Neutrino Interactions and Deep Learning

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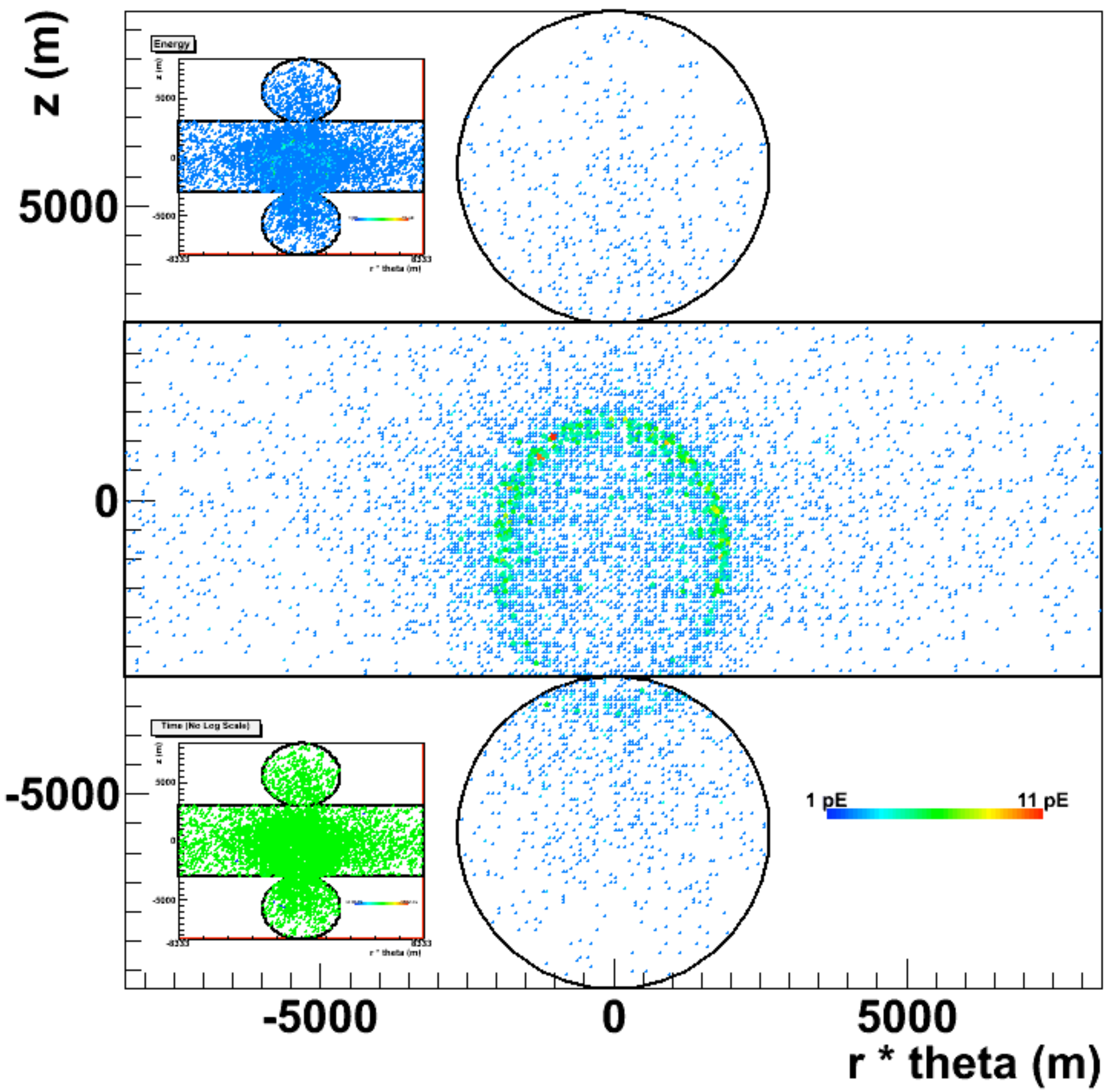
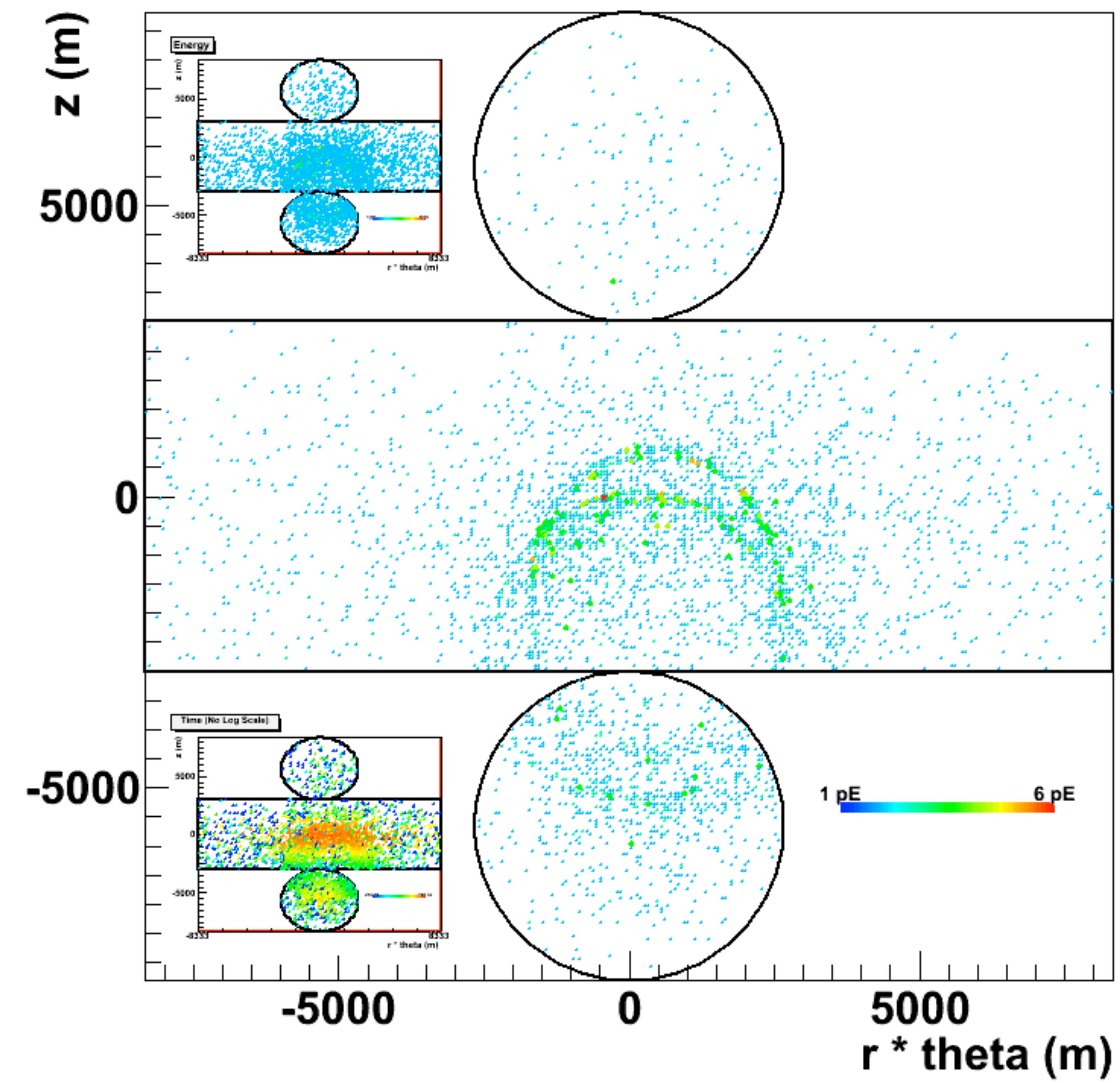
Disclaimer

- Limited and biased view based on personal experiences.
- More focusing on the needs for the neutrino-interaction side than deep learning.
- More focusing on the neutrino physics in few-GeV energy region.

A little bit of History: “Hand Scan”

H. Duyang, TIPP 2011: “A Scan Study of ve-CC and NC Event Simulated in the LBNE Water Cherenkov Detector”





- **Question: which is a ν_e-CC interaction and which is a NC?**

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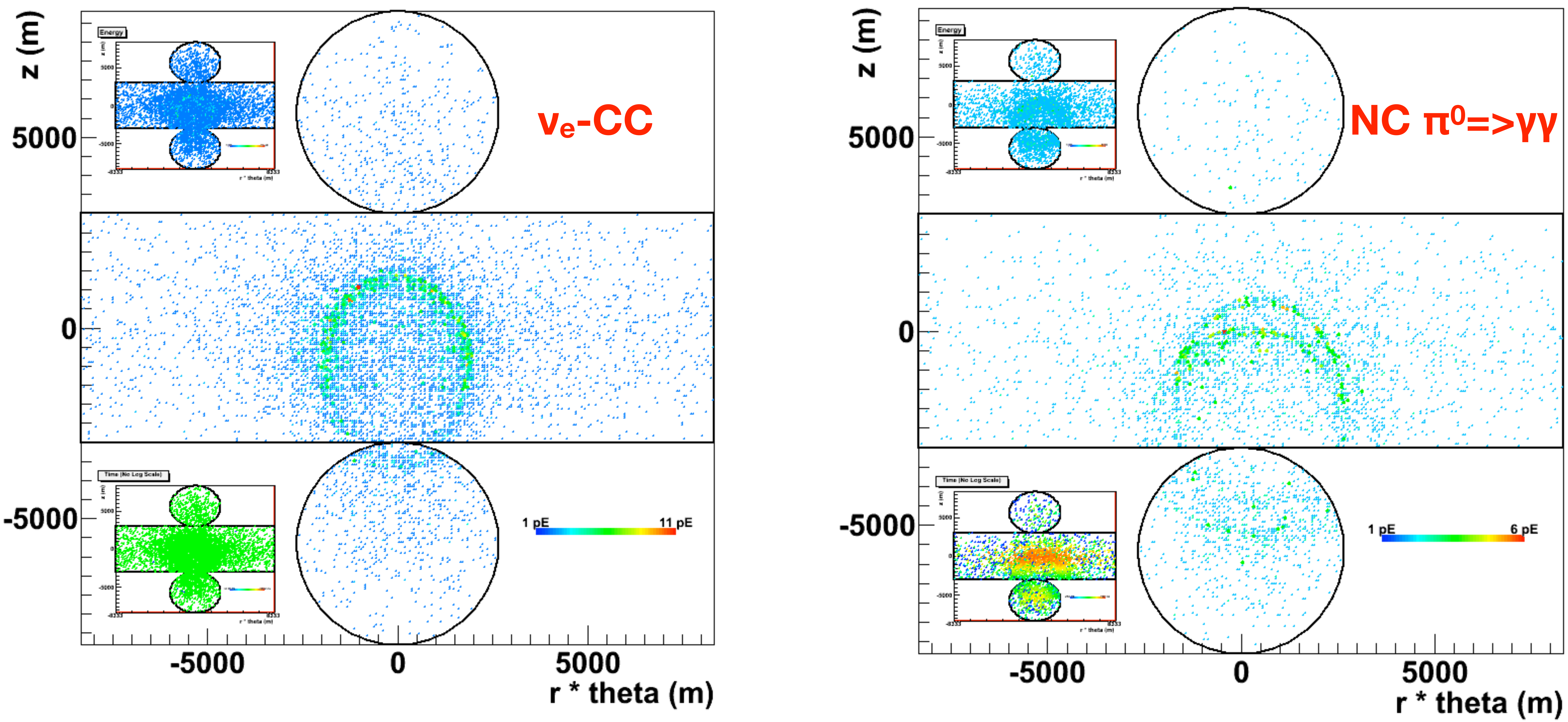
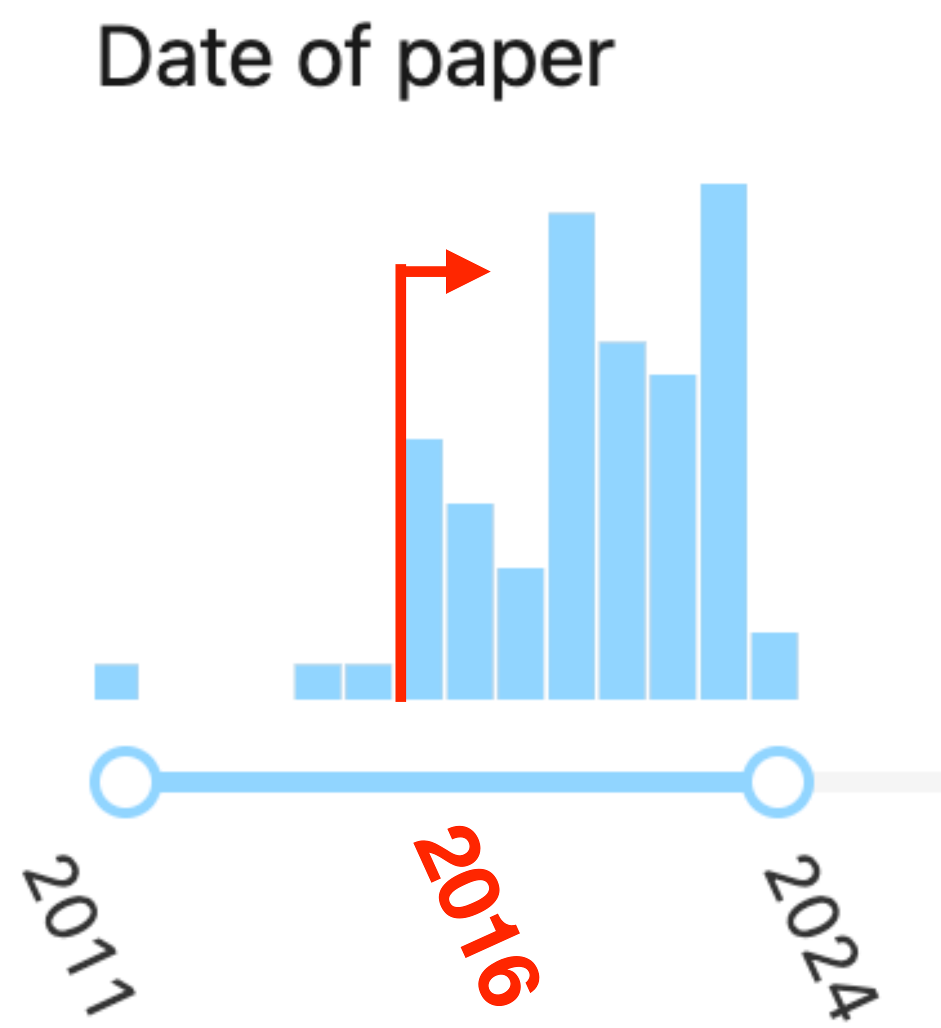


- Historically, large number of event display pictures are hand-scanned (by innocent students) to search for signal in data or estimate the detector’s performance at the early stage of detector design.
- I personally scanned tens of thousands of such pictures for the water Cherenkov design of FD for the LBNE experiment (now known as DUNE).

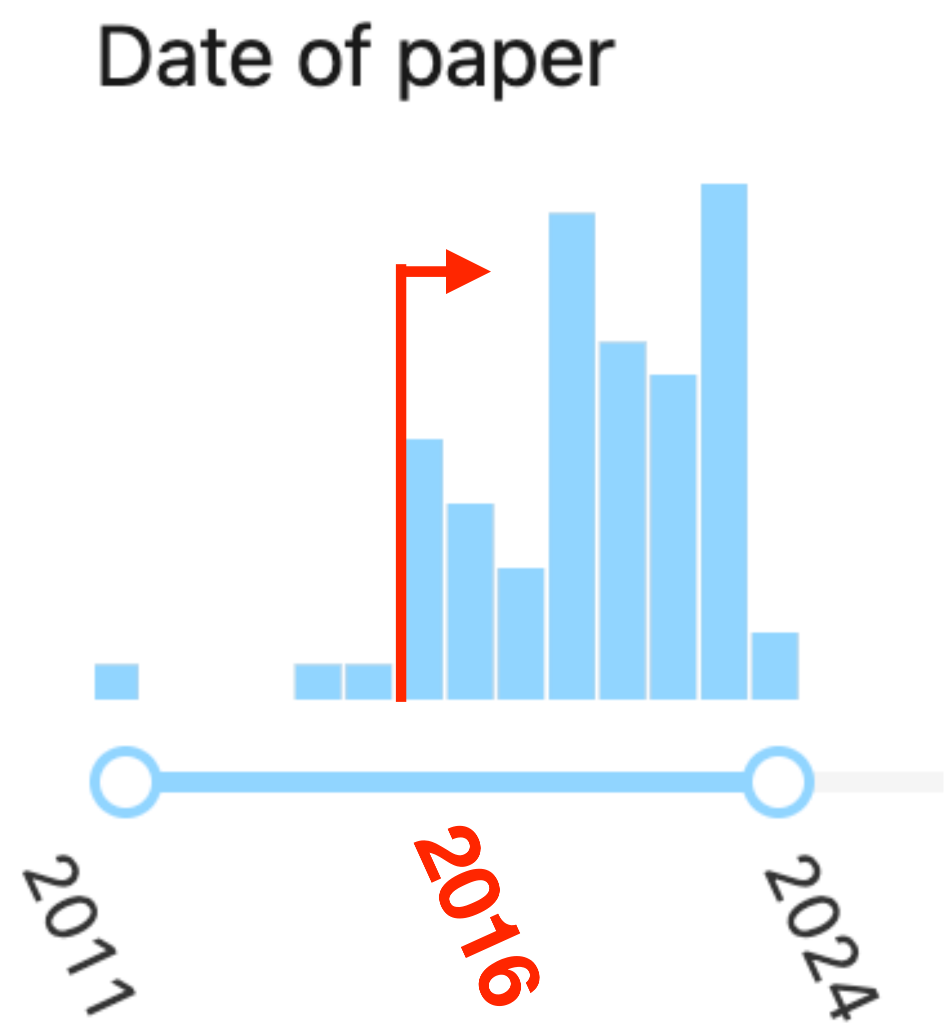
"Neutrino interactions and deep learning" in Inspire



Searching result for "Neutrino interactions and deep learning" in inspire

Explosion of literatures since 2016

DL Applications in Neutrino Experiments: NOvA



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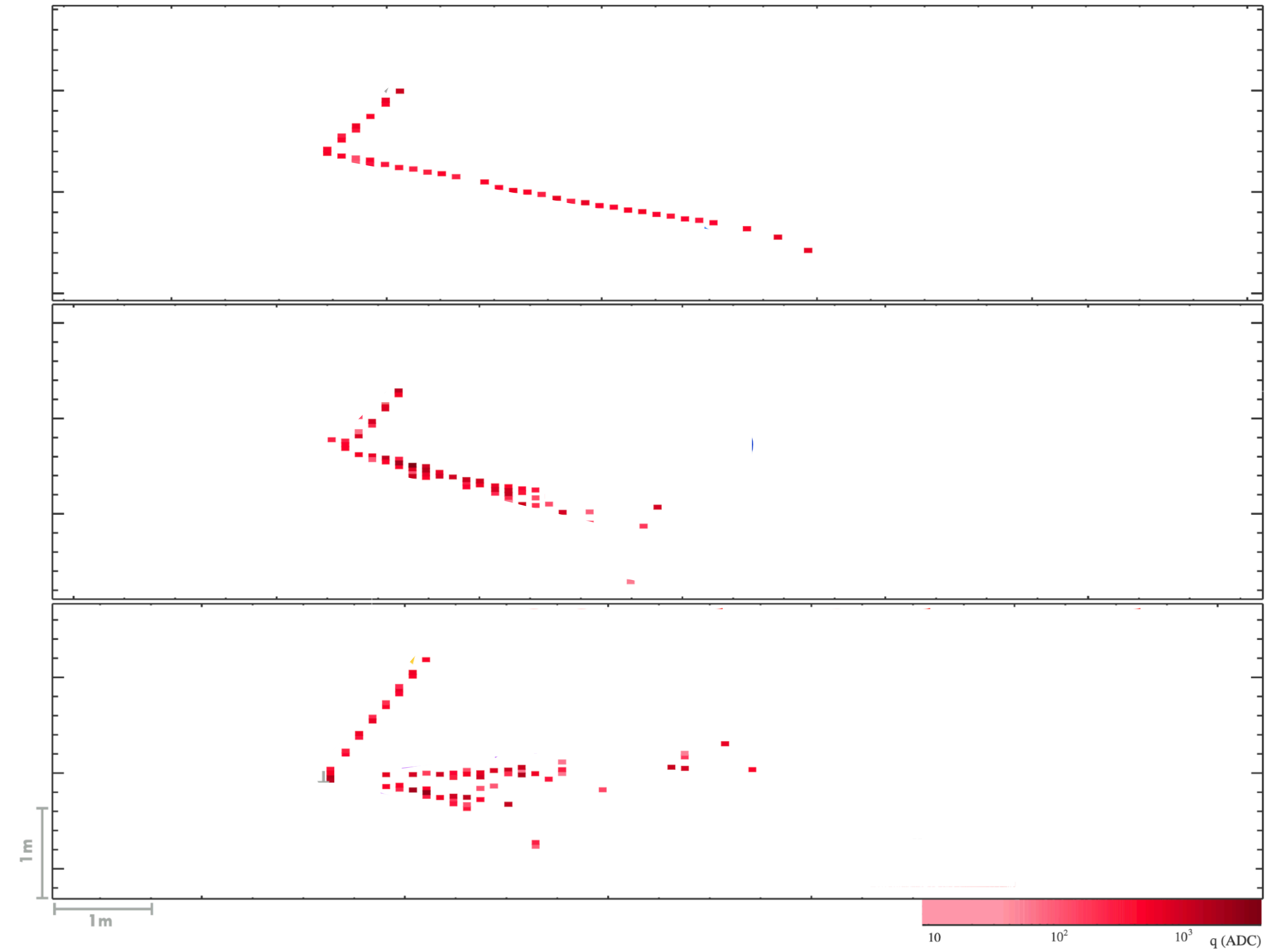

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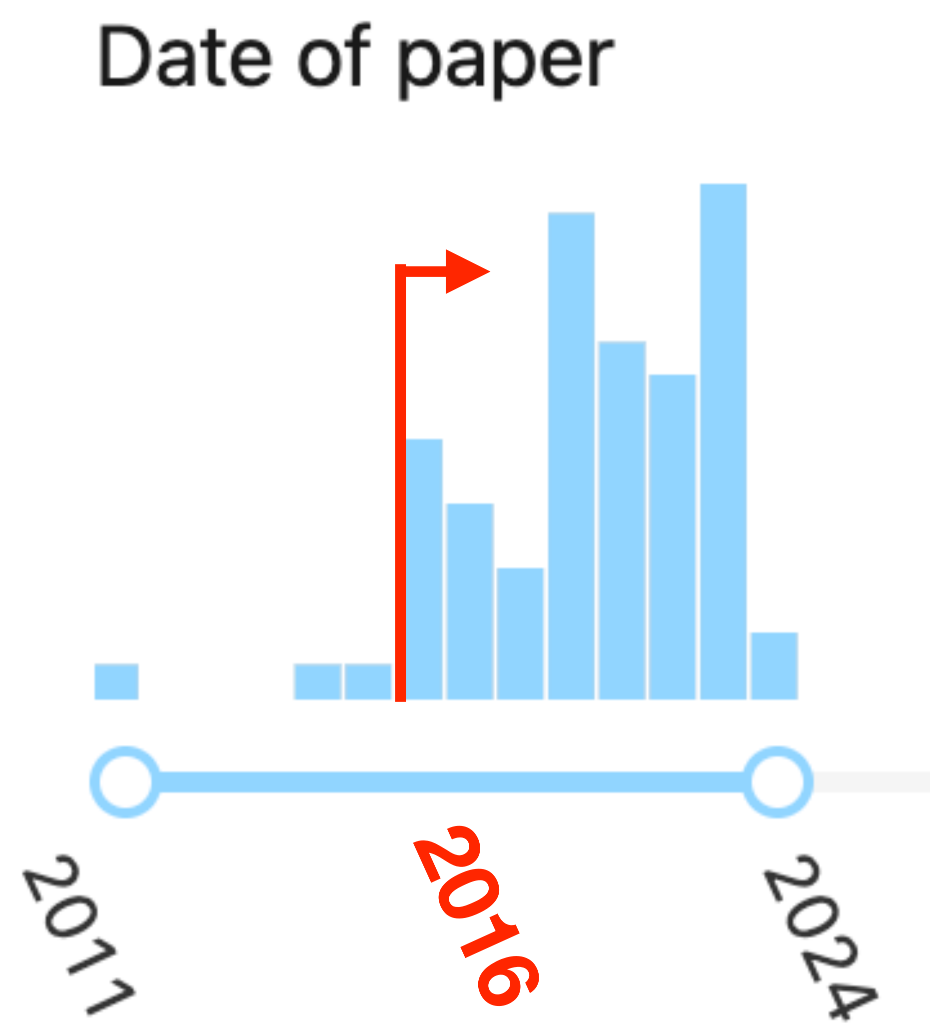
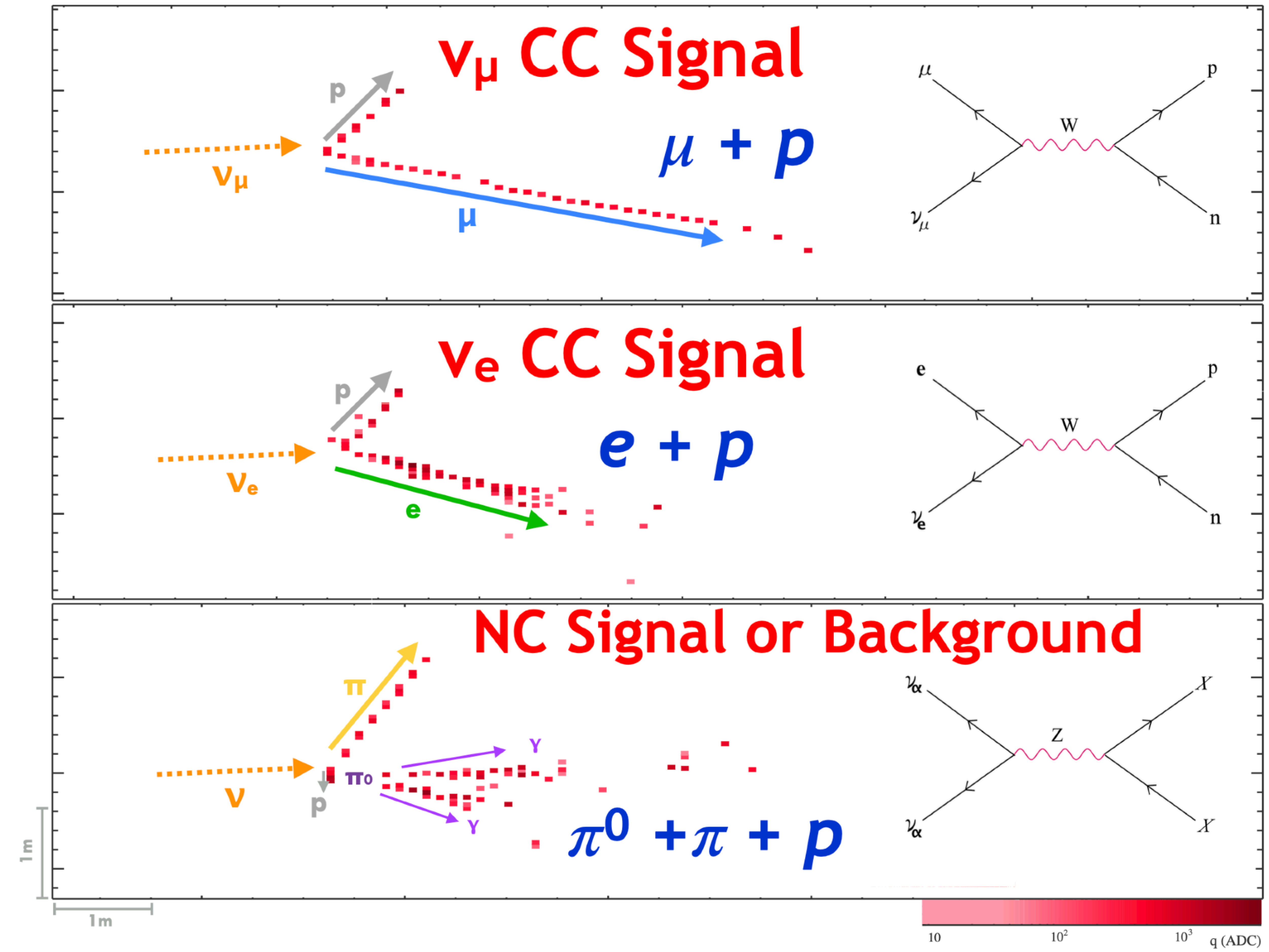


Searching result for "Neutrino interactions and deep learning" in inspire

The selection criteria are chosen to maximize the figure of merit defined as $S/\sqrt{S+B}$, where S and B are the number of signal and background events, respectively. The final ν_e selection criteria select a contained appearance signal with 73.5% efficiency and 75.5% purity, representing a gain in sensitivity of 30% compared to the ν_e classifiers used in the previously reported results [1]. These criteria also reject 97.6% of the NC and 99.0% of the ν_μ CC beam backgrounds. The cosmic ray backgrounds are suppressed by 7 orders of magnitude, and only 0.53 ± 0.14 cosmic events are estimated to be selected in the final ν_e appearance sample based on the performance of ν_e selection criteria on cosmic data. Of the beam backgrounds that pass all ν_e selection, 91% contain some form of

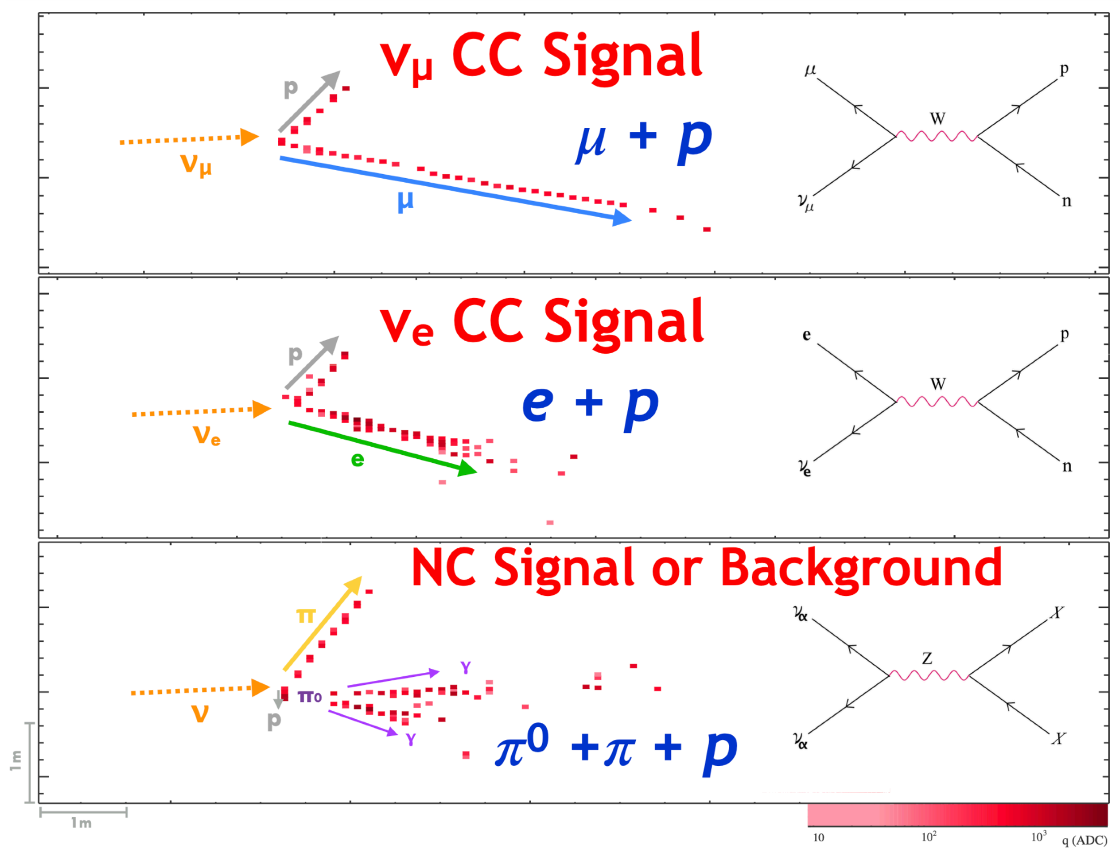
PRL 118, 231801 (2017)

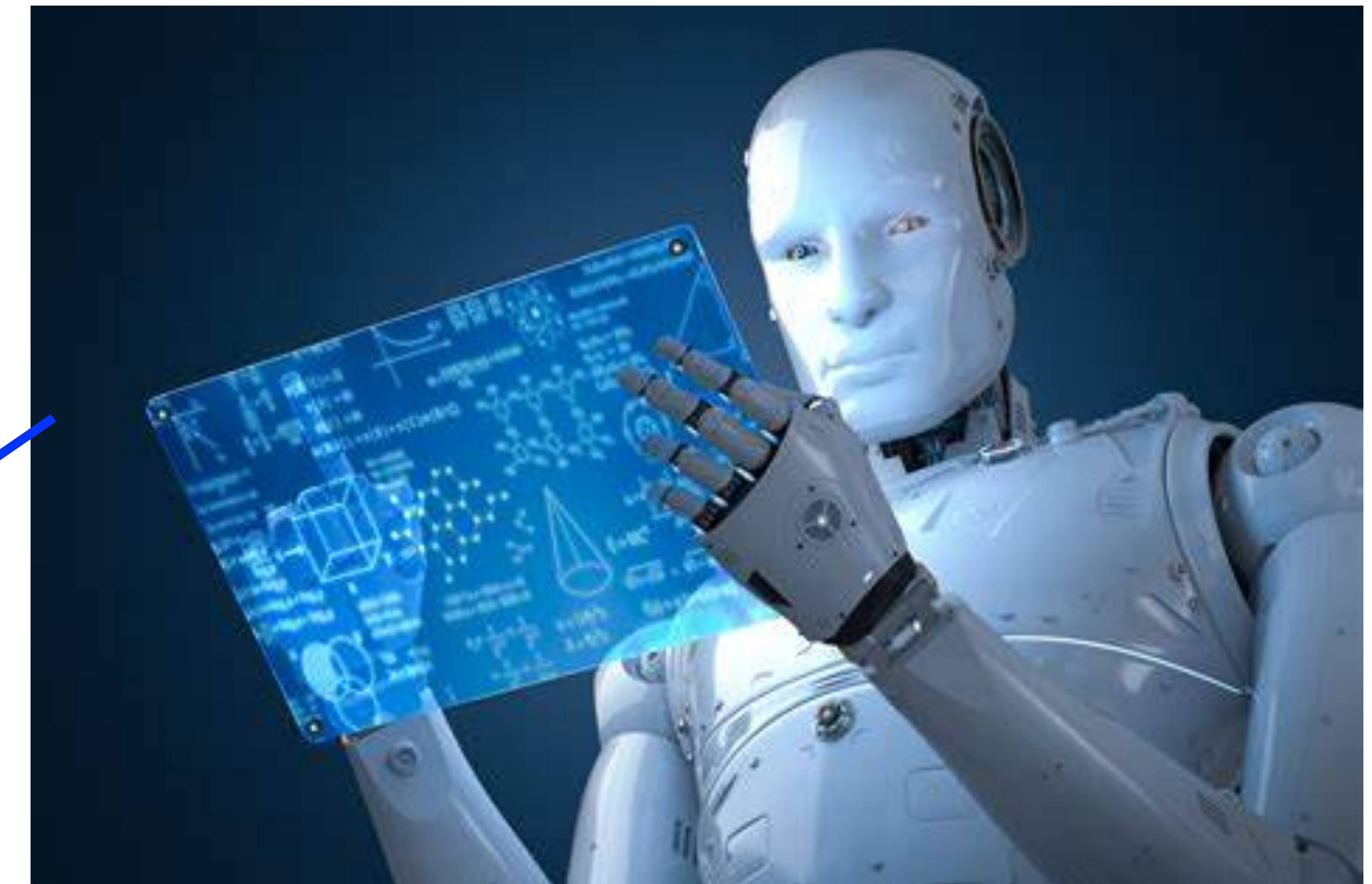


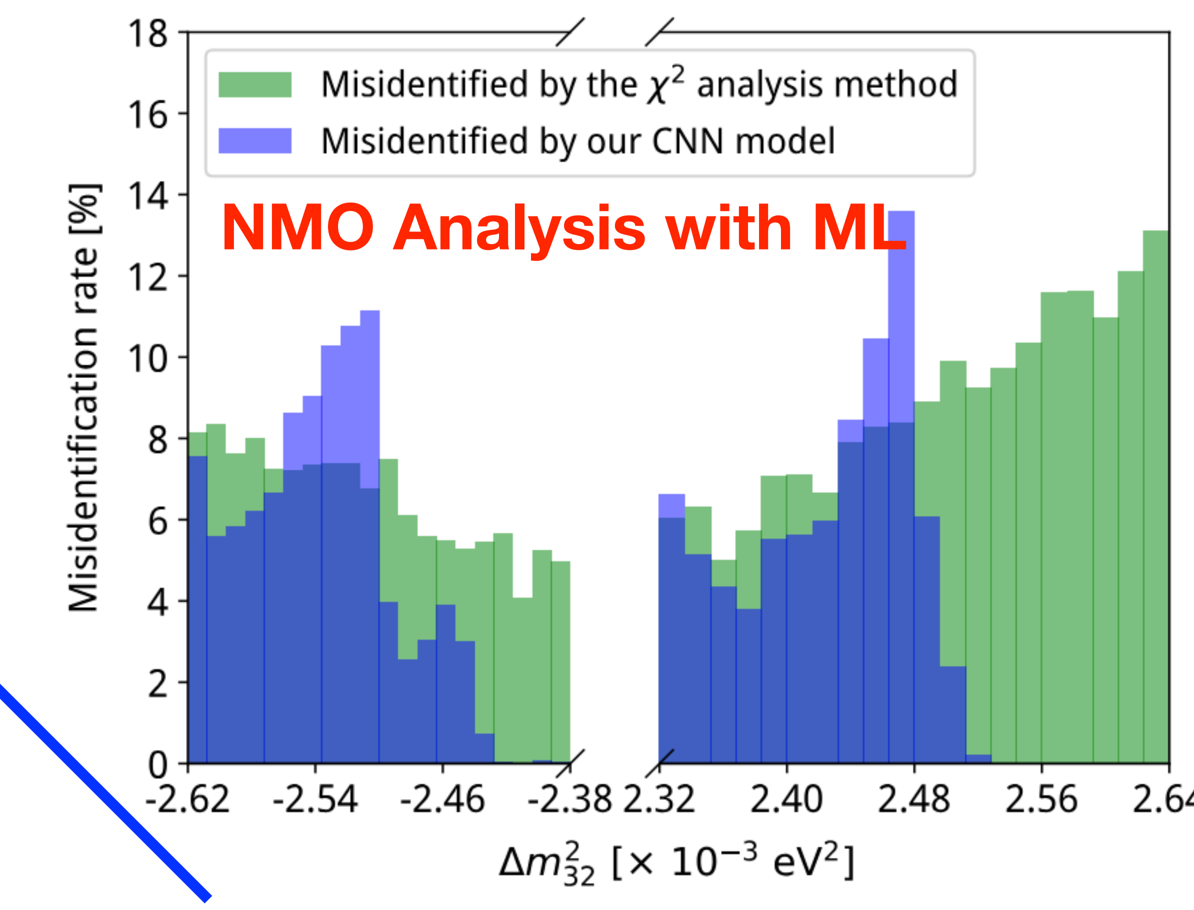
- In 2016, NOvA pioneers in the application of **convolutional neural networks** in event classification in neutrino experiments for its ve-CC appearance analysis.

