Event Classification for the ESSnuSB+ Using GNNs

ν_μ- and ν_e-events for neutrino oscillation studies

Outline

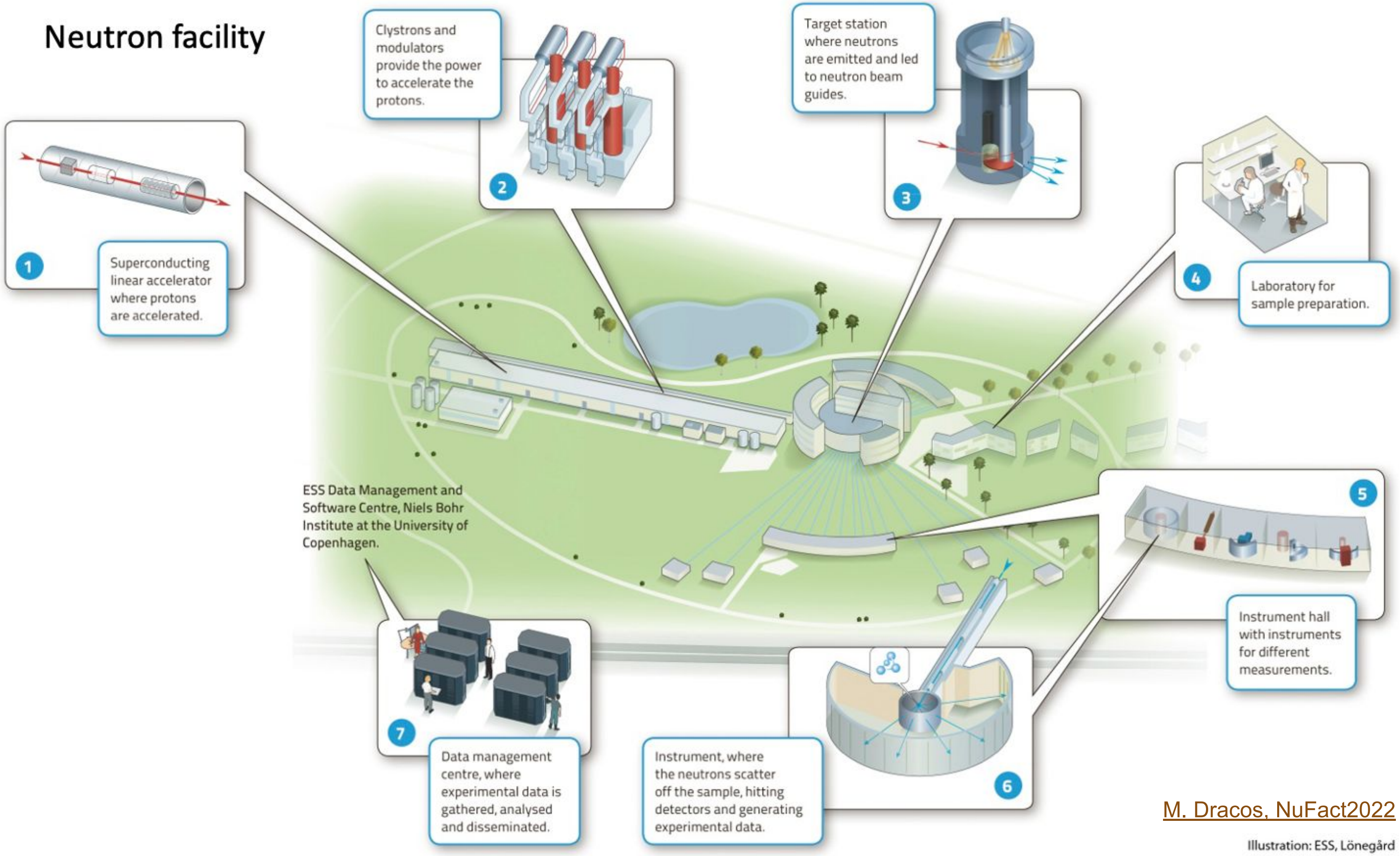
- ESSnuSB Detector Overview
- Current Framework and Challenges
- GNN Implementation

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

- Future Investigations

ESSnuSB Detector Overview

The European Spallation Source



M. Dracos, NuFact2022

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ESSnuSB - Physics goal

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

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

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

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

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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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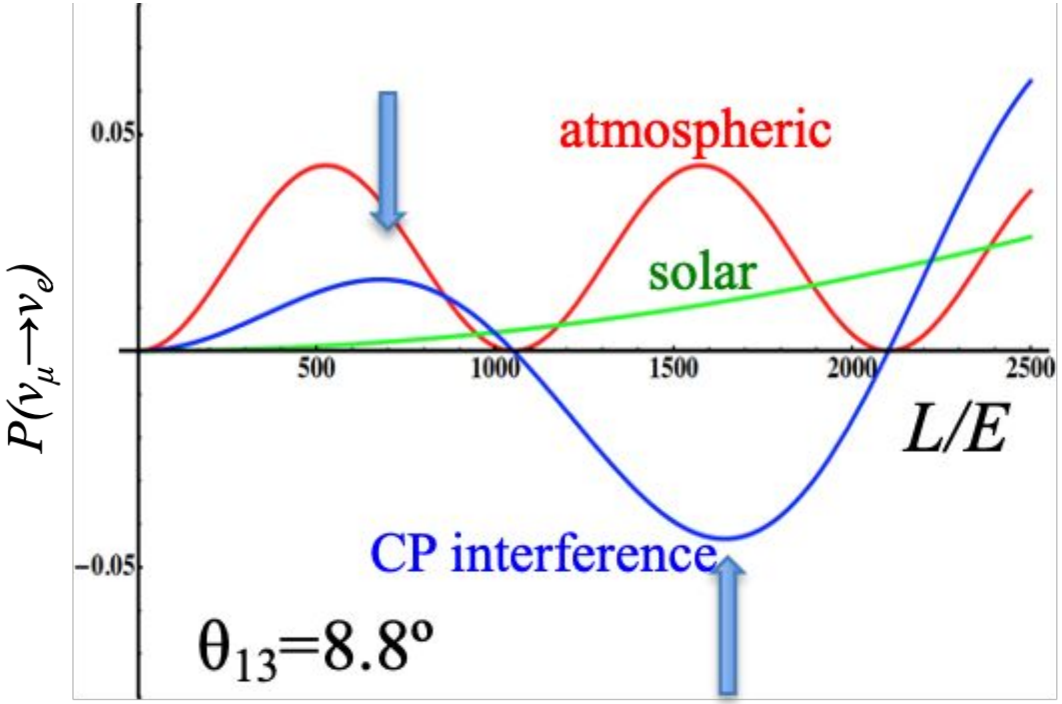
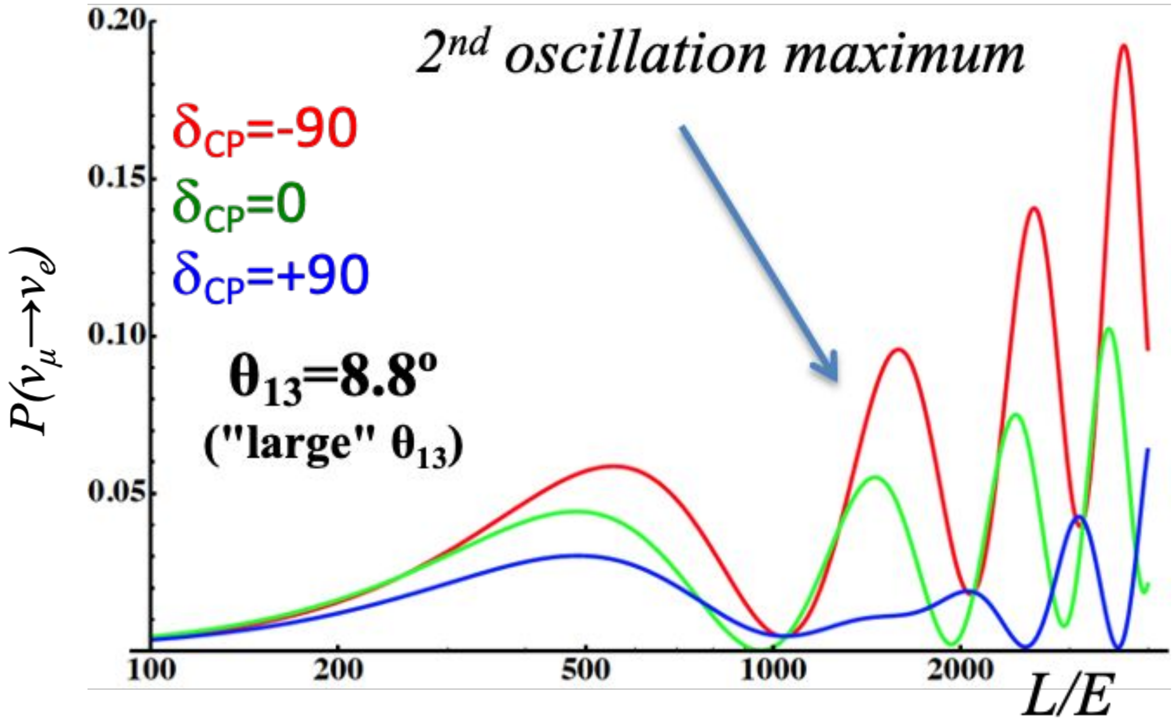
ESSnuSB - Physics goal





