Muon Neutrino & Antineutrino Event Separation with Machine Learning at MicroBooNE

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Outline

Part I: Introduction

- CP Violation with Neutrinos
- Experimental Setup: MicroBooNE LArTPC
- Muon vs. Antimuon Separation - How?

Part II: Event Selection Chain

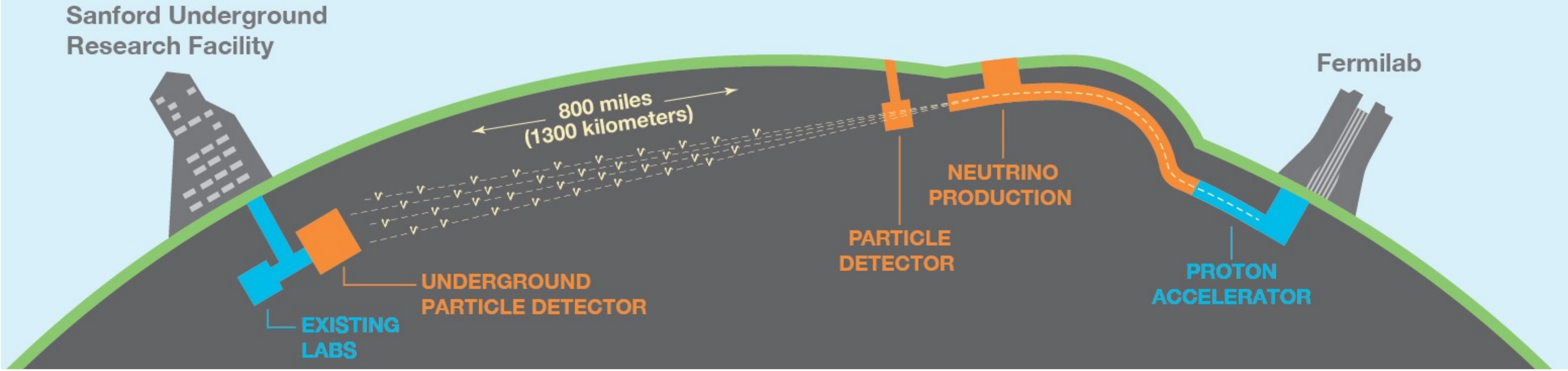
- MicroBooNE & The NuMI Beam Exposure
- General Selection Cuts
- BDT Selection Cuts

Part III: Selected Samples

- Charged Current ν_μ Sample
- Charged Current $\bar{\nu}_\mu$ Sample

Part I: Introduction

Introduction: CP Violation & Upcoming Experiments



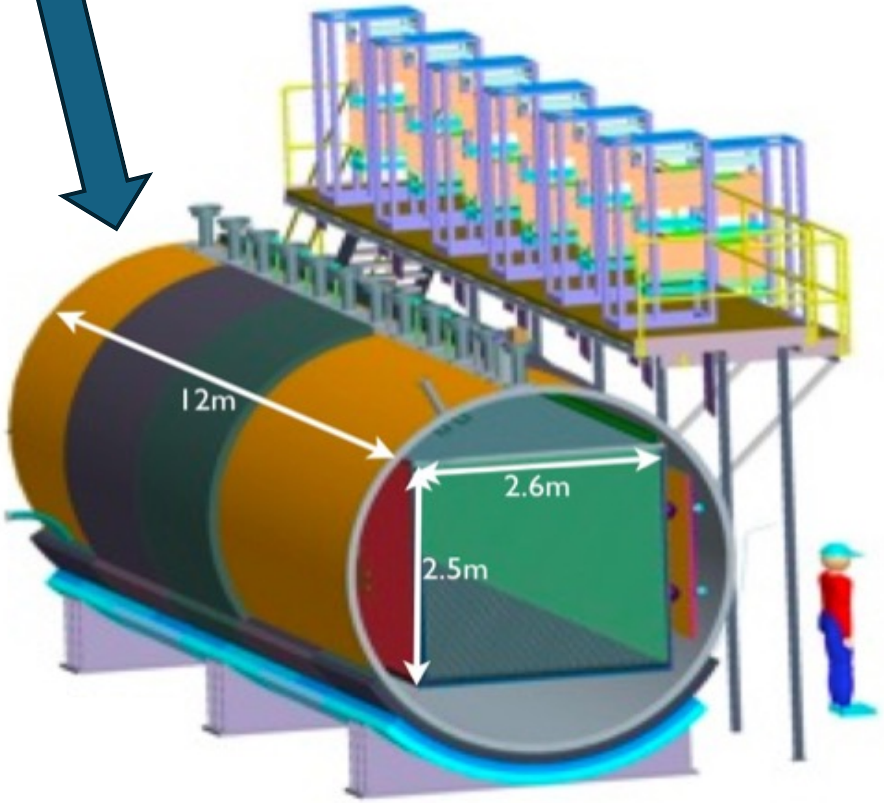
- The upcoming neutrino experiment DUNE aims to definitively measure the degree to which Charge-Parity (CP) symmetry is violated in the lepton sector of the Standard Model, using a **Liquid Argon Time Projection Chamber (LArTPC).**
- It will do this using a neutrino beam, focused in **either neutrino or anti-neutrino mode**.

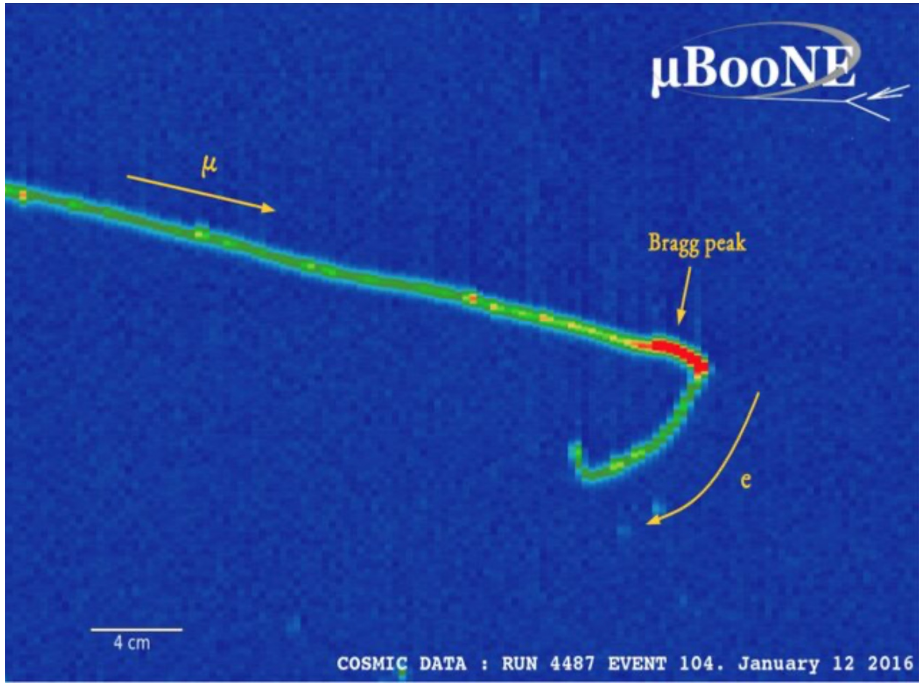
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

MicroBooNE Detector & Run 3 Flux

MicroBooNE is another large (~10 x 2.5 x 2.5 m^2) Liquid Argon Time Projection Chamber

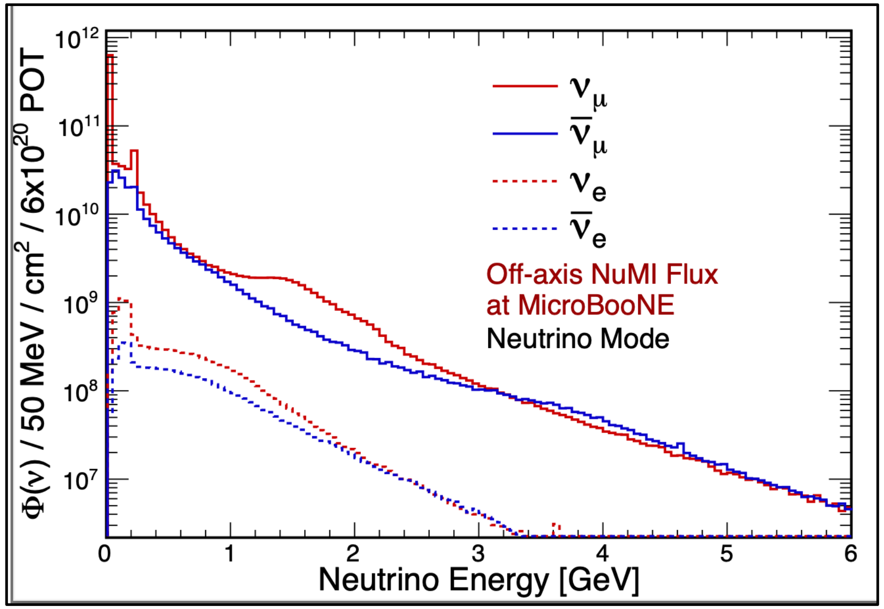
The samples used in this analysis correspond to the **Run 3 Flux (2017 – 2018)**

