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Co-funded by the European Union

# Classification of ESSnuSB WC Near Detector Events Using Graph Neural Networks

**$\nu_\mu$- and $\nu_e$-events for neutrino oscillation studies**

Kaare Endrup Iversen - Lund University

# Outline

- Neutrino Physics
- Experiment and Motivation

- Performance on Charged Lepton Simulations
- Performance on Full Neutrino Simulations
- Investigation of Performance Differences

# Neutrino Physics

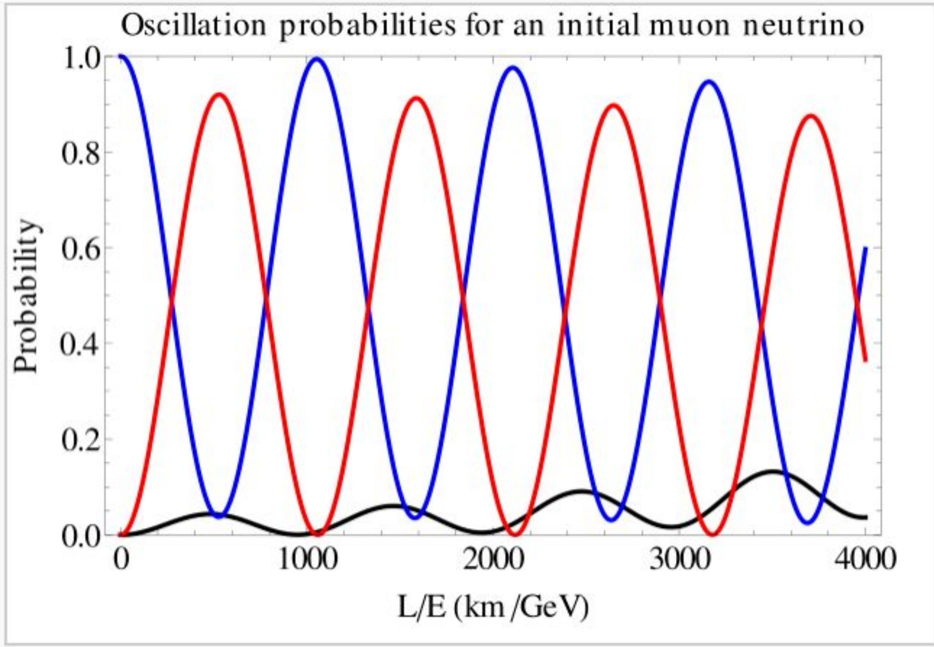
# Neutrino Physics

- Neutrinos **oscillate**!

$\nu_\mu$

$\nu_\tau$

$\nu_e$



Muon neutrino oscillations, short range

# Neutrino Physics

$$P_{\nu_\mu \to \nu_e (\overline{\nu_\mu} \to \overline{\nu_e})} \simeq 4 s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta L}{2}$$

$$+8 J_r \frac{r_\Delta}{r_A(1-r_A)} \cos\left(\delta_{CP} - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2}$$

$$+4 c_{23}^2 c_{12}^2 s_{12}^2 \left(\frac{r_\Delta}{r_A}\right)^2 \sin^2 \frac{r_A \Delta L}{2}$$

$$J_r \equiv c_{12} s_{12} c_{23} s_{23} s_{13}, \Delta \equiv \frac{\Delta m_{31}^2}{2E_\nu}, r_A \equiv \frac{a}{\Delta m_{31}^2}, r_\Delta \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}, a = 2\sqrt{2} G_F N_e E_\nu$$

# Neutrino Physics

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"atmospheric"

$$+8 J_r \frac{r_\Delta}{r_A(1-r_A)} \cos\left(\delta_{CP} - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2}$$

"interference"

$$+4 c_{23}^2 c_{12}^2 s_{12}^2 \left(\frac{r_\Delta}{r_A}\right)^2 \sin^2 \frac{r_A \Delta L}{2}$$

"solar"

$$J_r \equiv c_{12} s_{12} c_{23} s_{23} s_{13},\ \Delta \equiv \frac{\Delta m_{31}^2}{2E_\nu},\ r_A \equiv \frac{a}{\Delta m_{31}^2},\ r_\Delta \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2},\ a = 2\sqrt{2} G_F N_e E_\nu$$

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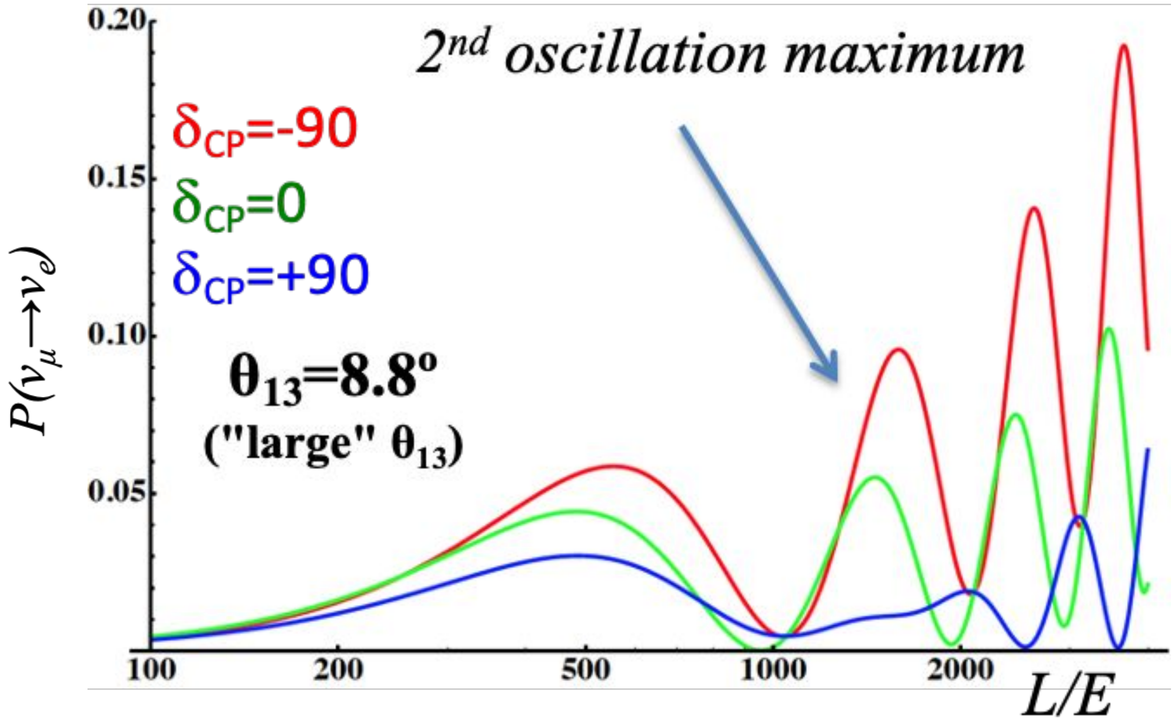
# Neutrino Physics

1st oscillation max: A=**0.3**sin$\delta_{CP}$
2nd oscillation max: A=**0.75**sin$\delta_{CP}$




M. Dracos, NuFact2022



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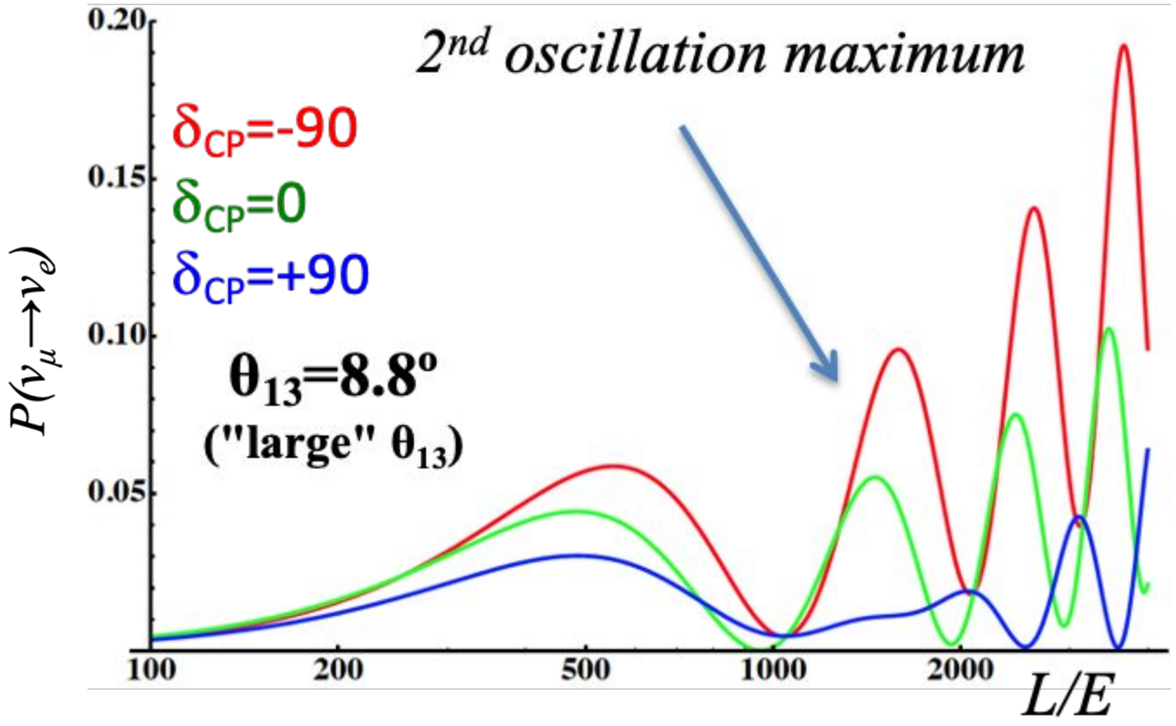
# Neutrino Physics

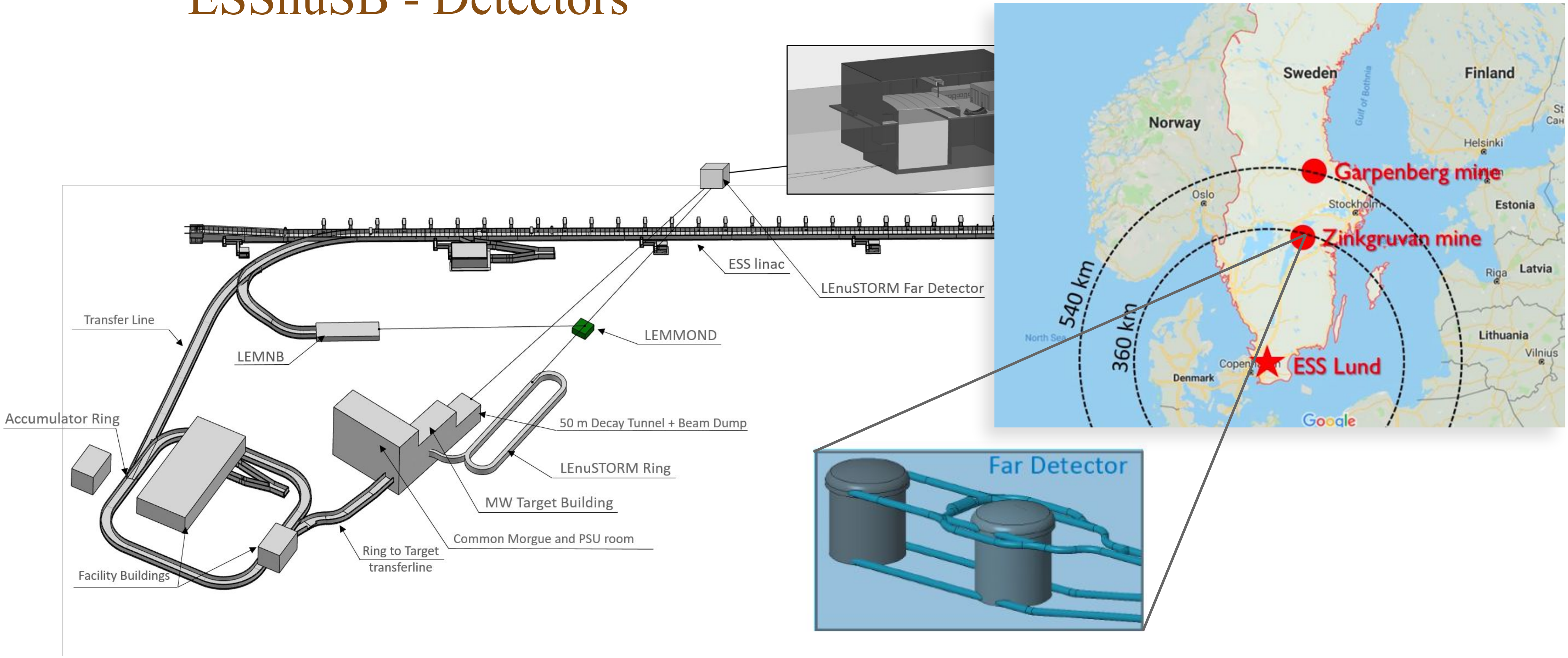
- Greater sensitivity to $\delta_{CP}$ at the second oscillation peak
- Within reach with the 5 MW proton beam produced at ESS




M. Dracos, NuFact2022

# Experiment and Motivation

# ESSnuSB - Detectors




Luckily, you are already Cherenkov detector experts!



