JUNO's Potential for GeV Events

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On behalf of the JUNO Collaboration

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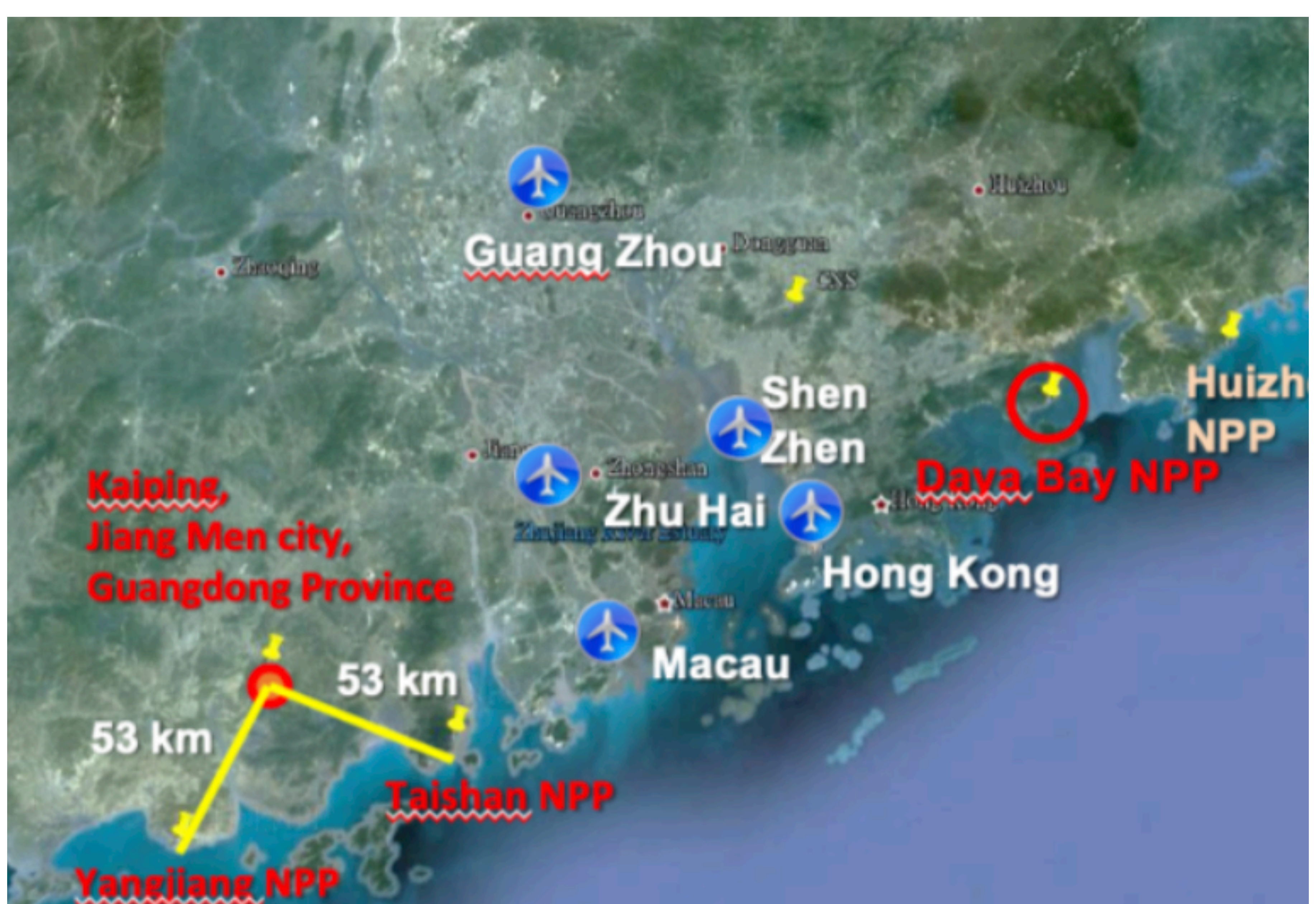
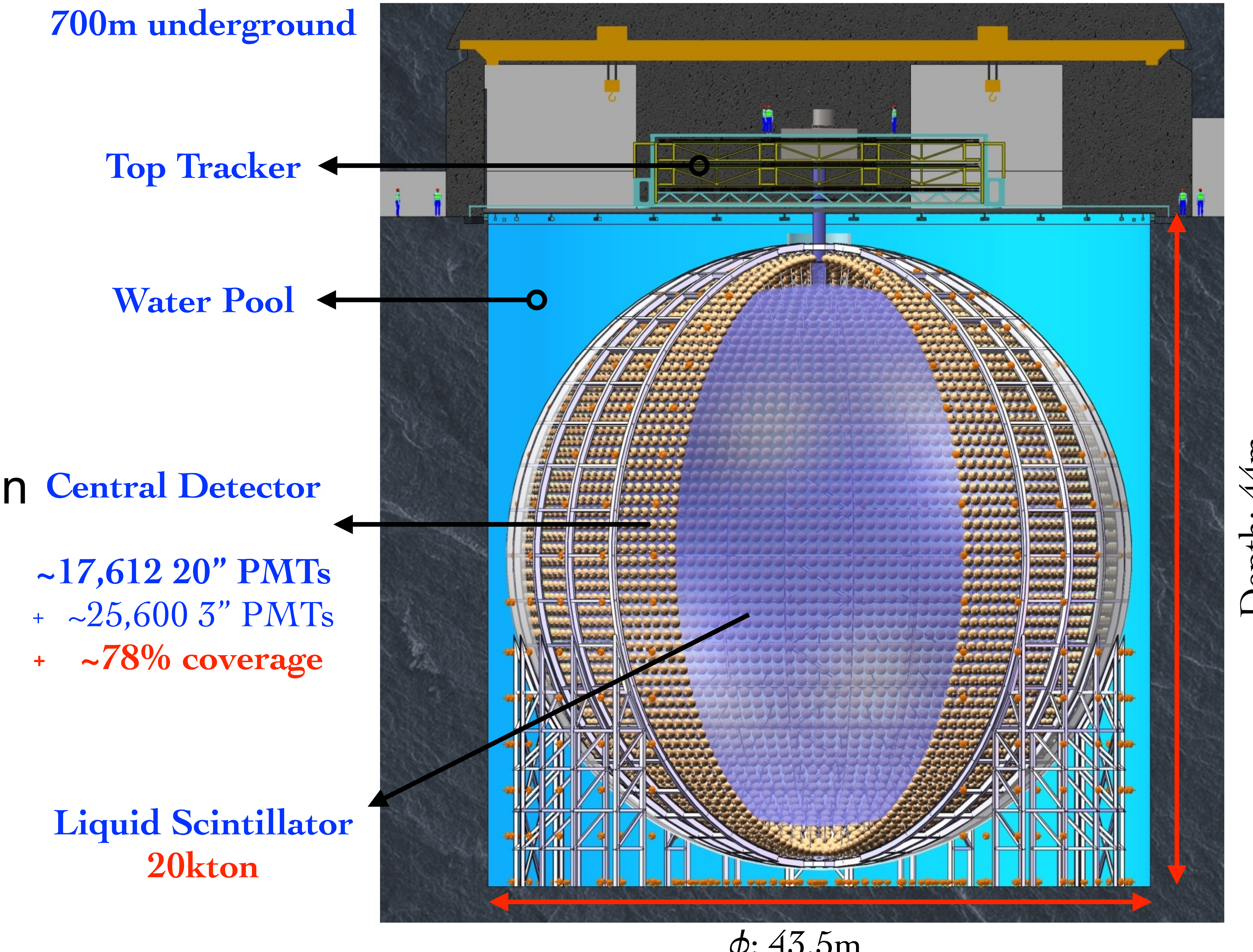
Introduction to JUNO

- Jiangmen Underground Neutrino Observatory (JUNO):
  - Determine the neutrino mass ordering（NMO） with reactor neutrinos.
  - Measure neutrino oscillation parameters to sub-percent level
  - Supernova, solar, geo., atm. ν, etc.
- Currently under construction. Physics run to start in 2024.

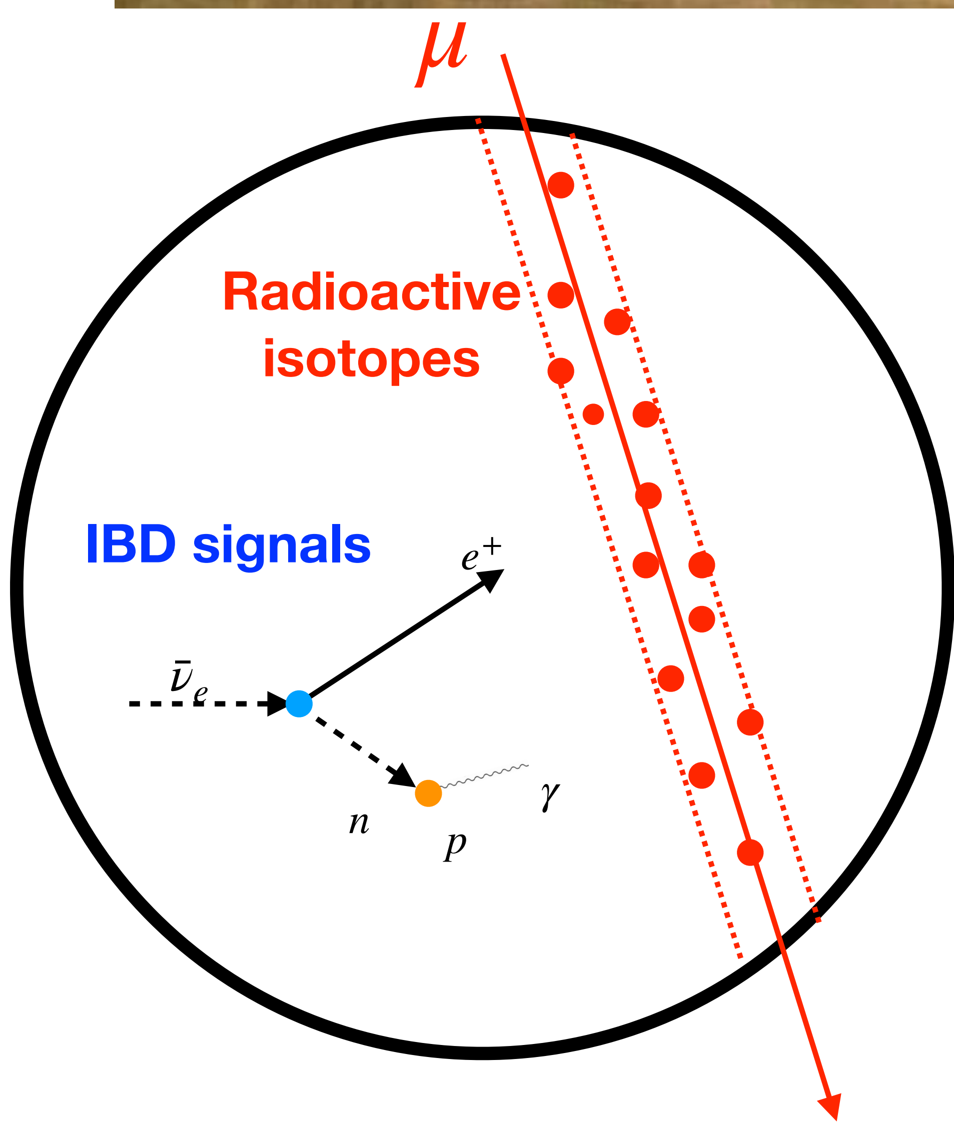


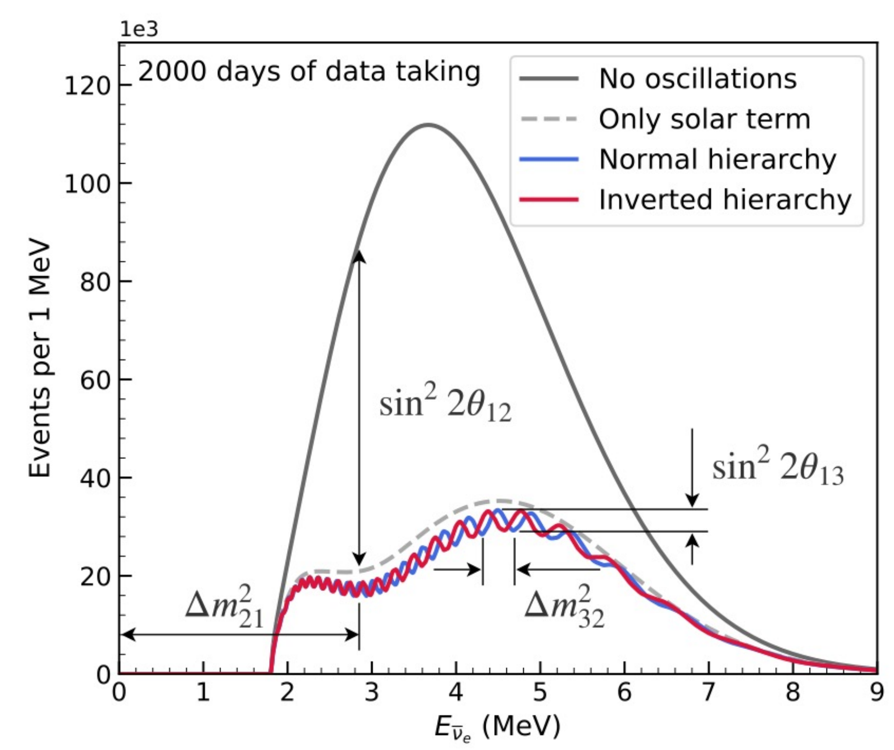


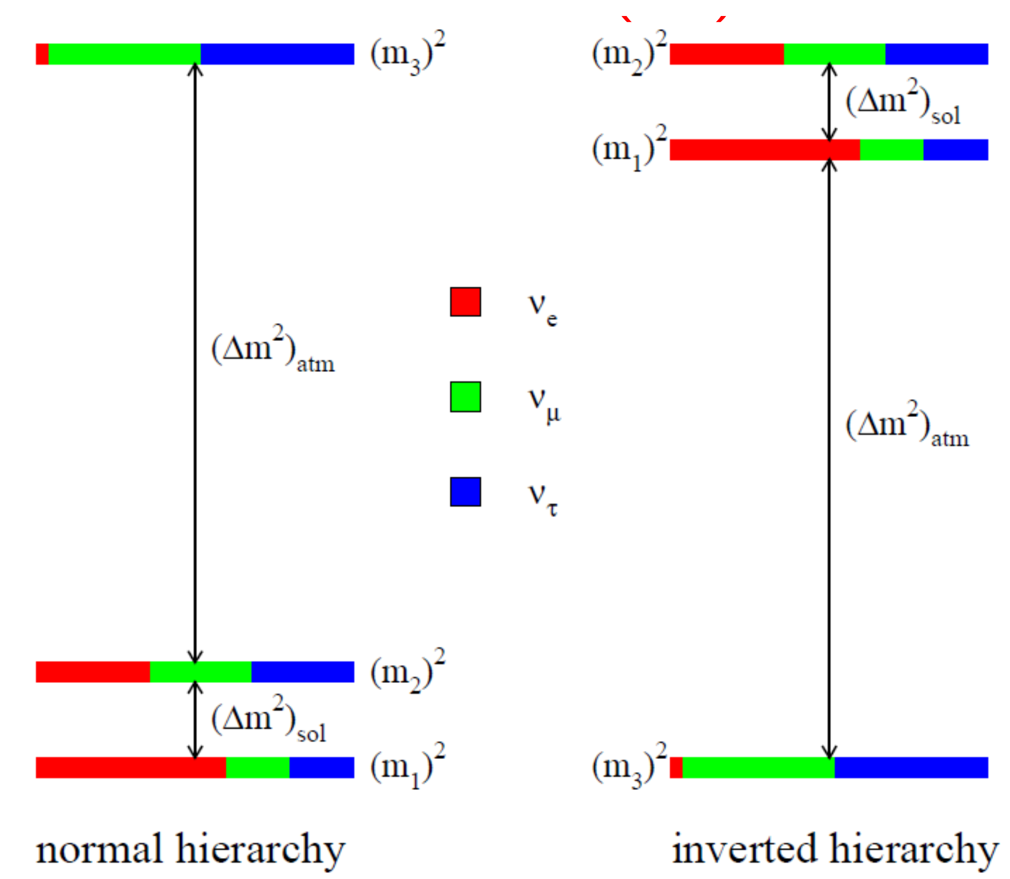
The largest liquid scintillator detector ever built.

Why Capability in GeV is Needed?

Reactor neutrinos:
Sensitivity to NMO via
oscillation in vacuum





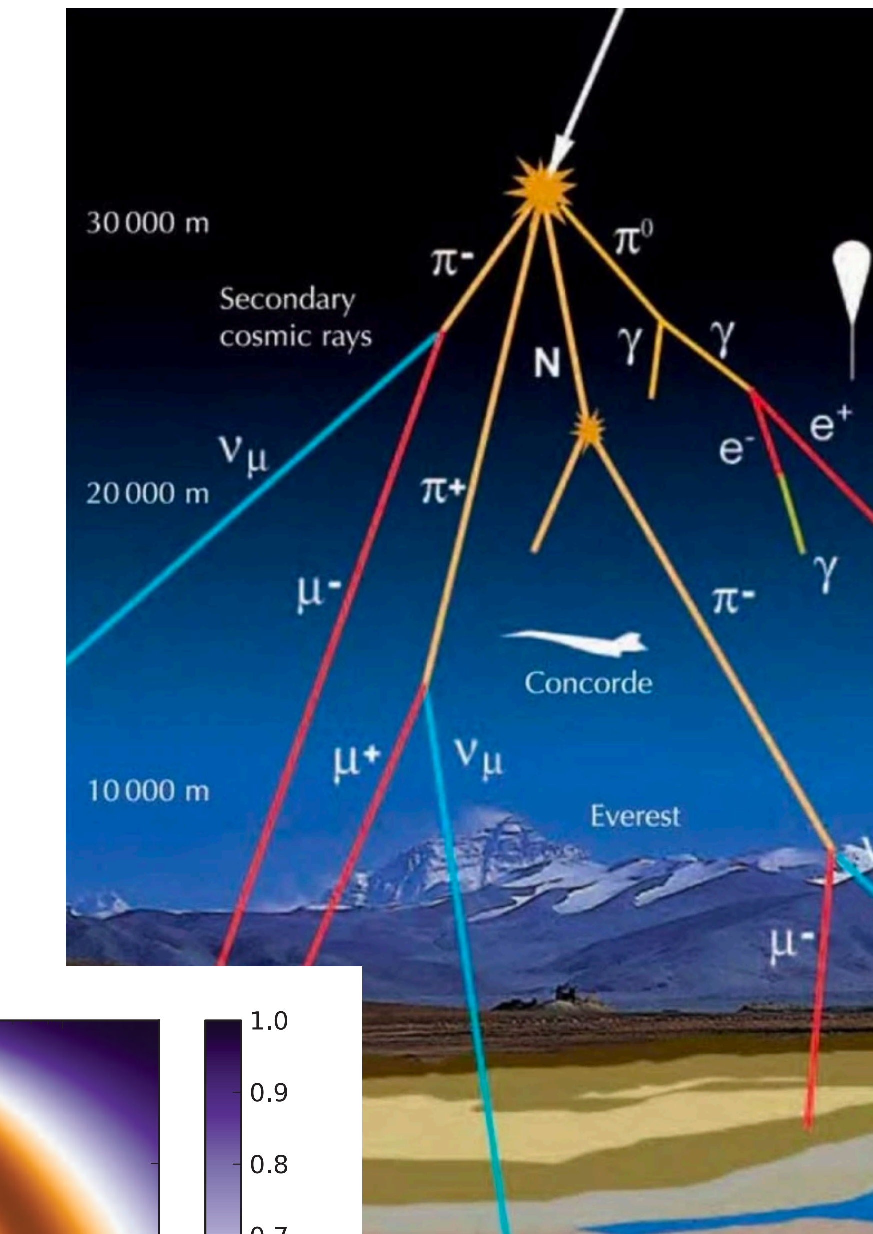


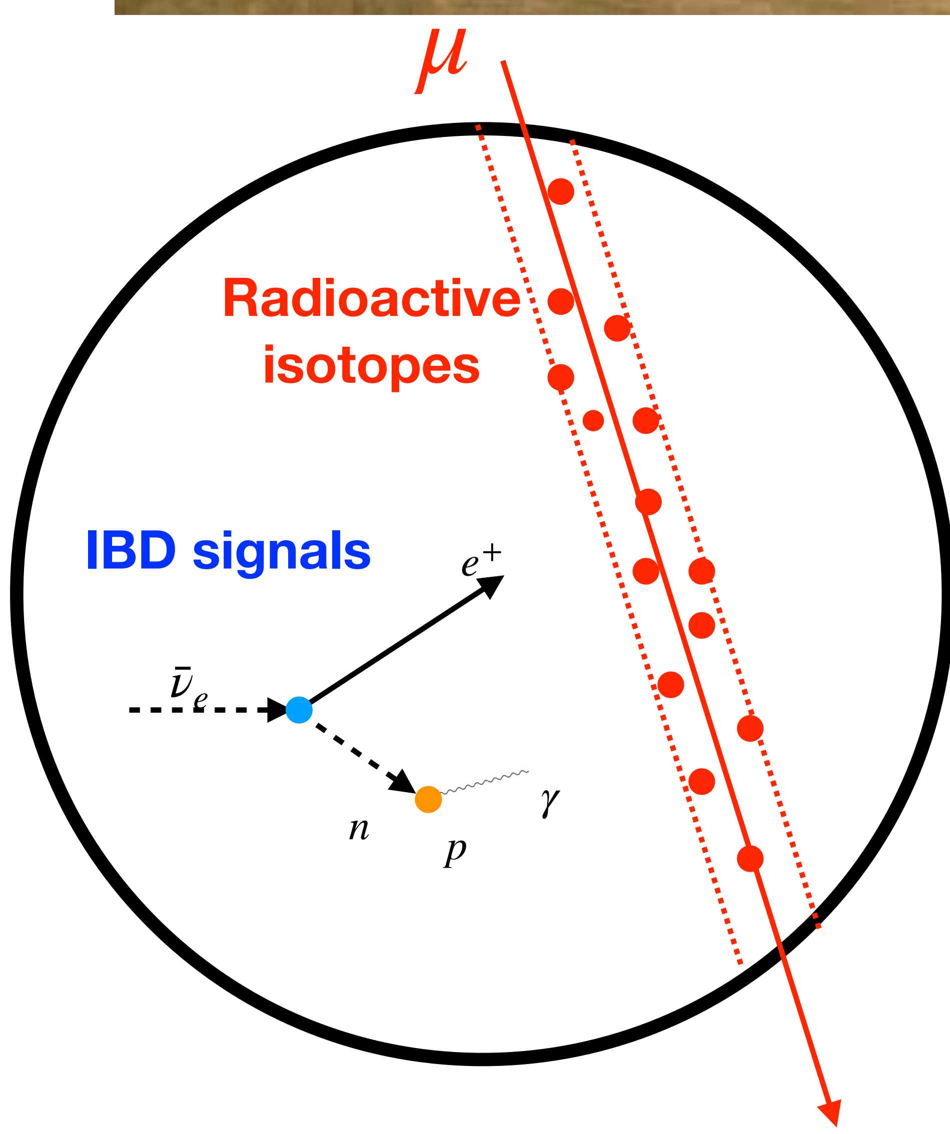
- **Cosmic muons** produce backgrounds to reactor neutrino IBD events.
  - Precise track and shower vertex reconstruction is needed to reduce these backgrounds.

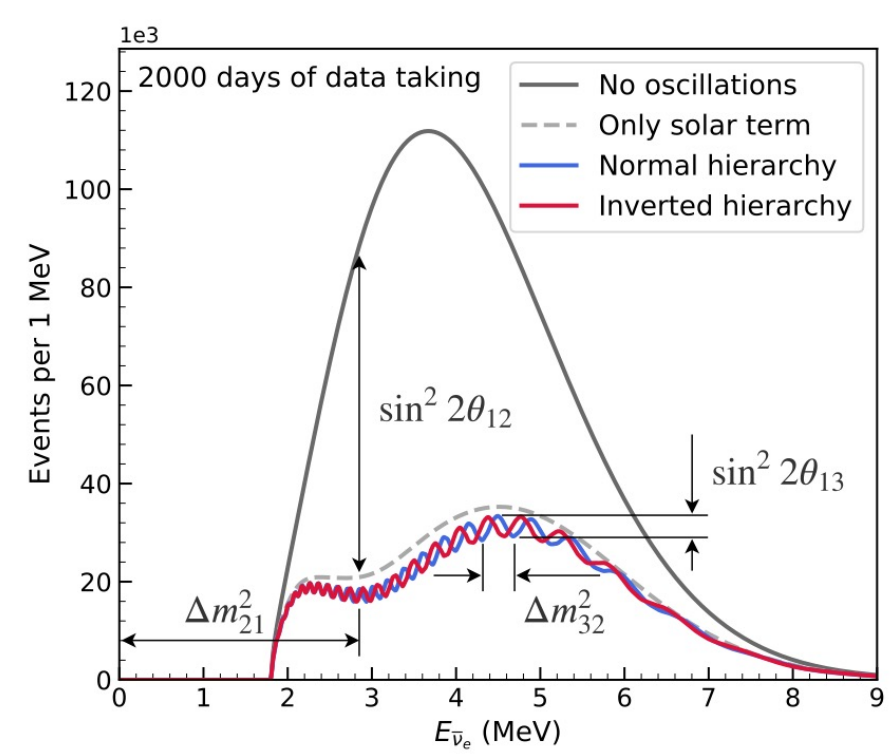
Why Capability in GeV is Needed?

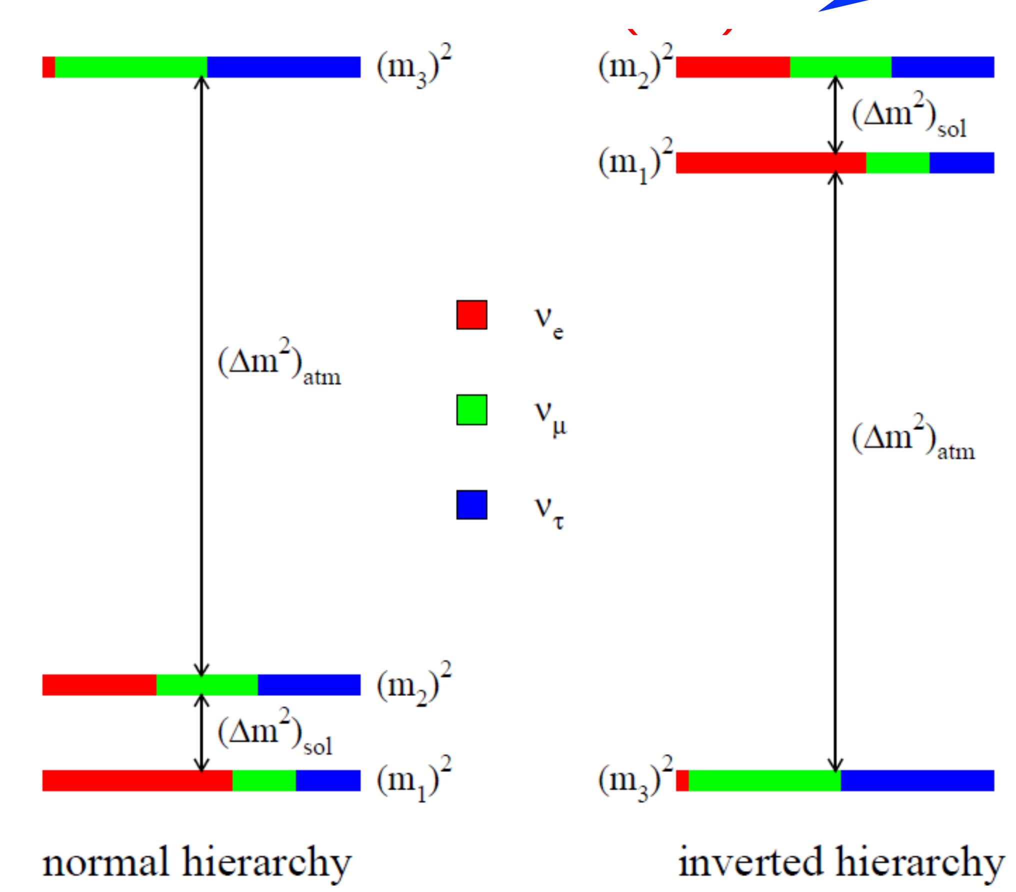
Reactor neutrinos: Sensitivity to NMO via oscillation in vacuum

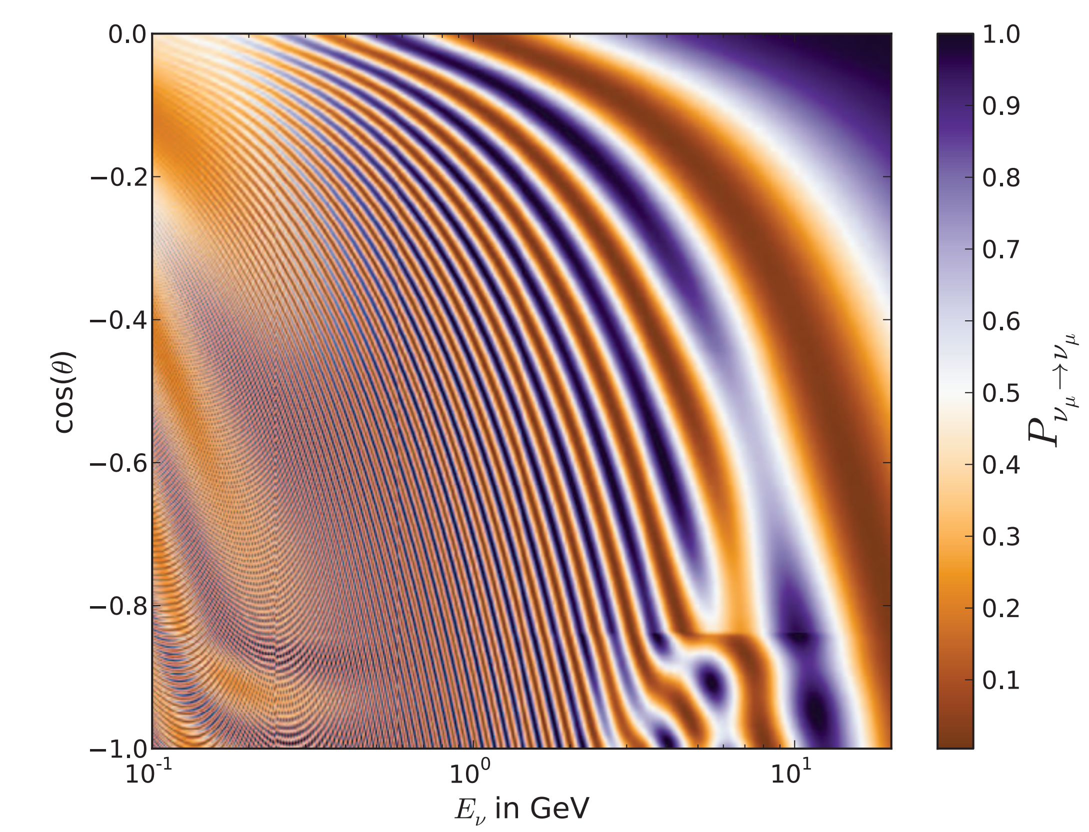
Atmospheric neutrinos: Sensitivity to NMO via matter effects







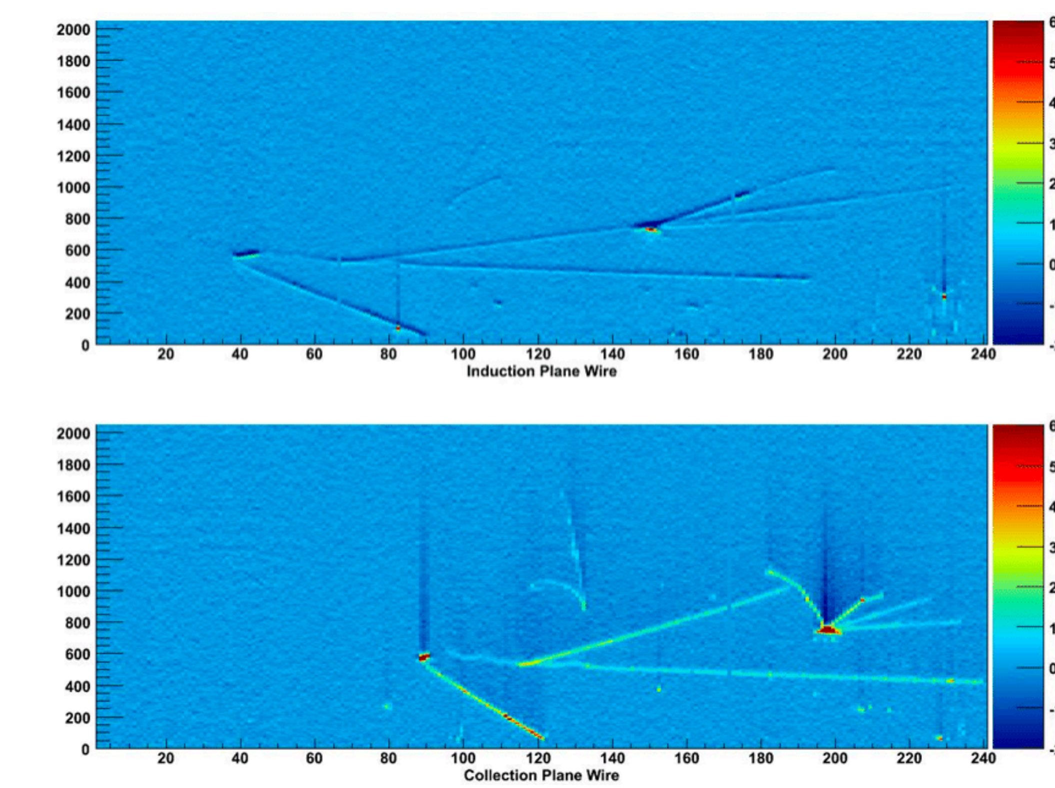


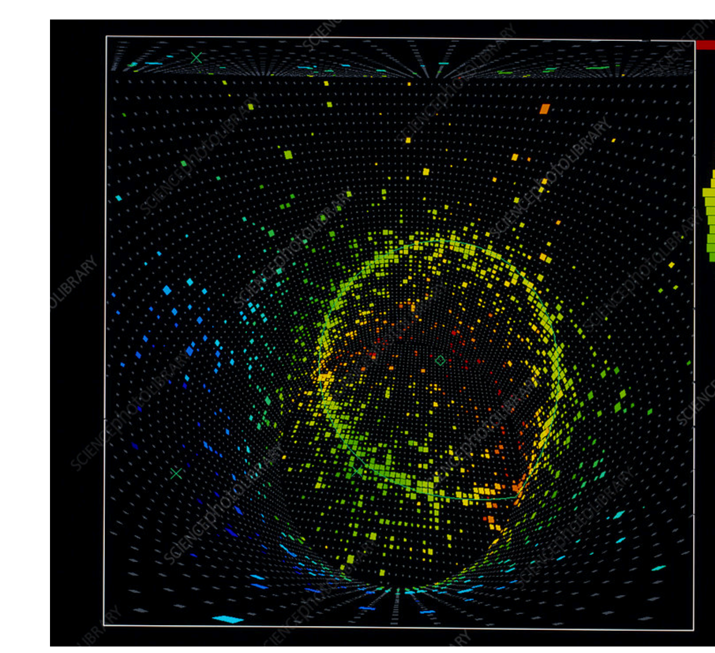


- **Cosmic muons** produce backgrounds to reactor neutrino IBD events.
  - Precise track and shower vertex reconstruction is needed to reduce these backgrounds.
- **Atmospheric neutrinos** provide independent sensitivity to NMO via matter effects (directionality and flavor identification are mandatory).
- Other physics topics like **indirect dark matter search**.

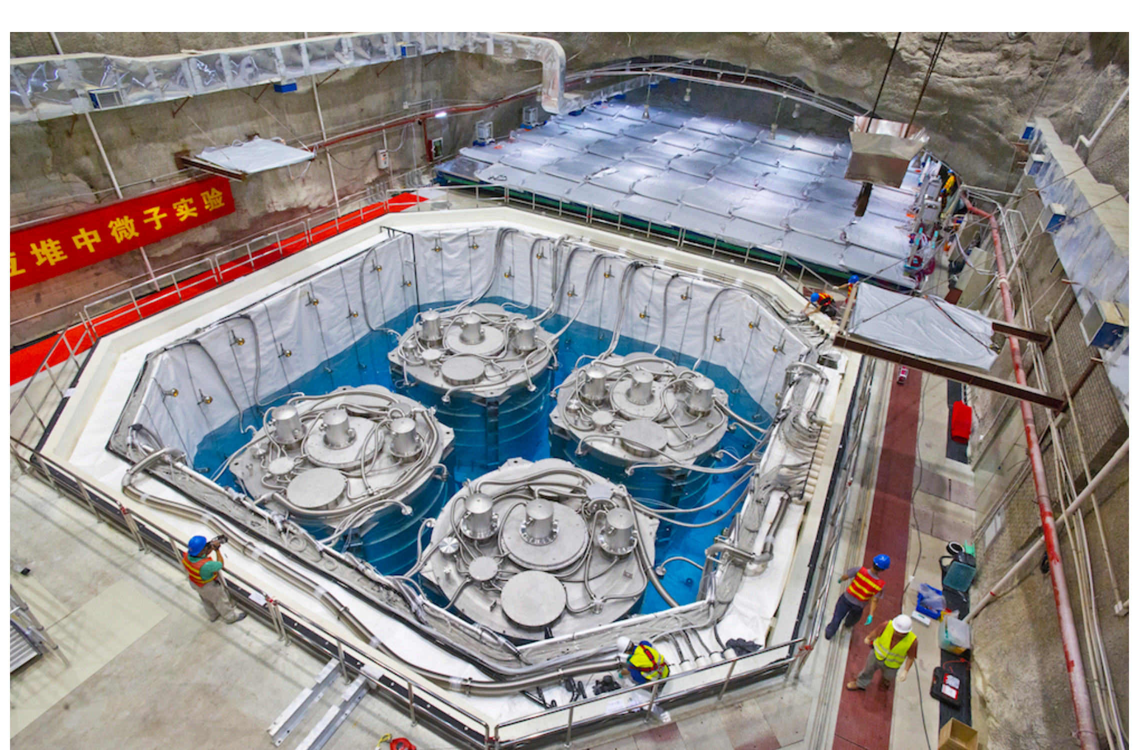
A Liquid Scintillator Detector for GeV Events?

- LS detectors are traditionally good for low-energy topics: reactor/solar neutrinos etc.
  - Low threshold, high energy-resolution.
- But
  - No direct tracking information.
  - Scintillation light is isotropic, Cherenkov light is only a few percent: no direct directional information.

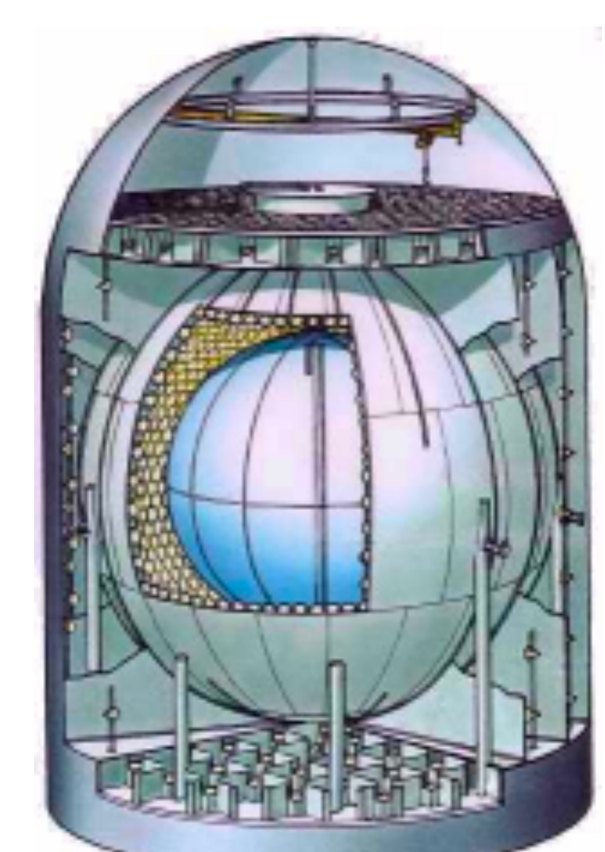




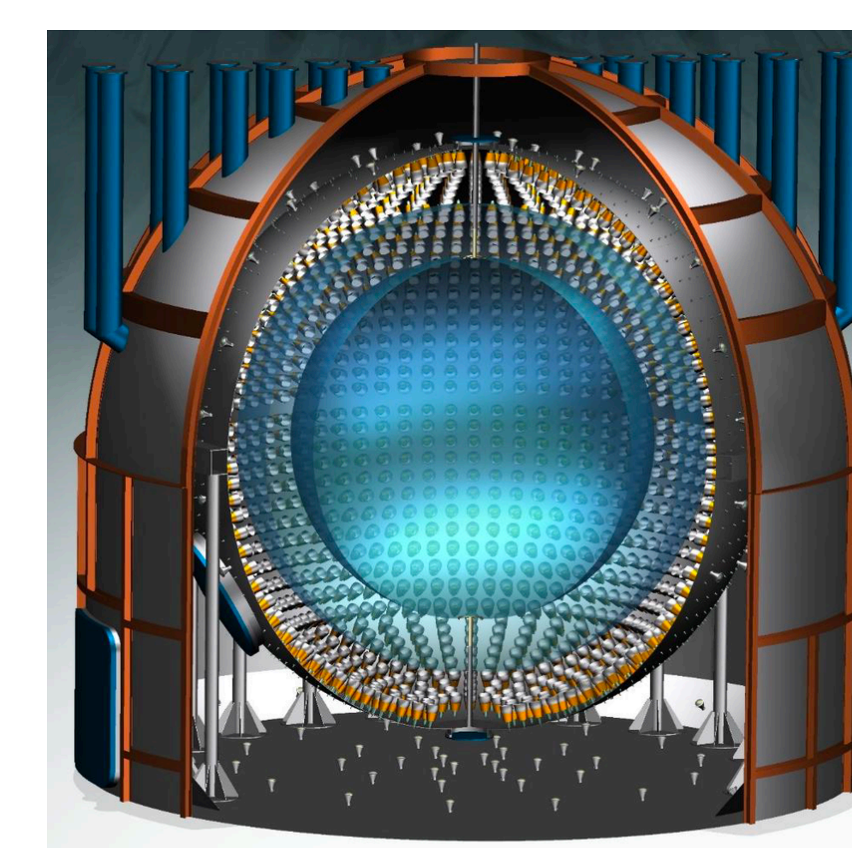
Typical LS detectors are designed with low-threshold, good energy resolution, ideal for low-energy physics.



