Co-funded by
the European Union

Classification of ESSnuSB WC Near Detector Events Using Graph Neural Networks

ν_μ- and ν_e-events for neutrino oscillation studies

Kaare Endrup Iversen - Lund University

Outline

- Current Framework and Motivation
- GNN Implementation

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

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Current Framework and Motivation

Current Framework

Charged Lepton Simulations

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

Neutrino Interaction Simulations

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

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LLH Based Reconstruction

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

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Current Framework

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LLH Based Reconstruction

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Challenges

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

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 provides a way to cross check and find systematic errors

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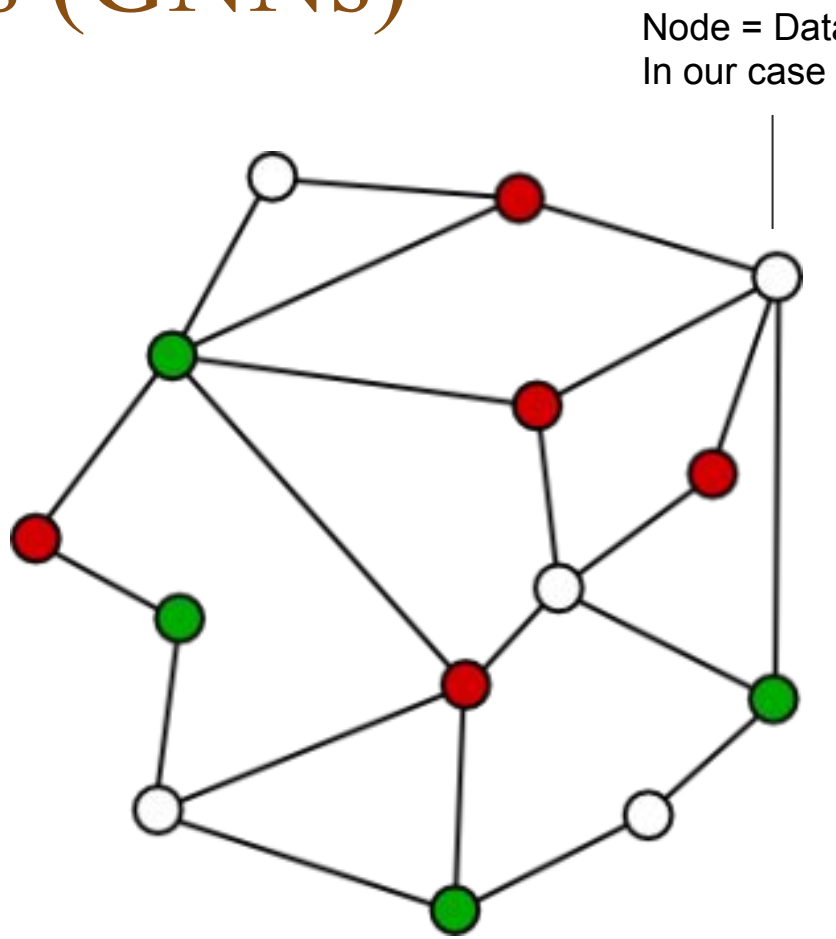
GNN Implementation

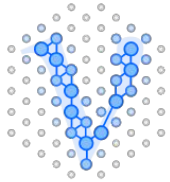
Graph Neural Networks (GNNs)

- 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

GraphNeT: Graph neural networks for neutrino telescope event reconstruction (Søgaard et al)

Pytorch Geometric - GNN framework for Pytorch

Model architecture: **DynEdge**

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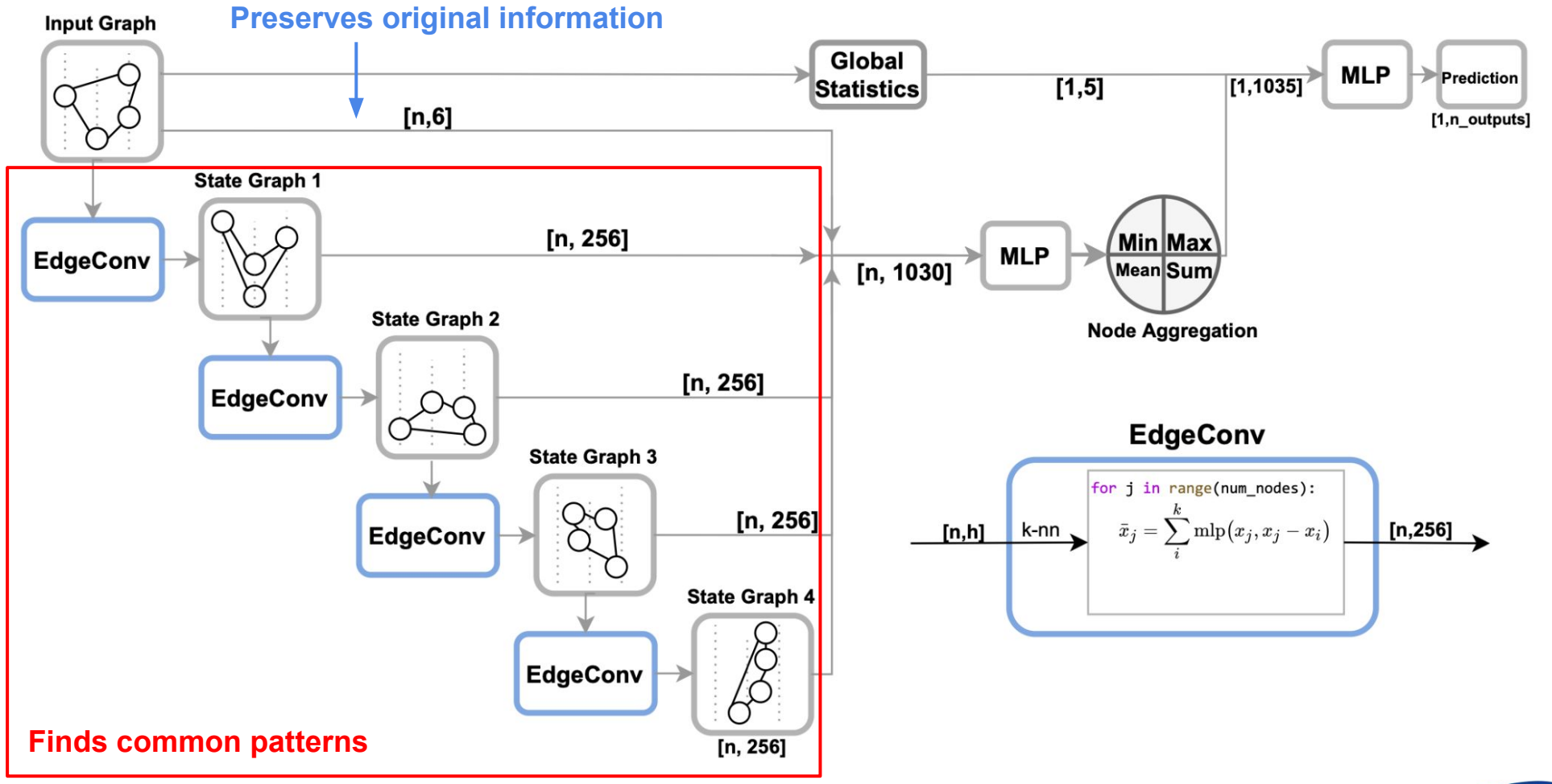
Graph Neural Networks - Architecture



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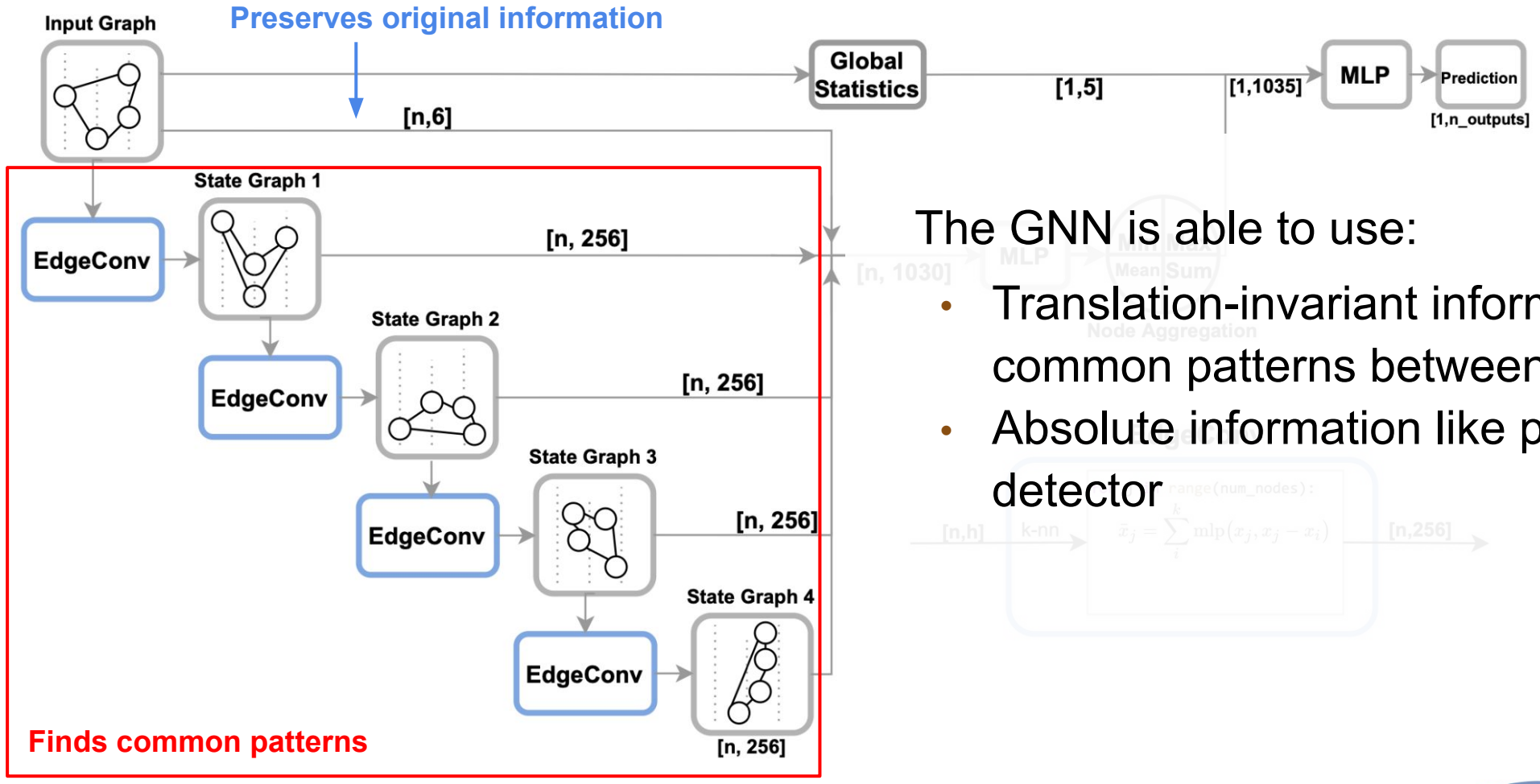
Graph Neural Networks - Architecture