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# Current Framework

**Charged Lepton Simulations**

WCSIM
https://github.com/WCSim/WCSim

**Neutrino Interaction Simulations**

GENIE
*Generator. Nucl. Instrum. Meth. A 614:87–104, 2010*

WCSIM
https://github.com/WCSim/WCSim

**LLH Based Reconstruction**

fiTQun
*J. Phys.: Conf. Ser.* 888 012066, 2017

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**Challenges**

- Likelihood reconstruction takes ~1 min/event
- To explore different detector proposals, fast reconstruction is crucial



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# Why Do We Need GNN Reconstruction?

- **Fast and reliable** event reconstruction enables testing of different detector layouts
- LLH-based methods are accurate, but reconstruction is **slow**
- ML methods are **fast once trained**, GNNs are well suited for sparse events with irregular geometry
- Multiple reconstruction methods provide a way to **cross check and find systematic errors**



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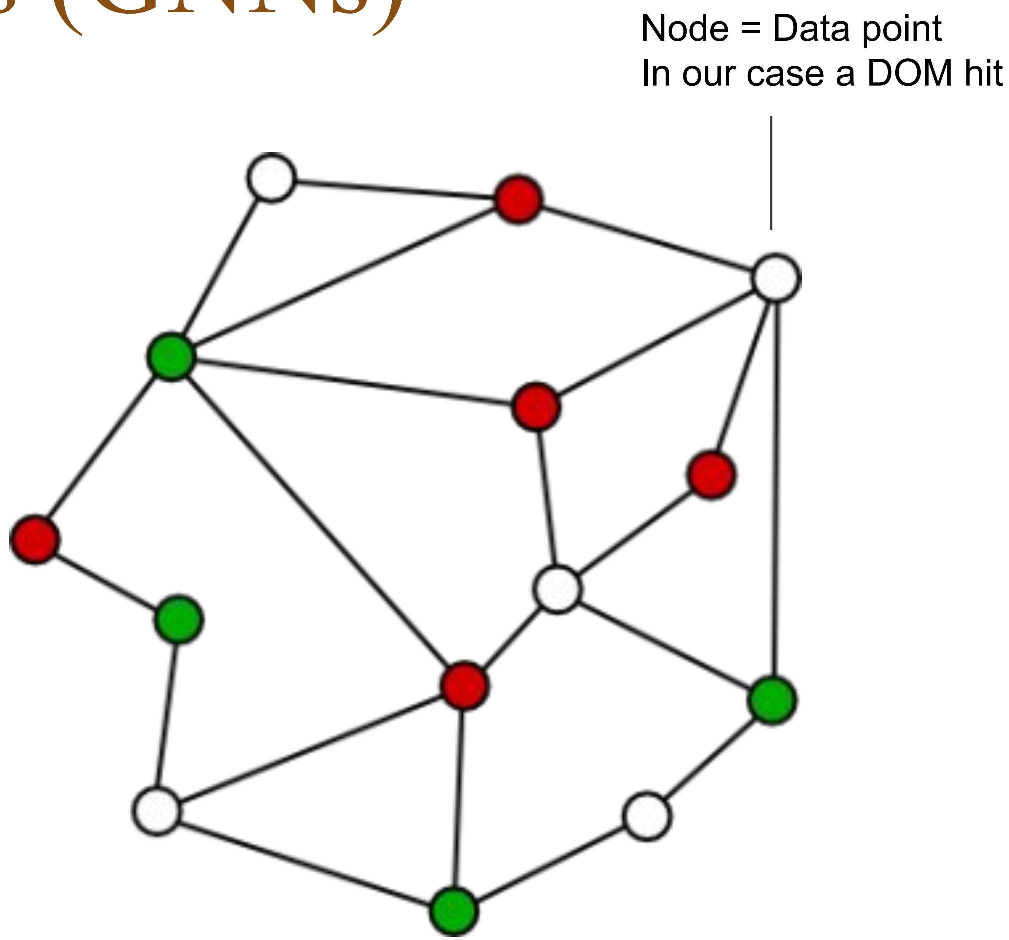
# Setup

# Graph Neural Networks (GNNs)

- Based on graph theory
- Each graph is a neutrino event
- Each data point is a node
- A node has features like xyz, time, charge

- Suited for non-euclidian data



# Graph Neural Networks - Framework

**GraphNeT** - Graph Neural Networks for Neutrino Telescopes

https://github.com/graphnet-team/graphnet

See plenary talk by Rasmus on Monday

**Pytorch Geometric** - GNN framework for Pytorch

Model architecture: **DynEdge**



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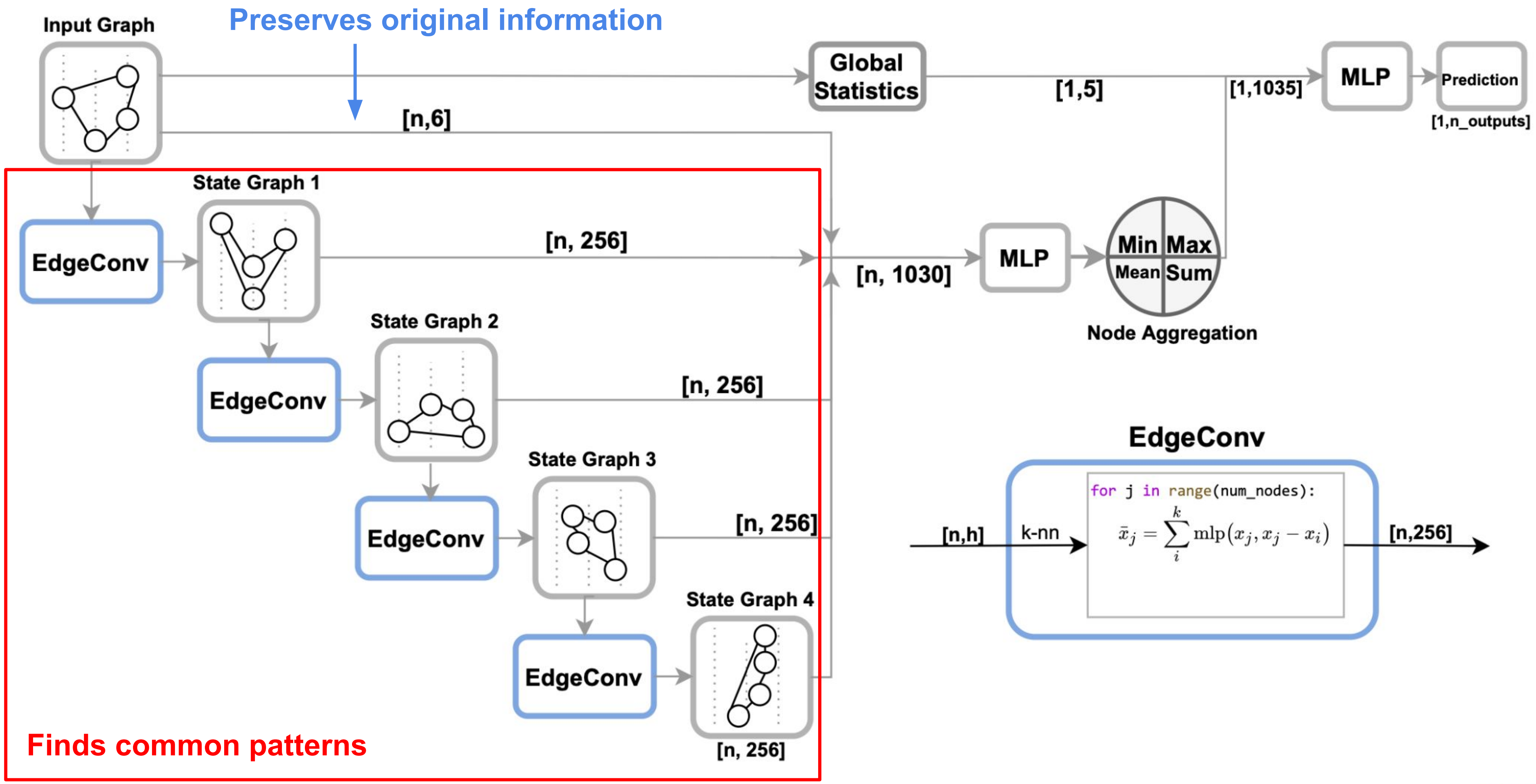
# Graph Neural Networks - Architecture



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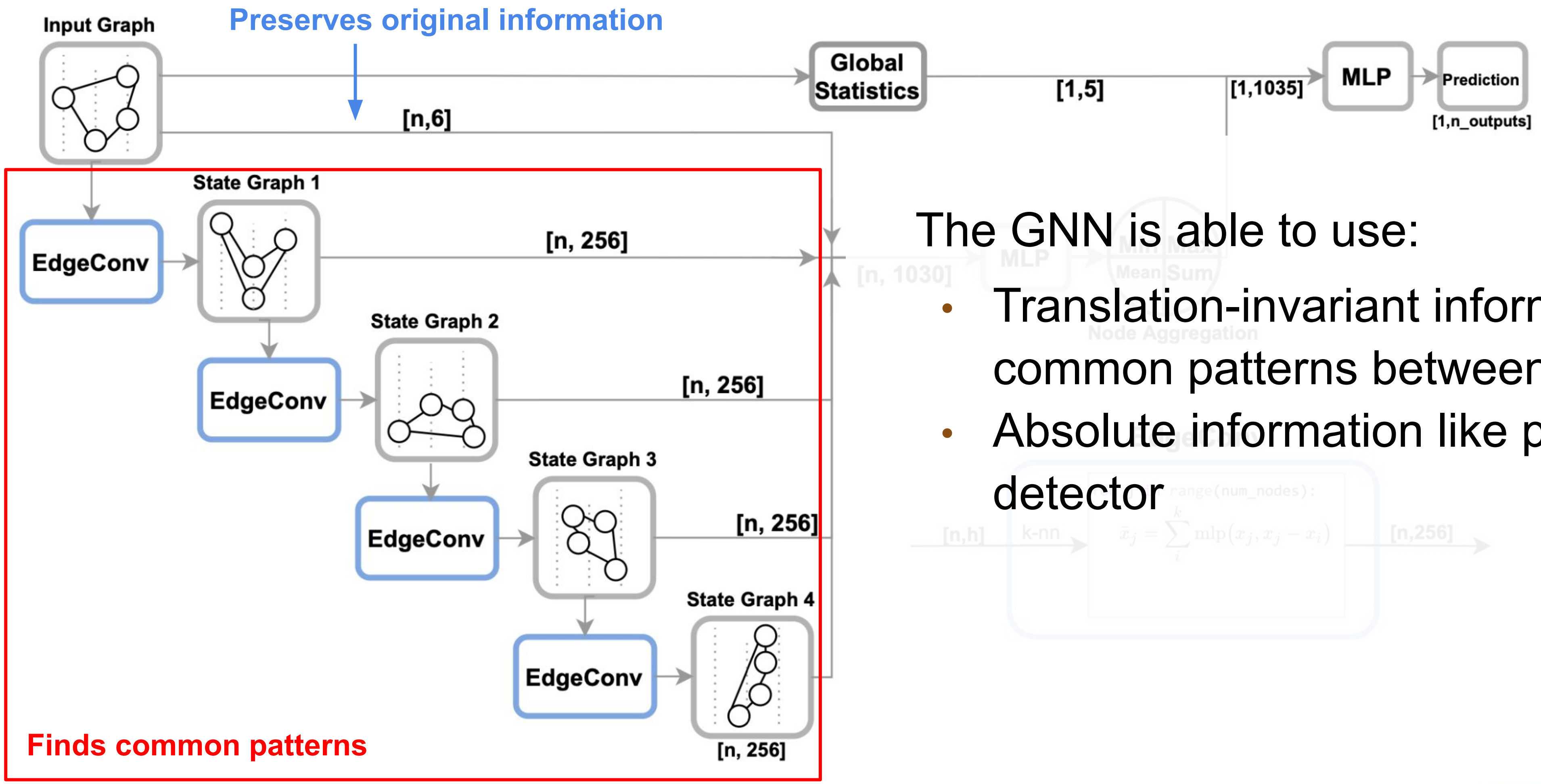
# Graph Neural Networks - Architecture




