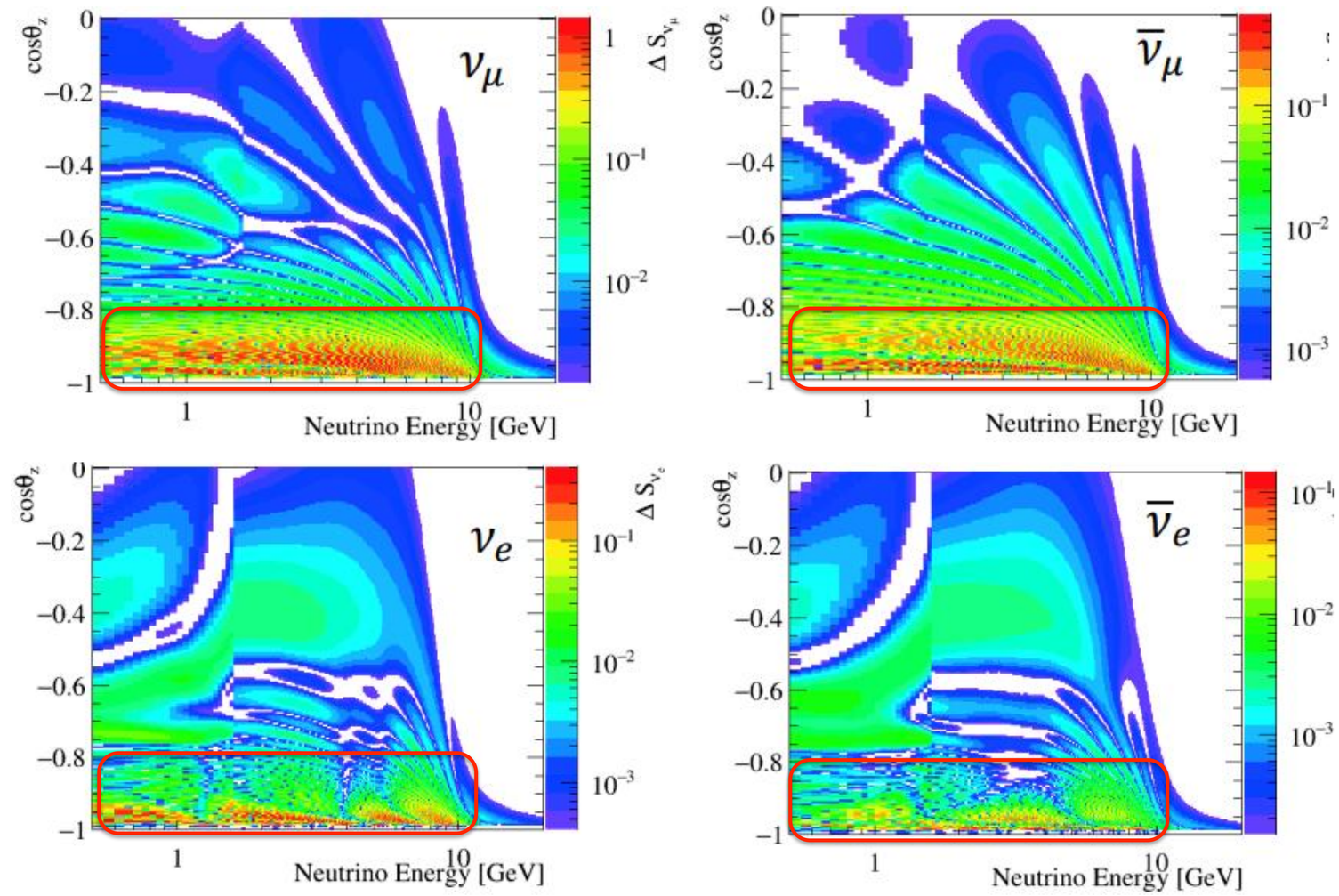
- Atmospheric neutrinos provide independent sensitivity to NMO via matter effects.
- Combing reactor and atmospheric neutrino oscillations has the potential to maximize JUNO's total sensitivity.

Key Factors



Differences between NO and IO in oscillation spectrum

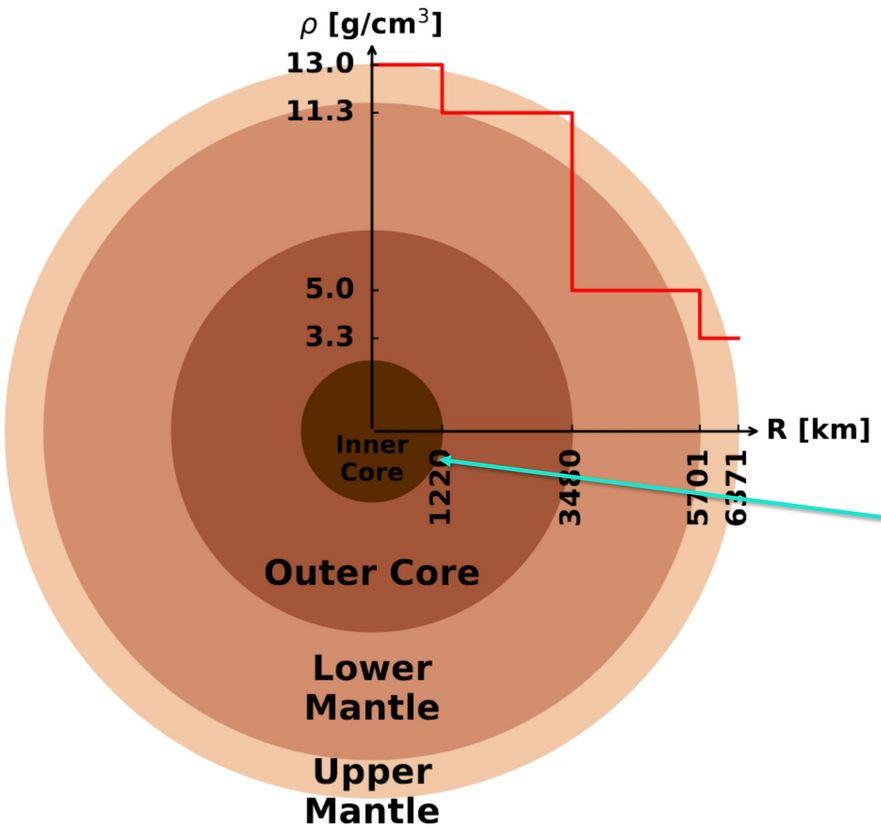
$|\varphi_{\text{Honda}}\,\sigma_{CC}\,(P_{NO} - P_{IO})|$



- Oscillation probability P(**L/E**), L~cosθ;
- **Neutrino directionality** (cosθ) is mandatory to the atmospheric neutrino oscillation measurement.

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

Key Factors



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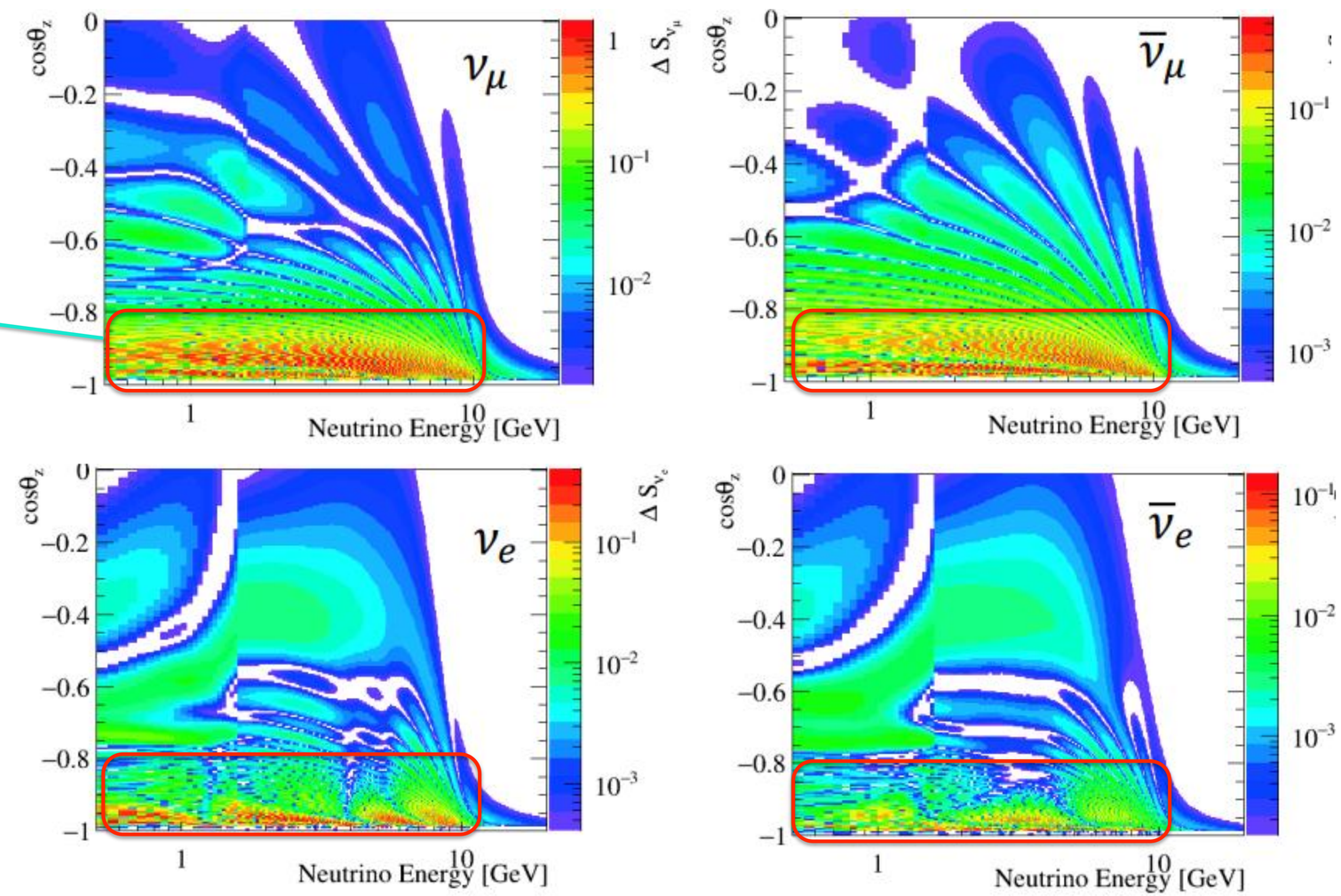

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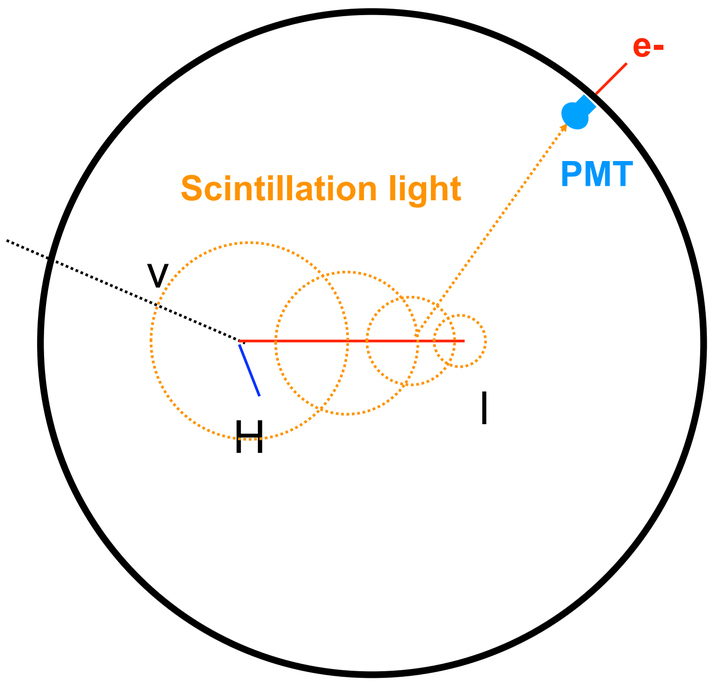
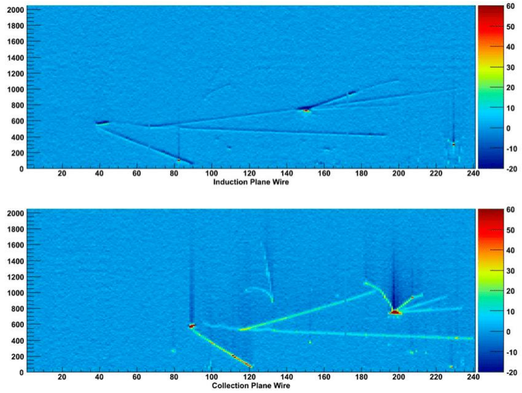
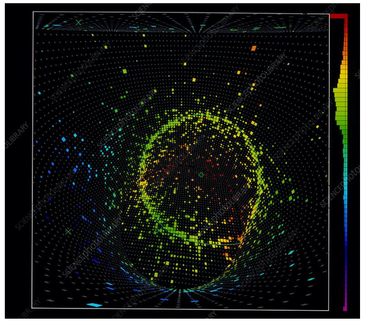
A Liquid Scintillator Detector for Atmospheric Neutrinos?

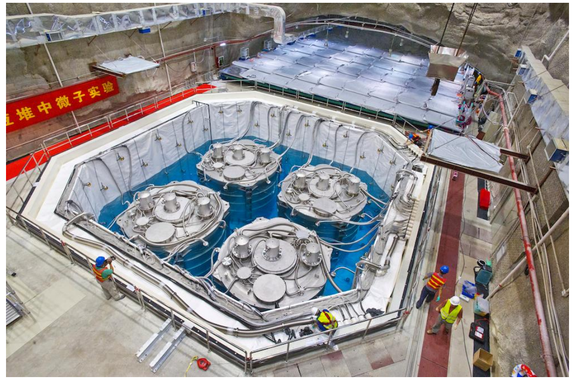


- Energy is not a problem, but
  - No direct tracking information.
  - Scintillation light is isotropic, Cherenkov light is only a few percent: no direct directional information.
  - PID for neutrino interactions in GeV?
- Atmospheric neutrino oscillation measurements in LS detectors have never been reported before.



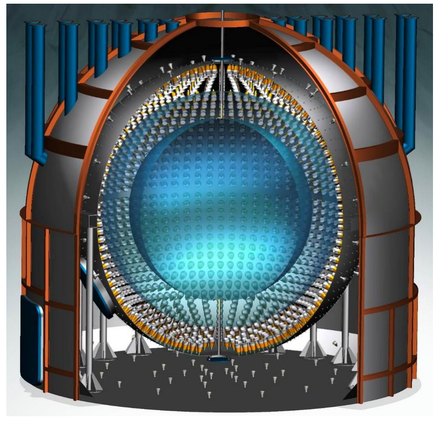


Typical LS detectors are designed with low-threshold, good energy resolution, ideal for low-energy neutrinos.



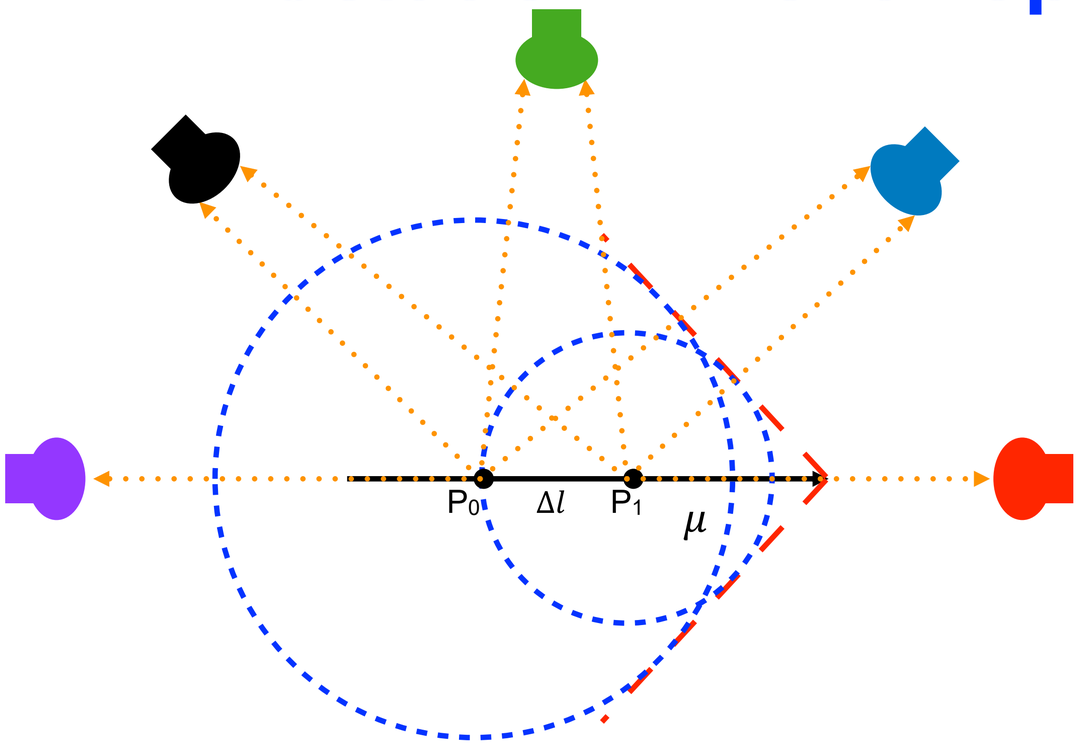
Daya Bay

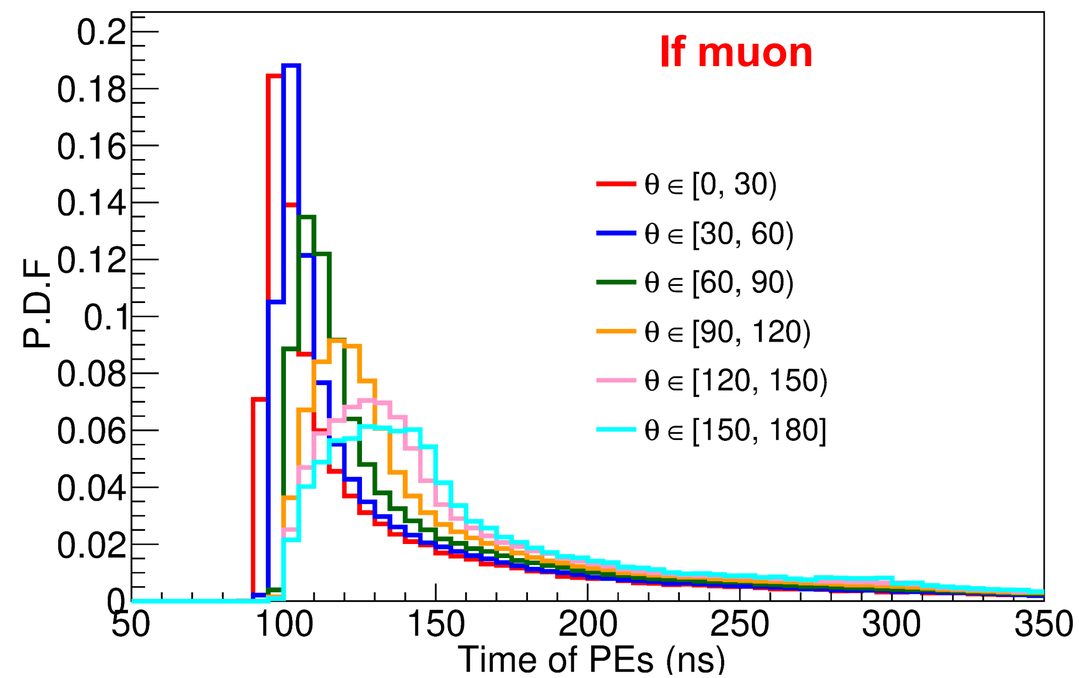
Kamland



Borexino

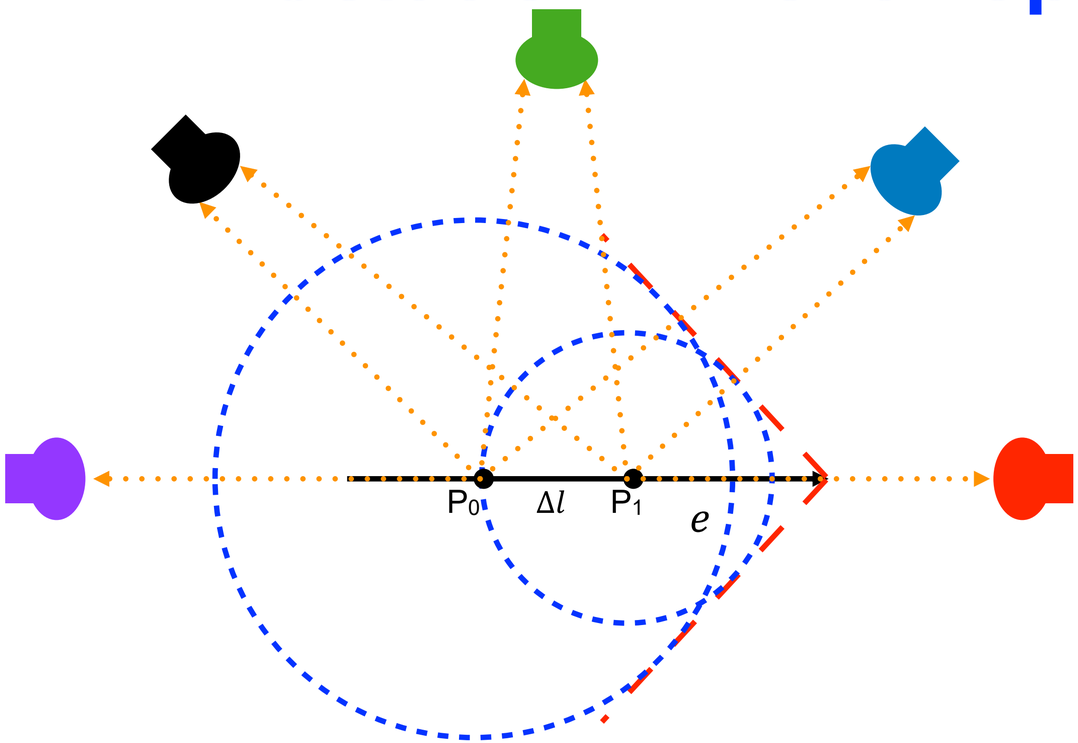
Solution: Event Topology in PMT Waveforms

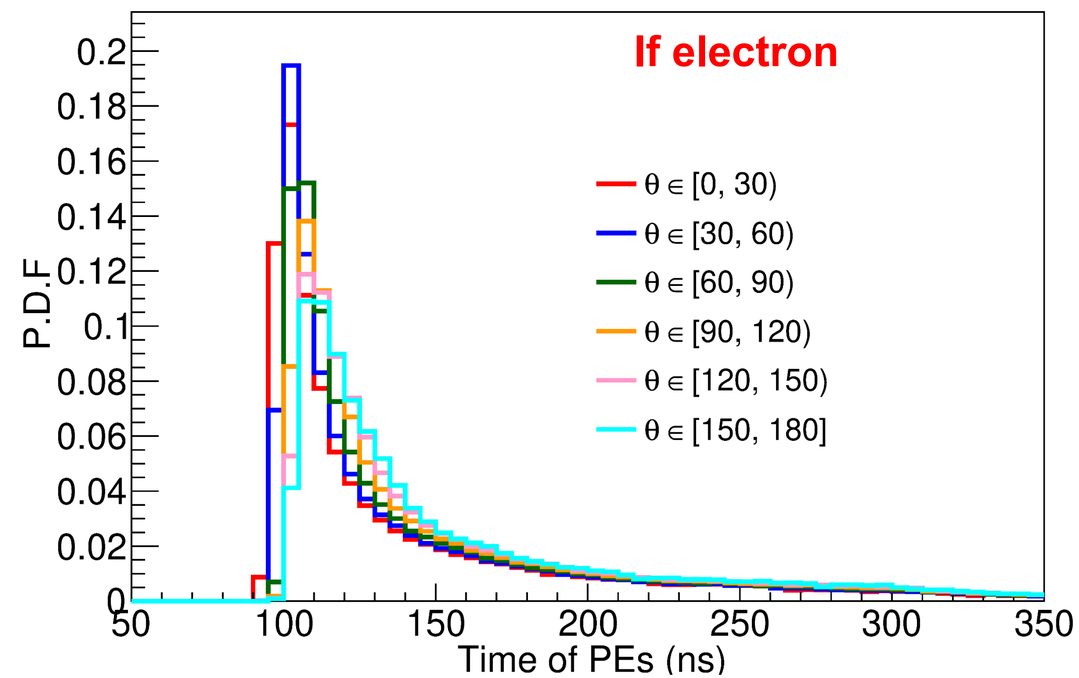




- PMTs at different angles wrt the track see distinct shapes of nPE(t)
- Exactly how nPE(t) looks depends on:
  - Track direction;
  - Track starting and stopping points;
  - Track dE/dx…
- Event topology information in the PMT waveform.

Solution: Event Topology in PMT Waveforms





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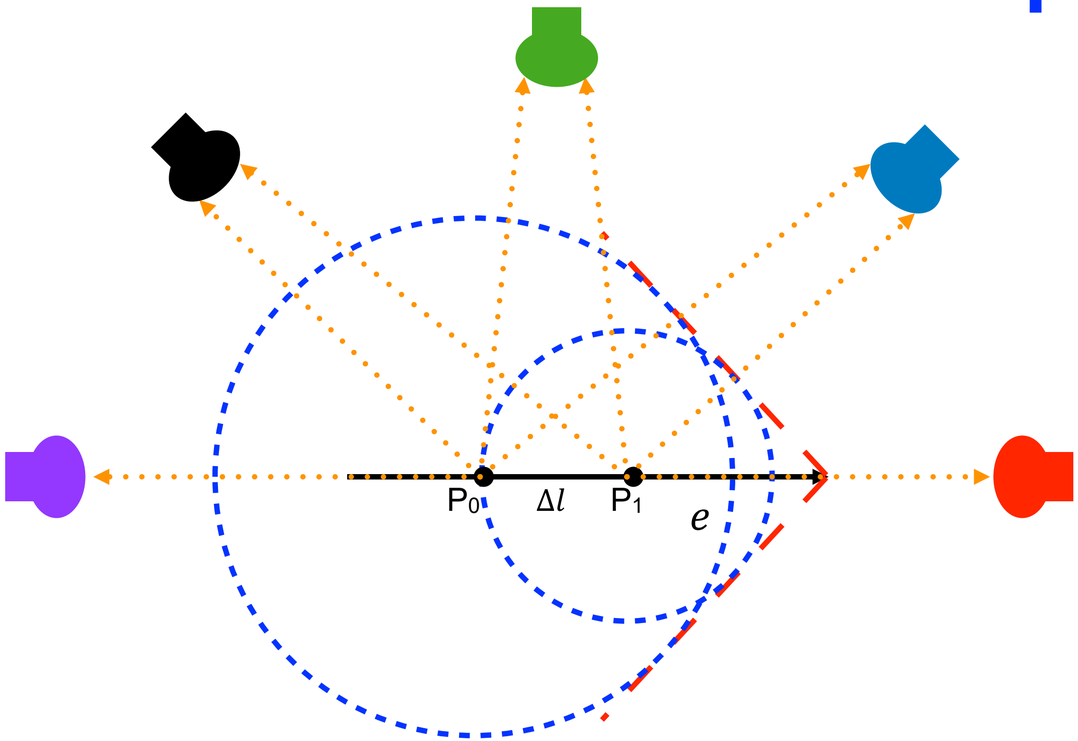

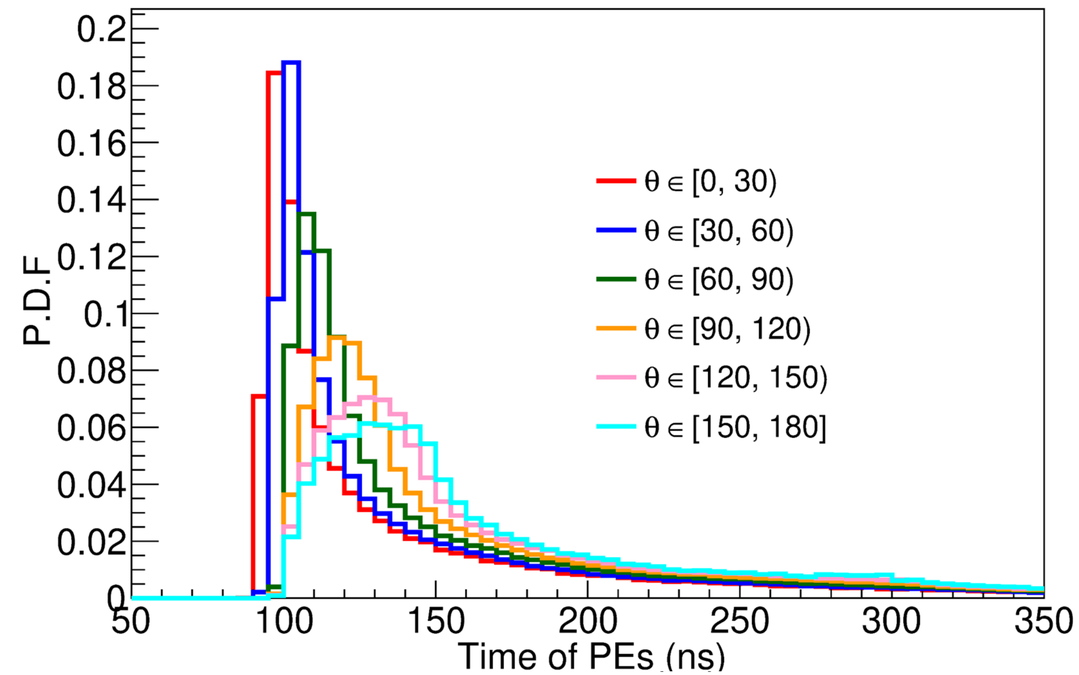

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→ **Directionality**
Energy
PID…

- Event topology information in the PMT waveform.

