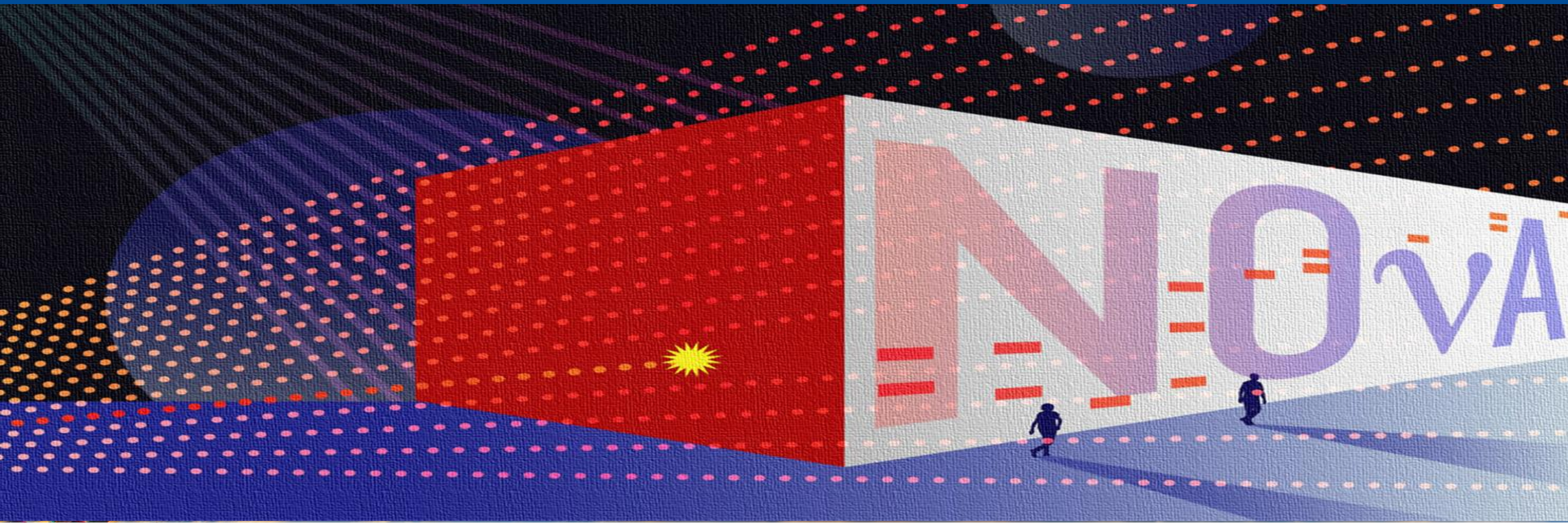

NOvA (NuMI Off-Axis ν_e Appearance) Neutrino Experiment – Neural Network Analysis

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SIST/GEM Summer Program - 2018
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08/09/2018

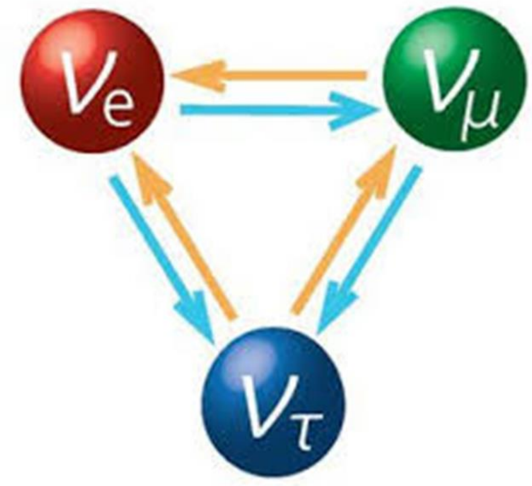
NOvA
THE NATIONAL GEM CONSORTIUM

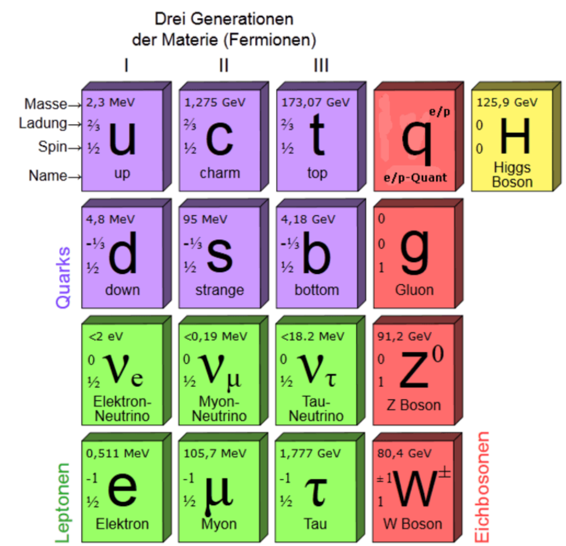
Outline

- Introduction and Theory
- The NOvA Experiment
- Project Goals
- Deep Learning and Convolutional Neural Networks
- Training
- Results and Analysis
- Conclusions

Properties of Neutrinos

- Come in three flavors – electron, muon, and tau
- Oscillate into one of three different flavors
- Once thought to be massless – extremely light
- Interact via the weak force mechanism





Neutrino Oscillations

- Create in one flavor (ν_μ), but detect in another (ν_e)

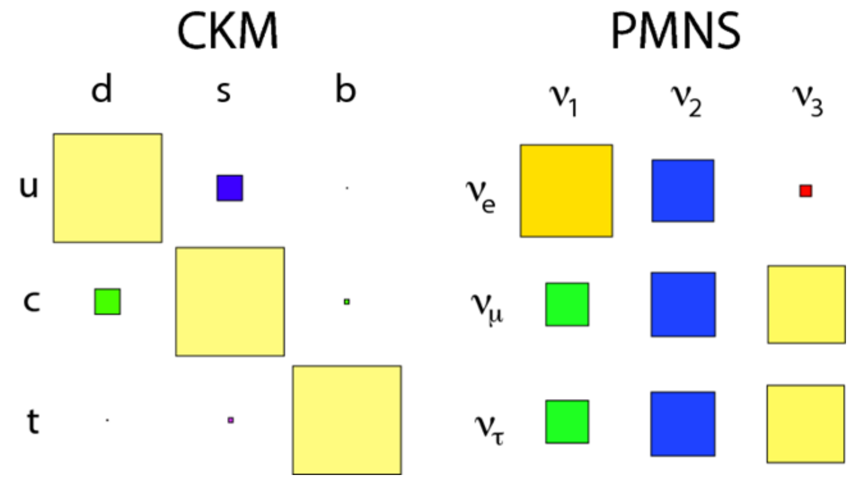
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}$$

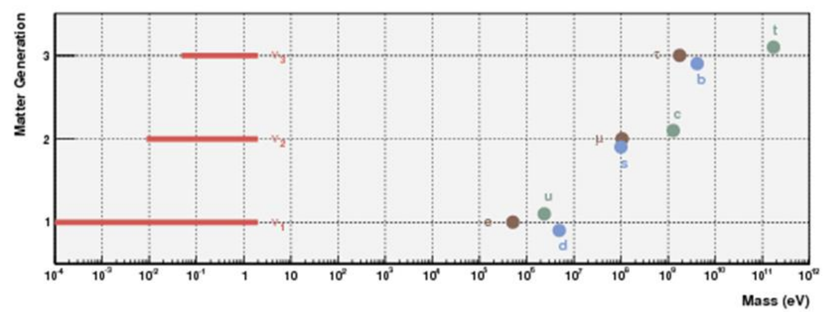
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Why study neutrinos?

- Neutrinos are unique:
  - Neutrino mixing looks very different from CKM.
  - Neutrino masses are *really* small compared to the rest of the SM.
- Potentially *CP*-violating:
  - Might be a window into matter-antimatter asymmetry.
- Physics beyond the standard model!
  - Oscillations are an interferometric effect – gives access to high-scale or unknown physics.





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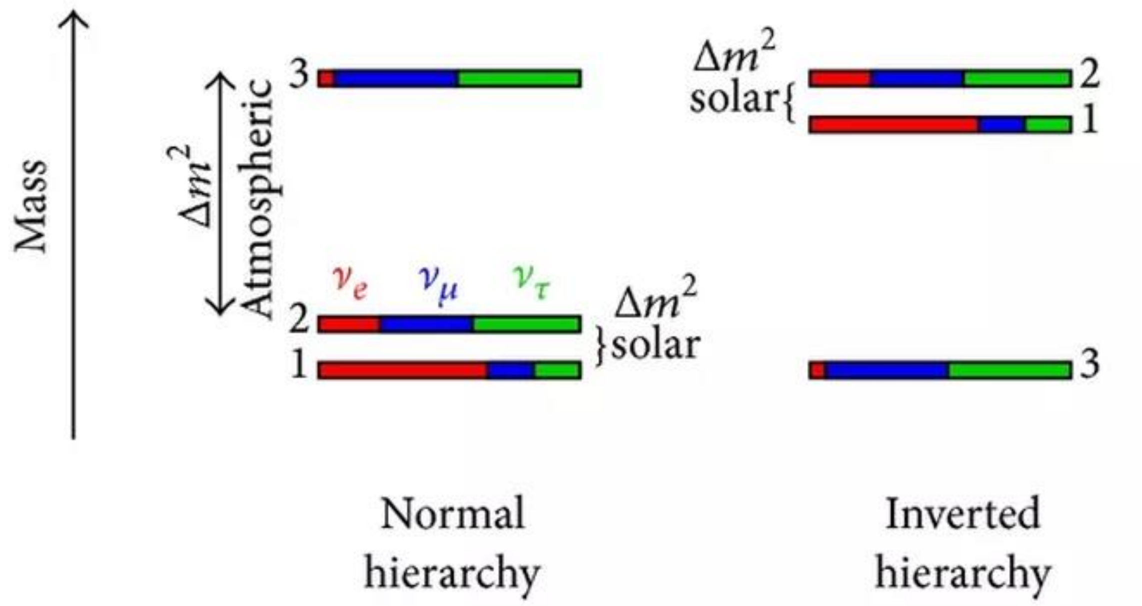
Ordering of neutrino masses?

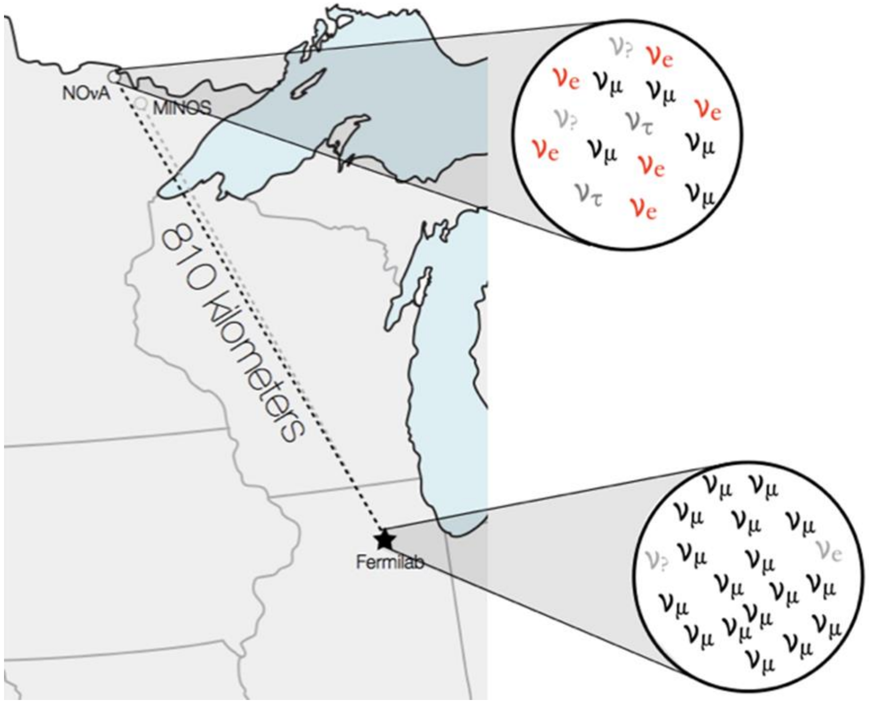


Matter-antimatter asymmetry?

