Acceptance Study for SciBooNE Charged-Current Coherent Pion Production Technical Note Rough Draft

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Abstract

Should there be an abstract?

1 Introduction

The purpose of this document is to serve as both a reference and guide for those who will work with the SciBooNE Acceptance Study Code that was written by Zachary Williams. Ideally, the order of the figures that appear in this document will follow the order that the same figures appear in the acceptance study slide show hyper-linked here. The code can be downloaded from this github repository labeled SciBooNE-MC. (Eventually need to put in where to go to download the root files that Callum generated for us)

1.1 The Goal

The goal of the reanalysis is to examine the acceptance modeling for the SciBooNE results in the presence of modern neutrino generators and updated models in order to understand why SciBooNE did not observe Charged-Current Coherent Pion Production at low neutrino energy. The purpose of this acceptance study is to blah blah blah... (coming back to this later...)

2 Selecting Charged-Current Coherent Pion Production Events

This section is intended to detail the nuances of this acceptance model, and to detail what assumptions are made in the acceptance modeling to result in accurate classifications of events as Charged-Current Coherent Pion Production, which starts by correctly simulating the detector.

2.1 The Detector

For the purposes of this acceptance study, there are two sub-detectors that the detector of the SciBooNE experiment is composed of. 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 [reference]. 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 momentums of the muons produced from charged-current neutrino interactions up to 1.2 GeV/c by using the observed range of the trajectory of the muon.

2.1.1 The Scintillator Bar Tracker (SciBar)

The Scintillator Bar Tracker (SciBar) sub-detector is a scintillator detector (go into more detail?). In this acceptance study, the z-direction starts at 0 at the front face of the SciBar sub-detector. The direction of the beam is in the z-direction, which means the xy-plane is perpindicular to the beam. The dimensions of the sub-detector have the x and y dimensions of the same length of 3.0 m. The z dimension is 1.7 m. This simulation models the scintillator materials as having a constant energy depostion (dE/dx) value of 2.04 MeV/cm.

2.1.2 The Muon Range Detector (MRD)

The Muon Range Detector (MRD) is located 0.55 m downstream of SciBar in the z-direction, and is a composition of 2 sets of 13 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" (yes, I just used sandwich as a verb) 25 steel layers inbetween 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 (dE/dx) of the muon for the scintillator layers is again a constant of 2.04 MeV/cm and the energy deposition for the steel layers are a constant with value 11.43 MeV/cm.

2.2 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 (need to put a reference) showed in his thesis. This was done by... etc.

Put in the code **for** how we made the vertex distributions of the interactions.

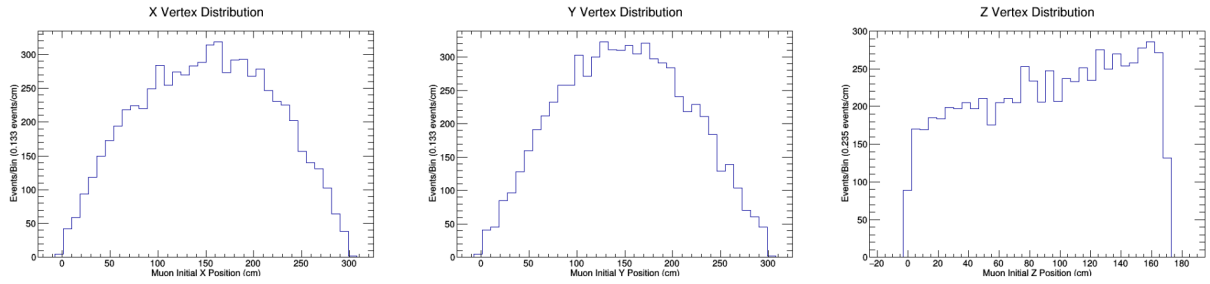

Figure 1: Vertex distributions of the events in the new Rein-Sehgal sample.

2.3 Event Classifications

There were three different classifications for events that qualified as CC-Coh Pion Production events, that the muon made it to the MRD, and the muon penetrated at least three layers of steel. These categories will be referenced multiple times throughout the remainder of this paper, which makes pertinent that the reader has an understanding of what each of the three specifically mean for any event that falls under any of these classifications.