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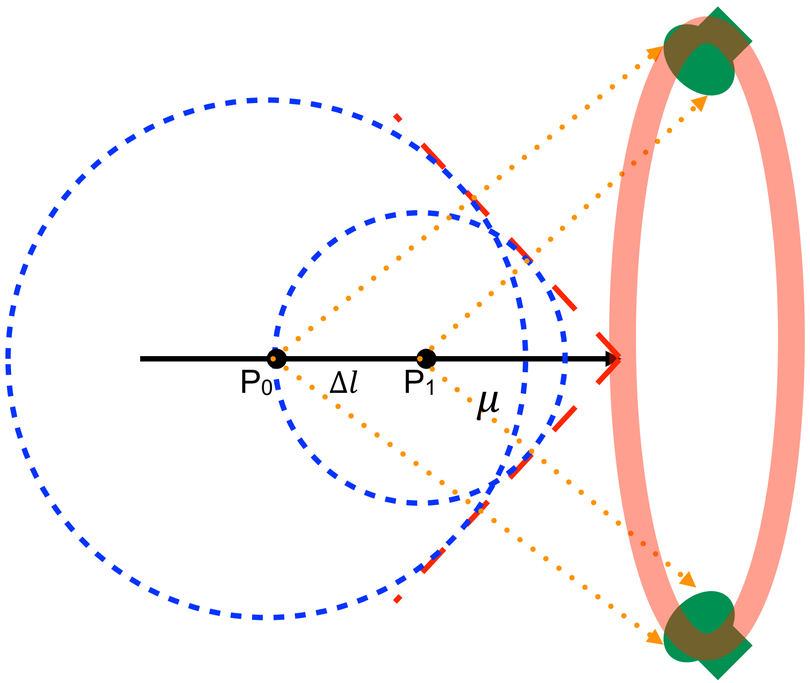

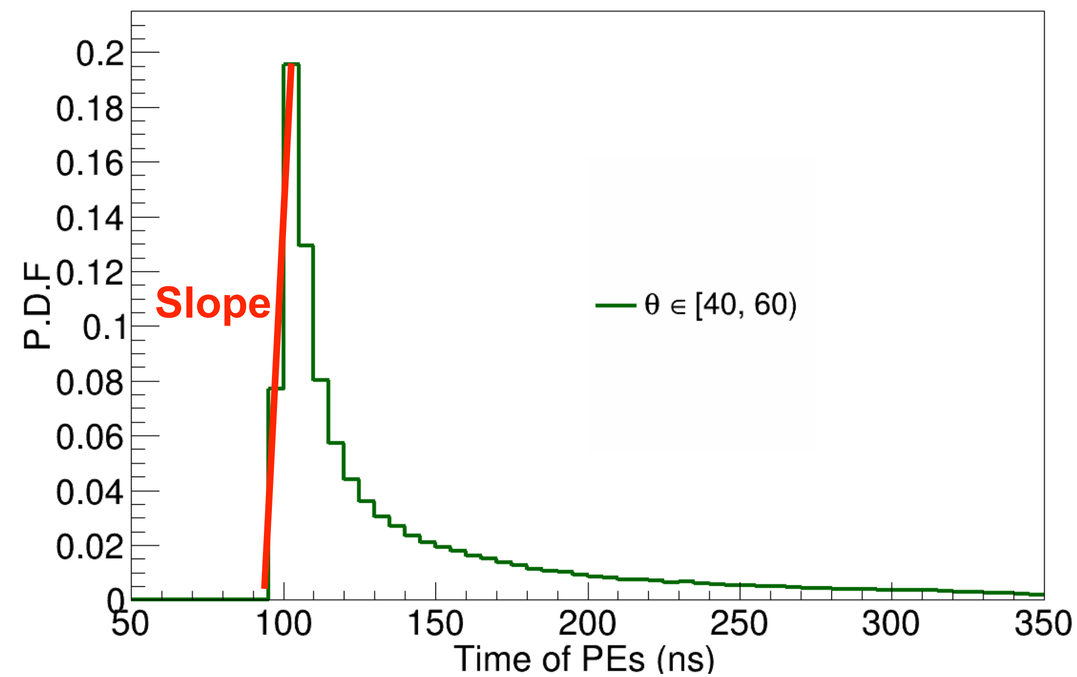

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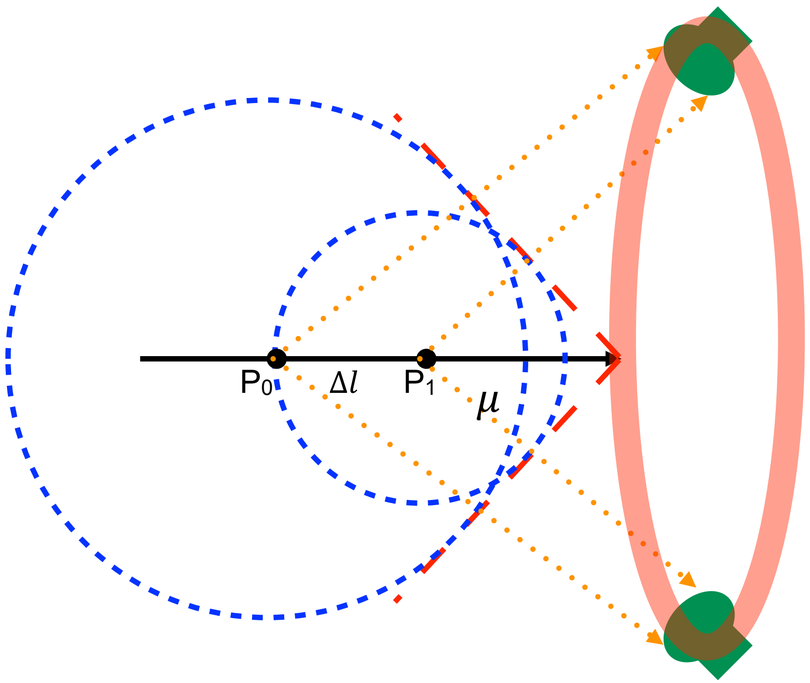

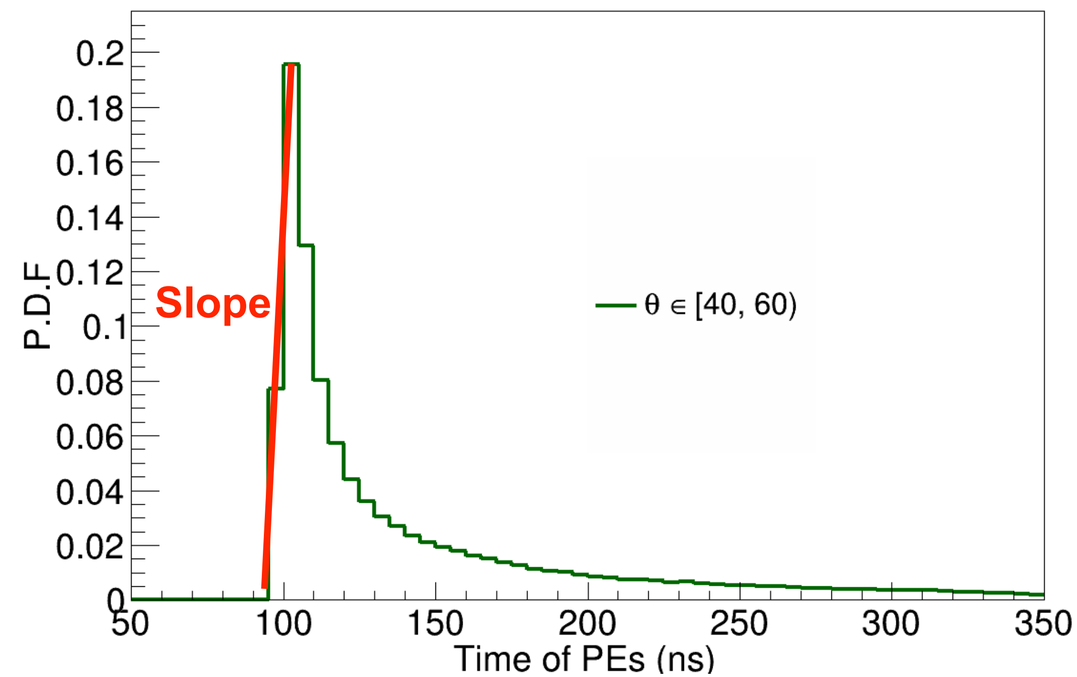

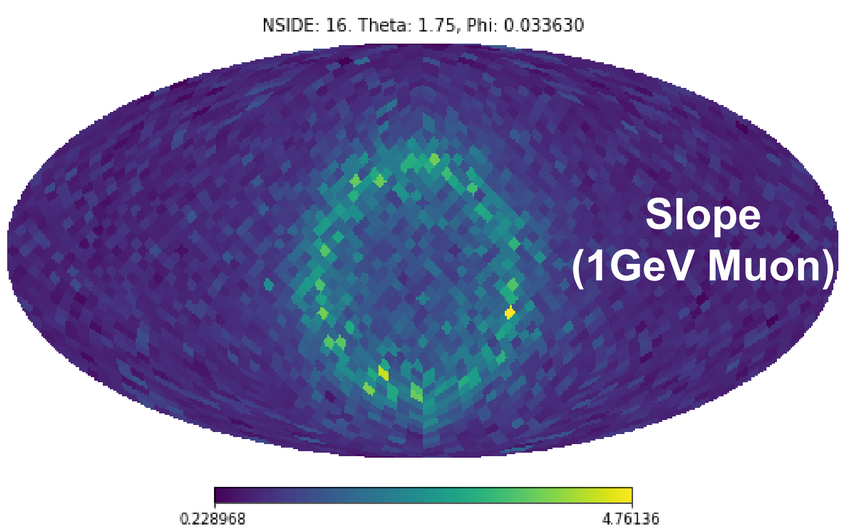

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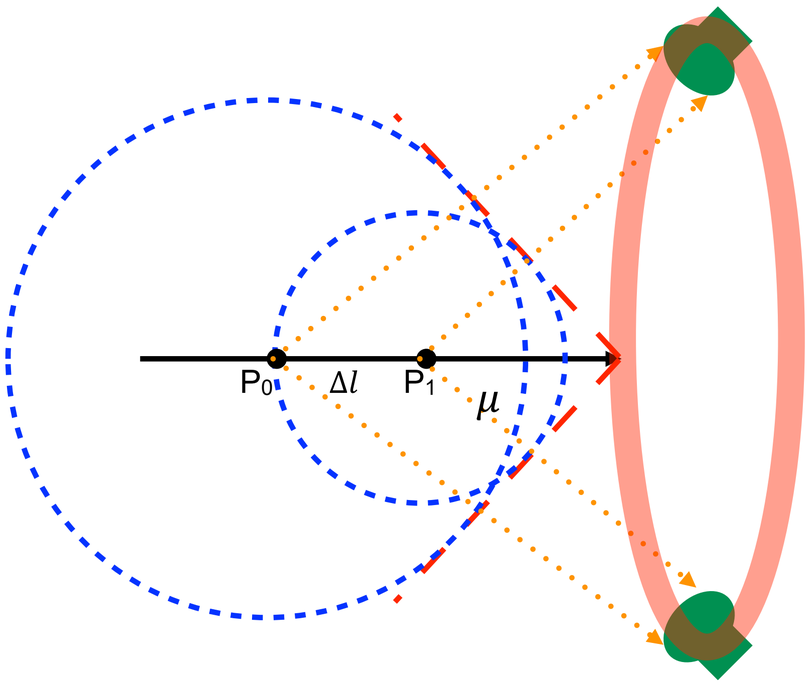
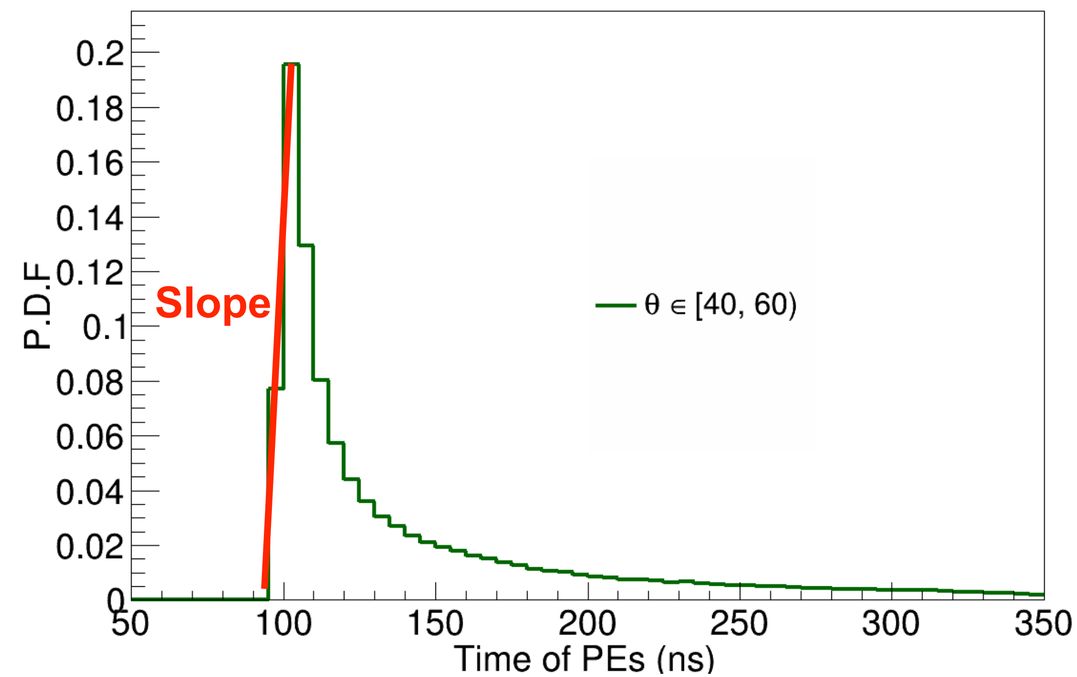
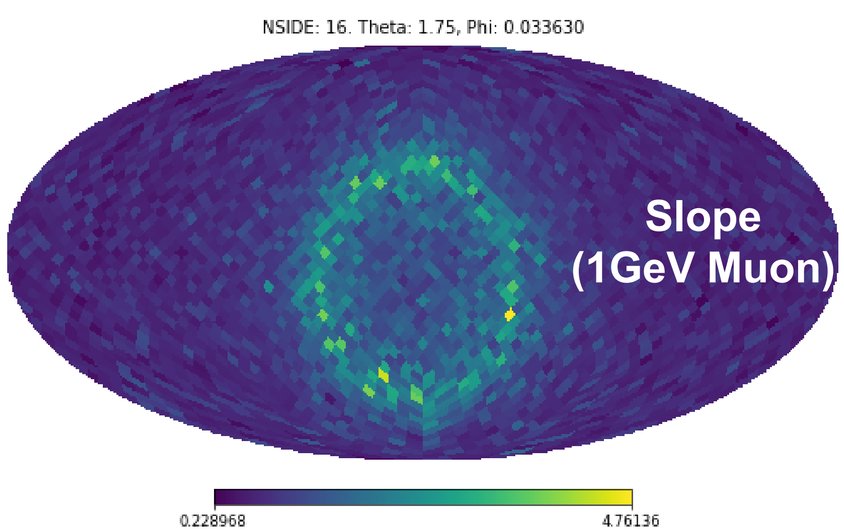
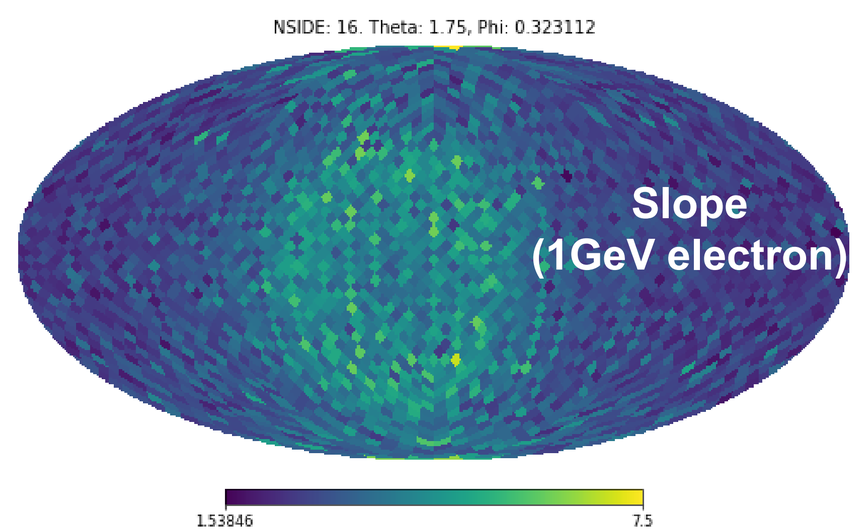


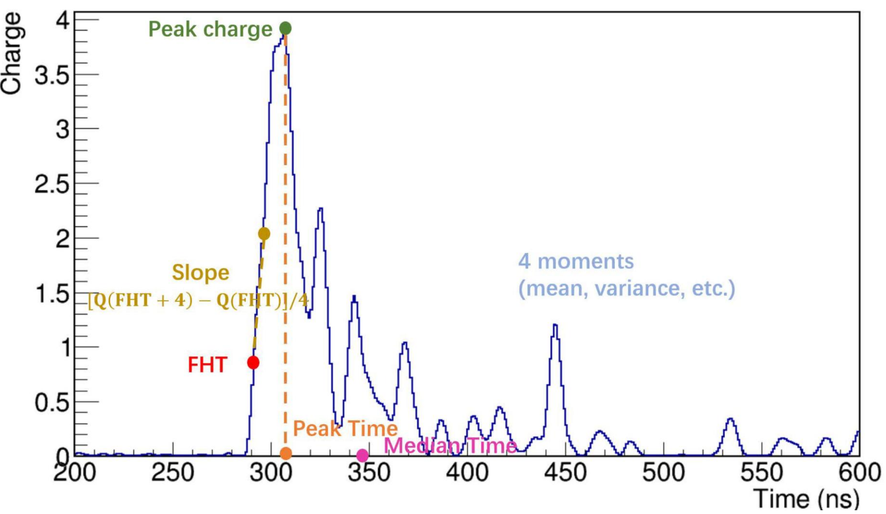






- e-like vs μ-like vs NC identification based upon PMT features.

A Multipurpose Machine Learning Solution



PMT Waveforms

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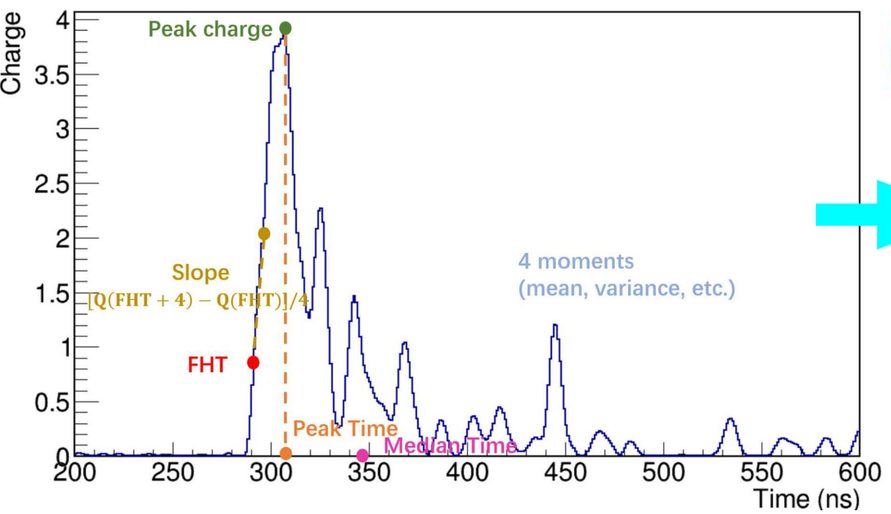

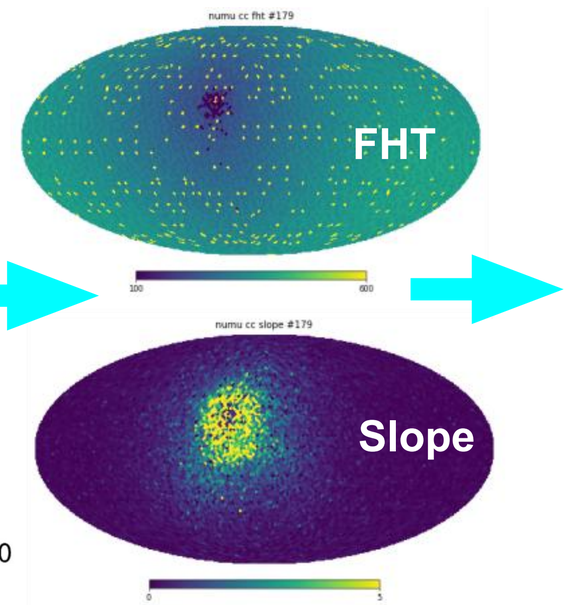

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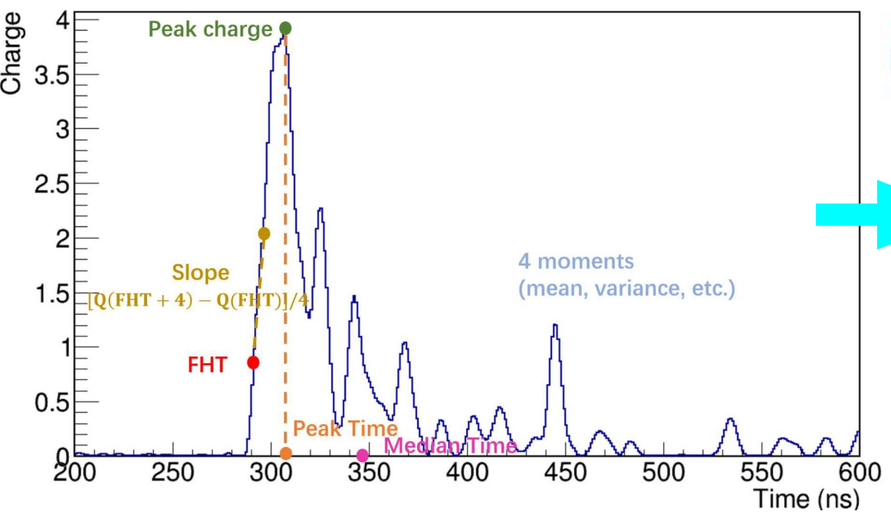
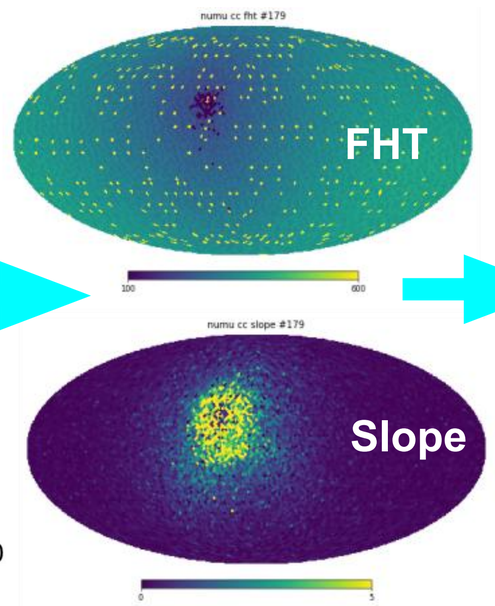
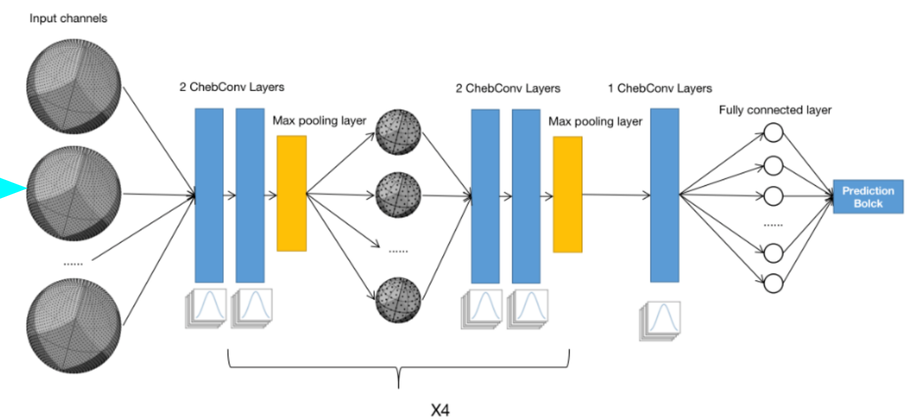
PMT Waveforms

Pictures of PMT Features

A Multipurpose Machine Learning Solution







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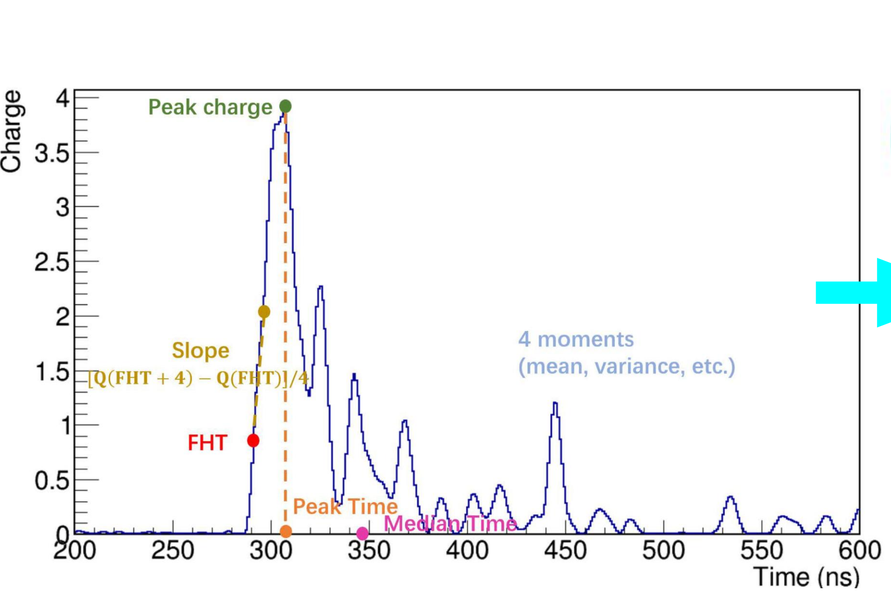
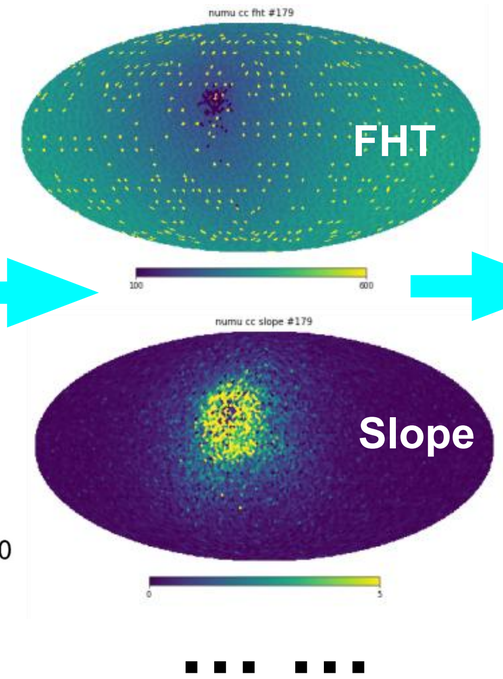
PMT Waveforms

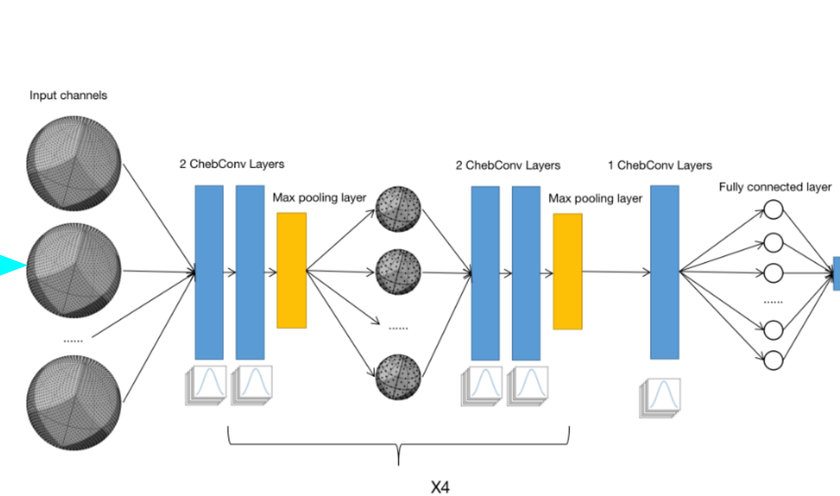
Pictures of PMT Features

Machine Learning Models

A Multipurpose Machine Learning Solution







Direction

Energy

Flavor

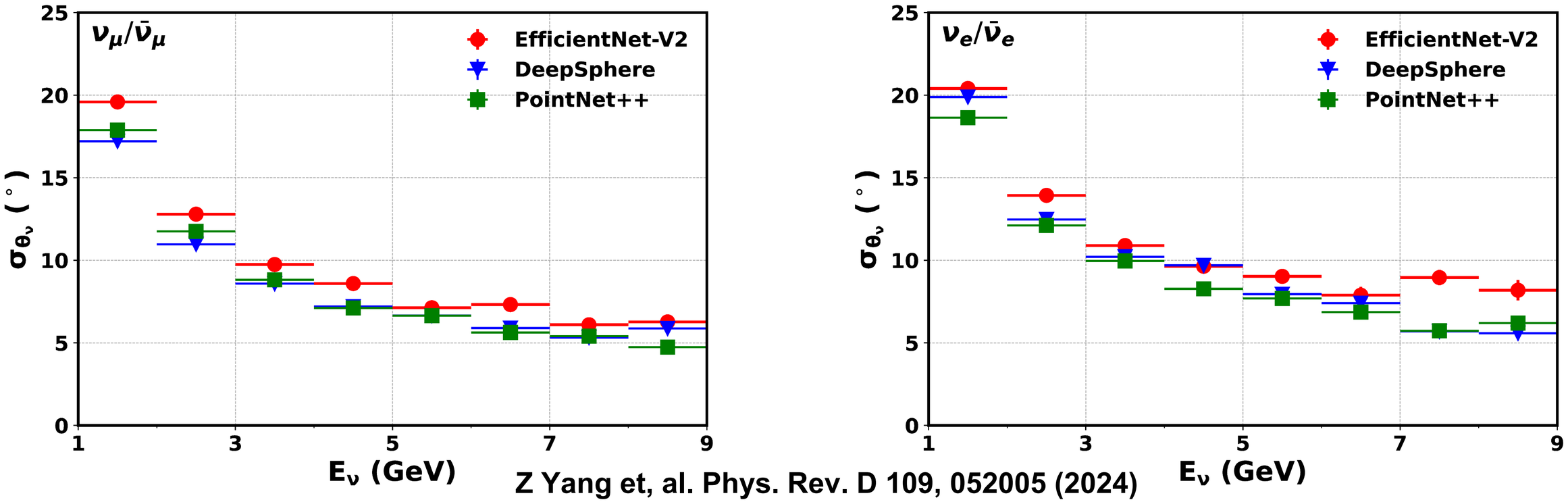
Track

Vertex

PMT Waveforms | **Pictures of PMT Features** | **Machine Learning Models** | **Outputs**

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

Directionality Reconstruction



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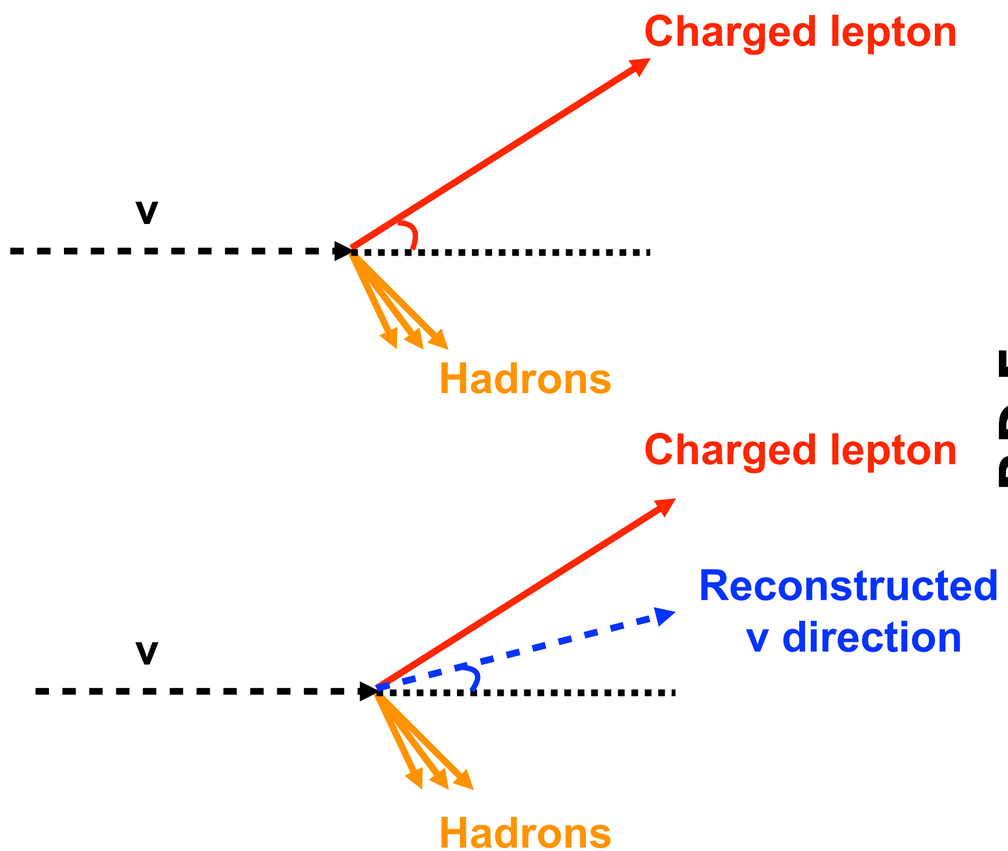
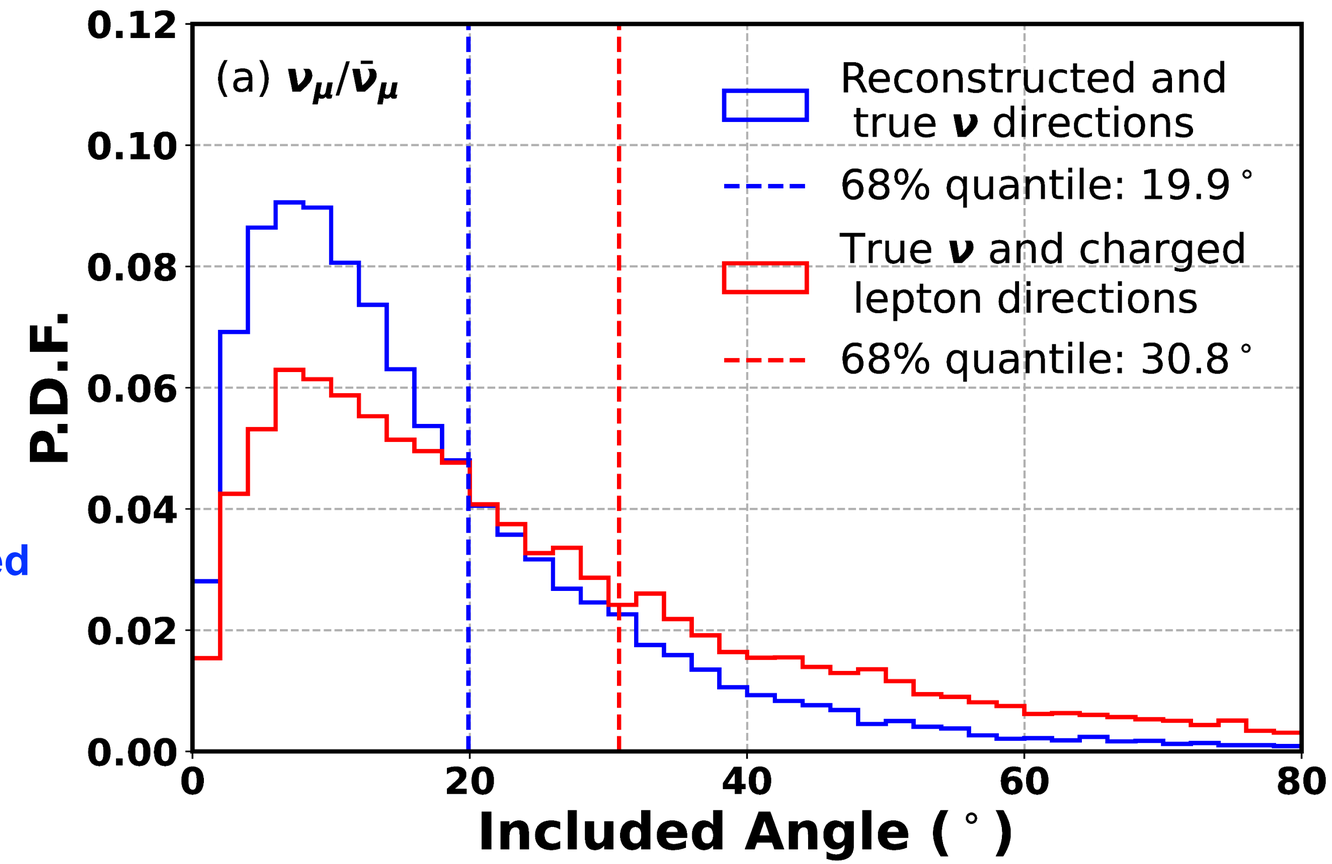
- Cross-checked with different ML models.
- Better than 10° zenith angle resolution for $E_\nu > 3$ GeV for both $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ CC events.

