SciBooNE Charged-Current Coherent Pion Production Acceptance Study Technical Note

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1 Introduction

This document is intended to serve as a reference for the acceptance study performed for the SciBooNE charged current coherent pion production (CC-Coh $\pi^{+/-}$) re-analysis, as well as provide documentation of the code used in this study (in the event anything needs to be revisited in the future). The code resides in the github repository labeled as and linked here: SciBooNE-MC. The corresponding ROOT files that were used in this acceptance study can be downloaded from here: SciBooNE-MC-ROOTFiles.

The paper is structured such that Section 2 outlines Monte Carlo samples used in this study, Section 3 describes the SciBooNE detector as it was simulated in this study, Section 4 describes the various event samples that were used to both validate and generate the acceptance studies for the CC-Coh $\pi^{+/-}$ sample. Section 5 gives a high level summary of the results including the event-reduction tables as well as the CC-Coh $\pi^{+/-}$ acceptance results.

The appendix is left to explain how the code is run and the details of the scripts within. The appendix also details the order in which the macros should be run in, and the important plots that each macro produces that play a role in making the plots shown in Section 5 (the Results section).

1.1 Goal of the Re-Analysis

The goal of the re-analysis is to examine the acceptance modeling for the SciBooNE results in the presence of modern neutrino generators and updated models in order to hopefully shed light on why SciBooNE did not observe charged-current coherent pion production at low neutrino energy.

This study is intended to examine the effects of the acceptance modeling for a sample of coherent pion interactions inside the SciBooNE detector and compare what these would have been for various coherent pion production models. We utilize a simple, but robust, simulation of the SciBooNE detector and the NEUT neutrino generator to select and classify these neutrino events.

2 Samples

Five different samples were used in this study, three samples were generated in neutrino mode (ν-mode) and two samples in antineutrino mode ($\bar{\nu}$-mode.)[1] Table 2 summarizes these samples. Details on these samples can be found in the Appendix.

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[1]All of these samples were generated by Callum Wilkinson (Thanks, Callum!)

Summary of Samples

Mode	NEUT version	Pion-Model	Number of simulated events
ν	5.3.6	Rein-Sehgal	1,000,000
ν	5.3.6	Berger-Sehgal	1,000,000
ν	5.0.1	Rein-Sehgal	100,000
$\bar{\nu}$	5.3.6	Rein-Sehgal	1,000,000
$\bar{\nu}$	5.3.6	Berger-Sehgal	1,000,000

Table 2: Summary of the samples used to build the acceptance model for this study.

3 Detector Simulation

This section is intended to detail the detector simulation done in this acceptance model, and to describe the assumptions made in order to accomplish accurate classifications of simulated events as charged-current coherent pion production.

3.1 The Detector

For the purposes of this acceptance study, the SciBooNE experiment is composed of two sub-detectors. The first (and the more upstream) of the sub-detectors, is the Scintillator Bar Tracker (SciBar) which was originally conceived and constructed to function as the near detector for the K2K experiment. The second (and more downstream) of the sub-detectors, is the Muon Range Detector (MRD), which is the detector designed and constructed specifically for SciBooNE for measuring the momentum of muons produced from charged-current neutrino interactions up to 1.2 GeV/c by using the observed range of the trajectory of the muon. The coordinate system used throughout this study, and illustrated in Figure 3.1, puts the origin in the lower corner of the SciBar detector, has z along the beam direction, y opposite to gravity, and x to beam left.
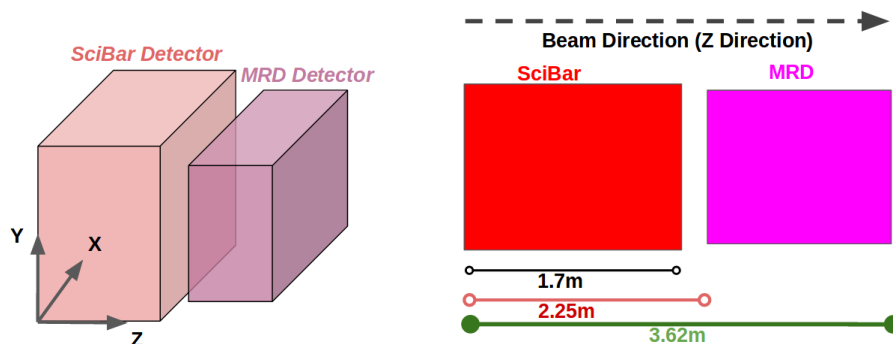
Figure 3.1: Representation of the SciBooNE detector and the coordinate frame we use in this study

3.1.1 The Scintillator Bar Tracker (SciBar)

The Scintillator Bar Tracker (SciBar) sub-detector is a scintillator detector which was used to identify neutrino interactions within SciBooNE. The dimensions of the SciBar detector used in this simulation are $0 < x < 3.0$ m, $0 < y < 3.0$ m, and $0 < z < 1.7$ m. This simulation models the scintillator materials as having a constant energy deposition per unit length (dE/dx) for both

muons and pions of 2.04 MeV/cm based on previous SciBooNE analyses and on mean values for typical particle momentum listed in the particle data group (PDG).

3.1.2 The Muon Range Detector (MRD)

The Muon Range Detector (MRD), depicted in Figure 3.1.2, is located 0.55 m downstream of SciBar in the z-direction, and is a composition of two sets of thirteen alternating slabs of steel-scintillator layers, where the scintillator layers alternate between being horizontally oriented or vertically oriented, in the xy-plane. The steel layers have a z-direction thickness of 5.08 cm and the scintillator layers have a z-direction thickness of 0.6 cm. Combining all the layers of the different alternating materials results in 26 scintillator layers that "sandwich" twenty five steel layers in-between and gives a total z-direction dimension of being $1.37m$. The xy-plane is modeled as a square again (as was the case with SciBar, too) with dimensions in the x-direction and the y-direction of 2.6 m. The energy deposition per unit length (dE/dx) of a muon penetrating the scintillator layers is assumed to be a constant 2.04 MeV/cm while the energy deposition for the muon in the steel layers is assumed to be a greater value of 11.43 MeV/cm. Both values are typical for muons at the energy range produced in SciBooNE and taken from the PDG.
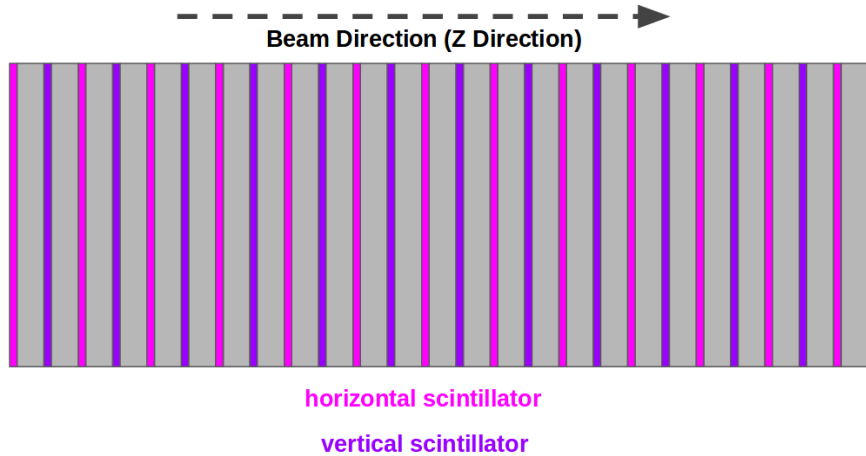
Figure 3.1.2: Depiction of the Muon Range Detector (MRD) which consists of alternating layers of horizontal scintillator (shown in pink) steel slabs (shown in grey) and vertical scintillator (shown in purple)

4 Event Selection

Two main samples are used in this study to generate the acceptance tables. The first is a charged current inclusive (CC-Inclusive) sample which requires a muon was created in the neutrino interaction and this muon intersects the MRD. This sample is described in Section 5.1 and is used to validate the building of the acceptance model by comparing it to previous SciBooNE analyses.

The second sample is the charged current coherent pion (CC-Coh $\pi^{+/-}$) sample which requires a muon and charged pion are created in the neutrino interaction exclusively (e.g. no other final state particles in the event). This sample is described in Section 5.2.

Both of these samples are selected using NEUT MC-truth flags which ensure we are treating pure samples which are classified by the neutrino generator as belonging to the appropriate sample.

Whether or not the event identified by our selection makes it into the final sample used in the acceptance study depends on the behavior of the muon with respect to the MRD. A muon which enters the MRD from a neutrino interaction will either come to stop in the MRD, exit out the back of the MRD (assuming it's momentum is great enough), or exit out the side of the MRD. In the next sections we explain this classification further.

4.1 Muon Stops within the MRD ("Stopped")

The requirement to classify a neutrino interaction as a "stopped" event requires the muon from the interaction to have reached the MRD, penetrated at least three layers of steel (giving activity in three layers of scintillator), and to then deposit all of its remaining energy prior to reaching a boundary of the MRD. An illustration of a CC-Coh $\pi^{+/-}$ event which would be classified as "stopped" is shown in Figure 4.1.
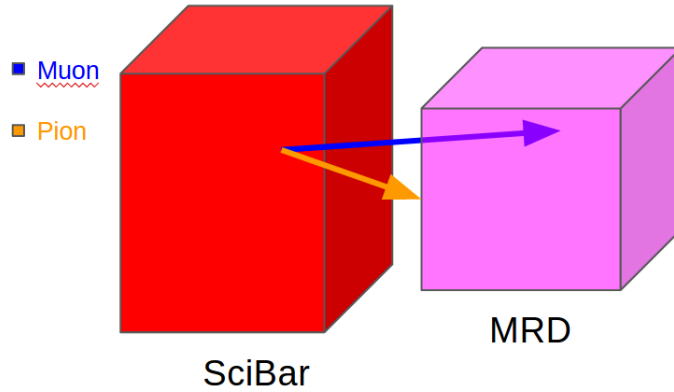
Figure 4.1: Depiction of an event that was classified as "Stopped."

These events allow for complete reconstruction of the muon's momentum based on the number of layers which the muon penetrated and the muons incident angle.

4.2 Muon exits out the back of the MRD ("Out-the-back")

The classification of a neutrino interaction as "out-the-back" requires that the muon from the interaction to have reached the MRD and to have had sufficient energy to have exited out the back face of the MRD without stopping. An illustration of such an event is given in Figure 4.2.

Figure 4.2: Depiction of an event that was classified as "out-the-back".

The exact momentum of muons which pass completely through the MRD could not be made in reconstruction, so these events were classified as having the minimum energy required to penetrate all the steel and scintillator layers of the MRD.

4.3 Muon exits out the side of the MRD ("Out-the-side")

The classification of a neutrino interaction as "out-the-side" requires that the muon from the interaction reached the MRD, penetrated at least three layers of steel, and then to have exited out the side of the active volume of the MRD (excluding the very back face). Events which are classified as "out-the-side" are excluded from this study because no accurate reconstruction of the muons momentum can be made when the muon exits out the side of the MRD. An illustration of such an excluded event which exits out the side of the MRD is given in Figure 4.3.
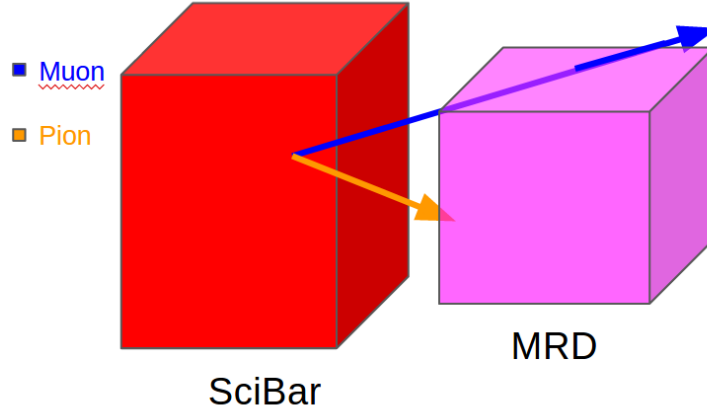
Figure 4.3: Depiction of an event that was classified as "Out-Side."

5 Results

The results of this acceptance study can be broken down into two different classification schemes of events. Those that met the conditions to qualify as CC-Inclusive events, and those that met the

conditions of classification as Charged-Current Coherent Pion events. The former is used to validate the acceptance modeling and detector simulation to reasonably reproduce previously published CC-Inclusive studies from SciBooNE, while the latter is used for the reanalysis.

5.1 Charged-Current Inclusive Events

Here we define the charged current inclusive sample (CC-Inclusive) which we use to validate our acceptance model against previously performed simulation studies.

5.1.1 ν-mode Charged-Current Inclusive Events

Table 5.1.1 goes through the event selection criteria for selecting a sample of CC-Inclusive events from the neutrino mode (ν-mode) Monte Carlo.

<div align="center">

ν-mode CC-Inclusive Event Reduction

Events Selection	NEUT v5.3.6 Rein-Sehgal	NEUT v5.3.6 Berger-Sehgal	NEUT v5.0.1 Rein-Sehgal
Total Sample	1,000,000	1,000,000	100,000
CC-Inclusive Interaction (μ + n-other particles in SciBar)	725,730	727,278	69,363
Muon enters the MRD	263,698	262,608	24,250
Muon enters the MRD and penetrates $\geq$ 3 layers of steel	231,089	230,054	21,001
"Stopped"-Events	177,406	175,799	16,062
"Out-the-back"-Events	15,389	15,952	1,421
"Out-the-side"-Events	38,294	38,303	3,518
Good CC-Inclusive Events	**192,795**	**191,751**	**17,483**

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Table 5.1.1: Event reduction table for a sample of ν-mode CC-Inclusive events simulated in the SciBooNE geometry.

Figure 5.1.1 shows the momentum and angular (θ) distribution for the sample of ν-mode CC-Inclusive events passing all our requirements for all three models considered in this study (NEUT v5.3.6 Rein-Sehgal, NEUT v5.3.6 Berger-Sehgal, NEUT v5.0.1 Rein-Sehgal). The distributions have been normalized to the same area and show no strong differences between them.
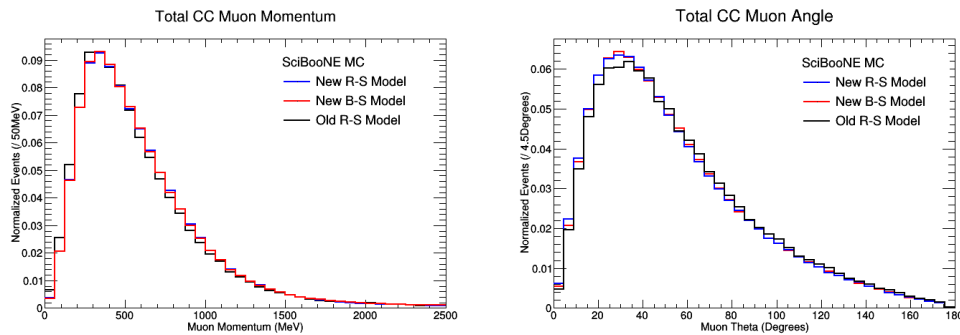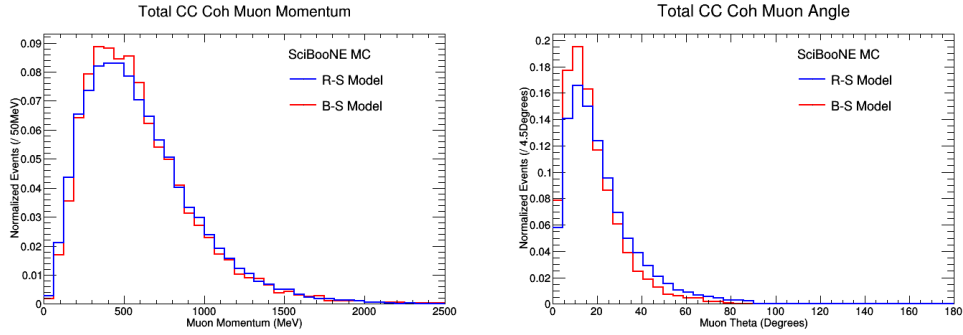

Figure 5.1.1: Muon Momentum (left) and Muon Angle (right) for ν-mode CC-Inclusive interactions for all three models included in this study. These samples kinematics are, unsurprisingly, very similar for the sample of CC-Inclusive

Figure 5.1.1 represents the one-dimensional efficiency for selecting ν-mode CC-Inclusive events for this study using all three different models compared to results derived from Hiraide's thesis [2] using the full SciBooNE Monte Carlo simulation. A few reference points are illustrated using dashed lines to guide the readers eye. A few perecent difference is seen, but overall agreement between the two simulations hold.
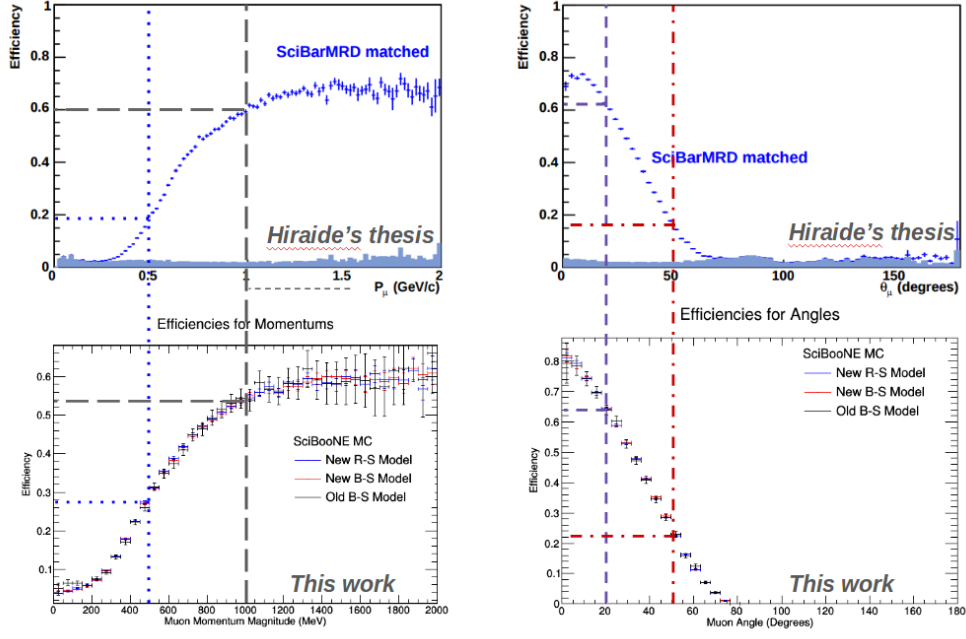
Figure 5.1.1: One-dimension efficiency plots for the ν-mode CC-Inclusive sample.

Figure 5.1.2 shows the two-dimensional efficiency for selecting ν-mode CC-Inclusive events. The left hand side is a reference plot provided by Morgan and the right hand side is for the Rein-Sehgal MC used in this study.
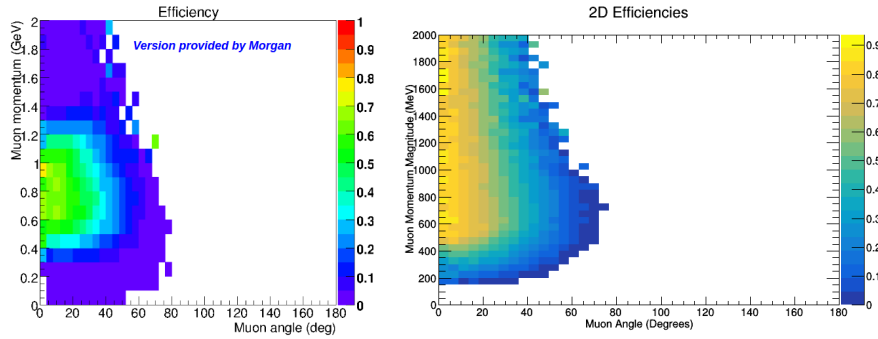
Figure 5.1.2: Two-dimensional efficiency plots for the ν-mode Rein-Sehgal CC-Inclusive sample.

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[2]Hiraide's thesis can be found here: http://www-he.scphys.kyoto-u.ac.jp/theses/doctor/hiraide_dt.pdf
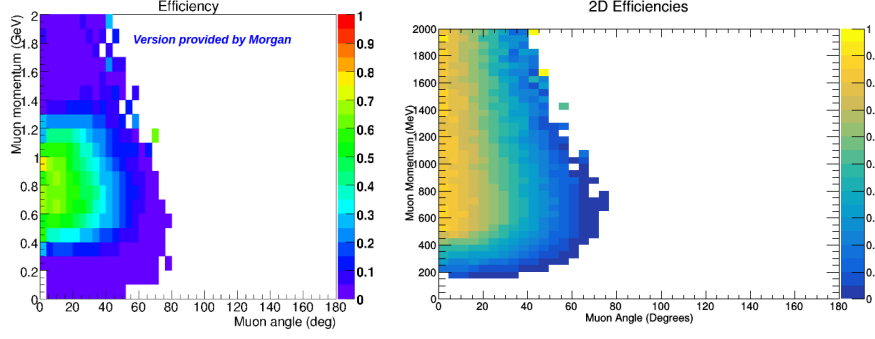
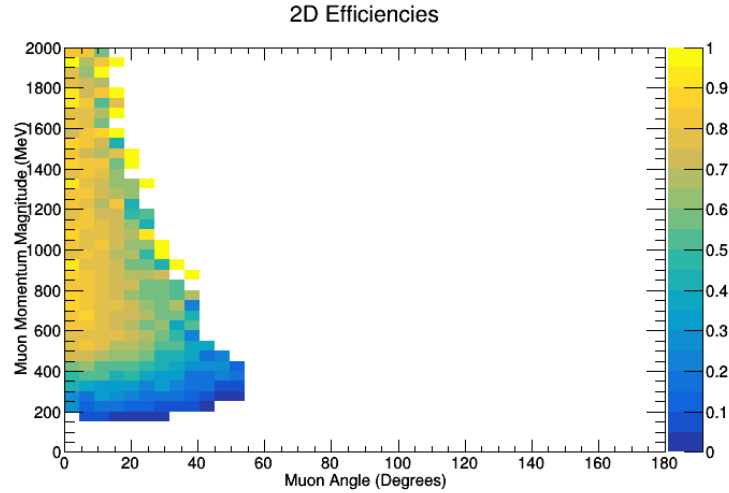Figure 5.1.2: Two-dimensional efficiency plots for the ν-mode Berger-Sehgal CC-Inclusive sample.
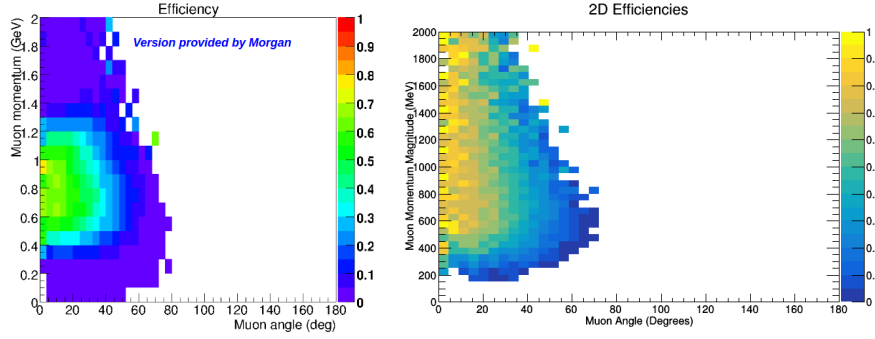
Figure 5.1.1: Two-dimensional efficiency plots for the ν-mode Old Rein-Sehgal CC-Inclusive sample.

5.1.2 $\bar{\nu}$-mode Charged-Current Inclusive Events

Similar to before, Table 5.1.2 goes through the event selection criteria for selecting a sample of CC-Inclusive events from the antineutrino mode ($\bar{\nu}$-mode) Monte Carlo.