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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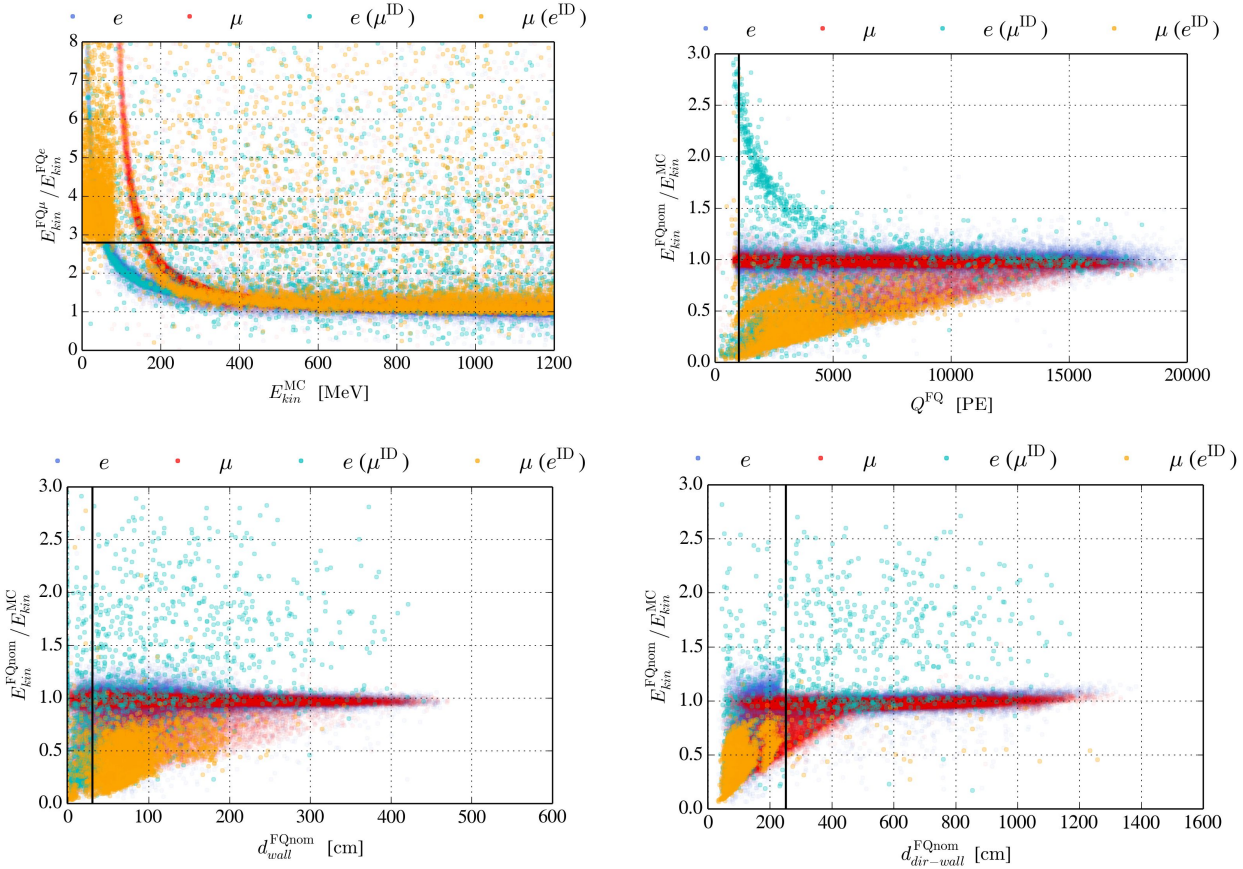
Data Processing and Performance Measures

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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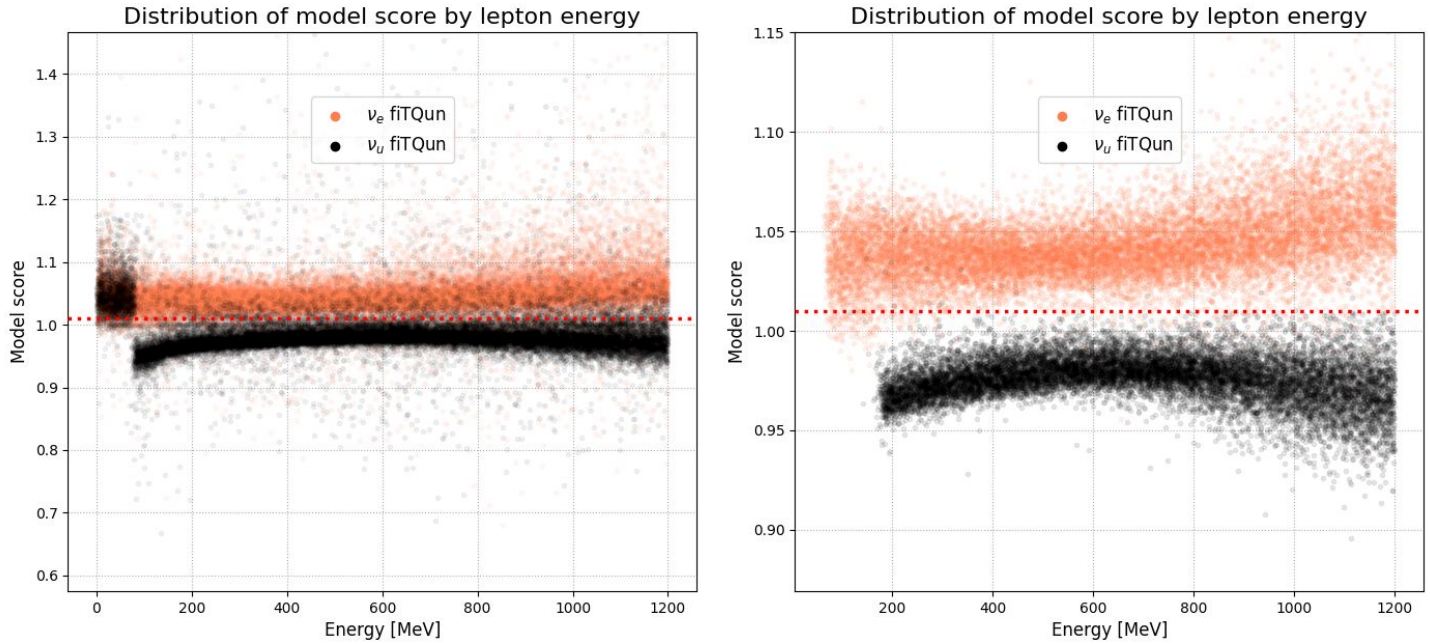

Event Classification - Performance Measures

False positive rate

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

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

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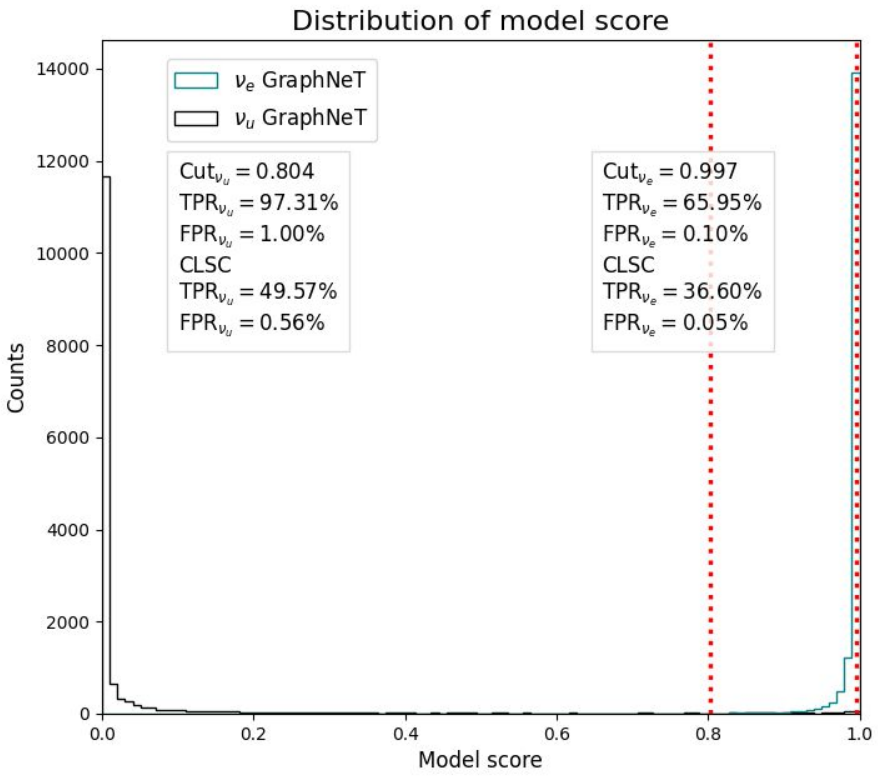
Charged Lepton Performance

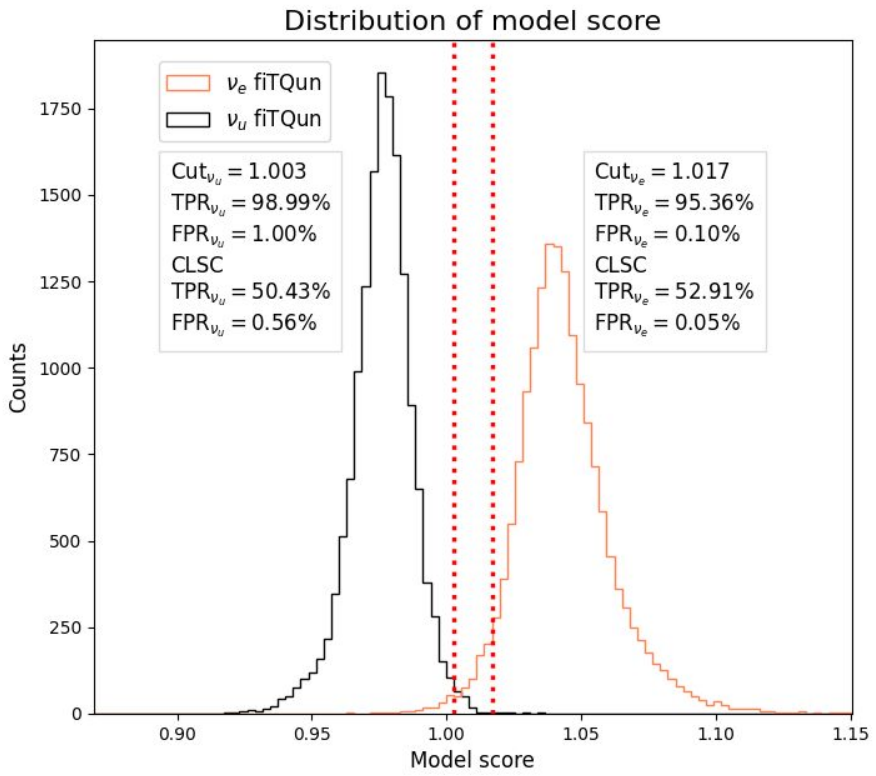
Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

