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2 μ/π separation using

3 Convolutional Neural Networks

4 for the MicroBooNE

5 Charged Current Inclusive Cross Section

6 Measurement

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DISSERTATION

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of the requirements for the degree
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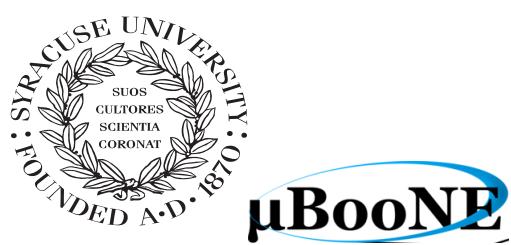
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μ BooNE



26

Abstract

27

The purpose of this thesis was to use Convolutional Neural Networks
28 (CNN) to separate μ' s and π' s for use in increasing the acceptance rate
29 of μ' s below the implemented 75cm track length cut in the Charged
30 Current Inclusive (CC-Inclusive) event selection for the CC-Inclusive
31 Cross-Section Measurement. In doing this, we increase acceptance
32 rate for CC-Inclusive events below a specific momentum range.

33

Dedication

34

I dedicate this dissertation to the two important women in my life; My
35 wife and my mom. Both have been there cheering me on giving me strength
36 and love as I worked towards the hardest accomplishment I've ever done.

37

Jessica Nicole Esquivel

38

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39 Of the many people who deserve thanks, some are particularly prominent, such as
40 my supervisor...

41 Contents

42	List of figures	xiii
43	List of tables	xv
44	1 Introduction	1
45	2 Neutrinos	3
46	2.1 What are Neutrinos	3
47	2.2 History of Neutrinos	4
48	2.3 Neutrino Oscillations	4
49	2.3.1 Solar Oscillations and the Solar Neutrino Problem	5
50	2.3.2 Atmospheric Oscillations and the Atmospheric Neutrino Anomaly	7
51	2.3.3 Two Flavor Neutrino Oscillation Formulation	9
52	2.3.4 Three Flavor Neutrino Oscillation Formulation	12
53	2.3.5 Reactor Oscillation	13
54	3 The MicroBooNE Experiment	15
55	3.1 Liquid argon time projection chambers	15
56	3.2 The MicroBooNE Time Projection Chamber	16
57	3.3 MicroBooNE’s Physics Goals	18
58	3.3.1 The low-energy excess	18
59	3.3.2 Cross sections	19
60	3.3.3 Astroparticle physics	19
61	3.3.4 Liquid argon detector development	19
62	3.4 The Booster Neutrino Beam	20
63	3.4.1 Creating the Booster Neutrino Beam	20
64	3.5 Event Reconstruction	21

65	4 Neutrino Identification: Finding MicroBooNE's first Neutrinos	23
66	4.1 Flash Finding	23
67	4.1.1 Flash Reconstruction	24
68	4.1.2 Beam Timing	25
69	4.1.3 Event Rates	26
70	4.2 TPC Topology Selection	26
71	4.2.1 Cosmic Tagging	27
72	4.2.2 2D Cluster Selection	27
73	4.2.3 3D Tracks and vertices Selection	29
74	4.2.4 TPC Updates	31
75	4.3 Conclusion	32
76	5 CC-Inclusive Cross Section Selection Filter	33
77	5.1 The importance of μ/π separation	34
78	6 Background on Convolutional Neural Networks	37
79	6.1 Image Classification	37
80	6.1.1 CNN Structure	38
81	6.1.2 Backpropagation	41
82	6.2 AlexNet	41
83	6.3 GoogleNet	41
84	7 Training Convolutional Neural Networks on particles WORKING TITLE	43
85	7.1 Hardware Frameworks used for Training	44
86	7.1.1 Syracuse CPU Machine setup	44
87	7.1.2 Syracuse University GPU Cluster Setup	44
88	7.2 Convolutional Neural Network Training	44
89	7.2.1 Image Making Scheme	44
90	7.2.2 Training CNN1075	45
91	7.2.3 Training CNN10000	45
92	7.2.4 Training CNN100000	47
93	8 Results of Convolutional Neural Networks on particles WORKING TITLE	61
94	8.1 Classification using CNN10000	61
95	8.1.1 Classification of MC data using Selection I Original CC-Inclusive Filter	61

97	8.1.2 Classification of MC data using Selection I Modified CC-Inclusive Filter	65
98	8.1.3 Conclusions and Future Work	73
99		
100	8.2 Classification using CNN100000	75
101	8.2.1 Classification of MC data using Selection I Modified CC-Inclusive Filter	75
102	8.2.2 Classification of MicroBooNE data using Selection I Modified CC-Inclusive Filter	75
103		
104	8.2.3 Comparing two CC-Inclusive Cross Section Selection Filters	75
105		
106	9 Conclusion	77
107	Bibliography	79

¹⁰⁸ List of figures

¹⁰⁹	2.1	The Standard Solar Model	5
¹¹⁰	2.2	Solar Neutrino Experiments	7
¹¹¹	2.2a	Ray Davis's Homestake Experiment	7
¹¹²	2.2b	Kamiokande Experiment	7
¹¹³	2.2c	SNO Experiment	7
¹¹⁴	2.3	Cosmic Ray Shower	8
¹¹⁵	2.4	Measurements of the double ratio for various atmospheric neutrino experiments	9
¹¹⁶	2.5	The flavor eigenstates are rotated by an angle θ with respect to the mass eigenstates	10
¹¹⁹	3.1	3.1b Flux of BNB at FNAL	21
¹²⁰	3.1a	Low Energy excess seen in MiniBooNE	21
¹²¹	3.1b	Energy spectrum of the Booster Neutrino Beam at Fermi National Laboratories	21
¹²³	4.1	Efficiency for selecting beam events as a function of minimum total PE cut for all PE cuts as well as zoomed into interesting region.	24
¹²⁵	4.2a	Predicted distribution of flash times with respect to trigger time for 1 day of data taking at nominal rate and intensity	29

127	4.2b Measured distribution of flash times with a 50 PE threshold cut, with respect to trigger time. Shown as a ratio to the expected cosmic rate from off-beam data. A clear excess from neutrinos is visible between 3- 5 μ s after the trigger time.	29
131	4.3 Percent of good clusters remaining for neutrinos and cosmics after the primary cuts were applied. This is relative to total number of initial clusters.	30
134	4.4 Percent matched cluster pairs remaining for neutrinos and cosmics after secondary cuts applied. This is relative to the number of events that contain clusters which pass the primary cuts.	30
137	5.1 5.1a Track range distribution for selection I. The track range is defined as the 3D distance between the start and end of the muon candidate track. No data is shown below 75 cm due to the track length cut described previously. 5.1b Efficiency of the selected events by process quasi-elastic (QE), resonant (RES), and deep-inelastic (DIS). Statistical uncertainty is shown in the bands and the distributions are a function of true muon momentum. The rise of the efficiency between 0 GeV and 0.5 GeV is due to the minimum track length cut and the decreasing efficiency for higher momentum tracks is caused by the containment requirement. .	35
146	5.1a Track range distribution of selection I	35
147	5.1b Selection efficiency as a function of the true muon momentum .	35
148	6.1 Pixel representation and visualization of a curve detector filter. As you can see, in the pixel representation, the weights of this filter are greater along a curve we are trying to find in the input image	39
151	6.2 Visualization of filters found in first layer of a CNN.	39
152	6.3 Applying a feature mask over a set of fashion items to extract necessary information for auto-encoding. Unnecessary information for example color or brand emblems are not saved. This feature map is an edge detec- tion mask that leaves only shape information which helps to distinguish between different types of clothes.	40

157	6.4	Pictorial Representation of Convolutional Neural Networks as well as a visual representation on CNN's complexity of layer feature extraction	40
159	7.1	Accuracy vs. Loss of ImageNet 2-output μ/π sample consisting of 10000 images each.	47
161	7.2	Description of confusion matrix variables: False pion rate = $false\pi/total\pi$ True pion rate = $true\pi/total\pi$ Accuracy = $(true\pi + true\mu)/2$ Pion prediction value = $true\pi/(true\pi + false\pi)$ Muon prediction value = $true\mu/(true\mu + false\mu)$ 7.2c The probability plot includes muons and pions that are classified as primary particles.	48
166	7.2a	Confusion Matrix showing Accuracy of CNN using training data	48
167	7.2b	Confusion Matrix showing Accuracy of CNN using testing data	48
168	7.2c	Probability plot of muons and pions from testing set. Images surrounding histogram are a random event from lowest bin and highest bin for each particle.	48
171	7.3	Confusion Matrix of all five particles	49
172	7.4	Training and testing accuracy of CNN trained on 100,000 images of $\mu/\pi/p/\gamma/e$ with 20,000 images of each particle. Each image was a size of 576x576 and the images per particle were split 90% use for training and 10% used for testing the network	50
176	7.5	Training and testing loss of CNN trained on 100,000 images of $\mu/\pi/p/\gamma/e$	50
177	7.6	t-SNE of CNN	51
178	7.7	Muon Prob	52
179	7.8	Pion Prob	52
180	7.9	Proton Prob	53
181	7.10	Electron Prob	53
182	7.11	Gamma Prob	54
183	7.12	Prob	54
184	7.13	mupi	55

185	7.14 mupi	55
186	7.15 mupi	56
187	7.16 mup	56
188	7.17 mup	57
189	7.18 mup	57
190	7.19 mue	58
191	7.20 mue	58
192	7.21 mue	59
193	7.22 mug	59
194	7.23 mug	60
195	7.24 mug	60
196	8.1 Snapshot of passing rates of Selection I from CC-Inclusive Filter	62
197	8.2 Results of CNN10000 classification of track candidate images output from cc-inclusive filter.	63
199	8.2a Confusion Matrix showing Accuracy of CNN using data with wrong normilazion	63
201	8.2b Probability plot showing μ/π separation of CNN using wrong normalization	63
203	8.2c Confusion Matrix showing Accuracy of CNN using data with correct normilazion	63
205	8.2d Probability plot showing μ/π separation of CNN using correct normalization	63
207	8.3 CNN10000 distributions of track candidate images output from Selec- tion I Original cc-inclusive filter with different image data normalizations	64
209	8.3a Track range distribution of events from Selection I Original passing CNN with 70% accuracy using image data with wrong normilazion	64

212	8.3b	Track range distribution of events from Selection I Original passing CNN with 70% accuracy using image data with correct normilazion	64
213			
214			
215	8.3c	Momentum distribution of events from Selection I Original passing CNN with 70% accuracy using image data with wrong normilazion	64
216			
217			
218	8.3d	Momentum distribution of events from Selection I Original passing CNN with 70% accuracy using image data with correct normilazion	64
219			
220			
221	8.4	Snapshot of passing rates of all cuts from Selection I Modified cc-inclusive filter	65
222			
223	8.5	Confusion matrix and probability plot of events passing selection I modified cc-inclusive cuts right before 75cm track length cut	66
224			
225	8.5a	Confusion Matrix for CNN10000 classified events from selection I modified	66
226			
227	8.5b	Probability plot for CNN10000 classified events from selection I modified	66
228			
229	8.6	CNN10000 distributions of track candidate images output from Selection I Modified cc-inclusive filter	67
230			
231	8.6a	Track range distribution of events from Selection I Modified passing CNN with 70% accuracy	67
232			
233	8.6b	Stacked signal and background track range distributions from Selection I Modified passing CNN with 70% accuracy	67
234			
235	8.6c	Stacked signal and background track range distributions from Selection I Modified passing 75 cm track length cut	67
236			
237	8.6d	Stacked signal muons and background muons/pions of track range distributions from Selection I Modified passing CNN with 70% accuracy	67
238			
239			

240	8.6e	Stacked signal muons and background muons/pions of track range distributions from Selection I Modified passing 75 cm track length cut	67
243	8.7	CNN10000 stacked signal/background track range distributions of track candidate images output from Selection I Modified cc-inclusive filter	68
245	8.7a	Stacked signal muons and background muons/pions of track range distributions from Selection I Modified passing CNN with 75% accuracy	68
248	8.7b	Stacked signal muons and background muons/pions of track range distributions from Selection I Modified passing CNN with 80% accuracy	68
251	8.7c	Stacked signal muons and background muons/pions of track range distributions from Selection I Modified passing CNN with 85% accuracy	68
254	8.7d	Stacked signal muons and background muons/pions of track range distributions from Selection I Modified passing CNN with 90% accuracy	68
257	8.8	CNN10000 momentum distributions of track candidate images output from Selection I Modified cc-inclusive filter	69
259	8.8a	Momentum distribution of events from Selection I Modified passing CNN with 70% accuracy	69
261	8.8b	Stacked signal and background momentum distributions from Selection I Modified passing CNN with 70% accuracy	69
263	8.8c	Stacked signal and background momentum distributions from Selection I Modified passing 75 cm track length cut	69
265	8.9	Track distribution comparisons of true CC muons plotted vs true CC muons and pions plotted	71
267	8.9a	Stacked signal μ /background μ and π track range distribution of CNN @ 70%	71

269	8.9b Stacked signal $\mu\&\pi$ /background $\mu\&\pi$ track range distribution of CNN @ 70%	71
271	8.10 Images of true CC events where the pion was the tagged track candidate	71
272	8.10a Pion reconstructed track range is less than 75 cm and longer than muon track due to dead wires	71
273	8.10b Pion reconstructed track range is less than 75 cm and larger than muon reconstructed track	71
274	8.10c Pion reconstructed track range is greater than 75 cm and larger than muon reconstructed track	71
278	8.11 Snapshot of signal and background event numbers of Selection I modified from cc-inclusive note [?]	74
280	8.12 CNN performance of classified muons and pions compared to the already implemented 75 cm track length cut	74
281		

²⁸² List of tables

²⁸³ 4.1	Passing rates for 2D cluster cuts for neutrino on MC set and a cosmic only MC set. First column shows event rates with no cuts applied to both sets. Columns two and three show event rates after primary and secondary cuts are applied. Line three shows the seccond line scaled with the flash finding factor of 0.008. All events are normalized to per day assuming we are running at 5 Hz.	²⁸⁴ 29
²⁸⁹ 8.1	Comparing passing rates of CNN at different probabilities versus 75 cm track length cut: Numbers are absolute event counts and Cosmic background is not scaled appropriately. The BNB+Cosmic sample contains all events. The numbers in brackets give the passing rate wrt the step before (first percentage) and wrt the generated events (second percentage). In the BNB+Cosmic MC Truth column shows how many true ν_μ CC-inclusive events (in FV) are left in the sample. This number includes possible mis-identifications where a cosmic track is picked by the selection instead of the neutrino interaction in the same event. The CNN MC True generated events were scaled wrt the MC True generated events for the 75 cm cut passing rates due to only running over 188,880 generated events versus the 191362 generated events. The last column Signal:Cosmic only gives an estimate of the ν_μ CC events wrt the cosmic only background at each step. For this number, the cosmic background has been scaled as described in [?]. Note that these numbers are not a purity, since other backgrounds canâŽt be determined at this step. . .	²⁹⁰ 72

305	8.2 Signal and background event numbers at modified selection level with	
306	CNN cut estimated from a BNB+Cosmic sample and Cosmic only sam-	
307	ple normalized to $5 * 10^{19}$ PoT. The last column gives the fraction of	
308	this signal or background type to the total selected events per CNN	
309	probability.	72

*"If they don't give you a seat at the table,
bring a folding chair."*

— Shirley Chisholm

³¹² **Chapter 1**

³¹³ **Introduction**

³¹⁴ This thesis will be a description of work done to further increase efficiency and purity
³¹⁵ of the charged current inclusive cross section measurement using the MicroBooNE
³¹⁶ detector. It will also describe the MicroBooNE detector, what neutrinos are, the charged
³¹⁷ current inclusive cross section measurement and its importance as well as convolutional
³¹⁸ neural networks and how they can be used in μ/π separation. Chapter 2 will talk
³¹⁹ about the background of neutrinos and the people and detectors that discovered
³²⁰ neutrinos as well as an in depth history of neutrino oscillation and the discovery that
³²¹ neutrinos have mass. Chapter 3 will discuss the MicroBooNE experiment, specifically,
³²² how Liquid Argon Time Projection Chambers work, the Light Collection System and
³²³ the Electronic and Readout Trigger systems. Chapter ?? will describe the Booster
³²⁴ Neutrino Beam sationed at Fermi National Accelerator Lab. Chapter 4 will discuss the
³²⁵ work that was done to detect the first neutrinos seen in the MicroBooNE detector and
³²⁶ the software reconstruction efforts required to create an automated neutrino ID filter
³²⁷ that was used to find the first neutrinos and then was later expanded on to create the
³²⁸ charged current inclusive filter that will be discussed in chapter 5 Chapter 6 will give a
³²⁹ brief description of what Convolutional Neural Networks are and how it will be used
³³⁰ for μ/π separation in this selection. Chapter 7 will discuss the hardware frameworks
³³¹ and training methods used to train multiple Convolutional Neural Networks for use
³³² in the charged current inclusive cross section measurement. Chapters 8, ?? and ?? will
³³³ discuss the results of using Convolutional Neural Networks on monte-carlo and data
³³⁴ to sift out charged current inclusive neutrino events.

³³⁵ Chapter 2

³³⁶ Neutrinos

³³⁷ 2.1 What are Neutrinos

³³⁸ Neutrinos are one of the fundamental particles which make up the universe. They are
³³⁹ also one of the least understood. Neutrinos are not affected by the electromagnetic
³⁴⁰ forces because they do not have electric charge. Neutrinos are affected by a "weak"
³⁴¹ sub-atomic force of much shorter range than electromagnetism, and are therefore able
³⁴² to pass through great distances in matter without being affected by it. Until the late
³⁴³ 90's, neutrinos were thought to have no mass. Due to their mass, neutrinos are also
³⁴⁴ affected by gravity. Neutrinos are created by radioactive decay or nuclear reactions
³⁴⁵ such as the ones that happen in the sun, in nuclear reactors or when cosmic rays hit
³⁴⁶ atoms. There are three types of neutrinos, ν_e , ν_μ and ν_τ which correspond to their
³⁴⁷ charged lepton pairs.

³⁴⁸ As previously stated, neutrinos are very weakly interacting; in fact, neutrinos can
³⁴⁹ pass unscathed through a wall of lead several hundred light-years thick. Because
³⁵⁰ neutrinos interact so rarely, studying neutrinos requires a massive detector and a
³⁵¹ powerful neutrino source. With that being said, we can only infer their existence when
³⁵² they interact in a detector. In a collision, distinct charged particles are produced with
³⁵³ each type of neutrino. An electron neutrino will create an electron, a muon neutrino
³⁵⁴ will create a muon, and a tau neutrino will create a tau. The track the particle leaves
³⁵⁵ in the detector is how one figures out what type of neutrino interaction was "seen".
³⁵⁶ Liquid Argon Time Projection Chambers are the newest type of detectors being used to
³⁵⁷ study neutrinos due to their excellent imaging and particle identification capabilities.

³⁵⁸ 2.2 History of Neutrinos

³⁵⁹ The neutrino was first postulated by Wolfgang Pauli in 1931 to explain how beta
³⁶⁰ decay could resolve the conservation of energy, momentum and angular momentum
³⁶¹ problem. Pauli suggested that this missing energy might be carried off, unseen, by a
³⁶² neutral particle (he called neutron) which was escaping detection. James Chadwick
³⁶³ discovered a much heavier nuclear particle in 1932 that he also named neutron, leaving
³⁶⁴ two particles with the same name. Enrico Fermi was the first person to coin the
³⁶⁵ term neutrino (which means little neutral one in latin) in 1933 to fix this confusion.
³⁶⁶ Fermi's paper, which was published in 1934, unified Pauli's neutrino with Paul Dirac's
³⁶⁷ positron and Werner Heisenberg's neutron-proton model and his theory accurately
³⁶⁸ explained many experimentally observed results. Wang Ganchang first proposed the
³⁶⁹ use of beta capture to experimentally detect neutrinos and in 1959 Clyde Cowan and
³⁷⁰ Frederick Reines published their work stating that they had detected the neutrino.
³⁷¹ The experiment called for antineutrinos created in a nuclear reactor by beta decay that
³⁷² reacted with protons producing neutrons and positrons: $\nu_e + p^+ \rightarrow n^0 + e^+$. Once
³⁷³ this happens, the positron finds an electron and they annihilate each other and the
³⁷⁴ resulting gamma rays are detectable. The neutron is detected by neutron capture and
³⁷⁵ the releasing of another gamma ray. In 1962 Leon M. Lenderman, Melvin Schwartz
³⁷⁶ and Jack Steinberger were the first to detect interactions of the muon neutrino. The
³⁷⁷ first detection of the tau neutrino was announced in the summer of 2000 by the
³⁷⁸ DONUT collaboration at Fermilab. In the late 1960s, many experiments found that the
³⁷⁹ number of electron neutrinos arriving from the sun was around 1/3 to 1/2 the number
³⁸⁰ predicted by the Standard Solar Model. This became known as the solar neutrino
³⁸¹ problem and remained unresolved for around thirty years. This problem was resolved
³⁸² by the discovery of neutrino oscillation and mass. [1]

³⁸³ 2.3 Neutrino Oscillations

³⁸⁴ Neutrino oscillation was first predicted by Bruno Pontecorvo. It describes the phe-
³⁸⁵ nomenon of a neutrino created with a specific lepton flavor (electron, muon or tau)
³⁸⁶ that is later measured to have a different flavor. Neutrino oscillation is important
³⁸⁷ theoretically and experimentally due to the fact that this observation implies that the
³⁸⁸ neutrino has a non-zero mass, which is not part of the original Standard Model of
³⁸⁹ particle physics. [2]

390 2.3.1 Solar Oscillations and the Solar Neutrino Problem

391 The solar neutrino flux derived from Bahcall's Standard Solar Model is shown in figure
 392 2.1. Nuclear fusion and decay processes produce an abundant amount of neutrinos.
 393 The standard solar model predicts that these reactions produce several groups of
 394 neutrinos, each with differing fluxes and energy spectra. The figure also shows the
 395 ranges of detection of existing solar neutrino experiments in different shades of blue
 396 to illustrate that they sample different portions of the solar neutrino energy spectrum.
 397 Three of these experiments, plus a new one, are discussed below.

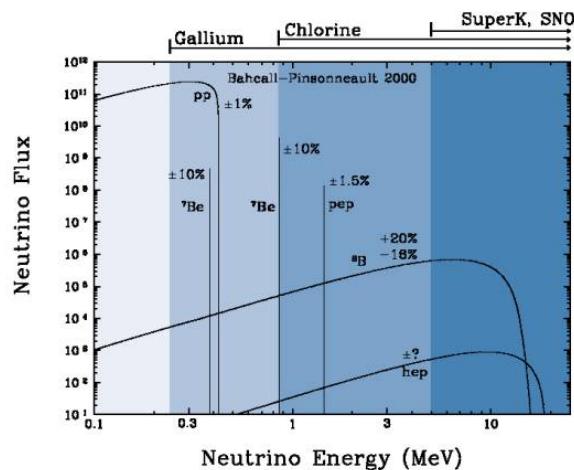


Figure 2.1: The Standard Solar Model

398 Since neutrinos rarely interact with matter, they pass through the sun and the earth
 399 undetected. About 65-billion neutrinos from the sun stream through every square
 400 centimeter on the Earth every second, yet we are oblivious to their passage in our
 401 every-day lives. [3]

402 The first experiment to detect the effects of neutrino oscillation was the Ray Davis's
 403 Homestake Experiment. The detector was stationed in the Homestake Gold Mine in
 404 Lead, South Dakota. It was 1,478 meters underground and was 380 m^3 . The detector
 405 was filled with perchloroethylene. Perchloroethylene was chosen because of its high
 406 concentrations of chlorine. When an ν_e interacted with chlorine-37 atom, the atom
 407 would transform to argon-37 which was then extracted and counted. The neutrino
 408 capture reaction is shown in equation 2.1. Davis observed a deficit of about 1/3
 409 the flux of solar neutrinos that was predicted by Bahcall's Standard Solar Model.