$\bar{\nu}$-mode CC-Inclusive Event Reduction

Events Selection	NEUT v5.3.6 Rein-Sehgal	NEUT v5.3.6 Berger-Sehgal
Total Sample	1,000,000	1,000,000
CC-Inclusive Interaction (μ + n-other particles in SciBar)	699,239	704,327
Muon enters the MRD	380,362	380,869
Muon enters the MRD and penetrates $\geq$ 3 layers of steel	336,373	337,979
"Stopped"-Events	288,289	288,206
"Out-the-back"-Events	7,608	7,857
"Out-the-side"-Events	40,476	41,916
Good CC-Inclusive Events	**295,897**	**296,063**

Table 5.1.2: Event reduction table for a sample of $\bar{\nu}$-mode CC-Inclusive evnets simulated in the SciBooNE geometry.

Figure 5.1.1 shows the momentum and angular distribution for the sample of $\bar{\nu}$-mode CC-Inclusive events passing all our requirements for both models considered in this study (NEUT v5.3.6 Rein-Sehgal, and NEUT v5.3.6 Berger-Sehgal). The distributions have been normalized to the same area and show no strong differences between them.
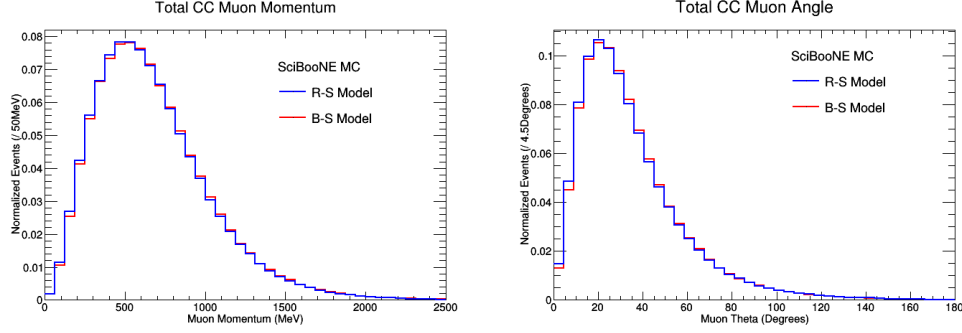
Figure 5.1.2: Muon Momentum (left) and Muon Angle (right) for $\bar{\nu}$-mode CC-Inclusive interactions for all three models included in this study. These samples kinematics are, unsurprisingly, very similar for the sample of CC-Inclusive

Figure 5.1.2 represents the one-dimensional efficiency for selecting $\bar{\nu}$-mode CC-Inclusive events for this study. No similar reference sample exists to be compared directly against, however we note that the shape and magnitude of the acceptance is nearly unchanged between $\bar{\nu}$ and ν-mode samples (as expected).
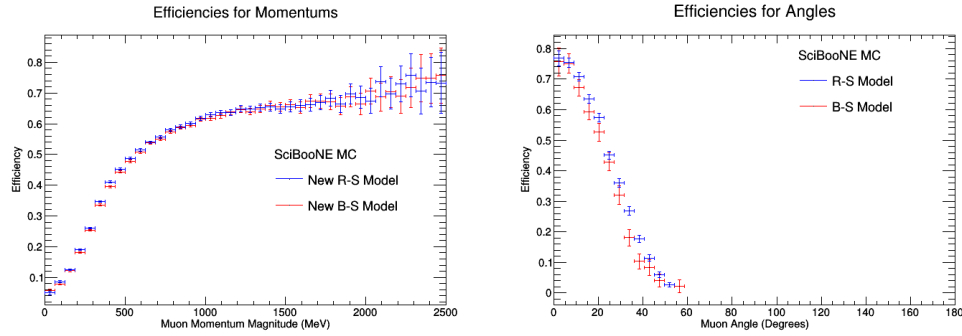
Figure 5.1.2: One-dimension efficiency plots for the $\bar{\nu}$-mode CC-Inclusive sample. Muon's Momentums is on the right and the Muon's Angles is on the left.

Figure 5.1.2 shows the two-dimensional efficiency for selecting $\bar{\nu}$-mode CC-Inclusive events for this study compared to results derived from Morgan's reference sample (need more words here about this....see email)
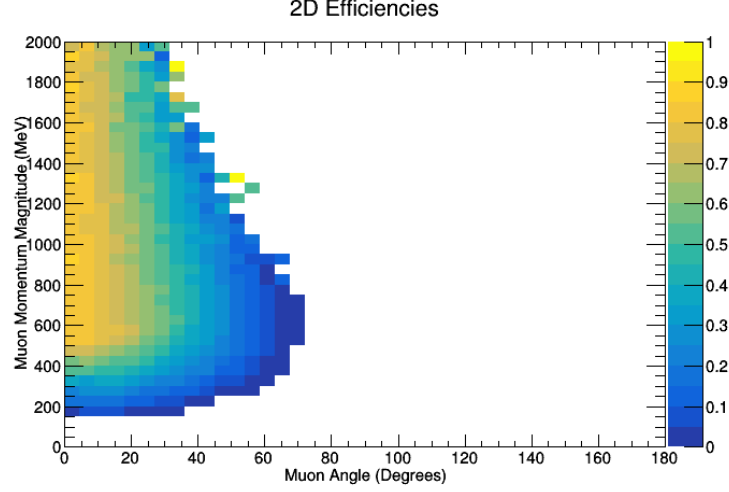
Figure 5.1.2: Two-dimensional efficiency plot for the $\bar{\nu}$-mode Rein-Sehgal CC-Inclusive sample.
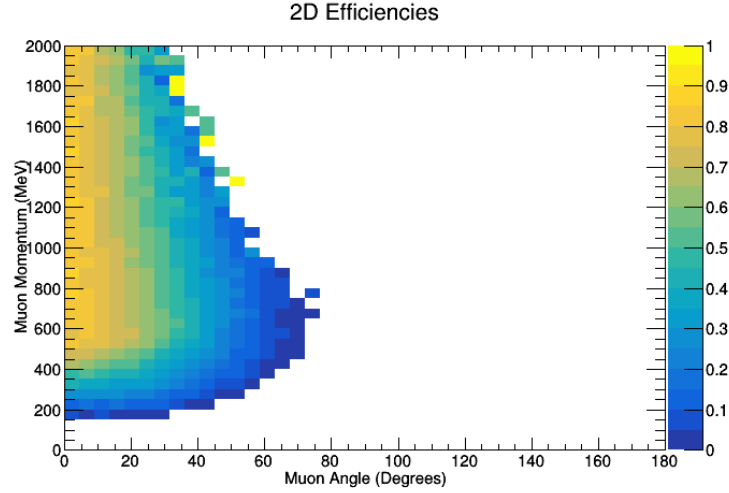
Figure 5.1.2: Two-dimensional efficiency plot for the $\bar{\nu}$-mode Berger-Sehgal CC-Inclusive sample.

5.2 Charged-Current Coherent Pion Production Events

Here we define the Charged-Current Coherent Pion Production sample (CC-Coh $\pi^{+/-}$) which we use to validate our acceptance model against previous simulation studies which were done.

5.2.1 ν-mode Charged-Current Coherent Pion Events

Table 5.2.1 goes through the event selection criteria for selecting a sample of CC-Coh $\pi^{+/-}$ events from the neutrino mode (ν-mode) Monte Carlo.

The first quantity that is calculated for the different events is the momentum of both the muon and the pion, which are both found from the equations:

ν-mode CC-Coherent Pion Event Reduction

Events Selection	NEUT v5.3.6 Rein-Sehgal	NEUT v5.3.6 Berger-Sehgal	NEUT v5.0.1 Rein-Sehgal
Total Sample	1,000,000	1,000,000	100,000
CC-Coherent Pion Interaction ($\mu + \pi + \varnothing$ in SciBar)	12,186	2,576	1,320
Both muon and pion are forward going	8,535	1,845	884
Muon enters the MRD and penetrates $\geq$ 3 layers of steel	7,407	1,592	767
"Stopped"-Events	6,448	1,350	669
"Out-the-back"-Events	530	150	56
"Out-the-side"-Events	429	92	42
Good Coherent Pion Events	**6,978**	**1,500**	**725**

Table 1: Event reduction table for a sample of ν-mode Charged Current Coherent Pion events simulated in the SciBooNE geometry.

$$|\vec{p}_\mu| = \sqrt{P_{\mu_x}^2 + P_{\mu_y}^2 + P_{\mu_z}^2} \tag{1}$$

$$|\vec{p}_\pi| = \sqrt{P_{\pi_x}^2 + P_{\pi_y}^2 + P_{\pi_z}^2} \tag{2}$$

where $|\vec{p}_\mu|$ represents the magnitude of the momentum for the corresponding particle, and P_{μ_x} represents the component of the four momentum for the corresponding particle. The momentum is reported in units of MeV/c.

The next quantity calculated is the angle from the beam-direction for both the muon and the pion, which are labeled as either θ_μ, or θ_π, respectively. The angle from the beam-direction is the same as the angle from the z-direction, and this angle is known as the azimuthal angle. The calculation of the azimuthal angle is slightly more involved than the simple calculation used for finding the magnitude of the momentum of the two particles, and is calculated using the equations:

$$\theta_\mu = tan^{-1}\left(\frac{\sqrt{P_{\mu_x}^2 + P_{\mu_y}^2}}{P_{\mu_z}}\right) \tag{3}$$

$$\theta_\pi = tan^{-1}\left(\frac{\sqrt{P_{\pi_x}^2 + P_{\pi_y}^2}}{P_{\pi_z}}\right) \tag{4}$$

The angles are reported in units of °, and should run from 0° to 180°. In the case of charged-current coherent pion production, the angle should never be larger than 90°.
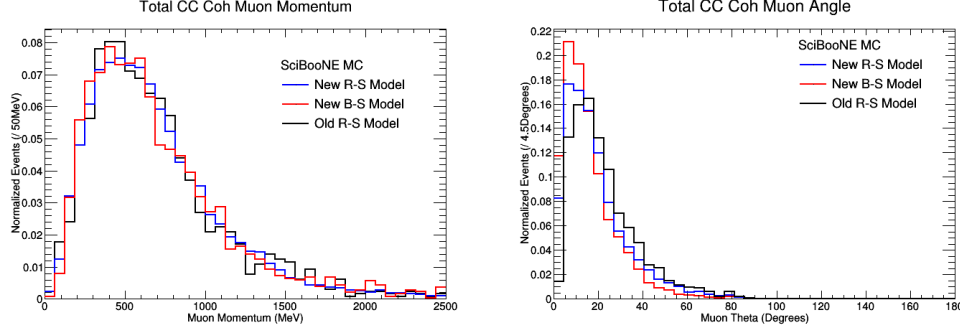
Figure 1: Muon Momentum for all of the muons of the events that made it to the MRD and penetrated at least three layers (left) and Muon Angle for the muons of the events that made it to the MRD and penetrated at least three layers (right) for ν-mode CC-Coh $\pi^{+/-}$ interactions for all three models included in this study. The "Total" classification means that all CC-Coh $\pi^{+/-}$ events are included in these histograms.

Here will be the plots for CC-Coh Pion with the good momentum efficiencies and the angle efficiencies!
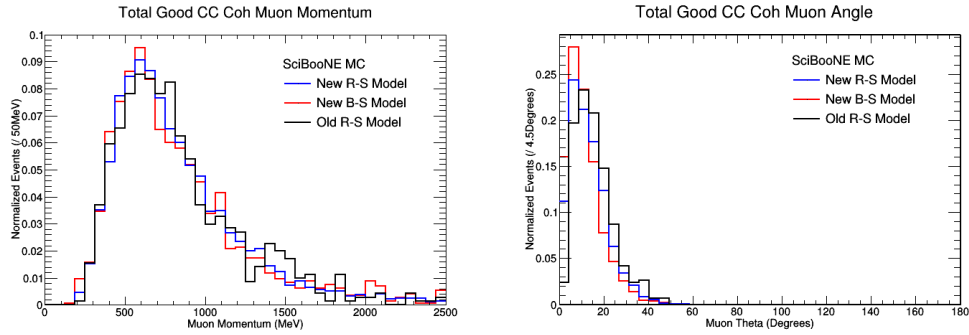
Figure 2: Muon Momentum of both the "stopped" and "not-stopped" samples (left) and Muon Angle of both the "stopped" and "not-stopped" samples (right) for ν-mode CC-Coh $\pi^{+/-}$ interactions for all three models included in this study. The "Good" classification means that only the stopped and not-stopped CC-Coh $\pi^{+/-}$ events are included for these histograms.

The last two quantities that are calculated are the two different types of four-momentum transfers specific to this interaction, which are Q^2 and $|t|$. The Q^2 corresponds to the four-momentum transfer from the neutrino and muon to the nucleus and pion, and is calculated using the equation:

$$Q^2 = |(P_{\nu_\mu} - P_\mu)^2| \tag{5}$$

This equation is the four-momentum notational form. The code follows the equation below in order to compute Q^2:

$$Q^2 = |(P_{\nu_{\mu,x}} - P_{\mu_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E})^2| \tag{6}$$

Q^2 is reported in units of $(MeV/c)^2$.

The $|t|$ corresponds to the four-momentum transfer from the neutrino, muon, and pion to the nucleus, and is calculated using the equation:

$$|t| = |(Q - P_\pi)^2| = |(P_{\nu_\mu} - P_\mu - P_\pi)^2| \tag{7}$$

This equation is the four-momentum notational form. The code follows the equation below in order to compute $|t|$:

$$|t| = |(P_{\nu_{\mu,x}} - P_{\mu_x} - P_{\pi_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y} - P_{\pi_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z} - P_{\pi_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E} - P_{\pi_E})^2| \tag{8}$$

$|t|$ is reported in units of $(MeV/c)^2$.

ν-Mode $|t|$ and Q^2 plots are below:
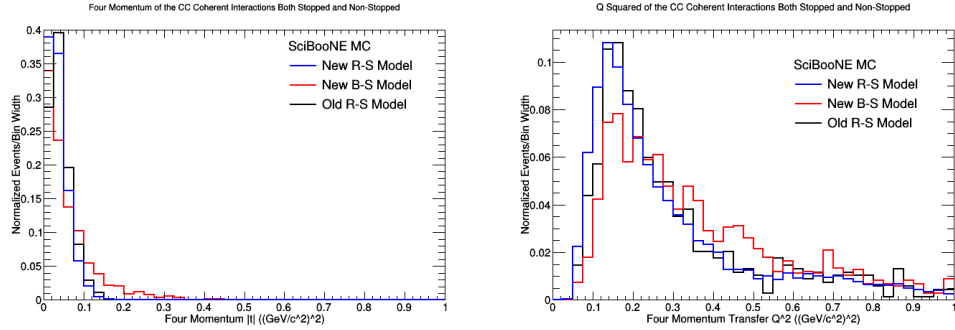
Figure 3: The $|t|$ Momentum Transfer for the "stopped" and "not-stopped" events (left) and Q^2 Momentum Transfer for the "stopped" and "not-stopped" events (right) for ν-mode CC-Coh $\pi^{+/-}$ interactions for the three models included in this study.
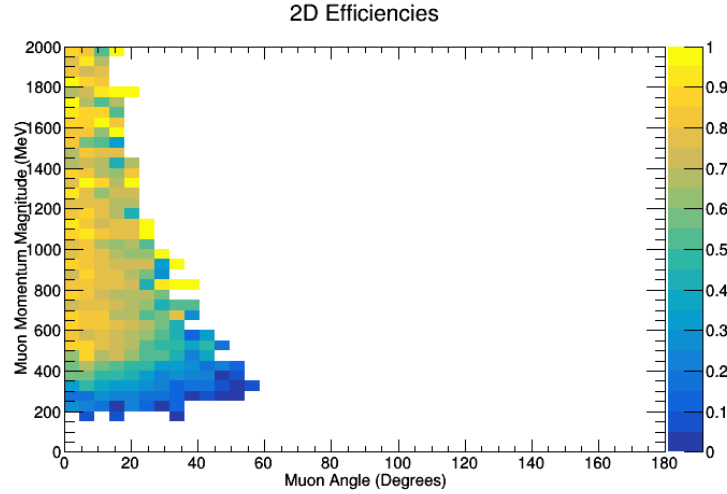
Figure 5.2.1: Two-dimensional efficiency plot for the new NEUT ν-mode Rein-Sehgal CC-Coherent sample.

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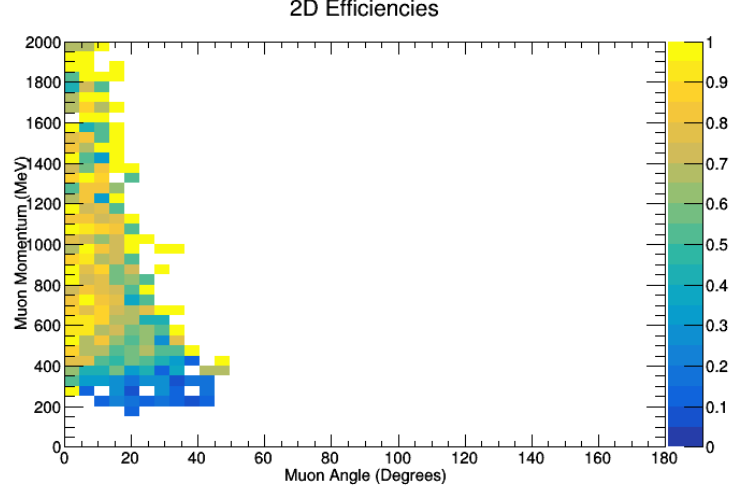
Figure 5.2.1: Two-dimensional efficiency plot for the new NEUT ν-mode Berger-Sehgal CC-Coherent sample.
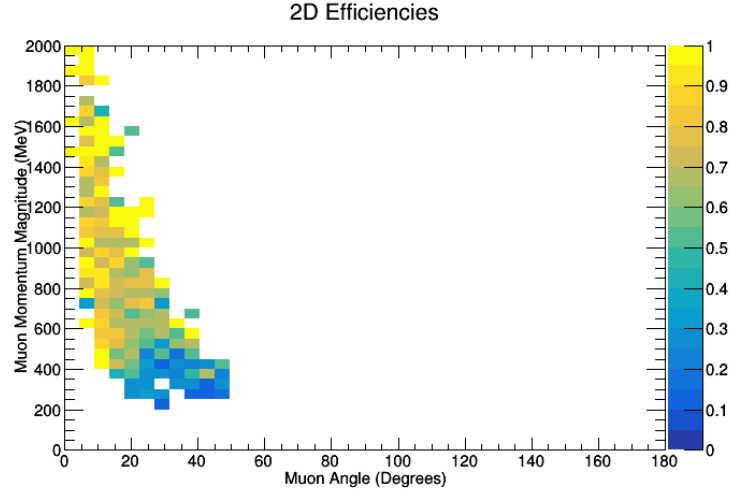
Figure 5.2.1: Two-dimensional efficiency plot for the old NEUT ν-mode Rein-Sehgal CC-Coherent sample.

5.2.2 $\bar{\nu}$-mode Charged-Current Coherent Pion Events

Similar to before, Table 5.2.2 goes through the event selection criteria for selecting a sample of CC-Coh $\pi^{+/-}$ events from the anti-neutrino mode ($\bar{\nu}$-mode) Monte Carlo.

Below are the plots for CC-Coh $\pi^{+/-}$ Events for $\bar{\nu}$-mode. The layout of the rest will be very similar to ν-mode, and the equations used previously are the same equations used for the plots below.

$\bar{\nu}$-mode CC-Coherent Pion Event Reduction

Events Selection	NEUT v5.3.6 Rein-Sehgal	NEUT v5.3.6 Berger-Sehgal
Total Sample	1,000,000	1,000,000
CC-Coherent Pion Interaction ($\mu + \pi + \varnothing$ in SciBar)	36,669	7,790
Both muon and pion are forward going	24,675	5,477
Muon enters the MRD and penetrates ≥ 3 layers of steel	20,445	4,517
"Stopped"-Events	18,935	4,203
"Out-the-back"-Events	372	82
"Out-the-side"-Events	1,138	232
Good Coherent Pion Events	**19,307**	**4,285**

Table 2: Event reduction table for a sample of $\bar{\nu}$-mode Charged Current Coherent Pion events simulated in the SciBooNE geometry.

Figure 4: Muon Momentum (left) and Muon Angle (right) for ν-mode CC-Coh $\pi^{+/-}$ interactions for all three models included in this study.

The structure of the plots in Figure: 5.2.2 very closely resembles the plots for the ν-mode above, and the rest of the plots in this section have that same characteristic.
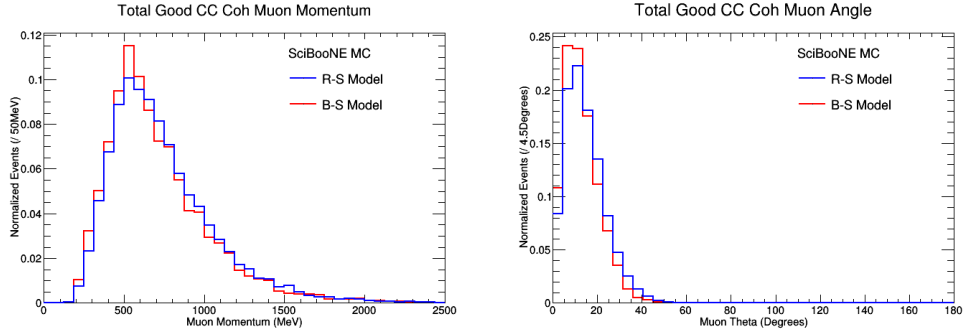
Figure 5: Muon Momentum (left) and Muon Angle (right) for $\bar{\nu}$-mode CC-Coh $\pi^{+/-}$ interactions for both the "stopped" and "not-stopped" samples of events.

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$\bar{\nu}$-mode $|t|$ and Q^2 plots are below. They also have the same overall shape as the plots for ν-mode above.
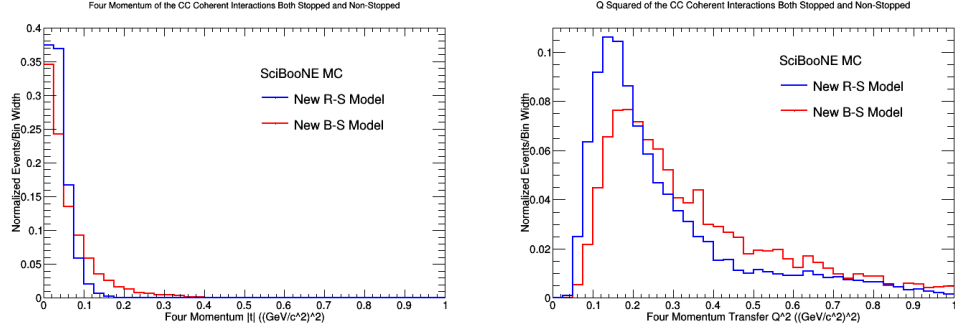
Figure 6: The $|t|$ Momentum Transfer (left) and Q^2 Momentum Transfer (right) for $\bar{\nu}$-mode CC-Coh $\pi^{+/-}$ interactions for both of the models included in this study which are the "stopped" and "not-stopped" events.

Figure 5.2.2: Two-dimensional efficiency plot for the new NEUT $\bar{\nu}$-mode Rein-Sehgal CC-Coherent sample.
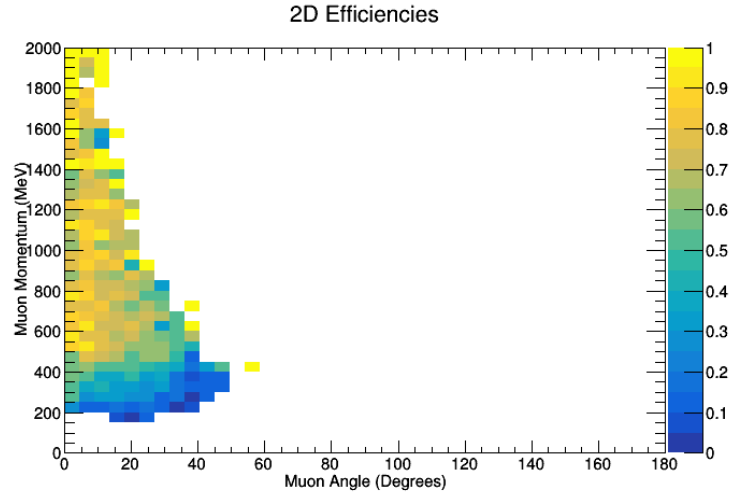
Figure 5.2.2: Two-dimensional efficiency plot for the new NEUT $\bar{\nu}$-mode Berger-Sehgal CC-Coherent sample.