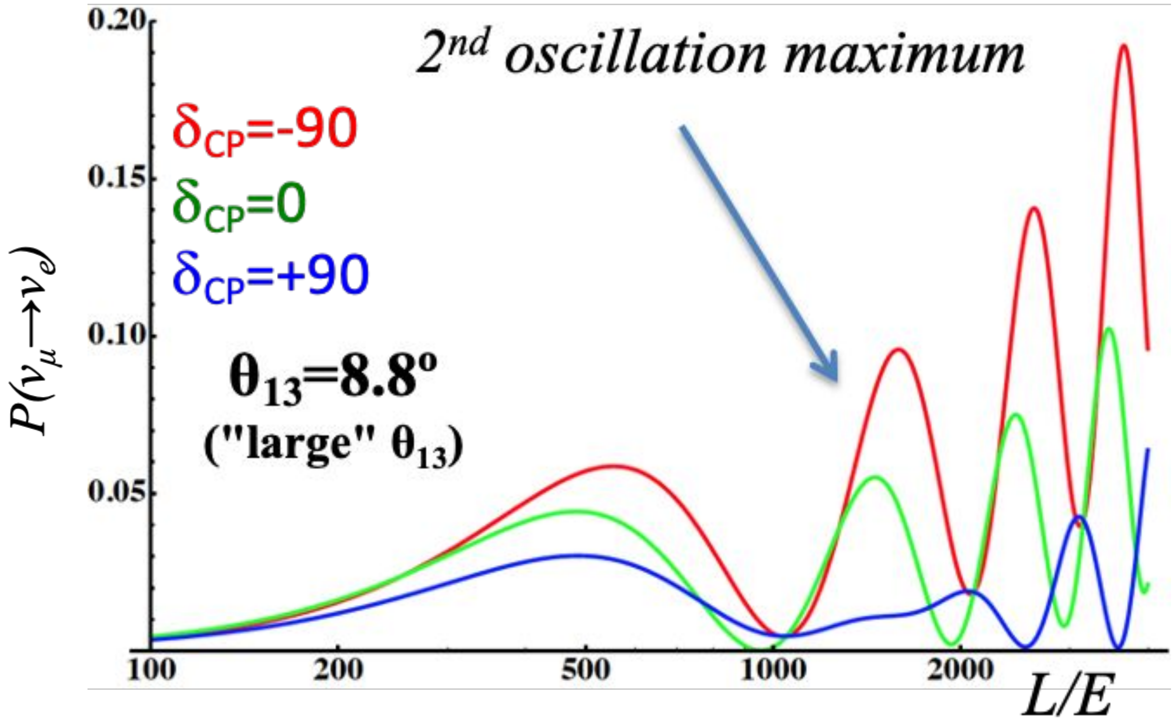
M. Dracos, NuFact2022

1st oscillation max: A=**0.3**sinδ_{CP}

2nd oscillation max: A=**0.75**sinδ_{CP}

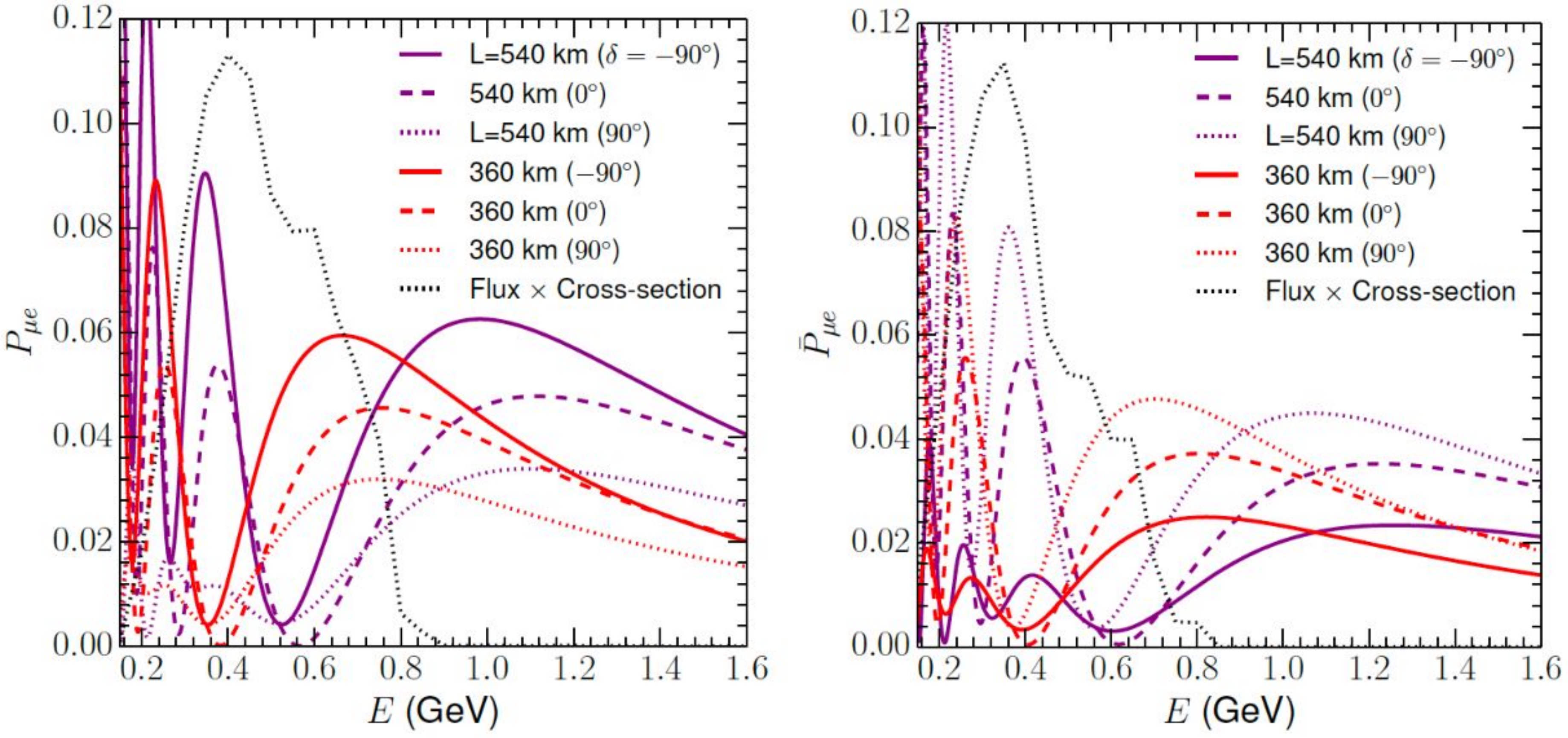
ESSnuSB - Physics goal

- Greater sensitivity to δ_{CP} at the second oscillation peak
- Within reach with the distance available and the 5 MW proton beam produced at ESS



M. Dracos, NuFact2022

ESSnuSB - Physics goal



The European Spallation Source neutrino Super Beam Conceptual Design Report

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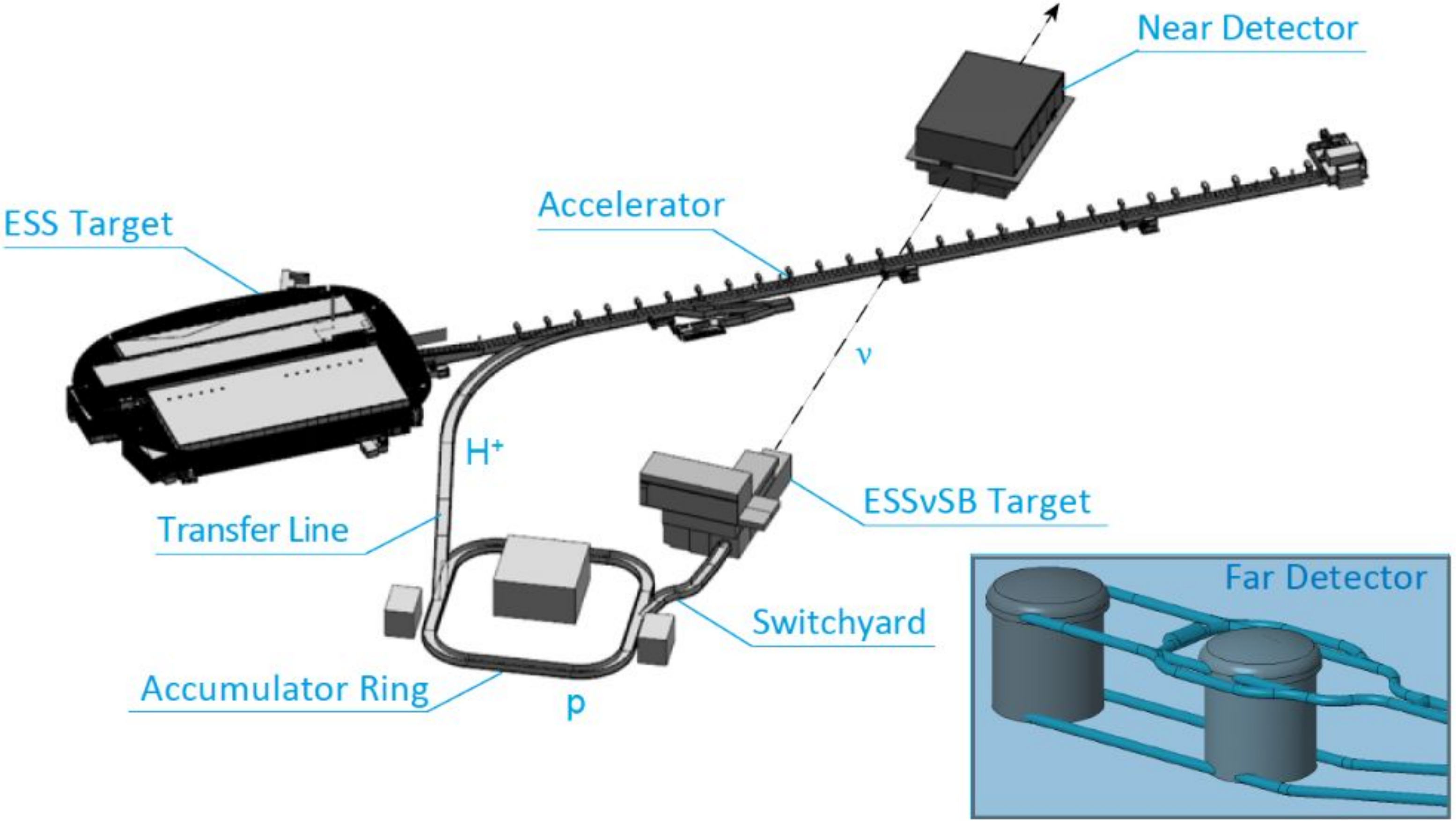
ESSnuSB - Detectors



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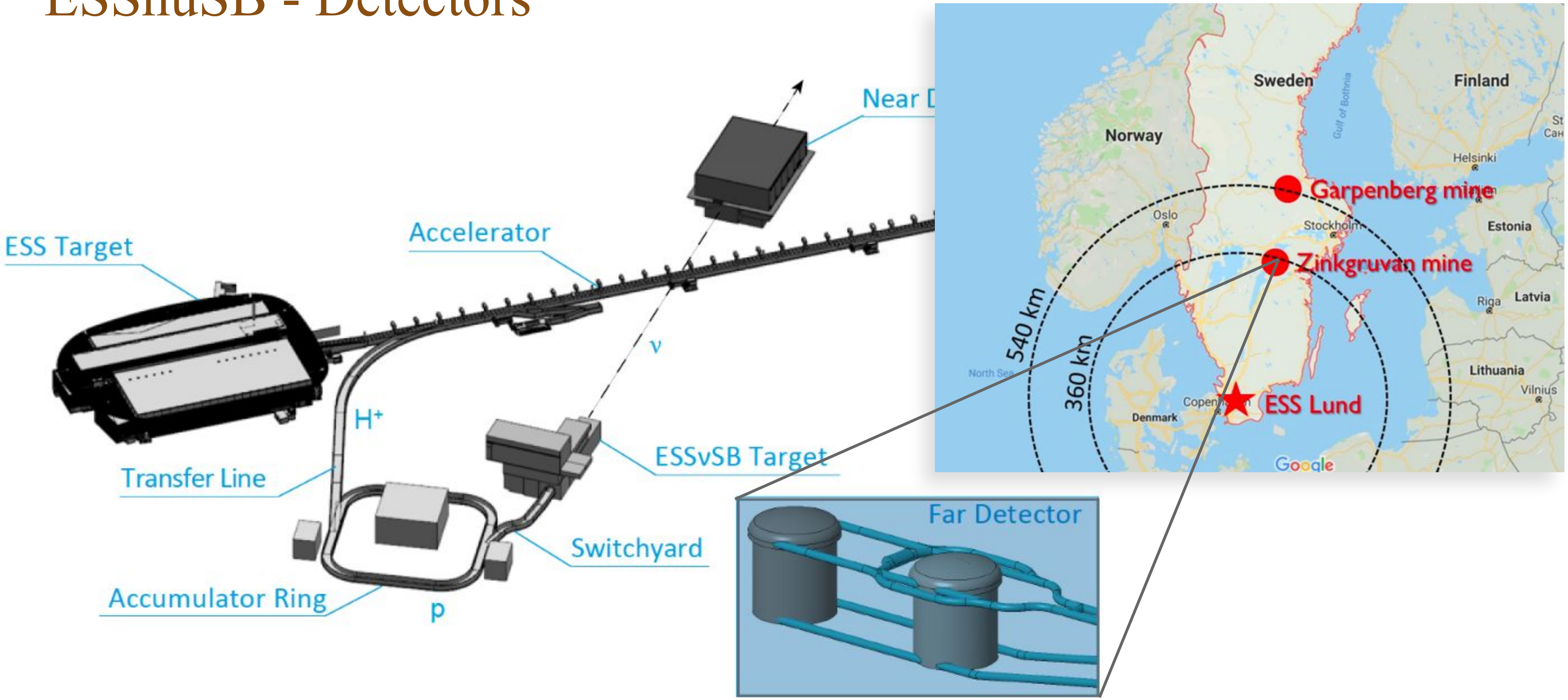

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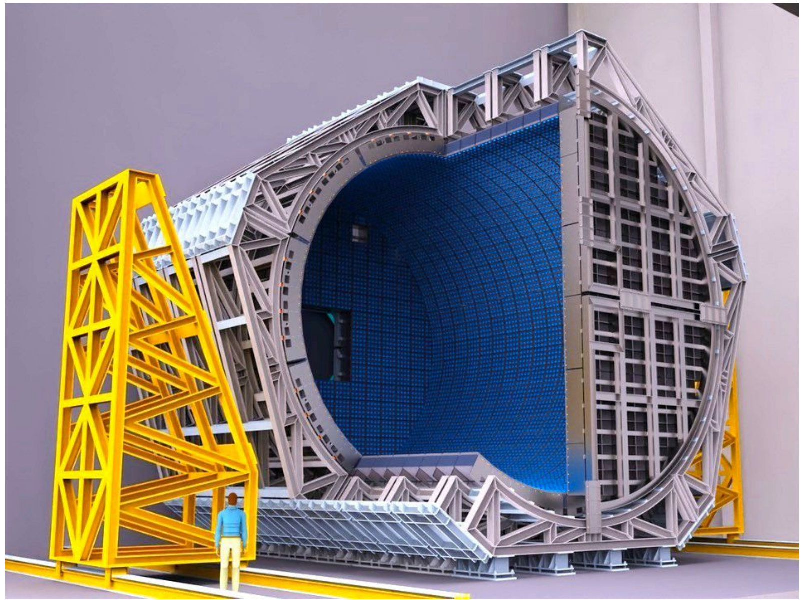
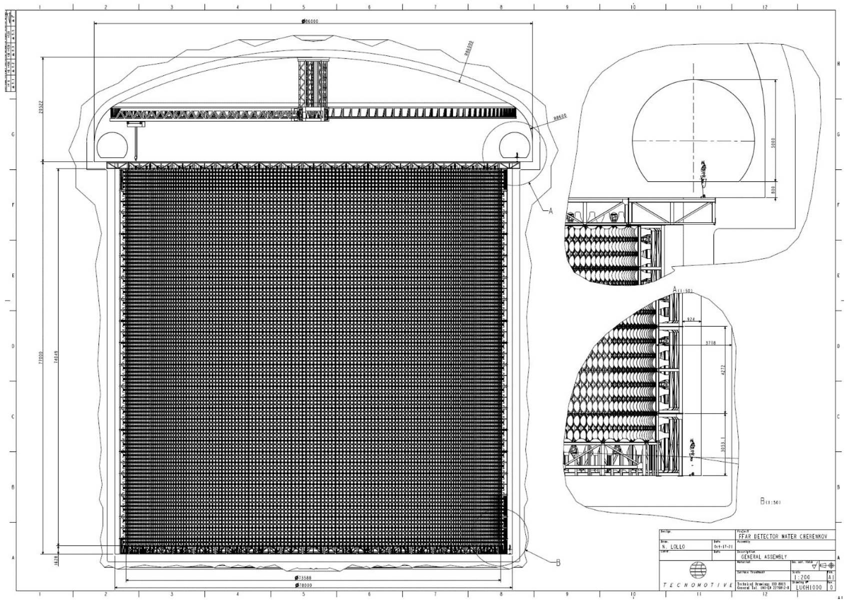
ESSnuSB - Detectors