The GNN is able to use:

- Translation-invariant information about common patterns between events
- Absolute information like position in the detector



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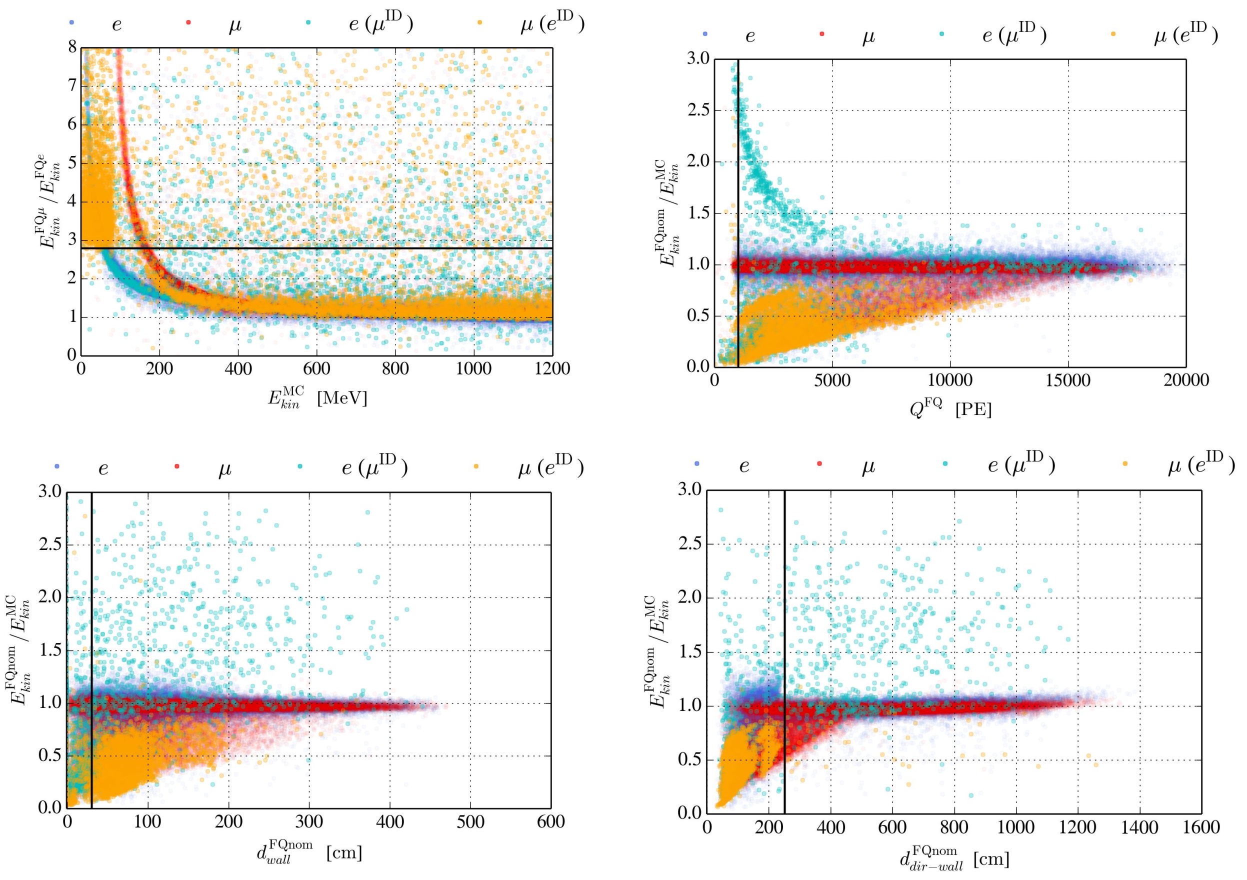
# Data Processing and Performance Measures

# Data processing

- Cuts based on reconstructed variables
- Removes events that are hard to classify
- Reduces events by a factor ~2




[The European Spallation Source neutrino Super Beam Conceptual Design Report]

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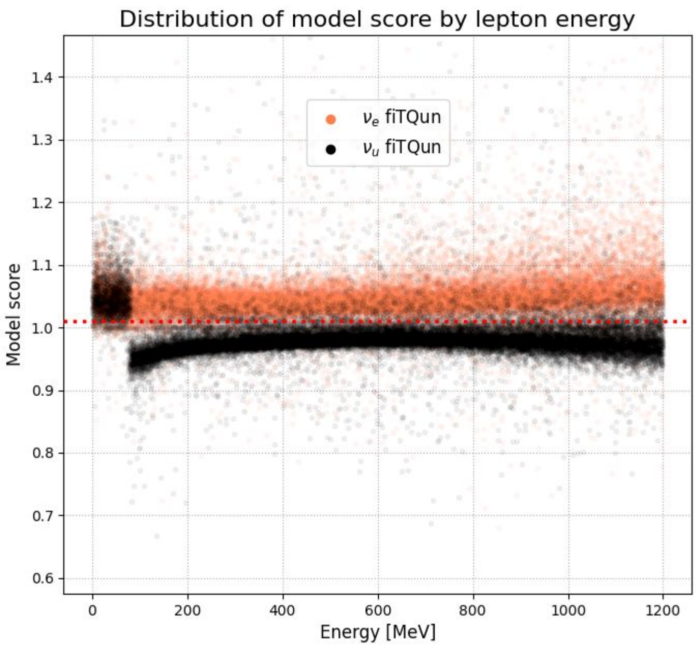


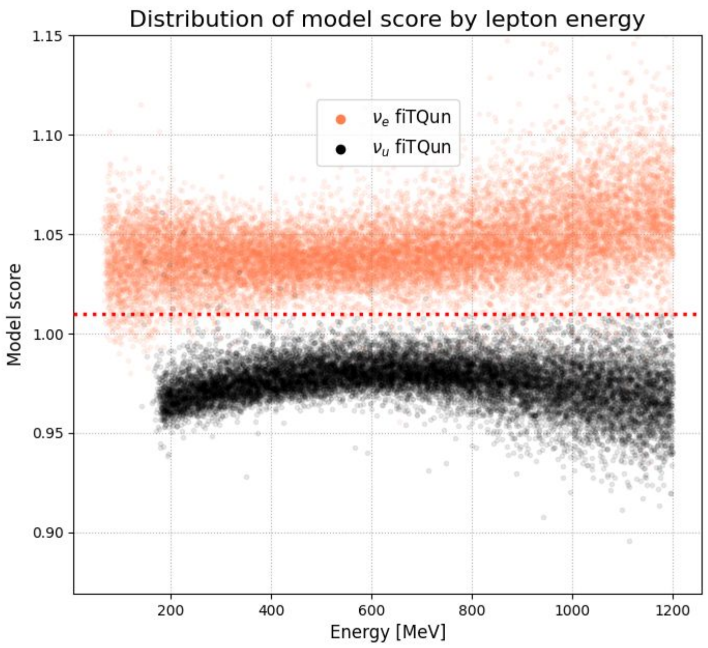


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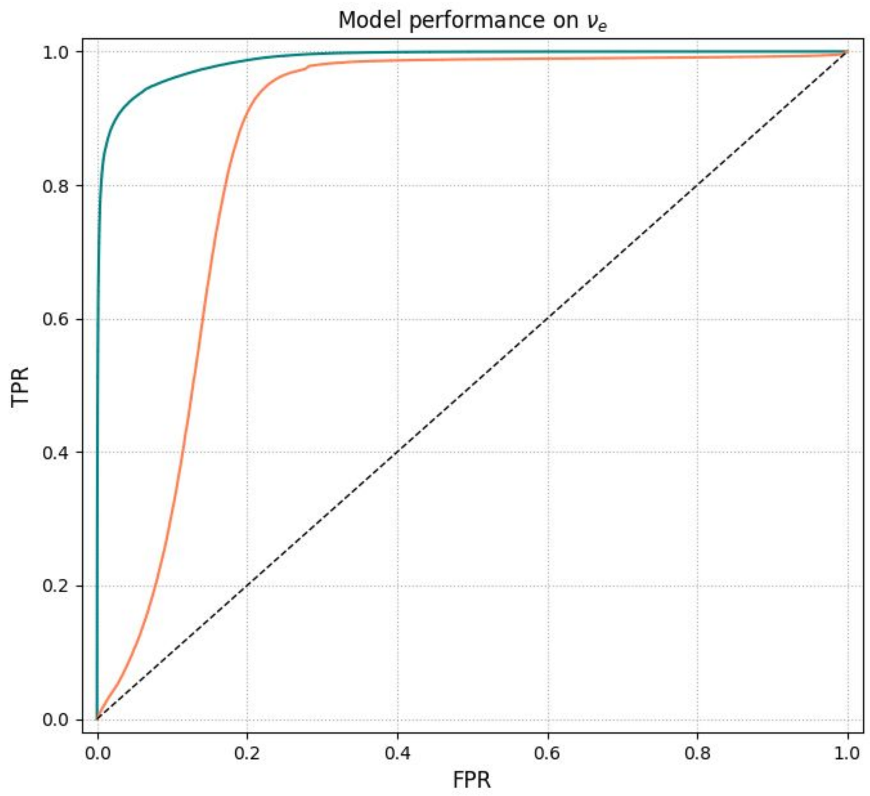
# Event Classification - Performance Measures

**False Positive Rate**

Due to the beam composition, we select samples that have:

- **1 % FPR** for muon neutrinos
- **0.1 % FPR** for electron neutrinos

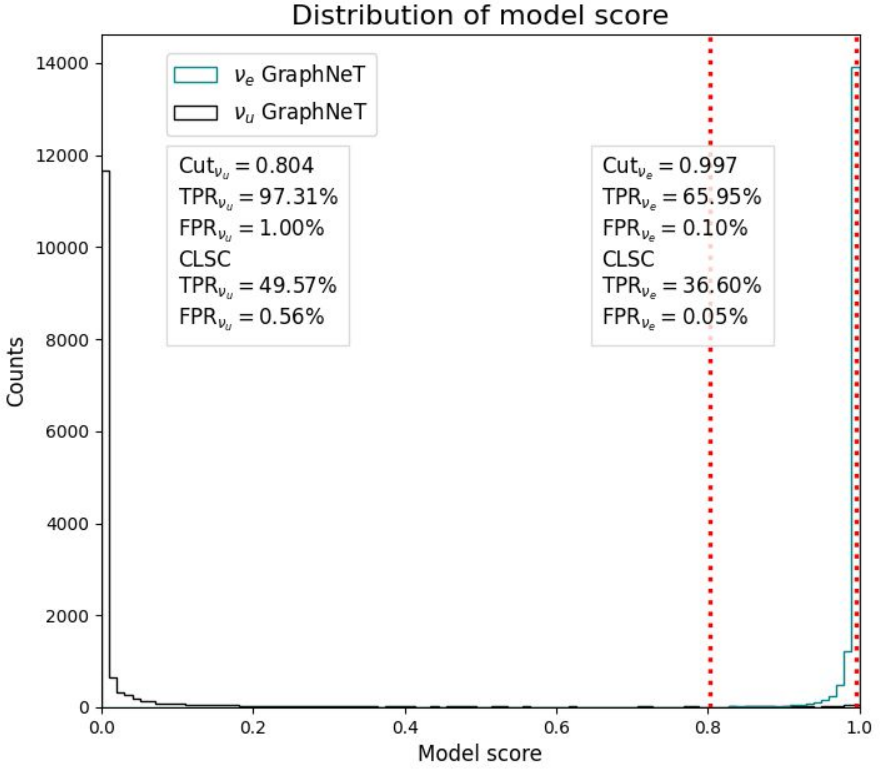


# Charged Lepton Performance

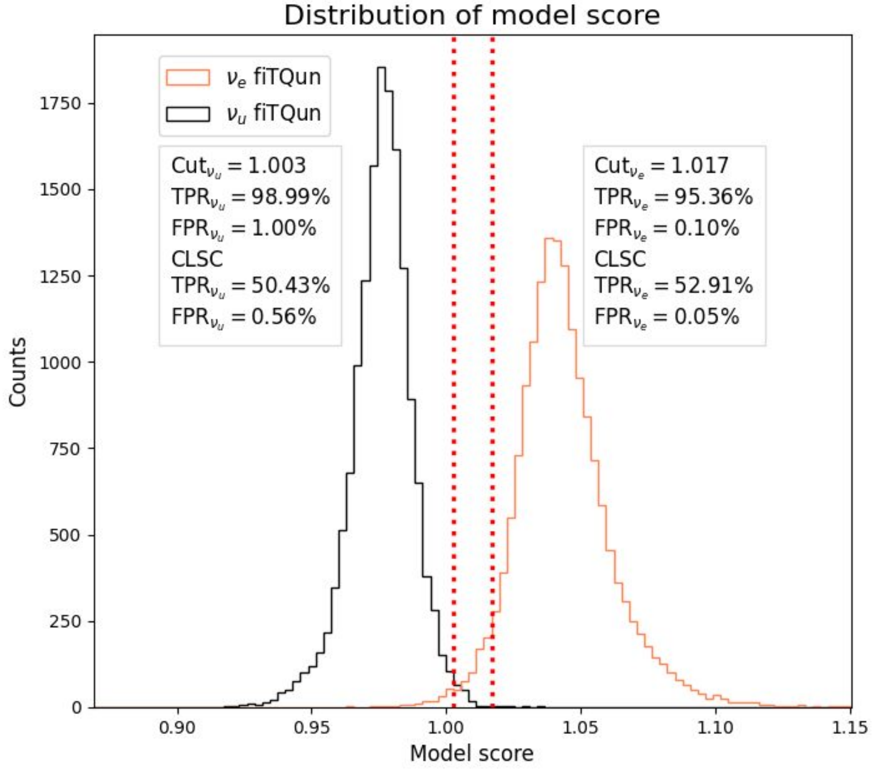
# Event Classification - GraphNeT vs. fiTQun

