# Neutrino Interaction Classification in SND@LHC based on Graph Neural Network

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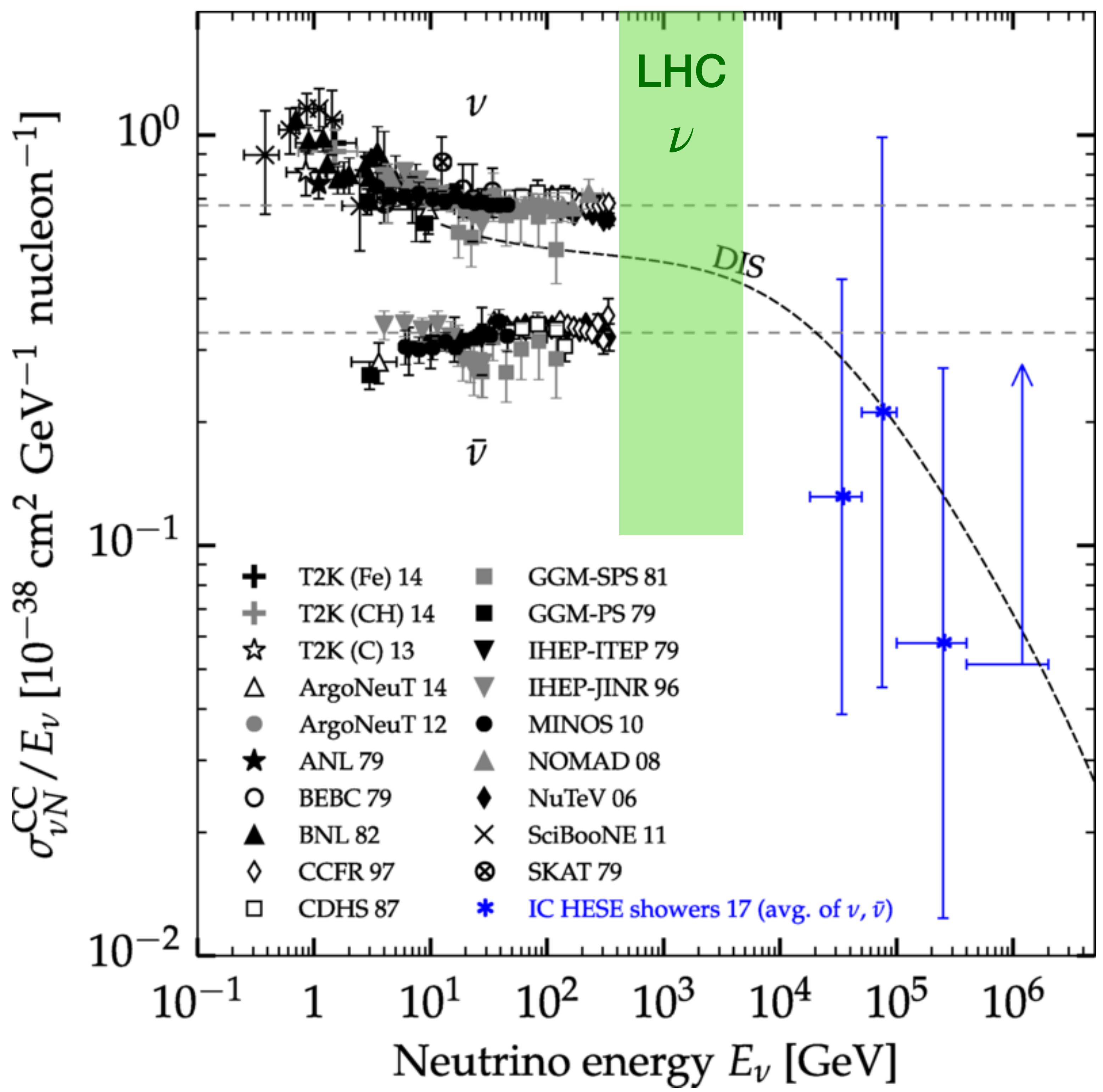
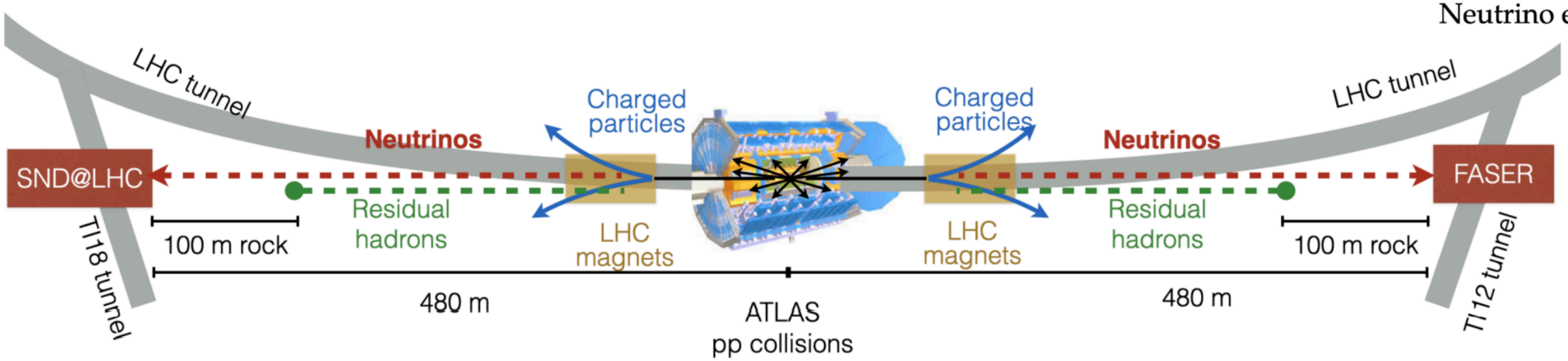
# Introduction

- Scattering and Neutrino Detector at LHC (SND@LHC)
- Neutrino from LHC
  - **Large flux** in the forward region
  - Unexplored **high energy region** (300 GeV ~ a few TeV)
- SND@LHC **(7.2 < $\eta$ < 8.4)** and FASER$\nu$ **($\eta$ > 9)**

PRL 122.041101

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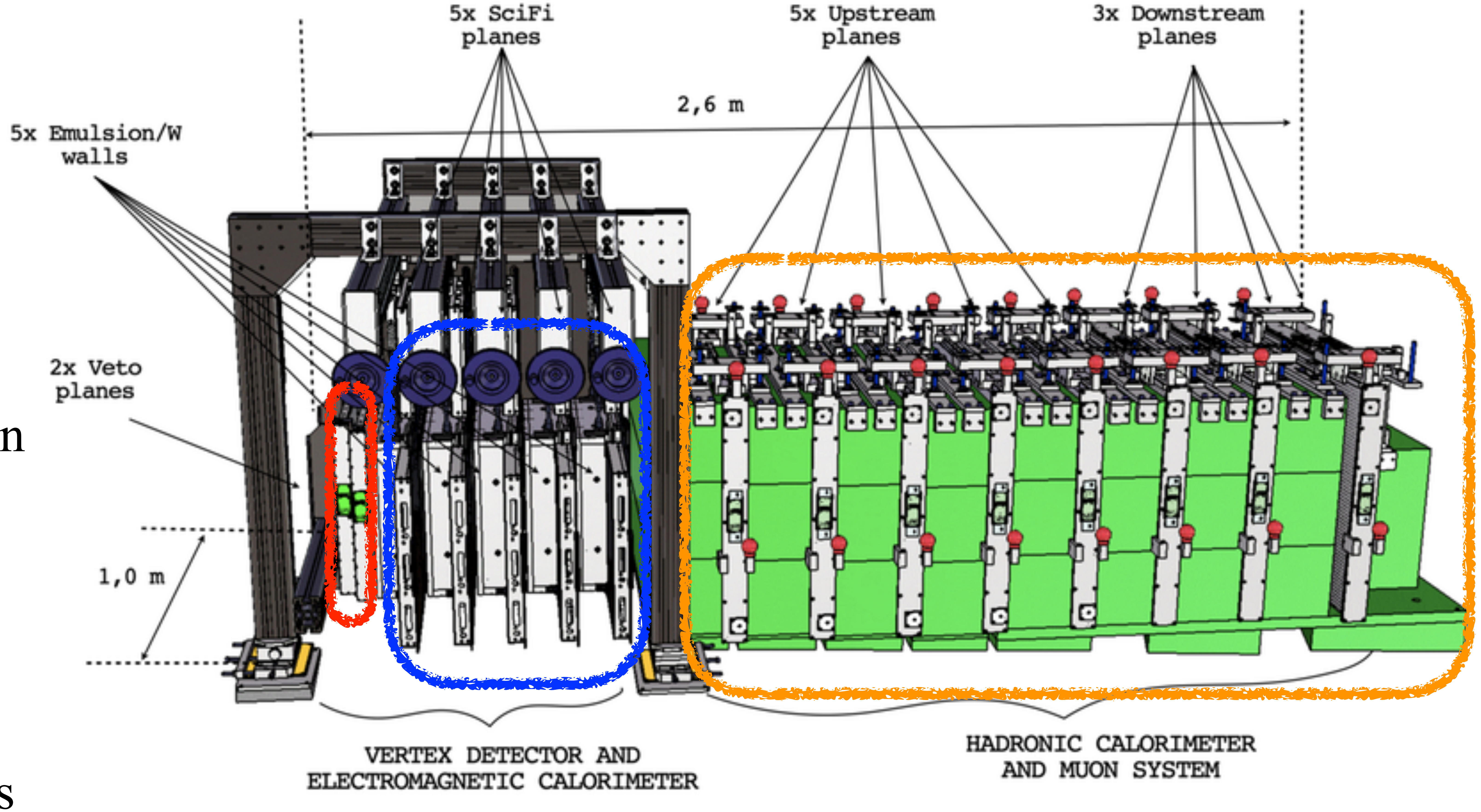
# SND@LHC Detector - Layout

- Veto System
  - 2 veto planes to tag charged particles
- Vertex Detector and ECAL
  - 5 walls of **Emulsion Cloud Chambers (ECC)** with tungsten
  - Each follow by a **Scintillating Fibre (SciFi)** plane
- Muon system and HCAL
  - 8 plastic scintillator planes interleaved with eight iron walls
  - High-granularity in the Downstream planes (The last 3 planes)