Daya Bay

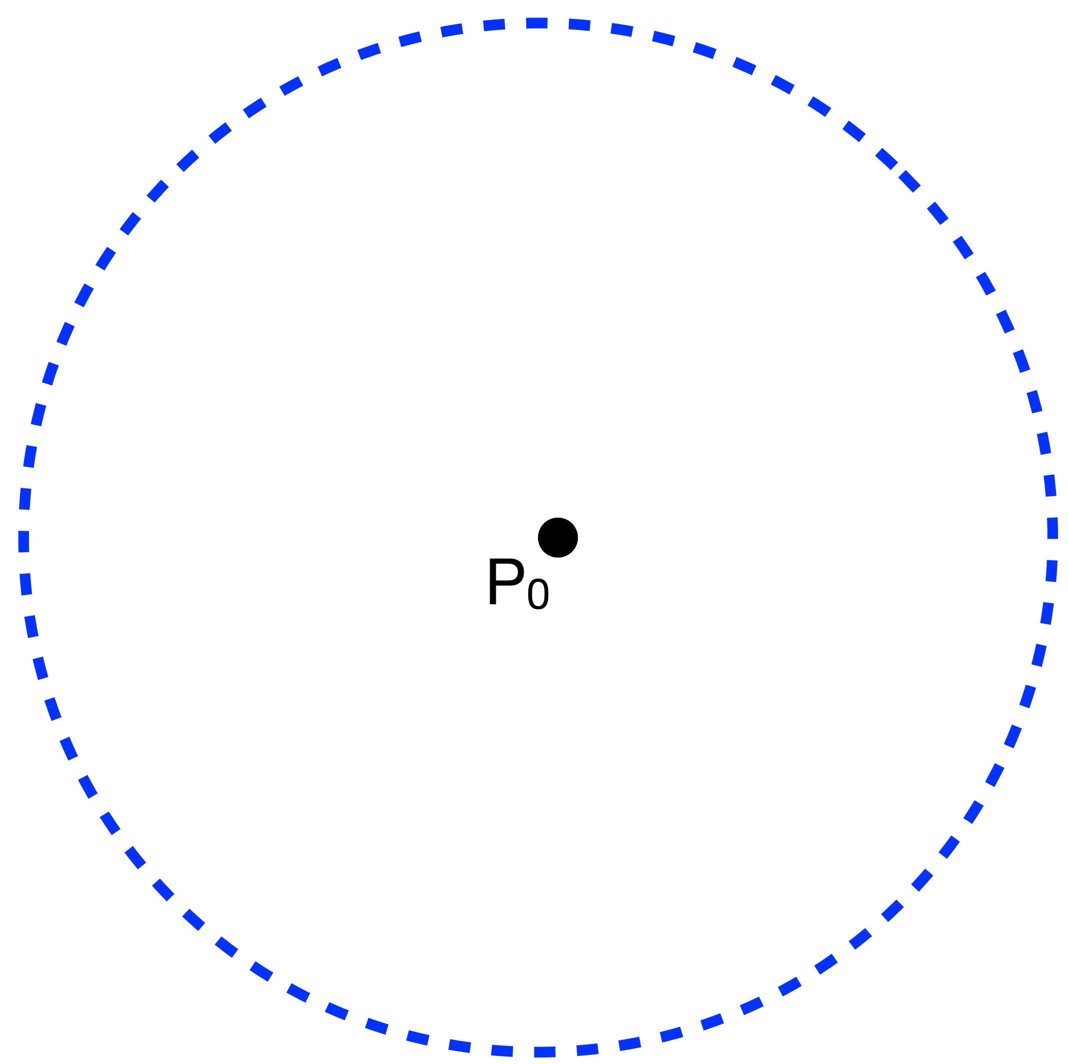


Kamland



Borexino

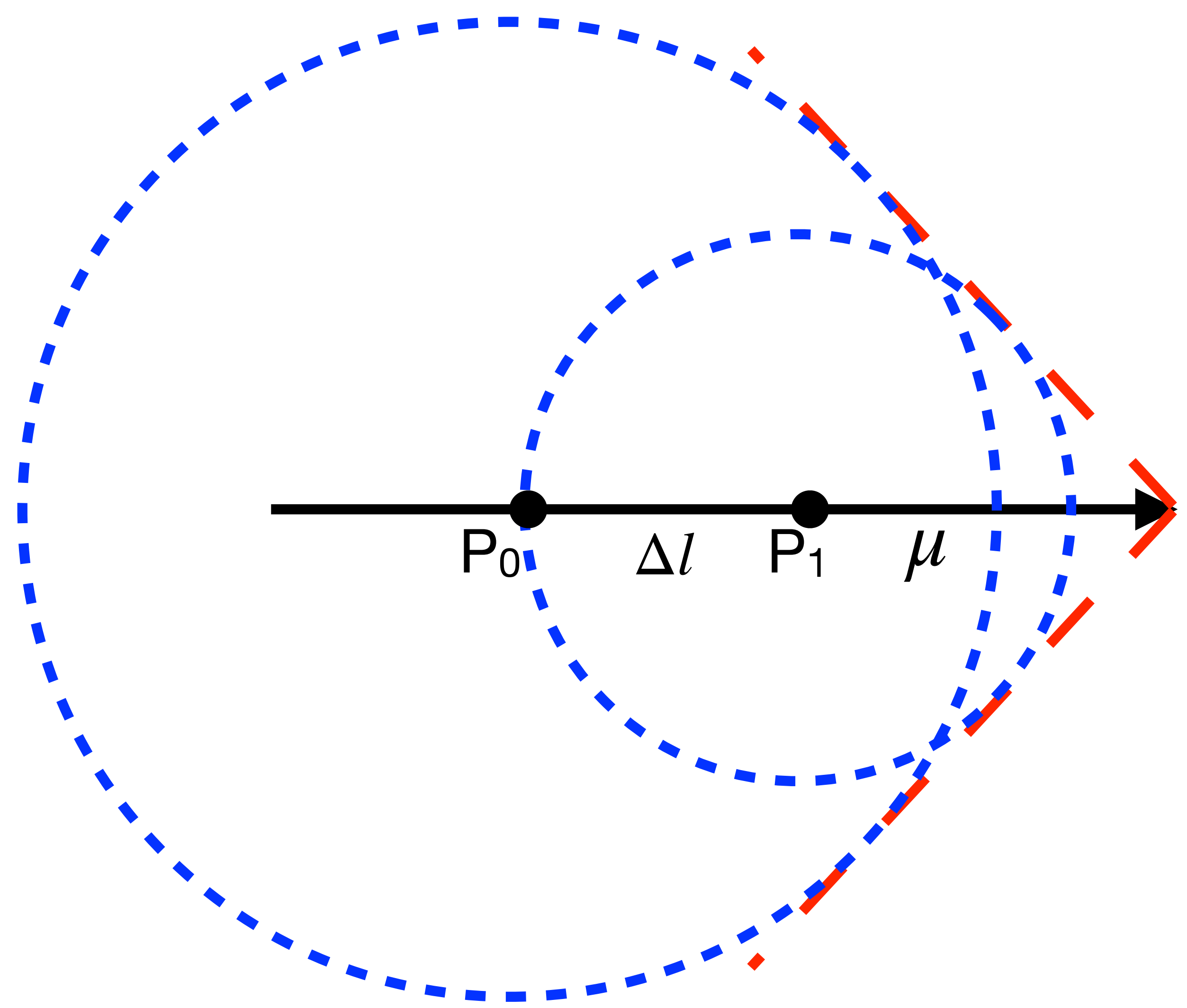
Solution: Event Topology in PMT Waveforms



Scintillation light from a point source is isotropic

- 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



Scintillation light photon distribution from a charged particle track in space and time is not isotropic

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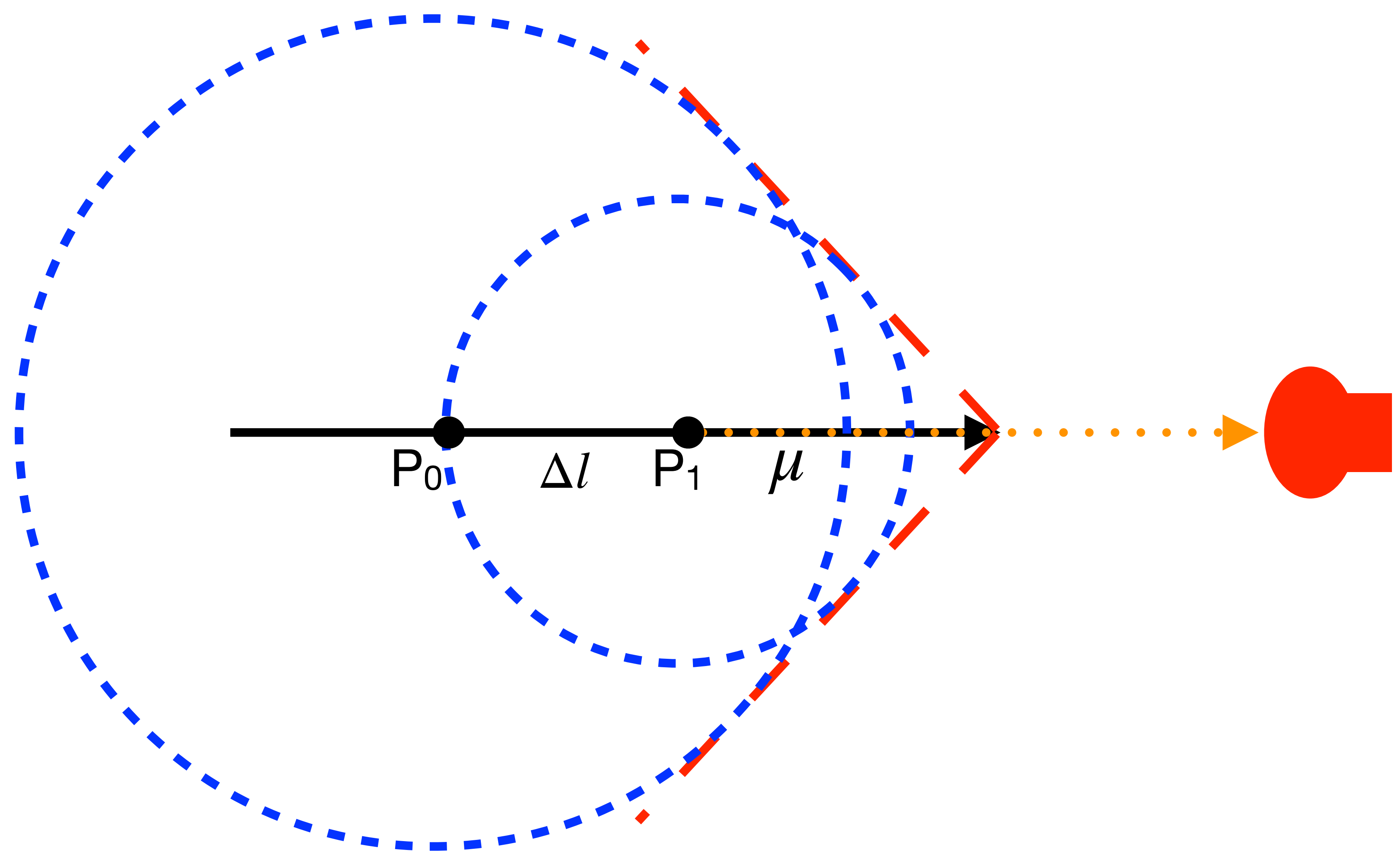

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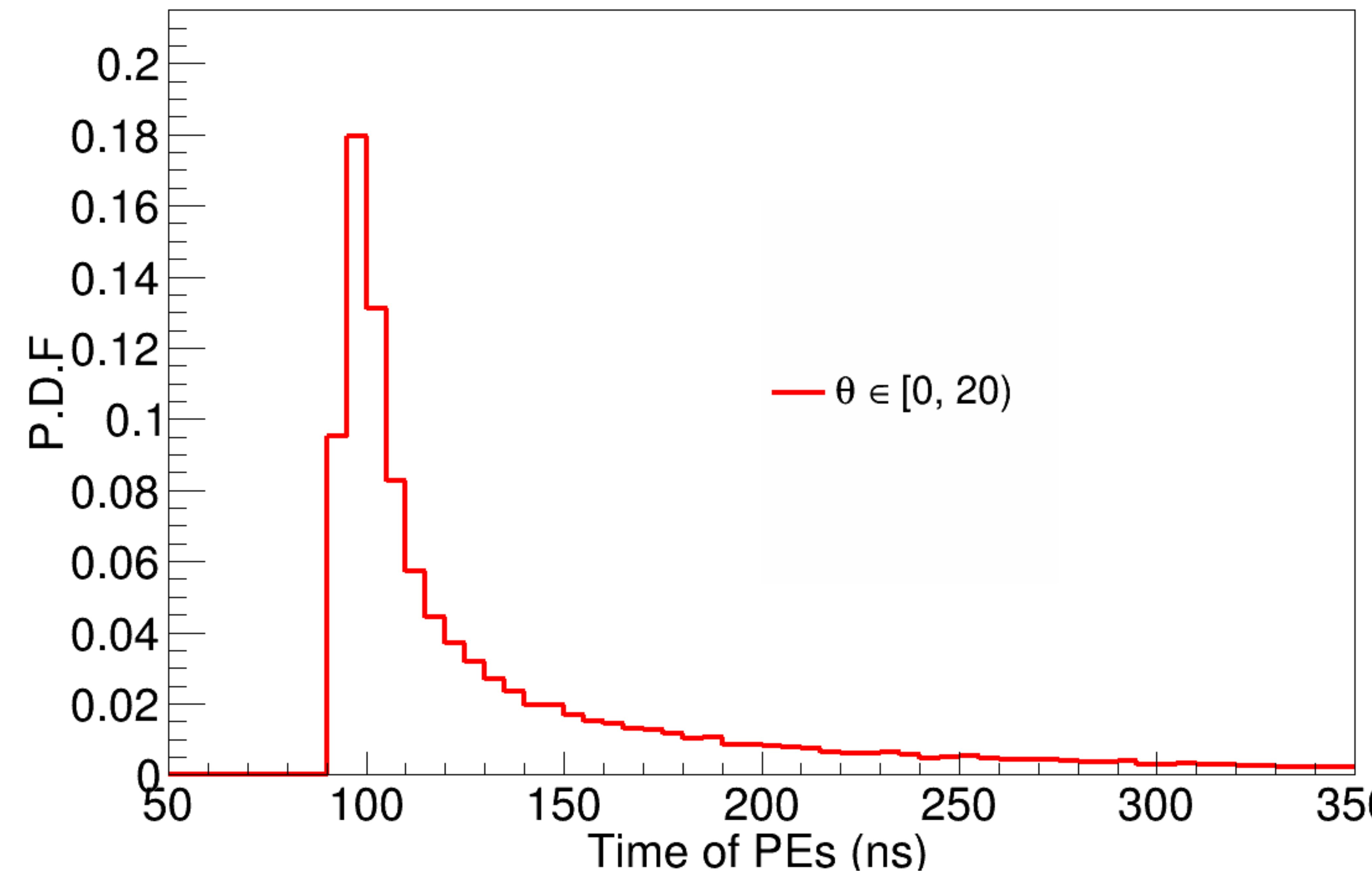

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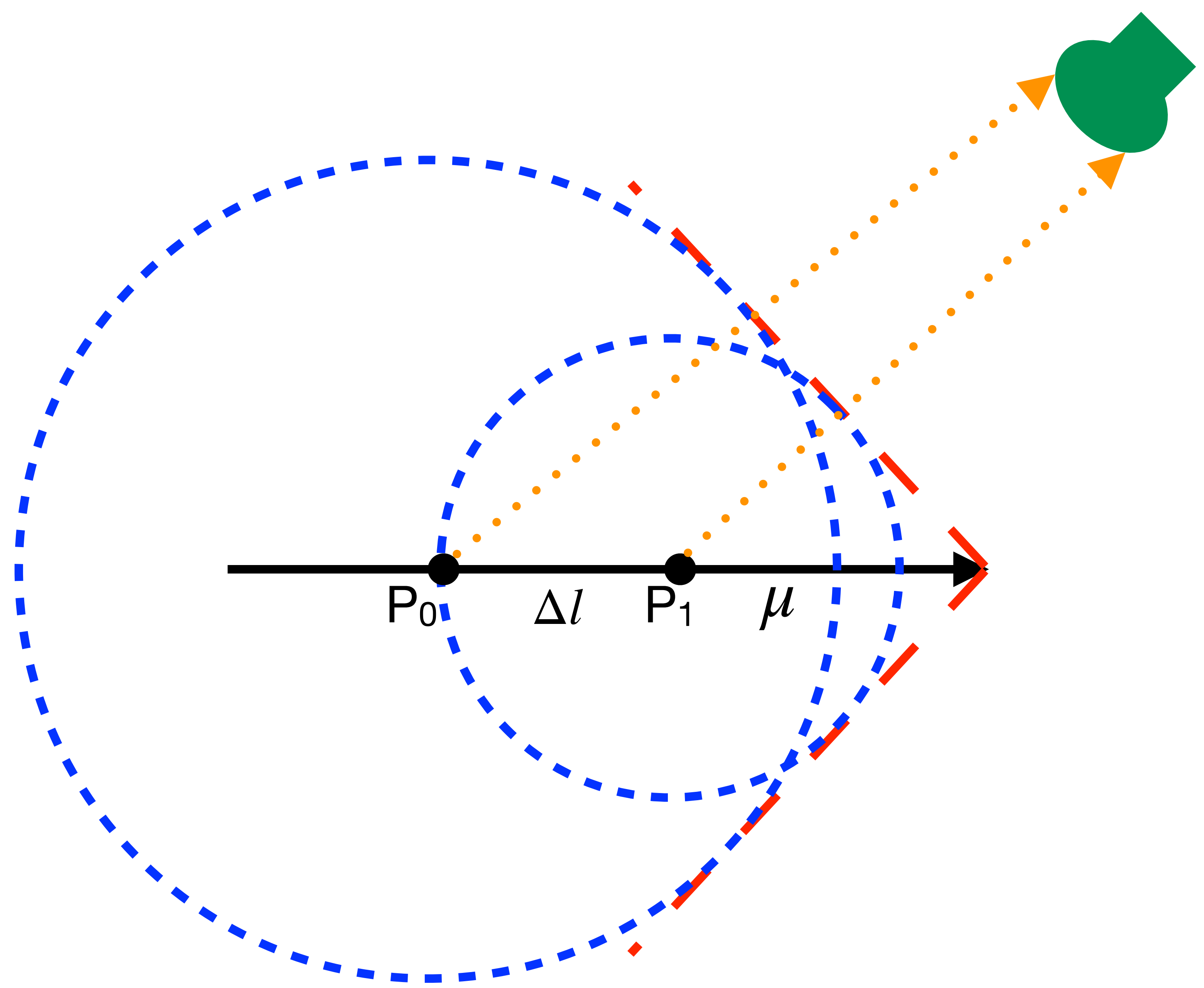

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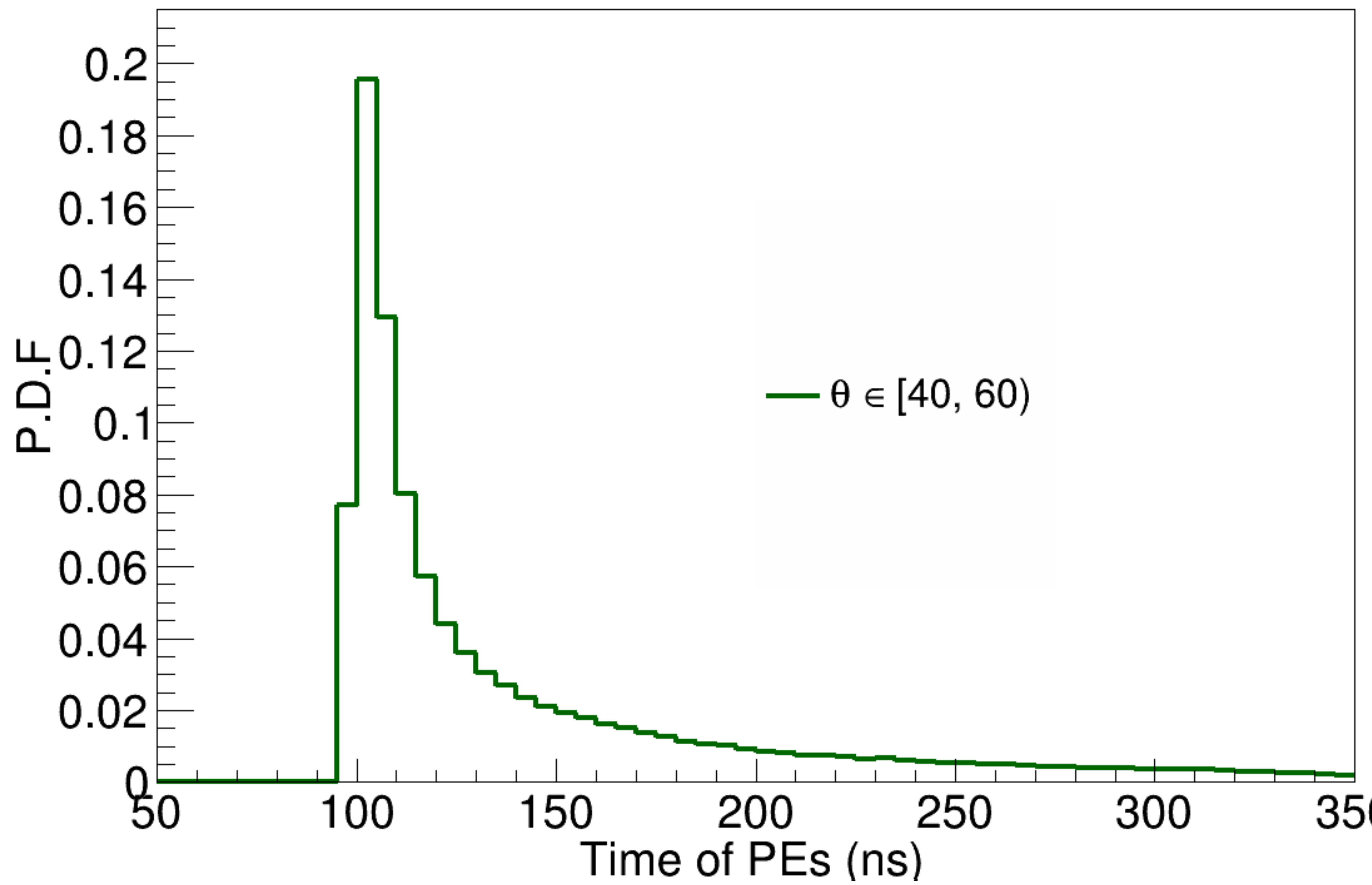

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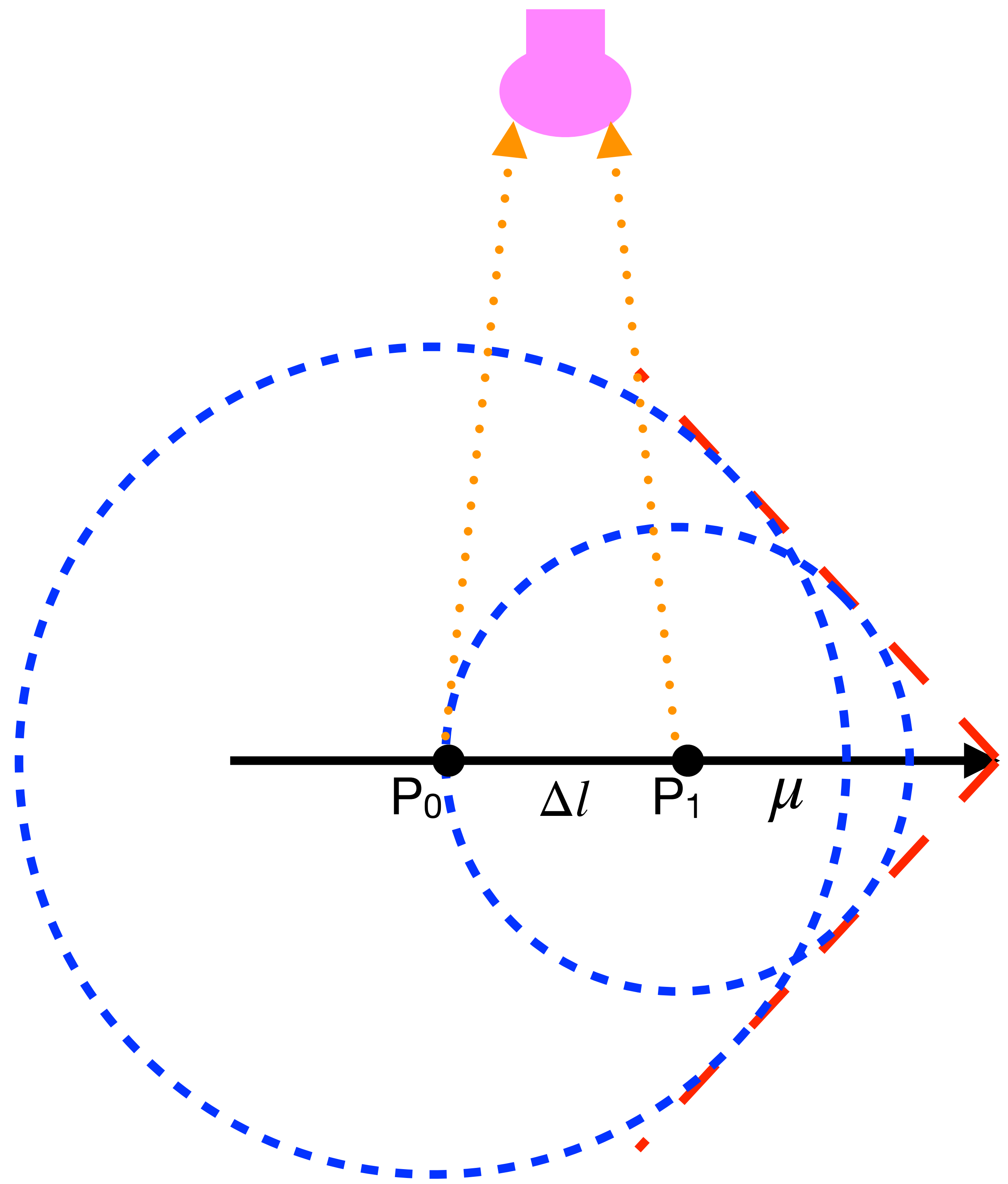

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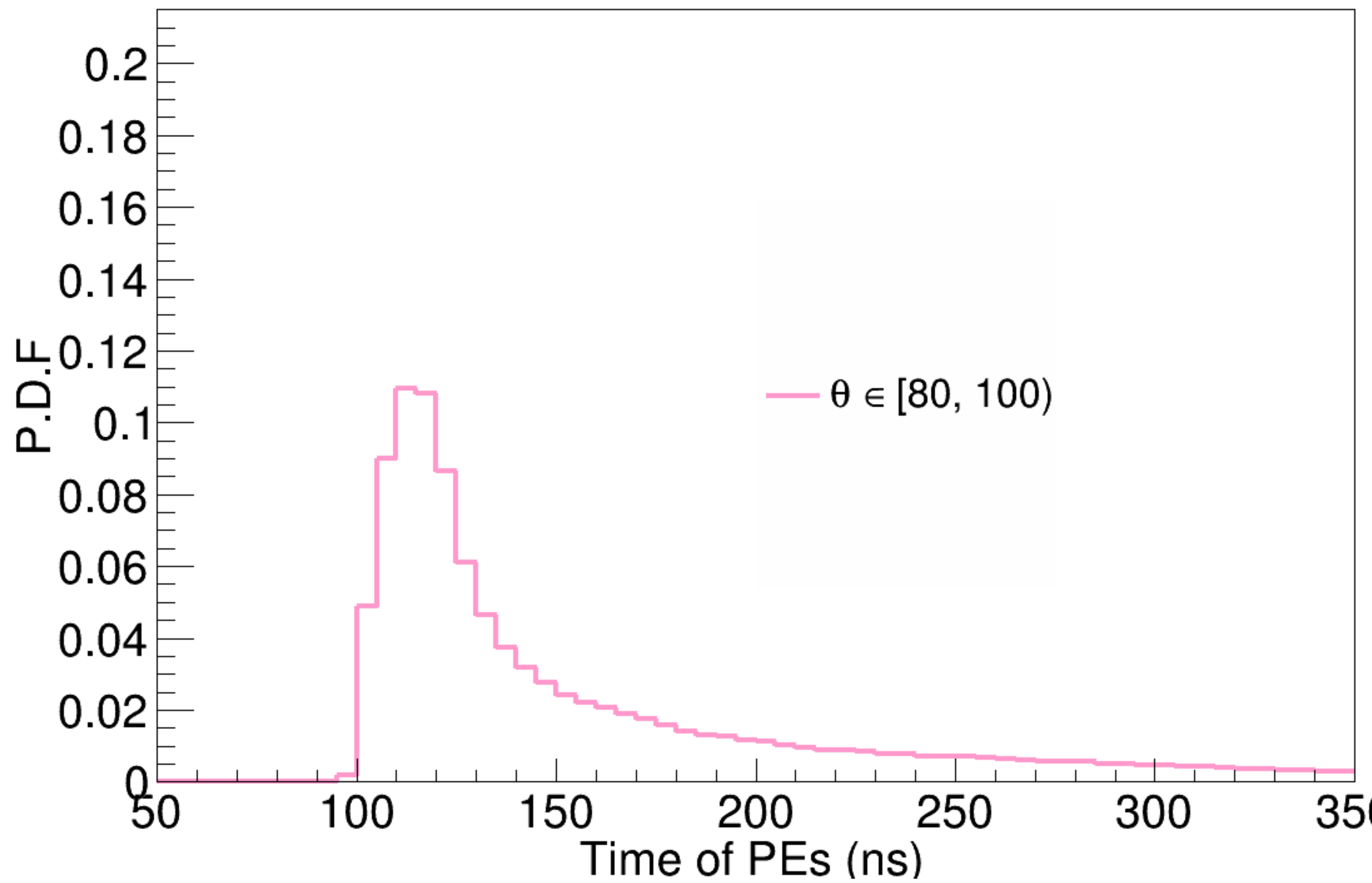

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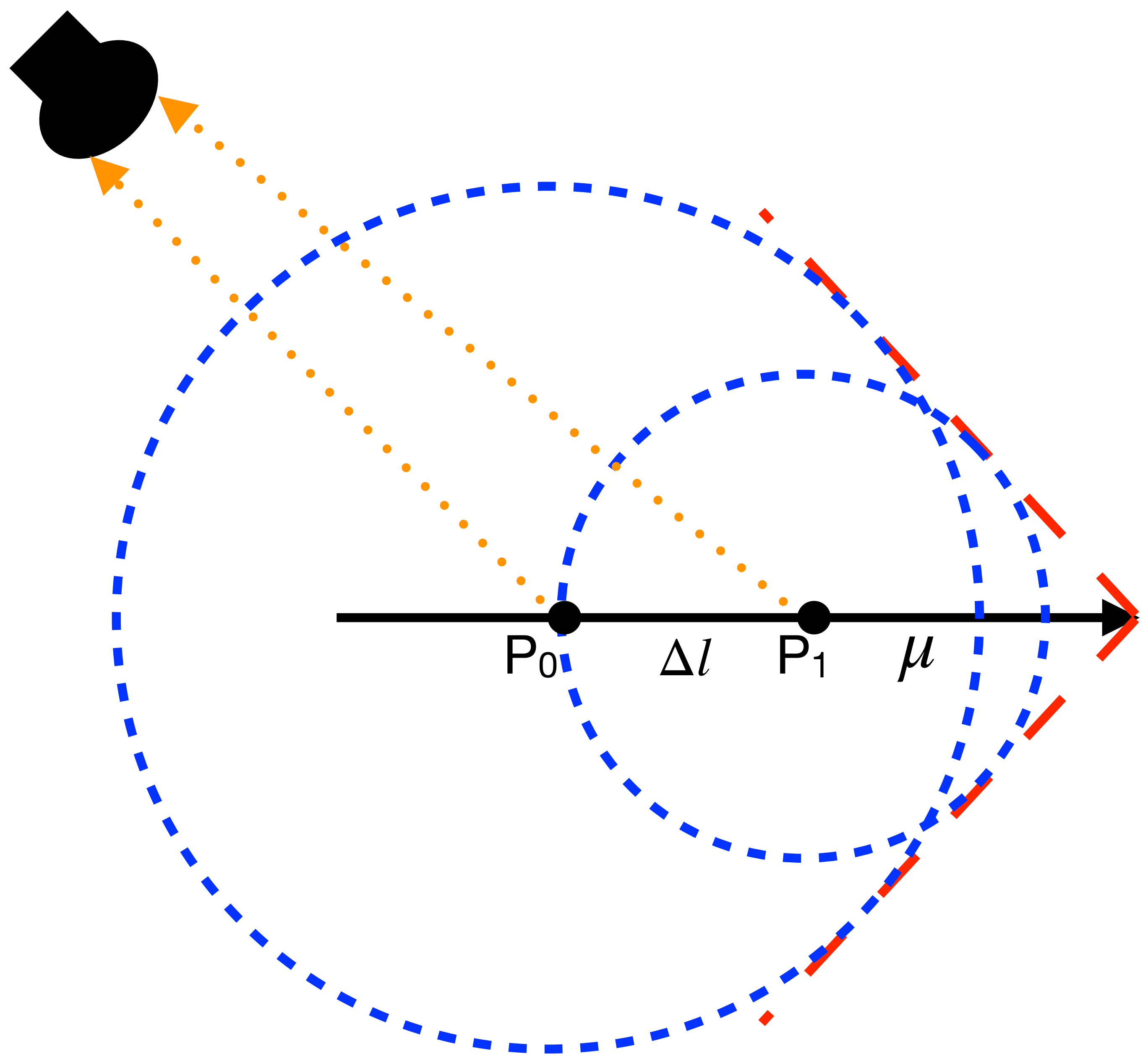

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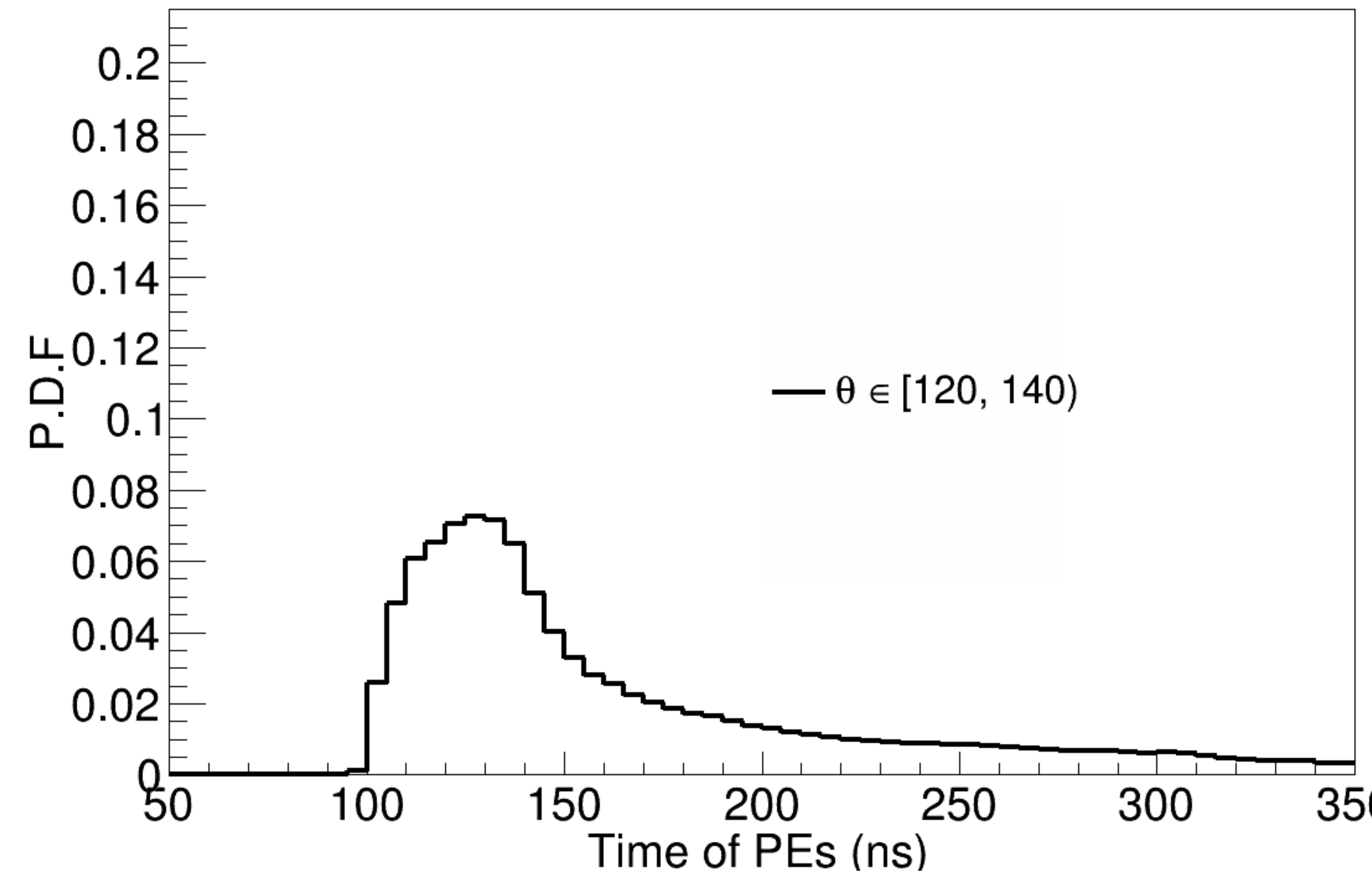

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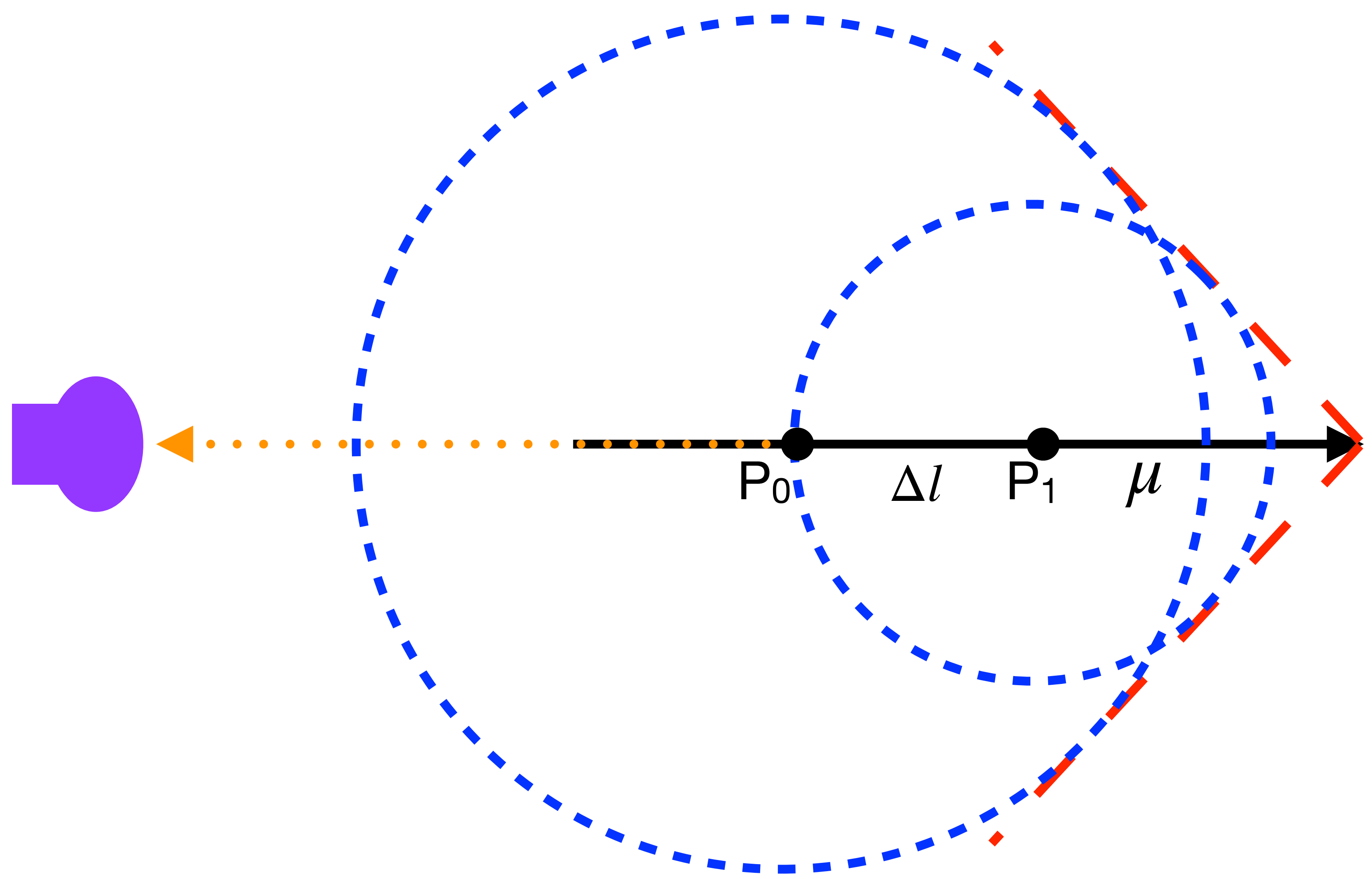