A   Appendix: Sample Details

Appendix on samples

A.1 ν-Mode Rein-Sehgal NEUTv5.3.6

A sample of 1,000,000 ν interactions were simulated using the NEUT generator (v5.3.6) and the Rein-Sehgal model for coherent pion production. This sample correspond to the file labeled

`SciBooNE_numu_coh_RooTrack.root`

found at the following link (put link to sample here).

A.2 ν-Mode Berger-Sehgal NEUTv5.3.6

A sample of 1,000,000 ν interactions were simulated using the NEUT generator (v5.3.6) and the Berger-Sehgal model for coherent pion production. This sample correspond to the file labeled

`SciBooNE_numu_coh_RooTrack_NEW.root`

found at the following link (put link to sample here).

A.3 ν-Mode Rein-Sehgal NEUTv5.0.1

A sample of 100,000 ν interactions were simulated using the NEUT generator (v5.0.1, believed to be the version used by the SciBooNE collaboration in the original publication) and the corresponding older Rein-Sehgal model for coherent pion production. This sample corresponds to the file labeled

`SciBooNE_numu_coh_OLDNEUT_RooTrack.root`

found at the following link (put link to sample here).

A.4 $\bar{\nu}$-Mode Rein-Sehgal NEUTv5.3.6

A sample of 1,000,000 $\bar{\nu}$ interactions were simulated using the NEUT generator (v5.3.6) and the Rein-Sehgal model for coherent pion production. This sample corresponds to the file labeled

`SciBooNE_numubar_coh_RooTrack.root`

found at the following link (put link to sample here).

A.5 $\bar{\nu}$-Mode Berger-Sehgal NEUTv5.3.6

A sample of 1,000,000 $\bar{\nu}$ interactions were simulated using the NEUT generator (v5.3.6) and the Berger-Sehgal model for coherent pion production. This sample corresponds to the file labeled

`SciBooNE_numubar_coh_RooTrack_NEW.root`

found at the following link (put link to sample here).

A.6   Vertex Distributions

The events were all given a random initial point that was generated with the goal that the vertex distributions of this simulation would closely match the vertex distributions that Hiraide [3] showed in his thesis. This was done by... etc.

```
TRandom3 *randX = new TRandom3();
TRandom3 *randY = new TRandom3();
TRandom3 *flat = new TRandom3();
randX->SetSeed(jentry/2);
randY->SetSeed(jentry*jentry);
flat->SetSeed(jentry*jentry*jentry);
double Xpos = randX->Gaus(1.5,1.3);
while (Xpos<0 || Xpos>3.0) { Xpos = randX->Gaus(1.5,1.3); }
double Ypos = randY->Gaus(1.5,1.05);
while (Ypos<0 || Ypos>3.0) { Ypos = randY->Gaus(1.5,1.05); }
double Zpos = flat->Uniform(0,1.7);
```
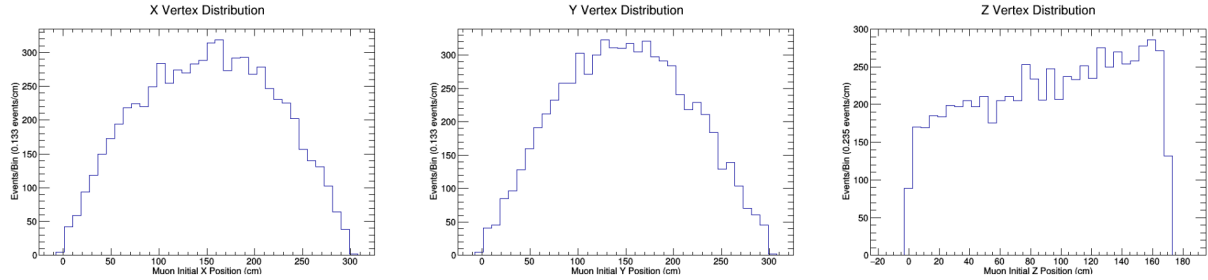

Figure 7: Vertex distributions of the events in the new Rein-Sehgal sample in ν-mode.

A.7   NewNMReinSehgal.C

This file is the macro that corresponds to the "NewNMReinSehgal.h" file, which connects with this file: "SciBooNE_numu_coh_RooTrack.root". This file performs the main analysis for this generated sample, and then organizes the information into many different histograms. The histograms are then written to a file titled "totalmuoninfoRS.root" inside the "ROOTFILES" directory. The "ROOTFILES" directory is included in the SciBooNE-MC repository (it is absolutely pertinent that this directory be located where the macro files are located due to how the calls of the combined data macros reference the now saved histograms). When this macro is run (which can take a while), it also plots a few different histograms. The histograms that are plotted are the ones shown in the figures below with descriptions included with the corresponding figures. The order that the histograms appear in this paper is the same order they will be shown when this macro is run in root.

---

[3]Hiraide's thesis can be found here: http://www-he.scphys.kyoto-u.ac.jp/theses/doctor/hiraide_dt.pdf
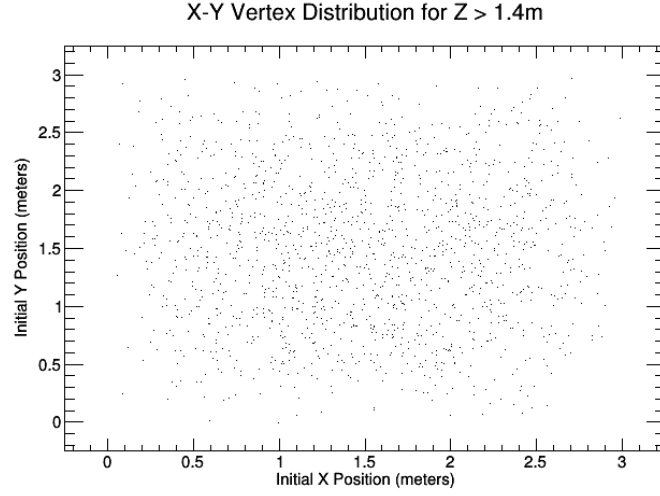
Figure 8: New ν-Mode Rein-Sehgal X-Y vertex distributions for muons that made it to the MRD and penetrated at least to the third layer of steel.
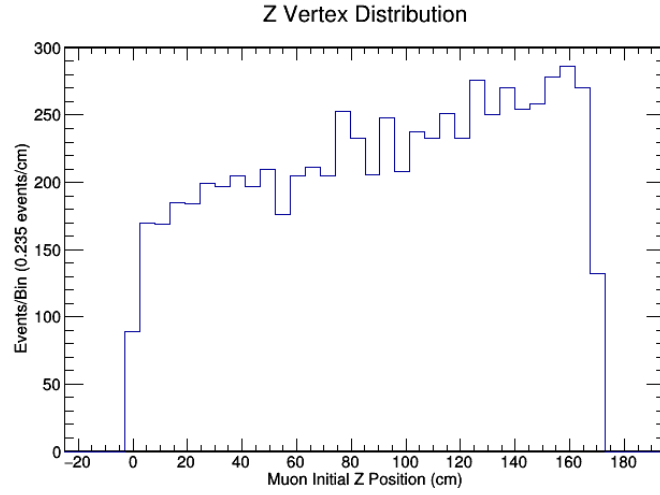
Figure 9: New ν-Mode Rein-Sehgal Z vertex distributions for the interactions.
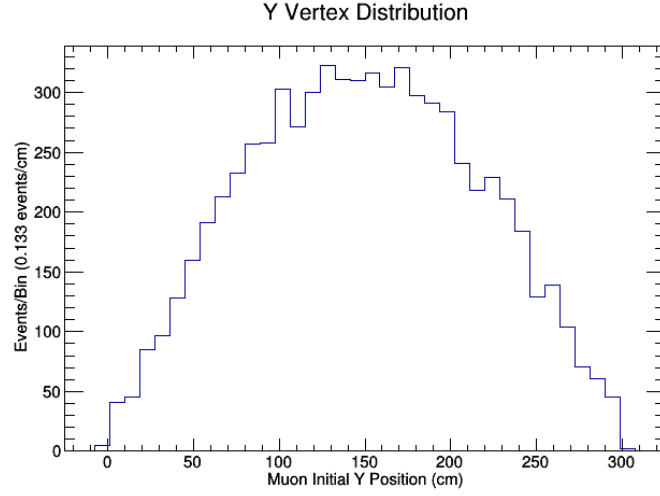
Figure 10: New ν-Mode Rein-Sehgal Y vertex distributions for the interactions.
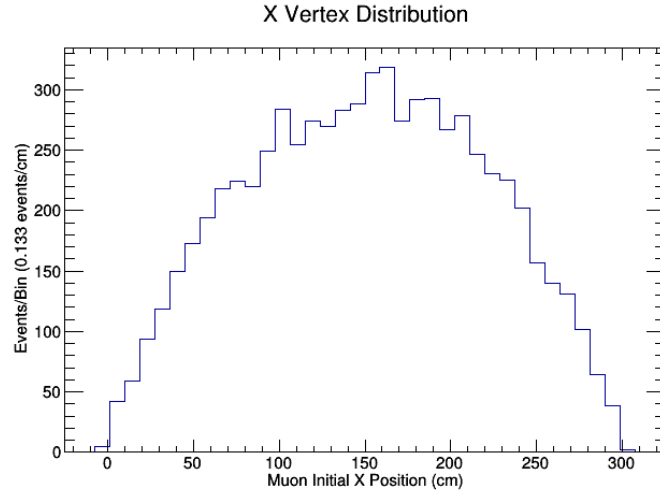
Figure 11: New ν-Mode Rein-Sehgal X vertex distributions for the interactions.
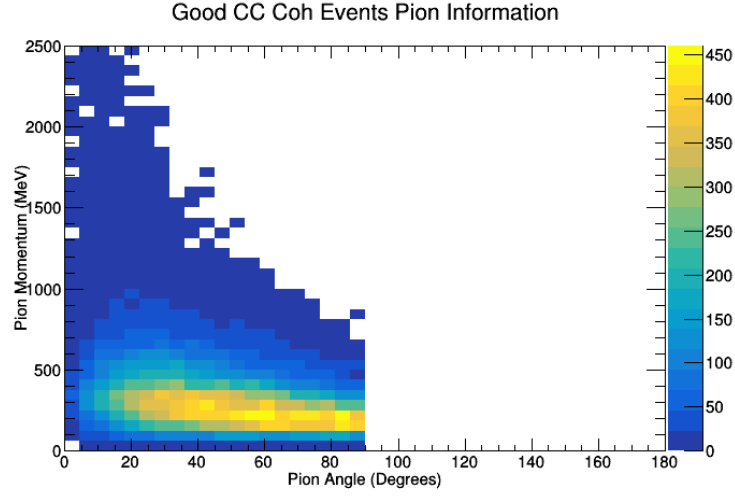
Figure 12: This is a 2D histogram for the momentum and angle of the pion in the CC Coh Pion events that met the qualification of being "good".
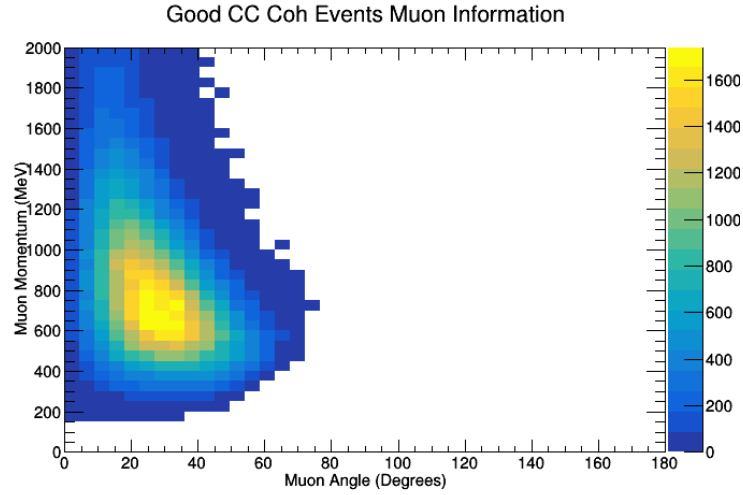
Figure 13: This is a 2D histogram for the momentum and angle of the muon in the CC Coh Pion events that met the qualification of being "good".
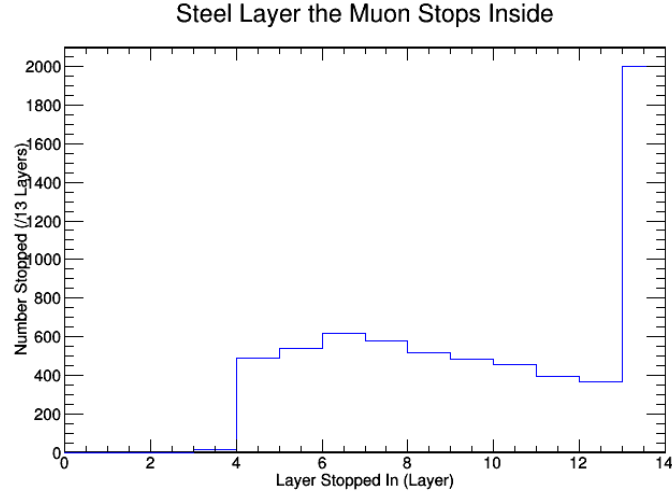
Figure 14: This histogram shows the amount of muons that embedded (or "Stopped") in a corresponding layer of steel in our simulation.
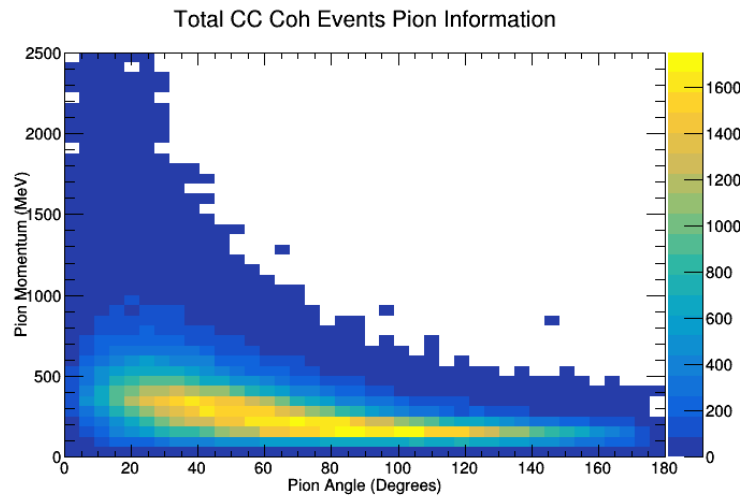
Figure 15: This is a 2D histogram for the momentum and angle of the pion in the total CC Coh Pion events.
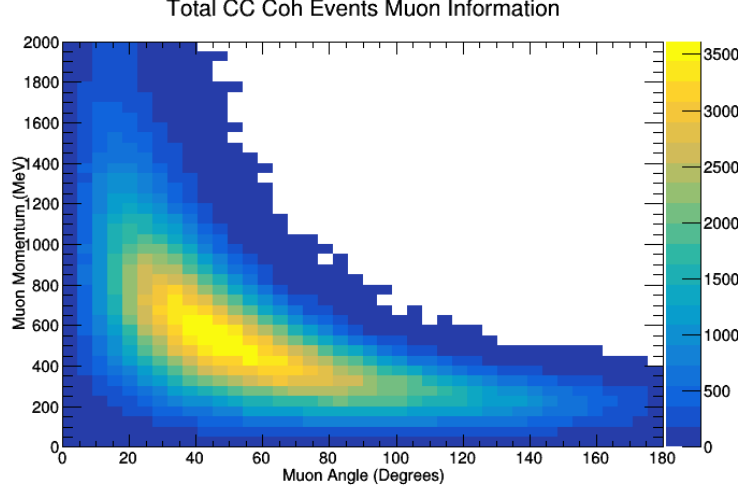
Figure 16: This is a 2D histogram for the momentum and angle of the muon in the total CC Coh Pion events.

The NewNMReinSehgal.C macro also calculates many different quantities for the generated simulation of the events and saves the information in histograms that are later called upon through the plotting macros (which are after all of the analysis macros). The first quantity that is calculated for the different vertexes is the momentum of both the muon and the pion, which are both calculated using the equations:

$$|\vec{p}_\mu| = \sqrt{P_{\mu_x}^2 + P_{\mu_y}^2 + P_{\mu_z}^2} \tag{9}$$

$$|\vec{p}_\pi| = \sqrt{P_{\pi_x}^2 + P_{\pi_y}^2 + P_{\pi_z}^2} \tag{10}$$

The momentum is reported in units of MeV/c.

The next quantity that is calculated in the macro is the angle from the beam-direction for both the muon and the pion, which are labeled as either θ_μ, or θ_π, respectively. The angle from the beam-direction is the same as the angle from the z-direction, and this angle is known as the azimuthal angle. The calculation of the azimuthal angle is slightly more involved than the simple calculation used for finding the magnitude of the momentum of the two particles, and is calculated using the equations:

$$\theta_\mu = tan^{-1}(\sqrt{P_{\mu_x}^2 + P_{\mu_y}^2}/P_{\mu_z}) \tag{11}$$

$$\theta_\pi = tan^{-1}(\sqrt{P_{\pi_x}^2 + P_{\pi_y}^2}/P_{\pi_z}) \tag{12}$$

The angles are reported in units of °, and should run from 0° to 180°. In the case of Charged-Current Coherent Pion Production, the angle should never be larger than 90°.

The last two quantities that this analysis macro calculates are the two different types of four-momentum transfers specific to this interaction, which are Q^2 and $|t|$. The Q^2 corresponds to the four-momentum transfer from the neutrino and muon to the nucleus and pion, and is calculated using the equation:

$$Q^2 = |(P_{\nu_\mu} - P_\mu)^2| \tag{13}$$

This equation is the four-momentum notational form. The code follows the equation below in order to compute Q^2:

$$Q^2 = |(P_{\nu_{\mu,x}} - P_{\mu_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E})^2| \qquad (14)$$

Q^2 is reported in units of $(MeV/c)^2$.

The $|t|$ corresponds to the four-momentum transfer from the neutrino, muon, and pion to the nucleus, and is calculated using the equation:

$$|t| = |(Q - P_\pi)^2| = |(P_{\nu_\mu} - P_\mu - P_\pi)^2| \qquad (15)$$

This equation is the four-momentum notational form. The code follows the equation below in order to compute $|t|$:

$$|t| = |(P_{\nu_{\mu,x}} - P_{\mu_x} - P_{\pi_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y} - P_{\pi_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z} - P_{\pi_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E} - P_{\pi_E})^2| \quad (16)$$

$|t|$ is reported in units of $(MeV/c)^2$.

A.8   NewNMBergerSehgal.C

This file is the macro that corresponds to the "NewNMBergerSehgal.h" file, which connects with this file: "SciBooNE_numu_coh_RooTrack_NEW.root". This file performs the main analysis for this generated sample, and then organizes the information into many different histograms. The histograms are then written to a file titled "totalmuoninfoBS.root" inside the "ROOTFILES" directory. The "ROOTFILES" directory is included in the SciBooNE-MC repository (it is absolutely pertinent that this directory be located where the macro files are located due to how the calls of the combined data macros reference the now saved histograms).

Figure 17: New ν-Mode Berger-Sehgal X-Y vertex distributions for muons that made it to the MRD and penetrated at least to the third layer of steel.