ML Applications in Neutrino Experiments

NOvA event identification







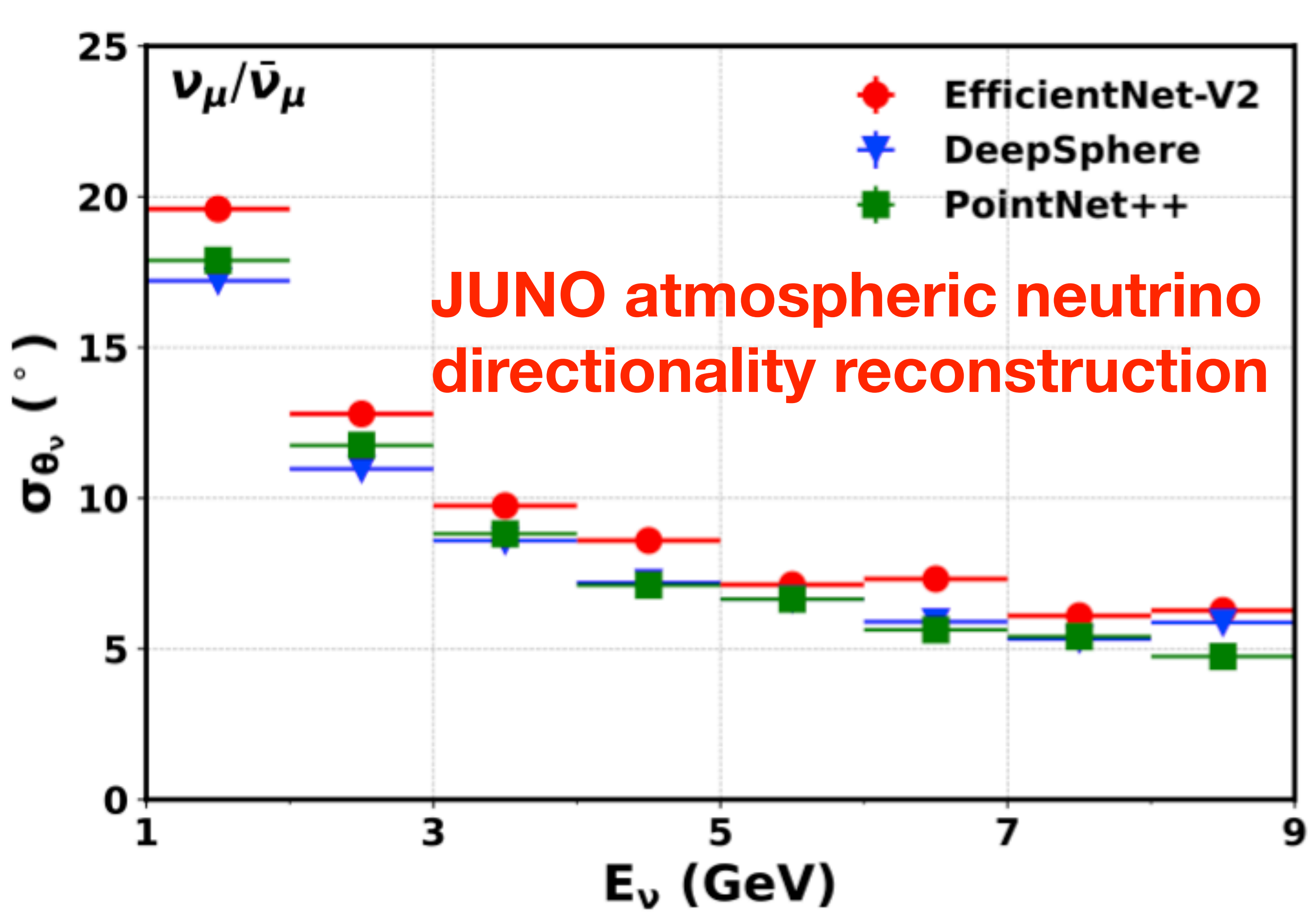
- Event/particle identification, rare event search

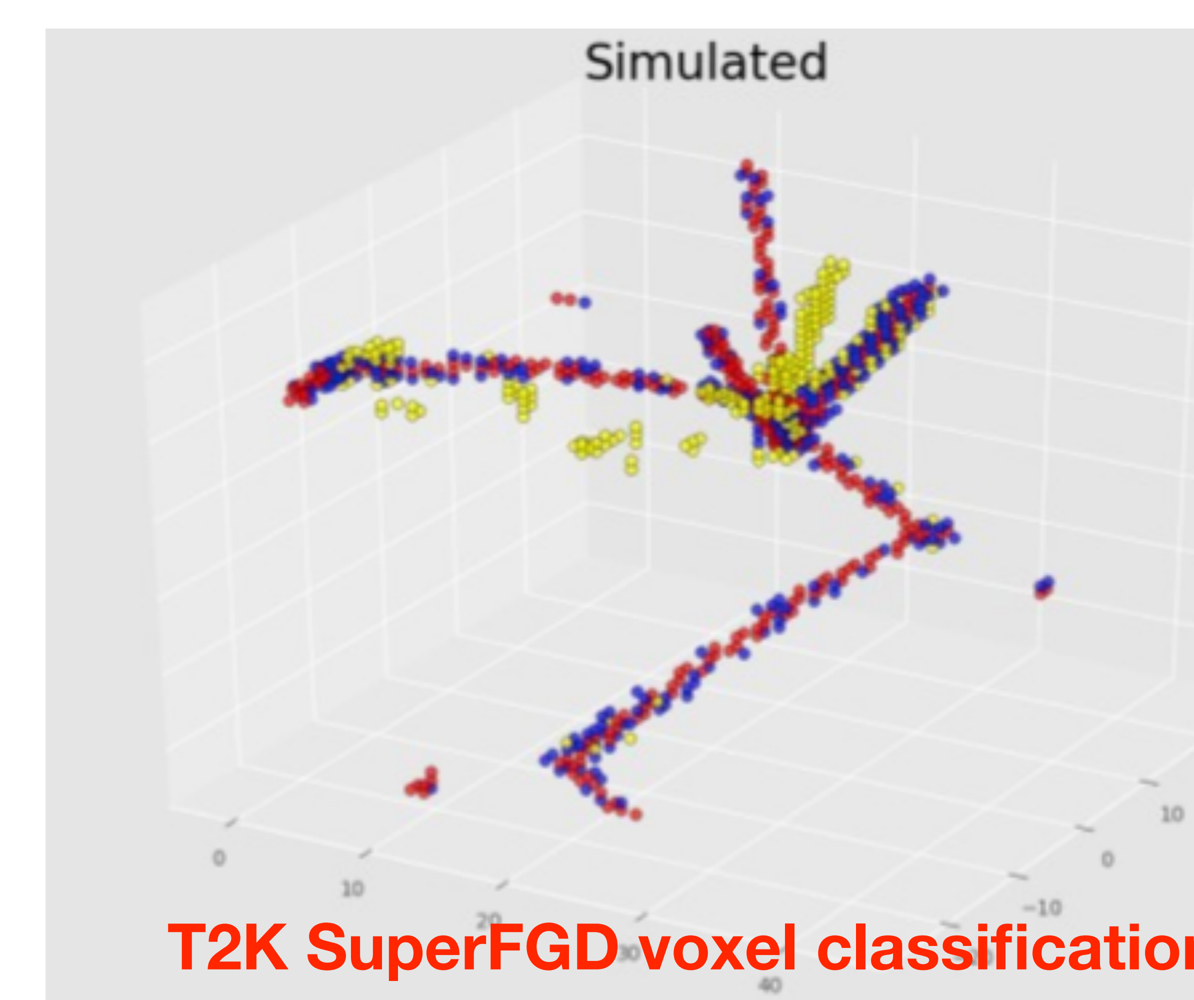
- Analysis

- Generative models: simulation

- Regression: Energy/momentum, direction reconstruction etc.

- clustering/tracking

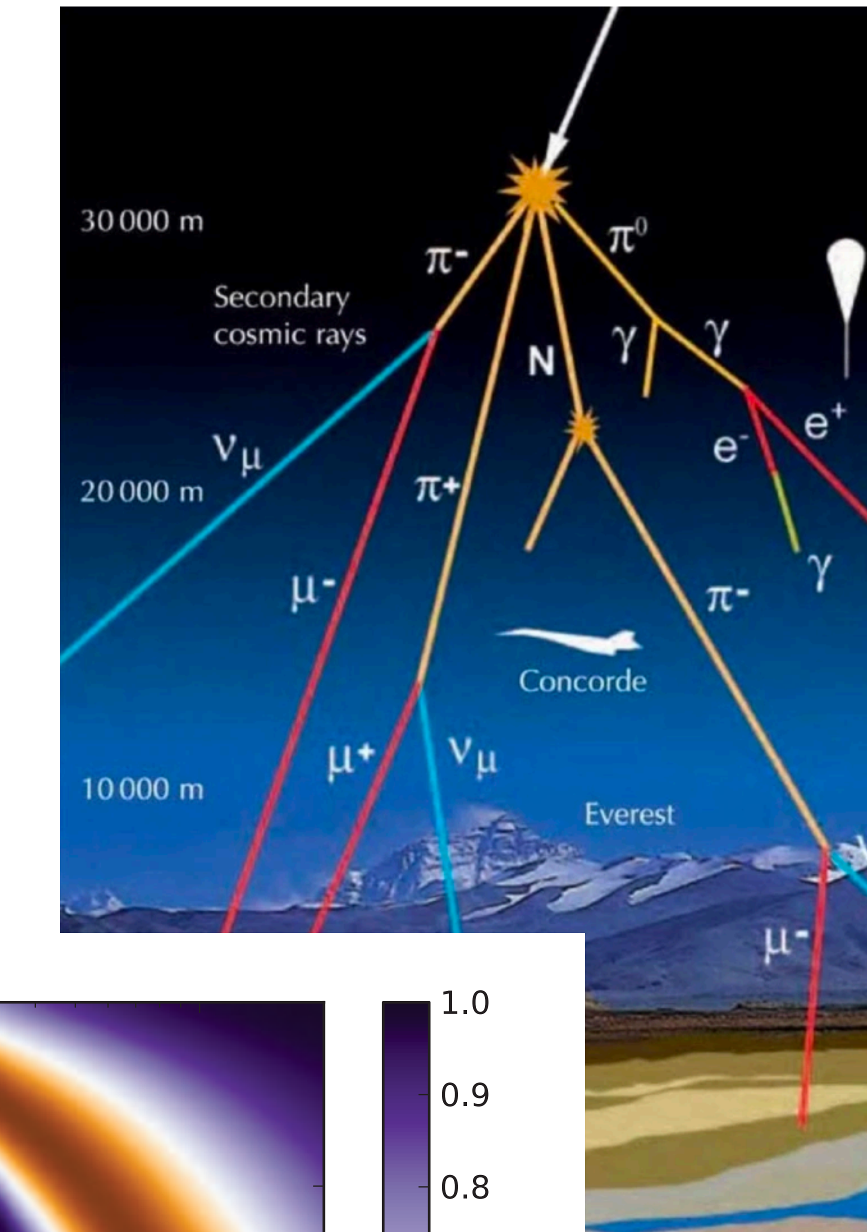


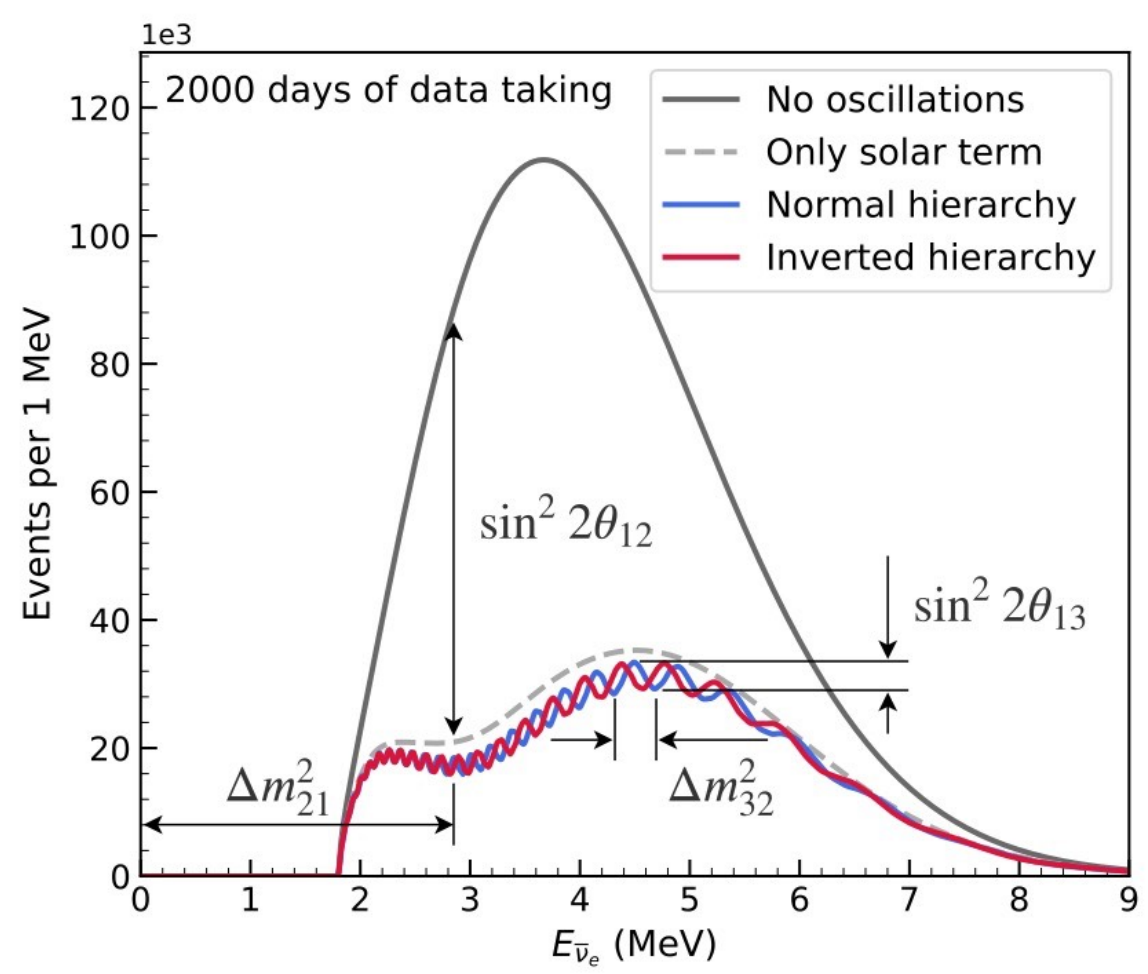


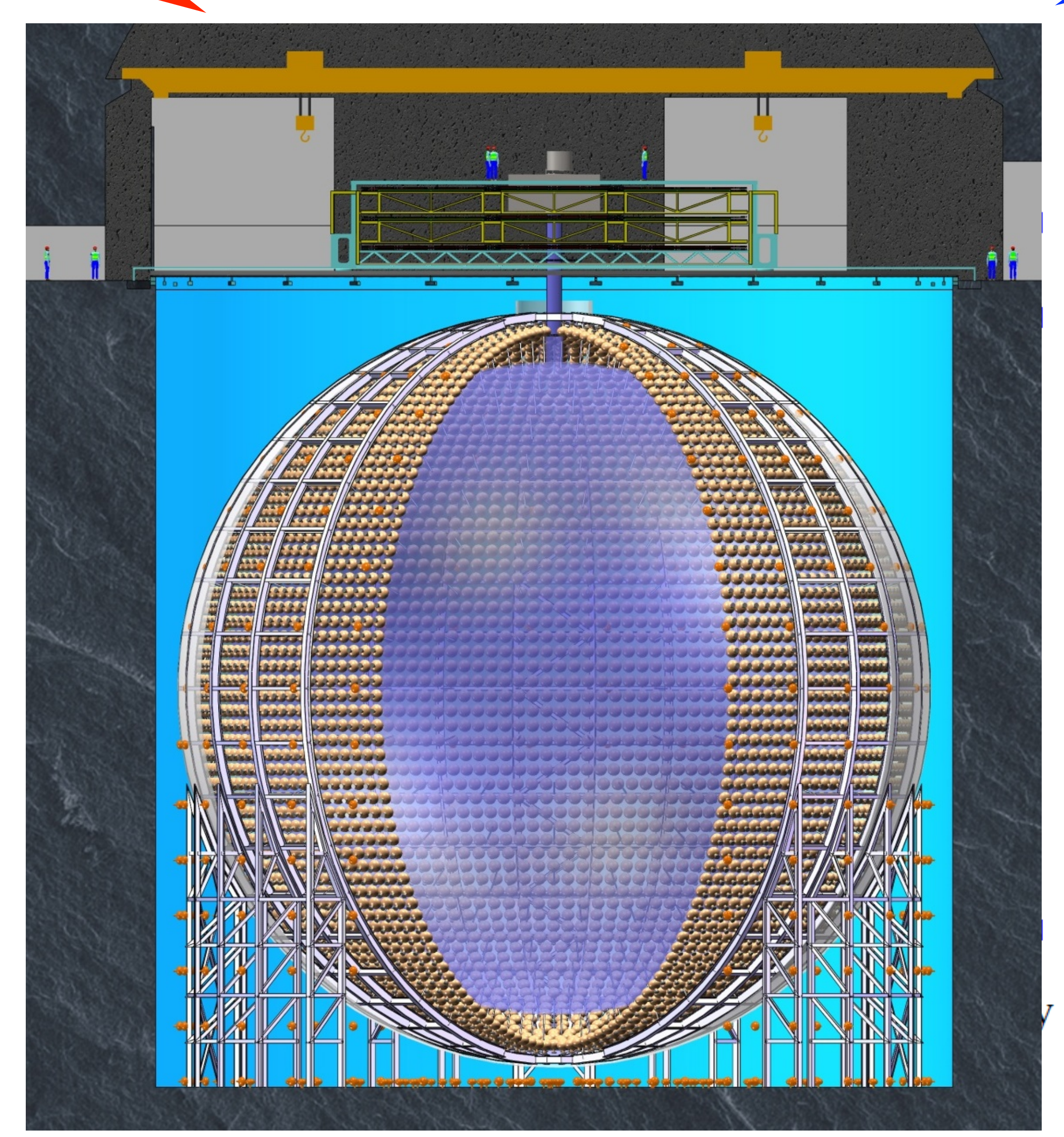
ML Applications: JUNO Atmospheric Neutrinos

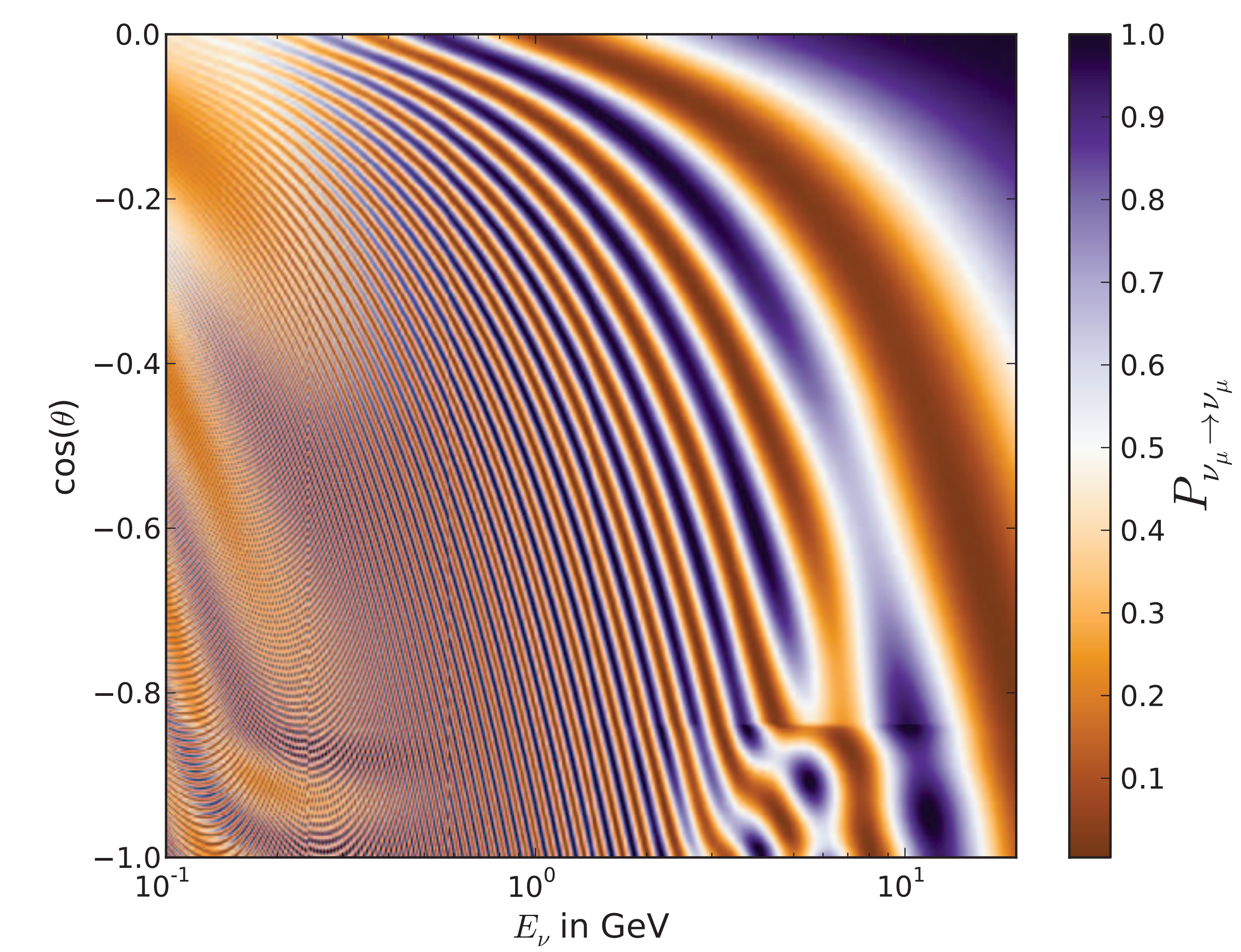
Reactor neutrinos: Sensitivity to NMO via oscillation in vacuum

Atmospheric neutrinos: Sensitivity to NMO via matter effects



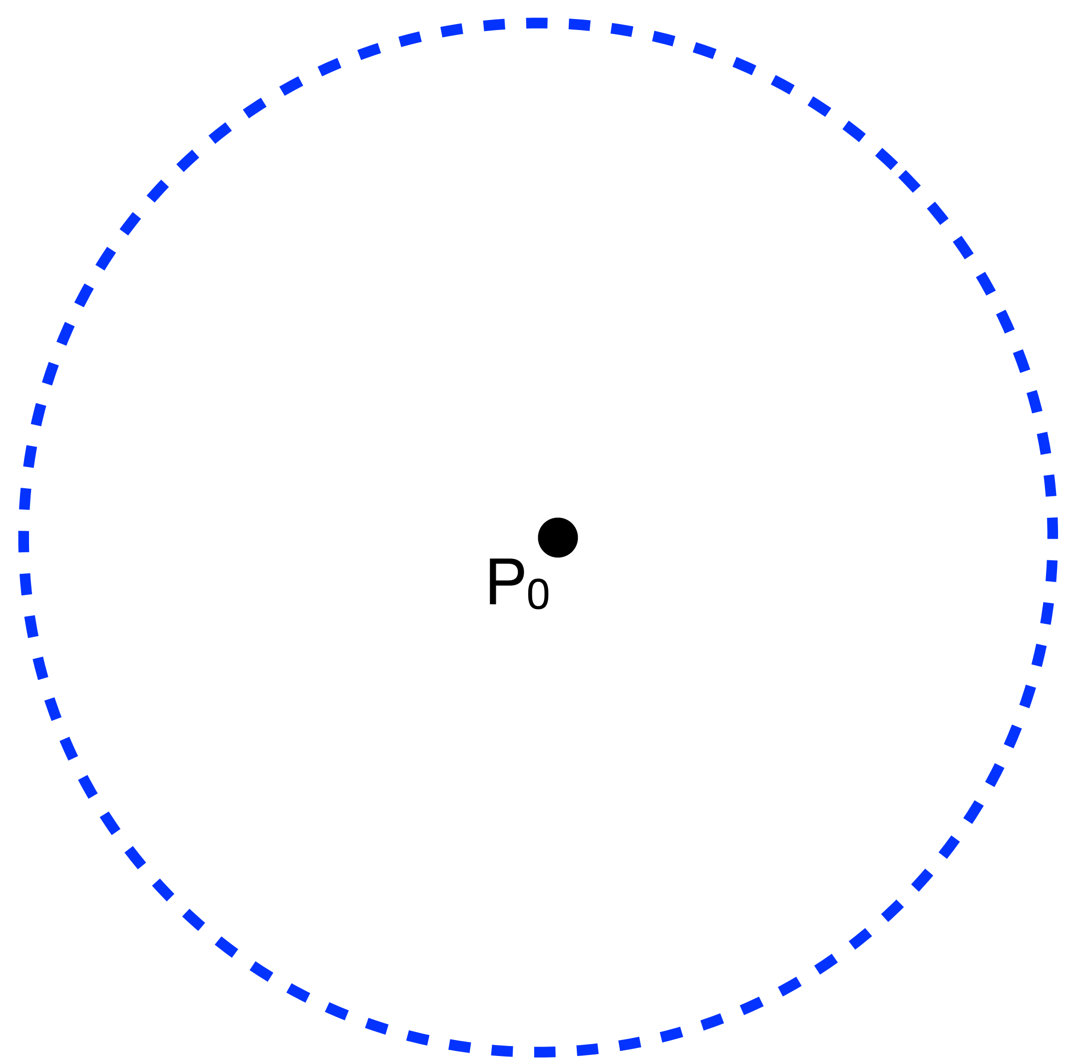






- **Atmospheric neutrinos** provide independent sensitivity to NMO via matter effects (directionality and flavor identification are mandatory).
- But LS detectors have never been used for atmospheric neutrino oscillations before.
  - No direct tracking or directional information.

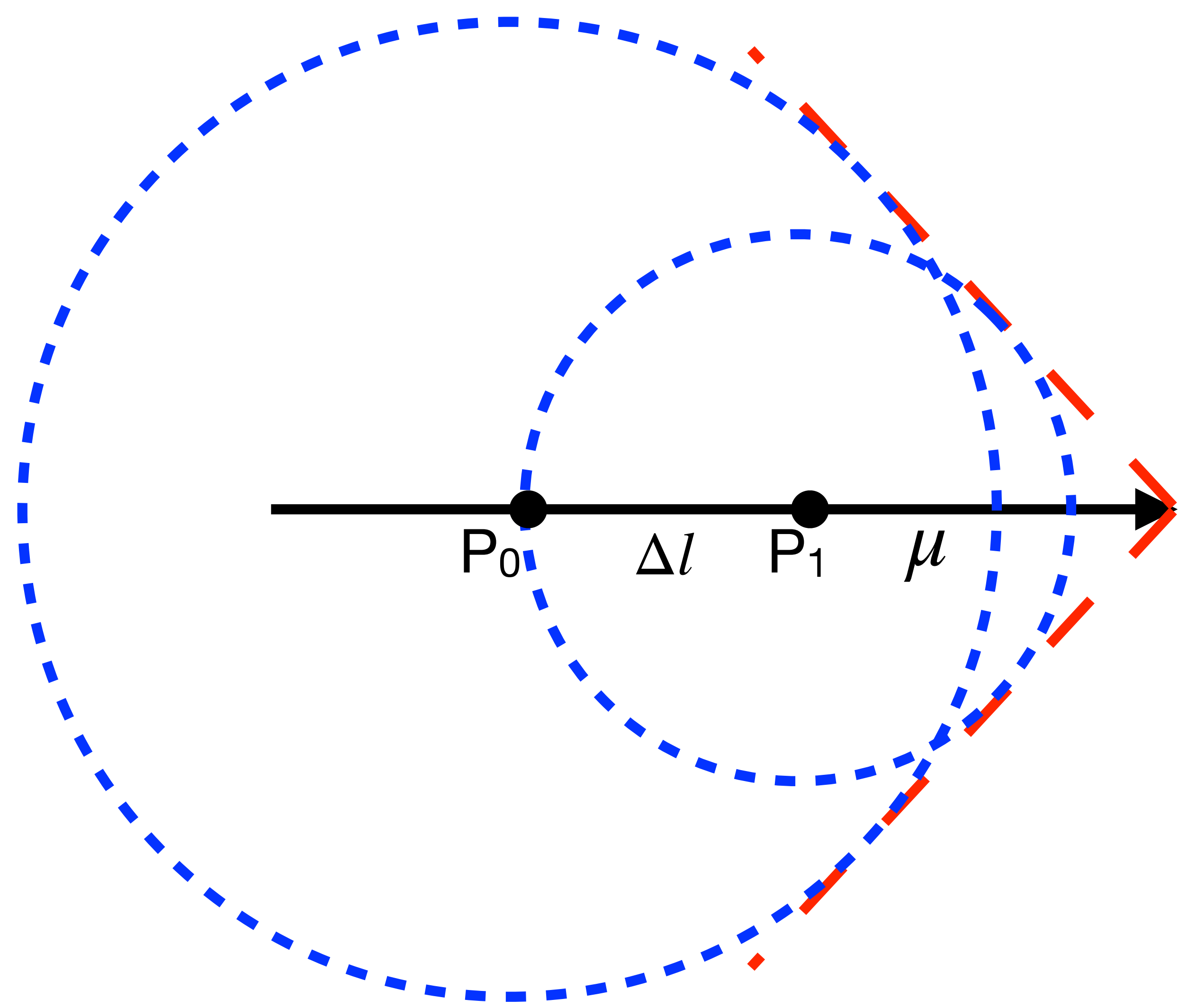
Event Topology in PMT Waveforms



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.

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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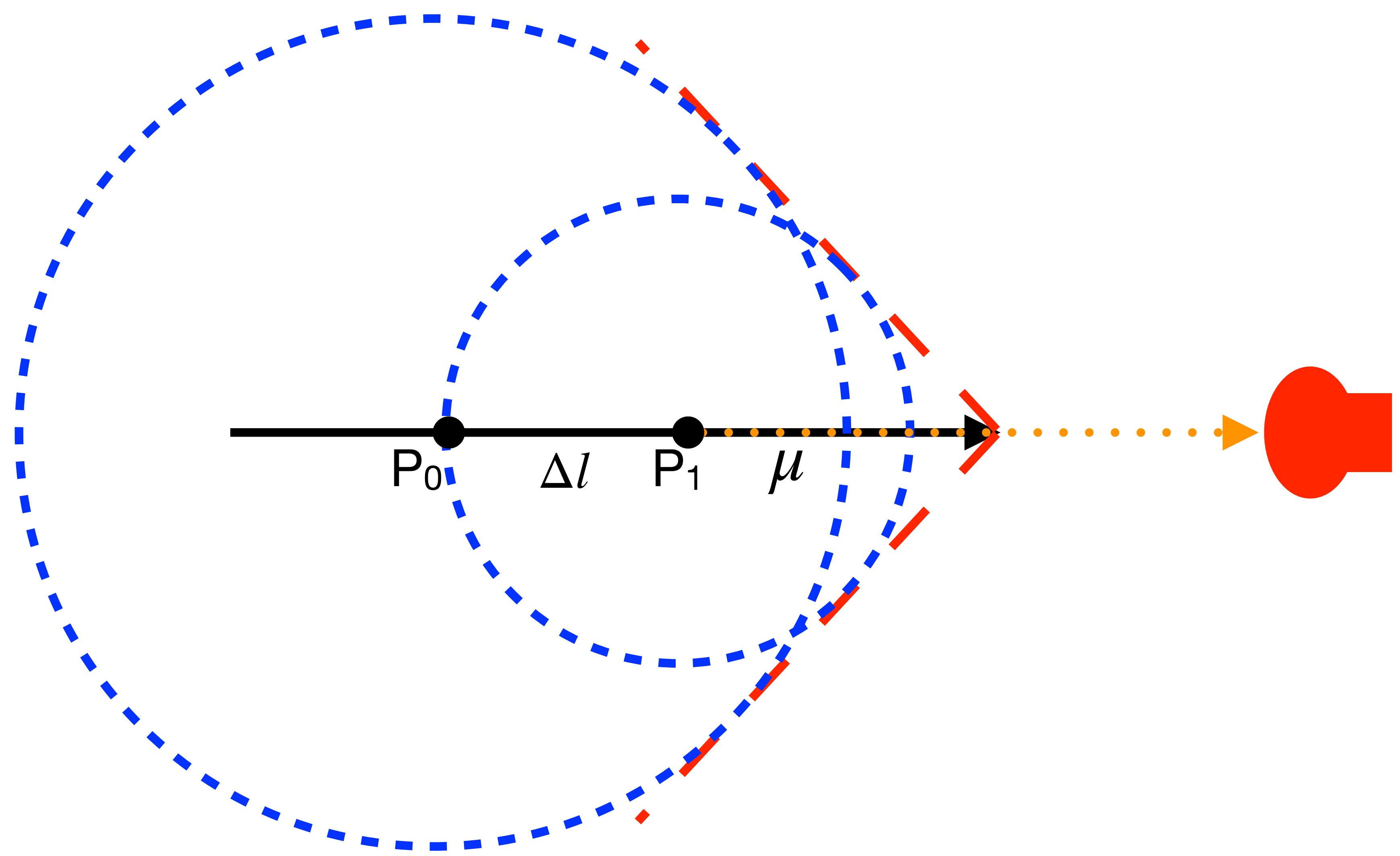

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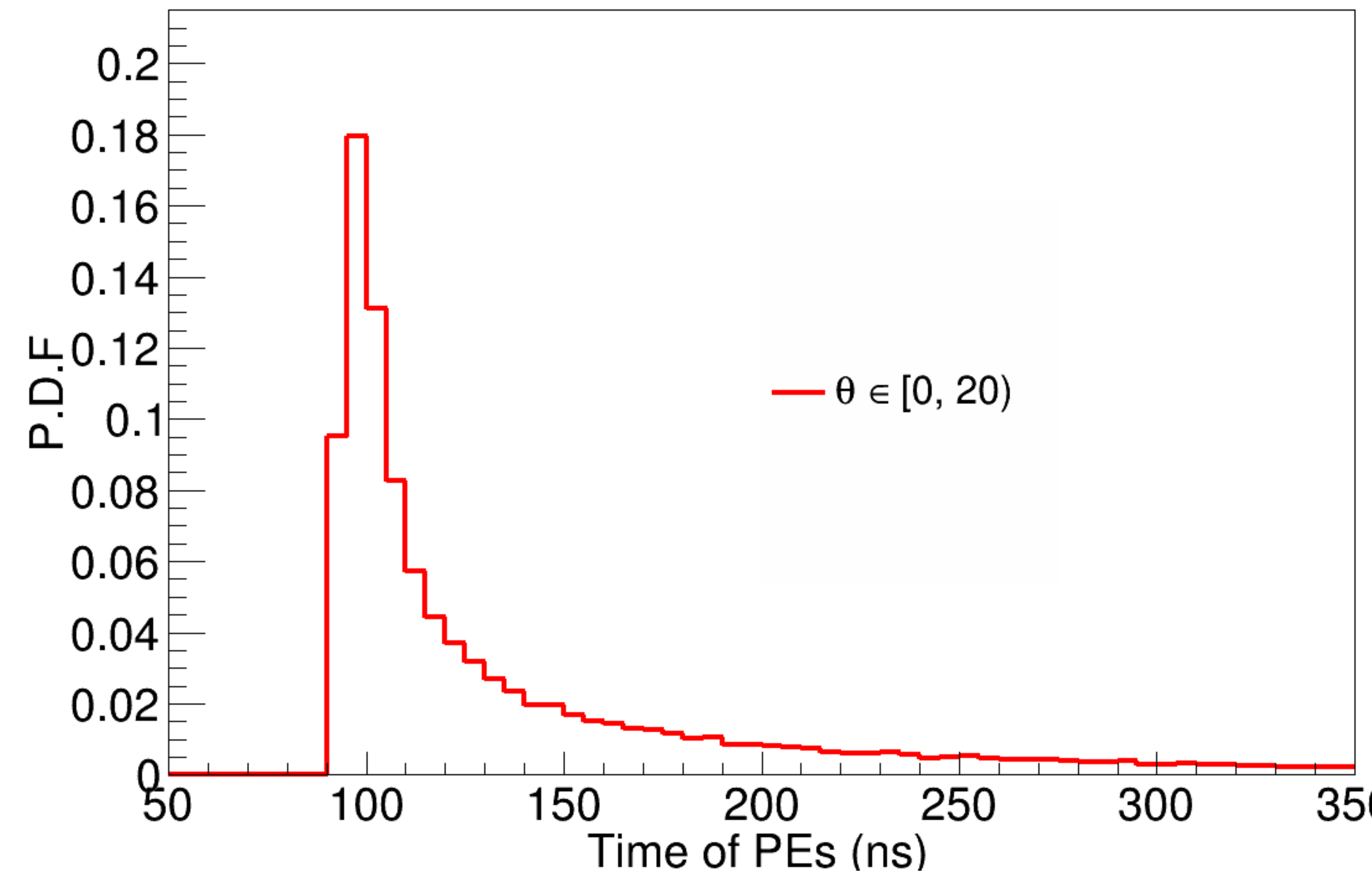