## Charged lepton simulations - with cuts

GraphNeT performance




fiTQun performance



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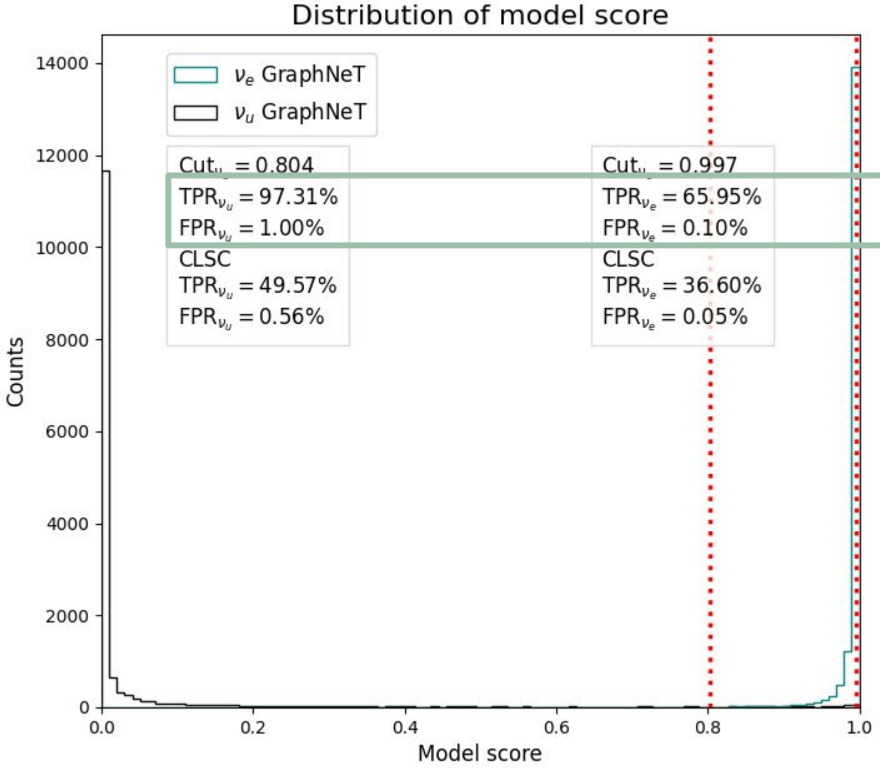
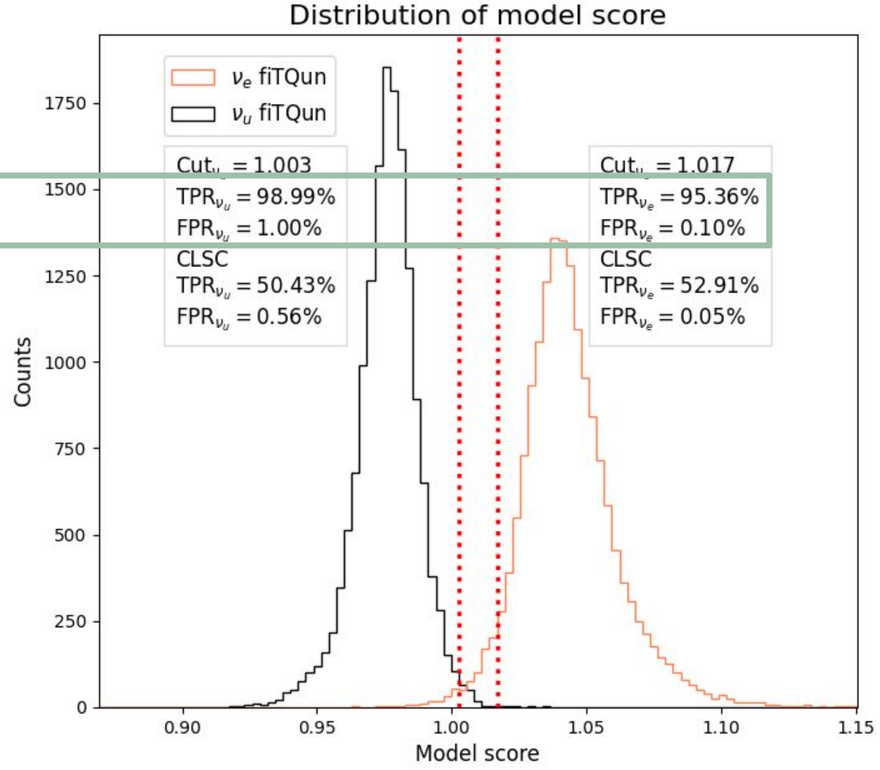
# Event Classification - GraphNeT vs. fiTQun

## Charged lepton simulations - with cuts

GraphNeT performance




fiTQun performance

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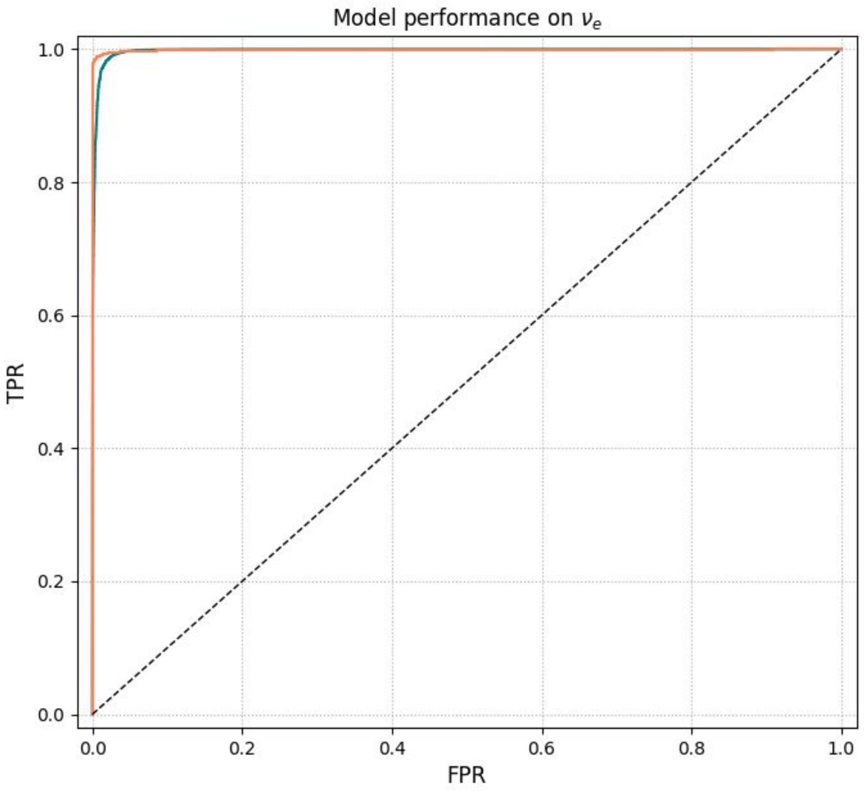
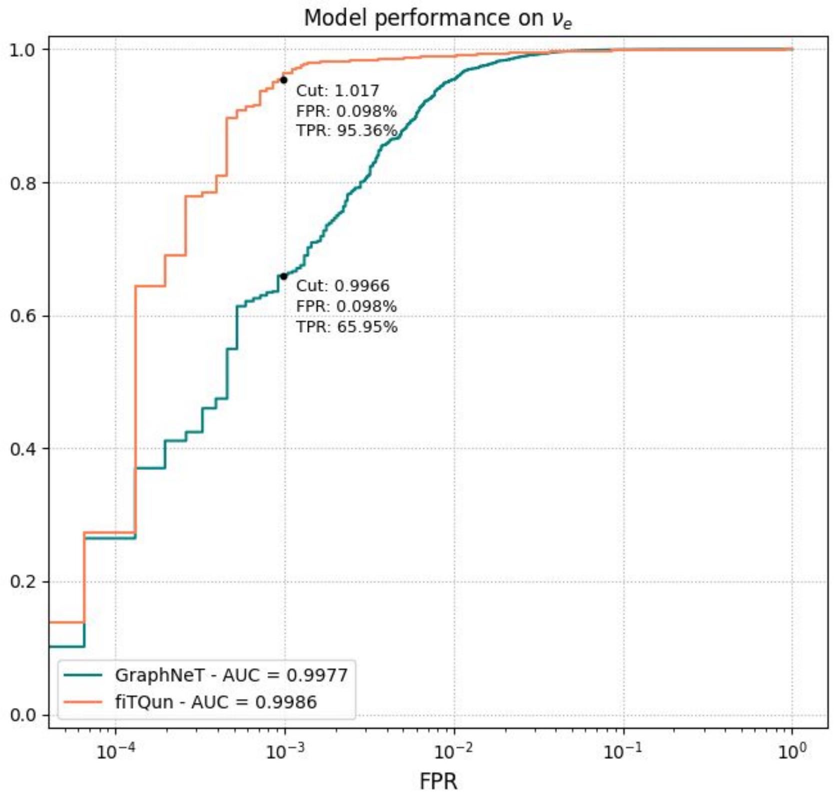
# Event Classification - GraphNeT vs. fiTQun