GraphNeT performance



fiTQun performance



Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

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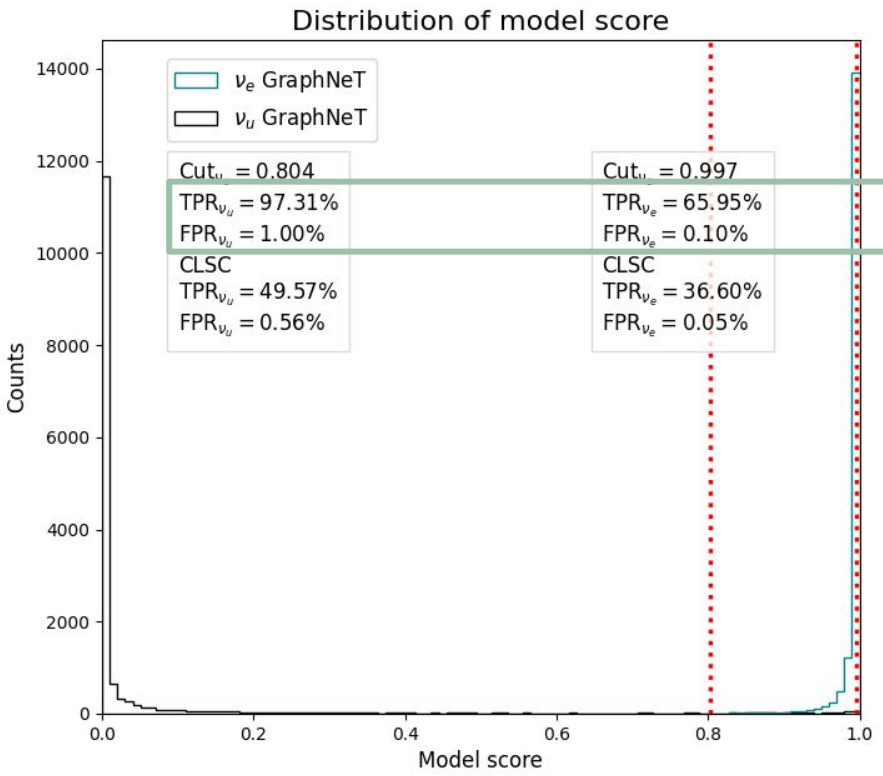
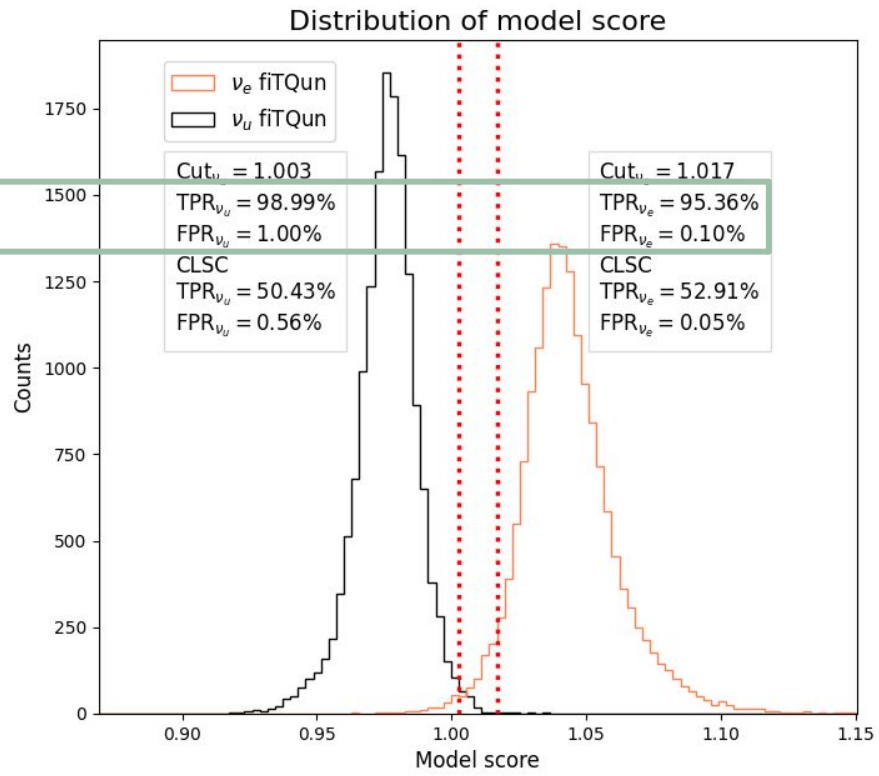


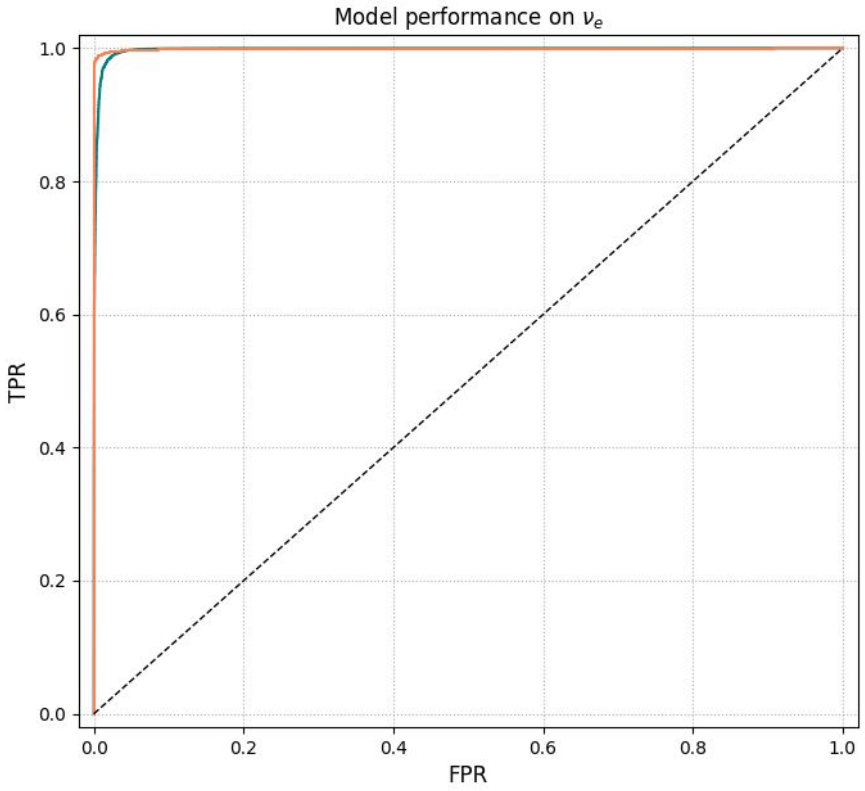
fiTQun performance



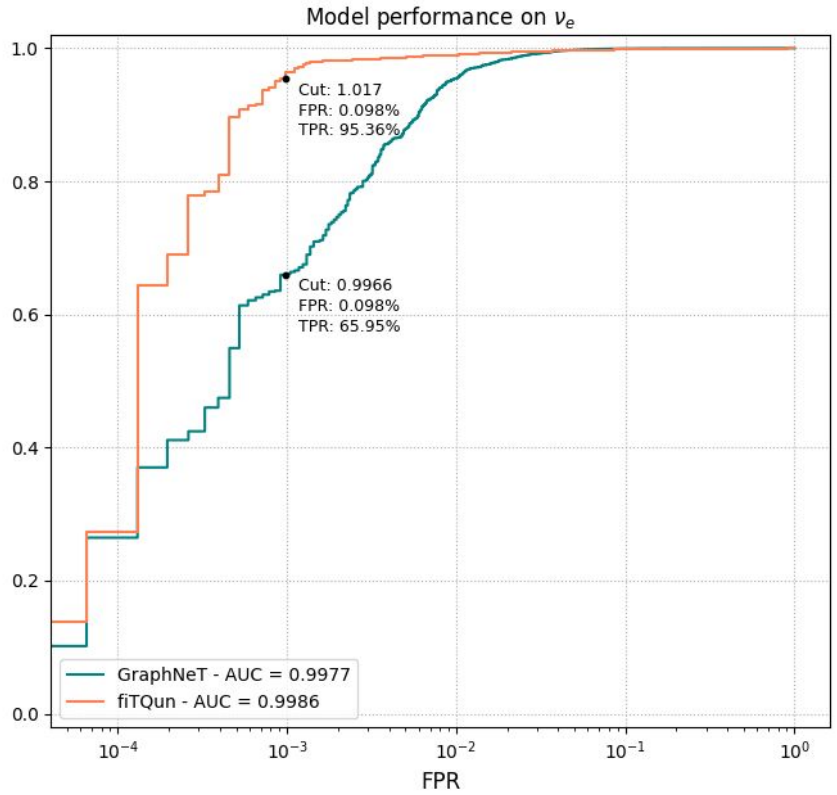
Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations (electron neutrino events)