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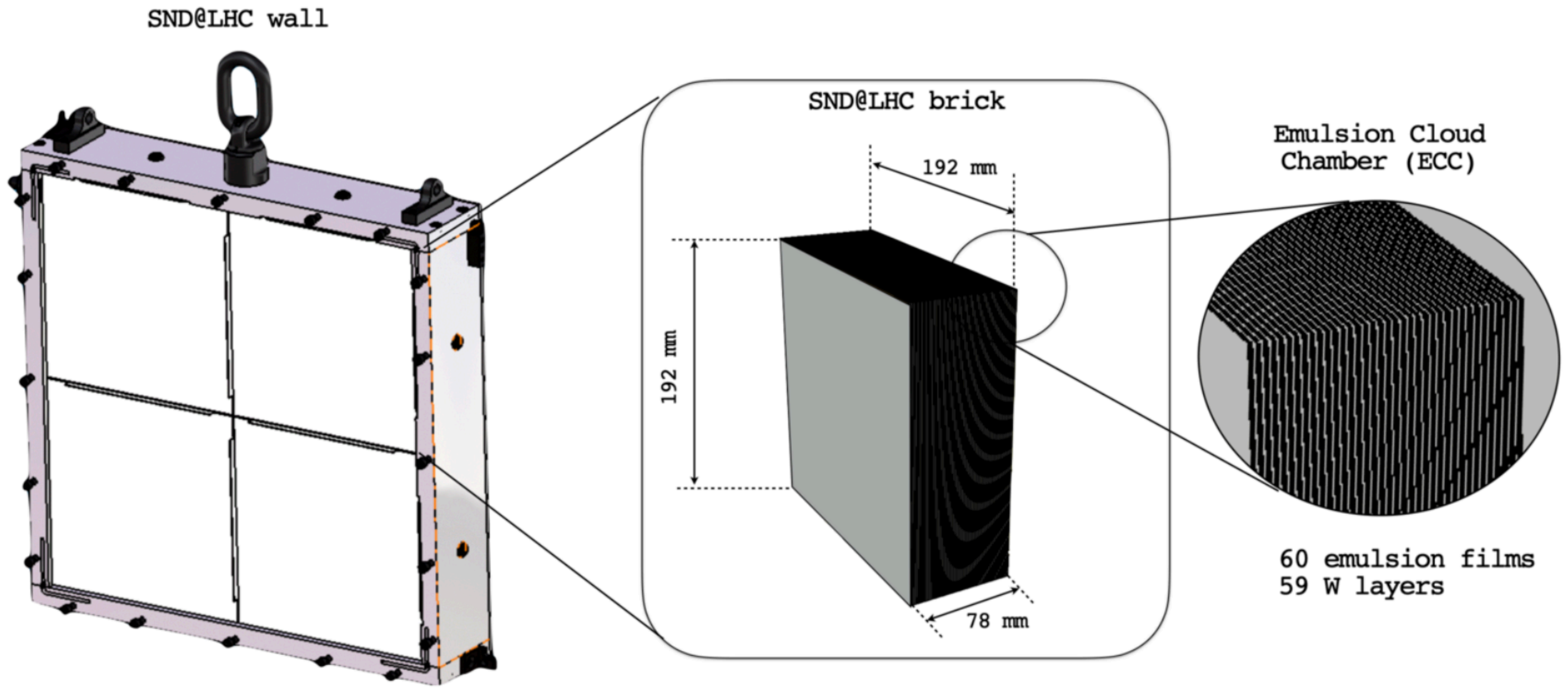
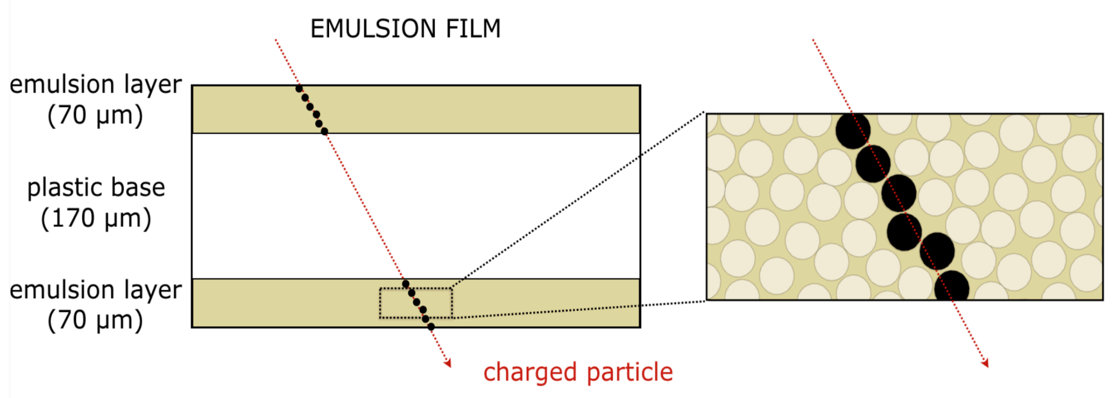
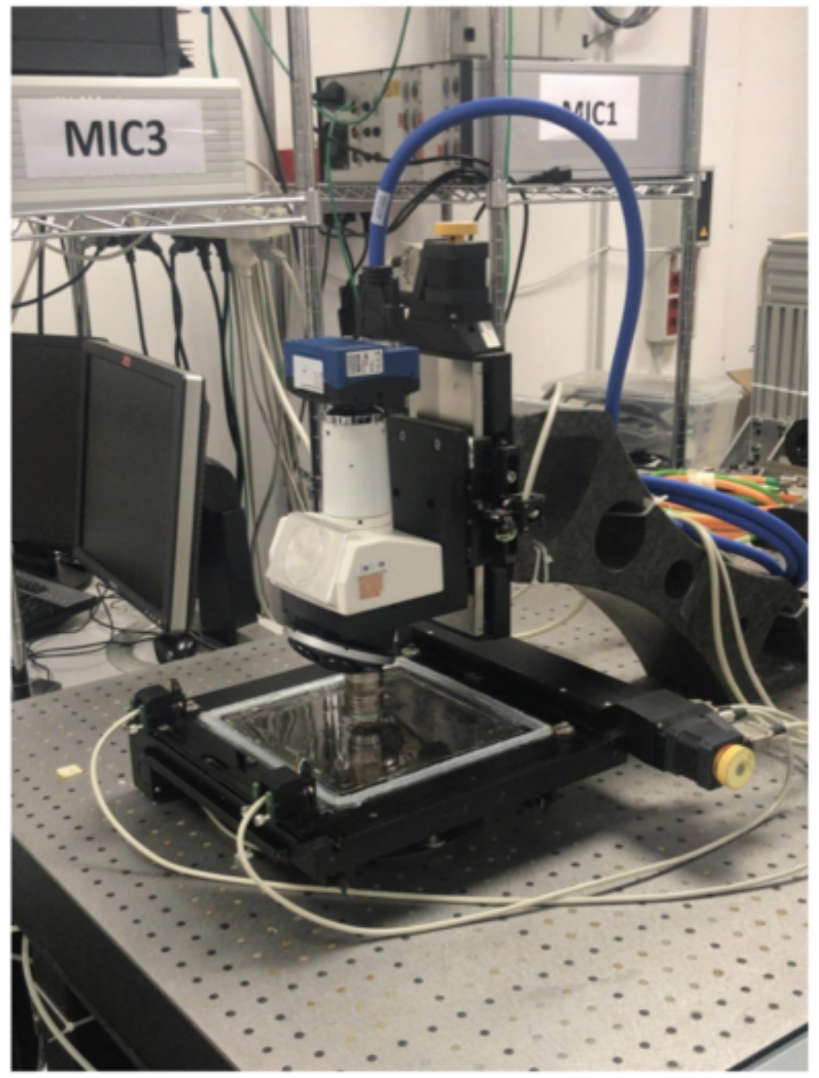
# SND@LHC Detector - Electronic and Emulsion