Near detector
Water Cherenkov Detector
22,000 PMTs (Ø 3.5'')
Measures the non-oscillated neutrino beam

Additionally: Emulsion detector and SFGD

Far detector x2
Water Cherenkov Detector
25,000 - 50,000 PMTs (Ø 20'')
Measures the oscillated neutrino beam





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Current Framework

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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Challenges

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

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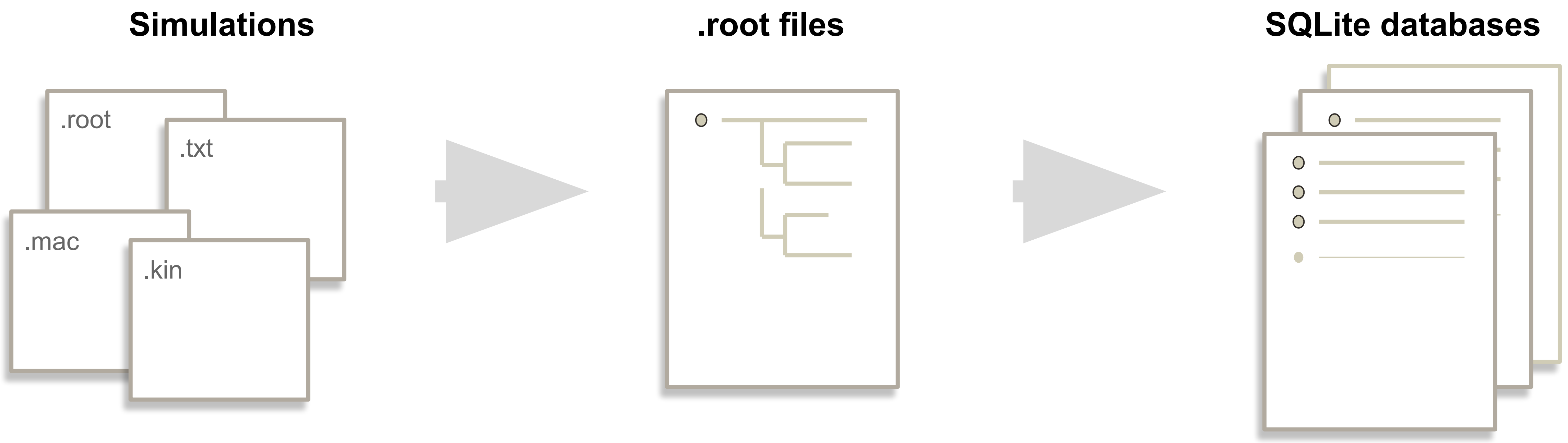
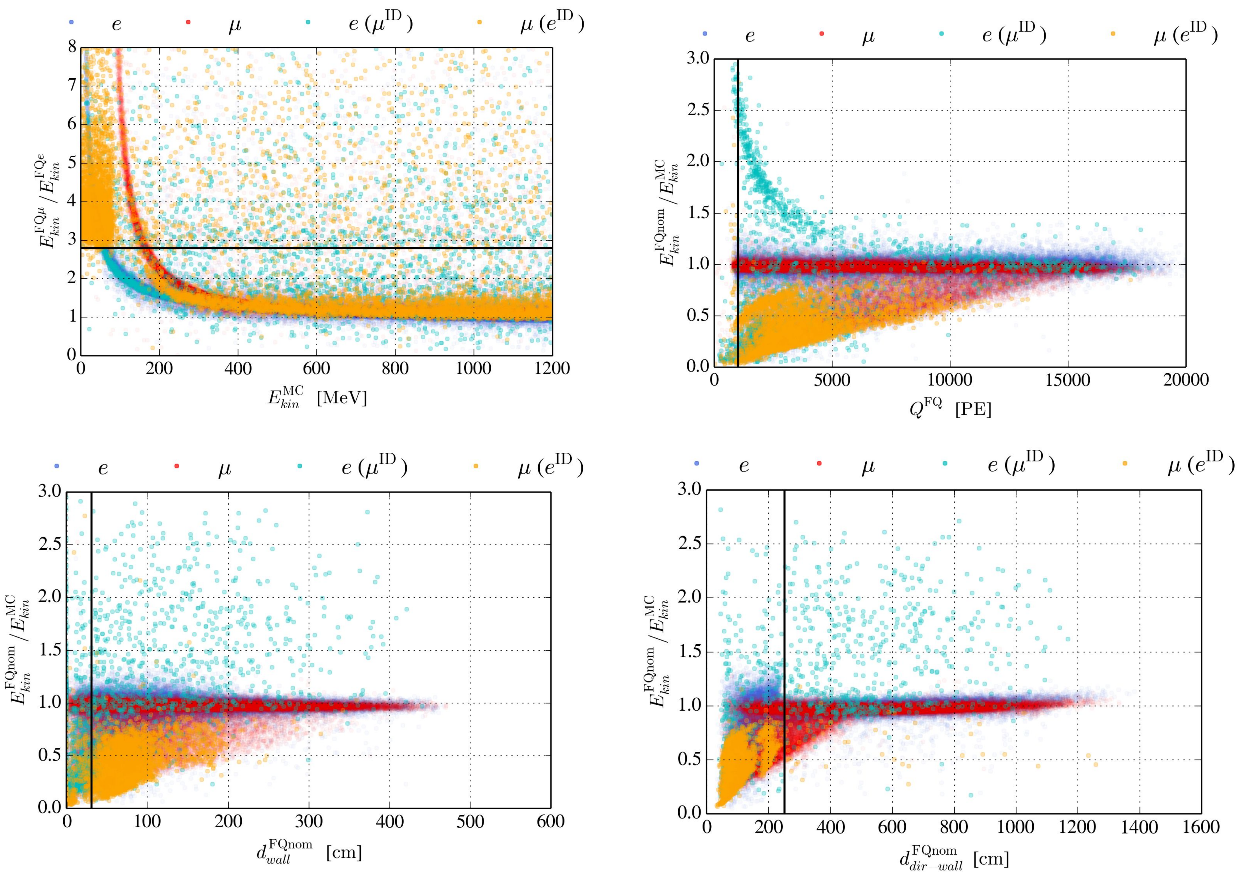
GNN Implementation

Data pipeline



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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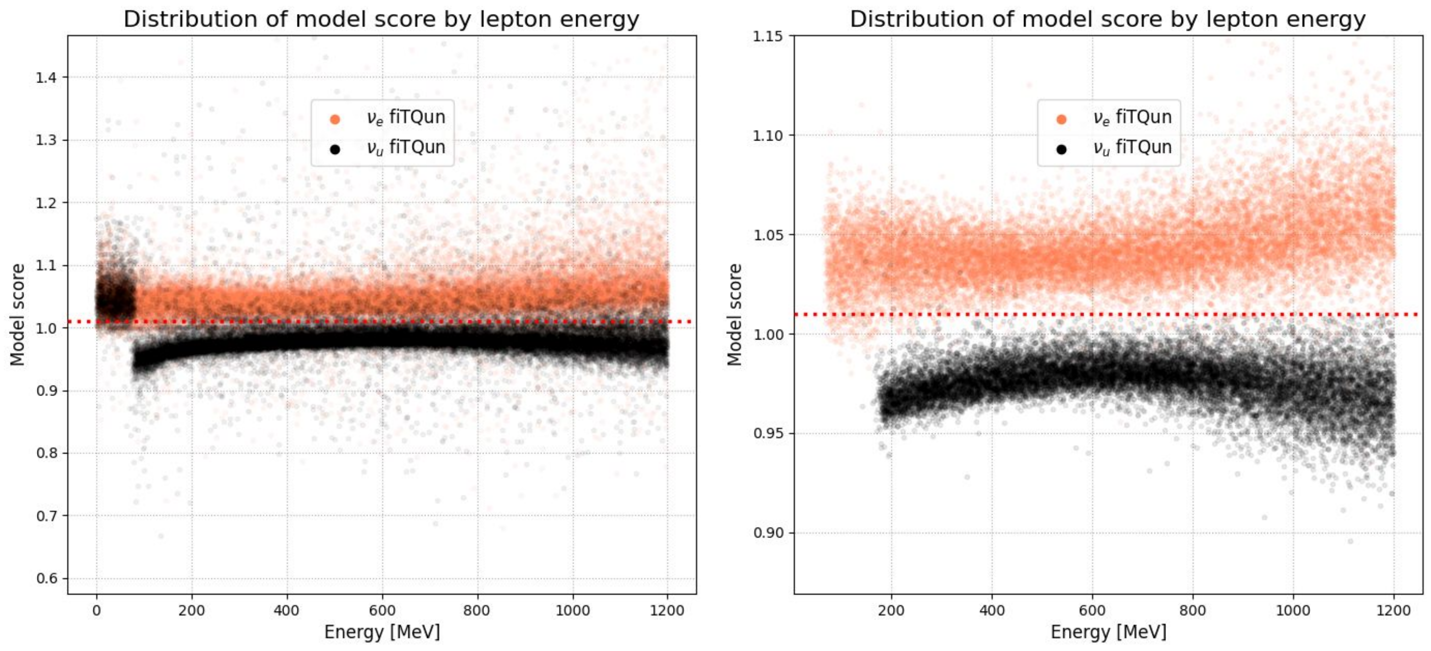

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Training configuration

Training set	100,000 events
Validation set	300,000 events
Network architecture	DynEdge
Loss function	BCE
Computing resources	2 Nvidia K80 (as four K40 cards) Lunarc Aurora cluster

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Training configuration

Training set	100,000 events
Validation set	300,000 events
Network architecture	DynEdge
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Computing resources	2 Nvidia K80 (as four K40 cards) Lunarc Aurora cluster

Dense events and 12800 MB memory limit/node limits the possible batch size

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Charged Lepton Performance

Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

Event ratios are unweighted, but from our knowledge of the neutrino beam, we can set the target FPRs to:

- Muons neutrinos: 0.1%
- Electron neutrinos: 1%

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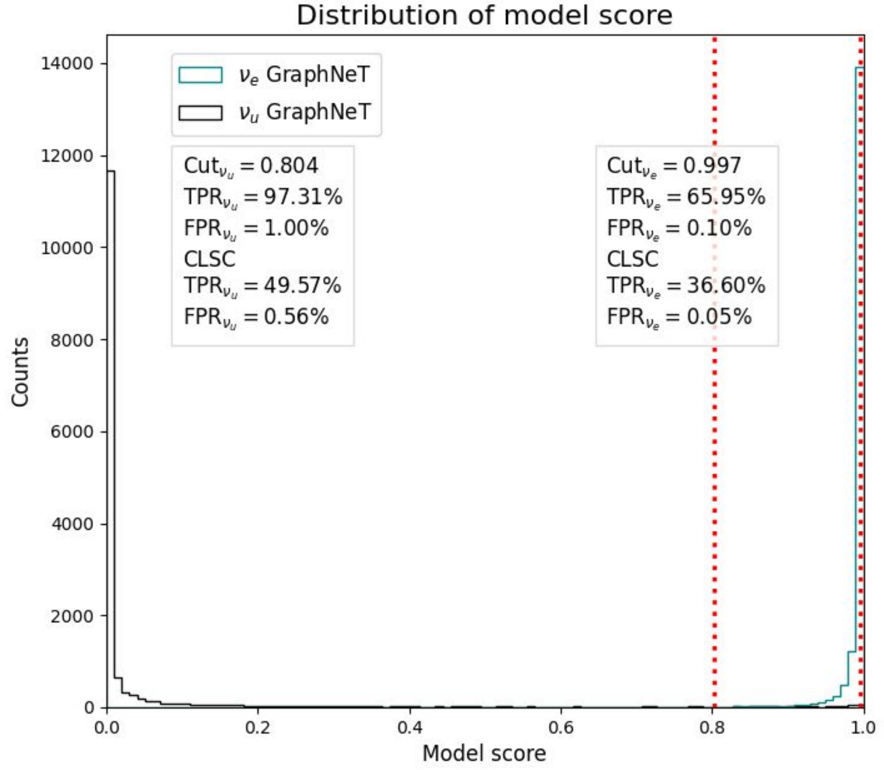
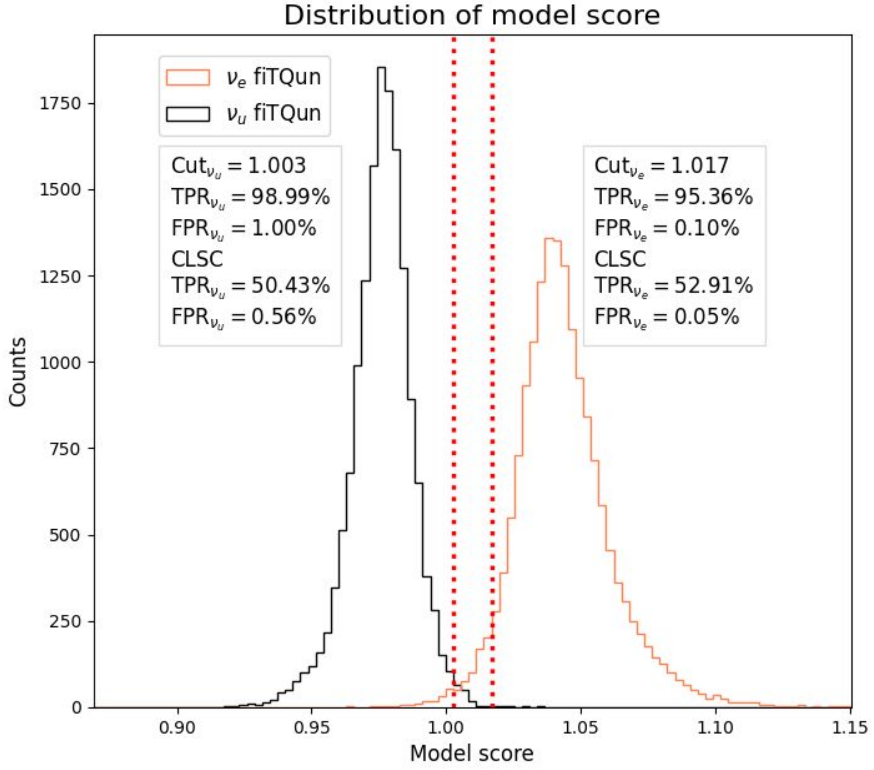
Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