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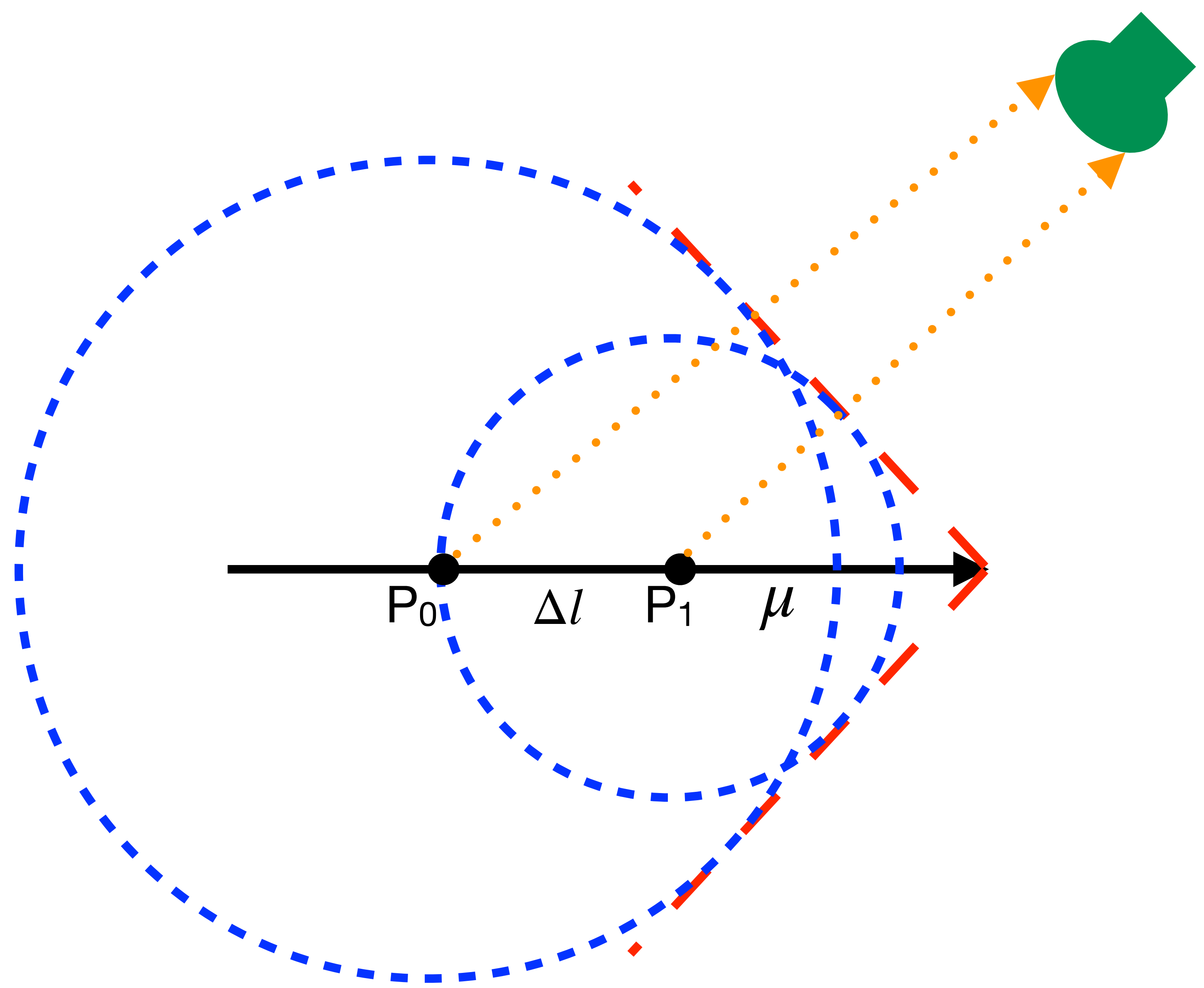

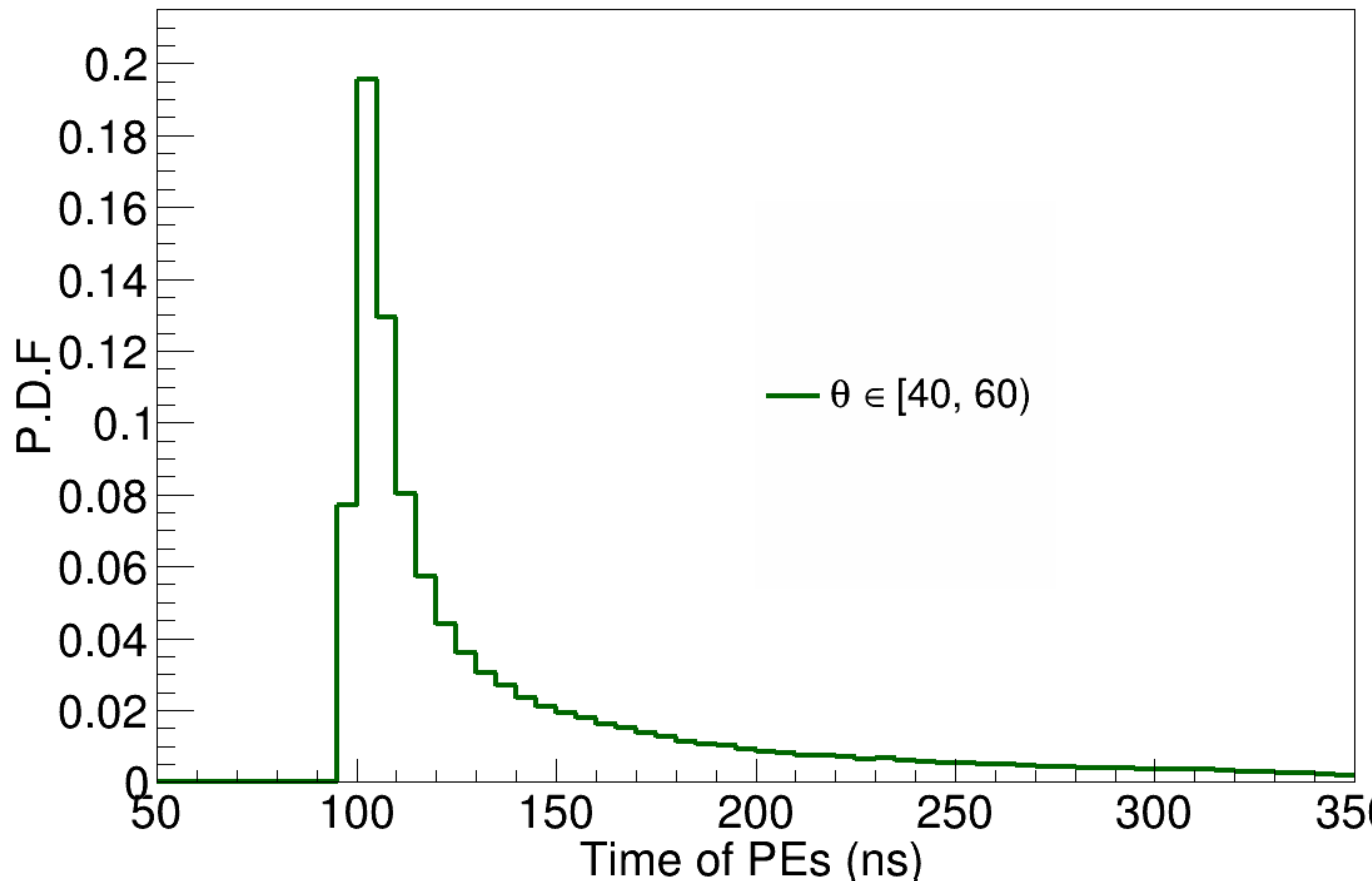

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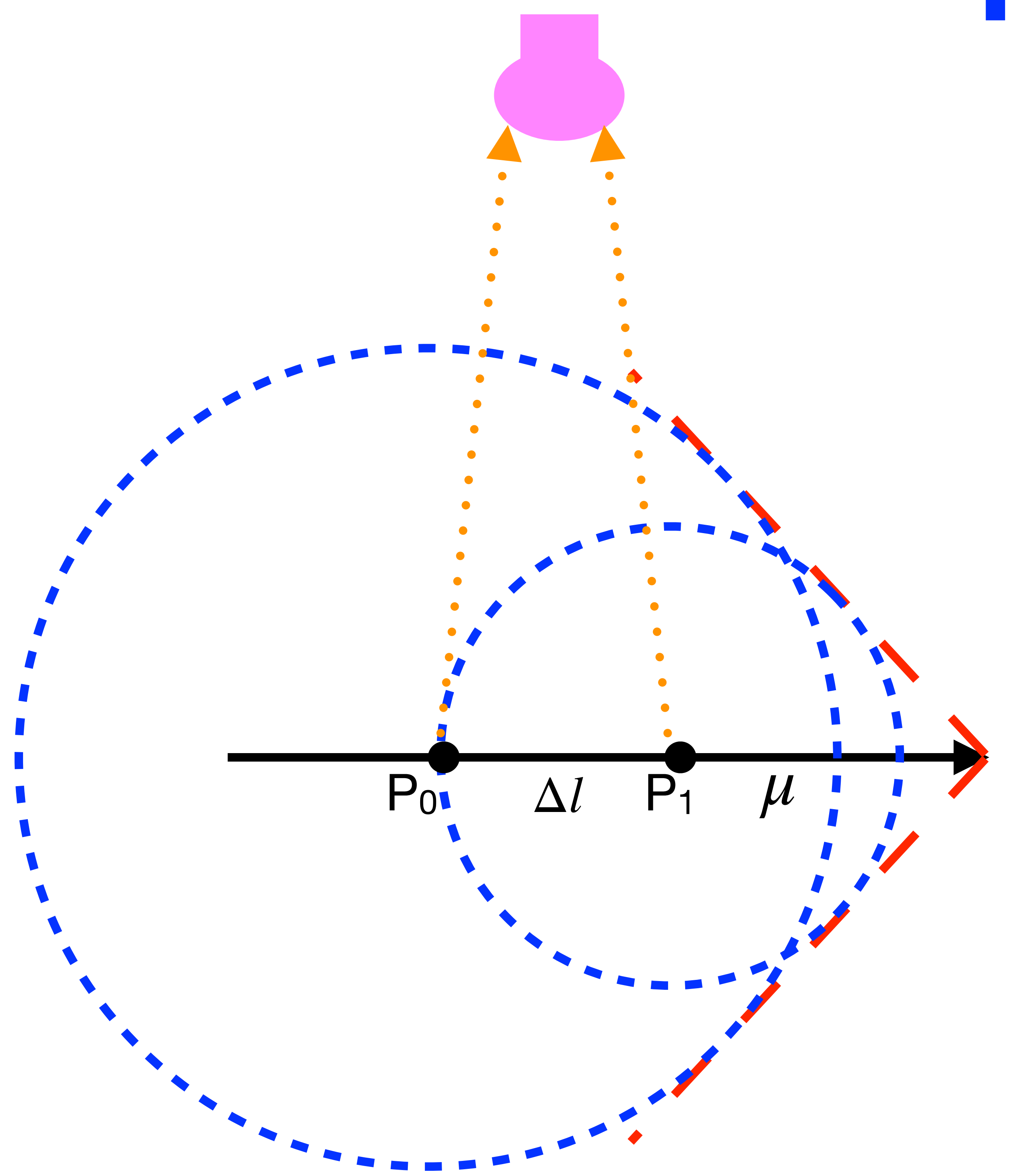

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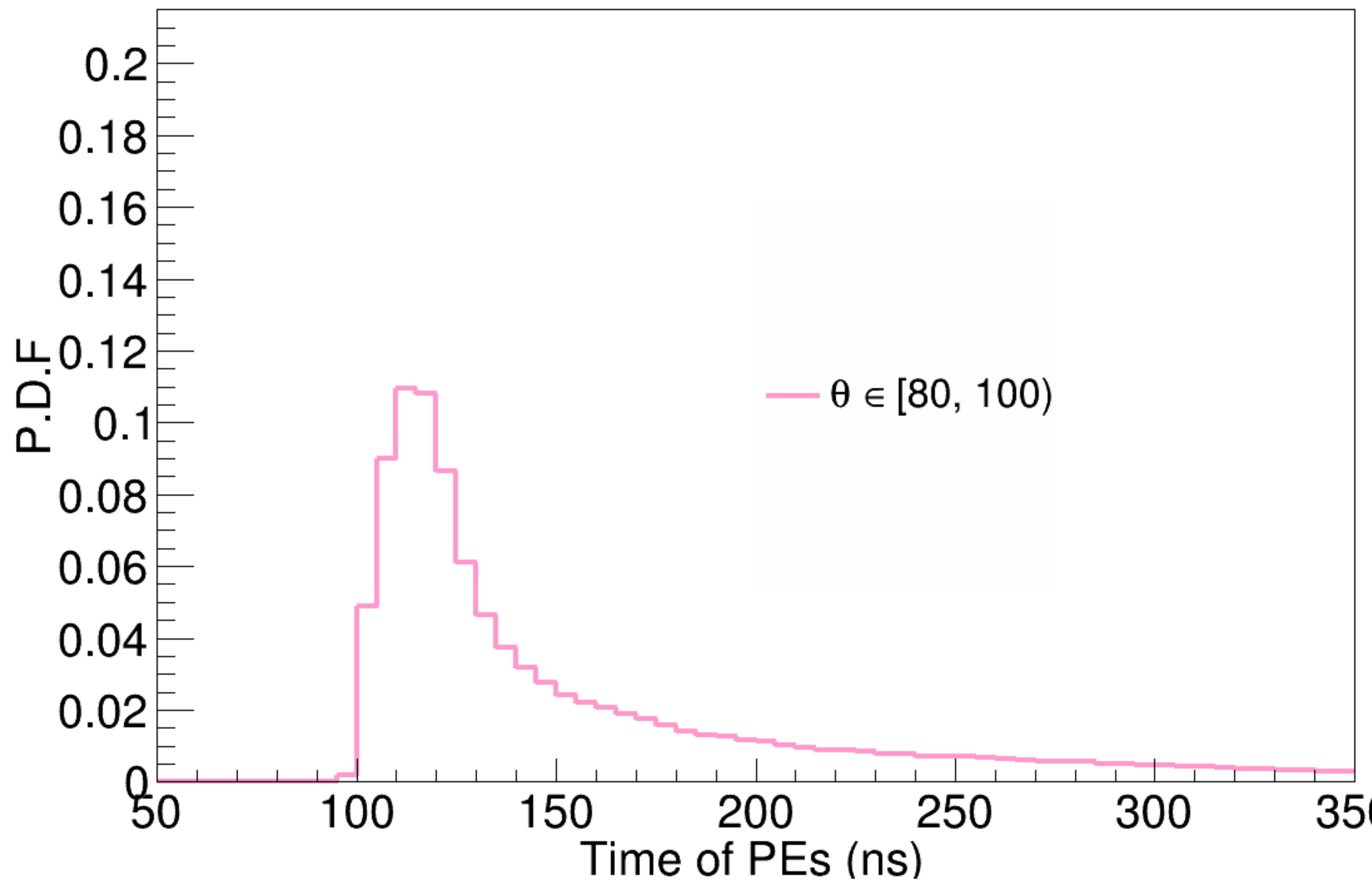

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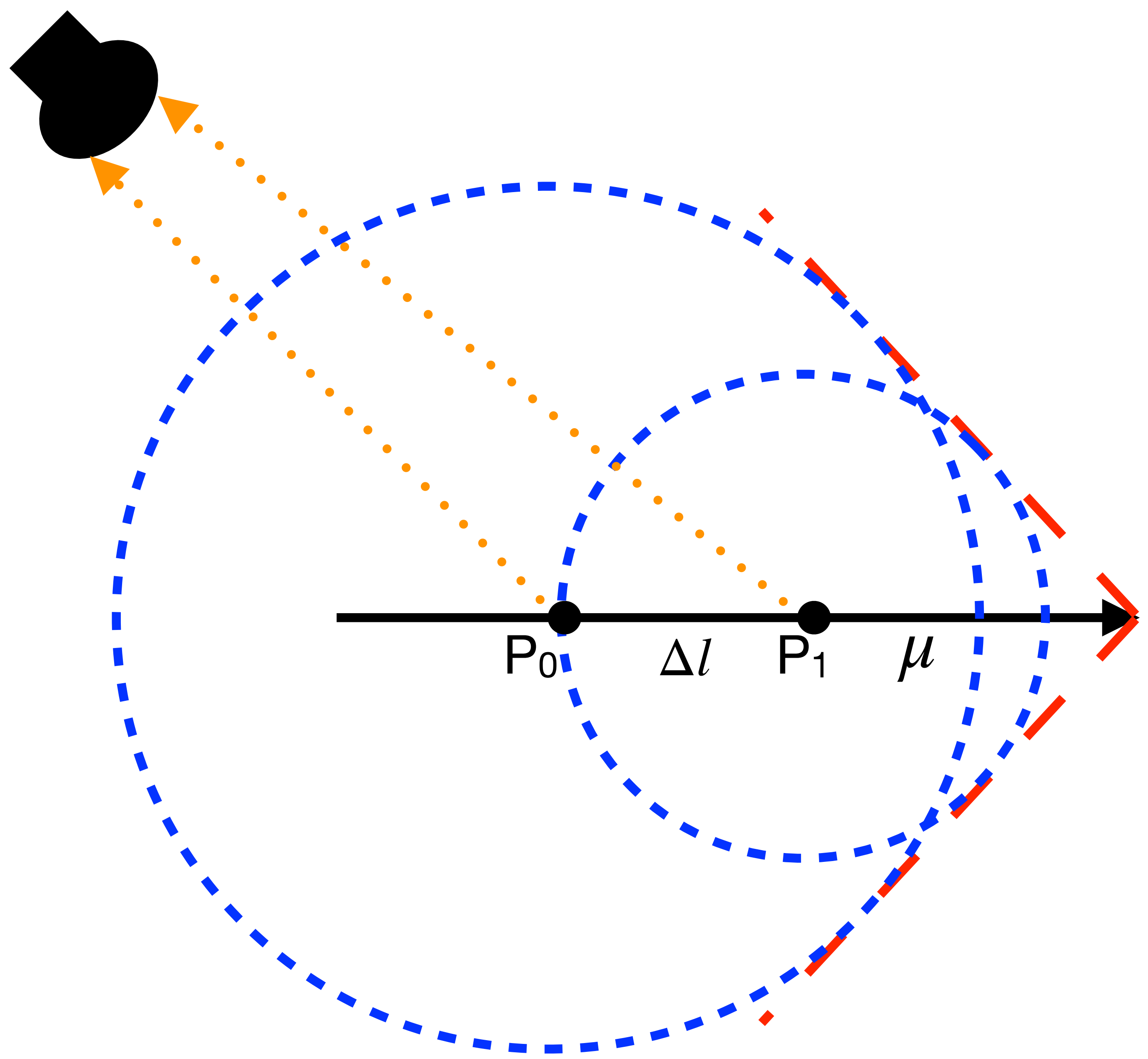

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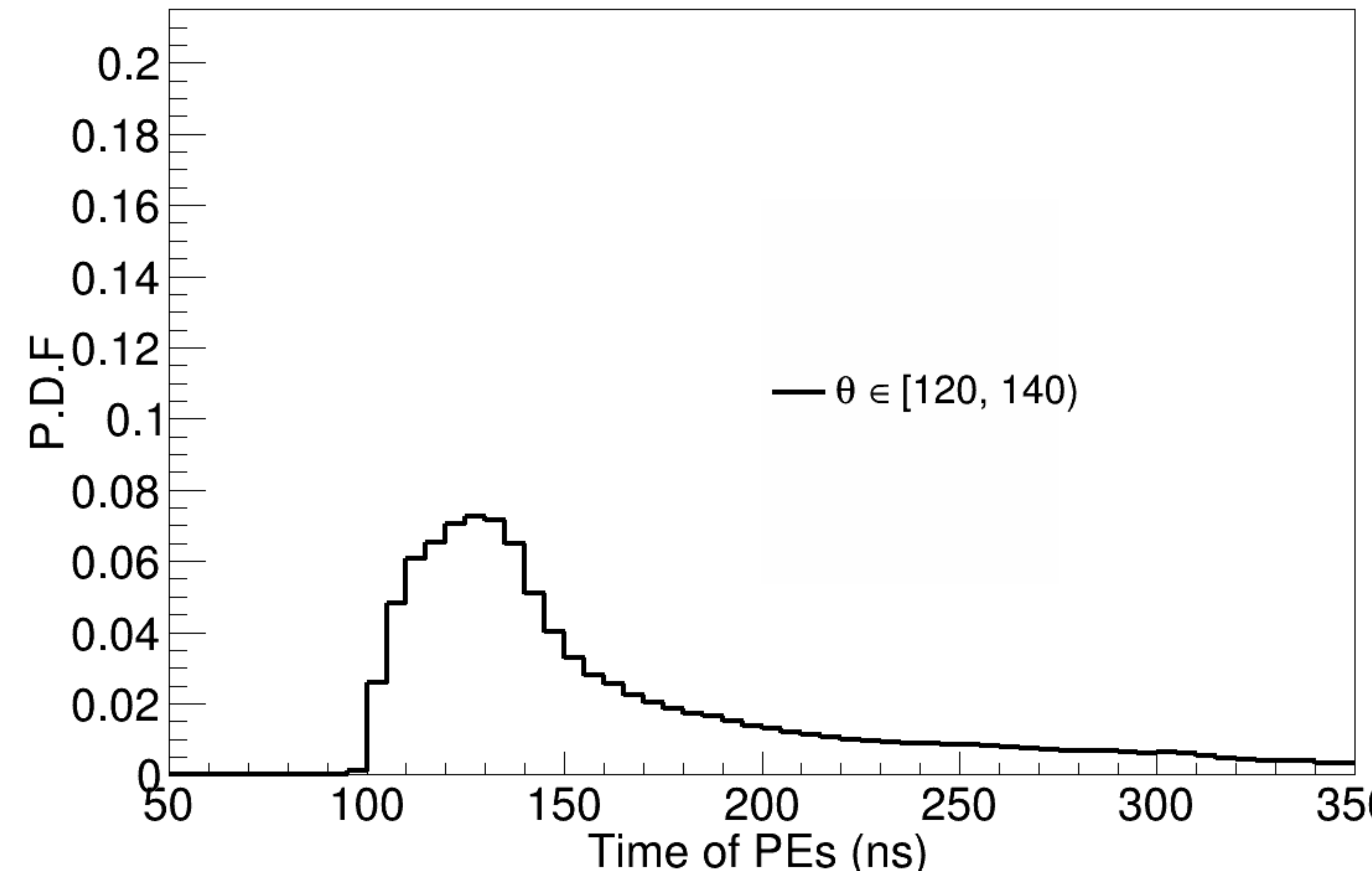

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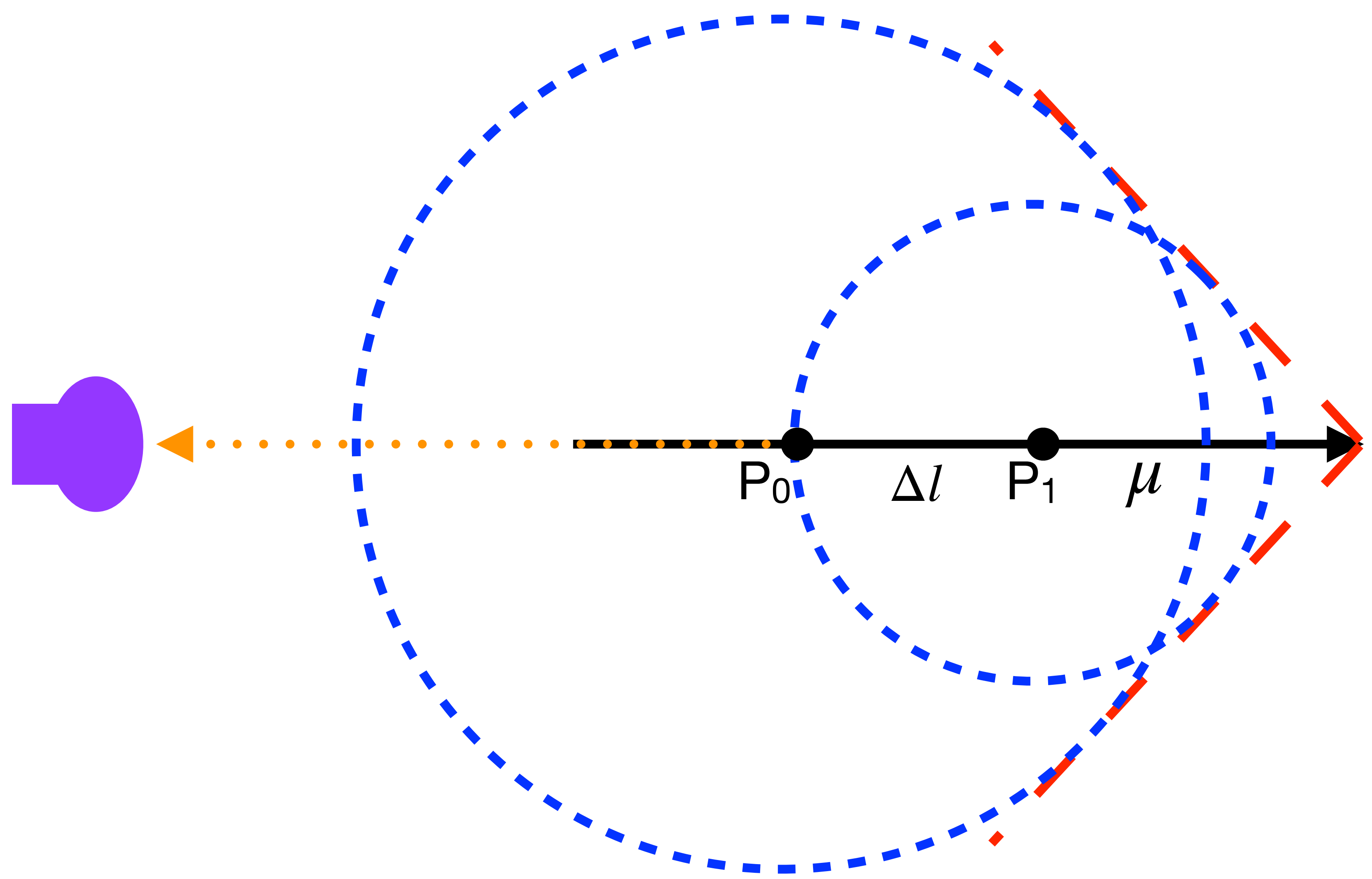

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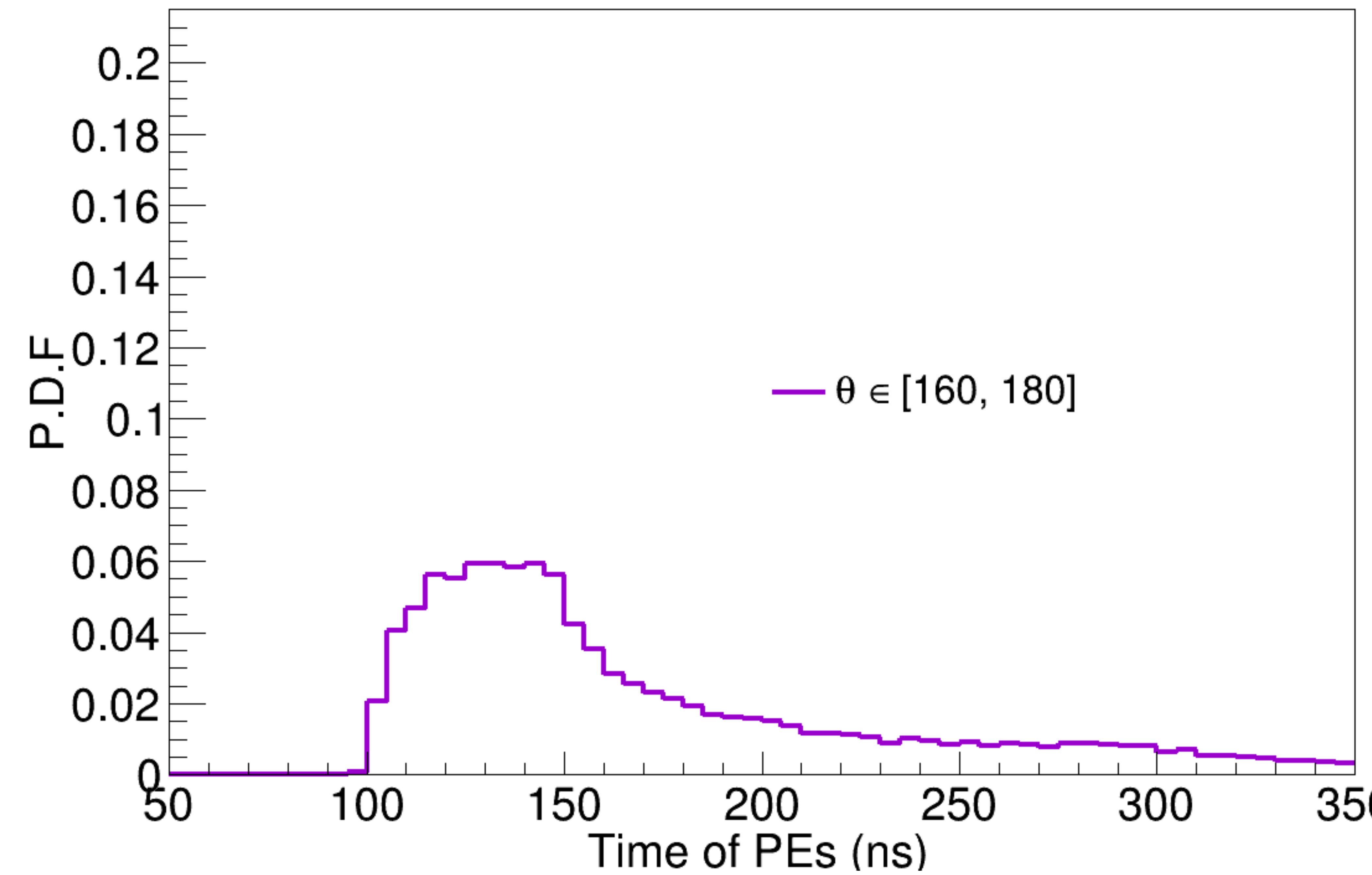

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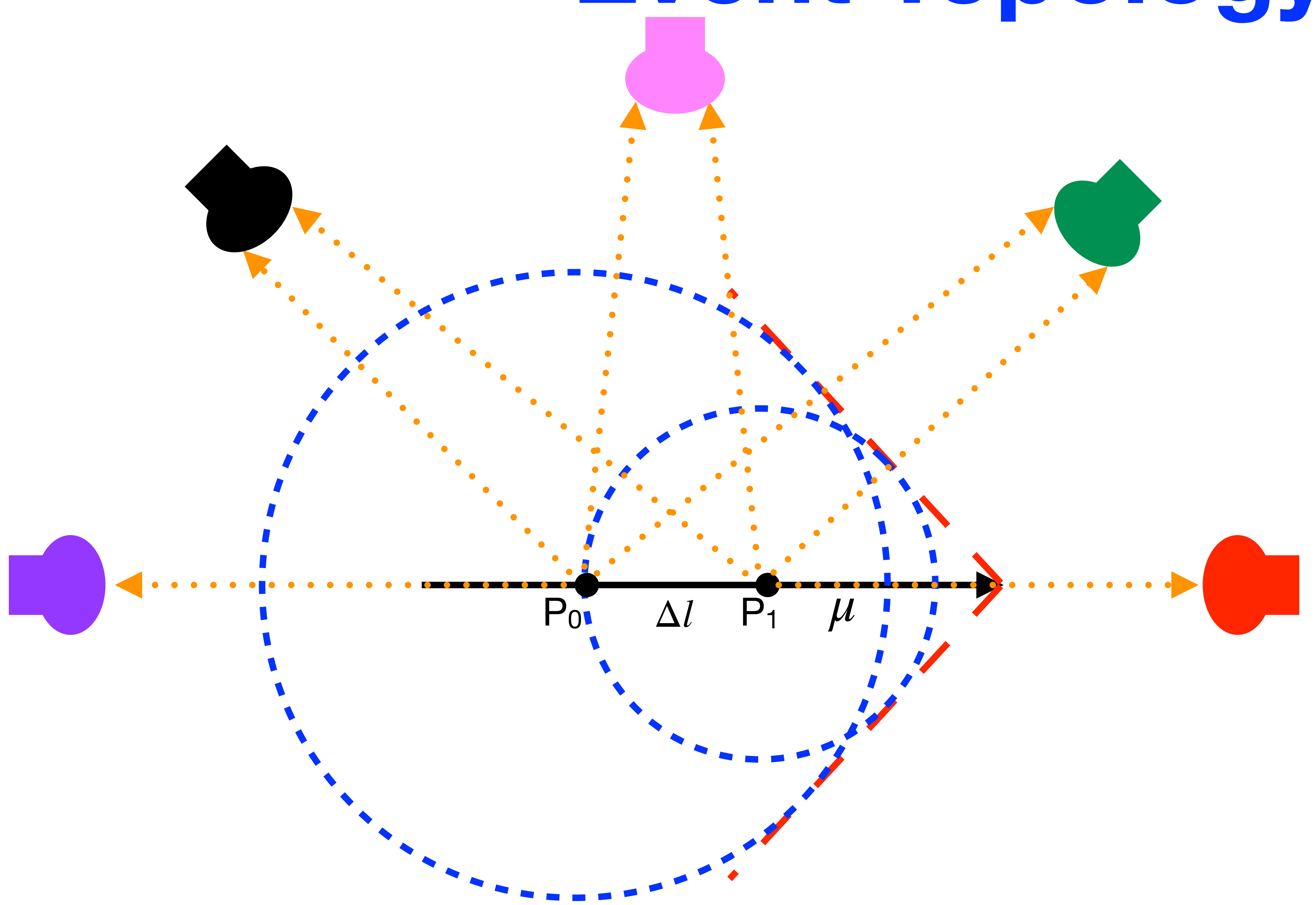

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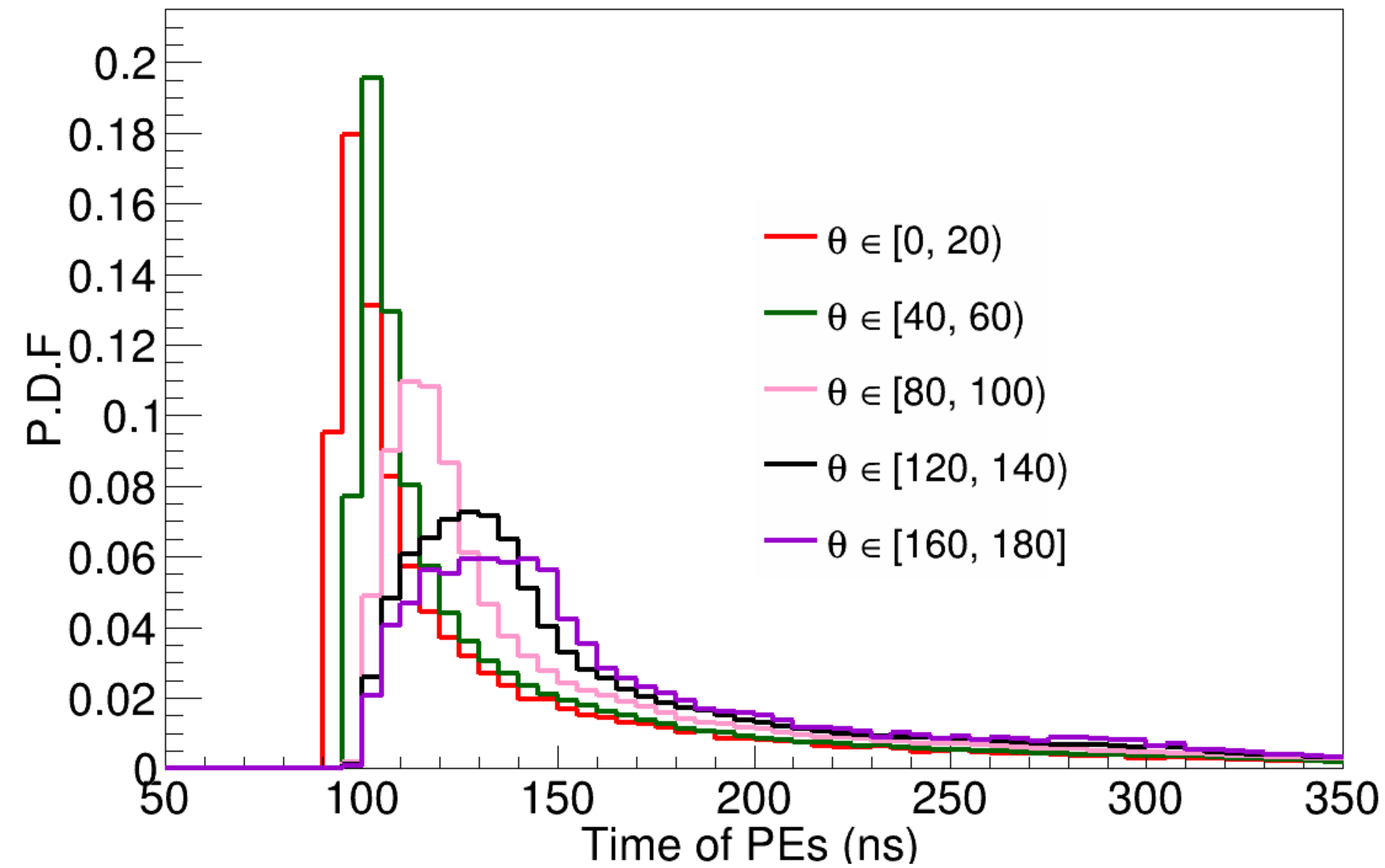