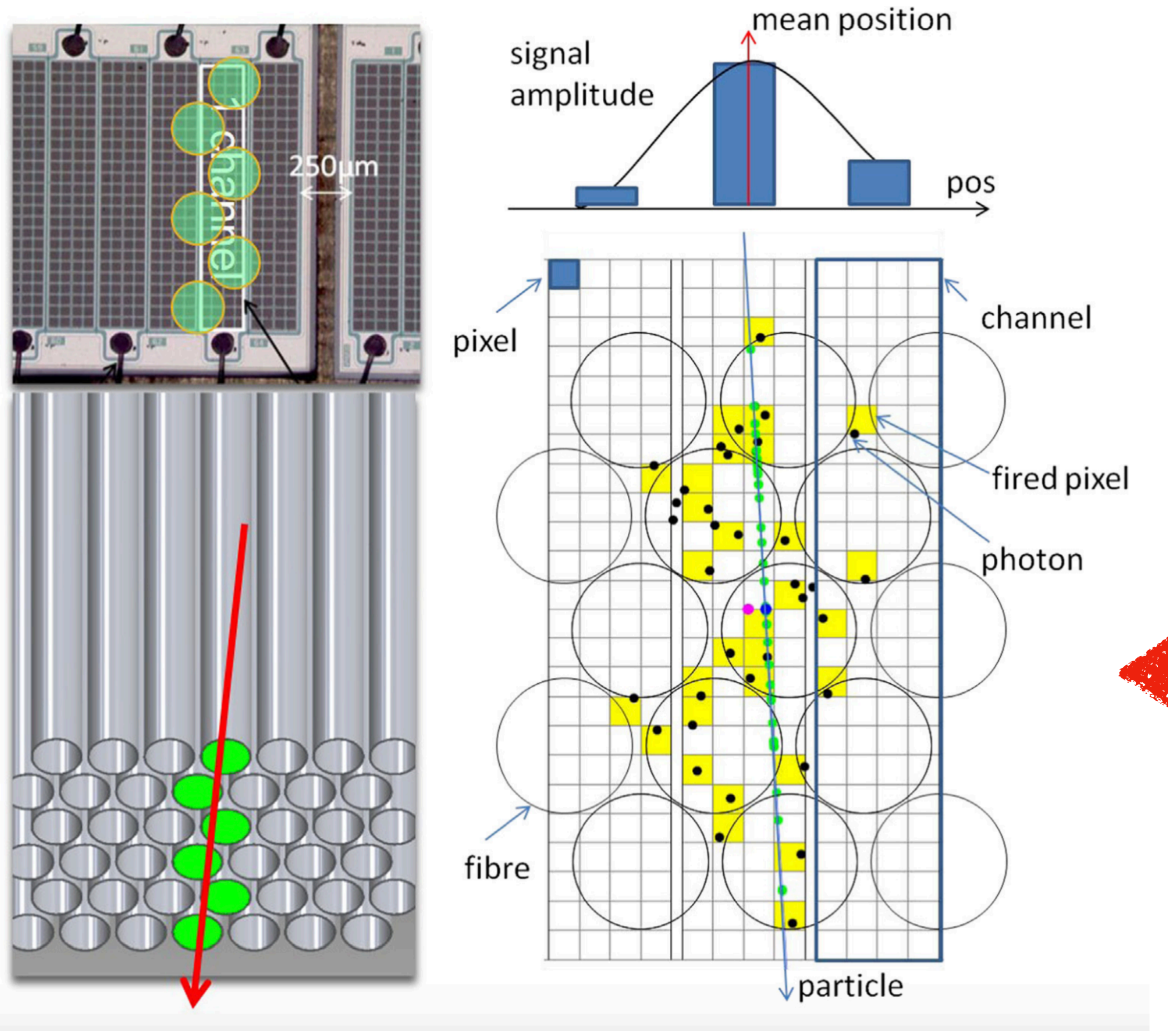




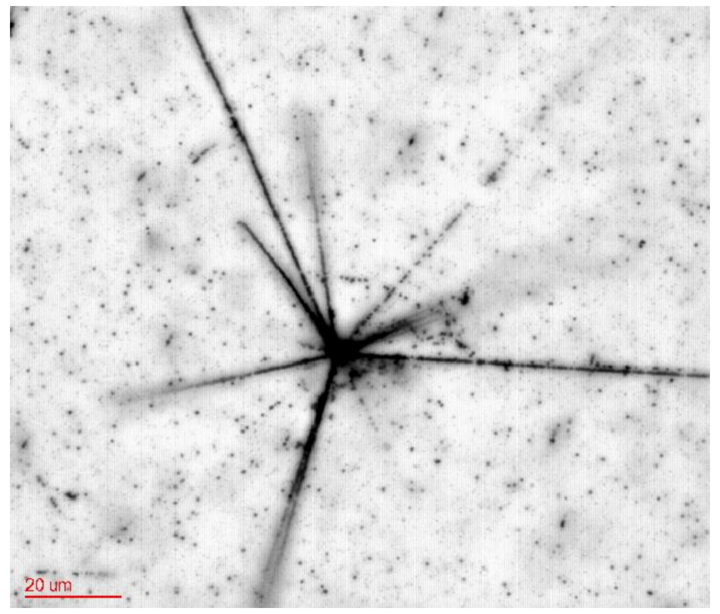

**Emulsion**



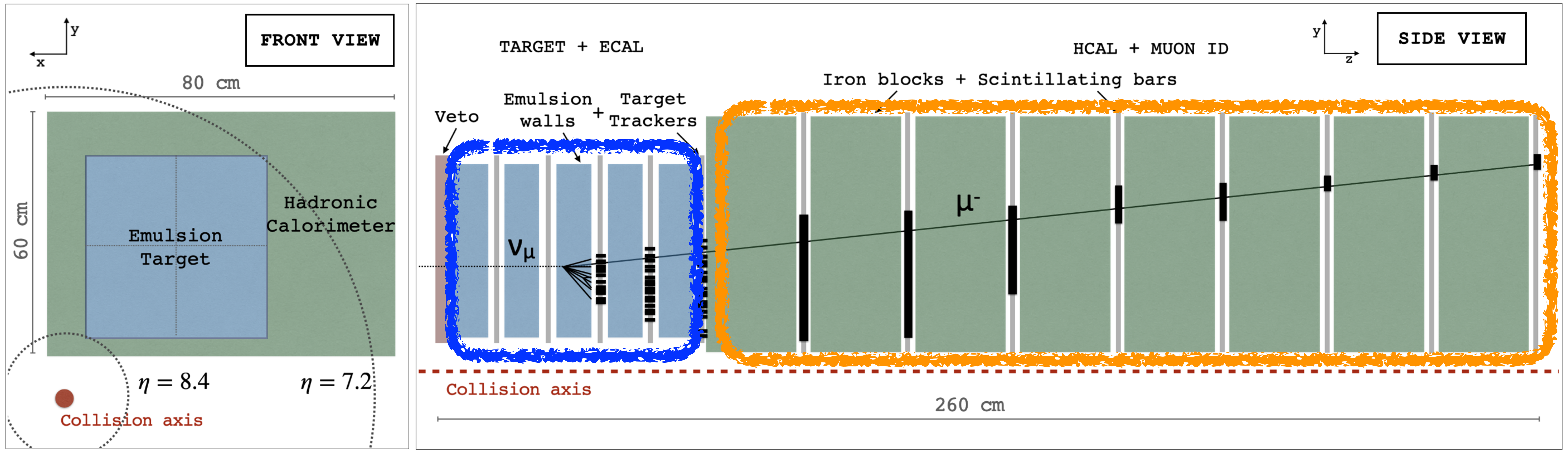



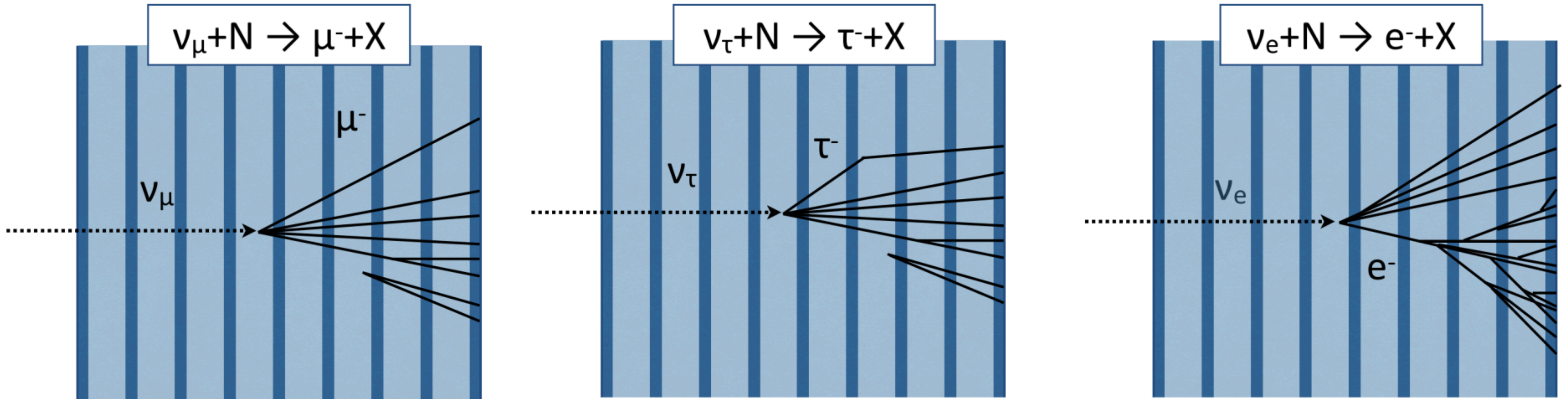

**Scintillating Fibre**
(Electronic signal)

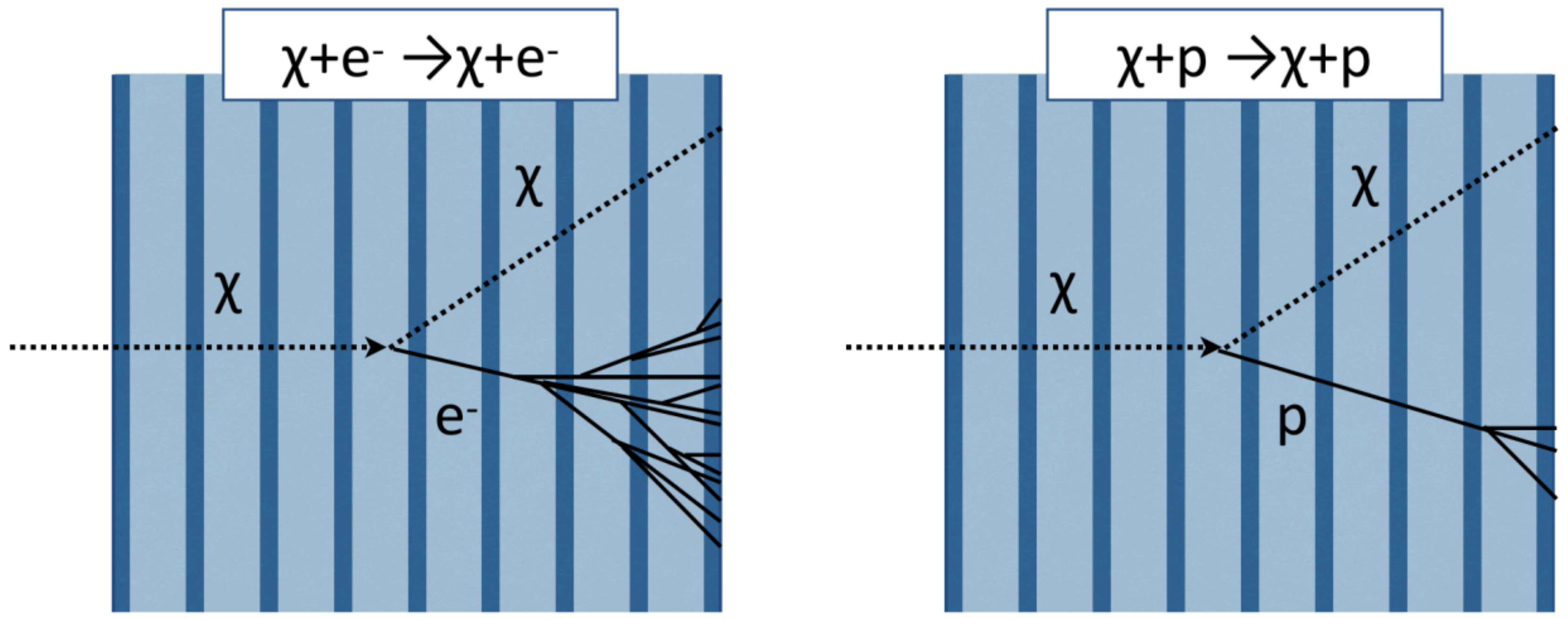


# Neutrino Signature

- **Vertex Detector and ECAL**
  - EM shower
  - Secondary vetex of $\tau$
- **Muon system and HCAL**
  - Muon Track
  - Hadronic shower

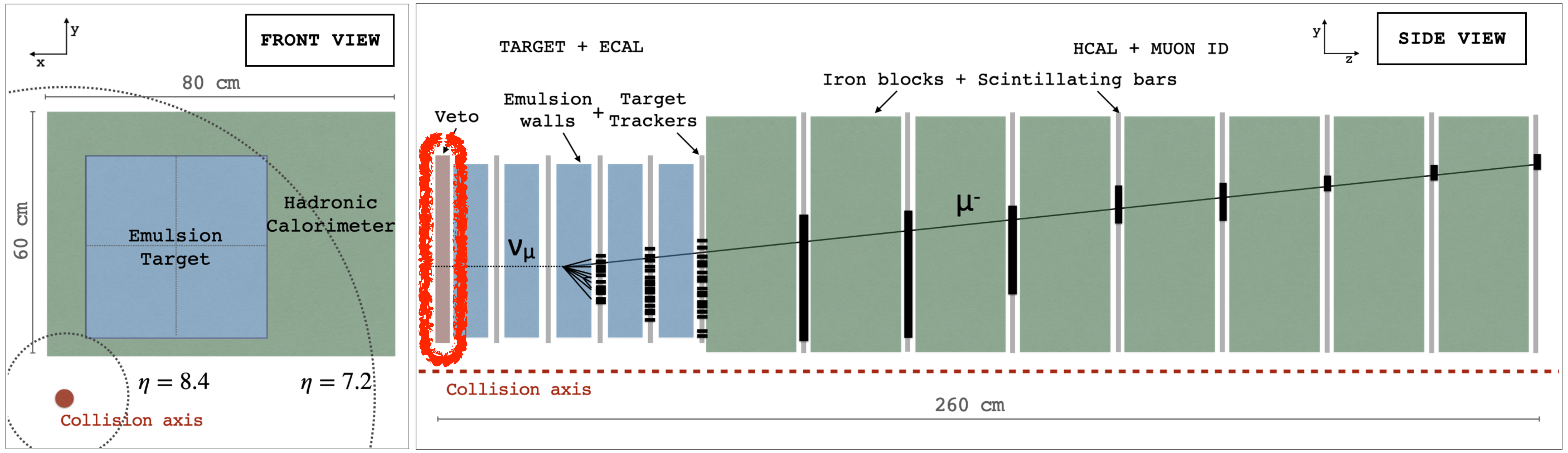


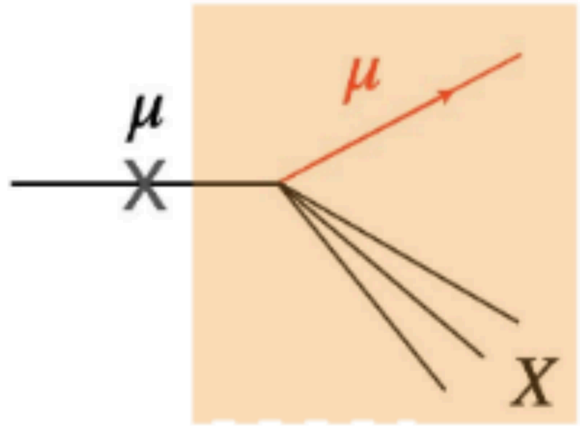



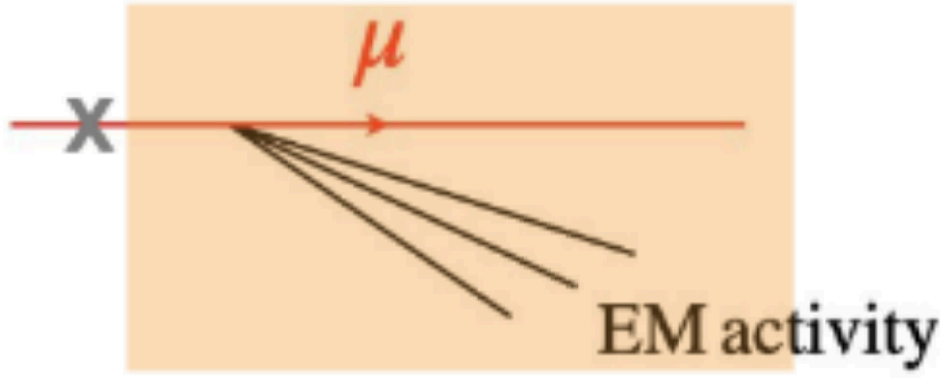
# Background - Muon and Neutral Hadron

- **Muon Background**
  - Generate showers via bremsstrahlung or deep inelastic
  - Can be tagged by Veto
- **Neutral Hadron**
  - Muon-induced neutral particles (mainly neutron And kaon)
  - Mimic a neutrino interaction
    - Charm production
    - Decay in flight