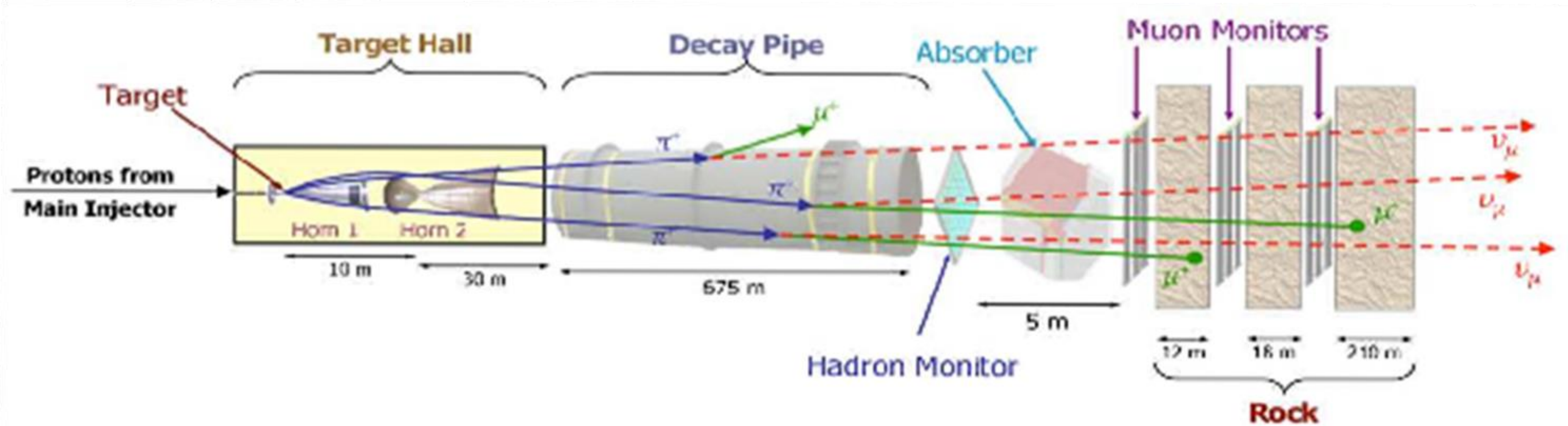
- Do muon antineutrinos oscillate at a different rate than muon neutrinos?
  - Would imply broken symmetry between neutrinos and anti-flavors are broken
- If antineutrinos do not follow the same pattern as neutrinos when they change from one flavor to another - a signal of CP violation

The NOvA Experiment

- Long-baseline neutrino oscillation experiment.
  - NuMI neutrino beam at Fermilab
  - **Near Detector** to measure the beam before oscillations
  - **Far Detector** measures the oscillated spectrum.
- Detectors located 14 mrad off-axis of the beam.
  - 2-body π decay gives narrow range of ν energies
  - Tune peak energy for oscillations
  - More events at max oscillations
  - Fewer backgrounds



NuMI (Neutrinos at the Main Injector) Beam



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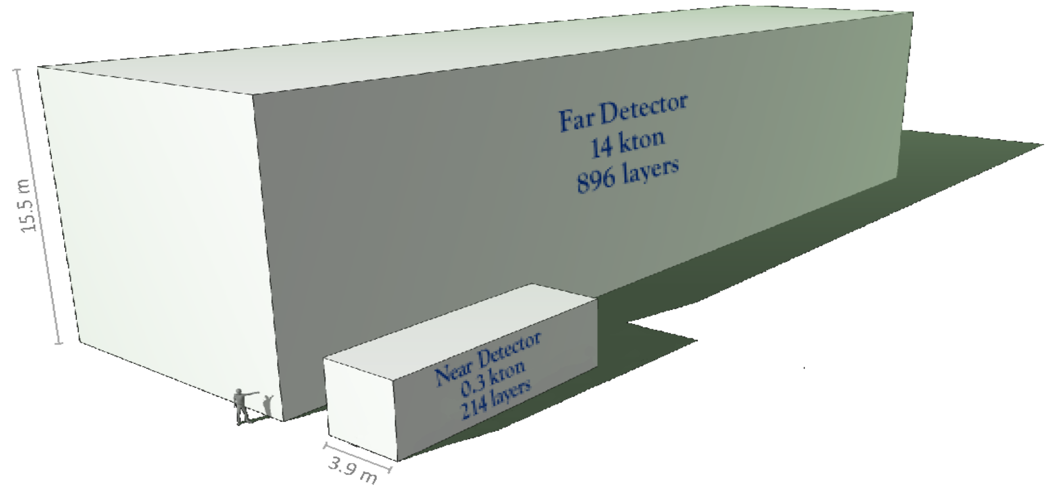
The NOvA Detectors



Large, 14 kTon at the Far Detector – 385,000 scintillator cells
Consist of plastic cells filled with liquid scintillator
Arranged in alternating directions for 3D reconstruction

- NOvA Measures:
  - *CP*-violating phase
  - θ_{23} octant
  - Sign of Δm^2_{32} – “Mass Hierarchy”

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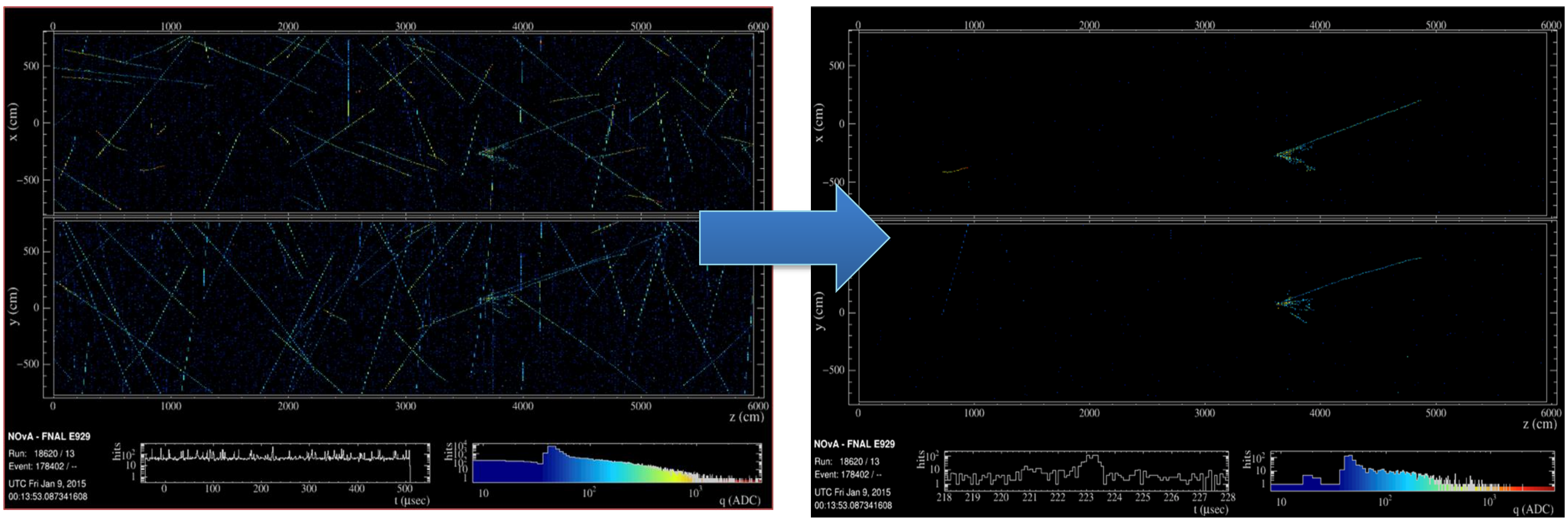
Project Goals

- The far detector is above ground
  - Subject to approximately 11 billion cosmic rays per day
  - Approximately 10^7 events need to be rejected to process and reconstruct pixel maps
- Construct a cosmic rejection network via machine learning able to identify events based on event topology

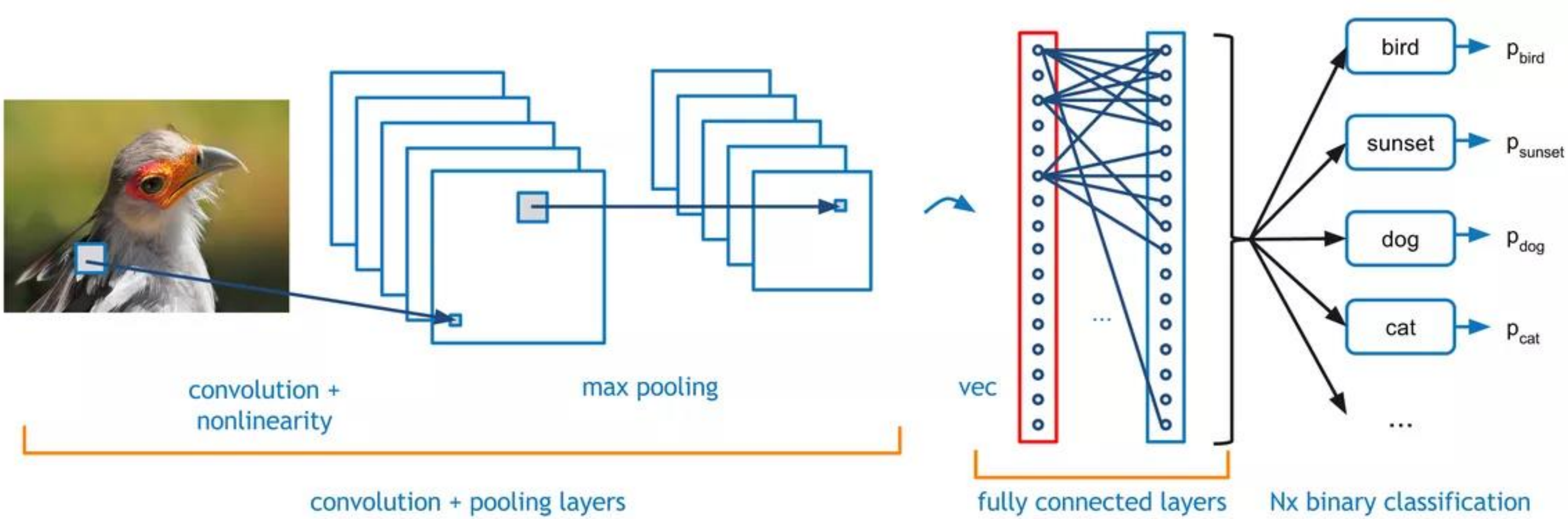


Deep Learning and Convolutional Neural Networks

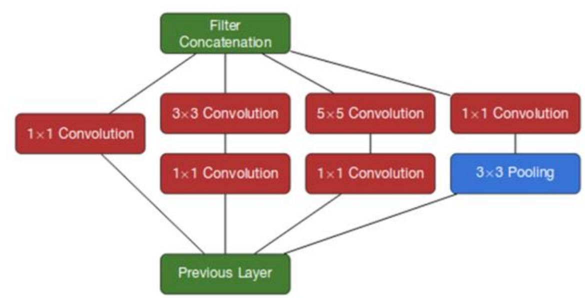
- The multilayer perceptron (MLP), or traditional neutral network- a machine learning algorithm
- Scales poorly to a large number of raw inputs.
  - The number of nodes necessary in that hidden layer may approach infinity
  - Large number of free parameters in a large network runs the risk of possibly over-training