Directionality Reconstruction



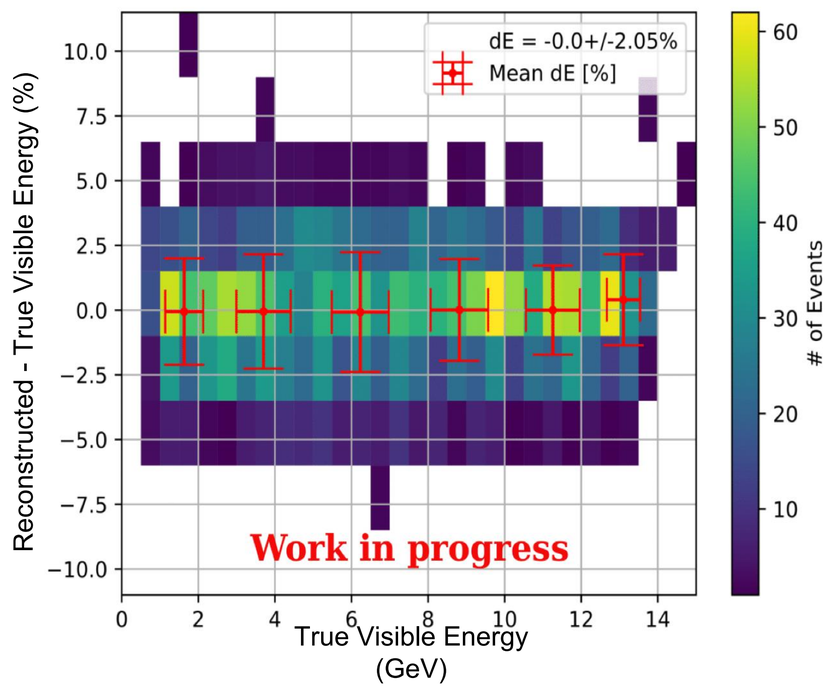


- Both lepton and hadron informations are used in the directionality reconstruction.
  - Low-threshold in LS detectors allows for more information from hadrons.
- The reconstructed neutrino direction is less smeared from true neutrino direction compared with the charged lepton direction.
  - An advantage for an LS detector with this method for atmospheric neutrino oscillation measurements.

Energy Reconstruction

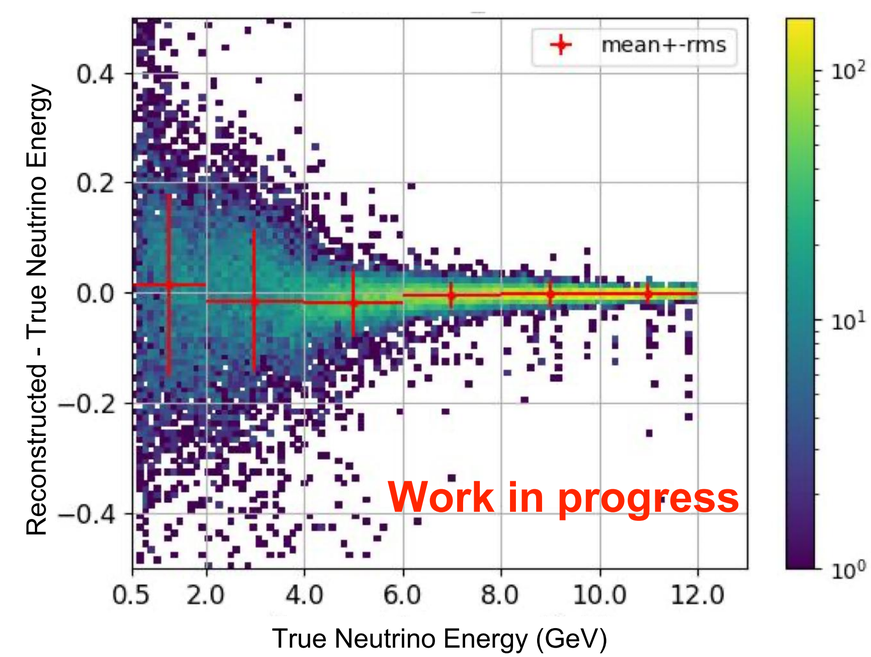
- Two possible strategies on energy reconstruction:

- Strategy 1: Reconstruct the **visible energy** (after quenching in the LS).



ML result with PMT features and summed nPE(t) information

- Strategy 2: Reconstruct the **neutrino energy**
  - For fully-contained CC events only.

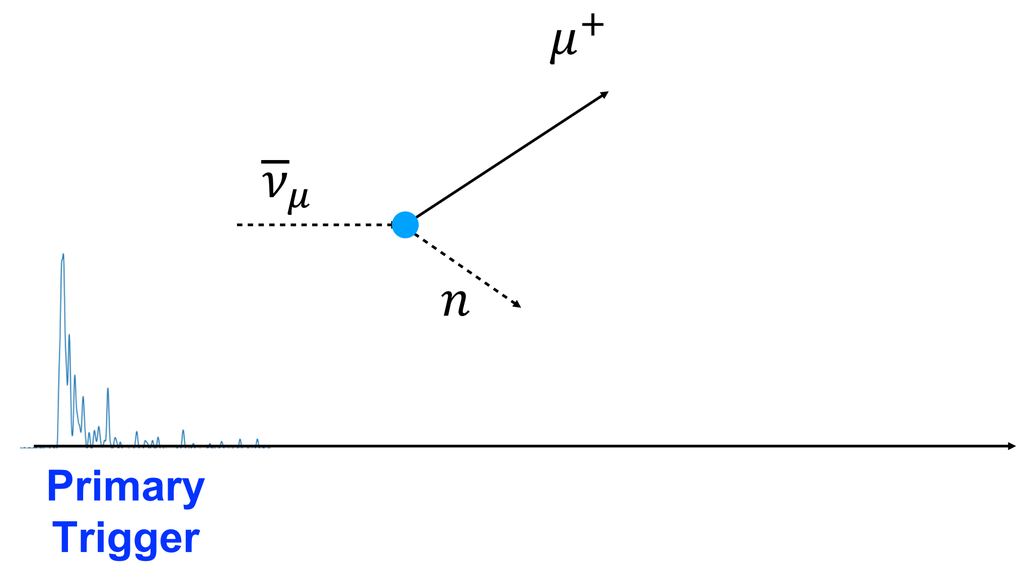


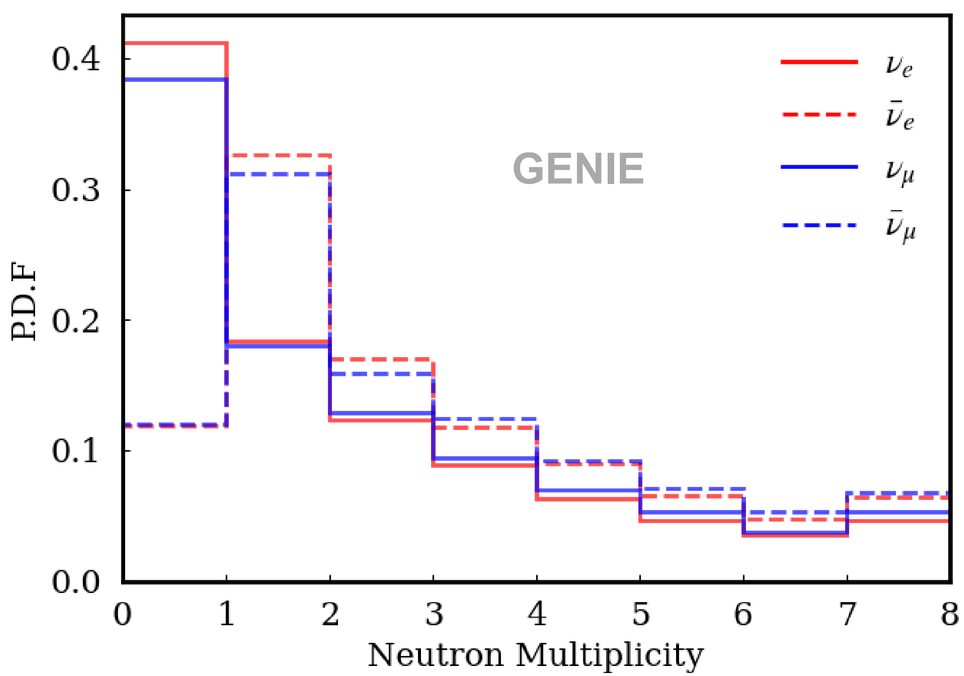
ML result with PMT features

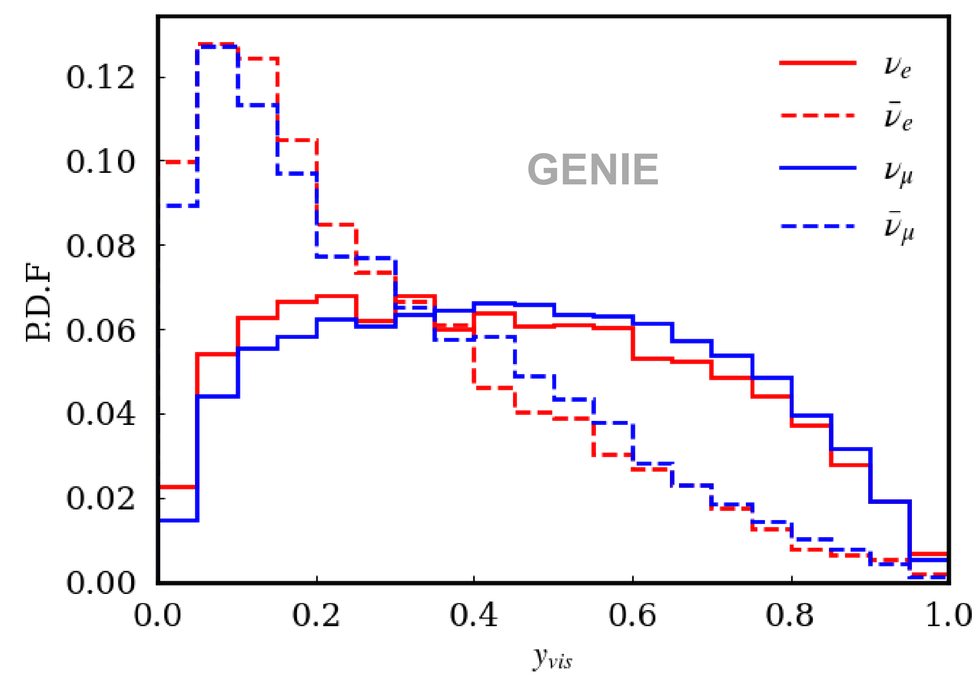
- Detailed study is on-going on their impact on oscillation analysis.

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





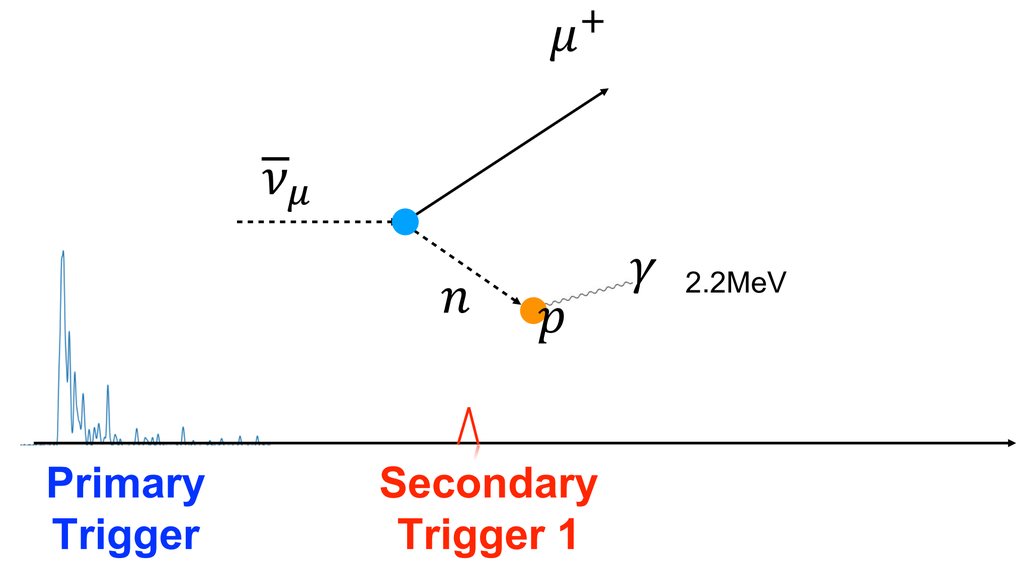


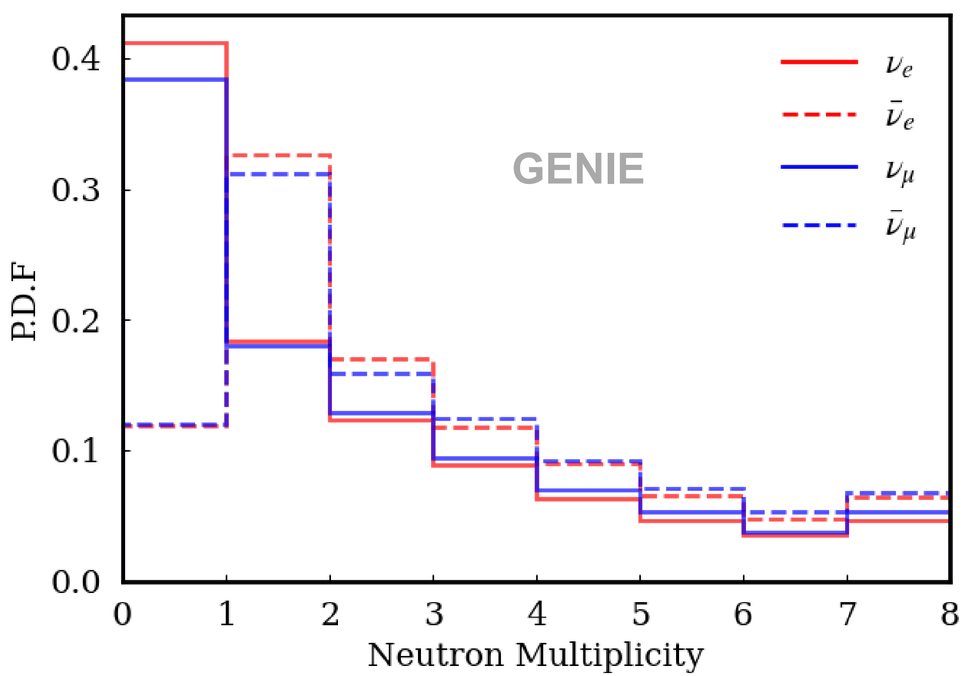
- It is possible to statistically separate ν and $\bar{\nu}$ with neutron-capture informations.

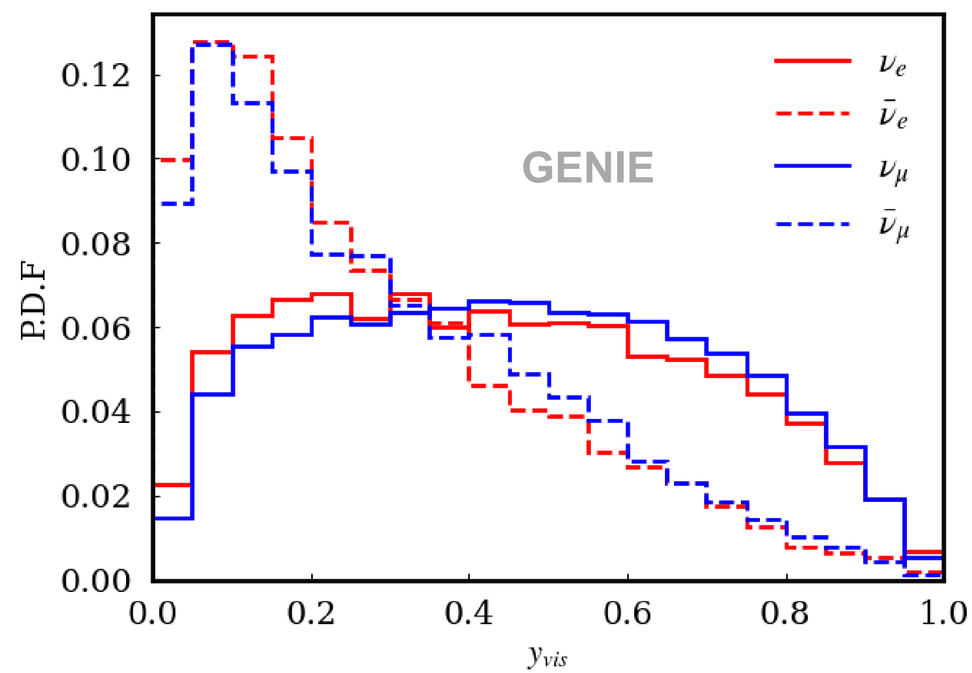
J Liu et, al. Phys. Rev. D 112, 012018 (2025)

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







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	$\nu_\mu + n \to \mu^- + n + \pi^+$	$\bar{\nu}_\mu + n \to \mu^+ + n + \pi^-$
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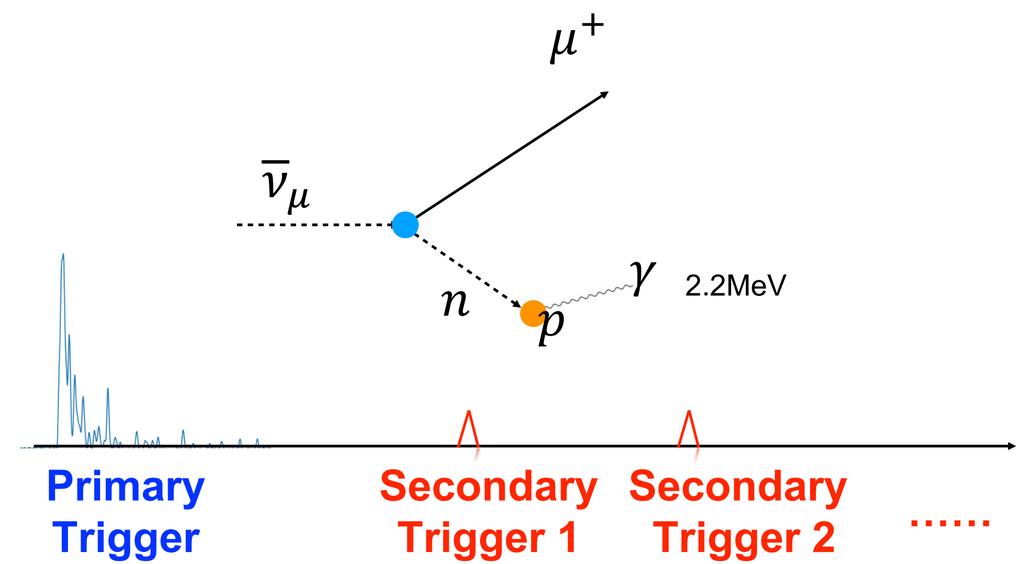

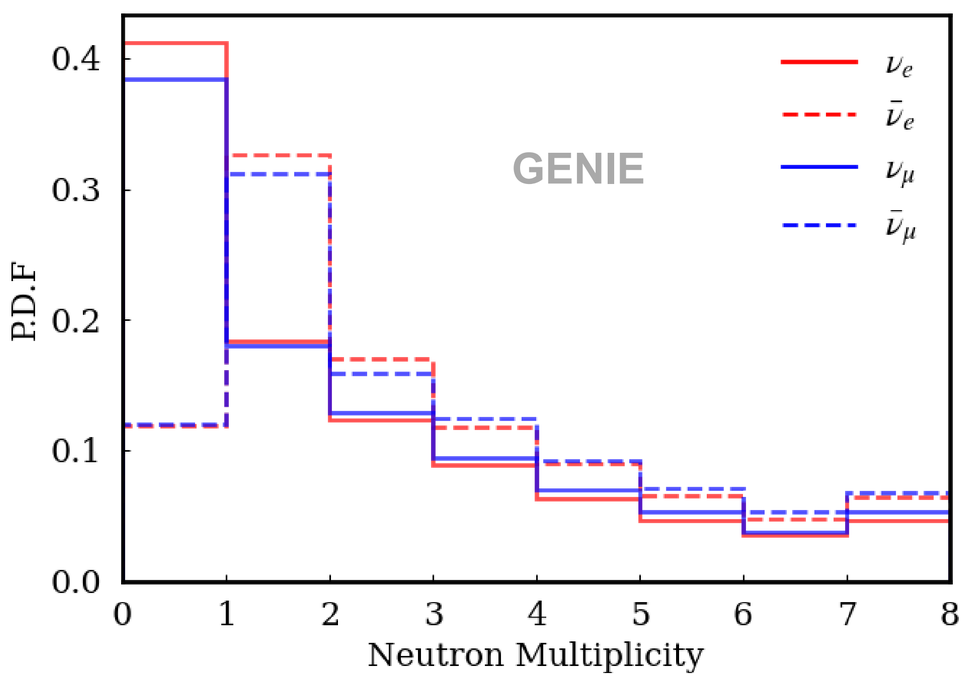

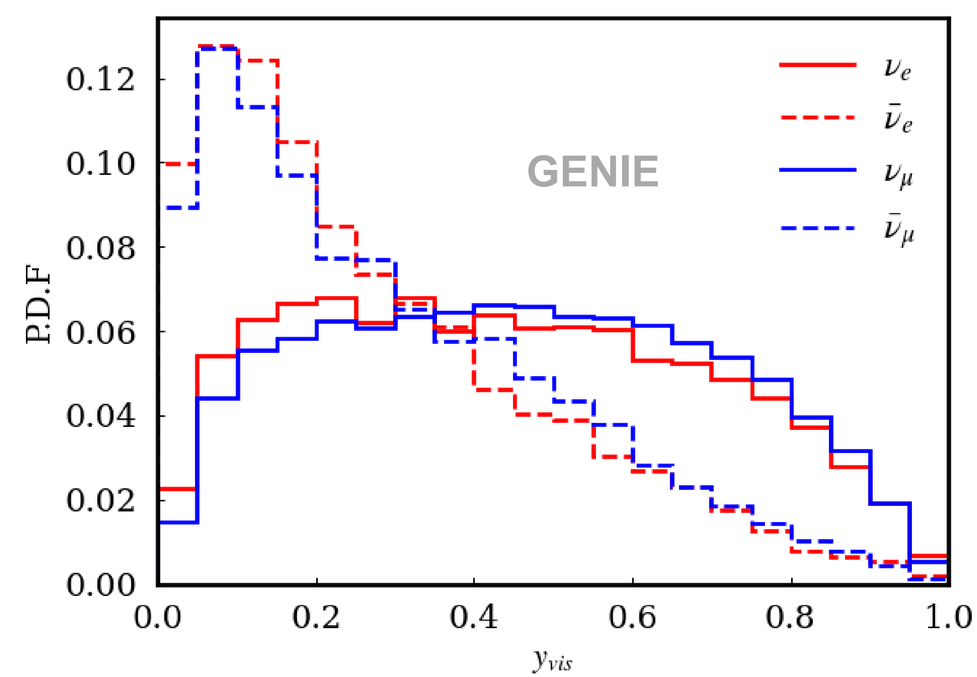

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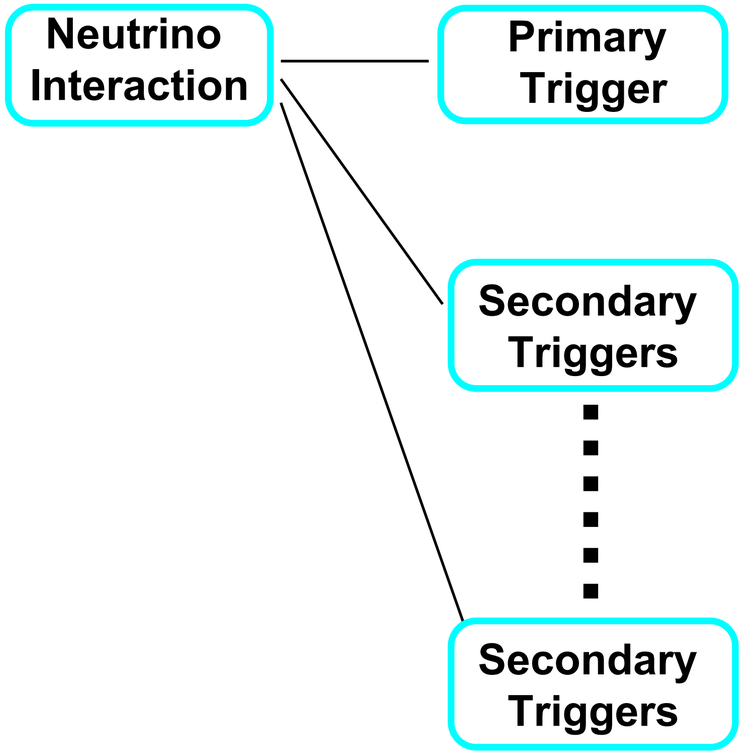
J Liu et, al. Phys. Rev. D 112, 012018 (2025)

Flavor Identification Strategies



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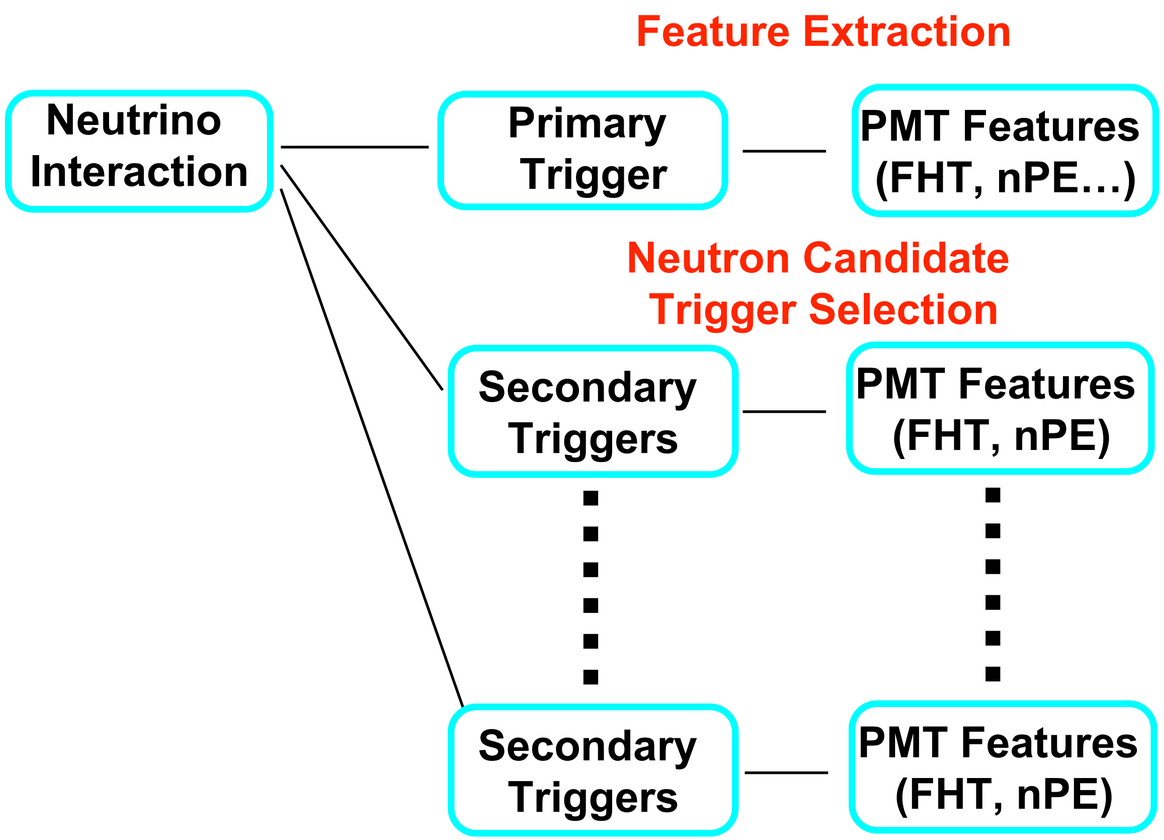

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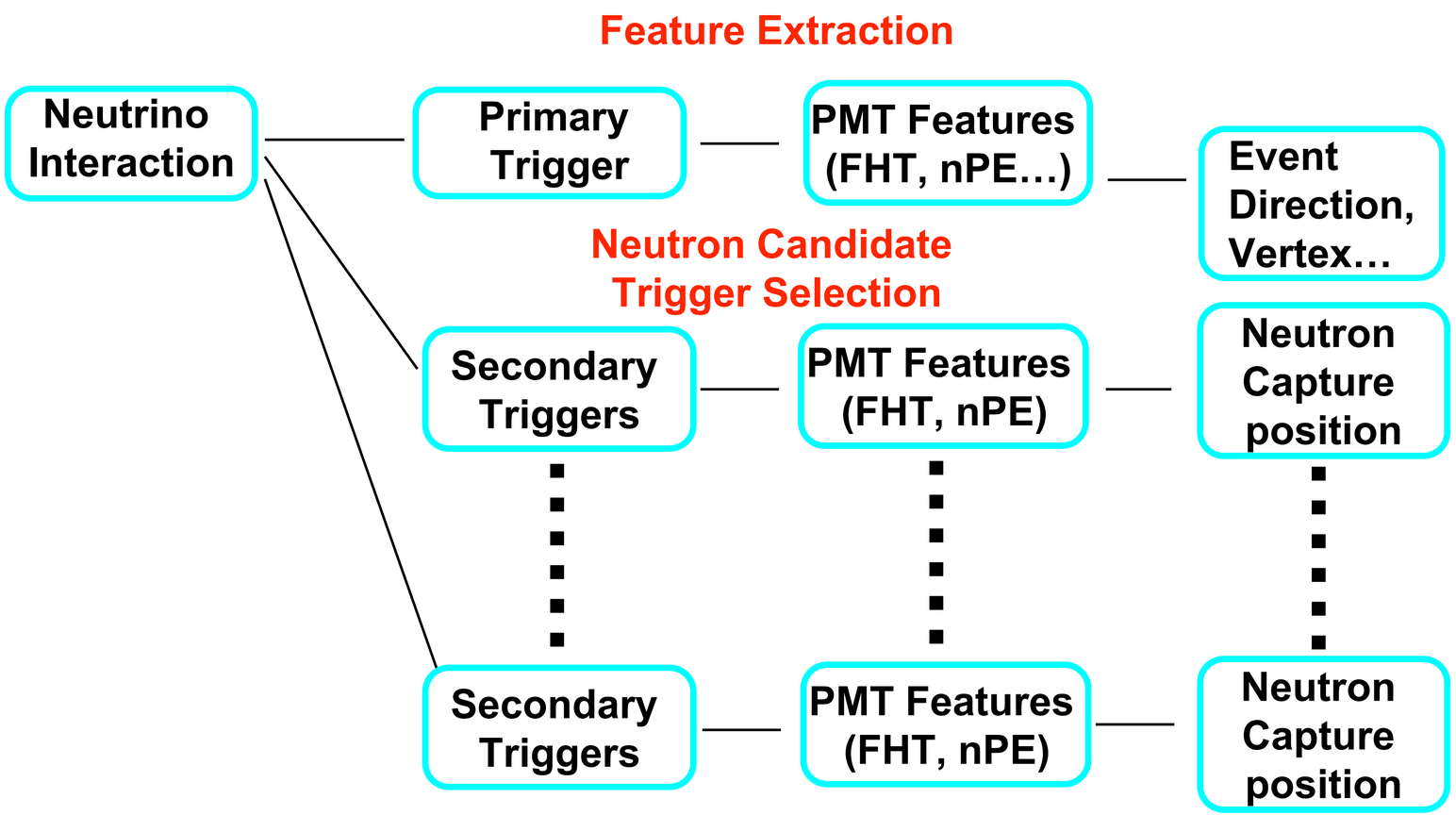
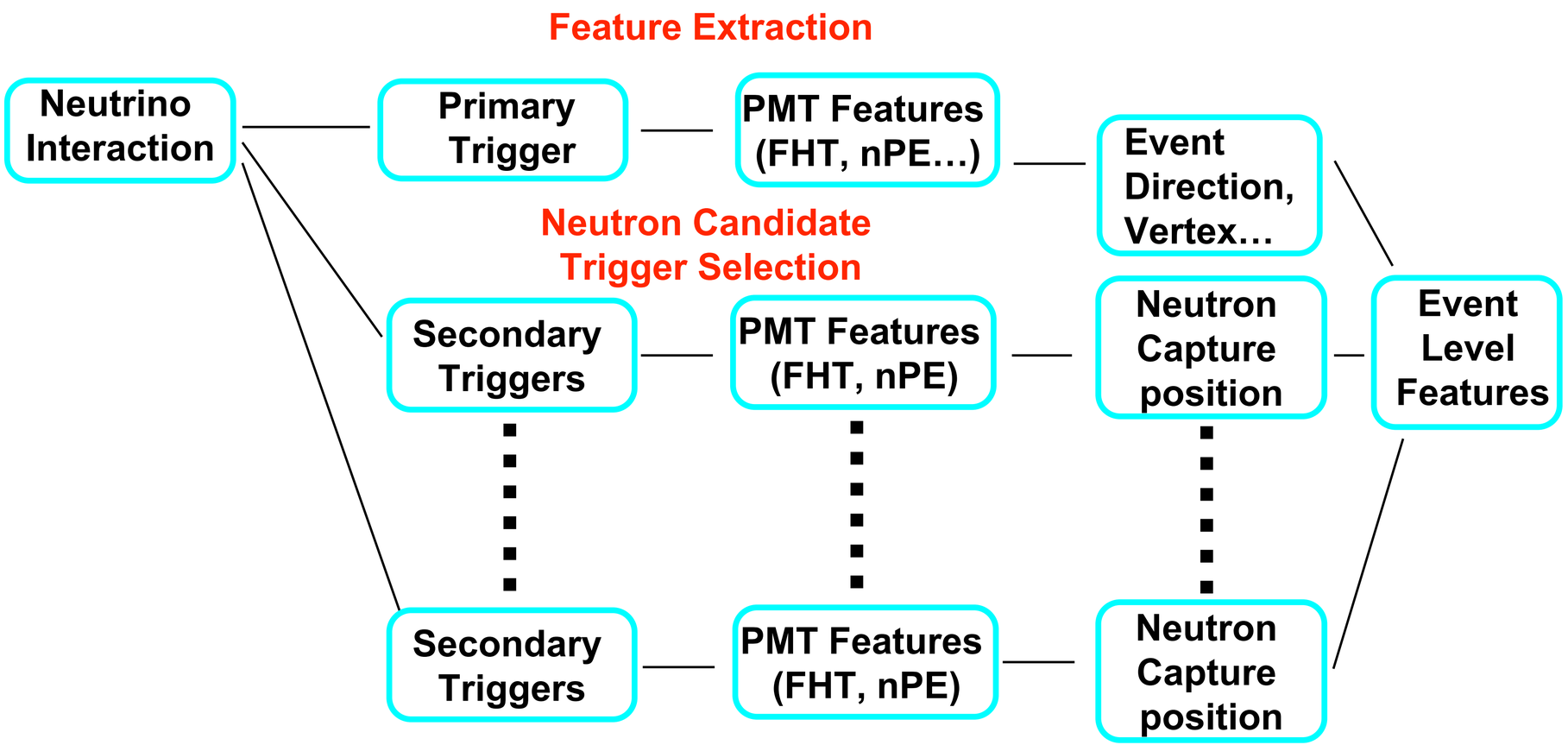
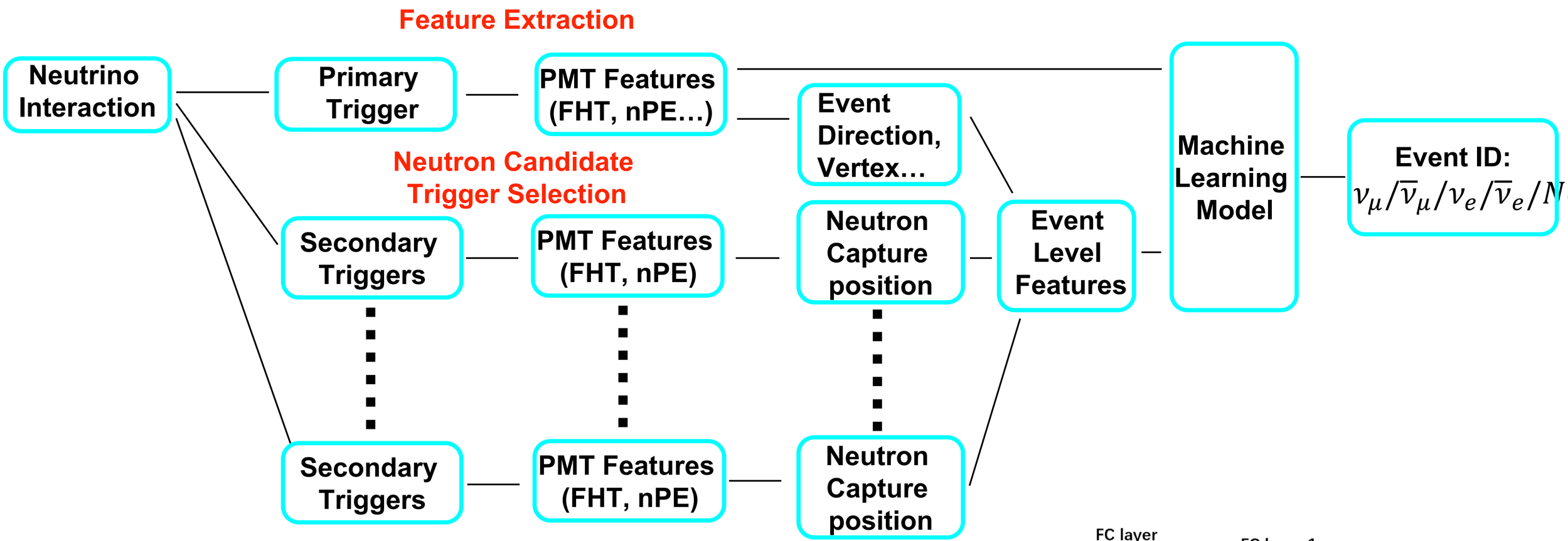