GraphNeT performance



fiTQun performance



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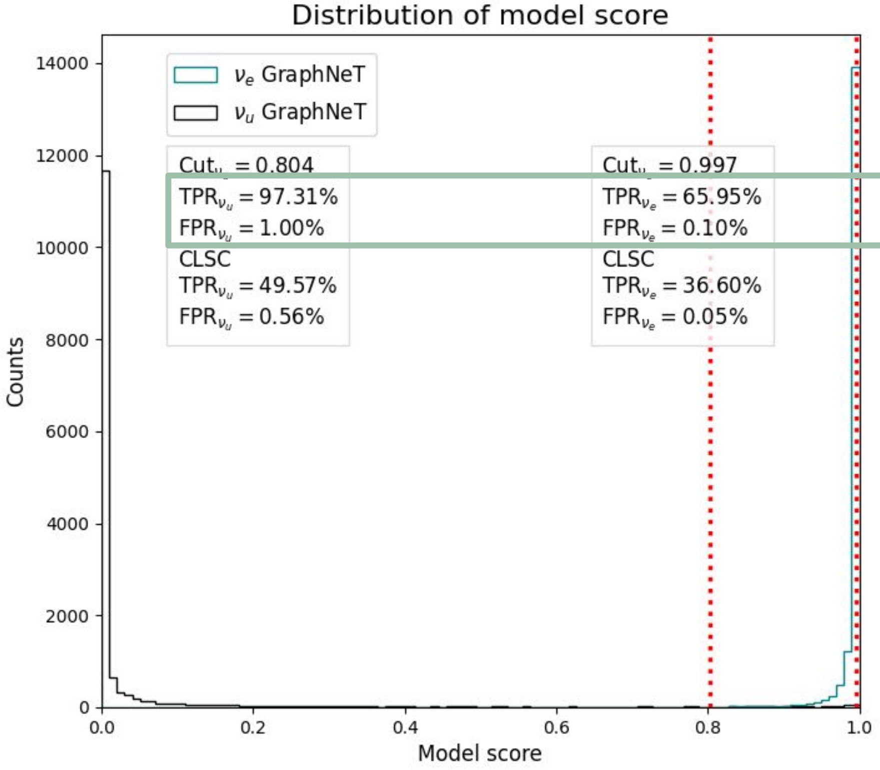
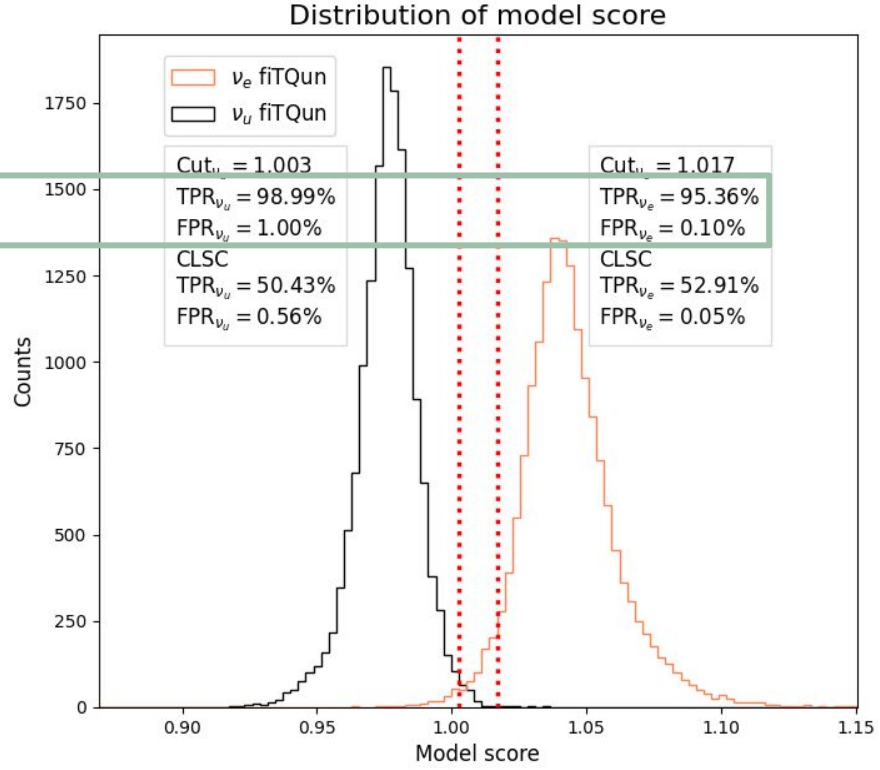
Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

GraphNeT performance



fiTQun performance



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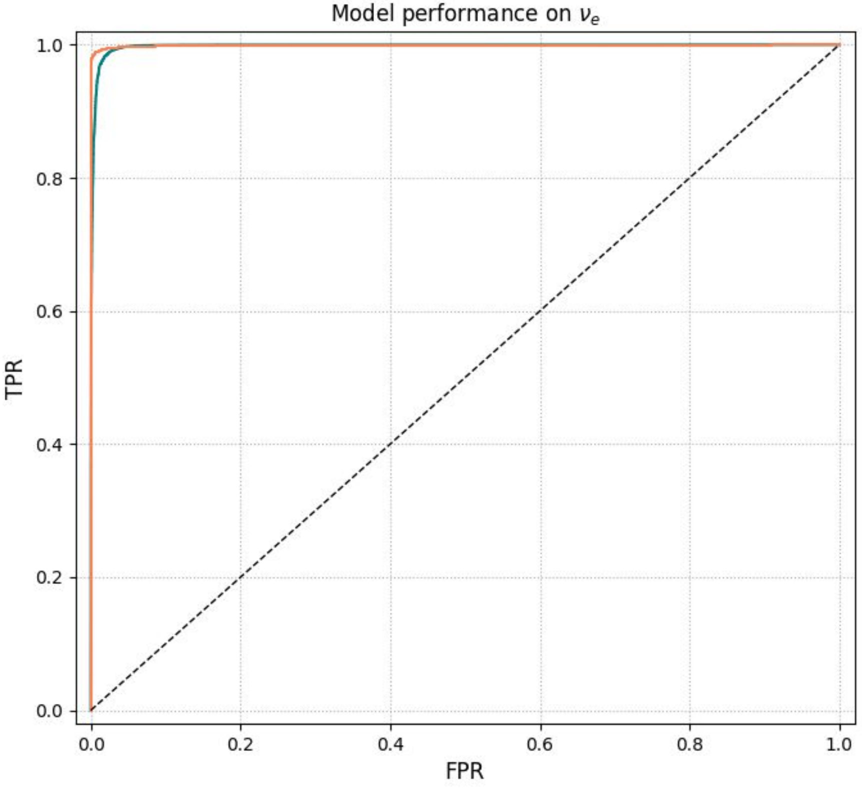
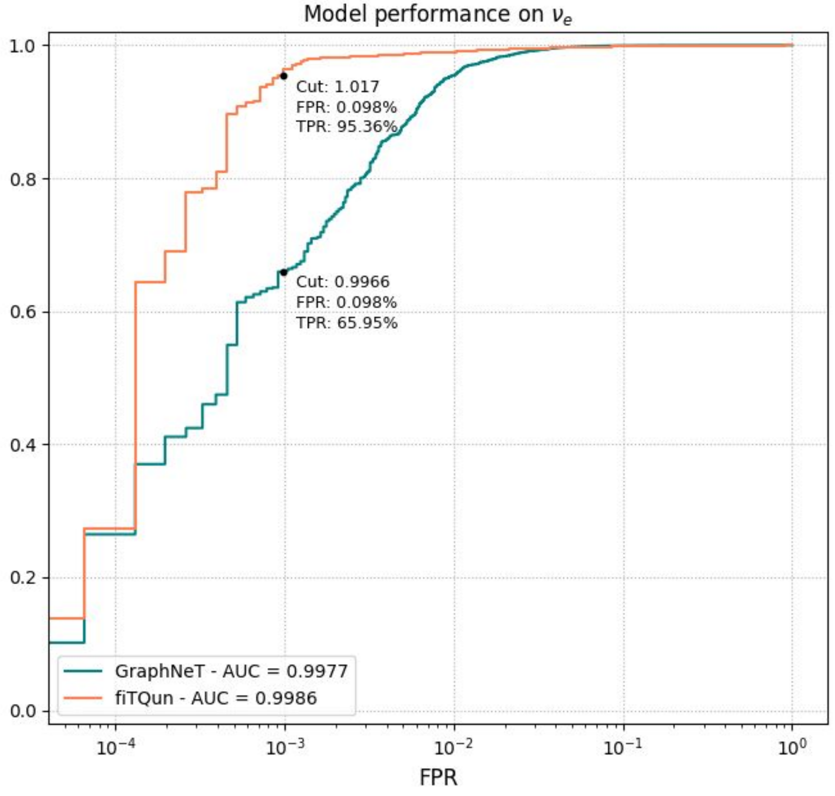
Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