- ⁴¹⁰ The unexplained difference between the measured solar neutrino flux and model
⁴¹¹ predictions lead to the Solar Neutrino Problem. [4]



⁴¹² While it is now known that the Homestake Experiment detected neutrinos, some
⁴¹³ physicist were weary of the results. Conclusive evidence of the Solar Neutrino Problem
⁴¹⁴ was provided by the Kamiokande-II experiment, a water Cherenkov detector with
⁴¹⁵ a low enough energy threshold to detect neutrinos through neutrino-electron elastic
⁴¹⁶ scattering. In the elastic scattering interaction the electrons coming out of the point of
⁴¹⁷ reaction strongly point in the direction that the neutrino was traveling, away from the
⁴¹⁸ sun. While the neutrinos observed in Kamiokande-II were clearly from the sun, there
⁴¹⁹ was still a discrepancy between Kamiokande-II and Homestake; The Kamiokande-
⁴²⁰ II experiment measured about 1/2 the predicted flux, rather than the 1/3 that the
⁴²¹ Homestake Experiment saw.

⁴²² The solution to the solar neutrino problem was finally experimentally determined
⁴²³ by the Sudbury Neutrino Observatory(SNO). The Ray Davis's Homestake Experiment
⁴²⁴ was only sensitive to electron neutrinos, and the Kamiokande-II Experiment was
⁴²⁵ dominated by the electron neutrino signal. The SNO experiment had the capability to
⁴²⁶ see all three neutrino flavors. Because of this, it was possible to measure the electron
⁴²⁷ neutrinos and total neutrino flux. The experiment demonstrated that the deficit was
⁴²⁸ due to the MSW effect, the conversion of electron neutrinos from their pure flavor
⁴²⁹ state into the second neutrino mass eigenstate as they passed through a resonance
⁴³⁰ due to the changing density of the sun. The resonance is energy dependent, and is
⁴³¹ visible near 2MeV. The water cherenkov detectors only detect neutrinos above about
⁴³² 5MeV, while the radiochemical experiments were sensitive to lower energy (0.8MeV
⁴³³ for chlorine, 0.2MeV for gallium), and this turned out to be the source of the difference
⁴³⁴ in the observed neutrino rates at the two types of experiments. Figure 2.2 shows
⁴³⁵ Homestake, Kamiokande-II and SNO experiments.

⁴³⁶ MSW Effect

⁴³⁷ The Mikheyev-Smirnov-Wolfenstein effect is a process which acts to modify neu-
⁴³⁸ trino oscillations in matter. The presence of electrons in matter changes the energy

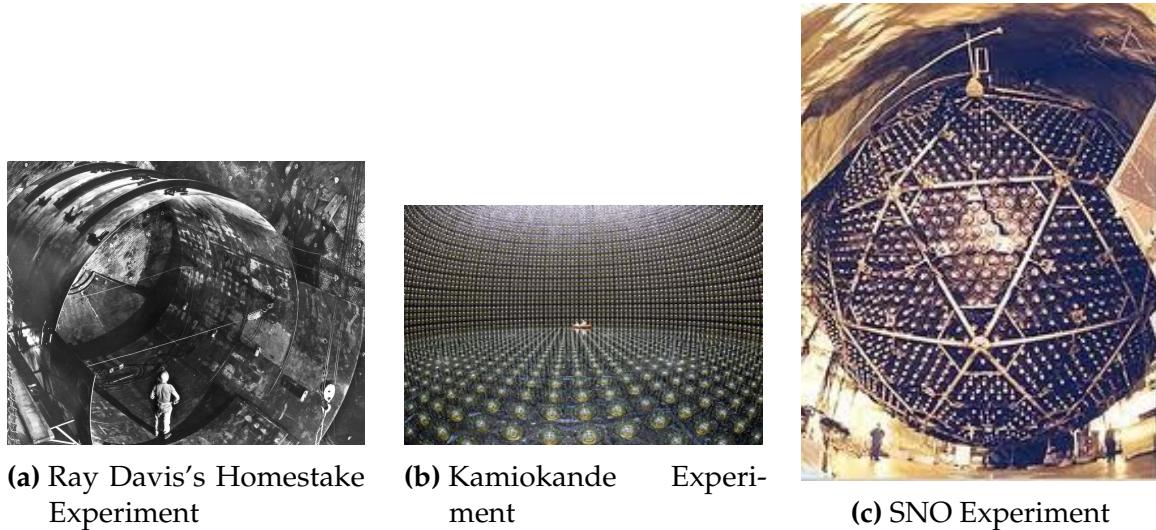


Figure 2.2: Solar Neutrino Experiments

439 levels of the mass eigenstates of neutrinos due to charged current coherent forward
 440 scattering of the electron neutrinos. This coherent forward scattering is similar to
 441 the electromagnetic process with respect to the refractive index of light in a medium.
 442 Because of this MSW Effect, neutrinos in vacuum have a different effective mass than
 443 neutrinos in matter and because neutrino oscillations depend on the squared mass
 444 difference of the neutrinos, the neutrino oscillations are different in matter than in
 445 vacuum. This effect is important at the sun where electron neutrinos are produced.
 446 The neutrinos of high energy leaving the sun are in a vacuum propagation eigenstate
 447 ν_2 that has a very small overlap with the electron neutrino $\nu_e = \nu_1\cos(\theta) + \nu_2\sin(\theta)$
 448 seen by the charged current reactions in Kamiokande-II and SNO. The discrepancy of
 449 the deficit between SNO, Kamiokande-II and Homestake is due to the energy of the
 450 solar neutrinos. The MSW effect "turns on" at about 2MeV and at lower energies, this
 451 MSW effect is negligible. [5]

452 **2.3.2 Atmospheric Oscillations and the Atmospheric Neutrino 453 Anomaly**

454 Atmospheric neutrinos are neutrinos that stem from the decay hadrons coming from
 455 primary cosmic rays. The dominant part of the decay chain is shown in equations 2.2
 456 and 2.3

$$\pi^+ \rightarrow \mu^+ \nu_\mu \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \quad (2.2)$$

457

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \quad (2.3)$$



Figure 2.3: Cosmic Ray Shower

458 Figure 2.3 shows the cosmic ray shower. In general, these neutrinos have energies
 459 from 1GeV to 100s of GeV and the ratio of ν_μ s to ν_e s equals to 2 (see equation 2.4)

$$R = \frac{(\nu_\mu + \bar{\nu}_\mu)}{(\nu_e + \bar{\nu}_e)} \quad (2.4)$$

460 There have been two types of detectors used to study atmospheric neutrinos: Water
 461 Cherenkov detectors and tracking calorimeters. Super-Kamiokande is the detector we
 462 will focus on. These atmospheric detector experiments measure the ratio of ν_μ to ν_e .
 463 They also measure the zenith angle distribution of the neutrinos. These experiments
 464 report a double ratio (shown in equation 2.5). This double ratio is the ratio measured
 465 in the detector to the ratio that's expected which is 2. If the double ratio equals to 1, the
 466 data agrees with the prediction. Various measurements from multiple experiments
 467 are shown in figure 2.4. Except for Frejus, all R measurements are less than 1. This
 468 discrepancy between the predicted R and the measured R became known as the
 469 Atmospheric Neutrino Anomaly.

$$R = \frac{(N_\mu / N_e)_{DATA}}{(N_\mu / N_e)_{SIM}} \quad (2.5)$$

470 Kamiokande-II has the the capability of measuring the direction of the incoming
 471 neutrinos. The expectation of atmospheric neutrino detection is that the flux be

Experiment	Type of experiment	R
Super-Kamiokande	Water Cerenkov	0.675 ± 0.085
Soudan2	Iron Tracking Calorimeter	0.69 ± 0.13
IMB	Water Cerenkov	0.54 ± 0.12
Kamiokande	Water Cerenkov	0.60 ± 0.07
Frejus	Iron Tracking Calorimeter	1.0 ± 0.15

Figure 2.4: Measurements of the double ratio for various atmospheric neutrino experiments

isotropic due to the fact that atmospheric neutrinos can reach the detector from all directions. Kamiokande-II noticed that muon-like data did not agree well with this expectation. At low energies approximately half of the ν_μ are missing over the full range of zenith angles. At high energies the number of ν_μ coming down from above the detector seems to agree with expectation, but half of the same ν_μ coming up from below the detector are missing. This anomaly can be easily explained by neutrino flavor oscillations. Due to the fact that the neutrino travels less distance coming straight down into the detector (about 15km) than coming up from the bottom of the detector(13000km) changes the probability of oscillation. The probability of oscillation for the muon neutrinos coming down into the detector is roughly zero, whereas for neutrinos coming up, the oscillation probability is $\sin^2(2\theta)$. Both the solar and atmospheric neutrino problems can be explained by neutrino oscillation so its fitting to derive this phenomenon mathematically. In the next two sections, two flavor and three flavor neutrino oscillation derivations will be explained.

2.3.3 Two Flavor Neutrino Oscillation Formulation

The flavor eigenstates can oscillate between each other because they are composed of an add-mixture of mass eigenstates(ν_1, ν_2). Figure 2.5 shows the mass and flavor eigenstates rotated by an angle θ which is the mixing angle.

In matrix form the wavefunctions are:

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} * \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad (2.6)$$

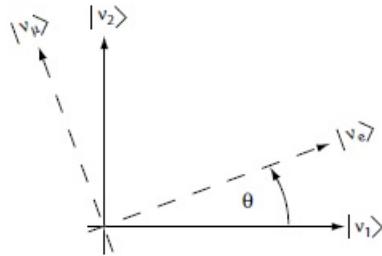


Figure 2.5: The flavor eigenstates are rotated by an angle θ with respect to the mass eigenstates

⁴⁹¹ Applying the time evolution operator to ν_μ :

$$|\nu_\mu(t)\rangle = -\sin\theta|\nu_1\rangle e^{-i\frac{E_1 t}{\hbar}} + \cos\theta|\nu_2\rangle e^{-i\frac{E_2 t}{\hbar}} \quad (2.7)$$

⁴⁹² where $E_1 = \sqrt{p^2 c^2 + m_1^2 c^4}$ and $E_2 = \sqrt{p^2 c^2 + m_2^2 c^4}$ and $p_1 = p_2$. For the time
⁴⁹³ being, let us assume $\hbar = c = 1$. With this assumption: $E_1 = \sqrt{p^2 + m_1^2}$ and $E_2 =$
⁴⁹⁴ $\sqrt{p^2 + m_2^2}$. The next modifications is to assume neutrinos are relativistic:

$$\gamma = \frac{E}{m_o c^2} = \frac{\sqrt{p^2 c^2 + m_o^2 c^4}}{m_o c^2} \gg 1 \quad (2.8)$$

⁴⁹⁵ because of this,

$$p \gg m_o \quad (2.9)$$

⁴⁹⁶

$$E = \sqrt{p^2 + m_o^2} = p\sqrt{1 + m_o^2/p^2} \simeq p + \frac{1}{2}\frac{m_o^2}{p} \quad (2.10)$$

⁴⁹⁷ where the binomial expansion is used. Now E_1 and E_2 can be written as:

$$E_1 \simeq p + \frac{1}{2}\frac{m_1^2}{p} \text{ and } E_2 \simeq p + \frac{1}{2}\frac{m_2^2}{p} \quad (2.11)$$

⁴⁹⁸ Now applying all these assumptions back into equation 2.7 gives us:

$$|\nu_\mu(t)\rangle = -\sin\theta|\nu_1\rangle e^{-i\left(p + \frac{1}{2}\frac{m_1^2}{p}\right)t} + \cos\theta|\nu_2\rangle e^{-i\left(p + \frac{1}{2}\frac{m_2^2}{p}\right)t} \quad (2.12)$$

$$|\nu_\mu(t)\rangle = e^{-i\left(p+\frac{1}{2}\frac{m_1^2-m_2^2}{p}\right)t} (-\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle) \quad (2.13)$$

₄₉₉ Substituting $\Delta m^2 = m_1^2 - m_2^2$ and $t = \frac{x}{c} = x$ and $e^{-iz} = e^{-i\left(p+\frac{1}{2}\frac{m_1^2}{p}\right)t}$ gives us:

$$|\nu_\mu(t)\rangle = e^{-iz} \left(-\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle e^{+ix\left(\frac{1}{2}\frac{\Delta m^2}{p}\right)} \right) \quad (2.14)$$

₅₀₀ Finding the Probability for a $\nu_\mu \rightarrow \nu_e$:

$$P(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2 \quad (2.15)$$

₅₀₁ Remembering that $\langle \nu_i | \nu_j \rangle = \delta_{ij}$

$$\langle \nu_e | \nu_\mu(t) \rangle = e^{-iz} \left(-\sin\theta\cos\theta + \sin\theta\cos\theta e^{\frac{i\Delta m^2 x}{p}} \right) \quad (2.16)$$

₅₀₂ Taking the absolute value squared gives us:

$$P(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu_\mu(t) \rangle|^2 = e^{+iz} e^{-iz} \sin^2\theta \cos^2\theta \left(-1 + e^{\frac{i\Delta m^2 x}{p}} \right) \left(-1 + e^{\frac{-i\Delta m^2 x}{p}} \right) \quad (2.17)$$

₅₀₃ Since the neutrino is relativistic we can set $p = E_\nu$ and change $x = L$. Also
₅₀₄ recognizing the trigonometric relation $(1 - \cos 2\theta)/2 = \sin^2\theta$ the above equation
₅₀₅ becomes:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right) \quad (2.18)$$

₅₀₆ All that's left to do now is re-introduce \hbar and c doing this we get:

$$P_{\nu_\mu \rightarrow \nu_e}(L, E) = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E_\nu} \right) \quad (2.19)$$

₅₀₇ This equations has three important variables.

- The angle θ : This angle, as mentioned before, is called the mixing angle. It defines the difference between the flavor and the mass eigenstates. When $\theta = 0$ the mass and flavor eigenstates are identical and now oscillations occur.
- The mass squared difference, Δm^2 : Again $\Delta m^2 = m_1^2 - m_2^2$. The reason this is an important variable is because it implies that for neutrinos to oscillate, neutrinos must have mass. Furthermore, the mass squared difference also tells us that the neutrino mass eigenstates must be different.
- L/E: This is the variable that is of most interest to experimental physicists due to the fact that it is the variable that we set. L is the distance between the source and detector and E is the energy of the neutrino. For a given Δm^2 , the probability of oscillation changes with respect to L/E.

2.3.4 Three Flavor Neutrino Oscillation Formulation

Seeing the quantum mechanics involved in deriving the probability of a two flavor neutrino oscillation, it is now possible to formulate the three flavor neutrino oscillation. The three flavor neutrino oscillation formulation begins similarly to the two flavor, but there is the Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS) instead of the 2X2 matrix in the previous section. The PMNS matrix is show below:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} * \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2.20)$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

Following the same steps as before we get:

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4\sum Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) 2\sum Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right) \quad (2.21)$$

The main things to notice here are δ_{ij} which is the CP violating term and has not been measured yet, and θ_{13} which has just been measured. CP violation is a violation

⁵²⁹ of the postulated CP-symmetry. CP-symmetry states that the laws of physics should
⁵³⁰ be the same if a particle were to be exchanged with its antiparticle and then if the left
⁵³¹ hand side of a decay were switched with the right hand side.

⁵³² **2.3.5 Reactor Oscillation**

⁵³³ Many experiments have searched for oscillation of electron anti-neutrinos produced at
⁵³⁴ nuclear reactors. Such oscillations give the value of the parameter θ_{13} . The KamLAND
⁵³⁵ experiment, started in 2002, has made a high precision observation of reactor neutrino
⁵³⁶ oscillation. Neutrinos produced in nuclear reactors have energies similar to solar
⁵³⁷ neutrinos, a few MeV. The baselines of these experiments have ranged from tens
⁵³⁸ of meters to over 100 km. On 8 March 2012, the Daya Bay team announced a 5.2σ
⁵³⁹ discovery that $\theta_{13} \neq 0$.

540 **Chapter 3**

541 **The MicroBooNE Experiment**

542 The purpose of this chapter is to discuss and understand the details of the MicroBooNE
543 detector. A thorough understanding of MicroBooNE and the technology behind liquid
544 argon time projection chambers is important for understanding results as well as
545 understanding how images were made for use in deep learning efforts that will be
546 outlined in later chapters.

547 **3.1 Liquid argon time projection chambers**

548 Liquid Argon Time Projection Chambers (LArTPCs) are an exciting detector technol-
549 ogy that provide excellent imaging and particle identification, and are now being
550 used to study neutrinos. The Time Projection Chamber (TPC) was first invented by
551 Nygren in 1974 [?] and the proposal for a LArTPC for neutrino physics was made
552 by Rubbia [?] in 1977 with the ICARUS collaboration implementing this concept [?].
553 A LArTPC is a three-dimensional imaging detector that uses planes of wires at the
554 edge of an active volume to read out an interaction. When a neutrino interacts with an
555 argon atom, the charged particles that are produced ionize the LAr as they travel away
556 from the interaction. By placing a uniform electric field throughout the LAr volume,
557 the ionization is made to drift towards a set of anode planes, which consist of wires
558 spaced very closely together collecting the ionized charge, which is subsequently read
559 out by electronics connected to the anode wires. The collected ionization creates a
560 spatial image of what happened in the detector on each anode plane. The position
561 resolution of the interaction along the beam direction (perpendicular to drift direction)
562 relies on the wire pitch, while the resolution in drift direction is dependent on the

563 timing resolution of the electronics used and the longitudinal diffusion in the volume.
 564 The drift time of the ionization relative to the time of the original signal allows the
 565 signal to be projected back along the drift coordinate, hence the name LArTPC. Having
 566 very small distances between each wire within an anode plane allows for very fine
 567 granularity and detail to be captured, and having multiple wire planes at different
 568 angles provides independent two-dimensional views that can be combined into a
 569 three dimensional picture of the interaction. Once the charge signal is created on the
 570 anode planes, software analysis packages identify particles in the detector by using
 571 deposited energy on the wires along their track length. The 30 year development of the
 572 ICARUS detector has led to LArTPCs being used as cosmic ray [?], solar neutrino [?]
 573 and accelerator neutrino [?] detectors. The ArgoNeuT experiment at Fermilab was
 574 the first United States based liquid argon neutrino program that has since produced
 575 short-baseline $\nu - Ar$ cross-section measurements in the NUMI beamline [?]. The
 576 MicroBooNE experiment is the second experiment in the US based LArTPC neutrino
 577 program and will be discussed thoroughly in the next sections. The next phases of
 578 the liquid argon neutrino program are under way and are the Fermilab Short Base-
 579 line Neutrino (SBN) program [?] and the Deep Underground Neutrino Experiment
 580 (DUNE) [6]. The SBN program will include three LArTPC detectors, including the
 581 MicroBooNE detector, on the Booster Neutrino Beam (BNB) to do multiple-baseline
 582 oscillation measurements. The detector closest to the beam will be the 40 ton Short
 583 Baseline Neutrino Detector (SBND) [?] at 150 m and the detector furthest is the 600 ton
 584 ICARUS T600 [?] detector positioned at 600 m. The DUNE collaboration will deliver
 585 a 30 GeV neutrino beam 1300 km from Fermilab to a 34 kiloton LArTPC detector
 586 at Homestake, SD. DUNE will study the leptonic CP phase, δ_{cp} , as well as measure
 587 neutrino and antineutrino oscillations.

588 3.2 The MicroBooNE Time Projection Chamber

589 MicroBooNE (Micro Booster Neutrino Experiment) is a 89 ton active volume (180 ton
 590 total mass) LArTPC which is then inserted into a cylindrical cryostat on axis of the
 591 Booster Neutrino Beam (BNB) stationed at Fermilab in Batavia, Illinois. Understanding
 592 LArTPC technology and detector physics is necessary to build a LArTPC the size of
 593 DUNE, and MicroBooNE has made many advances in developing this technology [7]
 594 [8].

MicroBooNE's Time Projection Chamber (TPC) is 10.3 m long (beamline direction), 2.3 m high and 2.5 m wide (which corresponds to the drift distance). The TPC is shown in figure ?? . MicroBooNE is the largest LArTPC currently running in the world [9]. This LArTPC has 3 wire planes: 1 plane that collects the ionization in the wires and is 0° to the vertical with 3456 wires spaced 3 mm apart, and 2 planes where the ionization drifts passed and induces a signal at $\pm 60^\circ$ to the vertical each with 2400 wires also spaced 3 mm apart. Each plane has a spacing also of 3 mm from eachother. The first two planes are the induction planes and the last is the collection. The 270 V/cm electric field of the TPC is created using 64 stainless steel tubes shaped into rectangles around the TPC and held in place by G10 to form a field cage. The cathode is charged at a high voltage of -70 kV and this voltage is stepped down across the field cage tubes using a voltage divider chain with an equivalent resistance of $240\text{ M}\Omega$ between the tubes. The field cage tubes are separated by 4 cm from center to center. The electron drift distance is 2.5 m in the x direction with a drift time of 2.3 ms. Maintaining high charge yield is done by continuously recirculating and purifying the argon. The purity is monitored using MicroBooNE's light collection system. Another use of the light collection system is initial timing and drift coordinate of the interaction.

MicroBooNE's light collection system is a crucial part for 3D reconstruction of all particle interactions in the LArTPC. The initial interaction time, t_0 , and initial drift coordinate, x_0 , are not known from the TPC alone. For beam events, the accelerator clock is used to determine t_0 of the interaction and the x_0 can be inferred using drift time. Non-beam events, however, do not have this capability, which is why scintillation light from an interaction is used. The $\nu - Ar$ interaction produces scintillation light which is collected by photomultiplier tubes (PMTs) which allows the exact time, t_0 of the neutrino interaction to be determined. The scintillation light created propagates within nanoseconds to the light collection system compared to the milliseconds it takes the ionized electrons from the interaction to reach the anode wire planes. Therefore we can precisely know where along the drift direction the particle interaction first took place. The scintillation light is also localized, so combining the PMT information with the wire plane information allows for cosmic background rejection happening outside the beam timing window.

The light collection system is made up of 32 Hamamatsu R5912-02mod cryogenic PMTs with a diameter of 8-inches. The PMTs are located behind the 3 wire anode planes and provides 0.85% photocathode coverage. Each PMT has an acrylic plate mounted in front of it that is coated with a wave-length shifting material called TPB.

630 The acrylic plates take in the scintillation light, at 128 nm, and re-emits it visible
631 wavelengths visible to the PMTs, with a peak at 425 nm.

632 Both the light collection system and the TPC create analog signal that is read out and
633 digitized by the electronics system. The process requires amplification and shaping of
634 the signal which then goes to the data acquisition (DAQ) software for writing of the
635 digitized data to disk. The anode plane wires are connected to detector specific circuit
636 boards (ASICS) that are submerged and operate inside the liquid argon volume. These
637 ASICS send amplified signal to 11 feed-throughs where further amplification of the
638 signal happens outside the cryostat. The signal is received by custom LArTPC readout
639 modules distributed over nine readout crates which do the digitization. The TPC wires
640 are digitized at 16 MHz then downsampled to 2 MHz. The TPC system reads out 4
641 frames of wire signal data per event, 1 frame before a trigger and 2 frames after the
642 triggered frame. The four frames allows for identification of a neutrino interaction as
643 well as cosmic background rejection. The process of digitization is similar for the light
644 collection system. Each PMT signal undergoes a shaping with a 60 ns peaking time
645 for digitization of multiple samples. The digitization occurs at 64 MHz but are not
646 read out continuously during the TPC readout time. Only shaped PMT signal samples
647 above a small threshold are read out and saved. Both the TPC and PMT readouts are
648 initiated via triggers on a separate trigger board located in a warm electronics crate.
649 The timing trigger is created by a timing signal from the BNB accelerator which is
650 shaped and sent to the trigger board. The PMT trigger is generated when the PMT
651 signal multiplicity is greater than 1 and the summed PMT pulse-height is more than 2
652 photo-electrons summed up over all PMT channels. When the trigger board gets both
653 a timing trigger and a PMT trigger in coincidence, at BNB trigger is then generated by
654 the board. This signal is then passed to all readout crates initiating the readout of data.
655 The data is then sent to the DAQ software which then saves the data to disk into one
656 event memory.

657 3.3 MicroBooNE's Physics Goals

658 3.3.1 The low-energy excess

659 The primary goal of the MicroBooNE experiment is to study and investigate the low-
660 energy excess seen in MiniBooNE. MicroBooNE has the capability of confirming or

denying this excess as electrons or photons due to the detector being in the same beam, having a similar baseline, and lastly the detector being able to clearly distinguish between electrons and photons. LArTPCs use the topology of events as well as energy loss near the vertex to differentiate between single e^- tracks and photon-induced induced pair production $\gamma \rightarrow e^+ e^-$, which wasn't possible in MiniBooNE, a Cherenkov detector. This technique has been shown in the ArogoNeuT detector [?] and a side by side comparison of both event types in a LArTPC can be seen in figure ?? . An excess in electrons would point towards new oscillation physics beyond the standard model, while photons would be within the standard model. MicroBooNE will observe a $4-5\sigma$ signal.