$$f : \mathbb{R}^n \rightarrow \mathbb{R}^m$$

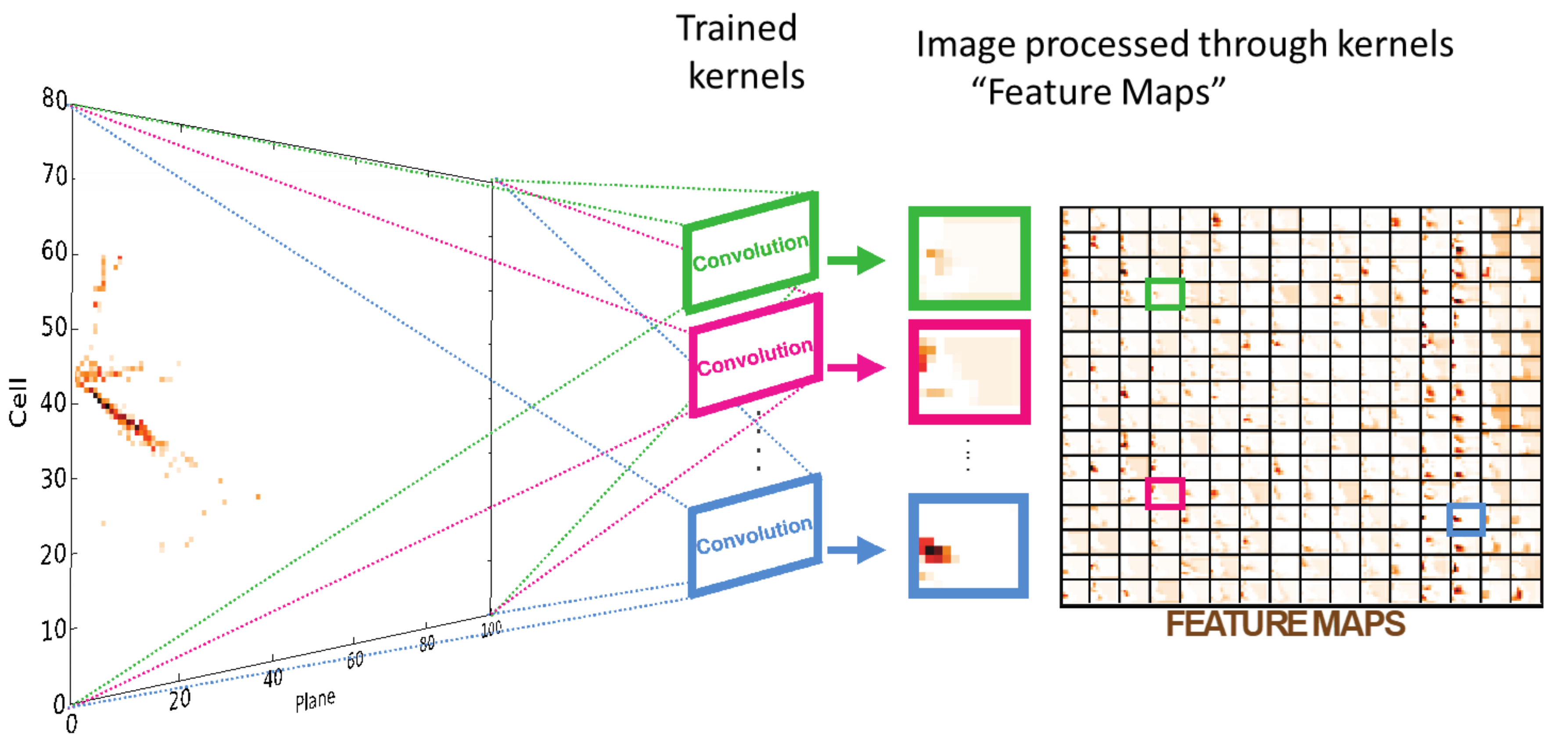
Convolutional Neural Network



$$(f \cdot g)_{p,q,r} = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{c} f_{i,j,k,r}\, g_{p+i,q+j,k}$$

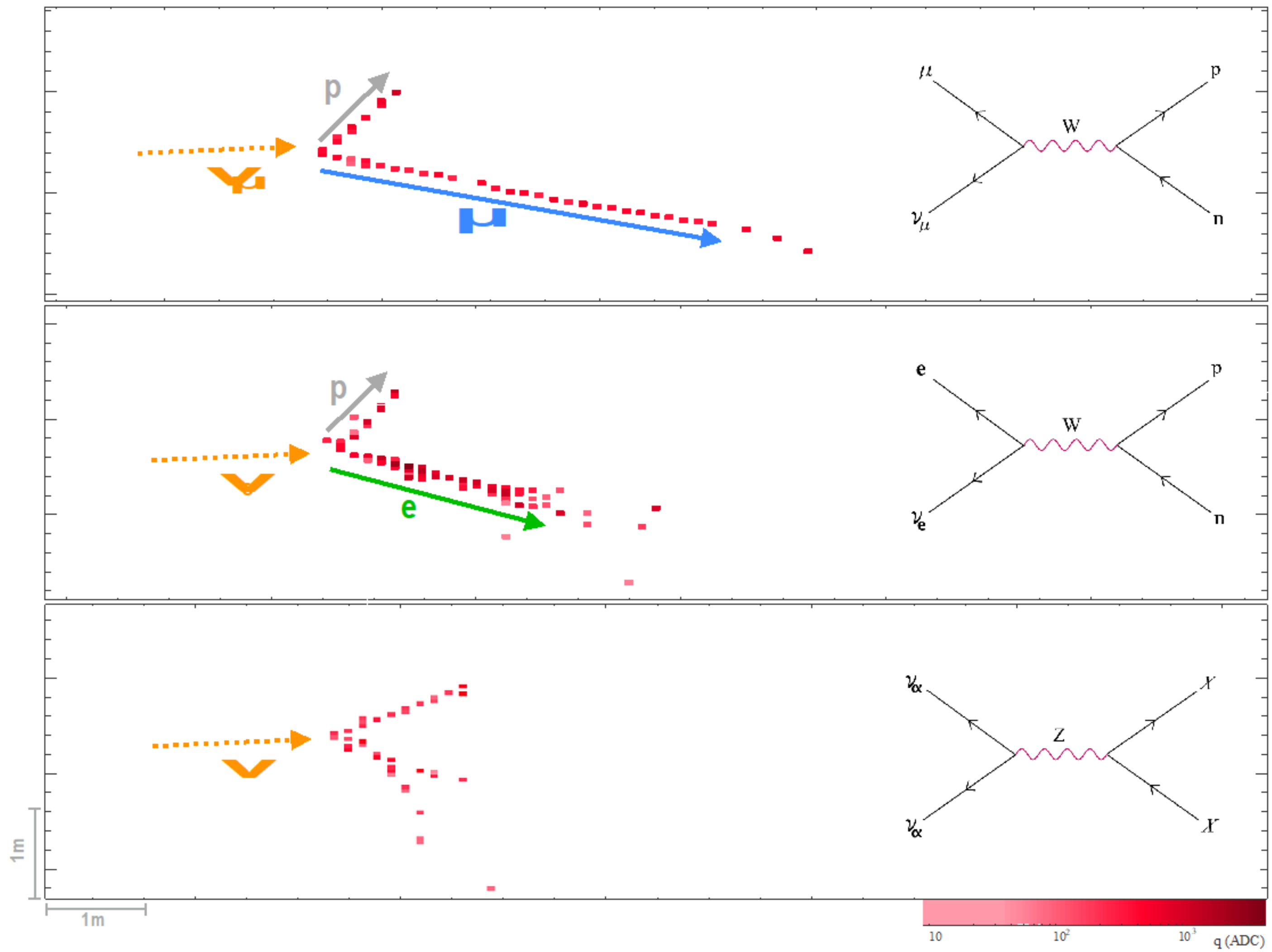


Caffe


Trained kernels
Image processed through kernels
“Feature Maps”
80
70
60
50
40
30
20
10
0
Cell
0
20
40
60
80
100
Plane
Convolution
Convolution
Convolution
FEATURE MAPS