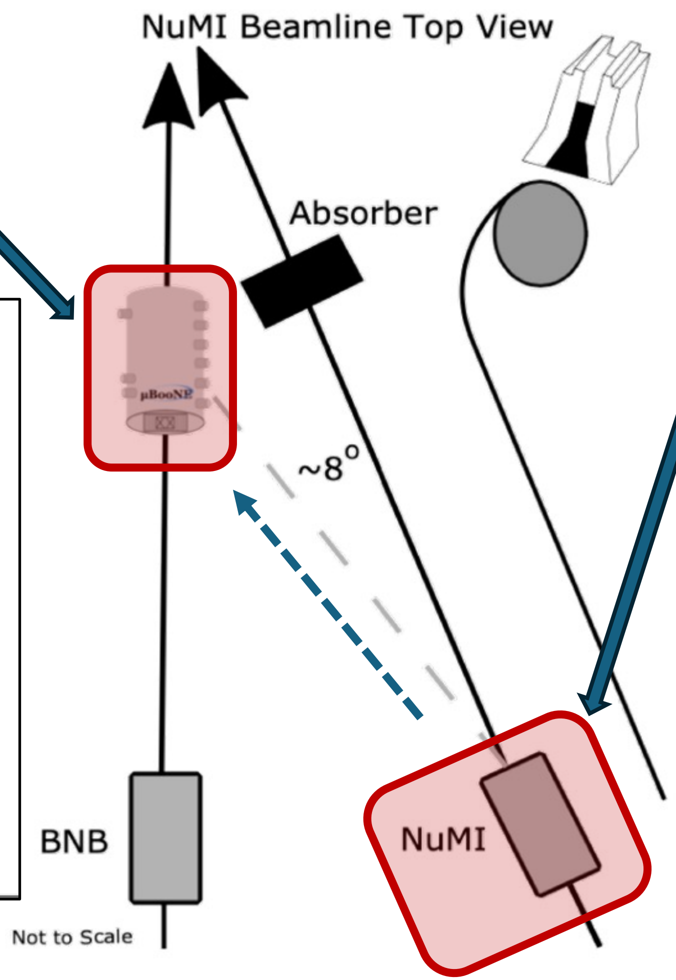




MicroBooNE & The NuMI Beam

- The **MicroBooNE detector** is a ground-level Liquid Argon Time Projection Chamber (LArTPC) that observes neutrinos at an **off-axis exposure** to the **Neutrino at the Main Injector (NuMI) beam**.



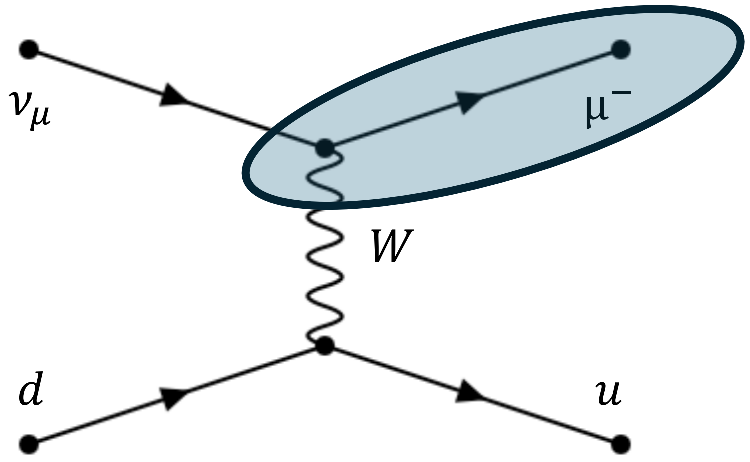


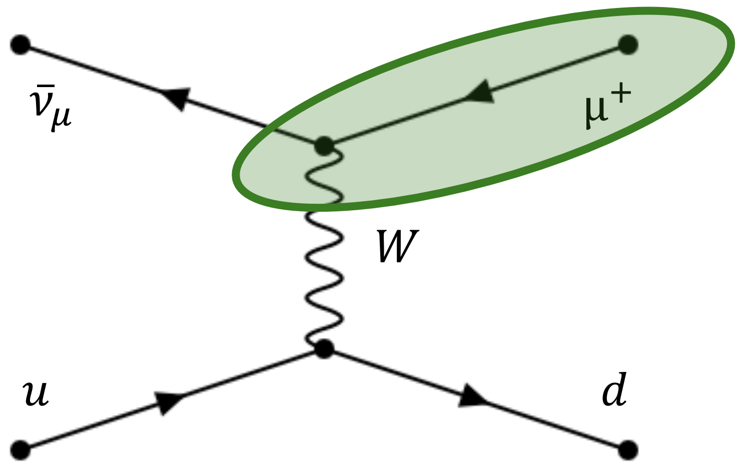
μBooNE

- Largest $\nu - Ar$ dataset to date
- **Ground-Level**: Large exposure to cosmic contamination
- **Off-Axis**: Significant mixture of $\nu/\bar{\nu}$, regardless of beam polarity

Tricky Bit: CC ν_μ and CC $\bar{\nu}_\mu$ Separation

- This is a challenging task, since the resulting μ^+ and μ^- leptons, in the absence of a magnetic field, behave in essentially the same way in liquid argon.





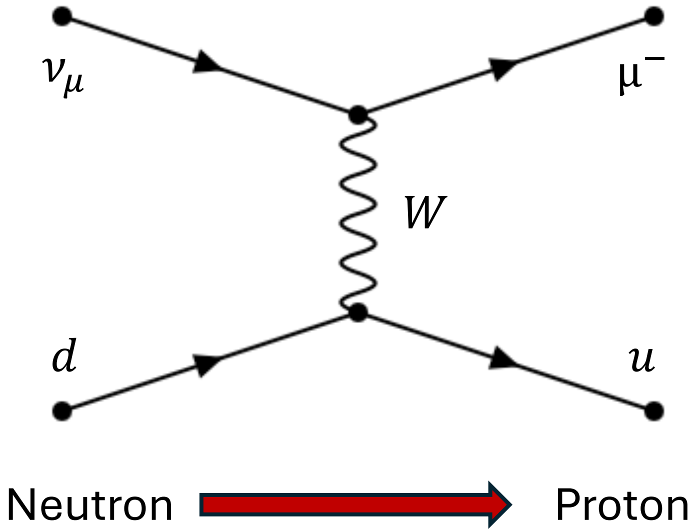
- However, we may have a few potential handles on this:

1. Number of proton tracks
2. Muon Absorption
3. Angular Dependence

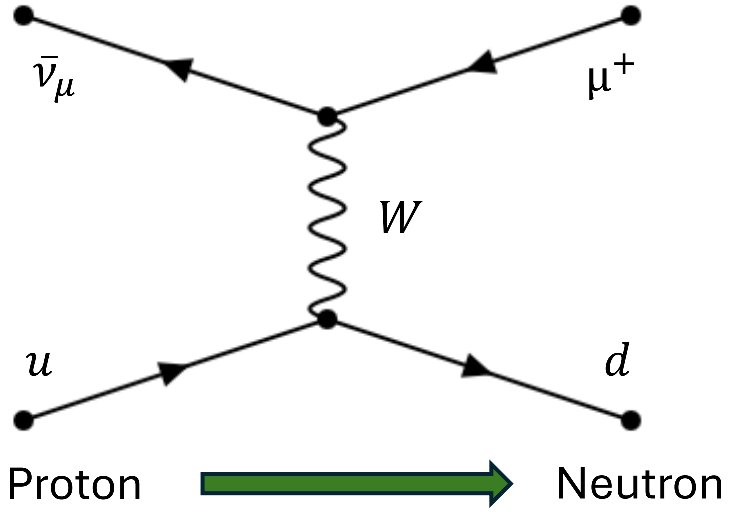
Handle 1: Additional Proton Track

In the Charged-Current Quasi-Elastic (CCQE) regime, we expect to **see an additional proton track for ν_μ**, but none for the $\bar{\nu}_\mu$.