3.3.2 Cross sections

MicroBooNE's neutrino cross-section program will be the first $\nu - Ar$ cross-section in the 1 GeV energy range and one of only a few cross-section measurements of $\nu - Ar$ in the world. MicroBooNE is also the first liquid argon detector to collect the highest statistics sample of neutrino interactions. Investigating final-state-interactions in the 1GeV energy range provides information about short range nuclear correlations that affect the interpretations of neutrino oscillation experiment data.

3.3.3 Astroparticle physics

99% of energy leaving a supernova leaves in the form of neutrinos which can be seen by detectors on earth's surface. MicroBooNE will have a dedicated supernova data stream and a connection to the SuperNova Early Warning System [?] so when a nearby supernova explosion occurs, continuous data will be written for several hours that can be later analyzed for supernova neutrino events. This information coupled with information from other experiments can be used to better understand supernovae.[add infograph of supernova here](#)

3.3.4 Liquid argon detector development

The last physics goal for the MicroBooNE collaboration is to provide important information regarding LArTPC technology. Being the first in large scale LArTPCs in the US,

689 MicroBooNE will be able to provide improvements to High Voltage (HV) distribution,
690 Noise Characterization [?], and Michel Electron Reconstruction [8].

691 **3.4 The Booster Neutrino Beam**

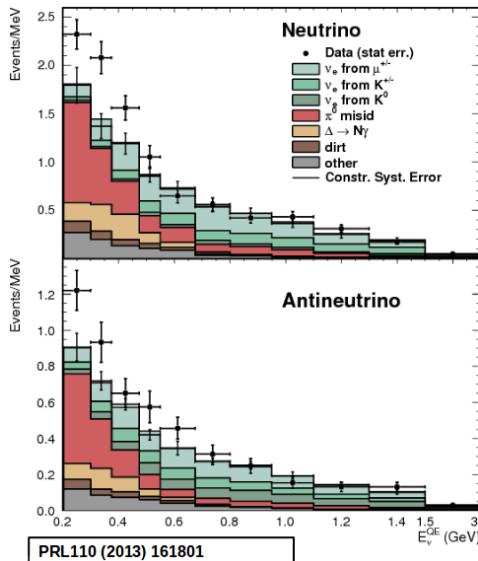
692 The MicroBooNE detector is stationed at Fermi National Accelerator Laboratory
693 (FNAL) where it receives neutrinos from both the Booster Neutrino Beam (BNB)
694 and Neutrinos from the Main Injector (NuMI) beams. MicroBooNE is on-axis for the
695 BNB and off-axis by 135 mrad for NuMI. For the purpose of this analysis, only data
696 from the BNB was used. This section will discuss how neutrinos are created using the
697 BNB. How these neutrinos are produced as well as their flux through the MicroBooNE
698 detector is necessary for any analysis because of the systematic uncertainties the beam
699 introduces to a measurement.

700 **3.4.1 Creating the Booster Neutrino Beam**

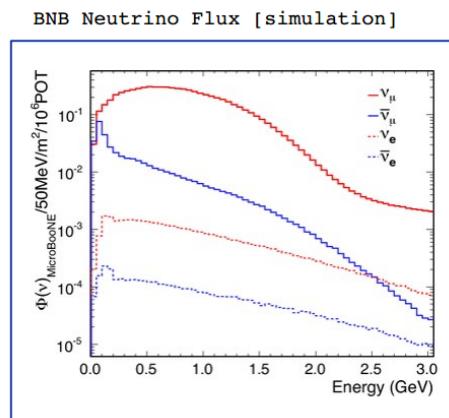
701 The BNB is a very pure ν_μ beam, with only 0.6% contamination from ν_e s. The energy
702 also peaks around 700 MeV which is desired based on the probability of oscillation
703 equation which depends on the the value of L/E , where L is the distance of the
704 detector from the neutrino beam and E is the energy of the neutrino beam. L/E was
705 chosen to increase the probability of seeing neutrino oscillations in the MiniBooNE
706 Low Energy Excess (LEE) range based on the probability of oscillation equation, which
707 is $P_{\nu_\mu \rightarrow \nu_e}(L, E) = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E} \right)$. The BNB collides 8.9 GeV/c momentum
708 protons from the FNAL booster synchrotron into a beryllium target which produces a
709 high flux of neutrinos. The protons originate from H^2 gas molecules that are turned
710 into H^- ions by a Cockcroft-Walton generator shown in figure ???. The H^- initially are
711 accelerated to 1MeV kinetic energy and are then passed to a linear accelerator using
712 alternating electromagnetic fields to increase their energy to 400MeV. The ions are
713 stripped of electrons by passing them through a carbon foil. The protons are bunched
714 into beam spills which contain $4 * 10^{12}$ protons in a 1.6 μ s time window per spill. It's
715 at this point that the protons are directed towards the beryllium target. The amount
716 of protons directed towards the target (POT) is measured by two toroids upstream of
717 the target with an error of 2%. Beam intensity, timing, width, position, and direction
718 are monitored by beam position monitors, multi-wire chamber and resistive monitors.

The beryllium target is 71.1 cm long, 1.7 proton interaction lengths, and is 0.51 cm in radius. The target is located inside a larger focusing electromagnet called the horn. The horn is an aluminum alloy pulsed toroidal electromagnet. The pulsed current peaks at 170 kA with a time-width of 143 μ s which coincides with the protons arriving on the target. The current flows from the inner conductor to the outer conductor with a maximum magnetic field of 1.5 Tesla. The magnetic field focuses the charged secondary particles produced by the p-Be interactions. The direction of current can be switched to change the polarity of the secondary particles being focused creating a beam of either primarily neutrinos, with positively charged secondary particles, or antineutrinos.

Further down the beamline is a concrete collimator which absorbs particles not necessary to the neutrino flux. The collimator is 214 cm long and 30 cm in radius. After the collimator comes a 45 meter long, 1 meter radius, air-filled cylindrical decay region which then ends in a beam-stop made of steel and concrete. The beam-stop contains an array of gas proportional counters to detect muons. **add beam diagram here**



(a) Low Energy excess seen in Mini-BooNE



(b) Energy spectrum of the Booster Neutrino Beam at Fermi National Laboratories

Figure 3.1: 3.1b Flux of BNB at FNAL.

3.5 Event Reconstruction

⁷³⁶ Chapter 4

⁷³⁷ Neutrino Identification: Finding ⁷³⁸ MicroBooNE's first Neutrinos

⁷³⁹ The goal of the Neutrino Identification analysis was to positively identify BNB neutrino
⁷⁴⁰ interactions in the MicroBooNE detector collected during the first days of running.
⁷⁴¹ Neutrino event candidates were identified in part by using a cut on detected flash of
⁷⁴² scintillation light during the $1.6 \mu\text{s}$ beam-spill length of the BNB as well as identifying
⁷⁴³ reconstructed object from the TPC that are neutrino like. After this selection, 2D
⁷⁴⁴ and 3D event displays were used for verification of the selection performance. This
⁷⁴⁵ selection was targeted to reduce the ratio of neutrino events to cosmic-only events from
⁷⁴⁶ the initial 1 neutrino to 675 cosmics to a ratio of 1 to 0.5 or better which is equivalent to
⁷⁴⁷ a background reduction by a factor of 1000 or more. These selected events were used
⁷⁴⁸ for MicroBooNE's public displays of neutrino interactions. A clearly visible neutrino
⁷⁴⁹ interaction with an identifiable vertex and at least 2 tracks originating from the vertex
⁷⁵⁰ was what the analysis focused on. This analysis wasn't optimized for high purity
⁷⁵¹ or efficiency, but rather for very distinguishable neutrino interactions that could be
⁷⁵² identified by the public.

⁷⁵³ 4.1 Flash Finding

⁷⁵⁴ Flash finding is the first step used in finding neutrino interactions. This section will
⁷⁵⁵ detail how optical information is reconstructed as well as analysis scripts and event
⁷⁵⁶ filters were used.

757 **4.1.1 Flash Reconstruction**

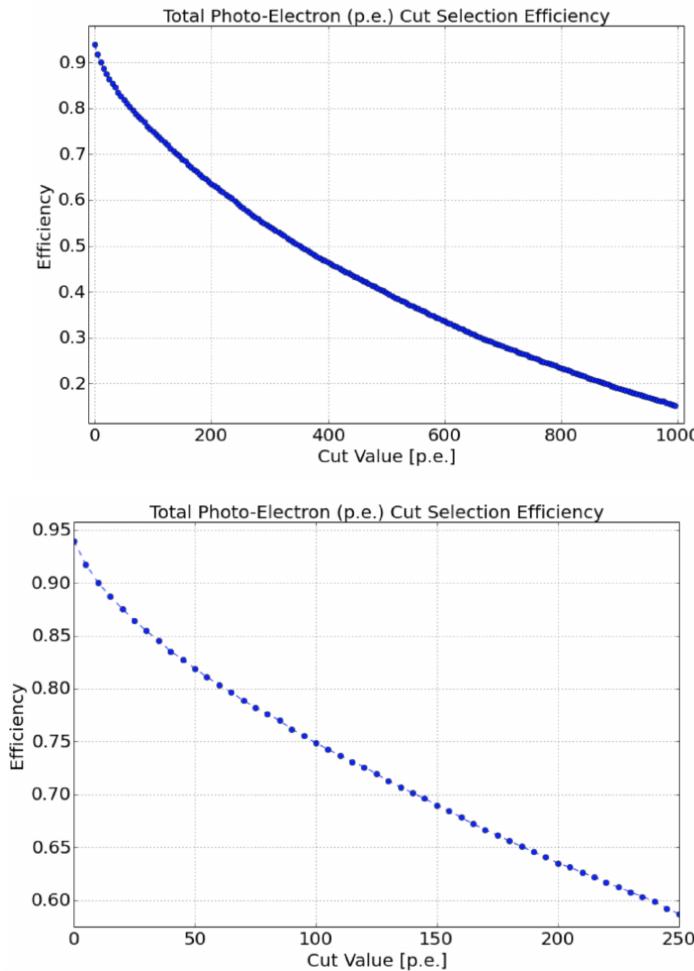
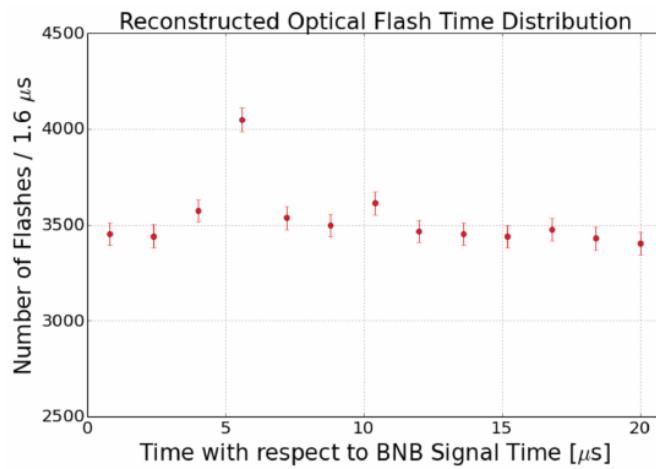


Figure 4.1: Efficiency for selecting beam events as a function of minimum total PE cut for all PE cuts as well as zoomed into interesting region.

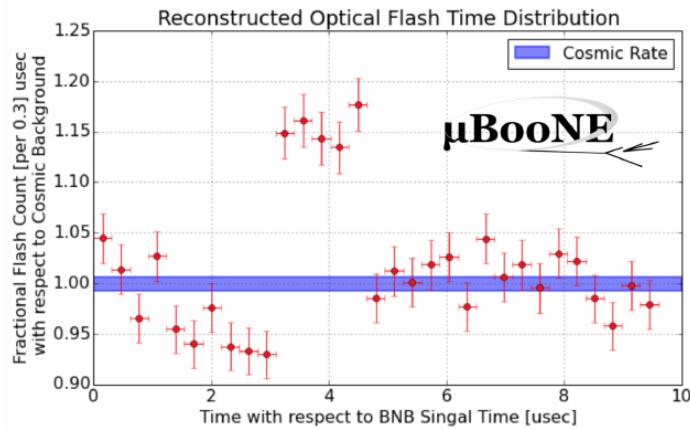
758 A flash is described as a collection of light seen at the same time within the detector.
759 They are then reconstructed by identifying signal from the PMTs above a specific
760 photoelectron (PE) threshold. These signals are called optical hits. Optical hits from
761 all the PMTs are then accumulated into $1\text{ }\mu\text{s}$ bins of time. If a specific bin is above a
762 set PE threshold, then the optical hits that overlap in time are the labeled as the hits
763 from the flash. All flash reconstructed properties like average time and x/y positions
764 are then found via the flash labeled optical hits. The total size of the flash is found by
765 summing up the total number of photoelectrons from all PMTs. Neutrino interactions
766 and cosmic muons will have a larger flash size compared to noise and other low-energy
767 backgrounds, therefore a total PE cut is used to reject these backgrounds. A total PE

⁷⁶⁸ cut of 50 PE was deemed sufficient for this analysis. Figure 4.1 show the total PE
⁷⁶⁹ versus the selection efficency of selecting neutrino beam events.

⁷⁷⁰ **4.1.2 Beam Timing**



(a) Predicted distribution of flash times with respect to trigger time for 1 day of data taking at nominal rate and intensity



(b) Measured distribution of flash times with a 50 PE threshold cut, with respect to trigger time. Shown as a ratio to the expected cosmic rate from off-beam data. A clear excess from neutrinos is visible between 3- 5 μ s after the trigger time.

⁷⁷¹ It is necessary to get the specific time from flashes if one uses flashes to filter out
⁷⁷² neutrino interactions coincident with the neutrino beam spill period and background.
⁷⁷³ Before a filter can be applied, an understanding of the timing of the trigger and PMT

⁷⁷⁴ readout with respect to the arrival of neutrinos from the BNB. To do this, a $1.6 \mu\text{s}$
⁷⁷⁵ window near the expected beamtime was created and verified by finding that the
⁷⁷⁶ number of flashes was significantly above the cosmic-ray background flashes. Beam
⁷⁷⁷ data during the first week of running, October 16th 2016 through October 22nd 2016
⁷⁷⁸ and were used for a timing measurement. The total POT uses corresponds to roughly
⁷⁷⁹ 24 hours of data taking at nominal intensity ($4 \times 10^{12} \text{ ppp}$) and a 5 Hz repetition rate.
⁷⁸⁰ Figure 4.2a shows size of the expected neutrino signal in time using Monte Carlo
⁷⁸¹ predictions and figure 4.2b shows the neutrino signal in data. The intensity in data is
⁷⁸² lower, however there can still be seen a significant excess above data.

⁷⁸³ 4.1.3 Event Rates

⁷⁸⁴ Applying a 50 PE threshold cut inside a $1.6 \mu\text{s}$ window reduces the cosmic-ray passing
⁷⁸⁵ rate to 0.8%. With a 5 Hz beam rate, this corresponds to 135 cosmics passing per
⁷⁸⁶ hour. The neutrino passing rate for this filter is about 22 events per hour. To further
⁷⁸⁷ increase the neutrino to cosmic ratio, TPC topology cuts were implemented and will
⁷⁸⁸ be discussed in the following section.

⁷⁸⁹ 4.2 TPC Topology Selection

⁷⁹⁰ In order to further reduce the background of cosmic events, two independent selection
⁷⁹¹ streams using TPC wire data reconstruction was implemented. The first using 2D
⁷⁹² reconstructed clusters, and the second using 3D reconstructed tracks. Both streams
⁷⁹³ look for neutrino interactions in the active TPC volume which are identifiable by two
⁷⁹⁴ or more tracks originating from the same vertex.

⁷⁹⁵ Both 2D and 3D channels were optimized using monte carlo simulation which
⁷⁹⁶ used a 128 kV cathode voltage. Passing rates were calculated using a 0.008 efficiency
⁷⁹⁷ factor for cosmic events passing to simulate the flash finding described in section 4.1.
⁷⁹⁸ This efficiency factor was an overestimation and was just used to get a general feel of
⁷⁹⁹ what signal and background rates we would actually see in data.

800 4.2.1 Cosmic Tagging

801 The first step in TPC selection was based on the geometry of cosmic tracks in an event.
802 The cosmic ray muon geometry tagger runs on 3D tracks and assigns a score to each
803 reconstructed track on the likeliness of the track originating from a cosmic. The cosmic
804 scores are detailed below:

- 805 • 1: The track is tagged as entering or entering the TPC
- 806 • 0.95: The track is a delta ray associated with a tagged track
- 807 • 0.5: The track is either entering or exiting, but not both
- 808 • 0.4: The track is entering or exiting through the Z boundary
- 809 • 0: The track isn't tagged

810 Clusters are assigned either a 0 or 1, 1 being a cosmic. In simulation, 90% of cosmics
811 are tagged as cosmics. These tracks are no longer considered when looking for a
812 neutrino topology. Requiring that the tracks be contained in turn affects the neutrino
813 efficiency by 20%. The algorithm checks that each track is contained within a boundary
814 region of 10 cm from all sides of the TPC. This boundary region was optimized via
815 handscanning of experimental data.

816 As can be expected, cosmic tagging is more efficient in the 3D channel (tracks) than
817 the 2D channel (clusters) because the reconstructed tracks can use the full 3D position
818 information of the entering and exiting points while the 2D channel mainly use the
819 reconstructed x position of the cluster which is associated to timing.

820 Cosmic tagging uses timing information to reject tracks and clusters that are outside
821 of drift window. The drift window for 128 kV is 1.6 μ s while for 70 kV, the actual
822 voltage MicroBooNE is running at, is 2.3 μ s. Due to this variation between simulation
823 and data, we expect to see $2.3/1.6 = 1.44$ times more cosmic induced tracks or clusters
824 in the drift window.

825 4.2.2 2D Cluster Selection

826 This selection was spearheaded by myself and Katherine Woodruff. After looking at
827 experimental cosmics data, 2D clustering performs well, while 3D track reconstruction
828 is affected by more variations in simulation, for example noise filters. This was the

829 motivation for having a selection only on 2D clusters in the collection (Y) plane. As
830 stated previously, the goal of this analysis was to find identifiable neutrino interactions
831 for use in public event displays, in future analyses, the 3D track reconstruction has
832 been modified to further increase the tracking efficiency and has more information
833 that just the clusters. For this analysis, however, 2D cluster information was sufficient
834 enough for neutrino selection.

835 **Primary Cuts**

836 The first cuts were used to select which clusters to consider. First the clusters must
837 have at least ten hits on the collection plane and have a cosmic tagging score < 0.4.
838 Only events that have at least two clusters that satisfy these primary cuts continue on.

839 After the initial cosmic tagging is applied, the following cuts are used to further
840 separate identifiable neutrinos from background cosmics.

841 The next cut was to remove long, vertical clusters. This was applied after seeing
842 that most cosmic induced clusters passing were long with high angles, while neutrino
843 induced clusters were mainly forward going. We required a good cluster to either
844 have a projected start angle less than 30 degrees from the z axis or be less than 200
845 wires long. The length cut was added to make sure we don't cut any short high angle
846 clusters that can correspond with a proton, or other highly ionizing particle associated
847 with a long muon cluster. The 200 wire cut roughly equates to 0.6 m in the z direction,
848 with a 3 mm wire pitch. Also, the projected angle is defined by $\tan \alpha = \Delta T / \Delta W$ where
849 T is the time ticks and W is the wires.

850 The last cut requires the clusters to be either 30 time ticks or 30 wires. This cut was
851 applied to reduce small delta rays associated with a cosmic without removing proton
852 clusters associated with a long muon cluster, which saves ideal neutrino events that
853 have both a long minimum ionizing muon like cluster and a short highly ionizing
854 proton like cluster.

855 **Secondary Cuts**

856 The secondary cuts look to match long, low-angle clusters with short, high-charge
857 clusters. Only clusters that have passed previous cuts are used. First clusters with
858 length greater than 100 wires are chosen, which is approximately 0.3 m in the z

Cluster set	No Cuts	Primary Cuts	Secondary Cuts
Neutrinos only	570	303	32
Cosmics only (no flash)	308,016	291,879	602
Cosmics only (w/ flash)	2464	2335	5
Neutrinos/Cosmics	0.23	0.13	6.4

Table 4.1: Passing rates for 2D cluster cuts for neutrino on MC set and a cosmic only MC set. First column shows event rates with no cuts applied to both sets. Columns two and three show event rates after primary and secondary cuts are applied. Line three shows the second line scaled with the flash finding factor of 0.008. All events are normalized to per day assuming we are running at 5 Hz.

859 direction. Then we search for any cluster that is within approximately 3 cm (10 wires
 860 and 30 time ticks) away from the low-z end of the long cluster. This cluster must also
 861 be shorter than the first. In our reconstruction, the start and end point of a cluster can
 862 be swapped so both ends of the short cluster are compared to the long cluster.

863 Now that there is a vertex match, cuts based on charge and projected opening angle
 864 are implemented. We require the short cluster to have a higher start charge than the
 865 long cluster or the long cluster be longer than 500 wires. Start charge is defined as
 866 the charge on the first wire in ADC counts. The projected opening angle must also
 867 be between 11 and 90 degrees. This last cut is intended to remove clusters that are
 868 entirely overlapping or are part of the same long track. The resulting neutrino/cosmic
 869 event rate per day is shown in table 4.1. Figures 4.3 and 4.4 shows the percentages of
 870 clusters that pass each primary and secondary cuts.

871 4.2.3 3D Tracks and vertices Selection

872 The neutrino selection for the 3D channel was based on a reconstructed vertex and
 873 two tracks. All vertices and tracks were looped over that had a cosmic tag score < 0.4
 874 and the distances below were calculated:

- 875 • d : distance between the start points of the two tracks.
- 876 • d_1 : distance between vertex and start of track 1.
- 877 • d_2 : distance between vertex and start of track 2.

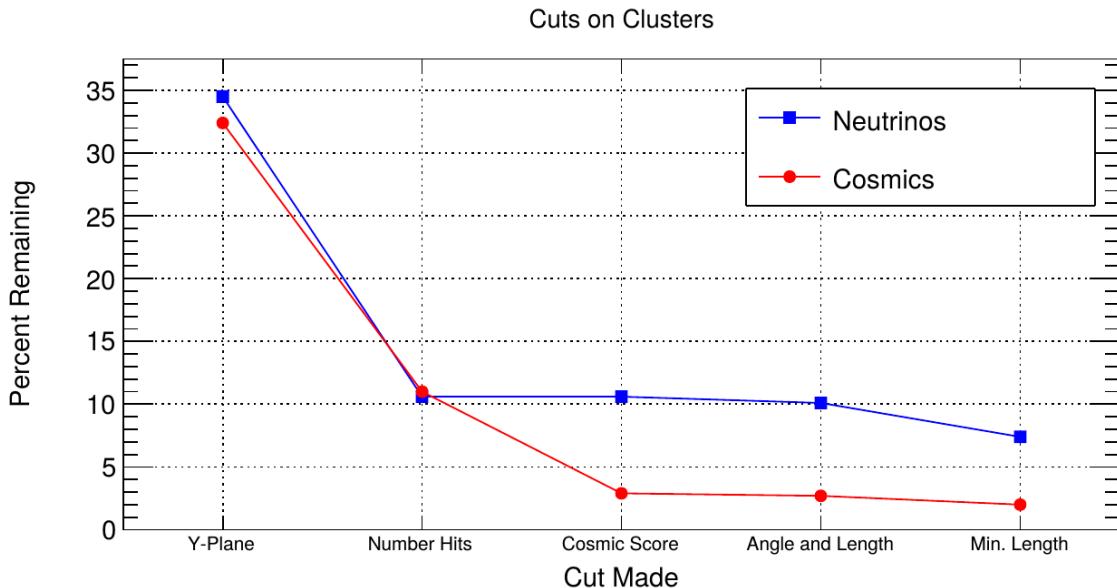


Figure 4.3: Percent of good clusters remaining for neutrinos and cosmics after the primary cuts were applied. This is relative to total number of initial clusters.