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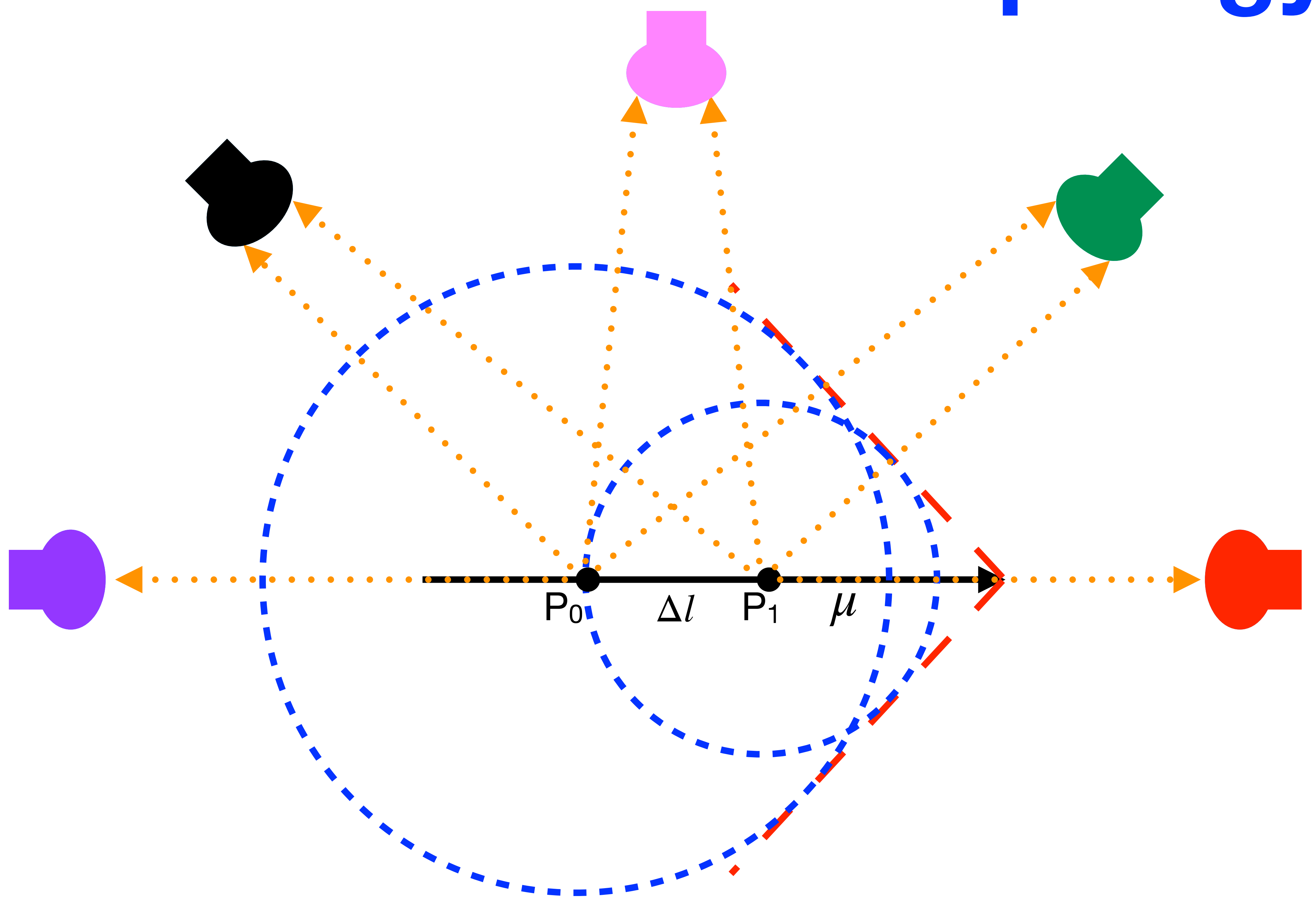

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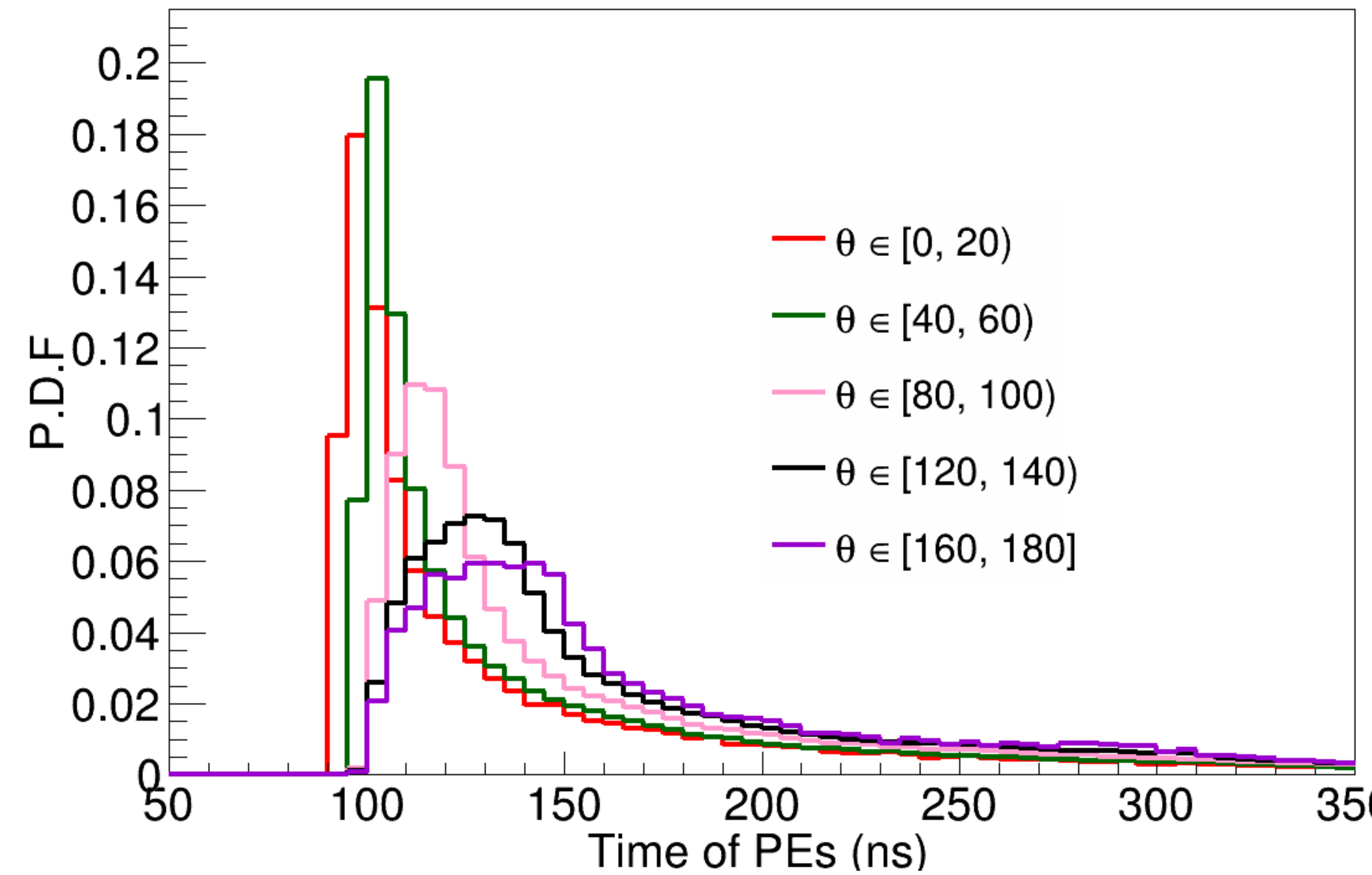

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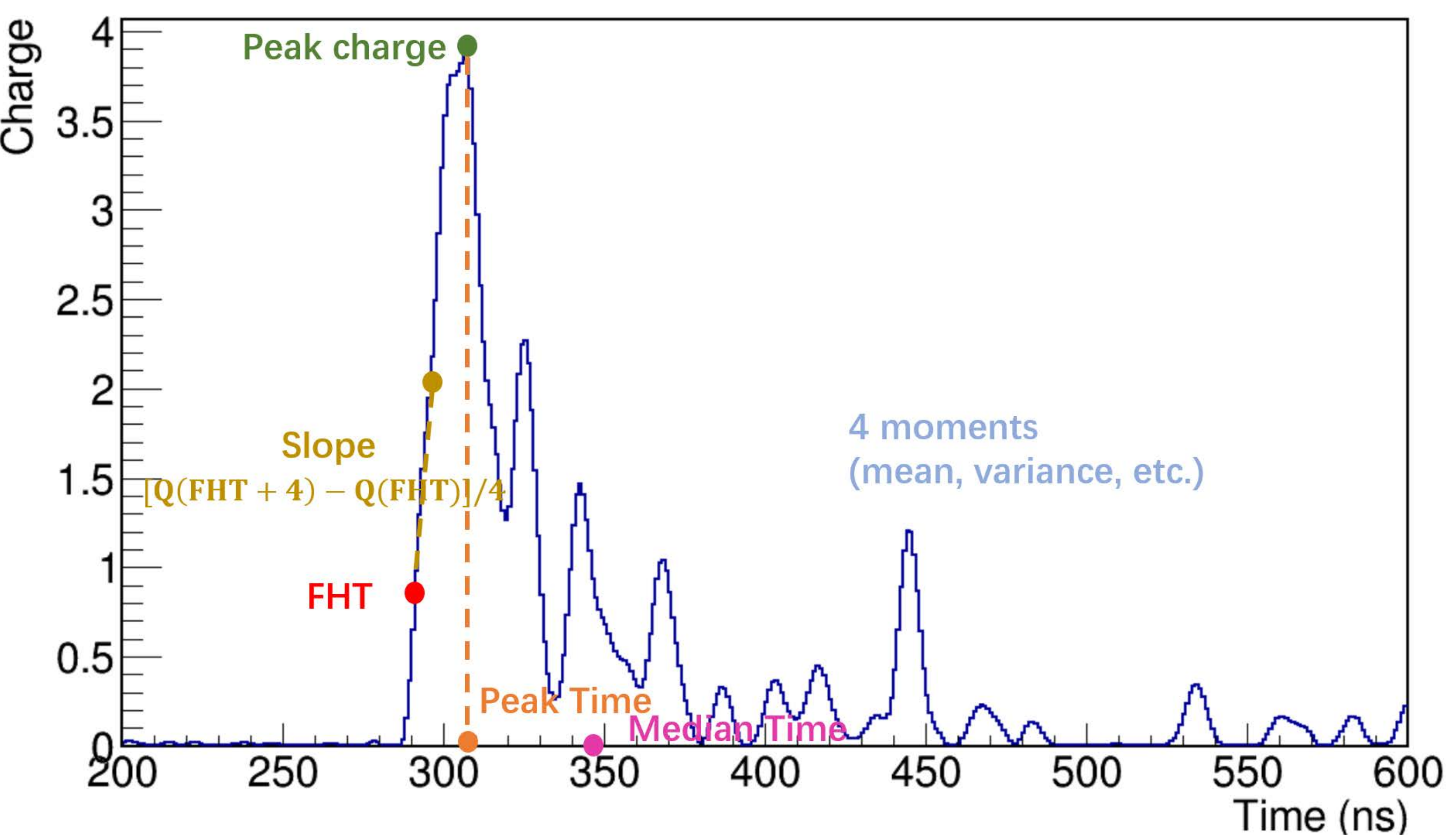
Directionality
Energy
PID…

- Event topology information in the PMT waveform.

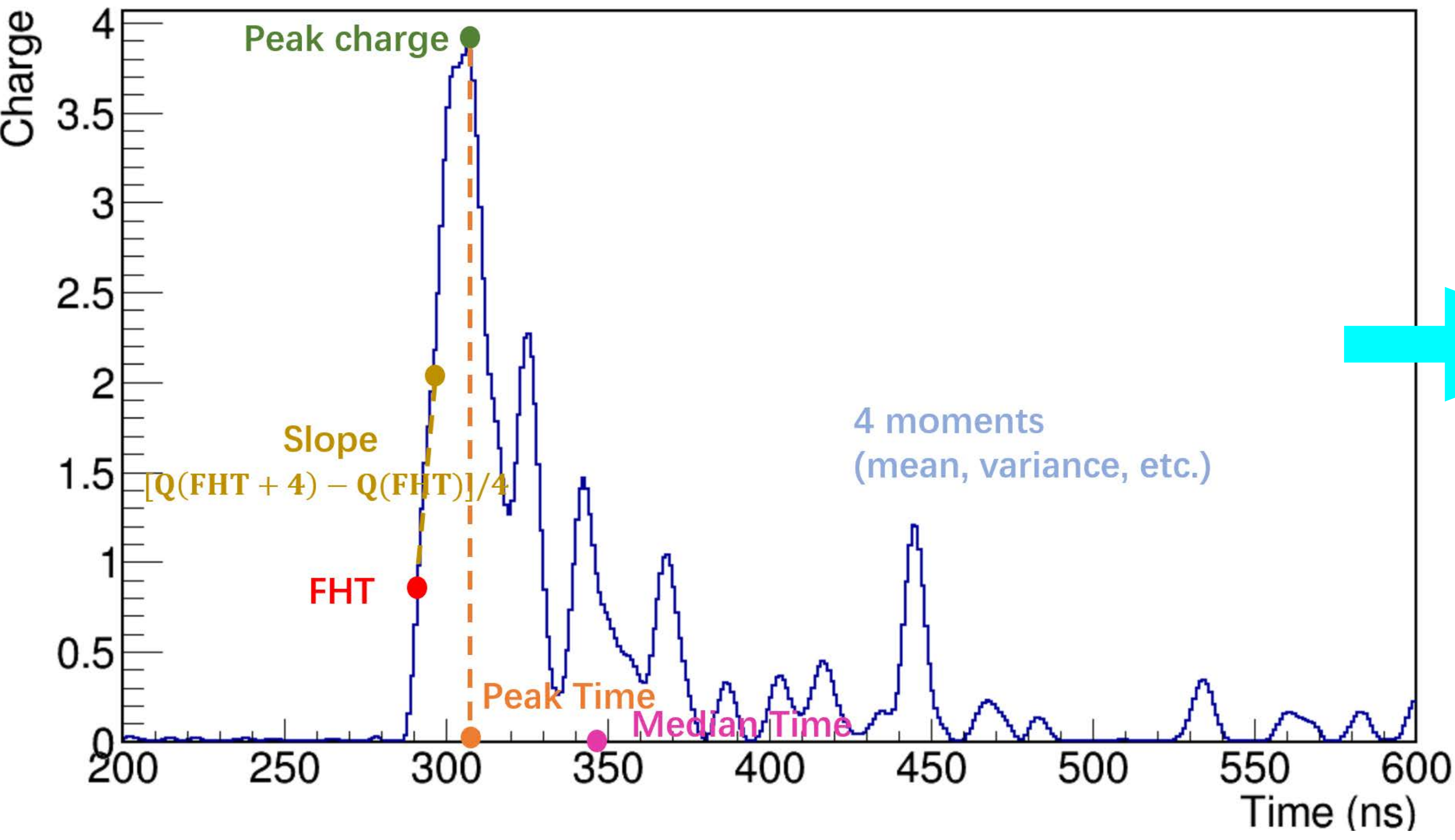
A Multipurpose Machine Learning Solution



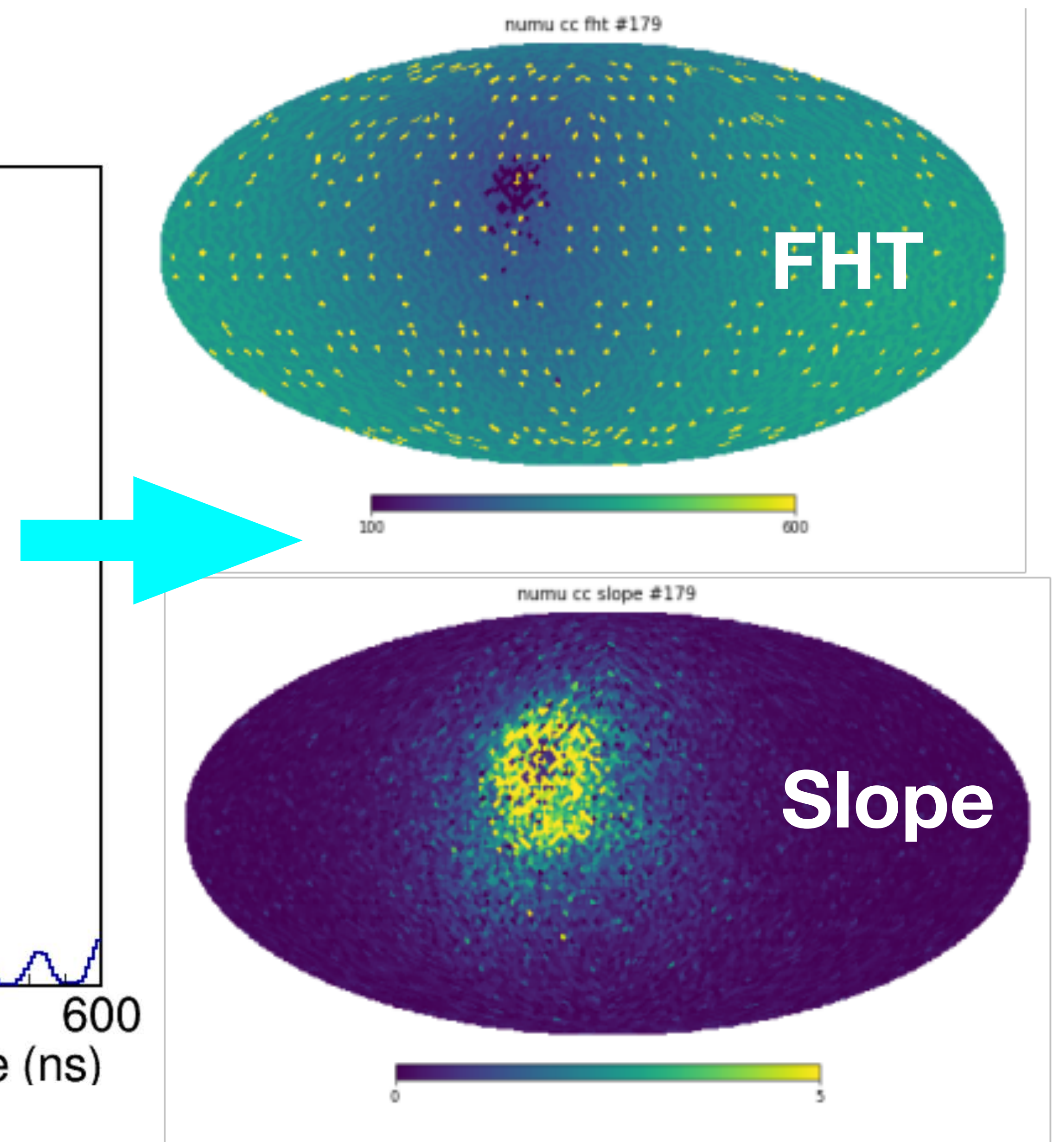
PMT Waveforms (After deconvolution and noise-removing)

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

A Multipurpose Machine Learning Solution



PMT Waveforms
(After deconvolution and noise-removing)



And more features… …

Pictures of PMT Features

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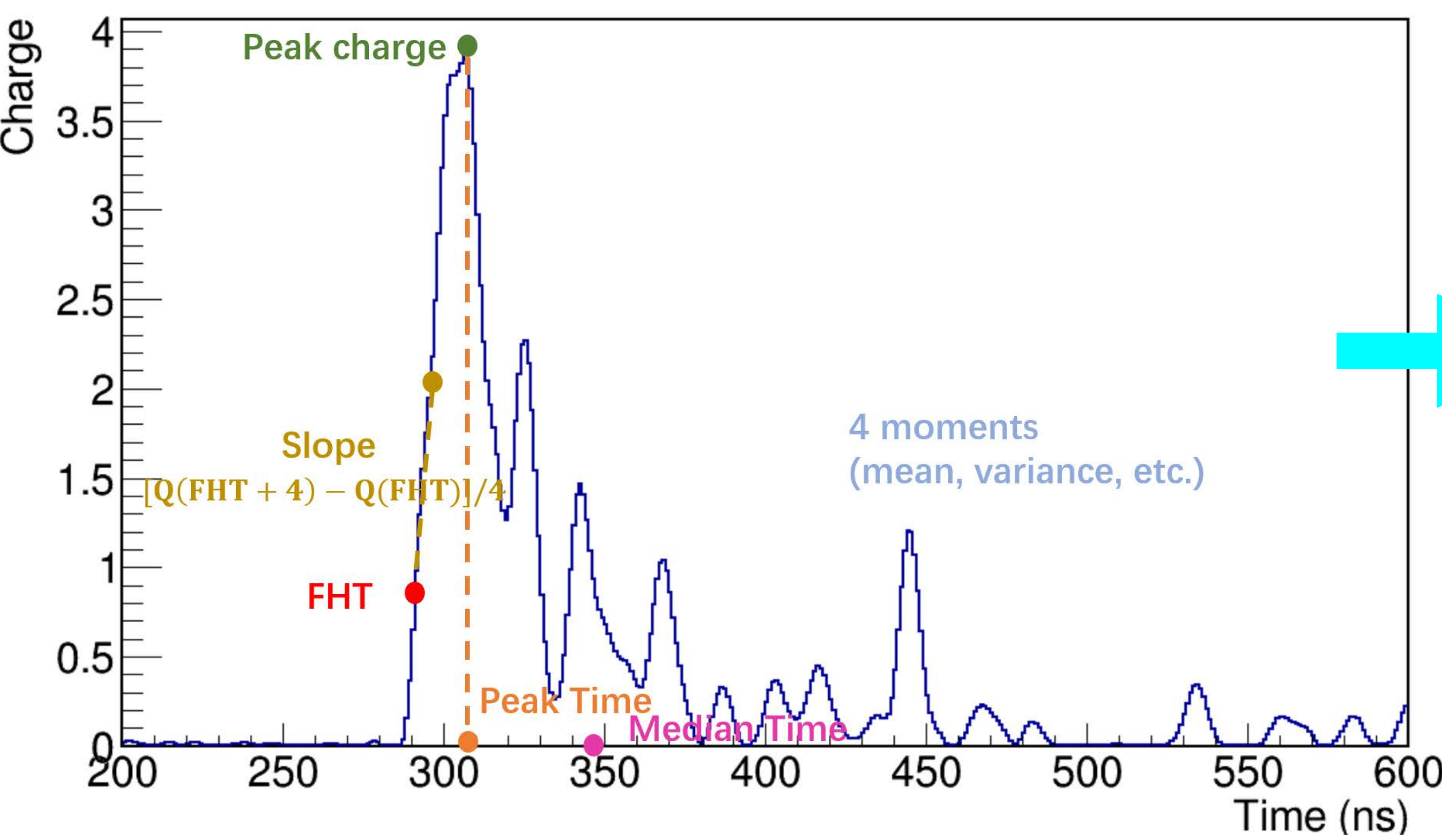

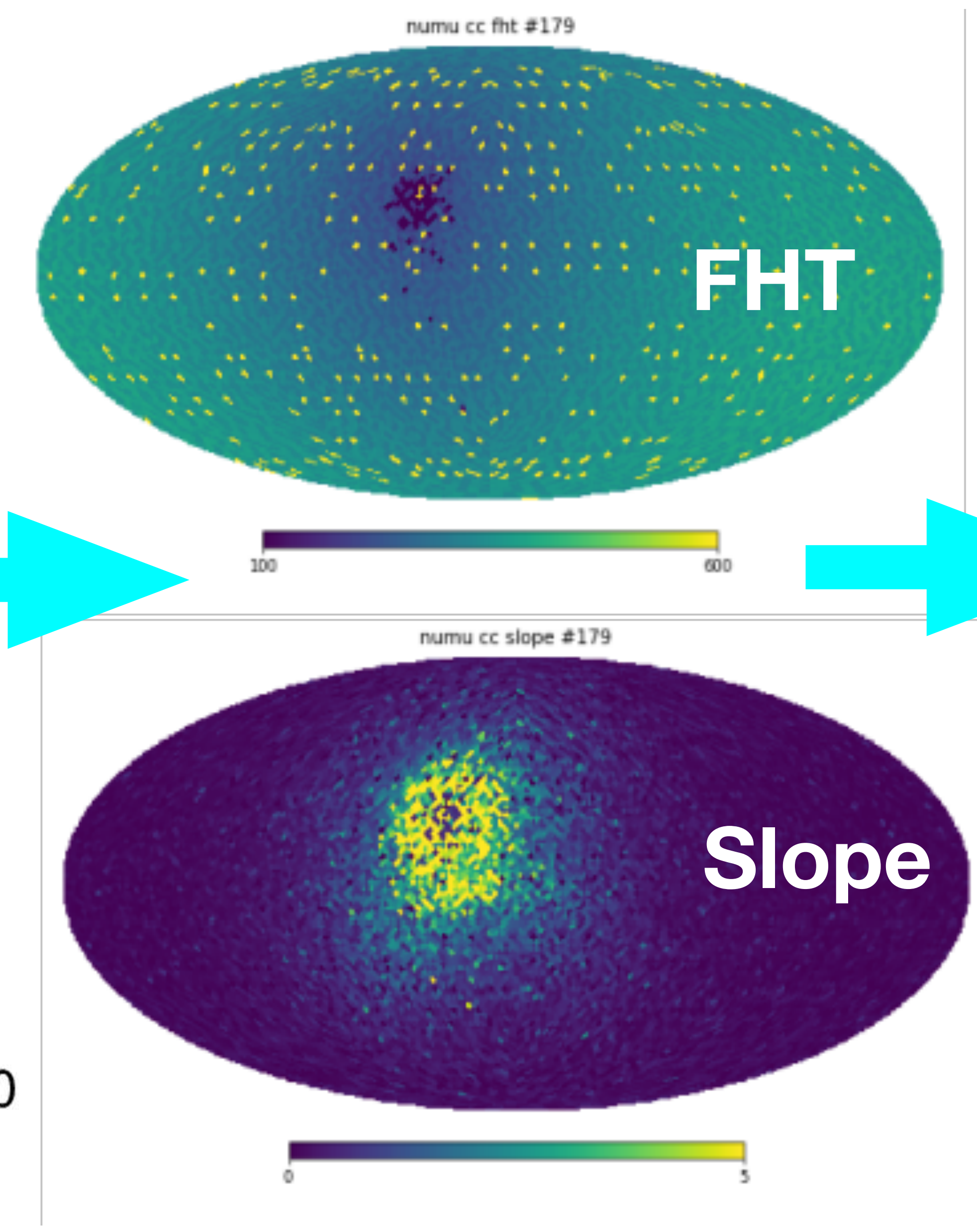

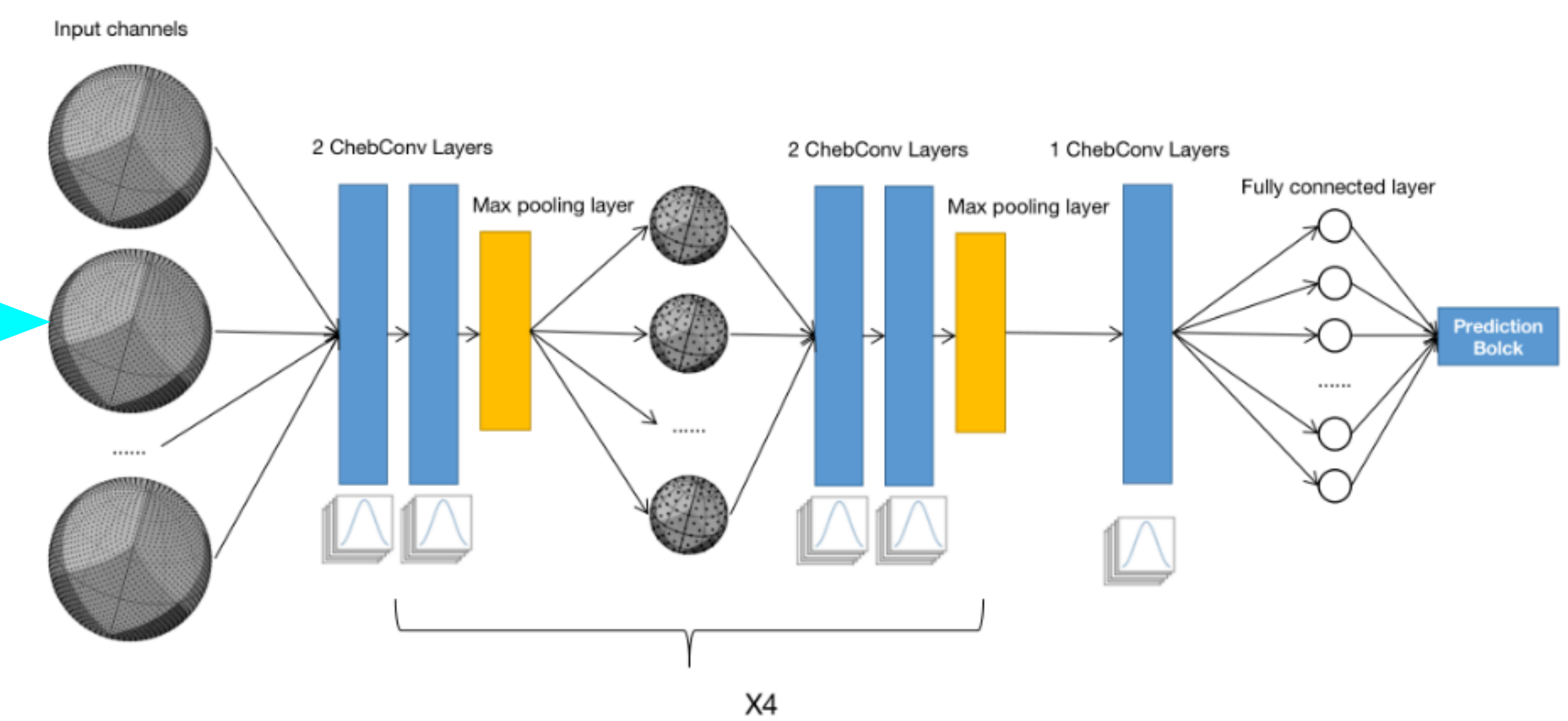

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PMT Waveforms (After deconvolution and noise-removing)

Pictures of PMT Features

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

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A Multipurpose Machine Learning Solution

And more features… …

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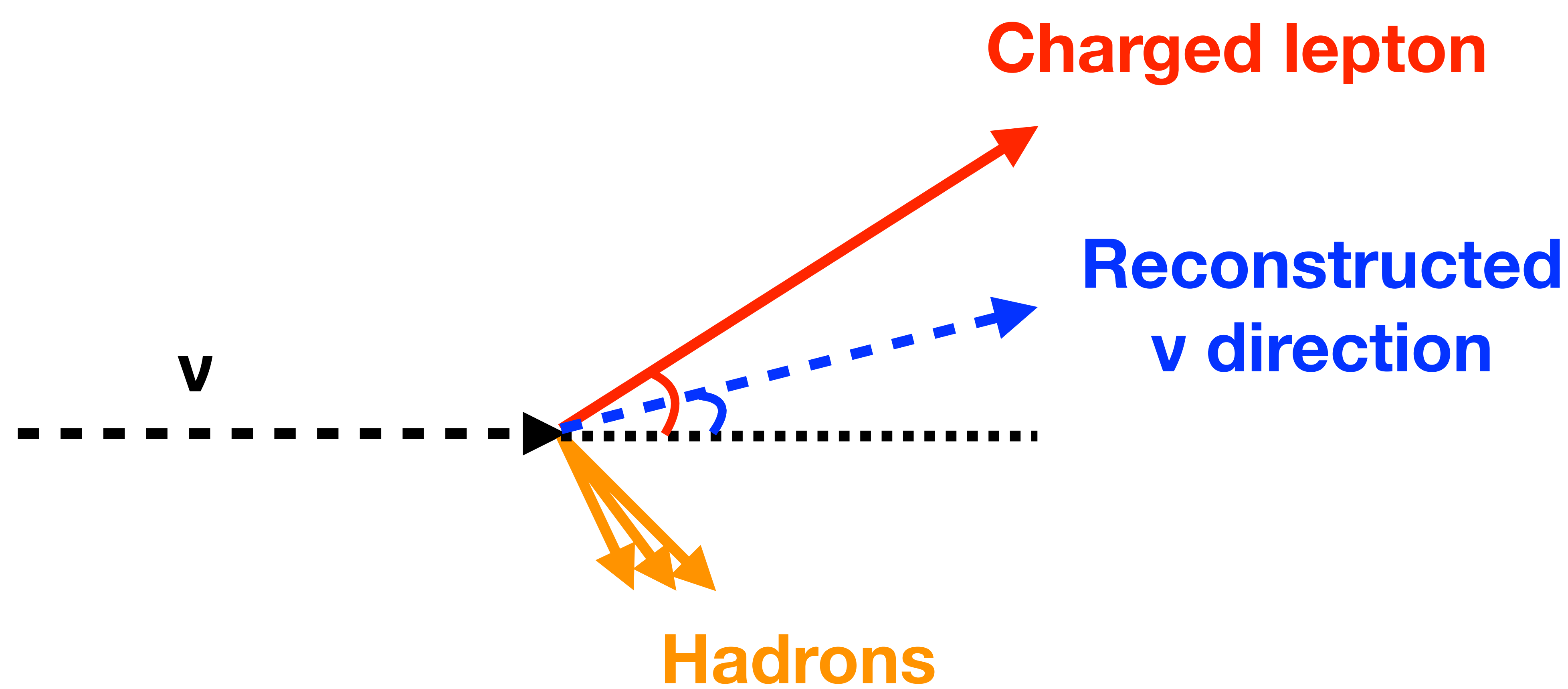
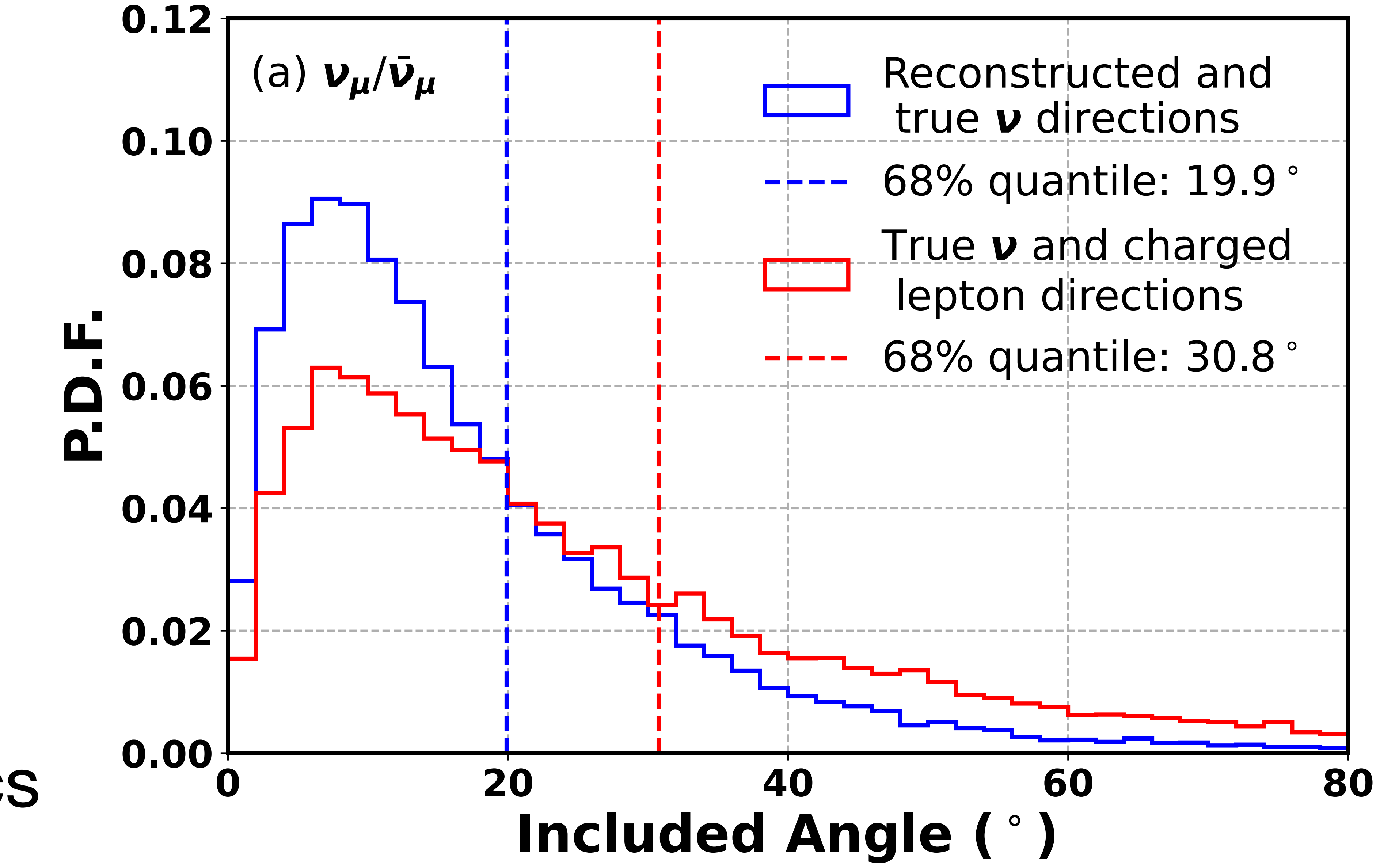
Outputs