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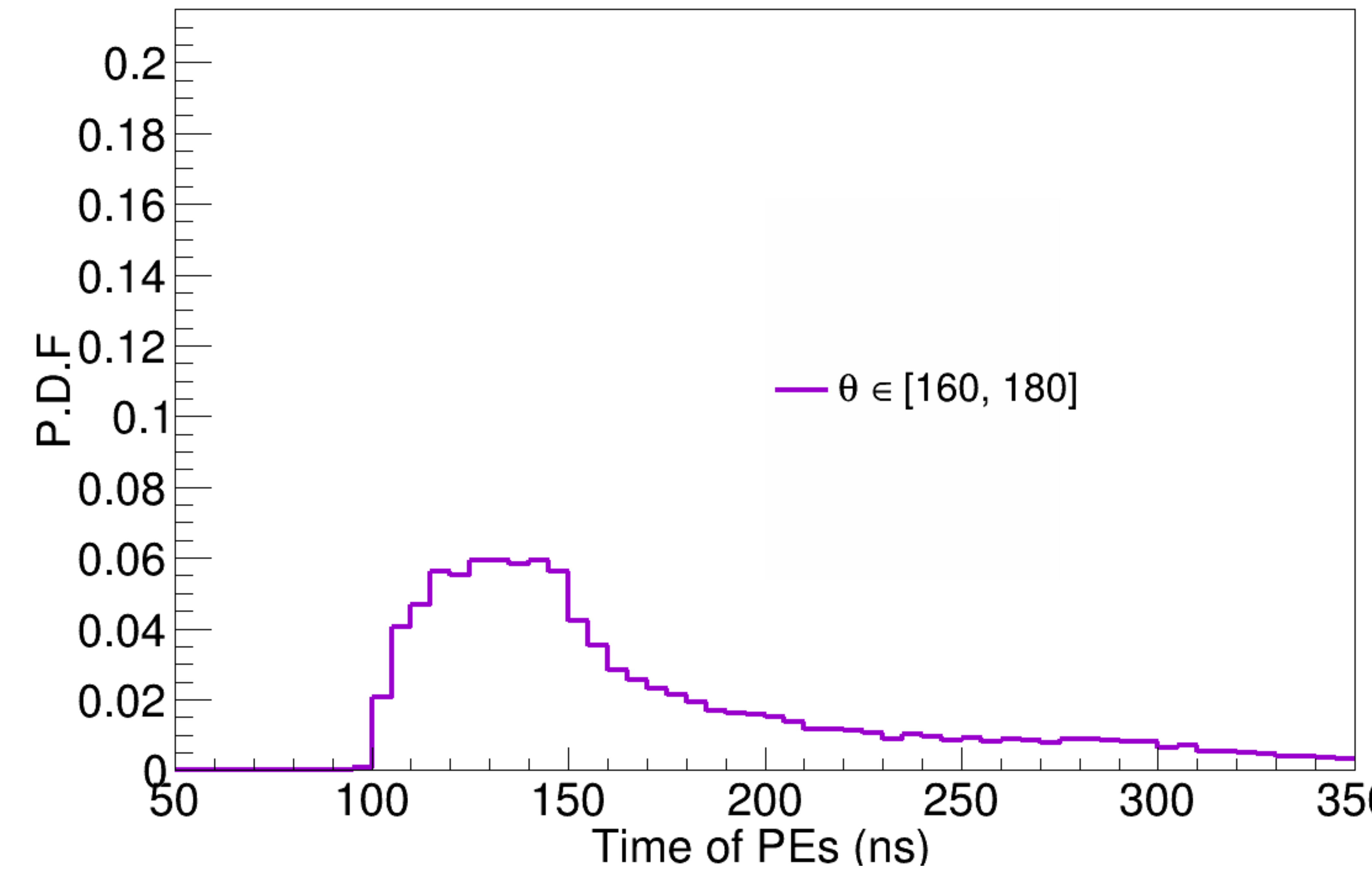

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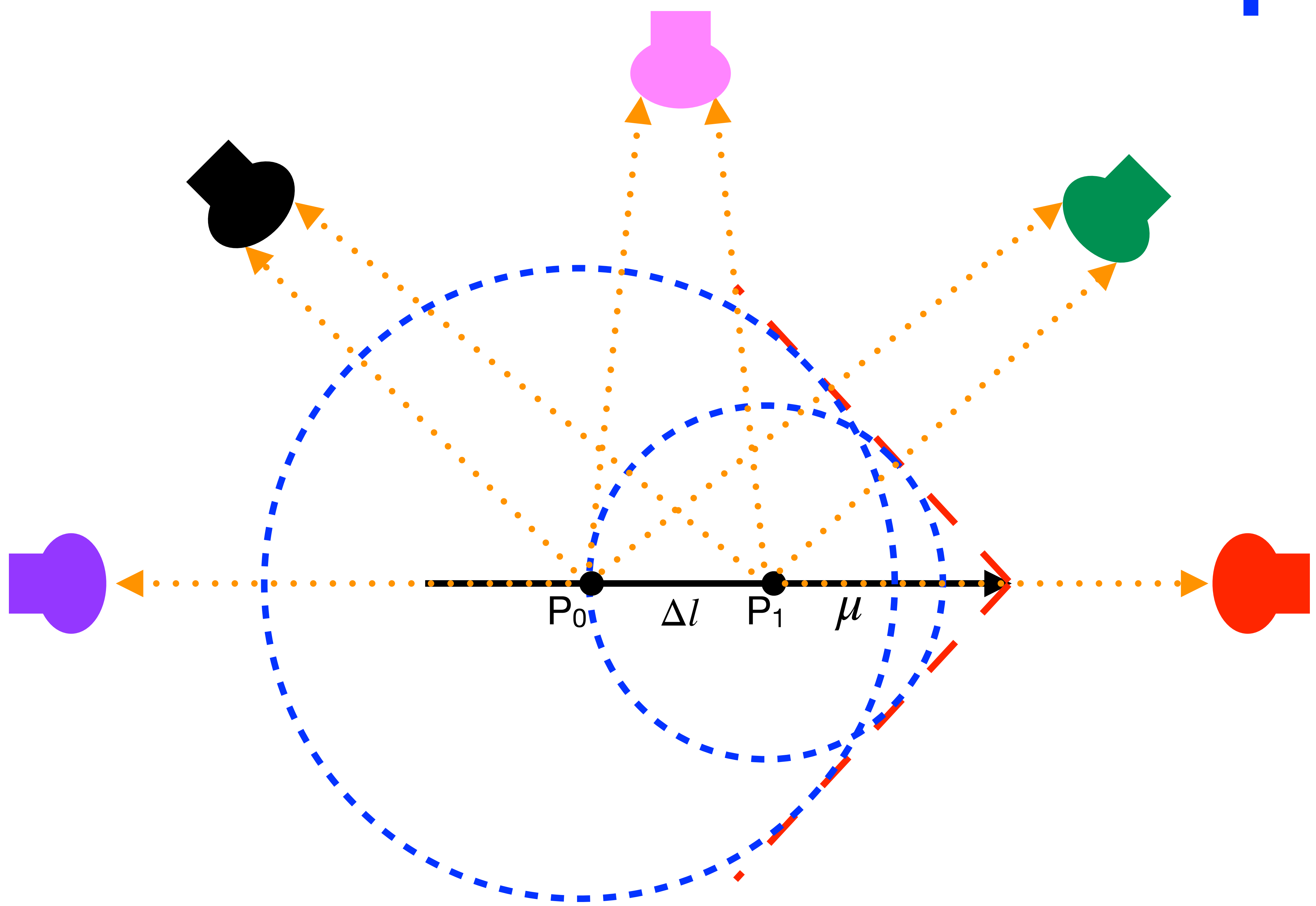

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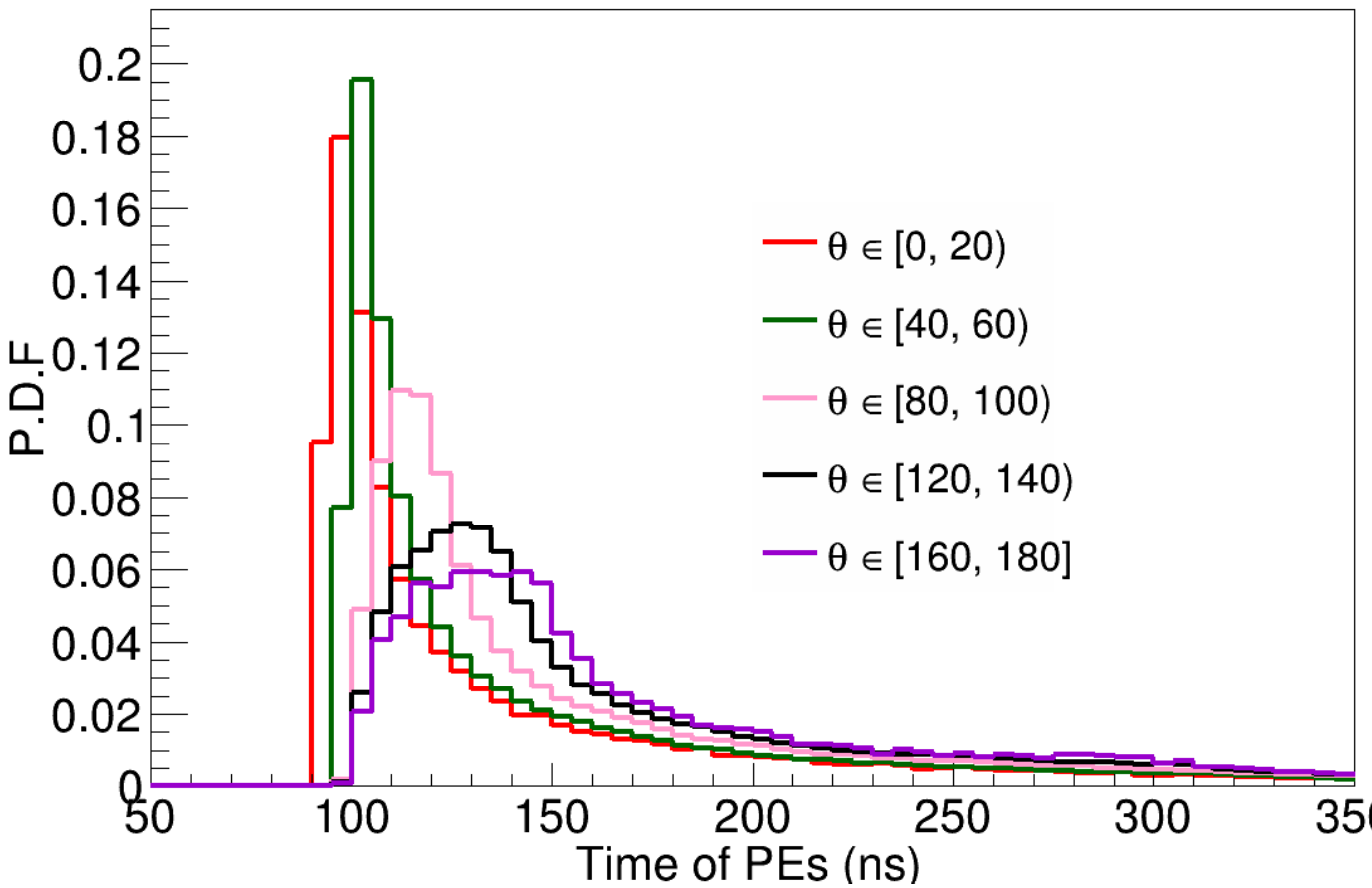

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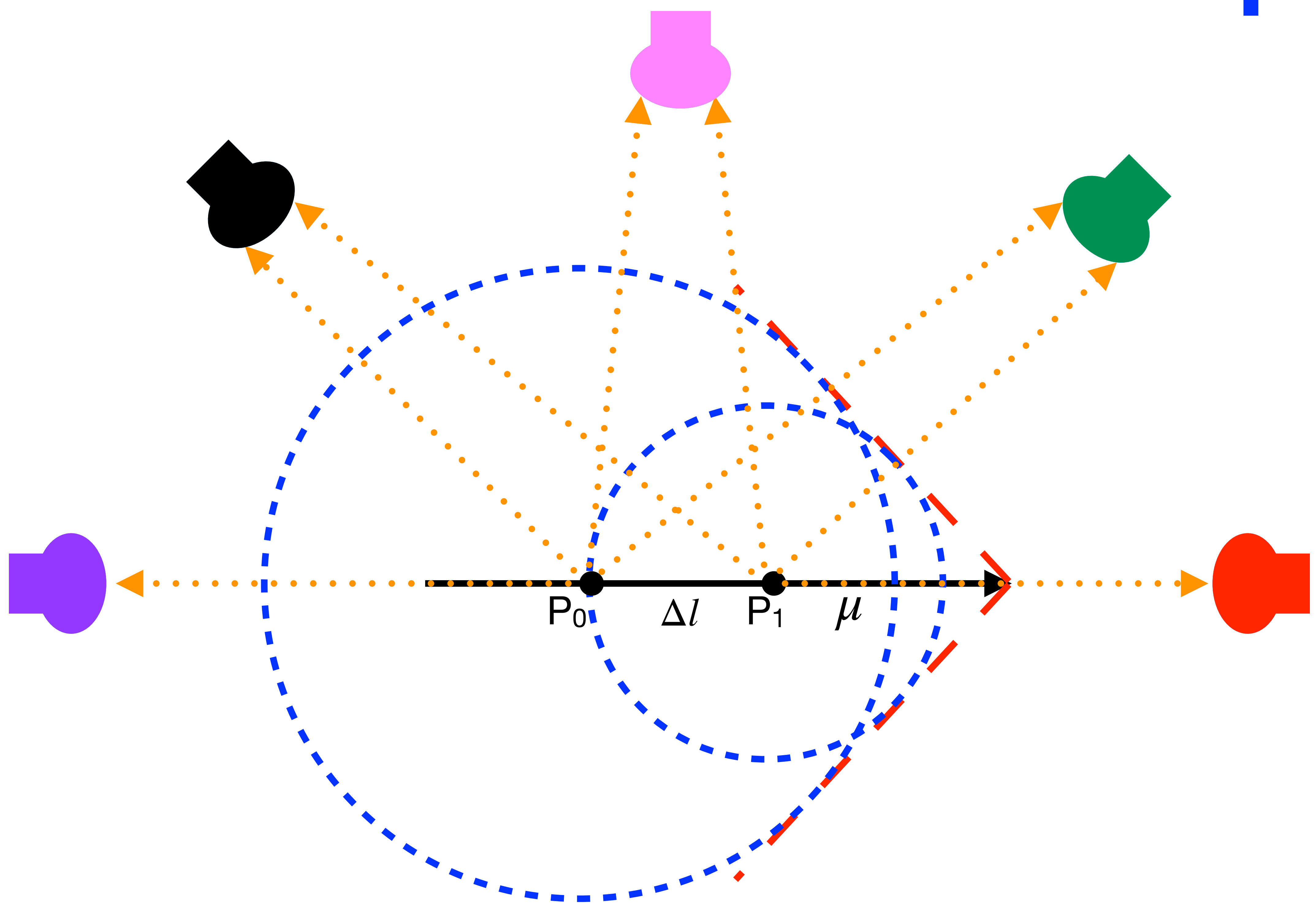

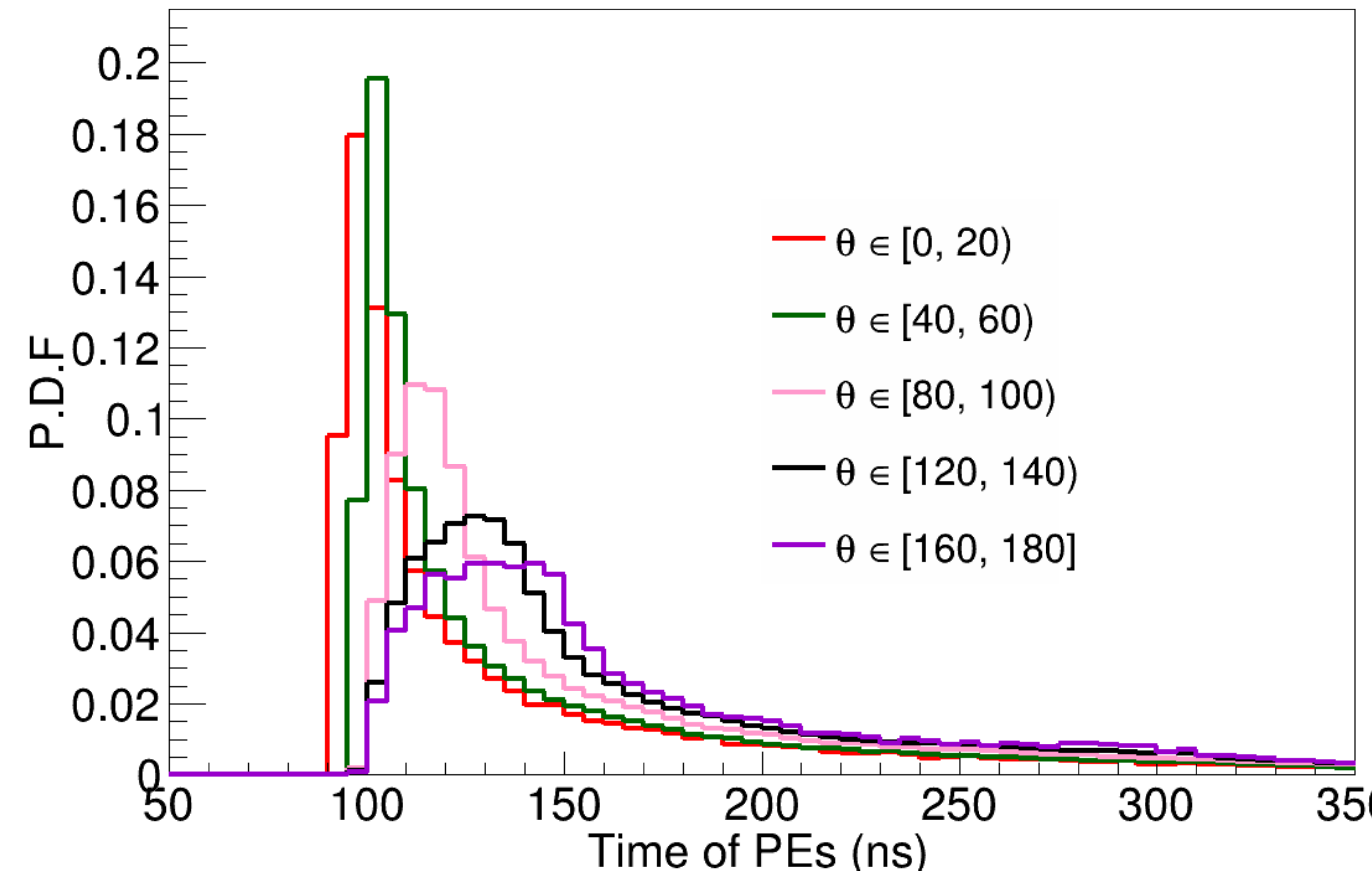

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Directionality
Energy
PID…

- Event topology information in the PMT waveform.

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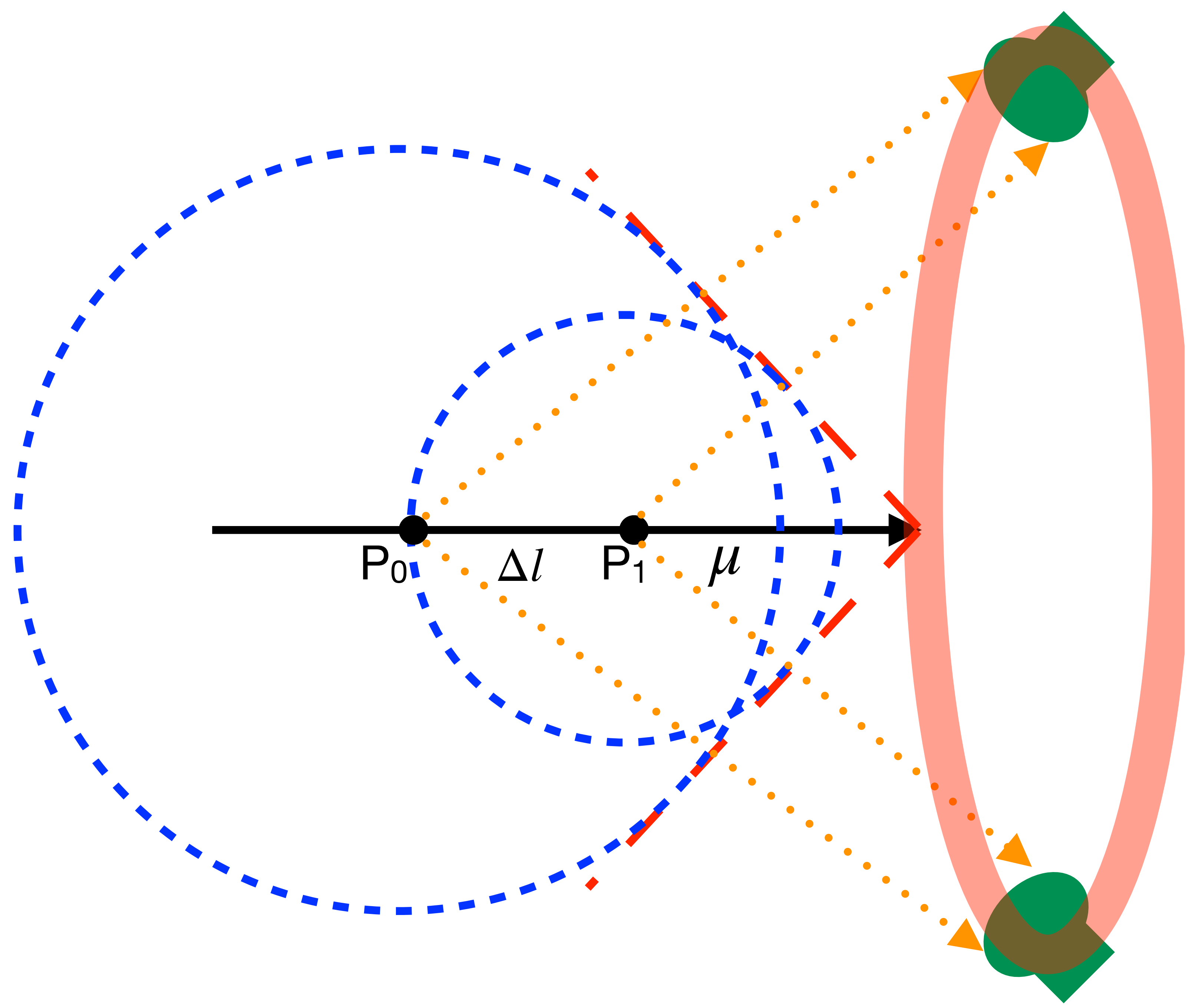

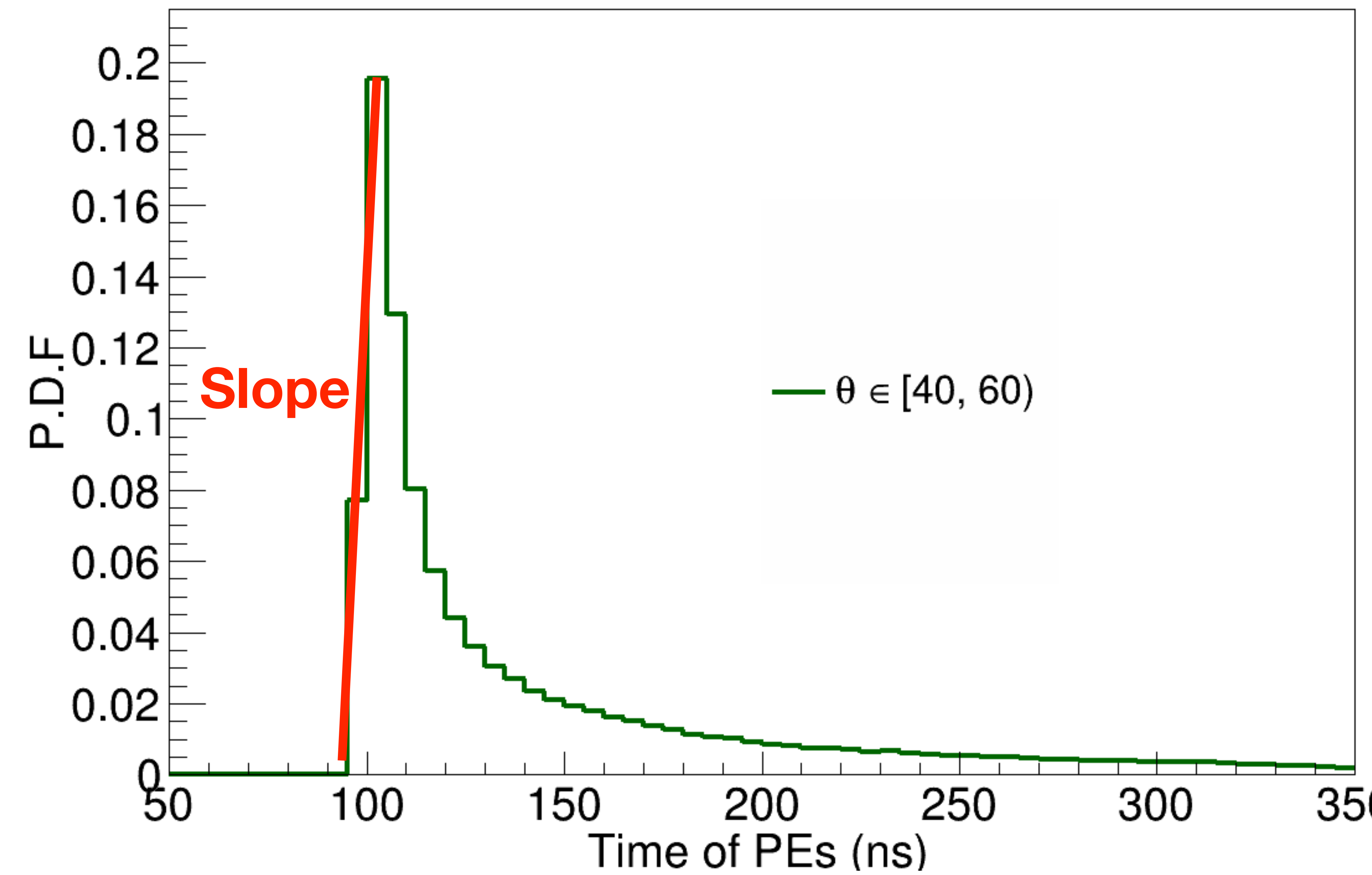

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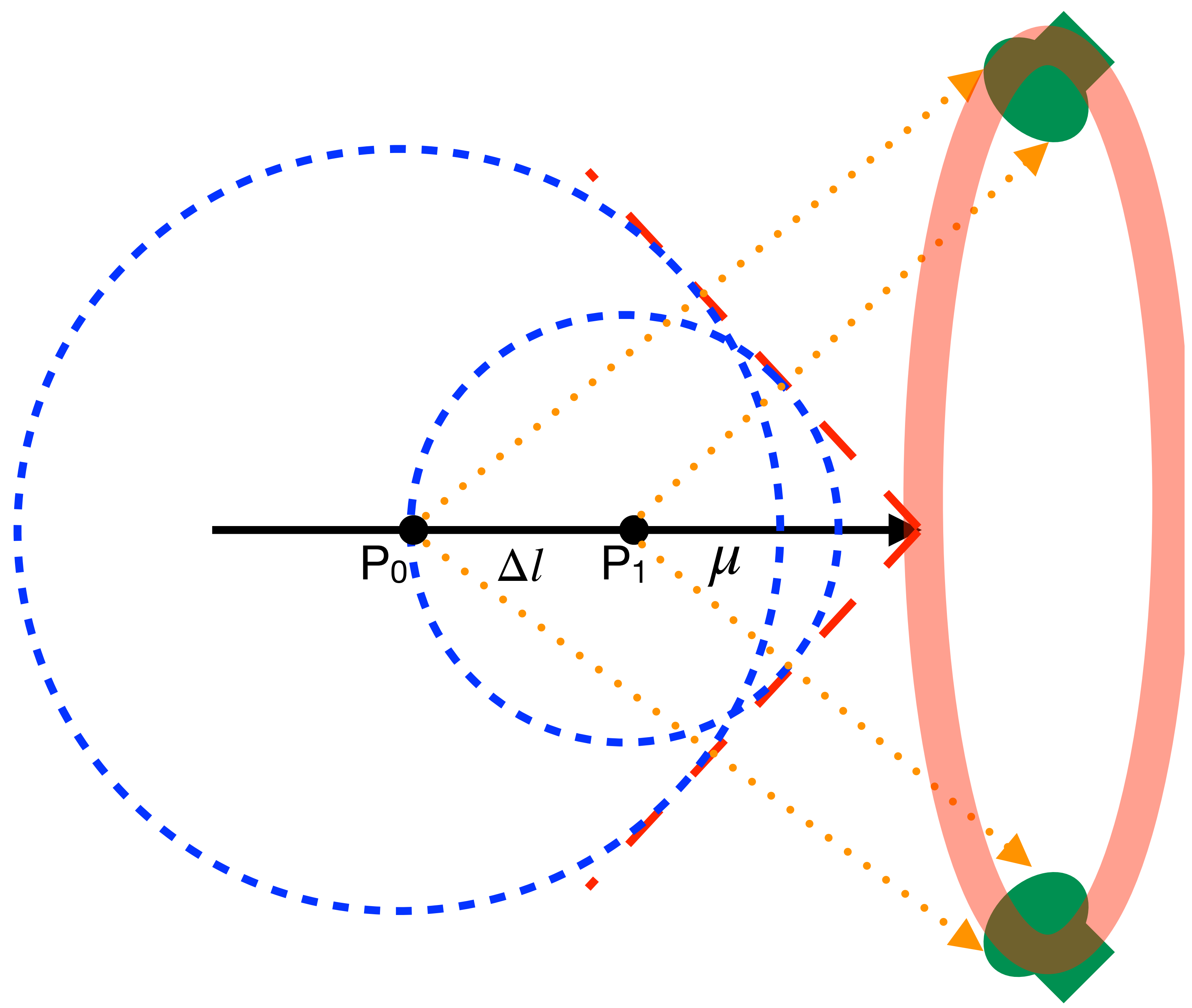