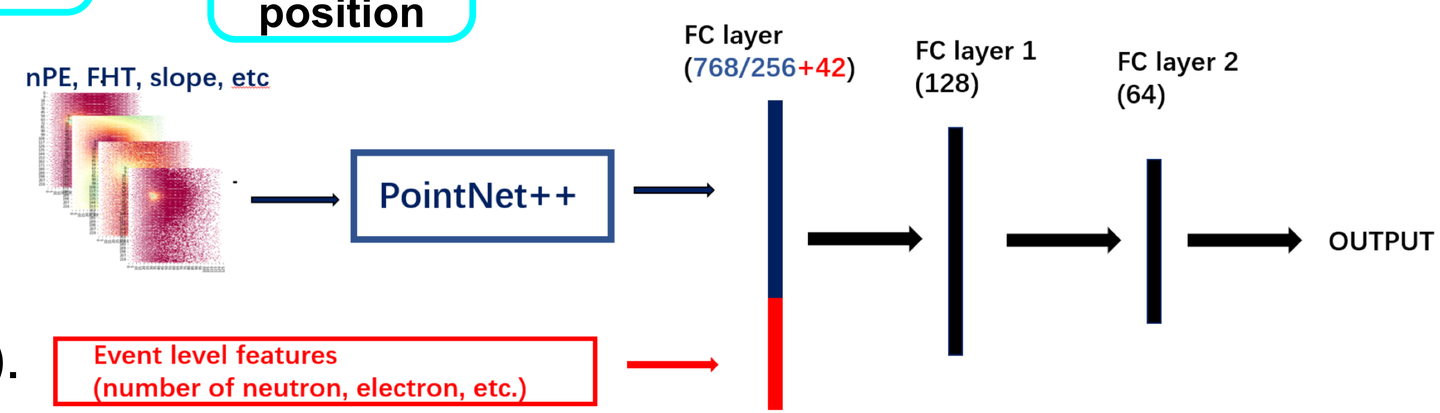
Flavor Identification Strategies



Flavor Identification Strategies



- **Strategy 1**: Combine the PMT-level features with event-level features (neutron-multiplicity, relative positions of neutrons to event vertex/directions, etc.).



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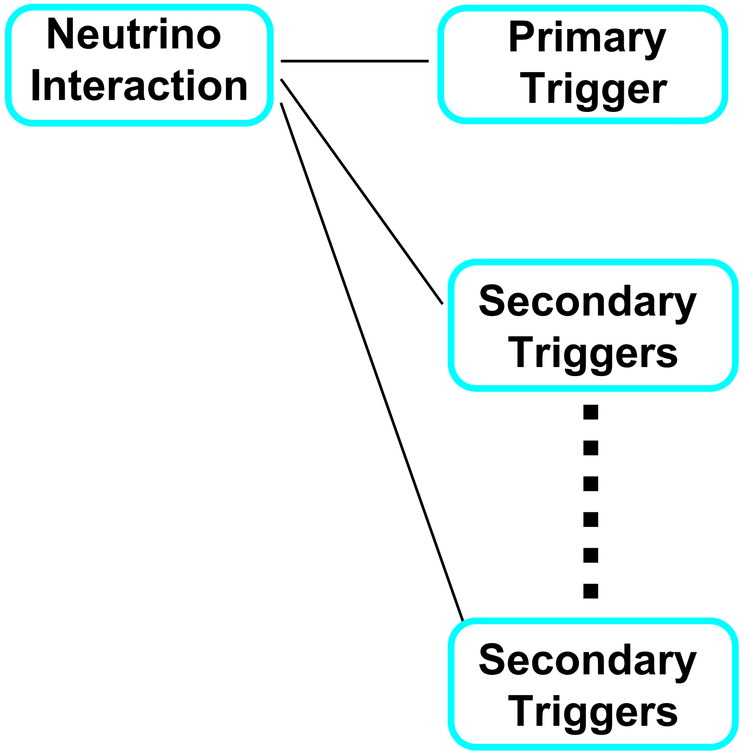
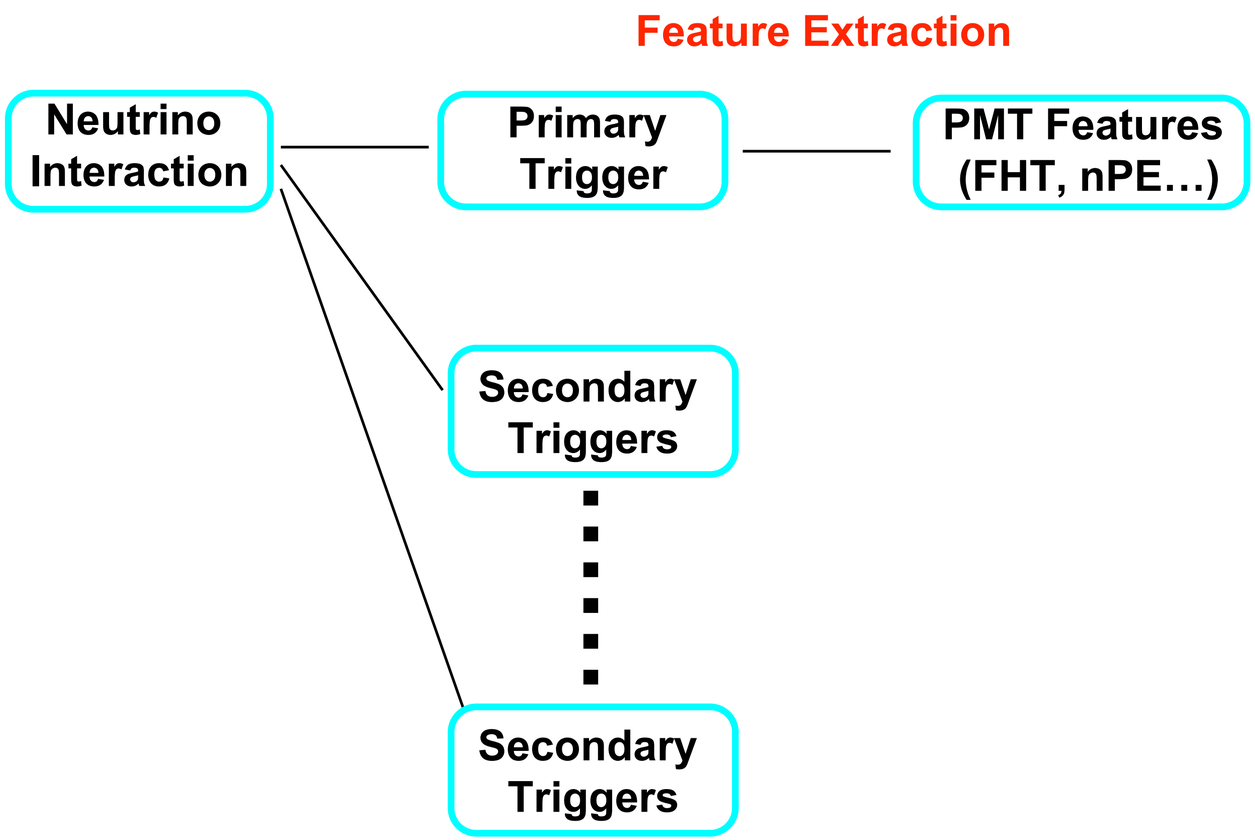


Flavor Identification Strategies



Flavor Identification Strategies

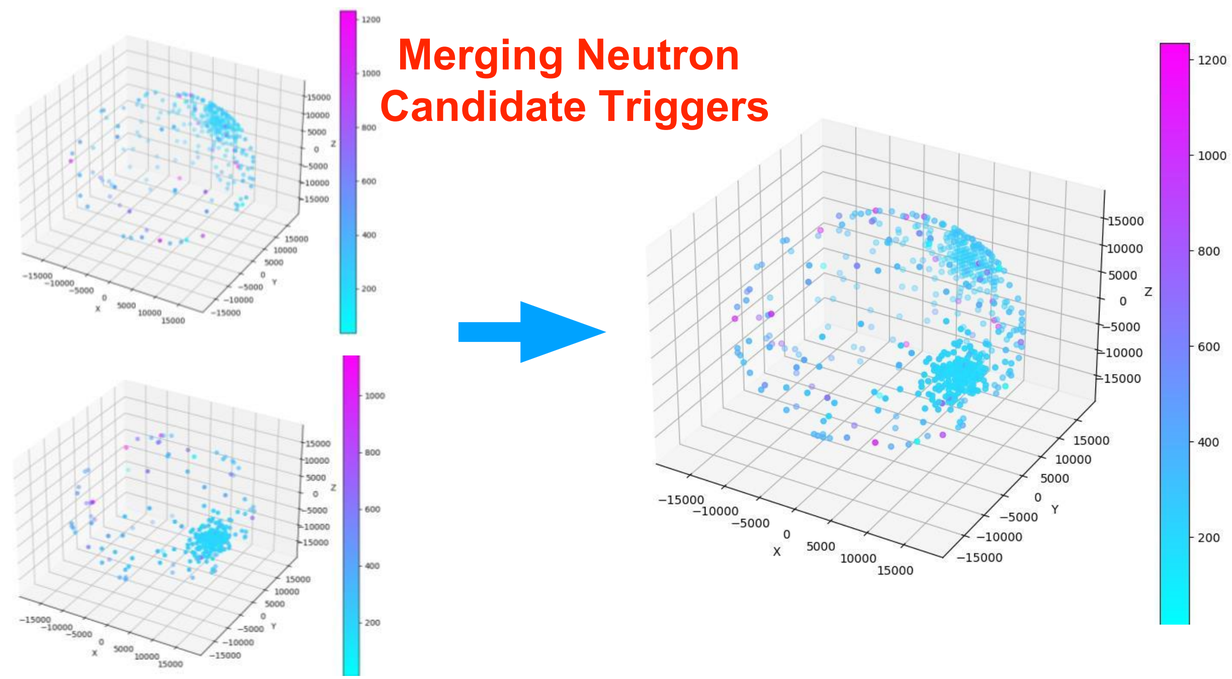
Feature Extraction

Neutrino Interaction — Primary Trigger — PMT Features (FHT, nPE…)

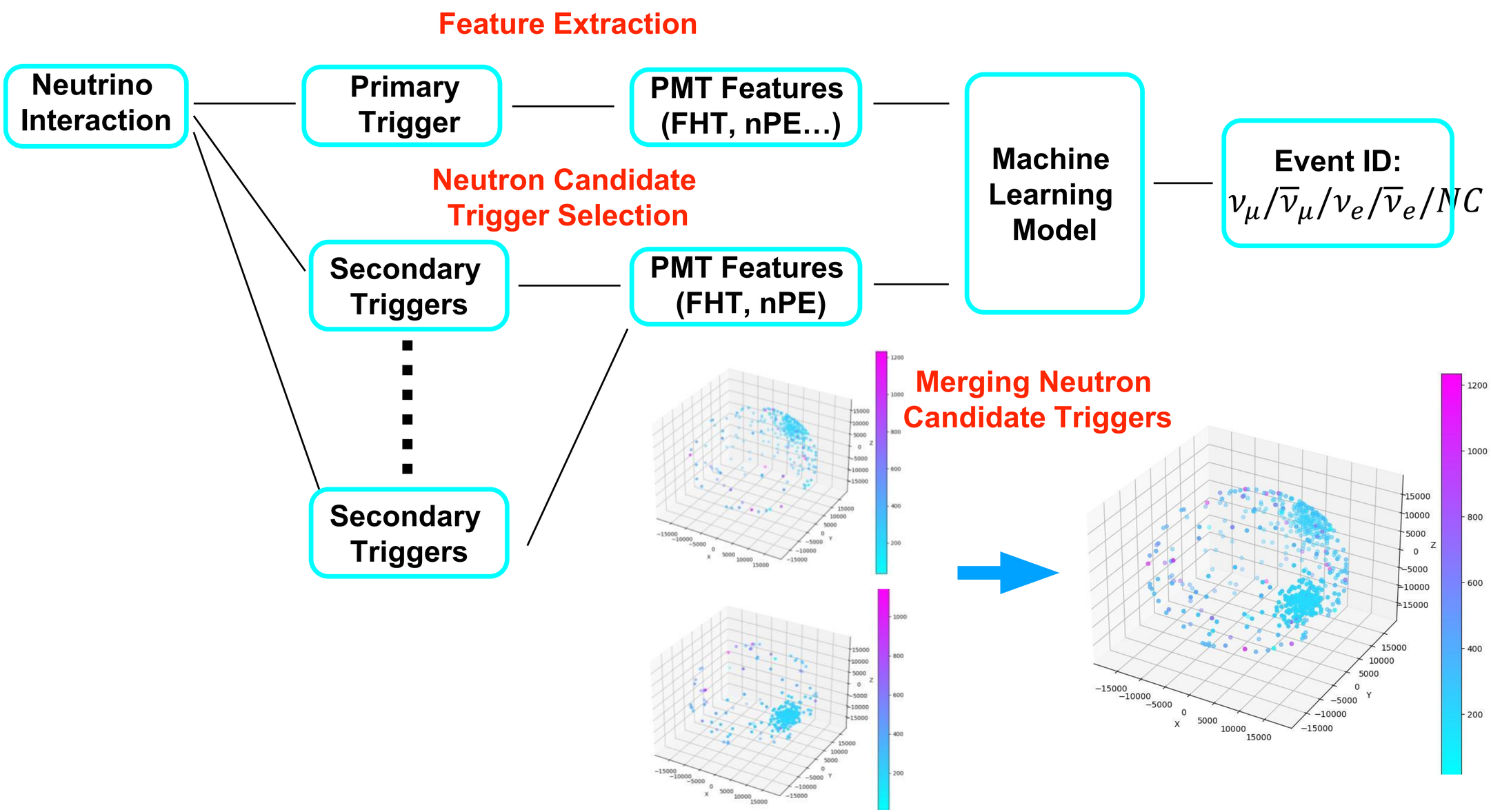
Neutron Candidate Trigger Selection

Secondary Triggers — PMT Features (FHT, nPE)

Secondary Triggers

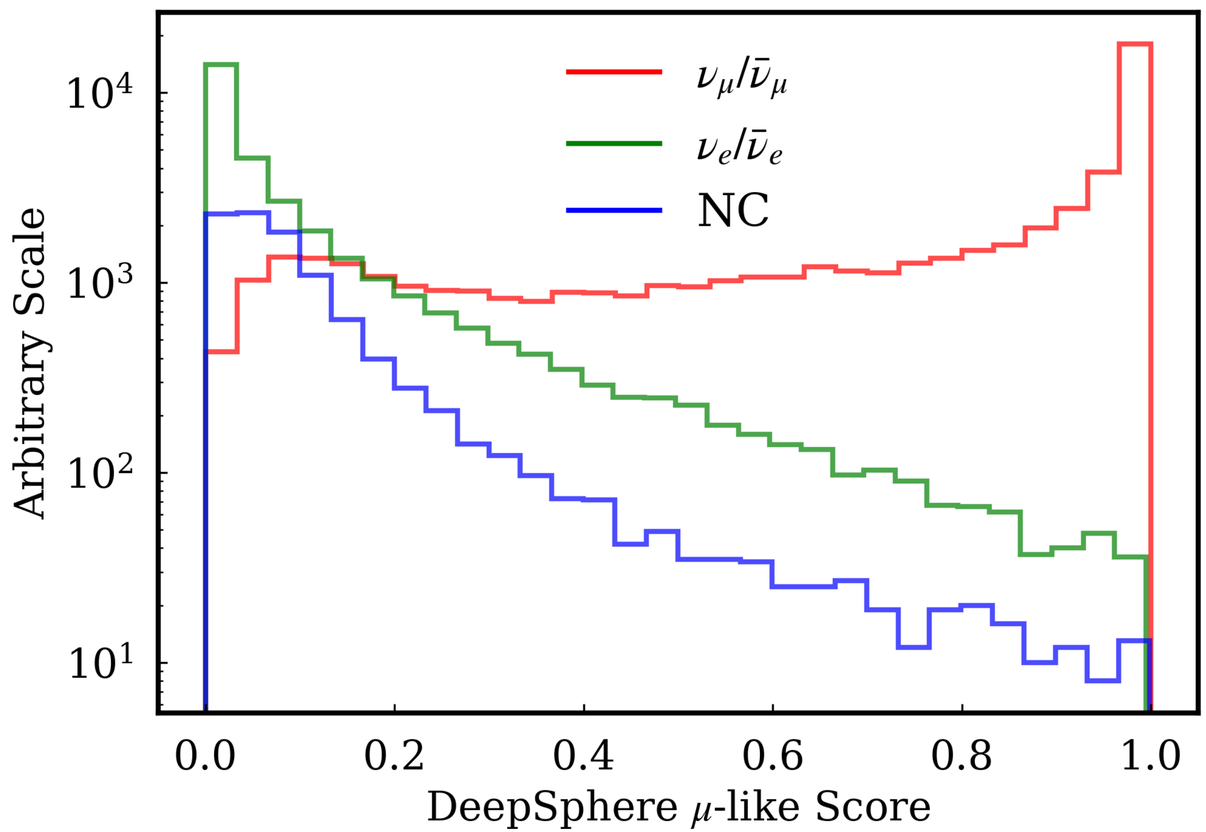


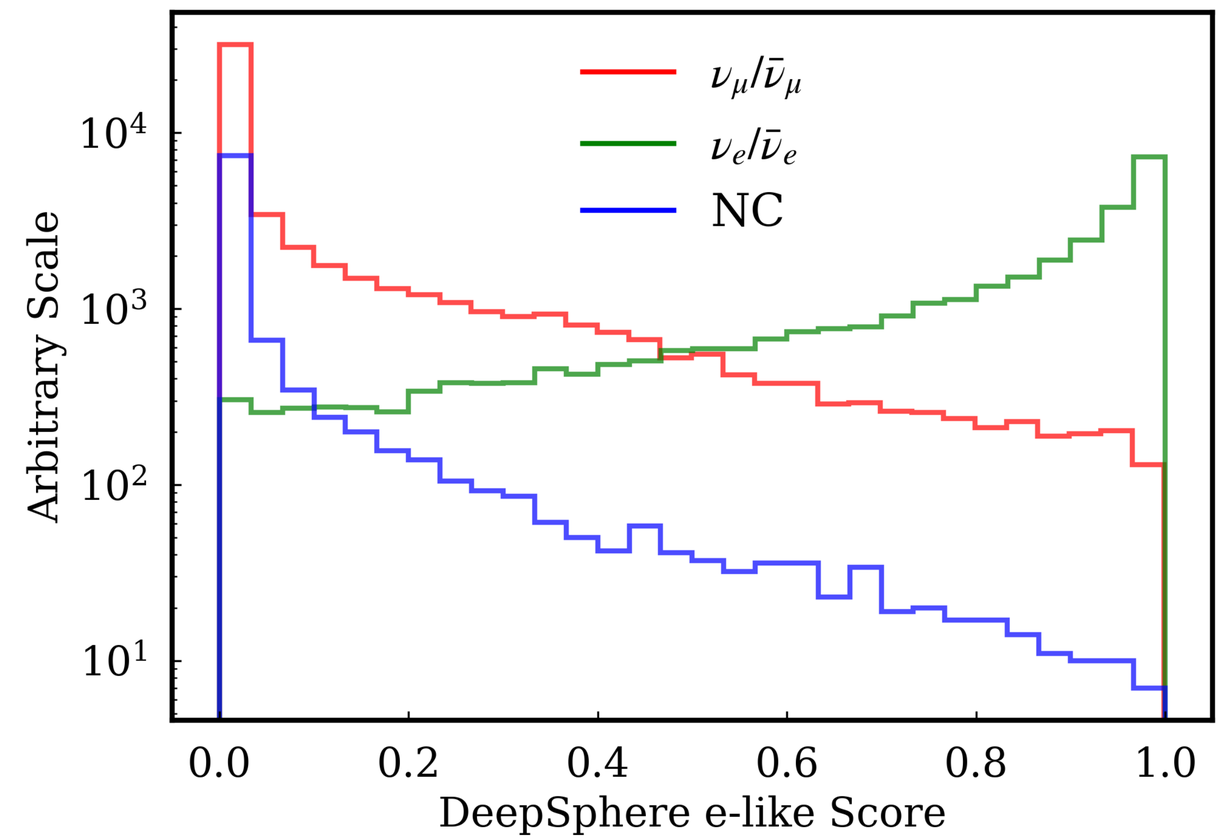
Flavor Identification Strategies



- **Strategy 2**: Directly input PMT features from multiple triggers into ML.