Identifying Events

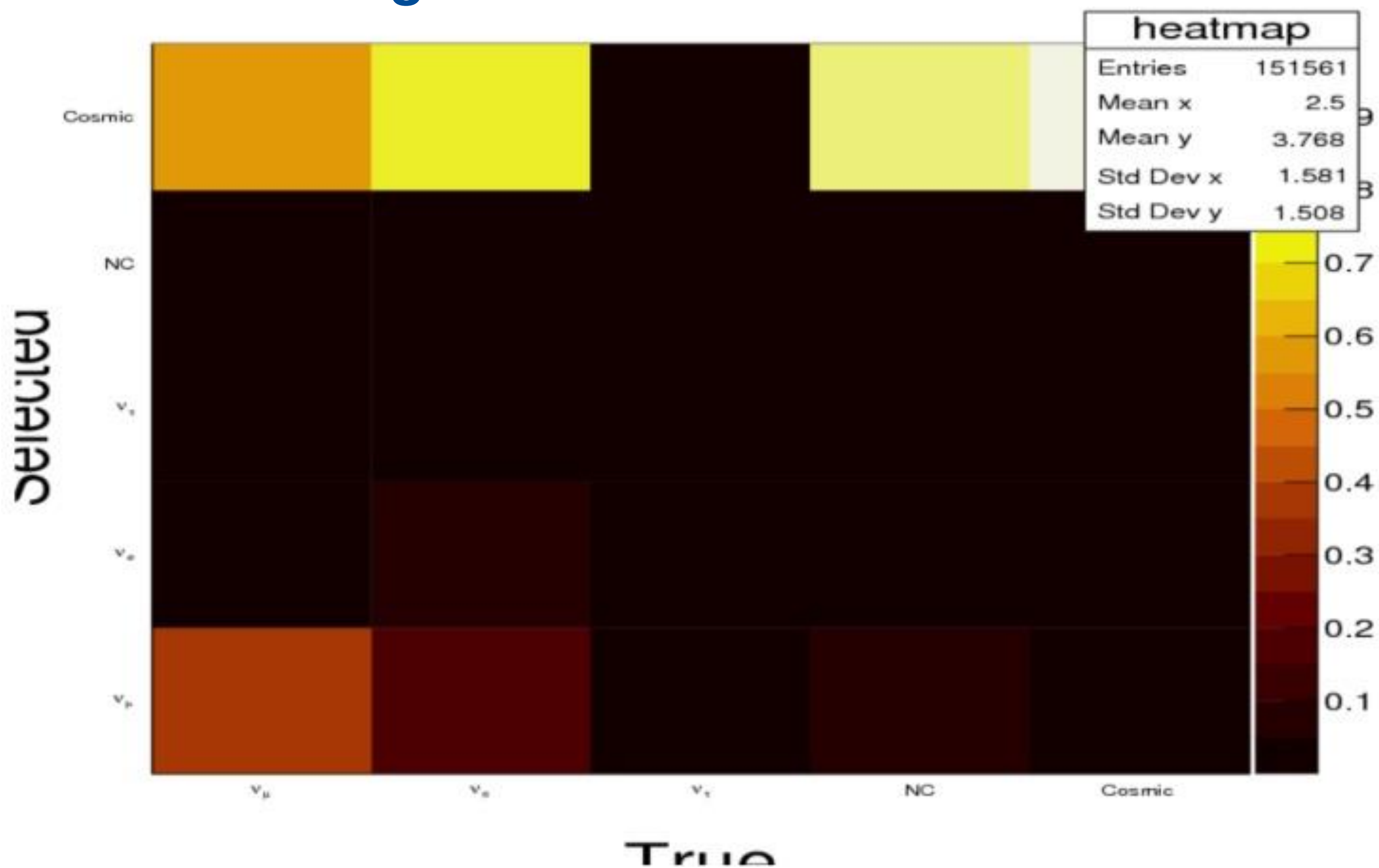
- ν_μ CC - A muon plus a hadronic component; long, low dE/dx track
- ν_e CC - An electron plus a hadronic component; is typically a wide shower
- ν_τ CC - A tau plus a hadronic component. The tau is extremely short lived and not visible in the detector; may produce pions, electrons, muons, and neutrinos.
- ν NC- The outgoing lepton in these interactions is a neutrino; will travel onward undetected; hadronic component only is visible
- Cosmic events – (Usually) Long muon tracks entering tops or sides


p
μ
e
p
μ
p
W
ν_μ
n
e
p
W
ν_e
n
ν_α
X
Z
ν_α
X
1m
1m
10
10^2
10^3
q (ADC)

Training

- Create Pixel Maps
  - Full FD events sliced in time to spill window width ~12 µS
  - Select one random window and the spill window
  - Cuts on empty windows and less than 10 interaction hits
- Create LevelDBs
  - Large LevelDBs needed to be “chunked”
  - 250 files per LevelDB = ~470k pixelmaps (over 12k files available)
  - 376k training / 94k testing (80/20)
  - Reduced Labeling

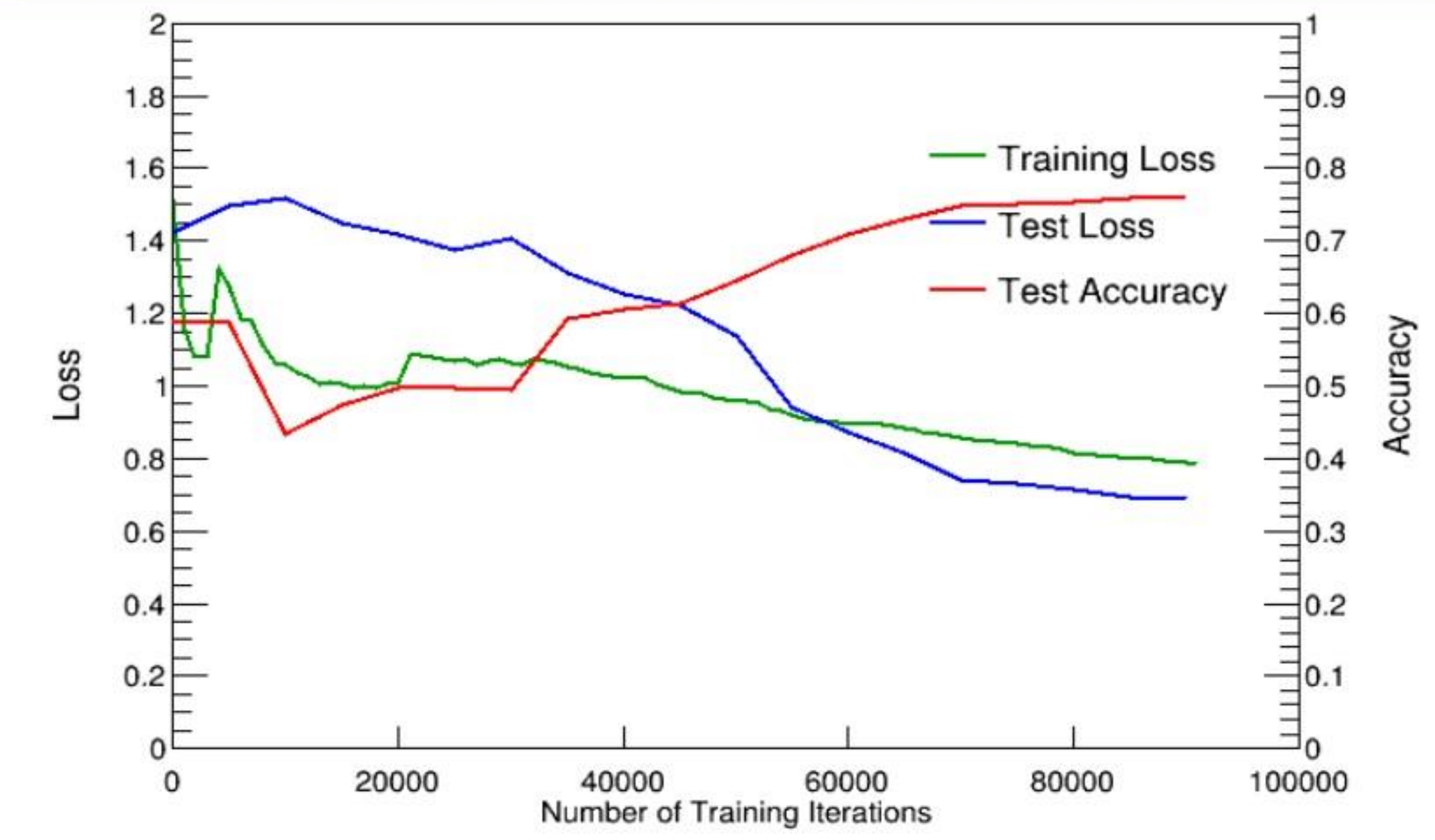
Before Training



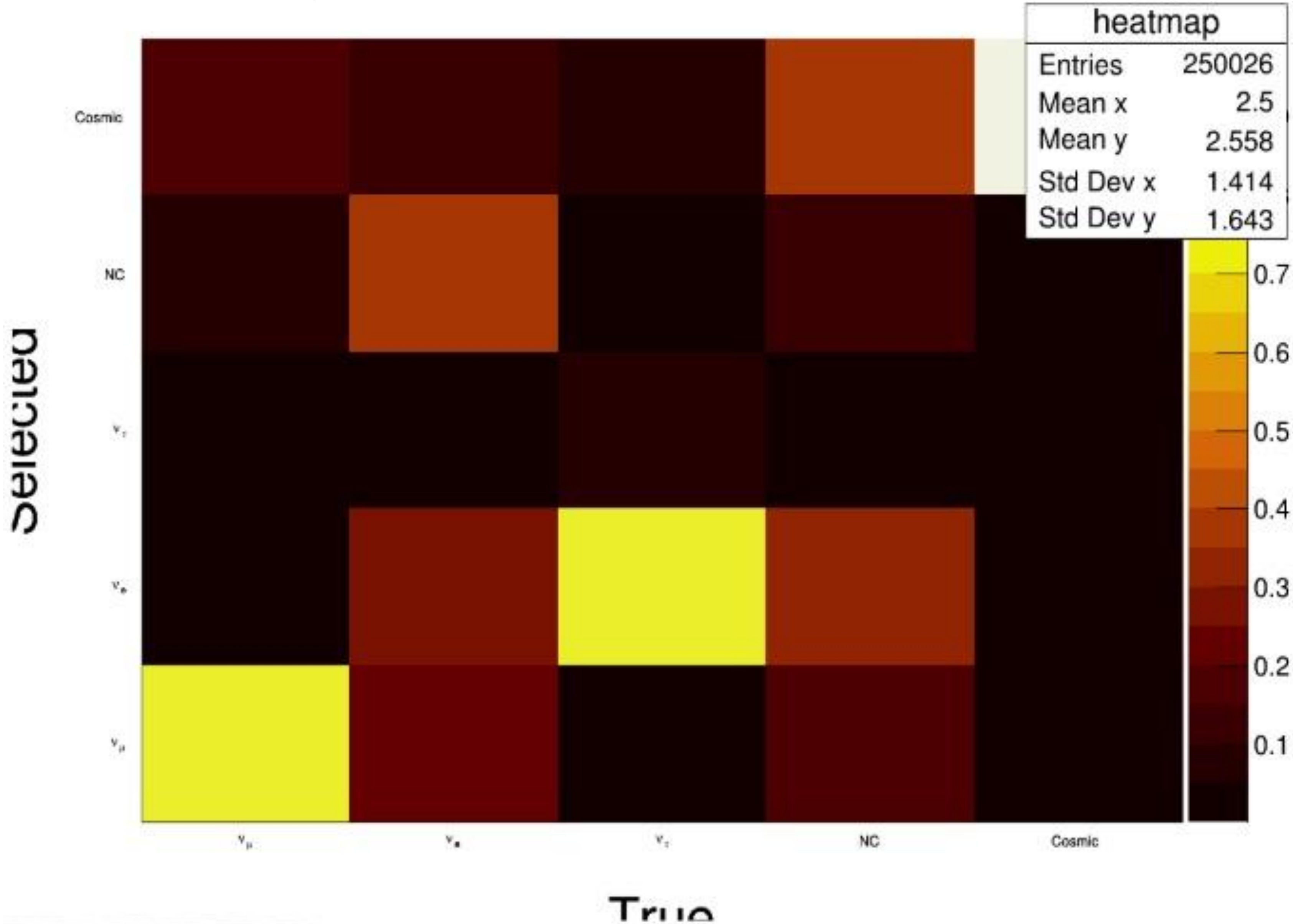
Composition ration of 34:1 cosmics

	ν_μ CC	ν_e CC	ν_τ CC	ν NC	cosmic	total
Chunk-05	13.0%	10.6%	3.4%	14.2%	58.8%	463708
Chunk-06	13.1%	11.4%	3.8%	15.9%	55.8%	460792