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

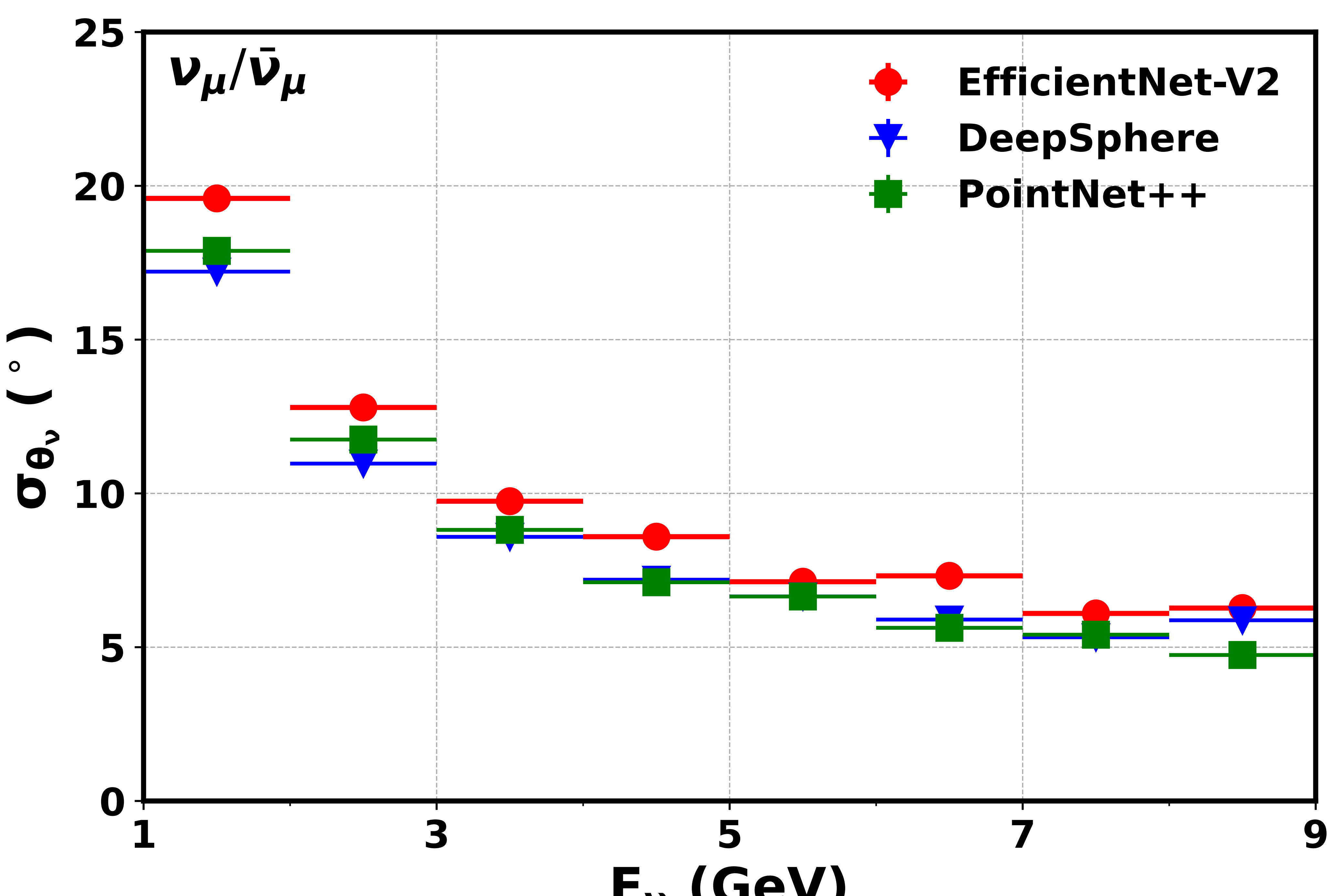
JUNO Atmospheric ν: Directionality Reconstruction





Reconstructing neutrino direction has better physics potential than reconstructing charged leptons

Directional resolution of atmo ν in JUNO



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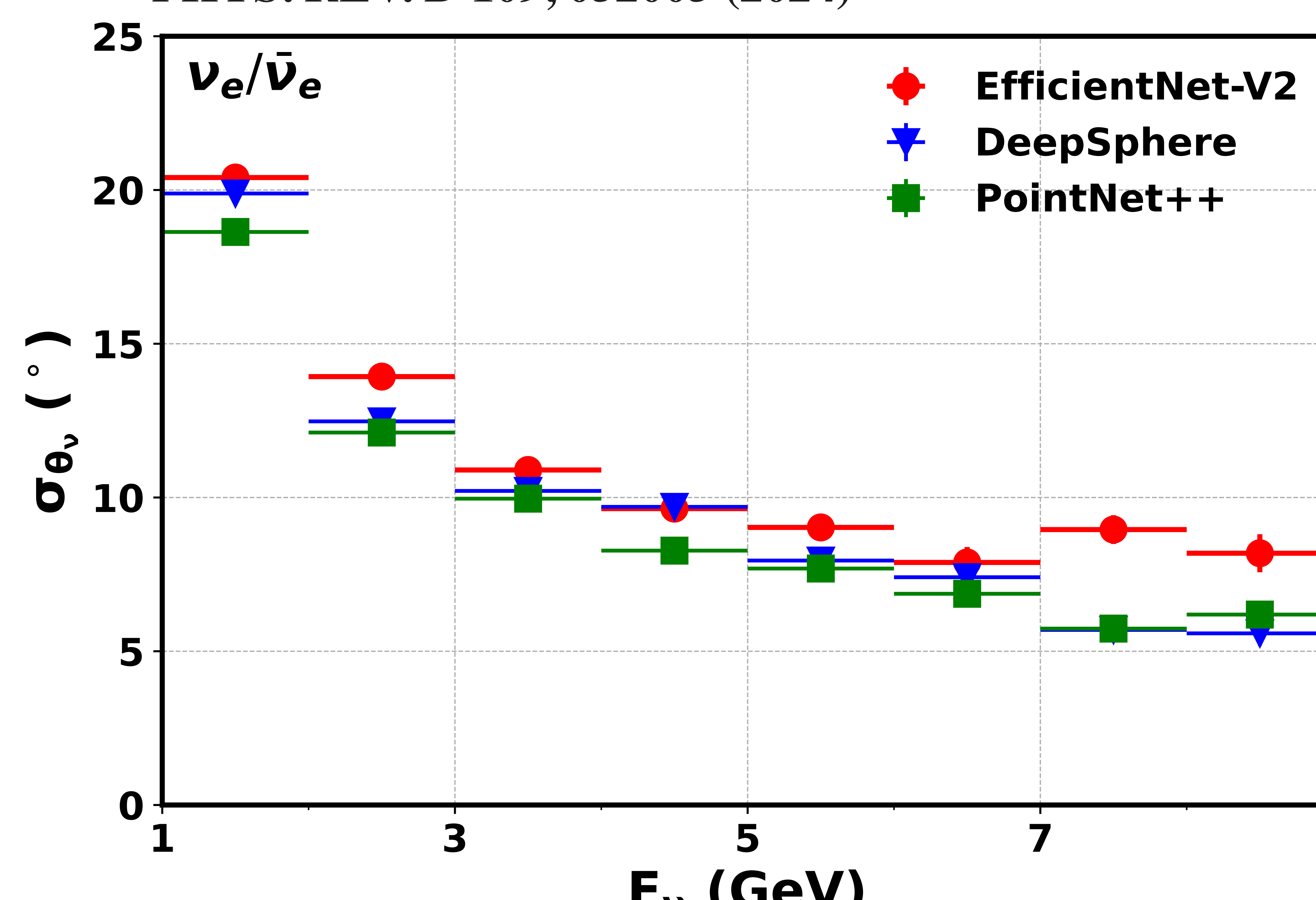
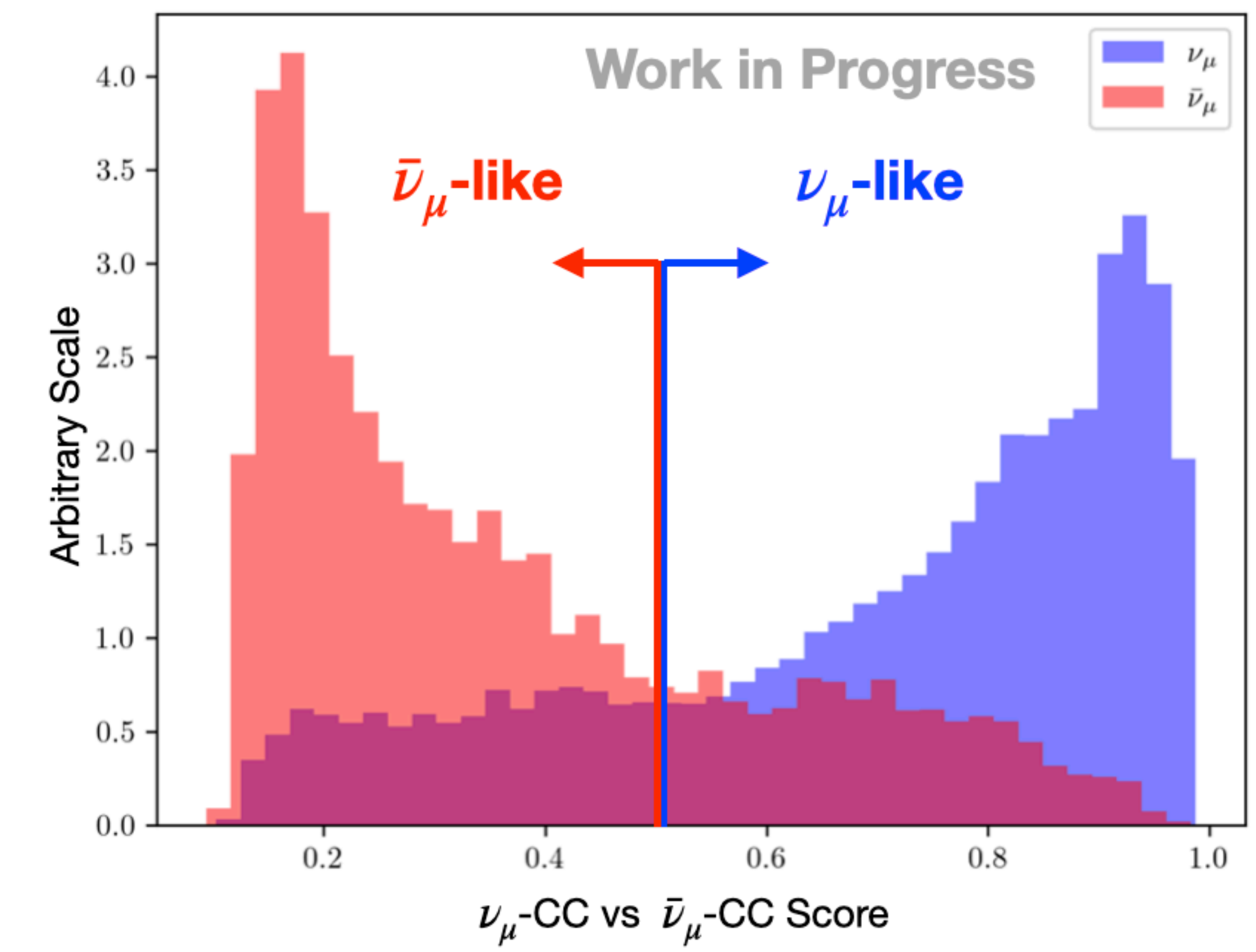
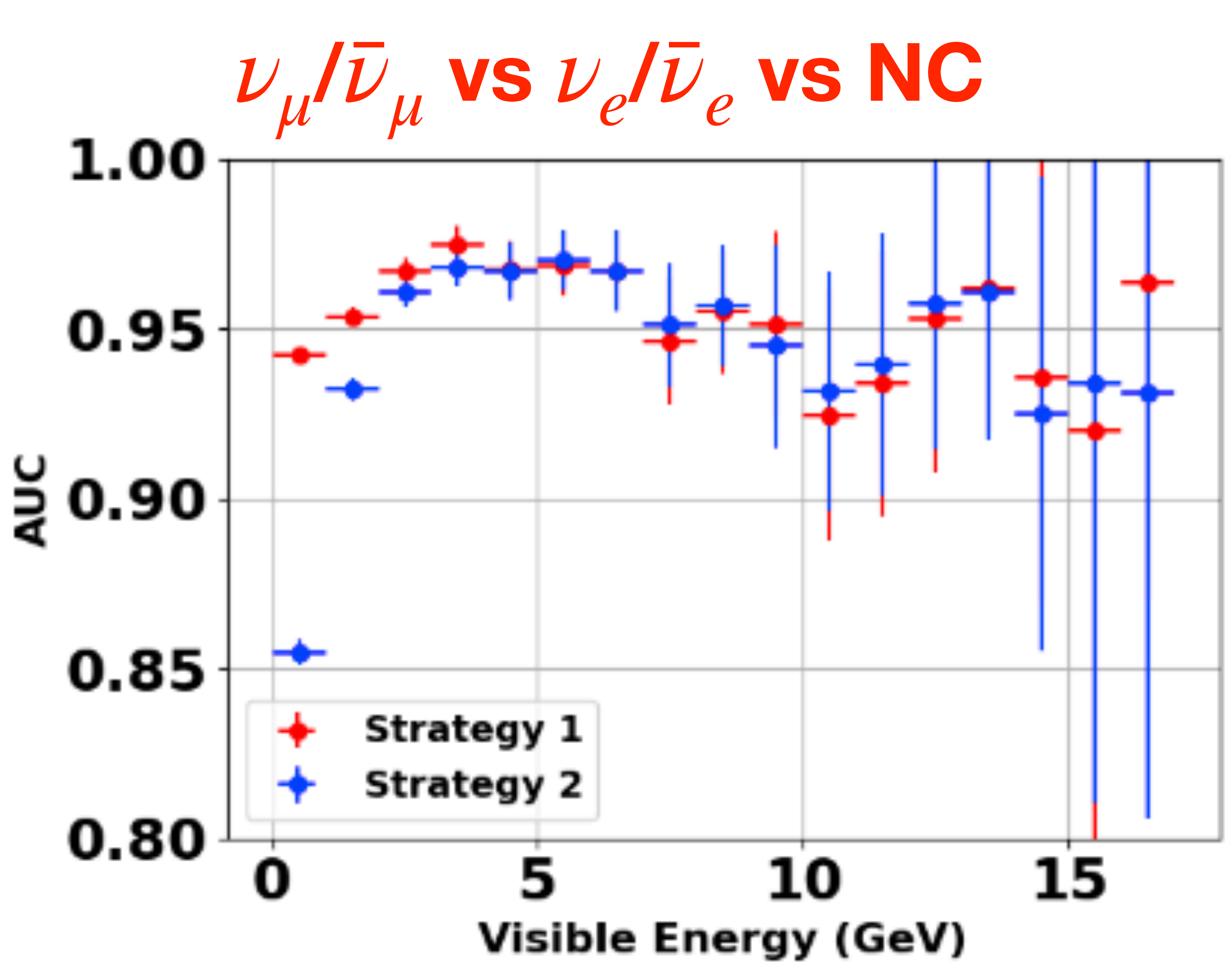
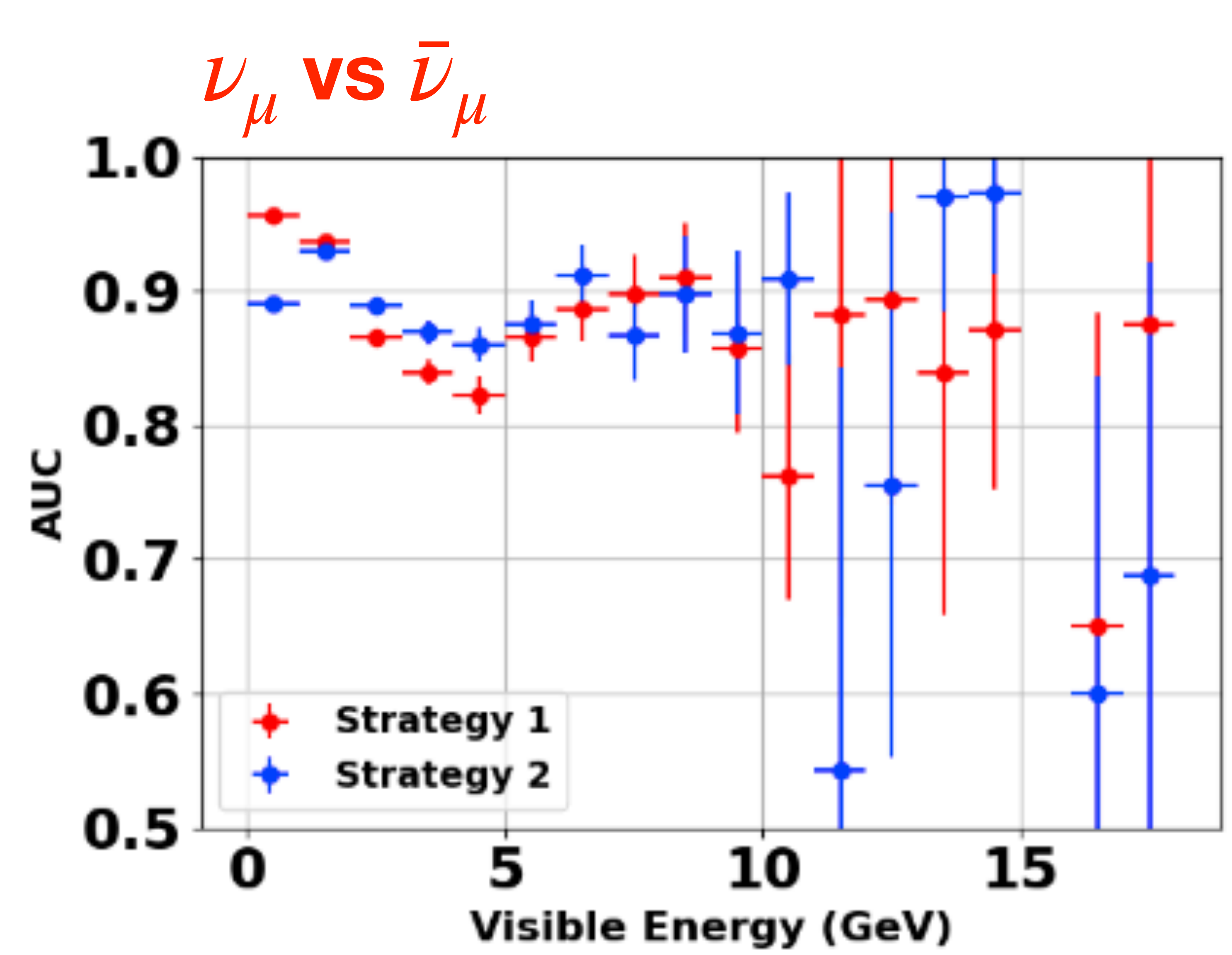


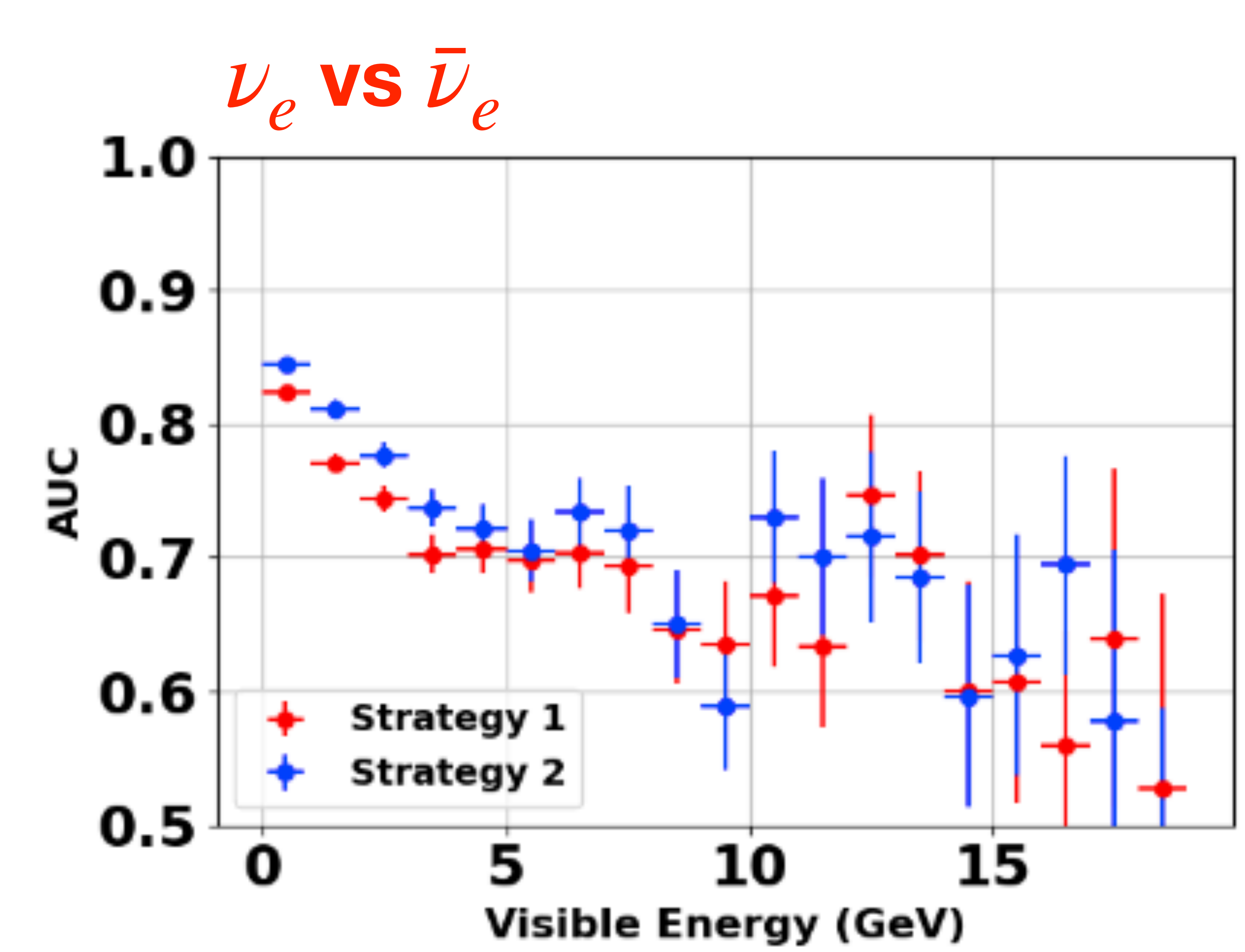
JUNO Atmospheric ν: PID Performance

- 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 and Michel electron informations.
- **In summary, ML significantly improves JUNO's capability to atmospheric neutrinos.**





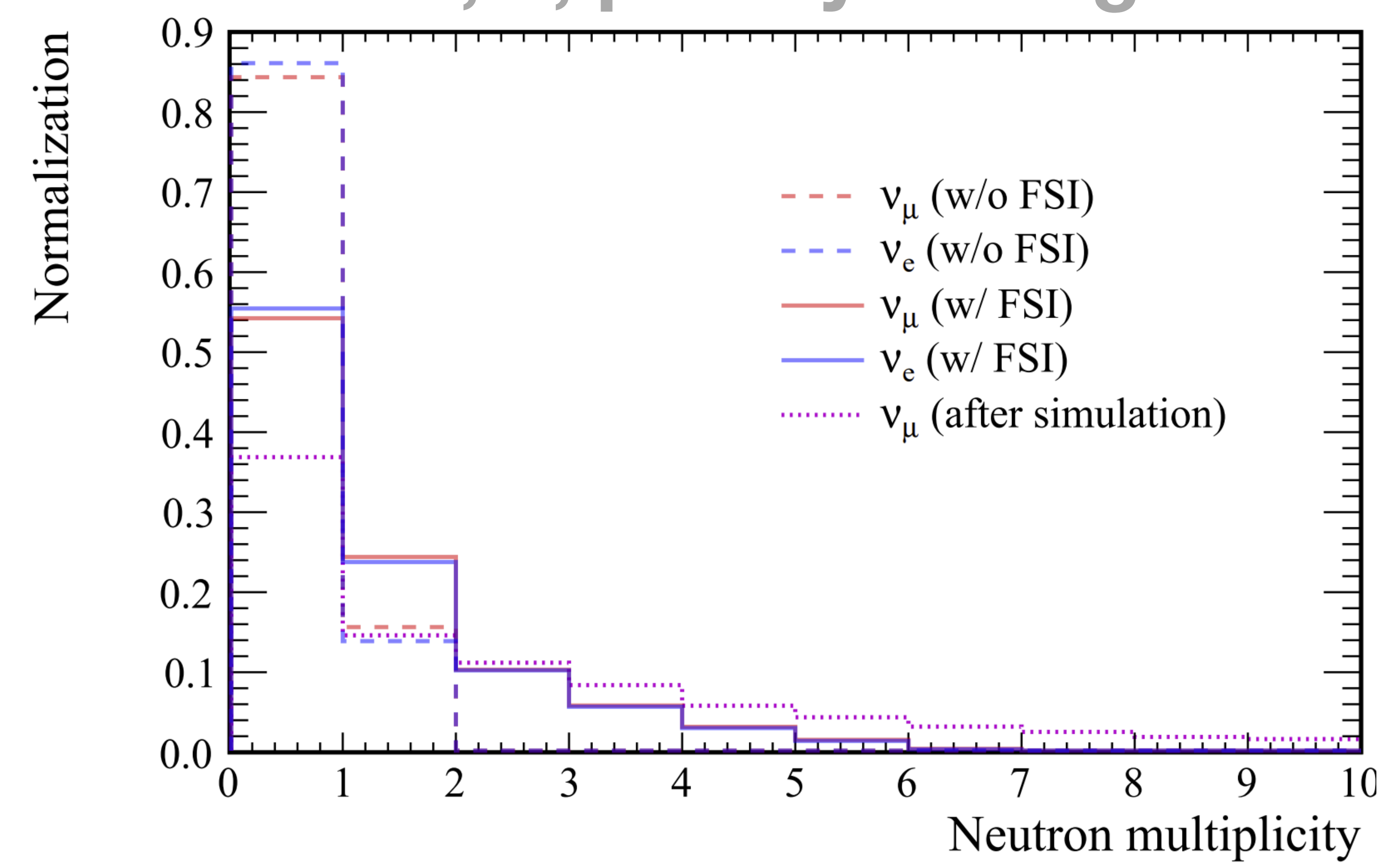




Deep-learning in the Precision Era of Neutrino Physics: Gains and Questions

- Gains:
  - More effective signal recognition.
  - More precise measurements.
  - Turn impossible into possible.

GENIE, ν, plot by Cheng Jie



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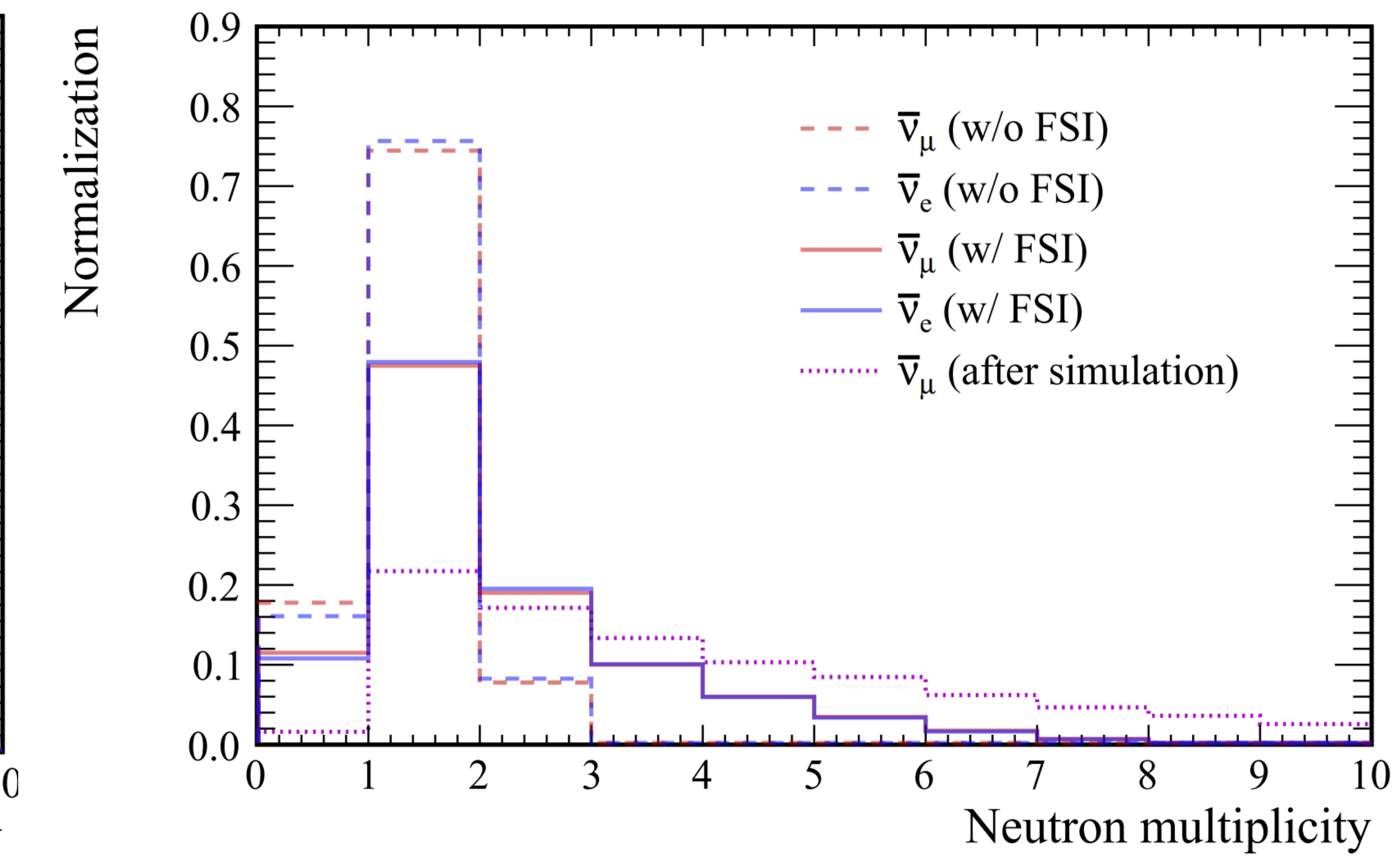
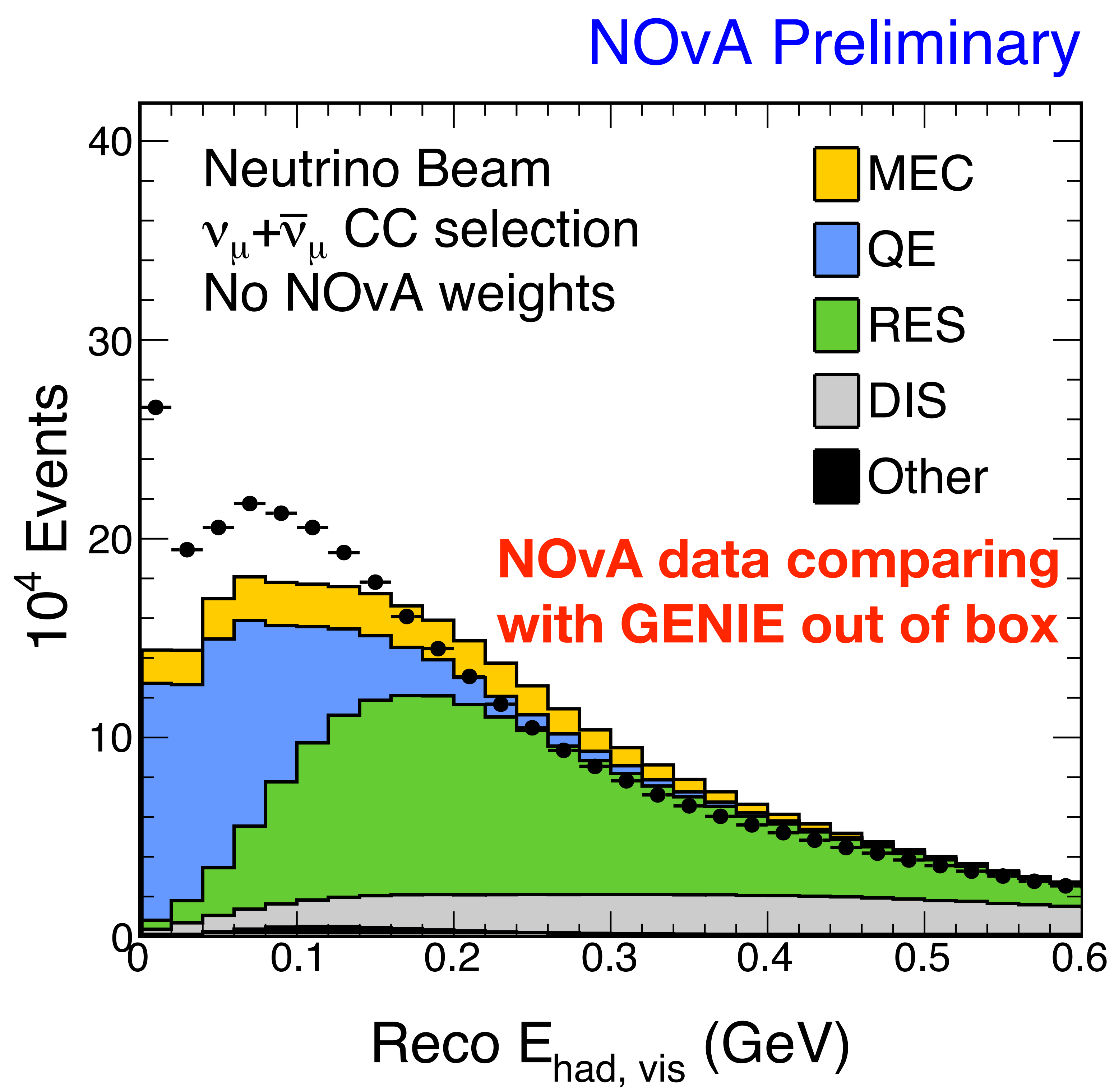
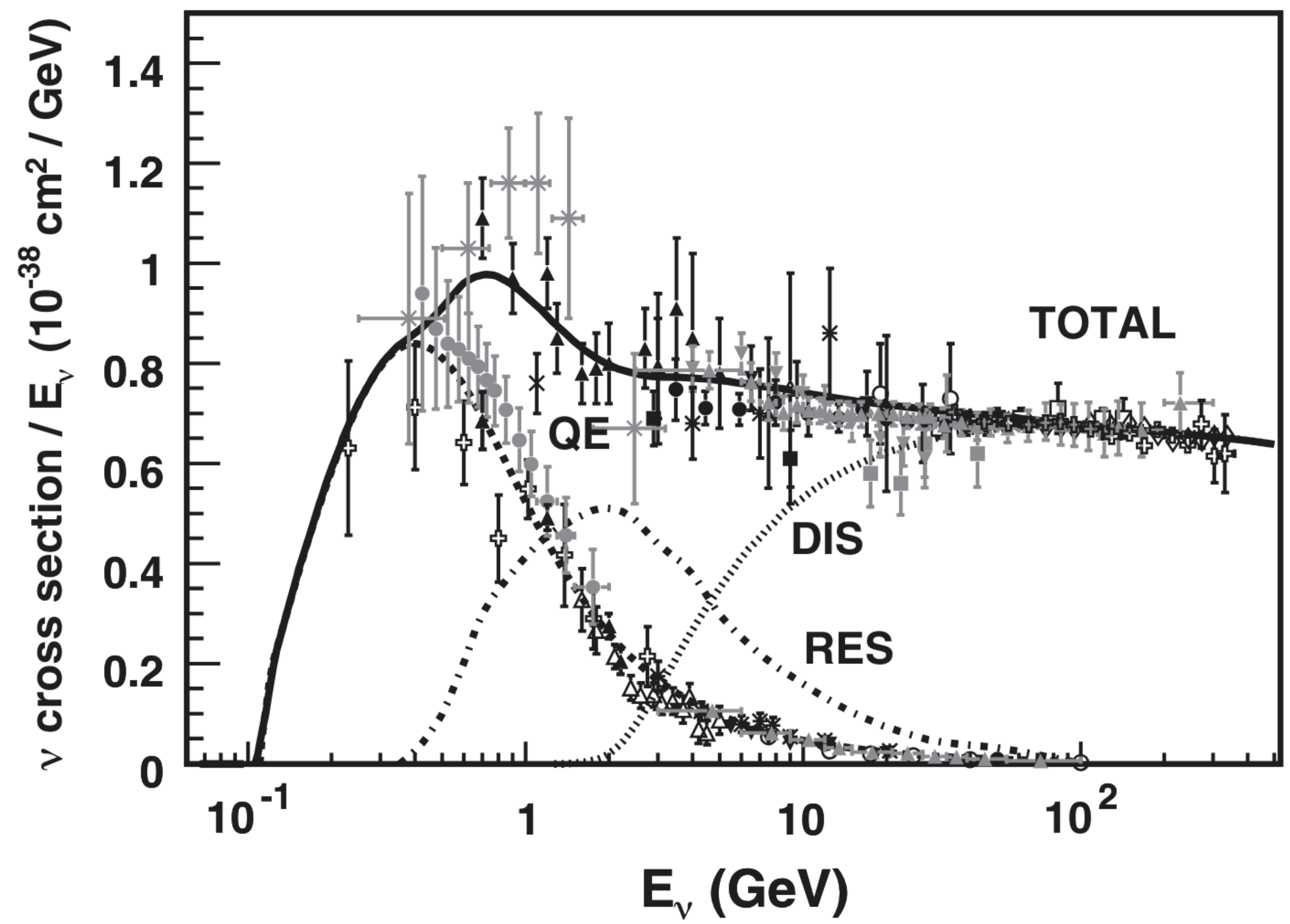