ROC Curve



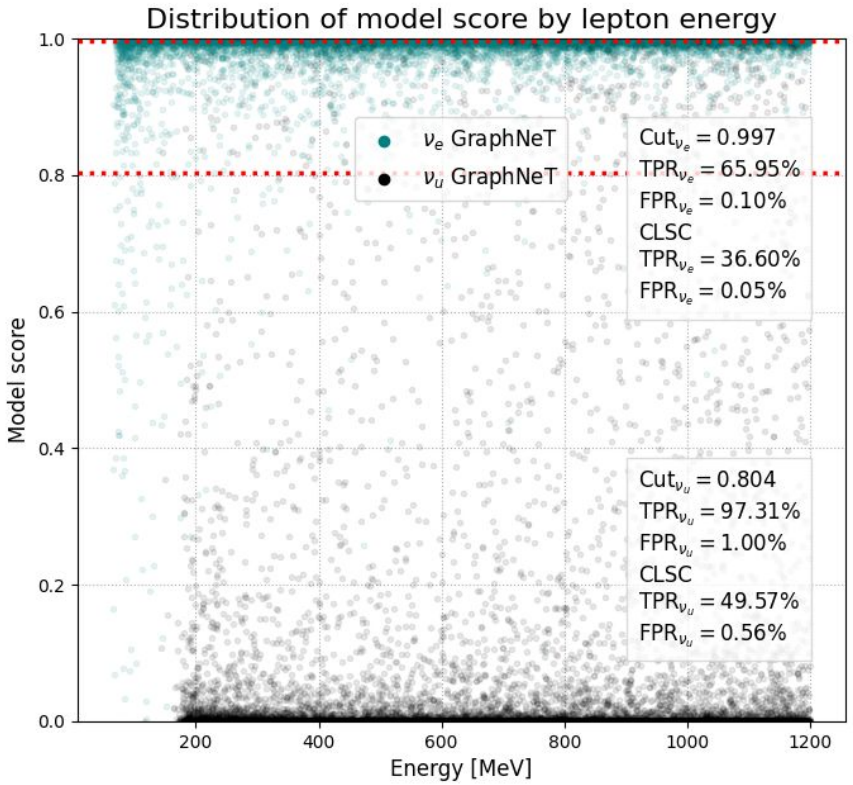
ROC Curve with logarithmic x axis



Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

GraphNeT performance



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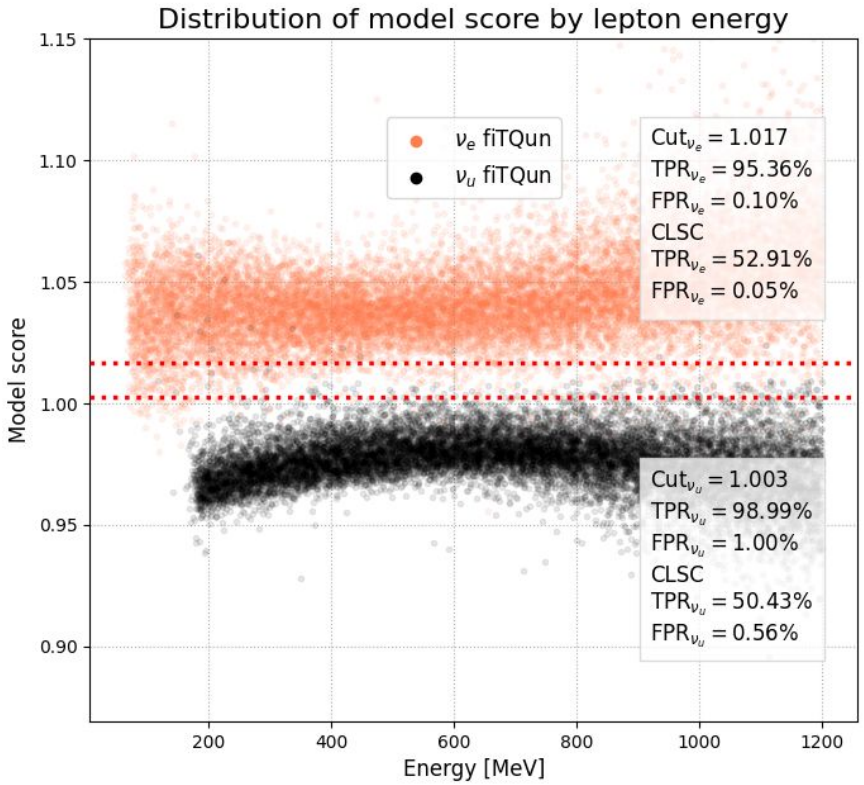

Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

- 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-bangs etc.)

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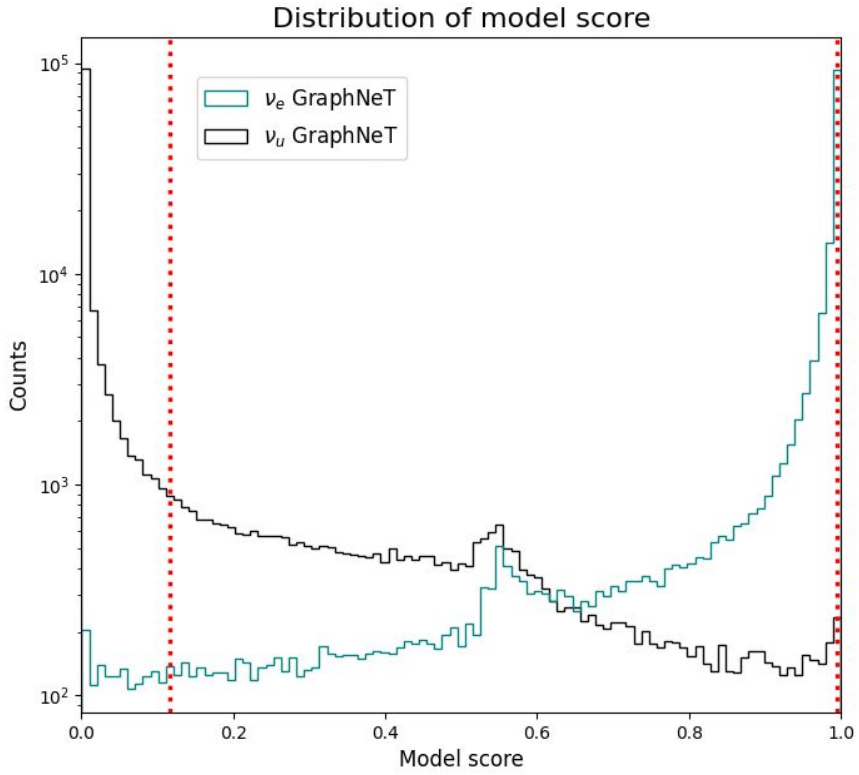
Neutrino Event Performance

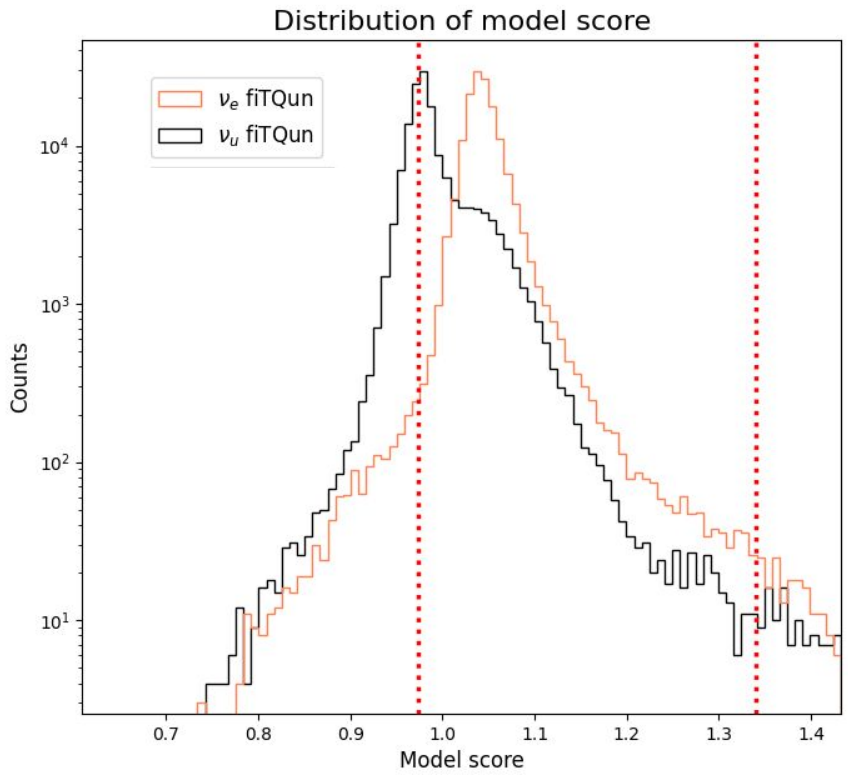
Event Classification - GraphNeT vs. fiTQun

Neutrino event simulations - without data cut

GraphNeT performance with logarithmic x axis



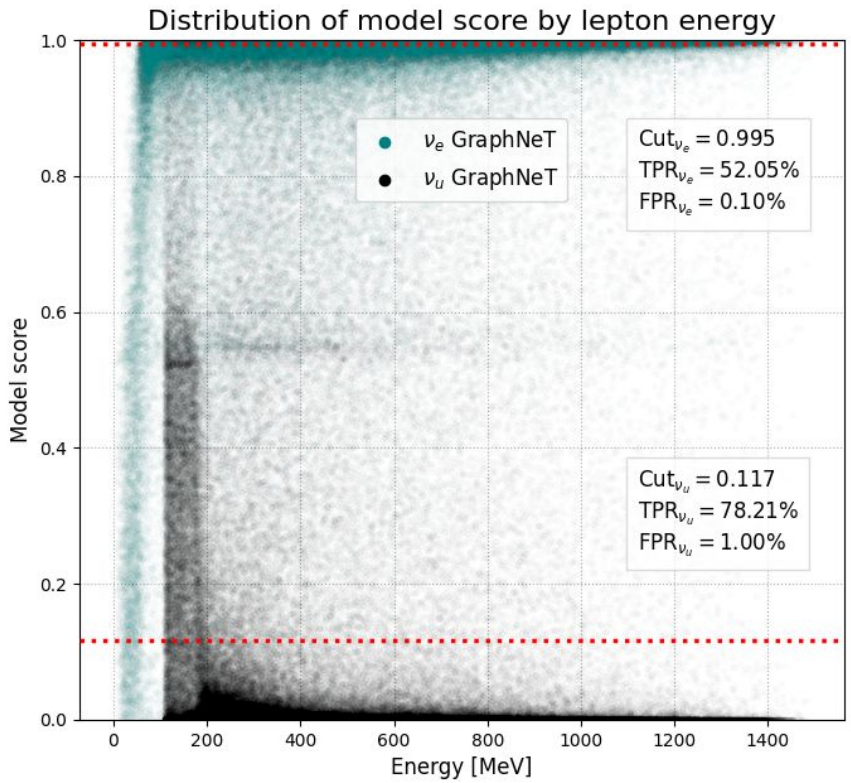
fiTQun performance with logarithmic x axis



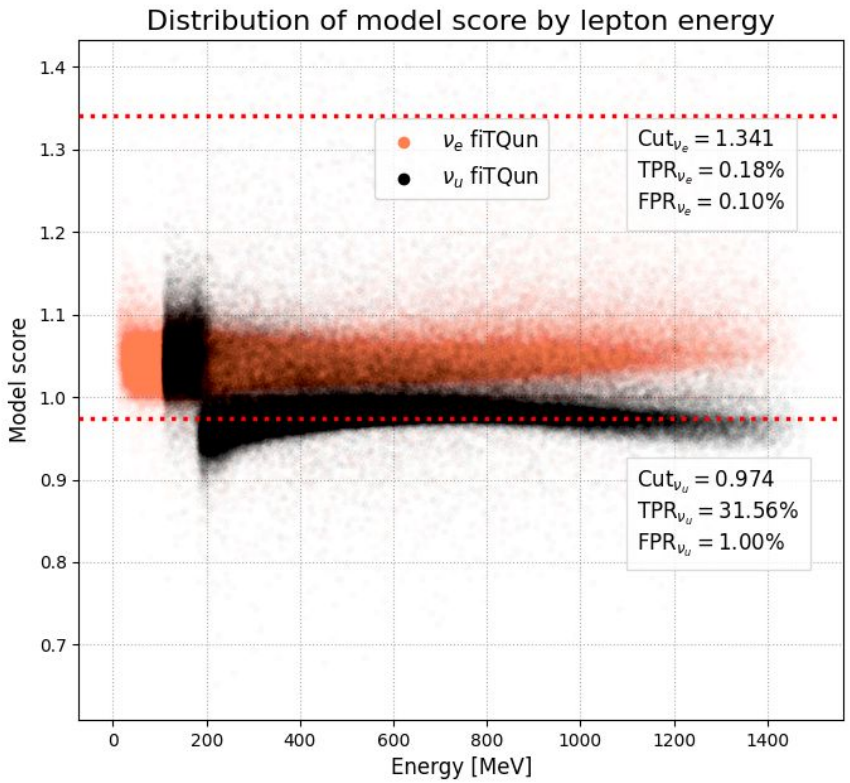
Event Classification - GraphNeT vs. fiTQun