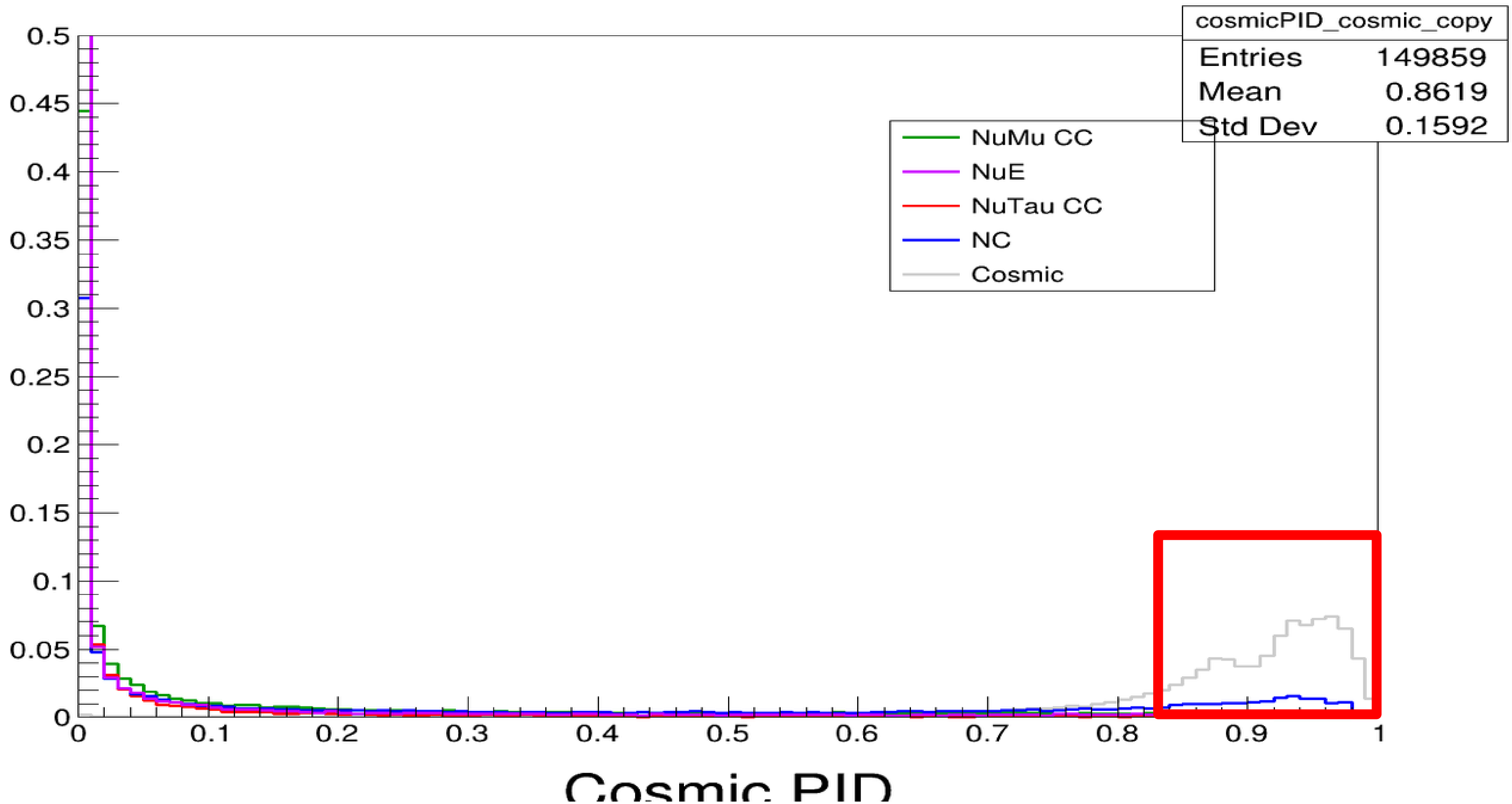
First Training (1st chunk)



First Training – Confusion Matrix



First Training – PID Plot (Cosmic)



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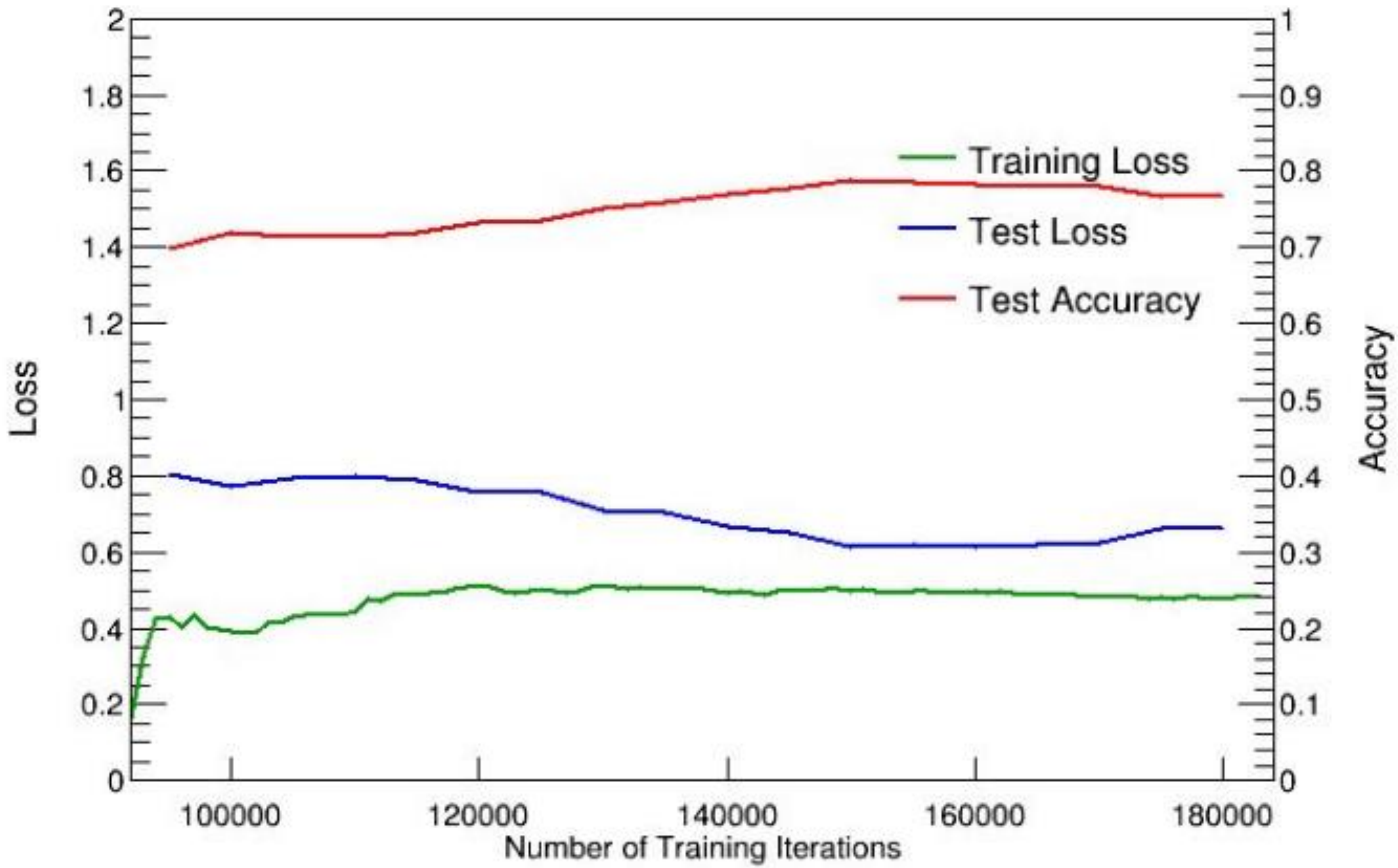
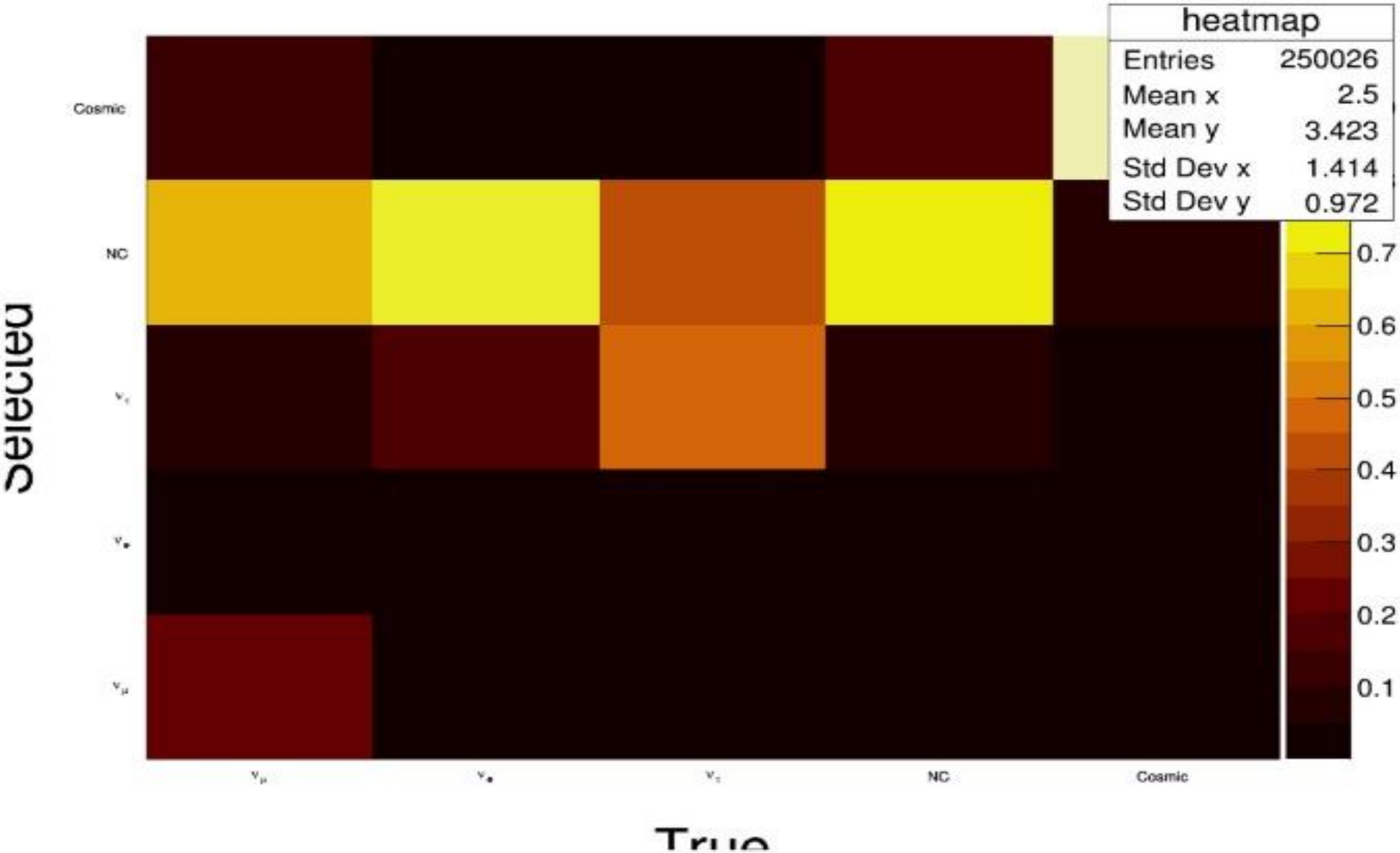
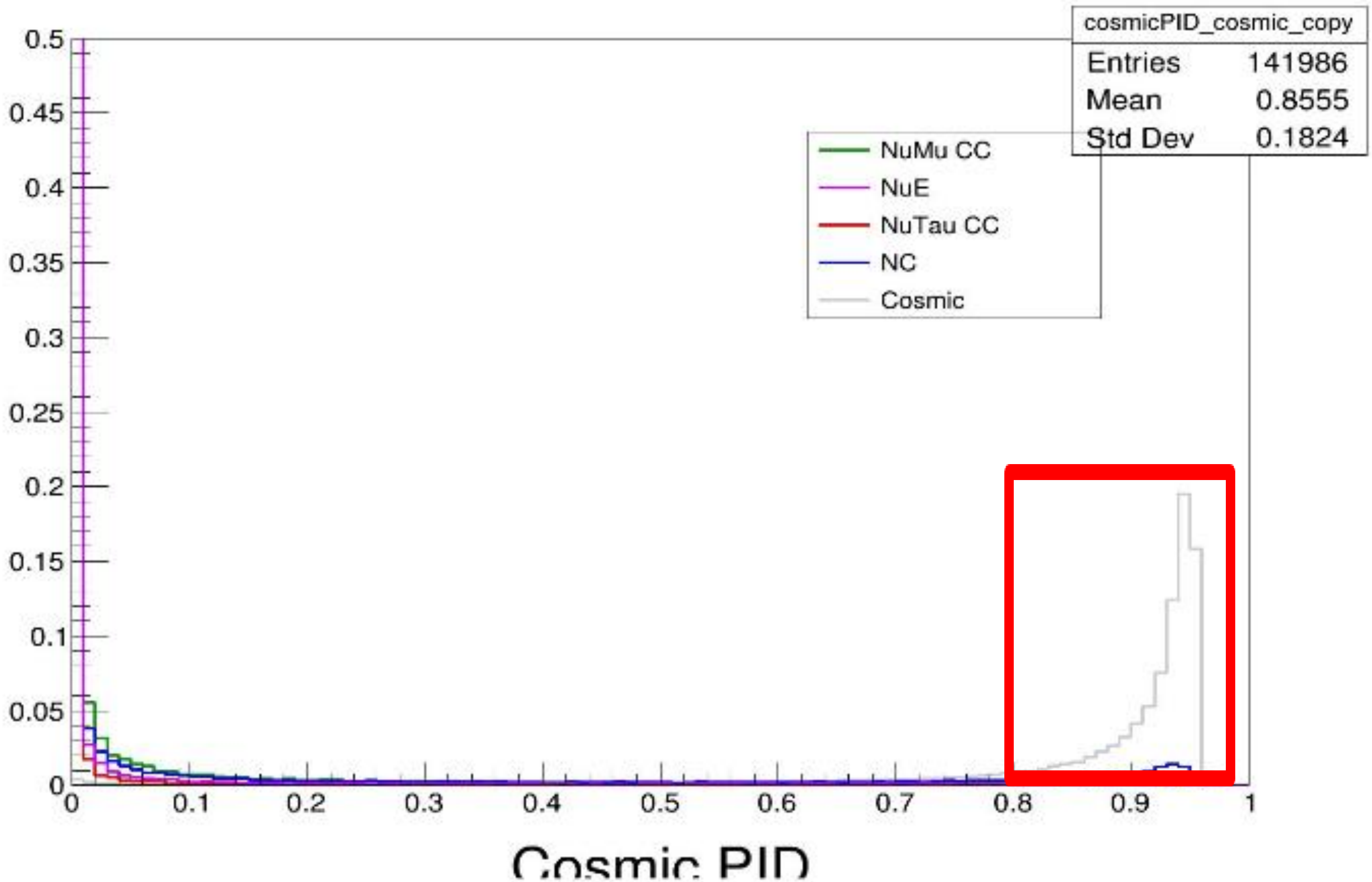
Second Training(2nd chunk)