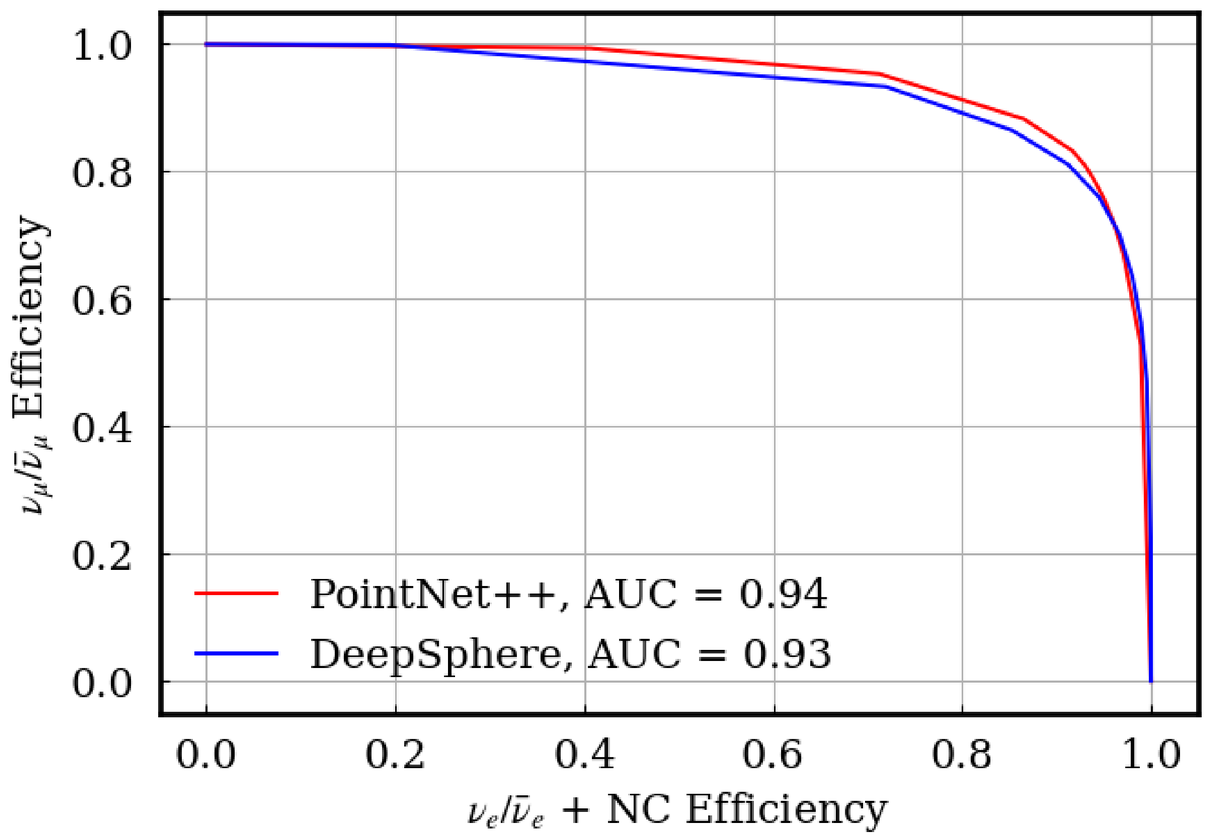
Flavor Identification Performances

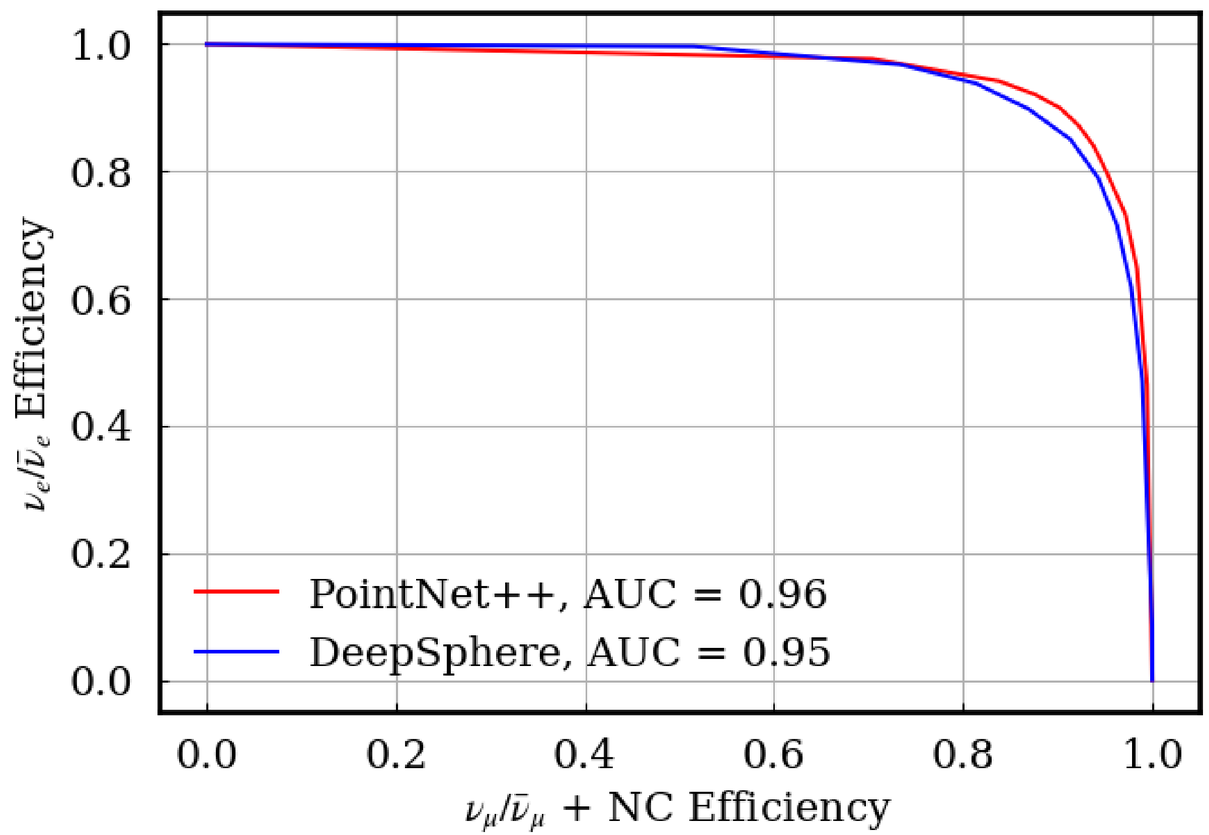




3 label (e, mu, NC) score

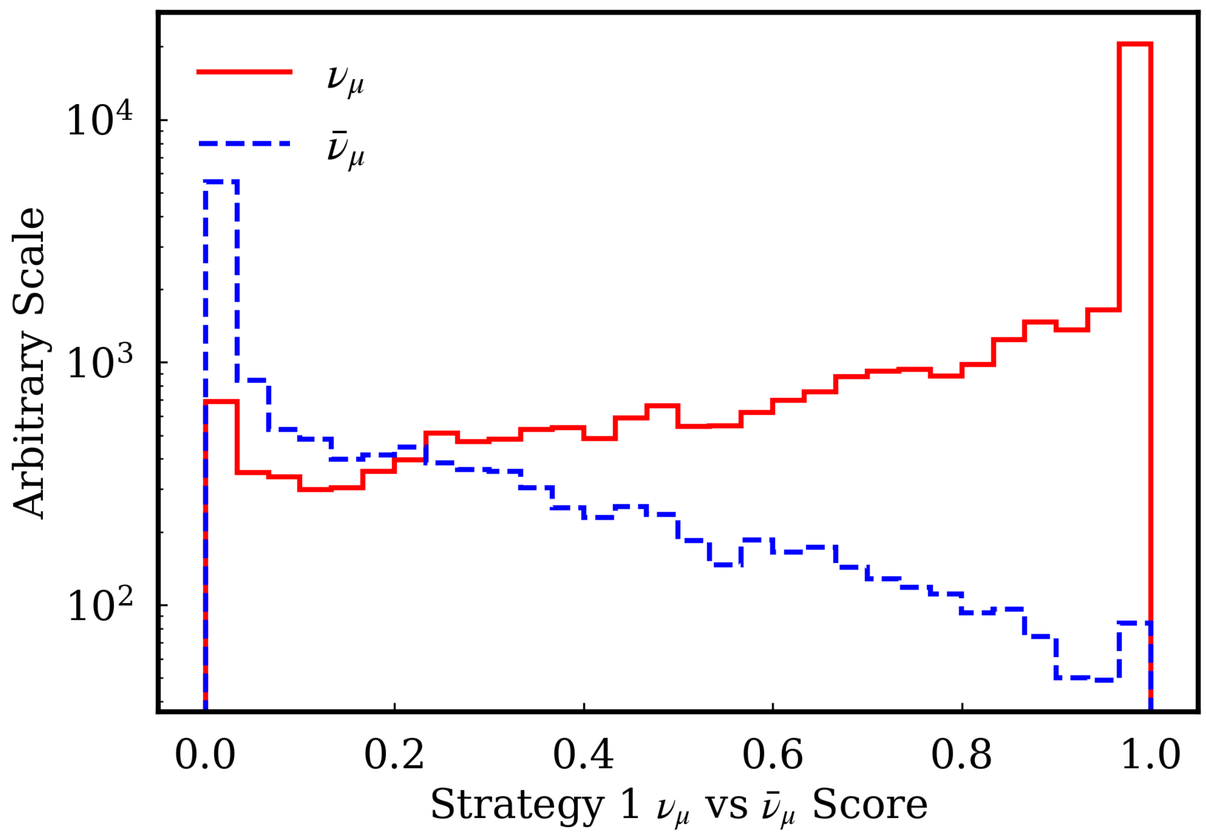
Flavor Identification Performances

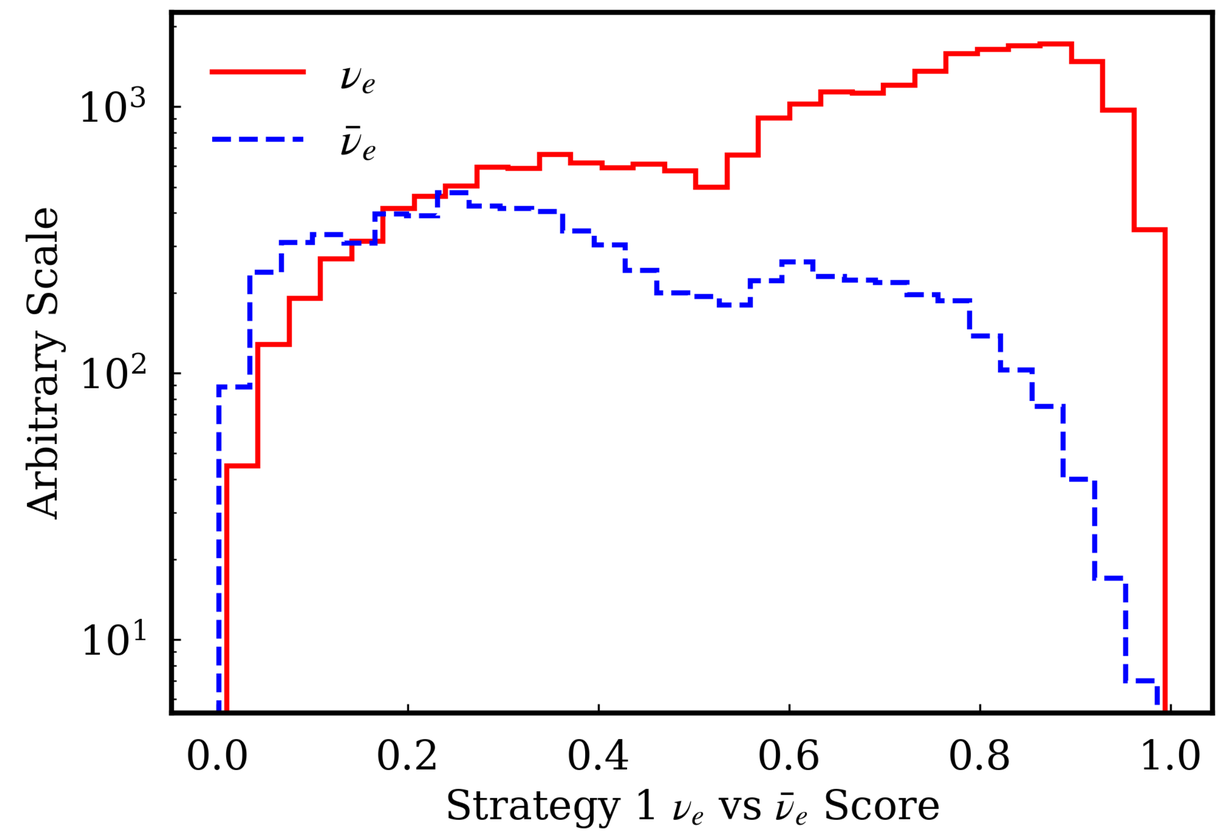




3 label (e, mu, NC) ROC curve

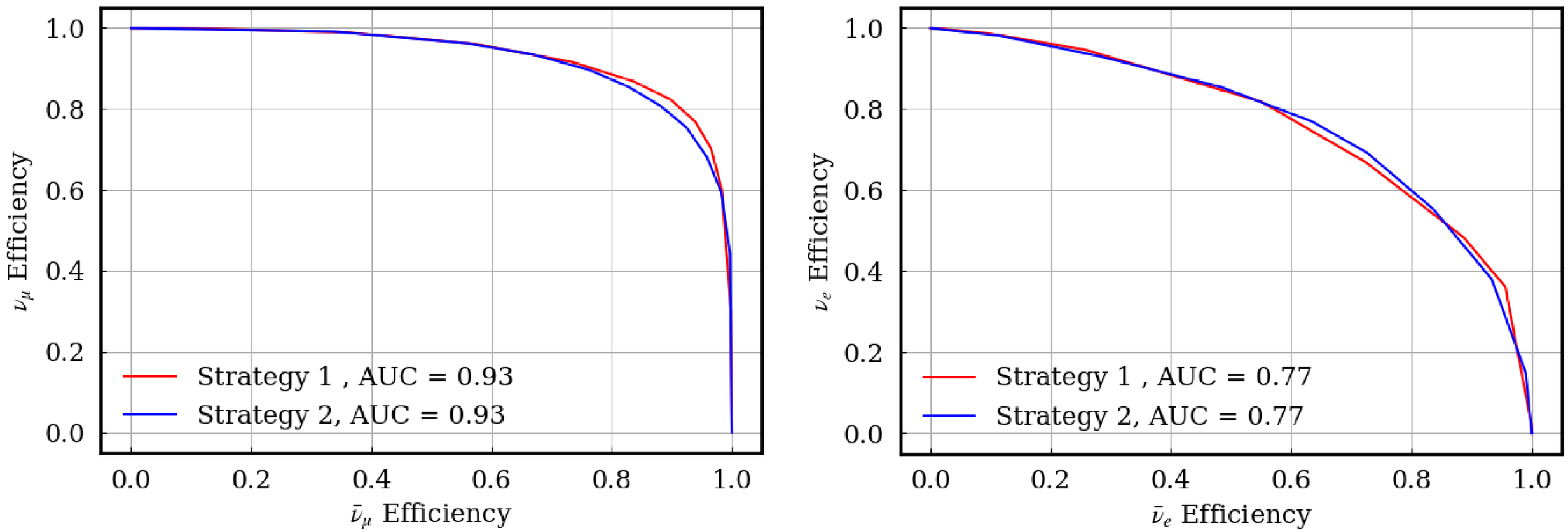
Flavor Identification Performances





$\nu, \bar{\nu}$ Identification – Score

Flavor Identification Performances



$\nu, \bar{\nu}$ Identification – ROC

Systematic Uncertainties

$$N(E_{rec}, \cos\theta_{rec}) \sim \int_{E_\nu} \int_{\cos\theta_\nu} \mathrm{d}E_\nu \mathrm{d}\cos\theta_\nu \Phi(E_\nu, \cos\theta_\nu) P_{osc}(E_\nu, \cos\theta_\nu) \sigma(E_\nu) R_{det}(E_\nu, \cos\theta_\nu, E_{rec}, \cos\theta_{rec})$$

Number of events (Observables)

Neutrino Flux

Oscillation Probability

Cross-sections

Detector response

Systematic Uncertainties

Honda flux with normalization and shape uncertainties

$$N(E_{rec}, \cos\theta_{rec}) \sim \int_{E_\nu} \int_{\cos\theta_\nu} dE_\nu d\cos\theta_\nu \Phi(E_\nu, \cos\theta_\nu) P_{osc}(E_\nu, \cos\theta_\nu) \sigma(E_\nu) R_{det}(E_\nu, \cos\theta_\nu, E_{rec}, \cos\theta_{rec})$$

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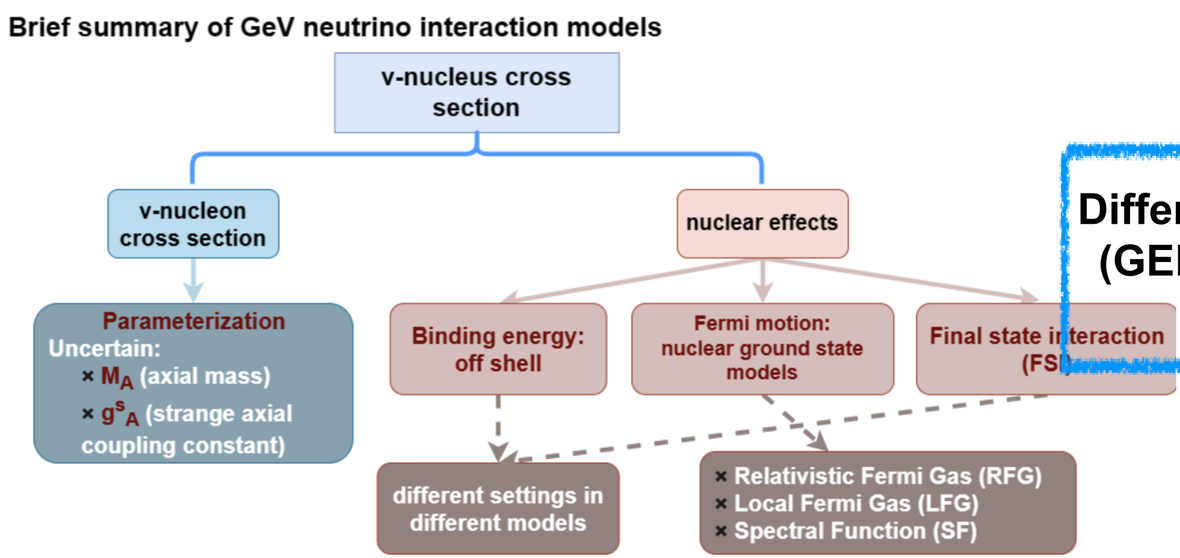
Number of events (Observables) | Neutrino Flux | Oscillation Probability | Cross-sections | Detector response



Different generators and models (GENIE, NuWro, GiBUU, NEUT) And ReWeight

Systematic Uncertainties

Honda flux with normalization and shape uncertainties

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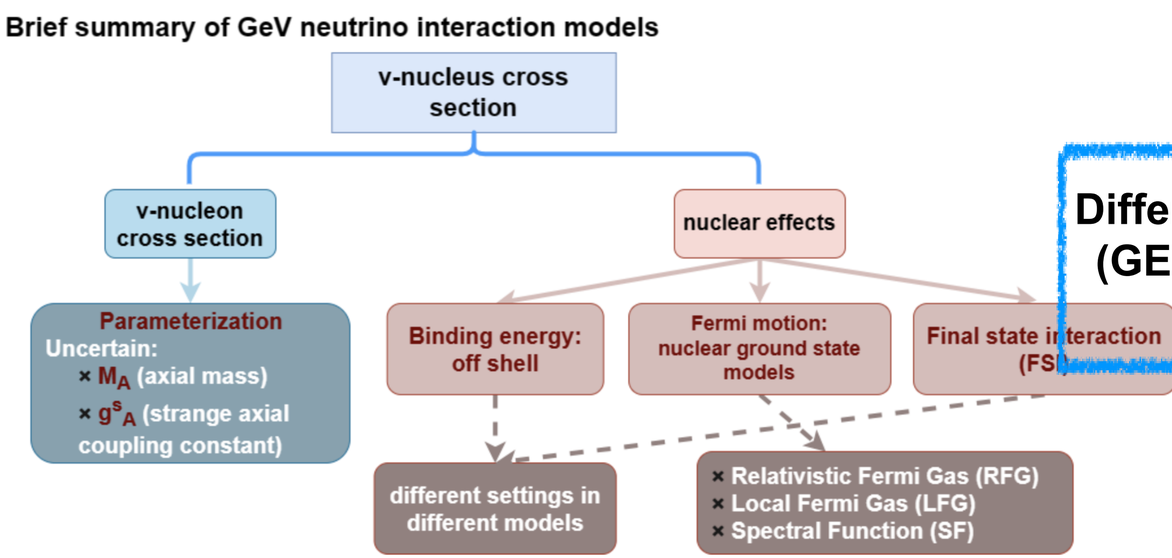

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Systematic Uncertainties

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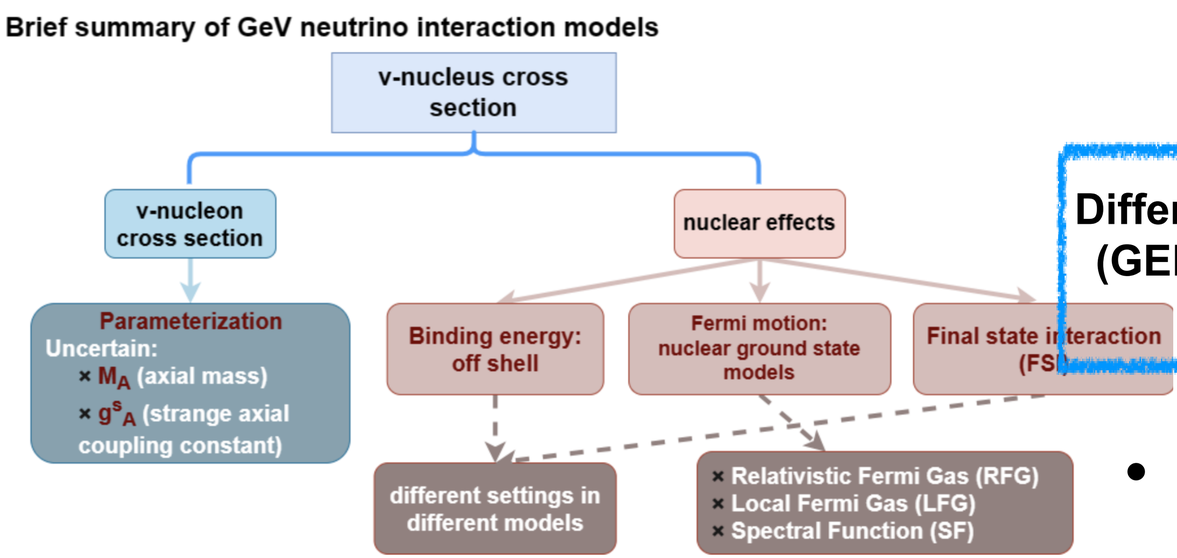

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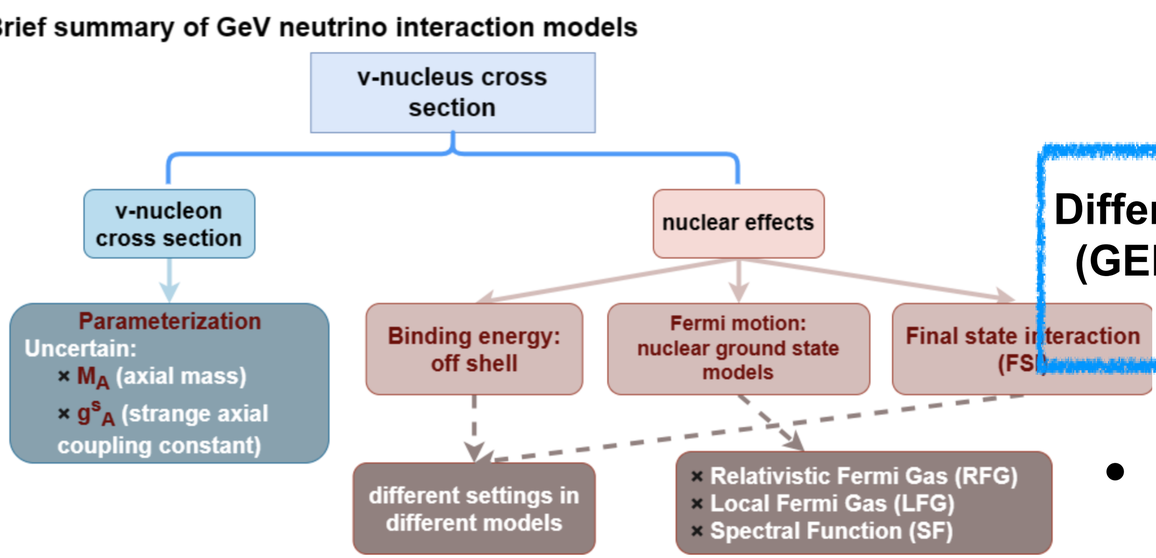
Number of events (Observables) | Neutrino Flux | Oscillation Probability | Cross-sections | Detector response



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Detector response

Cross-check with different ML models and non-ML methods

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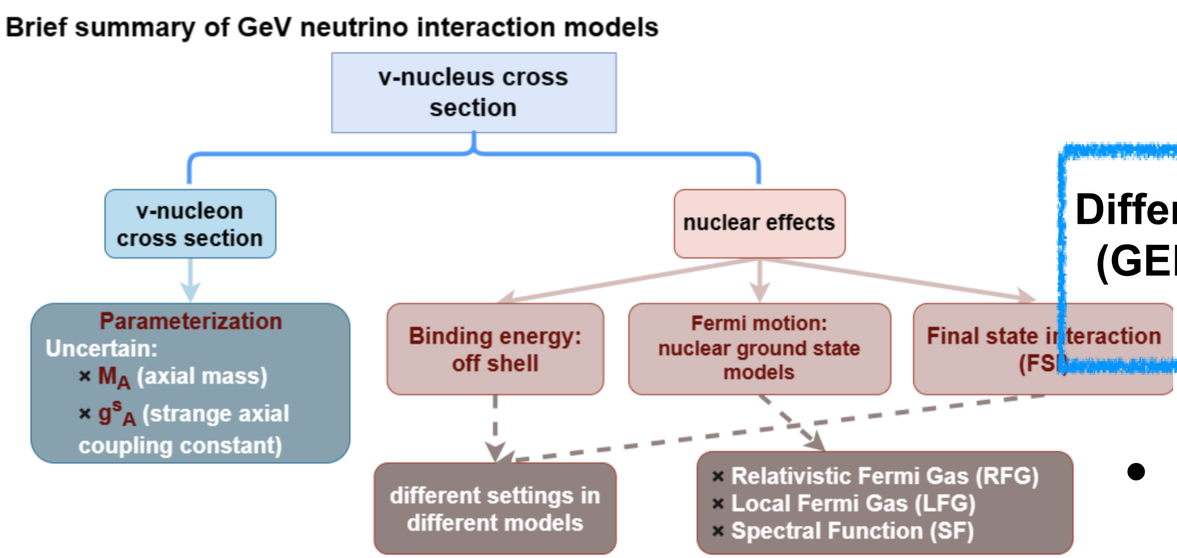

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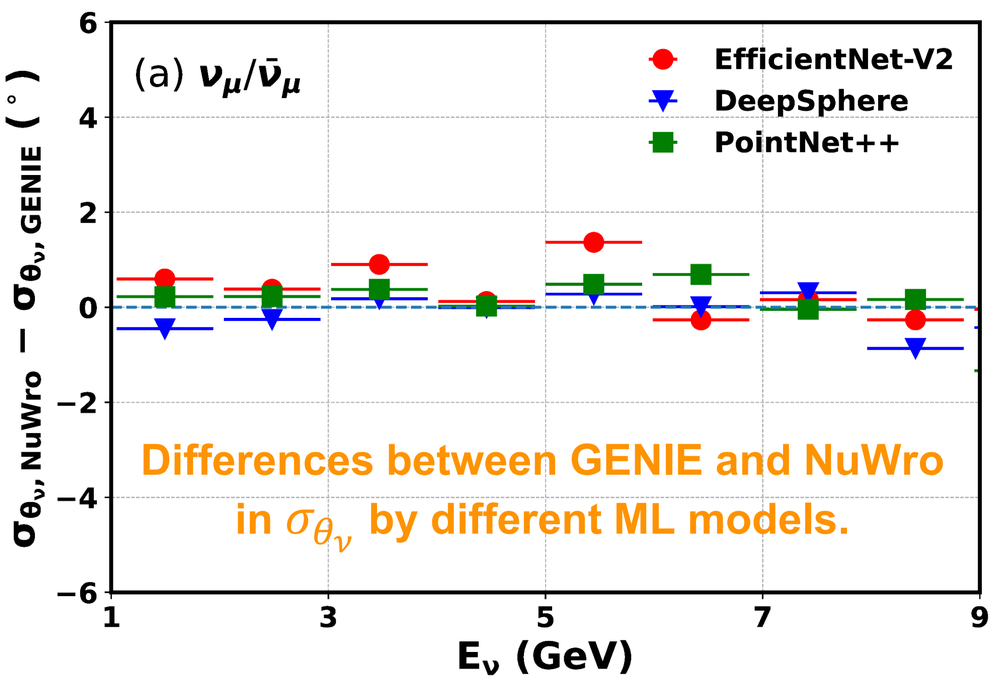

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nerators and models
Wro, GiBUU, NEUT)
d ReWeight

External data constraints (MiNERvA, T2K, NOvA…)

Our nominal model

Generator	Version	Model Name	Details
GENIE	3.04.02	G18_10b_02_11b	Nominal tune
		G21_11b_00_000	More recent models
NuWro	21.09.2	Δ Model	NuWro with Default configuration
	latest	Hybrid Model	New 1π production model
GiBUU	2025p1	Default	With 2π-BG contribution

Well tested generators to produce uncertainty estimation

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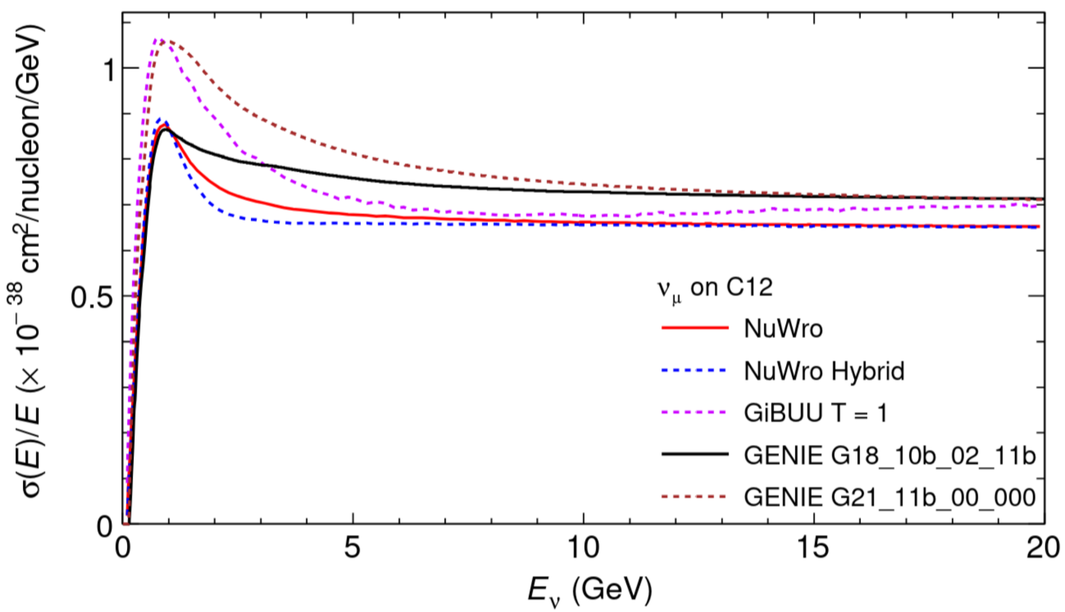

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Oscillation parameter uncertainties from PDG

Possible data-driven approaches with cosmic muons

$$N(E_{rec}, \cos\theta_{rec}) \sim \int_{E_\nu}\int_{\cos\theta_\nu} dE_\nu d\cos\theta_\nu \Phi(E_\nu, \cos\theta_\nu) P_{osc}(E_\nu, \cos\theta_\nu) \sigma(E_\nu) R_{det}(E_\nu, \cos\theta_\nu, E_{rec}, \cos\theta_{rec})$$

Number of events (Observables)

Neutrino Flux

Oscillation Probability

Cross-sections

Detector response

Cross-check with different ML models and non-ML methods

Different generators and models (GENIE, NuWro, GiBUU, NEUT) And ReWeight

External data constraints (MiNERvA, T2K, NOvA…)

Model	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
G18_10a_02_11a	1320.82	549.73	531.92	194.49
G21_11b_00_000	1421.83	610.52	573.47	216.28
NuWro SF+LFG+Δ	1180.13	487.56	476.81	173.16
NuWro SF+LFG+Hybrid	1145.74	513.89	462.91	182.67
GiBUU	1249.34	497.10	502.57	175.62
Max Rel. Diff (%)	21.64	22.50	20.28	21.30
Max Rel. Diff w/o G21_11b_00_000 (%)	14.88	12.76	13.91	11.75

3-10 GeV, 6 yrs exposure, unoscillated

- A dedicated group is established to study the neutrino interactions for JUNO's atmospheric neutrino studies.

Systematic Uncertainties

Honda flux with normalization and shape uncertainties

Oscillation parameter uncertainties from PDG

Possible data-driven approaches with cosmic muons

$$N(E_{rec}, \cos\theta_{rec}) \sim \int_{E_\nu}\int_{\cos\theta_\nu} dE_\nu d\cos\theta_\nu \Phi(E_\nu, \cos\theta_\nu) P_{osc}(E_\nu, \cos\theta_\nu) \sigma(E_\nu) R_{det}(E_\nu, \cos\theta_\nu, E_{rec}, \cos\theta_{rec})$$

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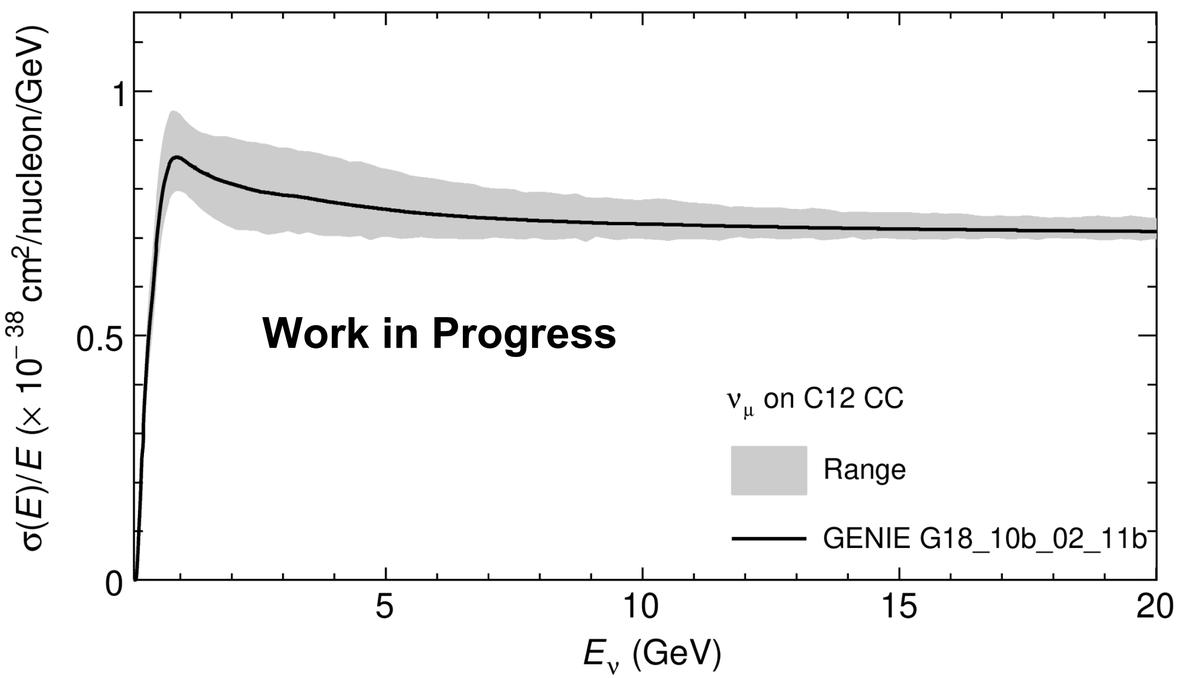


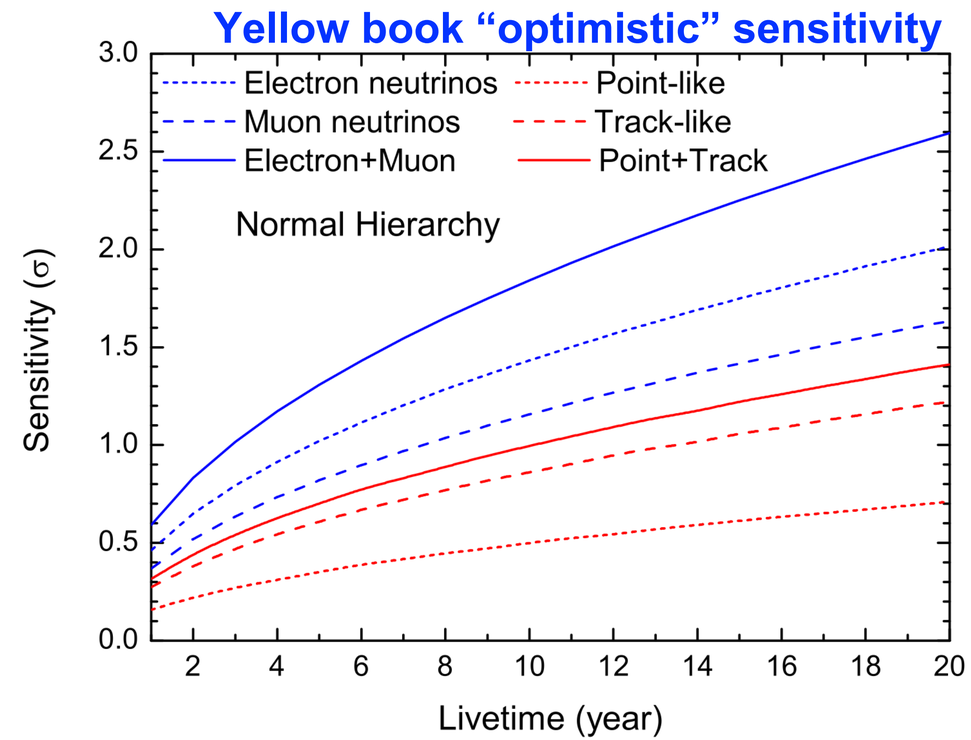
Integration with GENIE ReWeight on going

- A dedicated group is established to study the neutrino interactions for JUNO's atmospheric neutrino studies.

Towards an Updated Sensitivity

	Yellow Book "Optimistic case"
Directionality	$\sigma_{\theta\mu} = 1^\circ$ $\sigma_{\theta\nu} = 10^\circ$
Energy	Visible energy
e-like Event Selection	$E_{vis} > 1GeV$, $Y_{vis} = E_h/E_{vis} < 0.5$
Classification	Simple classification with Michel e, Y_{vis} cuts
Sensitivity	1.8 σ in 10 years

Neutrino physics with JUNO
J. Phys. G 43, 030401 (2016)



Towards an Updated Sensitivity

	Yellow Book "Optimistic case"	Recent Improvements
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Neutrino physics with JUNO
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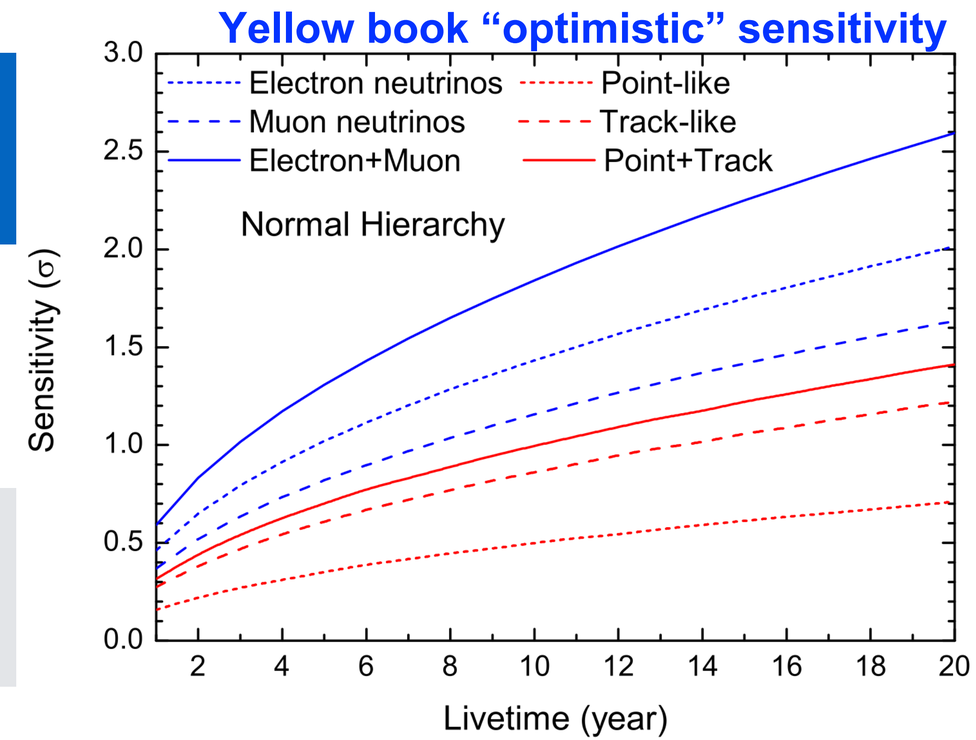

- A lot of recent progress in reconstruction and event identification.