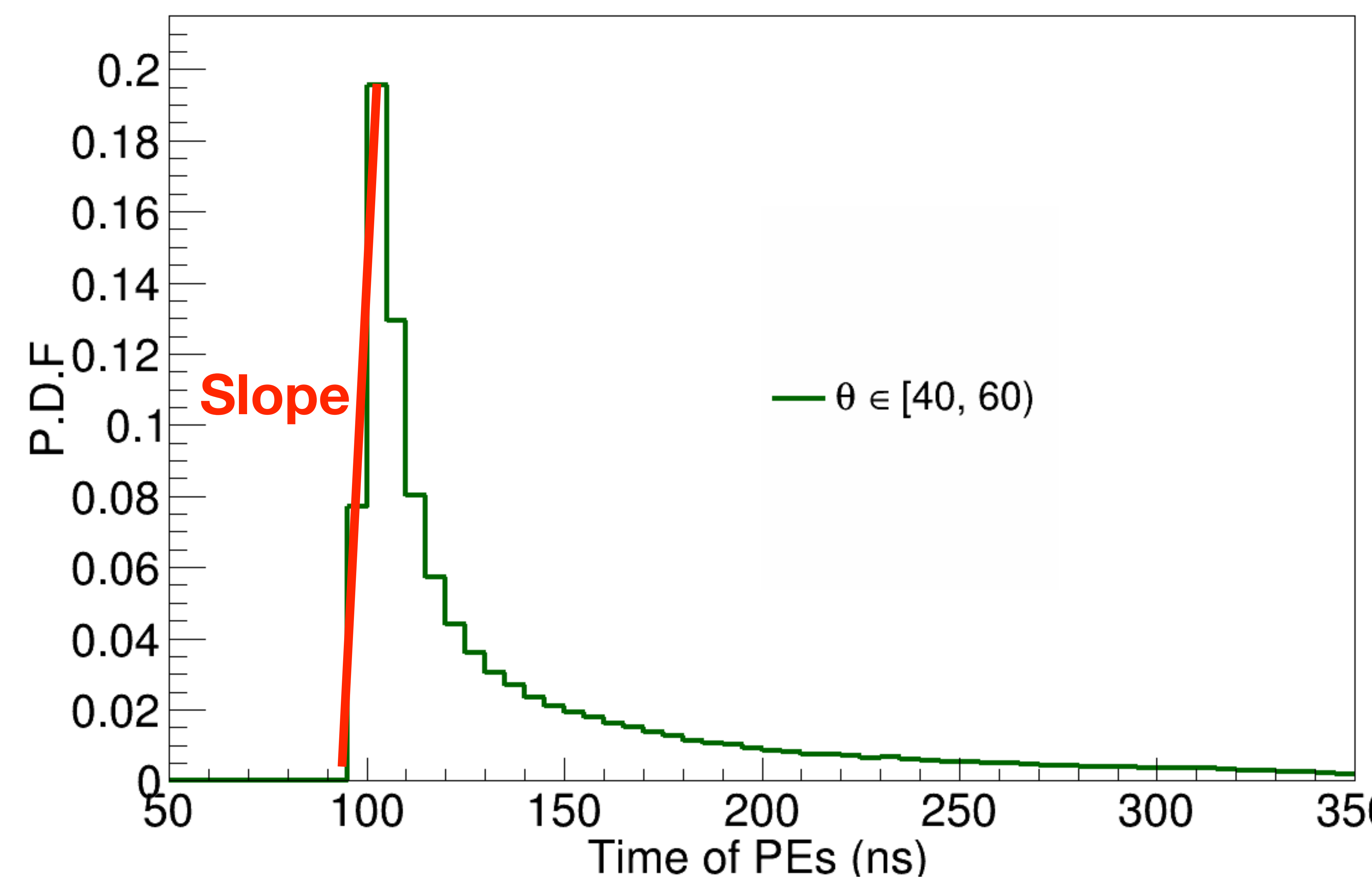

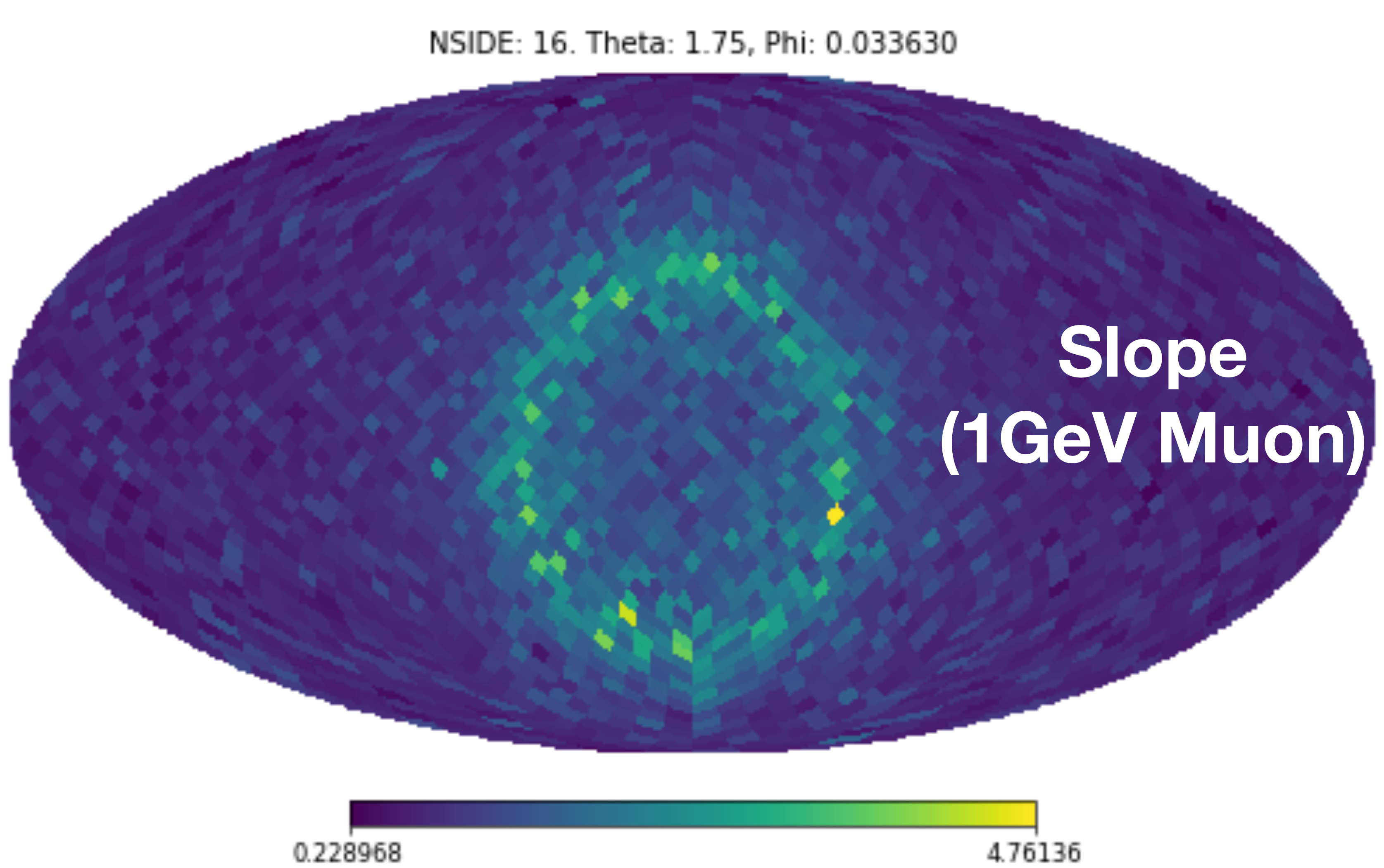

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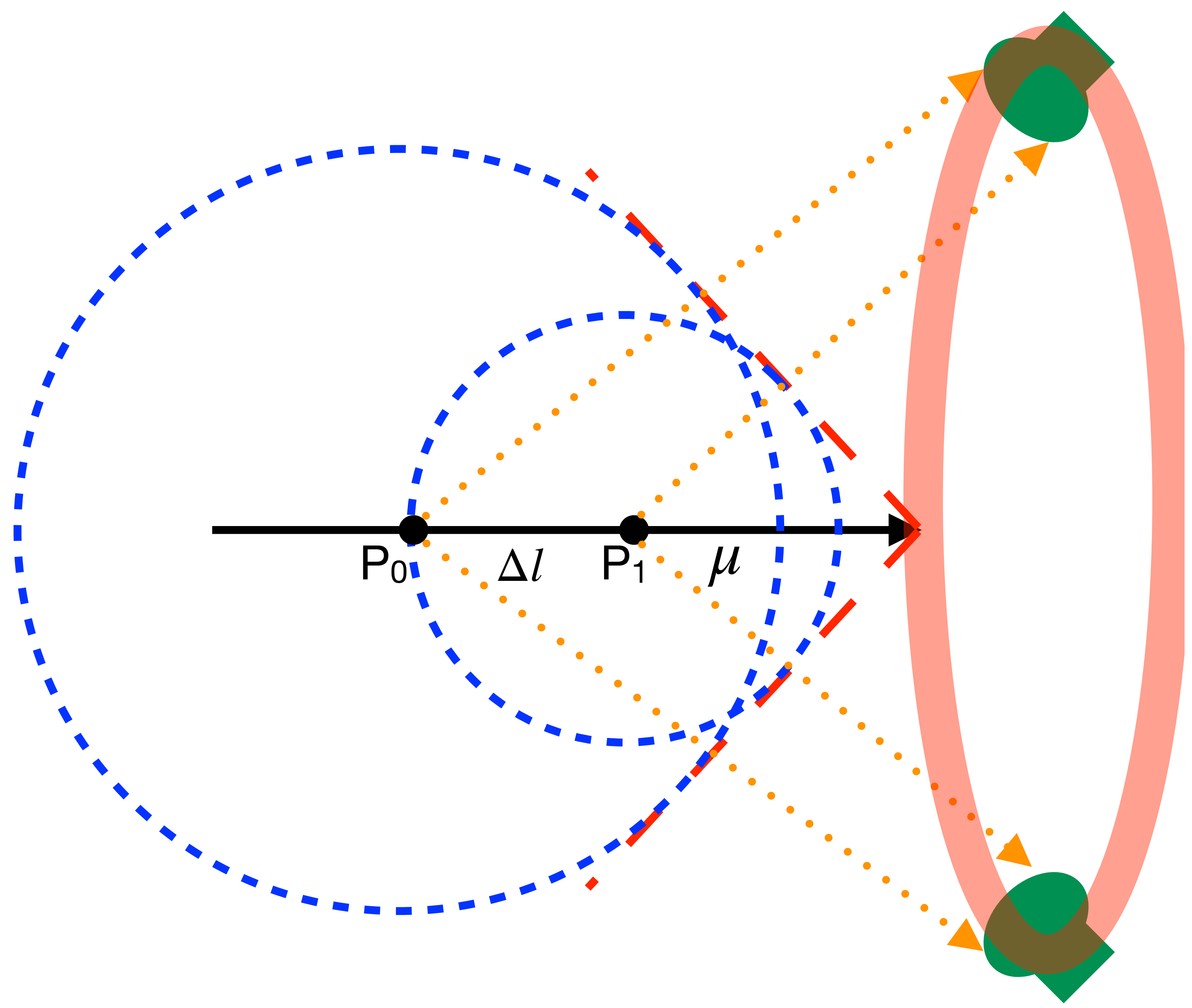
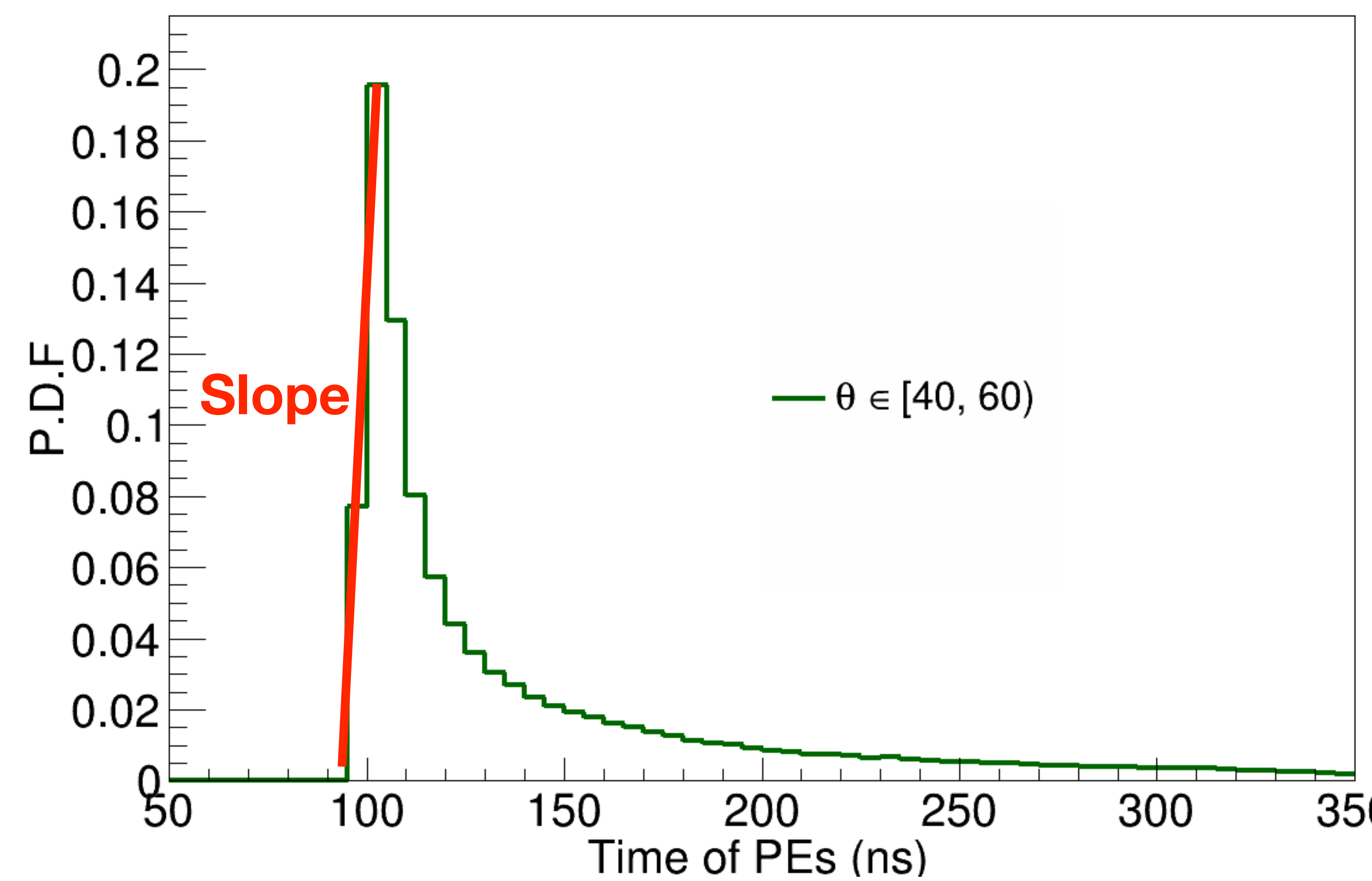
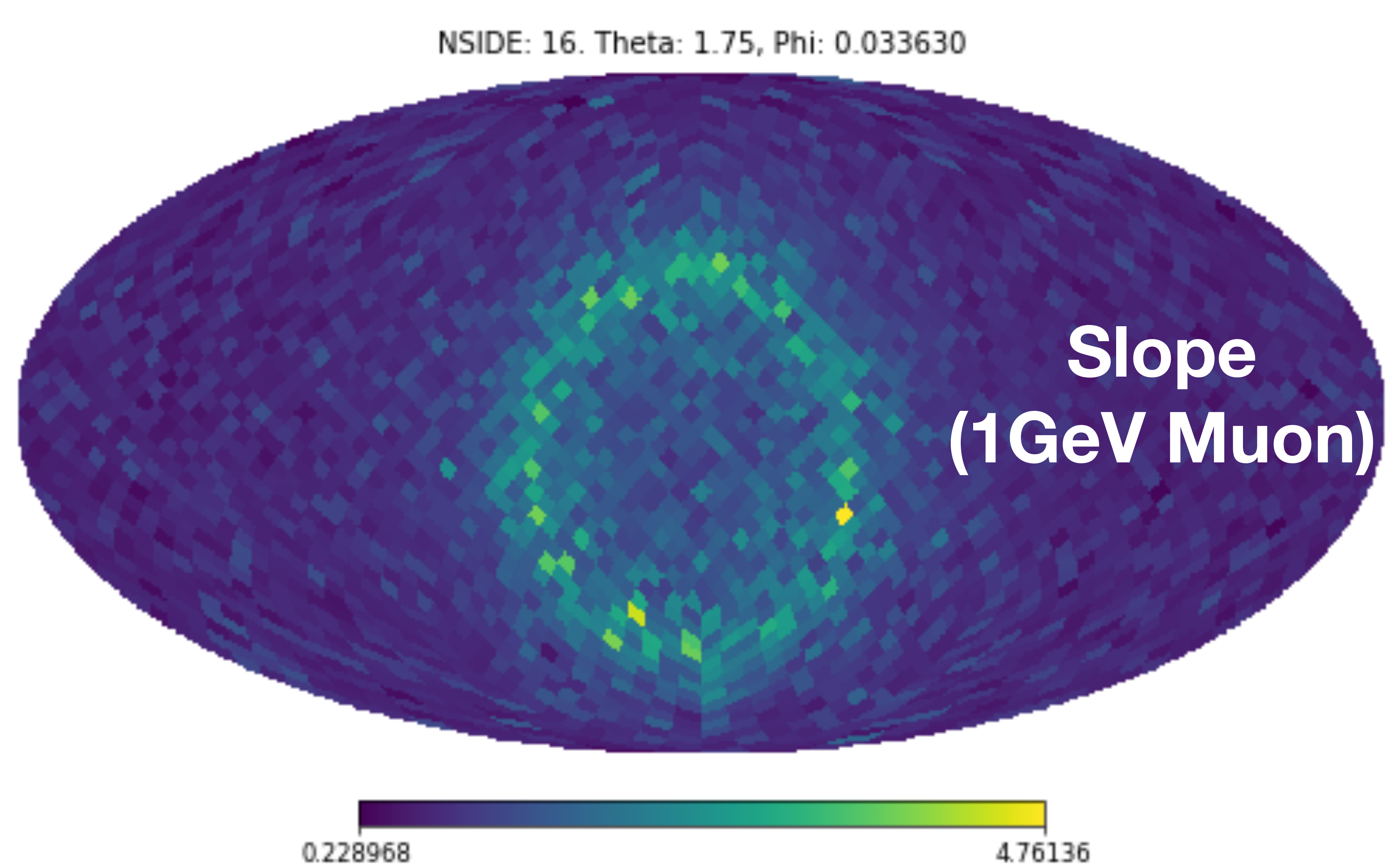
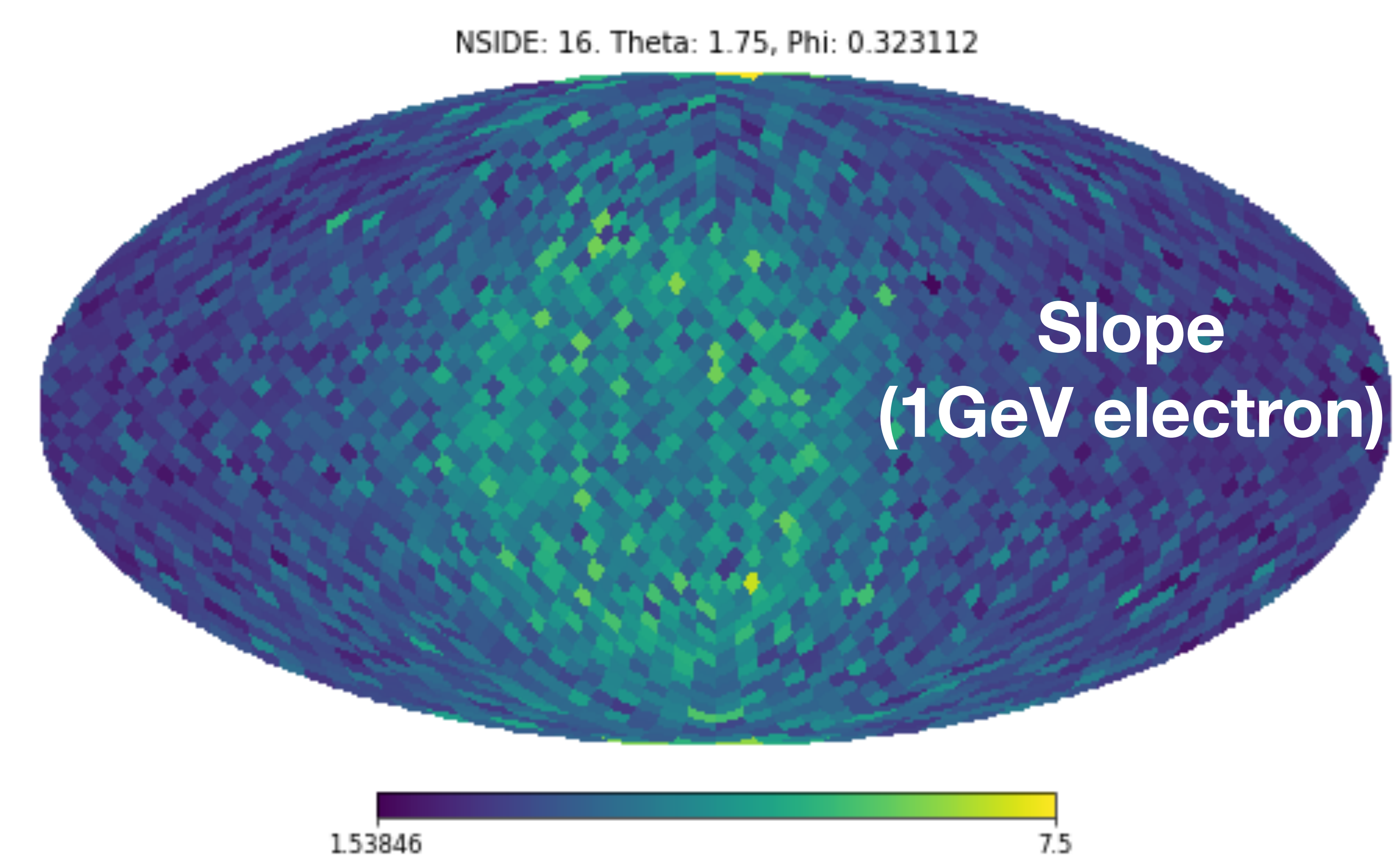


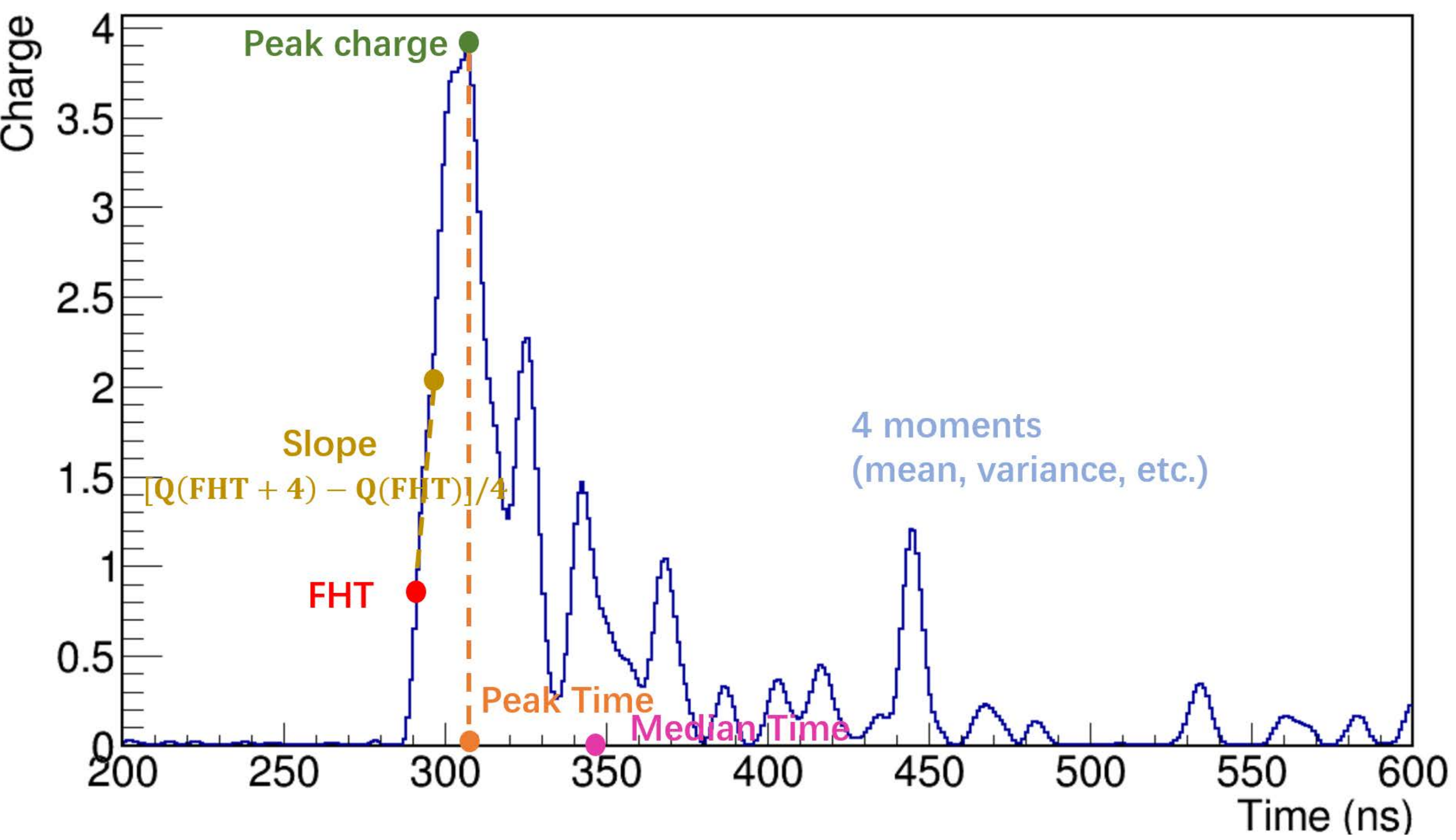






- e-like vs μ-like vs NC identification based upon PMT features.

A Multipurpose Machine Learning Solution



PMT Waveforms (After deconvolution and noise-removing)

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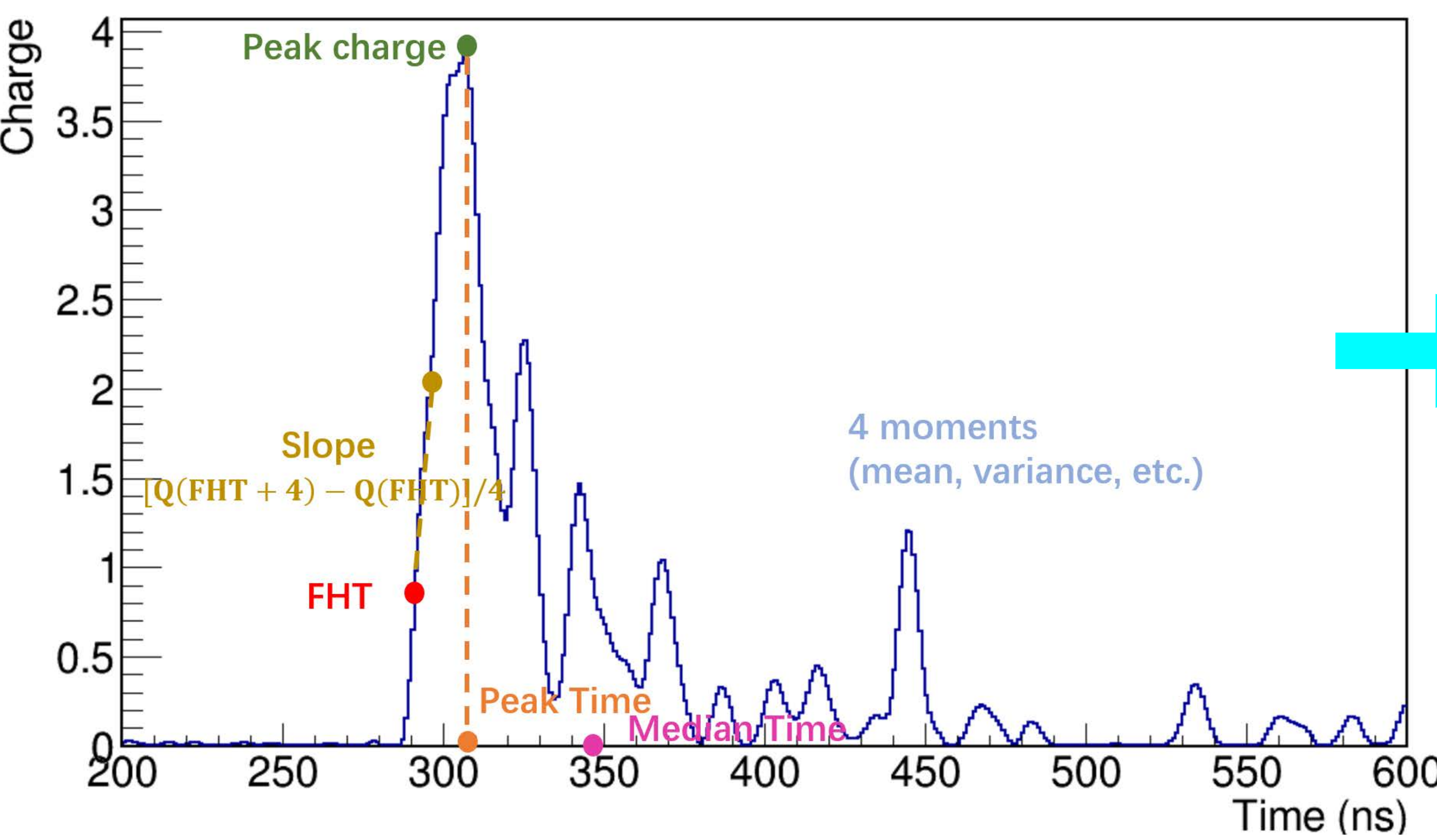

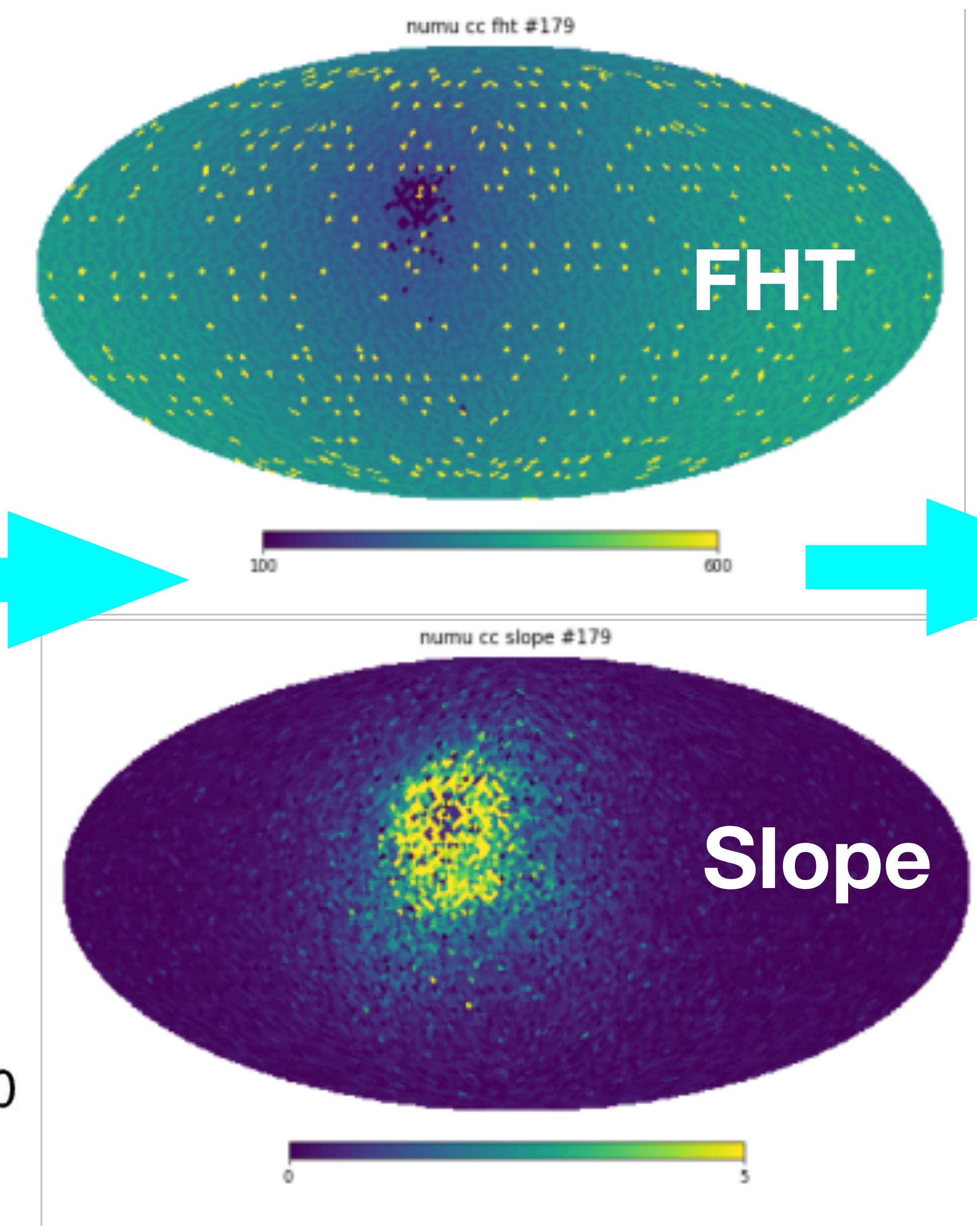

And more features… …

PMT Waveforms (After deconvolution and noise-removing)

Pictures of PMT Features

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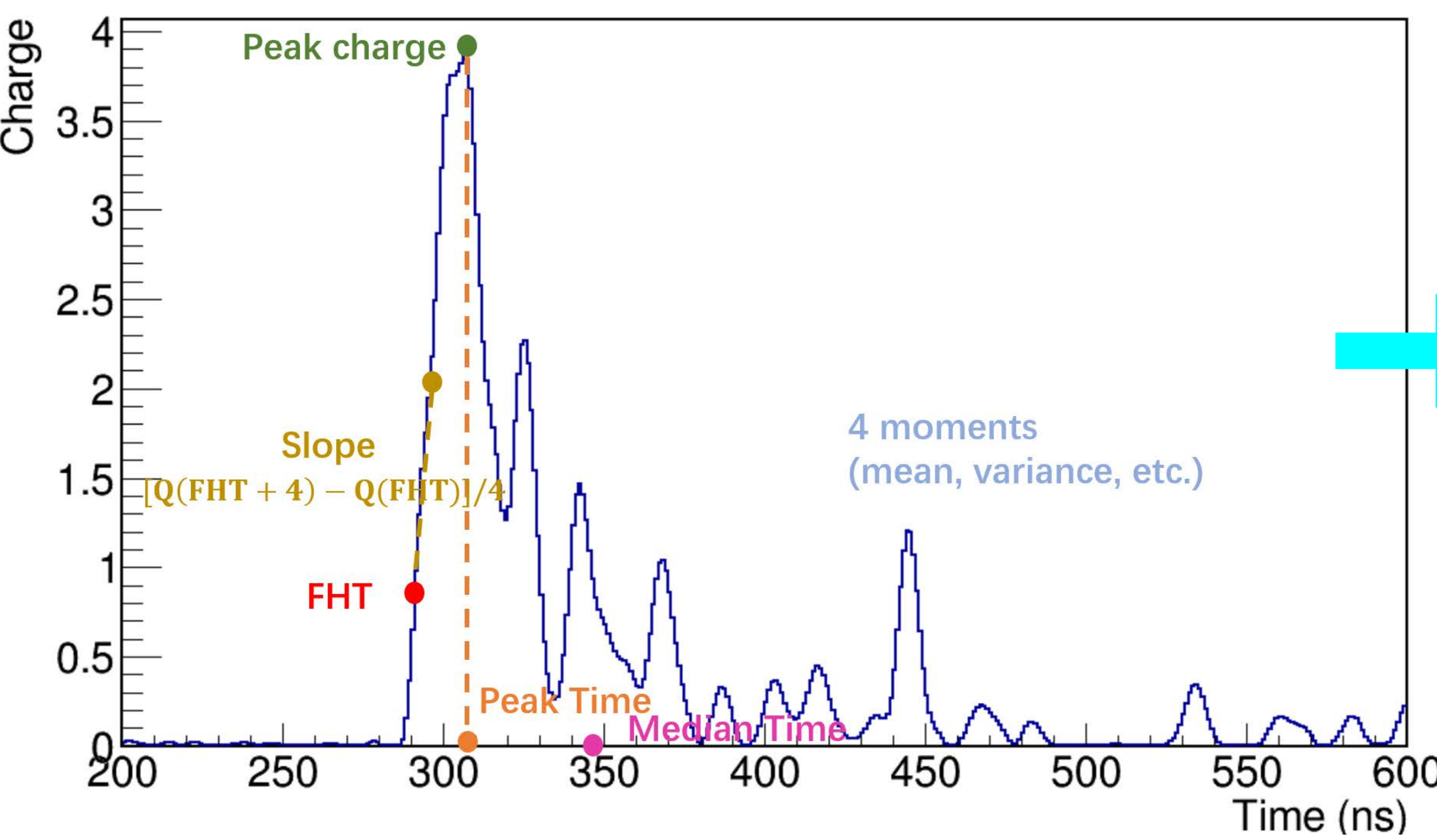

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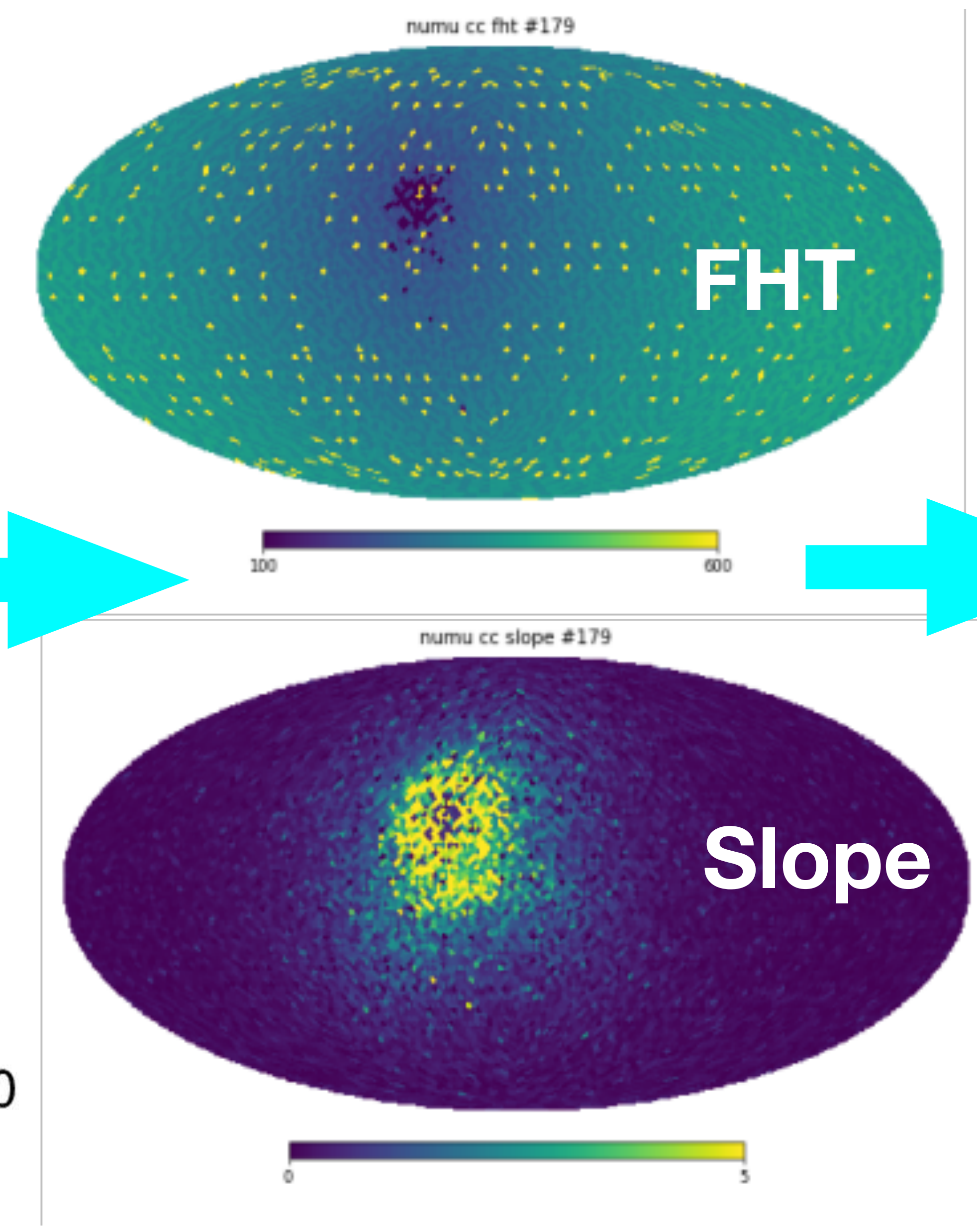

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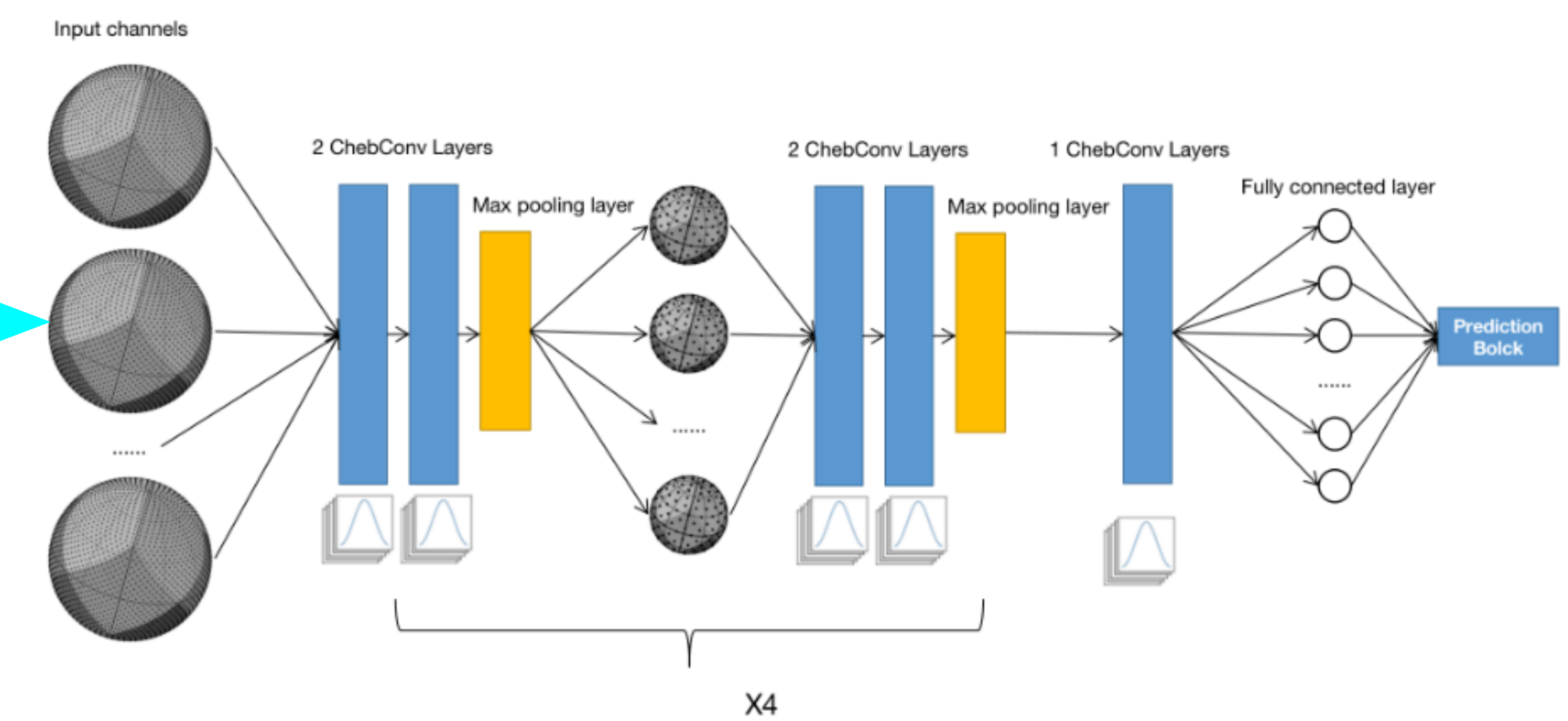

Machine Learning Models
(Planer: EfficientNetV2;
Spherical: Deepsphere;
3D: PiontNet++)

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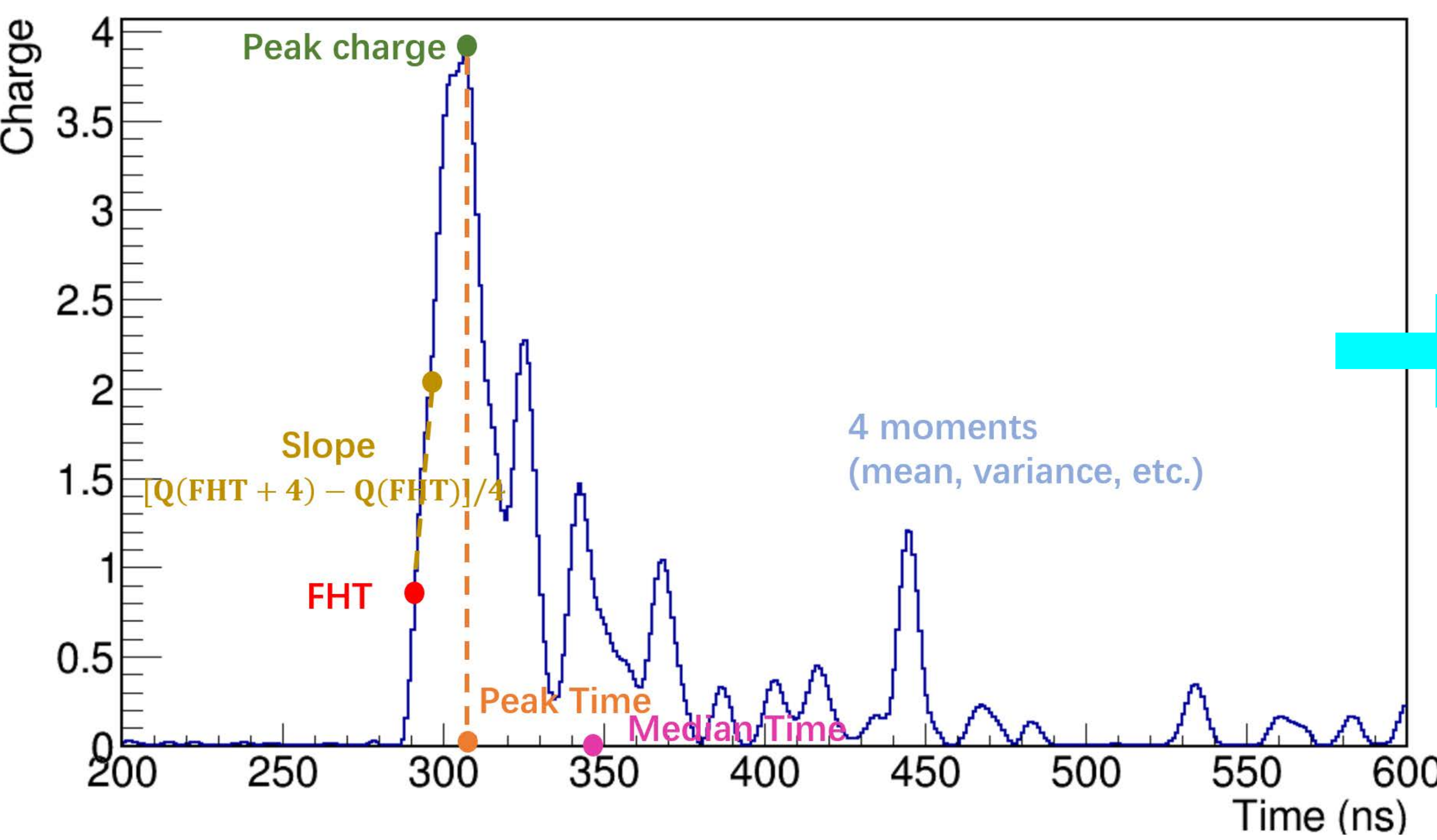