Neutrino event simulations - without data cut

GraphNeT performance



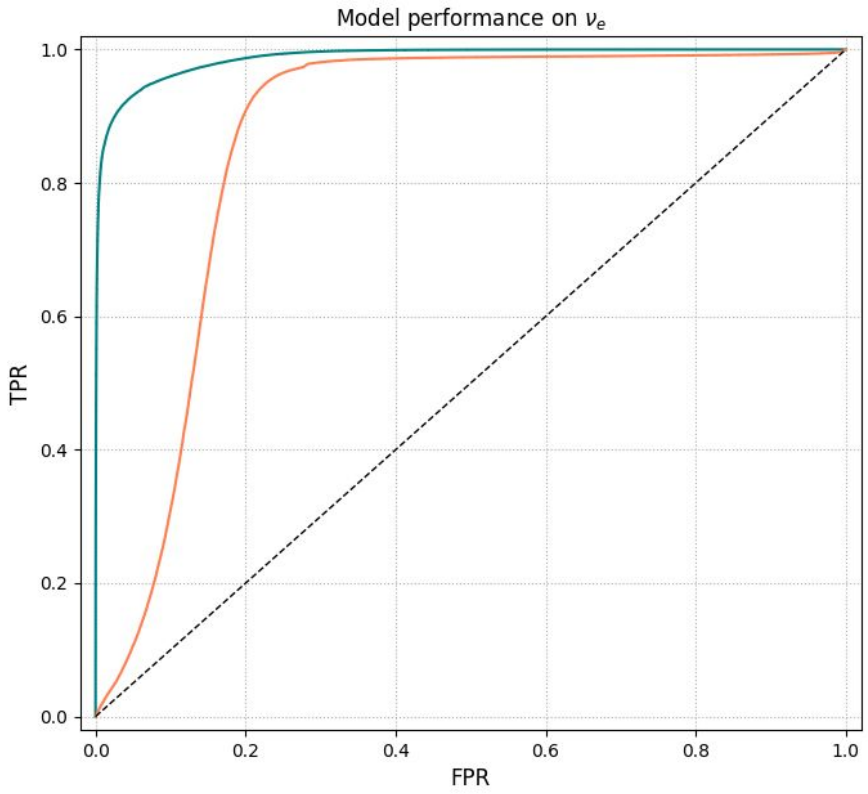
fiTQun performance



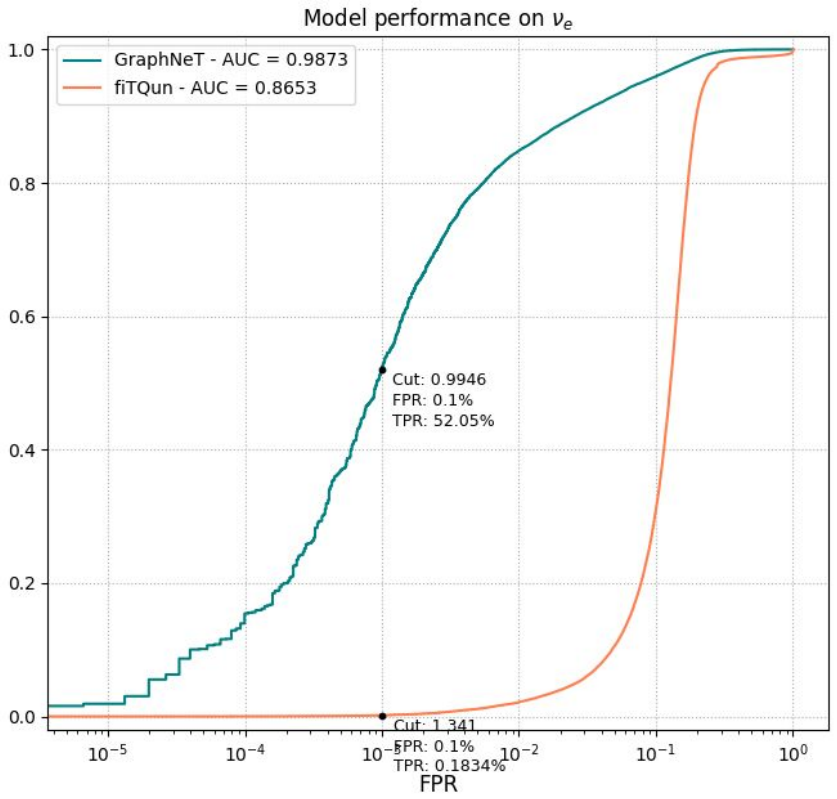
Event Classification - GraphNeT vs. fiTQun

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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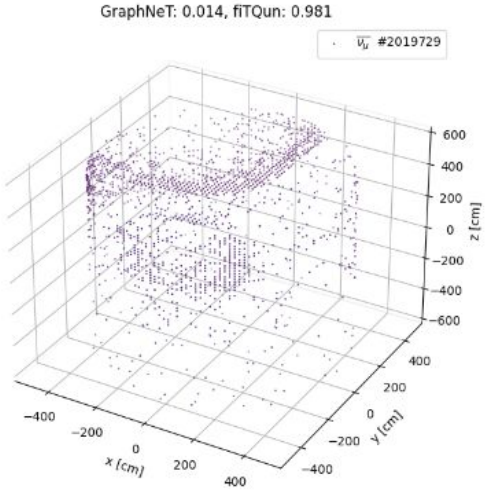
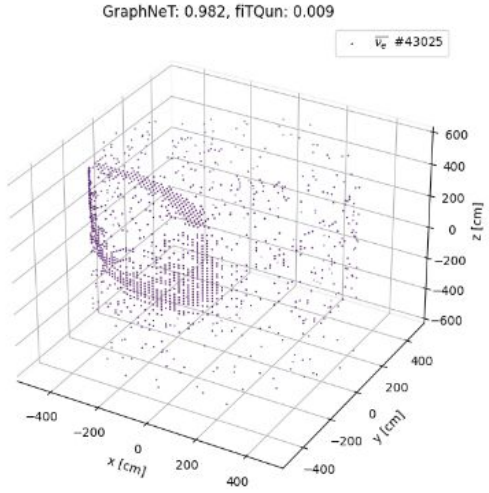
Performance Investigations

Factors impacting performance - multiple charged lepton signatures

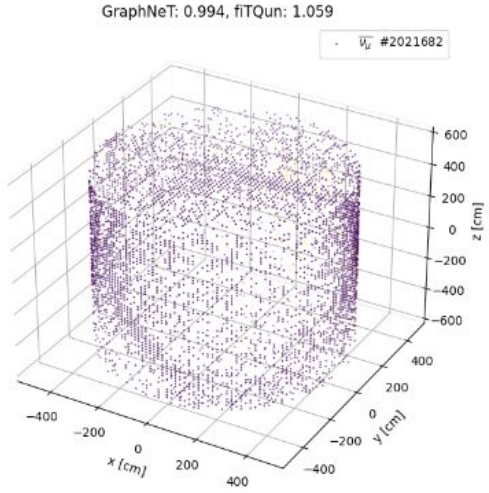
Neutrino event simulations - **with** data cut



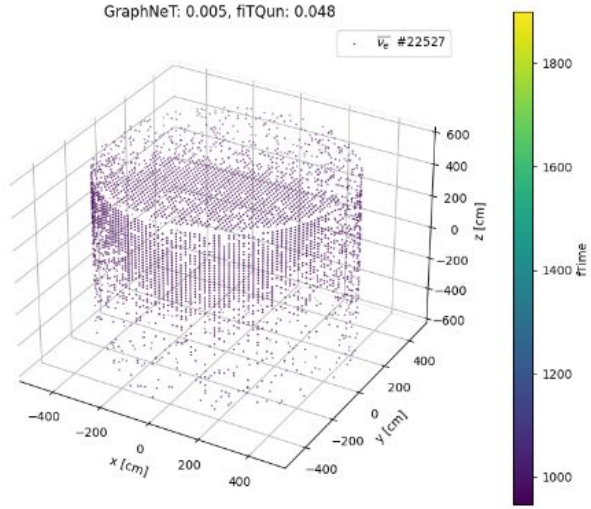
GNN > fiTQun



fiTQun > GNN



Both wrong



Both correct

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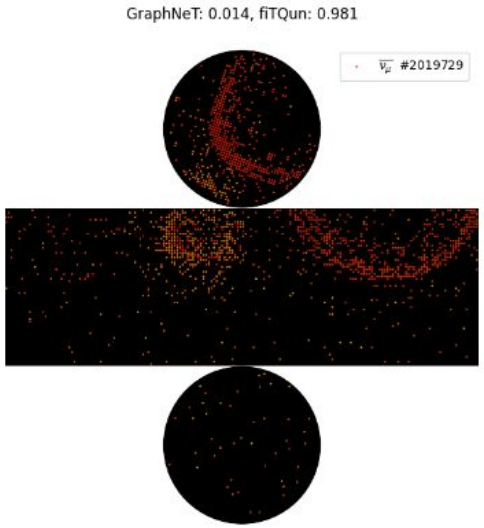
Factors impacting performance - multiple charged lepton signatures

Neutrino event simulations - with data cut



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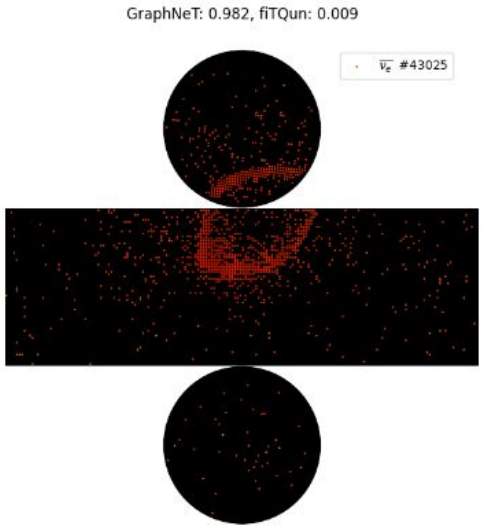
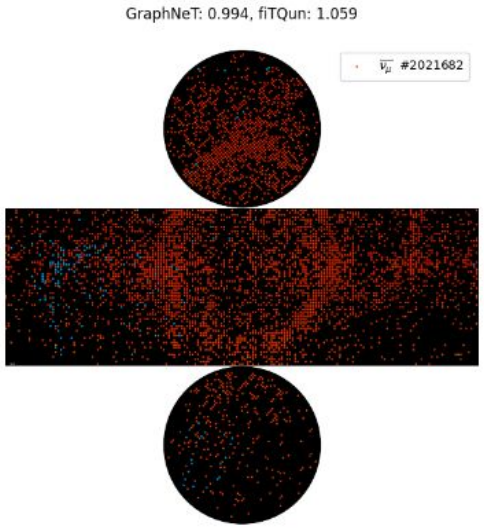