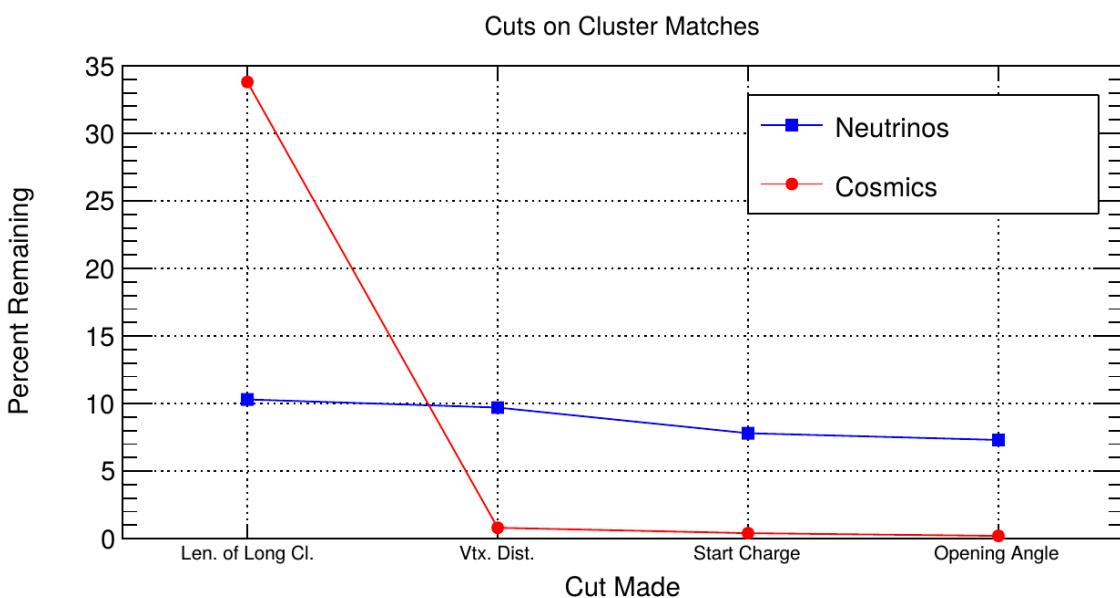


Figure 4.4: Percent matched cluster pairs remaining for neutrinos and cosmics after secondary cuts applied. This is relative to the number of events that contain clusters which pass the primary cuts.

878 The maximum distance of all three is then selected as the important characteristic per
879 trio. The best trio is the one that has the smallest maximum distance. The $\min(\max_d)$
880 for all trios in an event were plotted for BNB neutrino events and for cosmics to
881 find the best cut value for each tracking algorithm. The distribution of $\min(\max_{d,i})$
882 is smaller for neutrinos than for cosmics. The cut values for different tracking and
883 clustering algorithms are shown below. These cut values were chosen to minimize the
884 cosmic background to 20%.

- 885 • trackkalmanhit with cccluster $\min(\max_{d,i}) < 3$ cm.
886 • trackkalmanhit with pandoraNu $\min(\max_{d,i}) < 4.5$ cm.
887 • pandoraNu with cccluster $\min(\max_{d,i}) < 5$ cm.

888 **4.2.4 TPC Updates**

889 After doing a visual hand-scanning of the first beam data processed with the filters
890 detailed above, the events passing had a larger contamination of background than
891 expected. This was mainly in part due to the reconstruction performing better on
892 simulation than on data. Due to this, additional cuts on both streams needed to be
893 implemented in order to increase signal/background ratio. These cuts were added on
894 top of the filters described above and further reduce the event count.

895 **2D Filter Updates**

896 The main background observed in the 2D filter were Michel events, where the muon
897 and electron formed two connected clusters. These events were rejected by comparing
898 the start and end charge deposition of the long cluster (i.e muon particle). The start
899 charge deposition must be less than the end charge deposition. This cut is implemented
900 because muons have a higher ionizaiton loss at the end.

901 **3D Filter Updates**

902 It was seen that cosmic tracks can often originate or end at the same point, therefore
903 faking a signal. Cosmic tracks, however, are mostly vertical. By requiring the angle
904 of the longer track have a cosine greater than 0.85 with respect to the z-axis as well

905 as requiring the longer track to have a length greater than 10 cm, we can reduce this
906 background.

907 **4.3 Conclusion**

908 After proccesing these filters in parallel, it was shown that the 3D filter had a higher
909 purity than the 2D filter because of the higher cosmic rejection being used due to 3D
910 reconstruction. The 2D filter is blind to track entering/exiting from the top or bottom
911 of the TPC. Although the 3D filter had a higher purity, the 2D filter was still able to
912 find identifiable events in data that were used as public event displays. A sample of
913 event displays are shown in figures ?? and ??.

914 **Chapter 5**

915 **CC-Inclusive Cross Section Selection
916 Filter**

917 One of the cross-section measurements MicroBooNE can make is an inclusive charged-
918 current cross-section measurement (referred to as CC-inclusive). CC-inclusive events
919 consist of a neutrino exchanging a W^\pm boson with an argon atom, producing a
920 charged lepton and any number of other final state particles. In MicroBooNE's case, a
921 CC-inclusive event will mostly have a defining muon track coming out of the vertex
922 due to our neutrinos being predominately ν_μ s. A cross-section measurement is the
923 energy dependent probability of $\nu - Ar$ interaction in the detector. Cross-sections
924 however are independent of the intensity or focus of the particle beam so they can
925 be compared among different experiments. A background for a CC-inclusive cross-
926 section measurement are the neutral-current events that contain a pion. It is possible
927 to have a neutral current interaction with a $\pi + p$ event signature that looks like a
928 charged current $\mu + p$ event. Reconstruction tools implemented to date don't efficiently
929 separate muons from pions. A common way to separate these two particles species is
930 to implement a track length cut. On average, muons tend to have longer track lengths
931 in LArTPCs so by requiring that the hypothesized lepton be above a threshold track
932 length, it is possible to increase signal to background.

933 MicroBooNE requires fully automated event reconstruction and selection algo-
934 rithms for use in the many physics measurements being worked on to date due to
935 the large data rate MicroBooNE receives. Being able to automatically pluck out the
936 neutrino interaction among a sea of cosmics proved to be challenging but was accom-
937 plished. MicroBooNE has developed two complementary and preliminary selection
938 algorithms to select charged-current $\nu_\mu - Ar$ interactions. Both are fully automated

and cut based. The results below focus on the first selection and the “In-Progress” plots presented on the poster associated with this proceeding will focus on further improving this algorithm using Convolutional Neural Network (CNN) implementations. The full details can be found in MicroBooNE public note [?] and for more information of CNN implementation on MicroBooNE data refer to [?]. Selection I is based on cuts developed in a MC performance study described in [?]. It identifies the muon from a neutrino interaction without biasing towards track multiplicity. To combat cosmic and neutral current background, the analysis is strongly biased towards forward-going long tracks which are contained. This limits phase space and reduces acceptance.

The efficiency and purity are used as performance values of selection I. Efficiency is described as the number of selected true ν_μ CC events divided by the number of expected true ν_μ CC events. The purity is described as the number of selected true ν_μ CC events divided by the sum of itself and all the backgrounds. The efficiency of selection I is 12% and the purity is 39.7%. The poster related to this proceedings will focus on the last cut which requires the longest track to be longer than 75 cm. This cut has a passing rate of 30% w.r.t the previous cut and is implemented in part to separate charged-current events from neutral-current events that mimic our signal. Implementing a CNN for $\mu - \pi$ separation picks out differences in these two particles that are track range independent therefore eliminating the need for the 75 cm track length cut and increase efficiency and passing rate at low muon momentum. Figure 5.1a shows the track distribution of selection I and the lack of data below the 75 cm track length cut. Figure 5.1b shows the efficiency of selection I as a function of muon momentum. The selection begins with a cut that requires an optical flash greater than 50 photo electrons (PE) in the 1.6 μs beam window. Next, two or more 3D reconstructed tracks must be within 5 cm from a 3D reconstructed vertex. The most forward going track vertex-track association is then selected for further cuts. The vertex from the chosen association must be in the fiducial volume, and the longest track from this association must be matched to a flash 80 cm in z. Lastly the longest track must be contained and longer than 75 cm.

5.1 The importance of μ/π separation

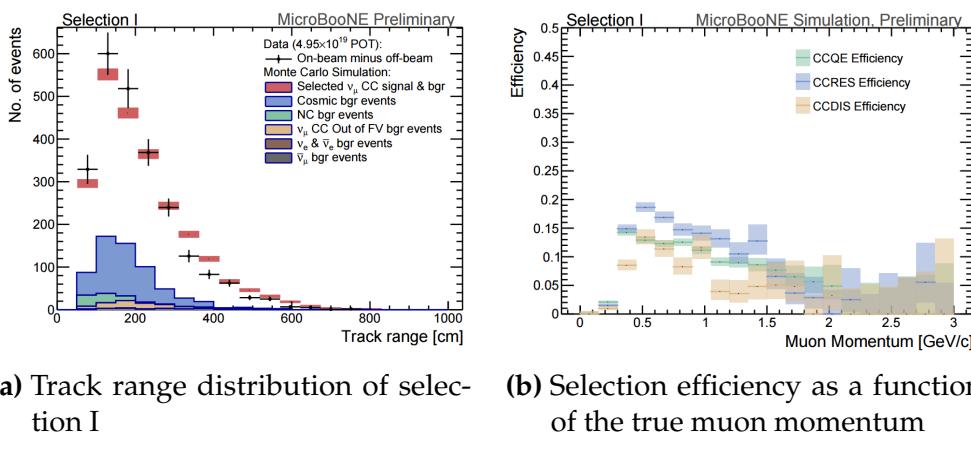


Figure 5.1: **5.1a** Track range distribution for selection I. The track range is defined as the 3D distance between the start and end of the muon candidate track. No data is shown below 75 cm due to the track length cut described previously. **5.1b** Efficiency of the selected events by process quasi-elastic (QE), resonant (RES), and deep-inelastic (DIS). Statistical uncertainty is shown in the bands and the distributions are a function of true muon momentum. The rise of the efficiency between 0 GeV and 0.5 GeV is due to the minimum track length cut and the decreasing efficiency for higher momentum tracks is caused by the containment requirement.

969 **Chapter 6**

970 **Background on Convolutional Neural
971 Networks**

972 Convolutional neural networks (CNNs) have been one of the most influential inno-
973 vations in the field of computer vision. Neural networks became popular in 2012
974 when Alex Krizhevsky used them to win that year's ImageNet competition [?] by
975 dropping the error from 26% to 15%. Since then, many companies are using deep
976 learning including Facebook's tagging algorithms, Google for their photo search and
977 Amazon for product recommendations. For the purpose of this thesis CNNs were
978 used for image classification, specifically, images of varying particles created using
979 LArTPC data.

980 **6.1 Image Classification**

981 Image classification is the process of inputting an image into the CNN and receiving a
982 probability of classes that best describes what is happening in the image. As humans,
983 image classification is something that is learned at a very young age and is easy to
984 do without much effort. This is also apparent when hand-scanning LArTPC images.
985 After learning what a neutrino event looks like in MicroBooNE, it is relatively easy
986 to recognize simple neutrino events from cosmic ray background as well as highly
987 ionizing particles like protons from minimum ionizing particles like muons. The very
988 detailed images LArTPC detectors output are prime candidates for input images into
989 a CNN. CNNs mimic a human's ability to classify objects by creating an architecture
990 that can learn differences between all the images it's given as well as figure out the

unique features that make up each object. CNNs are modeled after the visual cortex. Hubel and Wiesel [?] found that there are small regions of neuronal cells in the brain that respond to specific regions of the visual field. They saw that some neurons fired when exposed to vertical edges while others fired when shown horizontal or diagonal edges. They also saw that these neurons were organized in columns. The idea of specific neurons inside of the brain firing to specific characteristics is the basis behind CNNs.

6.1.1 CNN Structure

When used for image recognition, convolutional neural networks consist of multiple layers that extract different information on small portions of the input image. How many layers is tunable to increase the accuracy. The output of these collections are then tiled so that they overlap to gain a better representation of the original image and allow for translation. The first of these layers is always a convolution layer. To the CNN, an image is an array of pixel values. For a RGB color image with width and height equal to 32x32 the corresponding array is 32x32x3. Filters, also known as neurons, of any size set by the user is then convolved with the receptive field of the image. If the filter is 5x5, the receptive field will be a patch of 5x5 on the input image. The filter is also an array of numbers called weights. The convolution of the filter and image are matrix multiplications of the weights and the pixel values. By stepping the receptive field by 1 unit, for an input image of 32x32x3 and a filter of 5x5x3 you'd get an output array of 28x28x1. This output array is called an activation map or feature map. The use of more filters preserves the spatial dimensions better. The filters can be described as feature identifiers. Examples of features in an image consist of edges, curves, and changes in colors. The first filters in a CNN will primarily be straight line and curve feature identifiers. An example of a curve filter is shown in figure 6.2. When a curve in the same concavity is found in the input image, the corresponding pixel in the output feature map will be activated. Going back to our example of a 32x32 input image and a 5x5 filter, if there were to be a curve in the top left corner of the input image, our output feature map would have a high pixel value in the top left. Therefore, feature maps tell us where a specific feature is located in the original image. Figure ?? shows a visualization of filters found in the first layers of many CNN architectures. These filters in the first layer convolve around the image and activate when the specific feature it is looking for is in the receptive field.

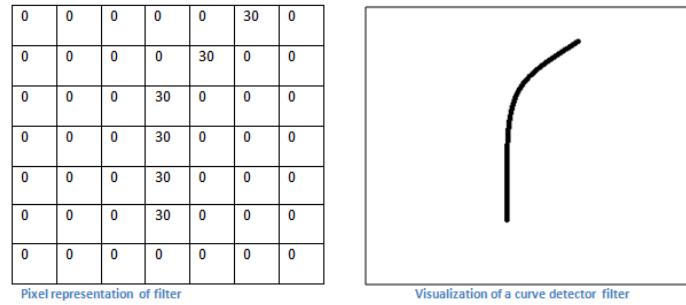


Figure 6.1: Pixel representation and visualization of a curve detector filter. As you can see, in the pixel representation, the weights of this filter are greater along a curve we are trying to find in the input image



Figure 6.2: Visualization of filters found in first layer of a CNN.

In figure 6.3 you can see how an edge detection filter is used to save only necessary information for recognizing different types of clothes. You can also see by having multiple filters you can get more detail or less detail from an image which can then simplify or complicate the object recognition task. Being able to distinguish between a shirt or a leg garment is as much information you want, having a filter that extracts outline edge or shape information would be all that you need. But if instead you wanted to distinguish between a formal cocktail dress or a summer dress, more information would need to be saved equating to many more filters for one image. Rather than trying to come up with how many filters and what features are important for detection, CNNs do this automatically. CNNs take input parameters, called hyperparameters, for example number of layers, number of filters per layers, number of weights per filter, and uses these to create the output feature maps. The layers build upon each-other, for example if we were creating a CNN for facial recognition the convolutional layers will start learning feature combinations off of the previous layers. The low level features like edges, gradients, and corners of the first layers become high level features like eyes, noses, and hairs. This process is visualized in figure 6.4



Figure 6.3: Applying a feature mask over a set of fashion items to extract necessary information for auto-encoding. Unnecessary information for example color or brand emblems are not saved. This feature map is an edge detection mask that leaves only shape information which helps to distinguish between different types of clothes.

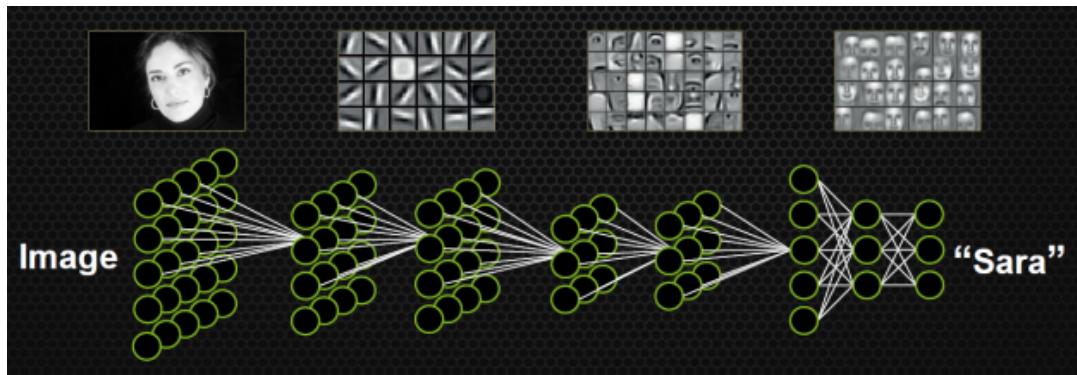


Figure 6.4: Pictorial Representation of Convolutional Neural Networks as well as a visual representation on CNN's complexity of layer feature extraction

1040 There are other layers in a CNN architecture that will not be covered in the scope
 1041 of this thesis but in a general sense, these layers are interspersed between convolution
 1042 layers to preserve dimensionality and control overfitting of the network. The last layer
 1043 is called a fully connected layer and its job is to output an N dimensional vector where
 1044 N is the number of classes the network has been trained on. Each number in this vector
 1045 represents the probability that the input image is a certain class. Fully connected layers
 1046 use the feature maps of the high level features to compute the products between the
 1047 weights of the previous layer to get the probabilities of each class. These weights are
 1048 then adjusted through the training process using backpropagation.

¹⁰⁴⁹ 6.1.2 Backpropagation

¹⁰⁵⁰ A CNN at it's onset has weights that are randomized. The filters themselves don't
¹⁰⁵¹ know how to pull out identifying information per class. For a neural network to learn,
¹⁰⁵² it must be trained on a training set that is labeled. Backpropagation has four seperate
¹⁰⁵³ steps: foward pass, loss function, backward pass and updating weights. In the forward
¹⁰⁵⁴ pass, a training image is passed through the whole network. All of our weights at this
¹⁰⁵⁵ time are randomly initialized so the output for the first image will have no preference
¹⁰⁵⁶ to a specific class. A common loss function is mean squared error (MSE):

$$E_{total} = \sum \frac{1}{2} (actualclass - predictedclass)^2 \quad (6.1)$$

¹⁰⁵⁷ If we assume that the MSE is the loss of our CNN, the goal would be that our
¹⁰⁵⁸ predicted label (output of CNN) is the same as our training label. To do this, we need
¹⁰⁵⁹ to minimize the loss function. To do this, it is necessary to find out which weights most
¹⁰⁶⁰ directly affect the loss of the network i.e $\frac{dL}{dW}$ where L is our loss function and W are
¹⁰⁶¹ the weights of a specific layer. The next step is the backward pass which determines
¹⁰⁶² which weights contribute the most to the loss and finds ways to adjust these weights
¹⁰⁶³ so that the loss decreases. After the derivative is computed, the last step updates the
¹⁰⁶⁴ weights in the opposite direction of the gradient.

$$w = w_i - \eta \frac{dL}{dW} \quad (6.2)$$

$$w = Weight \quad (6.3)$$

$$w_i = InitialWeight \quad (6.4)$$

$$\eta = LearningRate \quad (6.5)$$

¹⁰⁶⁵ 6.2 AlexNet

¹⁰⁶⁶ 6.3 GoogleNet

1067 **Chapter 7**

1068 **Training Convolutional Neural
1069 Networks on particles WORKING
1070 TITLE**

1071 Three Convolutional Neural Networks CNNs were trained throughout this analysis.
1072 There are differences to each CNN and will be described fully in the next sections but
1073 the main difference are the amount of particle images used for training and validation.
1074 CNN1075 used 1,075 muons and 10,75 pions for training and the same amount of each
1075 particle for validation. CNN10000 used 10,000 muons and 10,000 pions split in half
1076 for testing and training. Lastly CNN100000 had muons, pions, protons, electrons,
1077 and gammas in its training and validation set. Each particle had 20,000 images and
1078 training and validation was split 90% training, 10% validation. This chapter will also
1079 describe the different hardware frameworks used for training beginning on a CPU
1080 and ending on a GPU cluster.

₁₀₈₁ **7.1 Hardware Frameworks used for Training**

₁₀₈₂ **7.1.1 Syracuse CPU Machine setup**

₁₀₈₃ **7.1.2 Syracuse University GPU Cluster Setup**

₁₀₈₄ **7.2 Convolutional Neural Network Training**

₁₀₈₅ **7.2.1 Image Making Scheme**

₁₀₈₆ **Images used for Traing/Validation of Convolutional Neural Networks**

₁₀₈₇ **add image making for CNN1075** The μ/π image dataset used to train and validate
₁₀₈₈ the CNN10000 was created using single generated isotropic muons and pions from
₁₀₈₉ 0-2 GeV energ range. 10,000 muons and 10,000 pions were used for training and
₁₀₉₀ testing split 50%. The images were created based on wire number and time tick in the
₁₀₉₁ collection plane. Uboonecode v06_23_00 was used instead of v05_08_00 which was
₁₀₉₂ used previously. The wire signal was the raw ADC value after noise filtering. Each
₁₀₉₃ collection plane grayscale image was 3456x1280x1 where 5 time ticks were pooled into
₁₀₉₄ 1 bin which is different than the previous dataset and was implemented due to the fact
₁₀₉₅ that the time ticks of an event went from 9400 to 6400 with the change of uboonecode
₁₀₉₆ version. The grayscale color standard is 8bit therefore the ADC value of wire and time
₁₀₉₇ tick was also downsampled due to the 12bit ADC value MicroBooNE has. To do this,
₁₀₉₈ the highest ADC pixel in the image was found and then this was divided by the rest
₁₀₉₉ placing all pixel values between 0-1. From there, all pixel values are then multiplied
₁₁₀₀ by 255. All images were made using a LArSoft module. Once the images were created,
₁₁₀₁ using and image manipulation framework called OpenCV images were read into a
₁₁₀₂ numpy array and cropped to the region of interest by only keeping rows and columns
₁₁₀₃ where all ADC values are higher than 0 and then resized it to 224x224 using OpenCV's
₁₁₀₄ resize function. This downsampling of ADC values creates a problem of information
₁₁₀₅ loss for example, a proton which is highly ionizing will have the same brightness as a
₁₁₀₆ minimum ionizing muon by virtue of how the images are created. Issues that arose
₁₁₀₇ in CNN1075 that were fixed in CNN10000 include zero-padding images in X and Y
₁₁₀₈ that are smaller than 224X224 to eliminate over-zooming effect and fixing a bug that
₁₁₀₉ shifted pixels separated by a dead-wire region.

1110 Images were also made from events that passed the cc-inclusive selection 1 filter
1111 right before the 75 cm track length cut and were classified using the CNN10000. The
1112 dataset used to create these images is the same one used in [?], prodgenie_bnb_nu_cosmic_uboone_mc
1113 These images were created using information from the track candidate that passed
1114 the filter. Only wire number and time ticks associated to the track candidate were
1115 drawn on the image to mimic a single particle generated image. These images were
1116 then classified using CNN10000. Two approaches were taken in making these images.
1117 The first was using the image normalization above where the maximum pixel in each
1118 image is used as a normalization constant to get all pixels between 0-1 then multiply
1119 all pixels by 255. As described above, this is the incorrect way to normalize; it should
1120 be normalized by dataset not by event, which is the second way the images were
1121 created. The results of CNN10000 performance are shown in section 7.2.

1122 7.2.2 Training CNN1075

1123 The work shown in these next sections are based on the previous work done described
1124 in [?]. That CNN (now referred to as CNN1075) was trained using single generated
1125 isotropic muons and pions from 0-2 GeV energy range. 1,075 muons and pions were
1126 used to train the network and 1,075 μ/π were used as a validation set. The accuracy is
1127 how well CNN1075 is doing by epoch and was 74.5%. The loss is gradient descent
1128 or minimization of the error of the weights and biases used in each neuron of each
1129 layer of CNN1075 and was 58% with a trend sloping downwards on the loss curve
1130 as well as a trend sloping upward in the accuracy curve. Due to the depth of the
1131 neural network framework, it was necessary to train with a larger dataset and for
1132 more epochs, however, the downward slope of the loss curve is an indication that once
1133 trained for longer with a higher training sample, neural networks can be used for μ/π
1134 separation. Updates in the image making and downsampling algorithm were made to
1135 fix issues that arose in CNN1075.