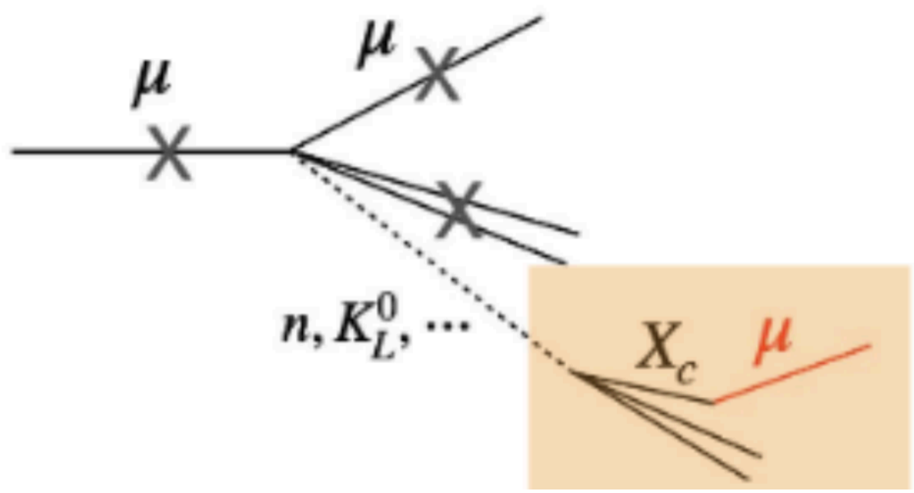


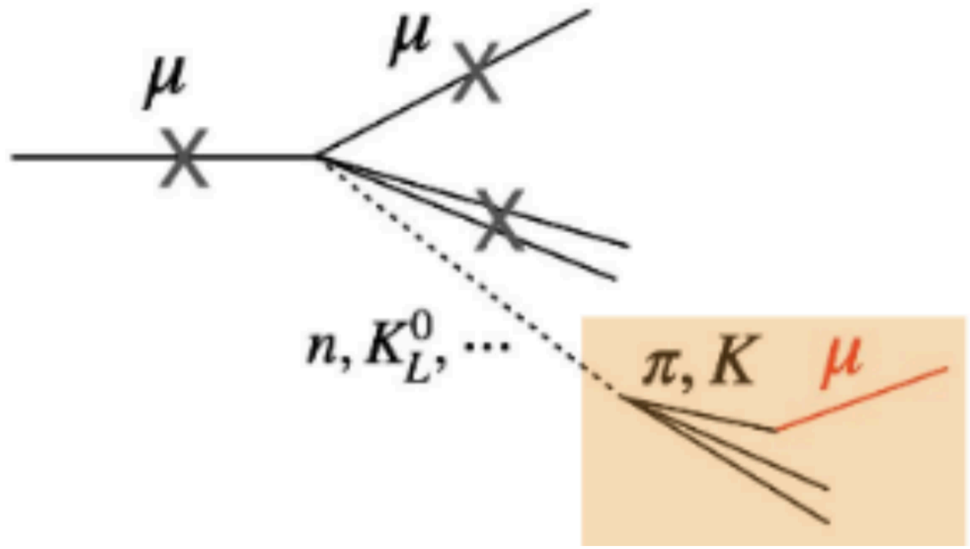

Muon DIS




Muon EM




Charm production




Decay in Flight

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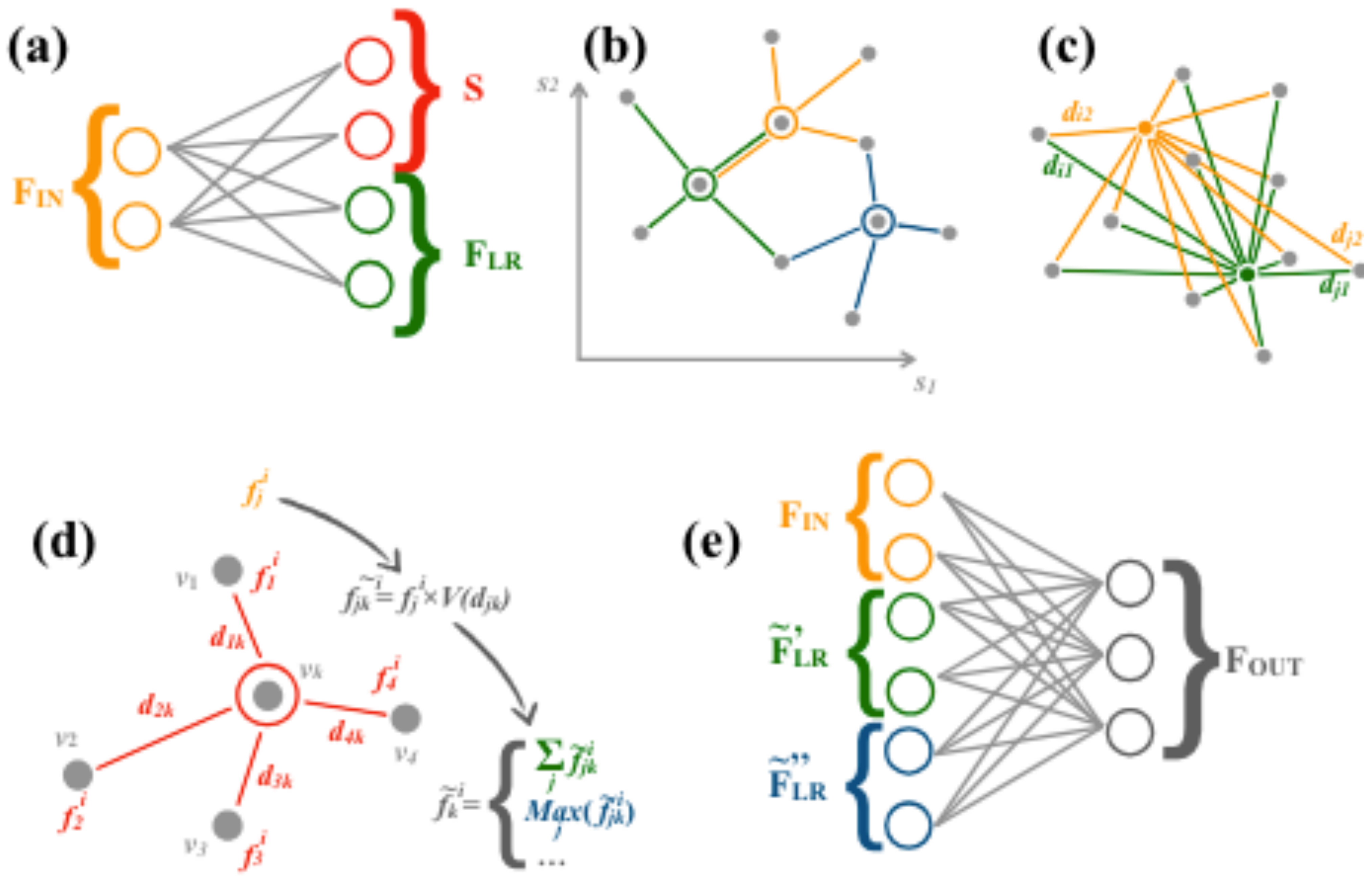
# Dataset and Approach

- Identifying $\nu_e$ interaction events is the current priority
- Monte Carlo simulation Data set
    - ~ 300 k neutrinos
    - ~ 30 million neutral background
- Graph Neural Network (GNN)
    - Hits from electronic detector as nodes
    - Relation between hits as edges
    - End-to-End and multi-classification model

```
bool orientation; // true for vertical (1), false for horizontal (0)
float x1, y1, z1; // coordinates of one end
float x2, y2, z2; // coordinates of the other end
int detType;      // detector type 0: scifi, 1: veto, 2: us, 3: ds
```




Pictorial representation of the data flow across the GravNet layers. [arXiv:2008.03601]

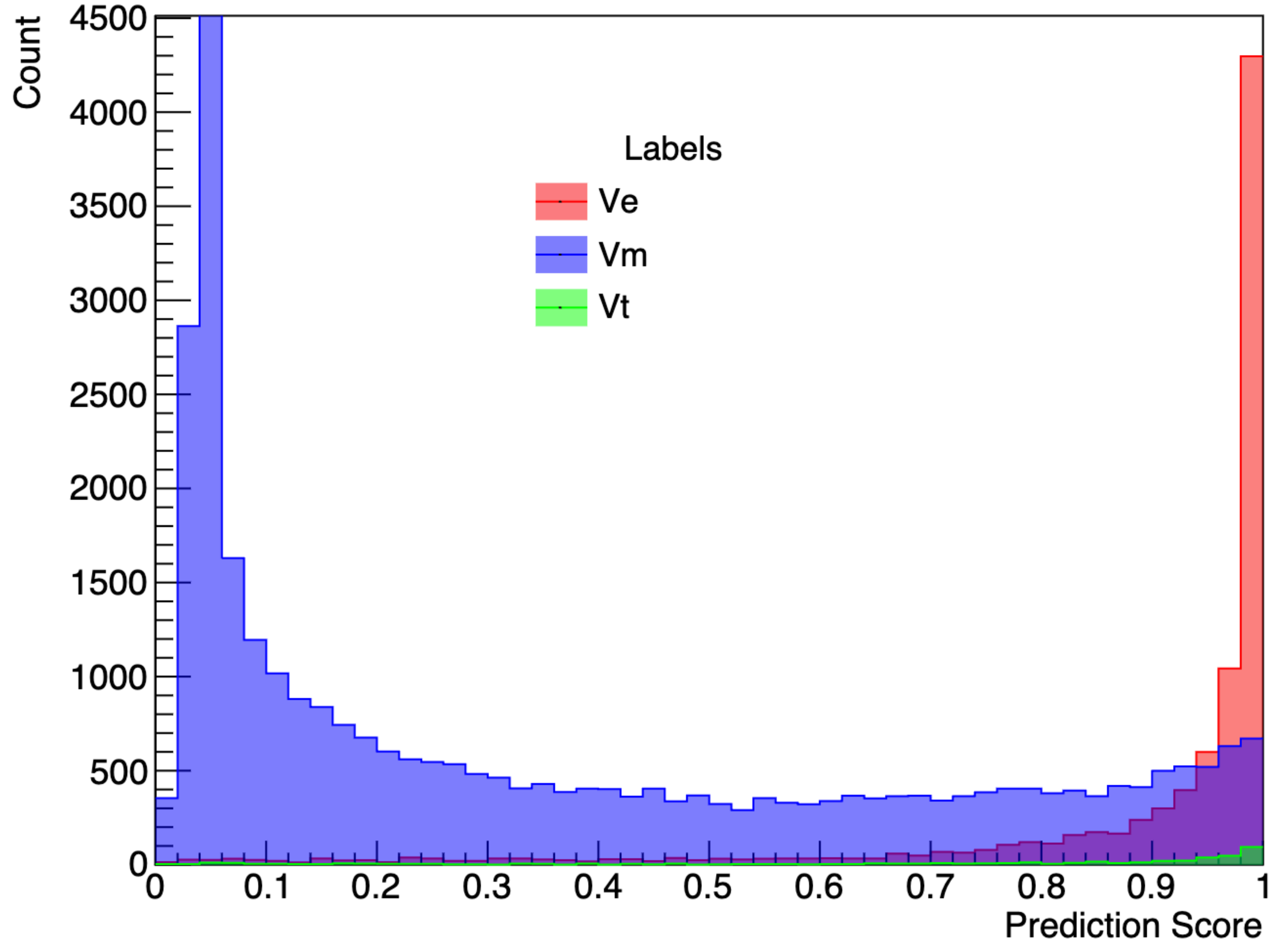
# Evaluation

- Observed **8** neutrino event candidates with a statistical significance of **6.8 $\sigma$** using **2022 data**. The backgrounds from penetrating muons and neutral hadrons background amount to **0.086** events