2.3.1 Stopped

An event is classified as "Stopped," if the event qualified as being a CC-Coh Pion Production event, the muon of the event reached the MRD, penetrated three layers of steel, and stopped (or embedded) in the MRD without exiting the sides or the back face. Events that are classified as "Stopped" are included in the combined samples of this acceptance study and are called "Good" events. Maybe put in the dimensions of the xy-plane and z-direction that meet this classification for the MRD? This is shown in the figure below.

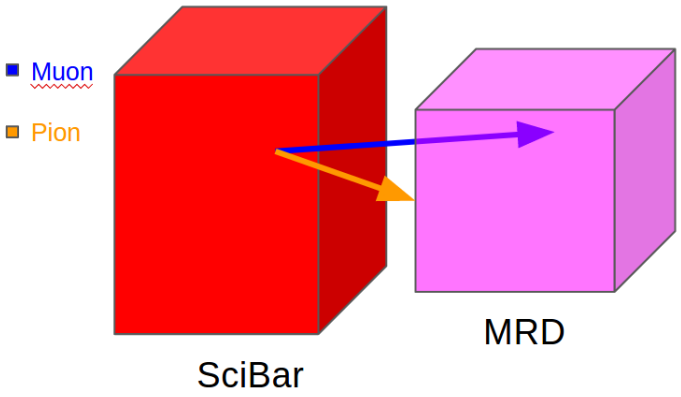

Figure 2: Depiction of an event that was classified as "Stopped."

2.3.2 Not-Stopped

An event is classified as "Not-Stopped," if the event qualified as being a CC-Coh Pion Production event, the muon of the event reached the MRD, and the muon passed out the back face of the MRD without stopping. Events that are classified as "Not-Stopped" are included in the combined samples of this acceptance study and are also called "Good" events. Maybe put in the dimensions of the xy-plane and z-direction that meet this classification for the MRD? This is shown in the figure below.

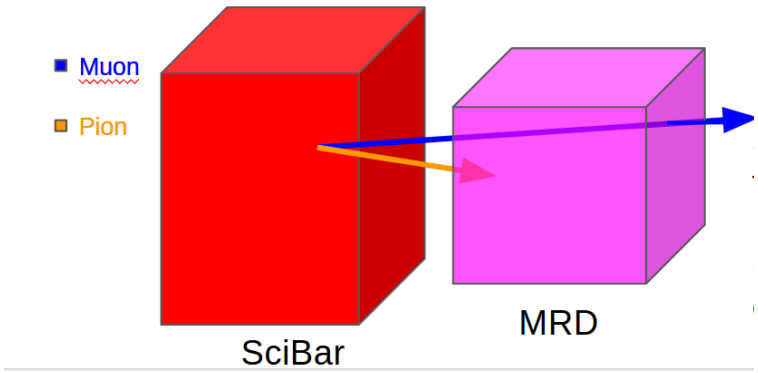

Figure 3: Depiction of an event that was classified as "Not-Stopped."

2.3.3 Out-Side

An event is classified as "Out-Side," if the event qualified as being a CC-Coh Pion Production event, the muon of the event reached the MRD, penetrated three layers of steel, and then passed through one of the sides of the MRD (not including the back face) without stopping. Events that are classified as "Out-Side" are not included in the combined samples because there was not enough material traversal for an accurate reconstruction of the particles momentum and energy to be made. Maybe put in the dimensions of the xy-plane and z-direction that meet this classification for the MRD? This is shown in the figure below.