Neutrino



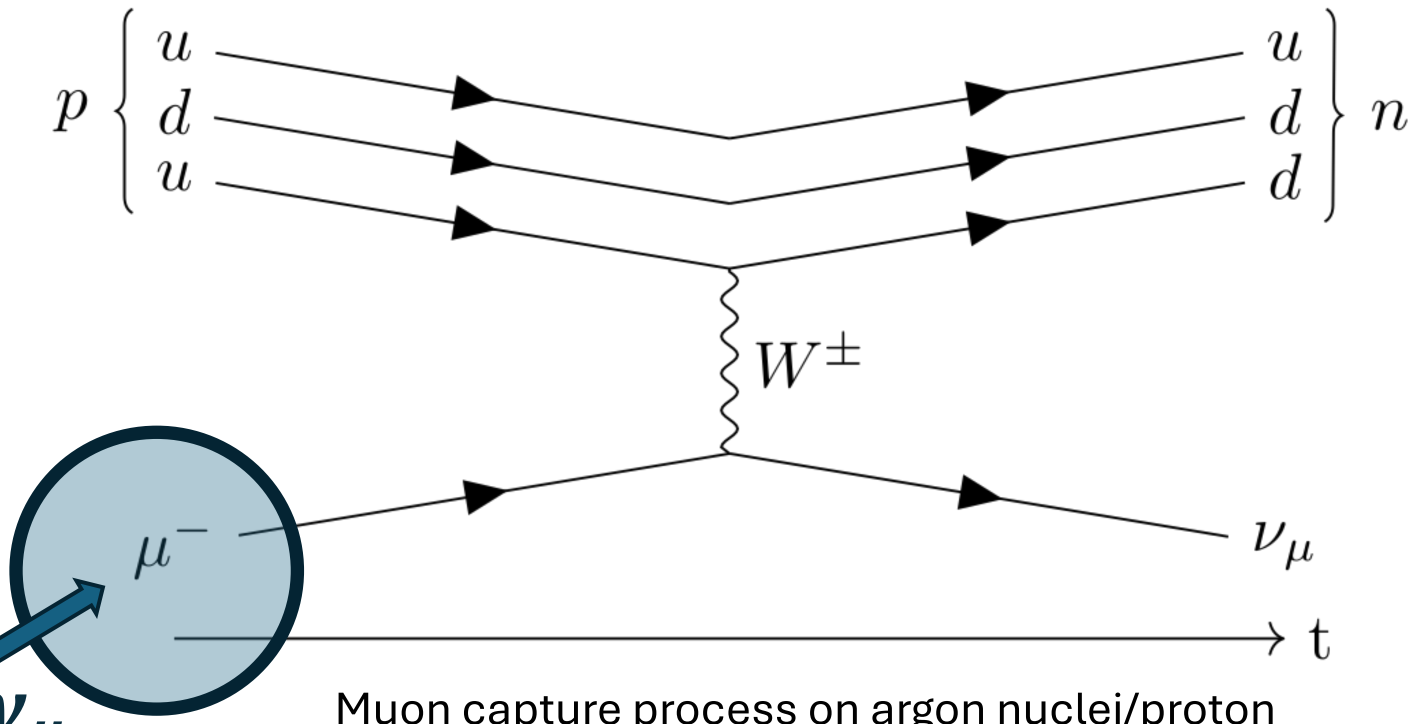
Antineutrino



Handle 2: Muon Absorption

For muons stopping in the detector, around **75% μ^- will be absorbed**, whereas **no μ^+ are absorbed.**

$$p + \mu^- \rightarrow n + \nu_\mu$$



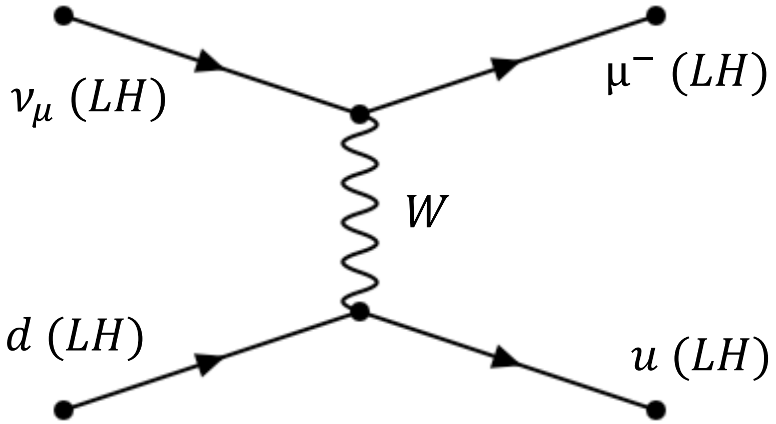
From CC ν_μ

Muon capture process on argon nuclei/proton

Handle 3: Angular Dependence

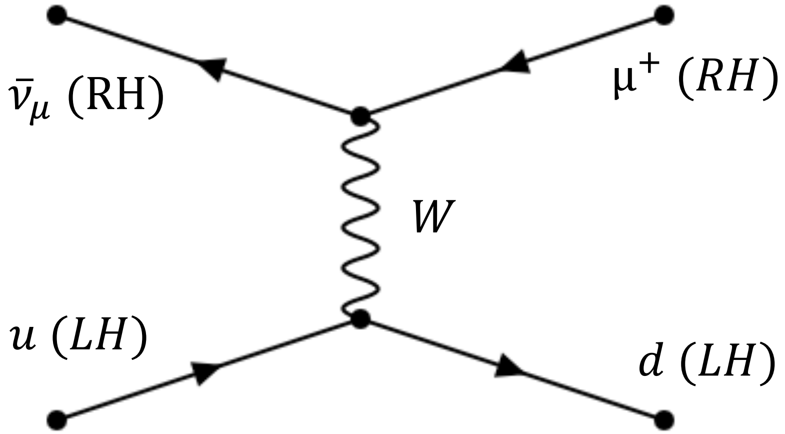
From helicity considerations, the cross section for the neutrino interaction is **independent of lepton polar angle $\boldsymbol{\theta}$** whereas the anti-neutrino process **is $\boldsymbol{\theta}$-dependent** and favors forward-going leptons.

Neutrino



$$\frac{d\sigma_\nu}{d\Omega} = \frac{G_F^2 \hat{s}}{4\pi^2}$$

Antineutrino



$$\frac{d\sigma_{\bar{\nu}}}{d\Omega} = \frac{G_F^2 \hat{s}}{16\pi^2}(1+\cos\theta)^2$$

Part II: Event Selection Chain

Overall Selection Chain

General Selection Cuts:

Reconstructed Neutrino & Optical Trigger

Muon-like Track

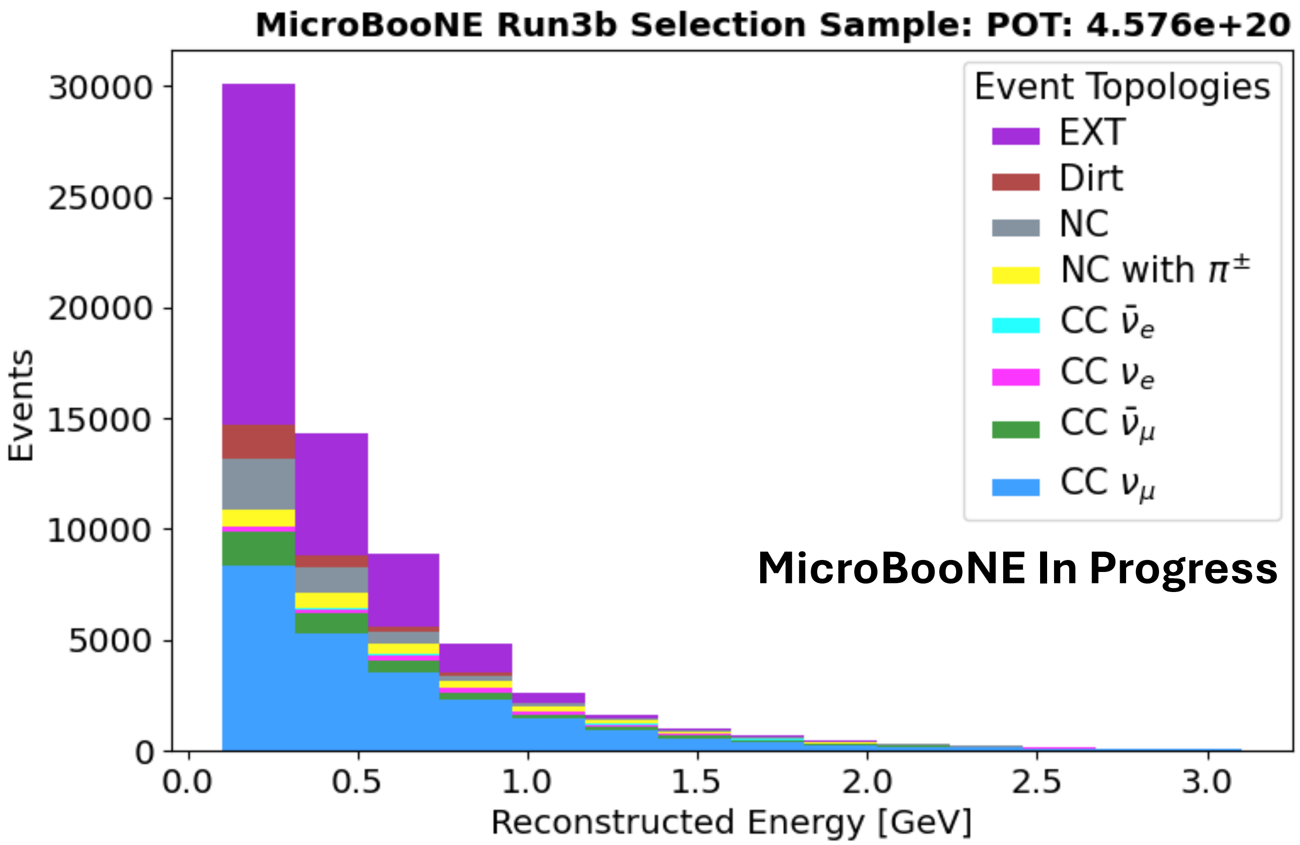
Energy Cut 200 MeV

Machine Learning Cuts (BDT):

1) Cosmic Removal
2) General Neutrino Background

CC ν_μ & CC $\bar{\nu}_\mu$ Separation

NuMI Beam at MicroBooNE: Run3b Exposure



EXT = Cosmic

Dirt = External Interaction

Signal Definition

- CC ν_μ or CC $\bar{\nu}_\mu$
- Interaction vertex contained within detector
- True neutrino energy above 200 MeV

(**Blue** & **Green** Contributions)

Purity:

$(\text{CC } \nu_\mu + \text{CC } \bar{\nu}_\mu)/(\text{CC } \nu_\mu + \text{CC } \bar{\nu}_\mu + \text{Backgrounds})$

Efficiency:

$(\text{CC } \nu_\mu + \text{CC } \bar{\nu}_\mu)/(\text{CC } \nu_\mu + \text{CC } \bar{\nu}_\mu$ (**Before Cuts**))

Efficiency	Purity
83.4%	15.7%

Reconstructed Energy = Summed reconstructed energy for the event, from Pandora reconstruction framework.

General Selection Chain Outline

ν

- We first require a single reconstructed neutrino!
- We also require matching optical trigger from detector

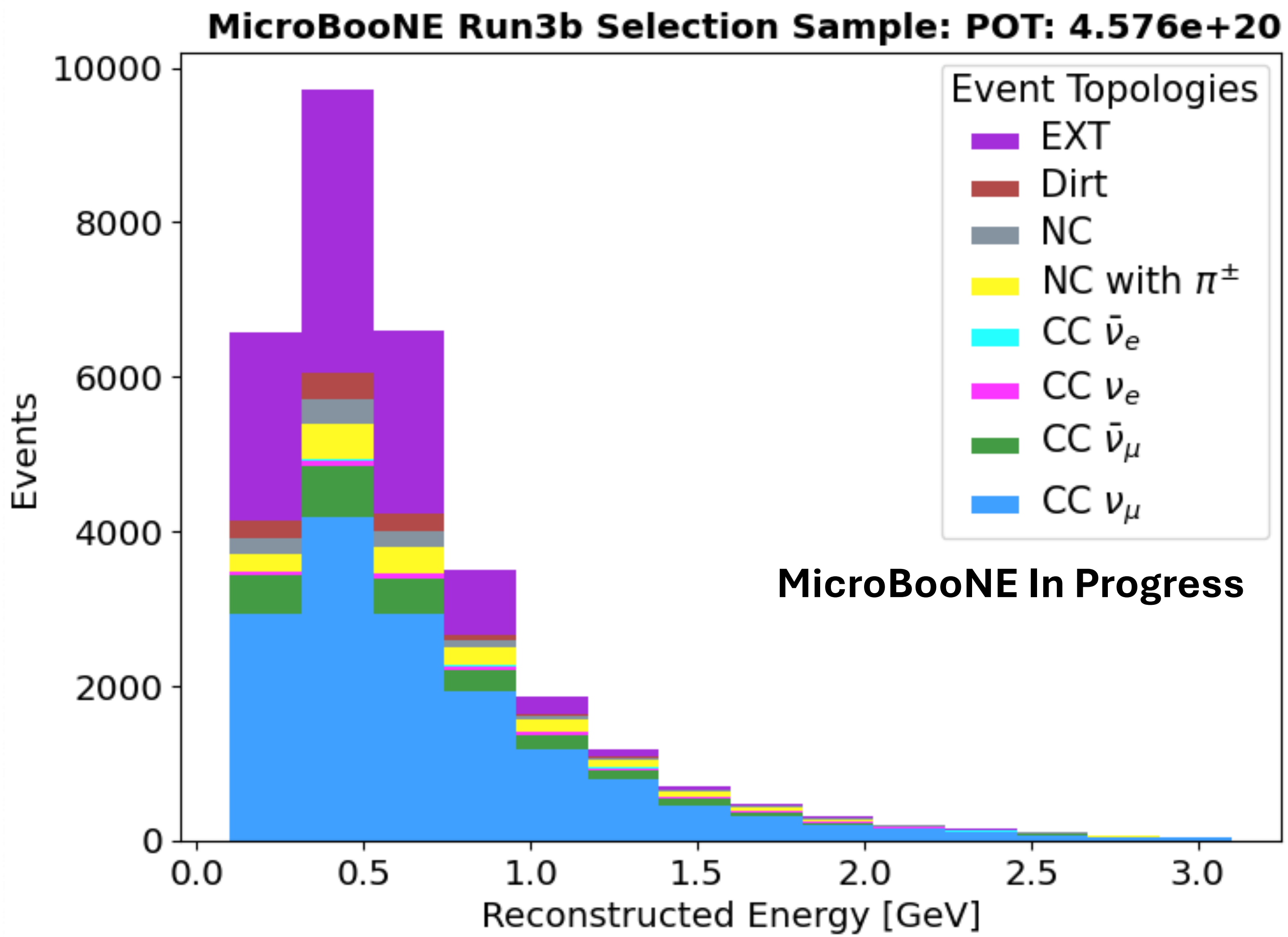
μ

- Require a reconstructed muon-like track

E

- We apply a threshold cut of 200 MeV in reconstructed energy to benefit from the best reconstruction performance.

General Selection Cuts: Current Sample



Efficiency	Purity
41.8% (↓ 41.6%)	50.6% (↑ 34.9%)

We have a purity-improved sample reconstructed well enough for further analysis.

Outstanding Tasks

1. Cosmic (EXT) Removal
2. General Neutrino Background Removal
3. CC ν_μ and $\bar{\nu}_\mu$ Separation

Overall Selection Chain

General Selection Cuts:

Reconstructed Neutrino & Optical Trigger

Muon-like Track

Energy Cut 200 MeV

Machine Learning Cuts (BDT):