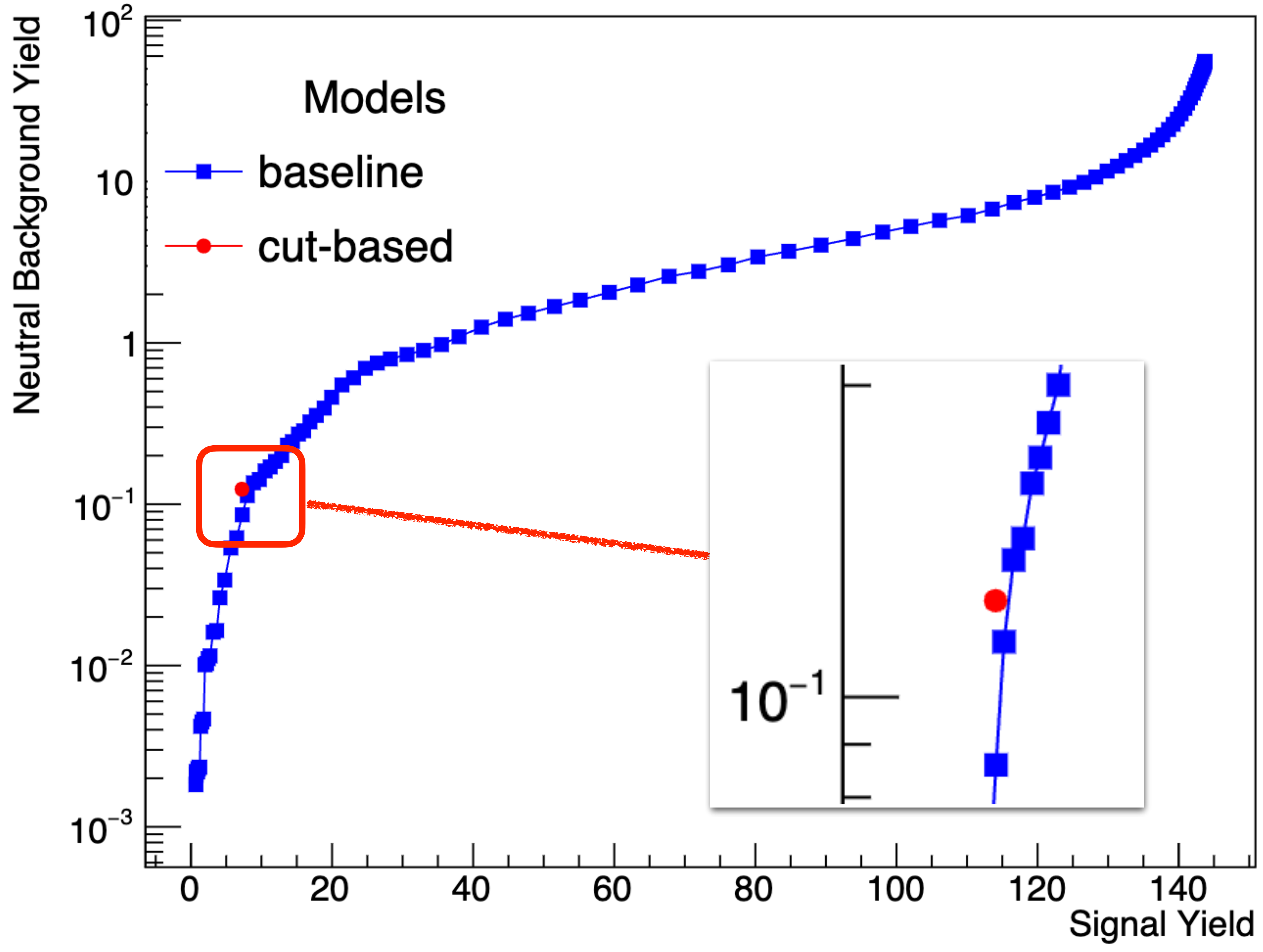
- Efficiency and Yield
  - $\epsilon = \dfrac{N_{pass}}{N_{total}}$
  - $Yield = N_{epected} \times \epsilon$

| | Data | Signal simulation |
|---|---|---|
| All | $8.4 \times 10^9$ | 157 |
| Fiducial volume | $4.9 \times 10^5$ | 11.9 |
| One muonlike track | 17 | 6.1 |
| Large SciFi activity | 13 | 5.1 |
| Large hadronic activity | 12 | 4.7 |
| Low muon system activity | 8 | 4.2 |

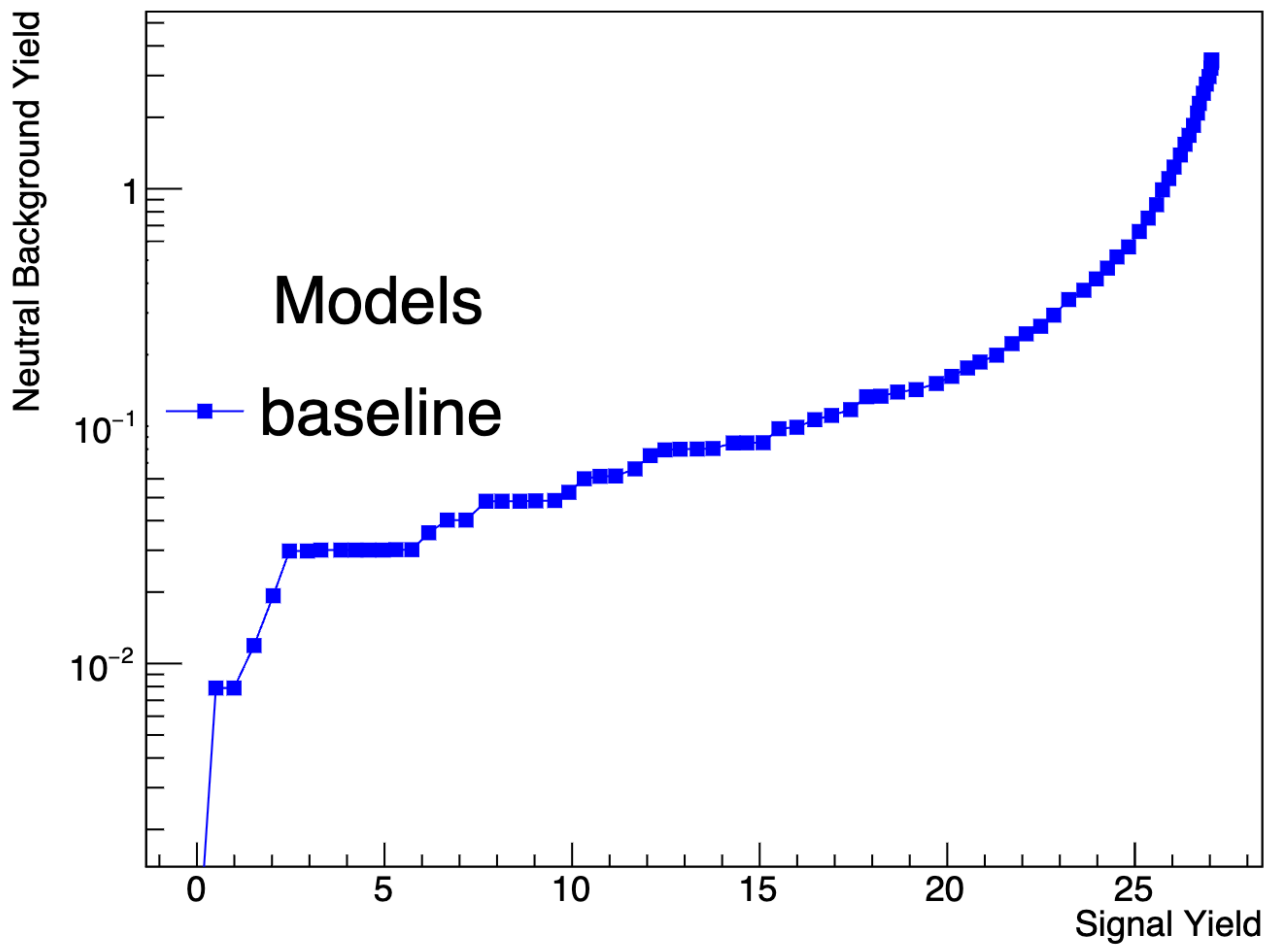
Number of events passing the selection cuts in the data and signal simulation [PRL 131, 031802]



# Neutrino and Neutral Hadron




$\nu_\mu$ selection




$\nu_e$ selection

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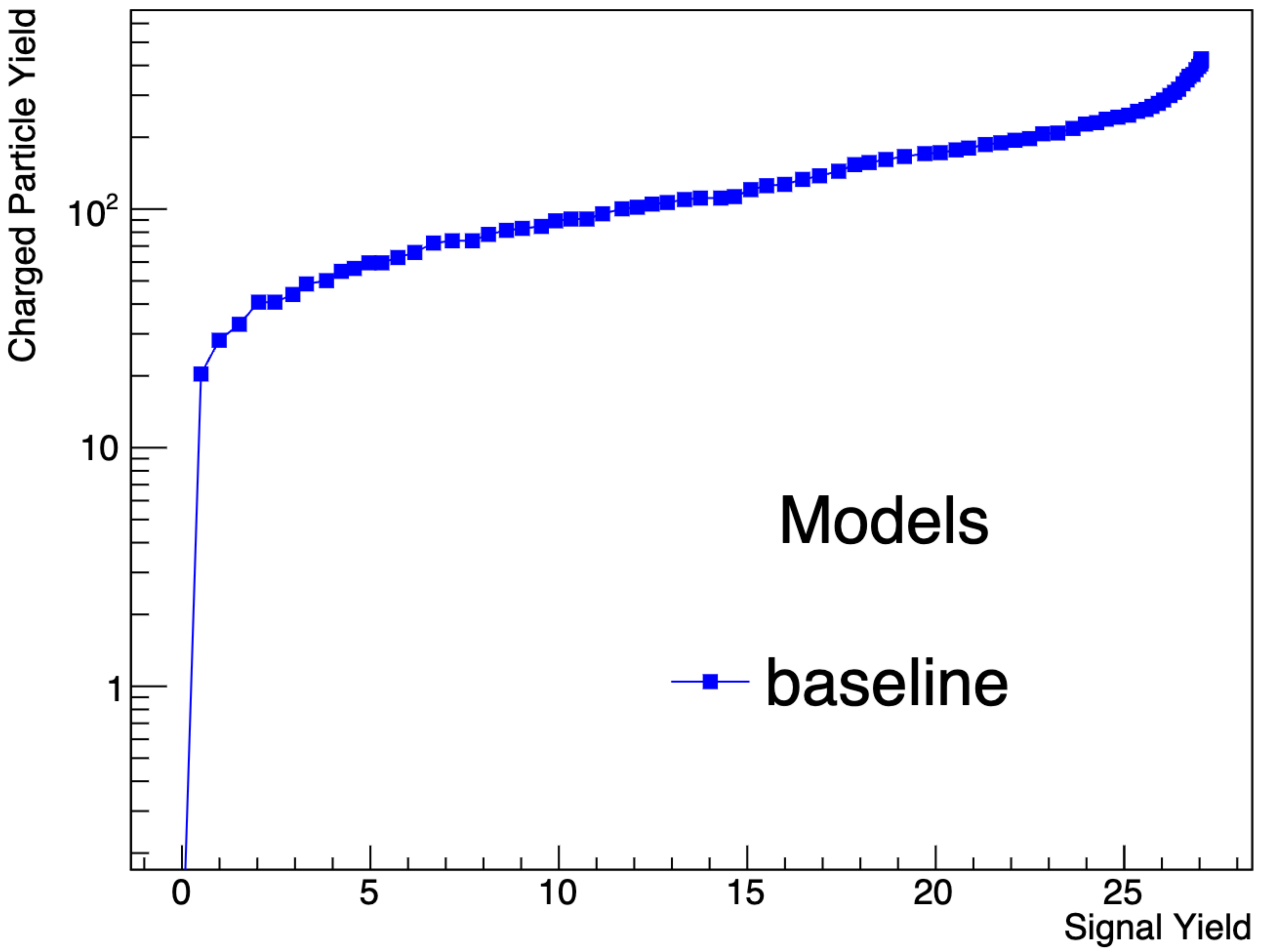
# Muon Background in Progress

- The overall veto system **inefficiency** during the 2022 run is the luminosity-weighted average of the two periods, amounting to $4.5 \times 10^{-4}$
- **Expected** penetrating muons $\sim 5.48 \times 10^5$
- Due to the lack of MC muon background, **real data tagged by veto system** are used to estimate the muon yield
- Baseline model is not trained with muon data




$\nu_e$ selection

# Summary

- We try to identify neutrino interaction out of background at SND@LHC using GNN
- Current model has promising results on identifying $\nu_\mu$ and $\nu_e$ against neutral background.
- Further work need to be done on muon background rejection.