ROC Curve



ROC Curve with logarithmic x axis



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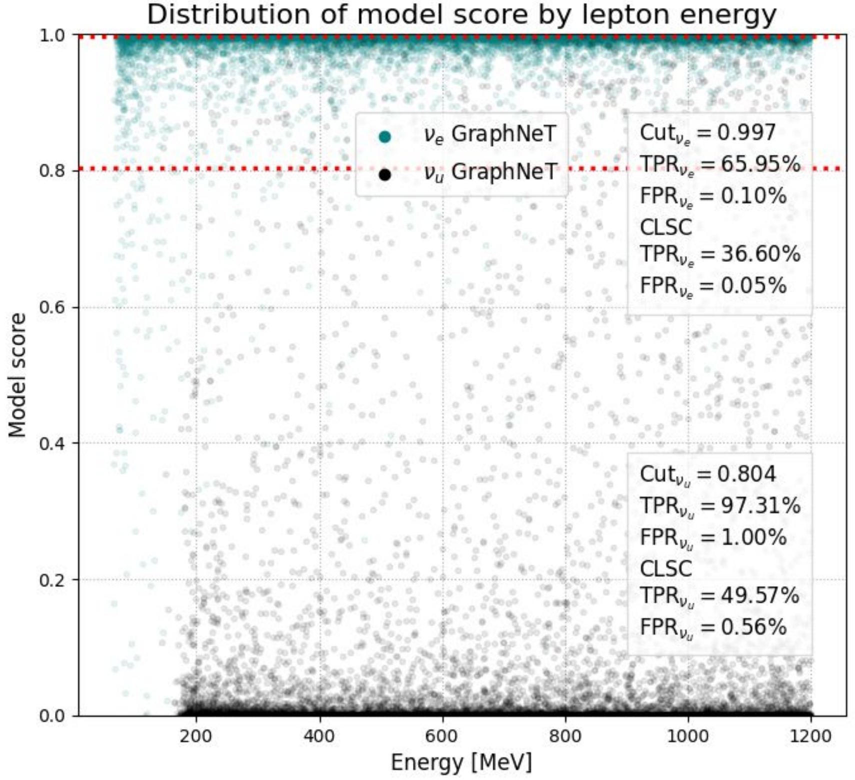
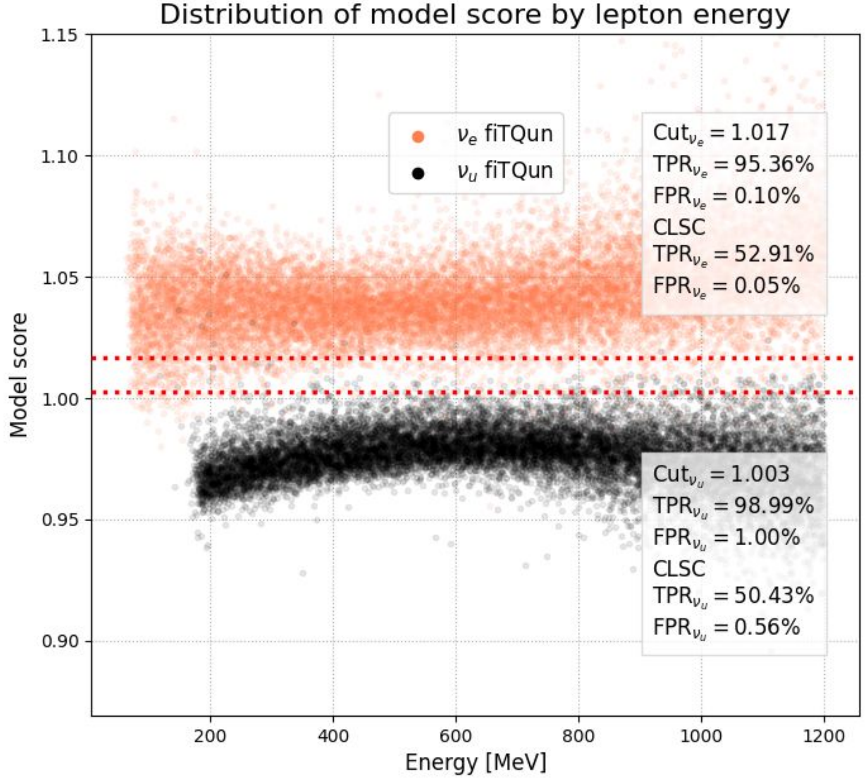
Event Classification - GraphNeT vs. fiTQun

Charged lepton simulations

GraphNeT performance



fiTQun 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.)

Neutrino Event Performance

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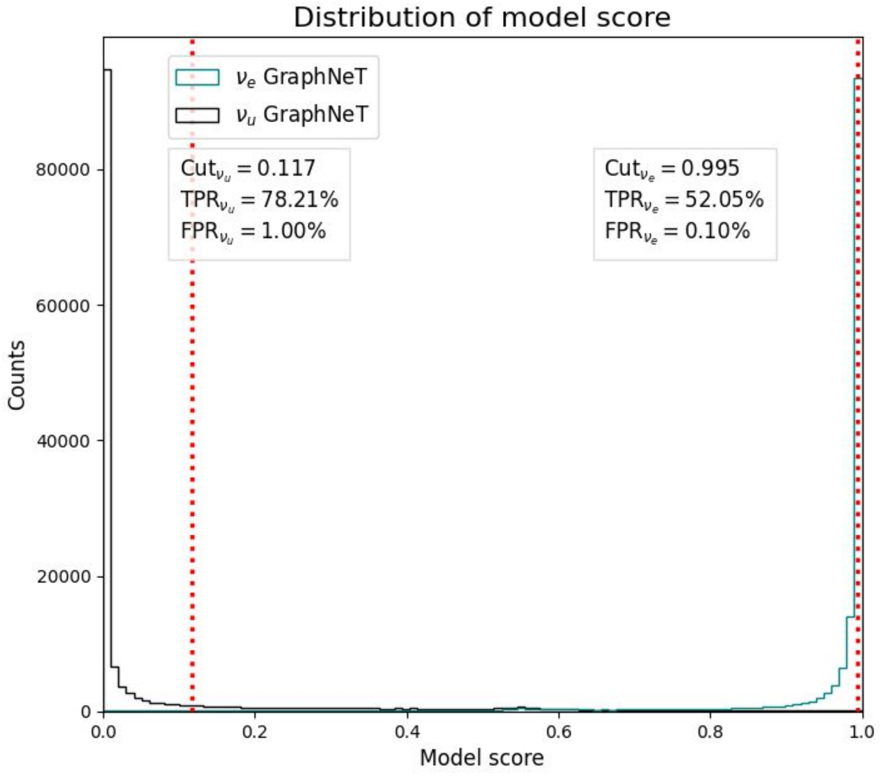
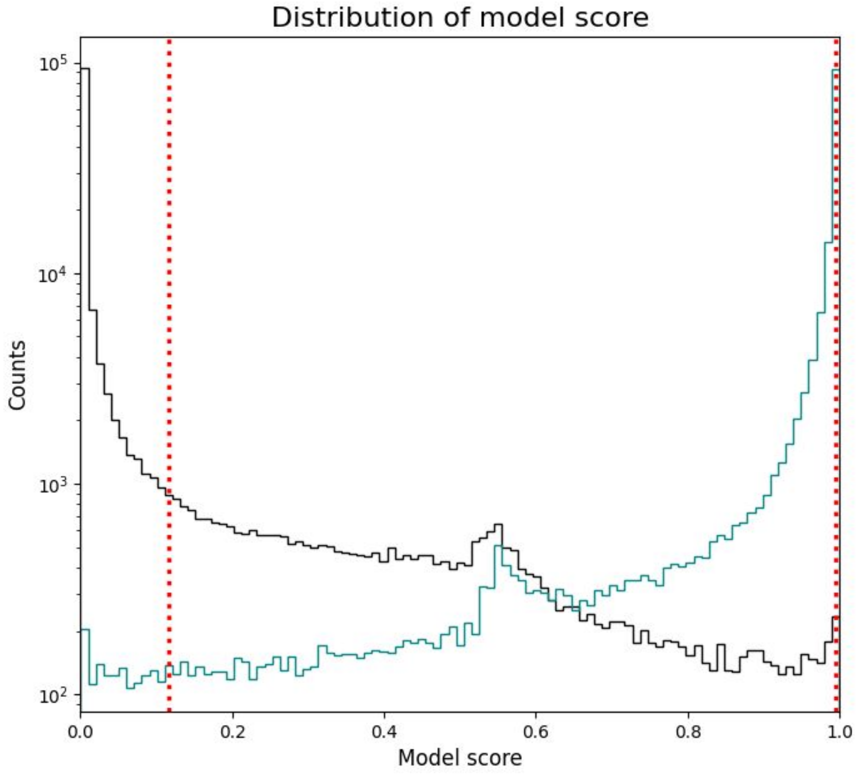
Event Classification - GraphNeT vs. fiTQun

Neutrino event simulations - without data cut

GraphNeT performance



GraphNeT performance with logarithmic x axis



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Event Classification - GraphNeT vs. fiTQun

Neutrino event simulations - without data cut

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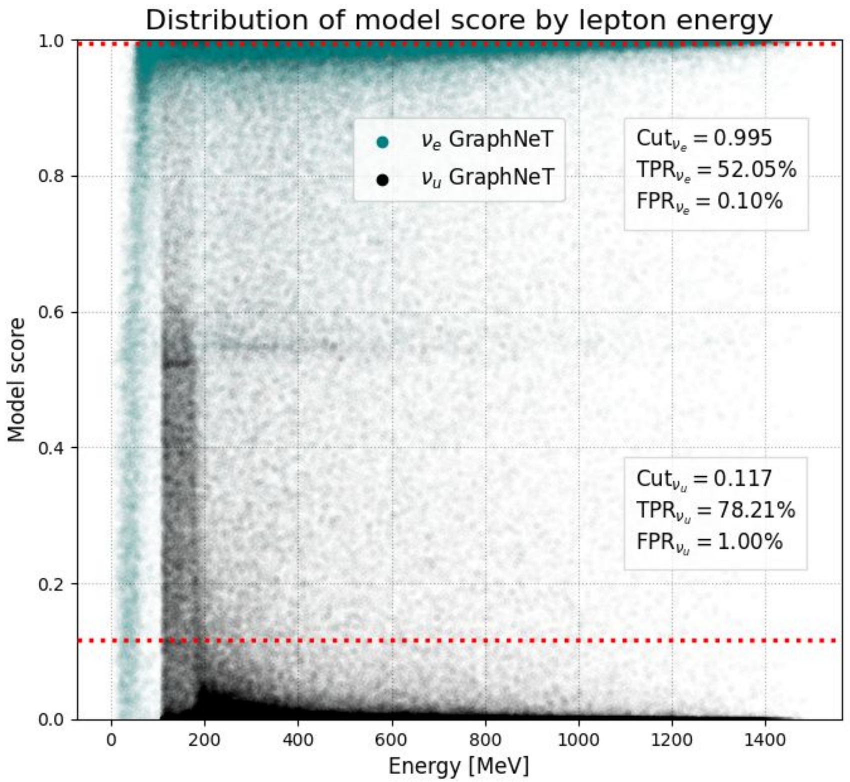
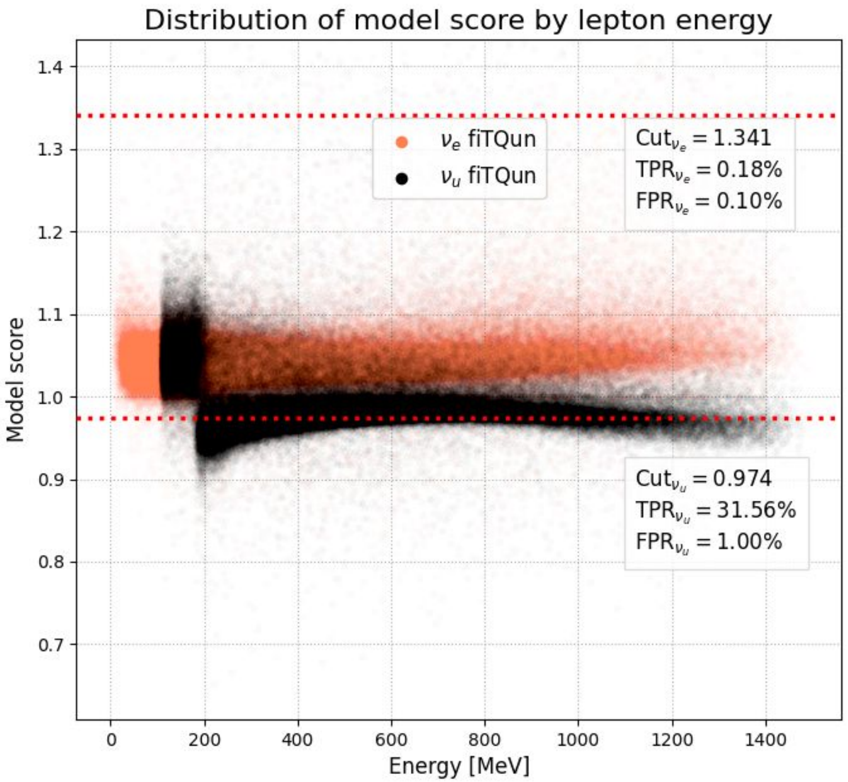