1) Cosmic Removal
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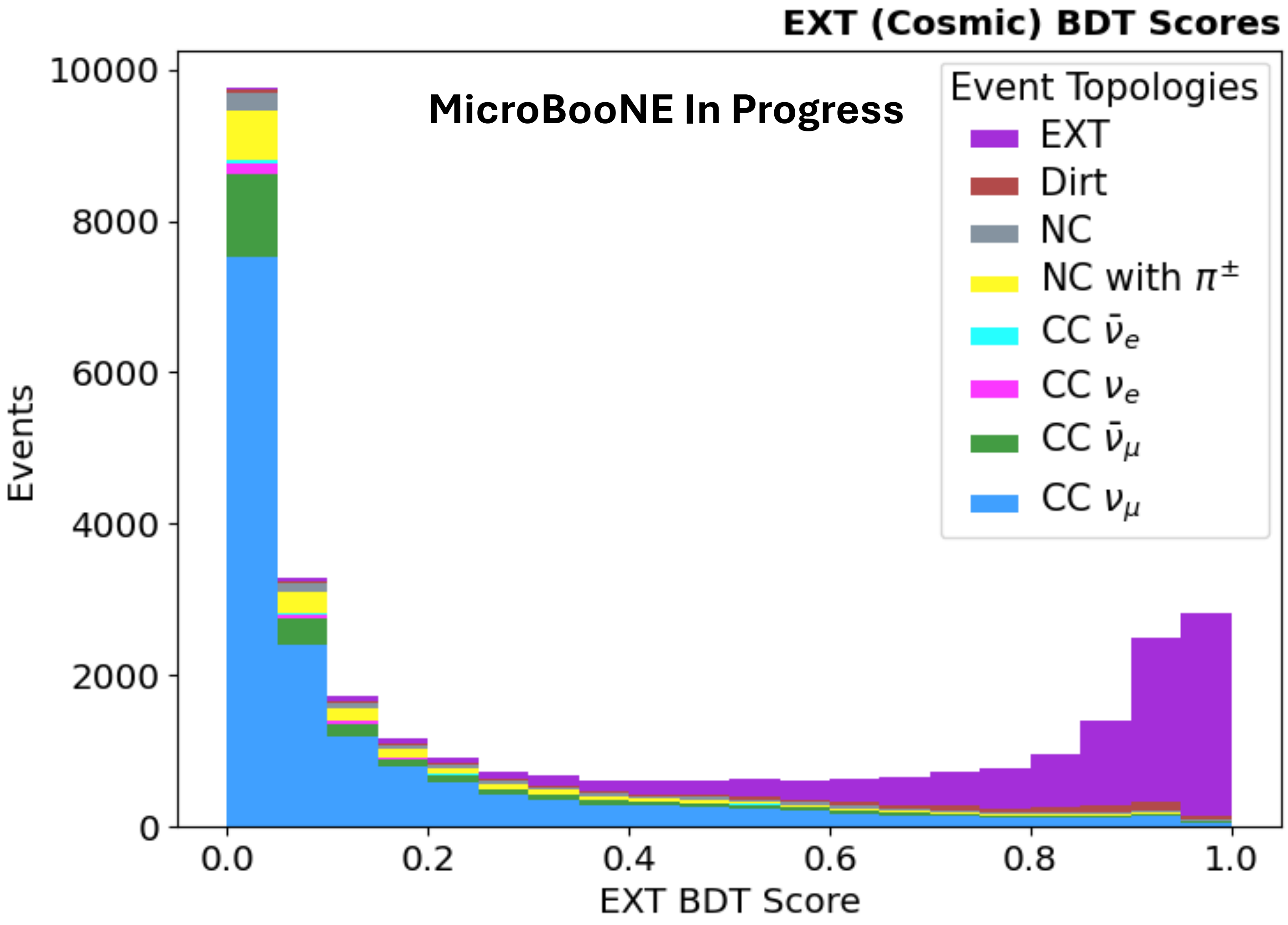
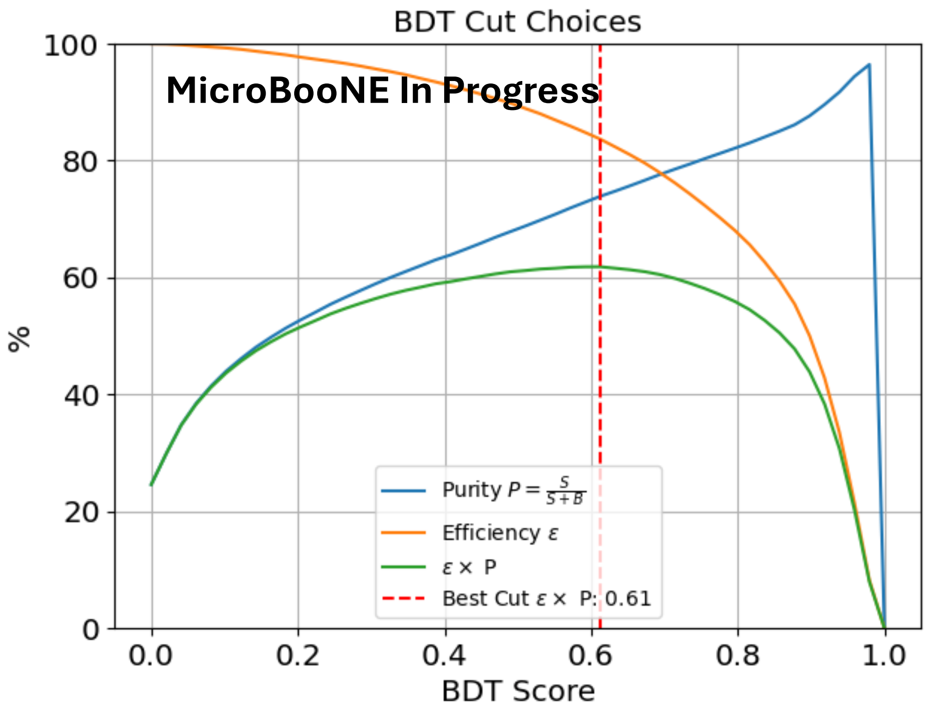
CC ν_μ & CC $\bar{\nu}_\mu$ Separation

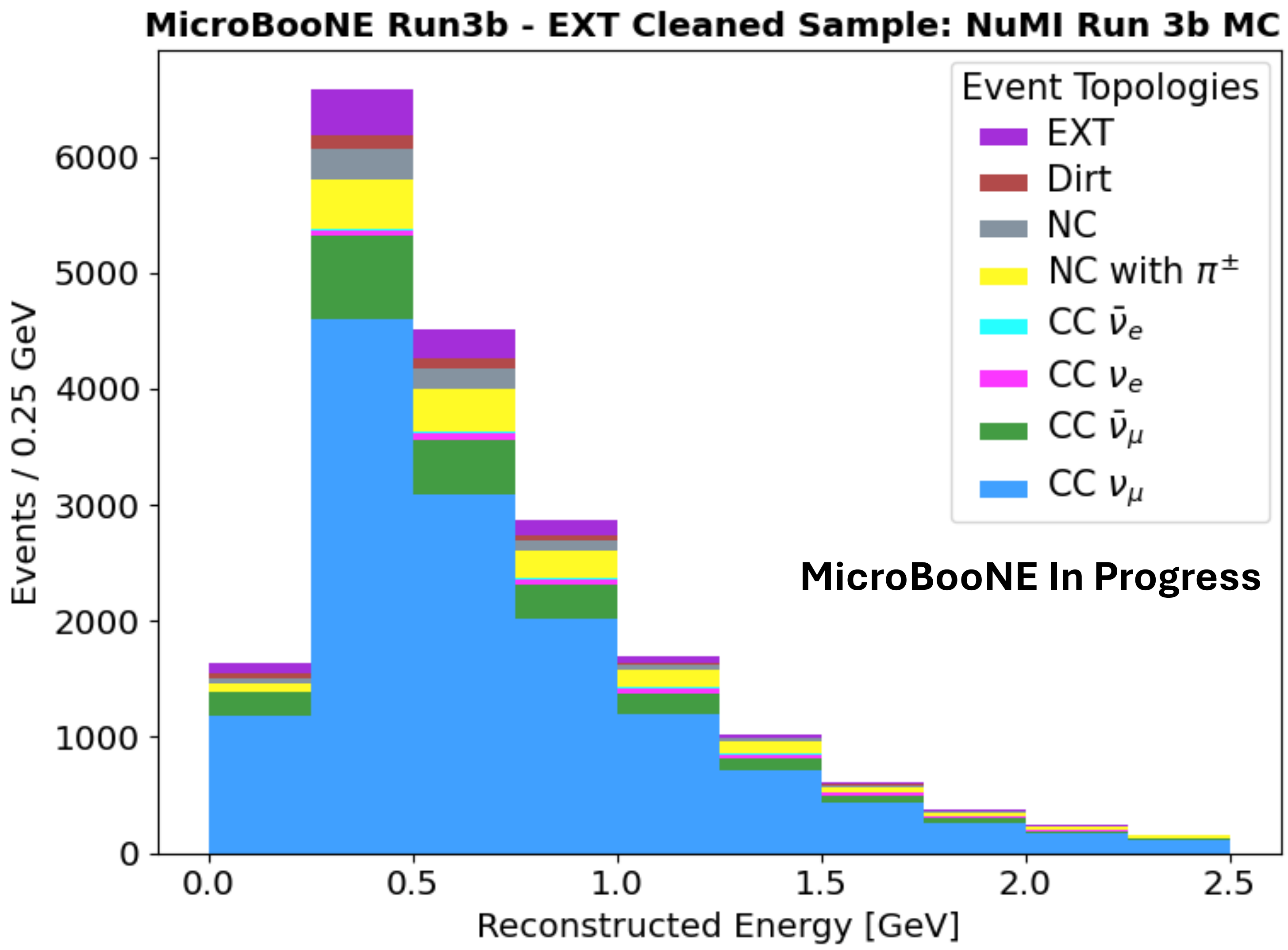
EXT BDT: Cosmic Removal



- We have a model that has good separation power, and the choice of cut is easy to define using the $\boldsymbol{\epsilon \times P}$ **metric**.