fiTQun > GNN



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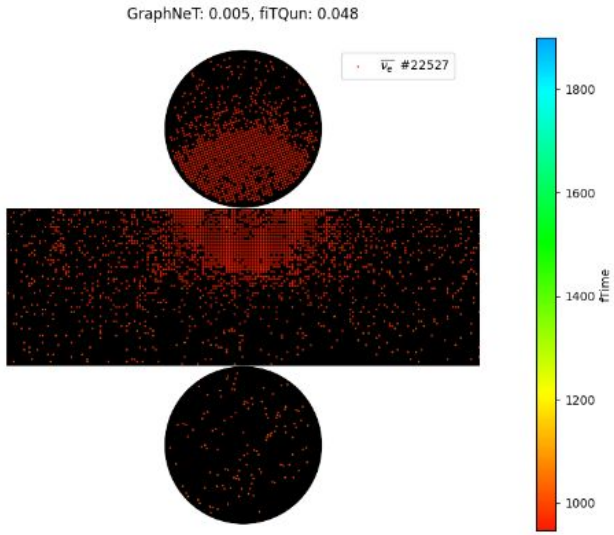
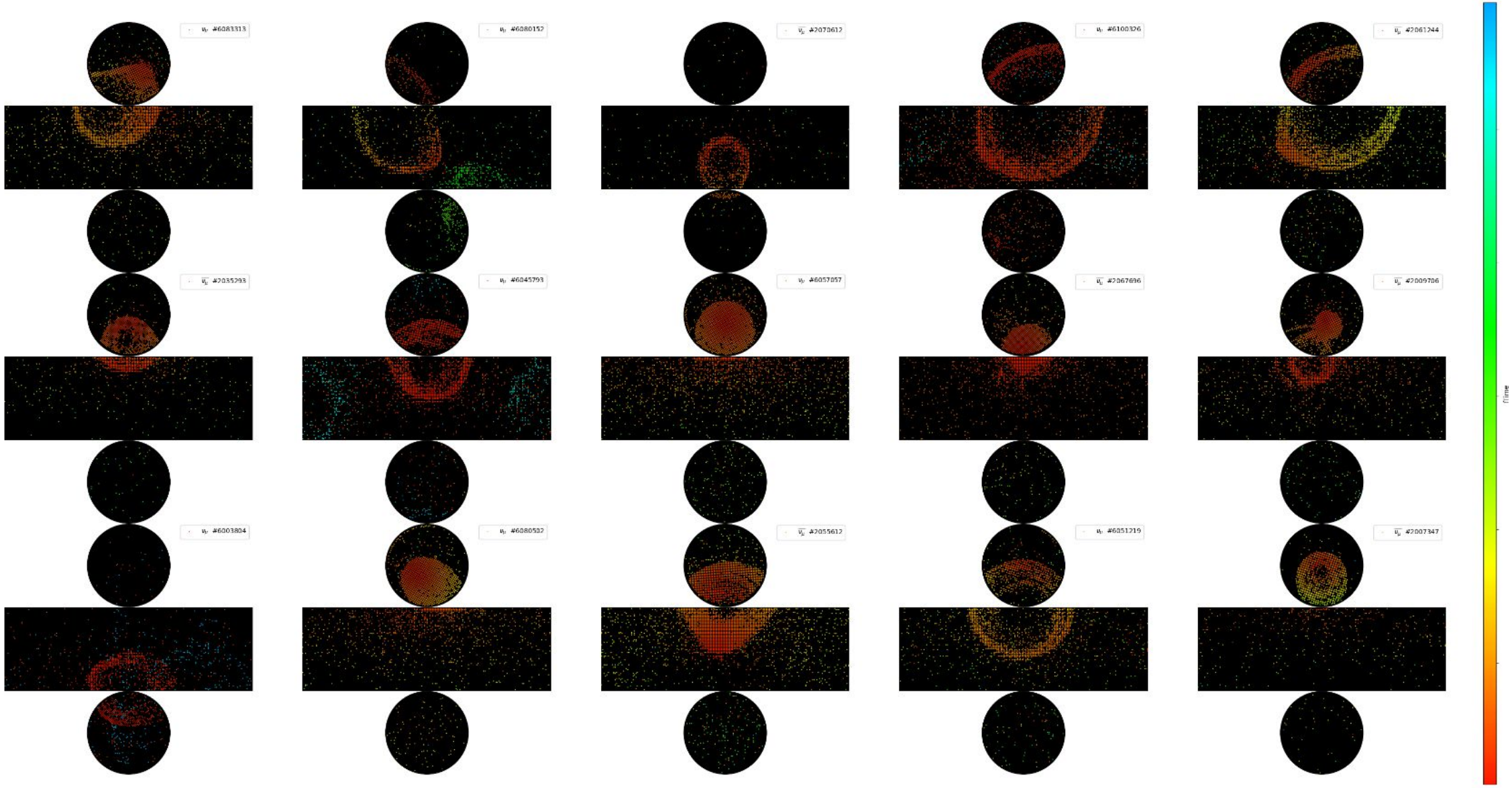


Both correct

Event for which GraphNeT performs significantly better than fiTQun



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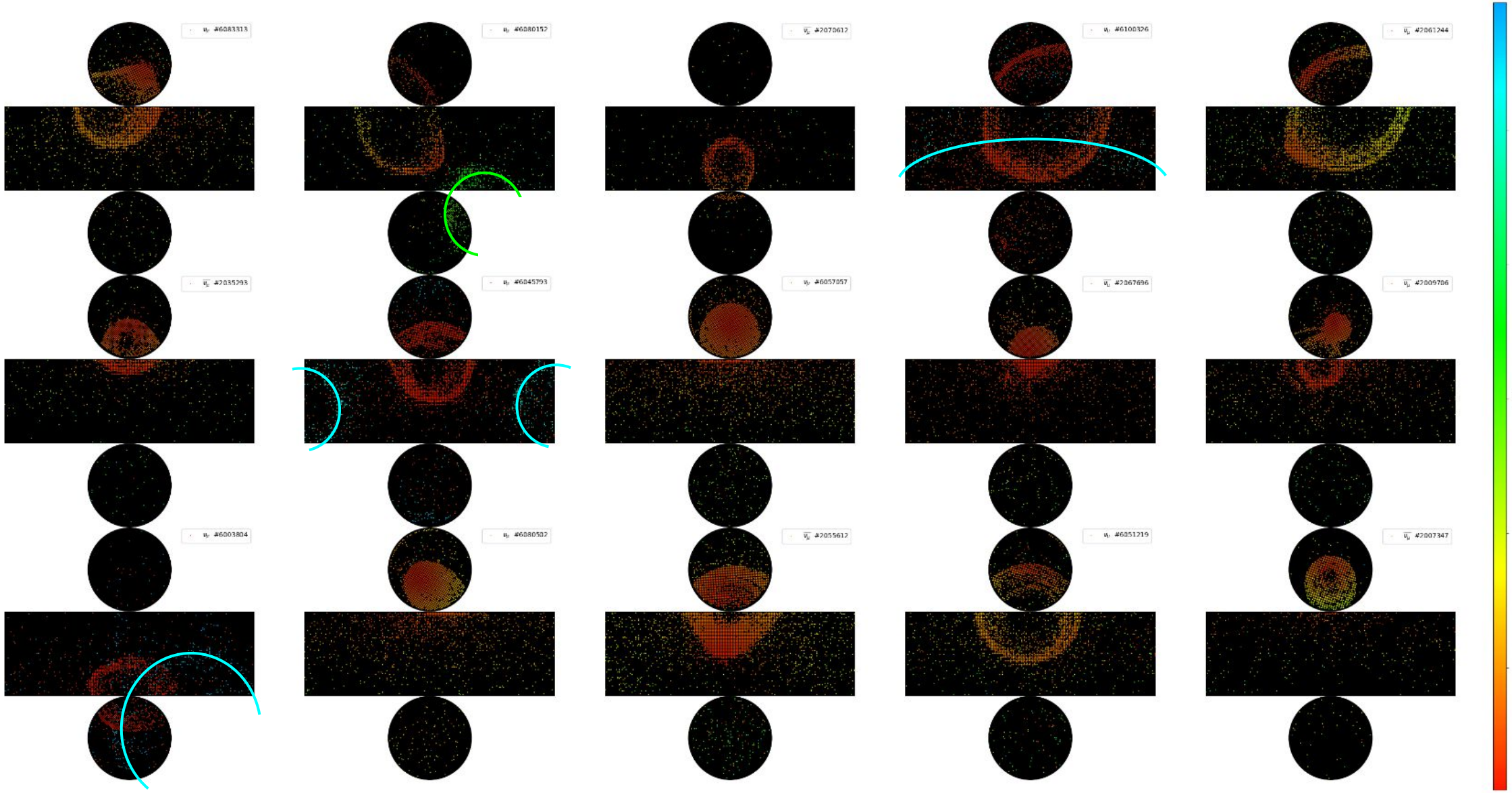
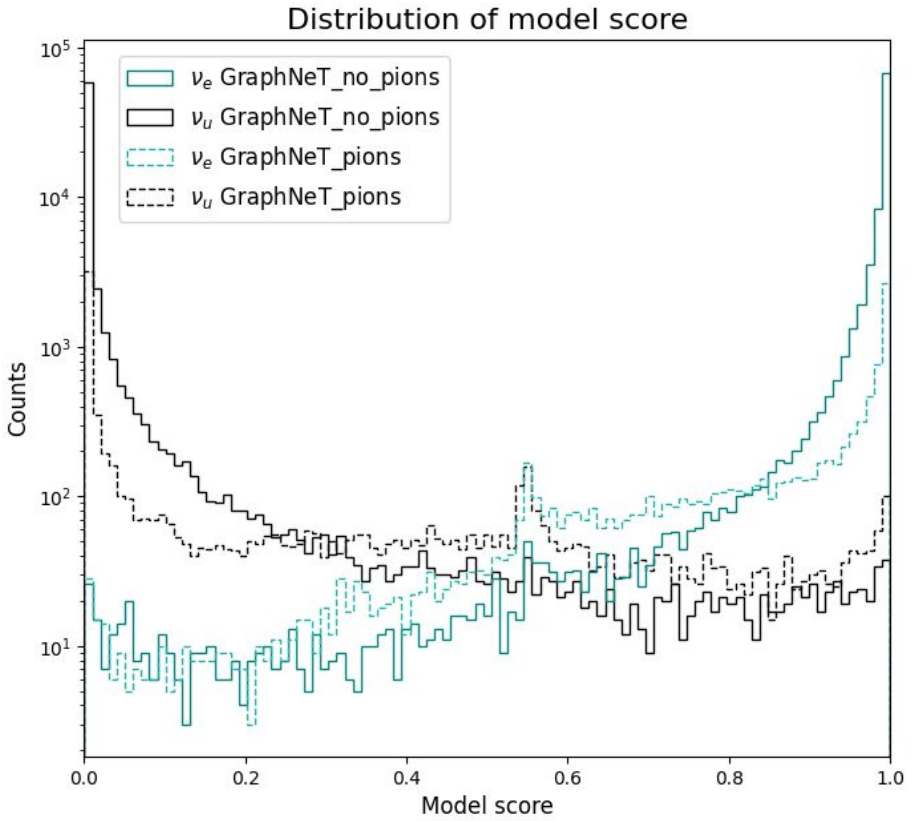