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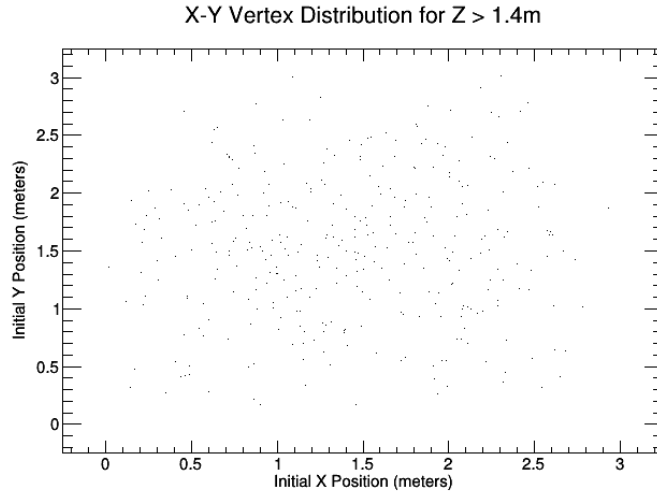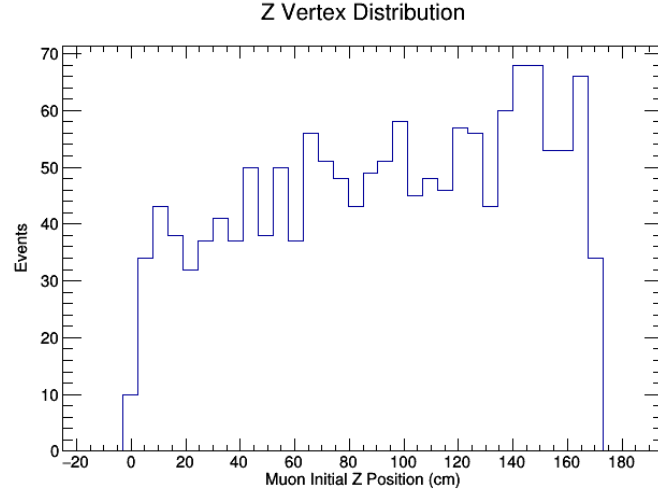
Figure 18: New ν-Mode Berger-Sehgal Z vertex distributions for the interactions.
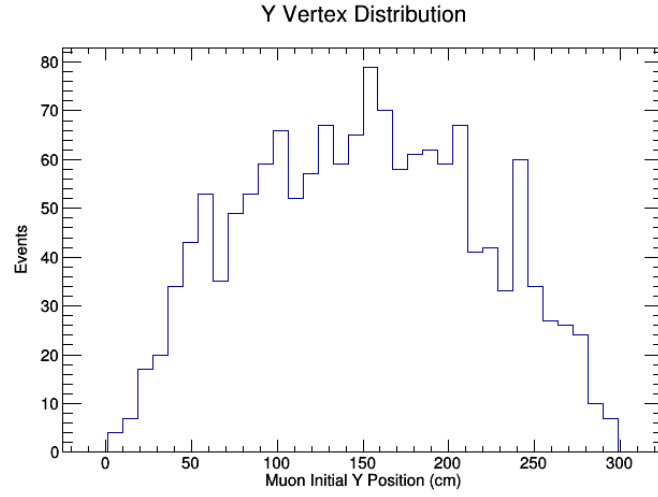
Figure 19: New ν-Mode Berger-Sehgal Y vertex distributions for the interactions.
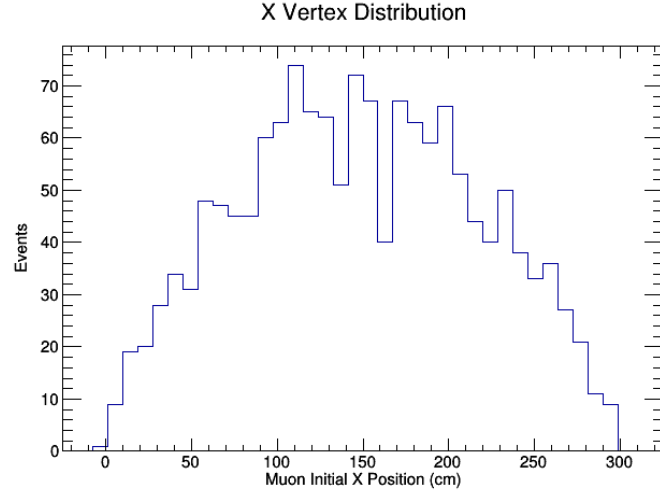
Figure 20: New ν-Mode Berger-Sehgal X vertex distributions for the interactions.
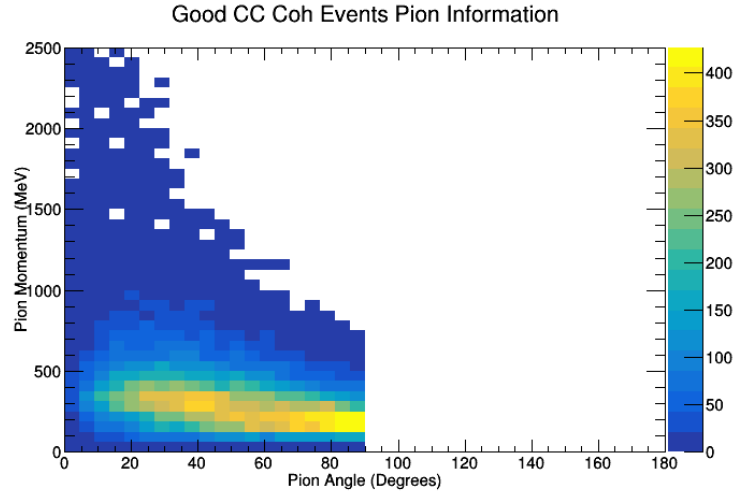
Figure 21: This is a 2D histogram for the momentum and angle of the pion in the CC Coh Pion events that met the qualification of being "good".
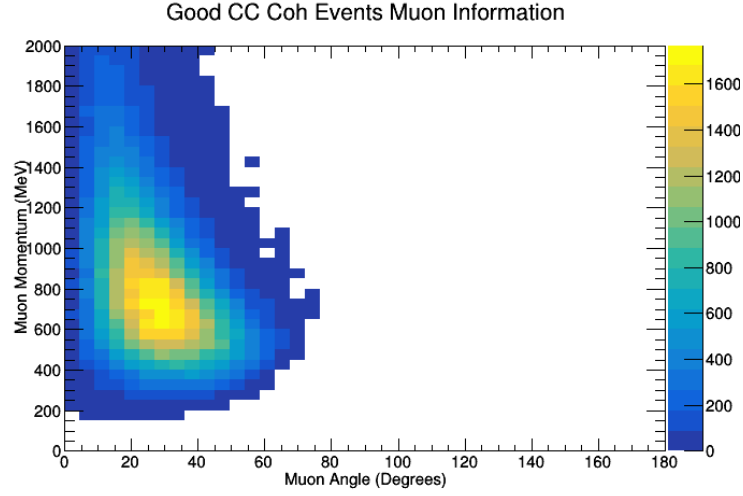
Figure 22: This is a 2D histogram for the momentum and angle of the muon in the CC Coh Pion events that met the qualification of being "good".!
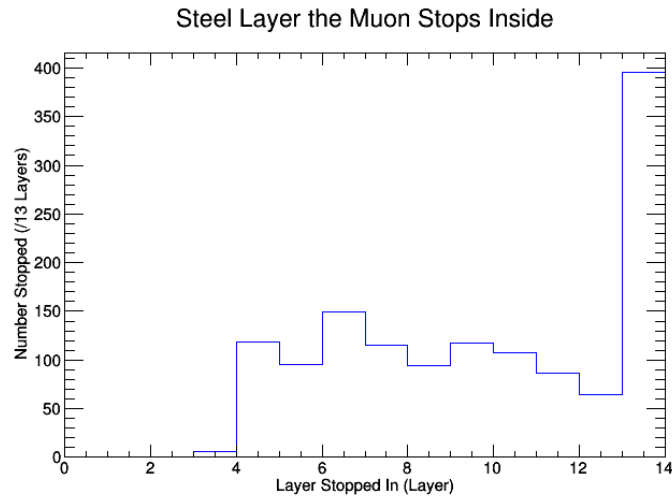
Figure 23: This histogram shows the amount of muons that embedded (or "Stopped") in a corresponding layer of steel in our simulation.
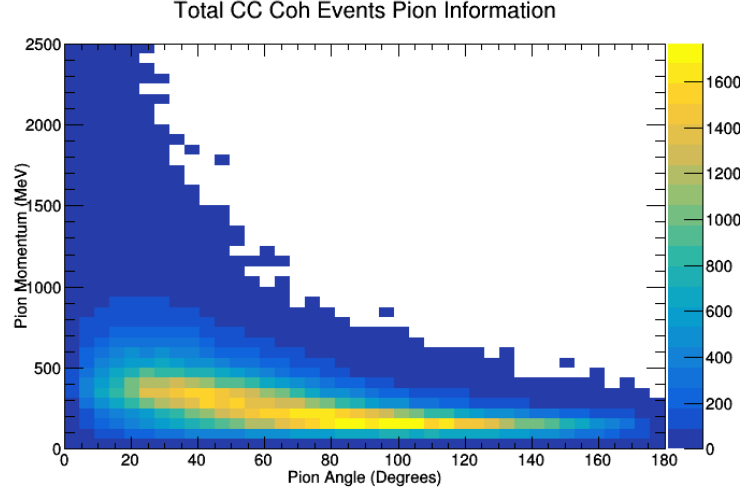
Figure 24: This is a 2D histogram for the momentum and angle of the pion in the total CC Coh Pion events.
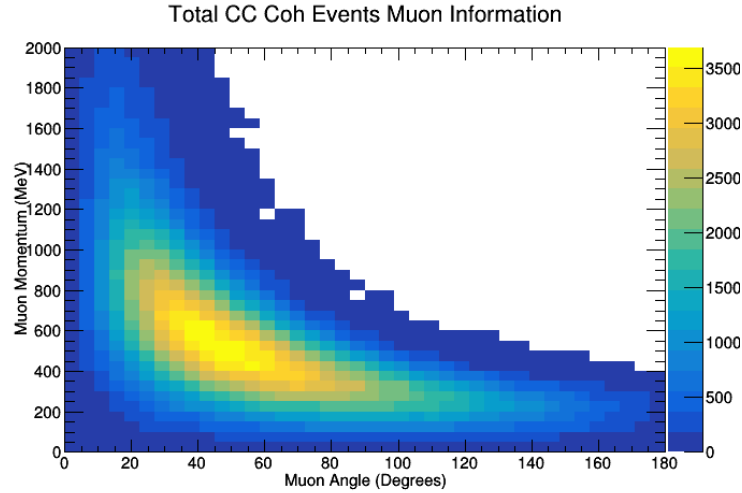
Figure 25: This is a 2D histogram for the momentum and angle of the muon in the total CC Coh Pion events.

A.9   OldNMReinSehgal.C

This file is the macro that corresponds to the "OldNMReinSehgal.h" file, which connects with this file: "SciBooNE_numu_coh_OLDNEUT_RooTrack.root". This file performs the main analysis for this generated sample, and then organizes the information into many different histograms. The histograms are then written to a file titled "totalmuoninfoOBS.root" inside the "ROOTFILES" directory. The "ROOTFILES" directory is included in the SciBooNE-MC repository (it is absolutely pertinent that this directory be located where the macro files are located due to how the calls of the combined data macros reference the now saved histograms).
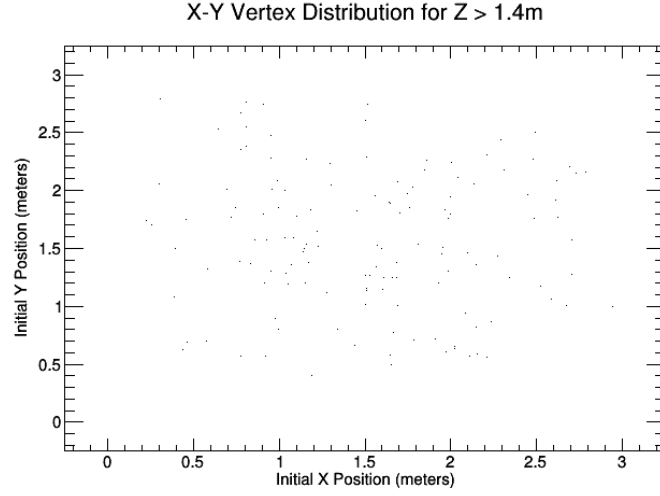
Figure 26: Old ν-Mode Rein-Sehgal X-Y vertex distributions for muons that made it to the MRD and penetrated at least to the third layer of steel.
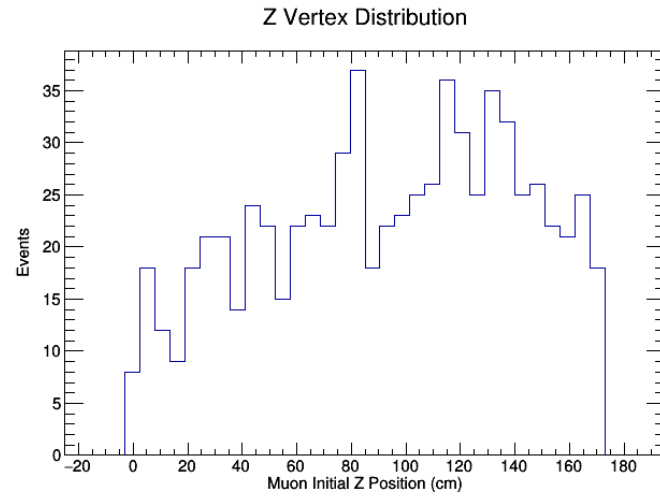
Figure 27: Old ν-Mode Rein-Sehgal Z vertex distributions for the interactions.
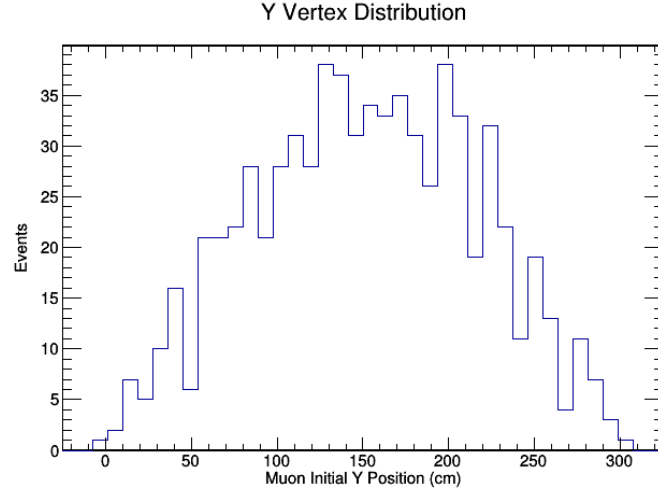
Figure 28: Old ν-Mode Rein-Sehgal Y vertex distributions for the interactions.
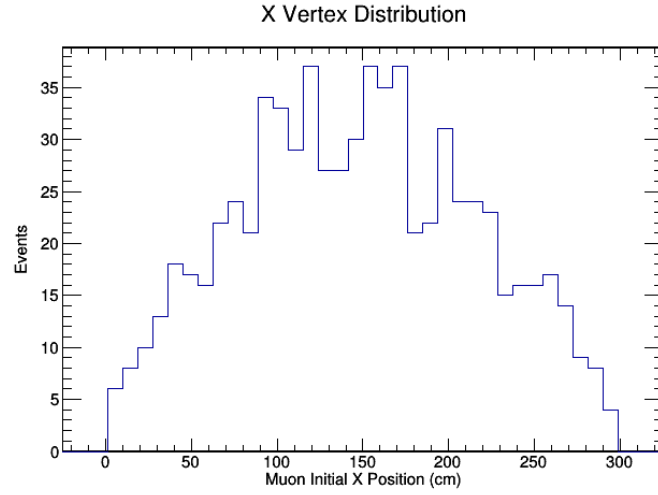
Figure 29: Old ν-Mode Rein-Sehgal X vertex distributions for the interactions.
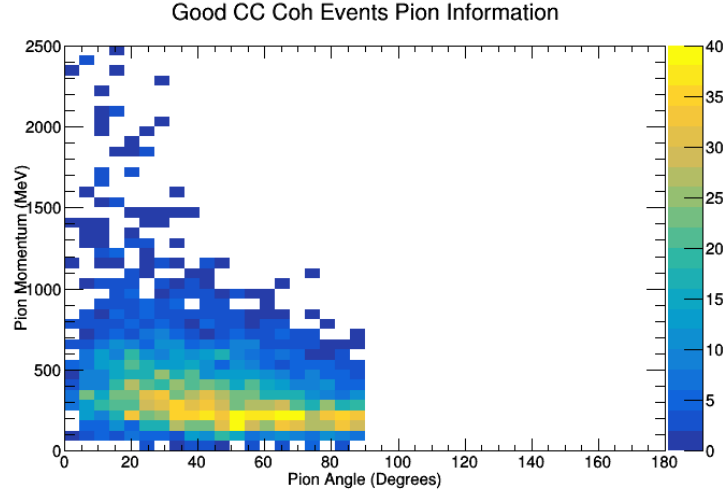
Figure 30: This is a 2D histogram for the momentum and angle of the pion in the CC Coh Pion events that met the qualification of being "good".
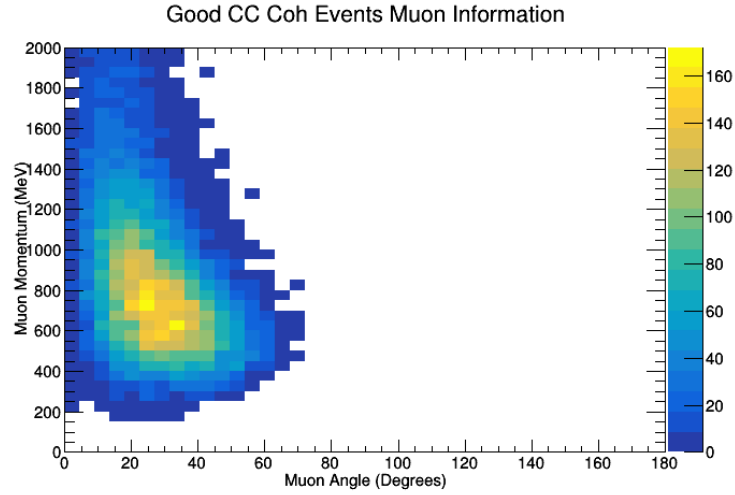
Figure 31: This is a 2D histogram for the momentum and angle of the muon in the CC Coh Pion events that met the qualification of being "good".
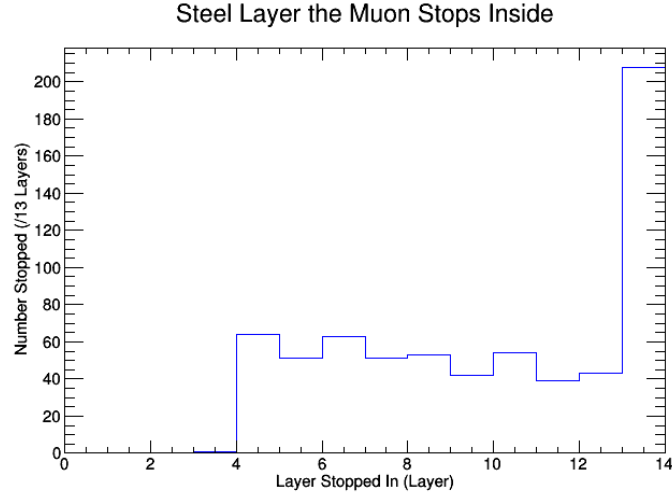
Figure 32: This histogram shows the amount of muons that embedded (or "Stopped") in a corresponding layer of steel in our simulation.
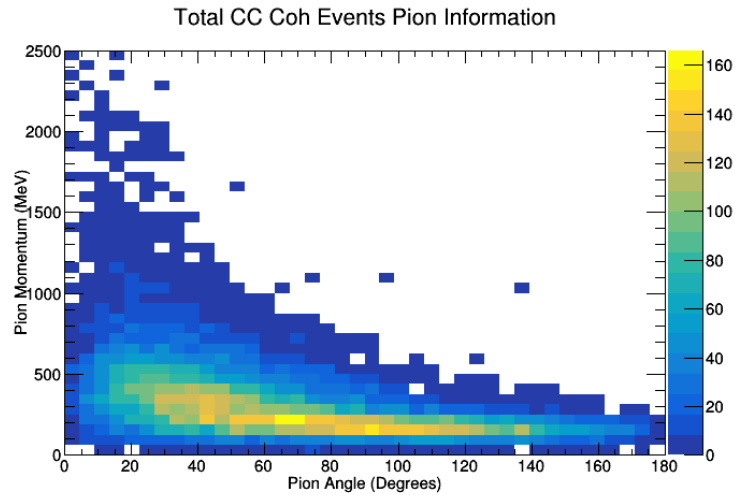
Figure 33: This is a 2D histogram for the momentum and angle of the pion in the total CC Coh Pion events.
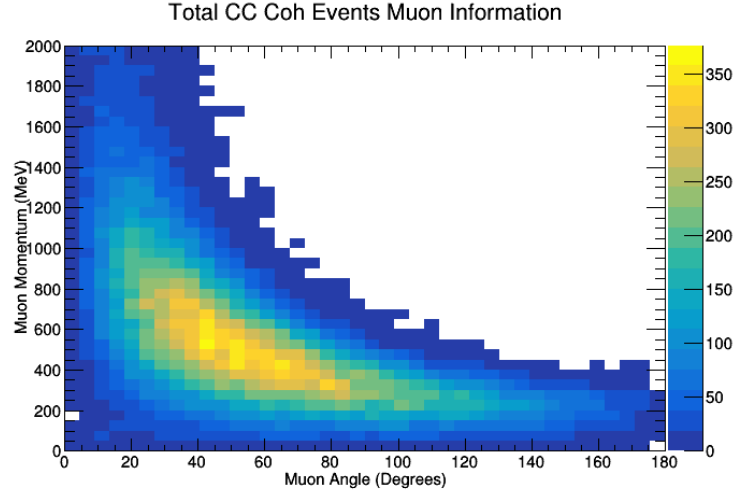
Figure 34: This is a 2D histogram for the momentum and angle of the muon in the total CC Coh Pion events.

A.10   NewANMReinSehgal.C

This file is the macro that corresponds to the "NewANMReinSehgal.h" file, which connects with this file: "SciBooNE_numubar_coh_RooTrack.root". This file performs the main analysis for this generated sample, and then organizes the information into many different histograms. The histograms are then written to a file titled "totalmuoninfoRSBar.root" inside the "ROOTFILES" directory. The "ROOTFILES" directory is included in the SciBooNE-MC repository (it is absolutely pertinent that this directory be located where the macro files are located due to how the calls of the combined data macros reference the now saved histograms).
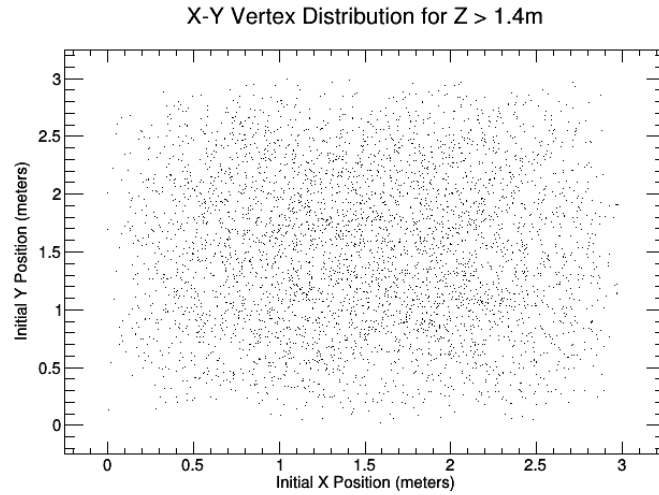
Figure 35: New $\bar{\nu}$-Mode Rein-Sehgal X-Y vertex distributions for muons that made it to the MRD and penetrated at least to the third layer of steel.
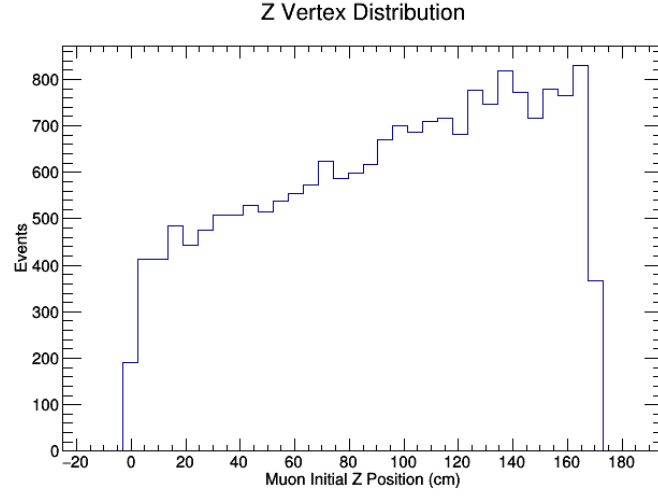
Figure 36: New $\bar{\nu}$-Mode Rein-Sehgal Z vertex distributions for the interactions.
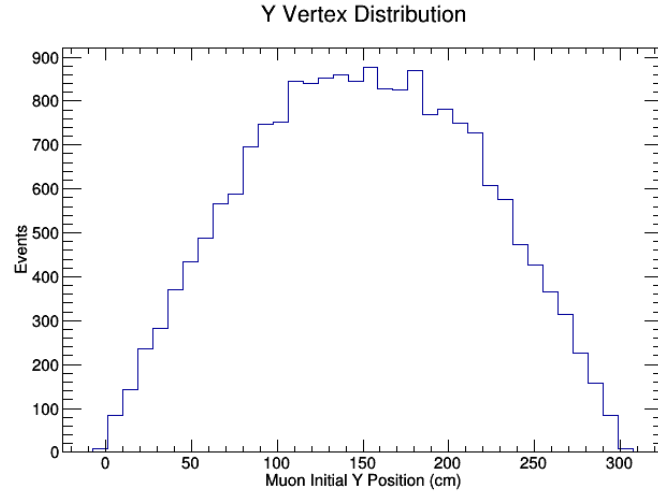
Figure 37: New $\bar{\nu}$-Mode Rein-Sehgal Y vertex distributions for the interactions.
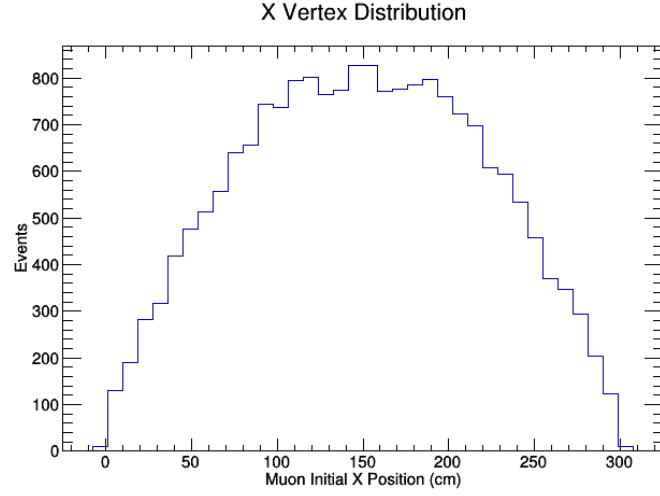
Figure 38: New $\bar{\nu}$-Mode Rein-Sehgal X vertex distributions for the interactions.
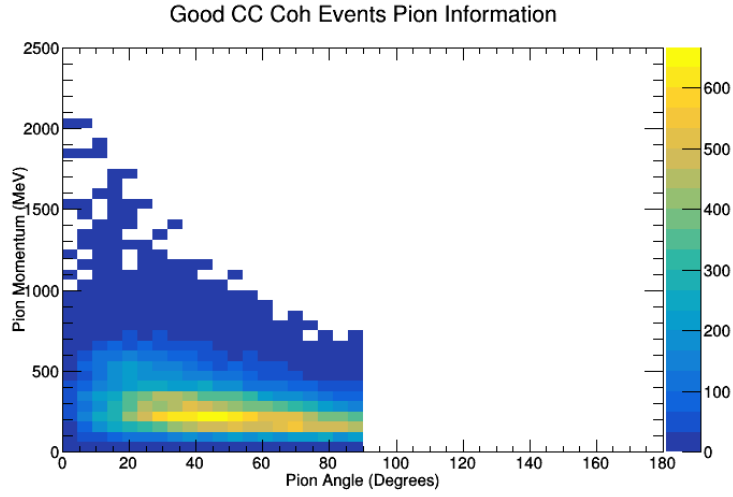
Figure 39: This is a 2D histogram for the momentum and angle of the pion in the CC Coh Pion events that met the qualification of being "good".
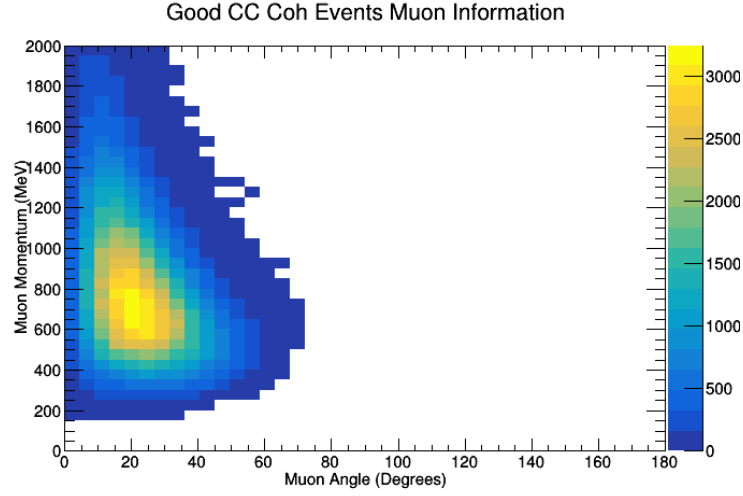
Figure 40: This is a 2D histogram for the momentum and angle of the muon in the CC Coh Pion events that met the qualification of being "good".
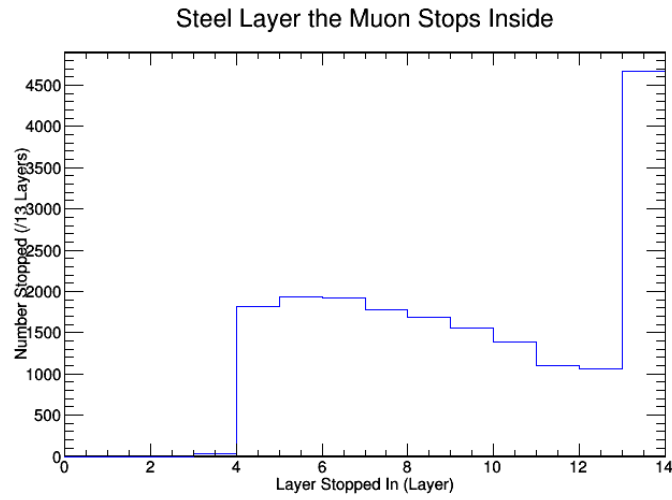
Figure 41: This histogram shows the amount of muons that embedded (or "Stopped") in a corresponding layer of steel in our simulation.
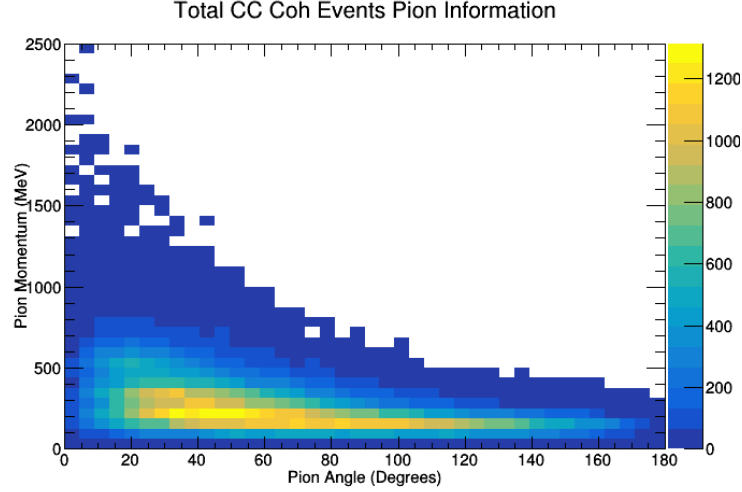
Figure 42: This is a 2D histogram for the momentum and angle of the pion in the total CC Coh Pion events.
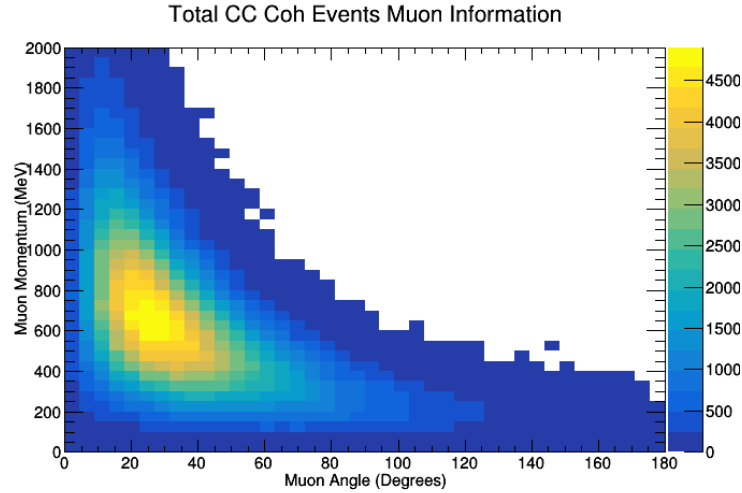
Figure 43: This is a 2D histogram for the momentum and angle of the muon in the total CC Coh Pion events.