## Charged lepton simulations - with cuts (electron neutrino events)

ROC Curve




ROC Curve with logarithmic x axis



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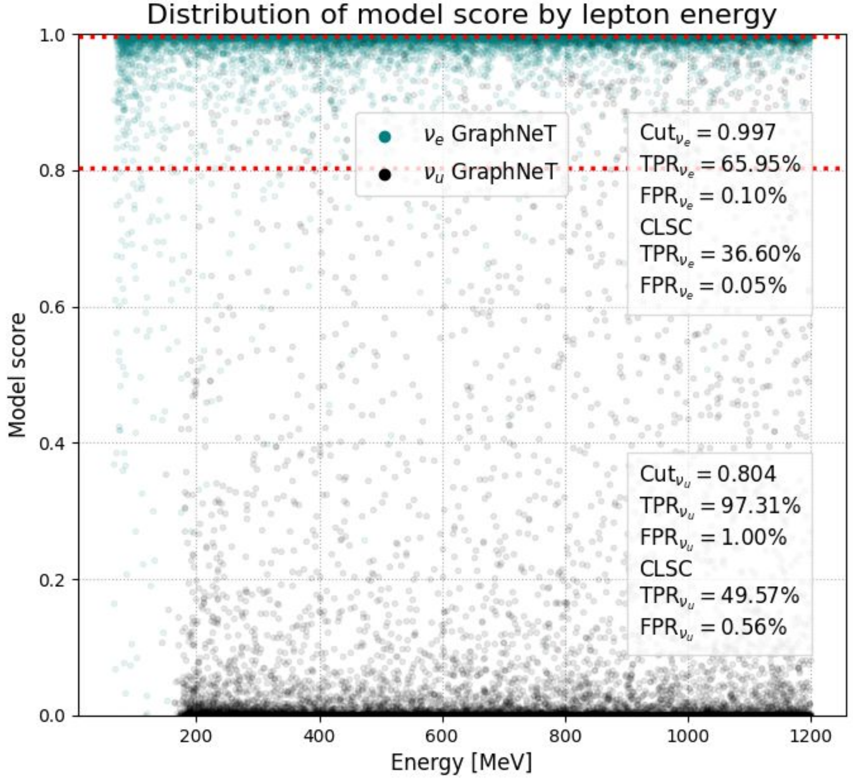
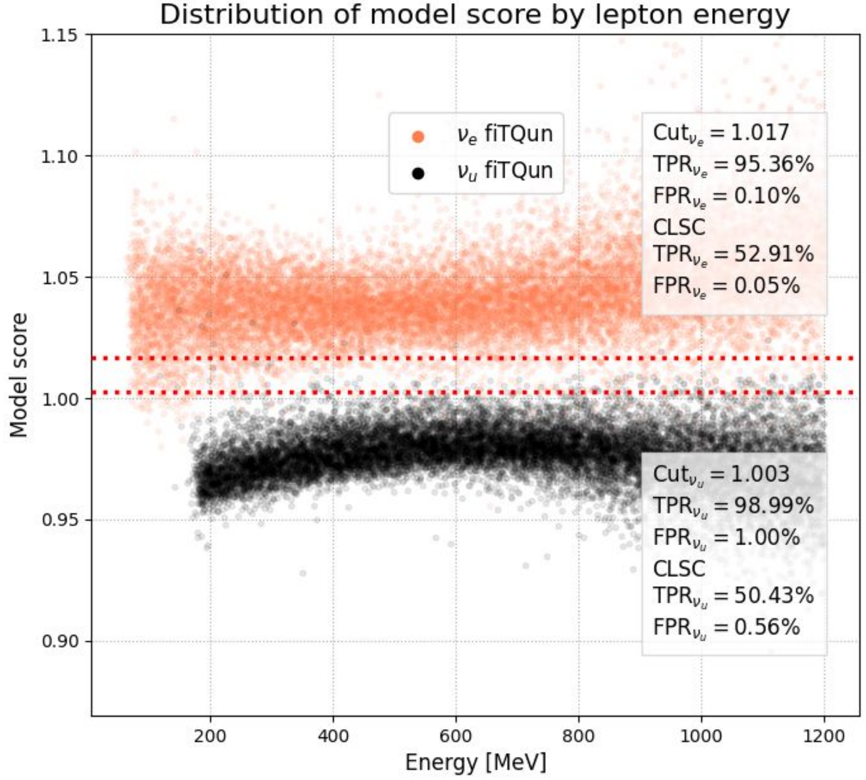
# Event Classification - GraphNeT vs. fiTQun

## Charged lepton simulations - with cuts

GraphNeT performance




fiTQun performance

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# Event Classification - GraphNeT vs. fiTQun

## Charged lepton simulations - with cuts

- For pure charged lepton simulations with filtering of difficult events, the GNN is on par with the fiTQun LLH method.

However:

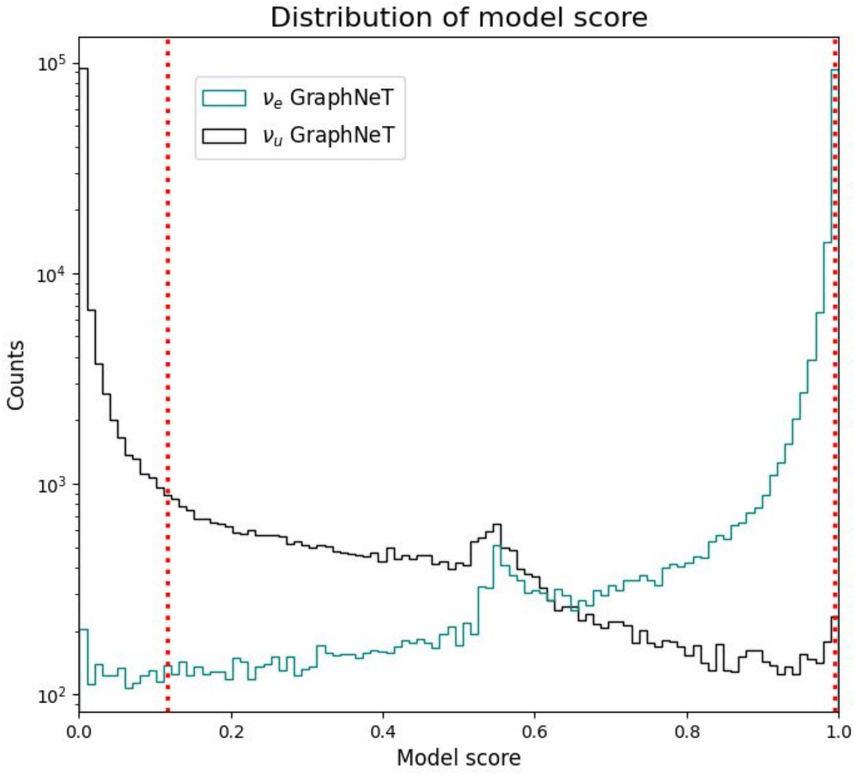
- Event filter relies on fiTQun reconstructed variables
- Full neutrino events can contain more than single charged leptons (pions, double-decays etc.)

# Neutrino Event Performance

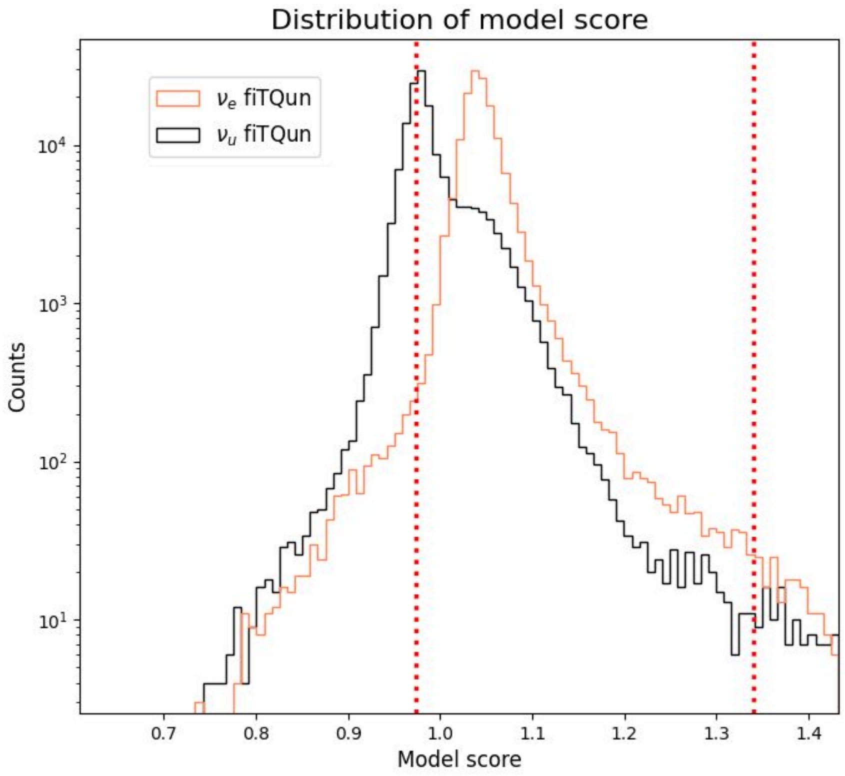
# Event Classification - GraphNeT vs. fiTQun

## Neutrino event simulations - without data cut

GraphNeT performance with logarithmic x axis




fiTQun performance with logarithmic x axis



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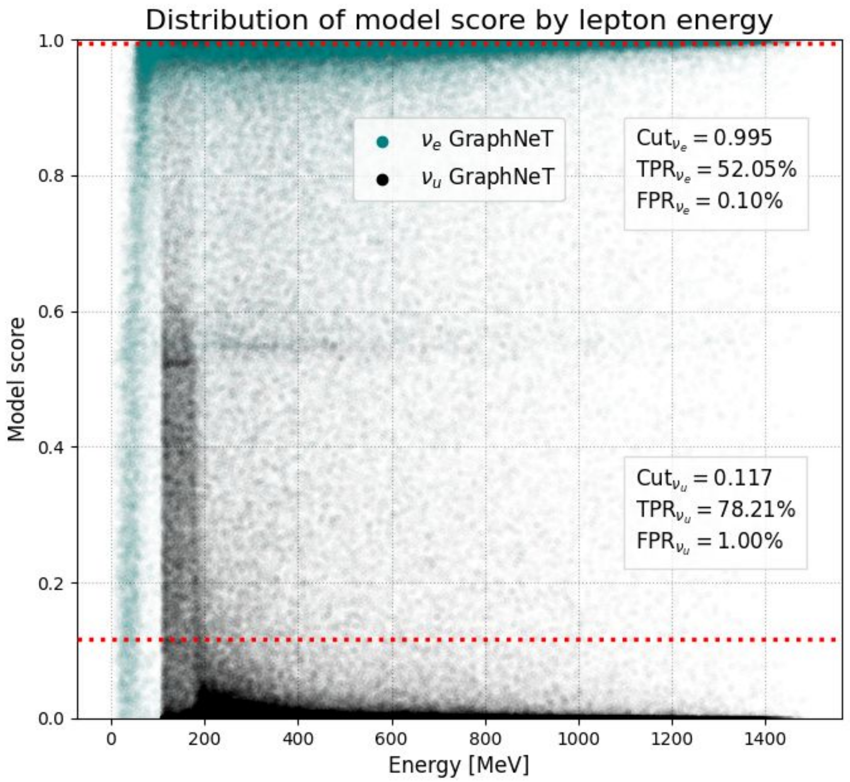
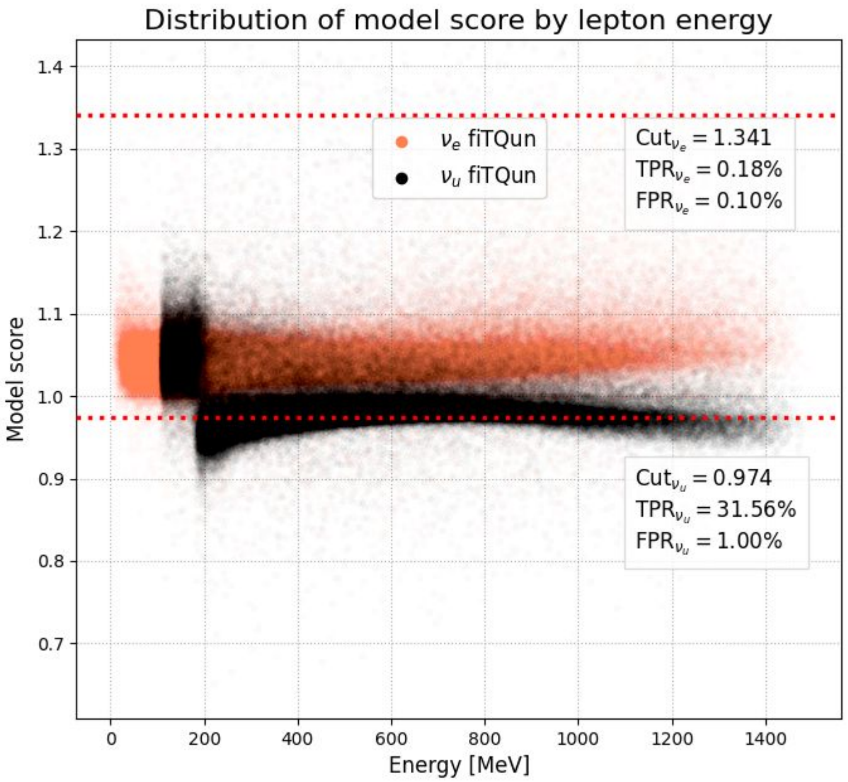
# Event Classification - GraphNeT vs. fiTQun