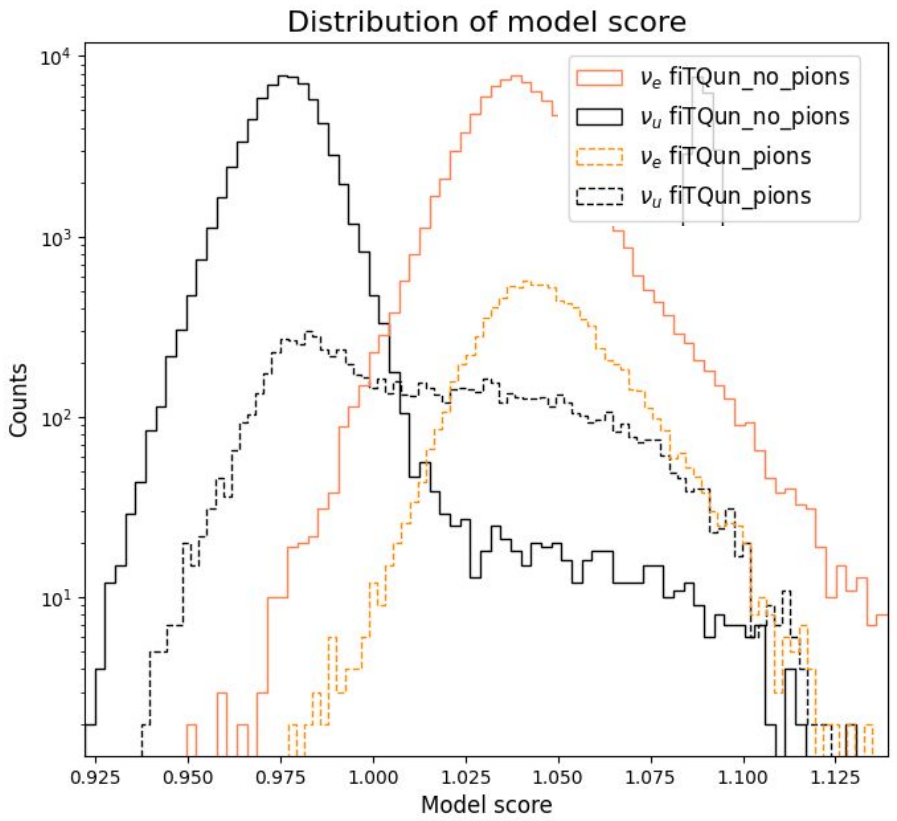
Factors impacting performance - pion creation

Neutrino event simulations - with data cut

GraphNeT performance with logarithmic x axis



fiTQun performance with logarithmic x axis



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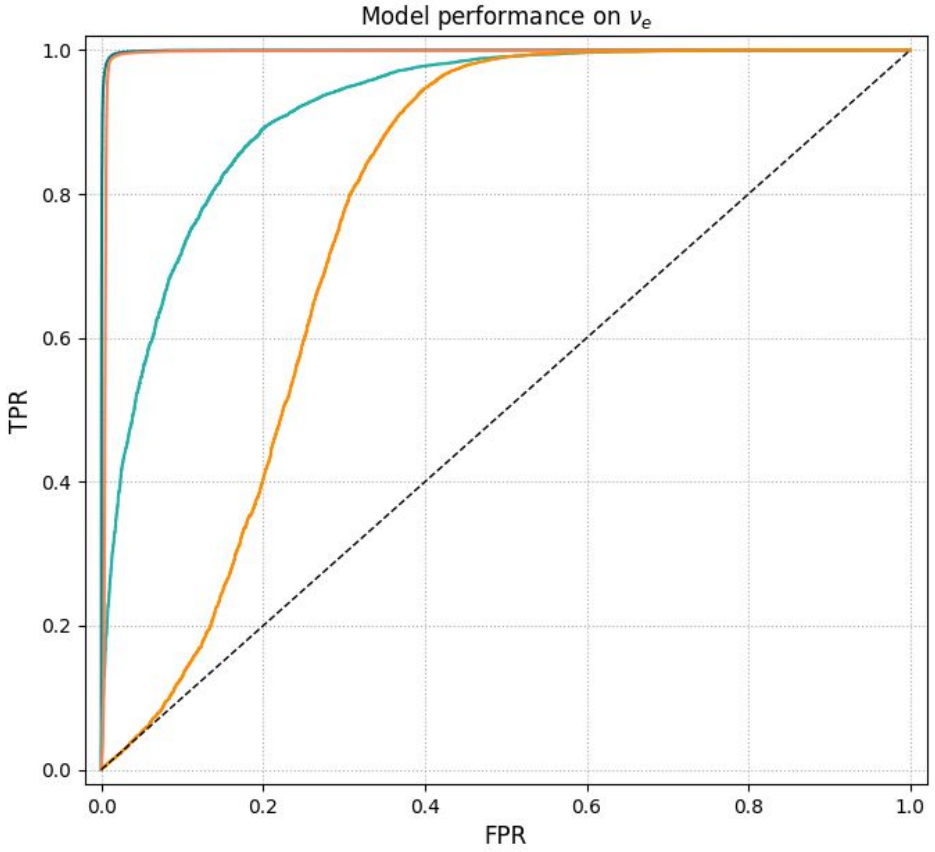
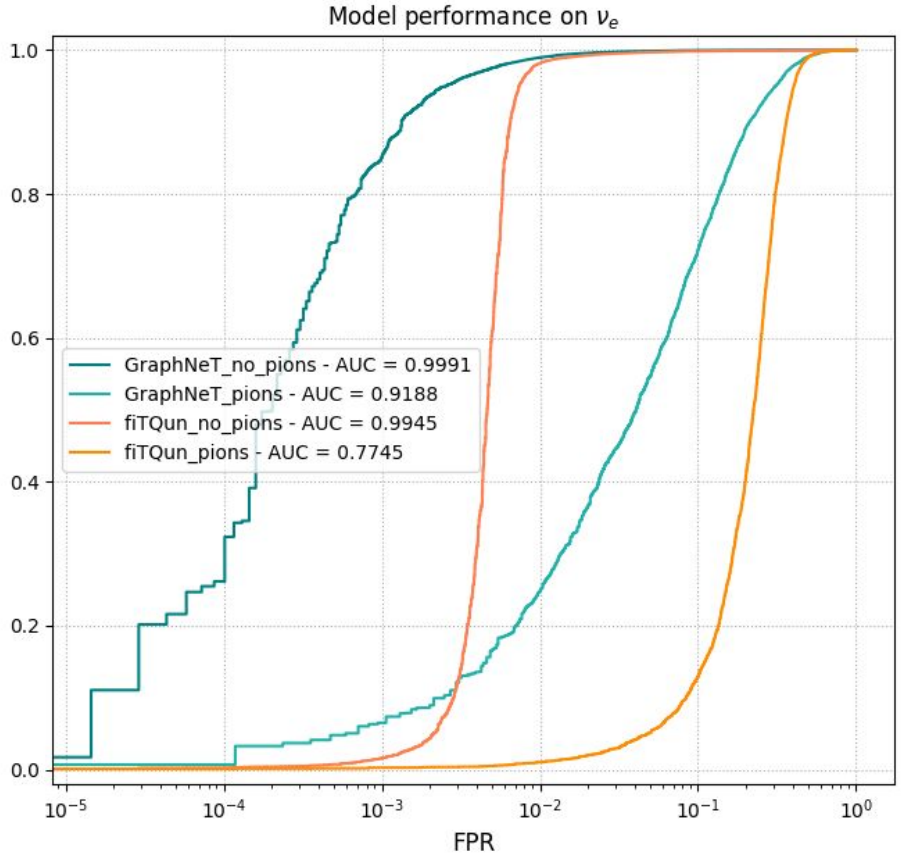
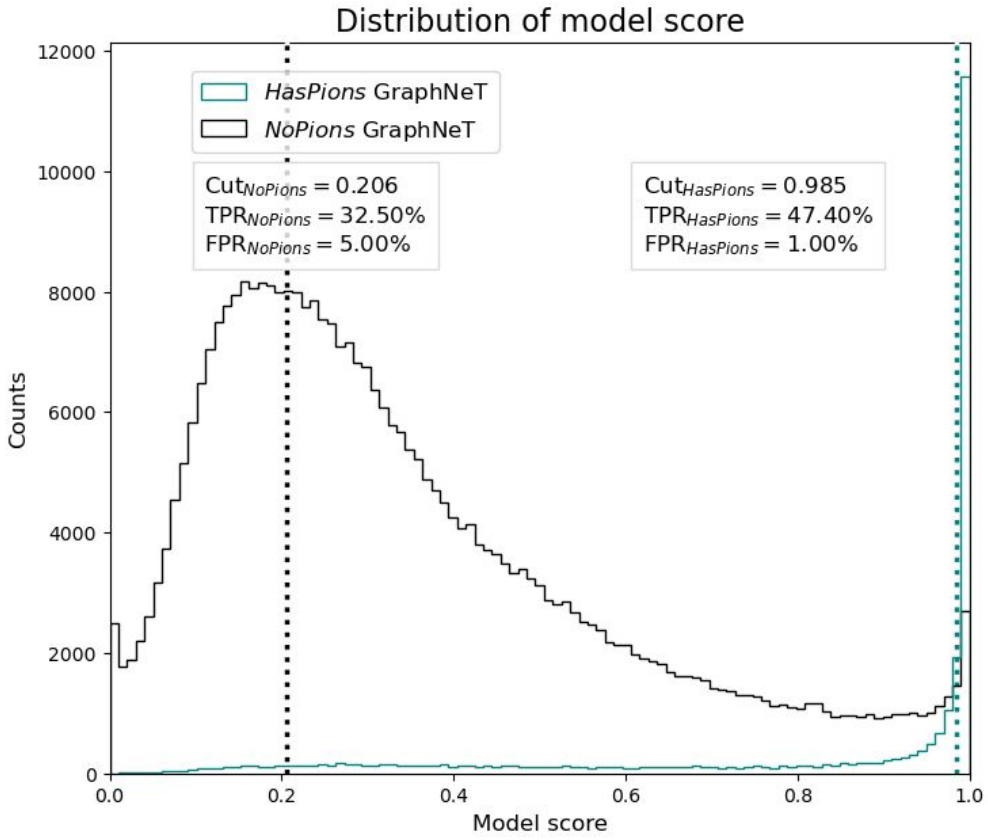