A.11   NewANMBergerSehgal.C

This file is the macro that corresponds to the "NewANMBergerSehgal.h" file, which connects with this file: "SciBooNE_numubar_coh_RooTrack_NEW.root". This file performs the main analysis for this generated sample, and then organizes the information into many different histograms. The histograms are then written to a file titled "totalmuoninfoBSBar.root" inside the "ROOTFILES" directory. The "ROOTFILES" directory is included in the SciBooNE-MC repository (it is absolutely pertinent that this directory be located where the macro files are located due to how the calls of the combined data macros reference the now saved histograms).
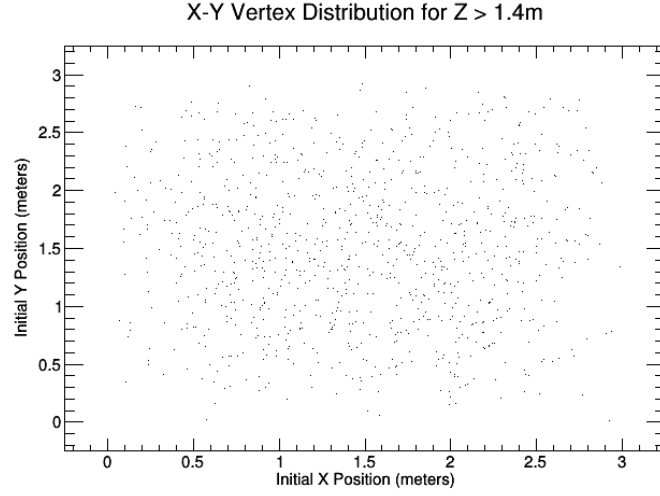
Figure 44: New $\bar{\nu}$-Mode Berger-Sehgal X-Y vertex distributions for muons that made it to the MRD and penetrated at least to the third layer of steel.
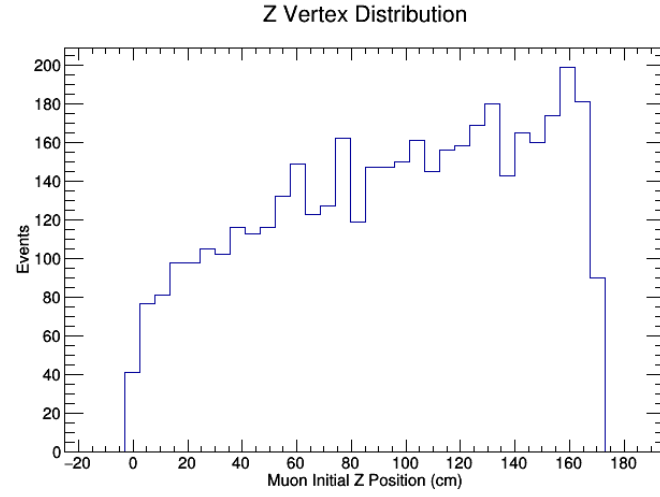
Figure 45: New $\bar{\nu}$-Mode Berger-Sehgal Z vertex distributions for the interactions.
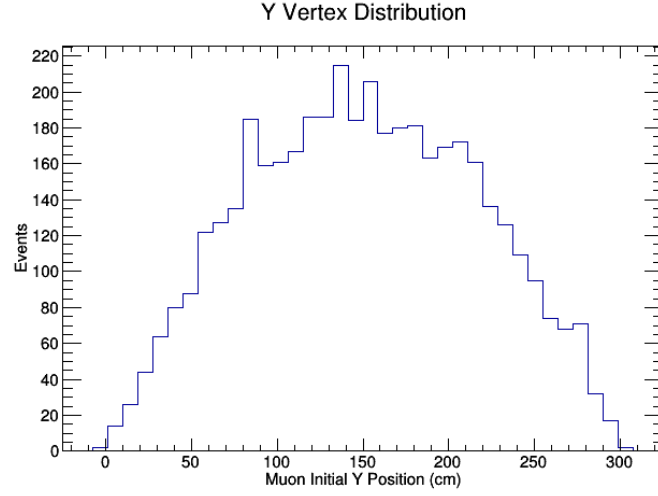
Figure 46: New $\bar{\nu}$-Mode Berger-Sehgal Y vertex distributions for the interactions.
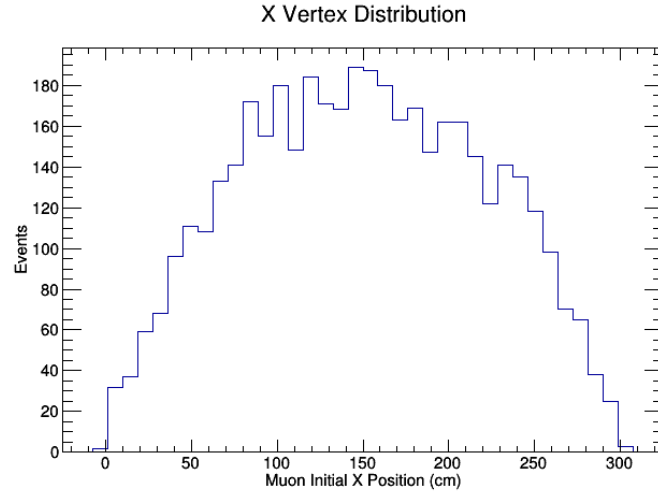
Figure 47: New $\bar{\nu}$-Mode Berger-Sehgal X vertex distributions for the interactions.
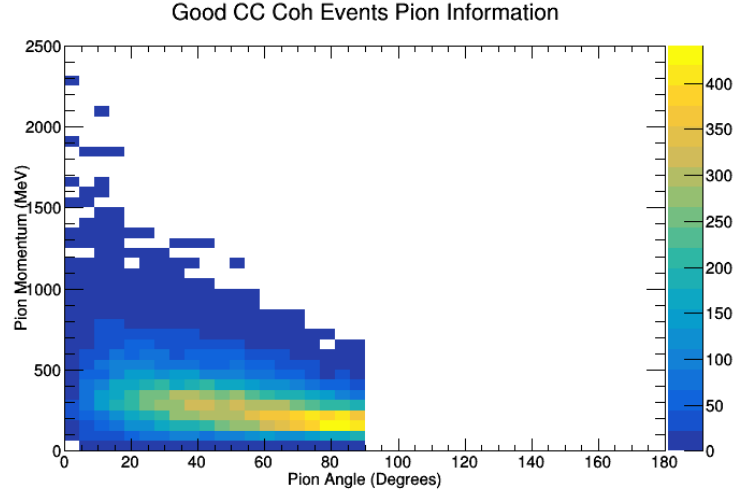
Figure 48: This is a 2D histogram for the momentum and angle of the pion in the CC Coh Pion events that met the qualification of being "good".
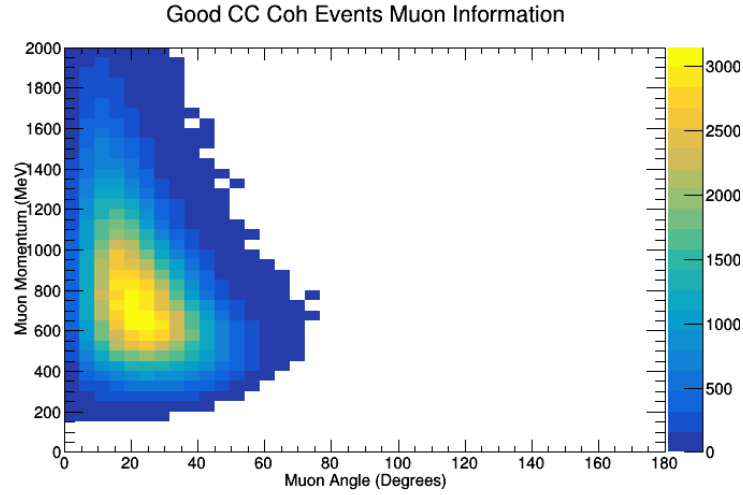
Figure 49: This is a 2D histogram for the momentum and angle of the muon in the CC Coh Pion events that met the qualification of being "good".
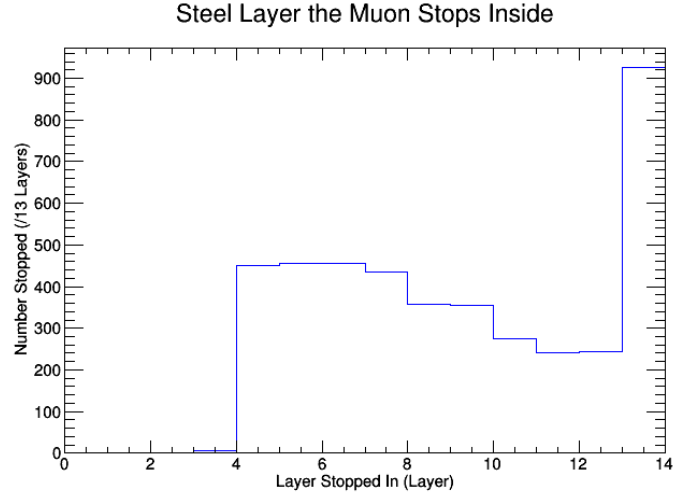
Figure 50: This histogram shows the amount of muons that embedded (or "Stopped") in a corresponding layer of steel in our simulation.
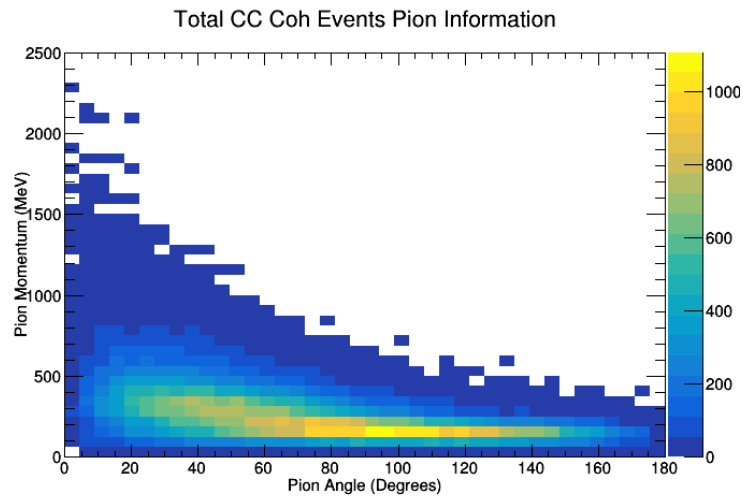
Figure 51: This is a 2D histogram for the momentum and angle of the pion in the total CC Coh Pion events.

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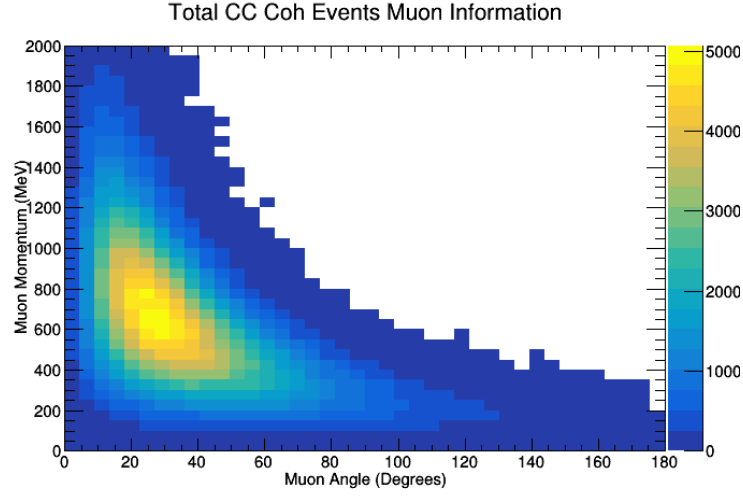
Figure 52: This is a 2D histogram for the momentum and angle of the muon in the total CC Coh Pion events.

A.12 NMCombinedPlots.C

This is the file that performs the main plotting operations for the neutrino mode samples using the muon's information. All of the muon efficiency plots for neutrino mode are made with this file.
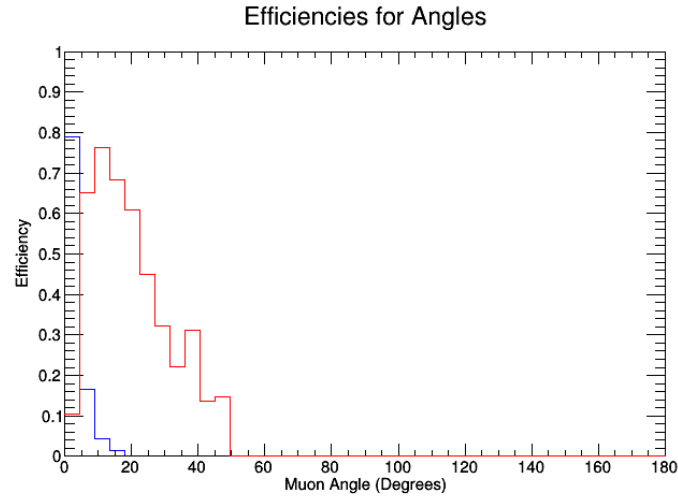
Figure 53
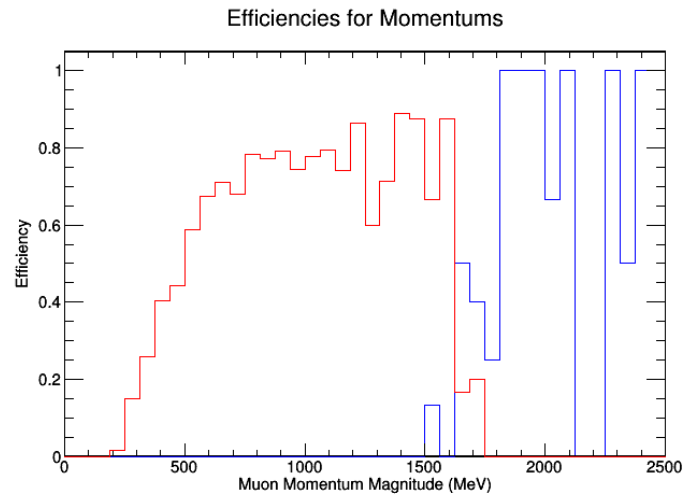
Figure 54

Figure 55

44
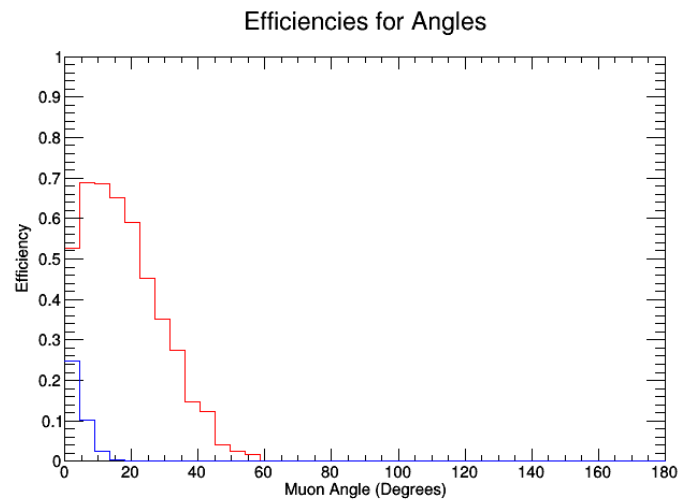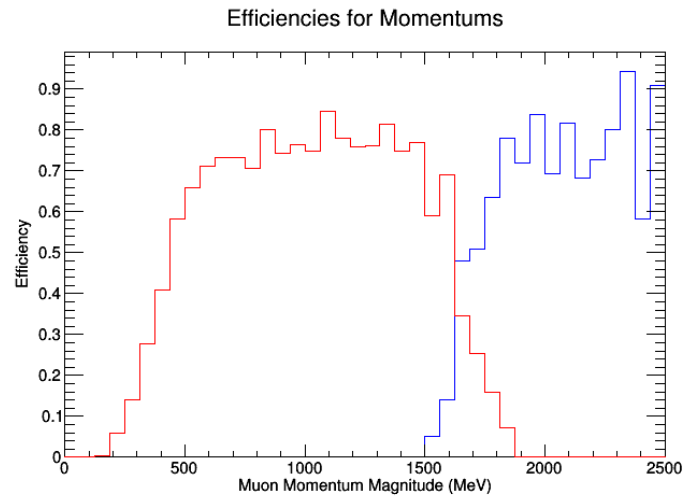
Figure 56

Figure 57

45
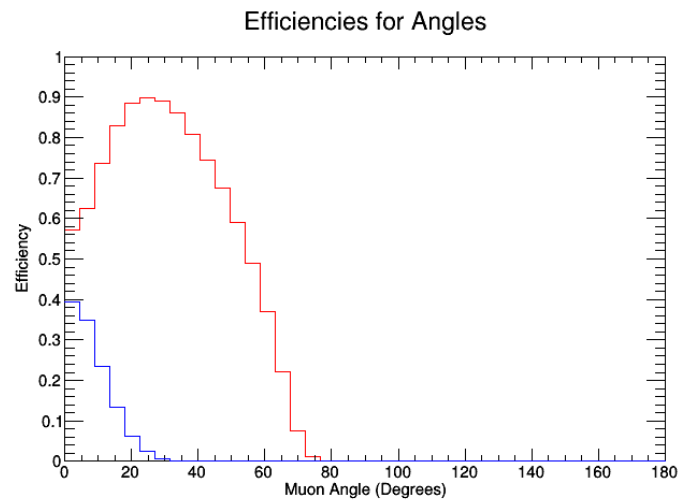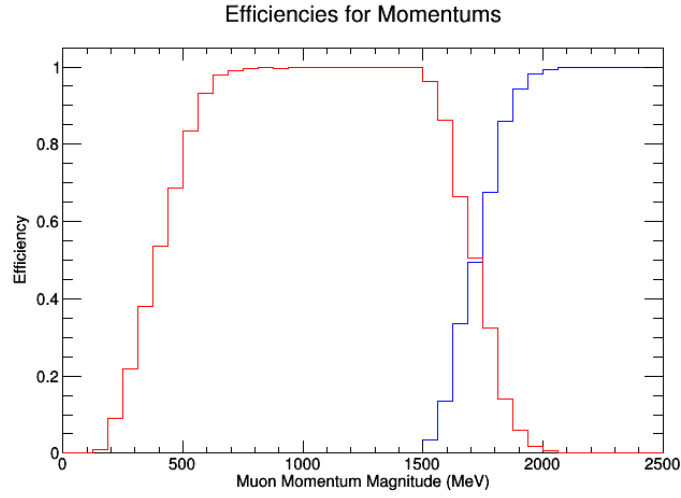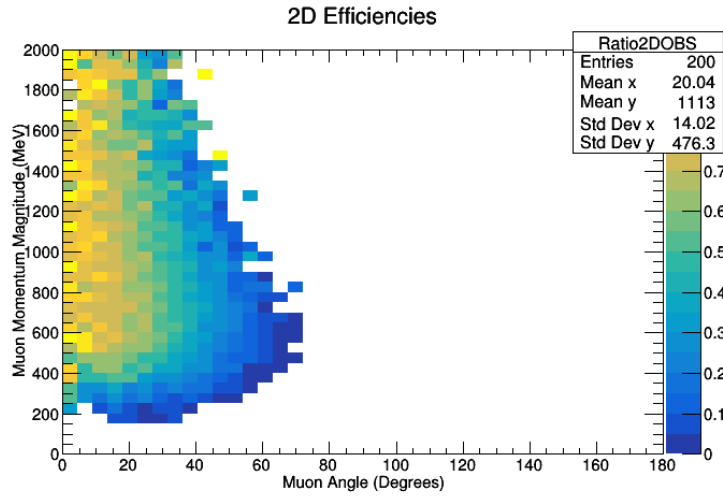
Figure 58