Thank You!

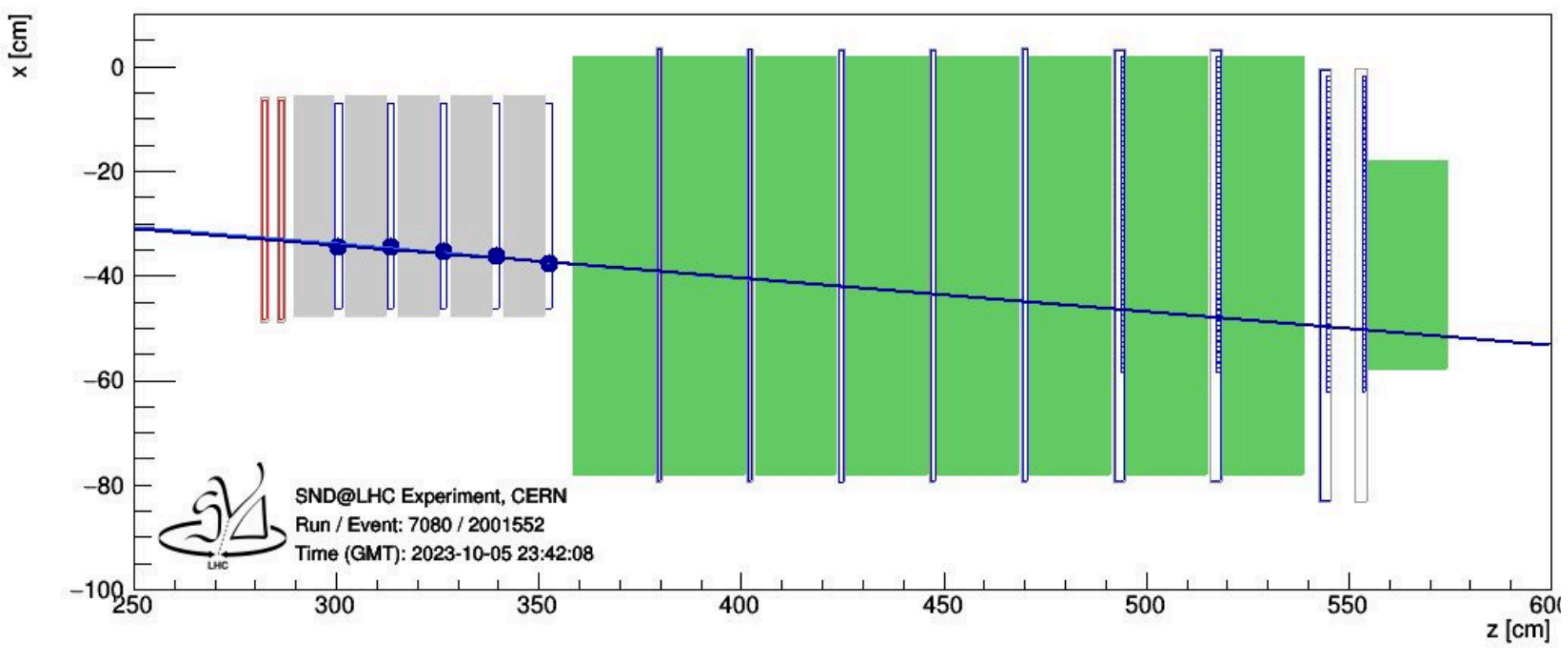
# Back Up

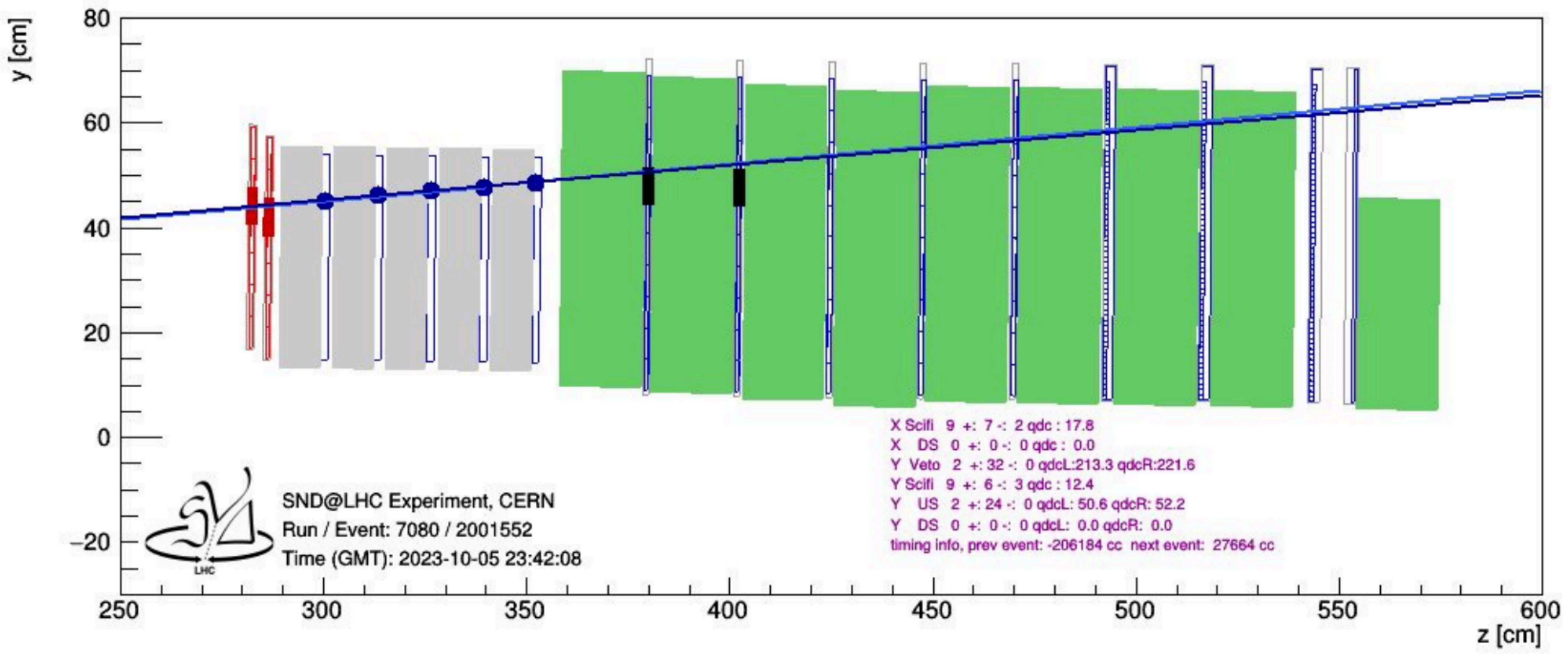
# Extra Training Features

- Weight
  - Normalized $w = \dfrac{Interaction\ Rate}{Number\ of\ Training\ Event}$

- Event features (reconstructed muon track)

```
float px, py, pz; // momentum components
float x, y, z;    // start positions
```