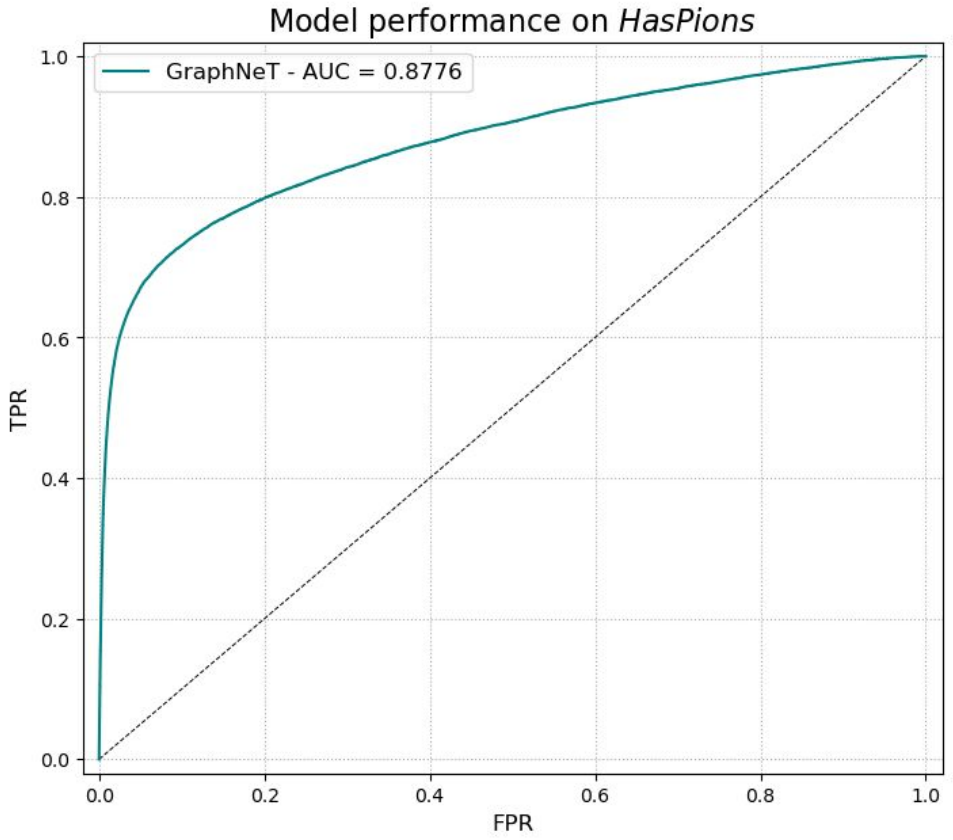
ROC Curve with logarithmic x axis



Pion production classifier

Neutrino event simulations - with data cut





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

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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Event Classification - Performance Measures

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We select samples that yield FPRs of:

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

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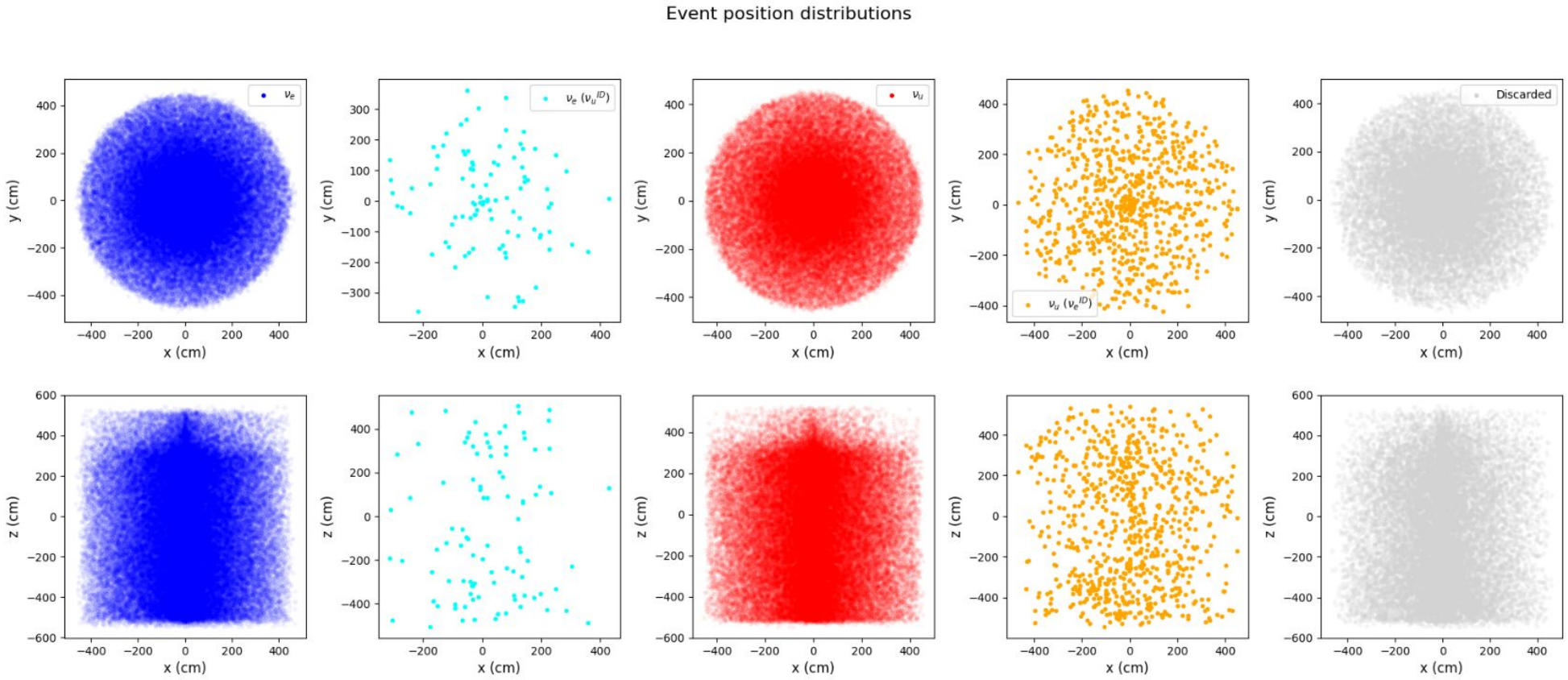
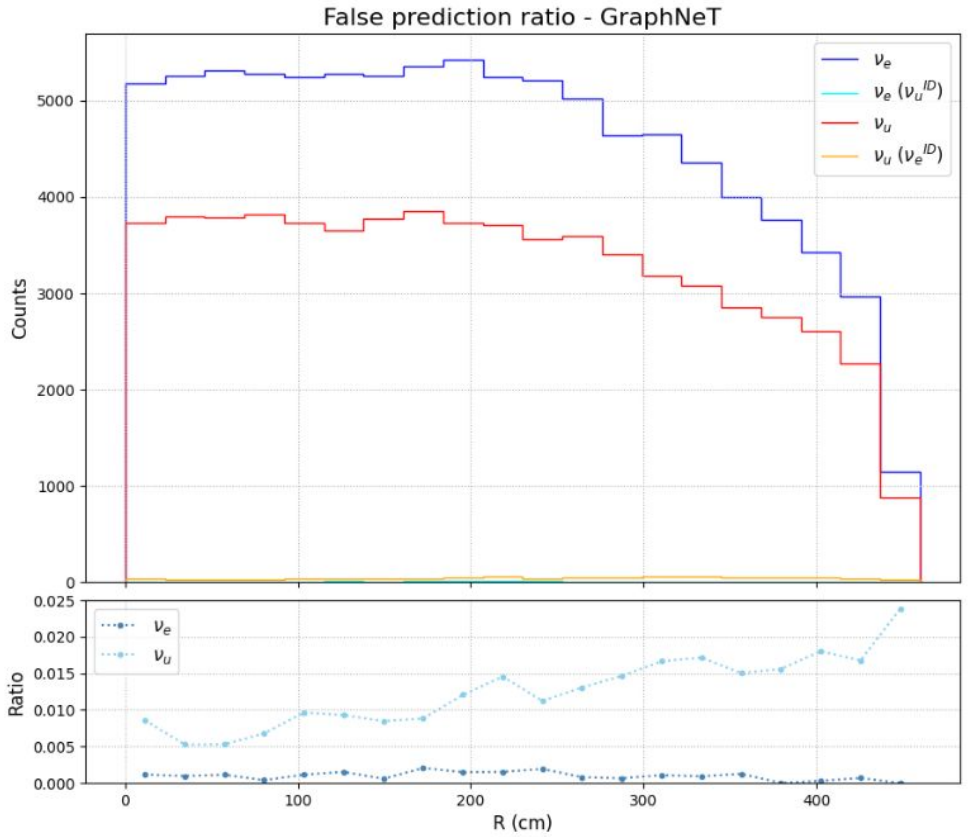
Relation between interaction position and reconstruction performance

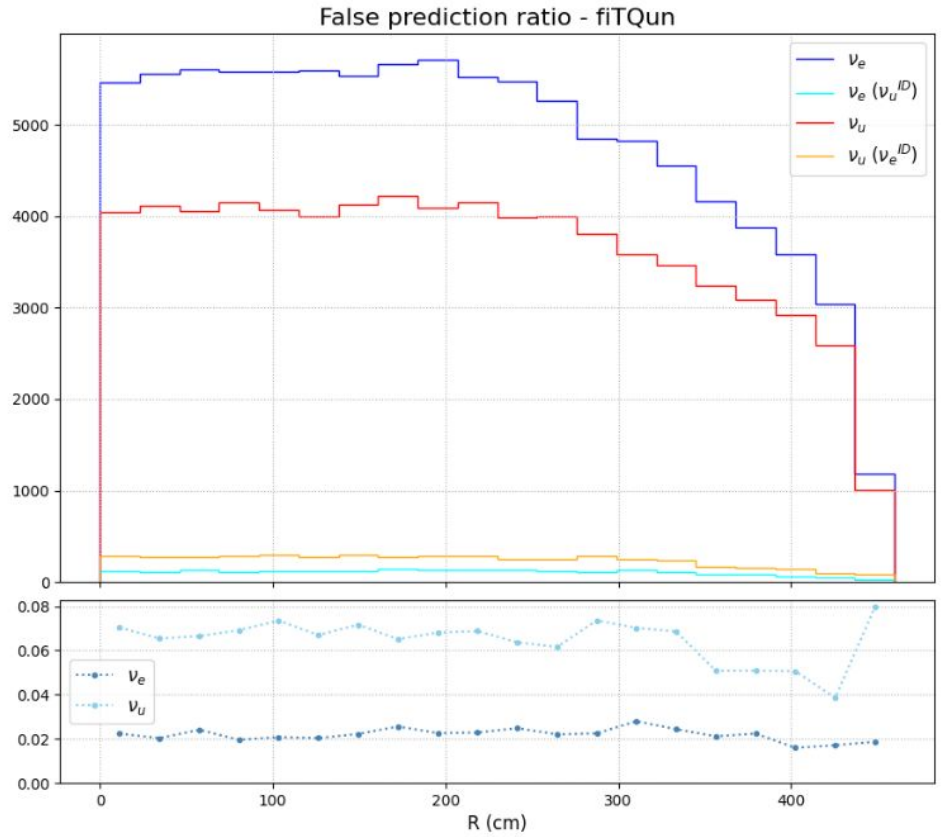
Neutrino event simulations - with data cut



Relation between interaction position and reconstruction performance

Neutrino event simulations - with data cut





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