Figure 59
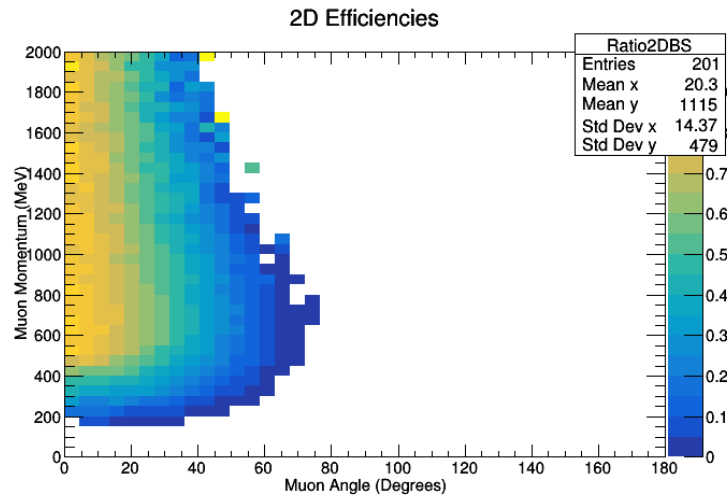
Figure 60
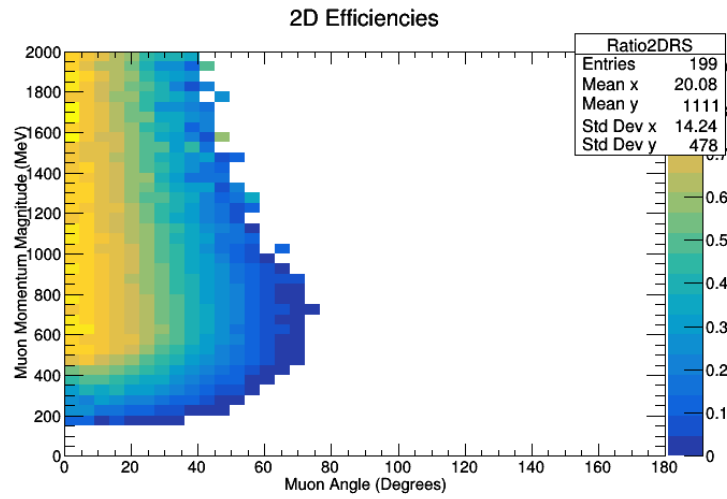
Figure 61

Figure 62

Figure 63

Good CC Coh Muon Momentum Non-Stopped

Figure 64

Good CC Coh Muon Momentum Stopped

Figure 65

Total Good CC Coh Muon Angle

SciBooNE MC
New R-S Model
New B-S Model
Old R-S Model

hGoodMuonAngleTotal
Entries 1501
11.6
7.631

Muon Theta (Degrees)

Normalized Events (/ 4.5Degrees)

Figure 66

Total Good CC Coh Muon Momentum

SciBooNE MC
New R-S Model
New B-S Model
Old R-S Model

hGoodMuonMomentumTotal
Entries 1501
788
352.1

Muon Momentum (MeV)

Normalized Events (/ 50MeV)

Figure 67

Figure 68

Figure 69

Efficiencies for Angles

SciBooNE MC

Neut B-S Model

Anti-Neut B-S Model

RatioCBS	
Entries	577
	16.38
	12.09

Figure 70

Efficiencies for Momentums

SciBooNE MC

Neut B-S Model

Anti-Neut B-S Model

RatioPBS	
Entries	203
	1193
	479.3

Figure 71

Efficiencies for Angles

RatioCRS	
Entries	3362
	16.78
	11.71

SciBooNE MC

—— Neut R-S Model

—— Anti-Neut R-S Model

Efficiency (y-axis), Muon Angle (Degrees) (x-axis)

Figure 72

Efficiencies for Momentums

RatioPRS	
Entries	1168
	1201
	472.6

SciBooNE MC

—— Neut R-S Model

—— Anti-Neut R-S Model

Efficiency (y-axis), Muon Momentum Magnitude (MeV) (x-axis)

Figure 73

Efficiencies for Angles

SciBooNE MC
New R-S Model
New B-S Model
Old B-S Model

RatioCBSCC	
	70305
	23.87
	16.72

Figure 74

Efficiencies for Momentums

SciBooNE MC
New R-S Model
New B-S Model
Old B-S Model

RatioPBSCC	
Entries	37780
Mean	1241
Std Dev	470.1

Figure 75

Figure 76

Figure 77

A.13 NMPionPlotting.C

This is the file that performs the main plotting operations for the neutrino mode samples using the pion's information. All of the pion efficiency plots for neutrino mode are made with this file.
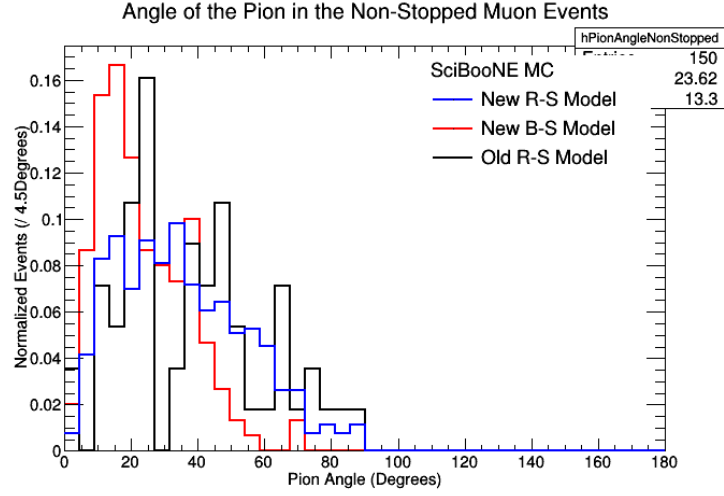
Figure 78
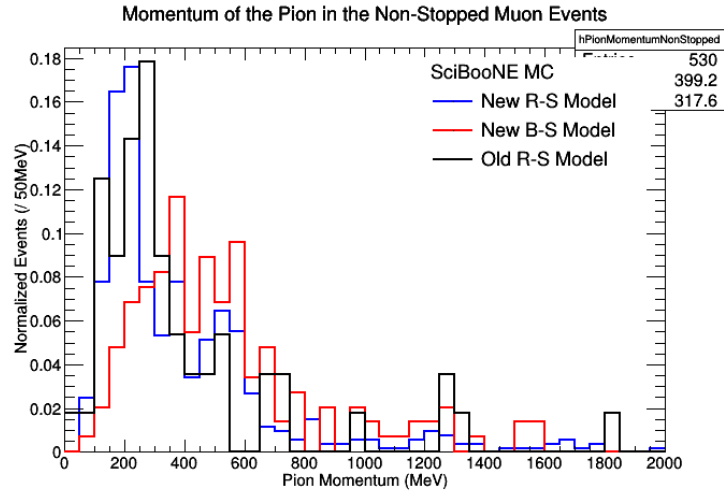
Figure 79
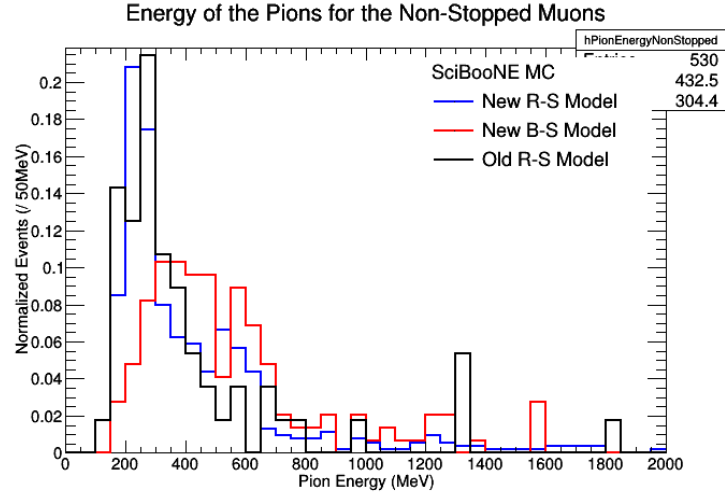
Figure 80
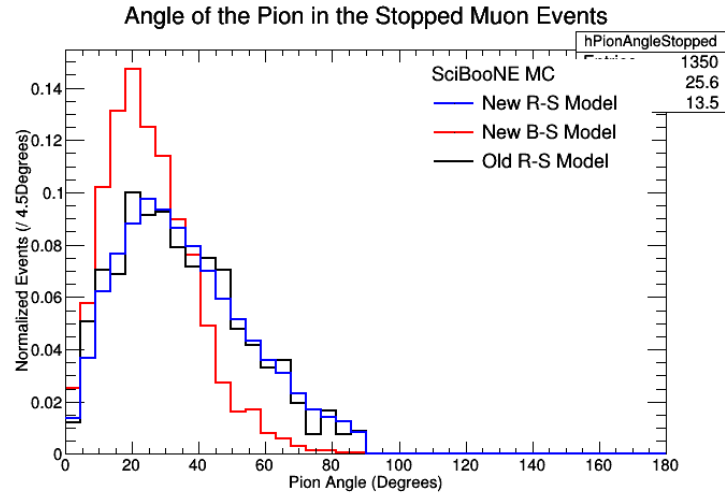
Figure 81
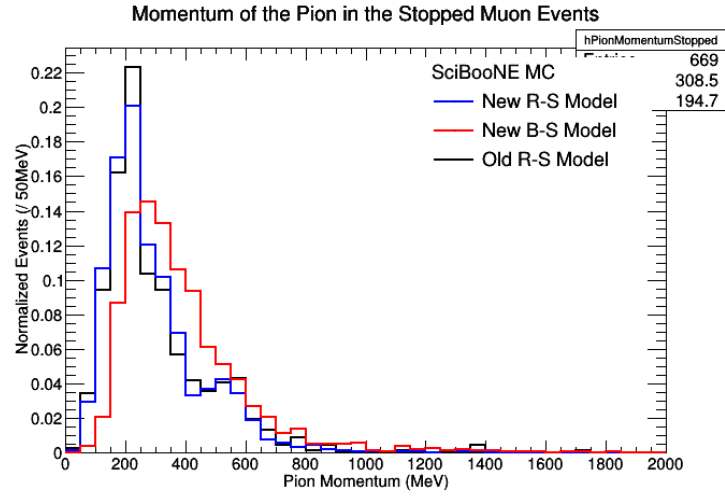
Figure 82
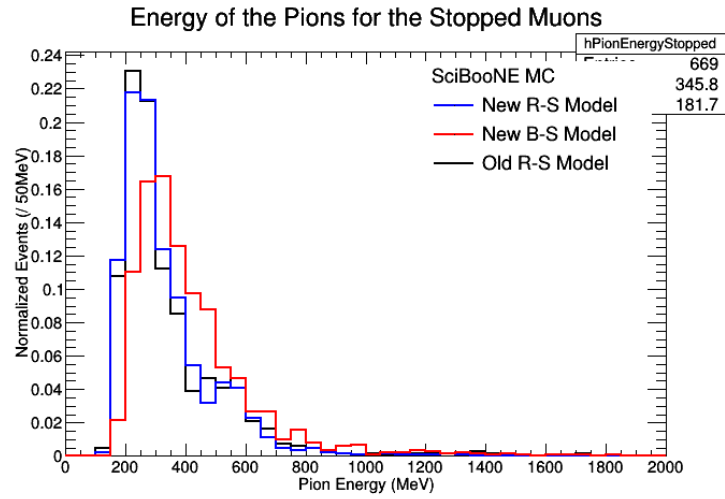
Figure 83

Figure 84

Figure 85

Energy of the Pion in Good CC Coh Events

hPionEnergyGood	
Entries	726
	352
	198.5

SciBooNE MC
New R-S Model
New B-S Model
Old R-S Model

Normalized Events (/ 50MeV)

Pion Energy (MeV)

Figure 86

Angle of the Pion in Total CC Coh Events

hPionAngle	
Entries	2576
	24.72
	13.3

SciBooNE MC
New R-S Model
New B-S Model
Old R-S Model

Normalized Events (/ 4.5Degrees)

Pion Angle (Degrees)
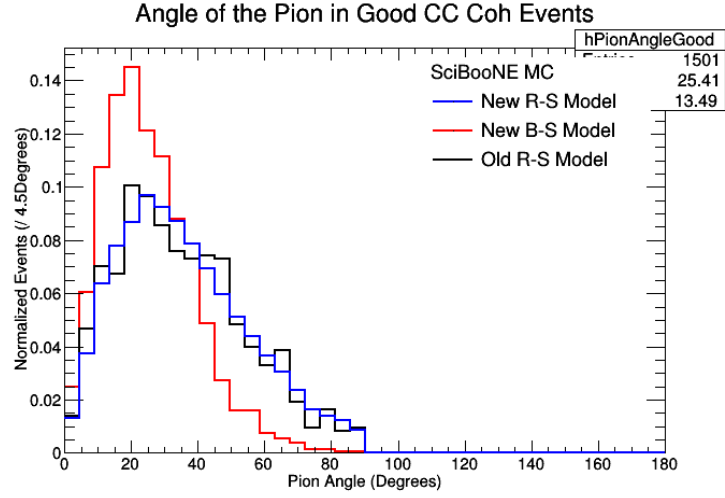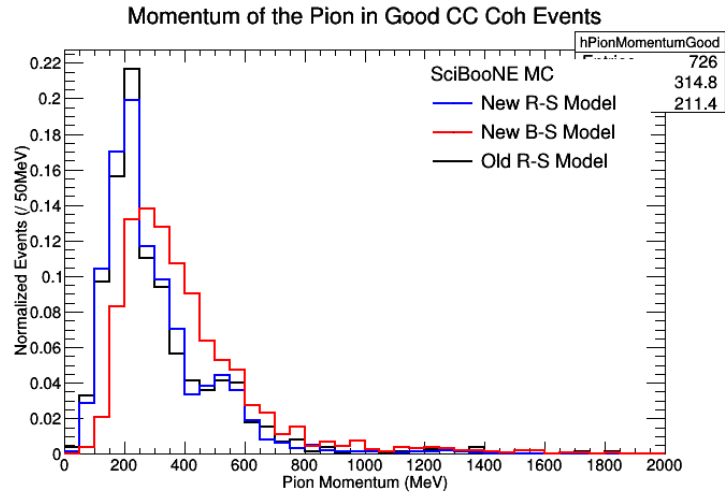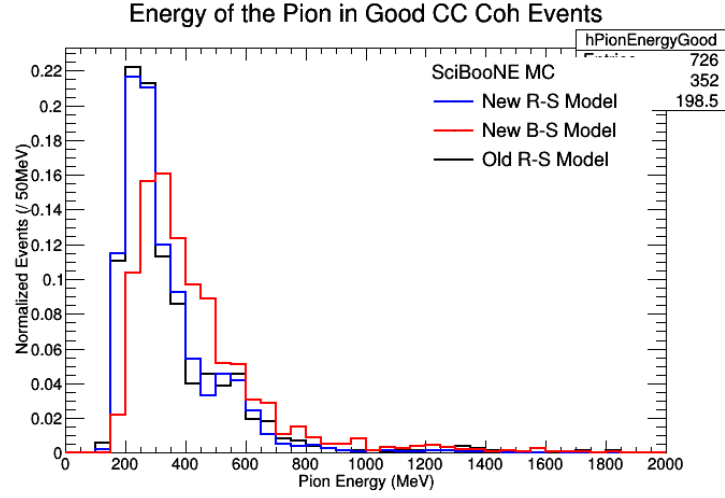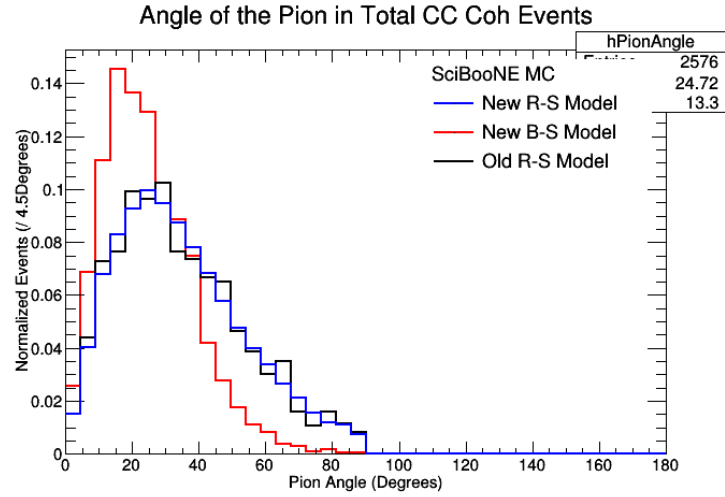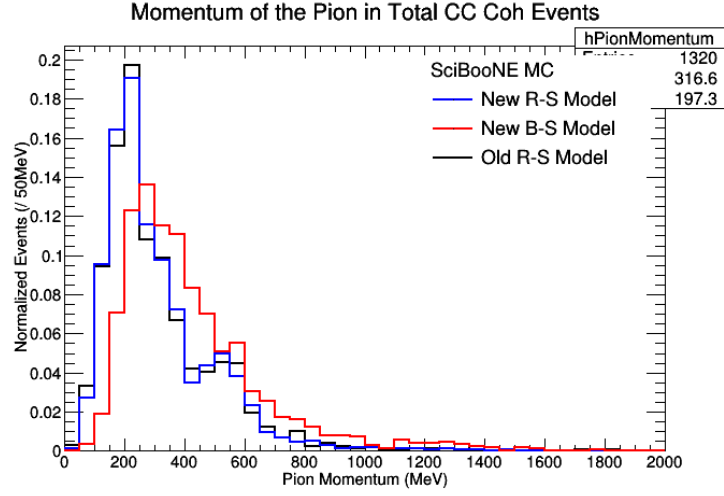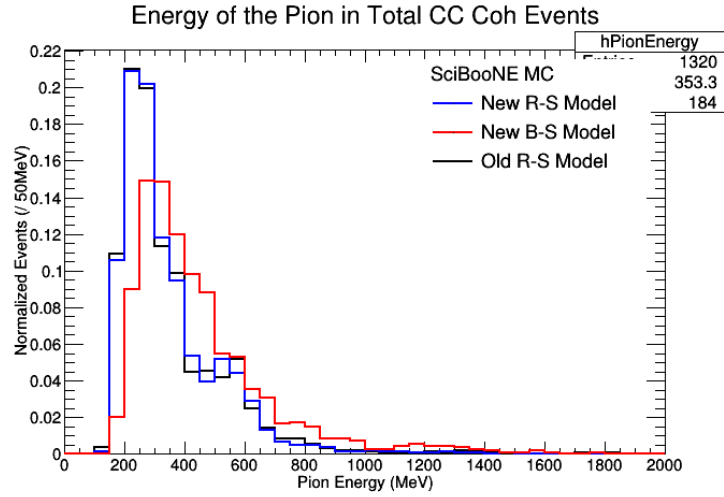
Figure 87

Figure 88

Figure 89

A.14 NMFourSquaredPlotting.C

All of the four-momentum transfer (both $|t|$ and Q^2) combined plots are made with this file for neutrino mode.
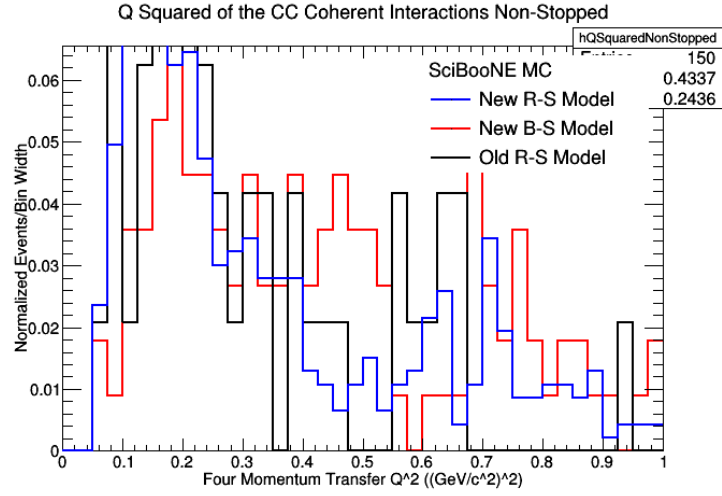
Figure 90
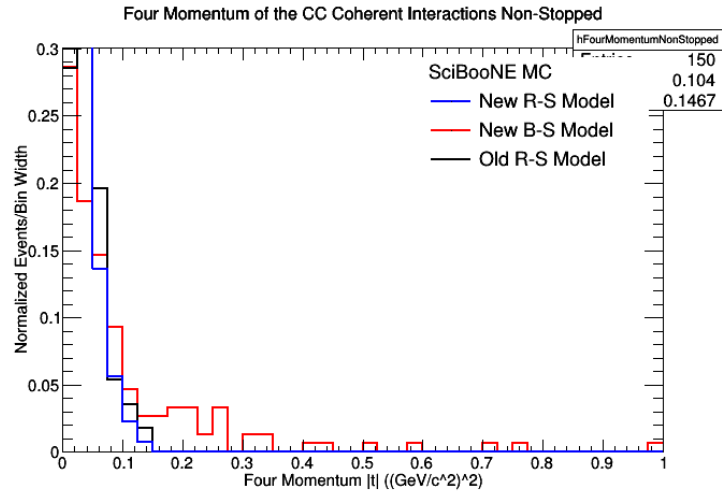
Figure 91
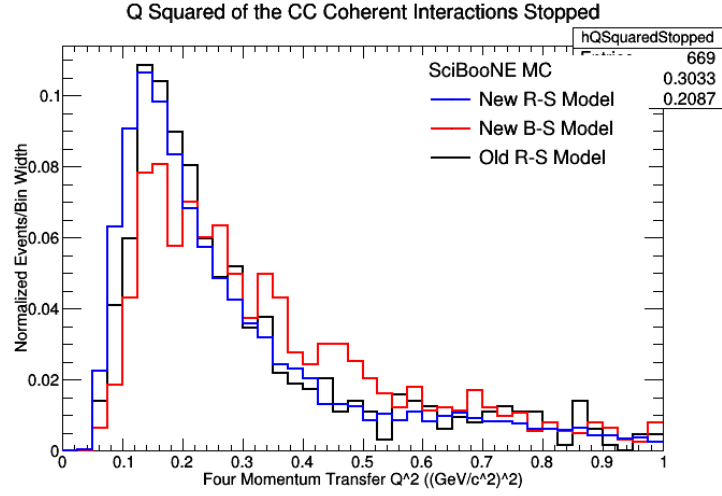
Figure 92
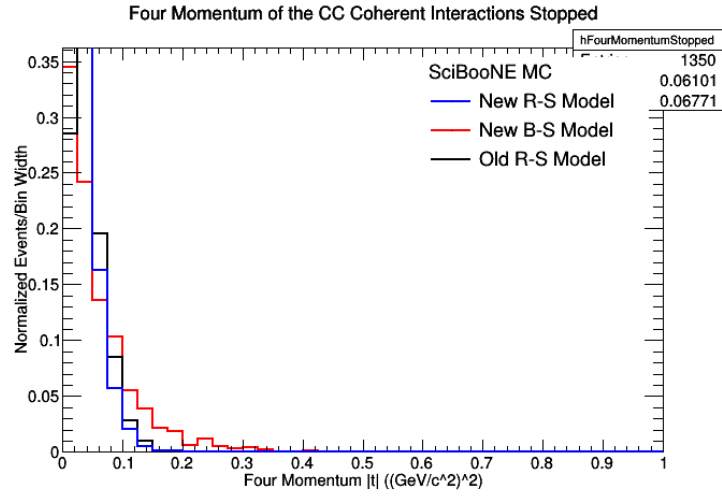
Figure 93
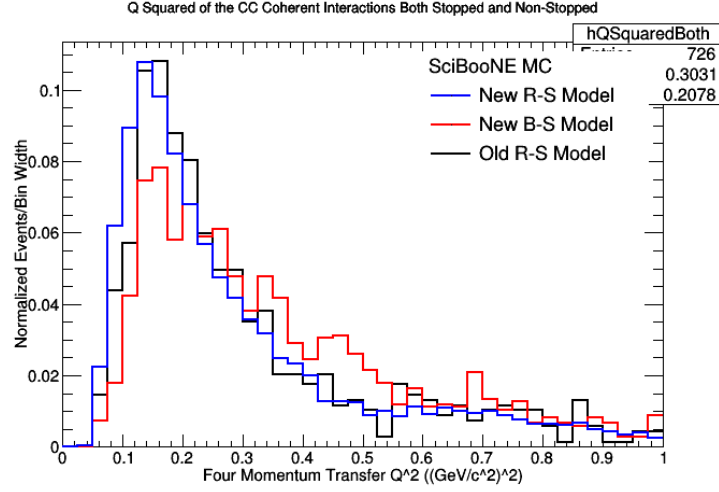
Figure 94
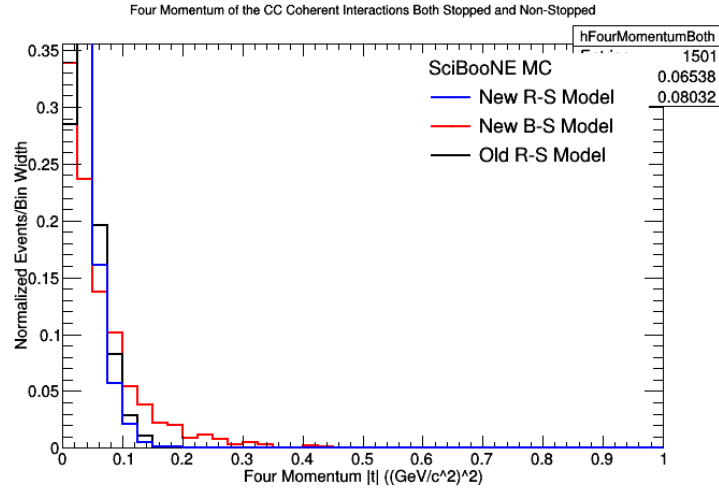
Figure 95