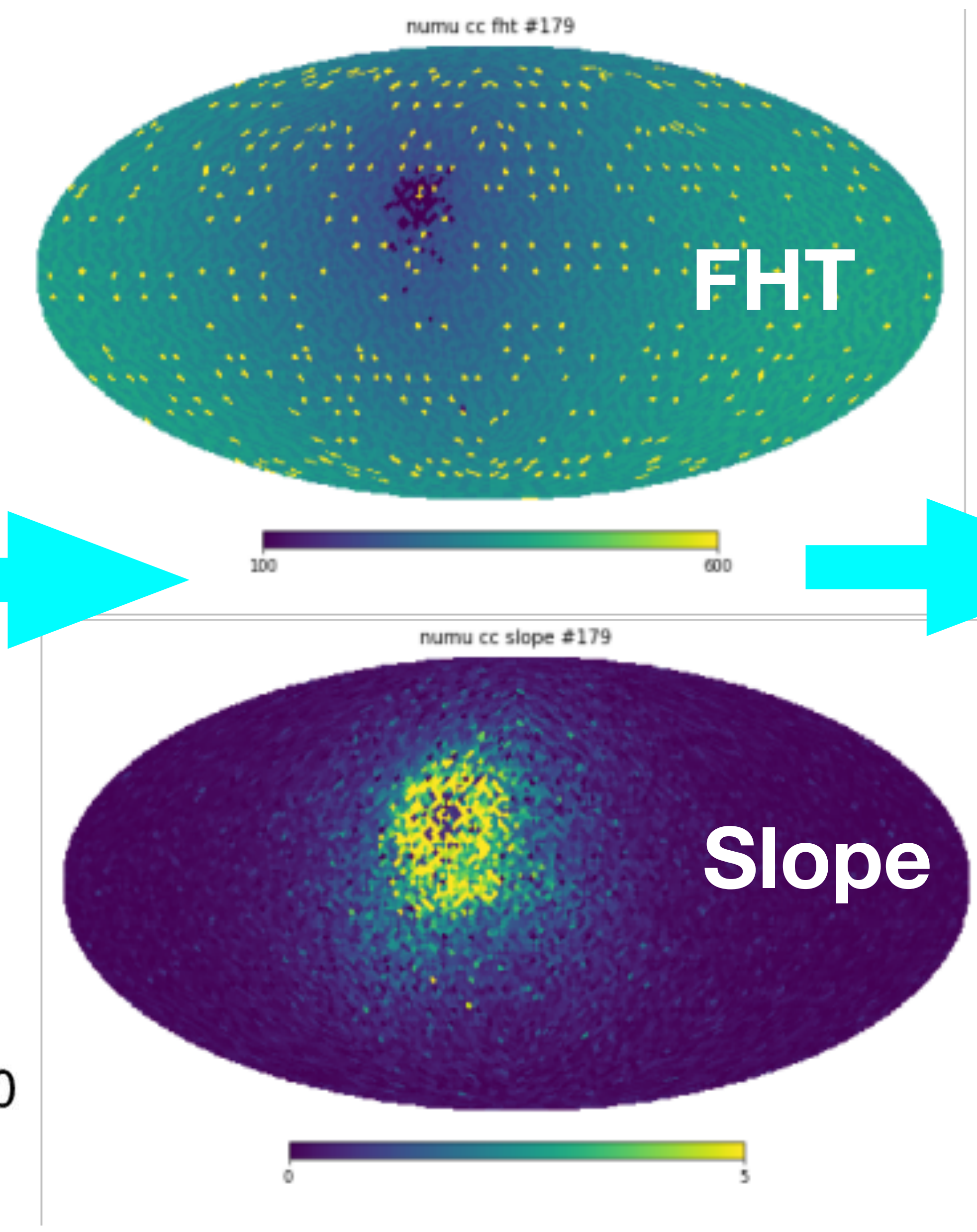

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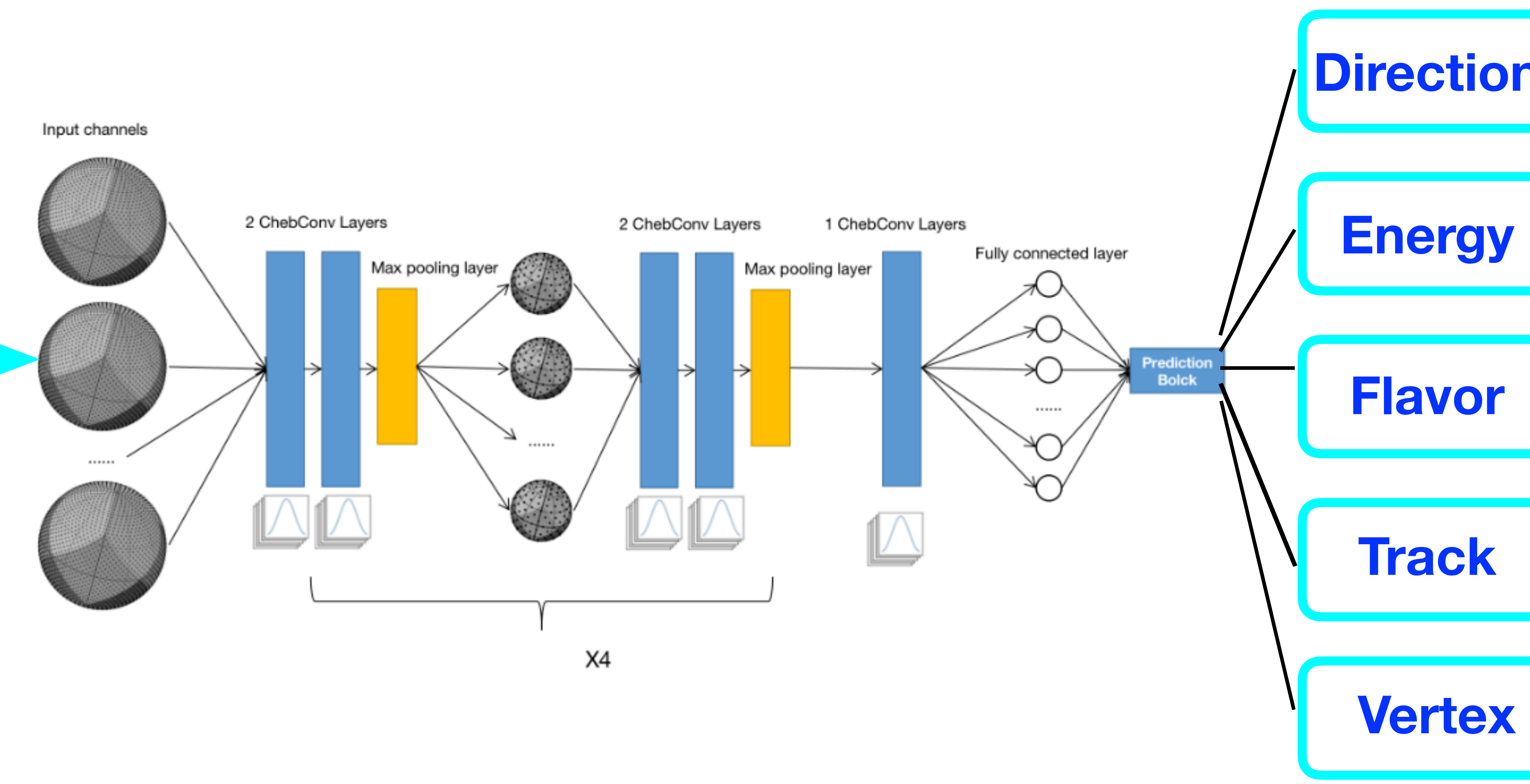


PMT Waveforms (After deconvolution and noise-removing)

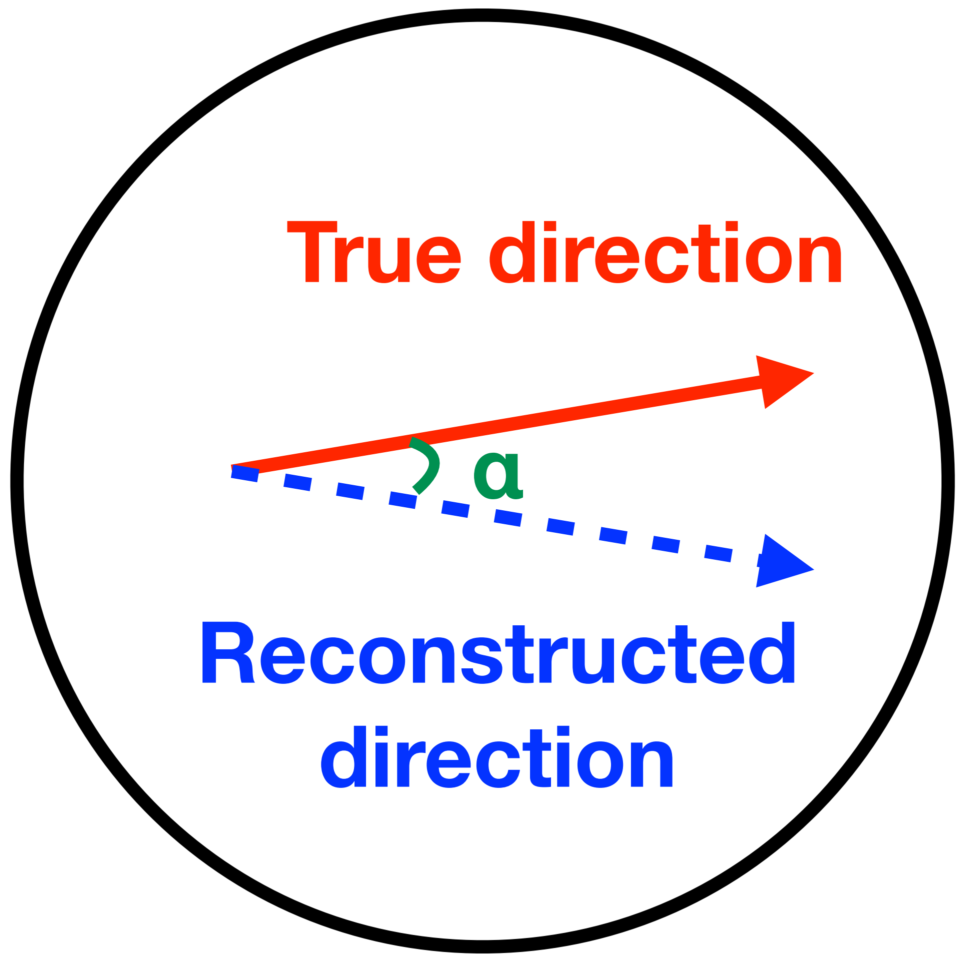
Pictures of PMT Features

Machine Learning Models
(Planer: EfficientNetV2;
Spherical: Deepsphere;
3D: PiontNet++)

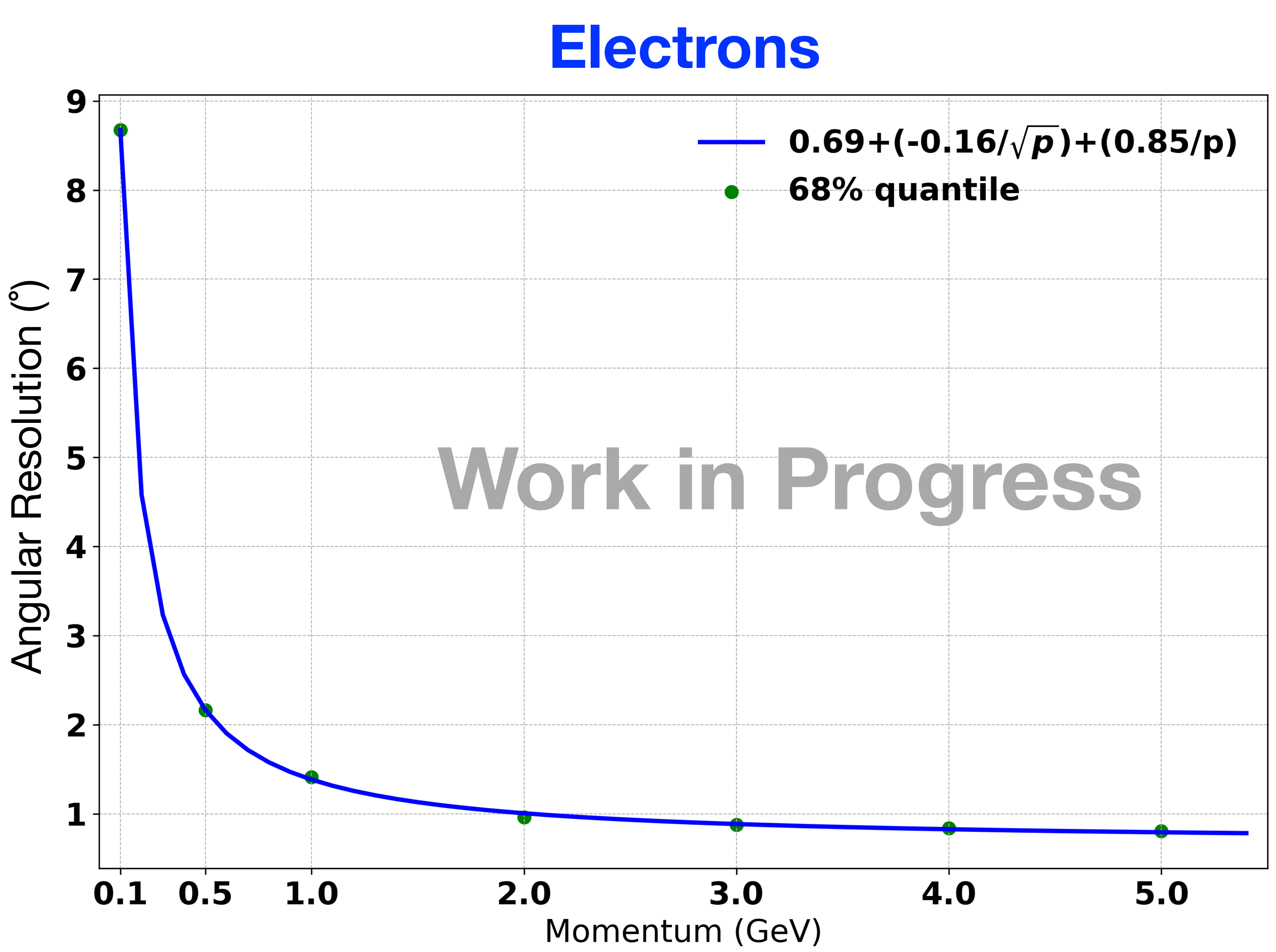
Outputs

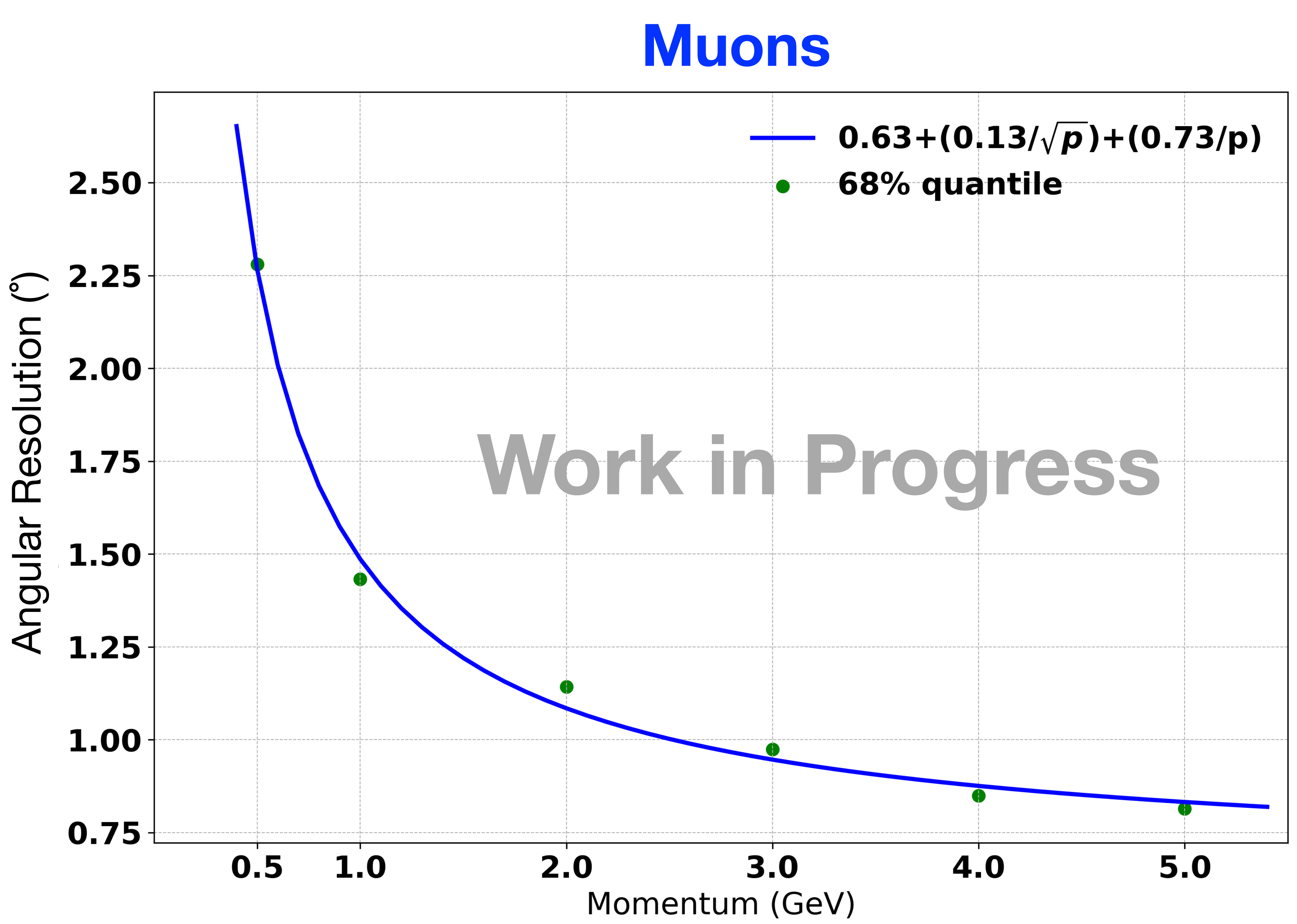
- Models are trained with large number of PMT feature pictures and learn to find direction/energy/flavor/vertex etc. from the feature patterns.

Charged Lepton Direction Reconstruction

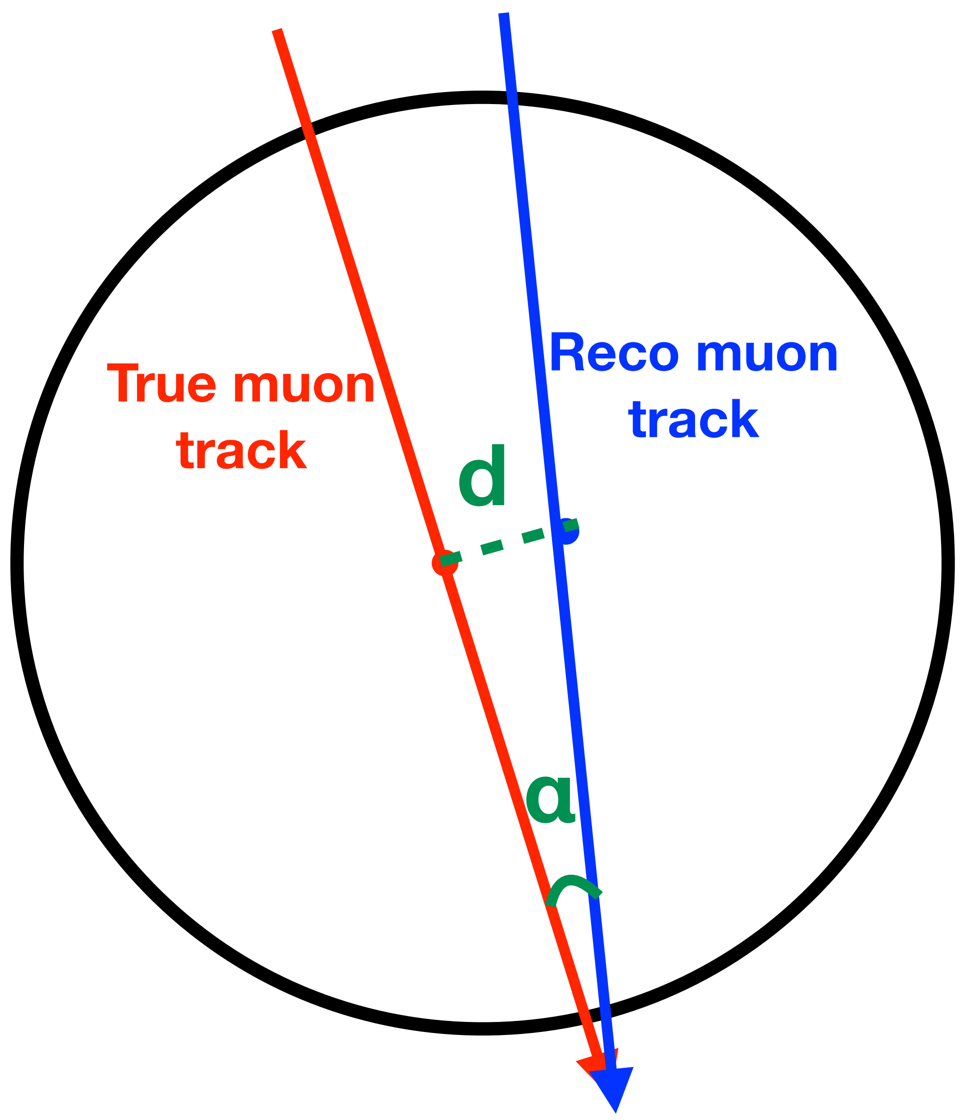


- Performances on simulated single charged leptons evaluated by the angle between true and reconstructed directions.
- ~1.5˚ angular resolution for electrons/muons at 1 GeV.

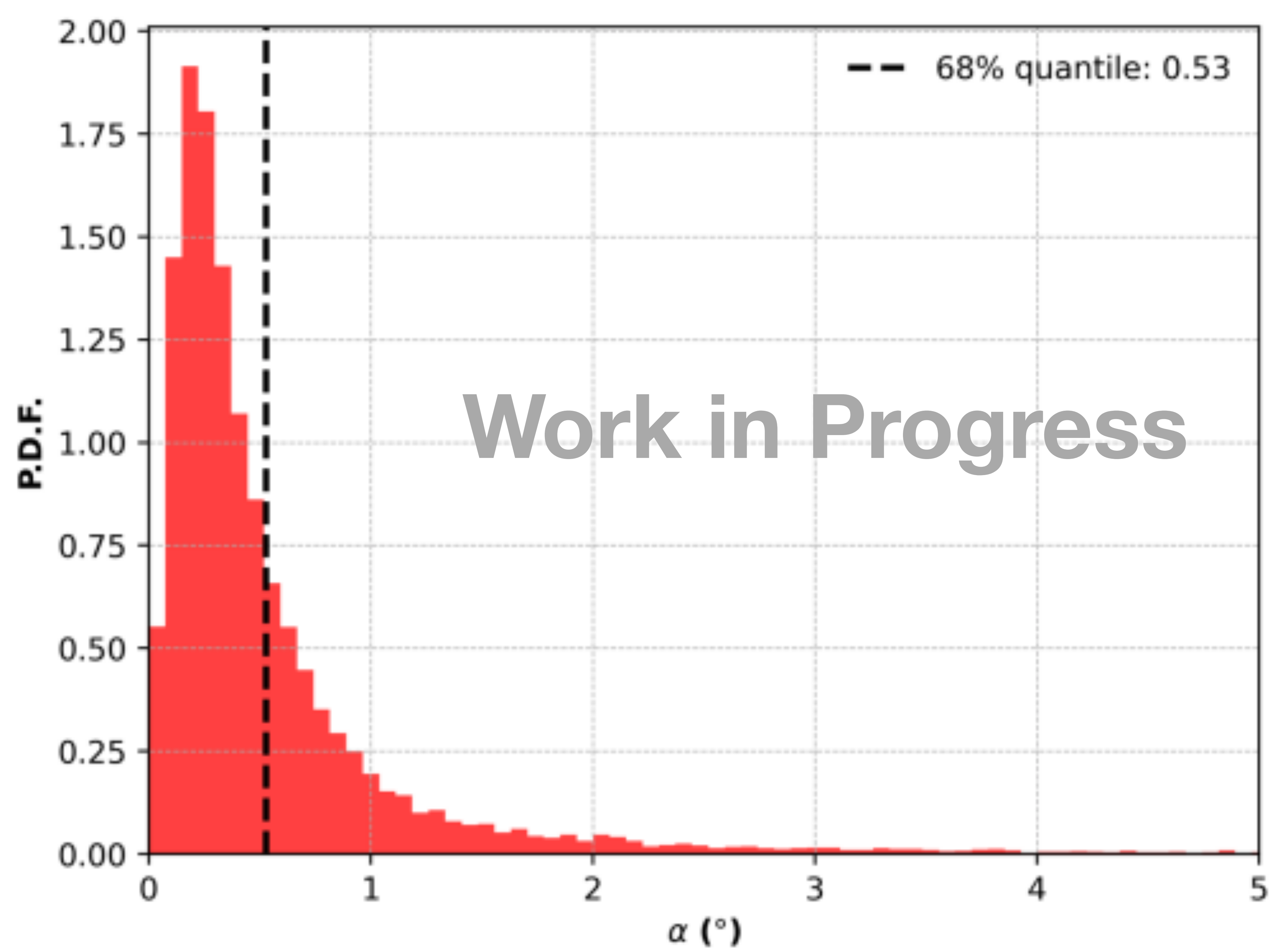


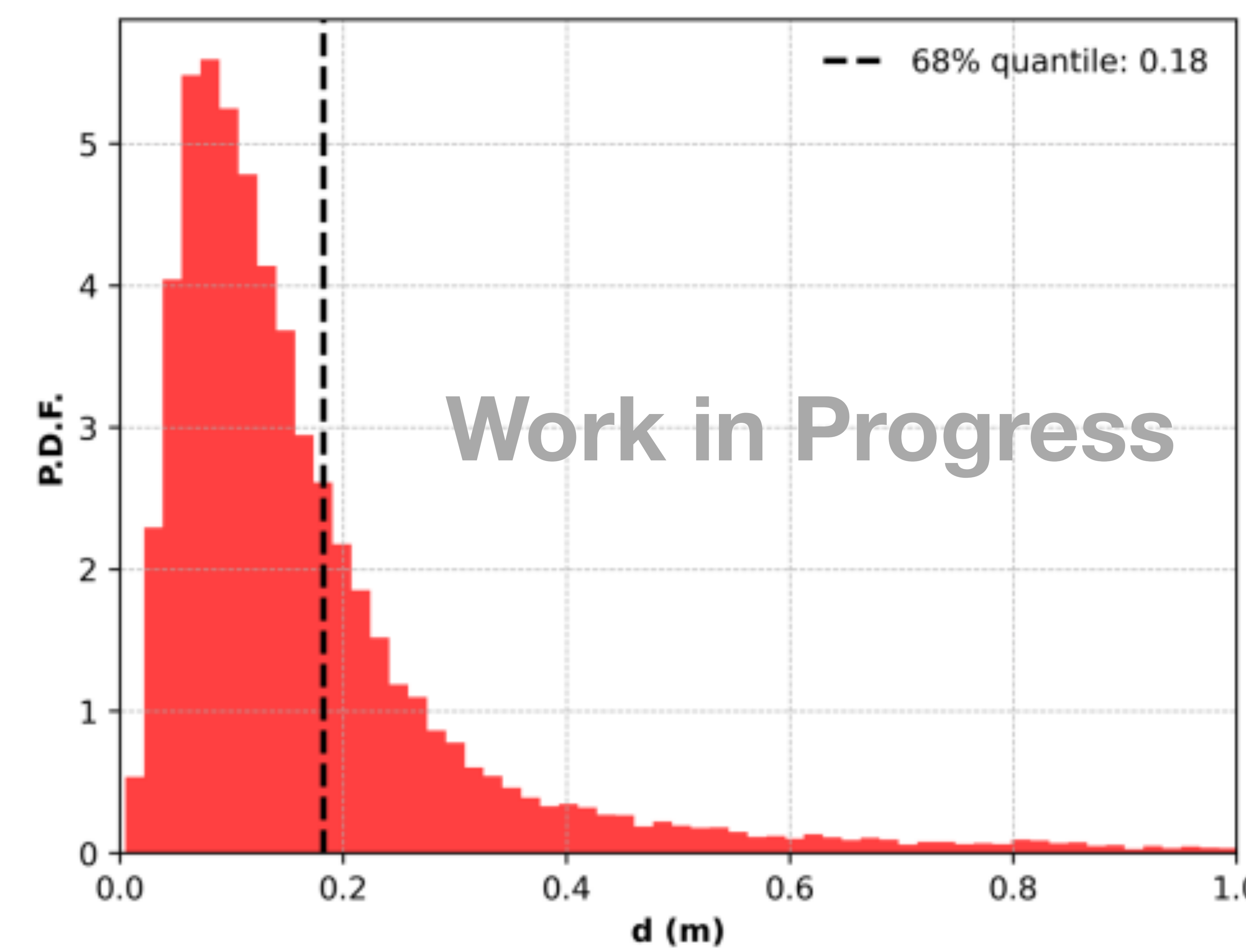


Cosmic Muon Track Reconstruction

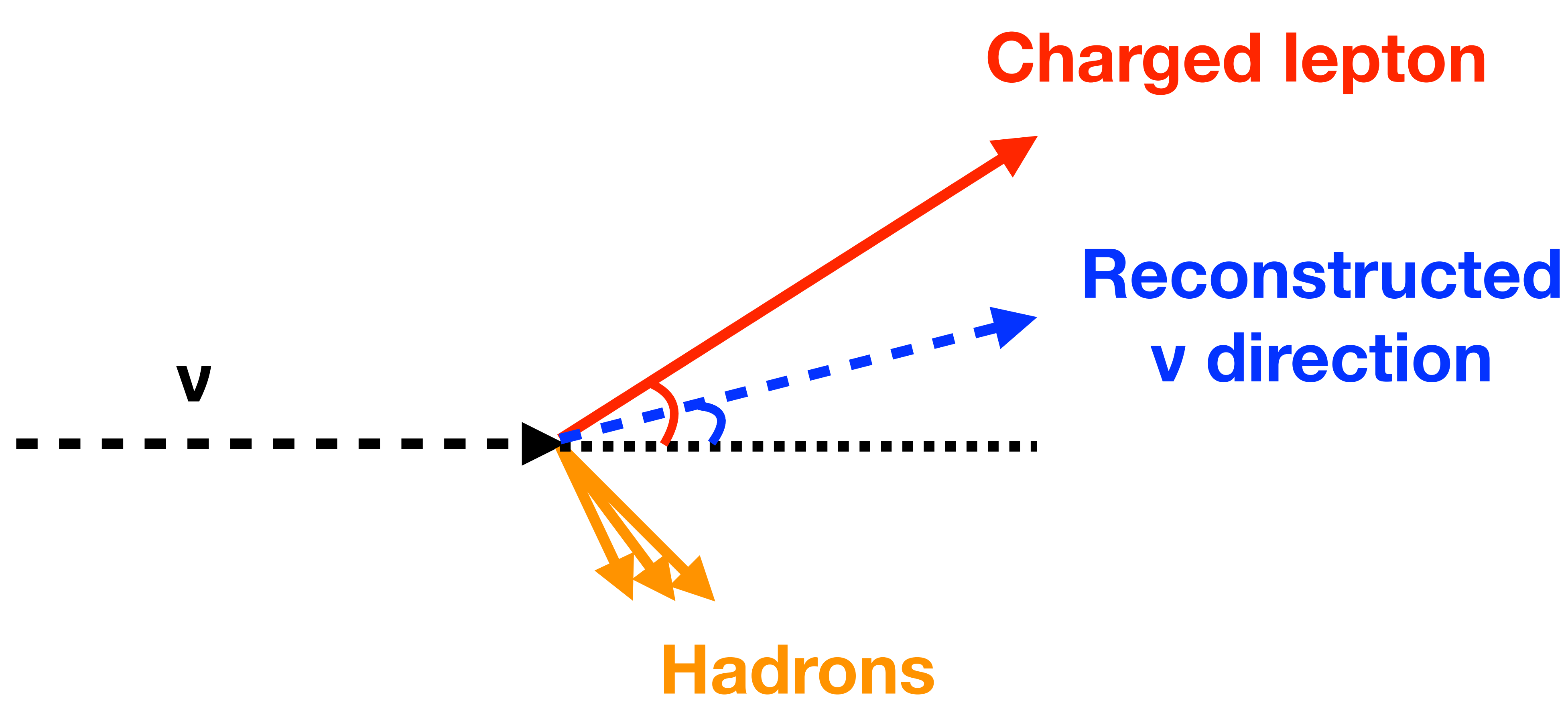


- Cosmic muon tracks are reconstructed by the incident and exit points on the detector sphere.
- Performances evaluated by the angle between true and reconstructed tracks (α) and the distance between the track midpoints (d).

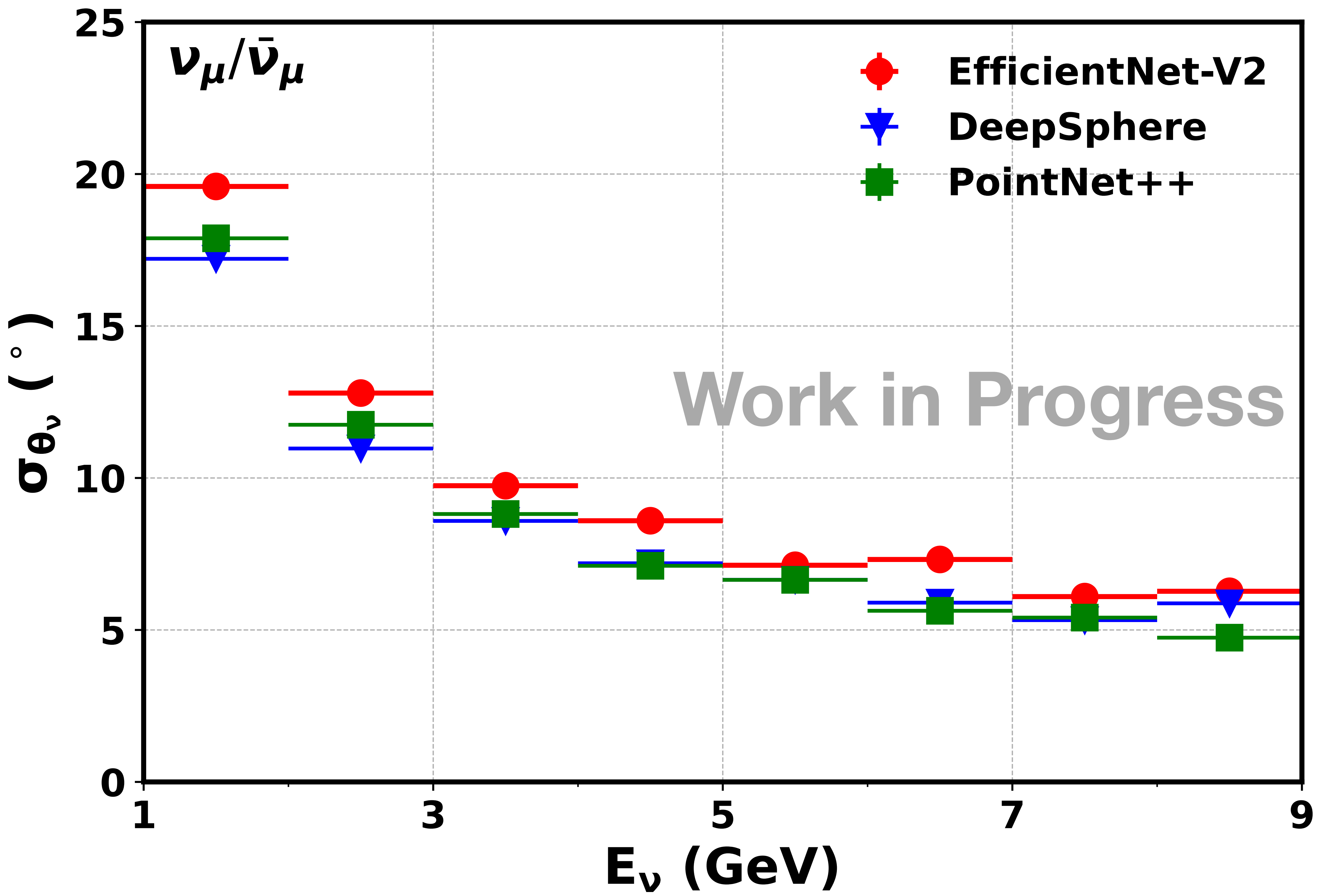


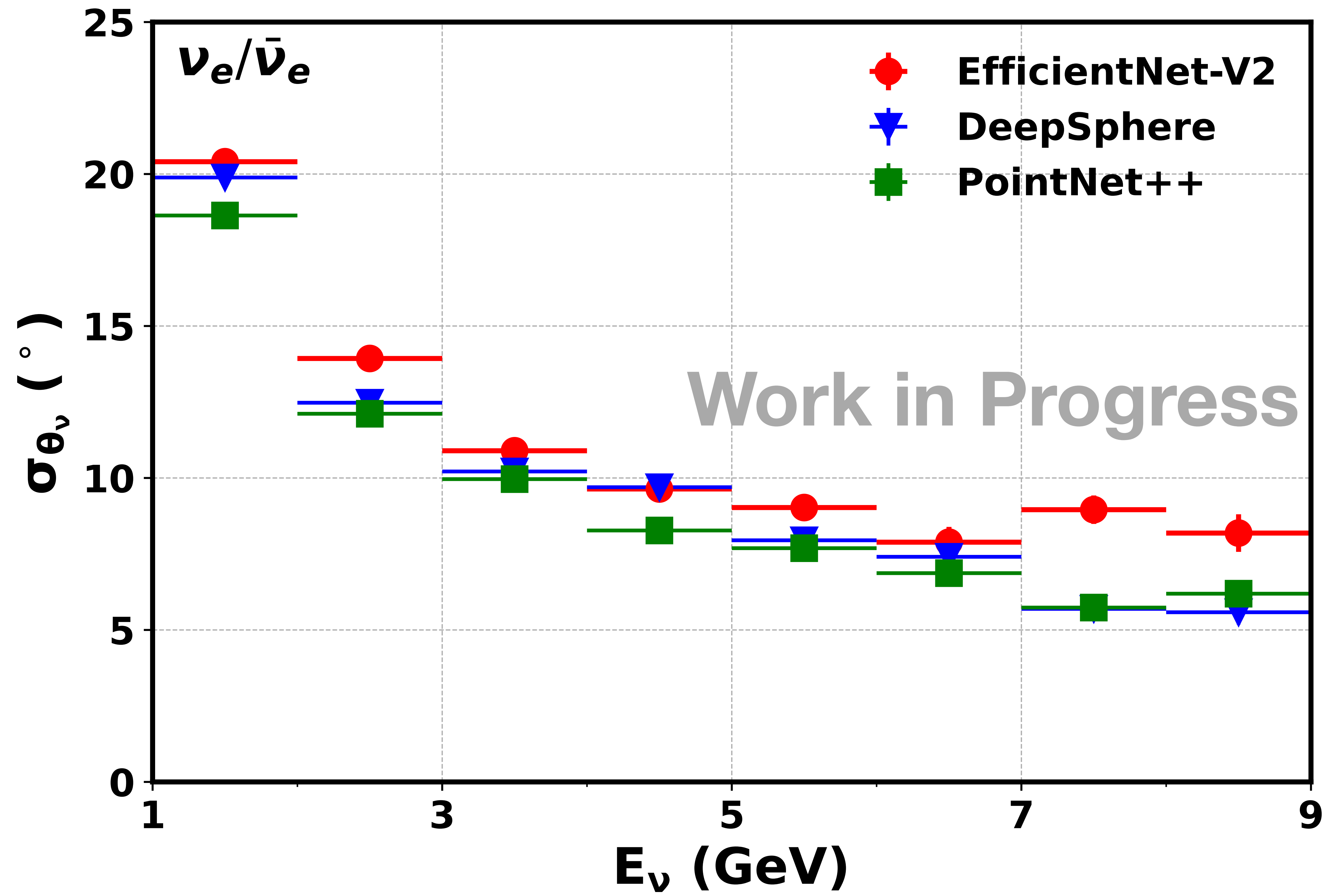


Atmospheric ν: Directionality Reconstruction



- Cross-checked with different ML models: EfficientNet, DeepSphere, PointNet+++.
- About/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.