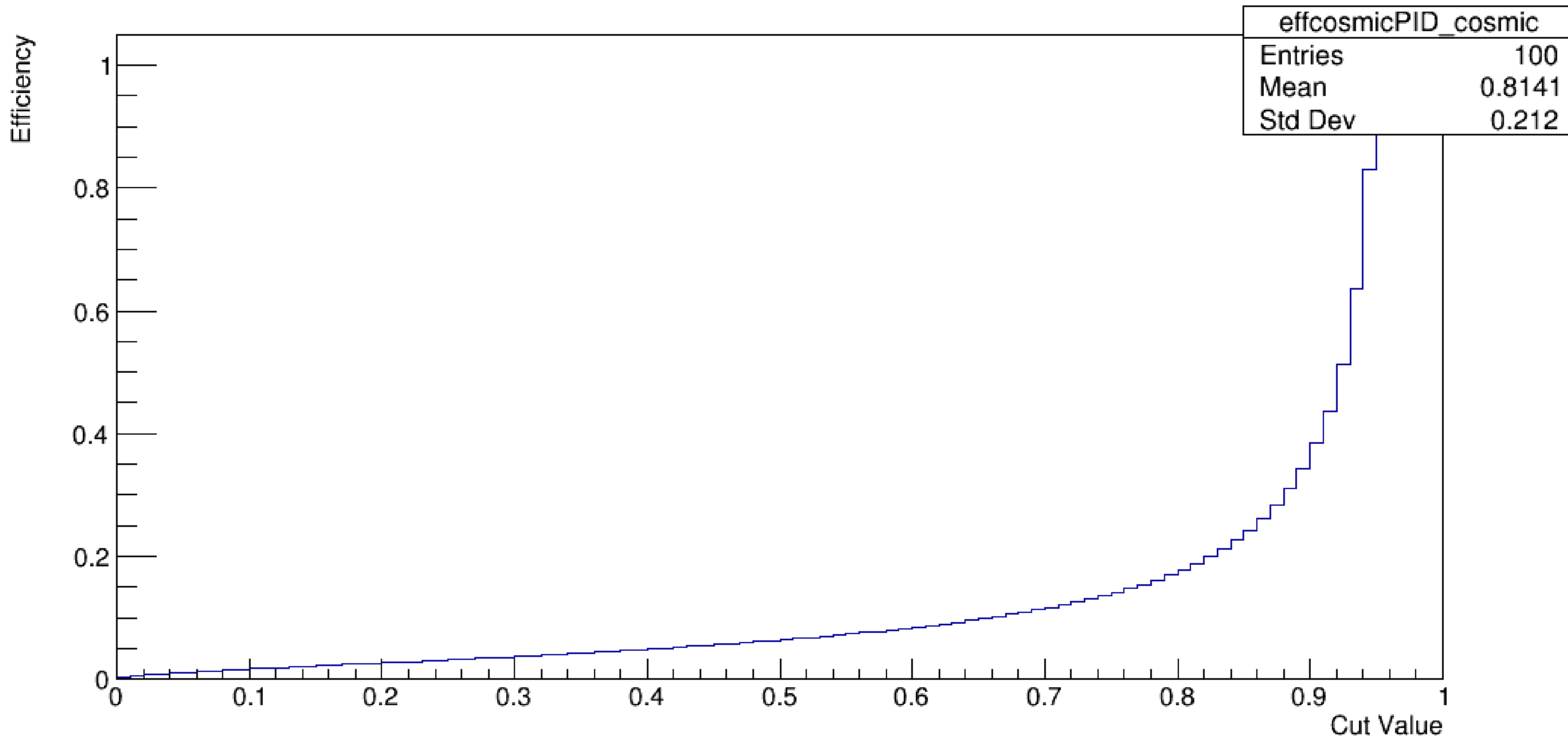
Second Training – Confusion Matrix



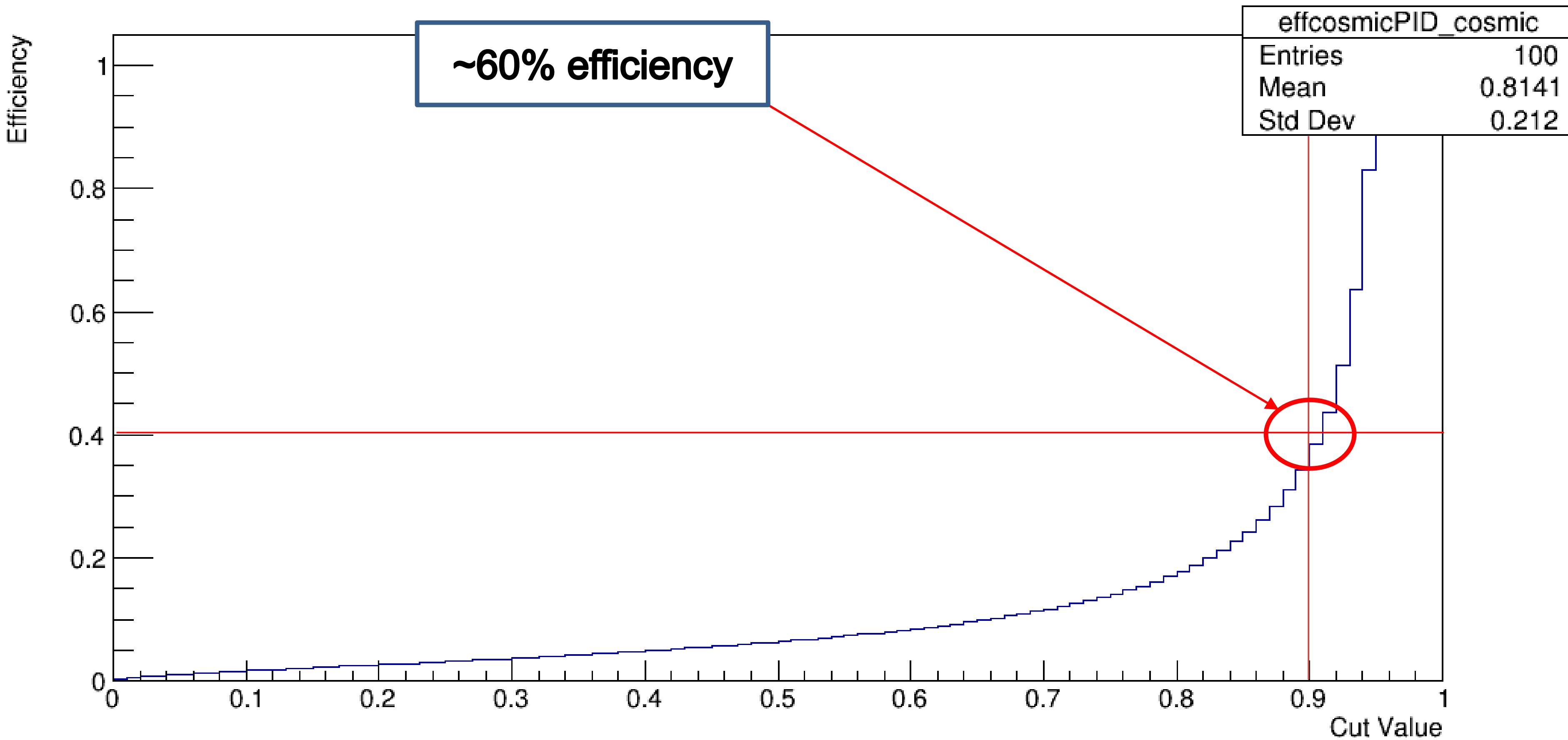
Second Training – PID Plots (Cosmic)