## Neutrino event simulations - without data cut

GraphNeT performance




fiTQun performance



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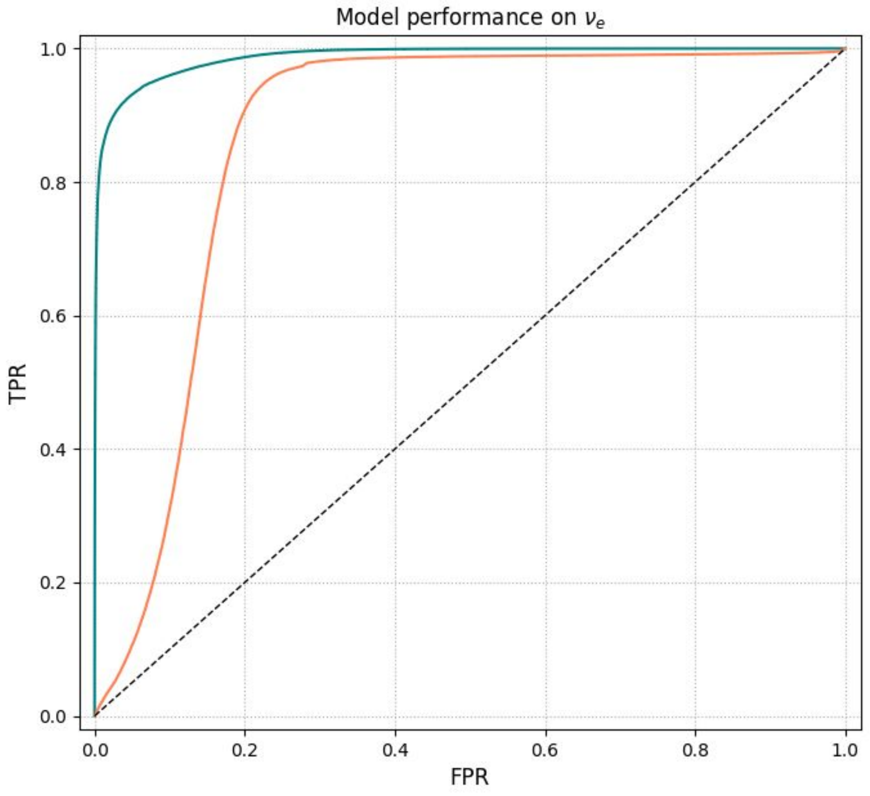
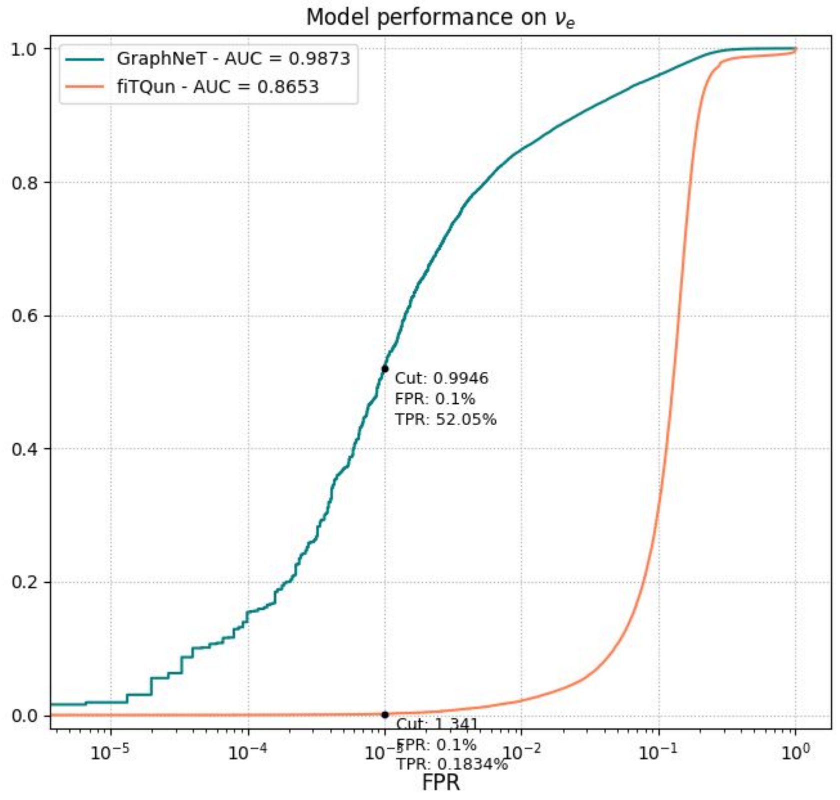
# Event Classification - GraphNeT vs. fiTQun

## Neutrino event simulations - without data cut (electron neutrino events)

ROC Curve




ROC Curve with logarithmic x axis



# Event Classification - GraphNeT vs. fiTQun

## Neutrino event simulations - without data cut

- The GNN has acceptable performance even on the full events
- Using the GNN, the data cuts can be made obsolete

Further investigations

- Look at performance differences on an event basis
- Make a GNN-filter for good/bad events



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# Event Classification - GraphNeT vs. fiTQun

## Neutrino event simulations - without data cut

| | |
|---|---|
| Data extraction | ~$10^{-4}$ mins/event |
| Training | ~$10^{-3}$ mins/event |
| Reconstruction | ~$10^{-4}$ mins/event |
| | |
| fiTQun Reconstruction | ~1 min/event |
| **Improvement** | **$10^3$** (w/ training) / **$10^4$** (w/o training) |

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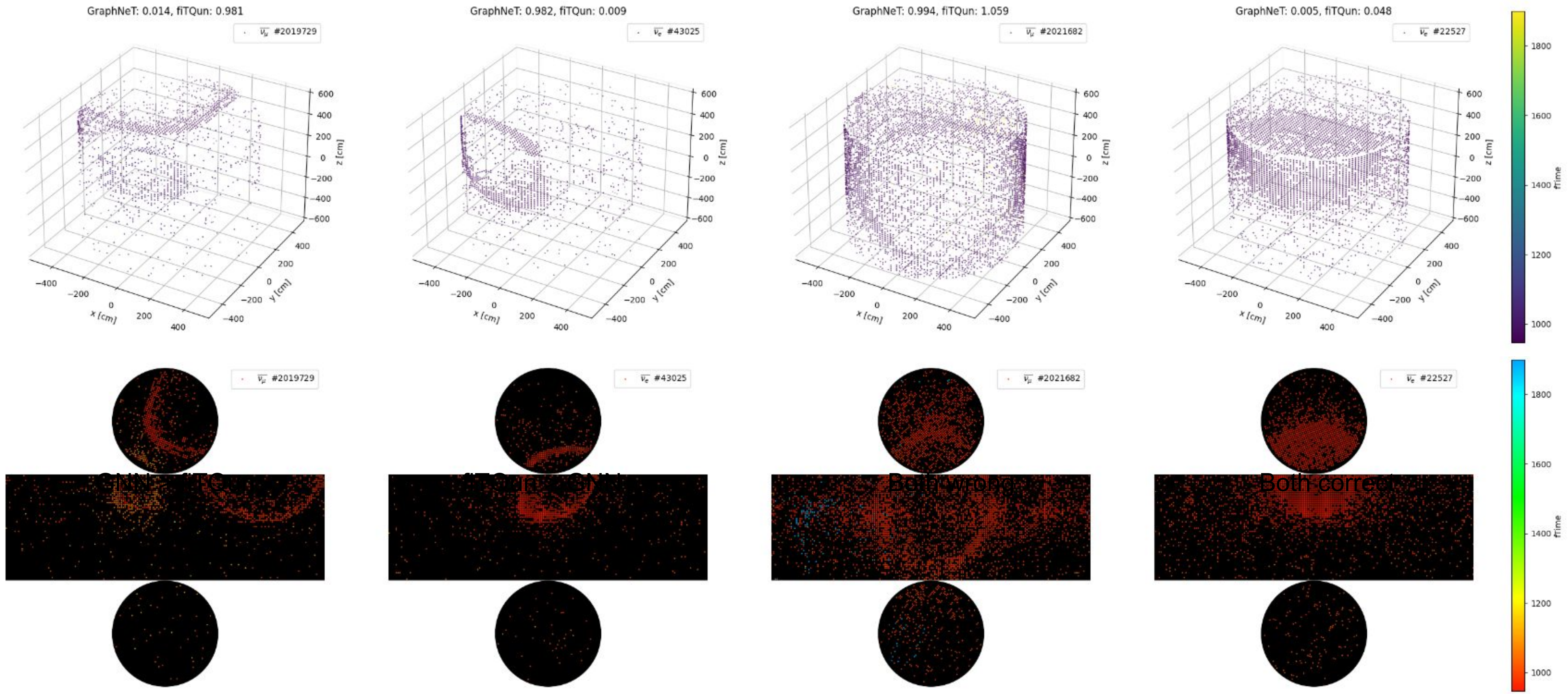
# Performance Investigations

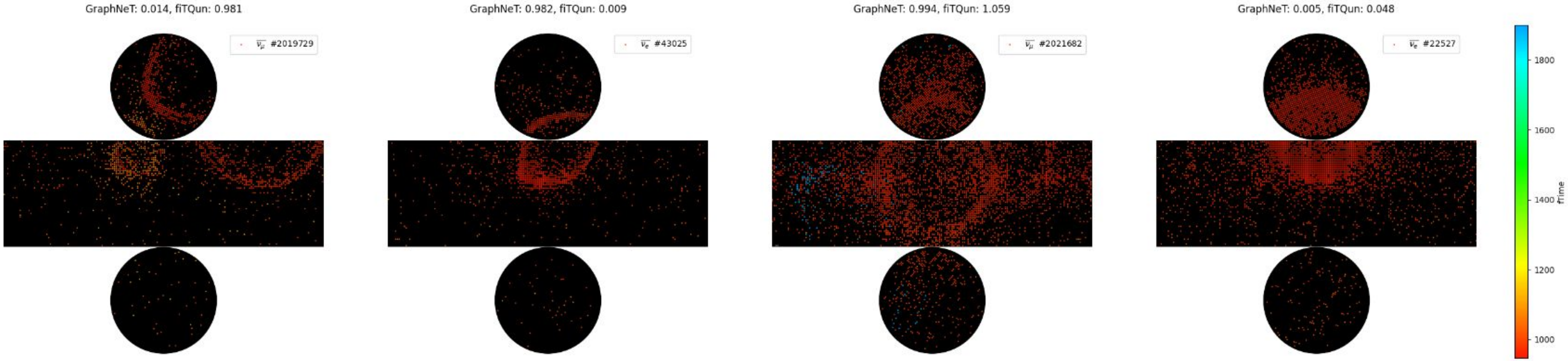
# Factors impacting performance - multiple charged lepton signatures

## Neutrino event simulations - **with** data cut



# Factors impacting performance - multiple charged lepton signatures

## Neutrino event simulations - **with** data cut




GNN > fiTQun | fiTQun > GNN | Both wrong | Both correct



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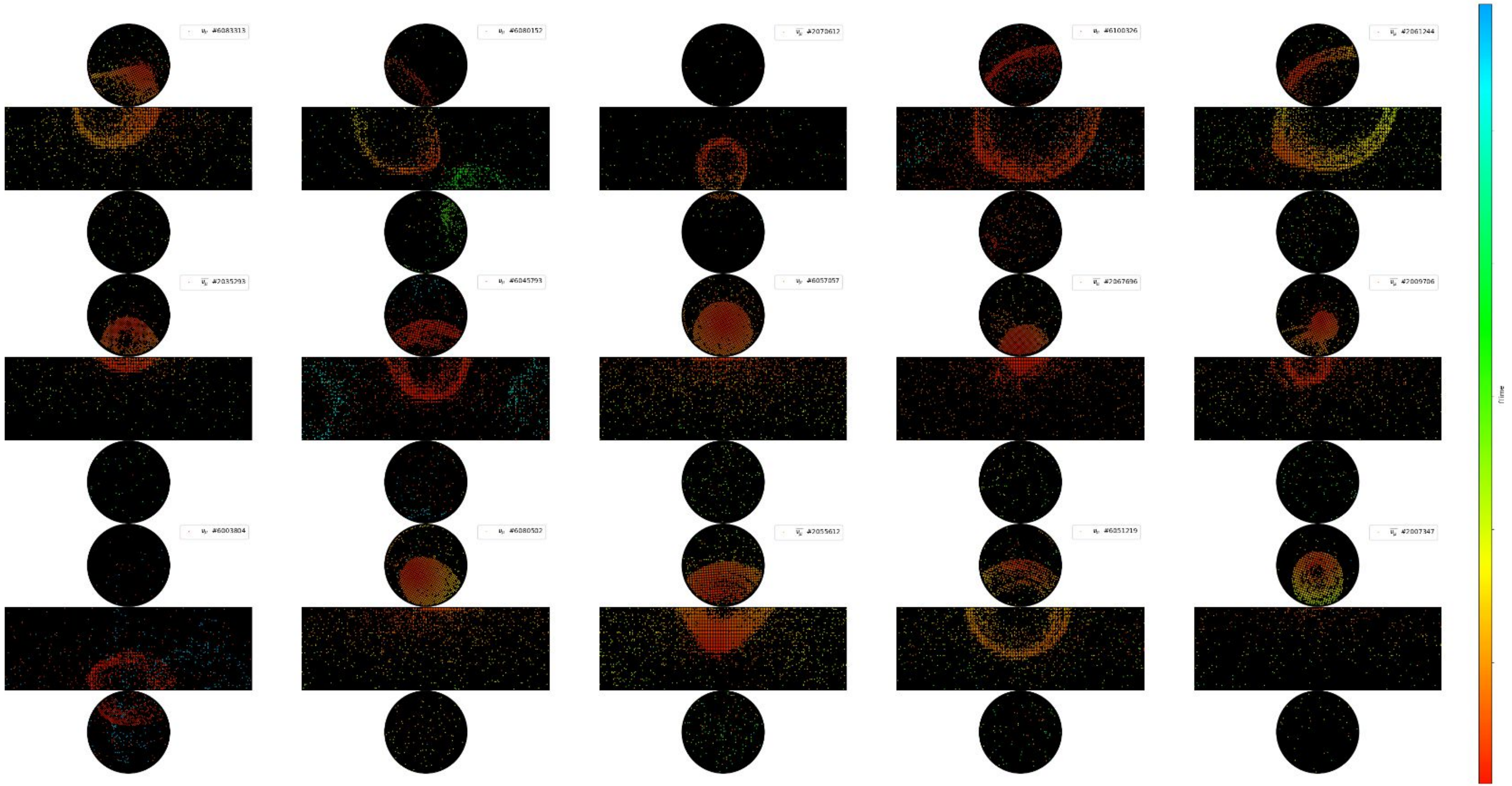
# Events for which GraphNeT performs significantly better than fiTQun