Towards an Updated Sensitivity

	Yellow Book "Optimistic case"	Recent Improvements
Directionality	$\sigma_{\theta\mu}=1^\circ$ $\sigma_{\theta\nu}=10^\circ$	$\sigma_{\theta\nu}<10^\circ$ (E_ν>3GeV)
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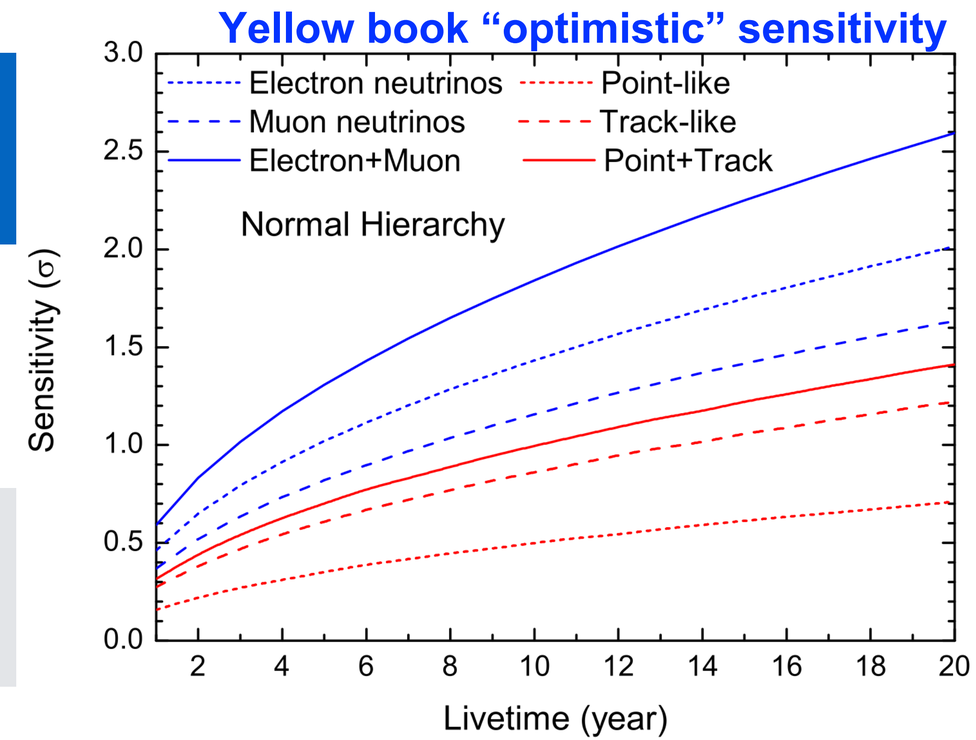
Neutrino physics with JUNO
J. Phys. G 43, 030401 (2016)



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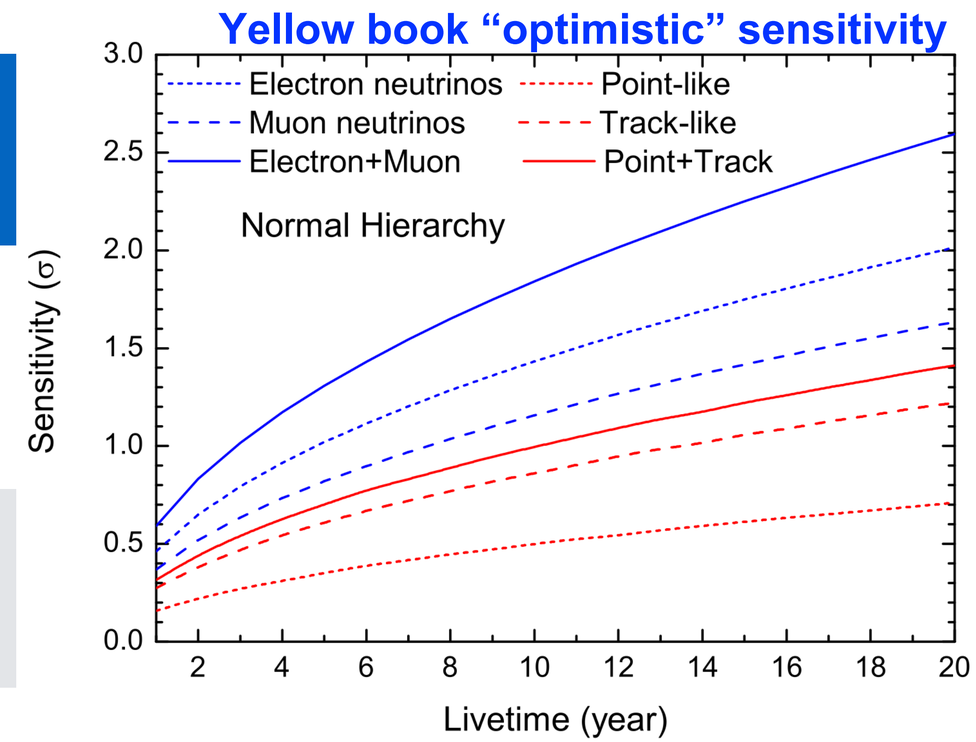

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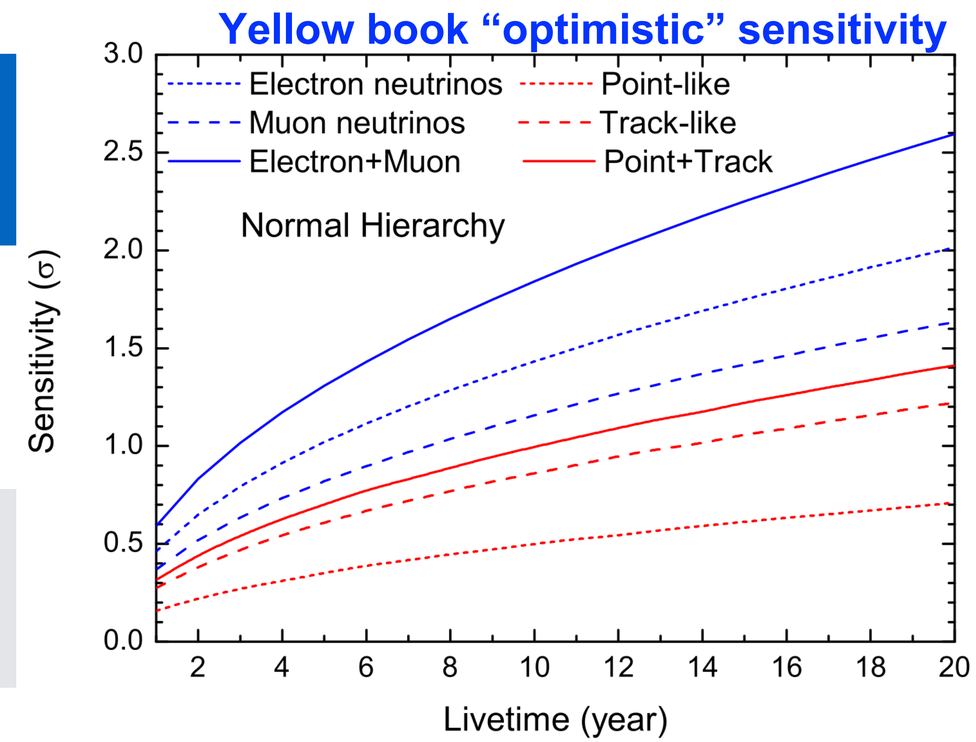
Neutrino physics with JUNO
J. Phys. G 43, 030401 (2016)



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Towards an Updated Sensitivity

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Classification	Simple classification with Michel e, Y_{vis} cuts	ν vs $\bar{\nu}$: 60%~80% eff.
Sensitivity	1.8 σ in 10 years	

Neutrino physics with JUNO
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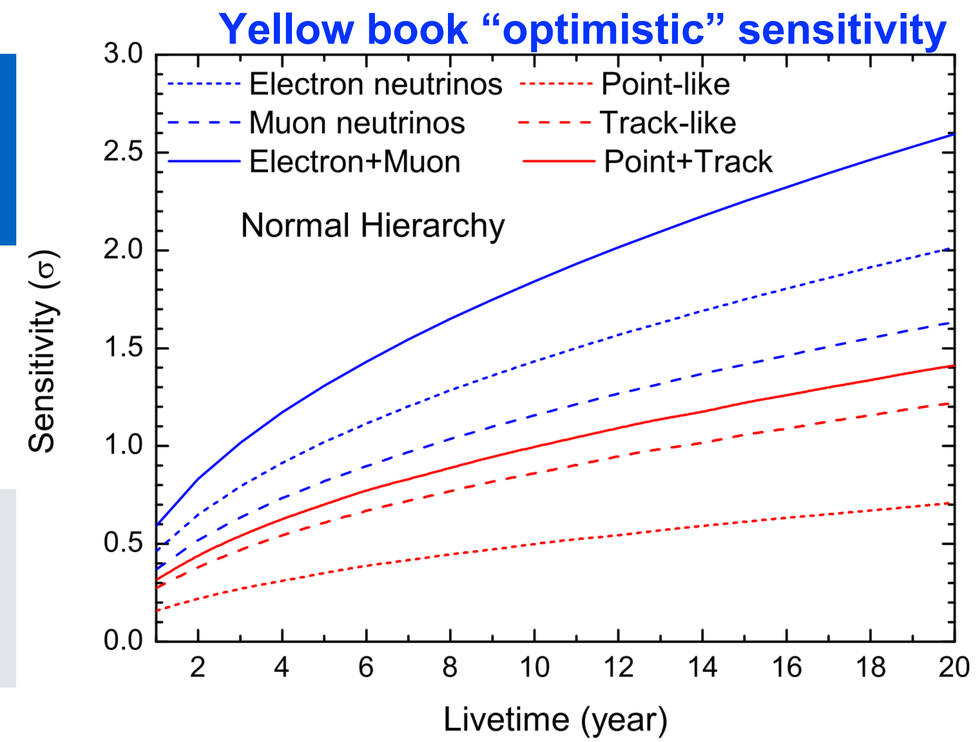

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Neutrino physics with JUNO
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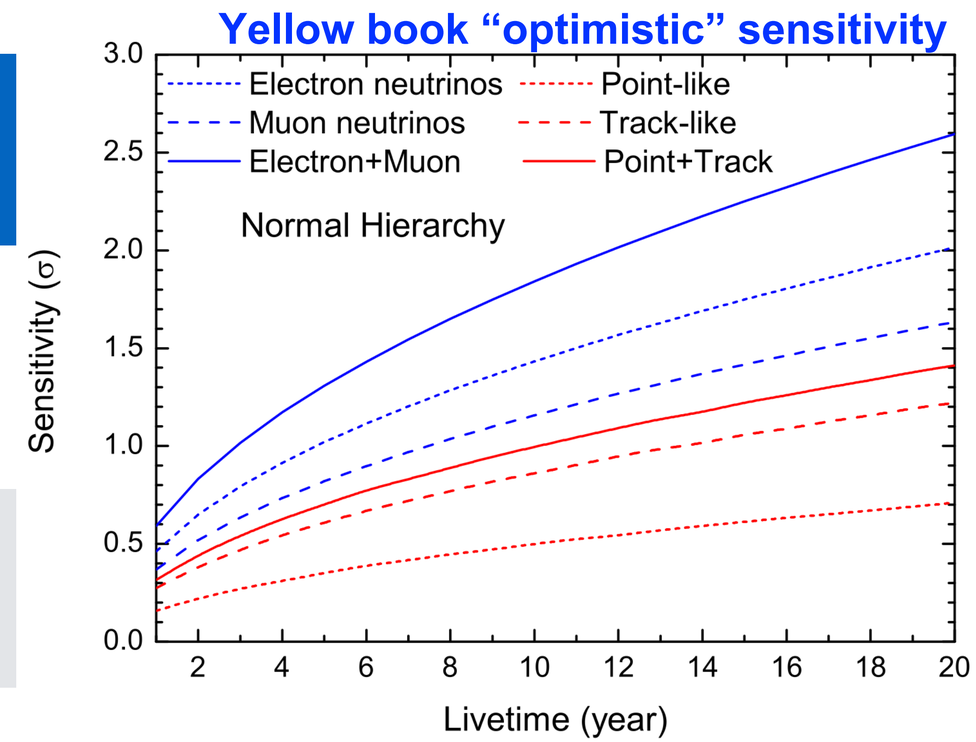


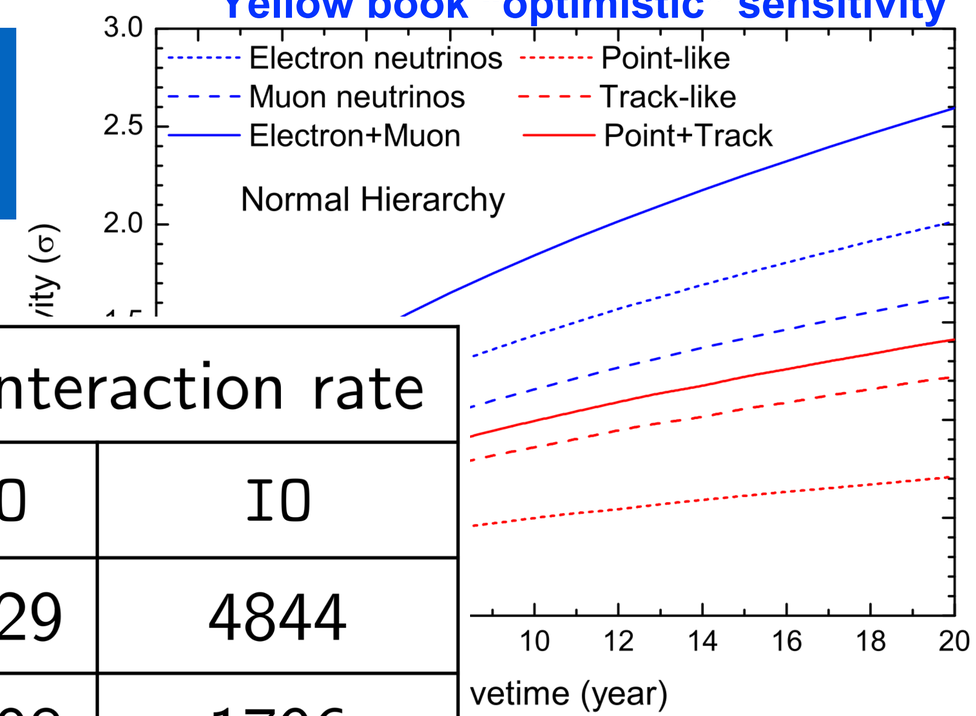
- A lot of recent progress in reconstruction and event identification.
- Aiming to release an updated NMO sensitivity soon.

Towards an Updated Sensitivity

	Yellow Book "Optimistic case"	Recent Improvements
Directionality	$\sigma_{\theta\mu}$ =1° $\sigma_{\theta\nu}$ =10°	
Energy	Visible energy	
e-like Event Selection	E_{vis} > 1GeV, $Y_{vis}=E_h/E_{vis}$ < 0.	
Classification	Simple classificatior Michel e, Y_{vis} cuts	60% - 80% eff.
Sensitivity	1.8 σ in 10 years	**To be updated**

0.1 - 20 GeV, 6yrs, interaction rate			
Flavor	No Osc	NO	IO
ν_μ	7025	4829	4844
$\overline{\nu_\mu}$	2603	1808	1796
ν_e	3629	3746	3693
$\overline{\nu_e}$	1173	1155	1173

Yellow book "optimistic" sensitivity



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Neutrino physics with JUNO
J. Phys. G 43, 030401 (2016)

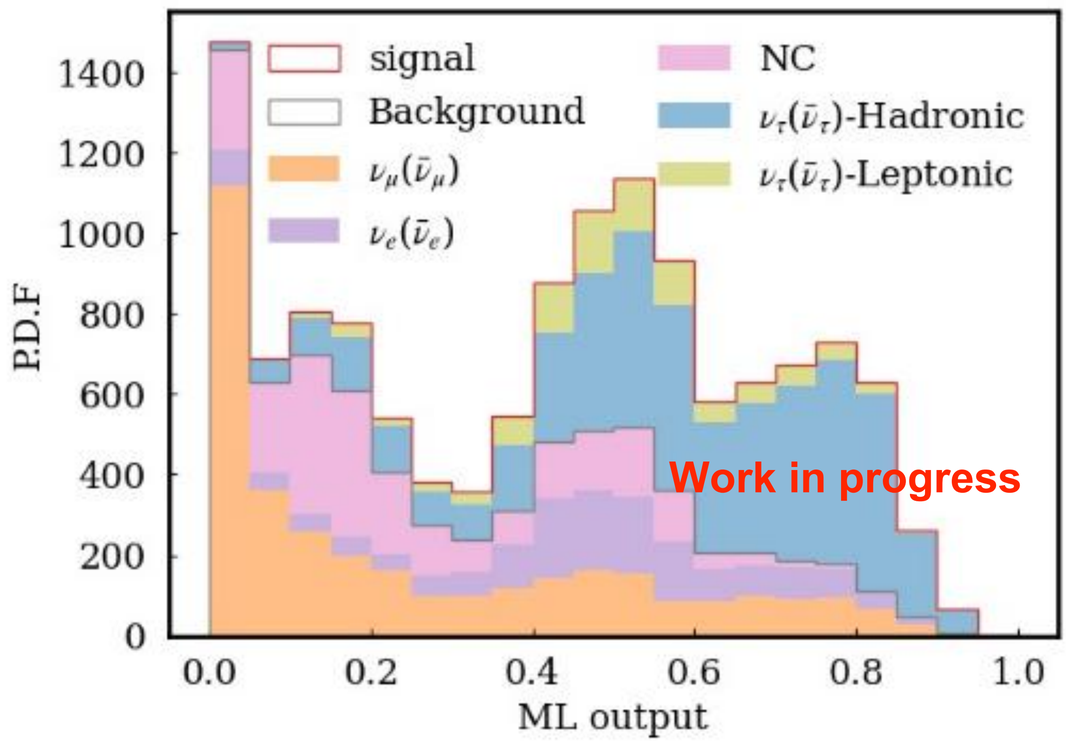
Summary and Outlook

- JUNO has a very active atmospheric neutrino program.
- A lot of recent progress in event reconstruction and identification.
  - Improvements over previous estimations in the yellow book;
  - Cross-checked with different ML/non-ML algorithms;
  - Systematic uncertainty study on-going.
- Aiming to release an updated NMO sensitivity soon.
- Will combine with JUNO's reactor neutrino oscillation measurement to maximum JUNO's NMO sensitivity.

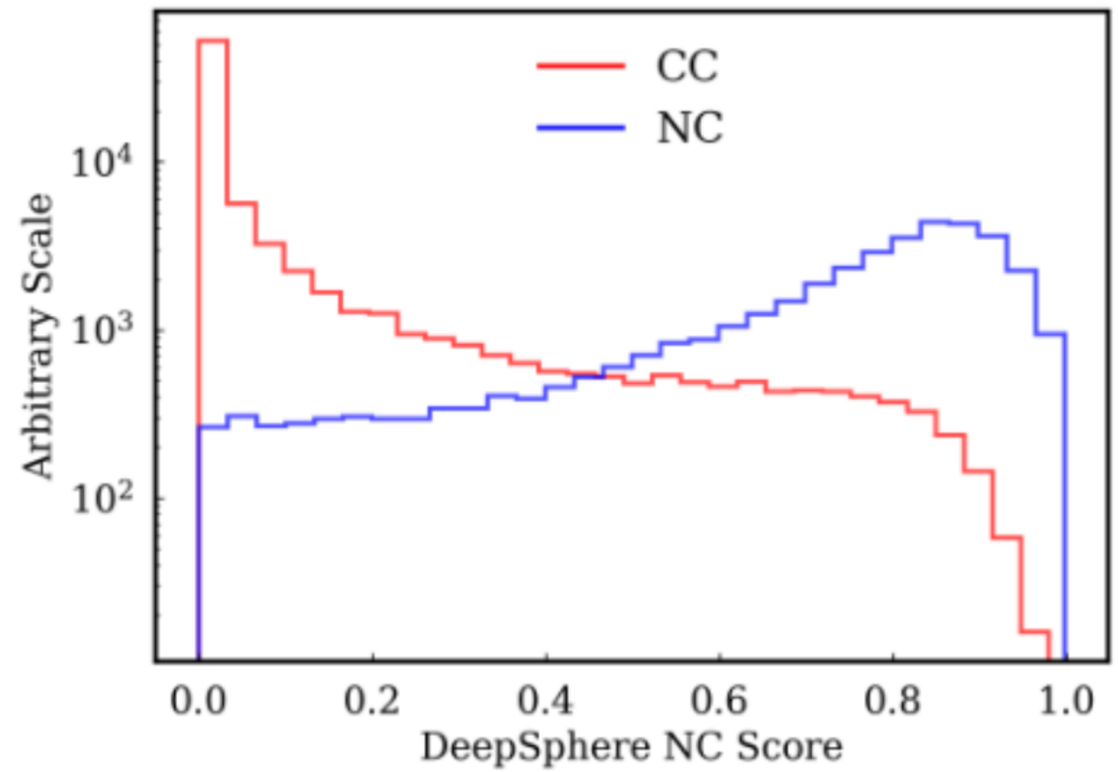
Stay tuned!

And More with Flavor Identification

The first single detector that sees all interaction channels from atmospheric neutrinos!



Identification and Reconstruction of Atmospheric Tau Neutrinos in JUNO, See **Poster #75 by Xiaohan**



Reconstruction of neutral current interactions by atmospheric neutrinos in JUNO, See **Poster #78 by Jiabin**

Back up slides

Outline

- Introduction

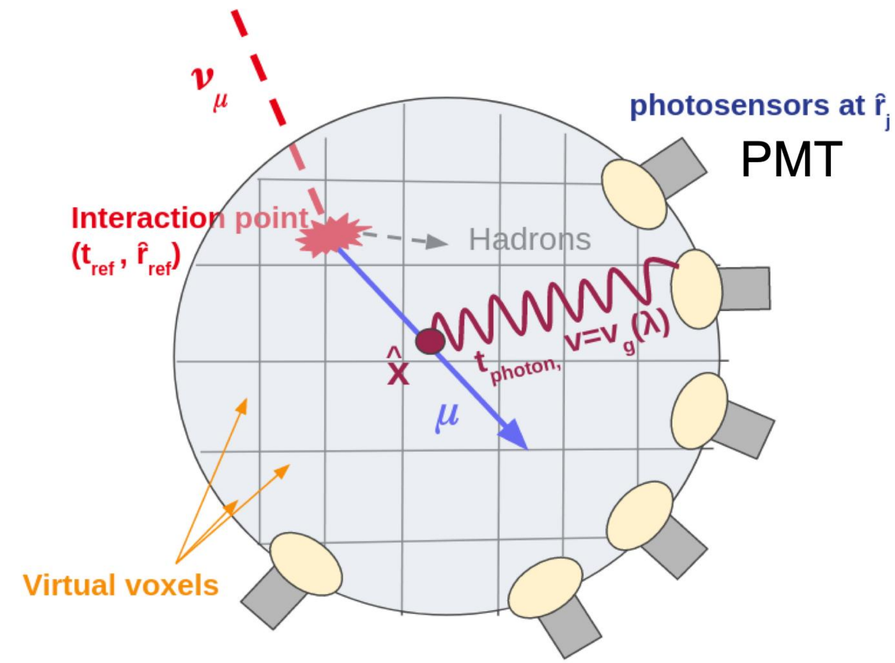
Topological Reconstruction Method

- Idea: Reconstruct the photon emission probability distribution based on the detected PMT hit charges and times.

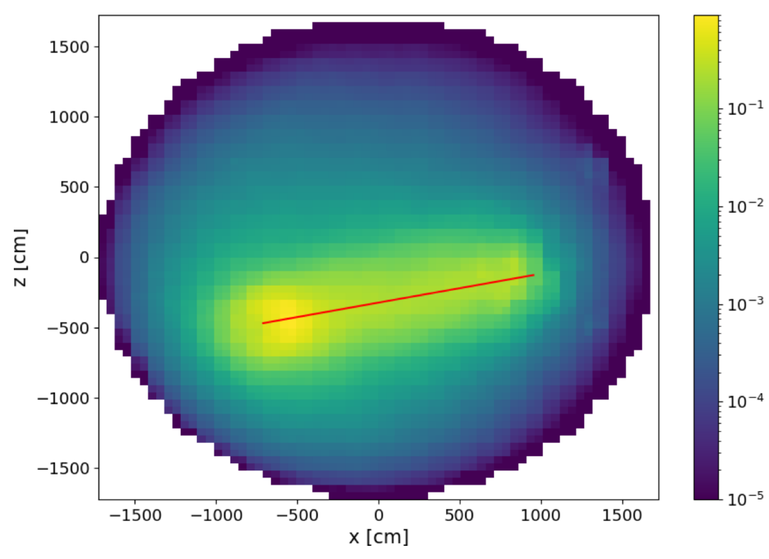
Principle: $\hat{t}(x) = t_{ref} \pm \frac{|\hat{x} - \hat{r}_{ref}|}{c_0} + \frac{|\hat{r}_j - \hat{x}|}{v_g}$

t_{ref}: reference time and vertex; $t_{particle}$ (μ/e); t_{photon}

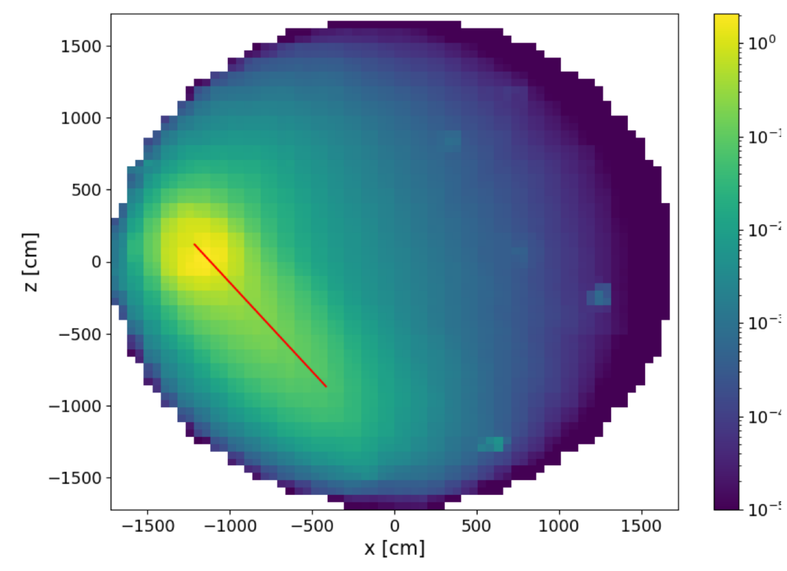
reference time and vertex: $(t_{ref}, \hat{r}_{ref})$



- Event directionality and more can be extracted from the reconstructed probability distribution.
- Will cross-check with the results from ML.



~3 GeV ν_μ-CC event with low y_{bj}



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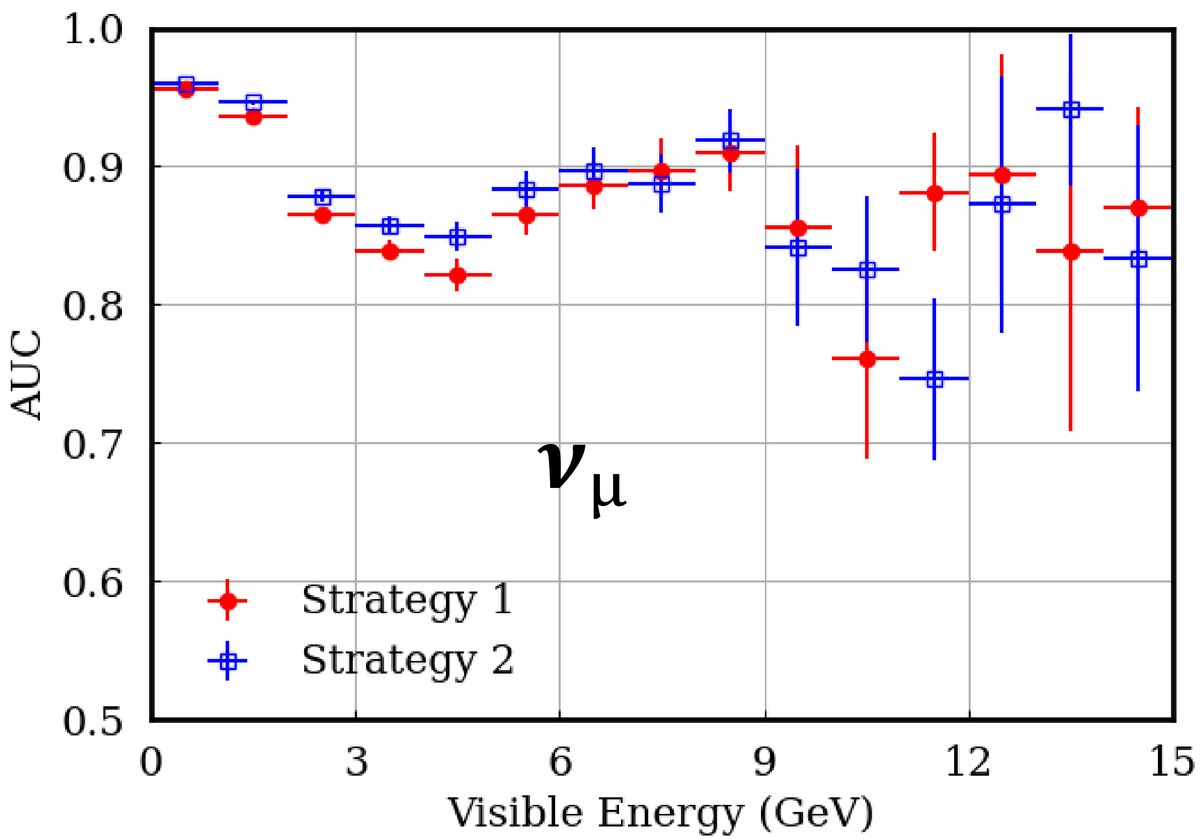
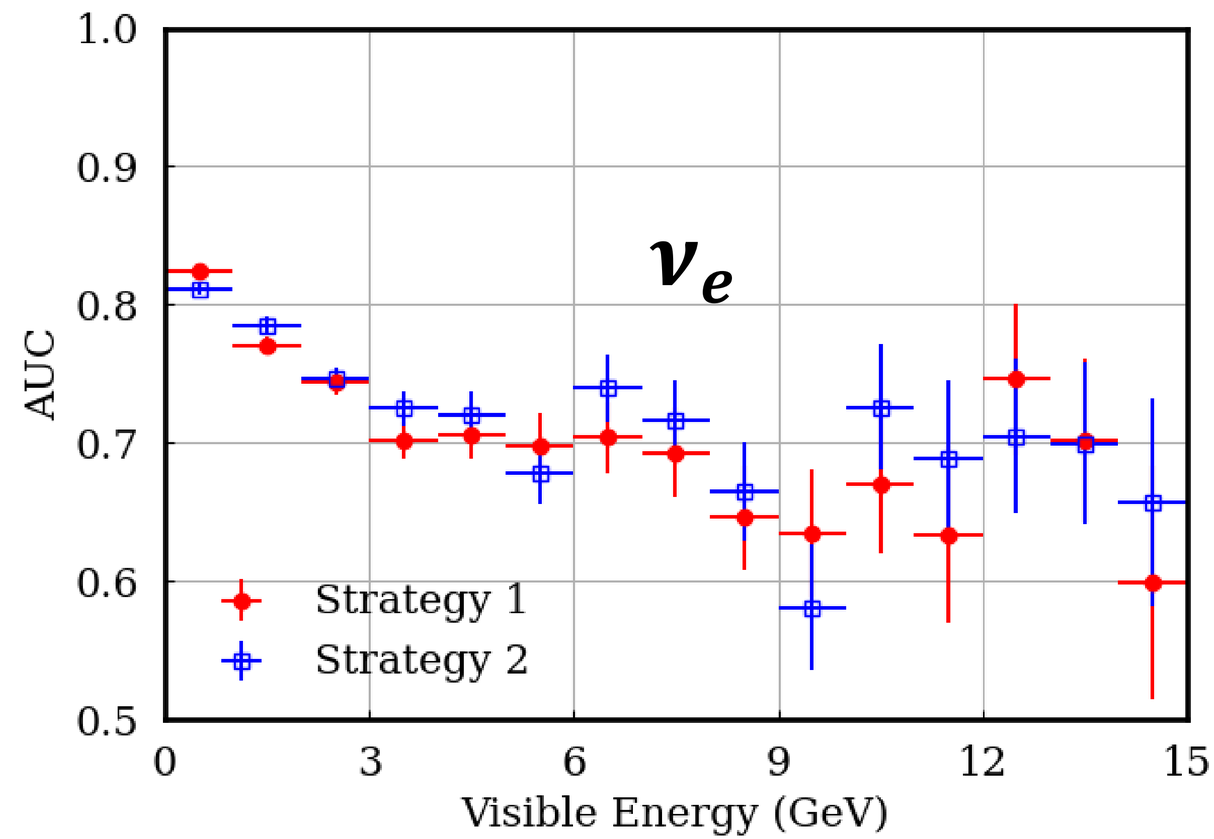
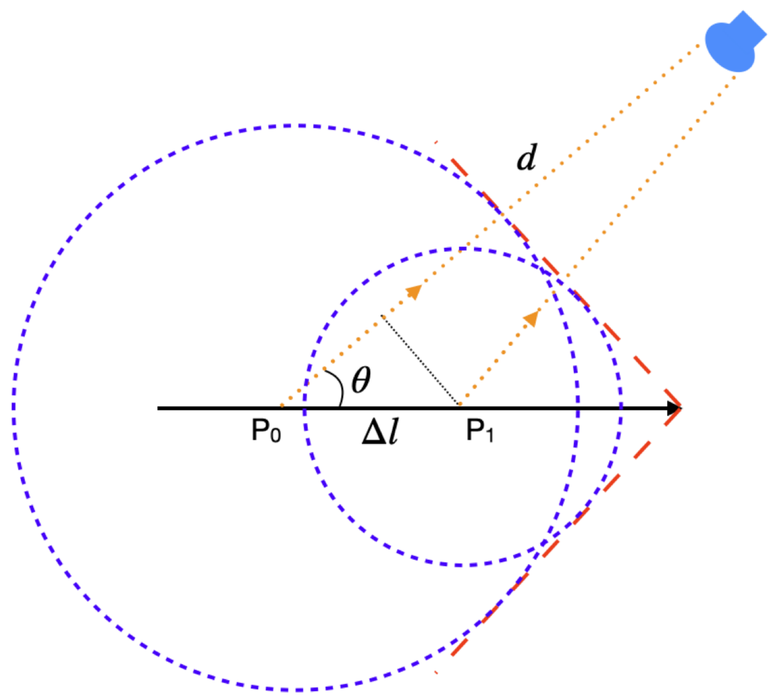
Flavor Identification Performances