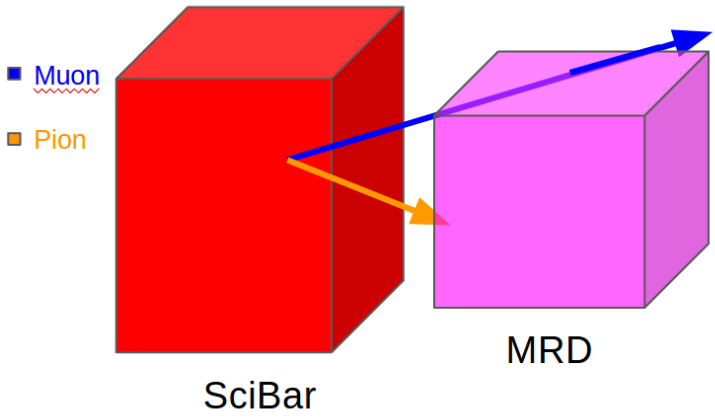

Figure 4: Depiction of an event that was classified as "Out-Side."

2.4 Stepping Through the Detectors Along an Event

I do not know if I am really going to include this here or not...

3 The Files and Their Outputs

This section details the different files, and what the files output.

3.1 SciBooNE_numu_coh_RooTrack.root

This is the root file that contains the Neutrino Mode Rein-Sehgal based events from a newer version of the NEUT generator with 1,000,000 events generated. The version of NEUT that was used is: NEUTv5.3.6. This was generated by Callum Wilkinson, so big thanks to Callum!

3.2 SciBooNE_numubar_coh_RooTrack.root

This is the root file that contains the Anti-Neutrino Mode Rein-Sehgal based events from a newer version of the NEUT generator with 1,000,000 events generated. The version of NEUT that was used is: NEUTv5.3.6. This was also generated by Callum Wilkinson, so big thanks again!

3.3 SciBooNE_numu_coh_RooTrack_NEW.root

This is the root file that contains the Neutrino Mode Berger-Sehgal based events from a newer version of the NEUT generator with 1,000,000 events generated. The version of NEUT that was used is: NEUTv5.3.6. This was again generated by Callum Wilkinson, so big thanks again!

3.4 SciBooNE_numubar_coh_RooTrack_NEW.root

This is the root file that contains the Anti-Neutrino Mode Berger-Sehgal based events from a newer version of the NEUT generator with 1,000,000 events generated. The version of NEUT that was used is: NEUTv5.3.6. This was again generated by Callum Wilkinson, so big thanks yet again!

3.5 SciBooNE_numu_coh_OLDNEUT_RooTrack.root

This is the root file that contains the Neutrino Mode Rein-Sehgal based events from an older version (believed to be the version used by the SciBooNE collaboration) of the NEUT generator with 100,000 generated events. This sample, as a result of being an order of magnitude smaller than the other samples, is statistics limited. This was generated by Callum Wilkinson, so big thanks to Callum again!

3.6 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.

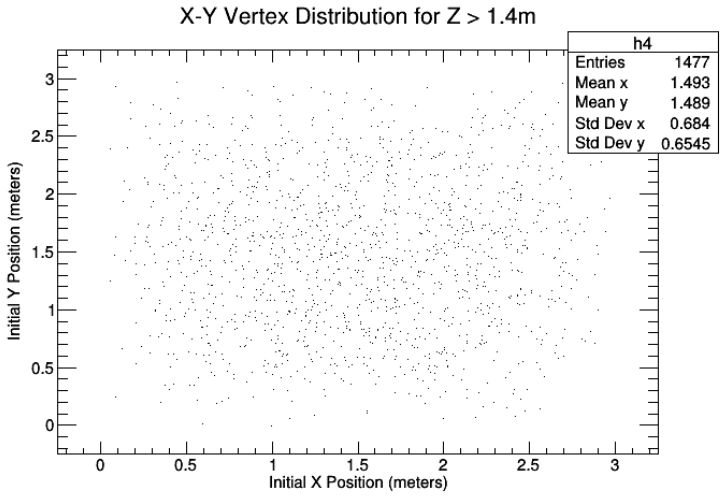

Figure 5: New Rein-Sehgal X-Y vertex distributions for muons that made it to the MRD.