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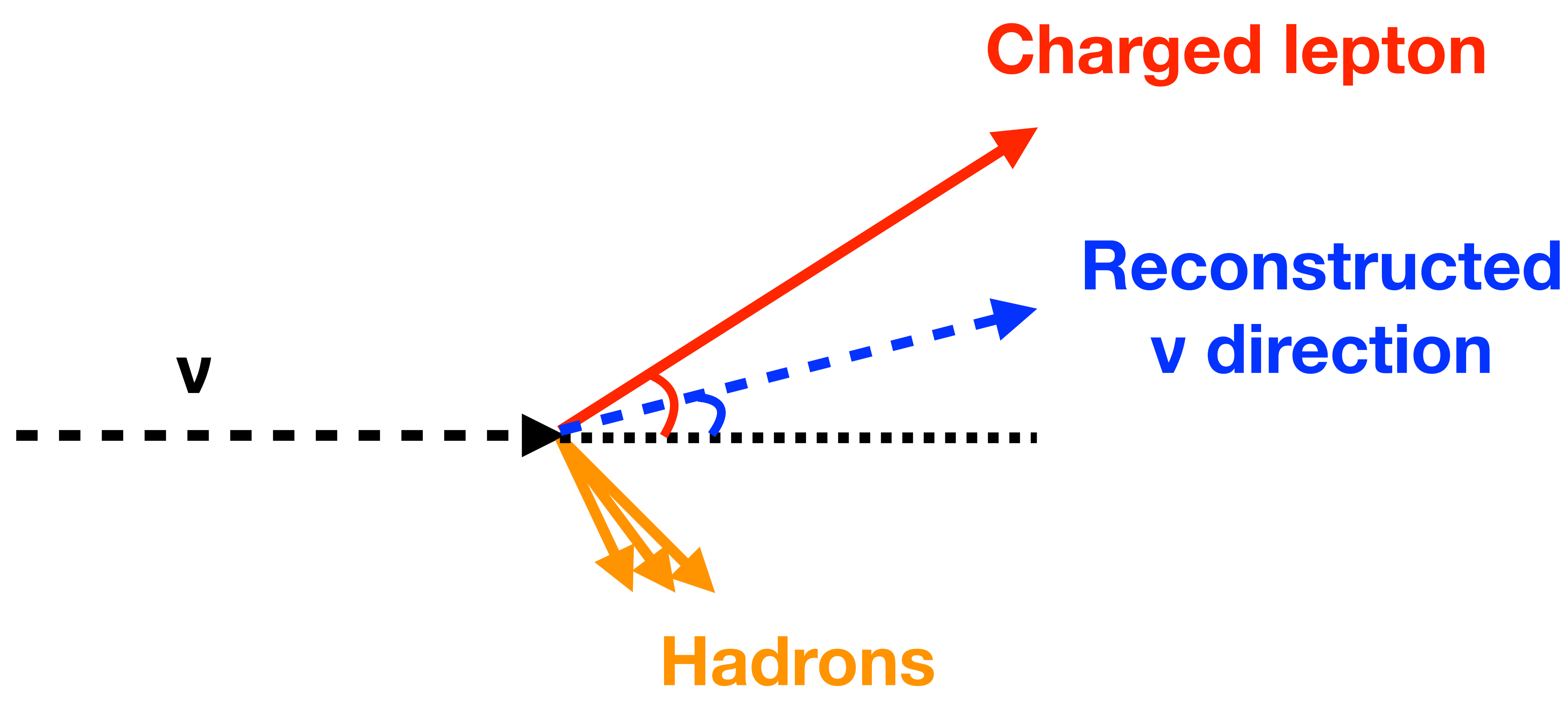
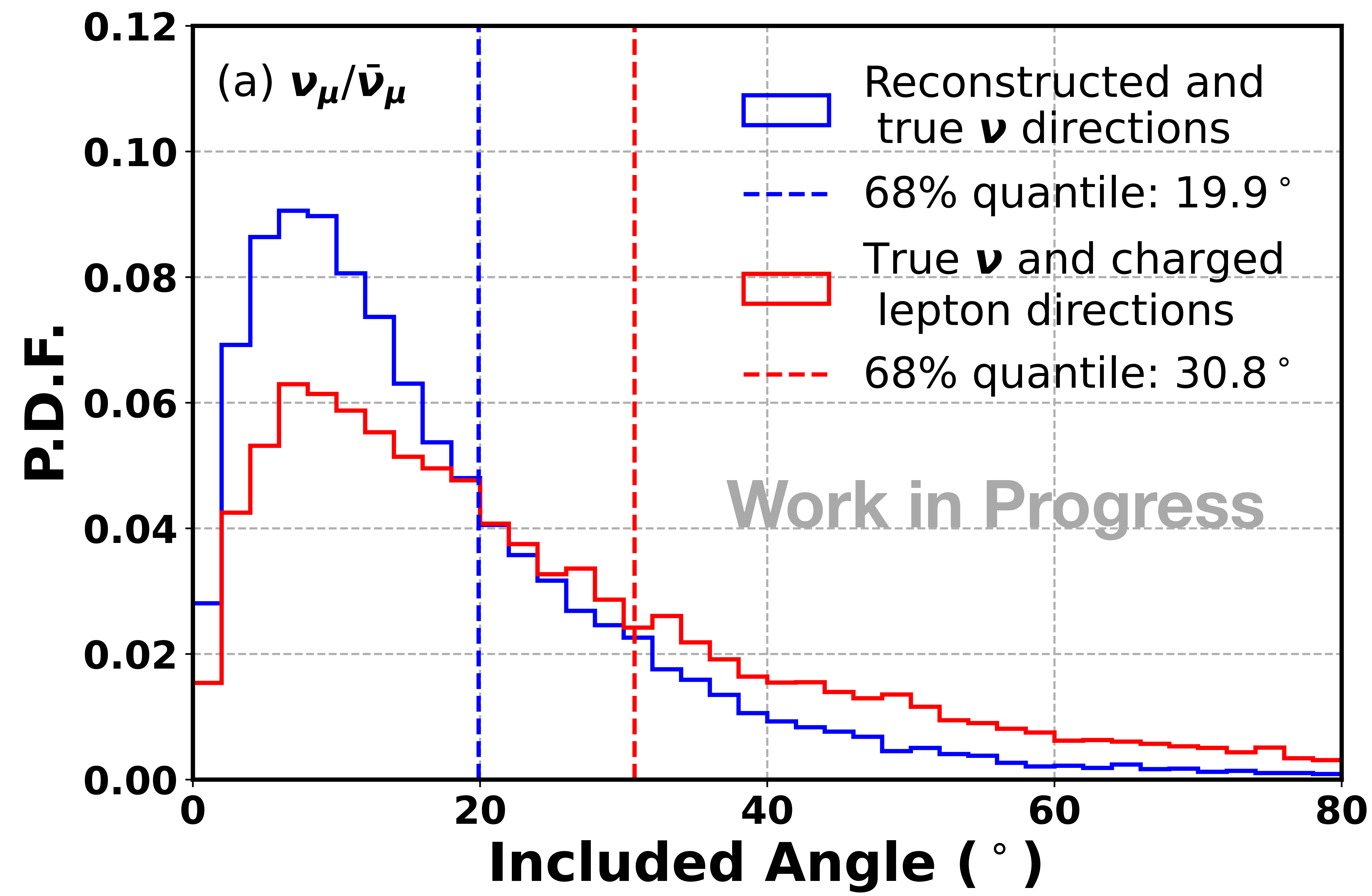




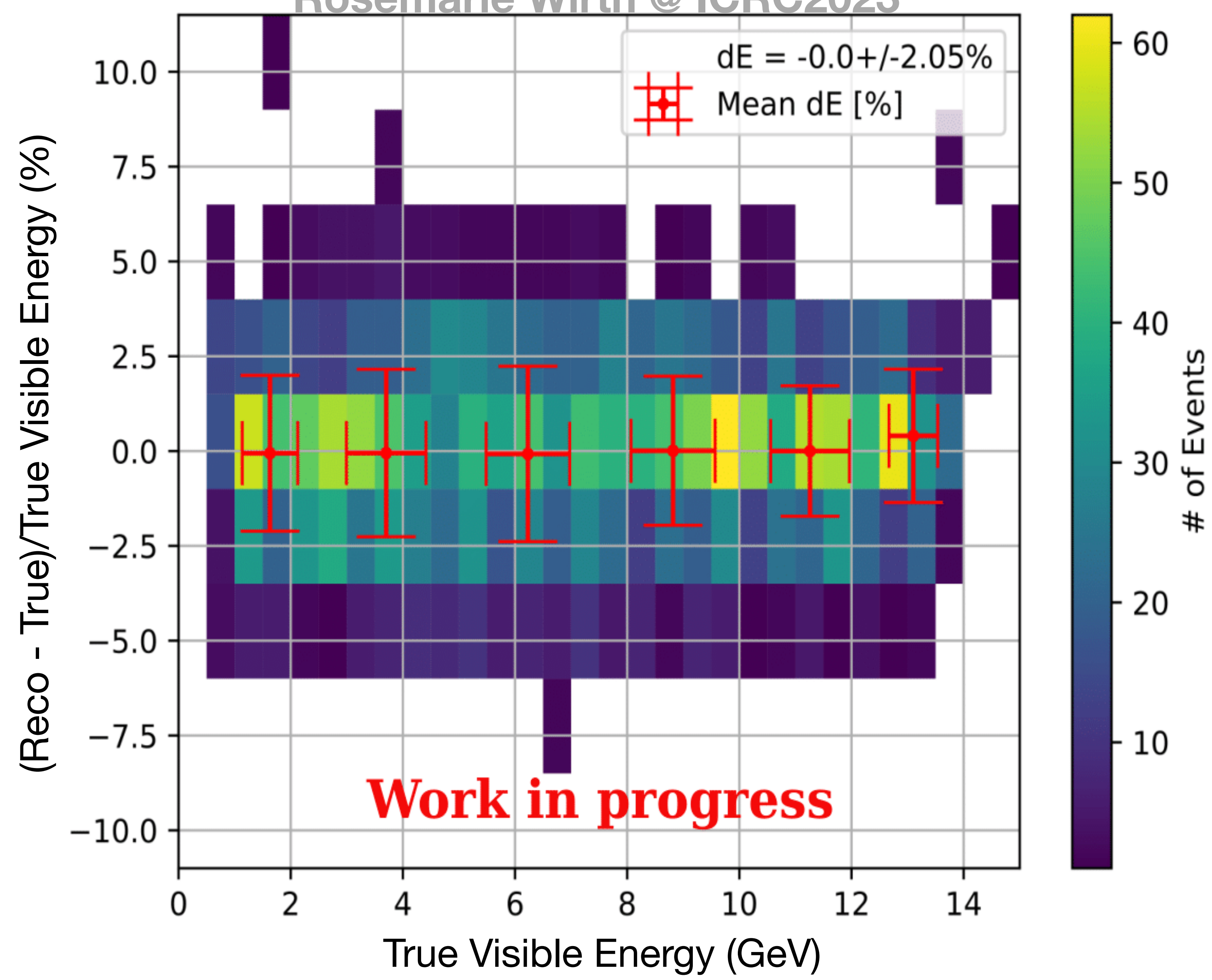
- Both lepton and hadron informations are used in the directionality reconstruction.
  - Low-threshold in LS detectors allows for more information from hadrons.
- The reconstructed neutrino direction deviates less from true neutrino direction compared with the charged lepton direction.
  - An advantage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

Atmospheric ν: Energy Reconstruction

- Two possible strategies on energy reconstruction:

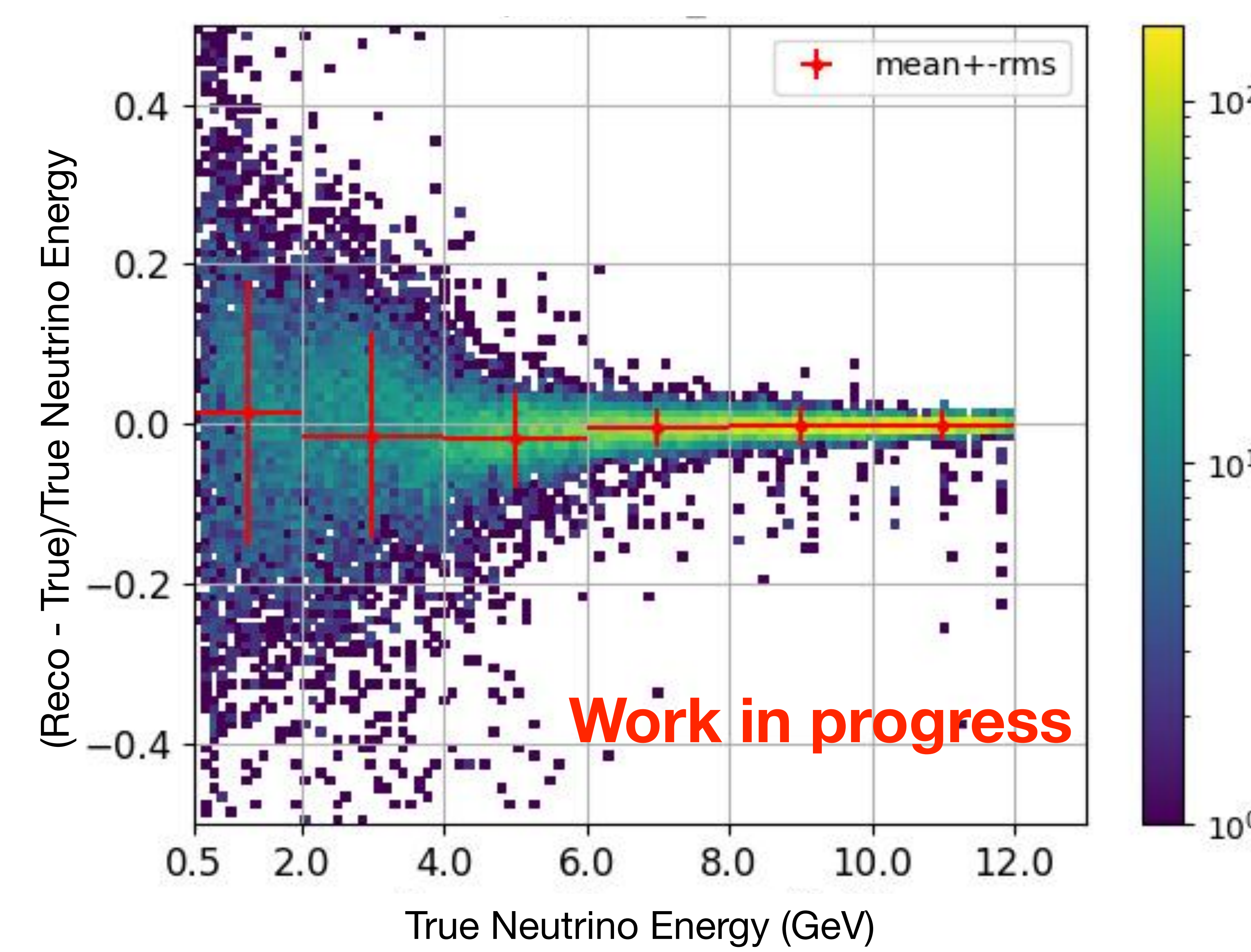
- Strategy 1: Reconstruct the **visible energy** (after quenching in the LS).

Marta Colomer Molla, Mariam Rifai, Rosemarie Wirth @ ICRC2023



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

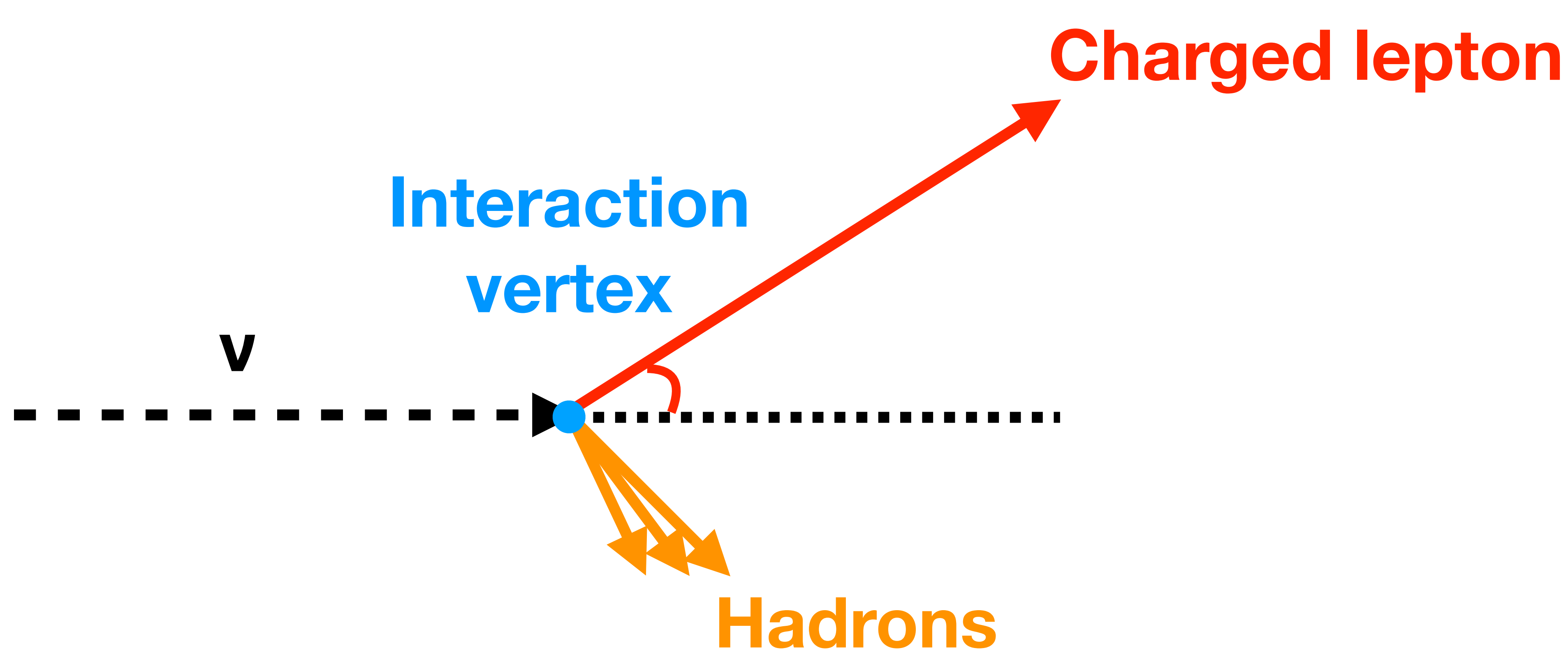
- Strategy 2: Reconstruct the **neutrino energy**
  - For fully-contained events only.



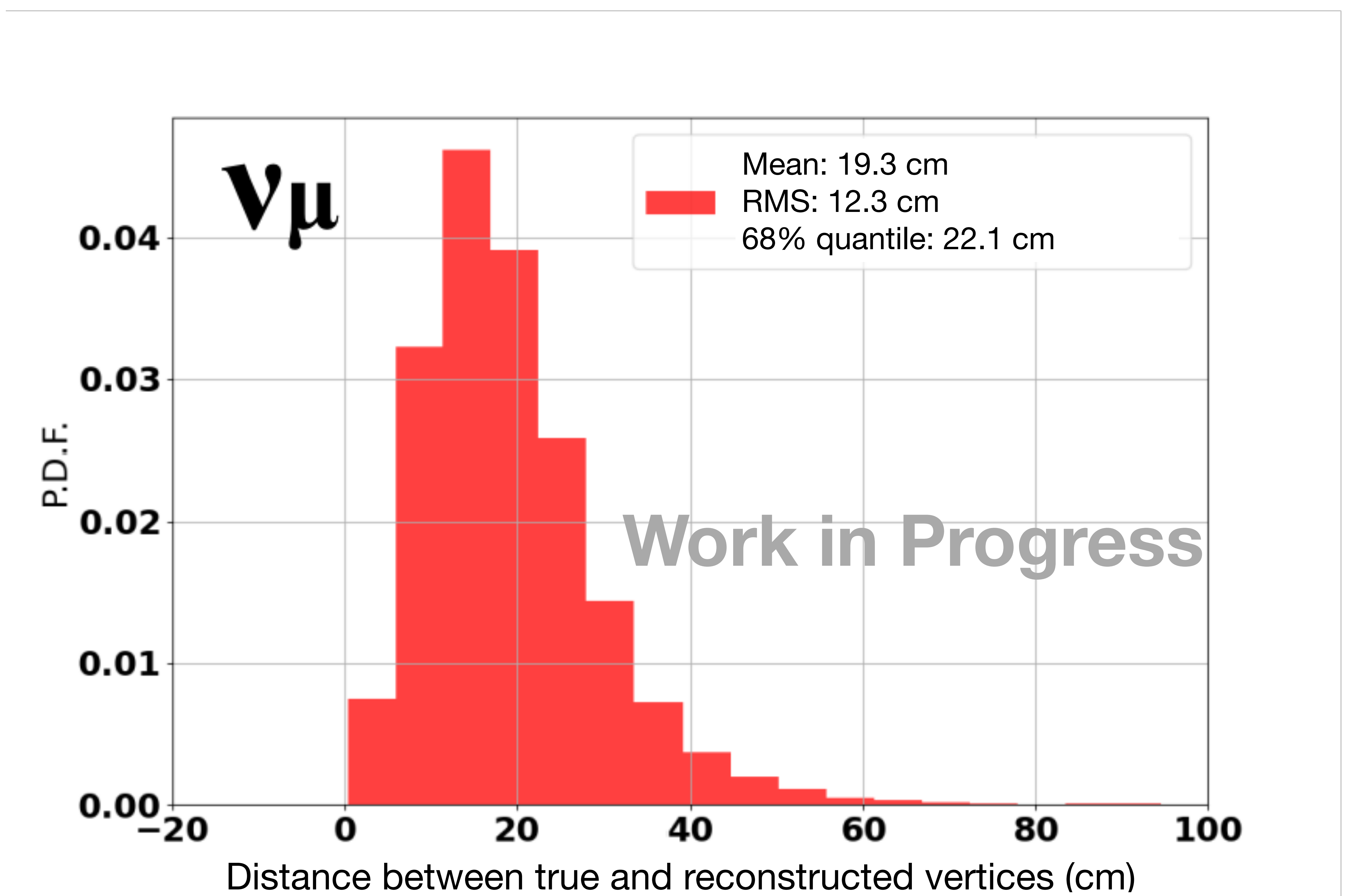
ML result with PMT features

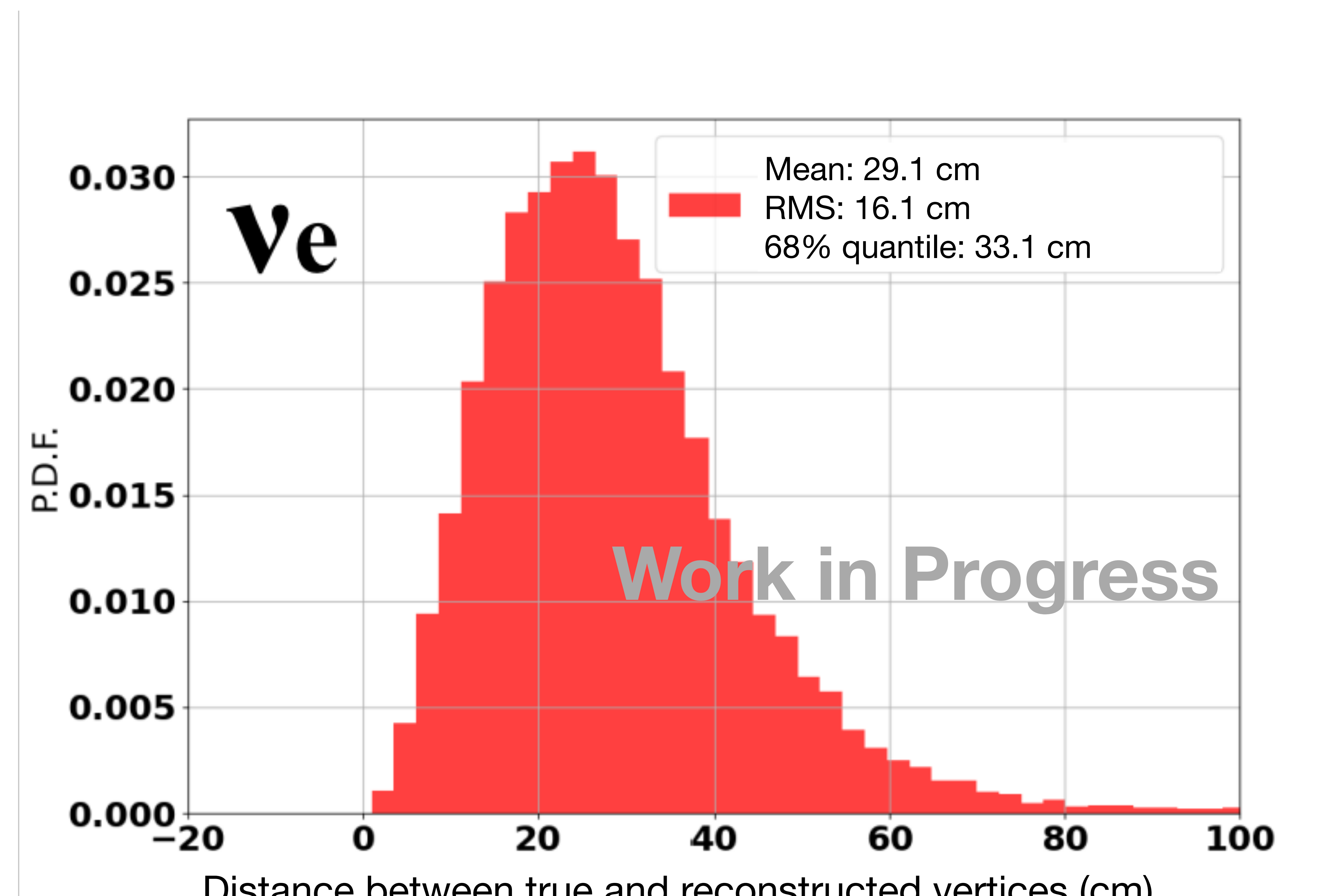
- Detailed study is on-going on their impact on oscillation analysis.

Atmospheric ν: Vertex Reconstruction



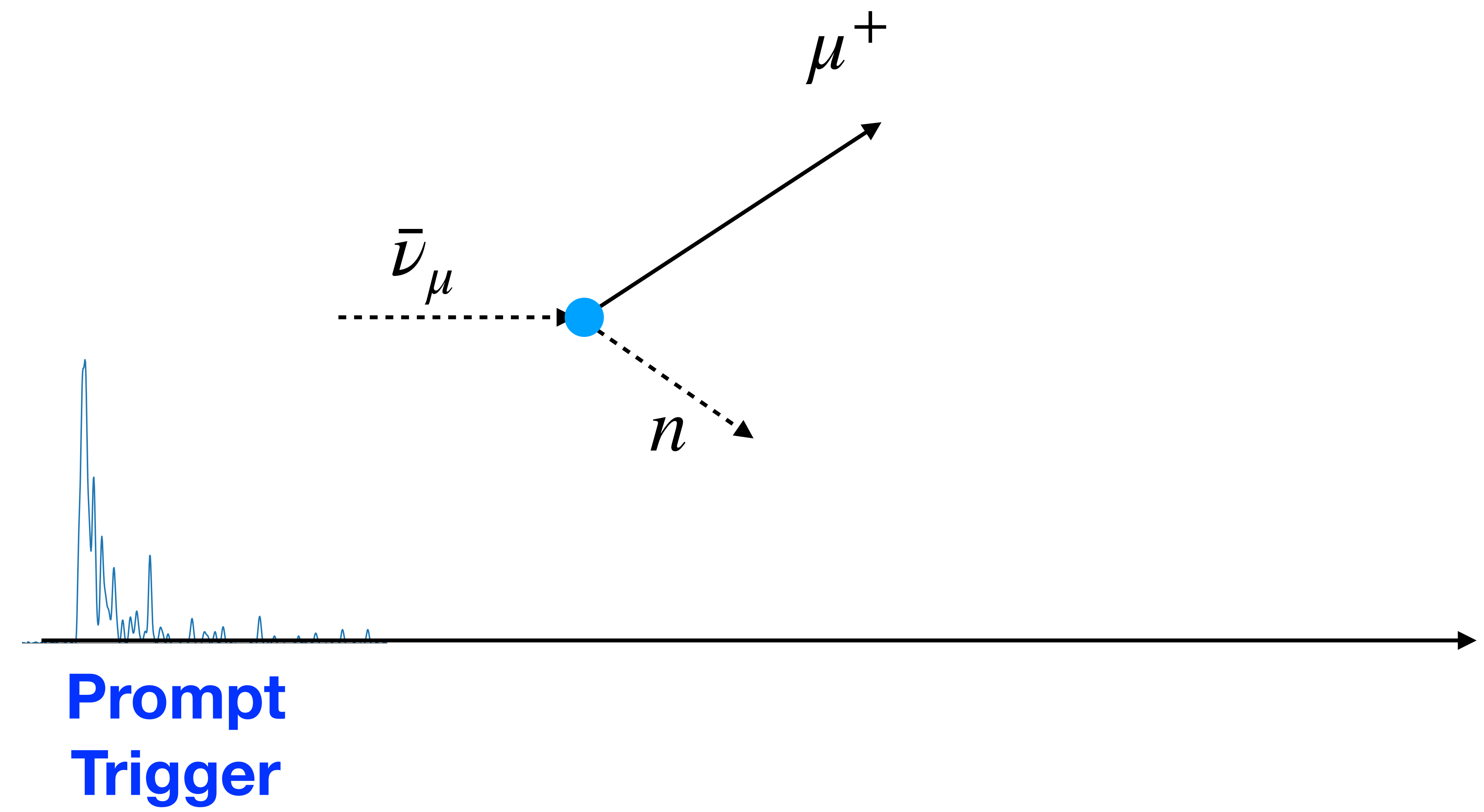
- Information of interaction vertex is useful for external background rejection and as input to other reconstruction algorithms.
- Performances evaluated by the distance between true and reconstructed vertices:
  - Resolution: ~22 cm for ν_μ-CC and ~33 cm for ν_e-CC

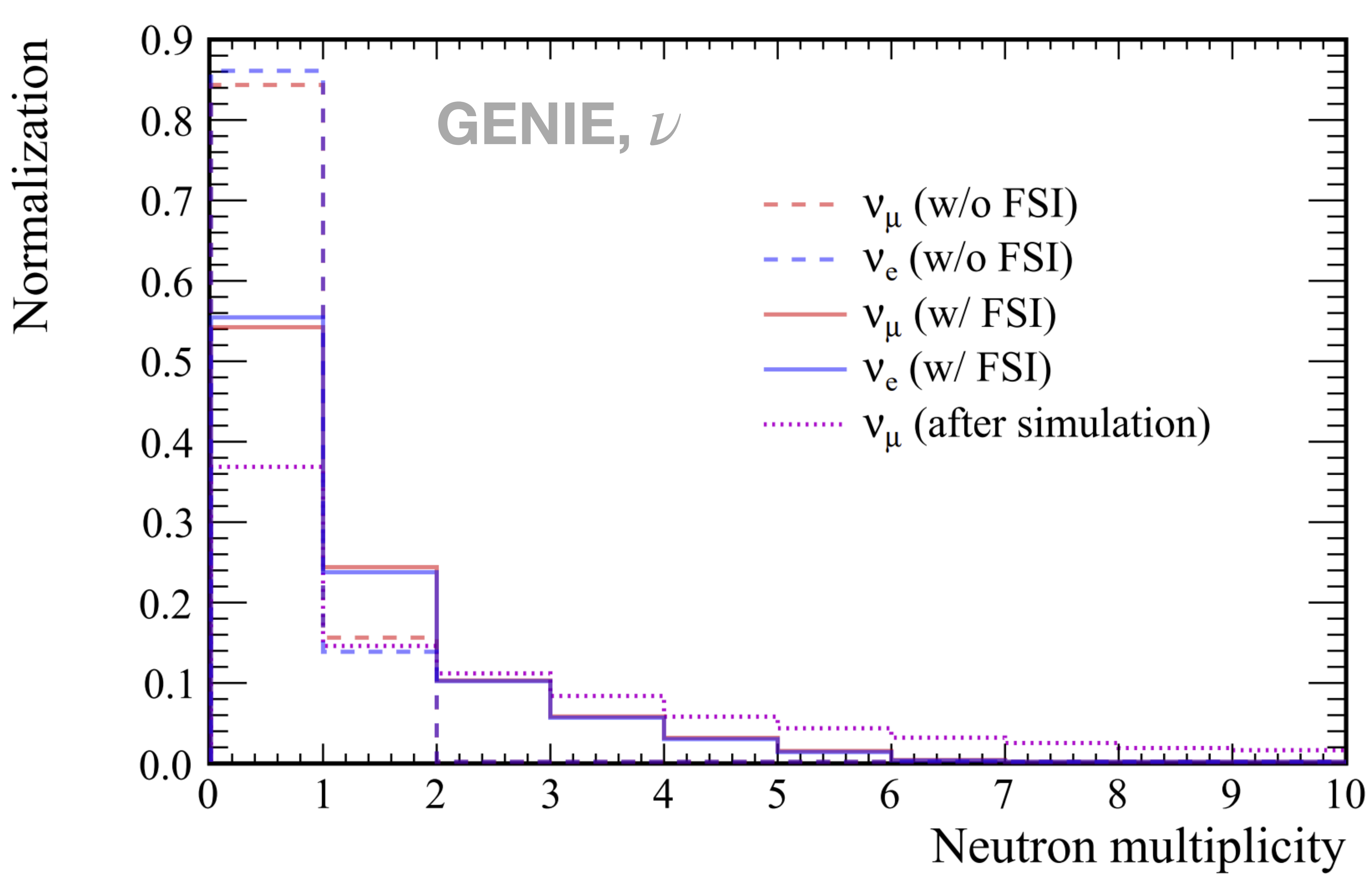


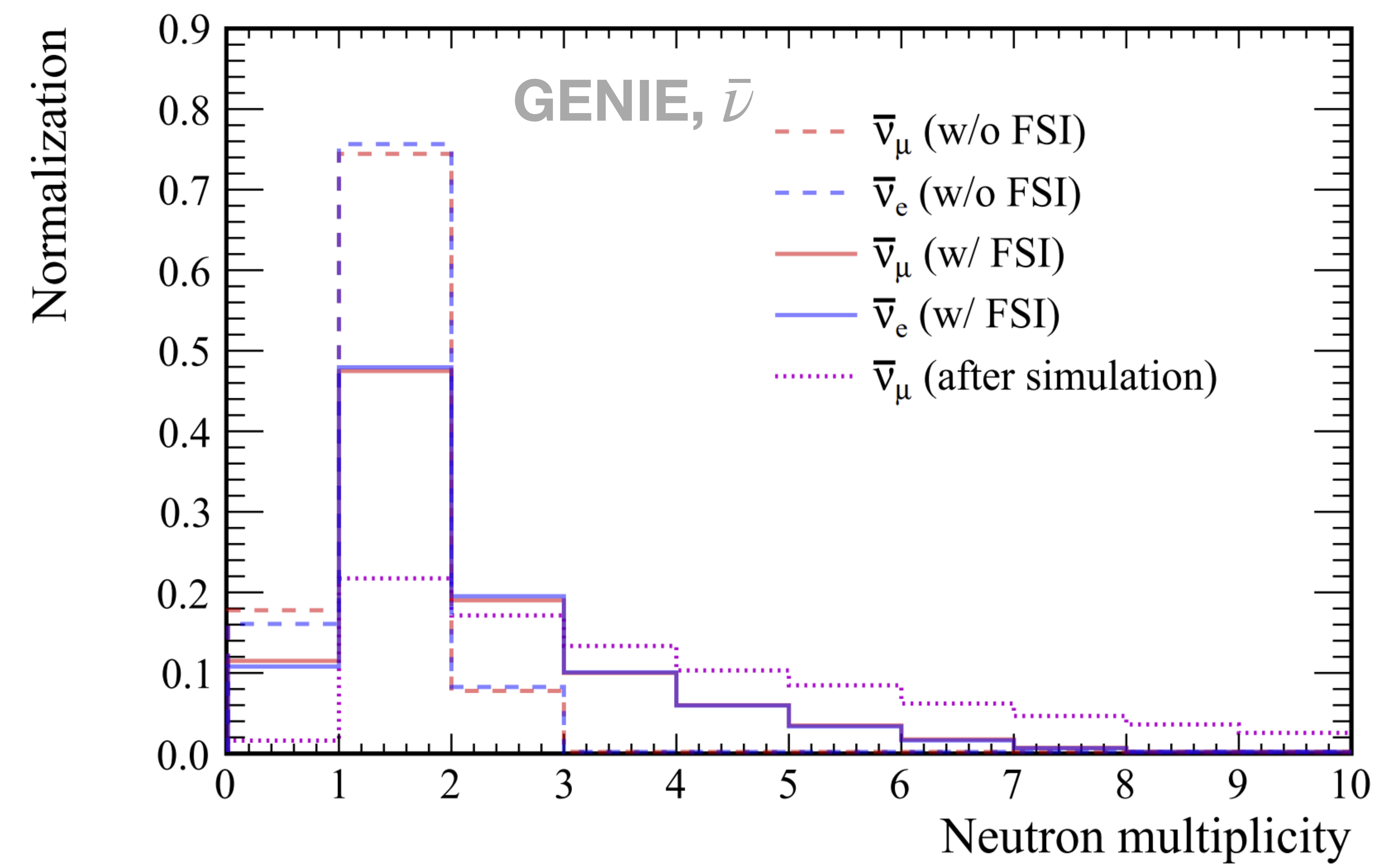


Neutrino vs Anti-neutrino

	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.

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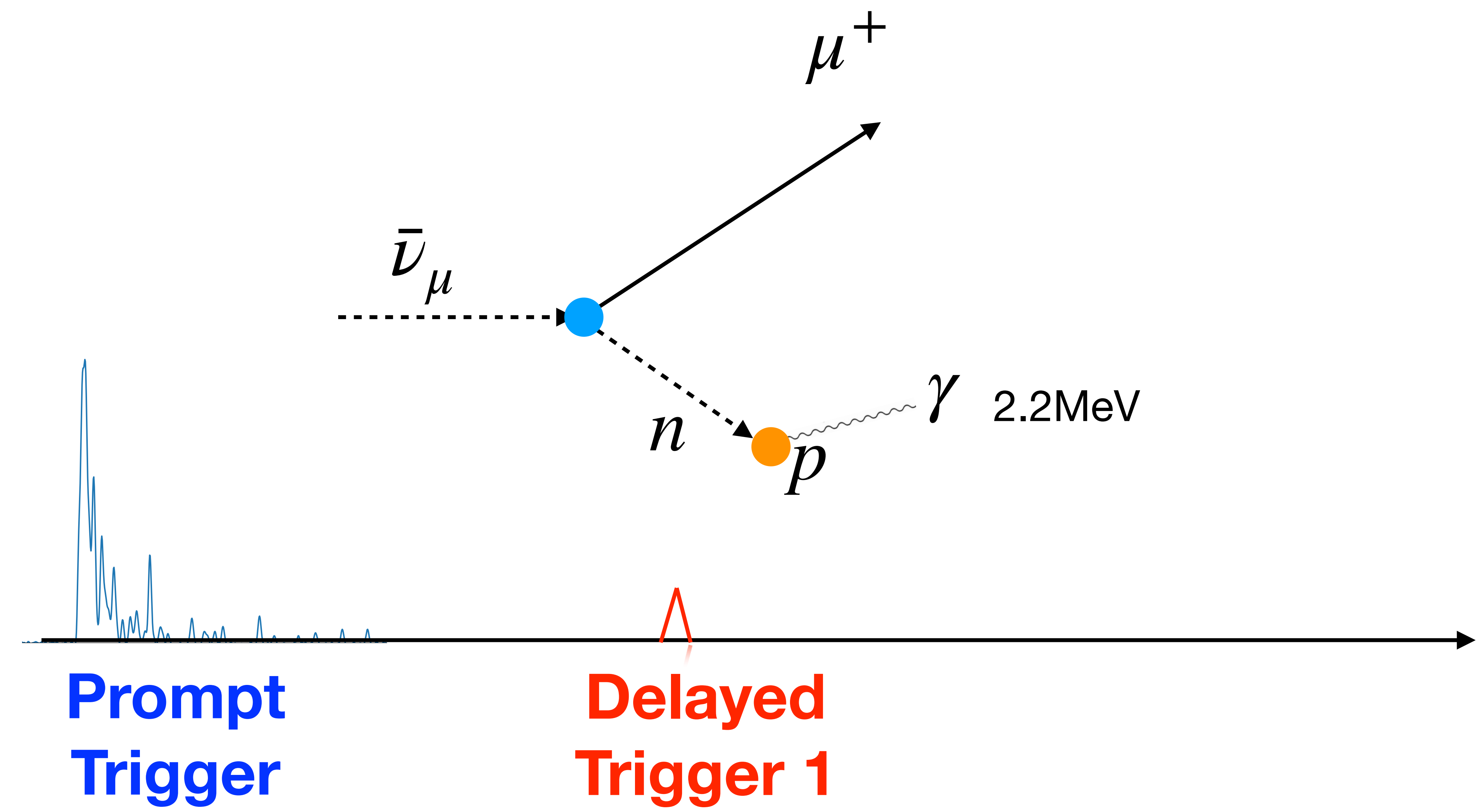