A.15 ANMCombinedPlots.C

This is the file that performs the main plotting operations for the anti-neutrino mode samples using the muon's information. All of the muon efficiency plots for anti-neutrino mode are made with this file.
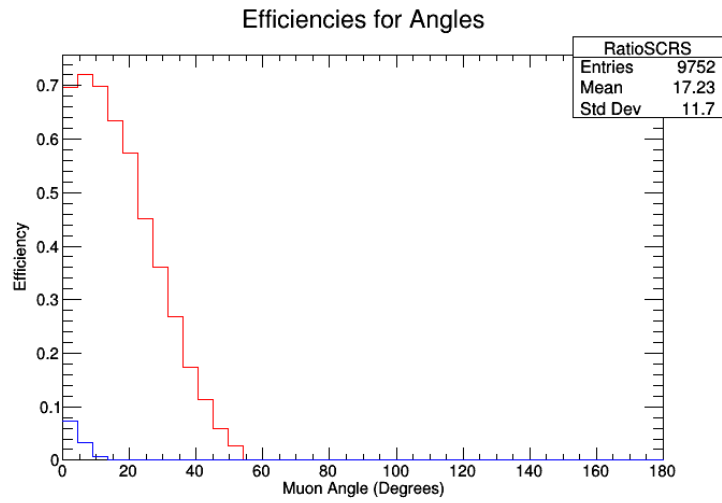
Figure 96
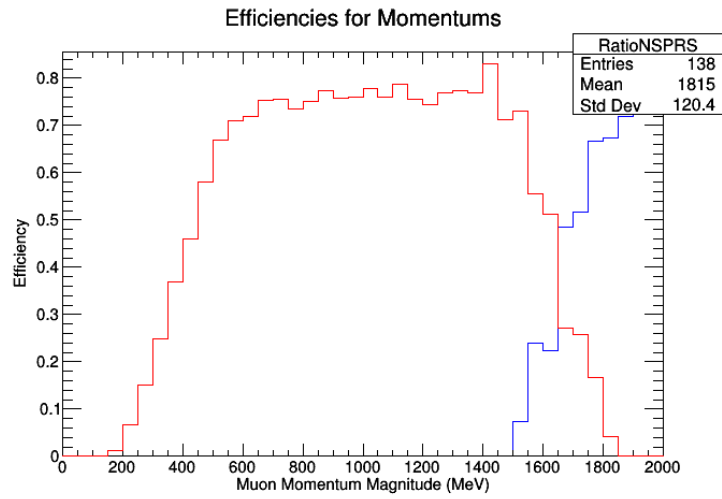
Figure 97
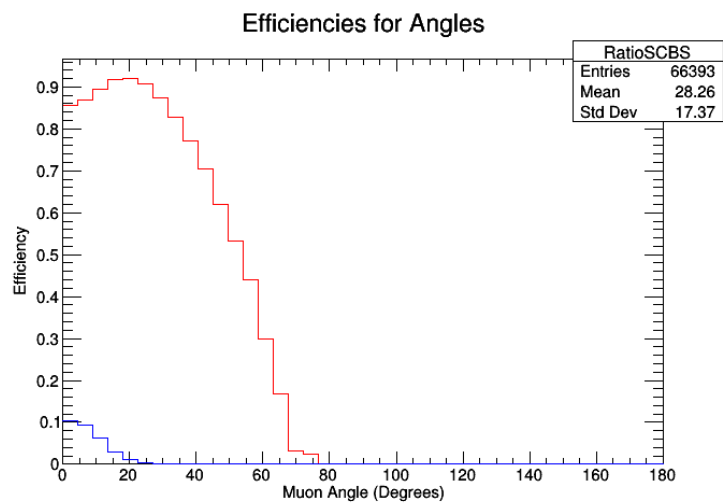
Figure 98
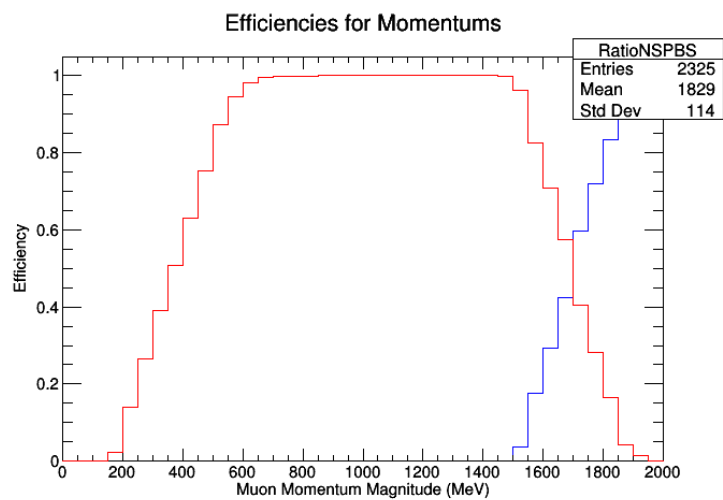
Figure 99
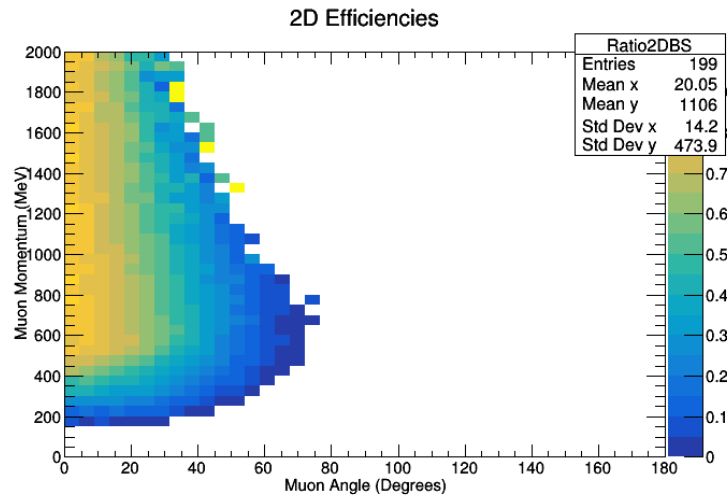
Figure 100
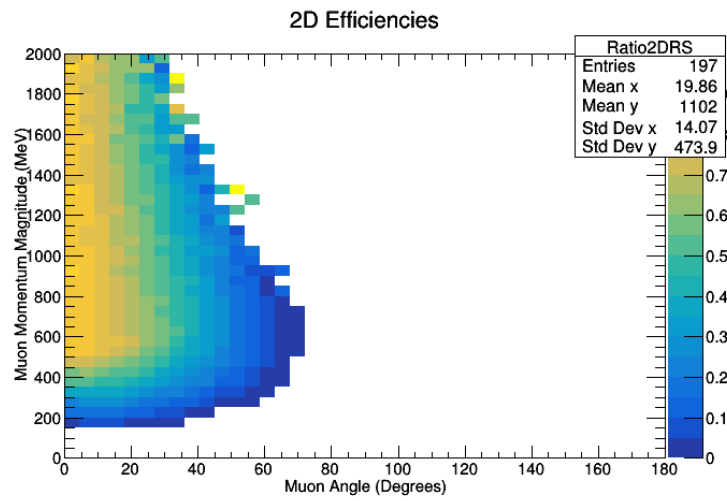
Figure 101
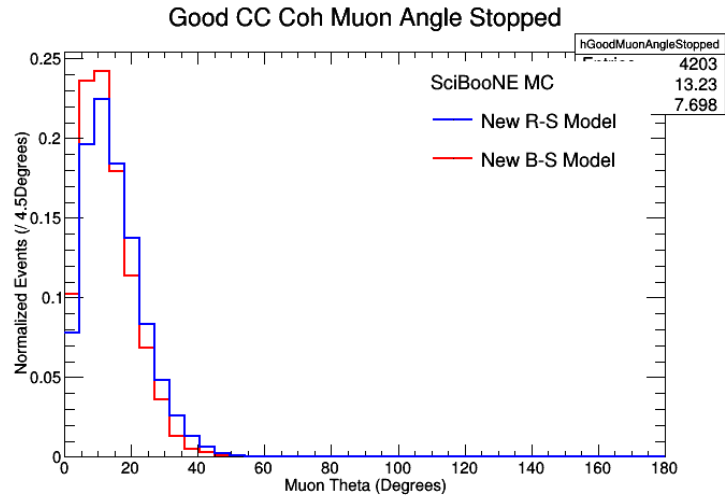
Figure 102
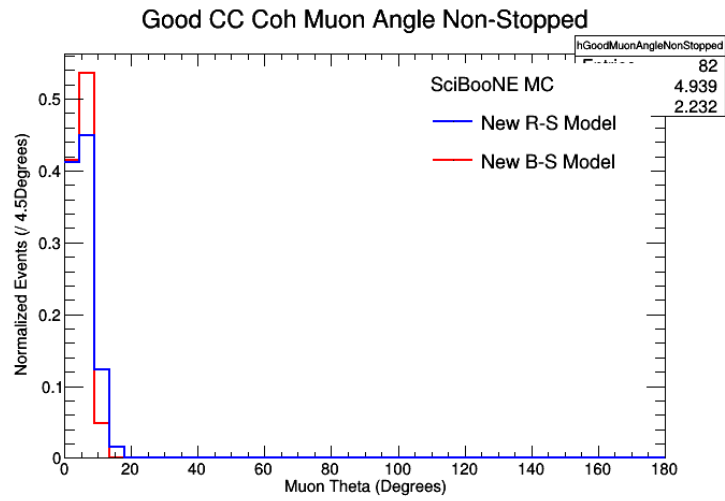
Figure 103

Figure 104

Figure 105

Total Good CC Coh Muon Angle

hGoodMuonAngleTotal	
Entries	4285
	13.07
	7.715

SciBooNE MC

R-S Model

B-S Model

Normalized Events (/ 4.5Degrees)

Muon Theta (Degrees)

Figure 106

Total Good CC Coh Muon Momentum

hGoodMuonMomentumTotal	
Entries	4285
	706.5
	304.8

SciBooNE MC

R-S Model

B-S Model

Normalized Events (/ 50MeV)

Muon Momentum (MeV)
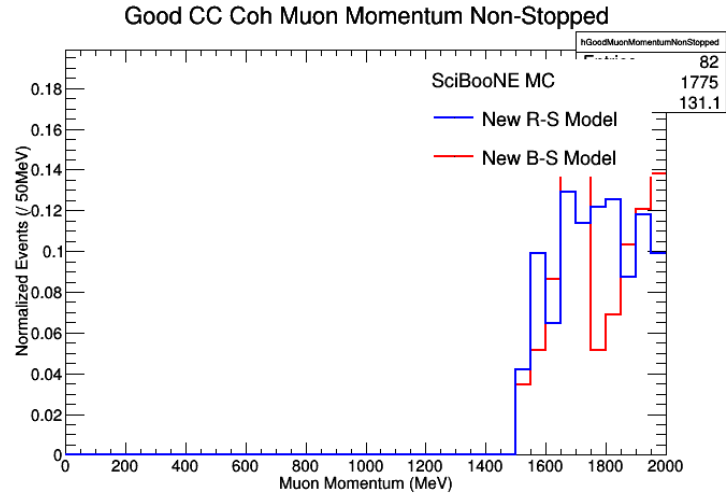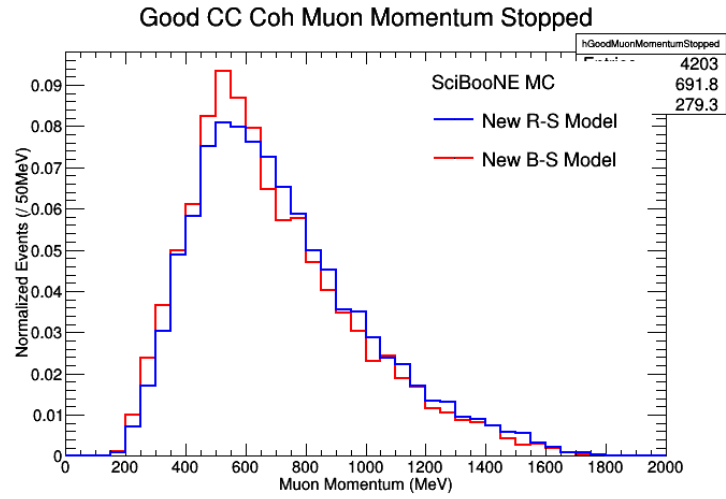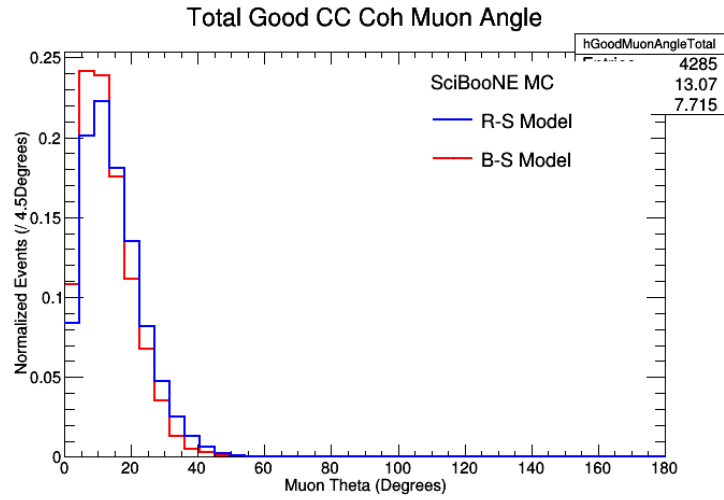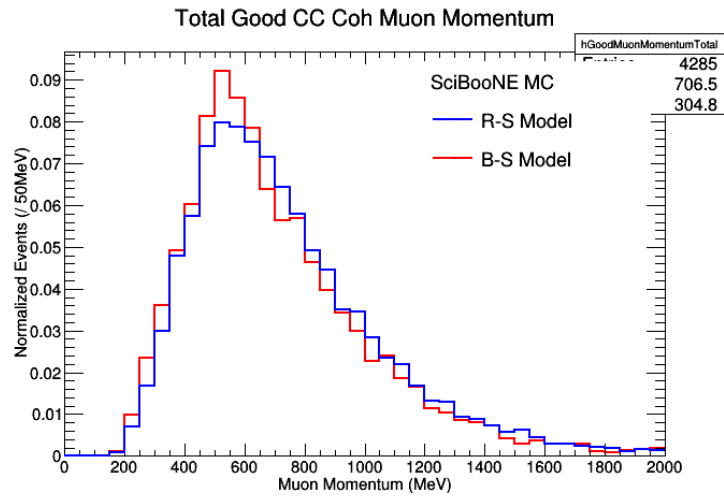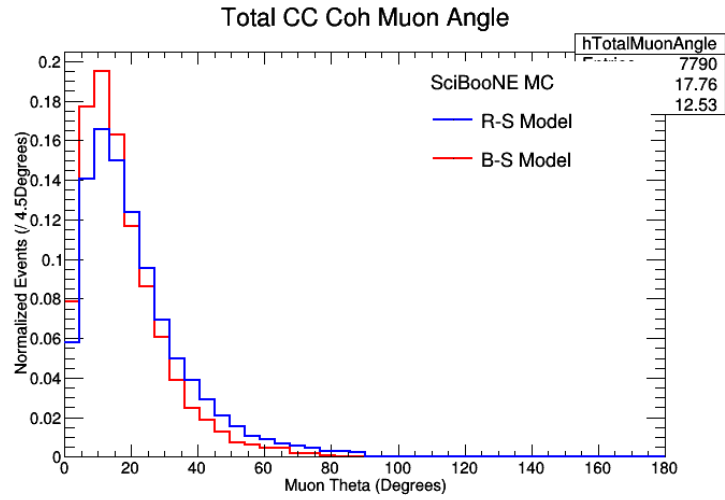
Figure 107

Figure 108

Figure 109

71
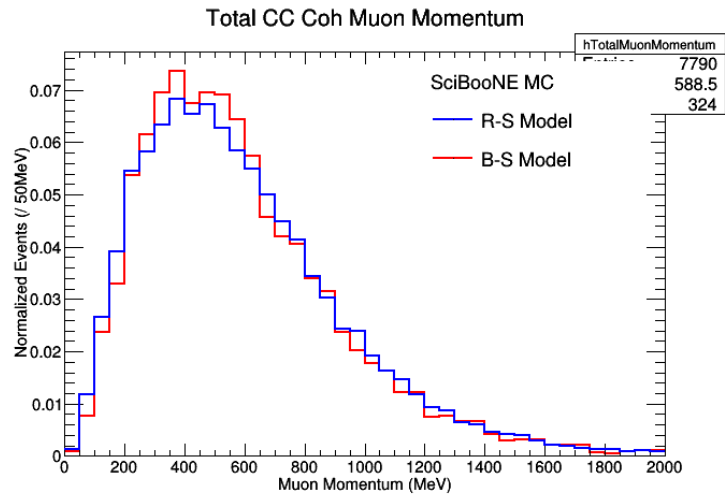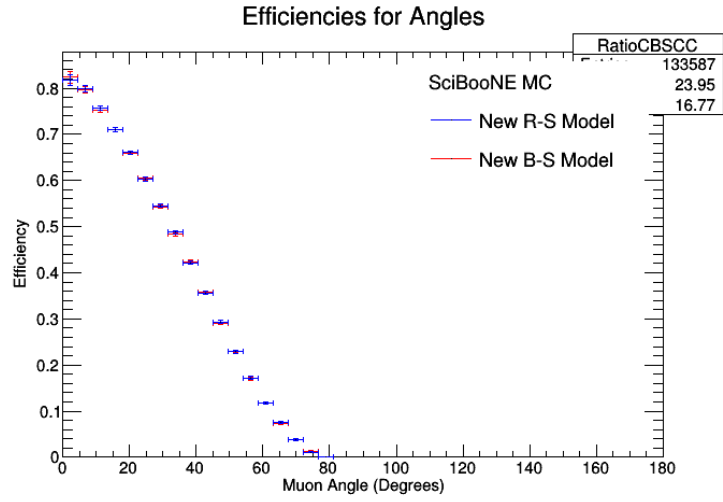
Figure 110

Figure 111

72
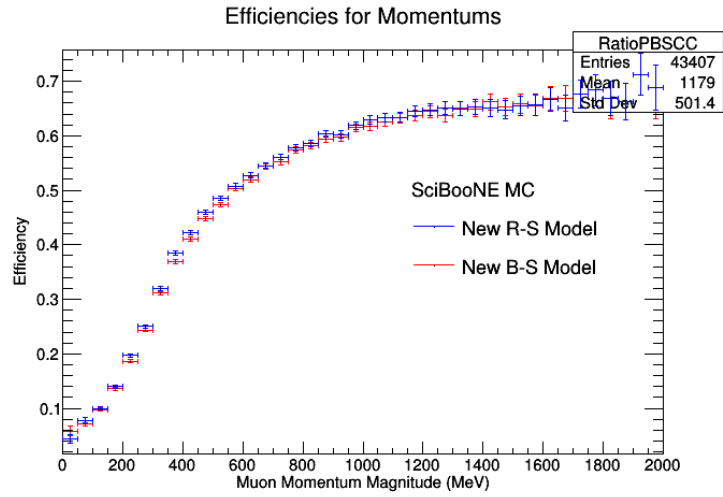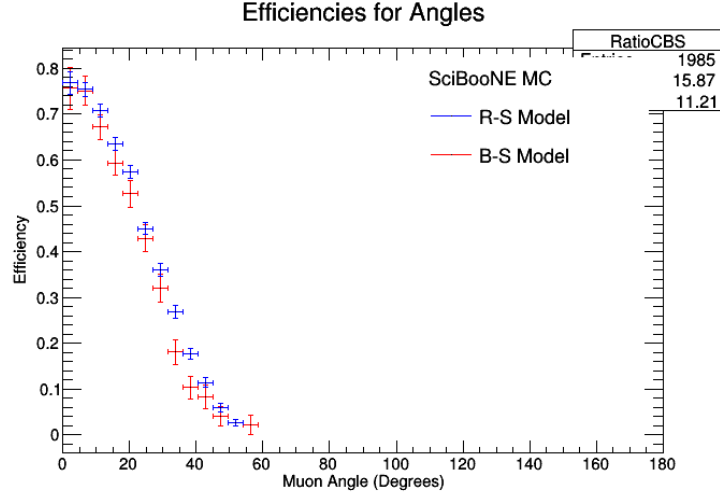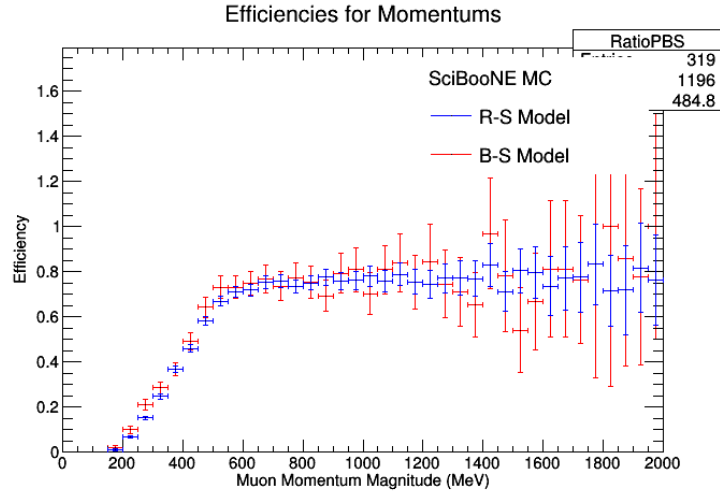
Figure 112

Figure 113

A.16   ANMPionPlotting.C

This is the file that performs the main plotting operations for the anti-neutrino mode samples using the pion's information. All of the pion efficiency plots for anti-neutrino mode are made with this file.