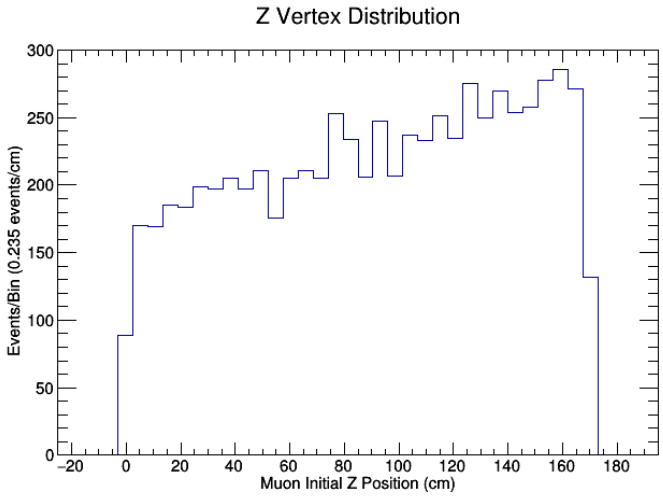

Figure 6: New Rein-Sehgal Z vertex distributions for the interactions.

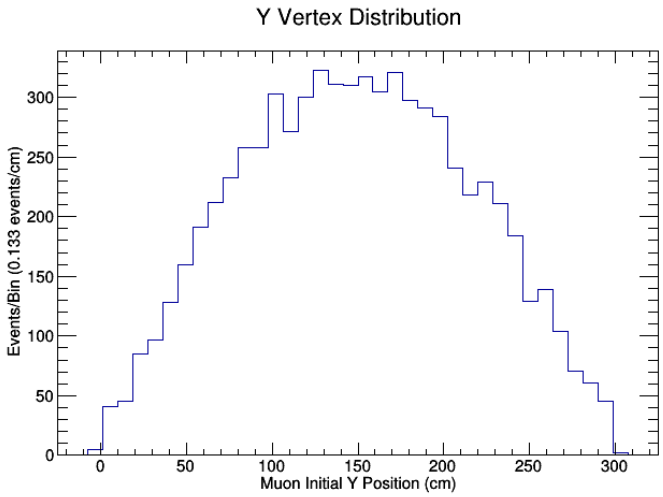

Figure 7: New Rein-Sehgal Y vertex distributions for the interactions.

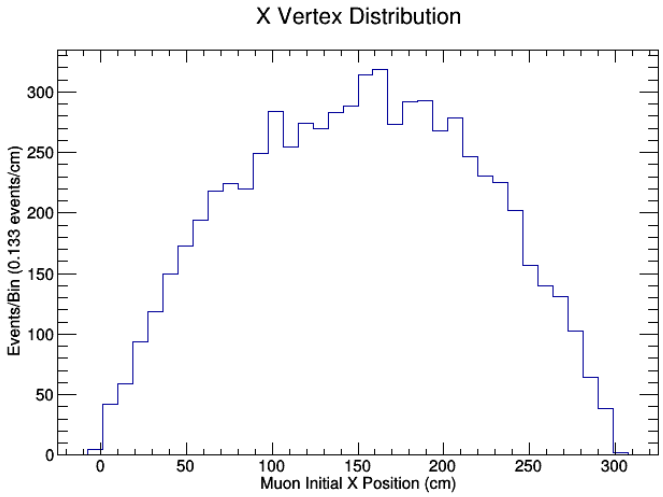

Figure 8: New Rein-Sehgal X vertex distributions for the interactions.

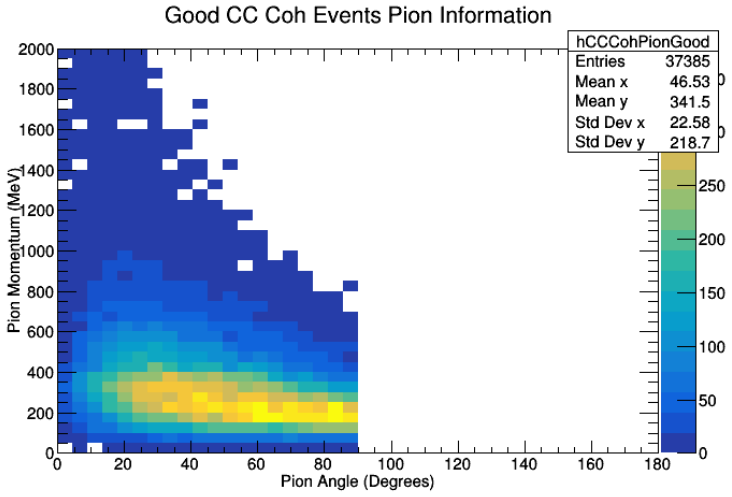

Figure 9: This is a 2D histogram for the momentum and angle of the pion in the CC Coh Pion events that met the qualification of being "good".