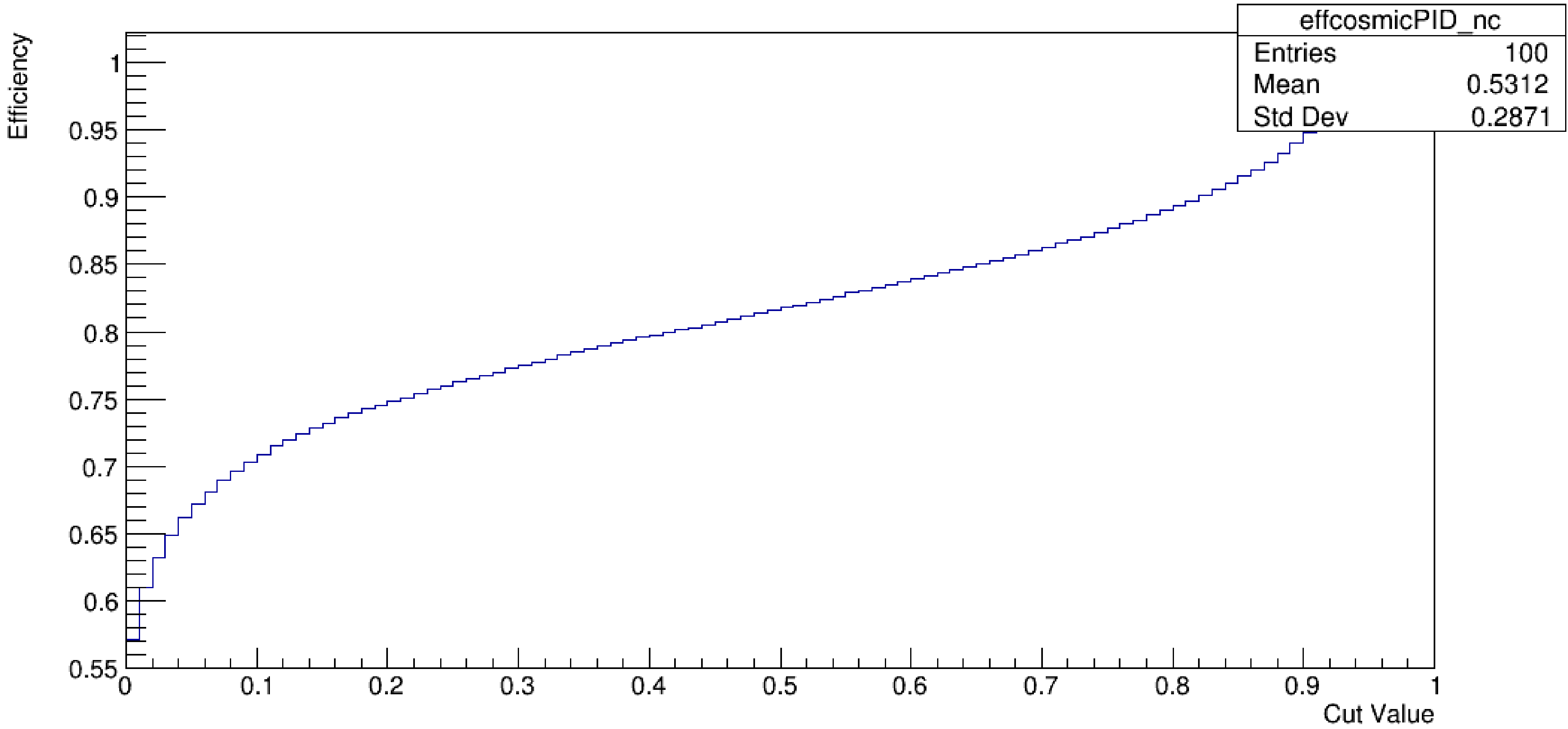
Efficiency vs. Cut(Cosmic)



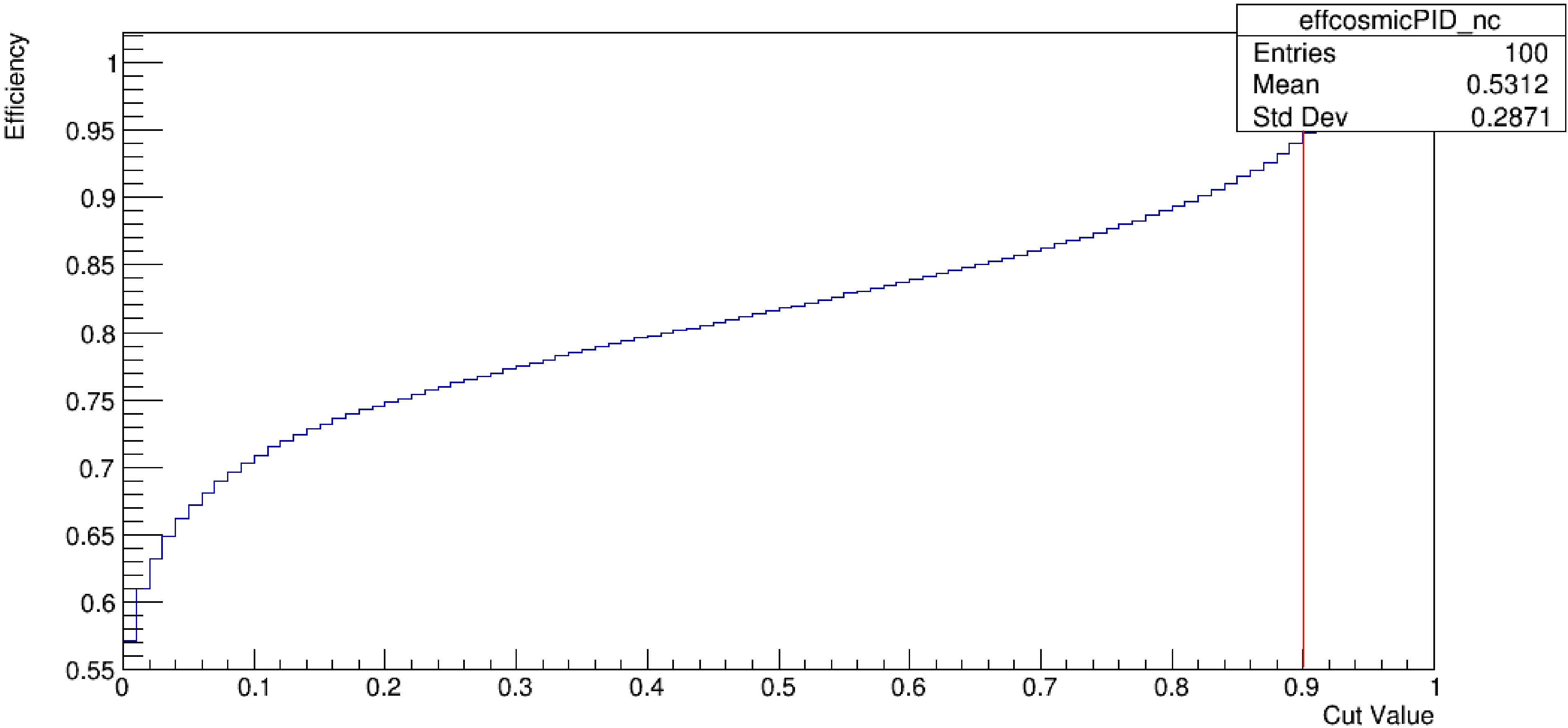
Efficiency vs. Cut(Cosmic)



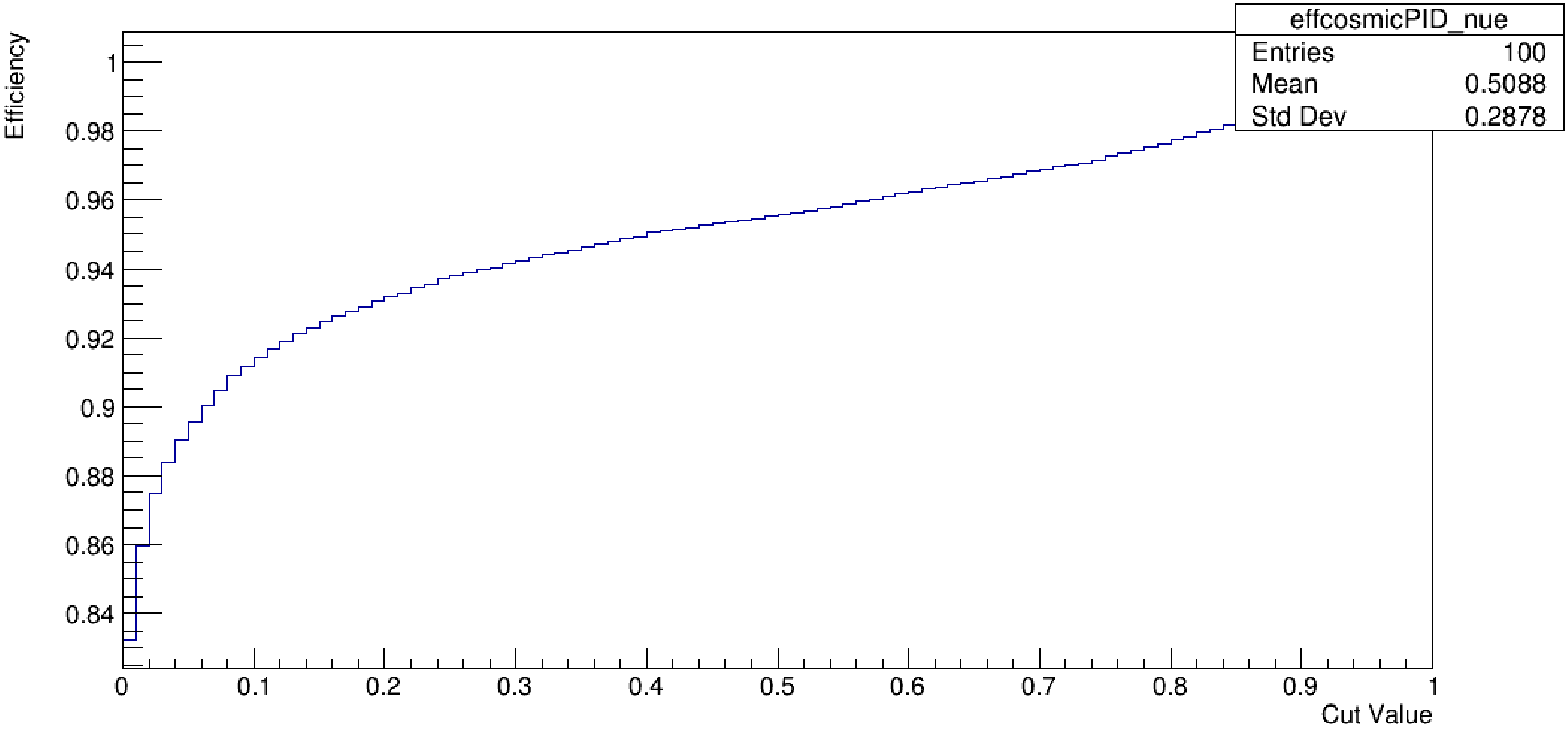
Efficiency vs. Cut(NC)