fiTQun performance



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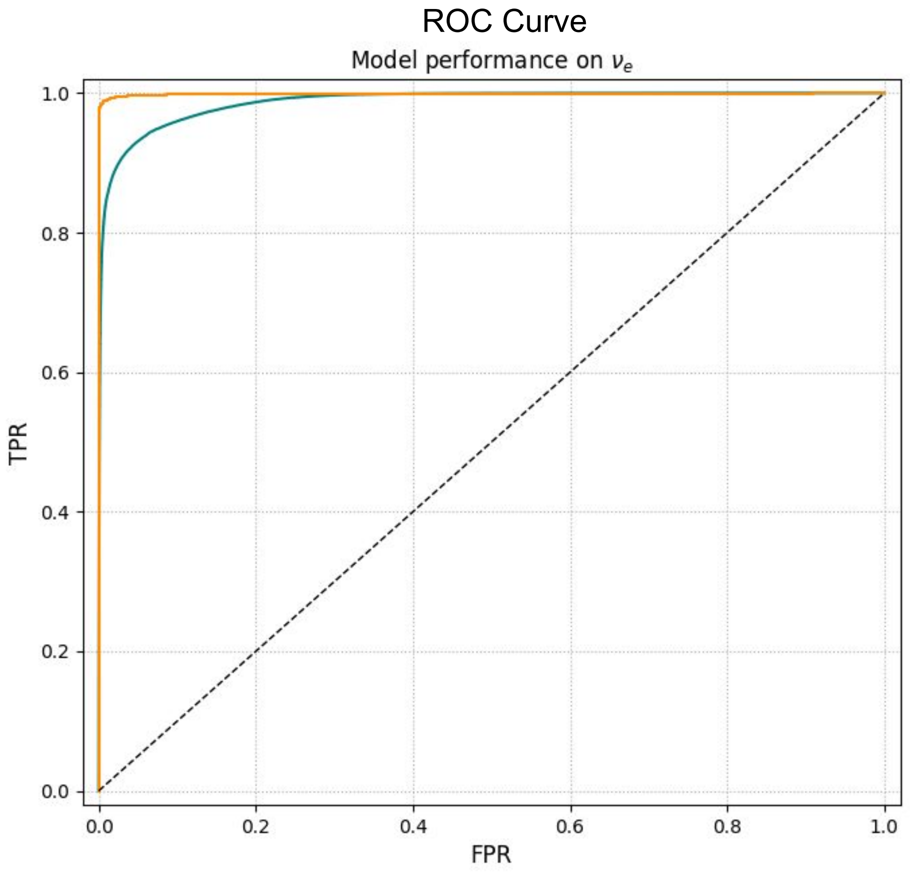
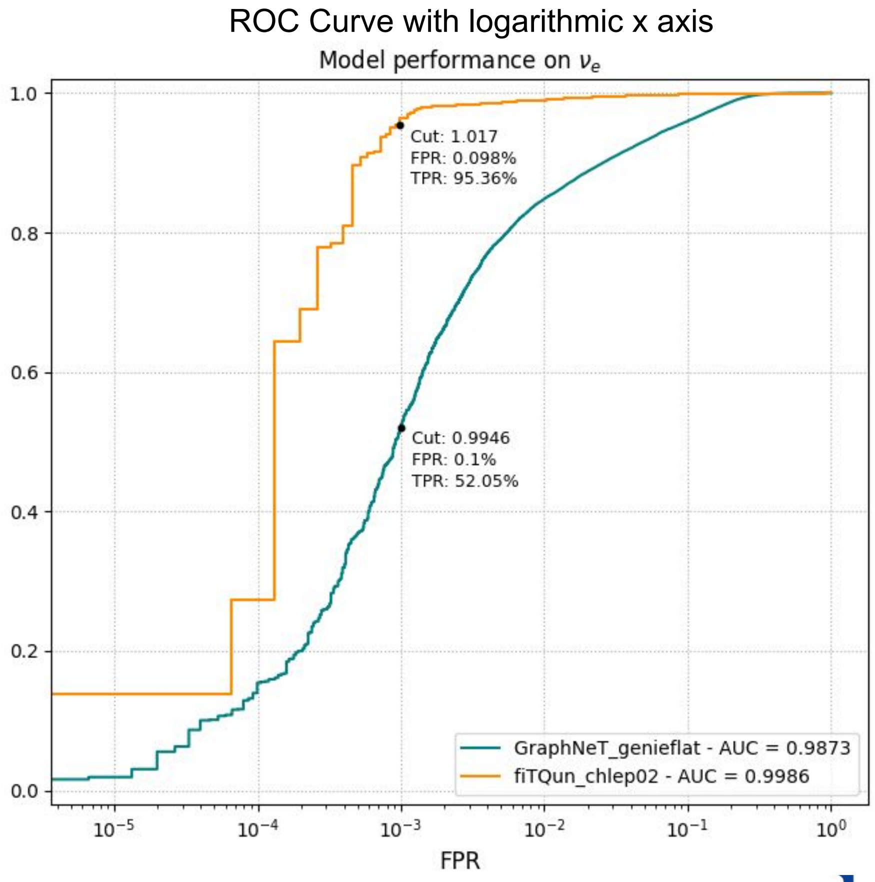
Event Classification - GraphNeT vs. fiTQun

Neutrino event simulations - without data cut





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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

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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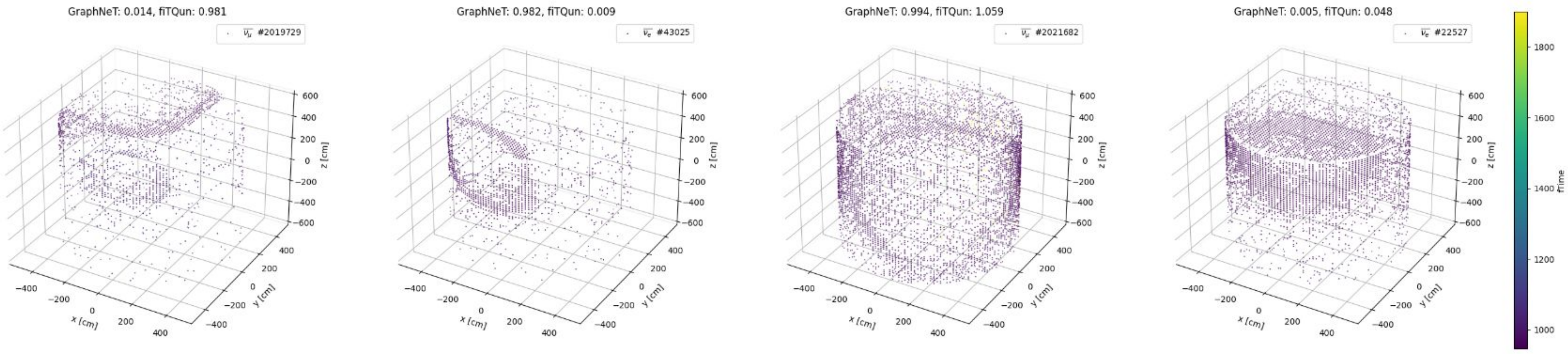
Performance Investigations

Factors impacting performance - multiple charged lepton signatures

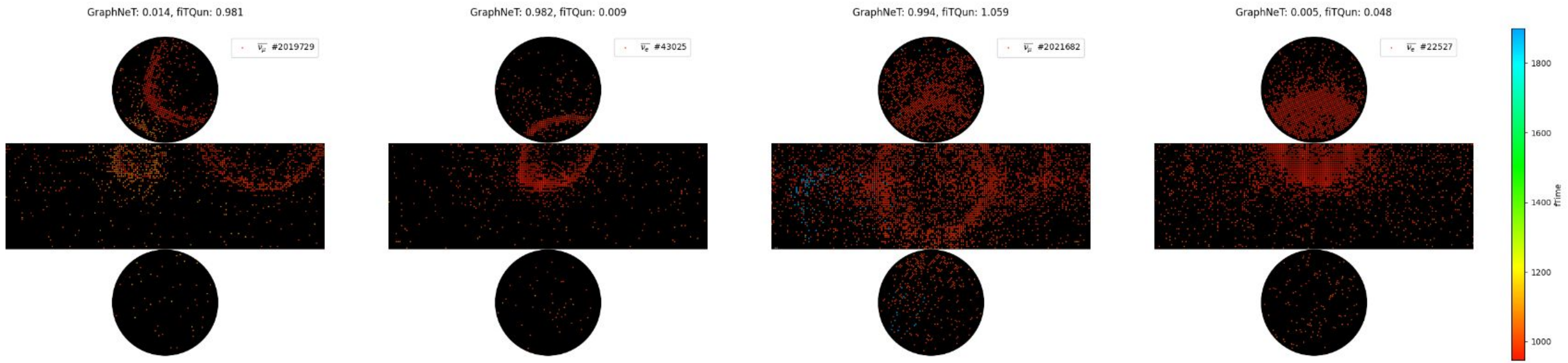
Neutrino event simulations - **with** data cut



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

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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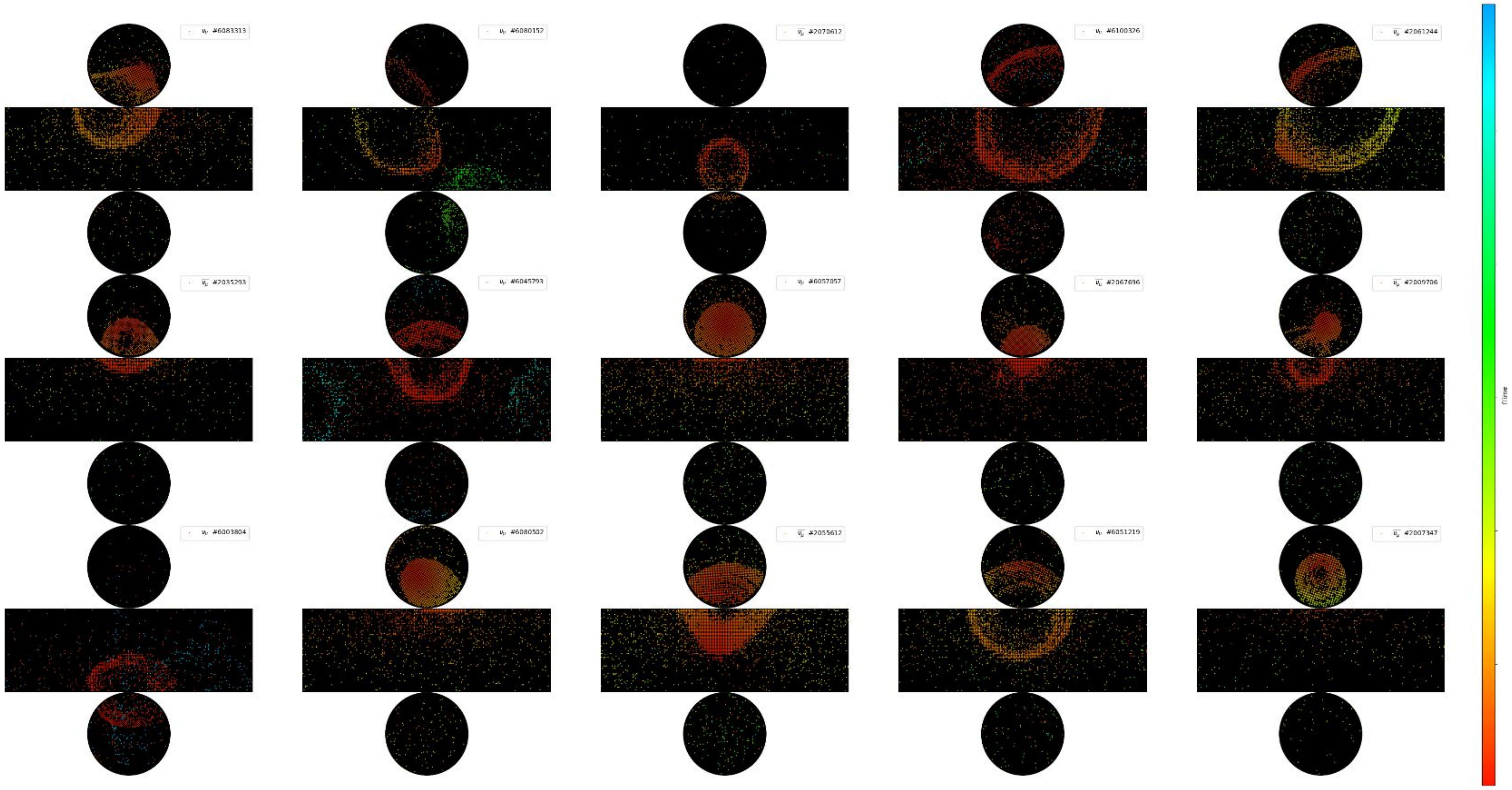
Event for which GraphNeT performs significantly better than fiTQun