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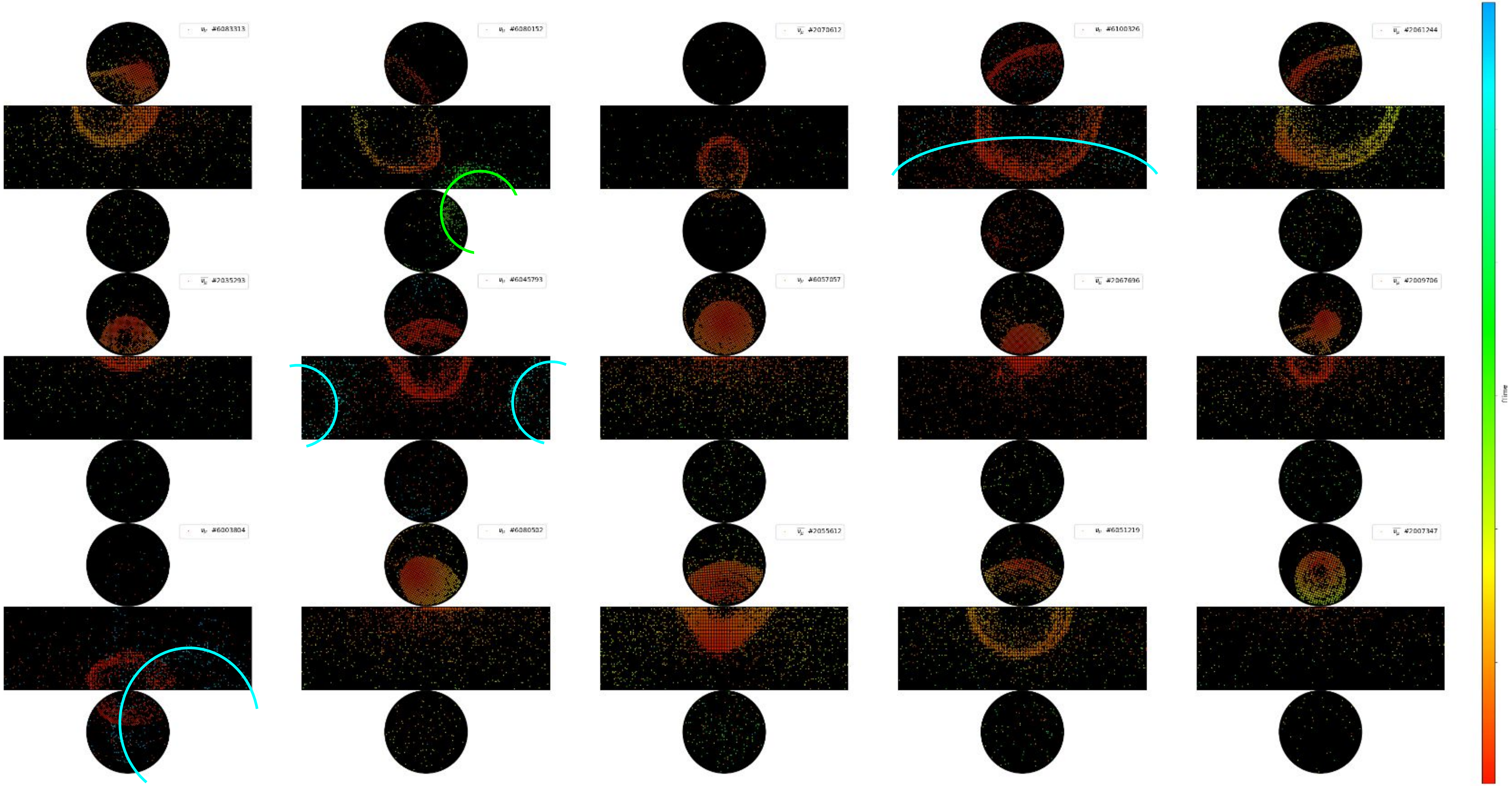
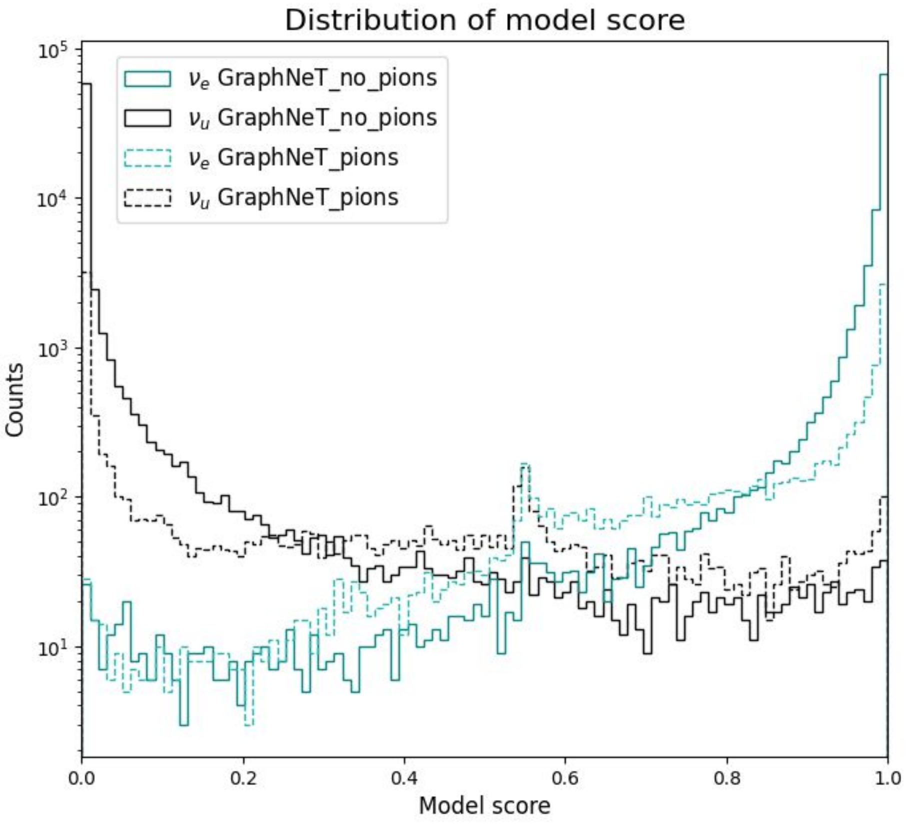
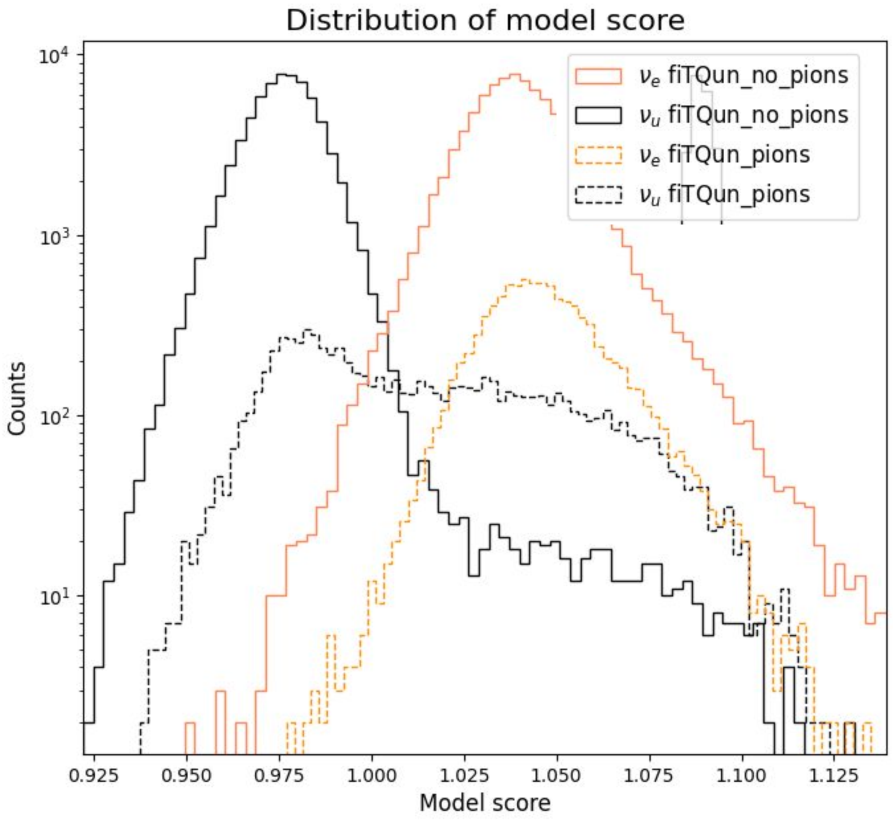


# Factors impacting performance - pion creation
## Neutrino event simulations - with data cut

GraphNeT performance with logarithmic x axis




fiTQun performance with logarithmic x axis



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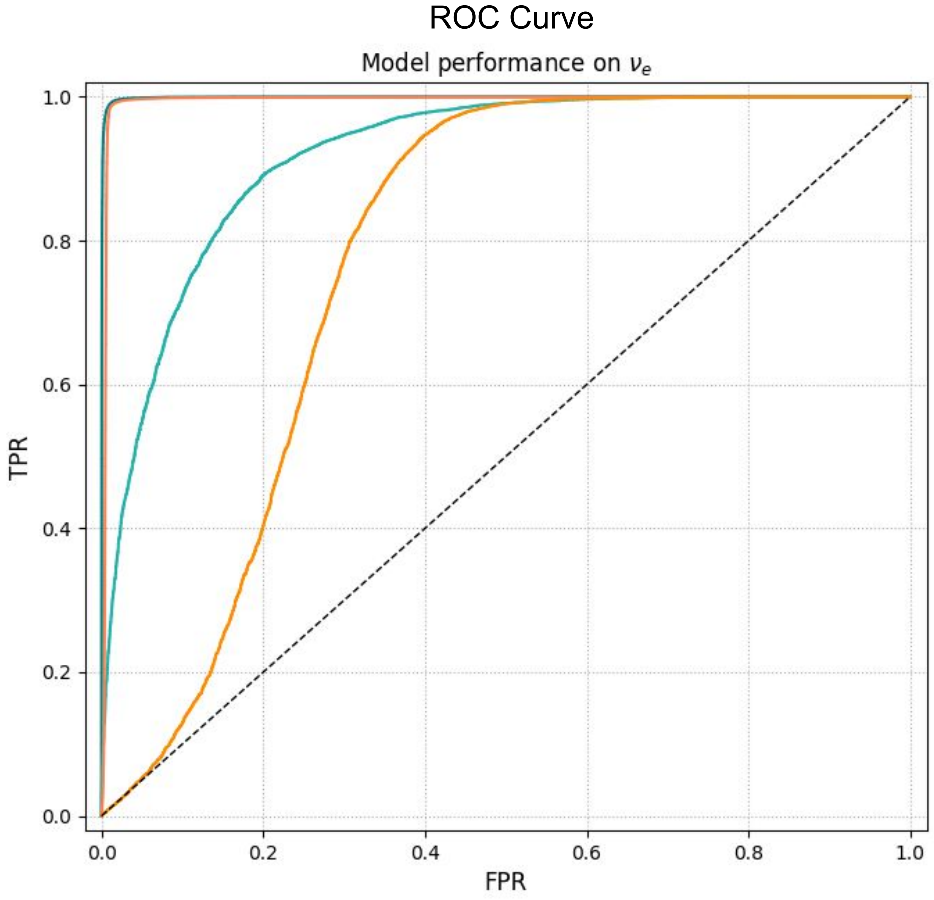