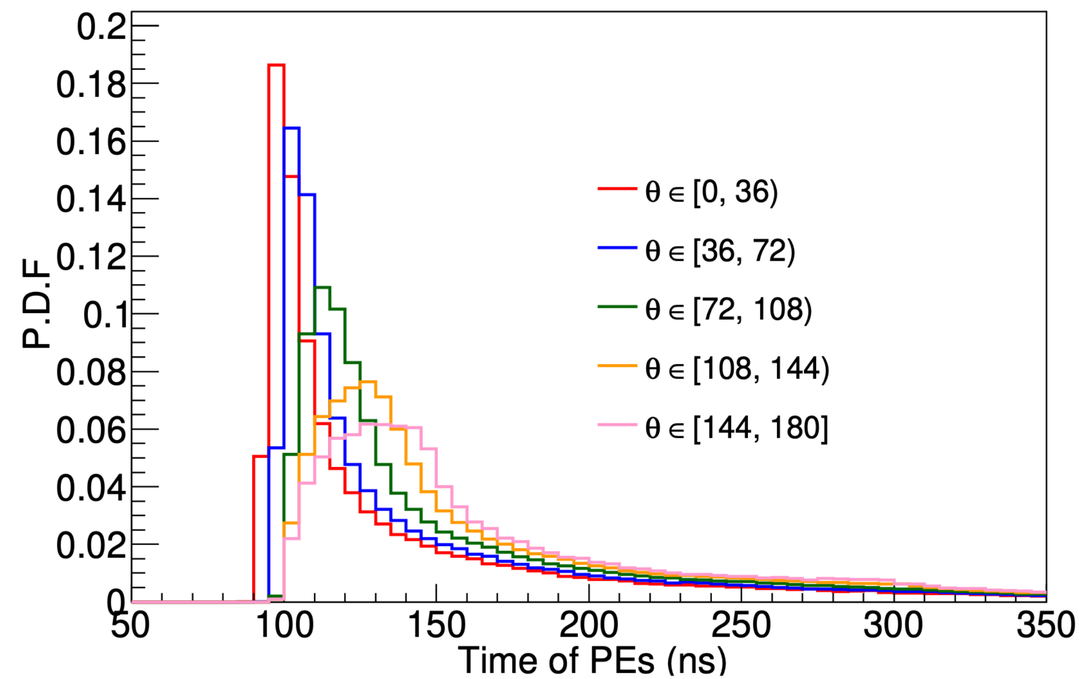




$\nu, \bar{\nu}$ Identification – AUC

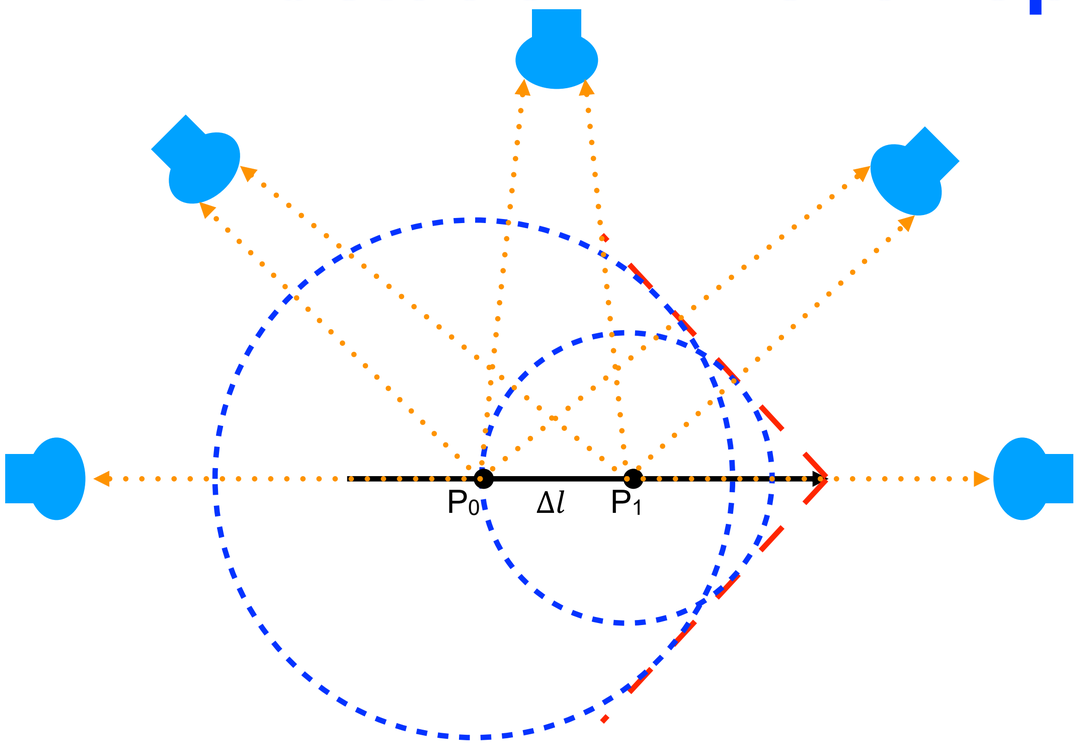
Solution: Event Topology in PMT Waveforms

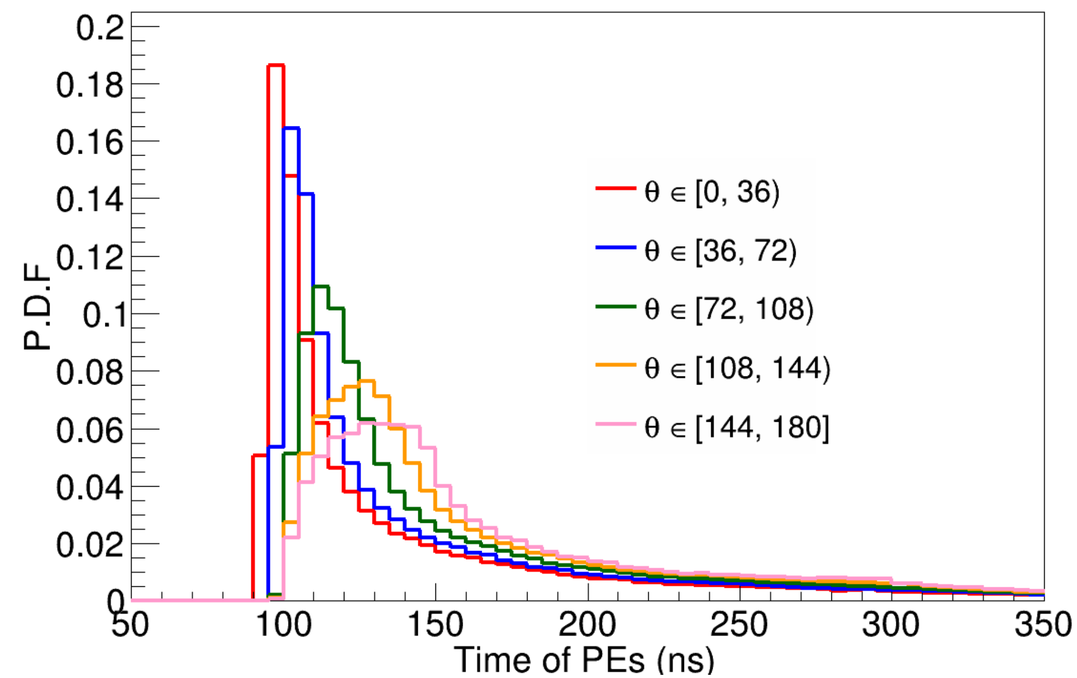




- PMTs at different angles wrt the track see distinct shapes of nPE(t)
- Exactly how nPE(t) looks depends on:
  - Track direction; → **Directionality**
  - Track starting and stopping points;
  - Track dE/dx… → **PID**
- Event topology information in the PMT waveform.

Solution: Event Topology in PMT Waveforms





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→ **Directionality**, **Energy**, **PID…**

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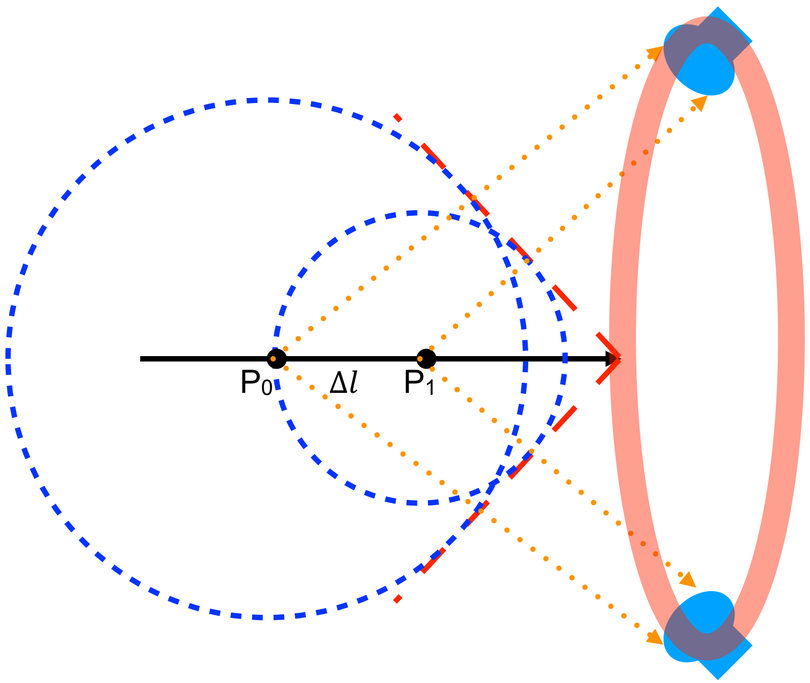

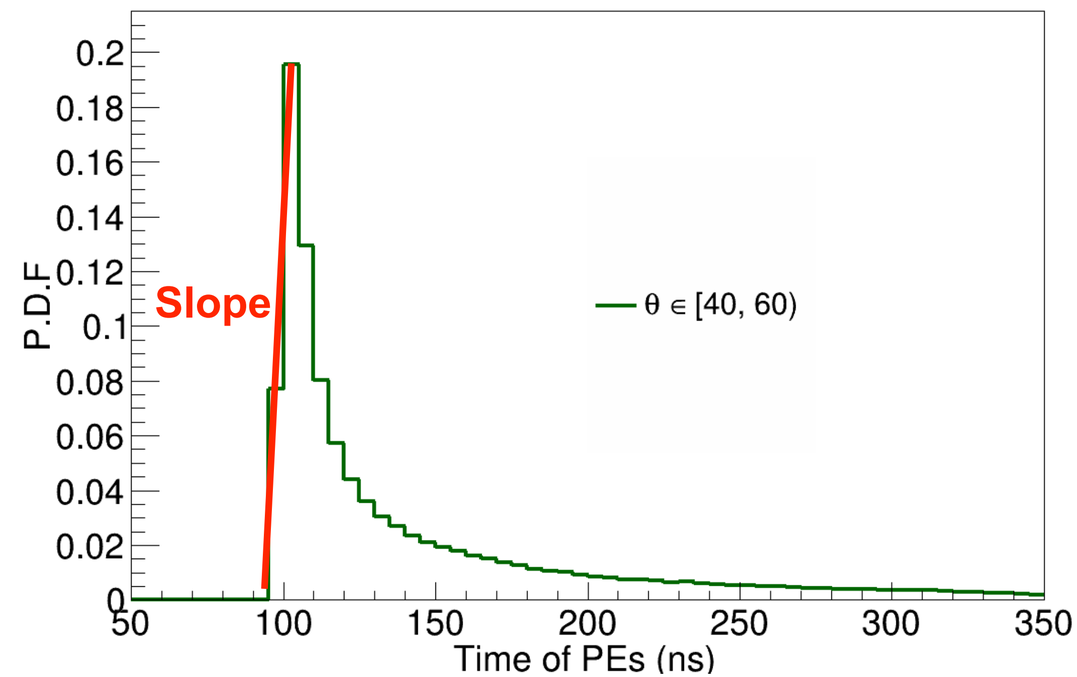

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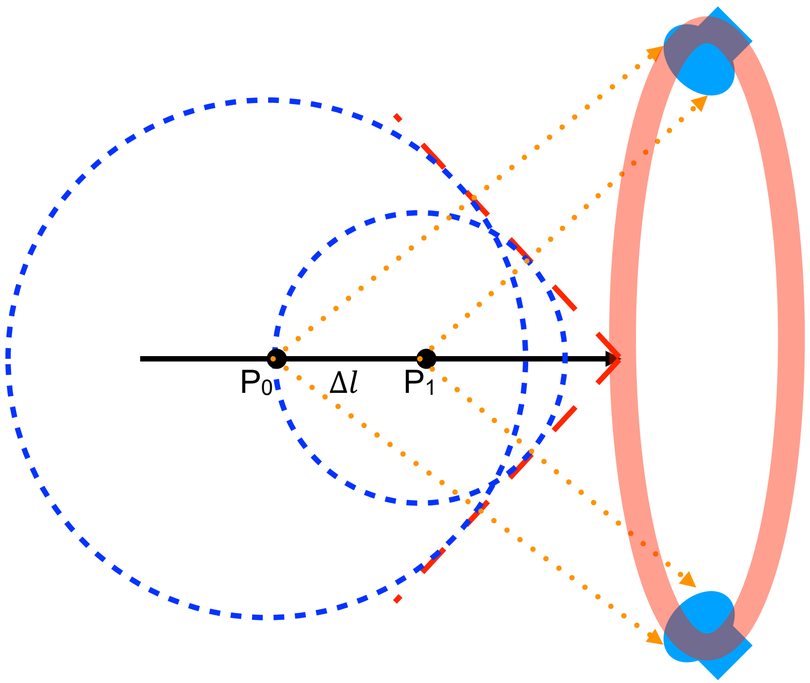

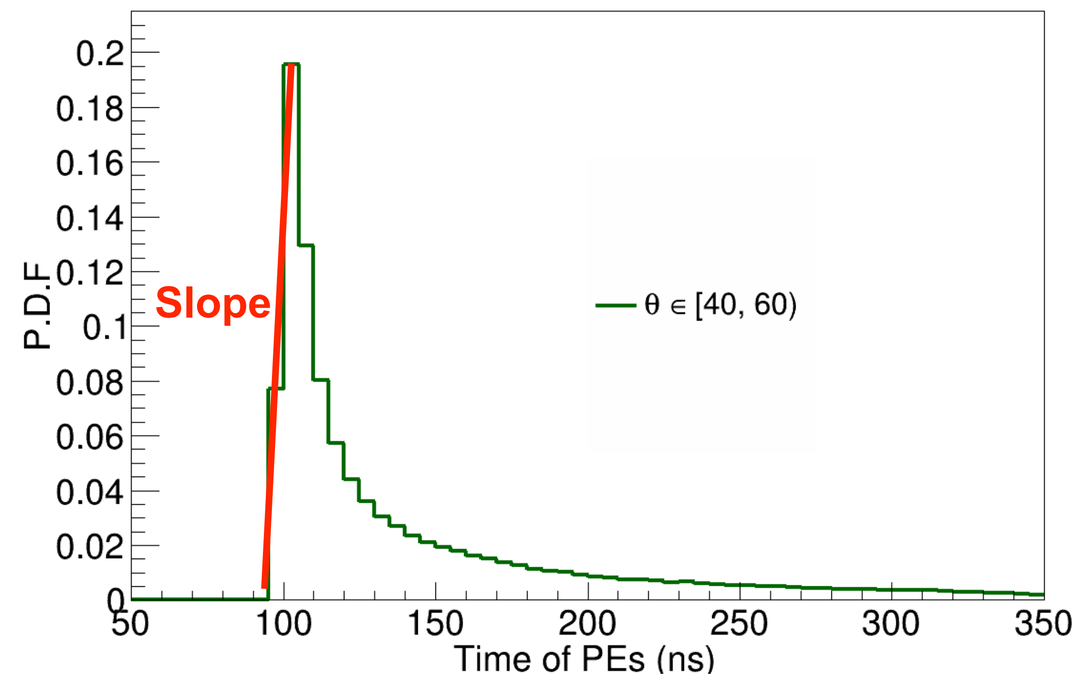

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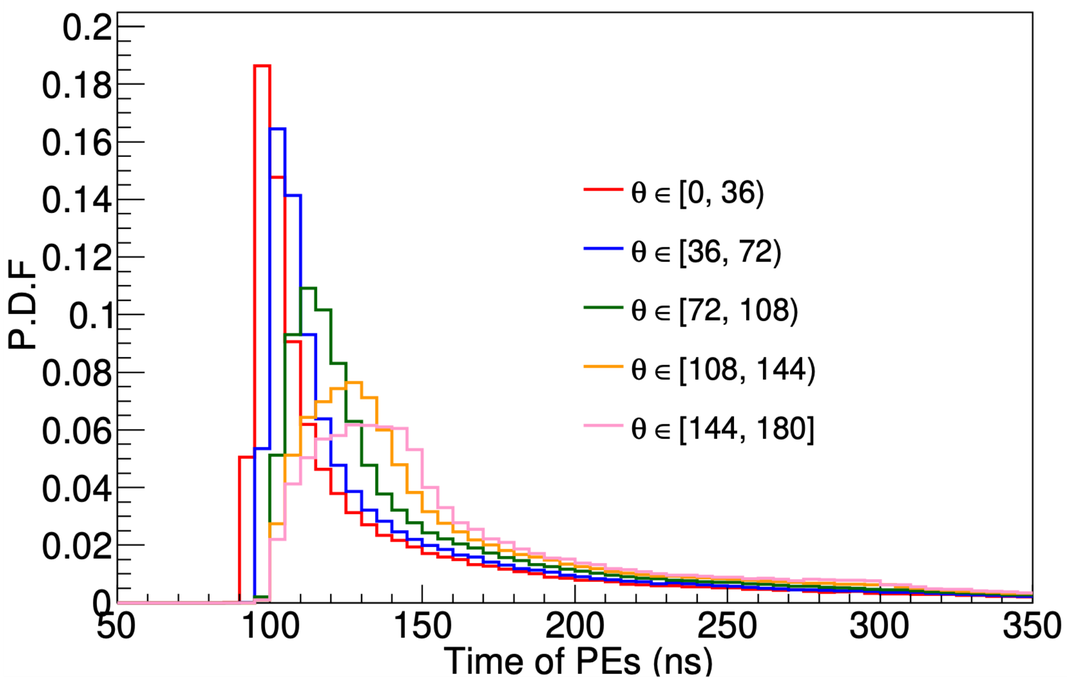
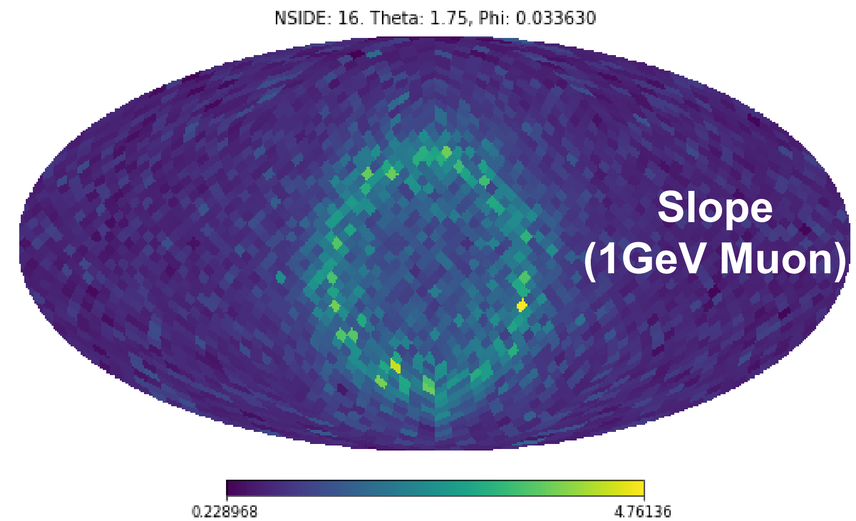
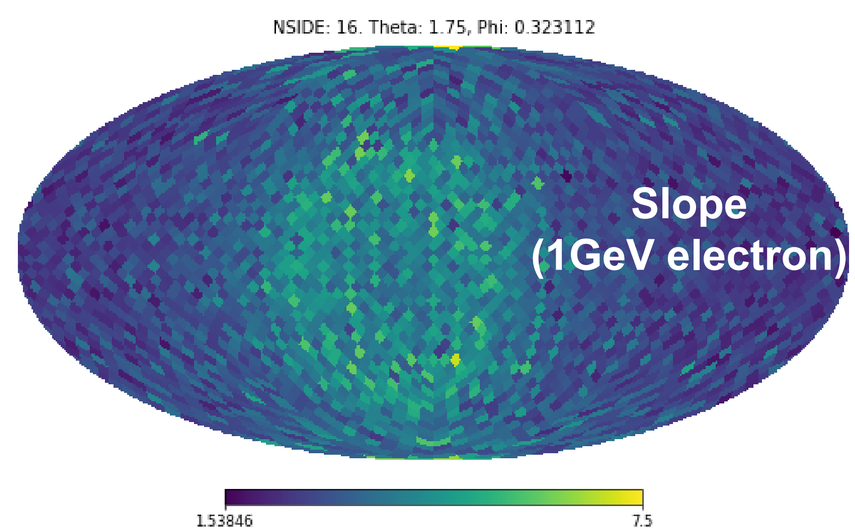
Flavor Identification





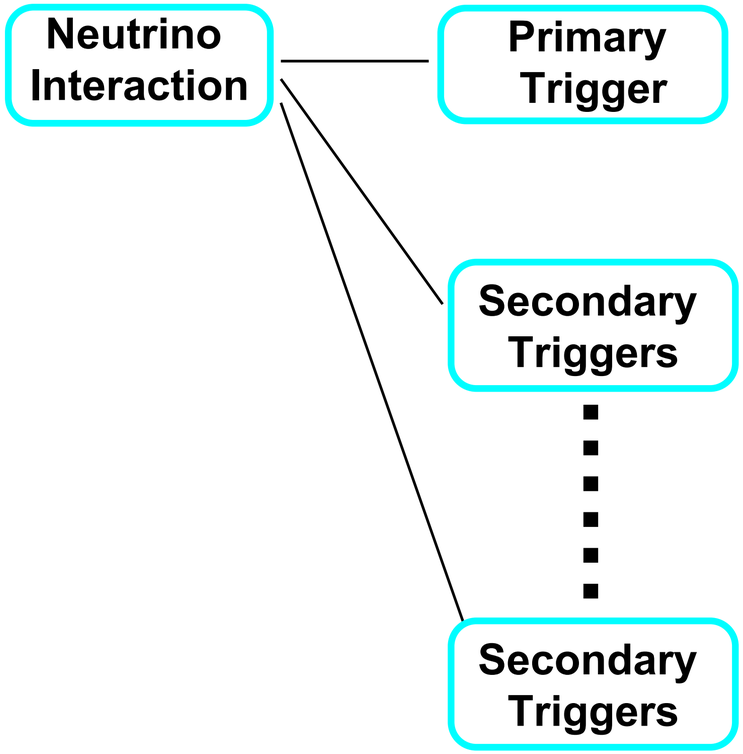


- e-like vs μ-like vs NC identification based upon PMT features.