1136 7.2.3 Training CNN10000

1137 The hyperparameters used for CNN10000 are shown. The batch size for the training
1138 and testing as well as the test iter were chosen to encompass the whole training/testing
1139 image set when doing accuracy/loss calculations. To do this, multiplying the test

1140 iter by the test batch size give you the amount of images used when calculating
1141 accuracy/loss curves. For reference, the accuracy and loss are defined as well.

```
1142     • train_batch_size: 100  
1143     • test_batch_size: 100  
1144     • test_iter: 100  
1145     • test_interval: 100  
1146     • base_lr: 0.001  
1147     • lr_policy: "step"  
1148     • gamma: 0.1  
1149     • stepsize: 1000  
1150     • display: 100  
1151     • max_iter: 10000  
1152     • momentum: 0.99  
1153     • weight_decay: 0.0005  
1154     • snapshot: 100  
1155     • Accuracy: How often the CNN predicts the truth over total number of images  
1156     • Loss: Error between truth and prediction. Minimize loss by gradient descent to  
1157       update weights and biases of CNN
```

1158 The same architecure that was used to train CNN1075 was employed on CNN10000,
1159 Imagenet. Caffe [?] was the software package used for both CNNs. The differences
1160 include batch size and test_iter and momentum to account for the larger dataset. Both
1161 CNNs were trained on a CPU machine, Syracuse01. Further training will be done
1162 on a GPU cluster stationed at Syracuse University. Figure 7.1 shows the loss and
1163 accuracy of CNN10000. There is around a 10% increase in accuracy from CNN1075 to
1164 CNN10000, 85%, and around a 20% decrease in loss, 36%.

1165 Figure 7.2 show a breakdown of μ/π separation for CNN10000. It also shows
1166 the network is not being overtrained due to the Accuracy of both the training and
1167 testing datasets being within .01% of eachother. The CNN is doing a very good job of

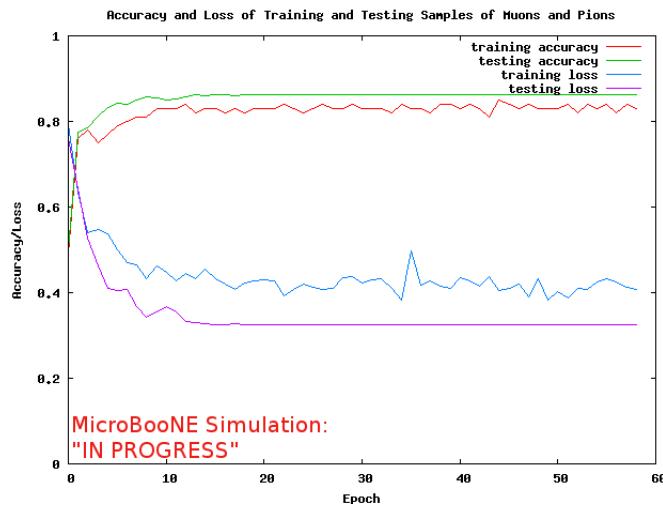
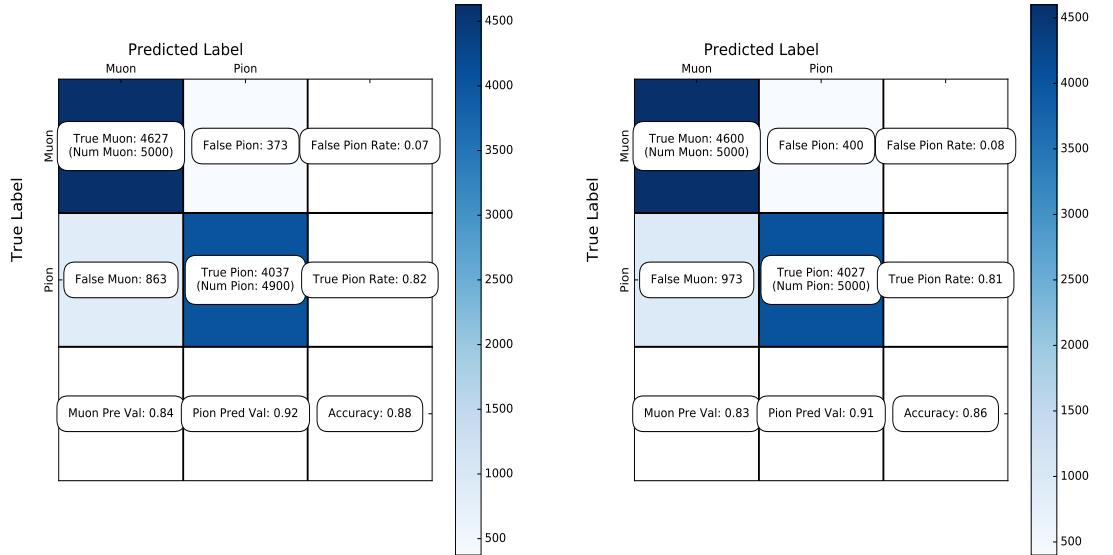


Figure 7.1: Accuracy vs. Loss of ImageNet 2-output μ/π sample consisting of 10000 images each.

₁₁₆₈ classifying true muons as muons, and our loss increase from CNN1075 is due to the
₁₁₆₉ increase in accurately classifying pions as pions.

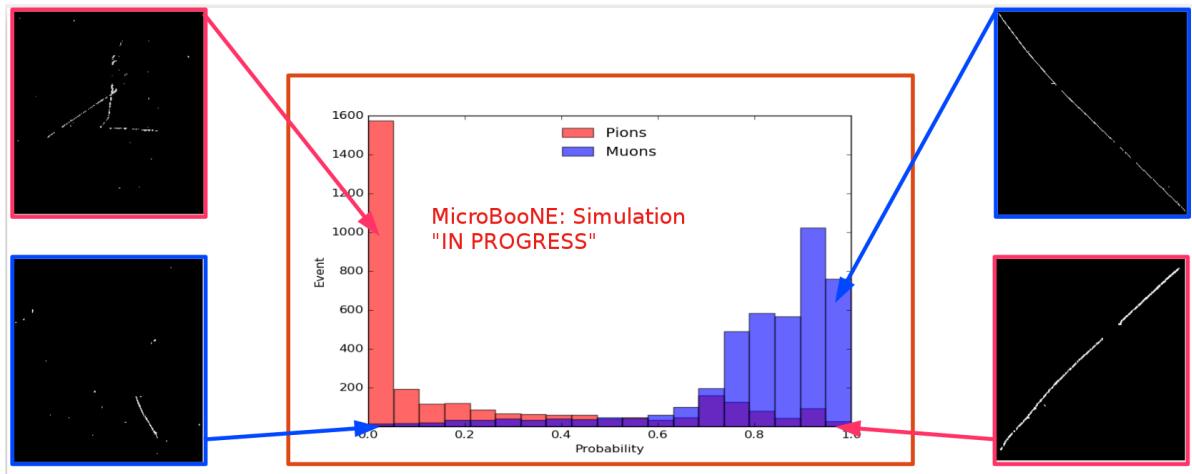
₁₁₇₀ 7.2.4 Training CNN100000

₁₁₇₁ Results of training using 100,000 images, 20,000 images per $\mu/\pi/p/\gamma/e$.



(a) Confusion Matrix showing Accuracy of CNN using training data

(b) Confusion Matrix showing Accuracy of CNN using testing data



(c) Probability plot of muons and pions from testing set. Images surrounding histogram are a random event from lowest bin and highest bin for each particle.

Figure 7.2: Description of confusion matrix variables: False pion rate = $false\pi / total\pi$ True pion rate = $true\pi / total\pi$ Accuracy = $(true\pi rate + true\mu rate) / 2$ Pion prediction value = $true\pi / (true\pi + false\pi)$ Muon prediction value = $true\mu / (true\mu + false\mu)$

7.2c The probability plot includes muons and pions that are classified as primary particles.

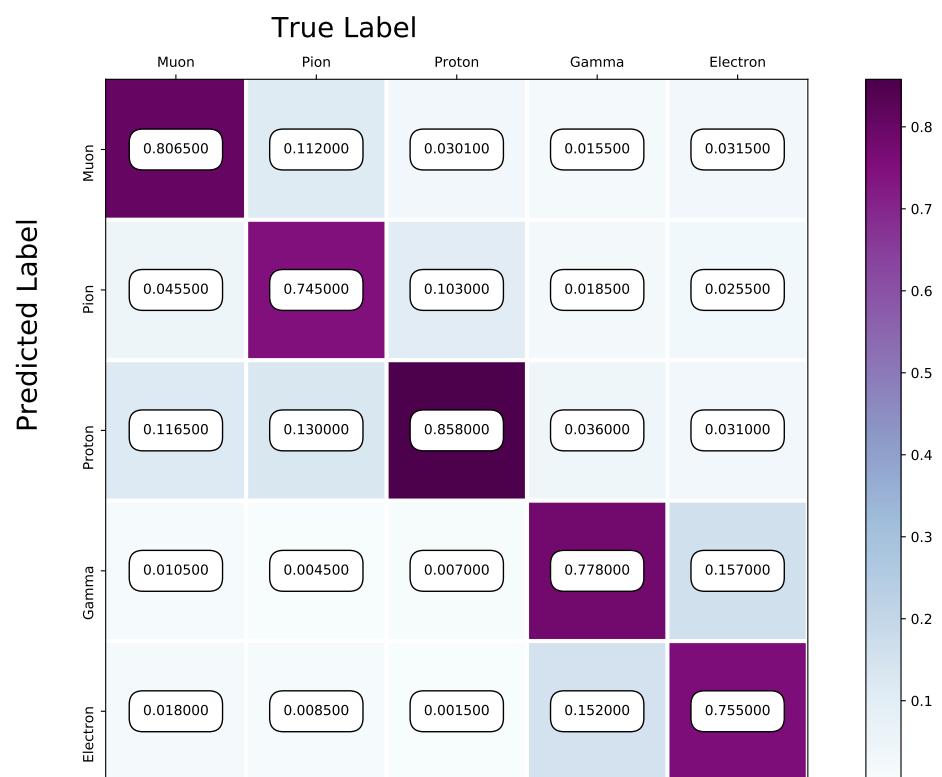


Figure 7.3: Confusion Matrix of all five particles

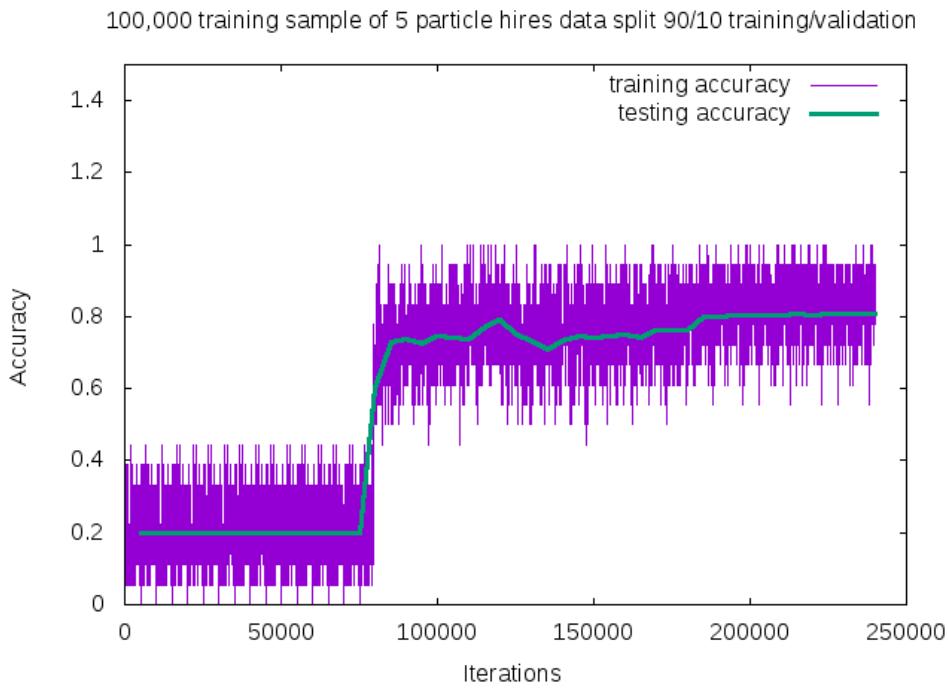


Figure 7.4: Training and testing accuracy of CNN trained on 100,000 images of $\mu/\pi/p/\gamma/e$ with 20,000 images of each particle. Each image was a size of 576x576 and the images per particle were split 90% use for training and 10% used for testing the network

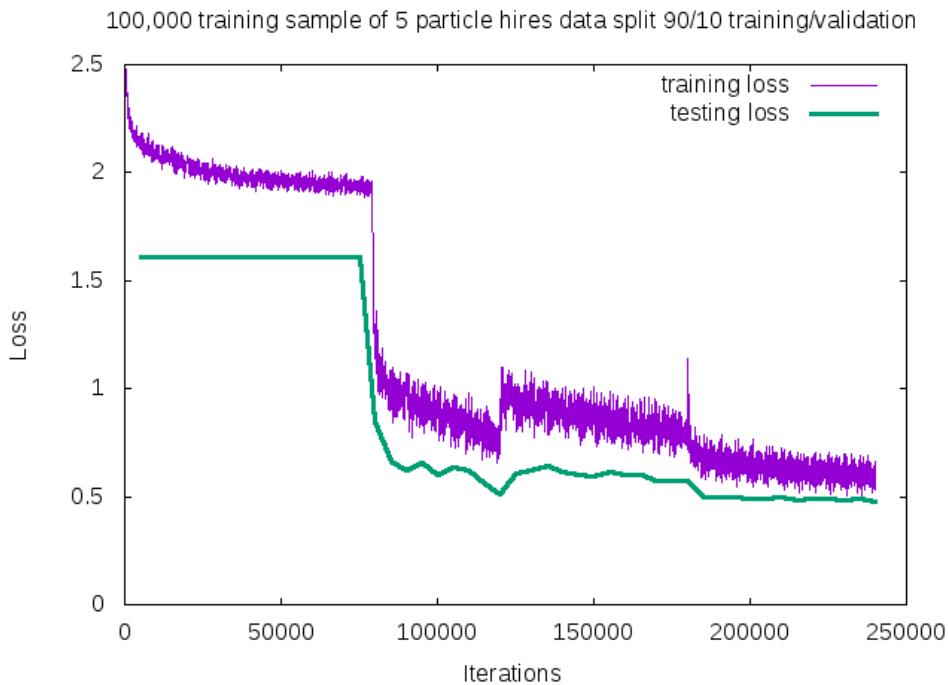


Figure 7.5: Training and testing loss of CNN trained on 100,000 images of $\mu/\pi/p/\gamma/e$