EXT BDT Cosmic Cut: Current Sample



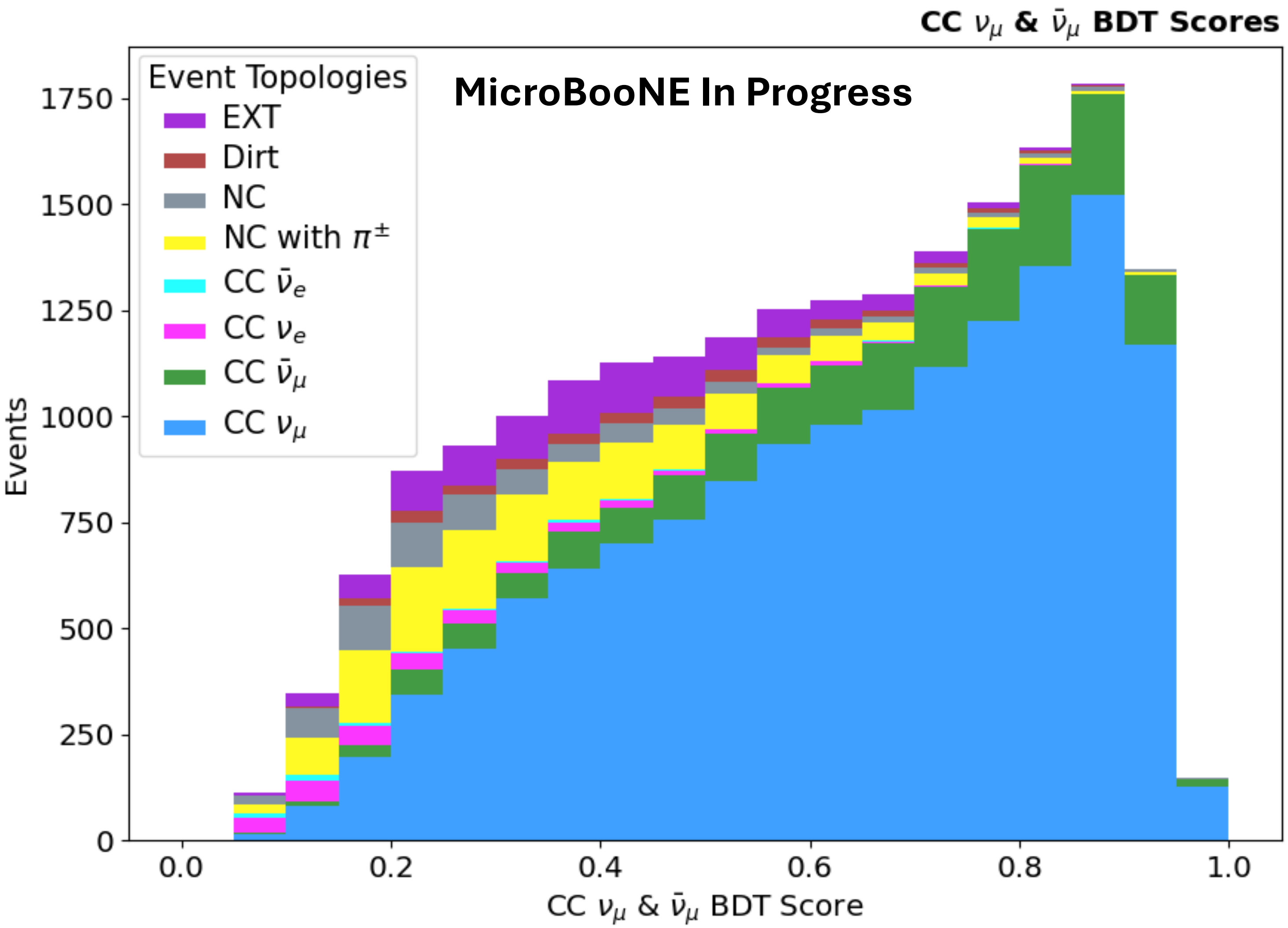
Efficiency	Purity
39.0% (↓ 2.8%)	76.6% (↑ 26.0%)

We have a sample cleansed of **cosmic** impurities.

Outstanding Tasks

1. ~~Cosmic (EXT) Removal~~
2. General Neutrino Background Removal
3. CC ν_μ and CC $\bar{\nu}_\mu$ Separation

BGD BDT: Neutrino Background Removal

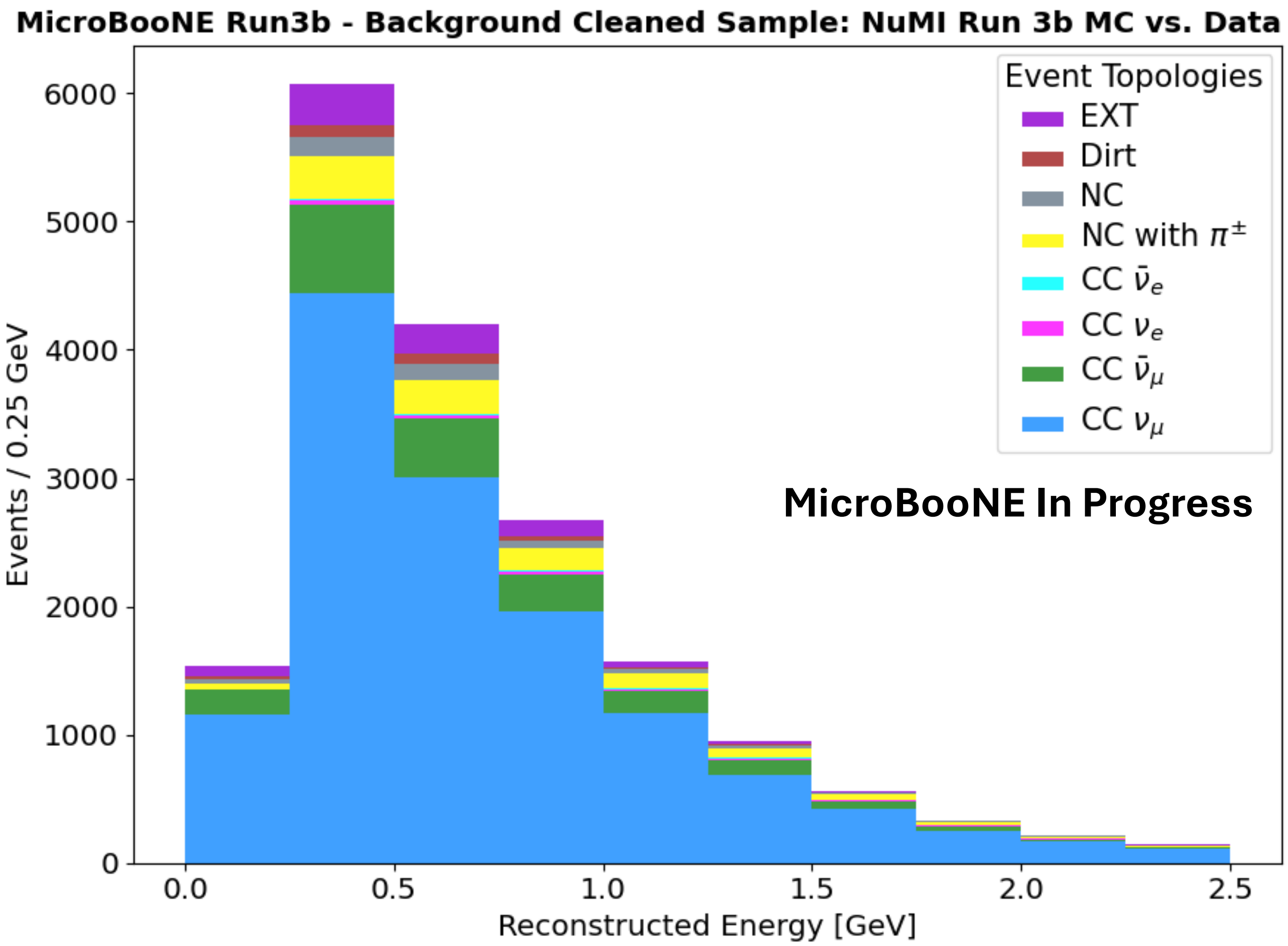


Observations

Remaining EXT and Neutral Current (NC) events with pions are majority of background. It is difficult to train a model to perfectly separate these backgrounds from our signal.

Cut at 0.25, according to our metric, keeping everything above that score.

BGD BDT Background Cut: Current Sample



We have a sample cleansed of general background impurities.

We have removed 30% of NC events and further 10% of EXT.