Angle of the Pion in the Non-Stopped Muon Events

Figure 114

Momentum of the Pion in the Non-Stopped Muon Events

Figure 115

Energy of the Pions for the Non-Stopped Muons

	hPionEnergyNonStopped
Entries	530
	432.5
	304.4

SciBooNE MC

New R-S Model

New B-S Model

Normalized Events (/ 50MeV)

Pion Energy (MeV)

Figure 116

Angle of the Pion in the Stopped Muon Events

	hPionAngleStopped
Entries	1350
	25.6
	13.5

SciBooNE MC

New R-S Model

New B-S Model

Normalized Events (/ 4.5Degrees)

Pion Angle (Degrees)
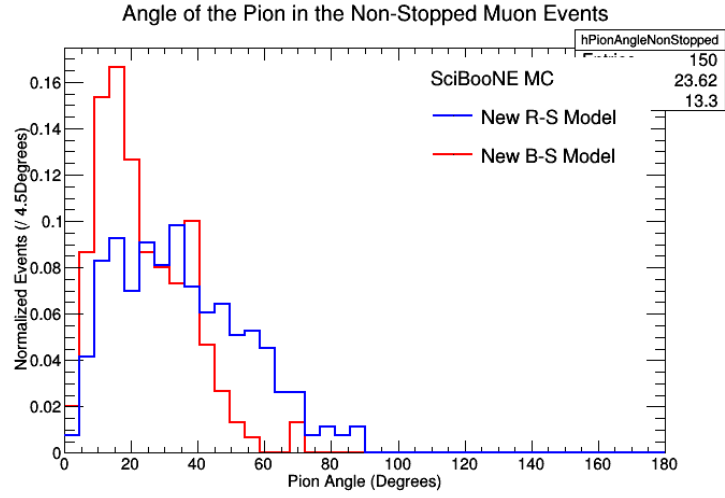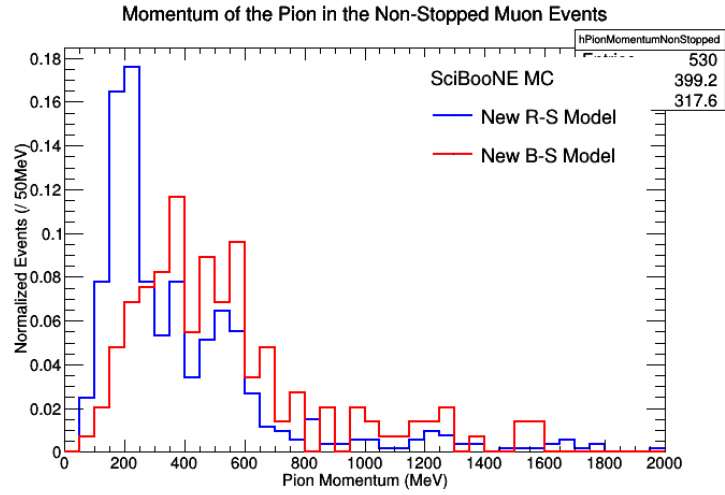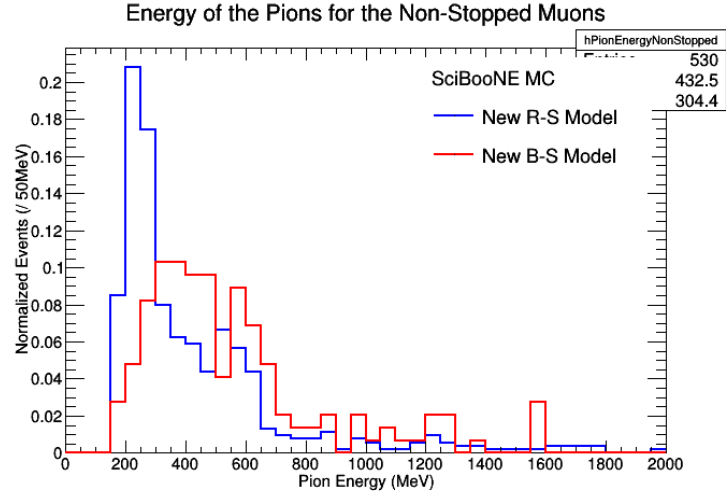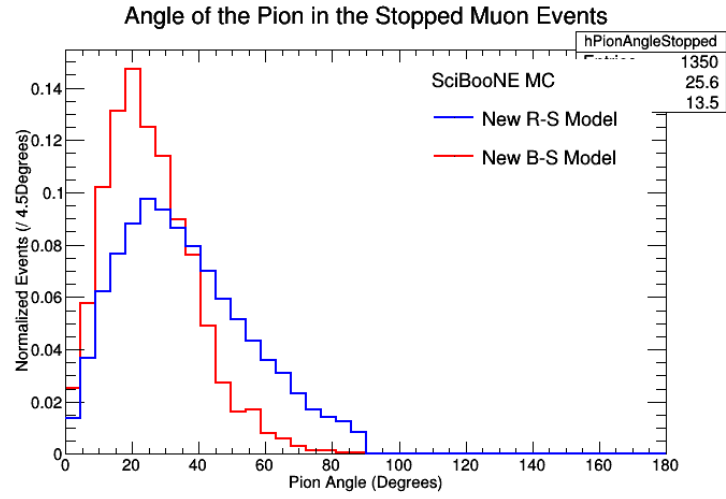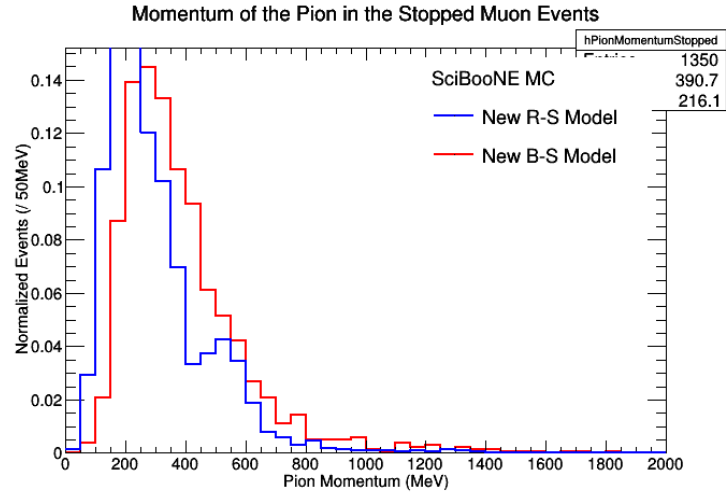
Figure 117
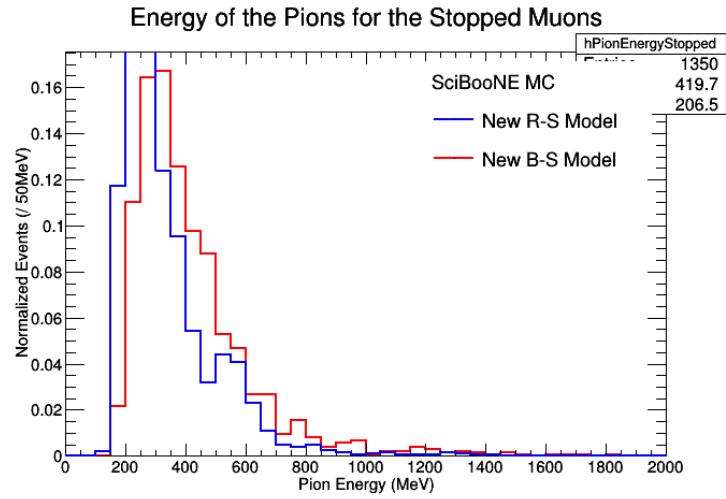
Figure 118

Figure 119

Figure 120

Figure 121

Energy of the Pion in Good CC Coh Events

Figure 122

Angle of the Pion in Total CC Coh Events
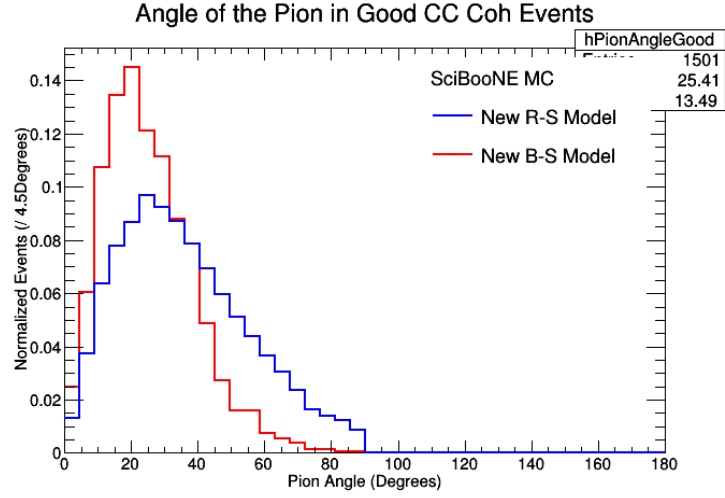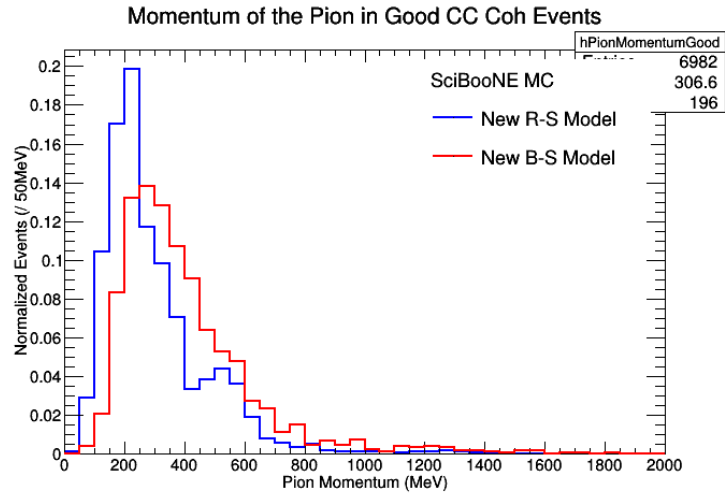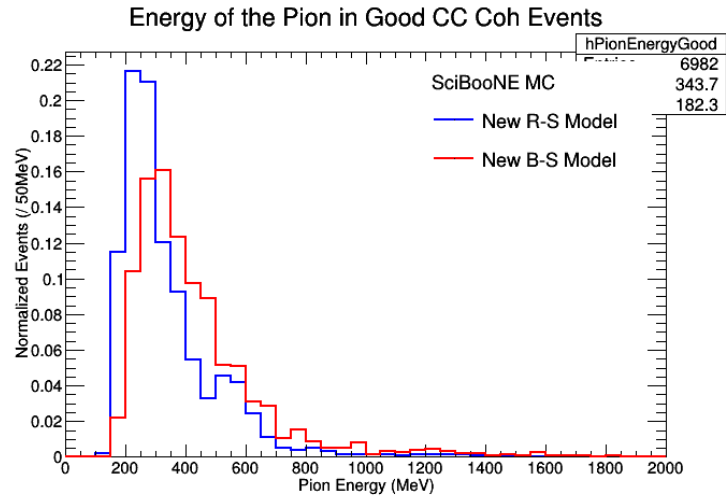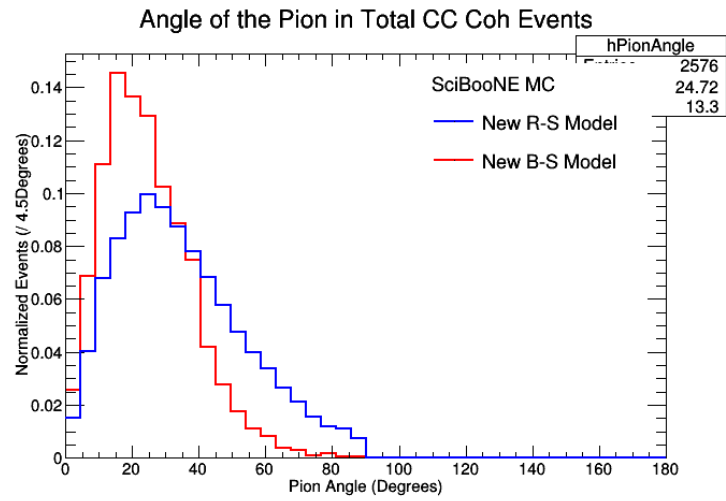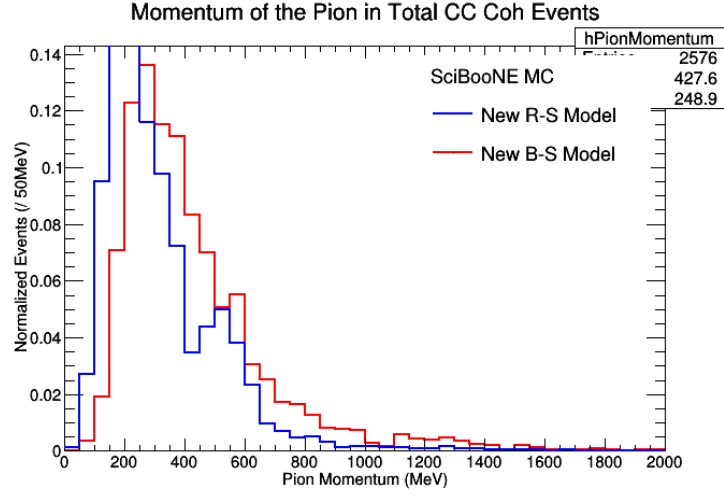
Figure 123
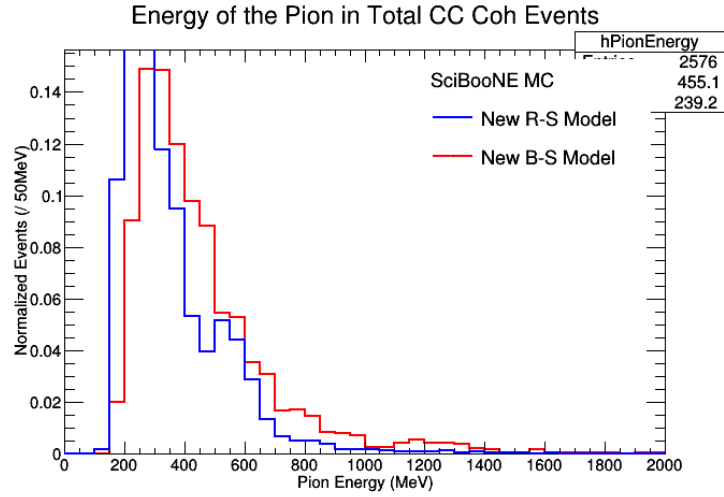
Figure 124

Figure 125

A.17 ANMFourSquaredPlotting.C

All of the four-momentum transfer (both $|t|$ and Q^2) combined plots are made with this file for anti-neutrino mode.
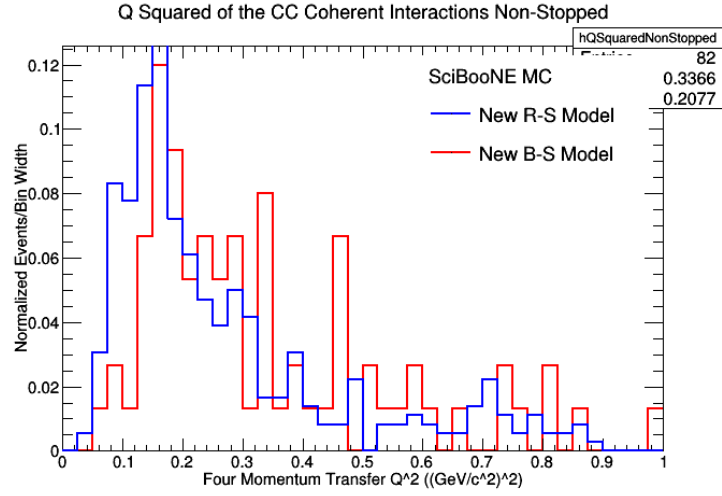
Figure 126
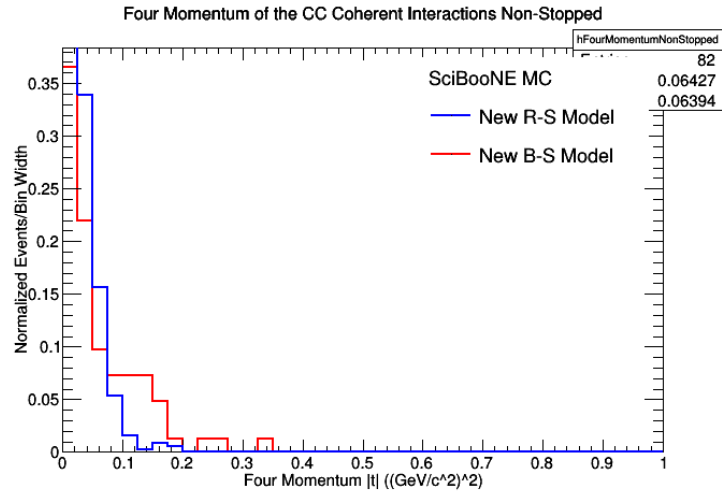
Figure 127
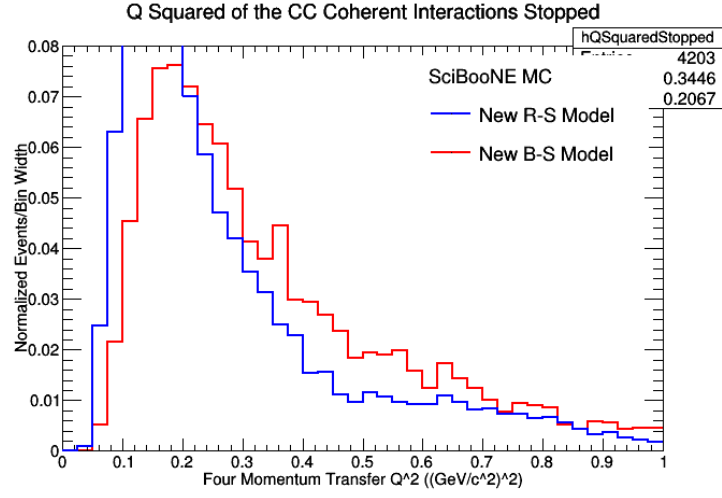
Figure 128
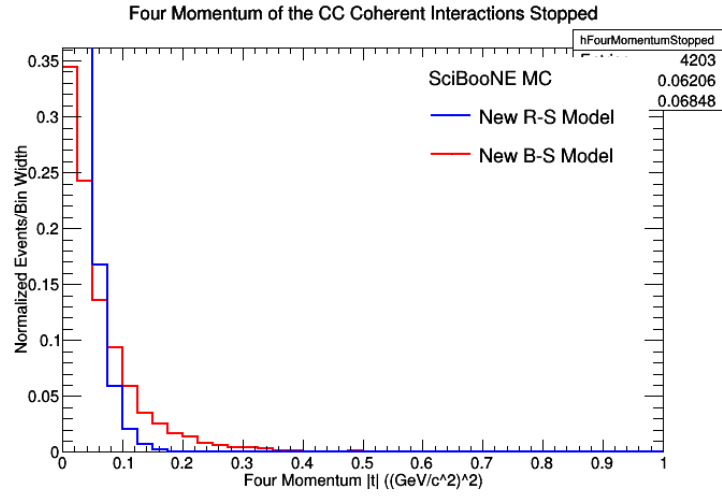
Figure 129
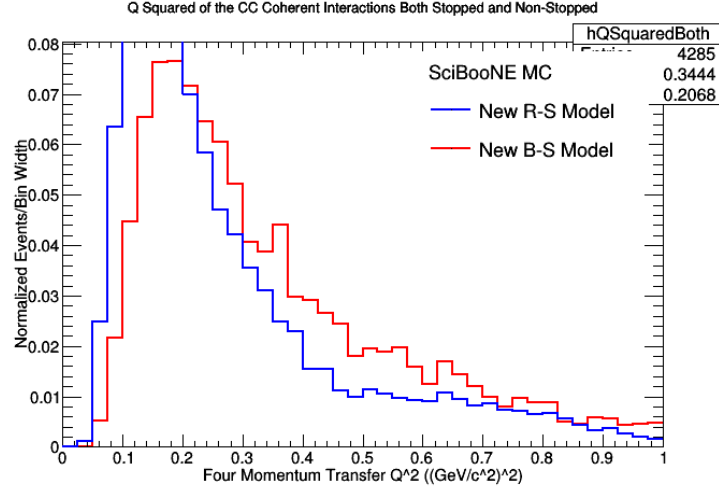
Figure 130
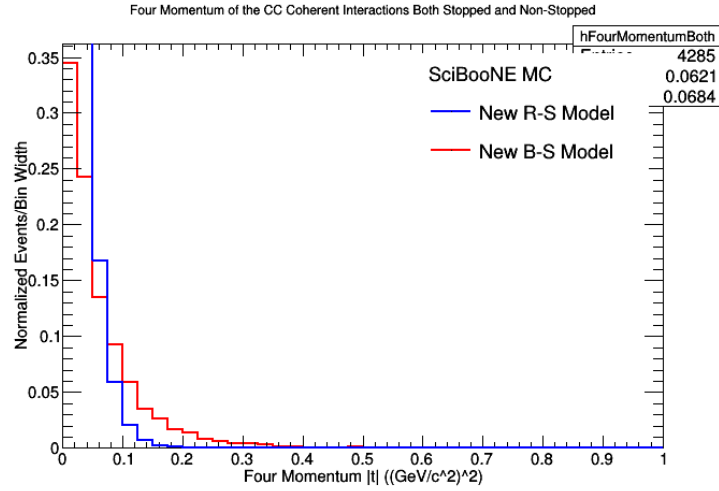
Figure 131

B Steps for Running the Code

The instructions on how to run the code and the order the files need to run in so that there are no resulting error messages, or other issues while running the code, are detailed in this section.

Step 1: This is the first step. (Run the NewNM macros and the NewANM macros and the OldNM macro.)

Step 2: This is the second step. (Run the combined plotting macros.)

Step 3: This is the third step. (Run the Pion Plotting macros.)

Step 4: Etc. (Run the FourSquaredMomentum macros.)

C   Efficiency Tables

These are the corresponding tables to the 2D Efficiency plots for CC-Inclusive events.

Table 3: Table for 2D Histogram for New NM-Rein-Sehgal

Table 4: Table for 2D Histogram for New NM-Berger-Sehgal

Table 5: Table for 2D Histogram for Old NM-Rein-Sehgal

Table 6: Table for 2D Histogram for New ANM-Rein-Sehgal

Table 7: Table for 2D Histogram for New ANM-Berger-Sehgal

These are the corresponding tables to the 2D Efficiency plots for CC-Coherent Pion events.

Table 8: Table for 2D Histogram for New CC-Coh Pion NM-Rein-Sehgal

Table 9: Table for 2D Histogram for New CC-Coh Pion NM-Berger-Sehgal

Table 10: Table for 2D Histogram for Old CC-Coh Pion NM-Rein-Sehgal

Table 11: Table for 2D Histogram for New CC-Coh Pion ANM-Rein-Sehgal

Table 12: Table for 2D Histogram for New CC-Coh Pion ANM-Berger-Sehgal

D   Acknowledgements

Thank everyone who helped, and thank everyone who gave their inputs into your acceptance study. YOU NEED TO GIVE A HUGE AND SPECIAL THANKS TO DR. ASAADI RIGHT HERE! (He has been suuuuuuuper patient...)