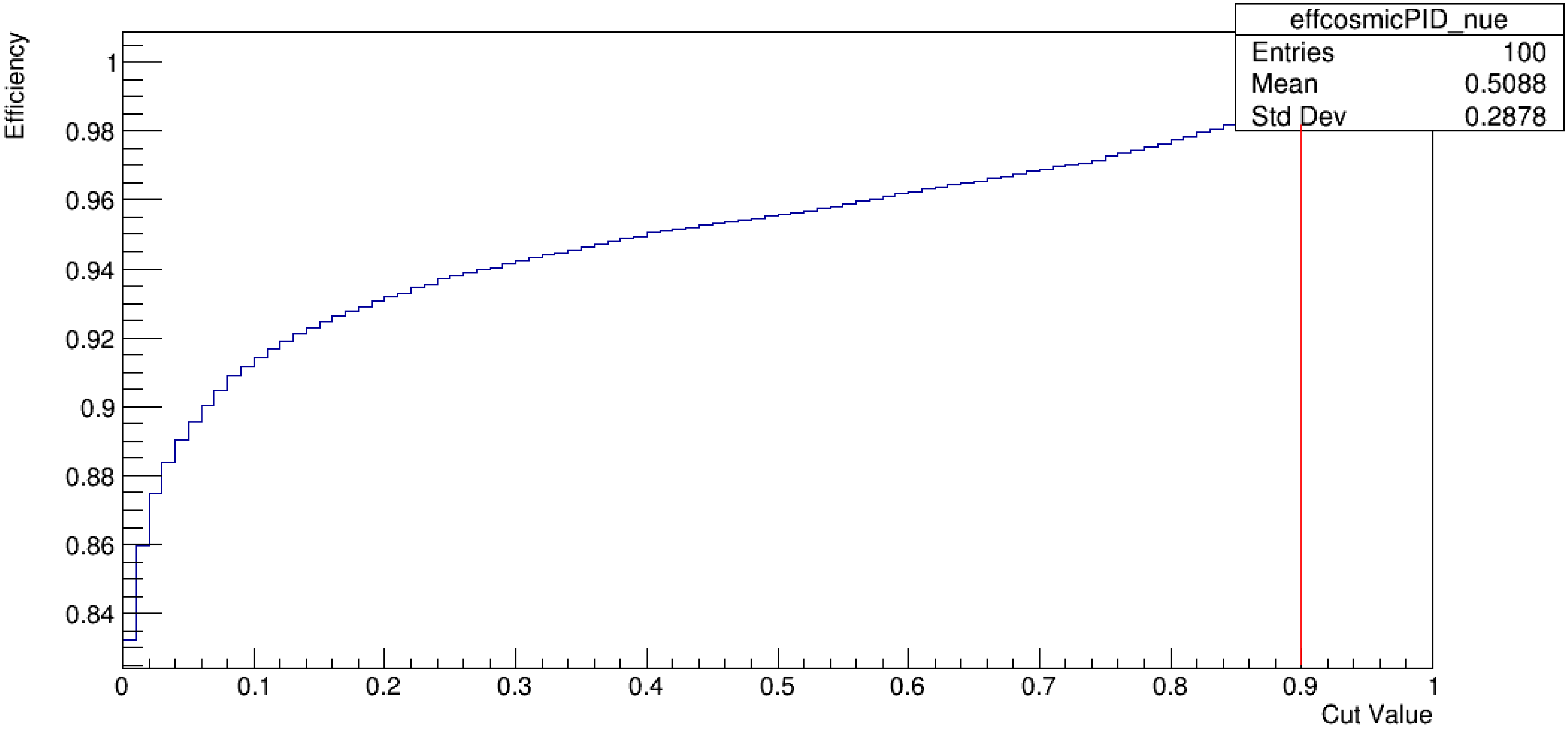
Efficiency vs. Cut(NC)



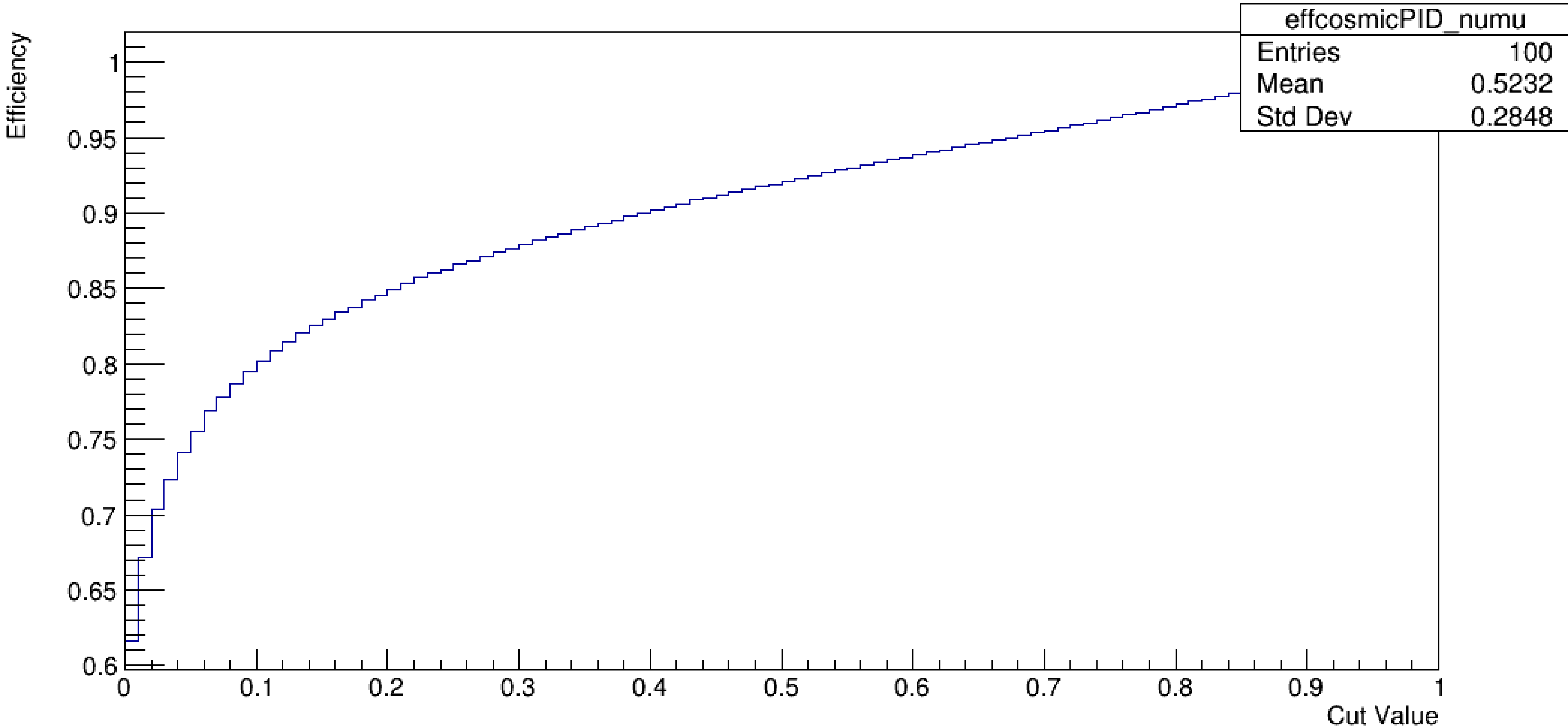
Efficiency vs. Cut(ν_e)



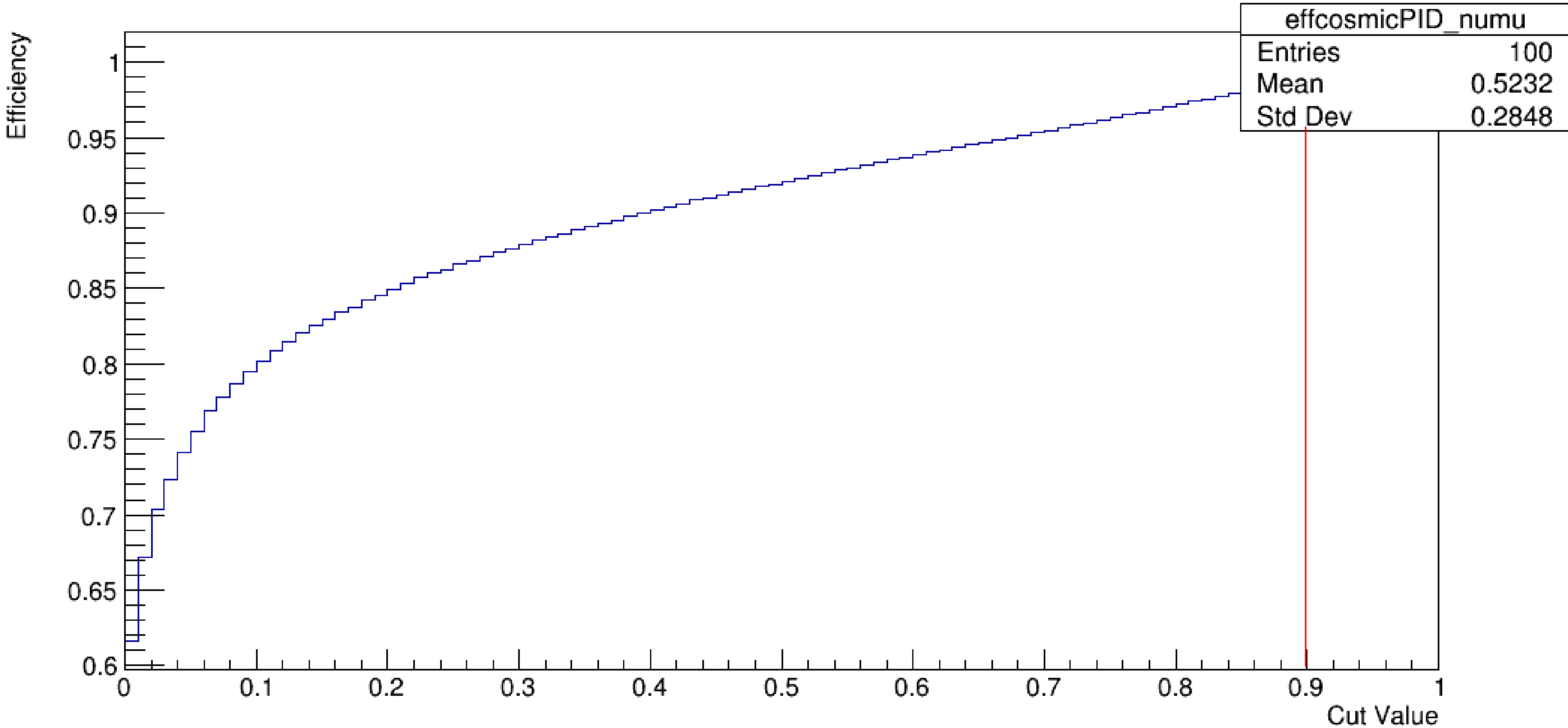
Efficiency vs. Cut(ν_e)



Efficiency vs. Cut (ν_μ)



Efficiency vs. Cut (ν_μ)



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Conclusions and Future Work

- Cosmic rejection network has potential for implementation
- Continue to tune/train the networks
- Utilize multi-access DBs
- Move to Keras/TensorFlow

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