<u>Outstanding Tasks</u>

1. ~~Cosmic (EXT) Removal~~
2. ~~General Neutrino Background Removal~~
3. CC ν_μ and $\bar{\nu}_\mu$ Separation

Efficiency	Purity
37.9% (↓ 1.1%)	80.3% (↑ 3.7%)

Overall Selection Chain

General Selection Cuts:

Reconstructed Neutrino & Optical Trigger

Muon-like Track

Energy Cut 200 MeV

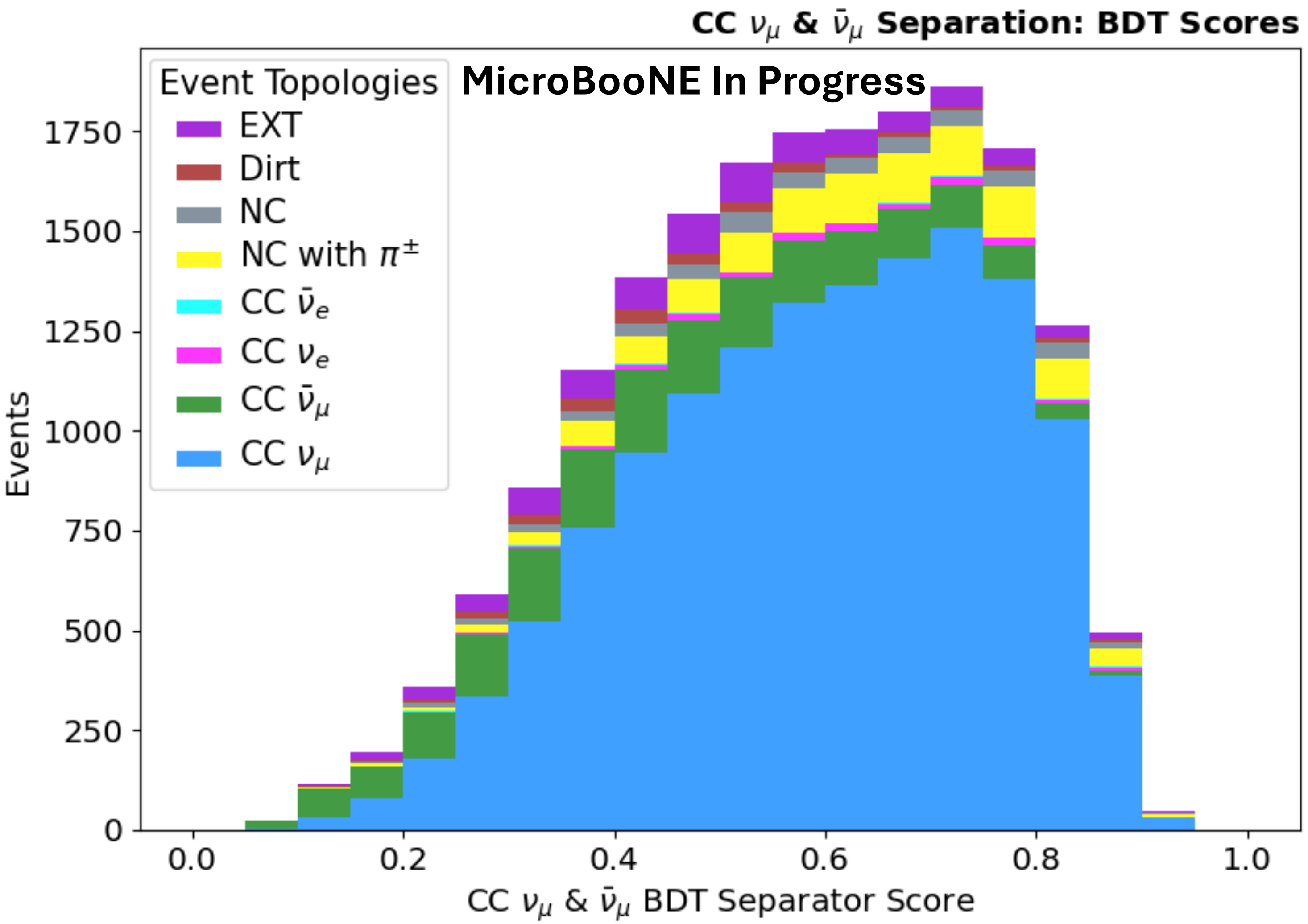
Machine Learning Cuts (BDT):

1) Cosmic Removal

2) General Neutrino Background

CC ν_μ & CC $\bar{\nu}_\mu$ Separation

NU BDT: CC ν_μ and $\bar{\nu}_\mu$ Separation

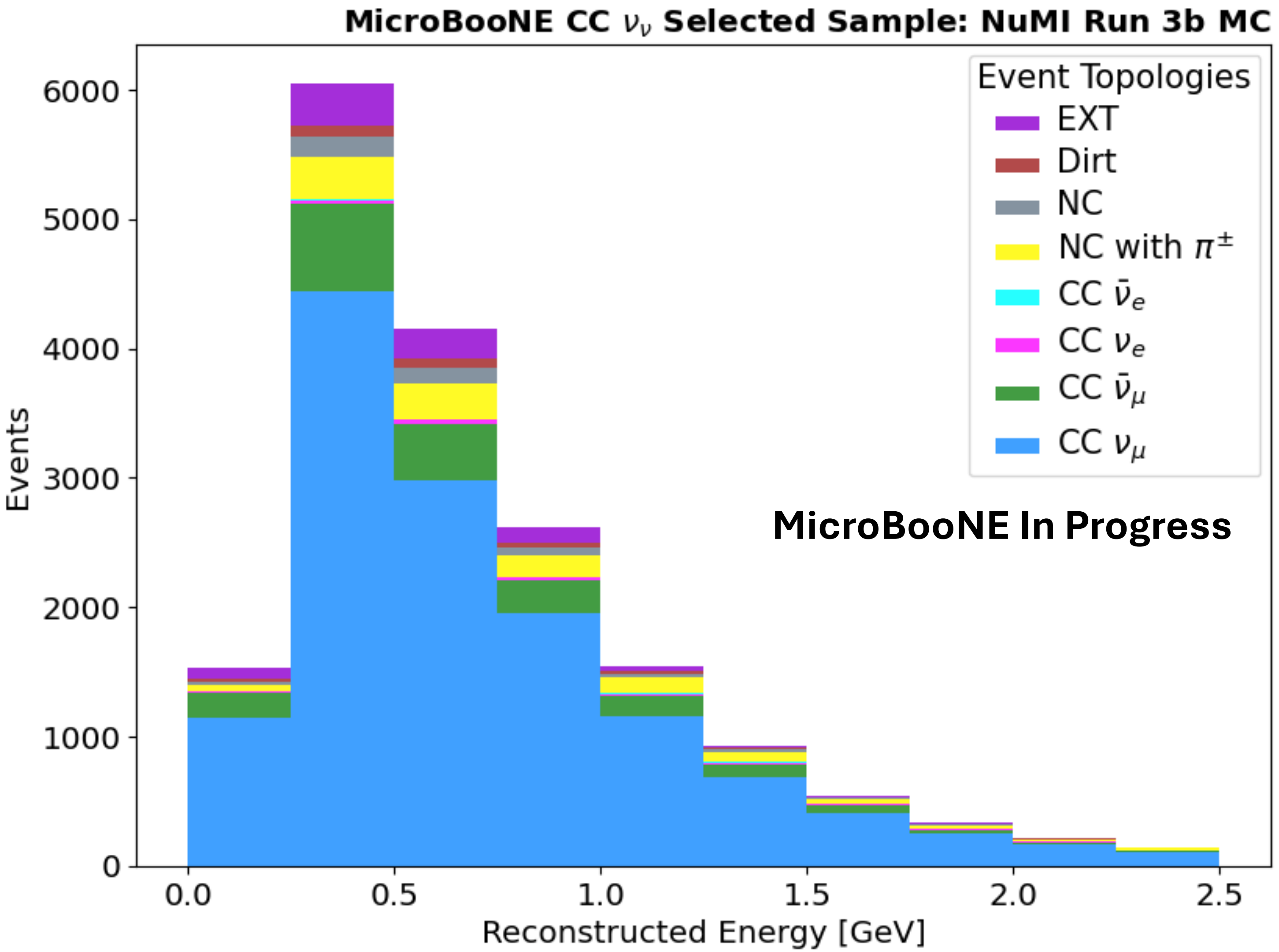


Observations

- Given that we should have enough statistics, we make the cut with the **$\epsilon \times \mathbf{P}$ metric** once more, informing us to cut at 0.18 which obtains a relatively clean sample of CC $\bar{\nu}_\mu$.