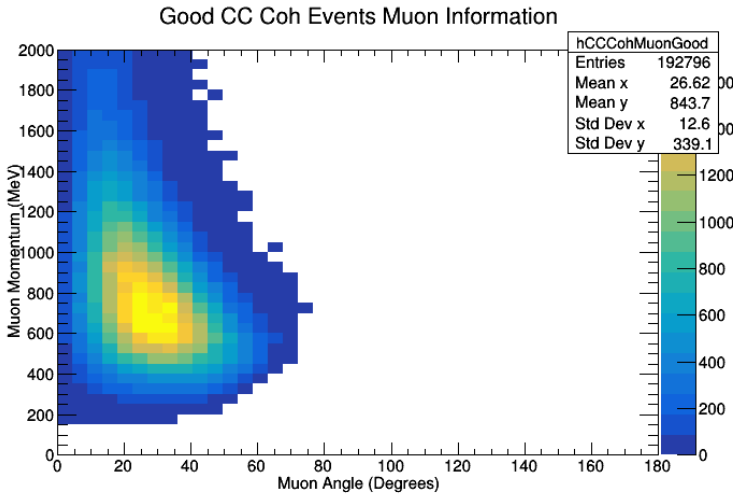

Figure 10: This is a 2D histogram for the momentum and angle of the muon in the CC Coh Pion events that met the qualification of being "good".

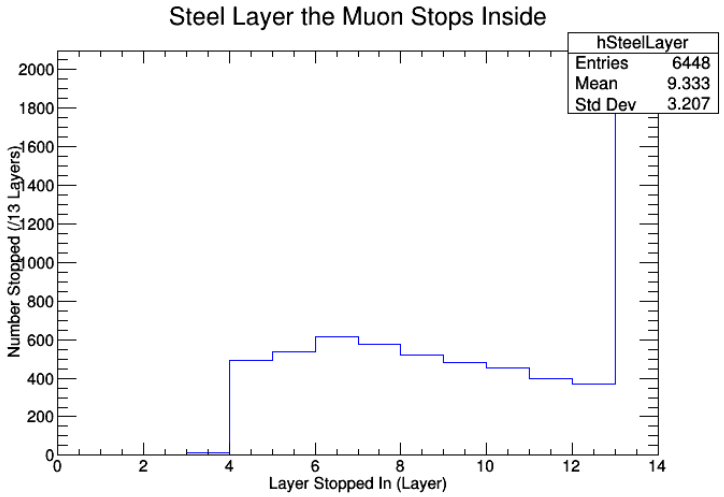

Figure 11: This histogram depicts the amount of muons that embedded in what layer of steel.

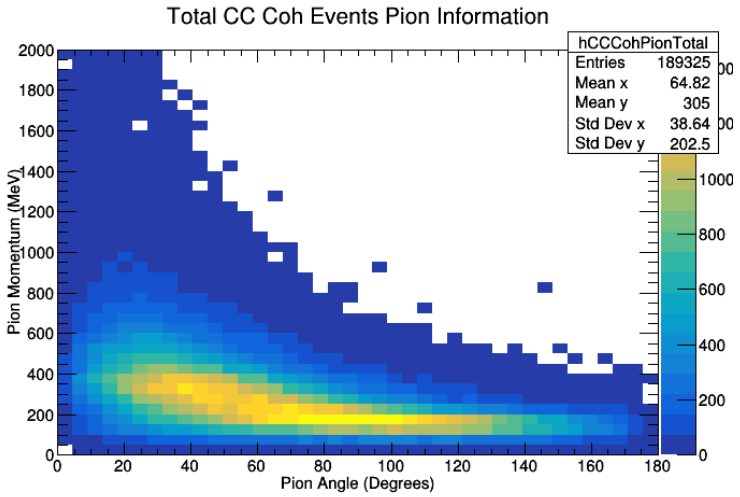

Figure 12: This is a plot right here. Nice of you to notice!