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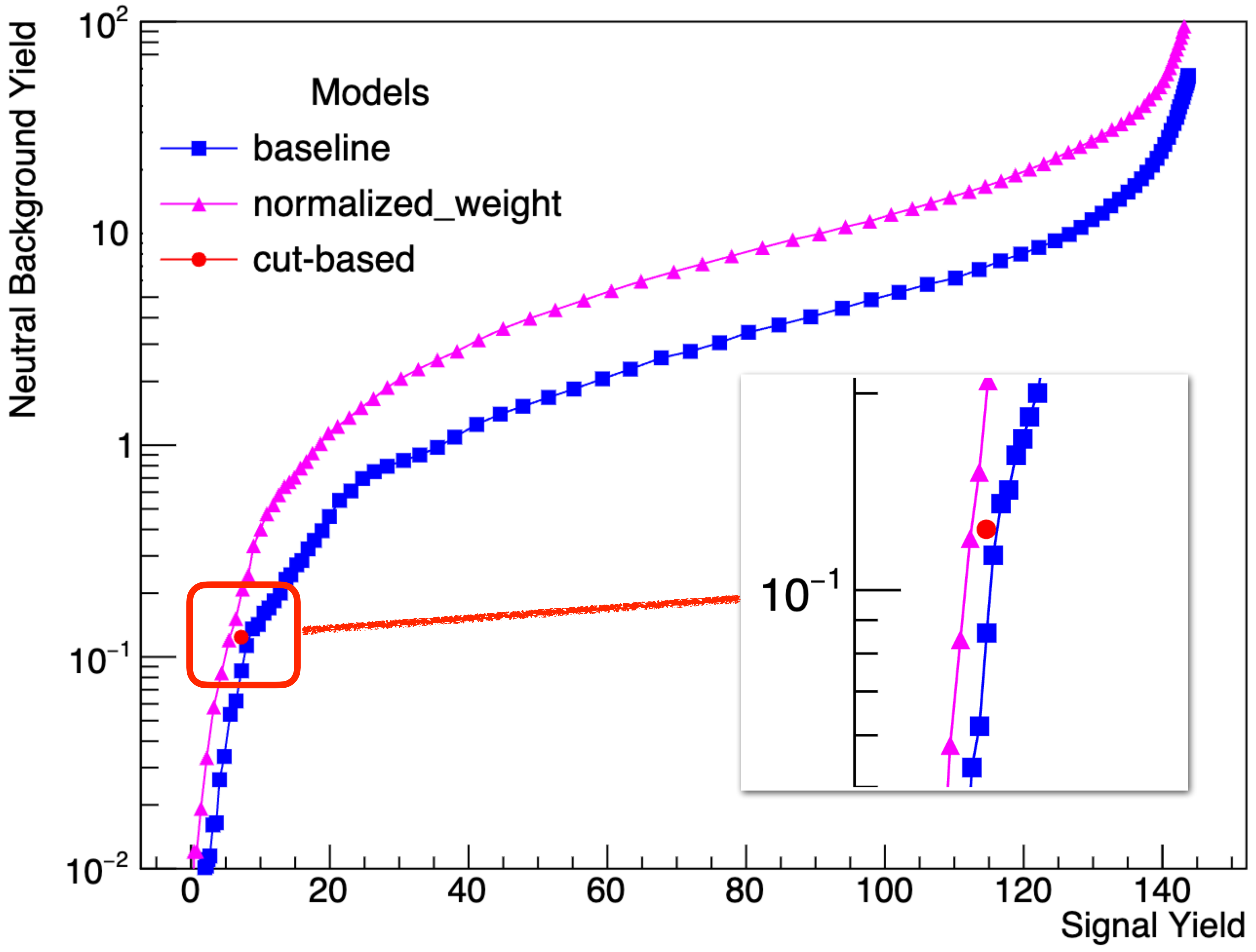
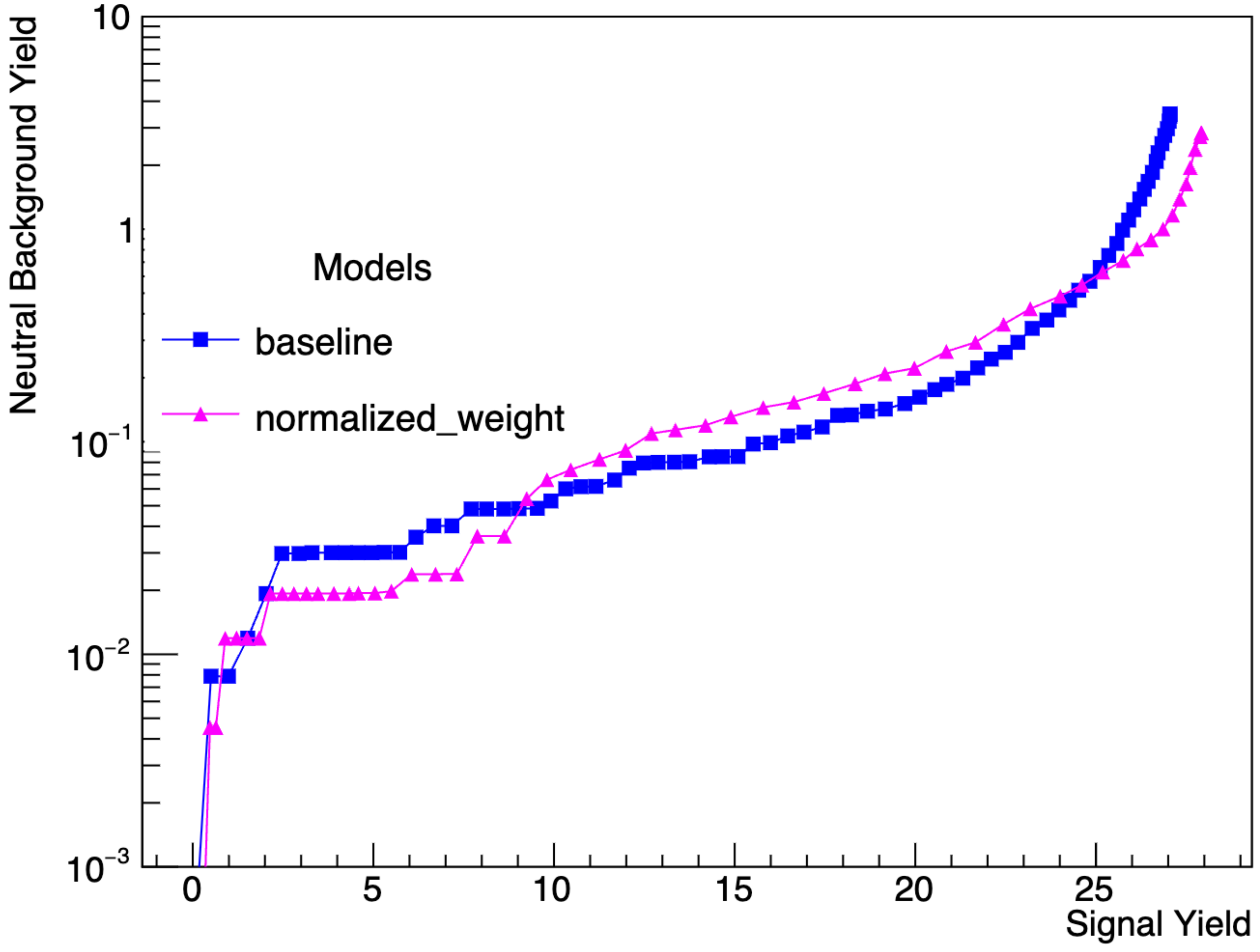
# Neutrino and Neutral Hadron - Weight

- Can not conclude that normalized weight improve the selection results nor the other way.




$\nu_\mu$ selection




$\nu_e$ selection

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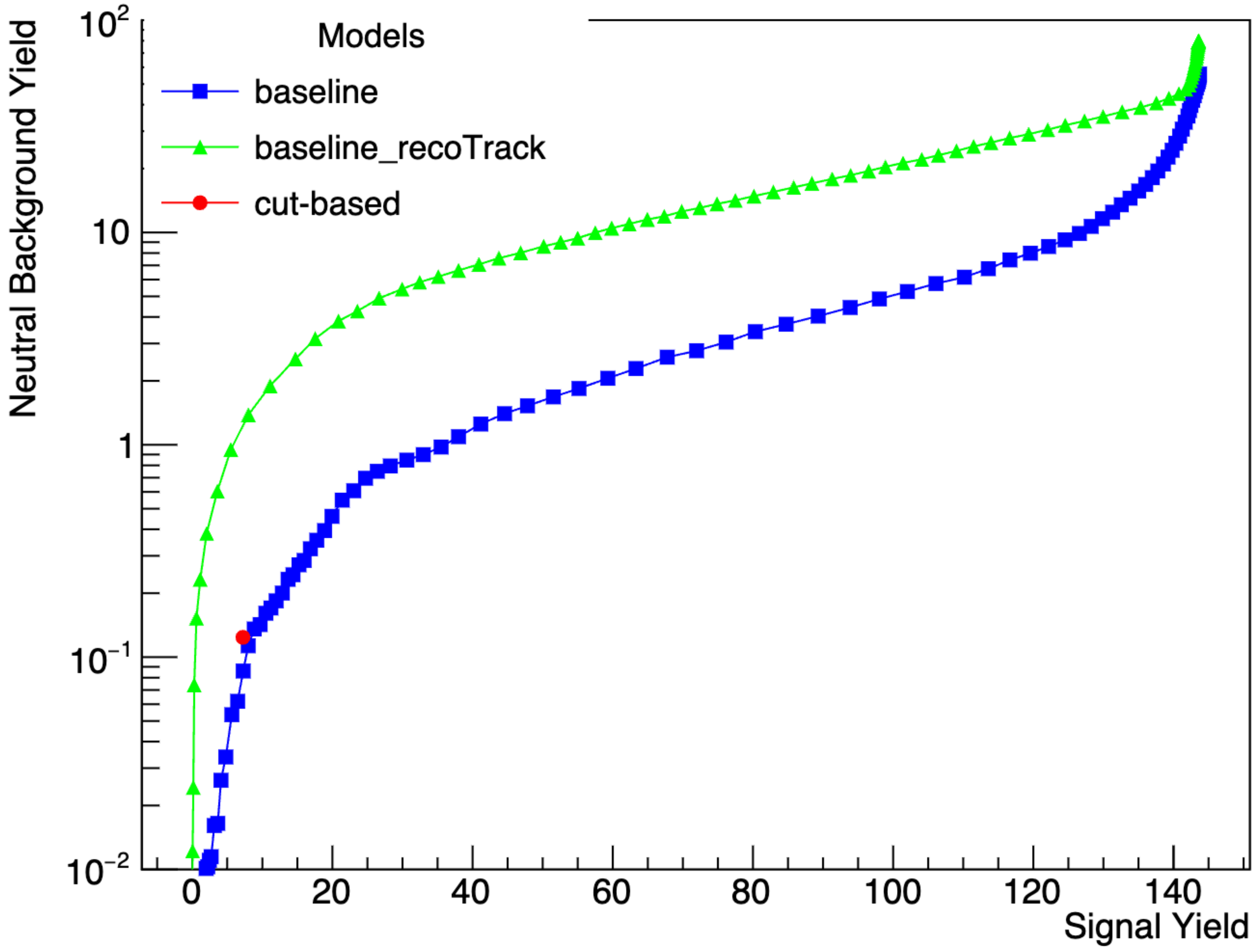
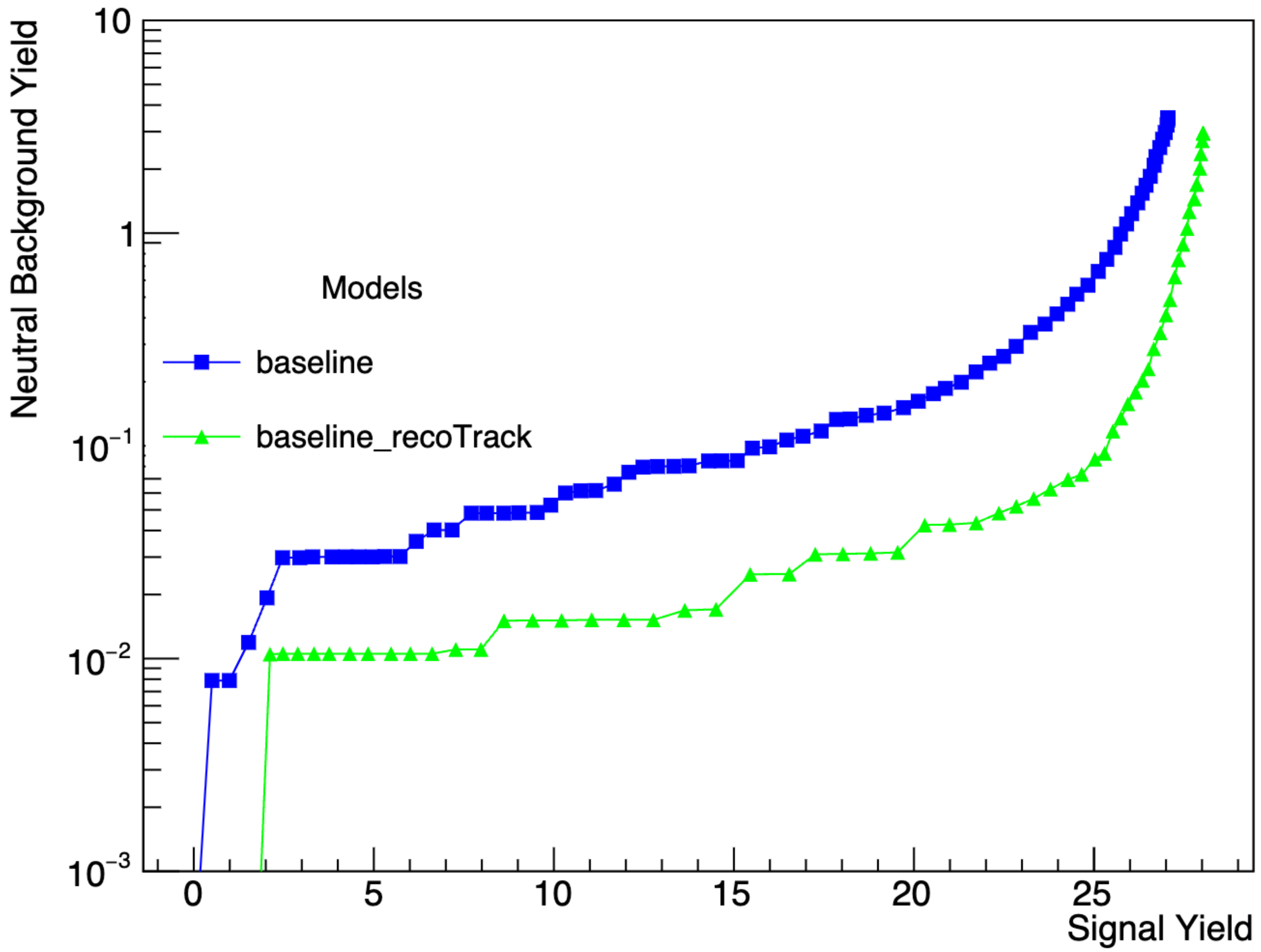
# Neutrino and Neutral Hadron - RecoTrack