Part III: Selected Samples

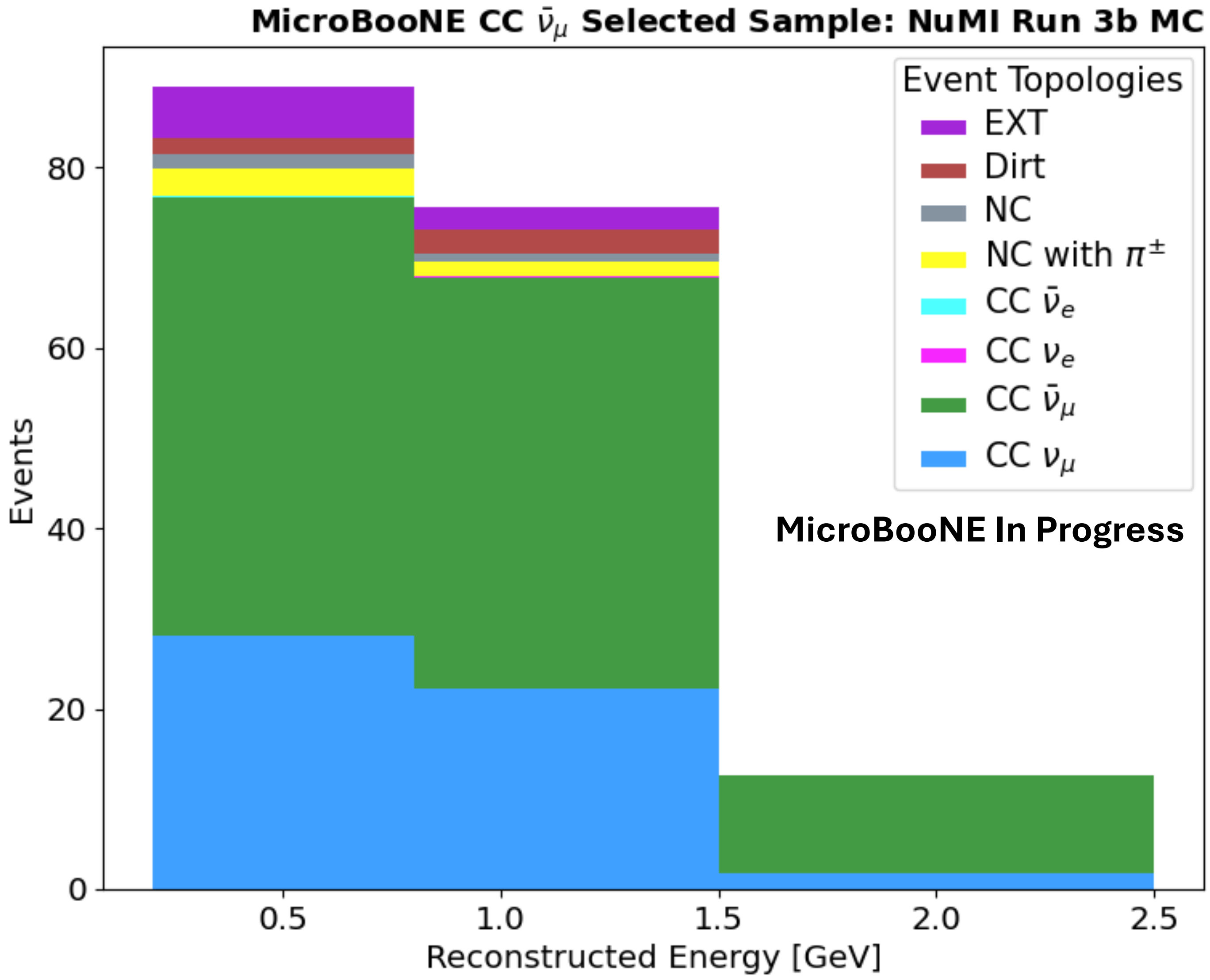
Resulting Sample: CC ν_μ Selection



- Application of all general selection cuts, and the three BDT model cuts results in the following sample of approximately **13500 selected CC ν_μ events**

Efficiency	Purity
39.9%	70.4%

Resulting Sample: CC $\bar{\nu}_\mu$ Selection



- Application of all general selection cuts, and the three BDT model cuts results in the following sample of around **150 selected CC $\bar{\nu}_\mu$ events**

- Sample is 56.2% pure in CC $\bar{\nu}_\mu$, but only 1.4% efficient!

Efficiency	Purity
1.4%	56.2%

Summary

- A selection chain using the **XGBoost BDTs** has been developed to select samples of CC ν_μ & CC $\bar{\nu}_\mu$ events from the run3b NuMI data at MicroBooNE.

- The main CC ν_μ & CC $\bar{\nu}_\mu$ separator model achieves a statistical separation, and we were able to extract the required samples for further analysis.

Thank you!

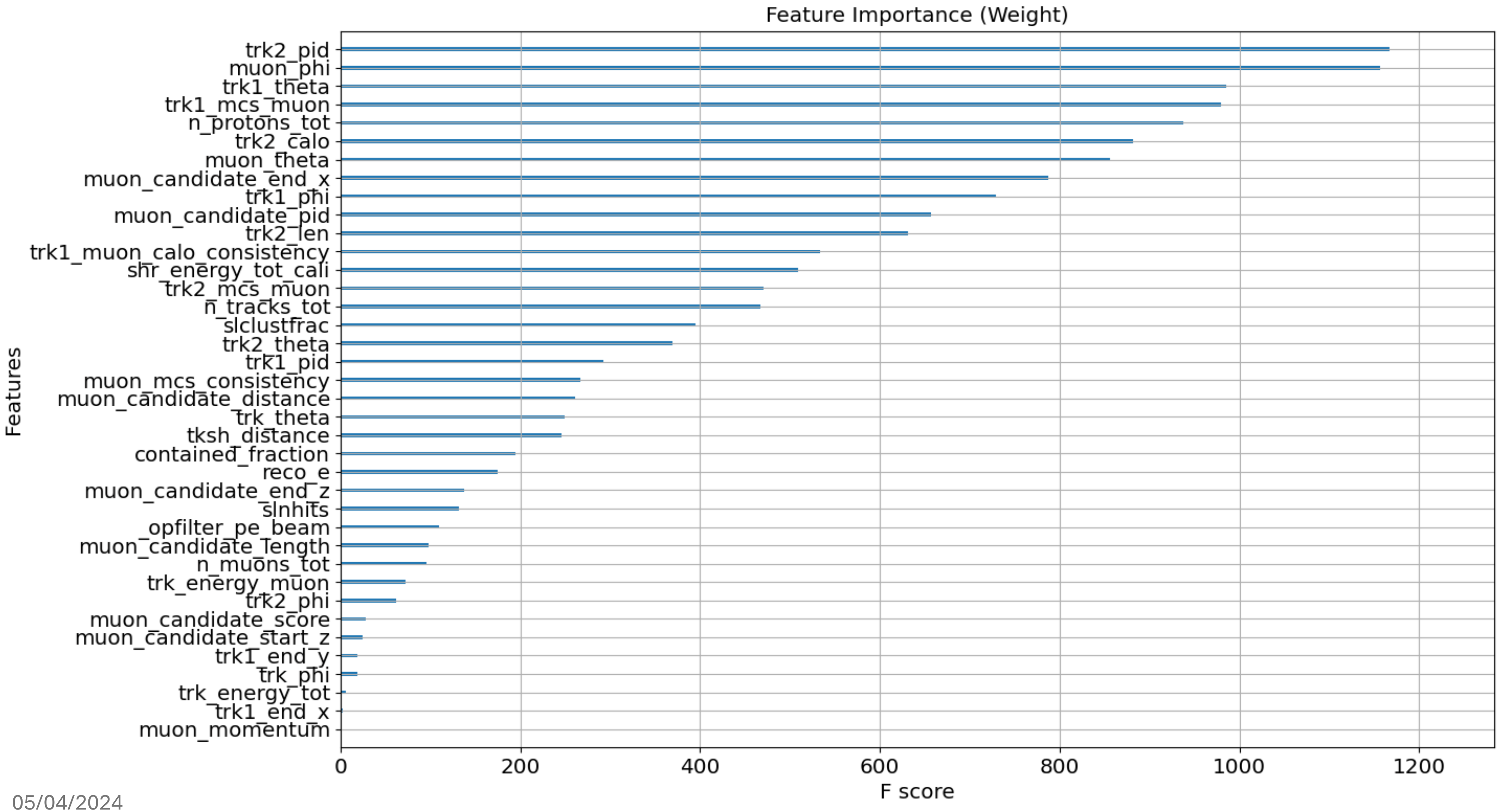
Related IOP Talks

Marina Guzzo's Work: Electron Neutrino & Antineutrino Separation

Holly Parkinson's Talk: "Understanding the Off-Axis Flux of Neutrinos from Neutral Kaons**"**

Back Up Slides

Muon and Antimuon Separator: Variable Importance



BDT Variables