Atmospheric neutrinos' neutron multiplicity predicted by GENIE

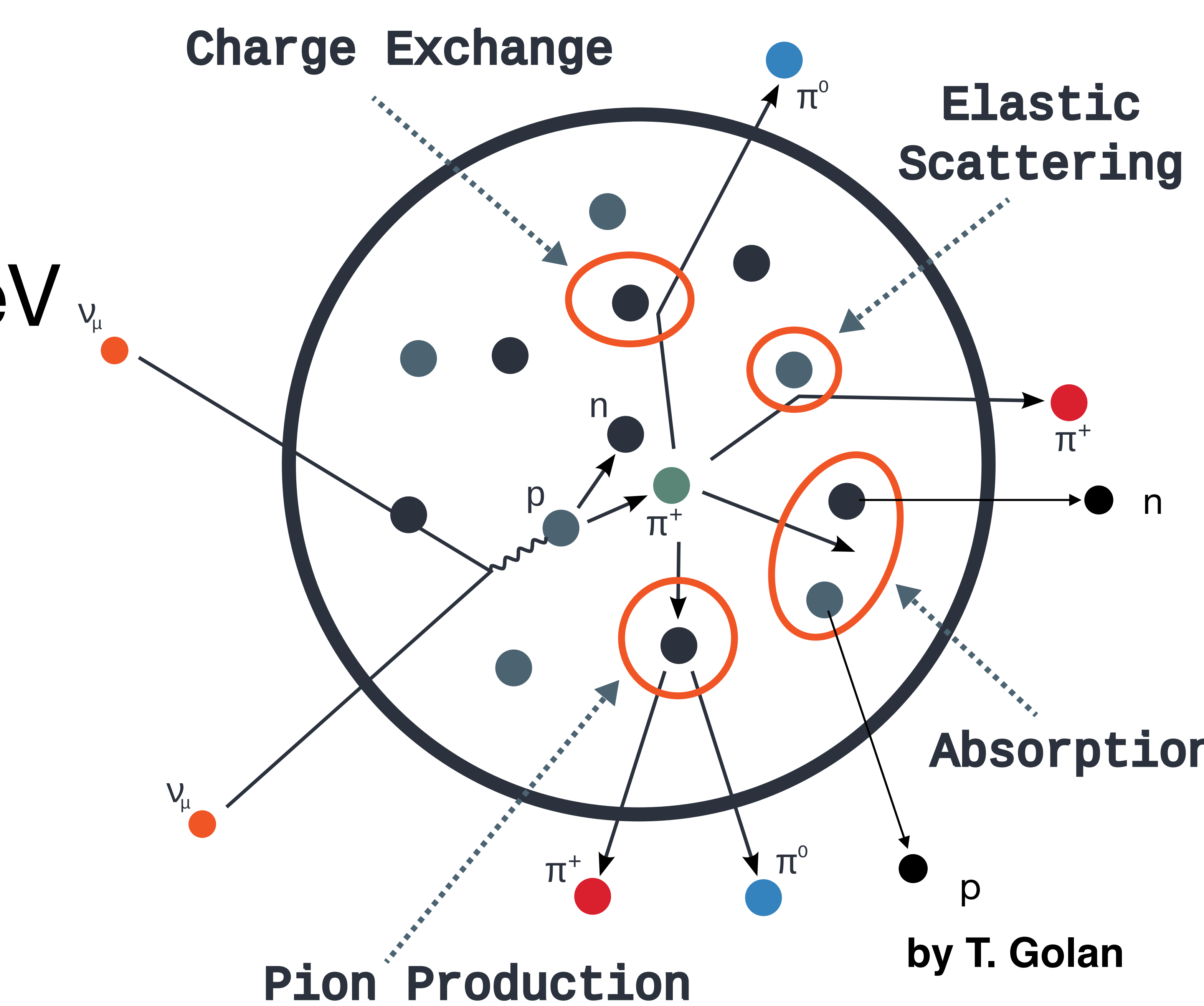
- Questions:
  - Can we trust it?
  - A black box trained with MC.
  - Largely depends on our understanding of exactly what happens in the detector
    - Neutrino interactions + detector response.
- Ultimate solution: improving the quality of training datasets.

Problems with Neutrino Interactions





- Unfortunately current neutrino interaction modeling does not describe data well.
- Neutrino scattering on heavy targets like argon at the few-GeV neutrino energy range is complex
- Most generators are many models glued together
  - Initial states + (QE + RES + DIS + COH + 2p2h…) + FSI
  - Some of the models are pretty old (40+ years)



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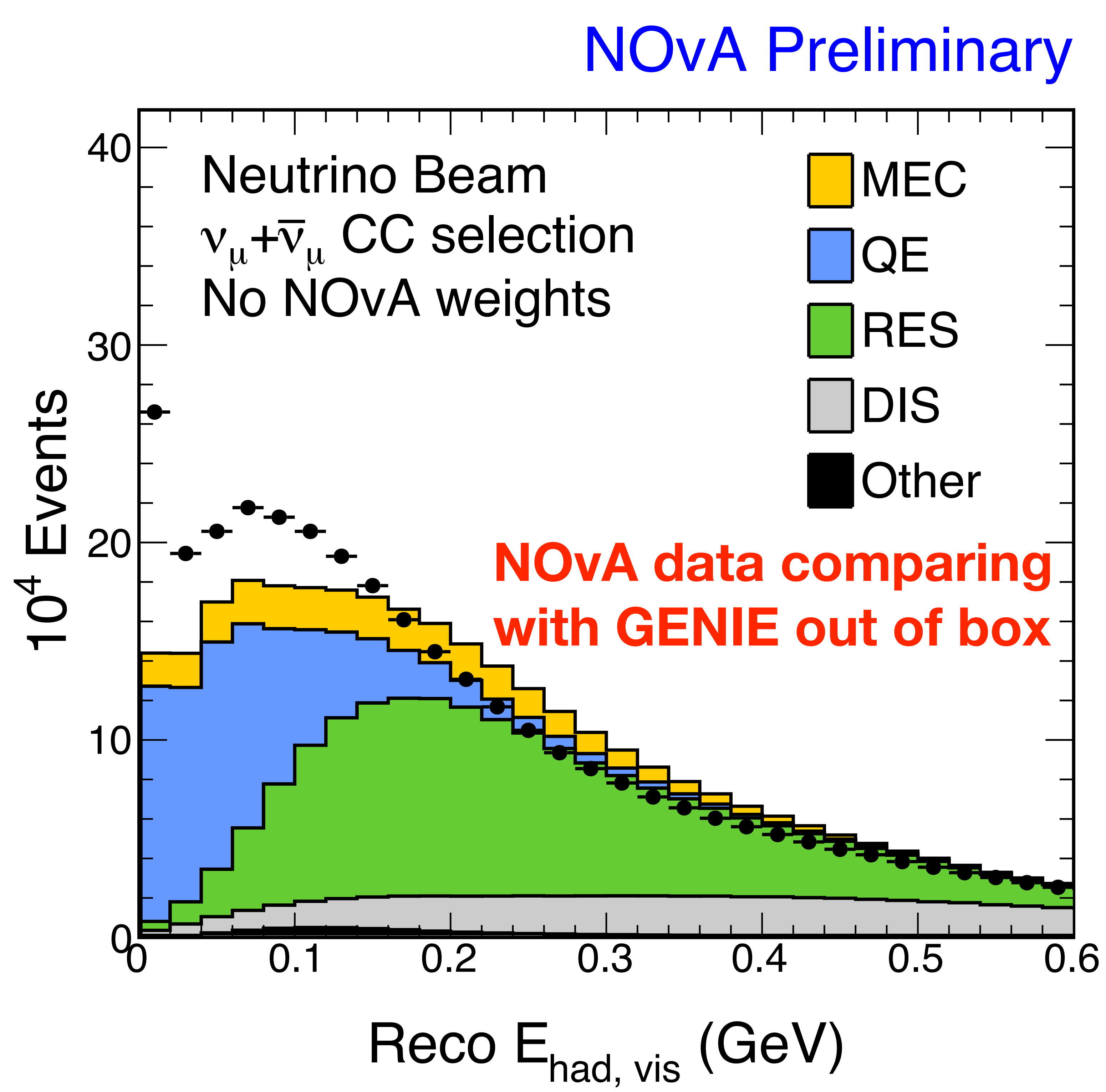

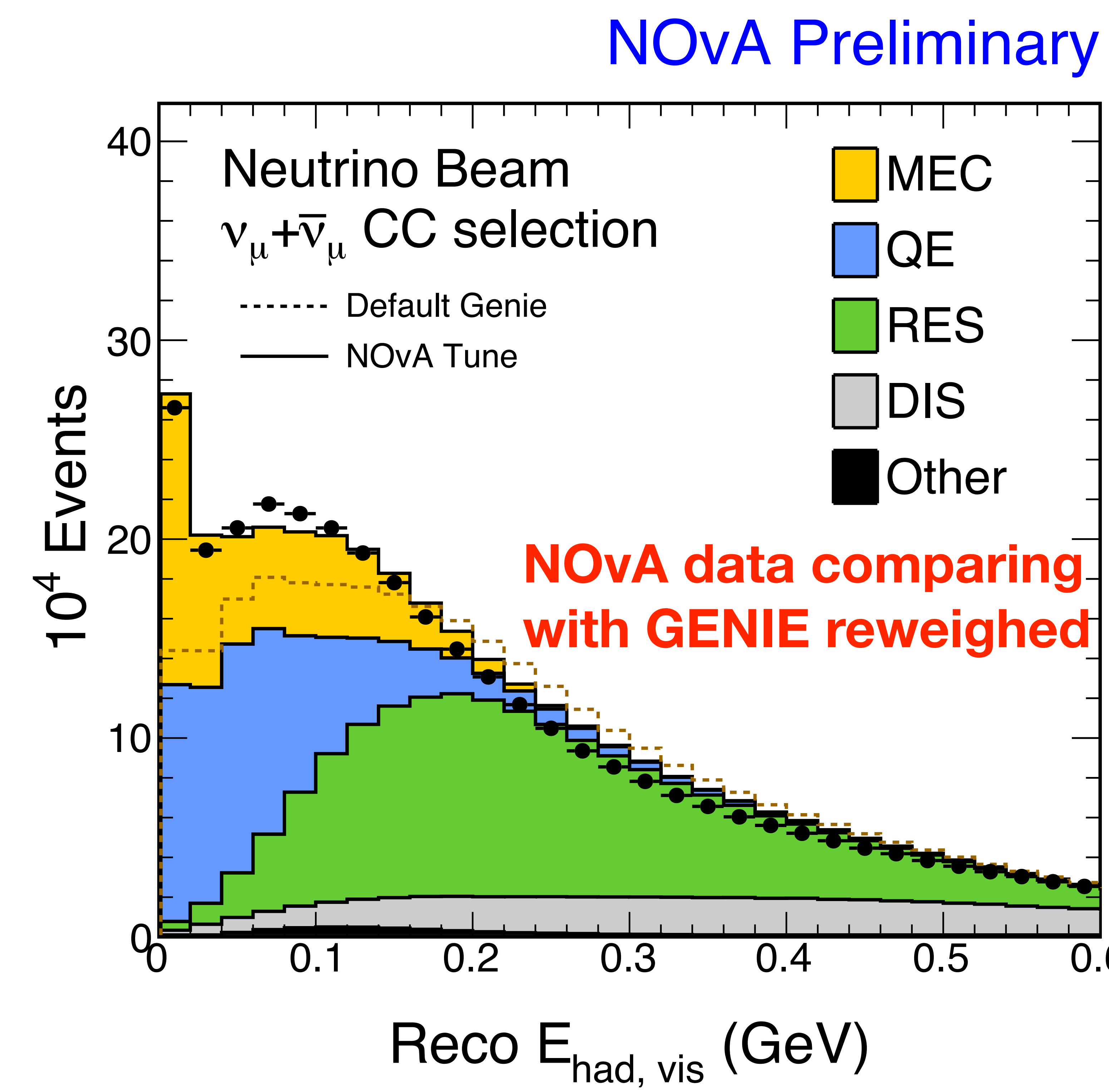

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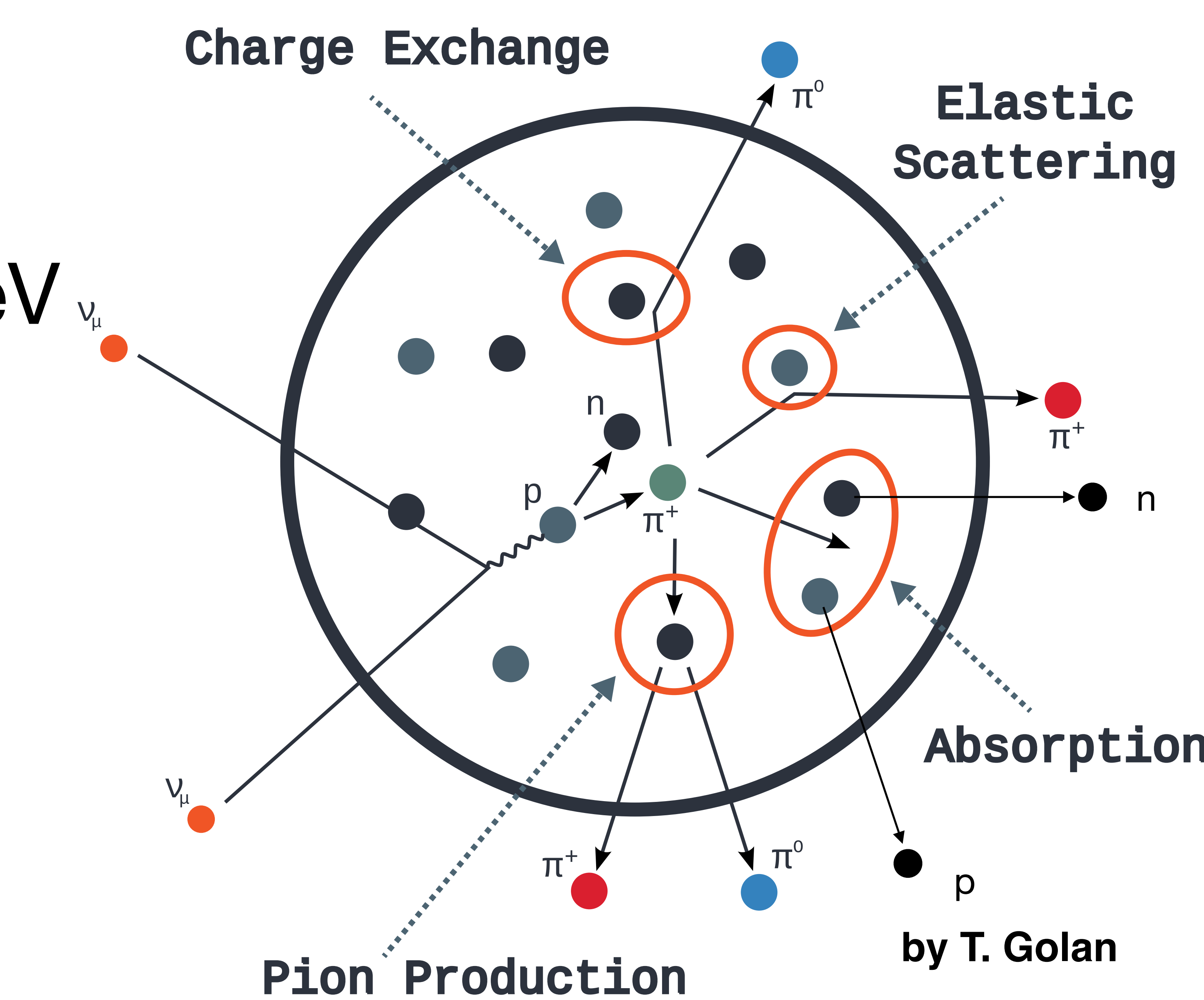
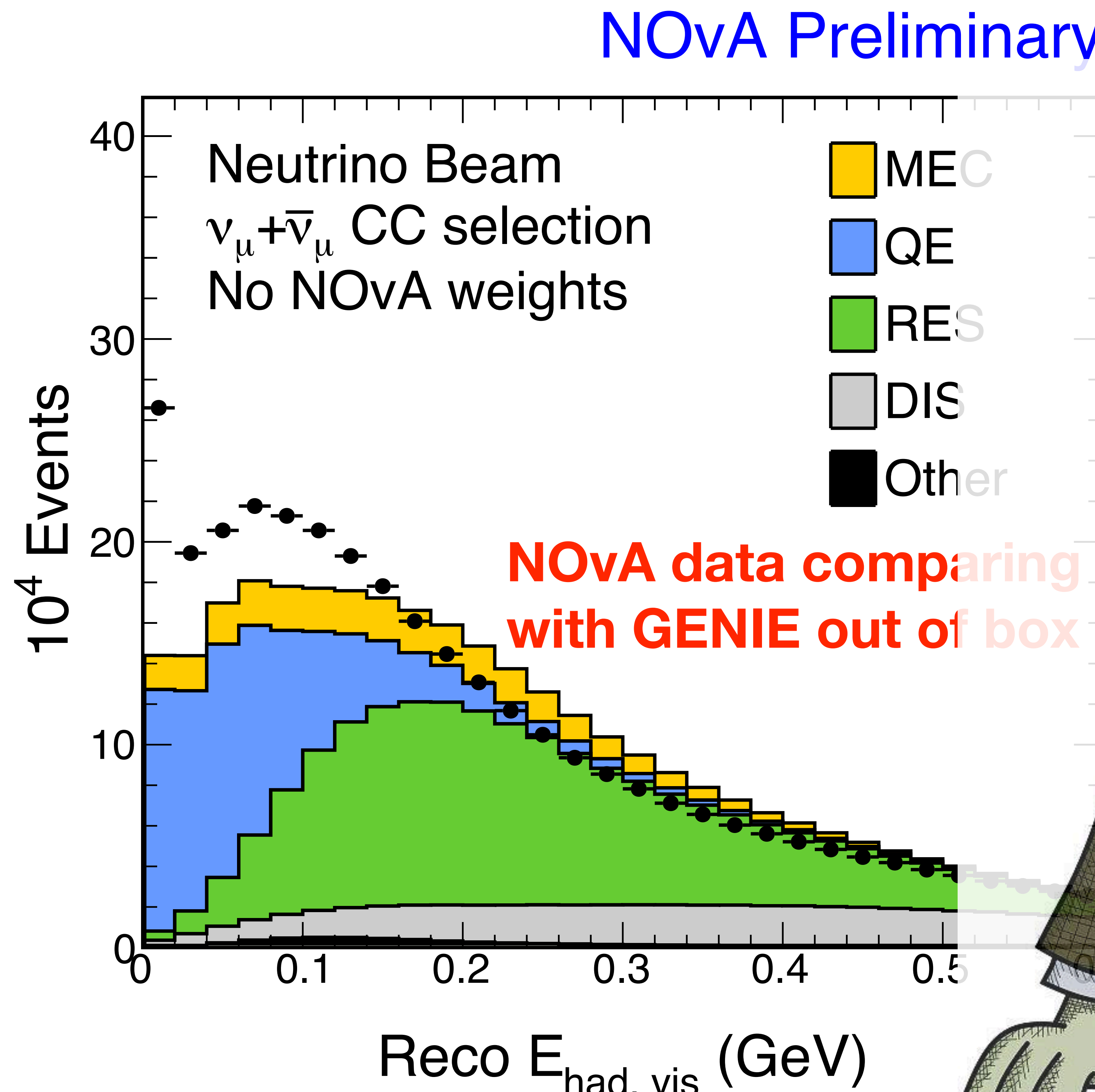
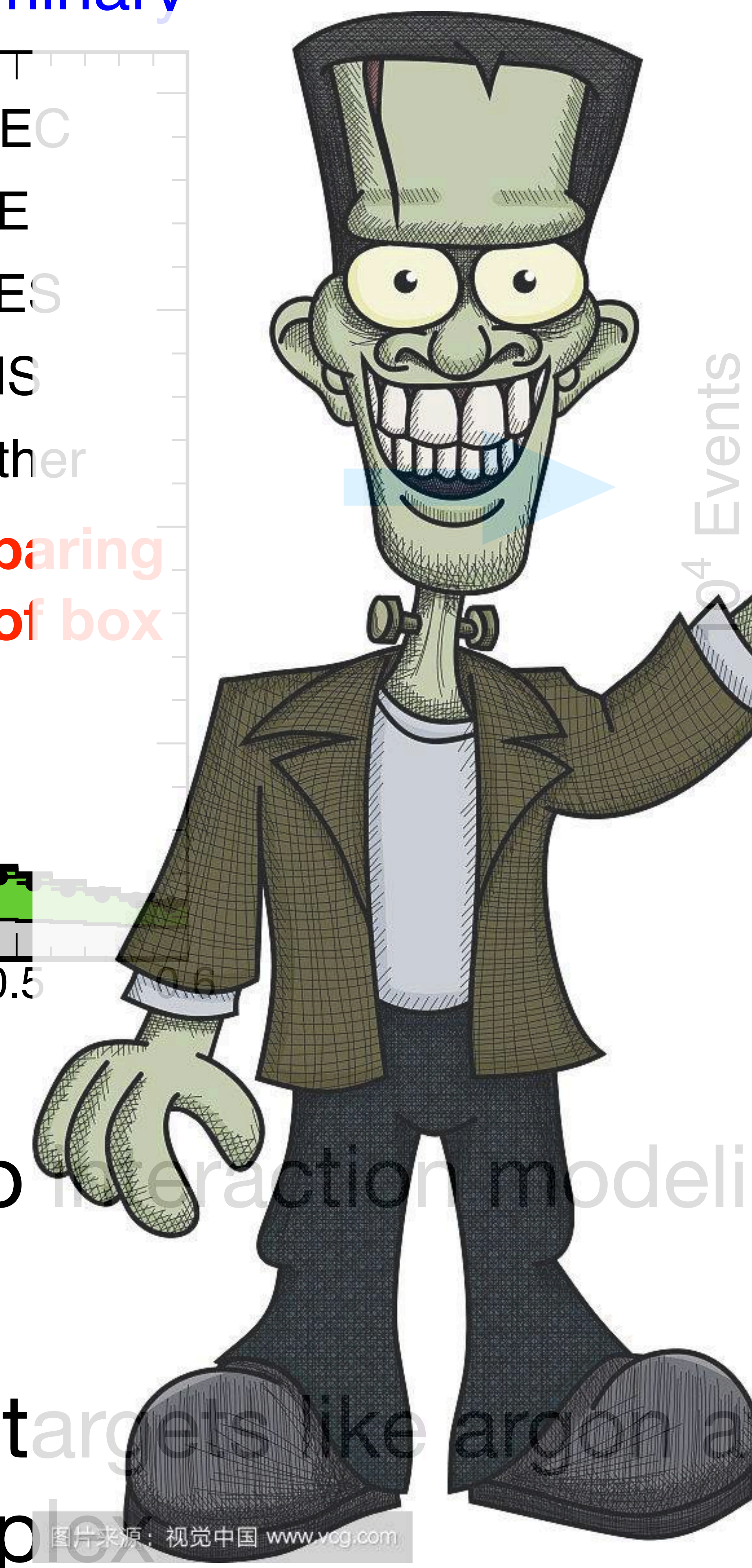
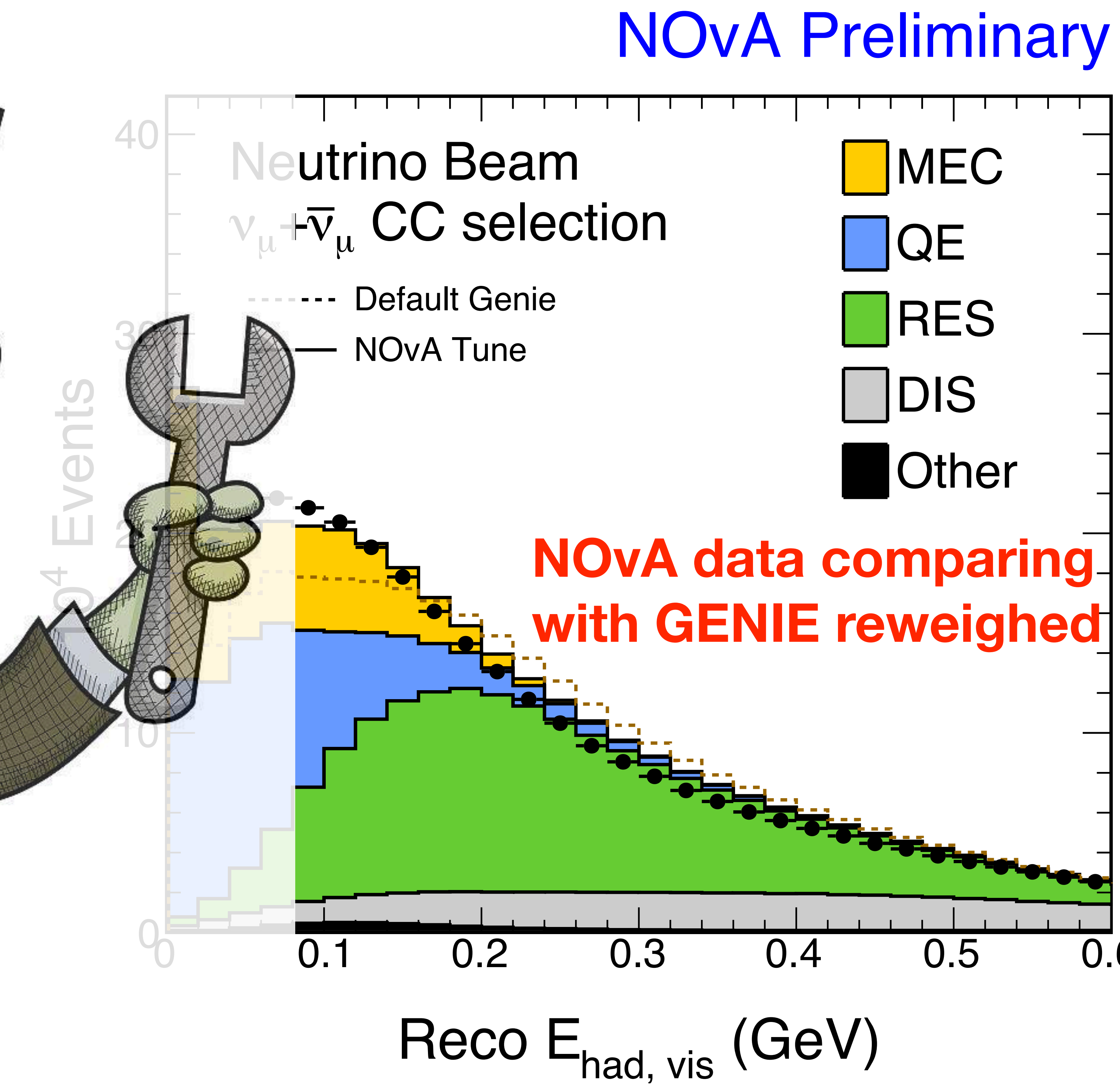


Problems with Neutrino Interactions

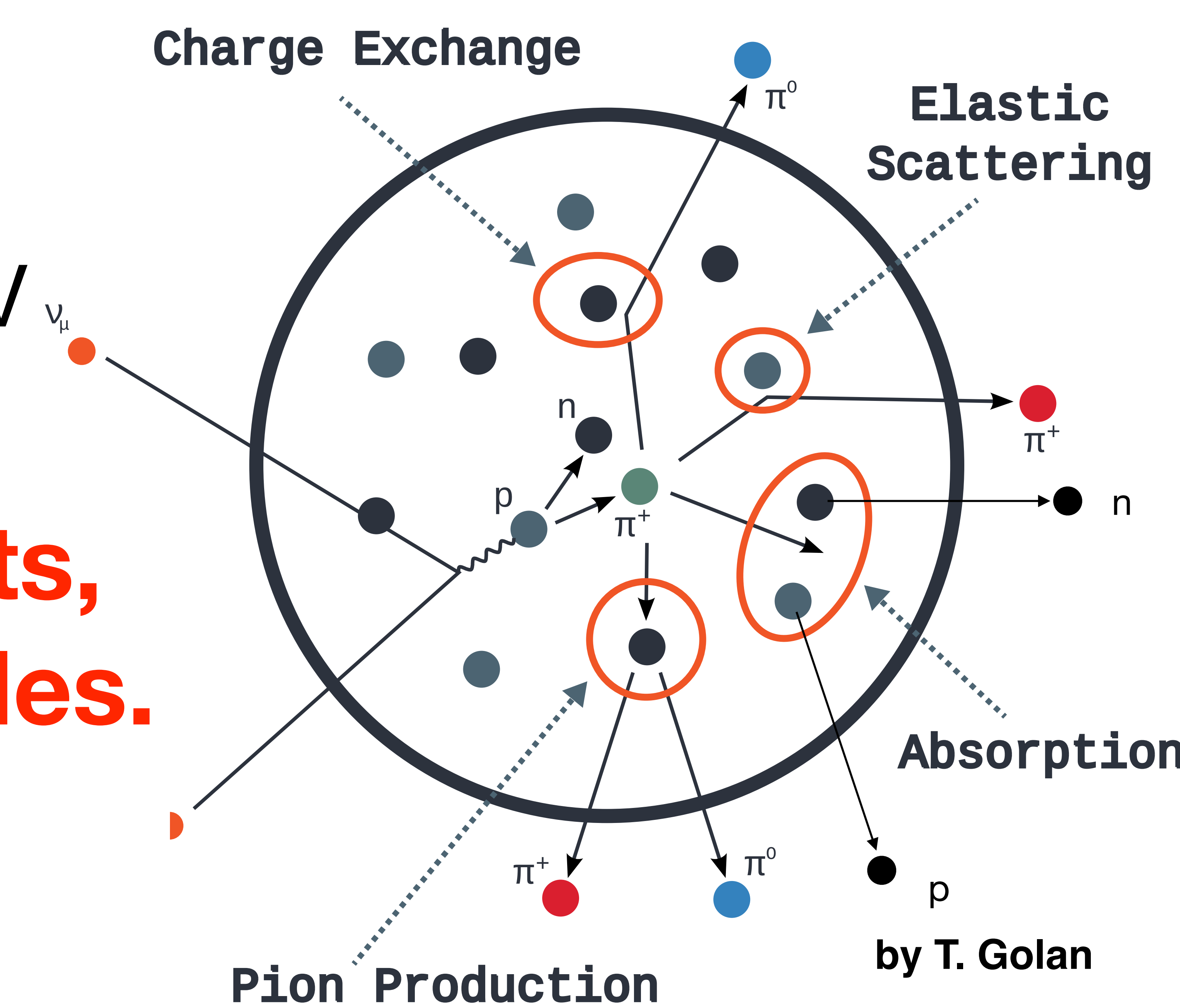






- Unfortunately current neutrino interaction modeling does not describe data well.
- Neutrino scattering on heavy targets like argon at the few-GeV neutrino energy range is complex.
- Most generators
    - Initial state
    - Some of th

Too many pieces in the experiments, but too limited number of observables. (Degeneracy!)



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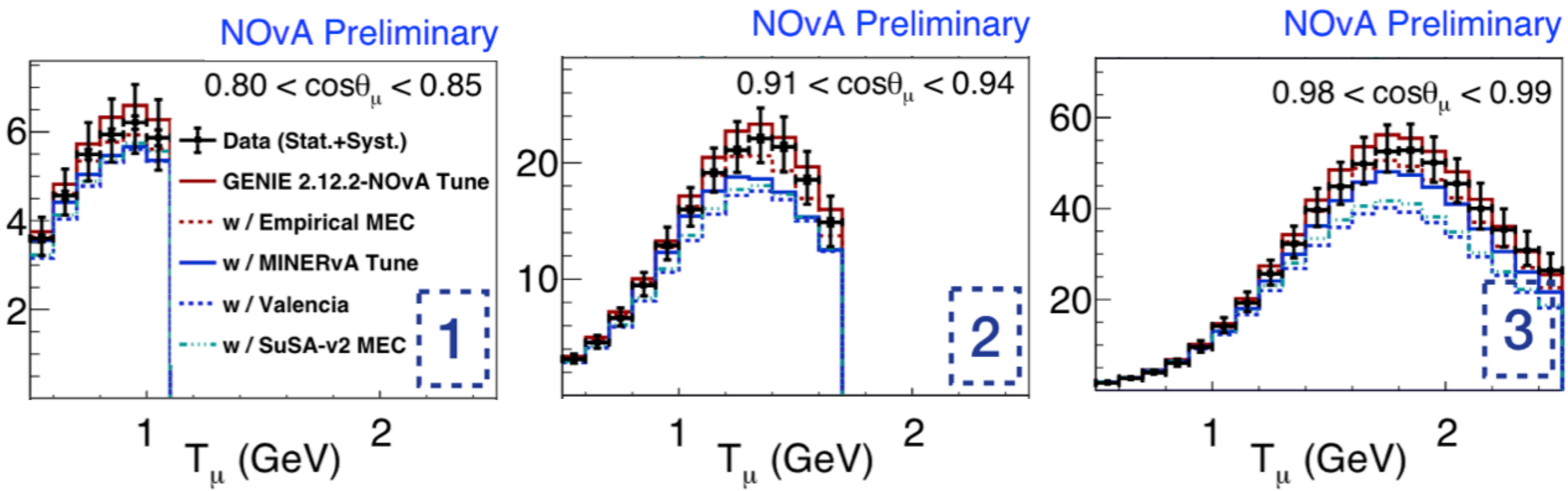

- Unfortunately the current tunings are very unlikely to be completely correct.
- **Data may not agree with data even with large uncertainties.**

A Near Detector for the Solution?