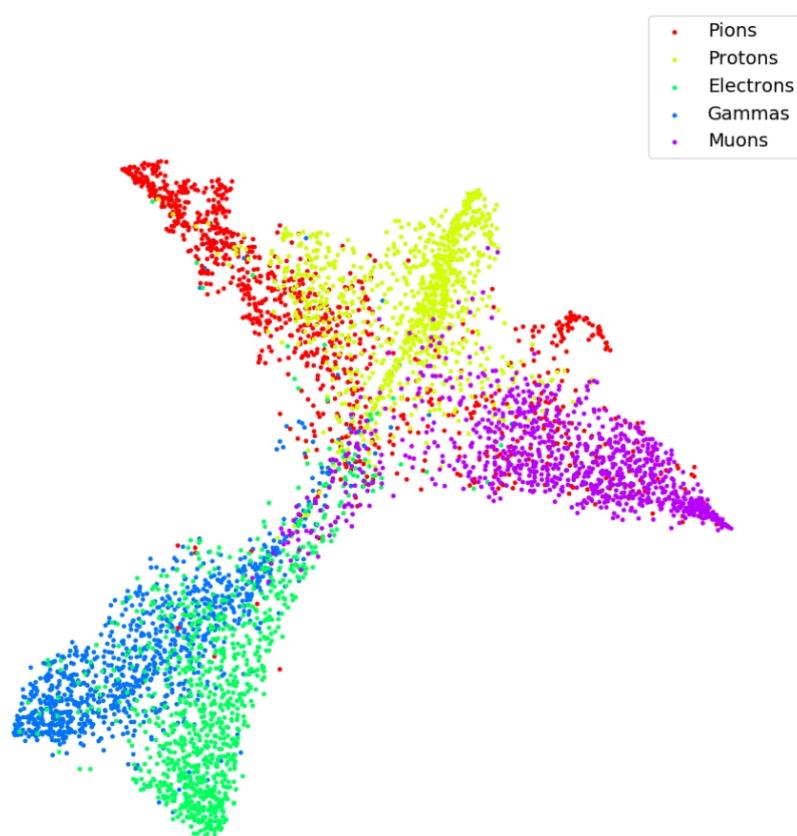


Figure 7.6: t-SNE of CNN

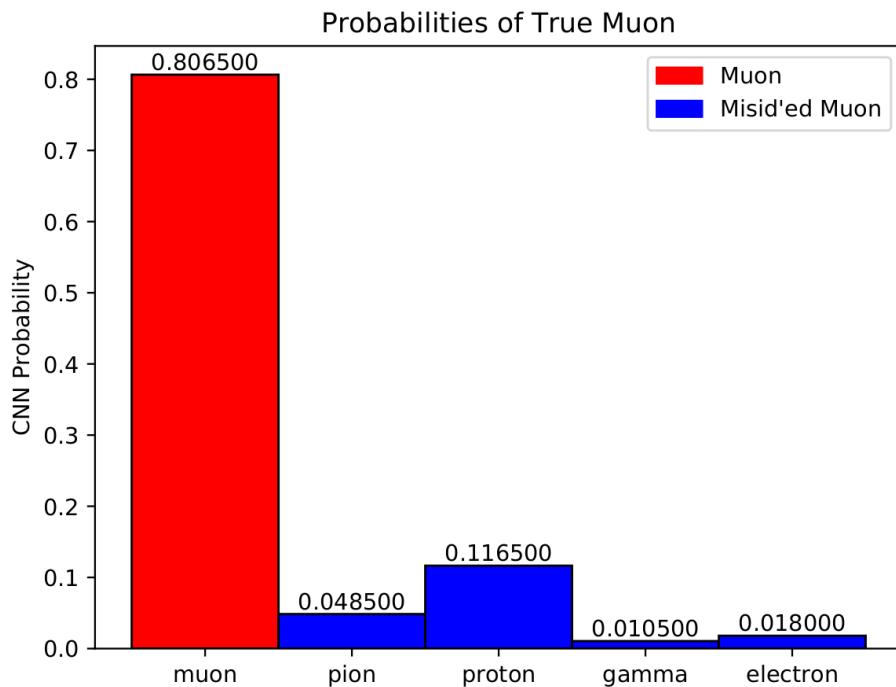


Figure 7.7: Muon Prob

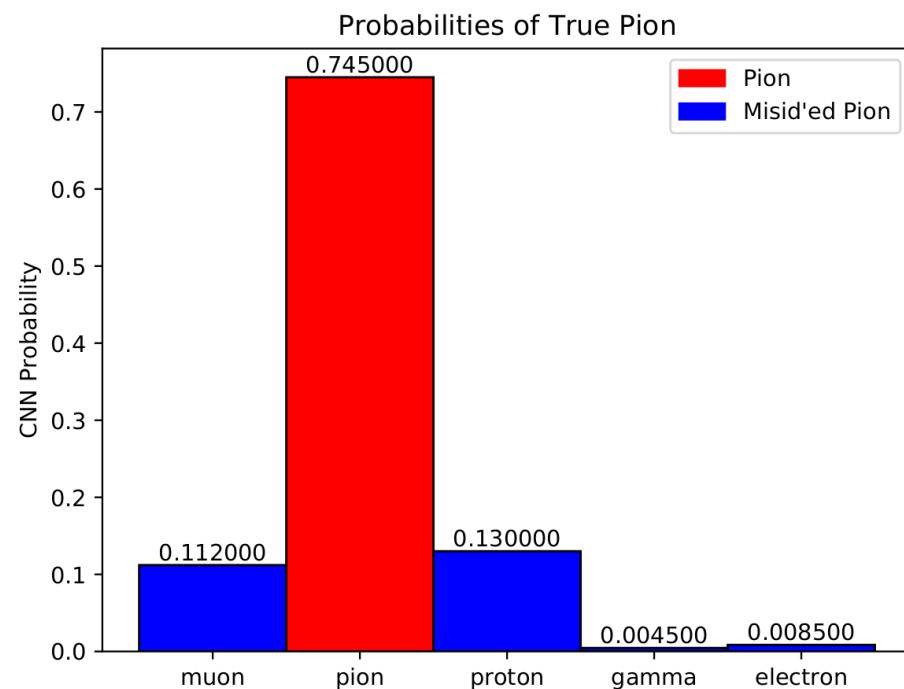


Figure 7.8: Pion Prob

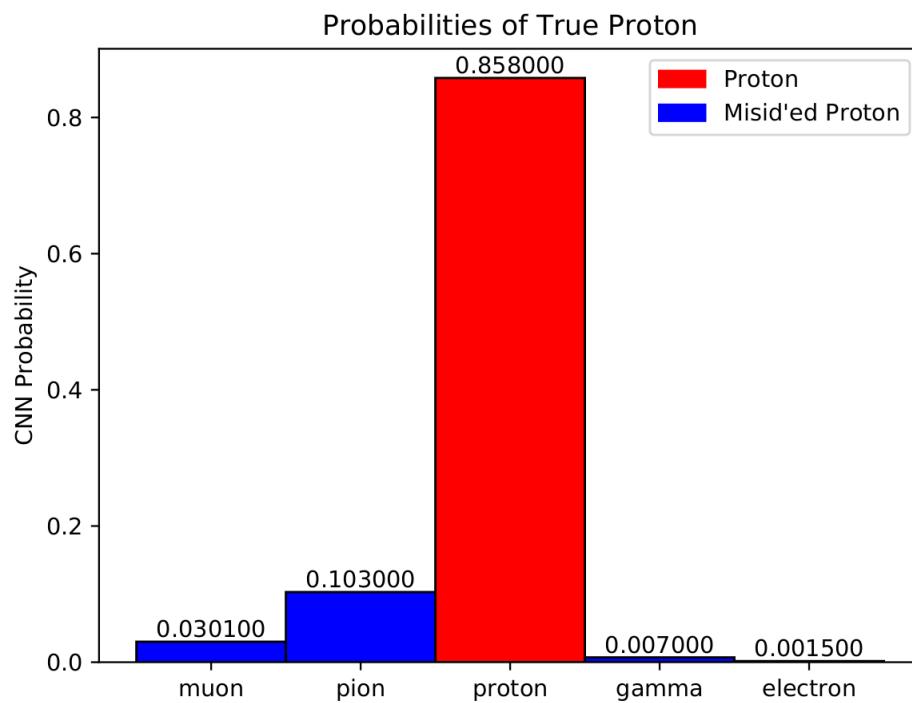


Figure 7.9: Proton Prob

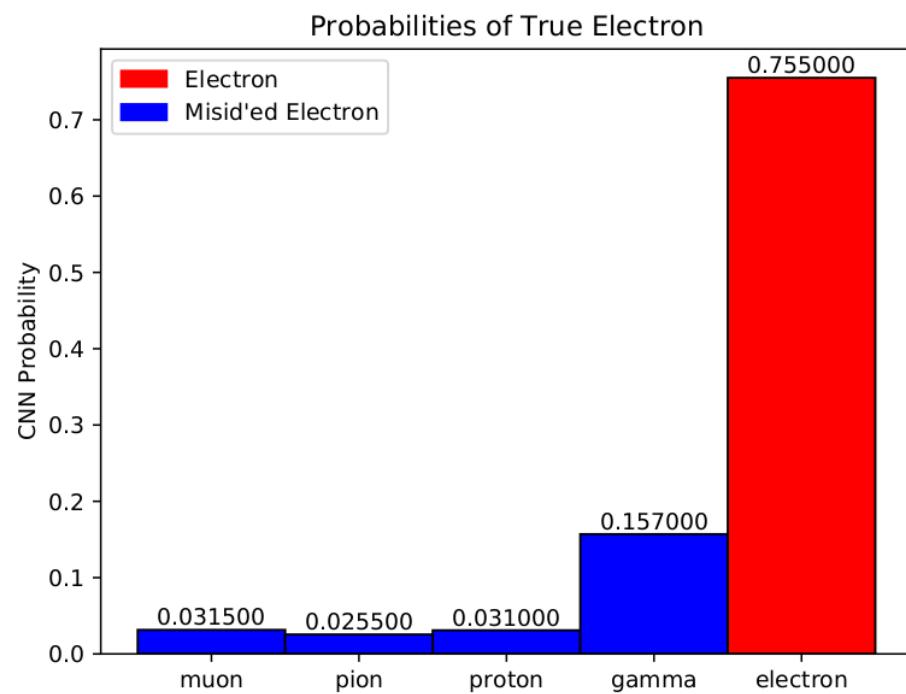


Figure 7.10: Electron Prob

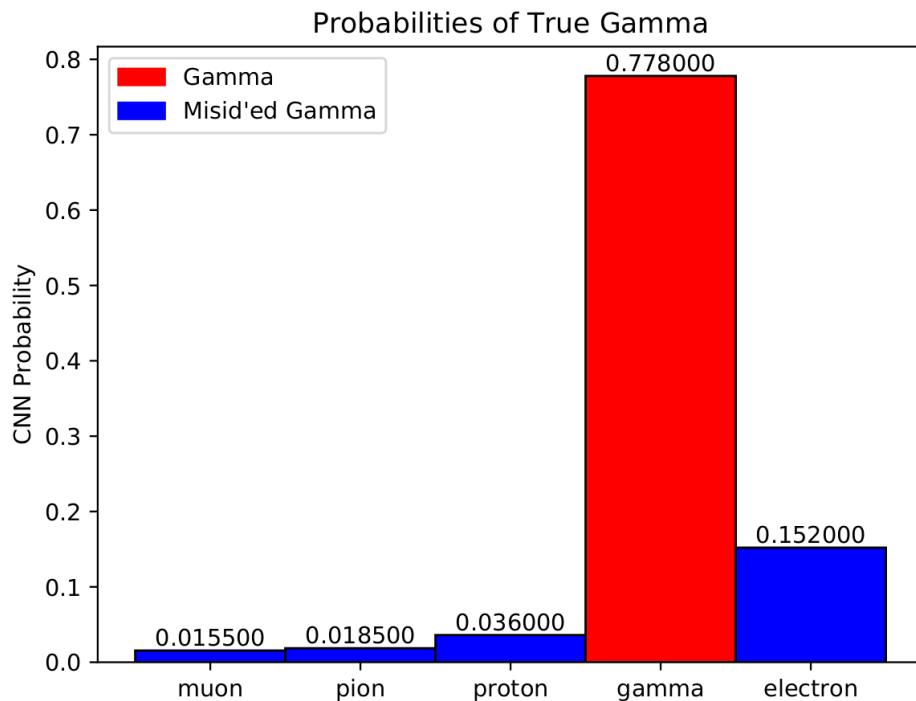


Figure 7.11: Gamma Prob

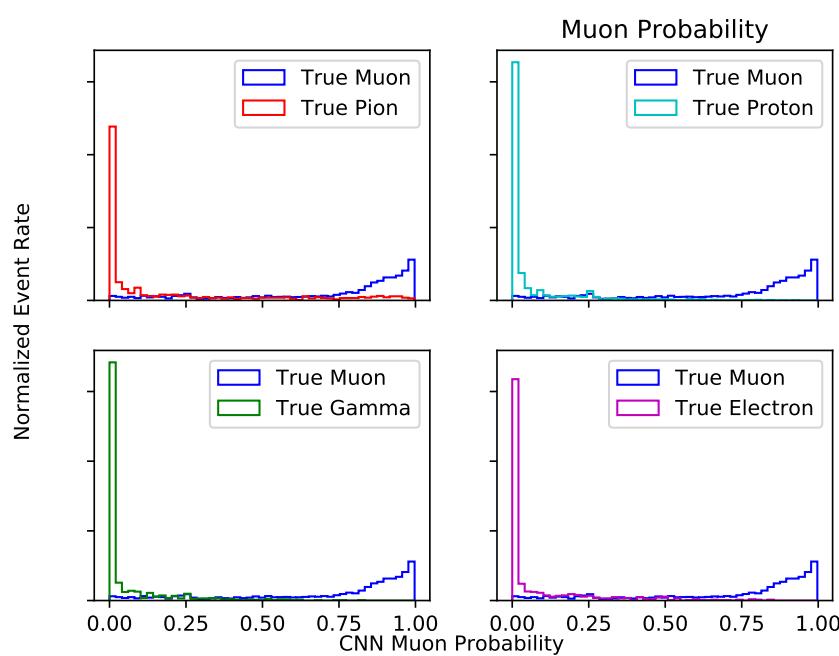


Figure 7.12: Prob

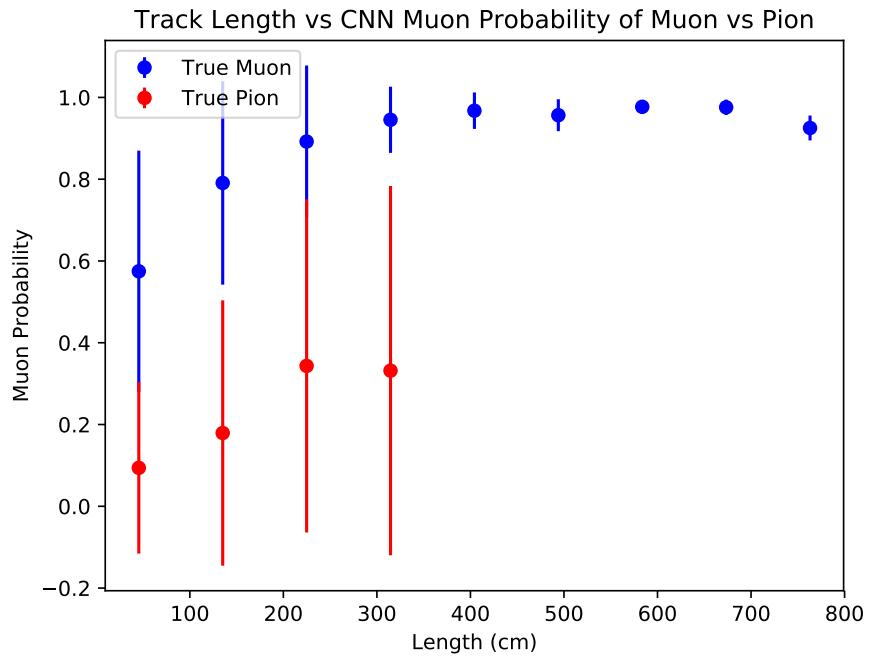


Figure 7.13: mupi

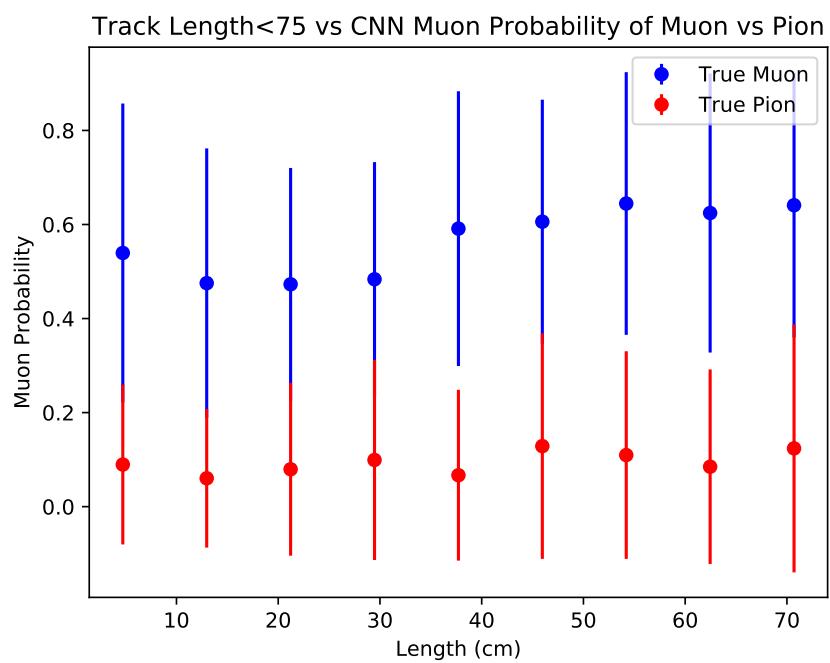
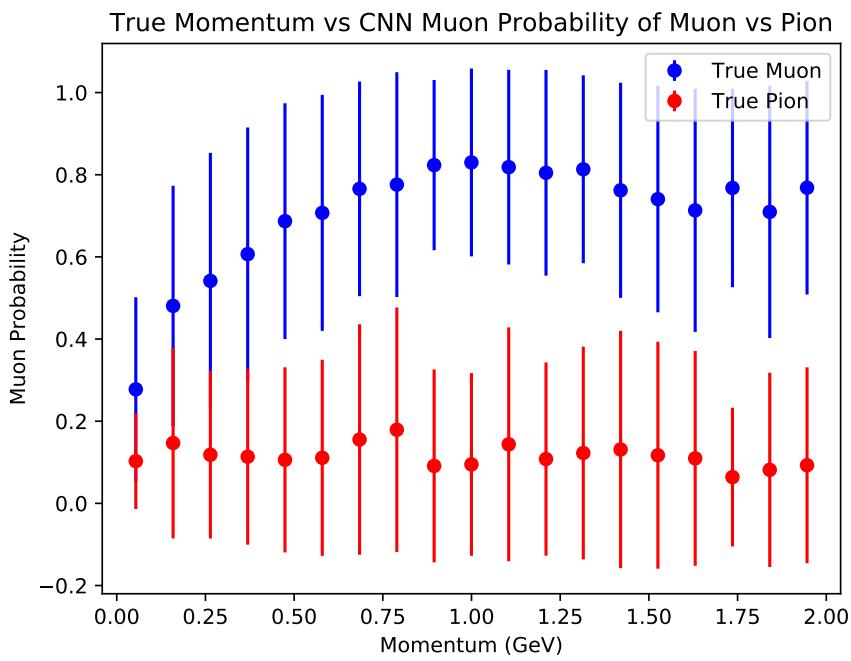
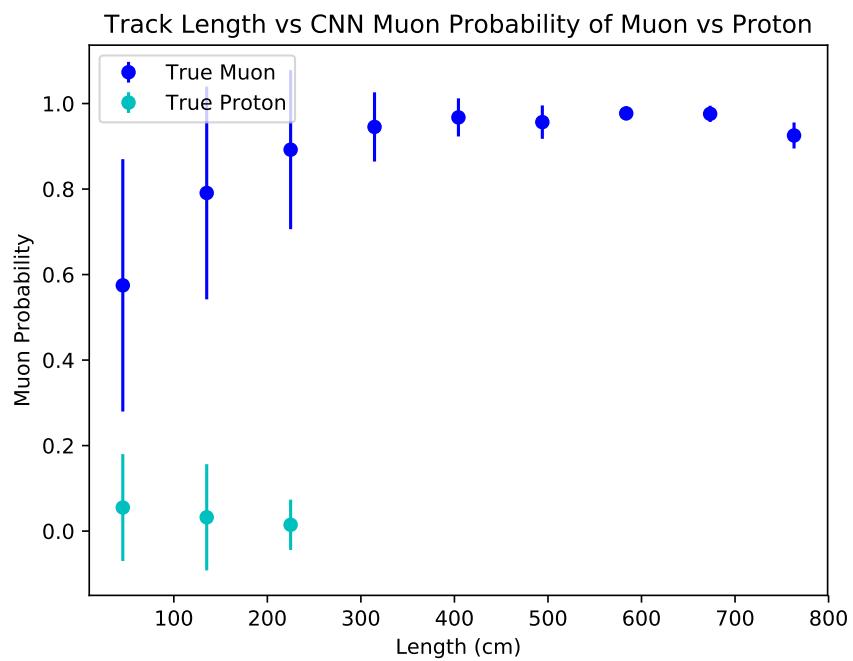
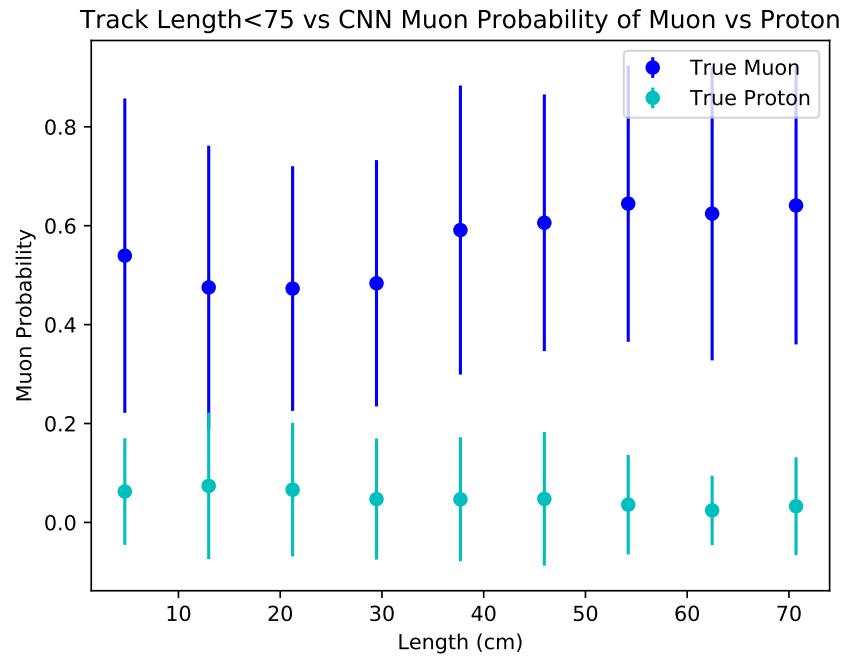
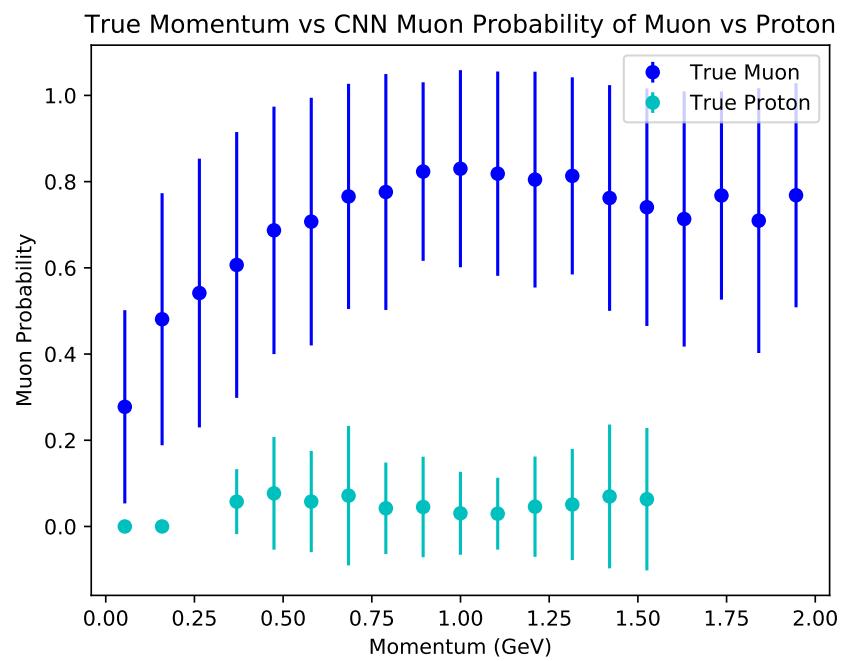


Figure 7.14: mupi

**Figure 7.15:** mupi**Figure 7.16:** mup

**Figure 7.17:** mup**Figure 7.18:** mup

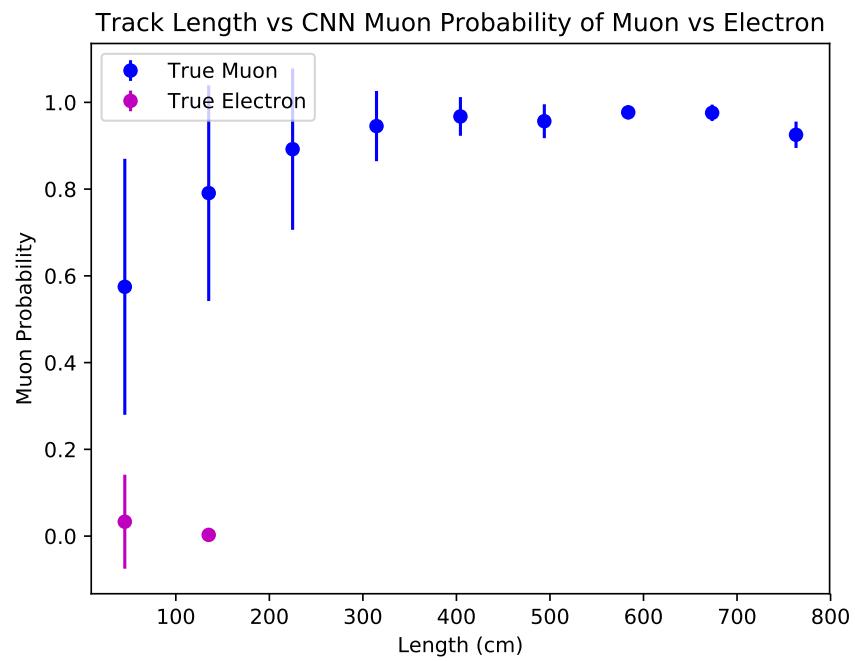


Figure 7.19: mue

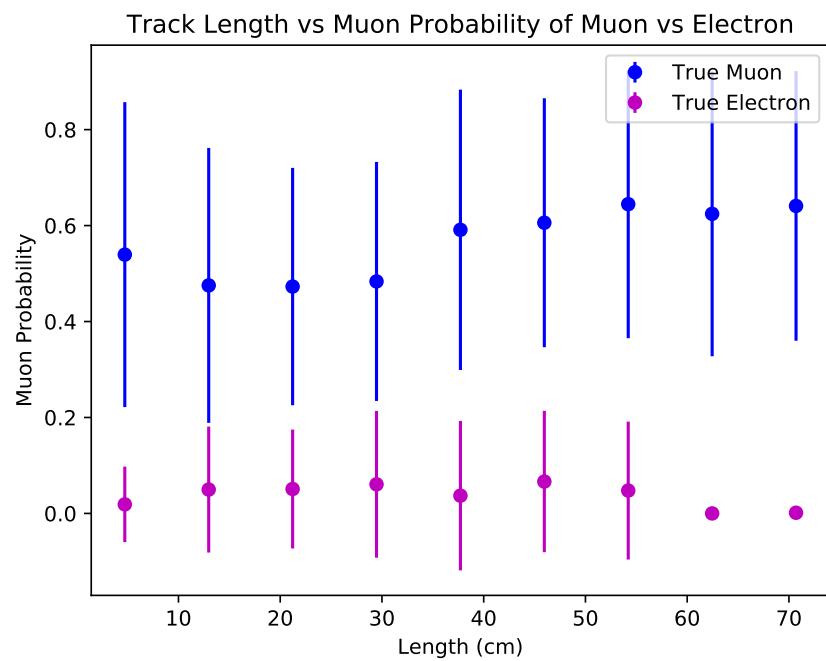


Figure 7.20: mue

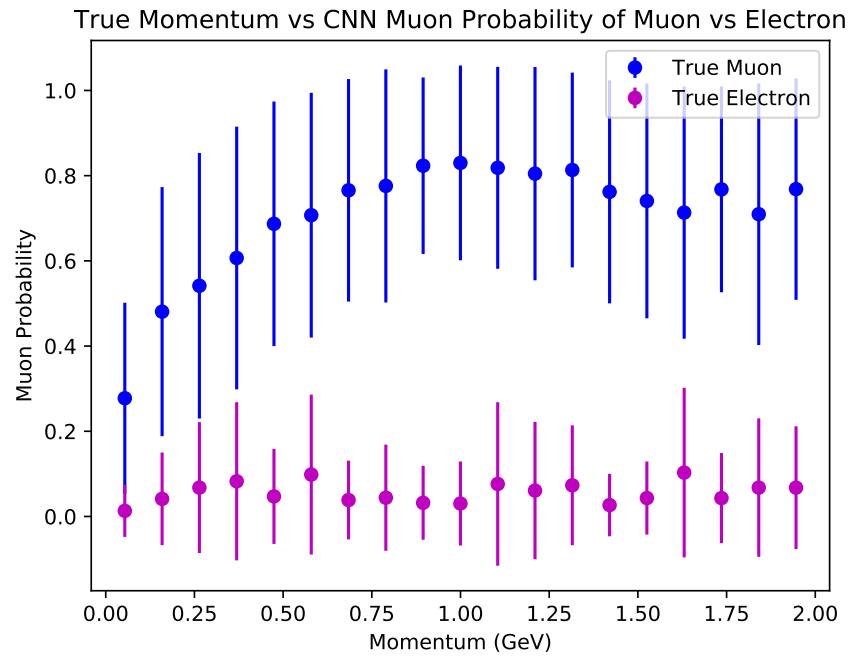


Figure 7.21: mue

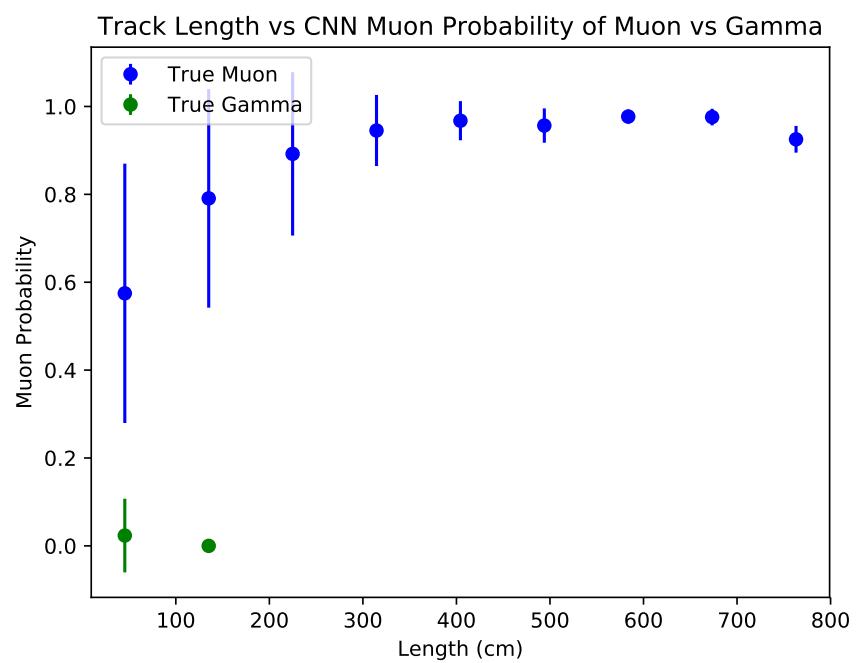


Figure 7.22: mug

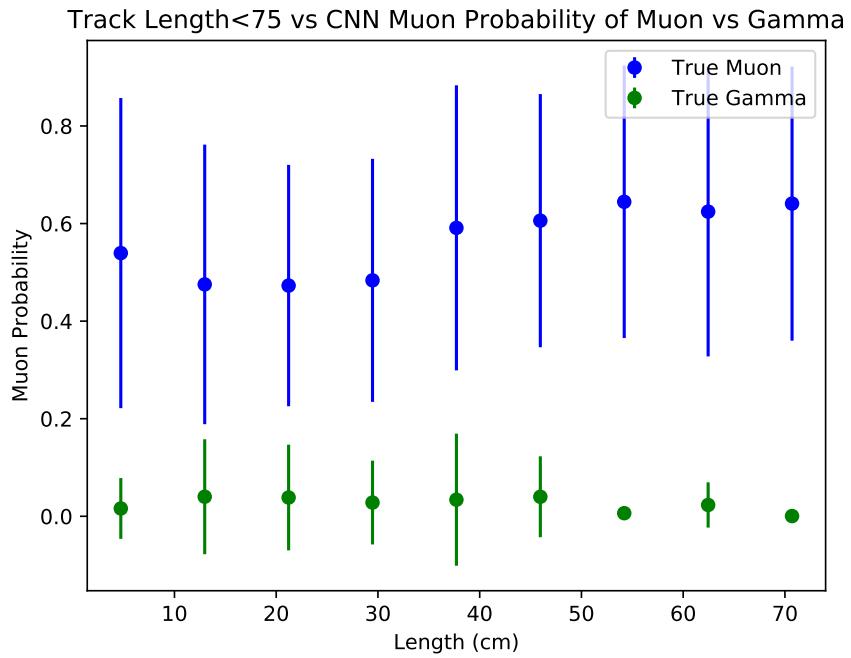


Figure 7.23: mug

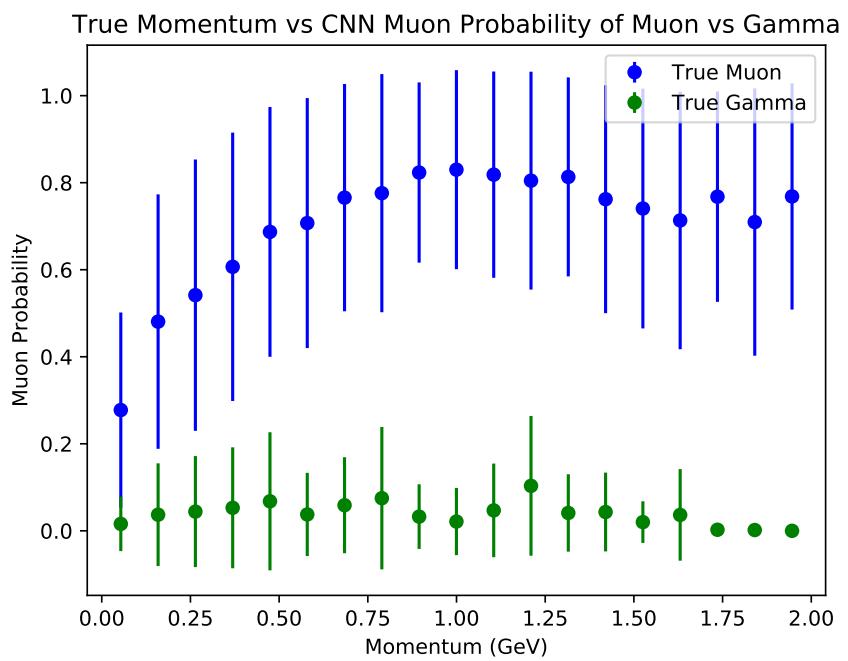


Figure 7.24: mug

1172 Chapter 8

1173 Results of Convolutional Neural 1174 Networks on particles **WORKING** 1175 **TITLE**

1176 8.1 Classification using CNN10000

1177 8.1.1 Classification of MC data using Selection I Original 1178 CC-Inclusive Filter

1179 The next step that was taken was to use CNN10000 to classify track candidate images
1180 that were identified by the selection I original cc-inclusive filter described in [?].
1181 Passing rates for each cut in cc-inclusive filter are show in figure 8.1. For the incorrect
1182 image making normalization dataset, out of 188,880 events, 7438 passed the cut right
1183 before 75 cm track length cut which is 3.9% of total data. Discrepancies in passing rates
1184 are due to grid submission issues, however, this dataset is used to check if changes
1185 in image making normalization affects μ/π separation probability due to CNN10000
1186 being trained with incorrectly image making normalized data. For the second dataset
1187 with correct image making normalization, out of 188,880 events, 9552 events passed the
1188 cut right before the 75 cm track length cut which is 5.1% passing rate and is comparable
1189 to figure 8.1. In time cosmics were also run over for efficiency and purity calculations.
1190 Out of 14395 in time cosmic events, 175 passed the cut right before the 75 cm track
1191 length cut which is a passing rate of 1.2% compared to 1.3% shown in figure 8.1.