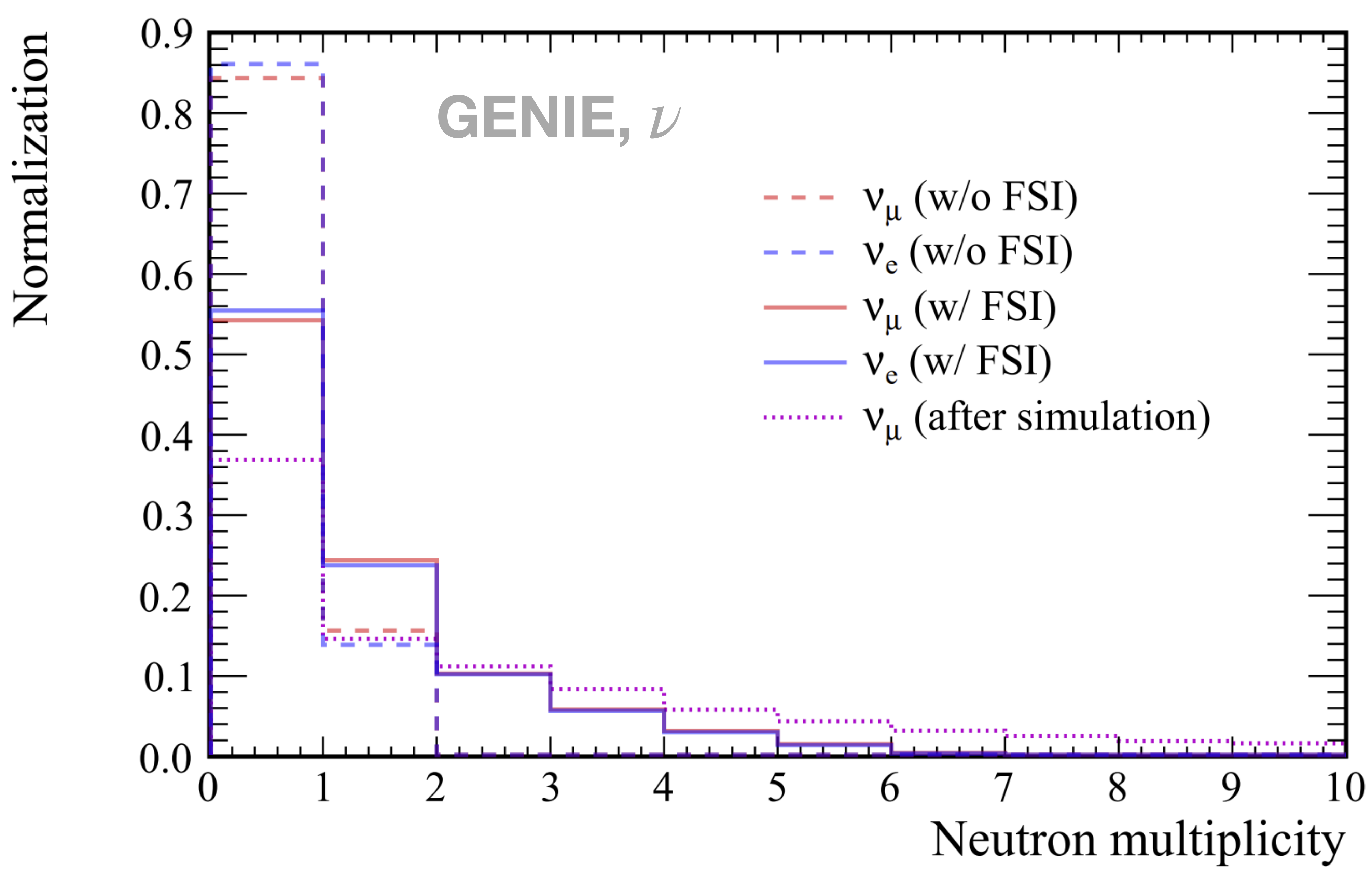

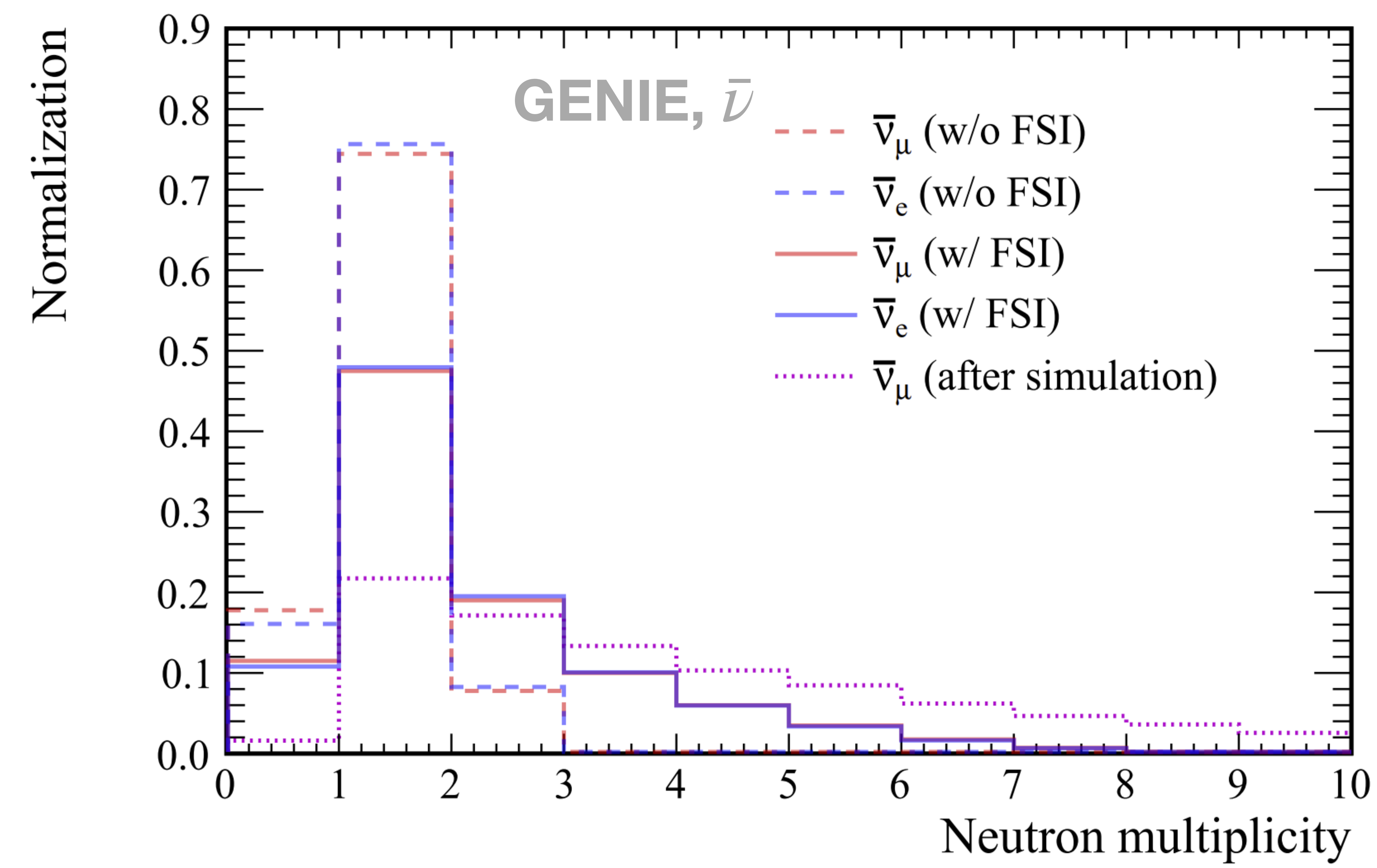

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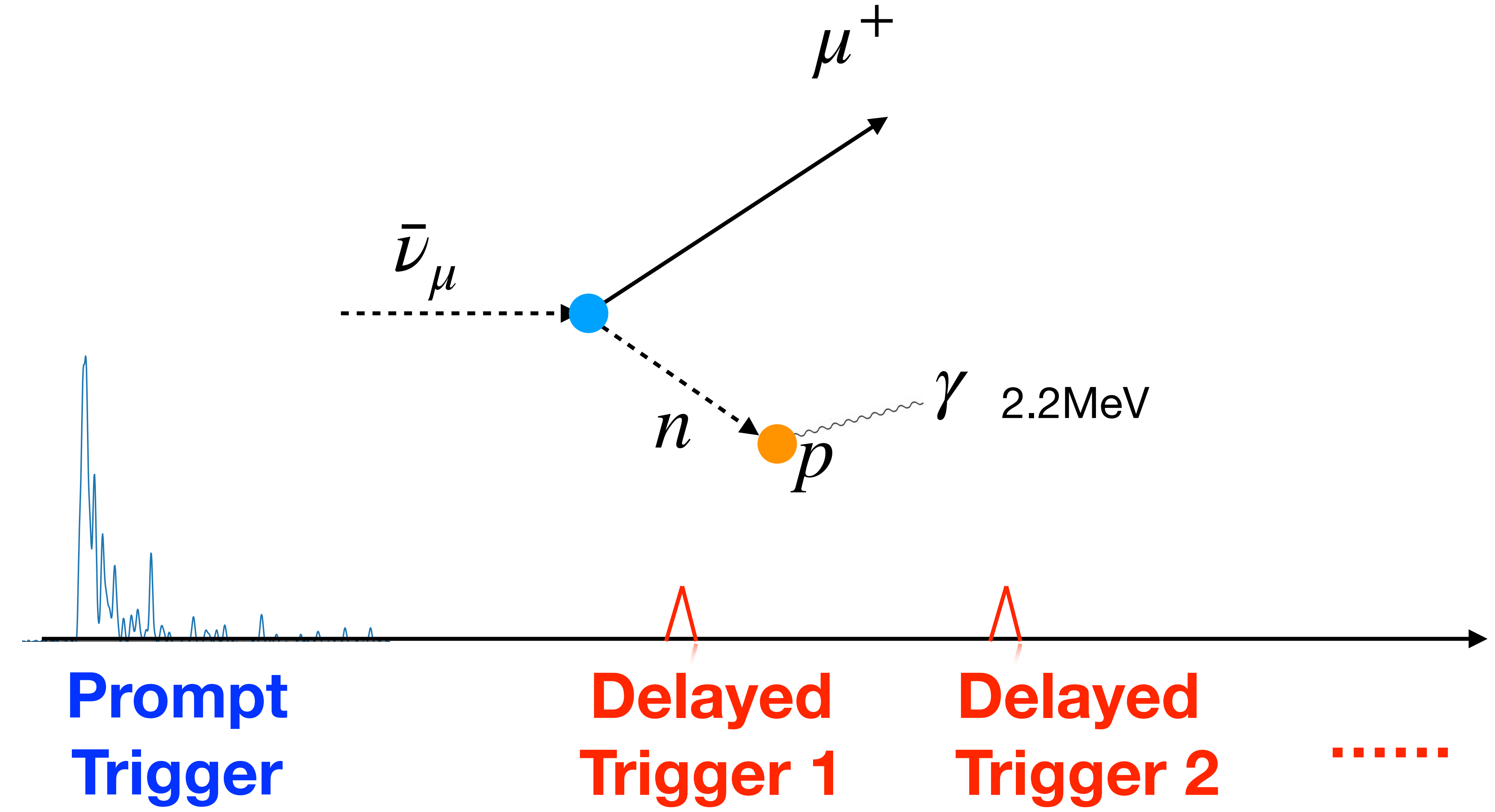
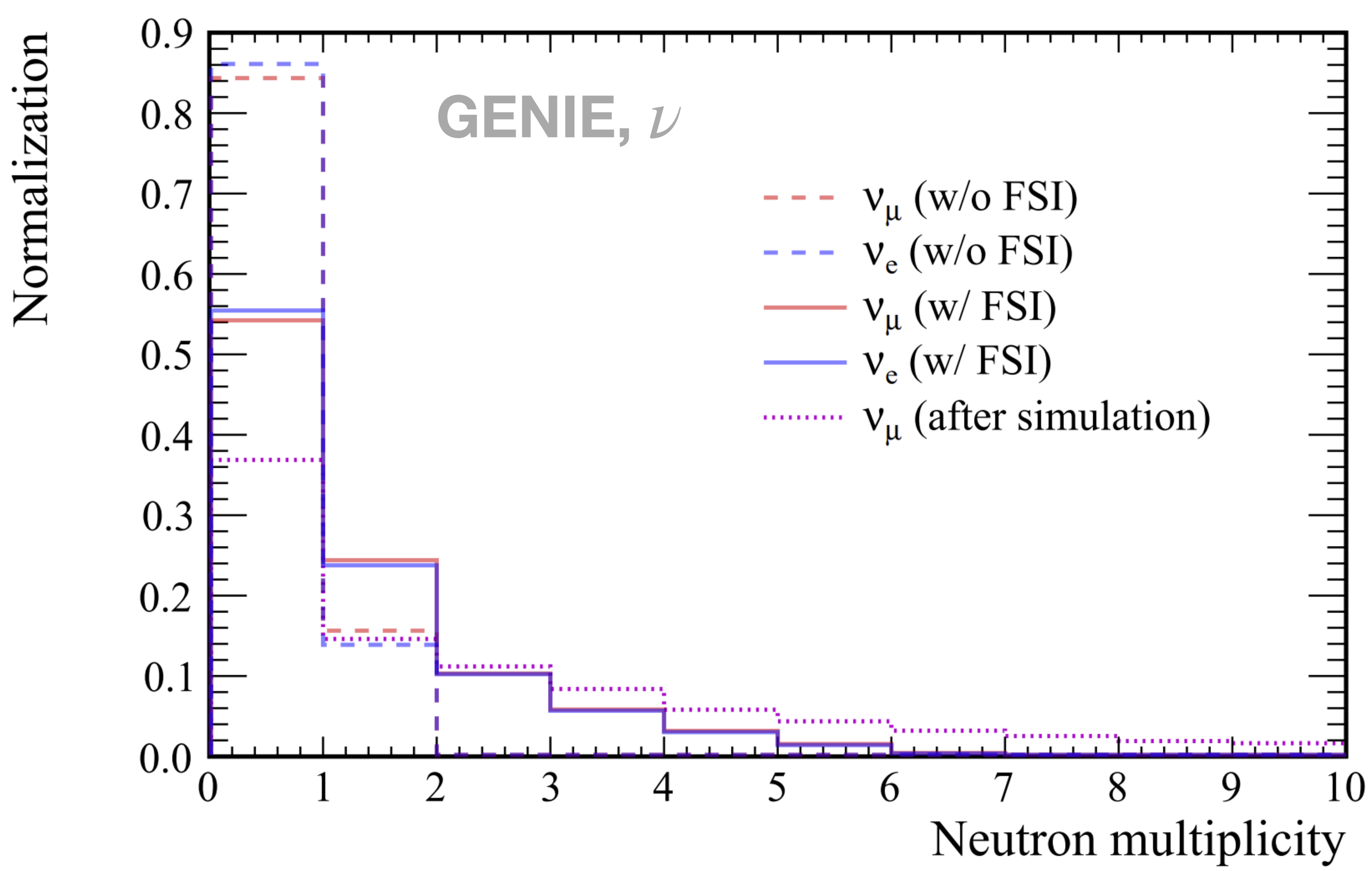
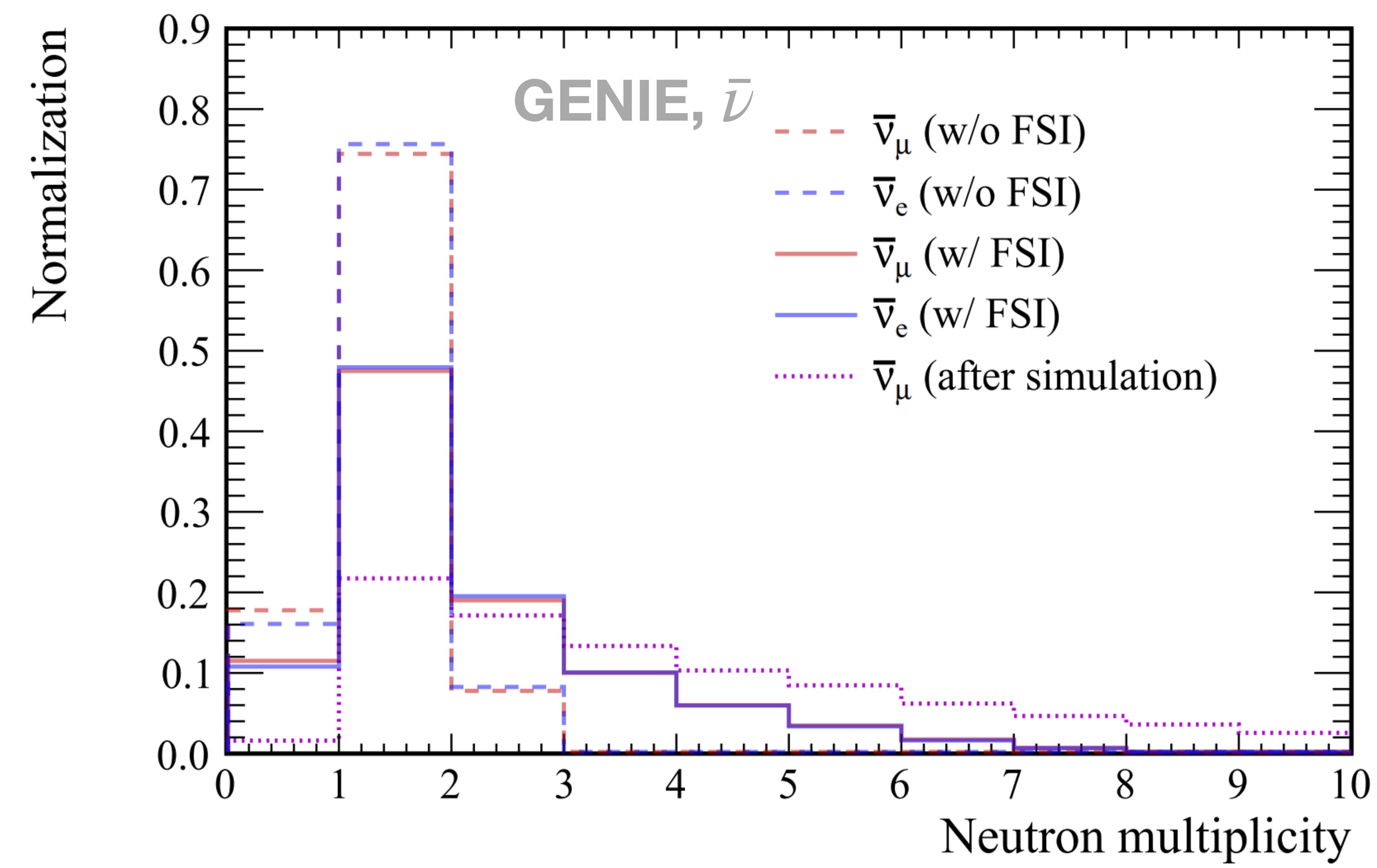
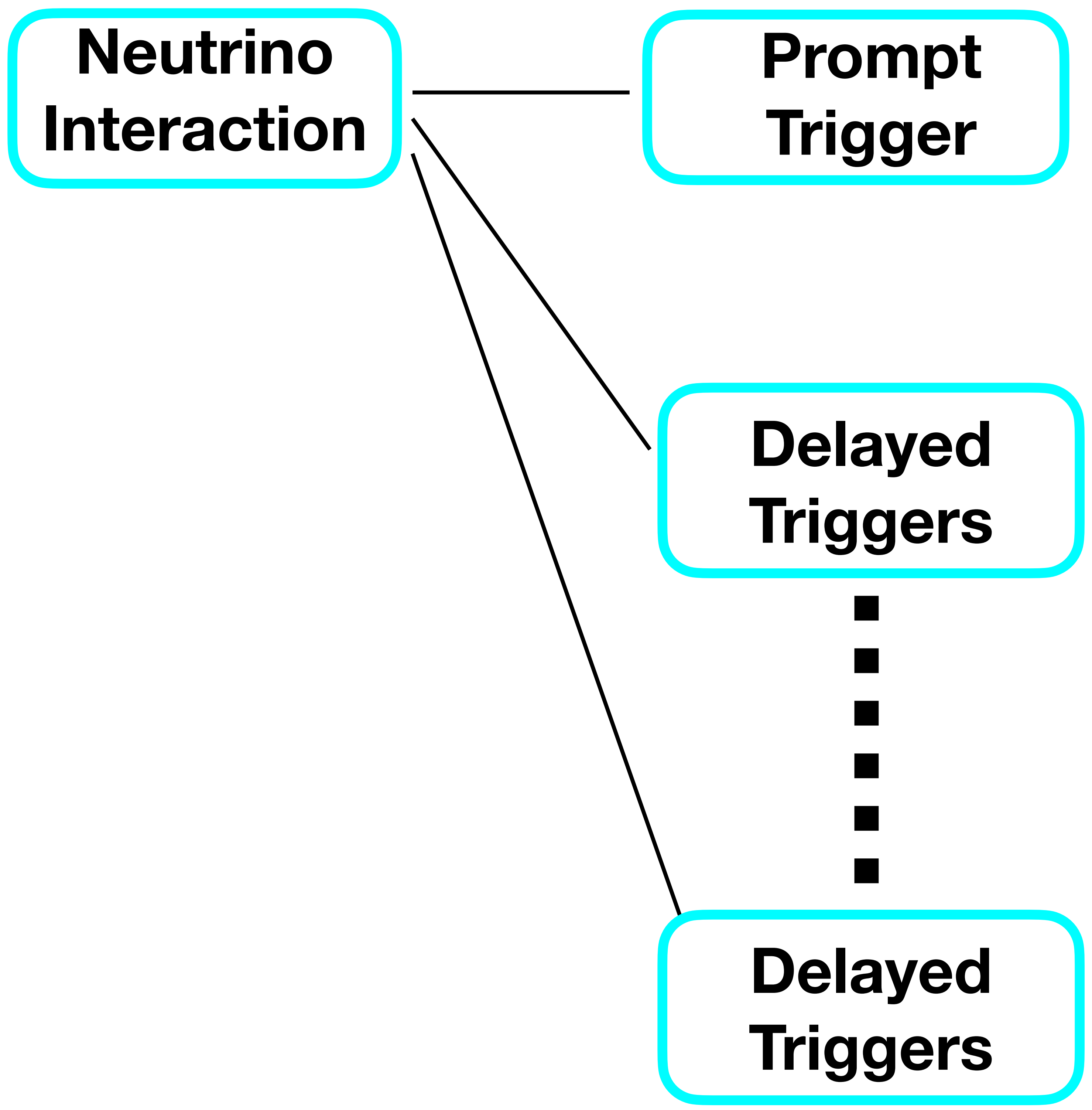




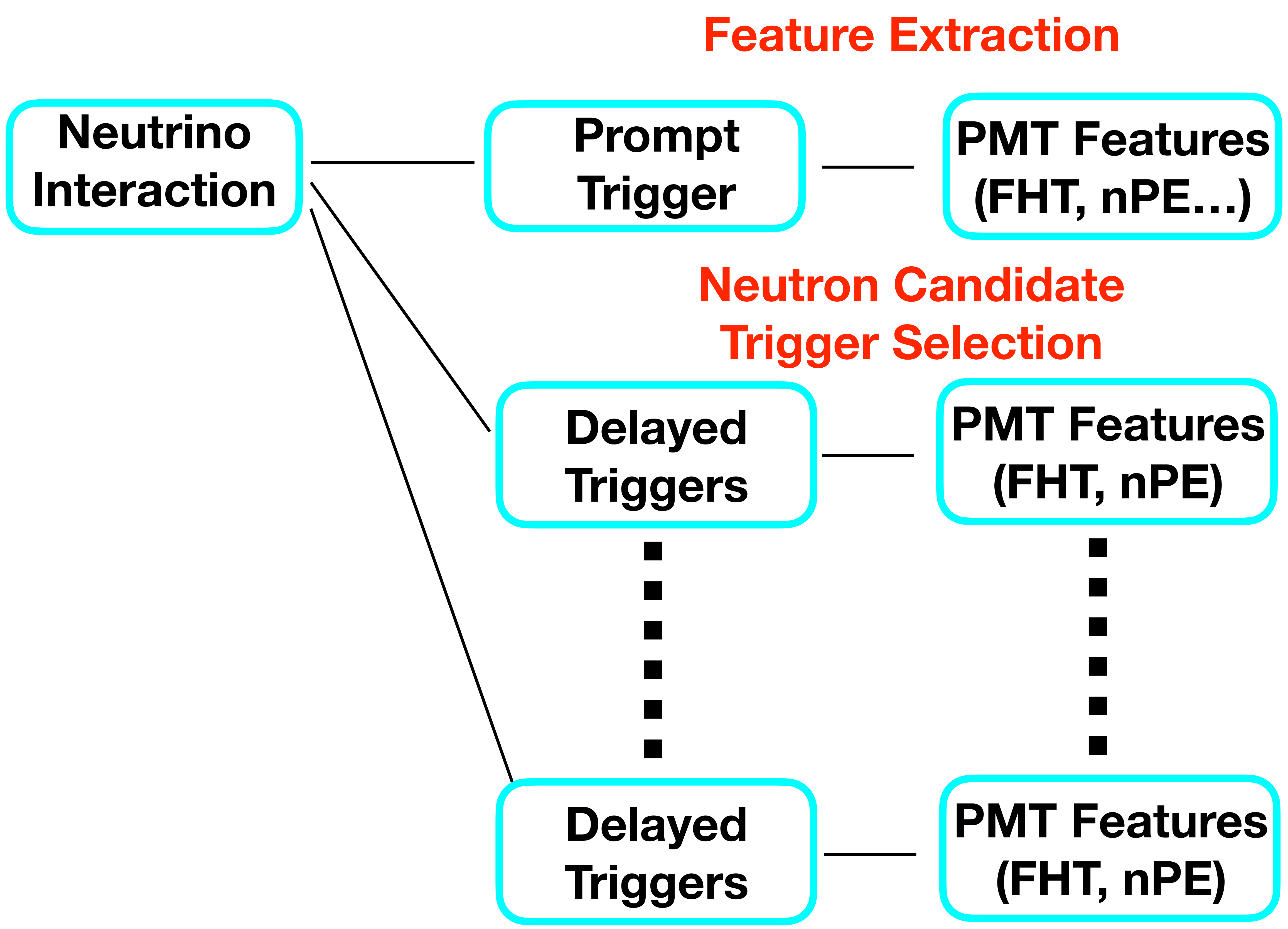


- It is possible to statistically separate ν and $\bar{\nu}$ with neutron-capture informations.

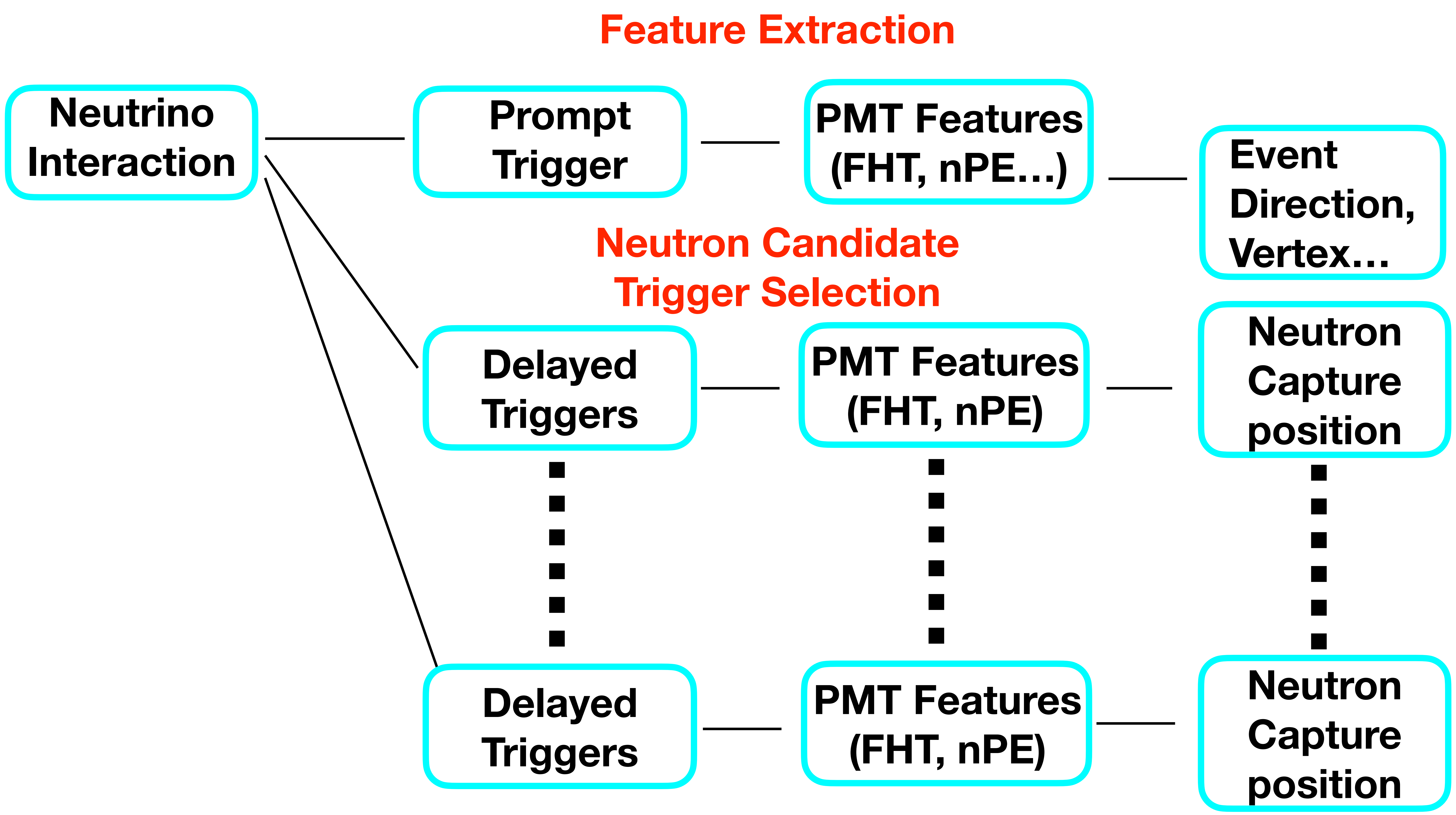
Neutrino Flavor Identification Strategies



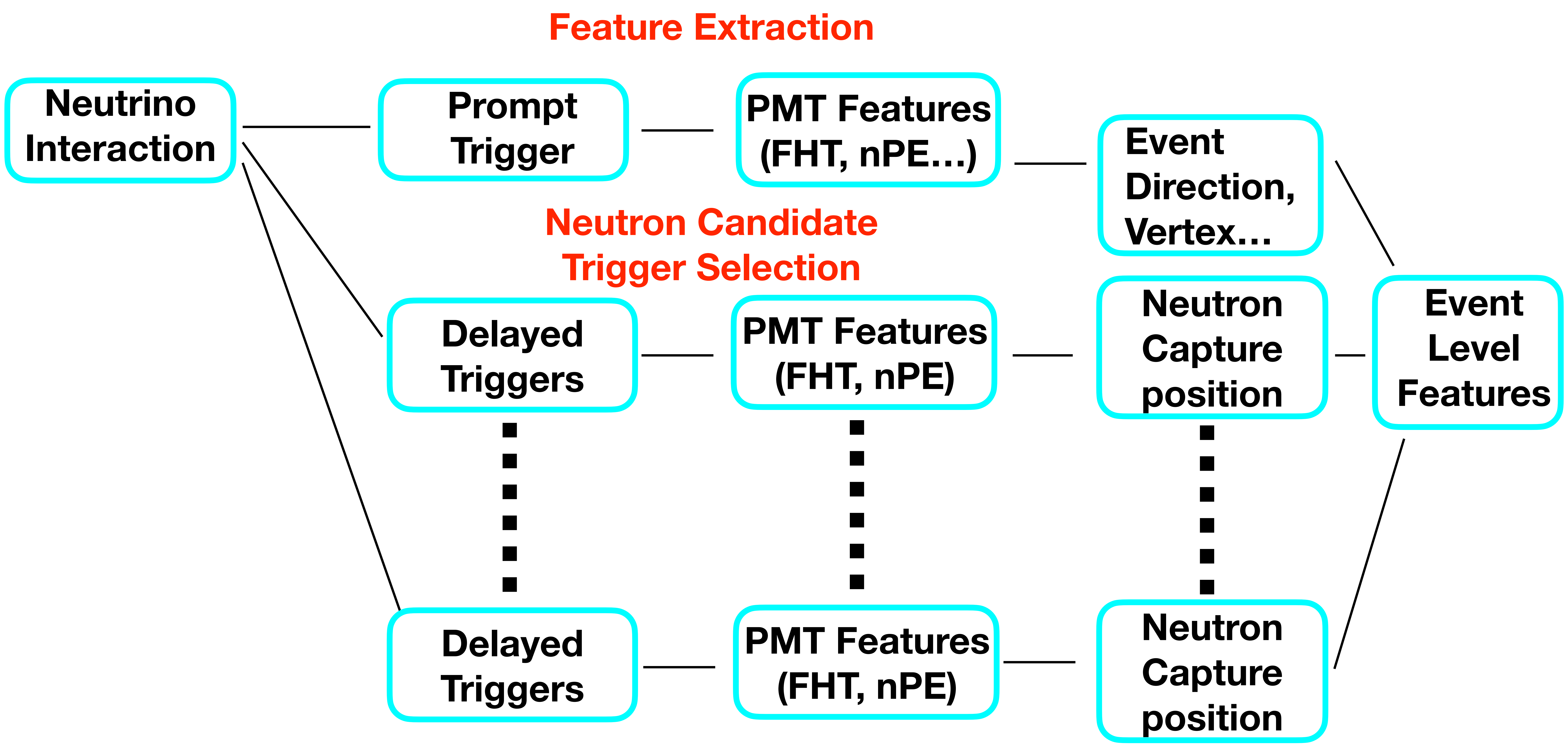
Neutrino Flavor Identification Strategies



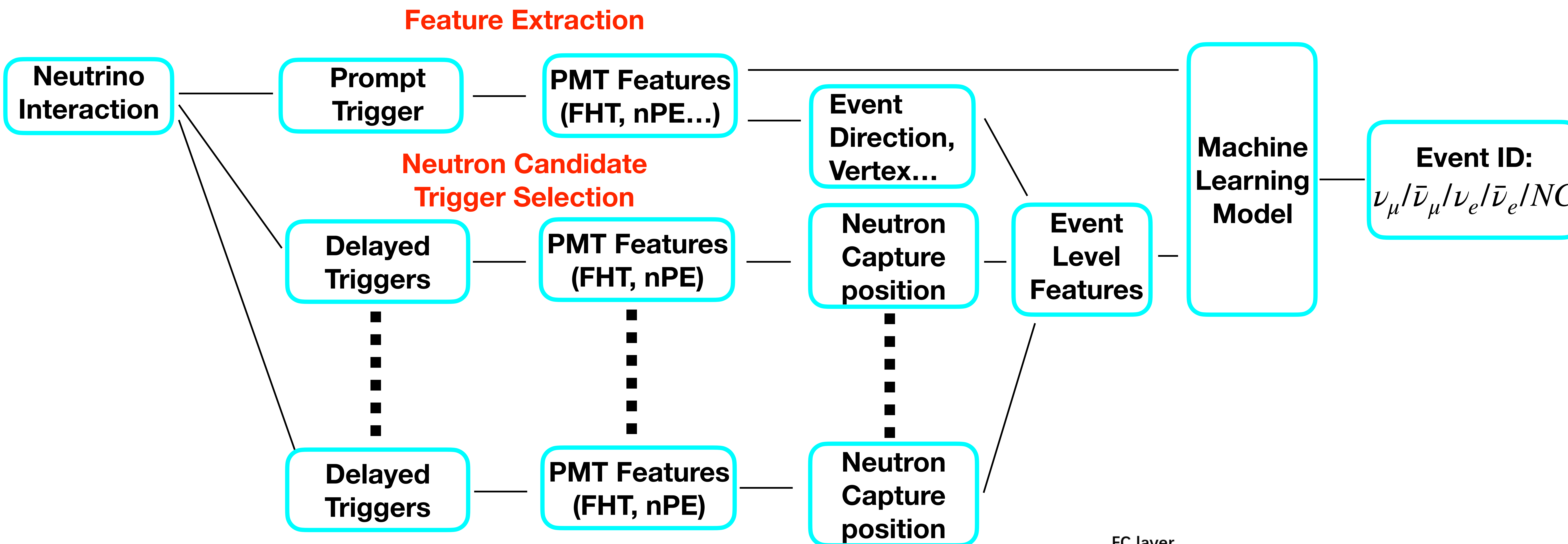
Neutrino Flavor Identification Strategies



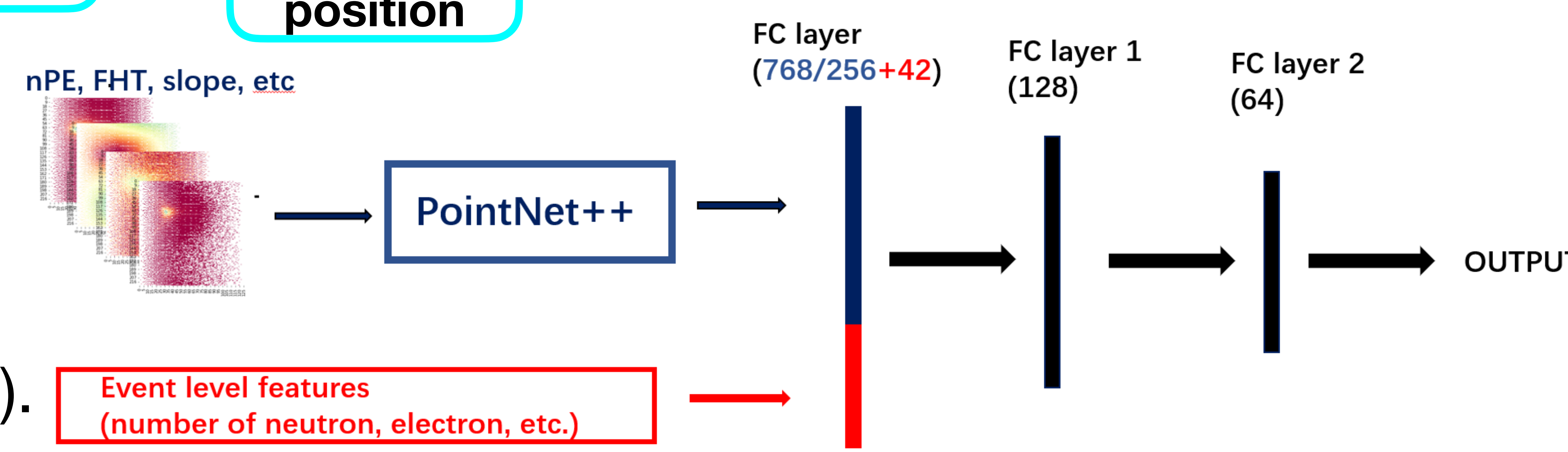
Neutrino Flavor Identification Strategies



Neutrino Flavor Identification Strategies

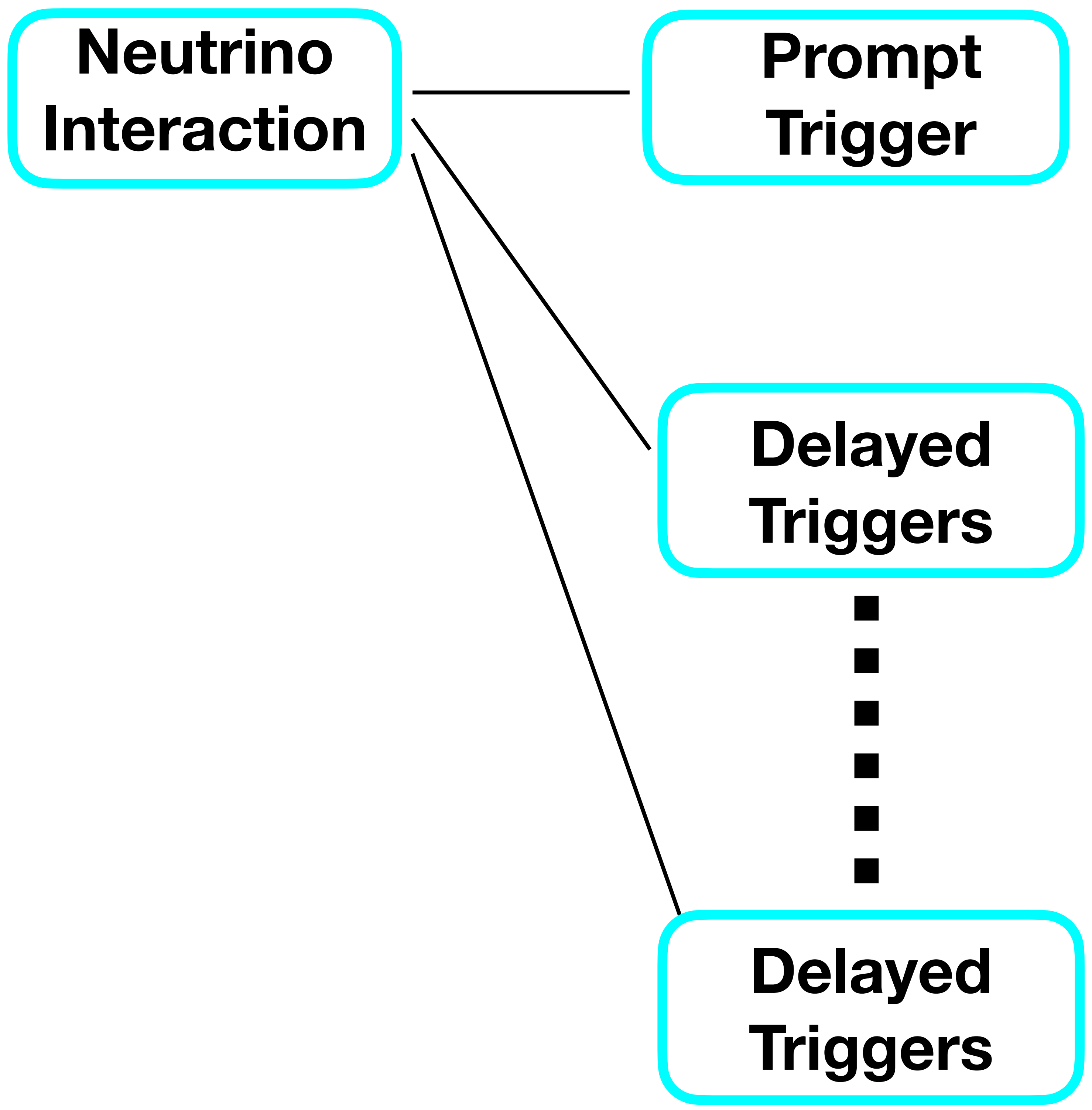


- **Strategy 1**: Combine the PMT-level features with event-level features (neutron-multiplicity, relative positions of neutrons to event vertex/directions, etc.).