FD:

$$N(E_{rec}) = \int_{E_\nu} dE_\nu \Phi(E_\nu) \boxed{P_{osc}(E_\nu)} \sigma(E_\nu) R_{det}(E_\nu, E_{rec})$$

Number of events observed in the FD

Neutrino flux

Oscillation probability

Cross section

Detector response

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Number of events observed in the ND

Not exactly the same neutrino flux

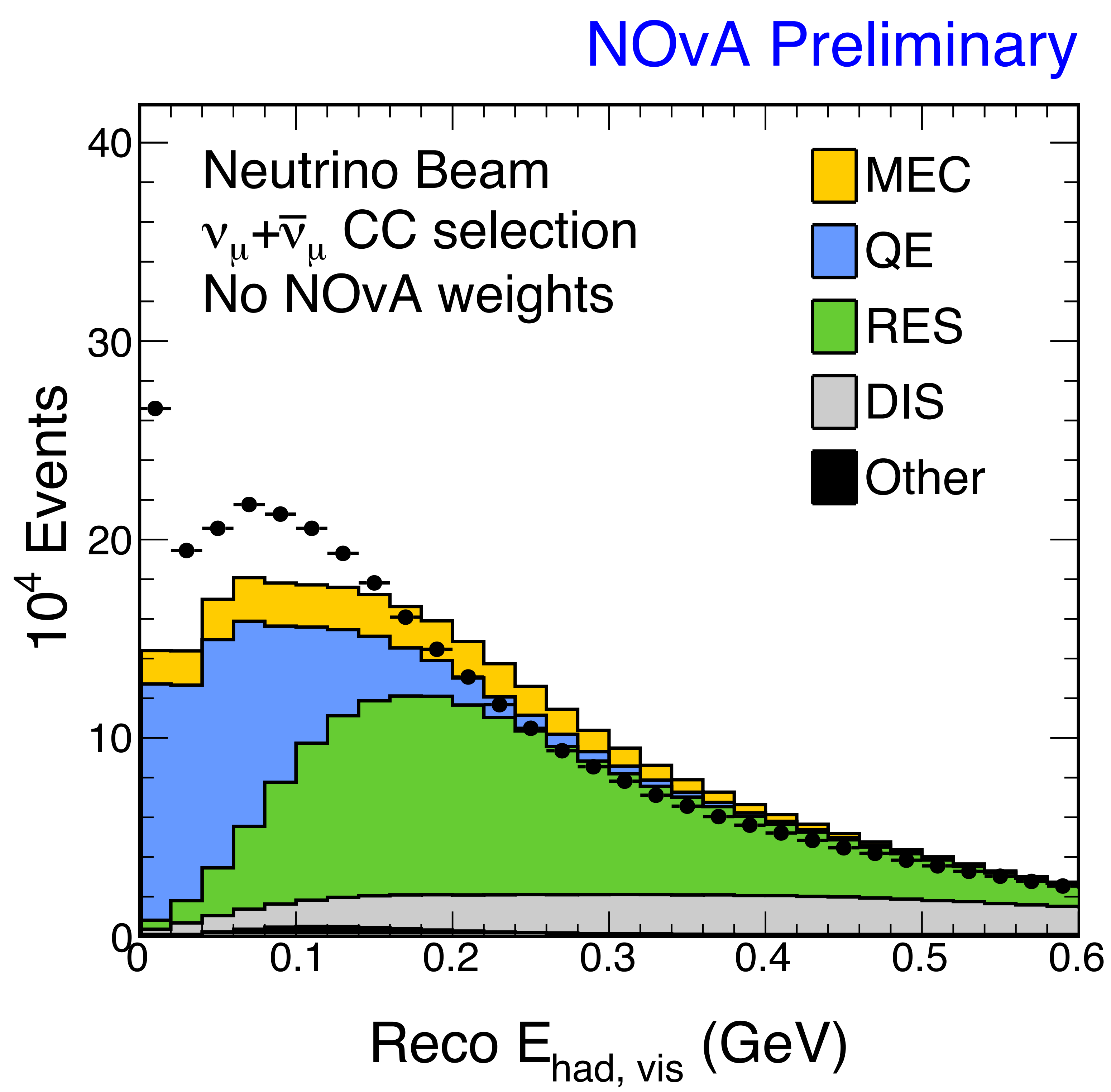
Oscillation probability (zero in the ND)

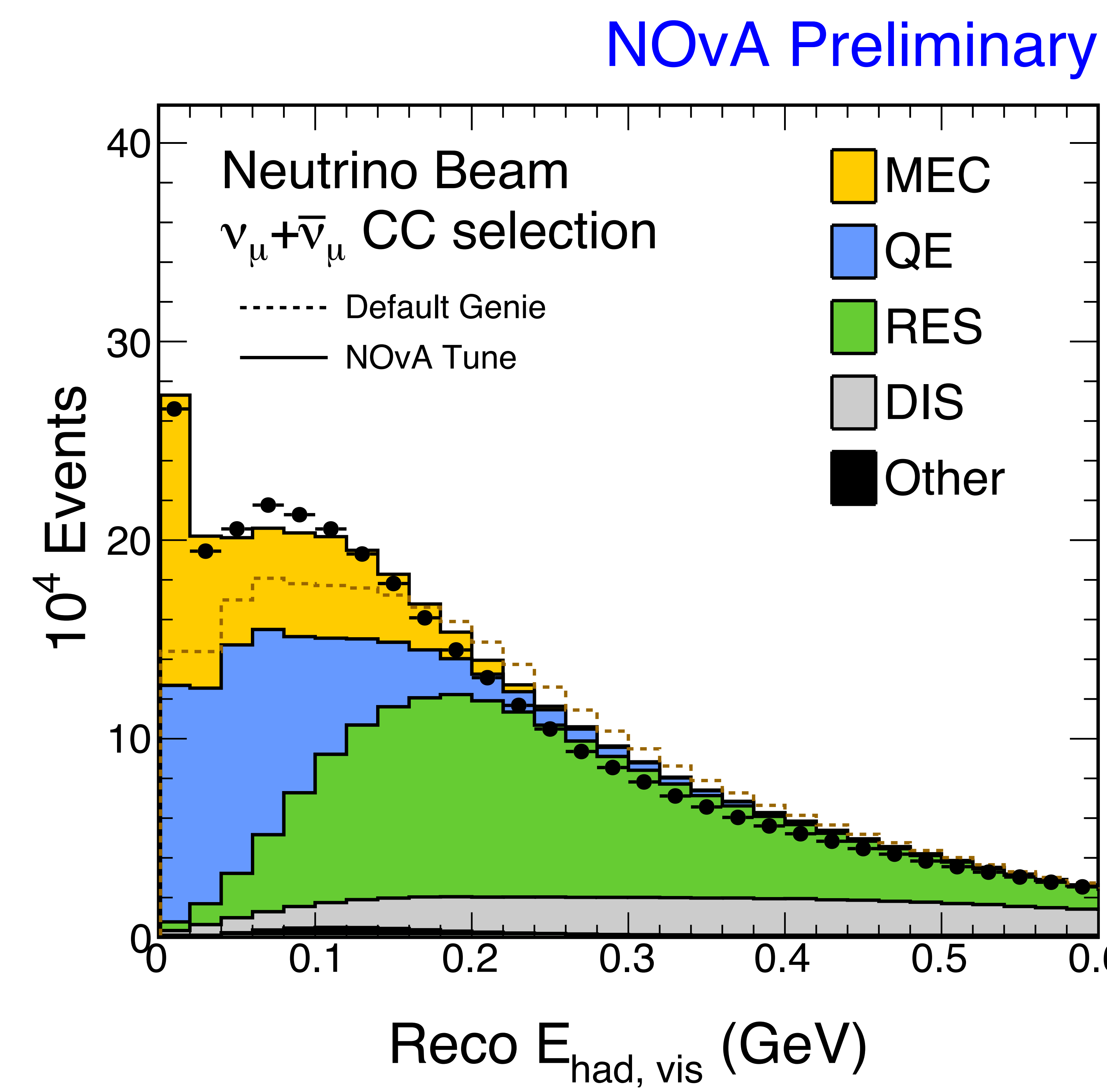
Not the same Detector response

Cross sections? Need Ar target

Need ways to disentangle those factors!

A Near Detector for the Solution?





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- **Question: is this really because of cross sections? nuclear effects? flux? detector simulation/calibration?**

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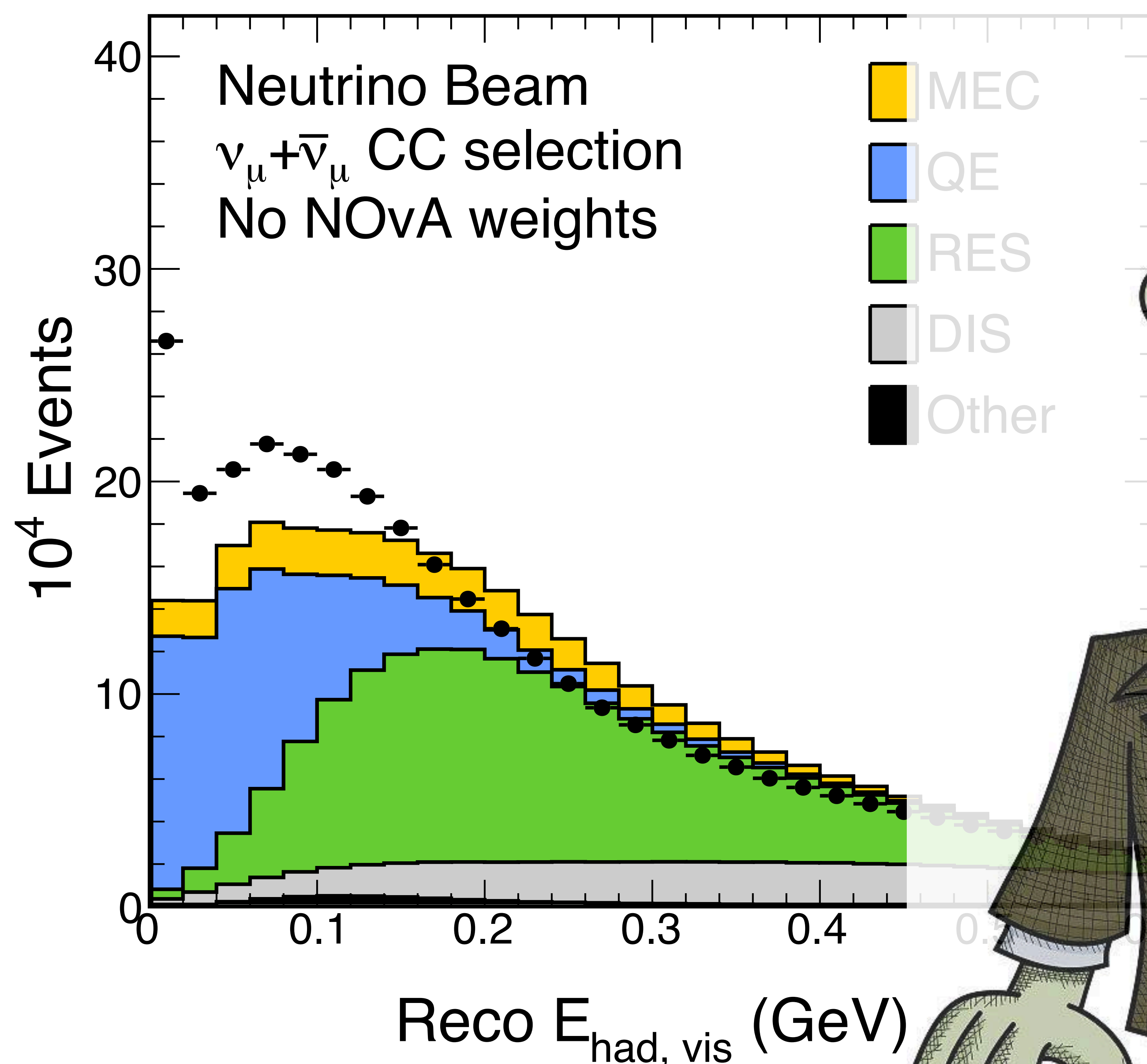

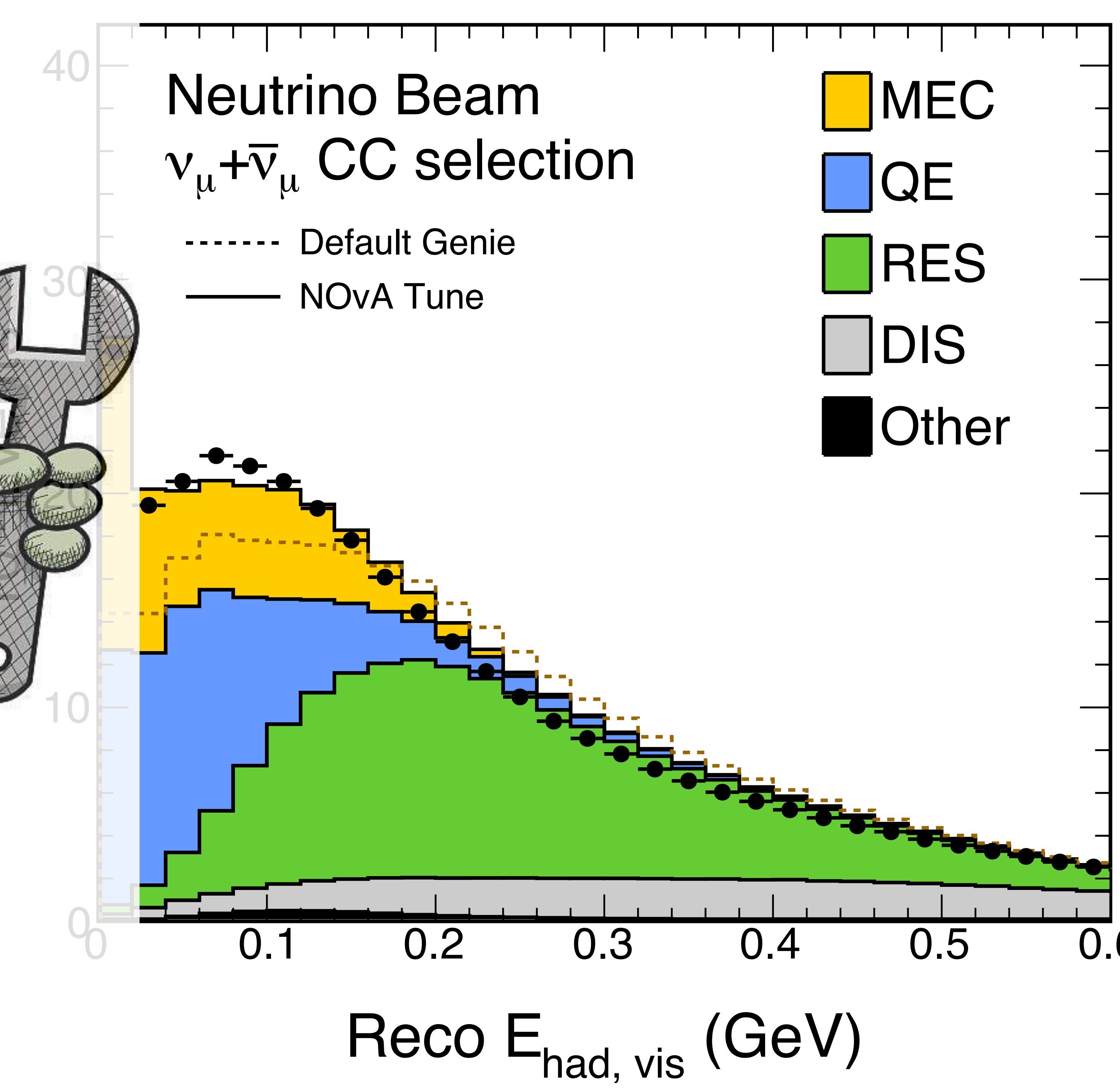

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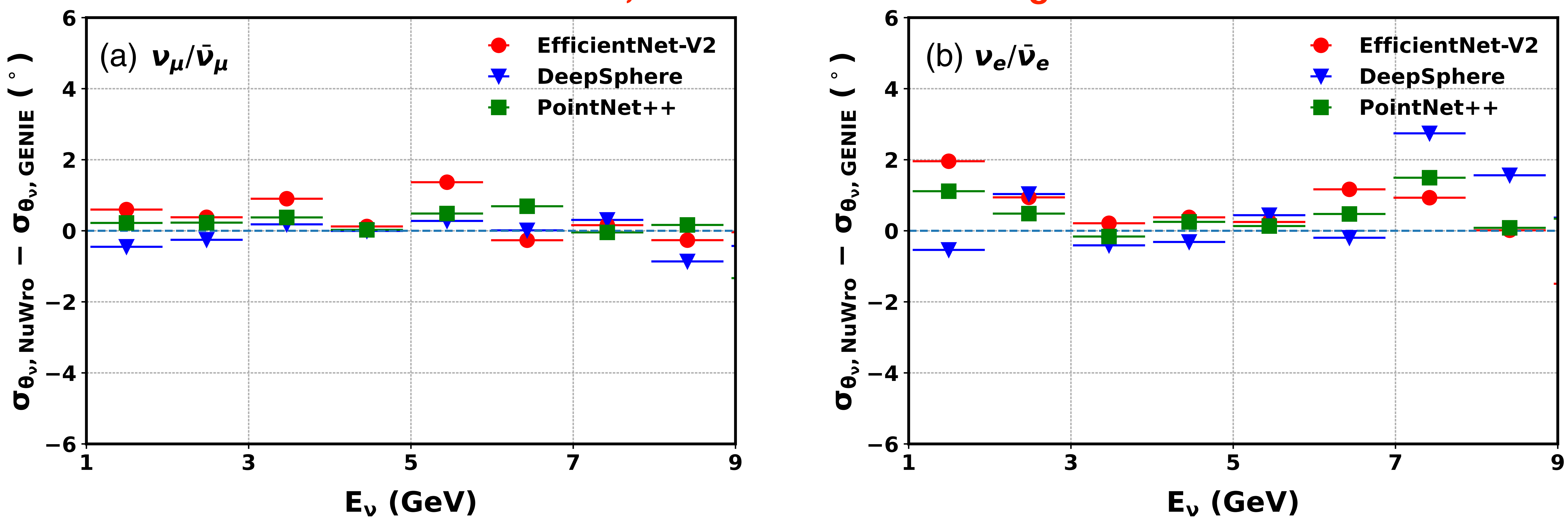
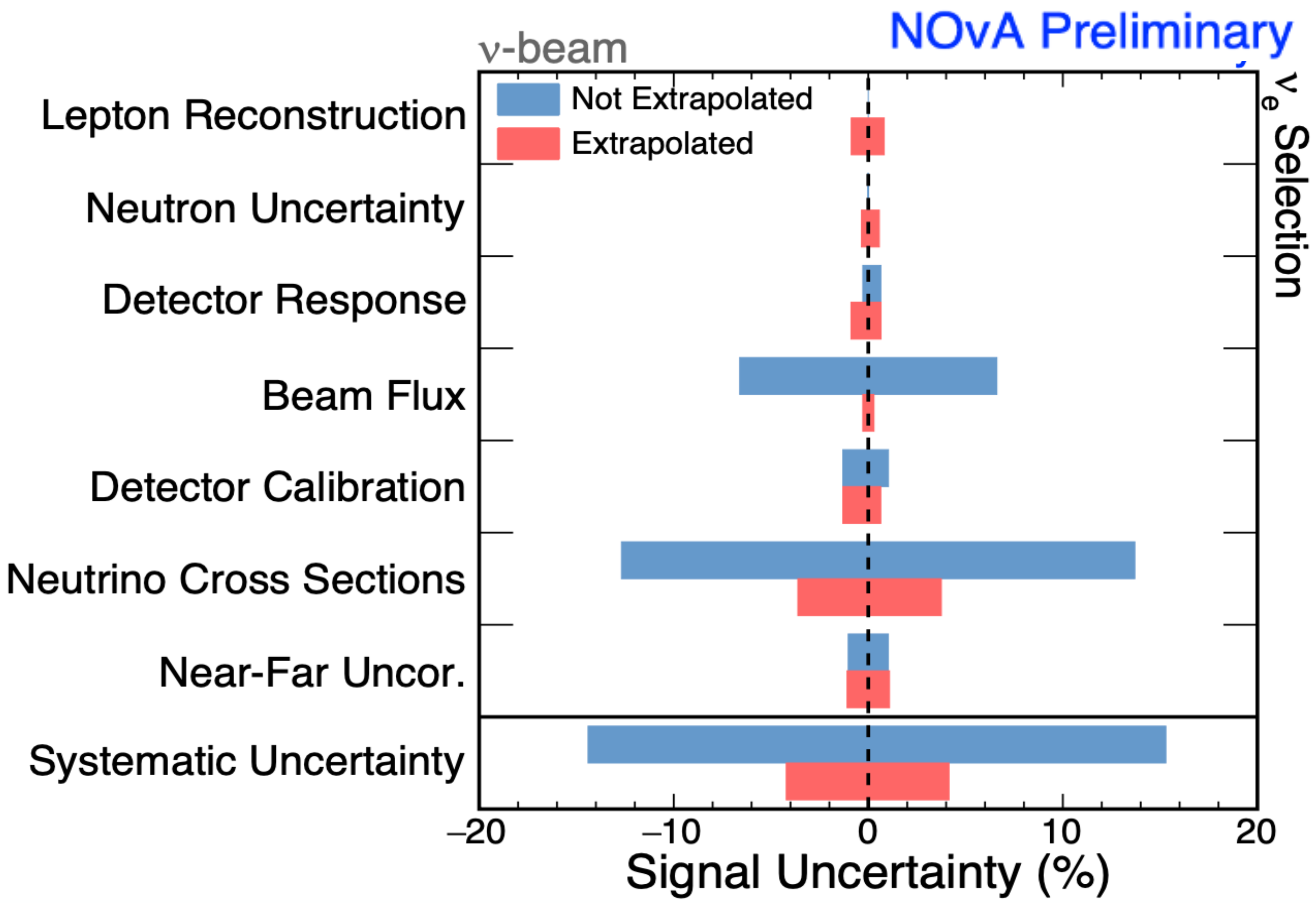
How to deal with interaction uncertainties?

JUNO directional reconstruction, checked with different generators



- Conventional approach is to vary the models/simulation parameters (GENIE "knobs" for example) to evaluate the uncertainties from ν-interactions.

Neutrino Interaction Model Uncertainties



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- Impossible to be complete cancelled by NDs.
- A too large uncertainty for precision measurement such as DUNE.

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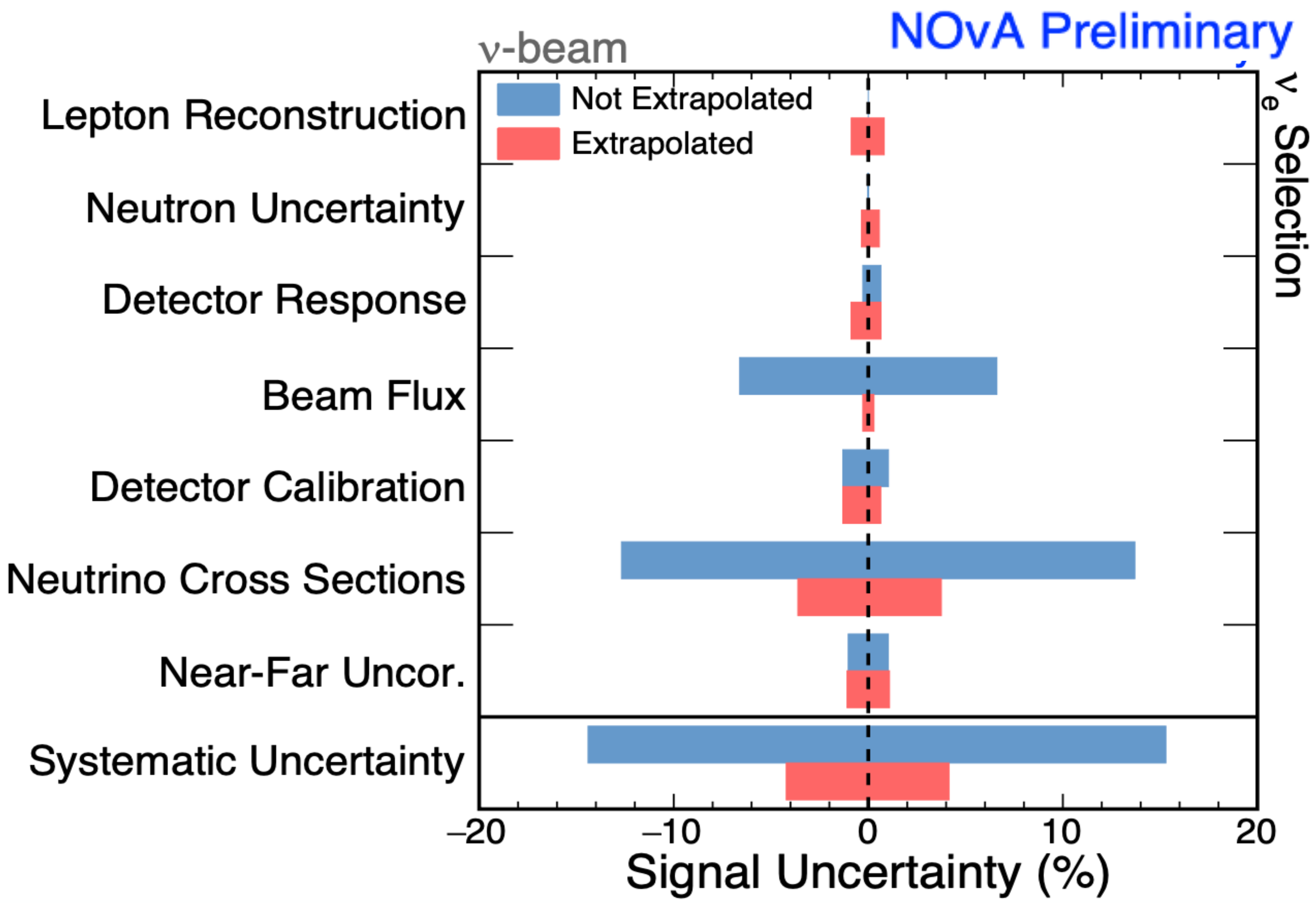

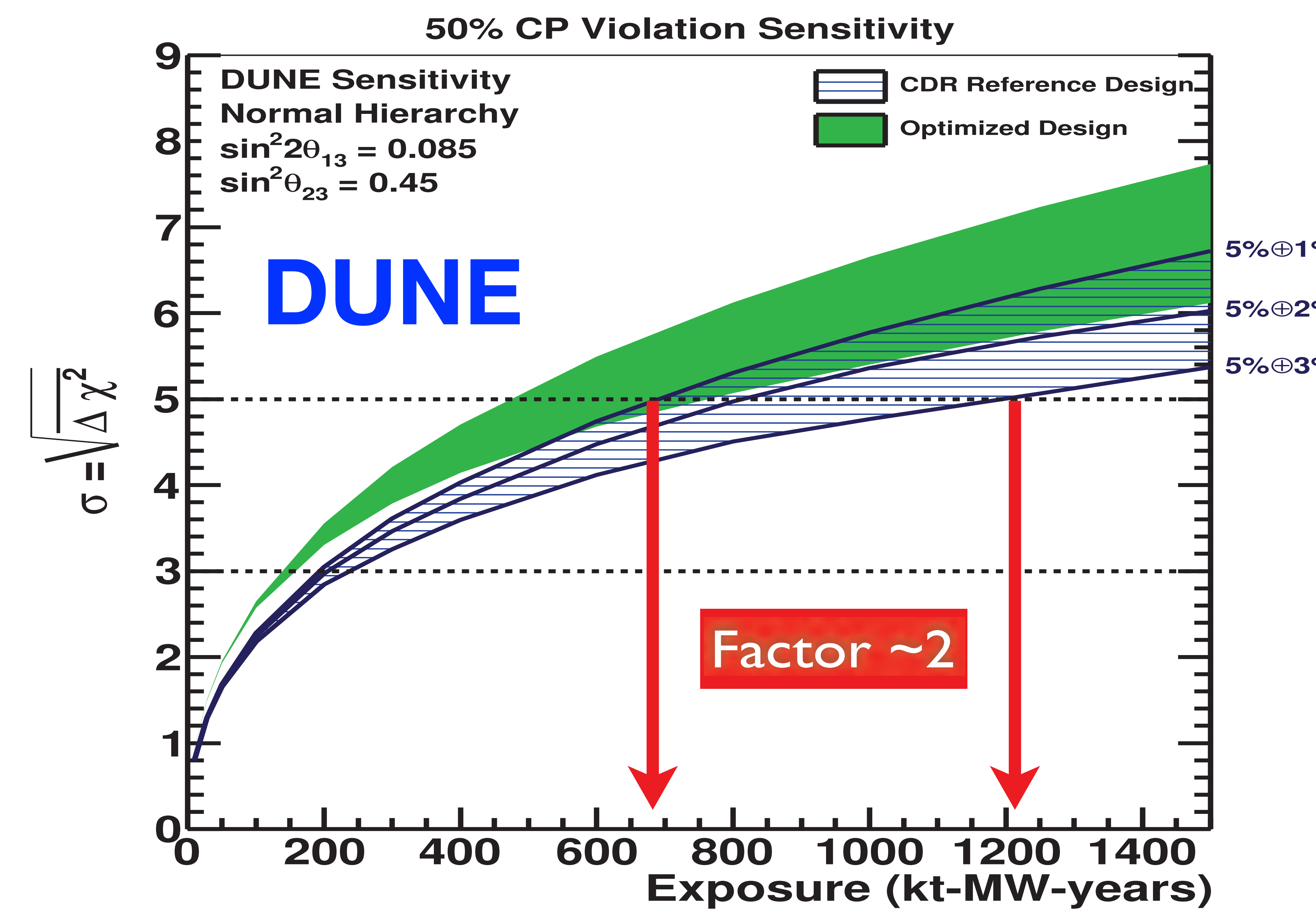

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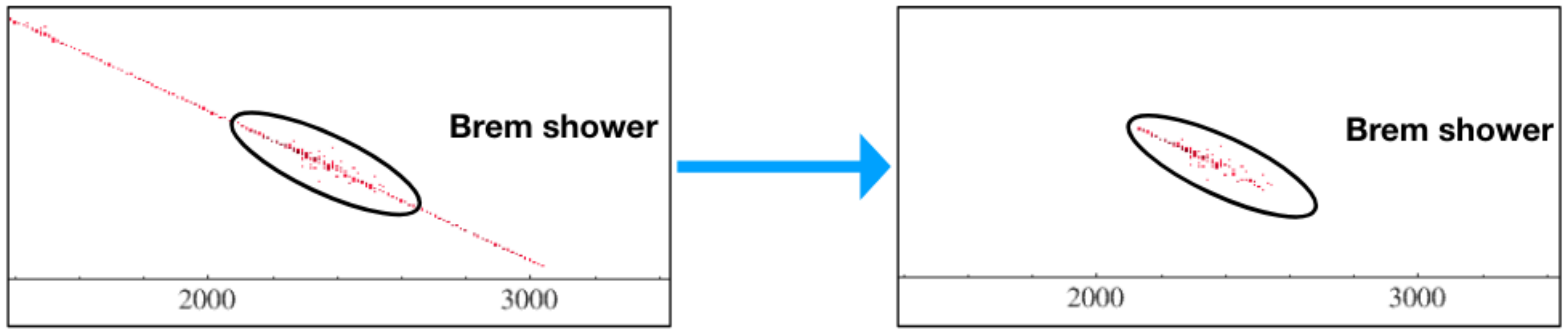
Data Driven Approaches: “Data-simulator”



- Cosmic-muon induced brem showers are identified, muons are then removed to create pure electron-like EM showers from data to check the detector’s response to electrons.

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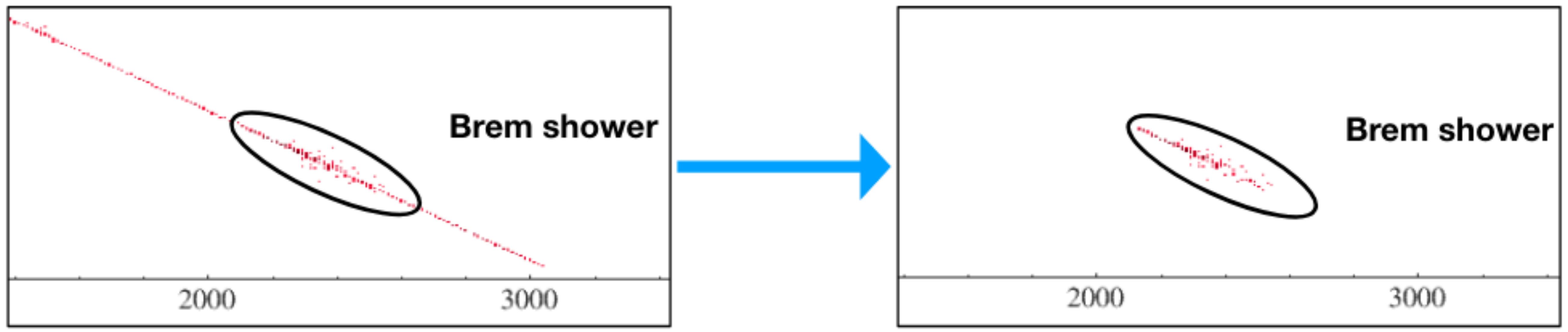

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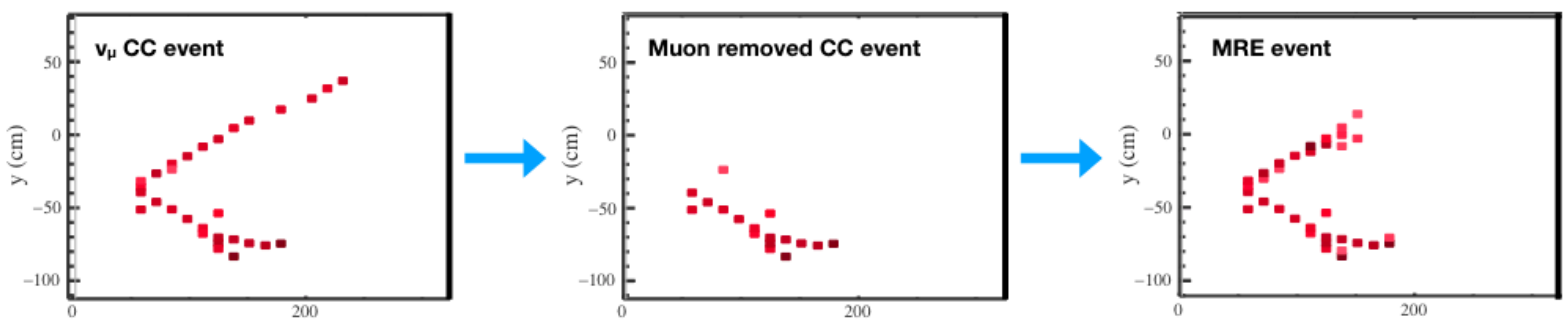

- ν_μ-CC events are identified with traditional methods from data, muons are then removed and replaced with a simulated electron to check the detector’s response to ν_e-CC.

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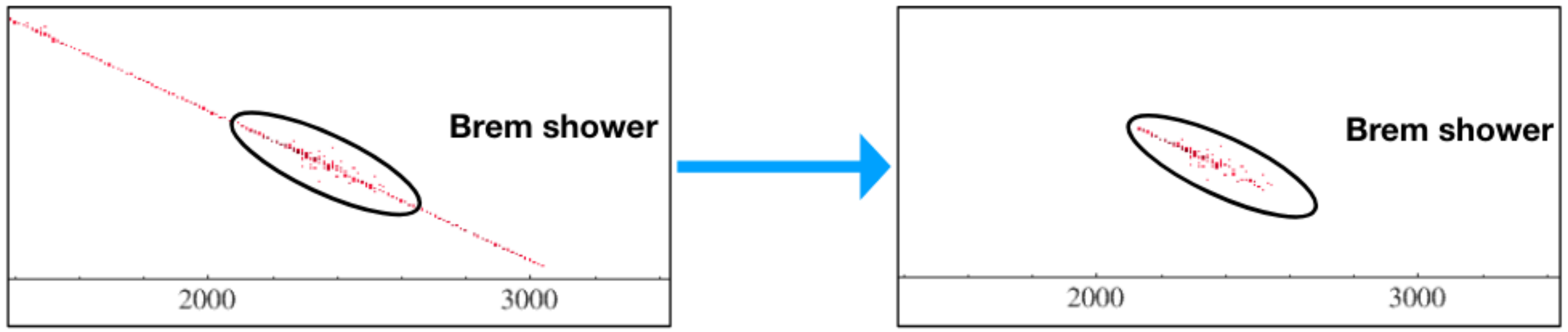

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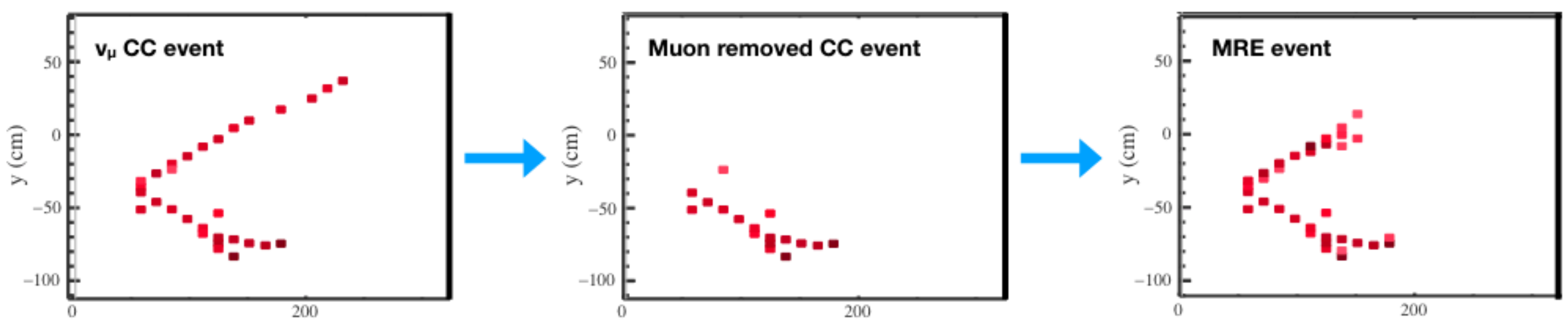

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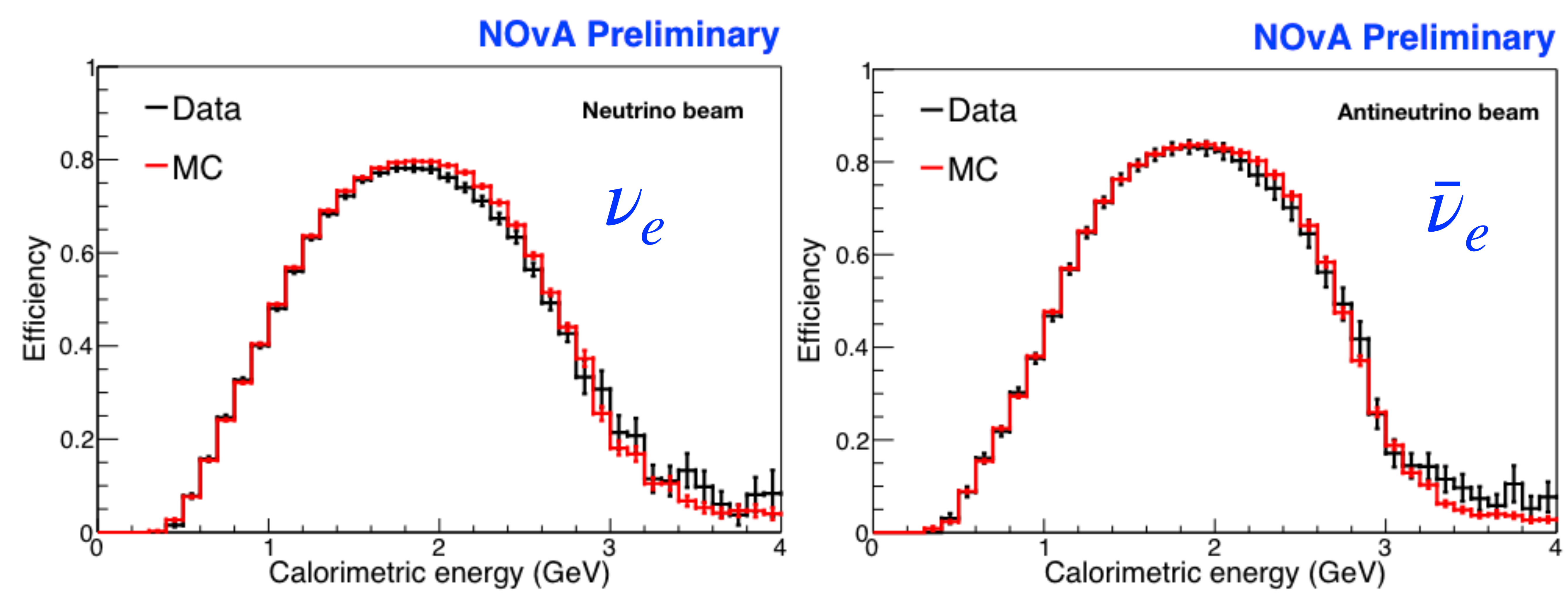
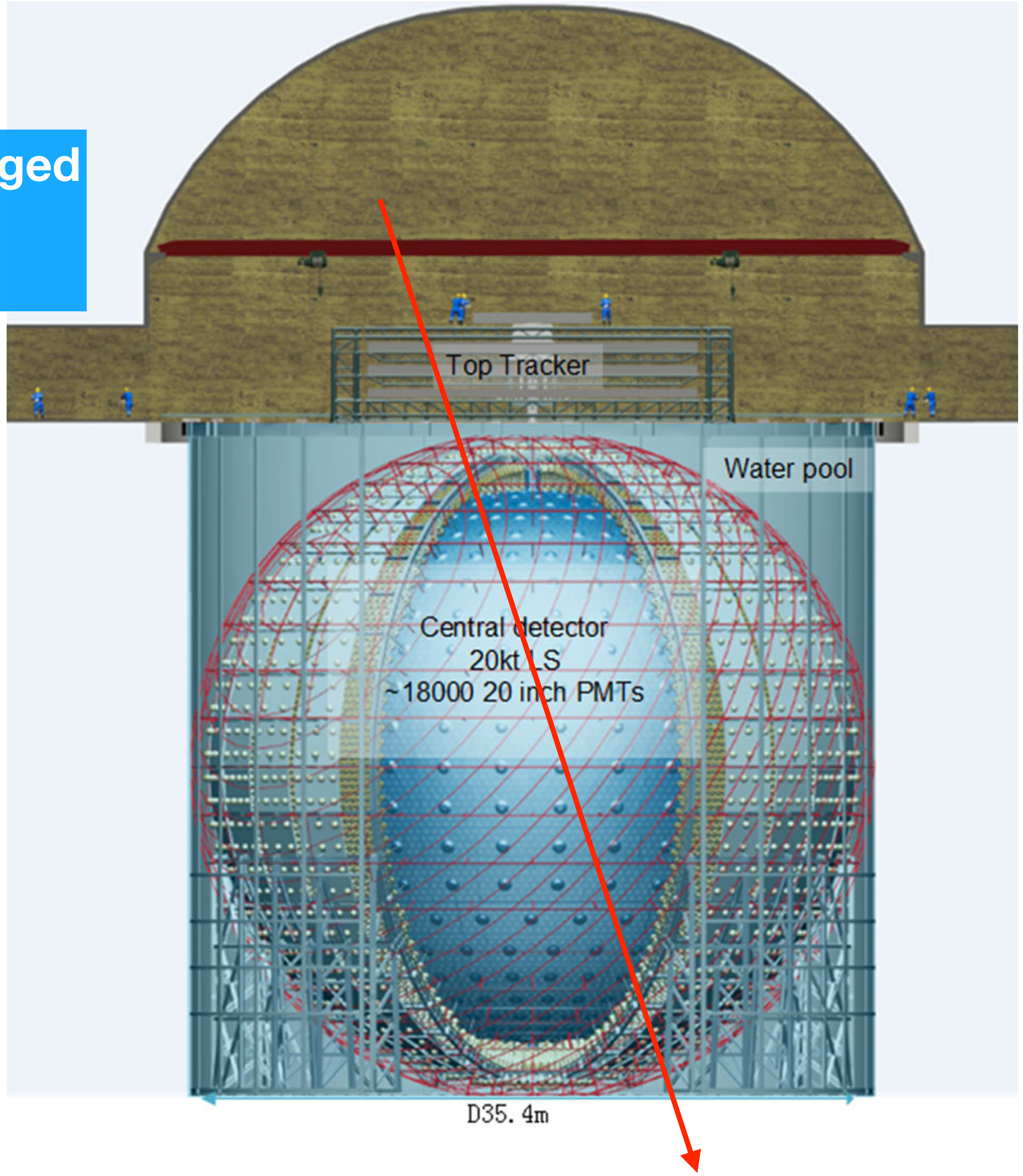
- CNN-based PID (trained with MC) is applied to the "simulated data" to check the selection efficiency.