Table 3: **Selection I: Original** The table shows passing rates for the above described event selection. Numbers are absolute event counts and Cosmic background is not scaled appropriately. The BNB+Cosmic sample contains all events, not just ν_μ CC inclusive. The selected events are further broken up in the following subsection. The numbers in brackets give the passing rate wrt the step before (first percentage) and wrt the generated events (second percentage). In the BNB+Cosmic MC Truth column shows how many true ν_μ CC inclusive events (in FV) are left in the sample. This number includes possible mis-identifications where a cosmic track is picked by the selection instead of the neutrino interaction in the same event. The cosmic only sample has low statistics, but please note that it is not used in any plots, it is just for illustrating the cut efficiency. The last column Signal:Cosmic only gives an estimate of the ν_μ CC events wrt the cosmic only background at each step. For this number, the cosmic background has been scaled as described in chapter 2. Note that this numbers is not a purity, since other backgrounds can't be determined at this step.

	BNB + Cosmic Selection	MC-Truth	Cosmic only	Signal: Cosmic only
Generated events	191362	45273	4804	1:22
≥ 1 flash with ≥ 50 PE	136219 (71%/71%)	44002 (97%/97%)	2979 (62%/62%)	1:14
≥ 1 vertex in FV	131170 (96%/69%)	43794 (99%/97%)	2805 (94%/58%)	1:13
≥ 1 track within 5 cm of vertex	129784 (99%/68%)	43689 (99%/97%)	2756 (98%/58%)	1:13
flash matching of longest track	44775 (34%/23%)	23647 (54%/52%)	647 (23%/13%)	1:5.7
track containment	10114 (23%/5.3%)	6882 (29%/15%)	61 (9.4%/1.3%)	1:1.9
track ≥ 75 cm	7358 (73%/3.8%)	5801 (84%/13%)	31 (51%/0.6%)	1:1.1

Figure 8.1: Snapshot of passing rates of Selection I from CC-Inclusive Filter

Figures 8.2a, 8.2b, 8.2c and 8.2d show the accuracy and μ/π separation of both the correct and incorrect normalized images. The confusion matrices are only composed of μ/π data. Other particles passed the cc-inclusive filter before the 75 cm track length cut and were all mis-id'ed as muons. Since CNN10000 has not seen any particles other than muons and pions, it makes sense that those get mis-id'ed. Figures 8.2b and 8.2d don't have μ/π separation comparable to 7.2c, but 8.2b does skew to higher probabilities compared to 8.2d. This is to be expected and further work on quantifying the performance of CNN10000 should use the incorrect image making normalization. It is also expected that the separation isn't as defined as the testing dataset for CNN10000. CNN10000 was trained and tested using single particle muons and pions and the track candidate dataset come from BNB+Cosmic events, not to mentions all track candidates have passed the cc-inclusive filter that tags "muon-like" tracks therefore the pions in this sample look much closer in muon topology than the network has seen. Also, these images were made from wire and time ticks associated to hits from the track candidate that passed the cc-inclusive filter. This is different from the training images where a bounding box was drawn over the total μ or π interaction. Spurious energy deposition from a $\pi - Ar$ interaction is most likely not included in the BNB+Cosmic images due to the tracking algorithm. To remedy this, the neural network needs to see more "muon-like" pions and muons and pions from a neutrino interaction passing the cc-inclusive filter as well as a larger particle variety including protons, photons

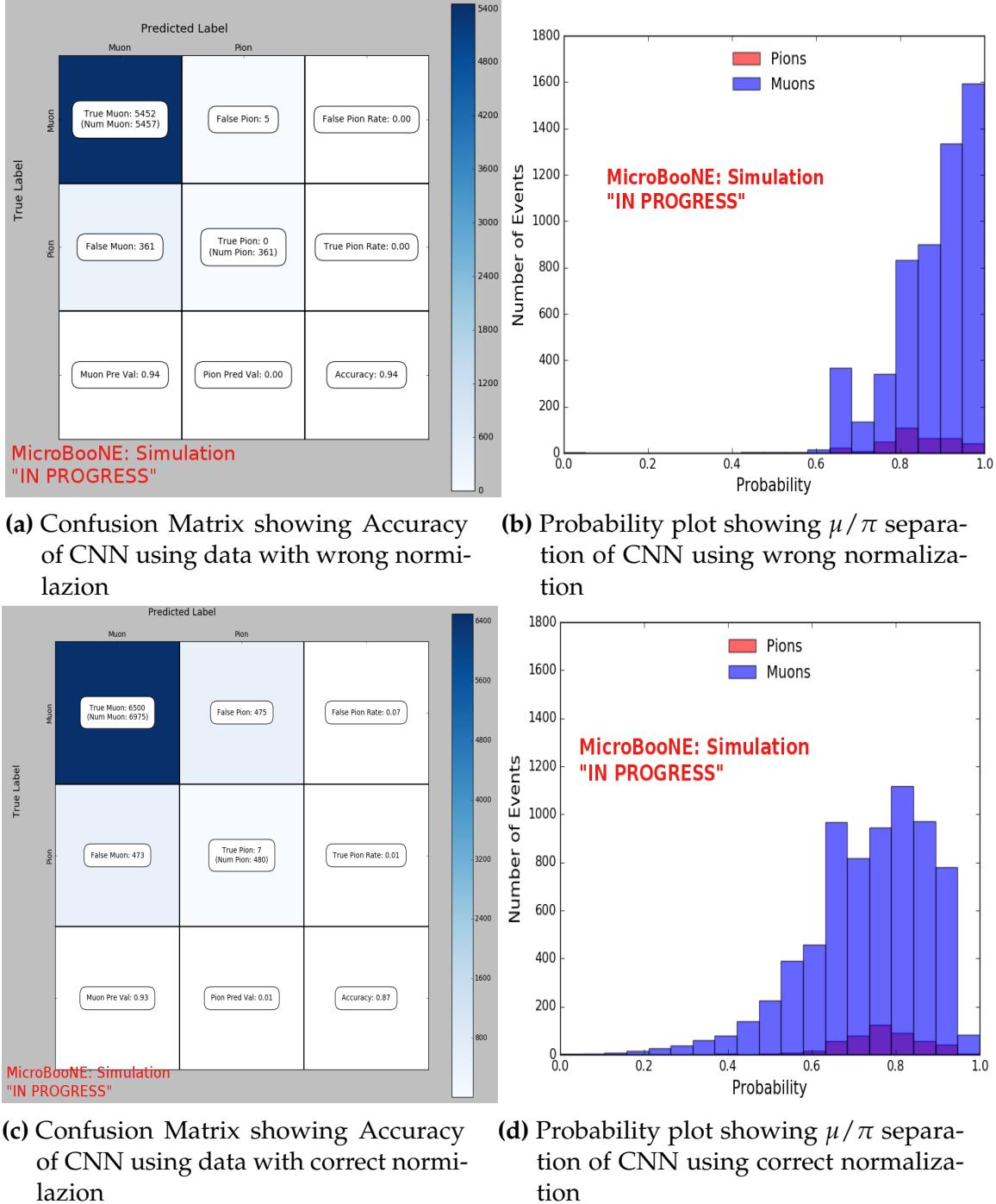


Figure 8.2: Results of CNN10000 classification of track candidate images output from cc-inclusive filter.

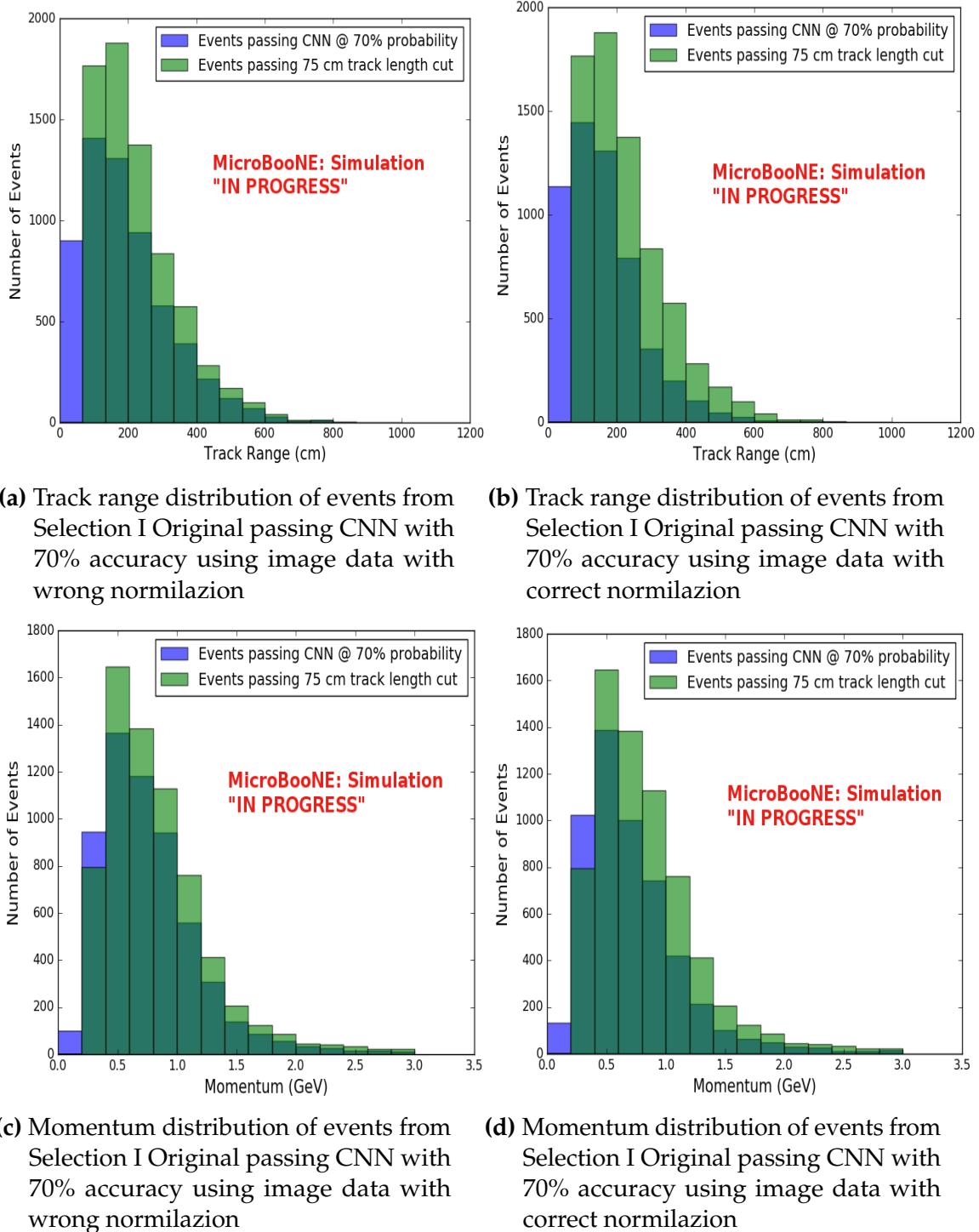


Figure 8.3: CNN10000 distributions of track candidate images output from Selection I Original cc-inclusive filter with different image data normalizations

and electrons. Although μ/π separation is lacking, CNN10000 does an excellent job of classifying muons and using higher CNN probability can increase purity. Figures 8.3a, 8.3b, 8.3c and 8.3d show the track and momentum distributions for these two datasets. In both sets you have an increase in data in the bin below 75 cm and at bins below 0.5 GeV. These distributions were made with events classified with 70% probability of being a muon regardless of true particle type.

8.1.2 Classification of MC data using Selection I Modified CC-Inclusive Filter

Table 5: **Selection I: Modified** The table shows passing rates for the above described event selection. Numbers are absolute event counts and Cosmic background is not scaled appropriately. The BNB+Cosmic sample contains all events, not just ν_μ CC inclusive. The selected events are further broken up in the following subsection. The numbers in brackets give the passing rate wrt the step before (first percentage) and wrt the generated events (second percentage). In the BNB+Cosmic Mc Truth column shows how many true ν_μ CC inclusive events (in FV) are left in the sample. This number includes possible mis-identifications where a cosmic track is picked by the selection instead of the neutrino interaction in the same event. The cosmic only sample has low statistics, but please note that it is not used in any plots, it is just for illustrating the cut efficiency. The last column Signal:Cosmic only gives an estimate of the ν_μ CC events wrt the cosmic only background at each step. For this number, the cosmic background has been scaled as described in chapter 2. Note that this numbers is not a purity, since other backgrounds can't be determined at this step.

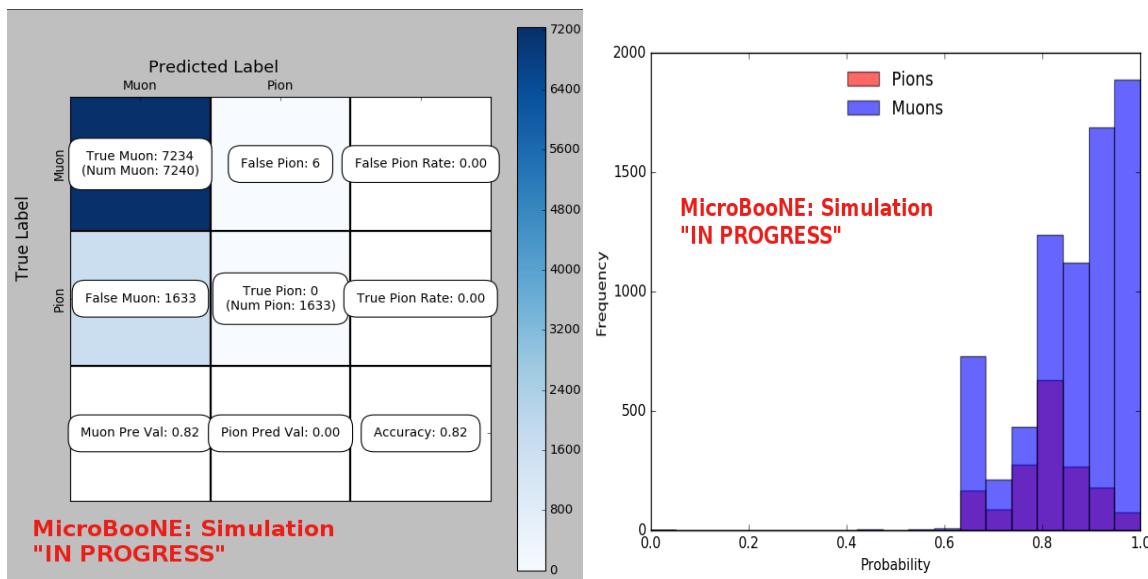
	BNB + Cosmic Selection		Cosmic only	Signal: Cosmic only
	MC-Truth			
Generated events	191362	45273	4804	1:22
≥ 1 flash with ≥ 50 PE	136219 (71%/71%)	44002 (97%/97%)	2979 (62%/62%)	1:14
≥ 1 track within 5 cm of vertex	135830 (99%/71%)	43974 (99%/97%)	2975 (99%/62%)	1:14
vertex candidate in FV	79112 (58%/41%)	34891 (79%/77%)	1482 (50%/31%)	1:8.9
flash matching of longest track	40267 (51%/21%)	25891 (74%/57%)	340 (23%/7.1%)	1:2.8
track containment	19391 (48%/10%)	11693 (45%/26%)	129 (38%/2.7%)	1:2.3
track ≥ 75 cm	6920 (36%/3.6%)	5780 (49%/13%)	17 (13%/0.4%)	1:0.6

Figure 8.4: Snapshot of passing rates of all cuts from Selection I Modified cc-inclusive filter

CNN10000 was also used to classify track candidate images that were identified by the selection I modified cc-inclusive filter described in [?]. Passing rates for each cut in this filter are shown in figure 8.4. As seen in section 8.1.1, wrong image normalization had a higher muon classification probability so all work done using selection I modified cc-inclusive filter was done using this normalization. Out of 188,880 events, 19,112 passed the cut right before the 75 cm track length cut which is a 10.1% passing rate and comparable to the 10% passing rate shown in figure 8.4. In time cosmics were also run over, out of 14,606 in time cosmics events, 302 passed the cut right before the 75 cm track length cut which is a 2.1% passing rate comparable to the 2.7% passing rate in the cc-inclusive tech-note. Figures 8.5a and 8.5b show the accuracy and μ/π separation. Both plots are only composed of muons and pions and like selection I original data,

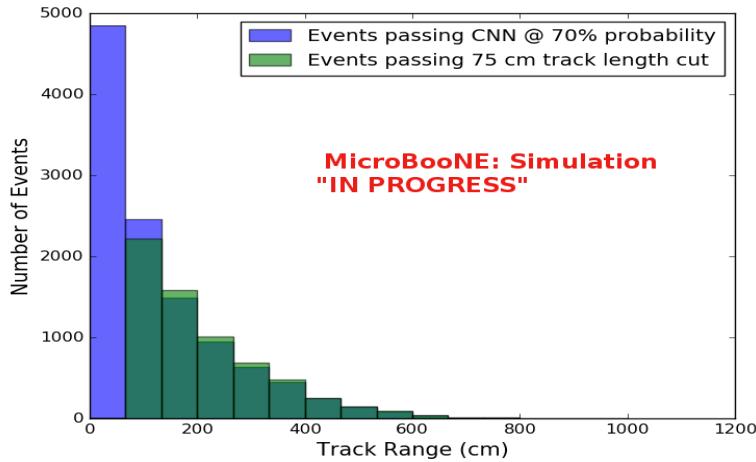
1231 all other particles were id'ed as muons. Also like selection I original data, muons are
 1232 being identified at a very high rate. Figure 8.6a shows the track range distributions
 1233 of all events from selection I modified being classified by the CNN as a muon with a
 1234 probability of 70% regardless of true particle type. We get entries for the CNN curve
 1235 in the lowest bin and none for the 75 cm curve. To see how many true CC events
 1236 were identified by CNN10000 breaking down figure 8.6a by event type was necessary.
 1237 Figures 8.6b and 8.6c show track range distributions separated by signal and various
 1238 backgrounds. Particle type was not taken into consideration in these plots so true CC
 1239 event images can be any track candidate particle passing selection I modified cut right
 1240 before track length cut including pions and protons.

1241 To gain an even deeper understanding on how CNN10000 is performing, plotting
 1242 these distributions with only muons and pions was done due to the fact that CNN10000
 1243 was trained with only those particles for μ/π separation. Figures 8.6d-8.7d show the
 1244 stacked histograms of signal and background of the track range distributions with
 1245 varying CNN probabilities starting from 70% and ending at 90% probability. With
 1246 higher probabilities we get a purer sample in the lower bin but we end up losing
 1247 events as well. Momentum distributions for all signal/background events are shown
 1248 in figure 8.8.