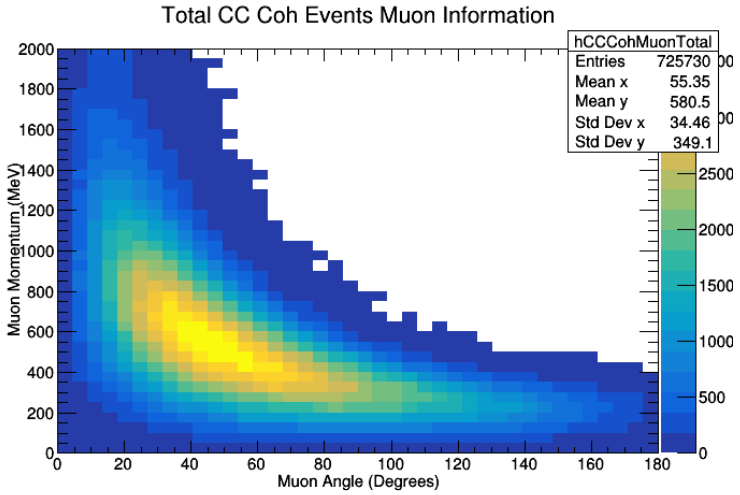

Figure 13: This is a plot right here. Nice of you to notice!

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:

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

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

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:

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

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

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°.

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:

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

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 $(MeV/c)^2$.

3.7 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).

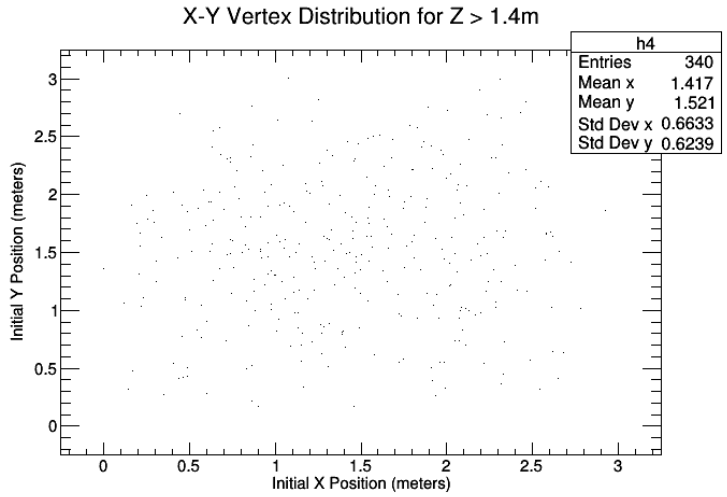

Figure 14: This is a plot right here. Nice of you to notice!

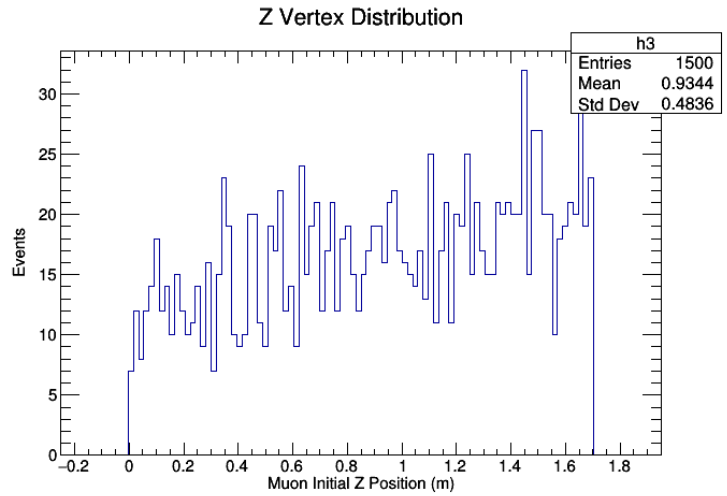

Figure 15: This is a plot right here. Nice of you to notice!