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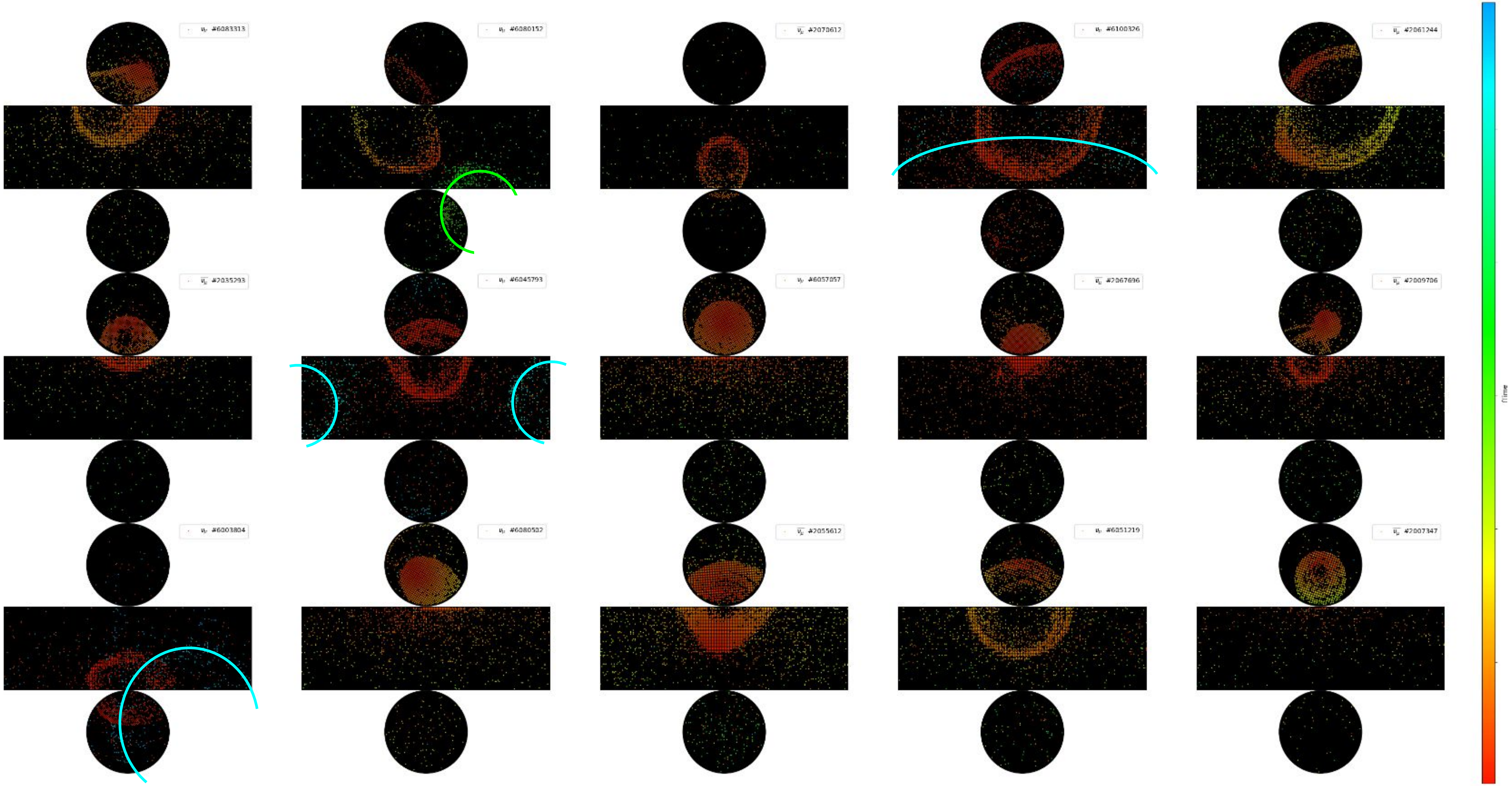
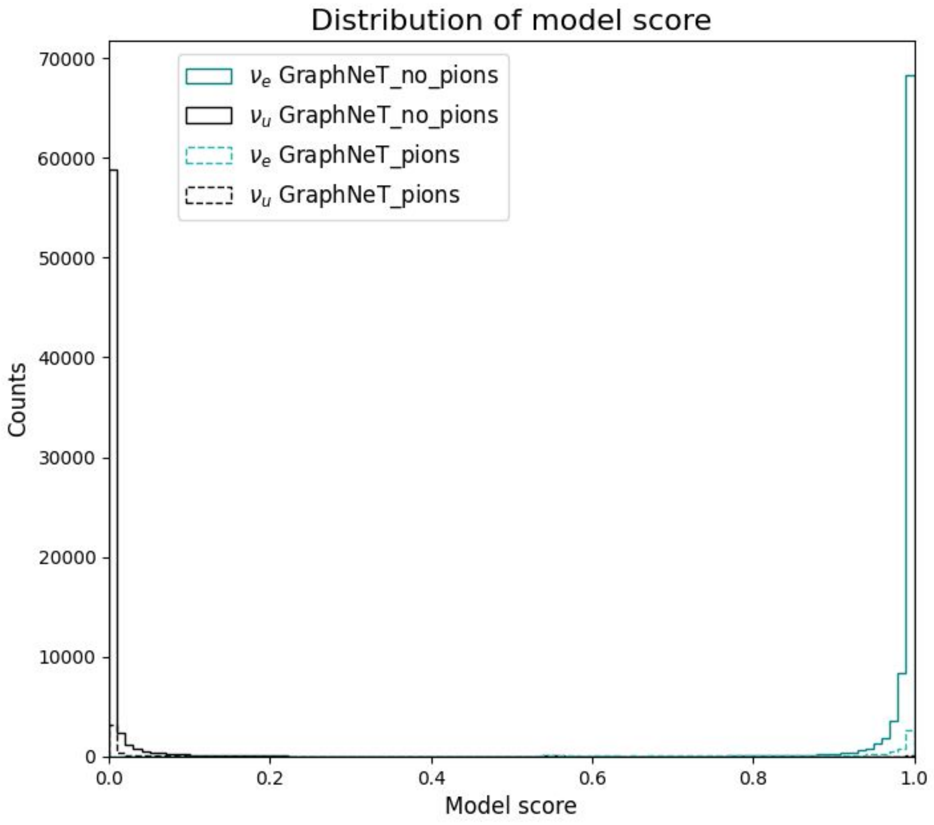


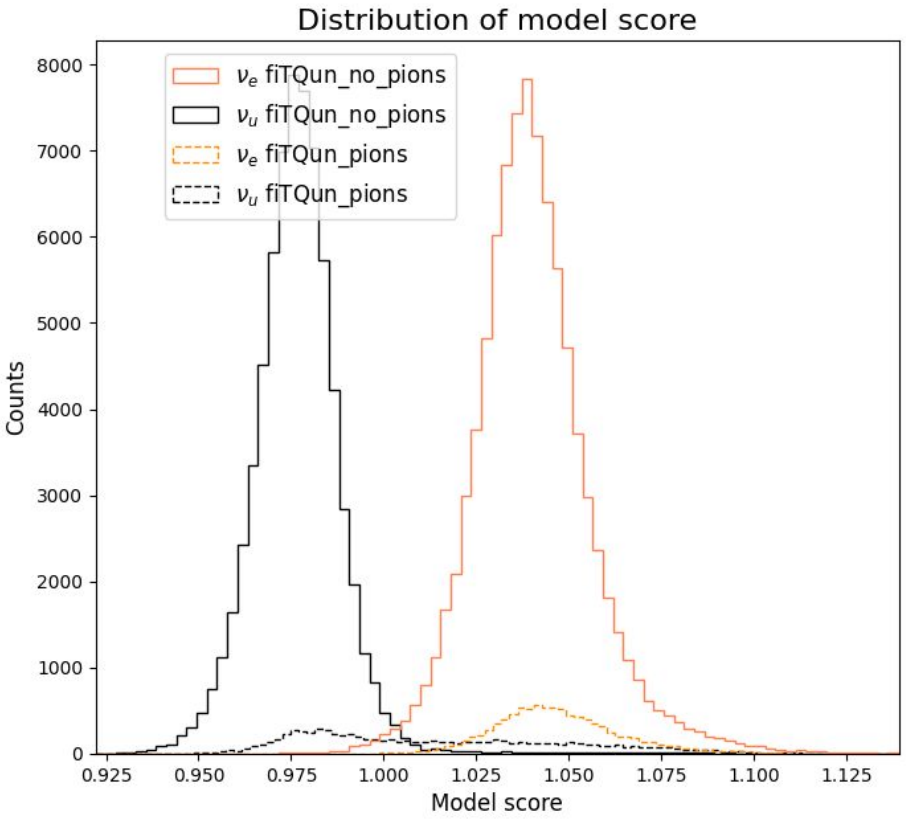
Factors impacting performance - pion creation

Neutrino event simulations - with data cut

GraphNeT performance



fiTQun performance



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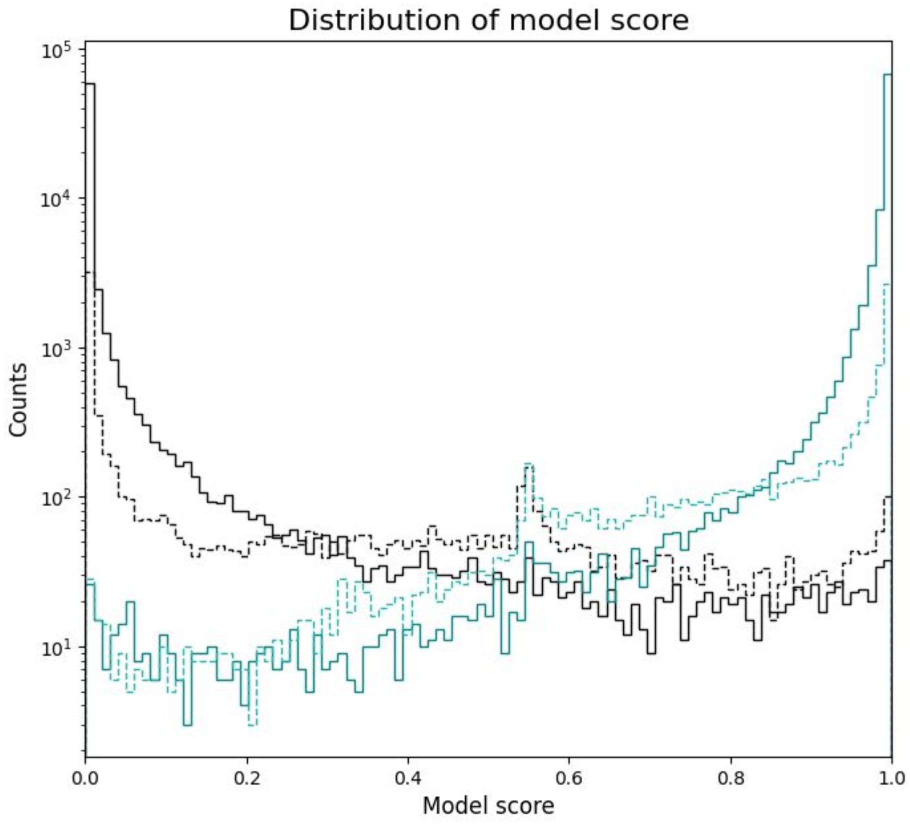
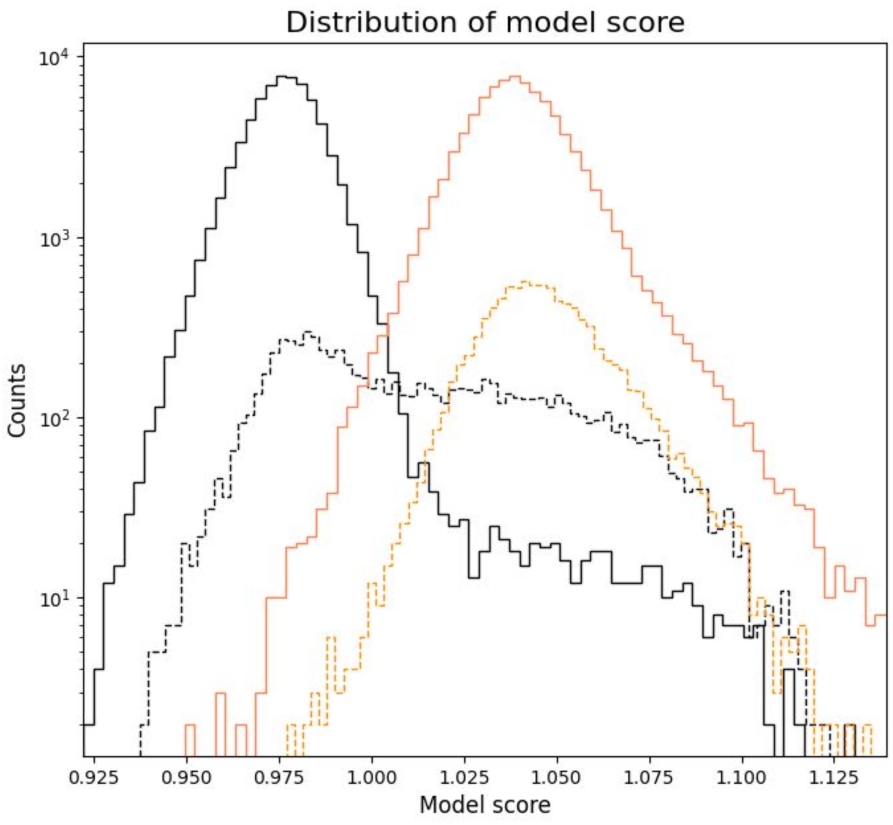
Factors impacting performance - pion creation