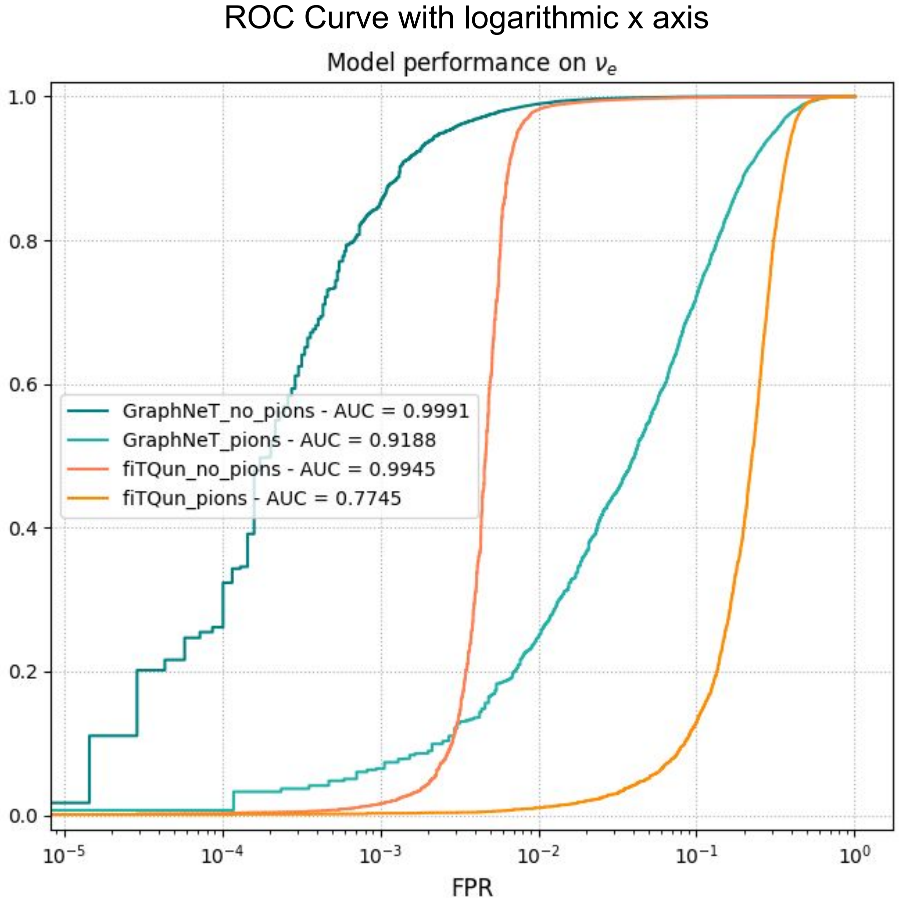


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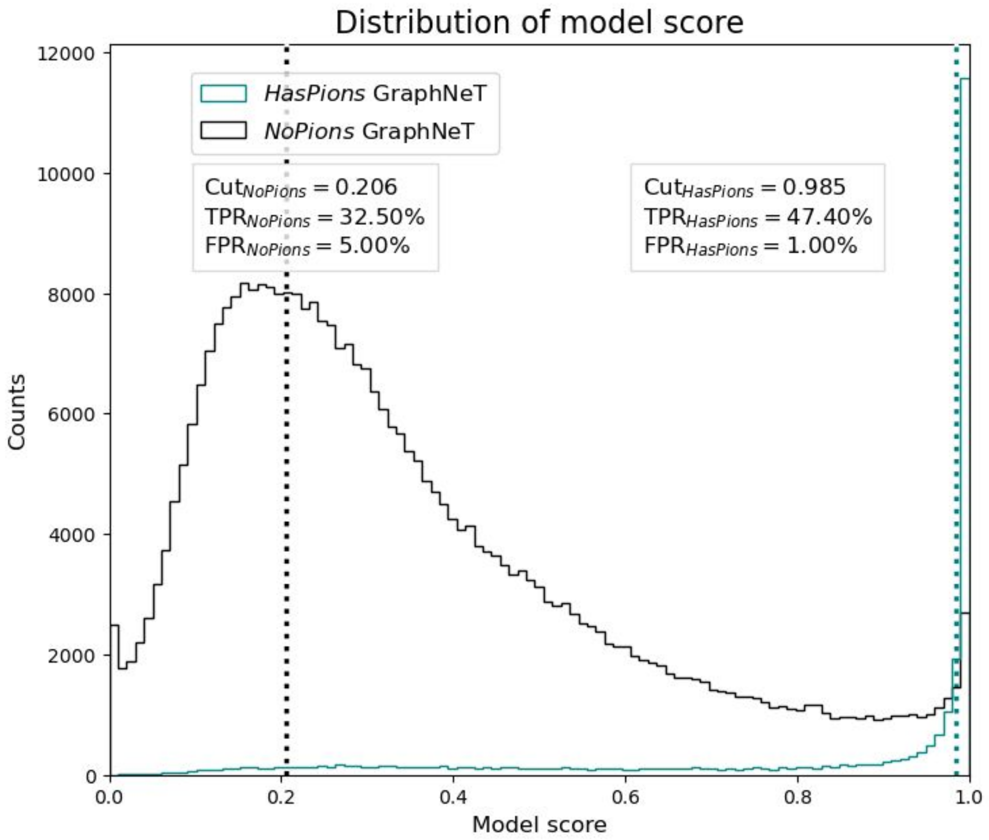
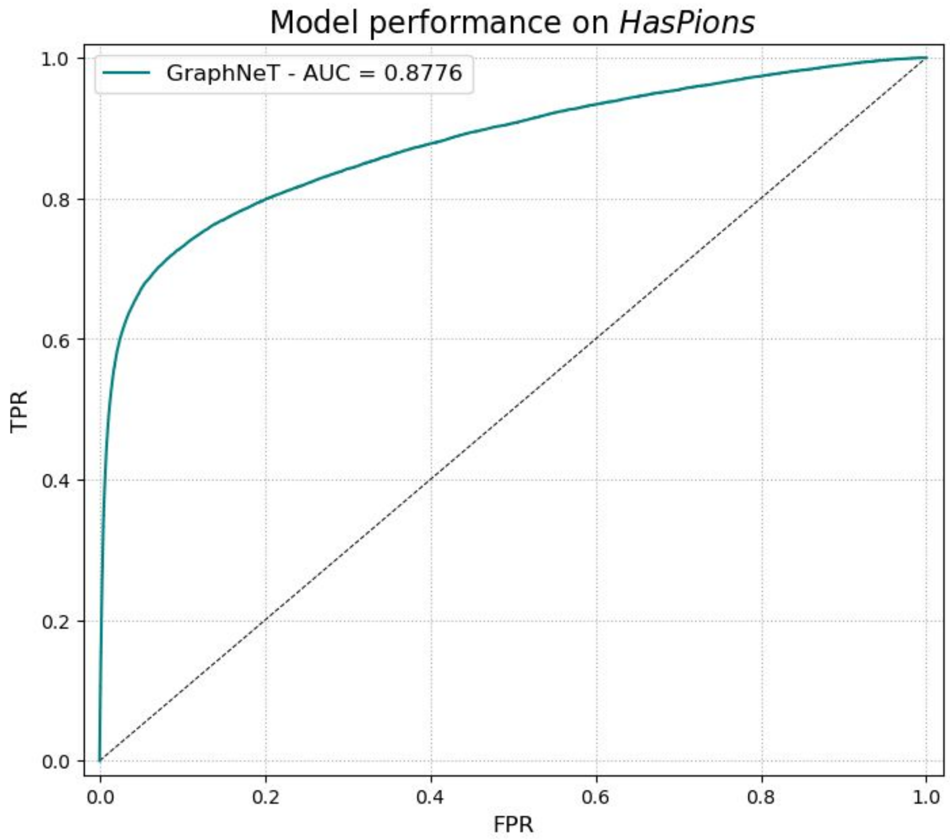
# Pion production classifier

## Neutrino event simulations - with data cut

GraphNeT Performance




ROC Curve

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# Factors impacting performance
## Neutrino event simulations - with data cut

The GNN is able to identify the characteristics of both

- Events with two Cherenkov rings due to decaying muons
- Events with pion production

Filtering these types of events and treating them separately could be beneficial



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# Thank you!

# Additional Slides

# Event Classification - Performance Measures

**The neutrino beam will consist of > 98 % muon neutrinos (at the near detector)**

- We can allow more electron neutrino events to be misidentified and still have a pure muon neutrino event sample

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**False positive rate (FPR) is the ratio of undesired events are identified as the desired type**

- Example: The **FPR** for **electron neutrino** events is the number of **muon neutrino** events identified as **electron neutrinos**, divided by the total number of **muon neutrino** events

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We select samples that yield FPRs of:

- **1 % for muon neutrinos**
- **0.1 % for electron neutrinos**



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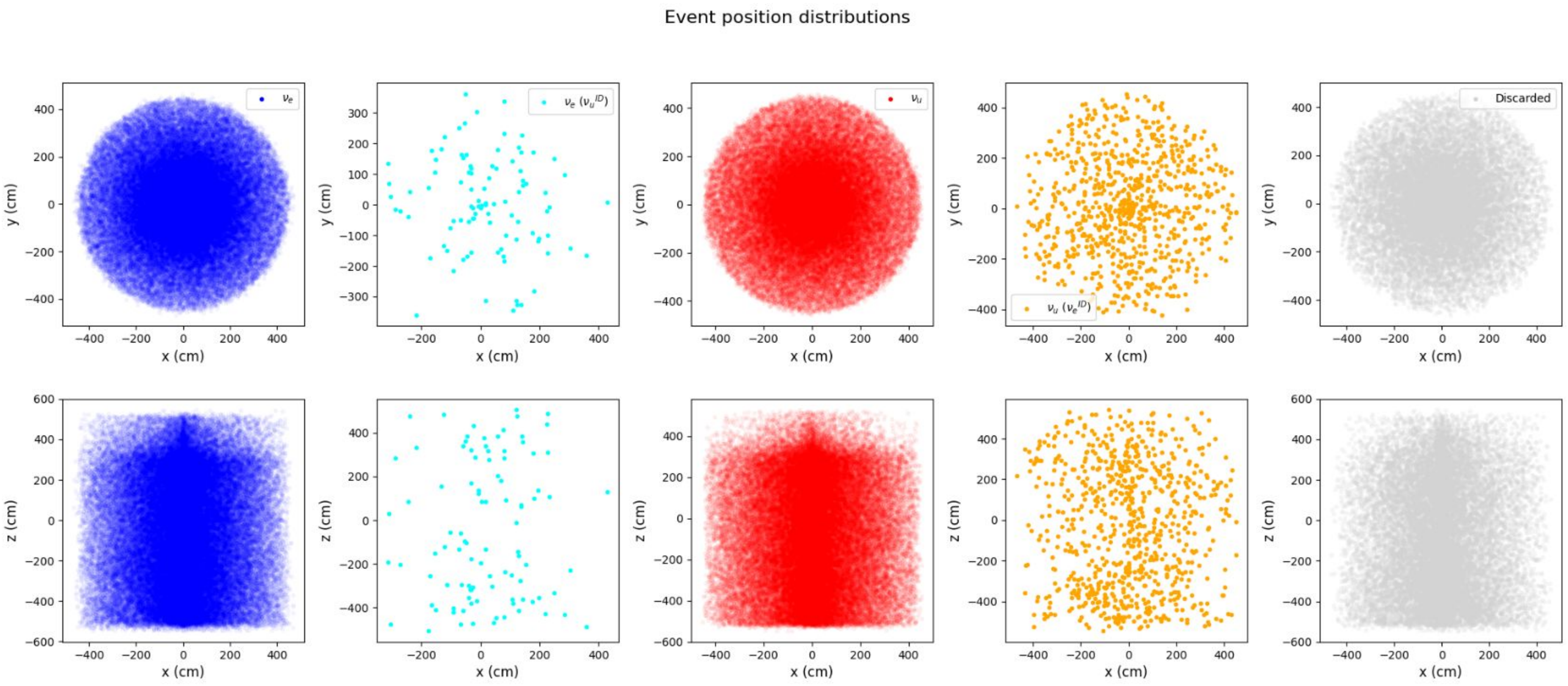
# Relation between interaction position and reconstruction performance

## Neutrino event simulations - with data cut



# Relation between interaction position and reconstruction performance

## Neutrino event simulations - with data cut