- Reconstructed track makes worse on $\nu_\mu$ selection, but improves $\nu_e$ selection

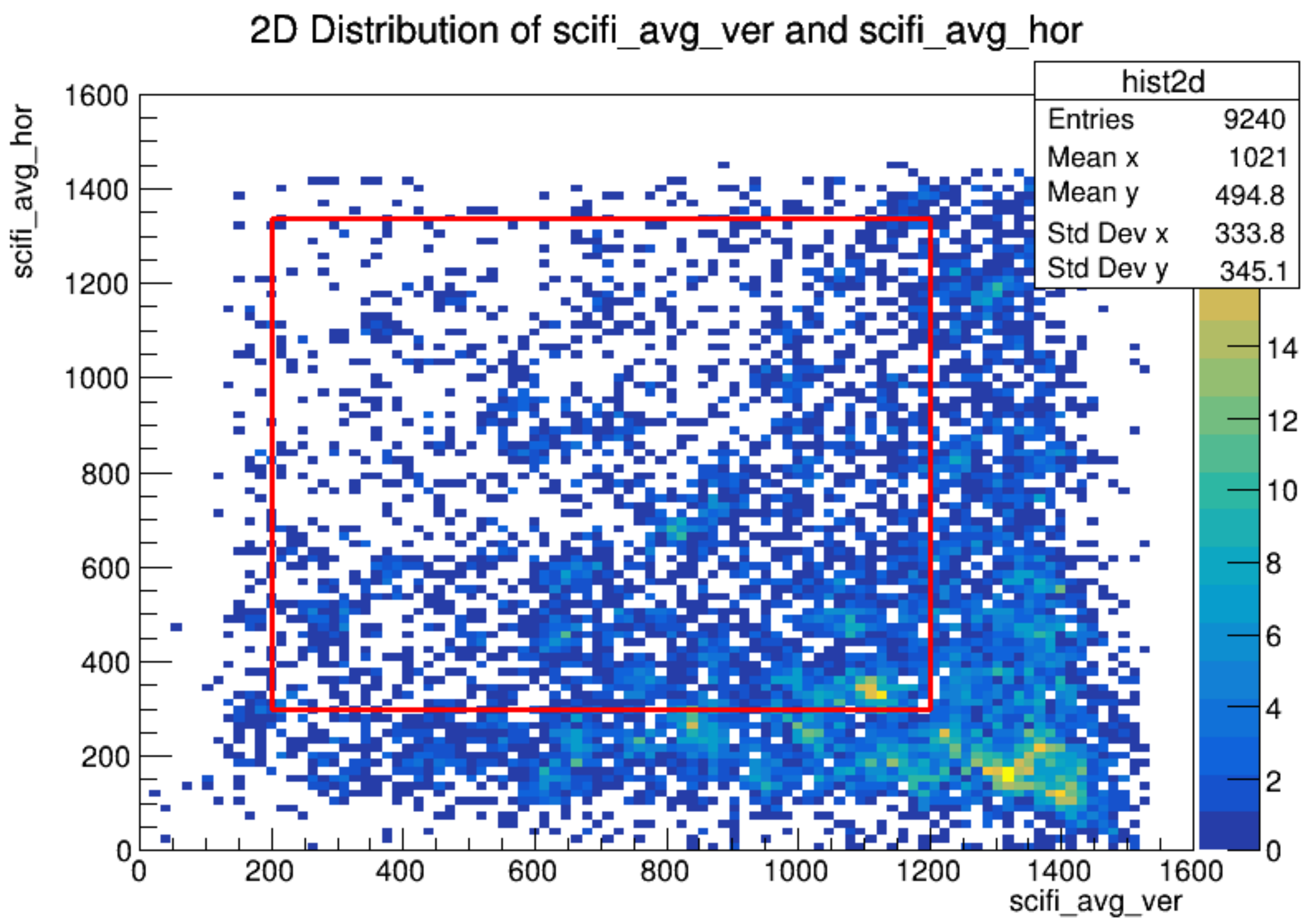


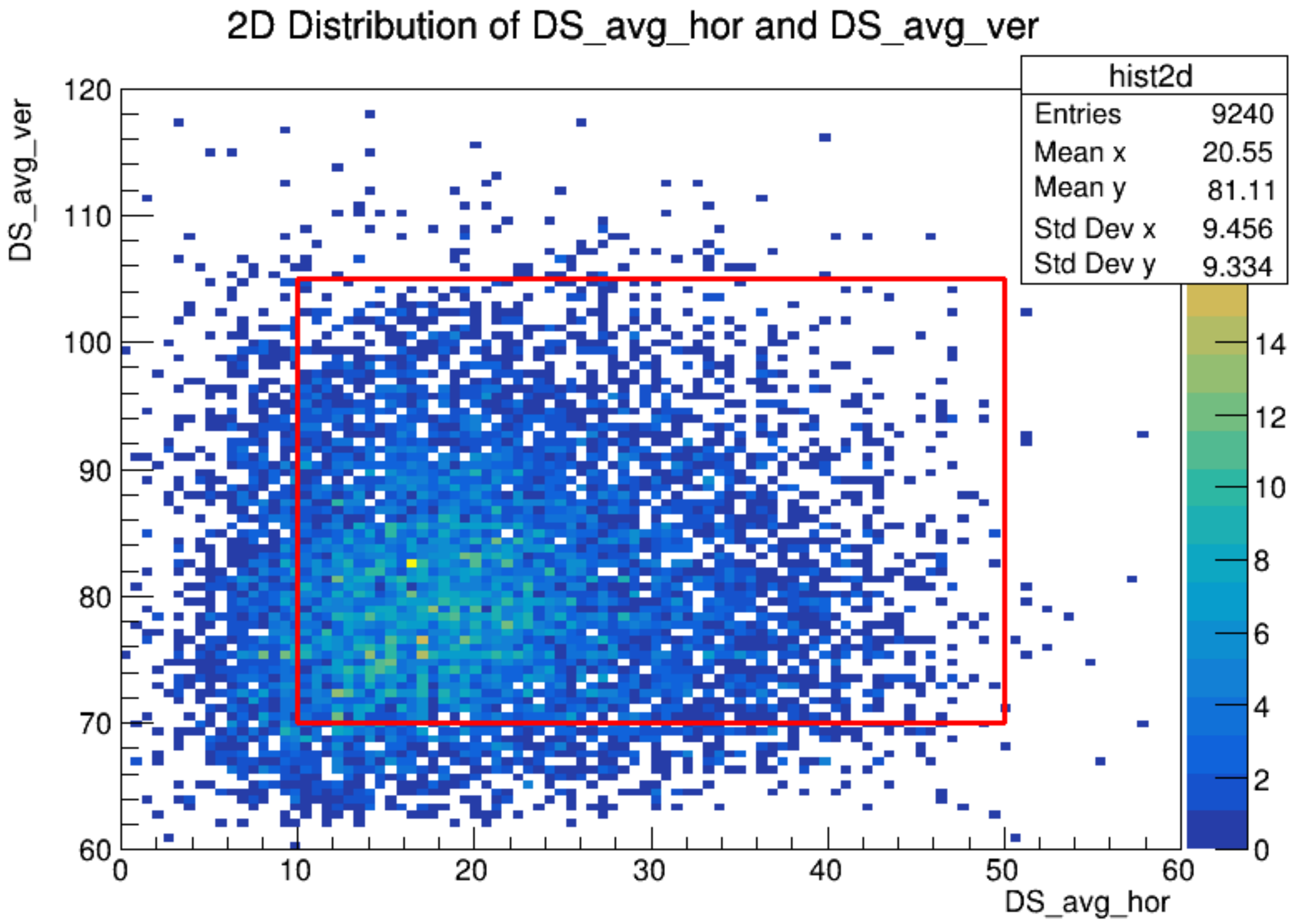

$\nu_\mu$ selection




$\nu_e$ selection

# $\nu_\mu$ Selection XY distribution

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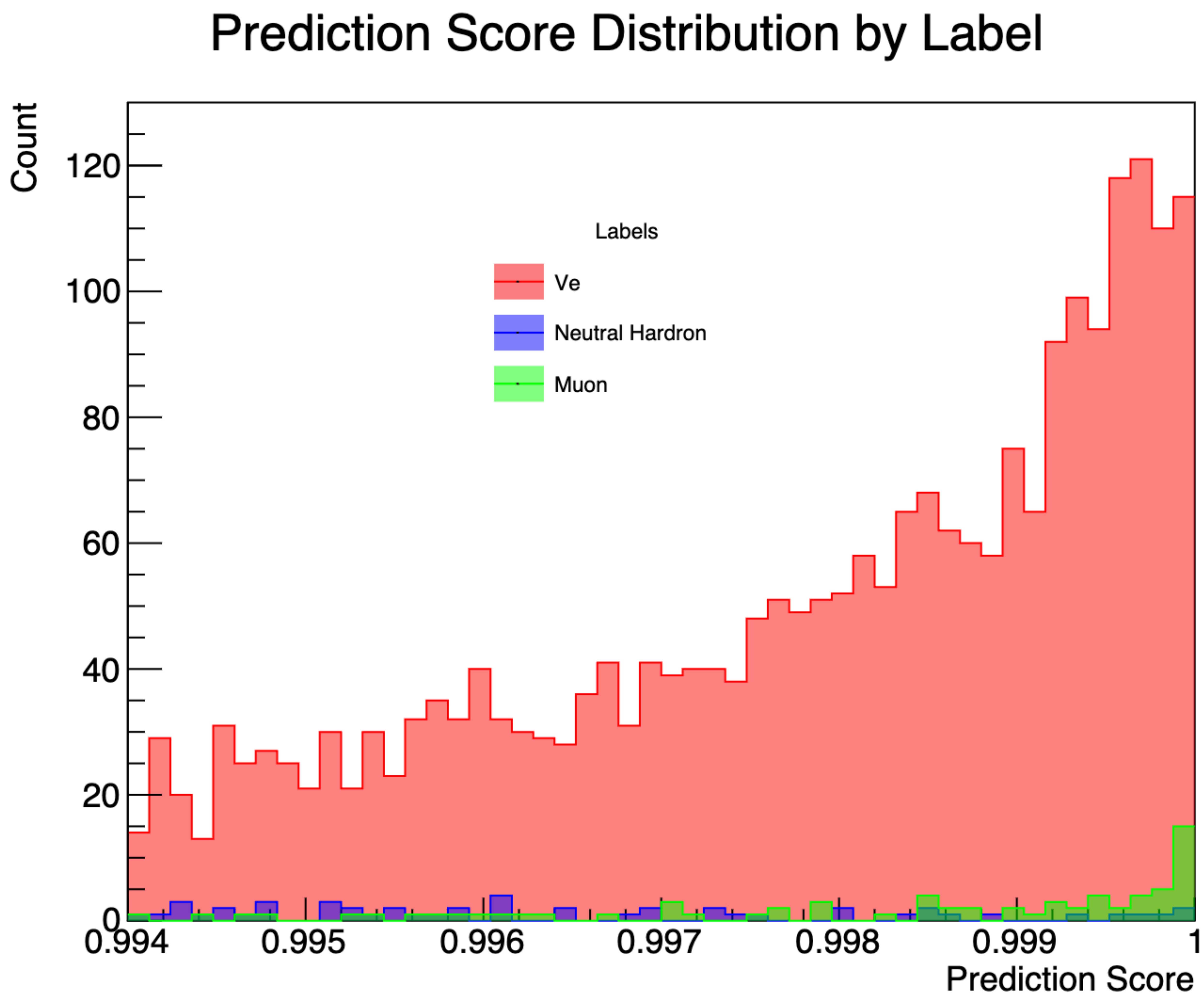

Prediction Score Distribution by Label
Count
120
100
80
60
40
20
0
0.994
0.995
0.996
0.997
0.998
0.999
1
Prediction Score
Labels
Ve
Neutral Hardron
Muon