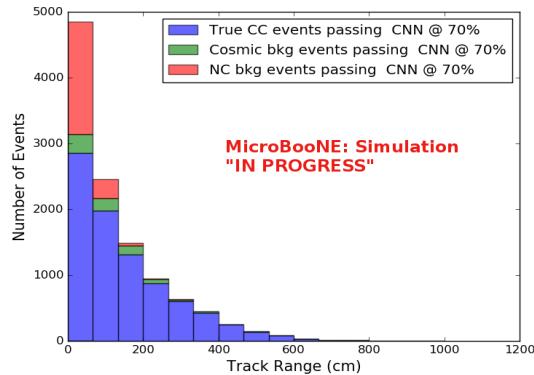


(a) Confusion Matrix for CNN10000 classified events from selection I modified (b) Probability plot for CNN10000 classified events from selection I modified

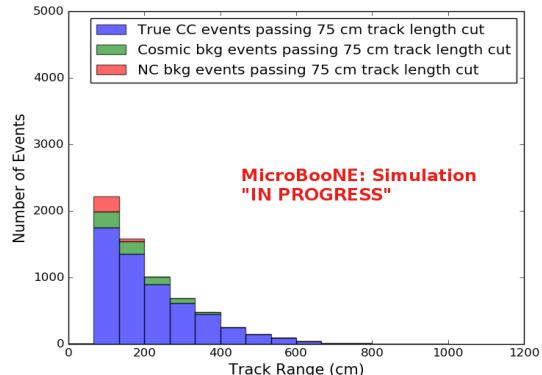
Figure 8.5: Confusion matrix and probability plot of events passing selection I modified cc-inclusive cuts right before 75cm track length cut



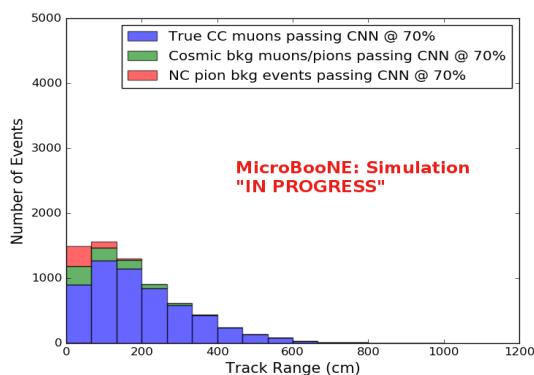
(a) Track range distribution of events from Selection I Modified passing CNN with 70% accuracy



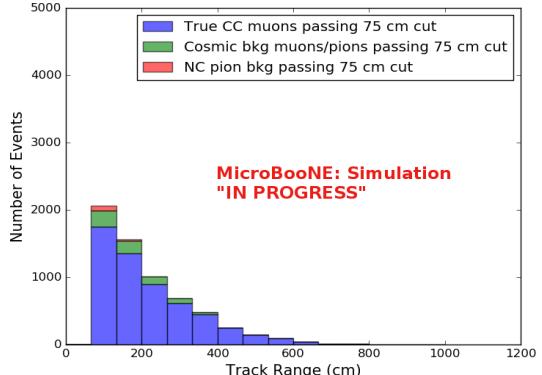
(b) Stacked signal and background track range distributions from Selection I Modified passing CNN with 70% accuracy



(c) Stacked signal and background track range distributions from Selection I Modified passing 75 cm track length cut



(d) Stacked signal muons and background muons/pions of track range distributions from Selection I Modified passing CNN with 70% accuracy



(e) Stacked signal muons and background muons/pions of track range distributions from Selection I Modified passing 75 cm track length cut

Figure 8.6: CNN10000 distributions of track candidate images output from Selection I Modified cc-inclusive filter

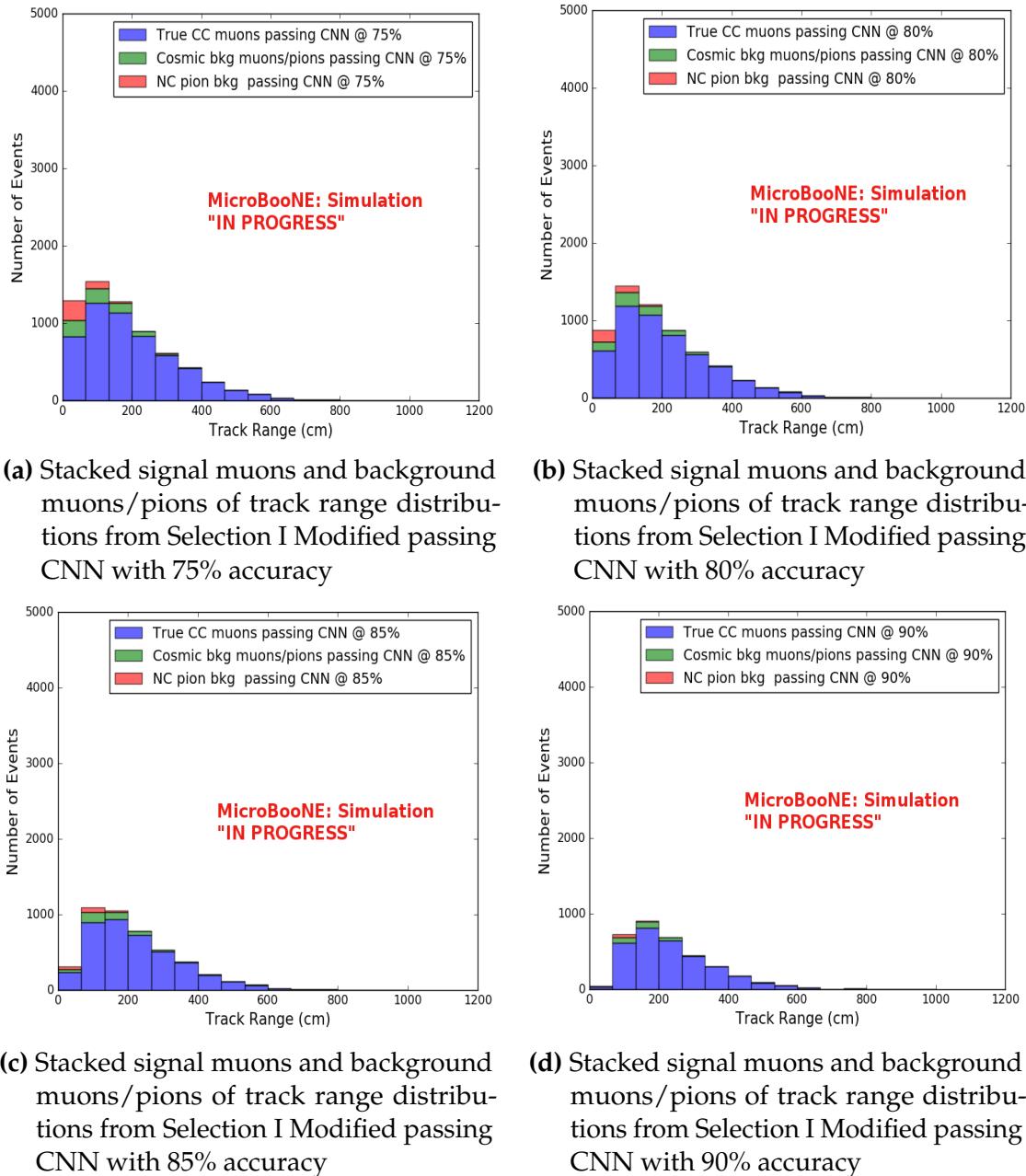
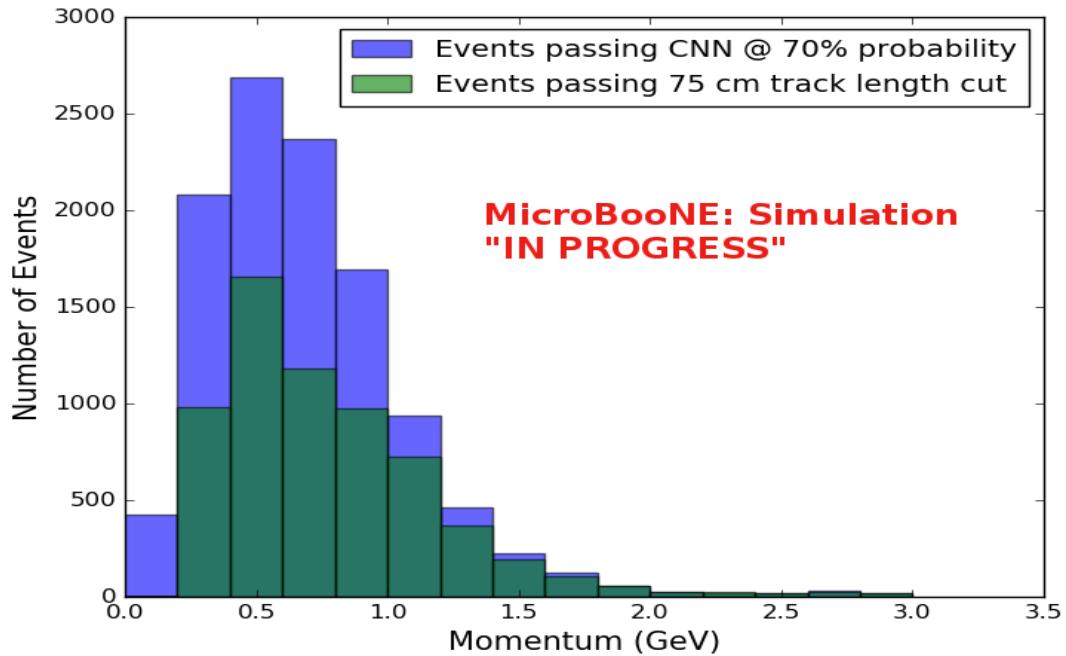
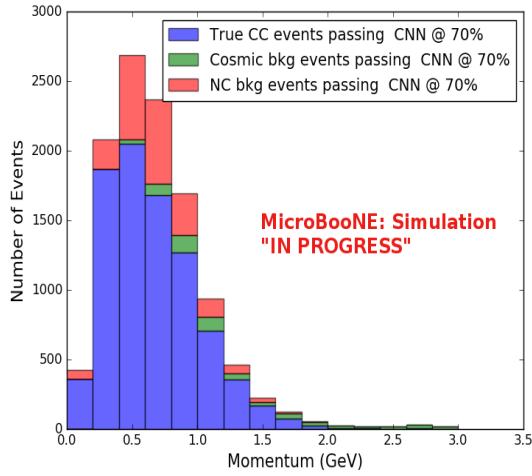


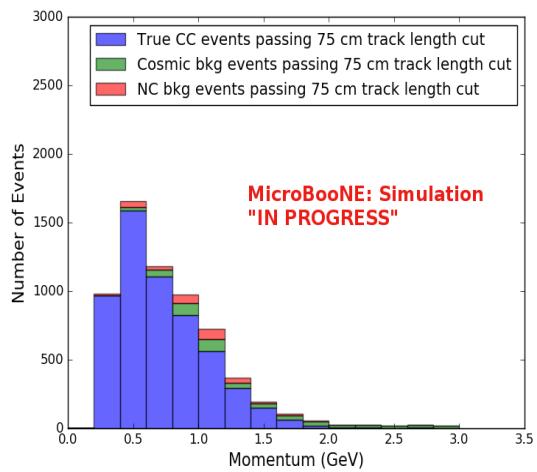
Figure 8.7: CNN10000 stacked signal/background track range distributions of track candidate images output from Selection I Modified cc-inclusive filter



(a) Momentum distribution of events from Selection I Modified passing CNN with 70% accuracy



(b) Stacked signal and background momentum distributions from Selection I Modified passing CNN with 70% accuracy



(c) Stacked signal and background momentum distributions from Selection I Modified passing 75 cm track length cut

Figure 8.8: CNN10000 momentum distributions of track candidate images output from Selection I Modified cc-inclusive filter

1249 Another check was to see if any true CC pions were passing through the cut right
1250 before the 75 cm track length cut. Figure 8.9 shows the comparison of the stacked
1251 track range distribution with only true CC muon signal versus the stacked distribution
1252 with true CC muons and pions signal. As you can see, we gain more events when
1253 plotting CC events with a particle type of either muons or pions due to the CNN
1254 classifying all pions in this dataset as muons. This is an interesting scenario and a
1255 sample of topologies of these images are represented in figure 8.10, at least 3 tracks
1256 are coming out of the vertex for these types of events. With the 75 cm track length cut,
1257 the selection is cutting event topologies like this where the pion is the tagged track
1258 candidate. Figure 8.10a has a defined longer muon track, but because of dead wires
1259 through the track, the reconstructed range is 1. less than 75 cm and 2. shorter than the
1260 reconstructed pion whose length is also less than 75 cm. This is a very interesting event,
1261 but because of issues with the tracking algorithm, the 75 cm cut would get rid of this
1262 event. The CNN was able to recover this event only because it has classified all pions
1263 as muons. Figure 8.10b shows the second case to think about, the pion, while still less
1264 than 75 cm has a reconstructed track length longer than the muon. Again, the CNN
1265 recovered this event due to pions being classified as muons. Lastly, figure 8.10c shows
1266 a pion with a reconstructed track length greater than 75 cm and the muon. These three
1267 cases show that a broader question must be asked when training the network other
1268 than is it a muon or pion. There are different routes to recover interesting events like
1269 these. One route is to ask the network “Is it a CC event or is it an NC event?” and
1270 obtain an image dataset consisting of whole CC/NC events that will train the network
1271 to answer this question. The other route is to ask the network “Is this a $\mu/\pi/p/$ from
1272 a CC event or NC event and obtain an image dataset consisting of primary particles
1273 from a CC/NC event. Both these paths will be explored in future work.

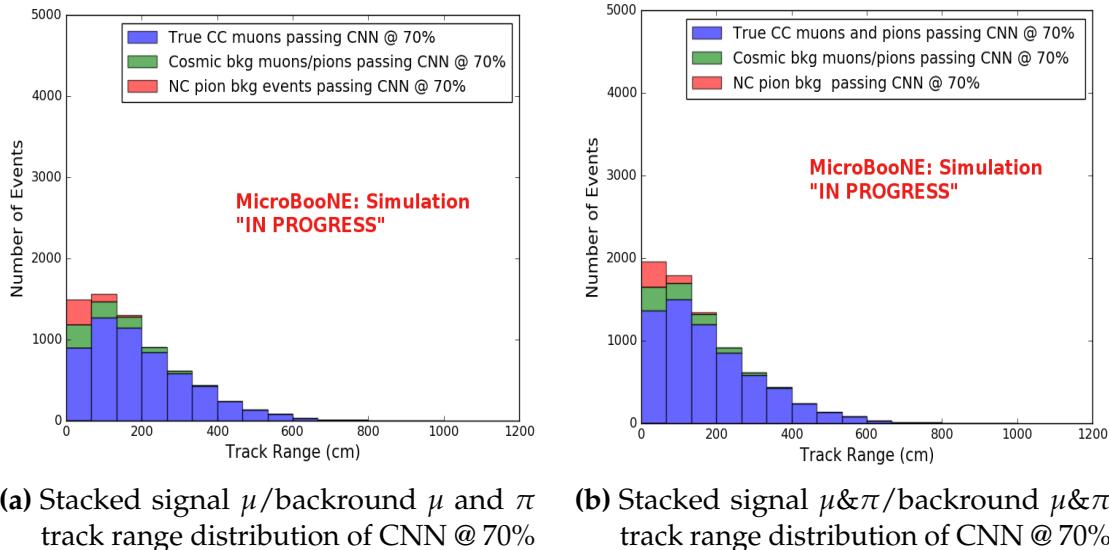


Figure 8.9: Track distribution comparisons of true CC muons plotted vs true CC muons and pions plotted

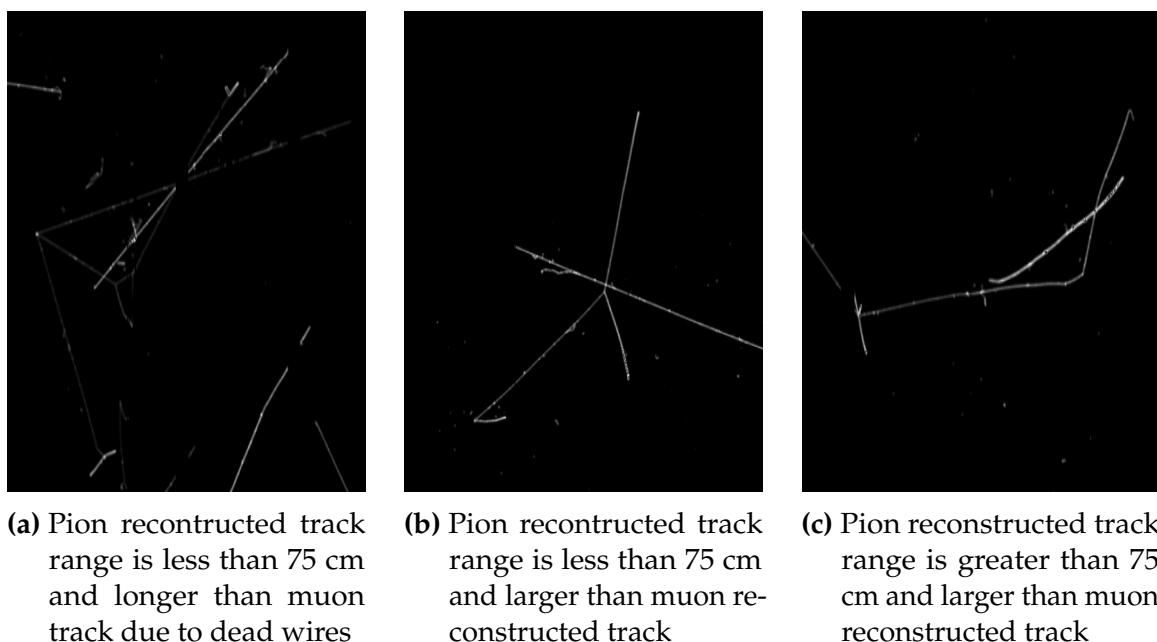


Figure 8.10: Images of true CC events where the pion was the tagged track candidate

		BNB + Cosmics		Cosmic Only	Signal: Cosmic Only
		Selection	MC Truth		
75 cm Cut passing rates	Generated Events	191362	45723	4804	1:22
	Track Containment	19391 (48%/10%)	11693 (45%/26%)	129 (38%/2.7%)	1:2.3
	track \geq 75 cm	6920 (36%/3.6%)	5780 (49%/13%)	17 (13%/0.4%)	1:0.6
CNN passing rates	Generated Events	188880	44689	14606	1:21
	Track Containment	19112 (/10%)	11554 (/26%)	302 (/2.1%)	1:1.73
	CNN cut @ 70% Probability	16502 (86%/8.7%)	10605 (92%/23%)	205 (68%/14%)	1:1.28
	CNN cut @ 83% Probability	7511 (46%/4.0%)	6142 (58%/14%)	32 (16%/0.2%)	1:0.4

Table 8.1: Comparing passing rates of CNN at different probabilities versus 75 cm track length cut: Numbers are absolute event counts and Cosmic background is not scaled appropriately. The BNB+Cosmic sample contains all events. The numbers in brackets give the passing rate wrt the step before (first percentage) and wrt the generated events (second percentage). In the BNB+Cosmic MC Truth column shows how many true ν_μ CC-inclusive events (in FV) are left in the sample. This number includes possible mis-identifications where a cosmic track is picked by the selection instead of the neutrino interaction in the same event. The CNN MC True generated events were scaled wrt the MC True generated events for the 75 cm cut passing rates due to only running over 188,880 generated events versus the 191362 generated events. The last column Signal:Cosmic only gives an estimate of the ν_μ CC events wrt the cosmic only background at each step. For this number, the cosmic background has been scaled as described in [?]. Note that these numbers are not a purity, since other backgrounds can't be determined at this step.

Signal	ν_μ CC events with true vertex in FV	#Events(Fraction)	#Events(Fraction)
		passing CNN @ 70% Probability	passing CNN @ 83% Probability
		10605(35%)	6142(61%)
Backgrounds	Cosmics Only Events	13573(45%)	2582(26%)
	Cosmics in BNB Events	2249(7.4%)	492(4.9%)
	NC Events	3412(11%)	778(7.7%)
	ν_e and $\bar{\nu}_e$ Events	139(0.5%)	32(0.3%)
	$\bar{\nu}_\mu$ Events	97(0.3%)	67(0.7%)

Table 8.2: Signal and background event numbers at modified selection level with CNN cut estimated from a BNB+Cosmic sample and Cosmic only sample normalized to $5 * 10^{19}$ PoT. The last column gives the fraction of this signal or background type to the total selected events per CNN probability.

Table 8.1 shows the passing rates for the 75 cm track length cut and the CNN cut at 70% and 83%. The passing rates at the track containment level for the 75 cm track length cut compared to the CNN are comparable with only a 0.6% difference in the in time cosmic bin which may be due in part to the larger in time cosmic statistics used for the CNN dataset. These passing rates need to be comparable to then be able to compare the passing rates after the CNN cut to the 75 cm cut. Again, the same BNB+Cosmic sample was used for both selection I modified with 75 cm cut and selection I modified with CNN cut. As it stands, a CNN cut at 83% probability has

1282 a MC true CC event passing rate of 14% compared to the 13% passing rate of the 75
 1283 cm track length cut. The Signal:Cosmic Only background is also reduced from 1:0.6
 1284 to 1:0.4 The total passing rate is also higher than the 75 cm cut, 3.6% vs 4.0%. Table
 1285 8.2 shows the breakdown of signal and backgrounds for the CNN at the different
 1286 probabilities. We have a 61% signal passing rate with the CNN cut @ 83% versus the
 1287 53.8% signal passing rate of the 75 cm cut.

1288 Based on these numbers, the following performance values of the modified selec-
 1289 tion with 75 cm cut versus modified selection with CNN @ 83% probability cut were
 1290 calculated:

- 1291 • Efficiency: Number of selected true ν_μ CC events divided by the number of
 1292 expected true ν_μ CC events with interaction in the FV.
 - 1293 – Selection I modified: 13%
 - 1294 – Selection I modified with CNN cut @ 83% probability: 14%
- 1295 • Purity: Number of selected true ν_μ CC events divided by sum of itself and the
 1296 number of all backgrounds.
 - 1297 – Selection I modified: 53.8%
 - 1298 – Selection I modified with CNN cut @ 83% probability: 61%

1299 Lastly, figure 8.12 shows a more representative performance of the CNN. Due to
 1300 the fact that the CNN was trained on muons and pions, showing the performance
 1301 of CC muon events versus NC pion events with respect to CNN probability gives a
 1302 better picture of how the network is performing. Figure 8.12 shows that at 83% we
 1303 are below the 75 cm cut NC pion threshold and still above the CC muon threshold.
 1304 Using 83% probability not only reduced the NC pion background, it also dramatically
 1305 reduced the in time cosmics and cosmics in the BNB.

1306 8.1.3 Conclusions and Future Work

1307 It was shown that even though CNN10000 was trained with single particle generated
 1308 muons and pions, it performs fairly well at classifying track candidate images from
 1309 BNB+Cosmic events. Events have been regained below the 75 cm track length cut and
 1310 the momentum and track range distributions have similar shapes to the distributions of
 1311 Selection I original and modified. Efficiencies and purities were calculated for selection

Table 8: **Selection I: Modified** Signal and background event numbers at modified selection level estimated from a BNB+Cosmic sample and Cosmic only sample normalized to 5×10^{19} PoT. The last column gives the fraction of this signal or background type to the total 2189 selected events.

Signal	#Events	
ν_μ CC events with true vertex in FV	1168	53.8%
Backgrounds		
Cosmics only events	725	33.4%
Cosmics in BNB events	144	6.6%
NC events	75	3.5%
ν_e and $\bar{\nu}_e$ events	4	0.2%
$\bar{\nu}_\mu$ events	15	0.7%
ν_μ CC events with true vertex outside FV	40	1.8%

Figure 8.11: Snapshot of signal and background event numbers of Selection I modified from cc-inclusive note [?]

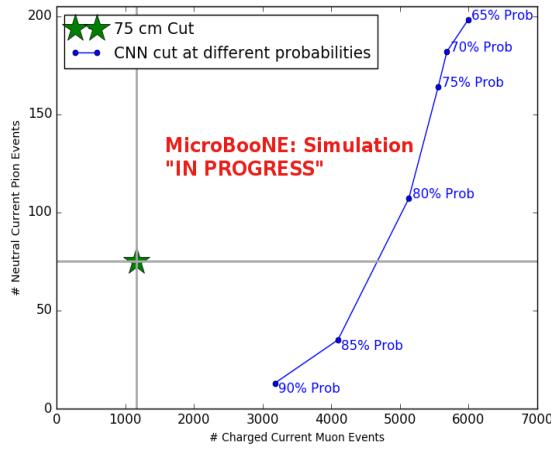


Figure 8.12: CNN performance of classified muons and pions compared to the already implemented 75 cm track length cut

1312 I modified events before 75 cm track length cut with the CNN at 83% probability and
1313 are 14% and 62% respectively. Although the CNN doesn't have separation between
1314 muons and pions and although all particles passing CNN are classified as muon,
1315 increasing CNN probability allows us to increase the purity as well as maintain an
1316 efficiency comparable to the 75 cm track length cut all while recovering events below
1317 that 75 cm cut. Out of the 6142 events that passed the CNN @ 83% 1470 events were
1318 below the 75 cm cut, a recovery of 3.3% of data with a purity of 15%. Although
1319 these numbers are low, it is an improvement from the selection I modified in both total
1320 efficiency and purity and an increase in phase space by recovering these events.

1321 **8.2 Classification using CNN100000**

1322 All future classifications will be done using Selection I Modified CC-Inclusive Filter
1323 because it has a higher efficiency and purity than Selection I Original CC-Inclusive
1324 Filter. To reiterate, CNN100000 was trained using 20,000 images of each $\mu/\pi/p/\gamma/e$.
1325 The results of using CNN100000 to classify BNB+Cosmics will be outlined below.

1326 **8.2.1 Classification of MC data using Selection I Modified 1327 CC-Inclusive Filter**

1328 **8.2.2 Classification of MicroBooNE data using Selection I Modified 1329 CC-Inclusive Filter**

1330 **8.2.3 Comparing two CC-Inclusive Cross Section Selection Filters**

¹³³¹ **Chapter 9**

¹³³² **Conclusion**

¹³³³ Your Conclusions here.

¹³³⁴

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