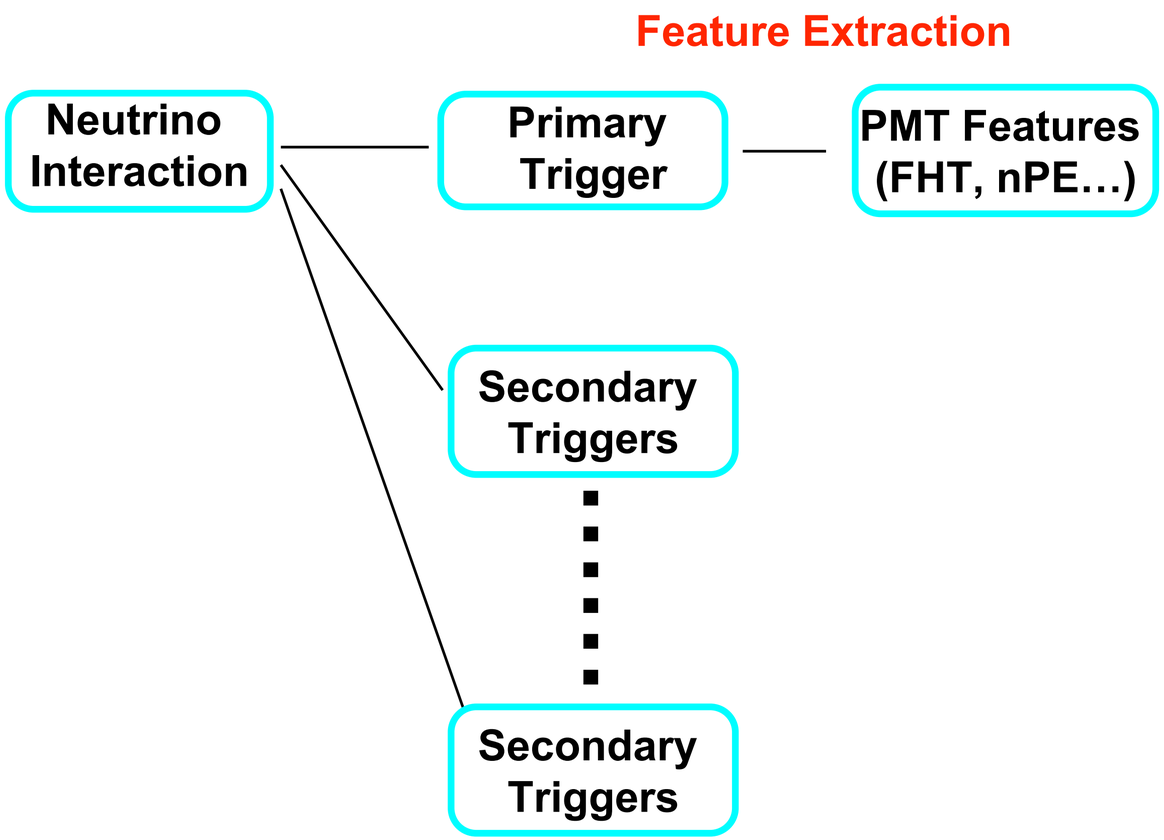
Flavor Identification Strategies

Neutrino Interaction

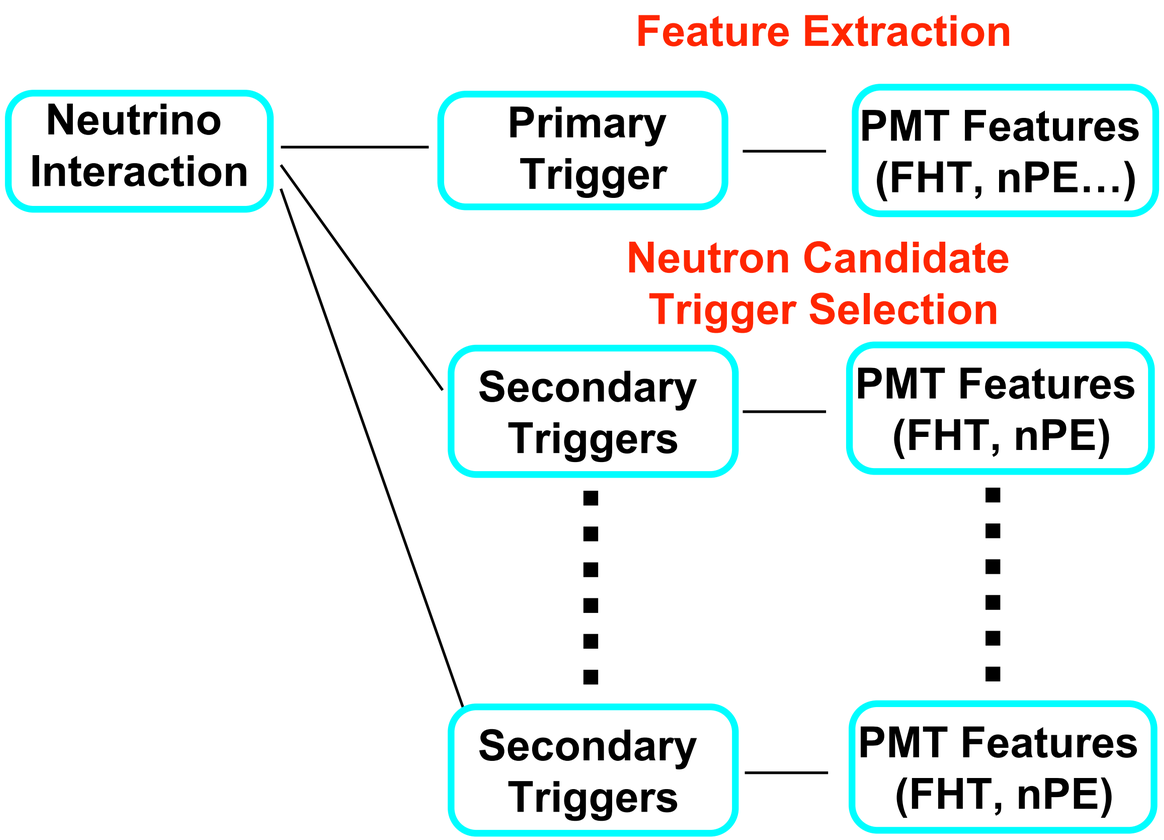
Flavor Identification Strategies



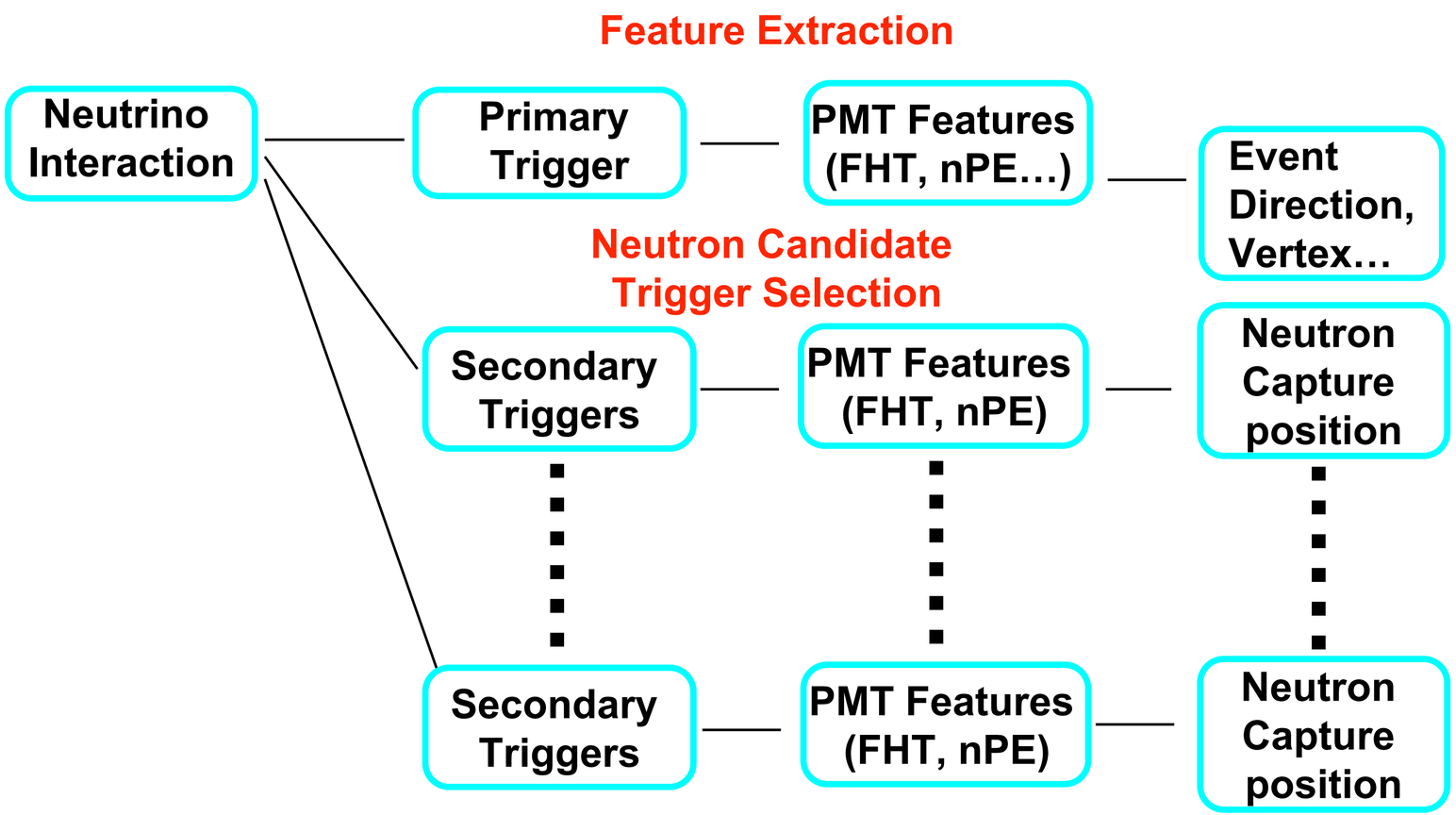
Flavor Identification Strategies



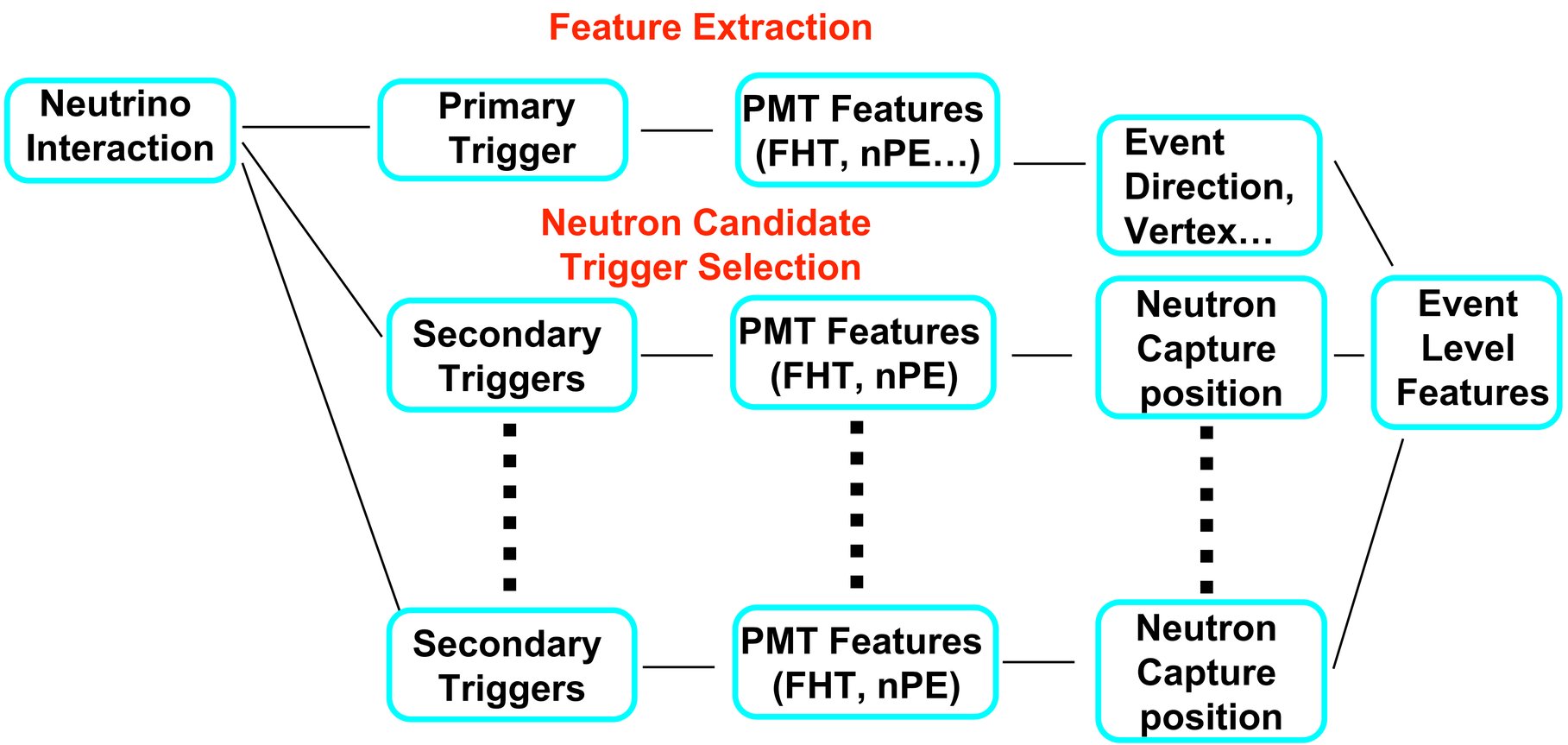
Flavor Identification Strategies



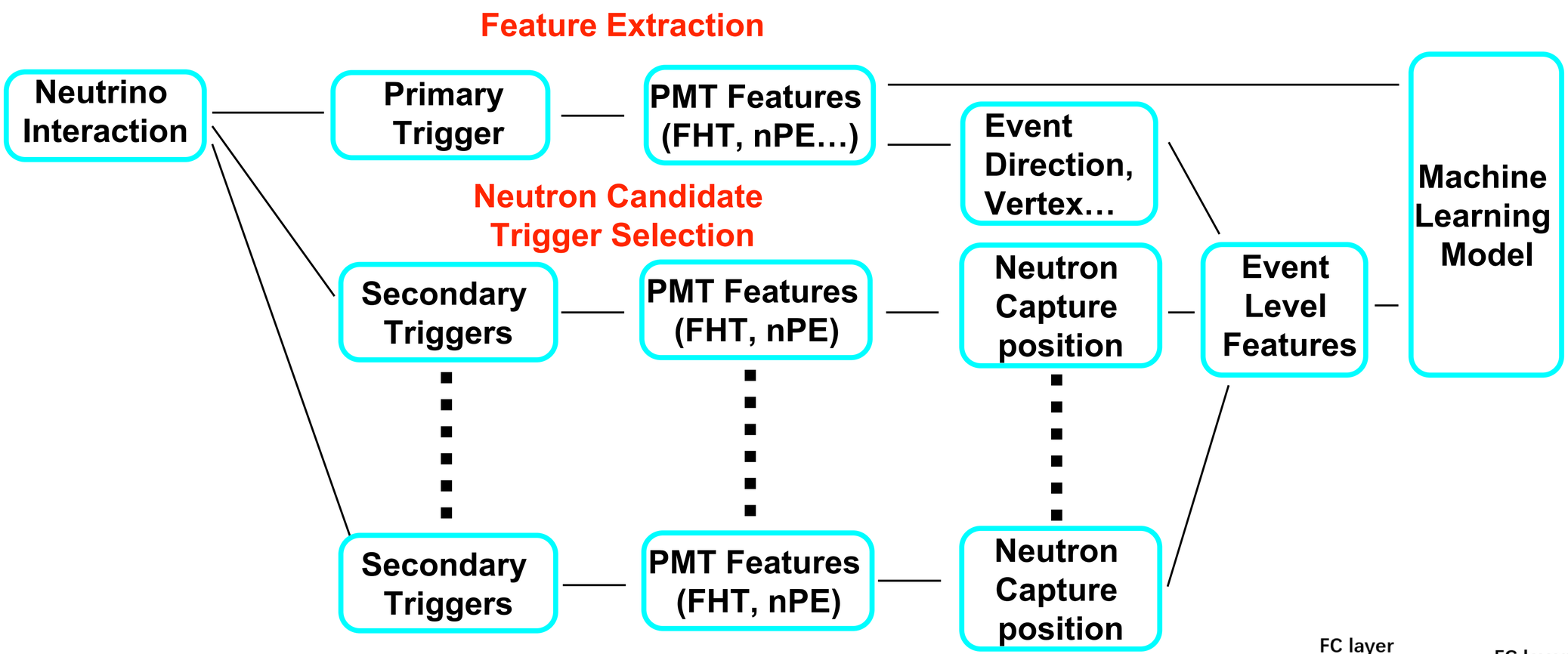
Flavor Identification Strategies



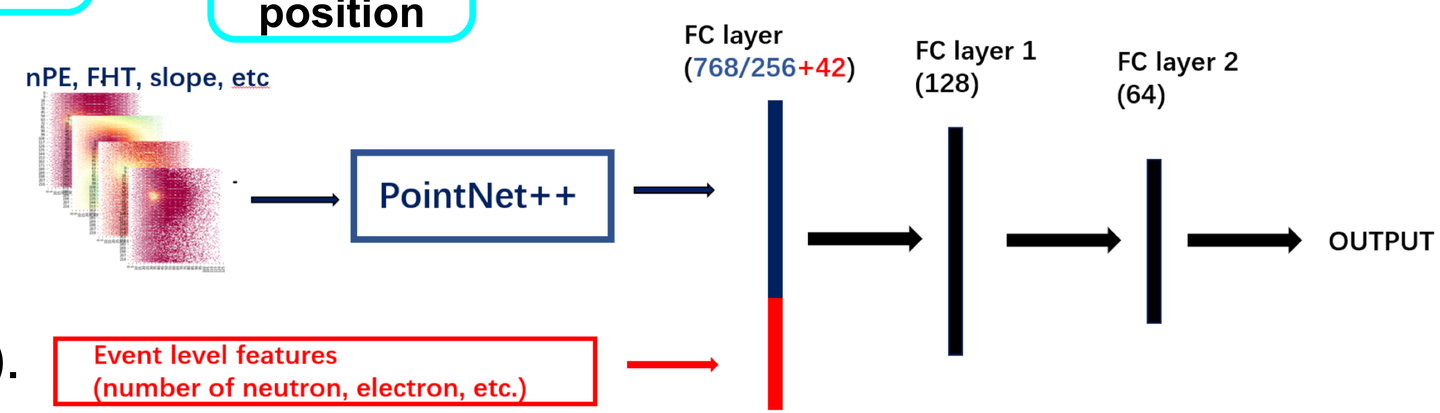
Flavor Identification Strategies



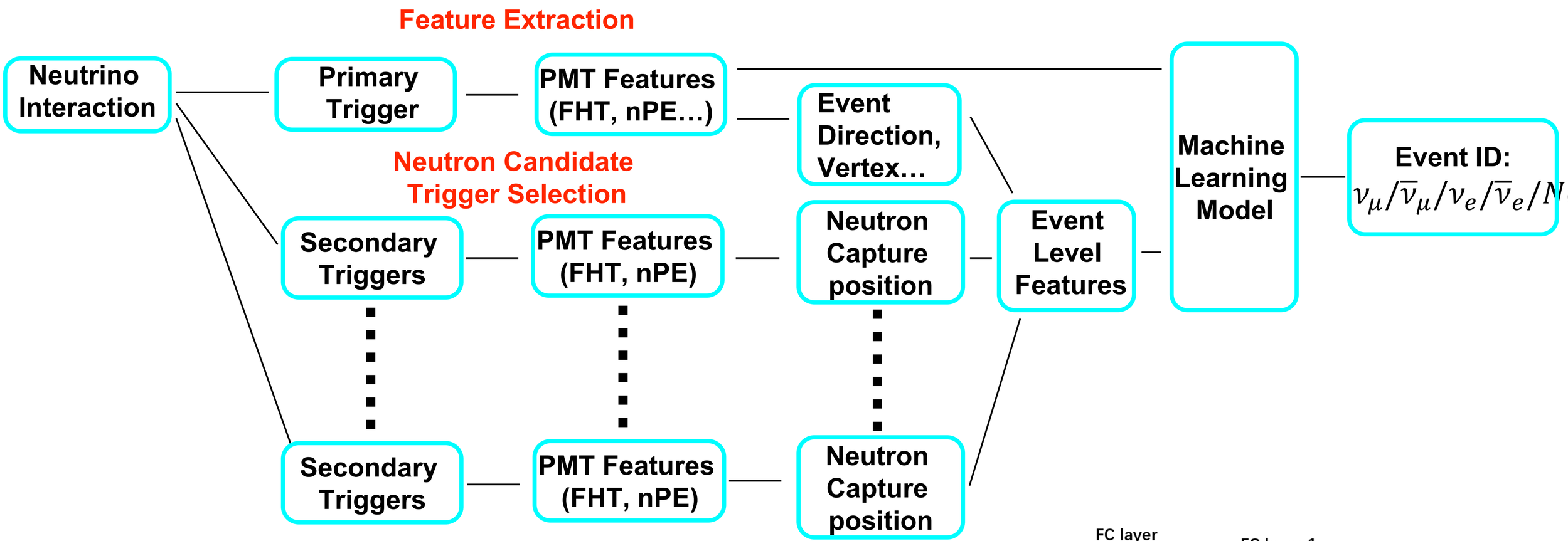
Flavor Identification Strategies



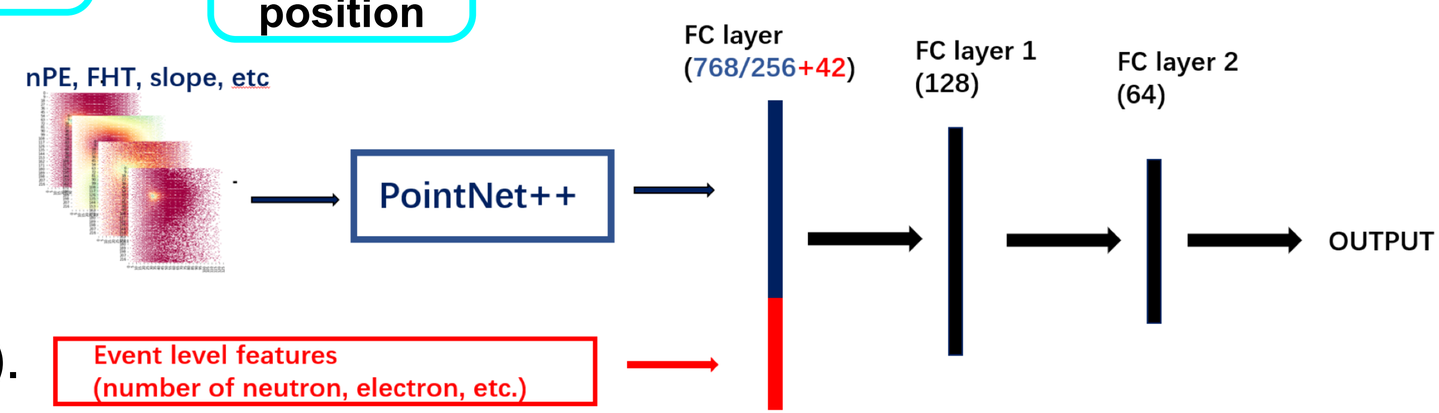
- **Strategy 1**: Combine the PMT-level features with event-level features (neutron-multiplicity, relative positions of neutrons to event vertex/directions, etc.).



Flavor Identification Strategies



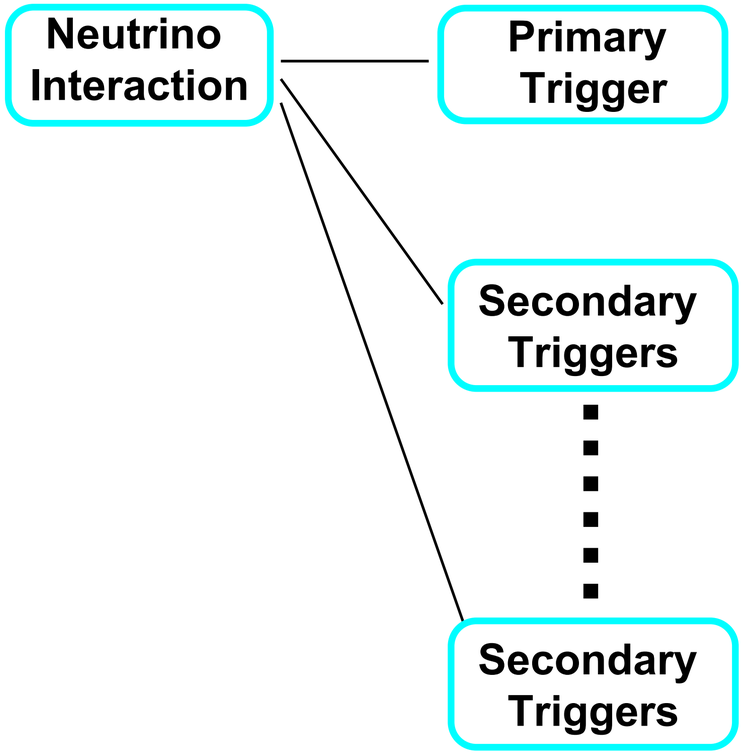
- **Strategy 1**: Combine the PMT-level features with event-level features (neutron-multiplicity, relative positions of neutrons to event vertex/directions, etc.).



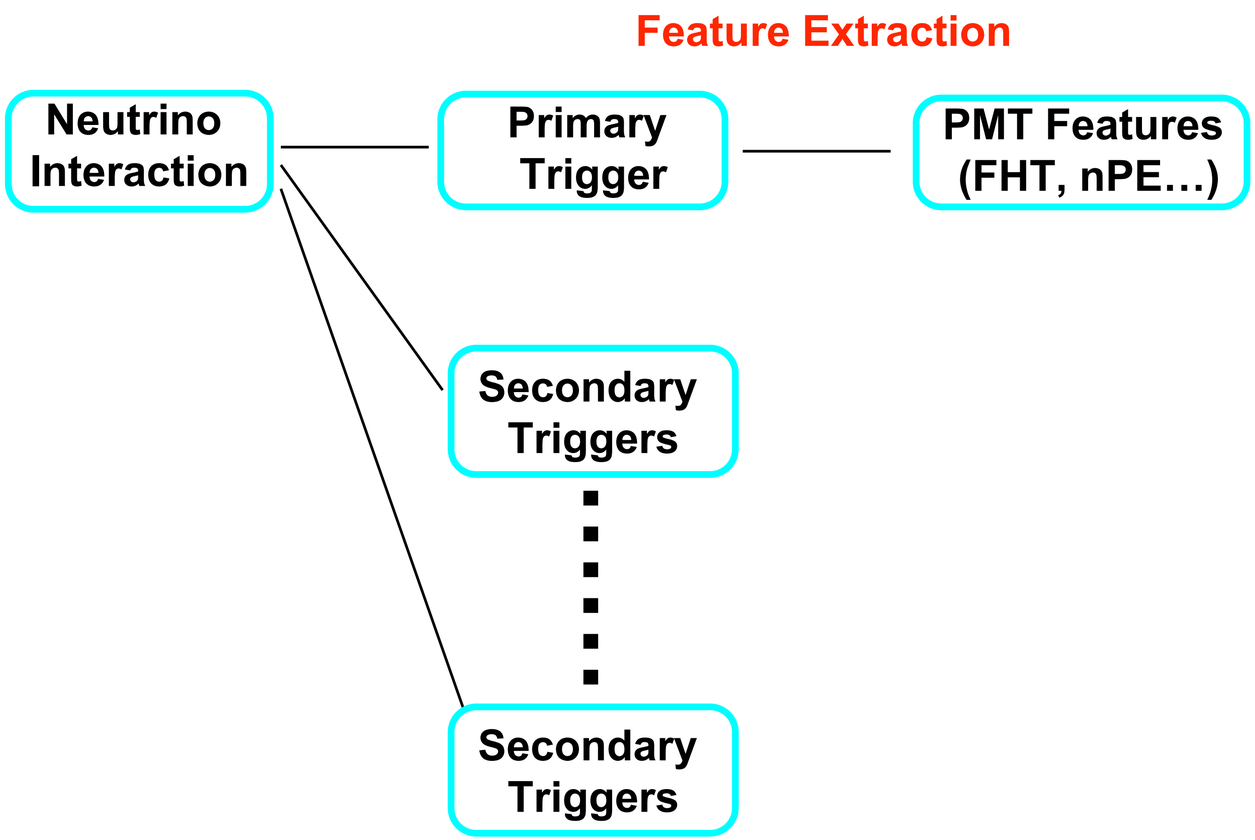
Flavor Identification Strategies

Neutrino Interaction

Flavor Identification Strategies



Flavor Identification Strategies



Flavor Identification Strategies

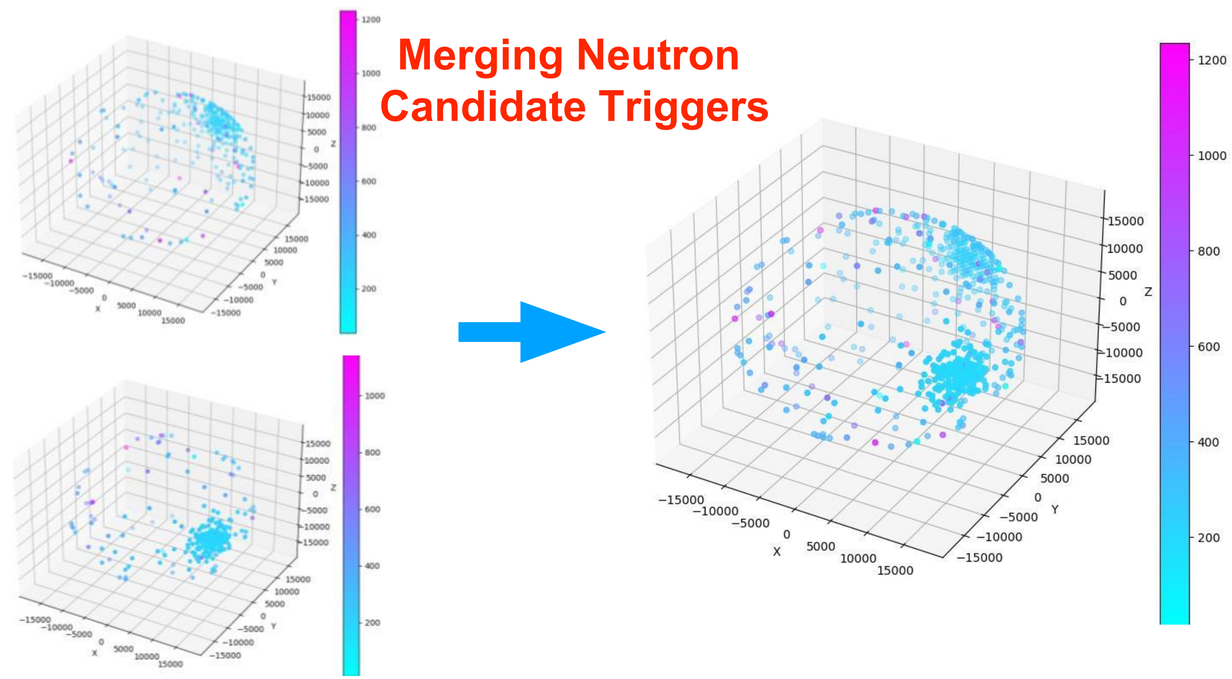
Feature Extraction

Neutrino Interaction — Primary Trigger — PMT Features (FHT, nPE…)

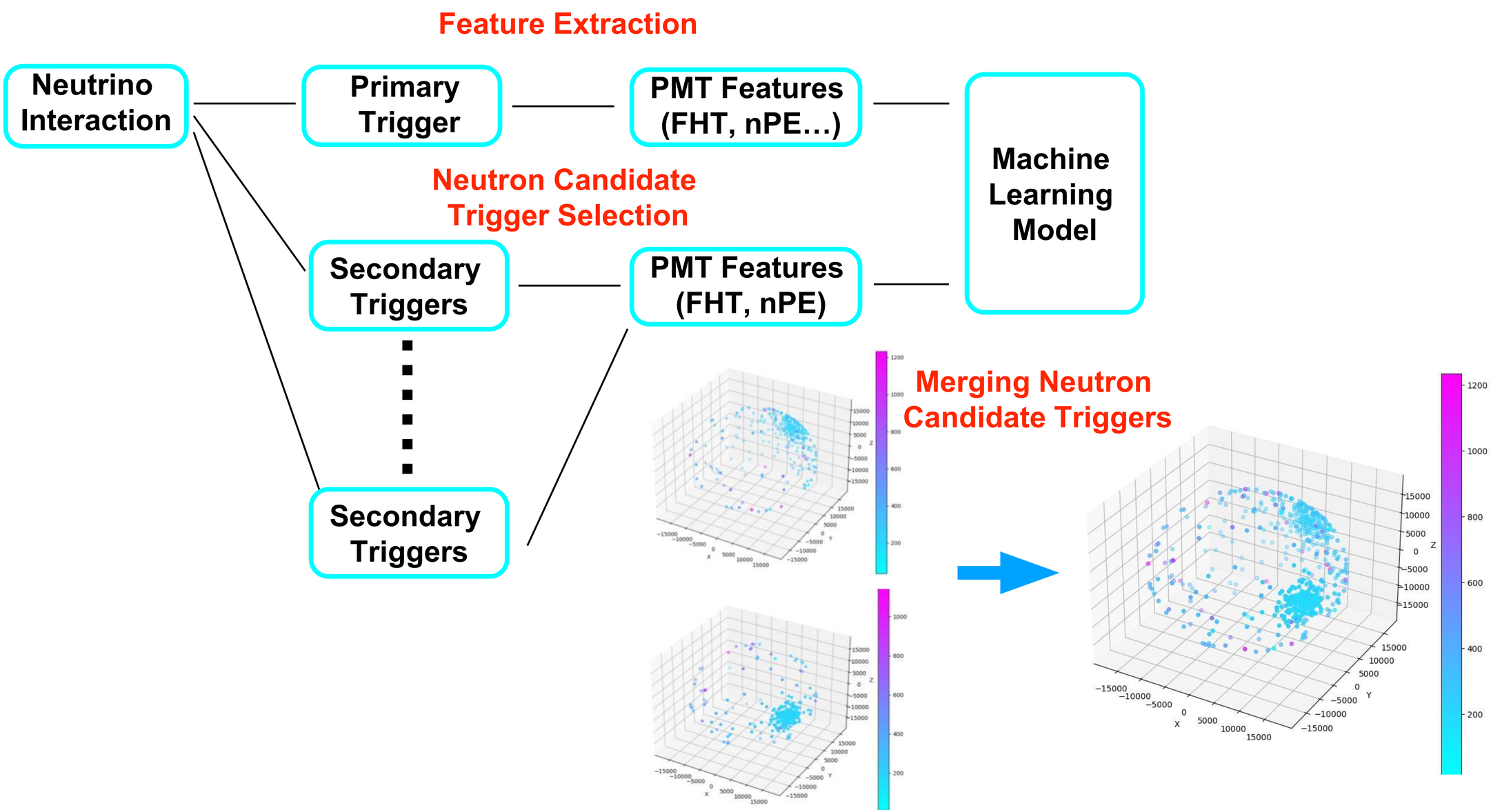
Neutron Candidate Trigger Selection

Secondary Triggers — PMT Features (FHT, nPE)

Secondary Triggers

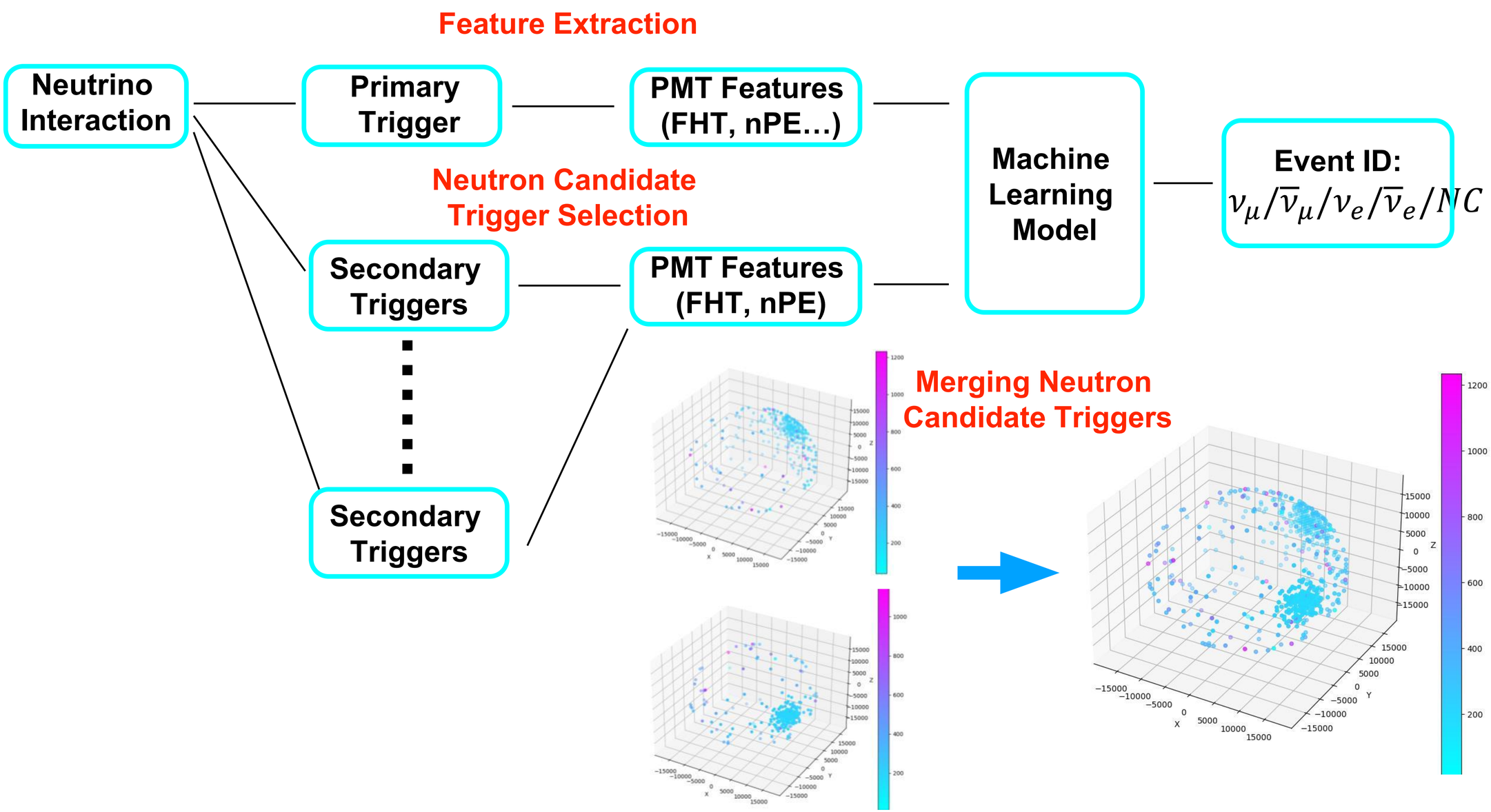


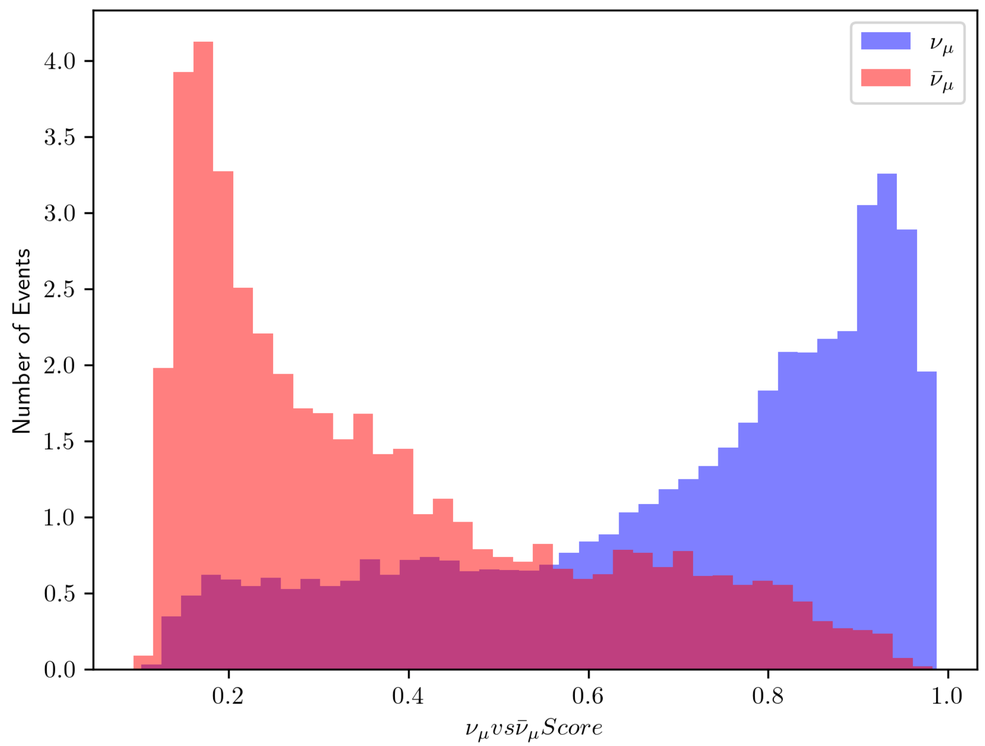
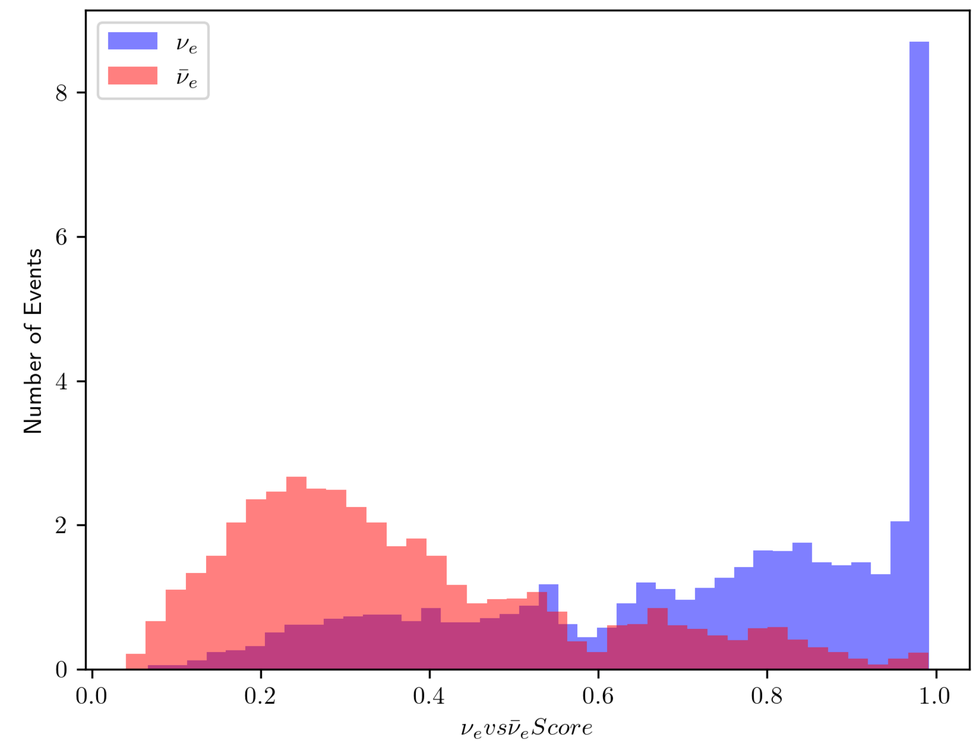
Flavor Identification Strategies



- **Strategy 2**: Directly input PMT features from multiple triggers into ML.

Flavor Identification Strategies



- **Strategy 2**: Directly input PMT features from multiple triggers into ML.

Neutrino vs Anti-neutrino