Neutrino event simulations - with data cut

GraphNeT performance with logarithmic x axis



fiTQun performance with logarithmic x axis



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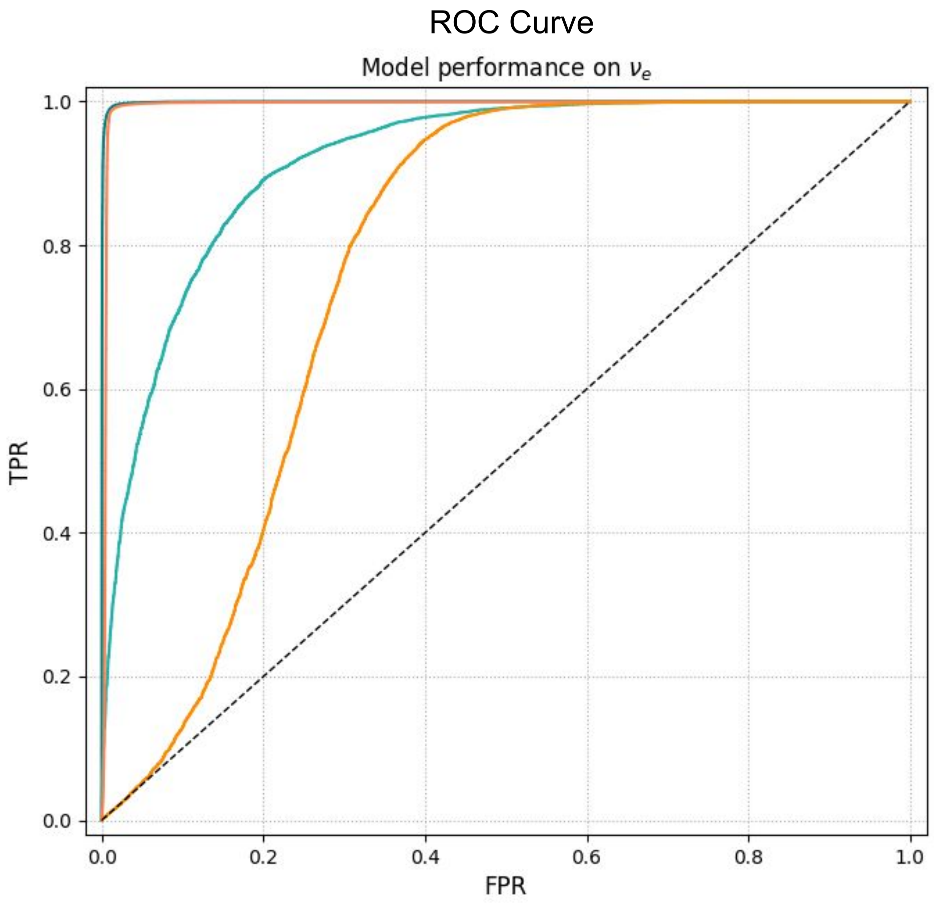
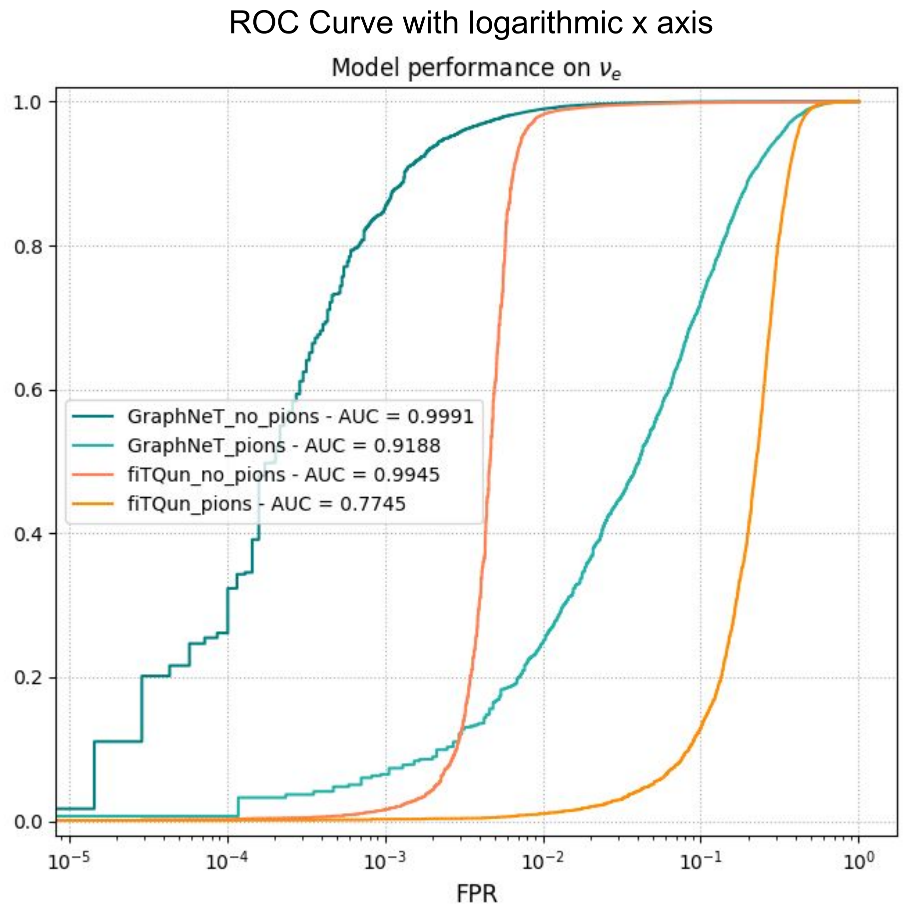
Factors impacting performance - pion creation

Neutrino event simulations - with data cut





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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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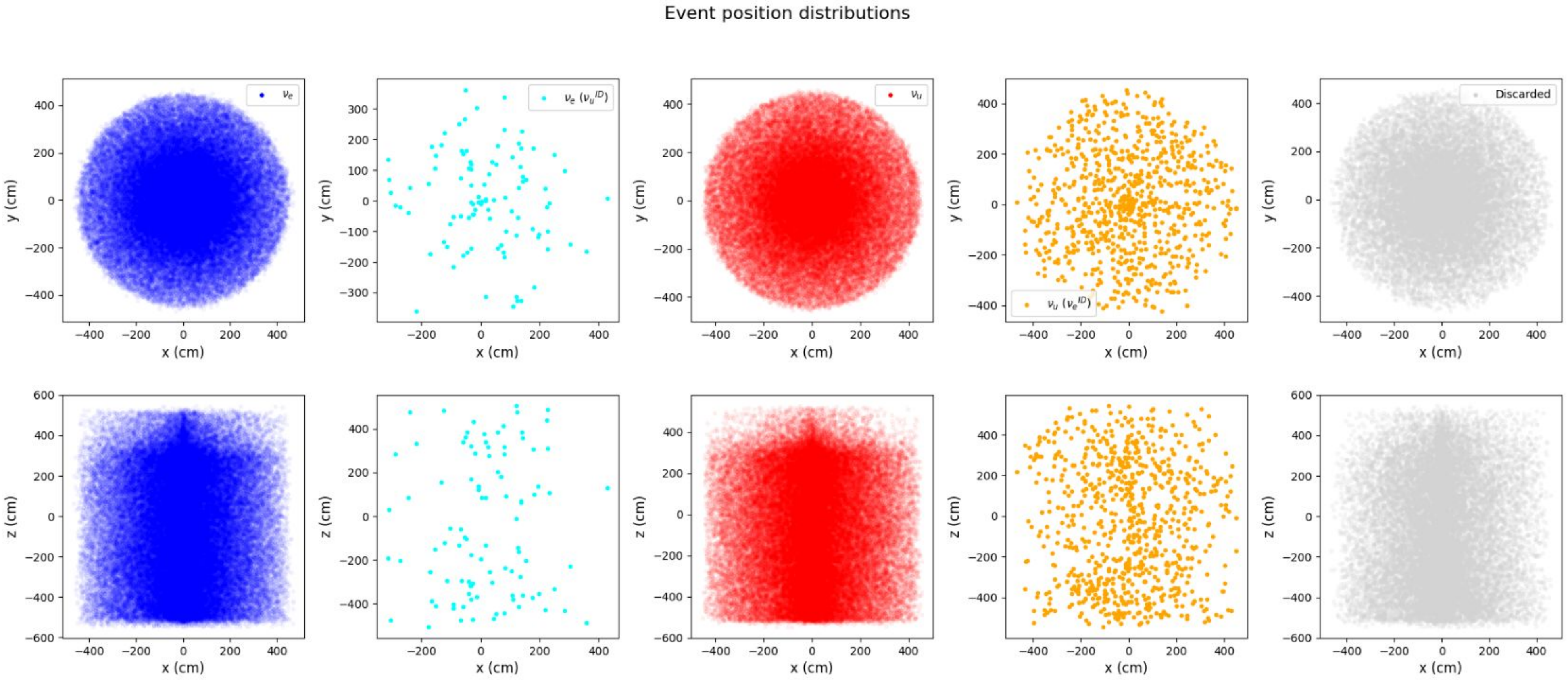
Thank you!

Additional Slides

Relation between interaction position and reconstruction performance

Neutrino event simulations - with data cut



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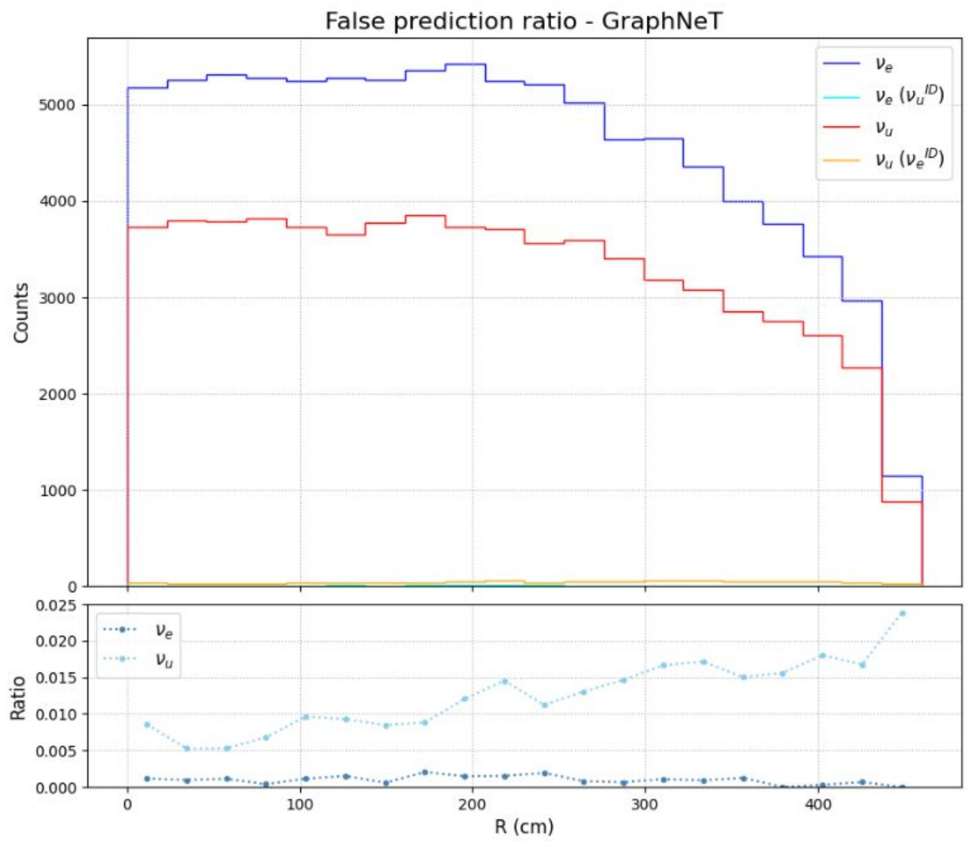

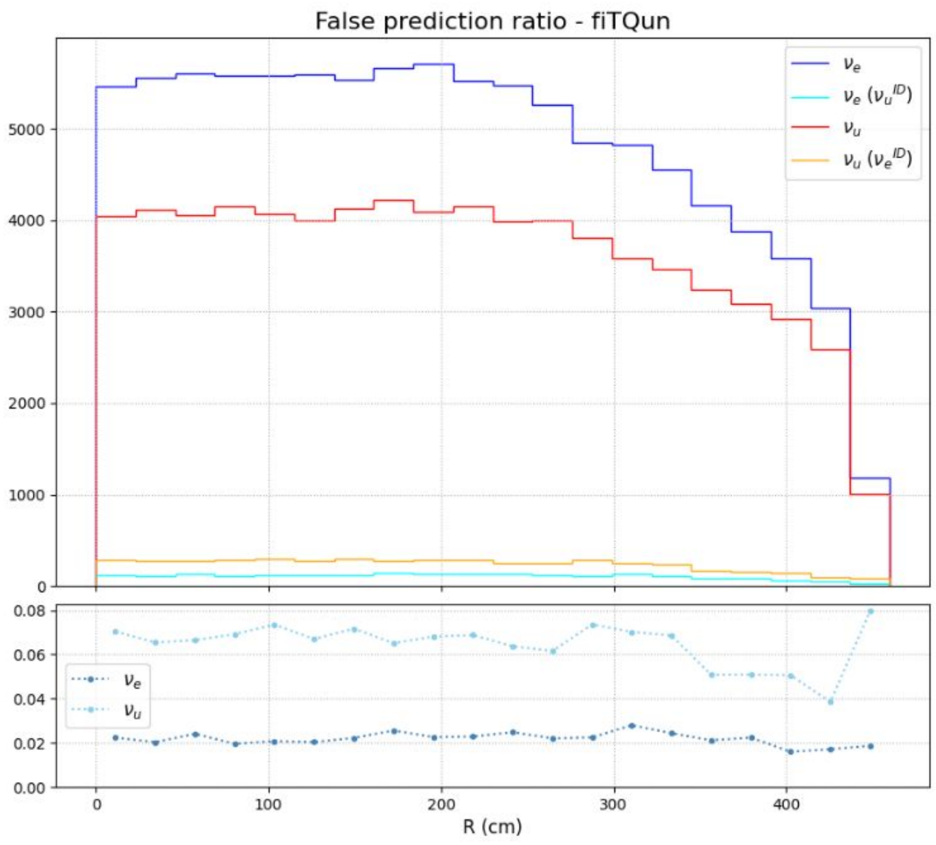

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