Data Driven Approaches: “Data-simulator”

Select cosmic muons tagged by the Top Tracker with direction well-measured

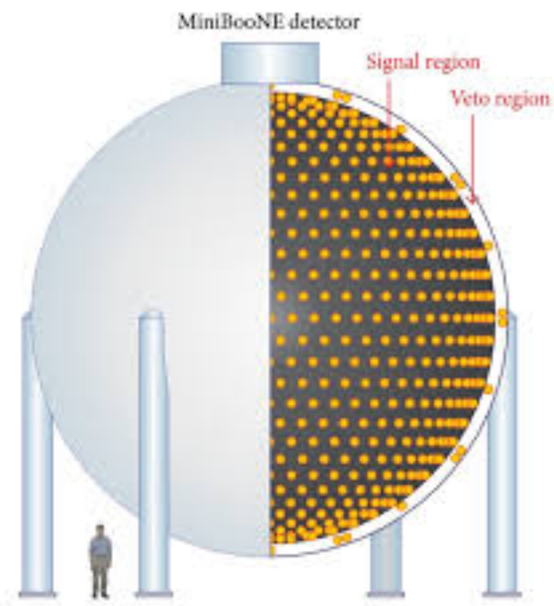


Use cosmic muon data to train/validate the DL models for direction/track reconstruction

Liu, Y., Li, WD., Lin, T. *et al.* *Radiat Detect Technol Methods* 5, 364–372 (2021).

Previous/Current/Future ν-Int Experiments

Bubble Chambers



MiniBooNE

MINERvA

MicroBooNE

NOvA

T2K

- Current data suffer from low-statistics/low-resolution/tensions.
- Future experiments are expect to give much stronger constraints.

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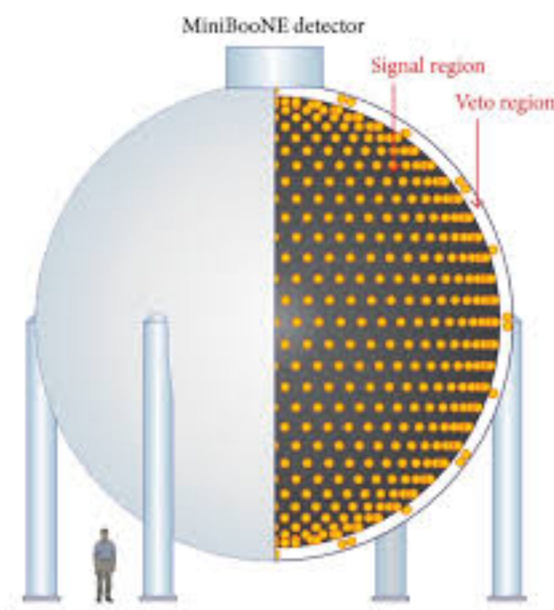

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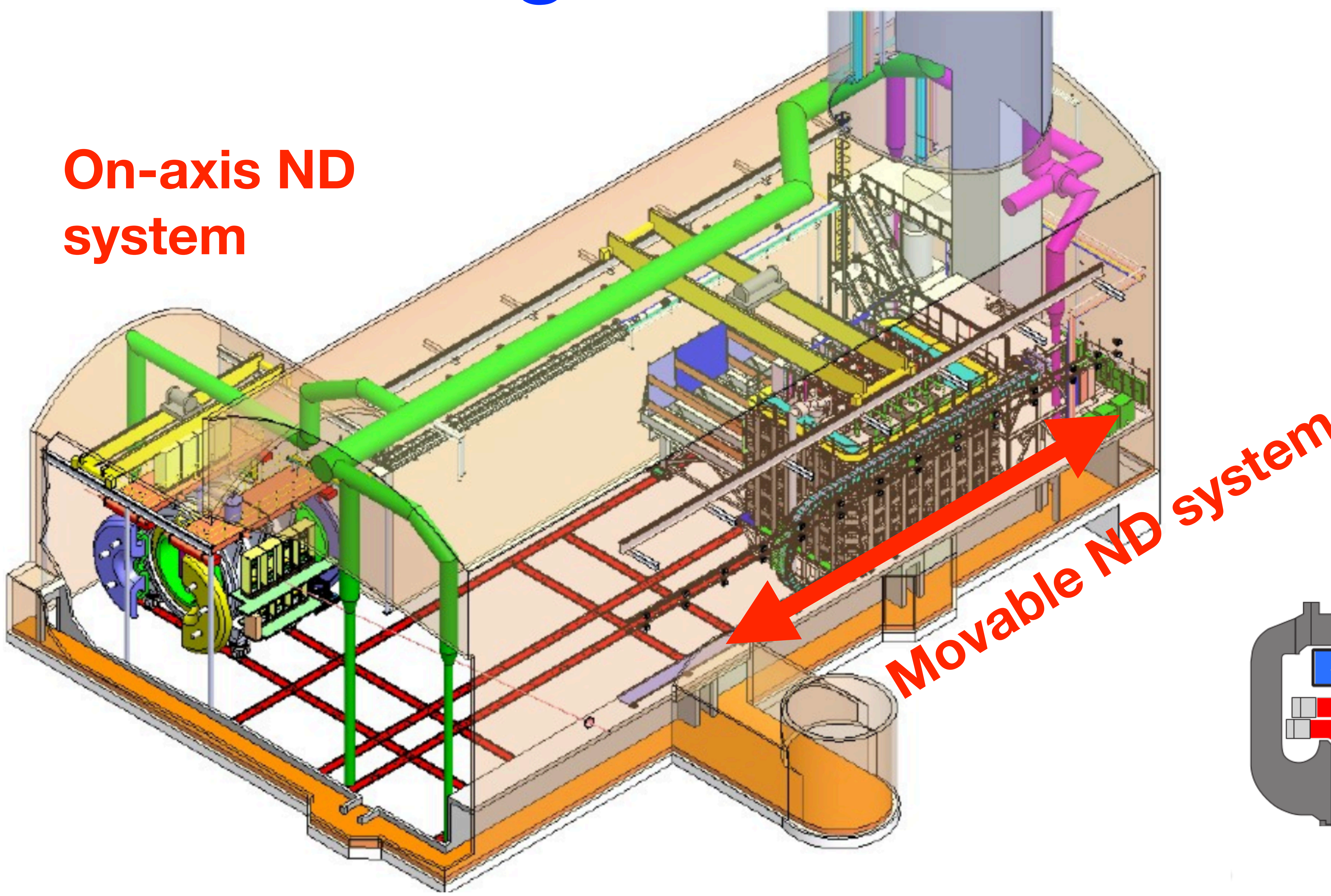
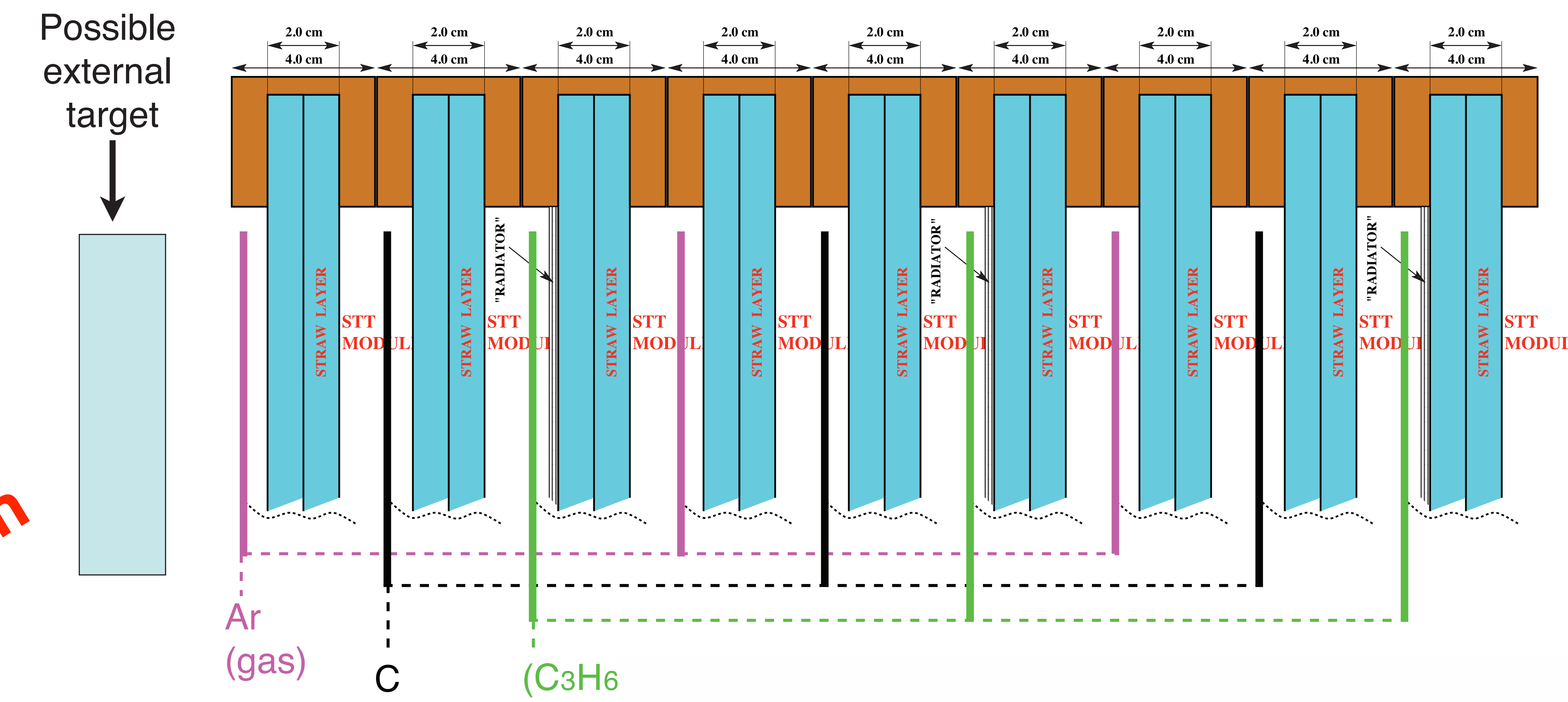
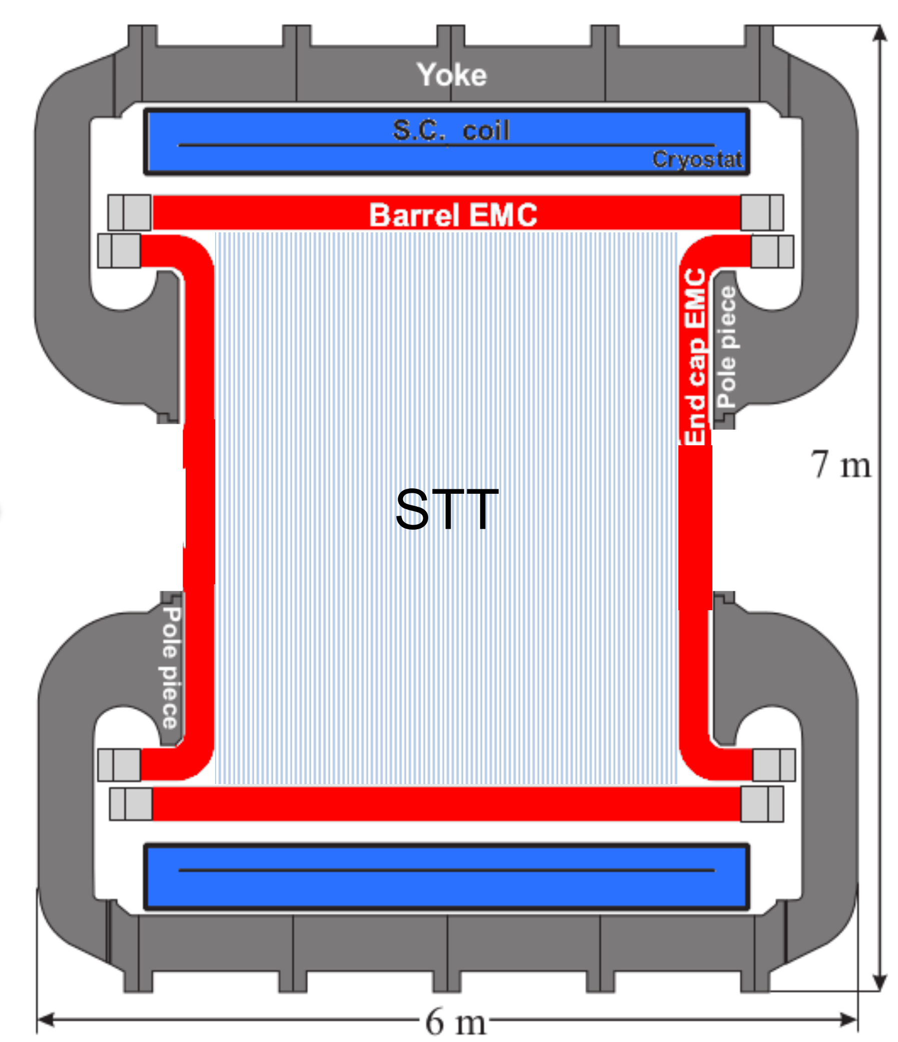
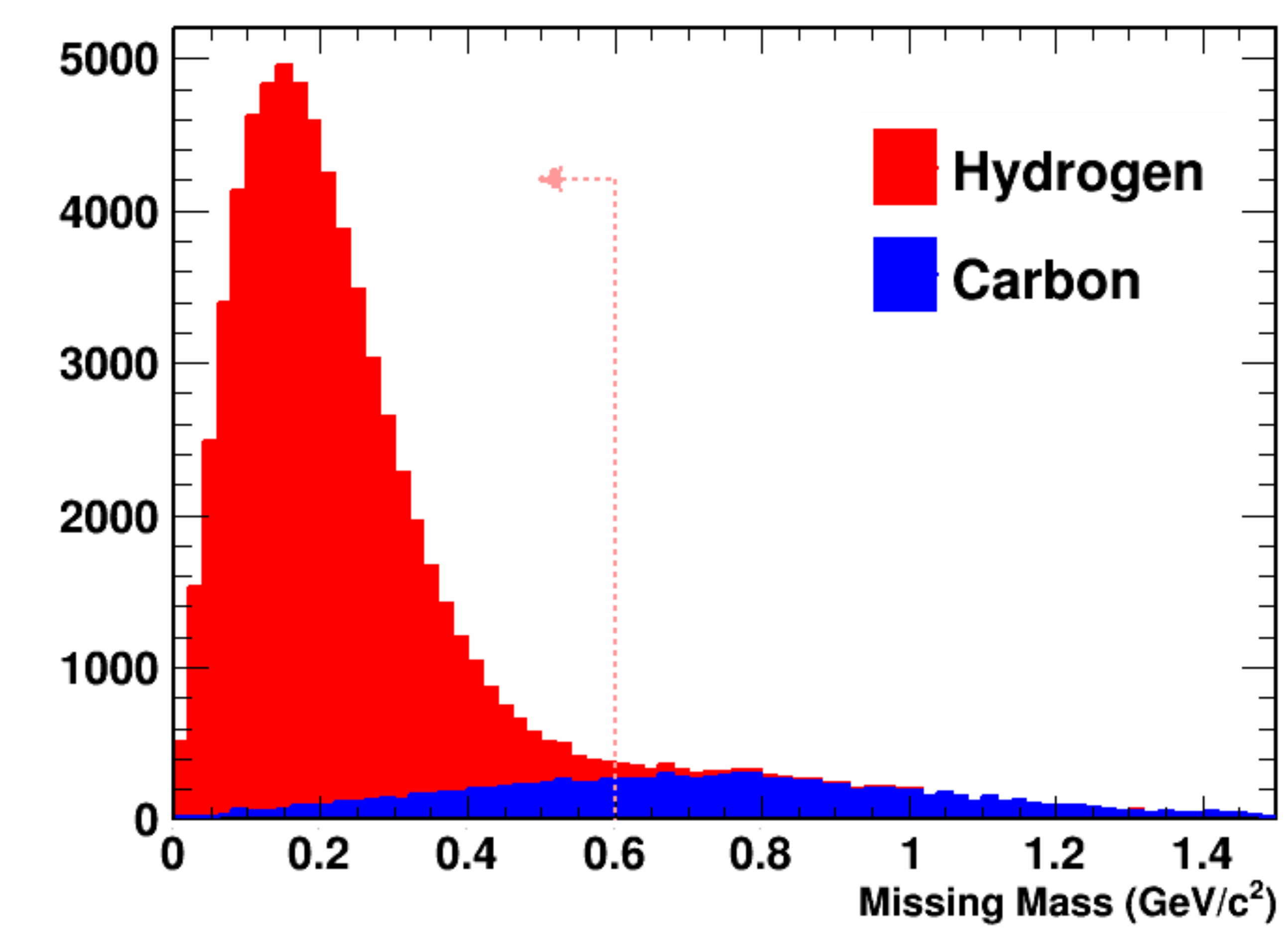
Next generation of ν-interaction measurements





- **The DUNE ND complex.**
- **SAND**: System for on-axis neutrino detection.

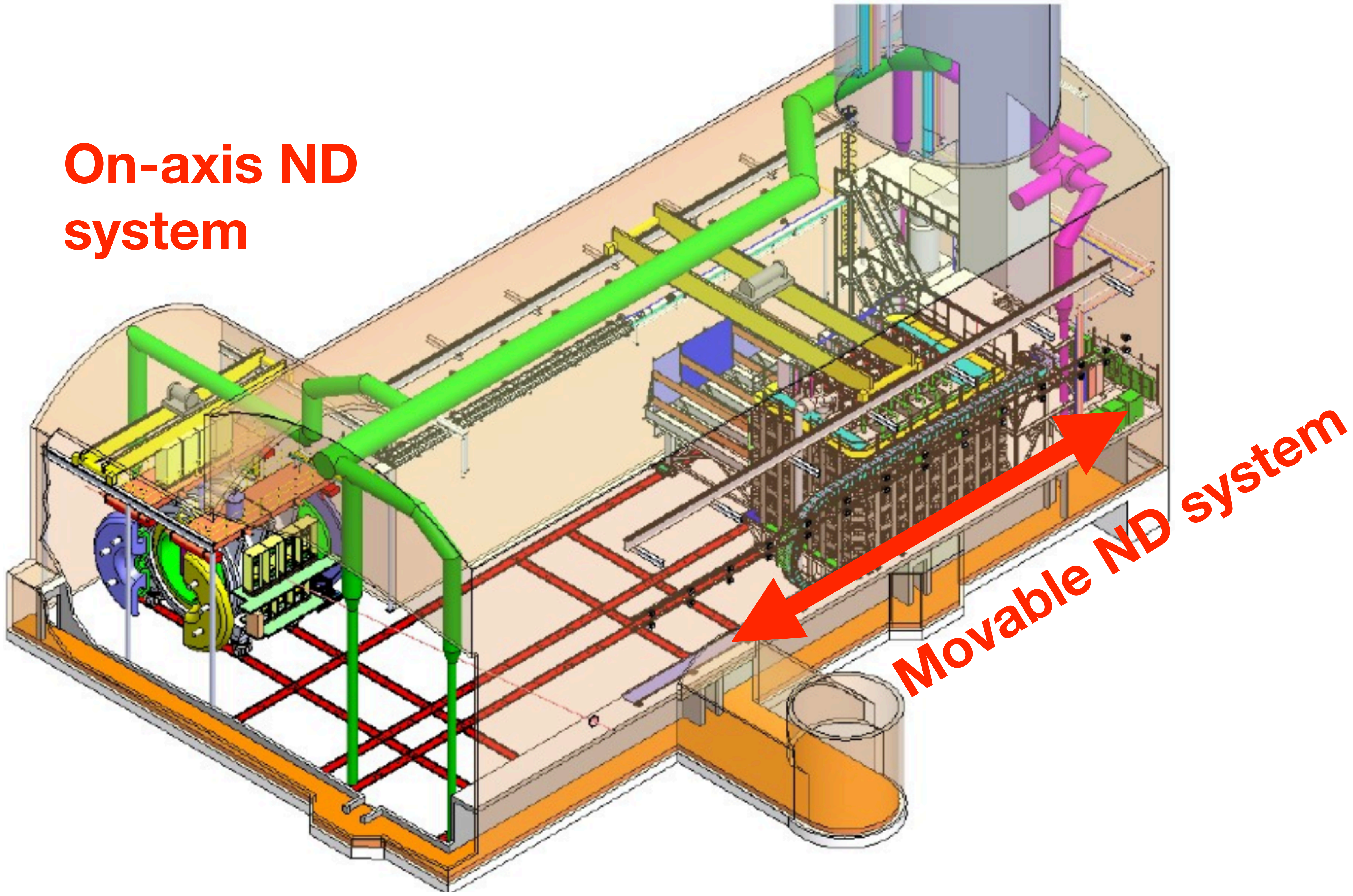


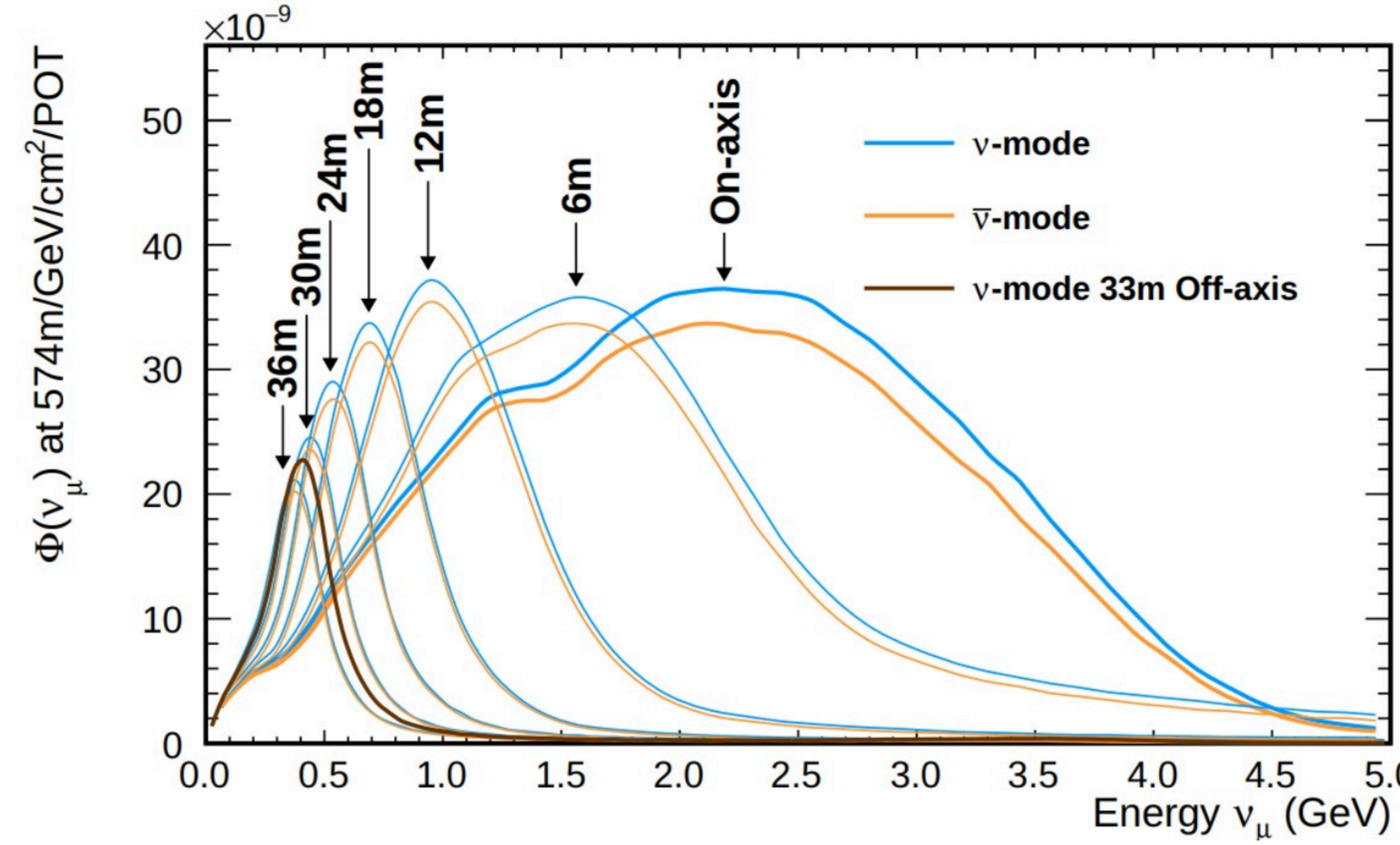


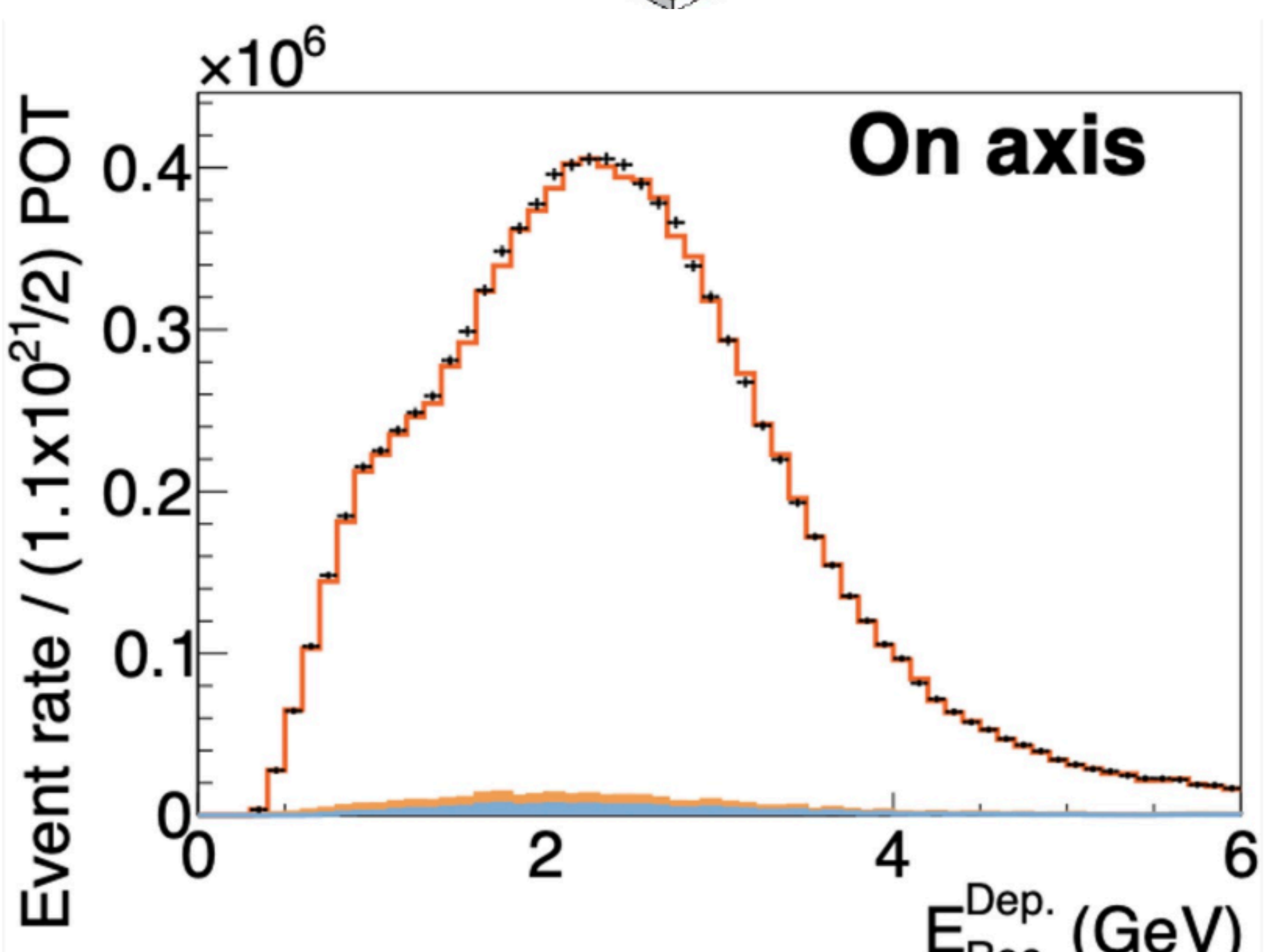
- Phys.Lett. B795 (2019) 424-431

- Multiple nuclear targets in a low-density straw tube tracker.
  - CH2 target and pure carbon target enables ν-H interaction measurements by statistically subtract carbon backgrounds.
  - Precise flux measurements with ν-H interactions and low-ν method.

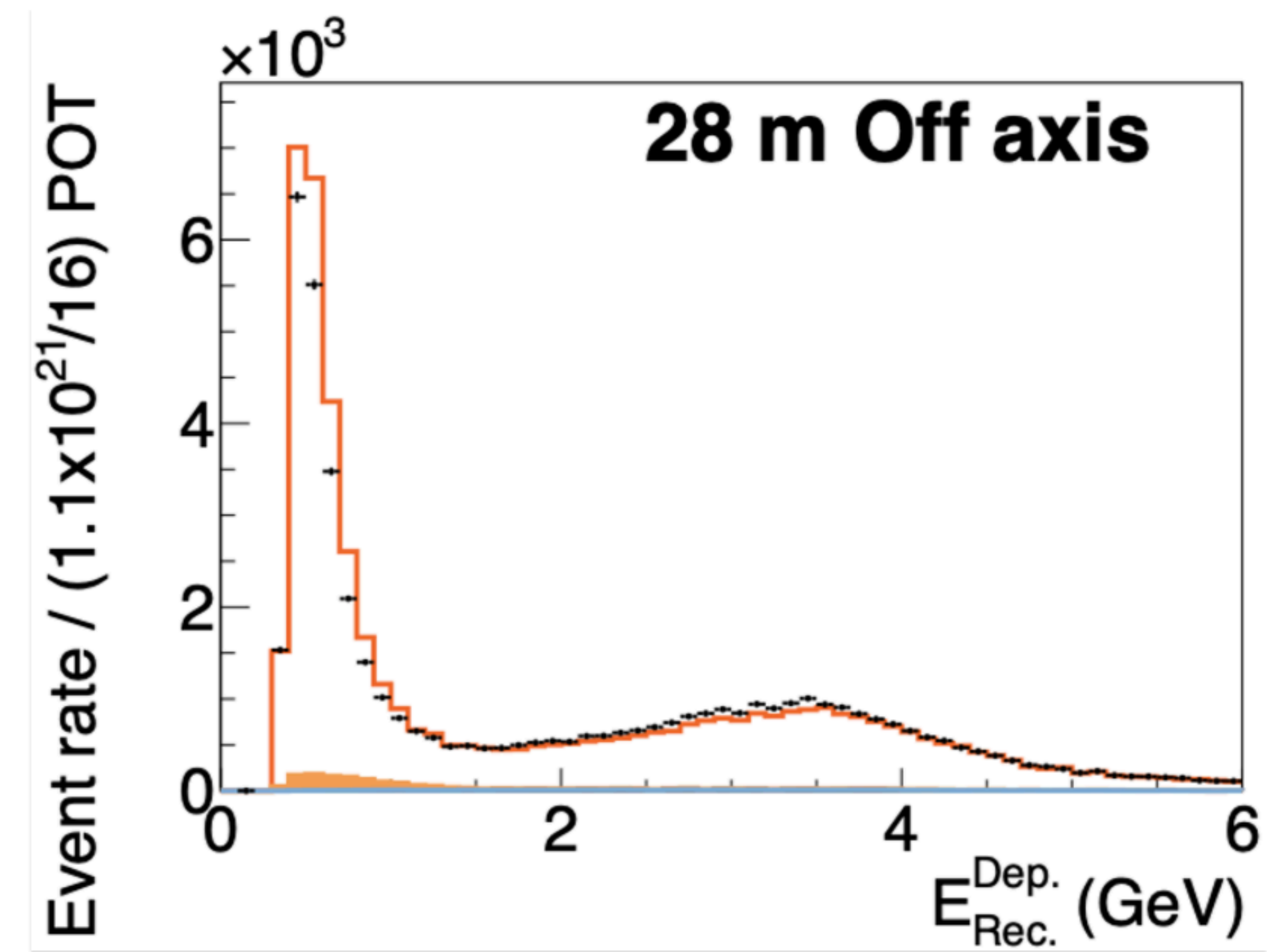
Next generation of ν-interaction measurements







De-coupling ν-int and flux effects by varying the flux by going different off-axis locations



Summary

- We are entering a precision era of neutrino physics, theoretically and experimentally.
- The applications of deep learning techniques greatly enhance detectors' capability
  - More effective signal recognition.
  - Higher resolution measurements.
  - Turn impossible into possible.
- **In the same time requires better understanding of neutrino interactions!**
  - Data-driven approaches may ease but not completely solve the problem.
  - Both theoretical and experimental efforts are needed.

Frankenstein's monster of ν-int

Deep-learning