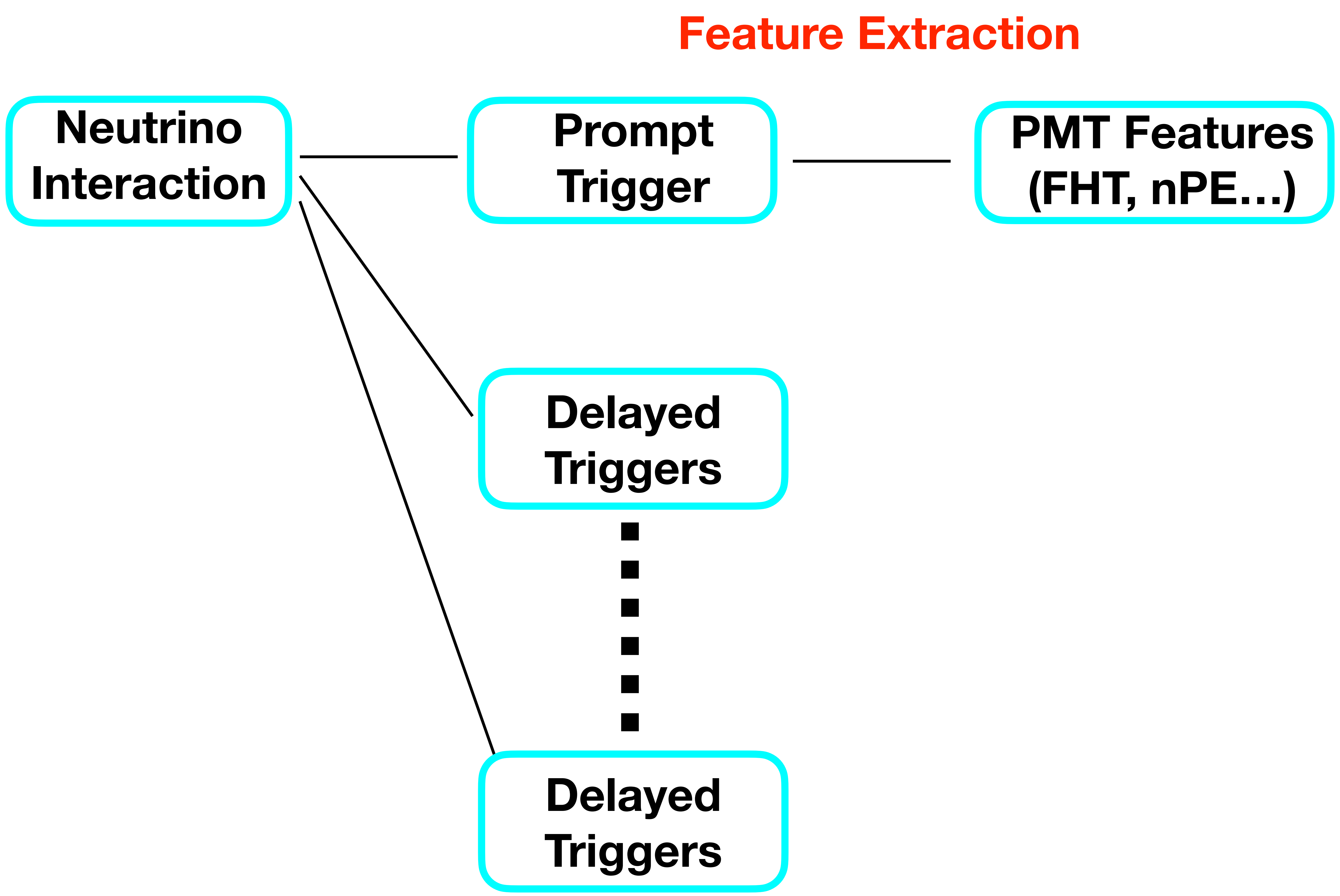


For more details see Talk by Yongpeng Zhang: "The methodology of atmospheric neutrino identification in JUNO"

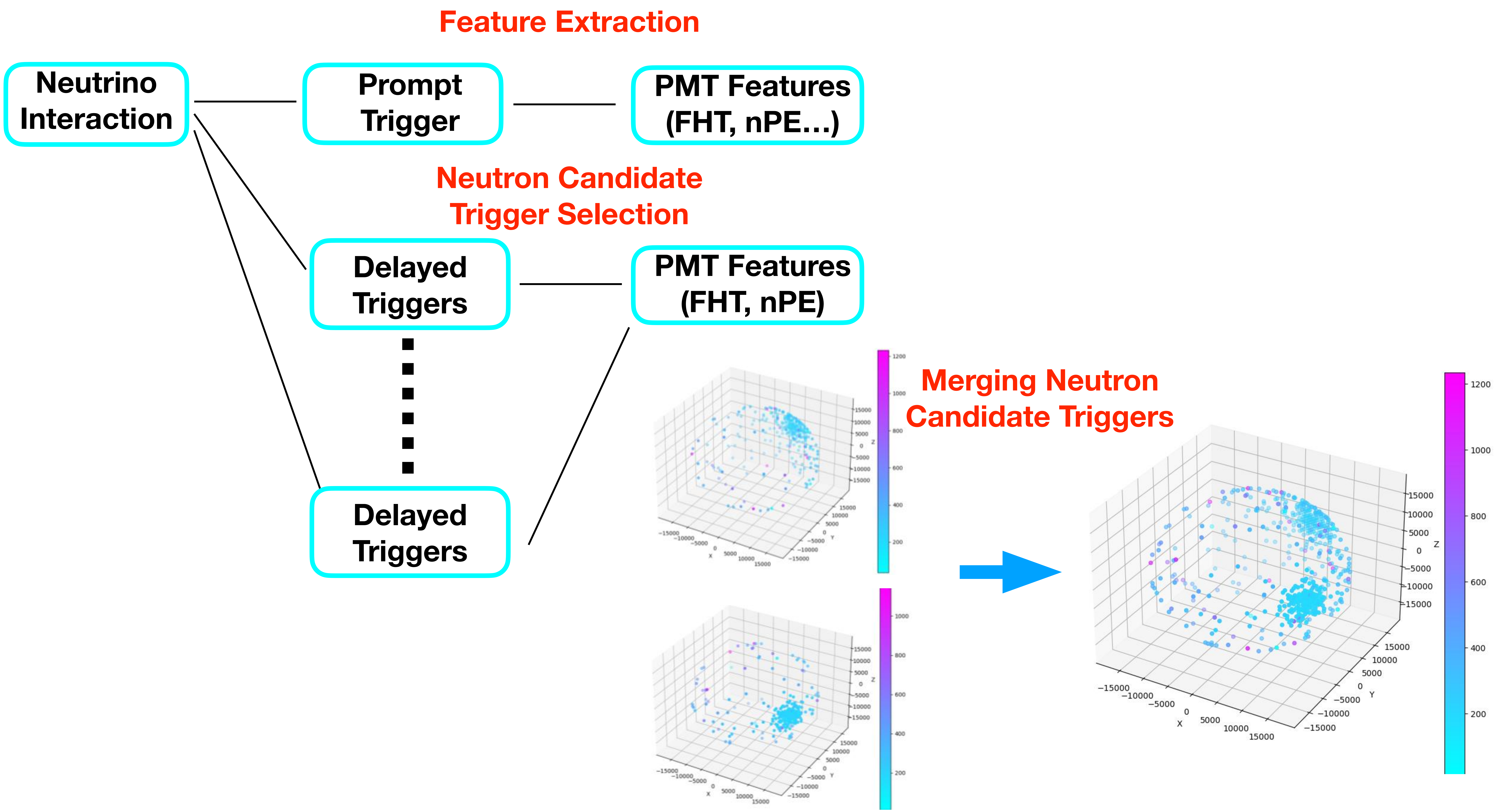
Neutrino Flavor Identification Strategies



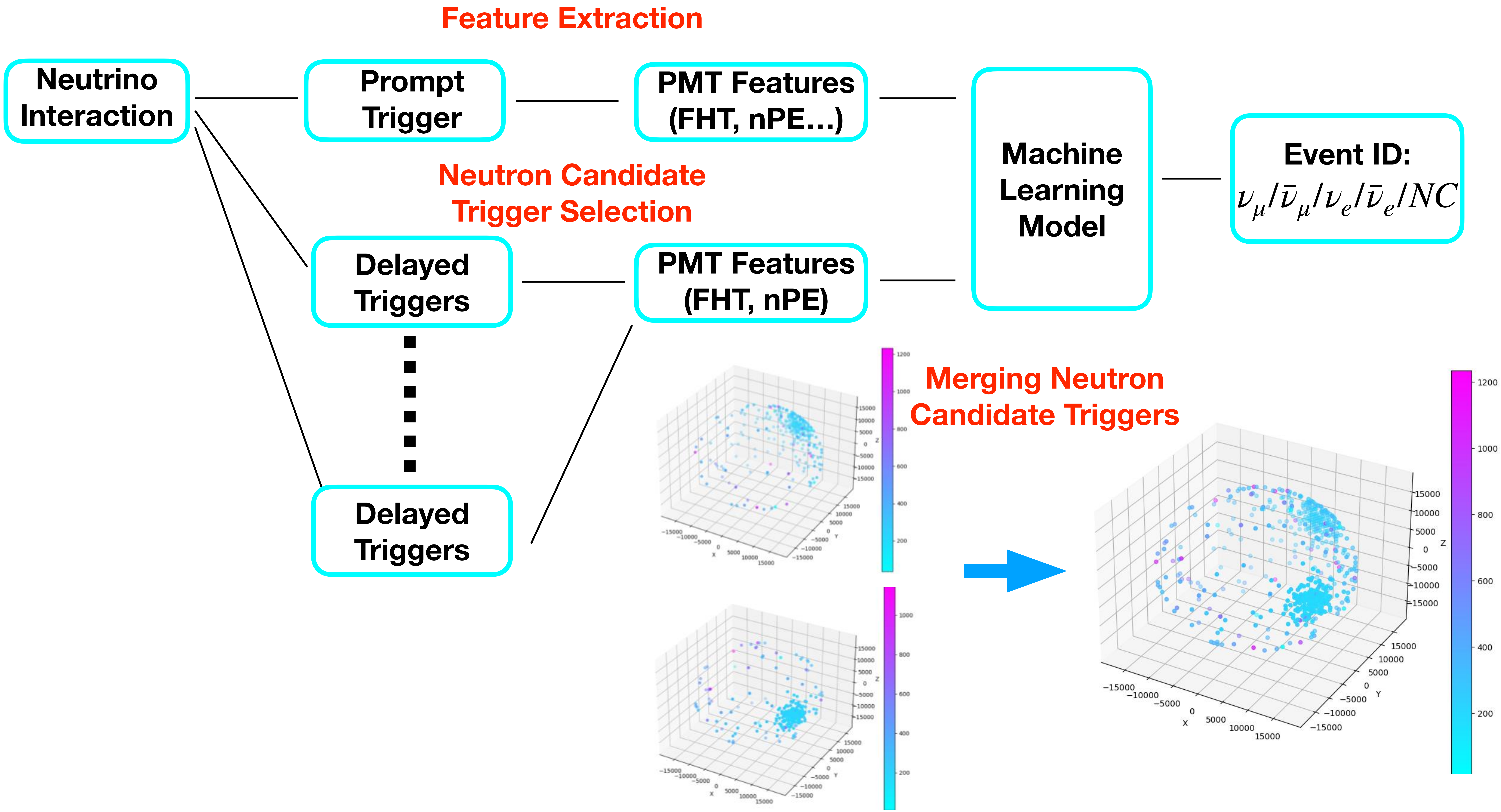
Neutrino Flavor Identification Strategies



Neutrino Flavor Identification Strategies

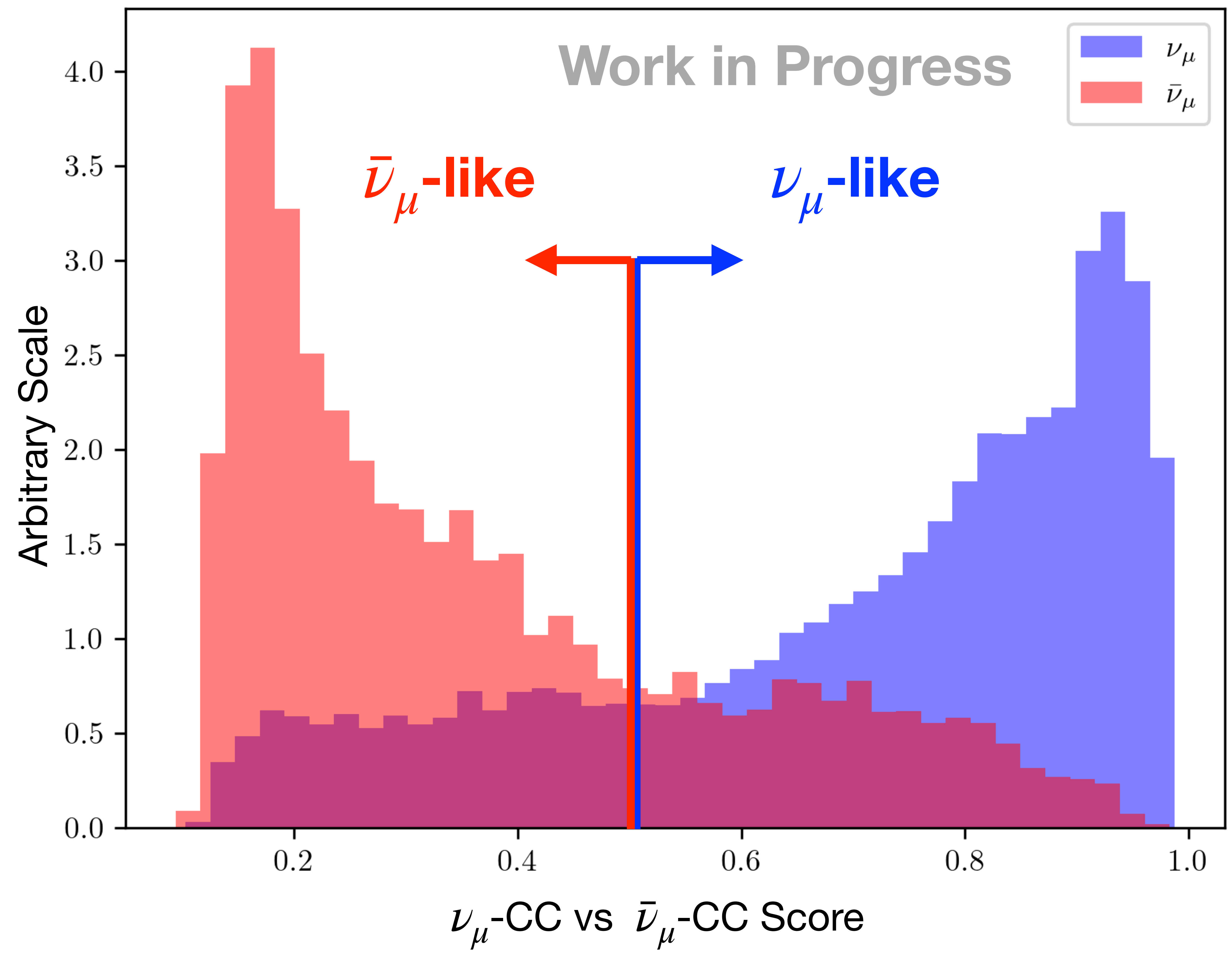


Neutrino Flavor Identification Strategies



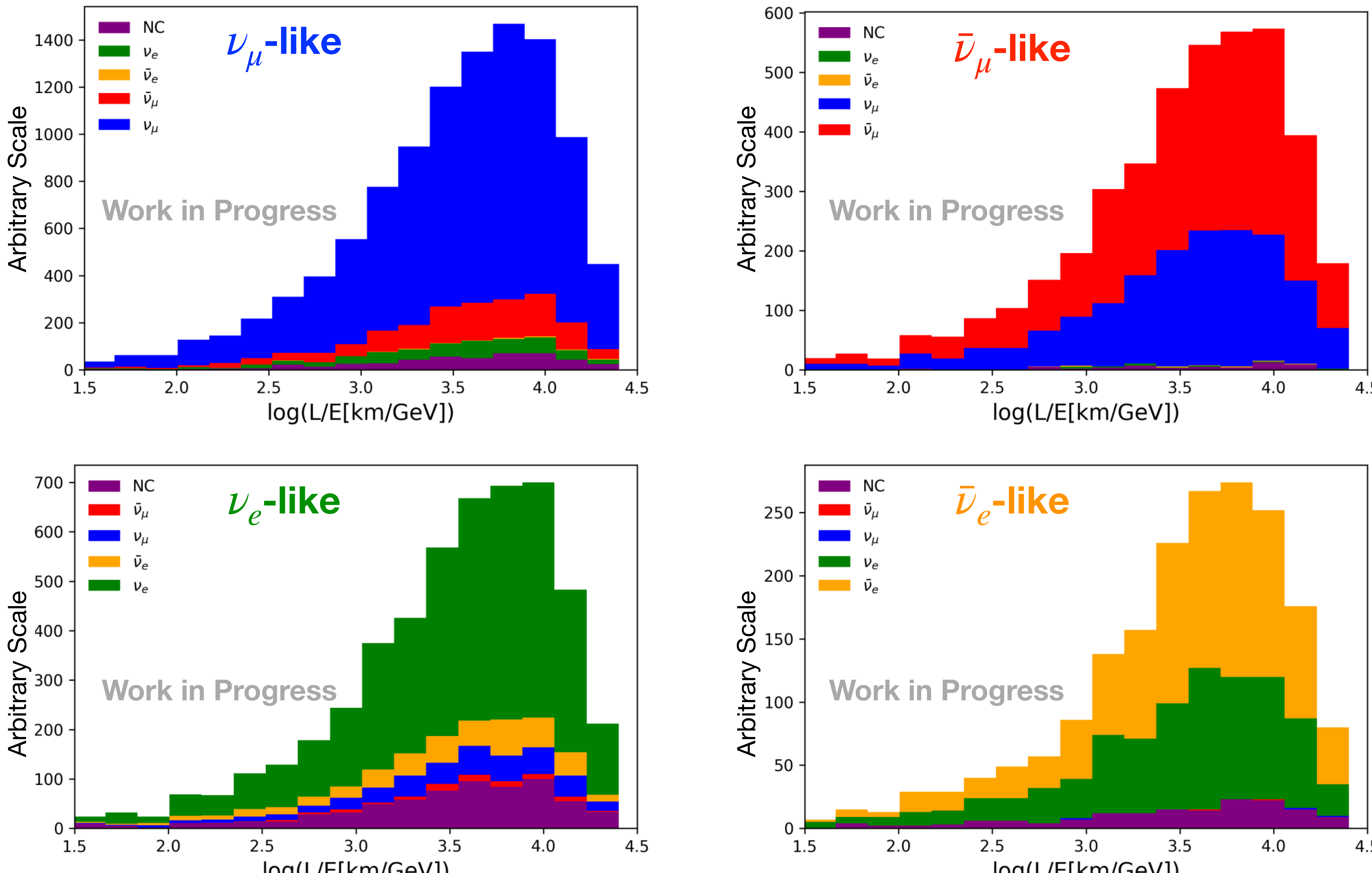
- **Strategy 2**: Directly input PMT features from multiple triggers into ML.

Neutrino vs Anti-neutrino Performance



- 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.

Neutrino Flavor Identification Performances



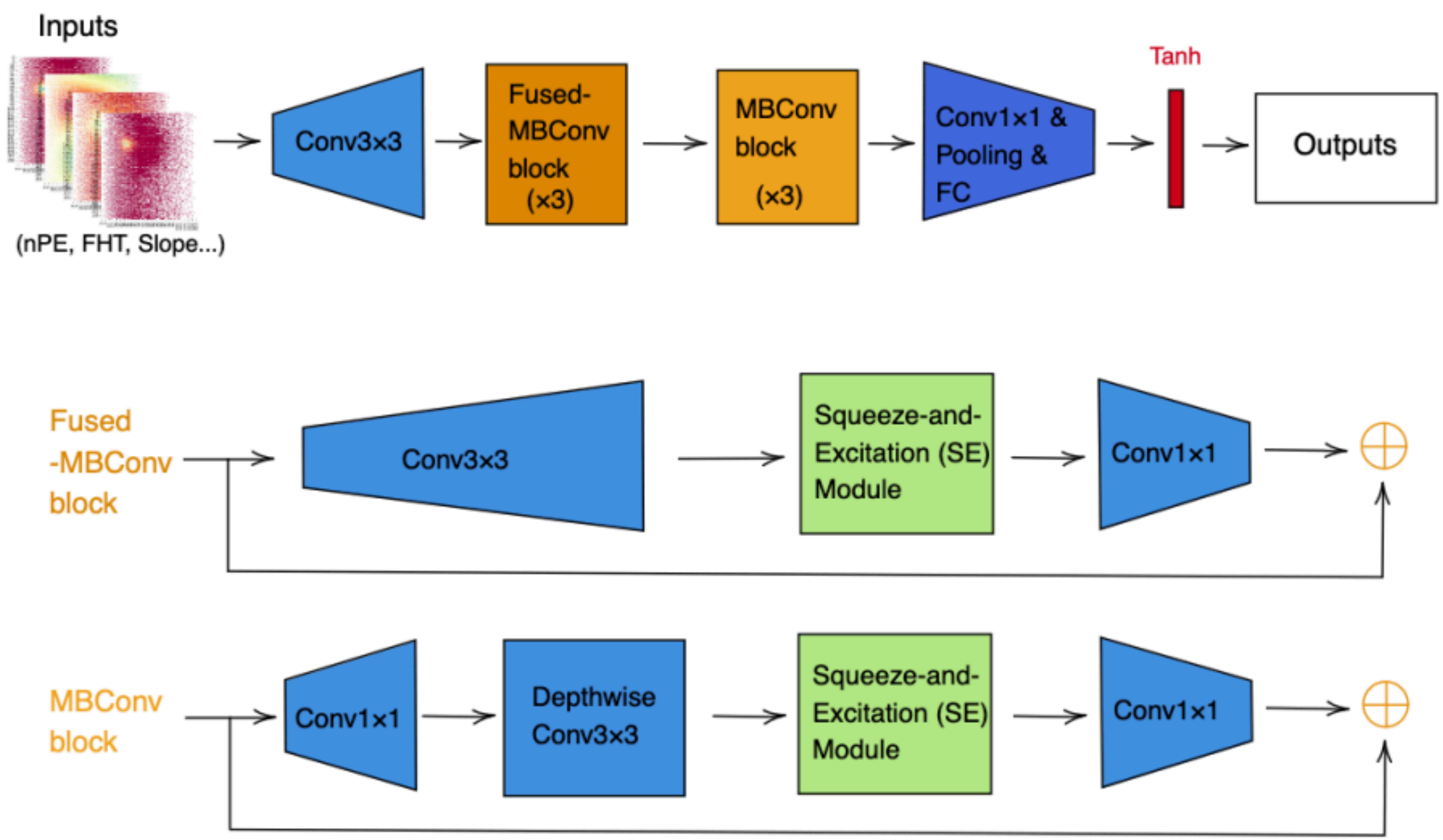
Upward-going events, $E_\nu > 0.5$GeV

Summary and Outlook

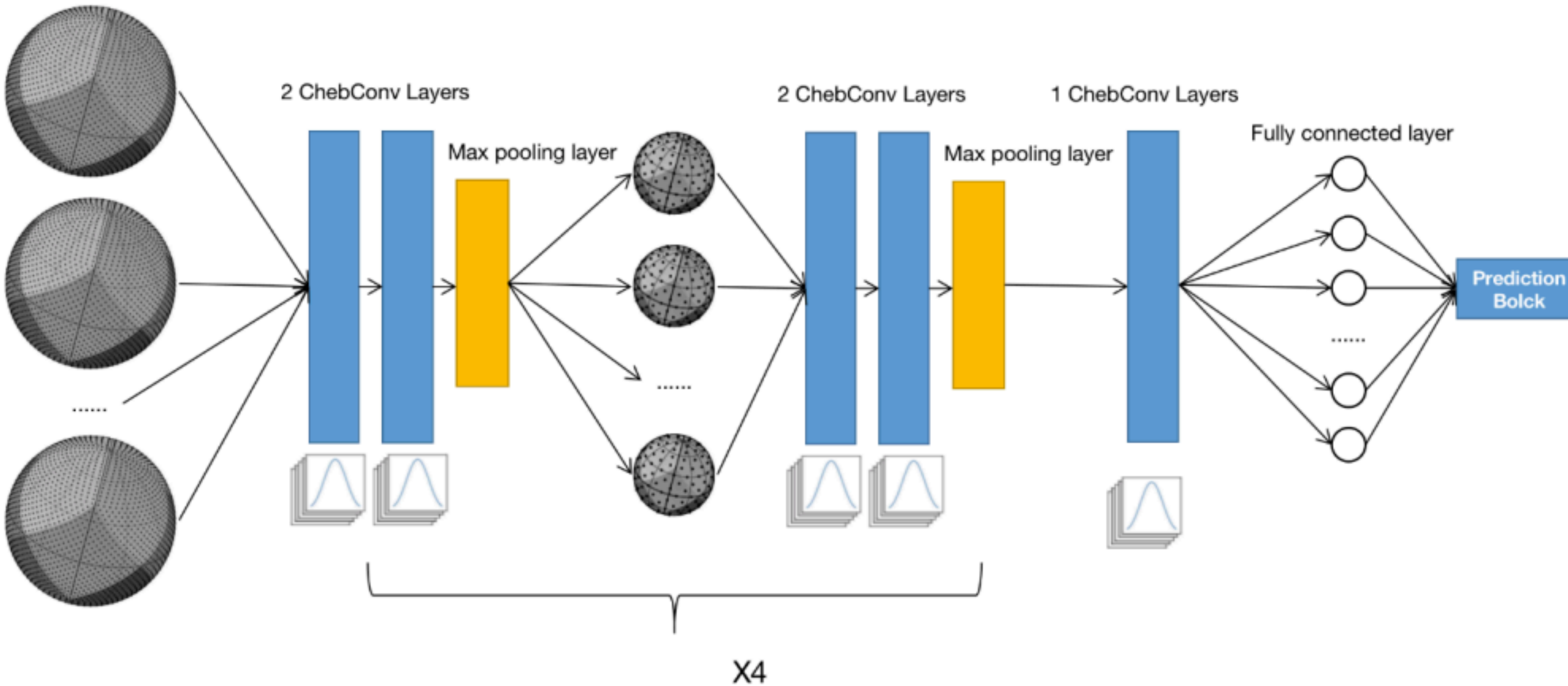
- Liquid scintillator detectors are traditionally limited to low-energy (MeV) topics.
- With machine learning techniques we have greatly expanded their capabilities in GeV energy region: cosmic muons, atmospheric ν and more.
  - Performance comparable or even better than traditional large detectors for GeV physics (for example a water Cherenkov detector.)
- Stay tuned for more excited GeV physics from JUNO!

Back up slides

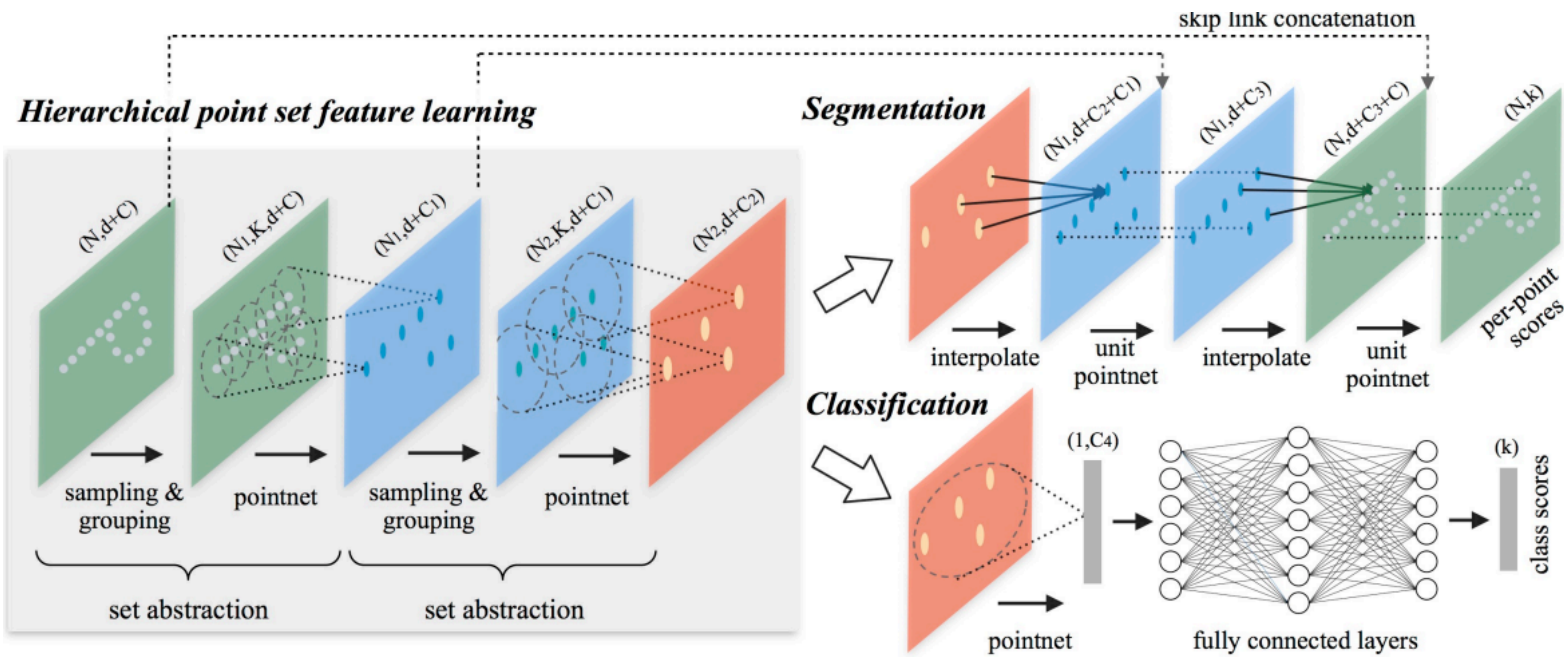
Planer Model: EfficientNetV2



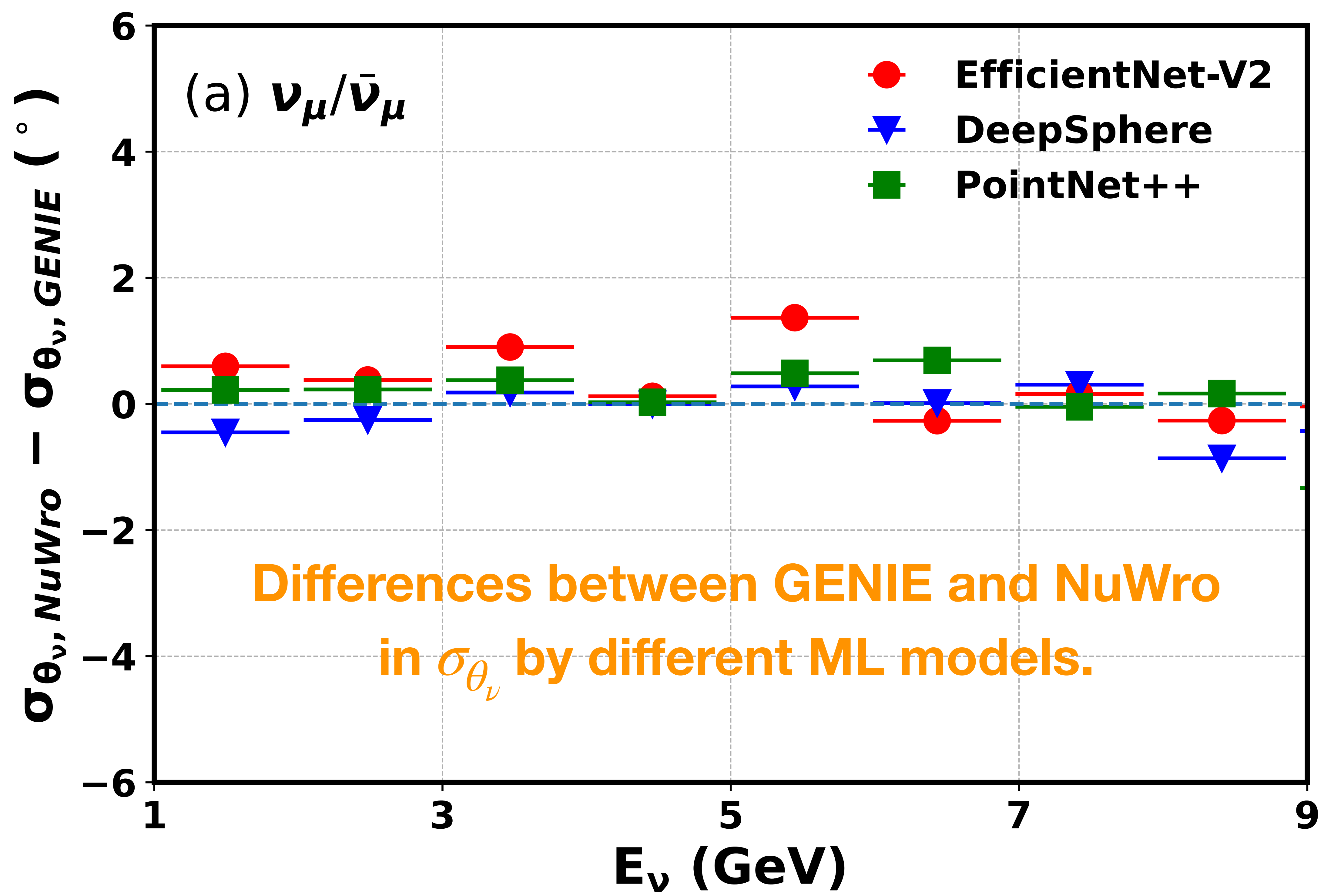
Spherical Model: DeepSphere



3D Model: PointNet++



Alternative Generator Check

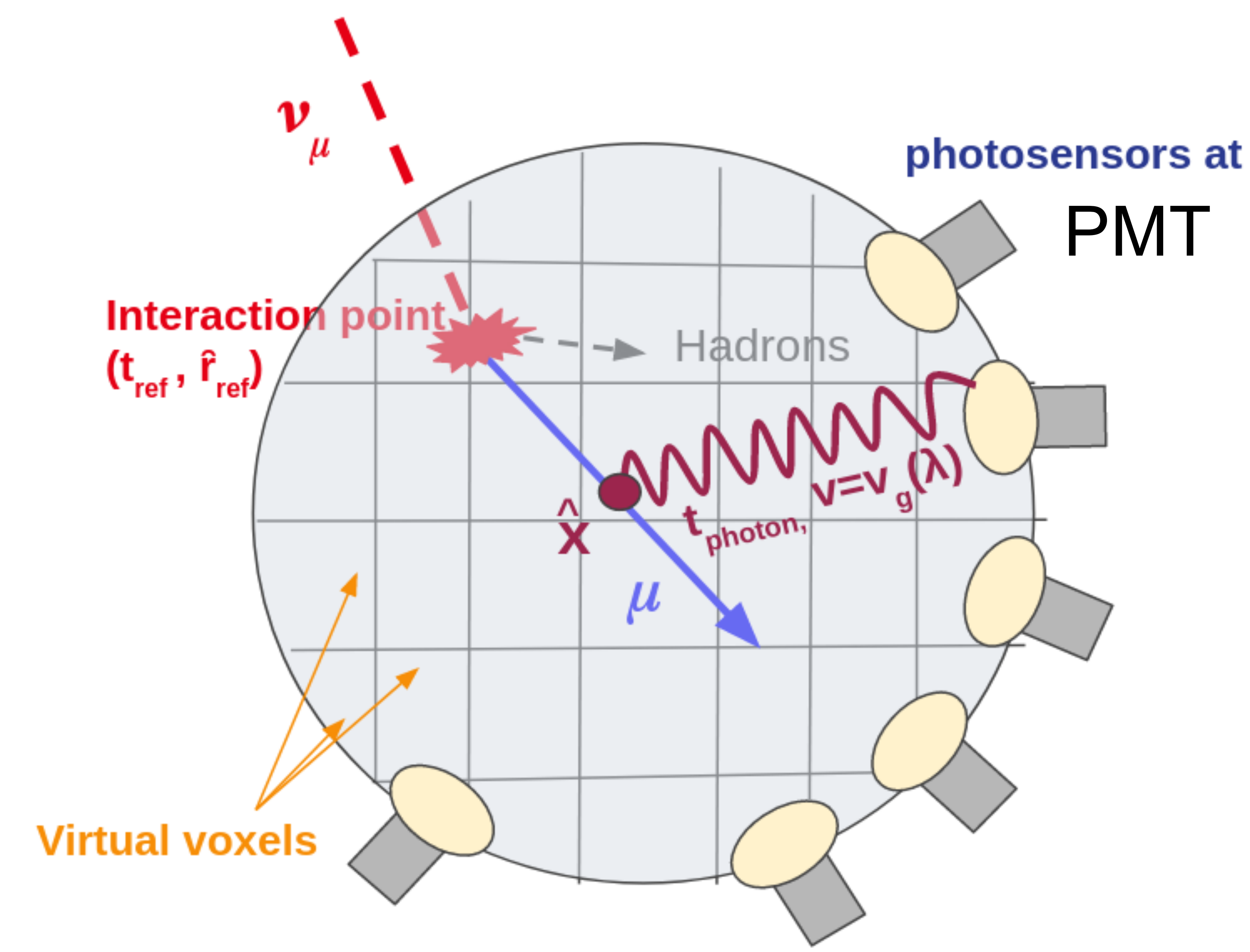


Topological Reconstruction Method

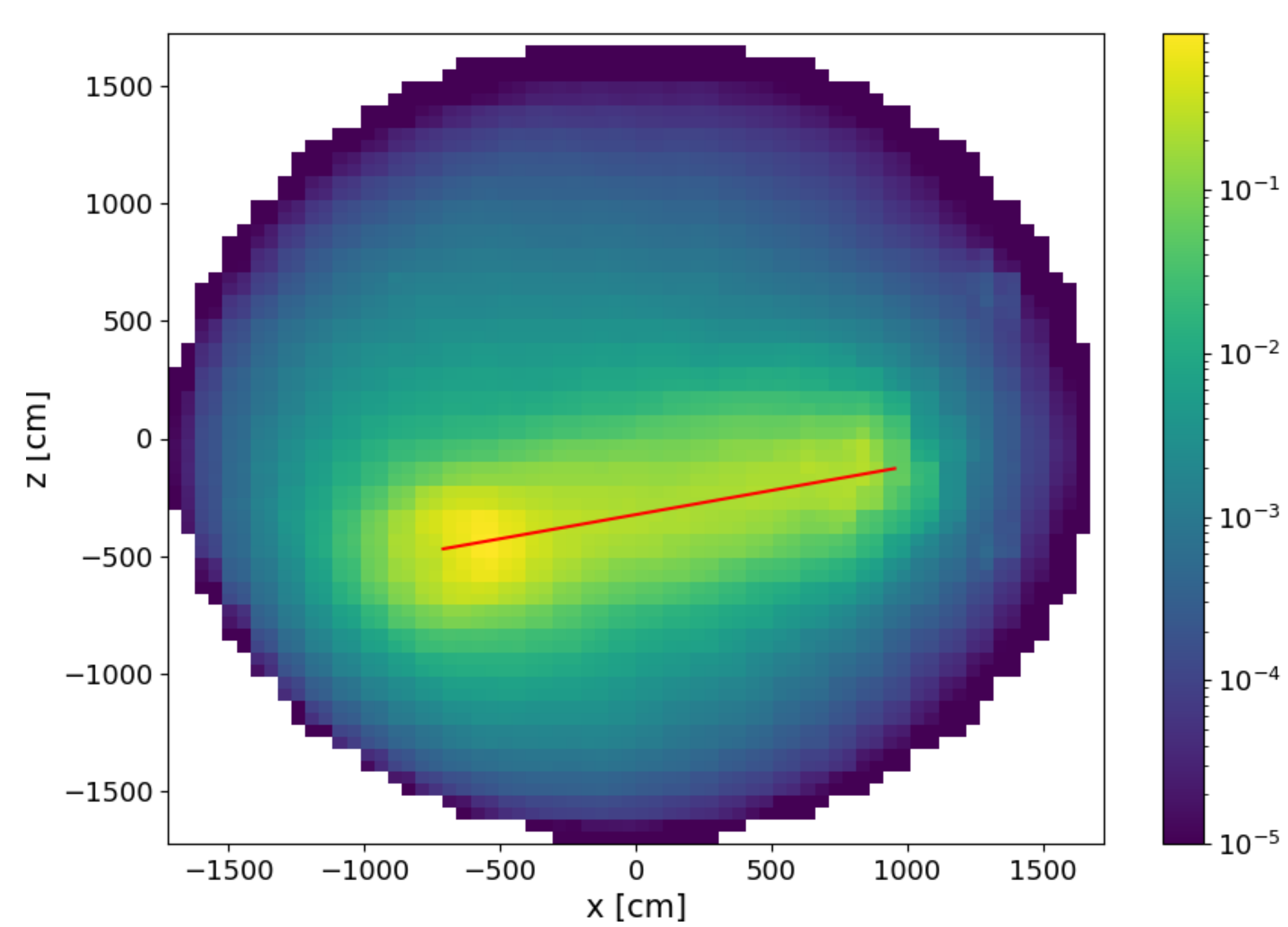
- Idea: Reconstruct the photon emission probability distribution based on the detected PMT hit charges and times.

Principle: $$\hat{t}(x) = \boxed{t_{ref}} \pm \boxed{\underbrace{\frac{|\hat{x}-\hat{r}_{ref}|}{c_0}}_{t_{particle\ \mu/e}}} + \boxed{\underbrace{\frac{|\hat{r}_j-\hat{x}|}{v_g}}_{t_{photon}}}$$

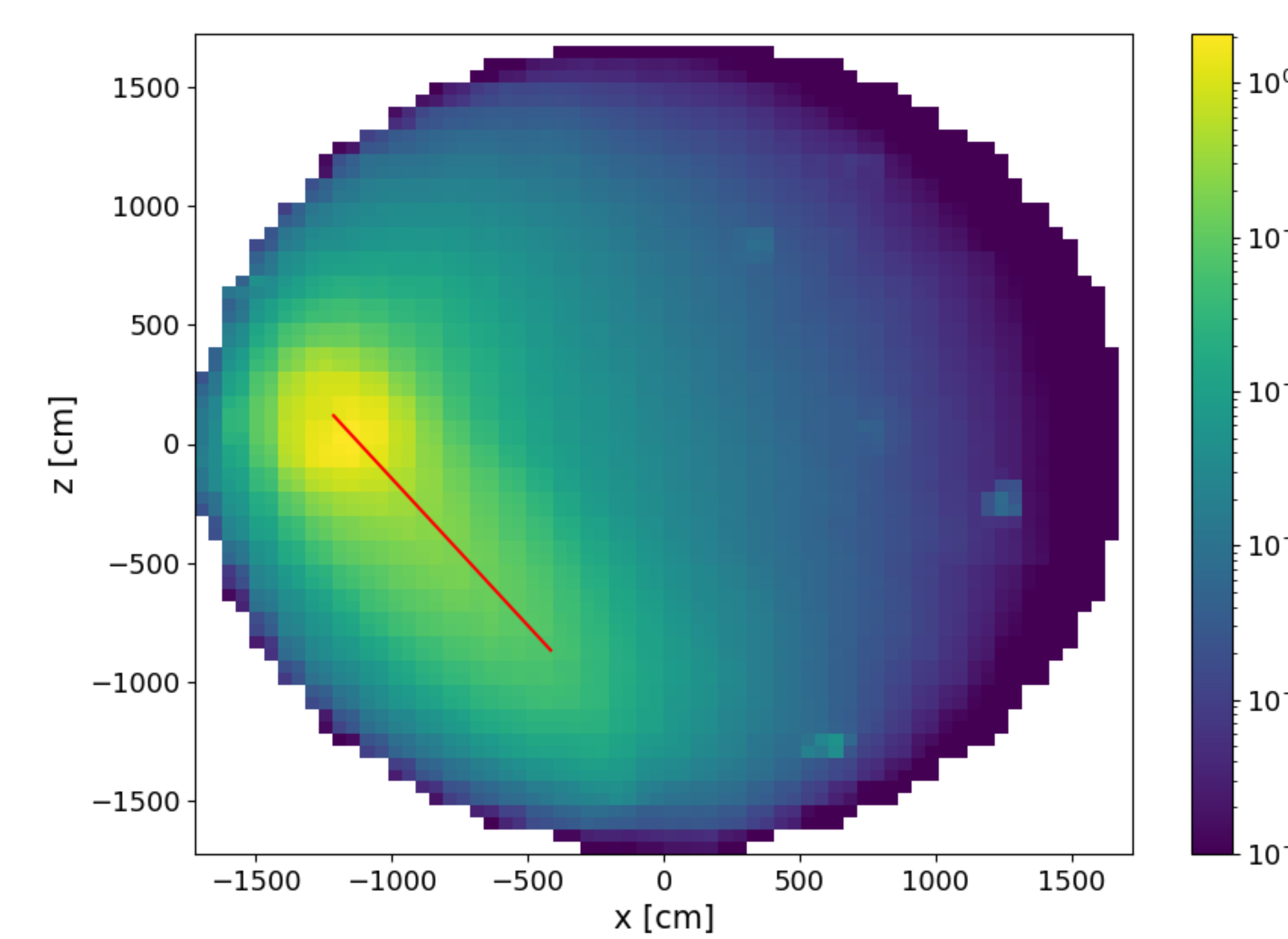
reference time and vertex: $(t_{ref}, \hat{r}_{ref})$



- 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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