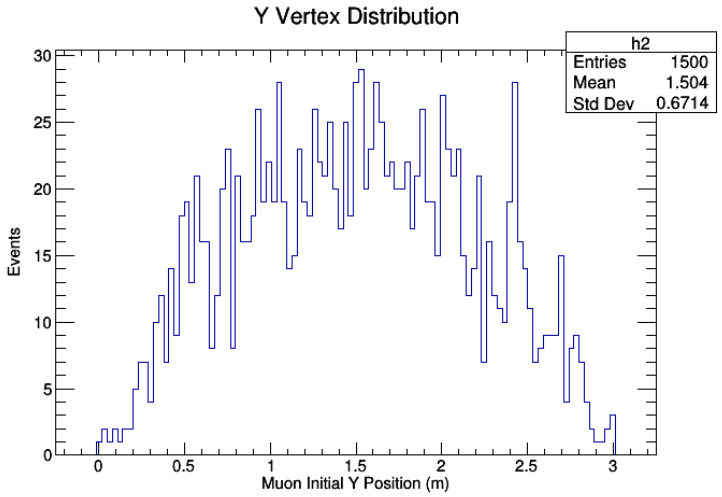

Figure 16: This is a plot right here. Nice of you to notice!

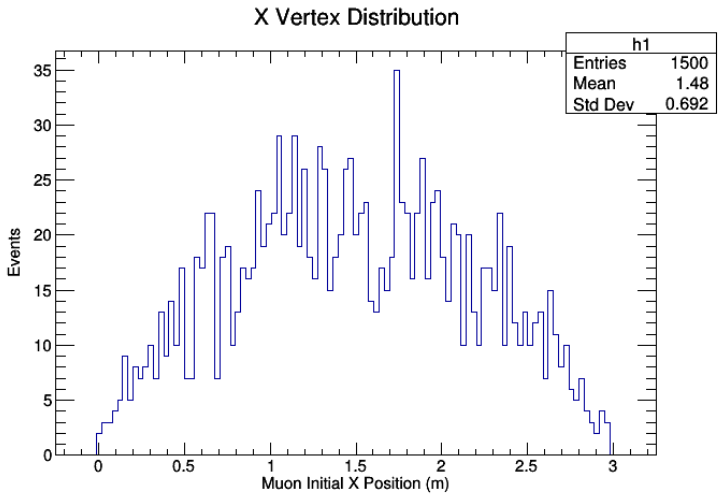

Figure 17: This is a plot right here. Nice of you to notice!

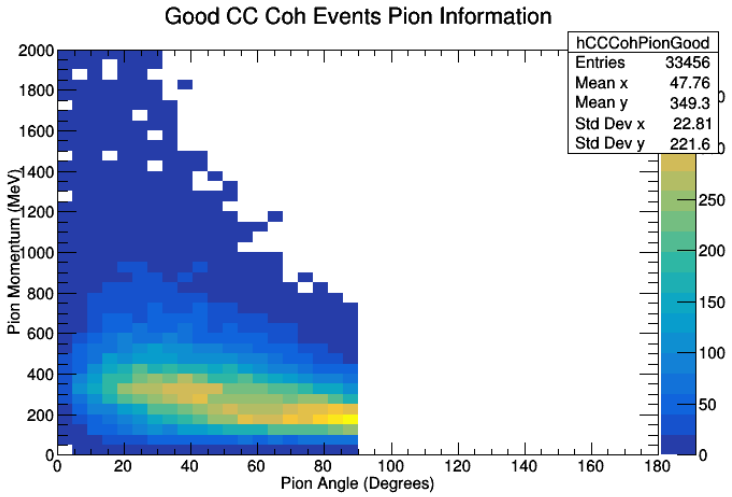

Figure 18: This is a plot right here. Nice of you to notice!

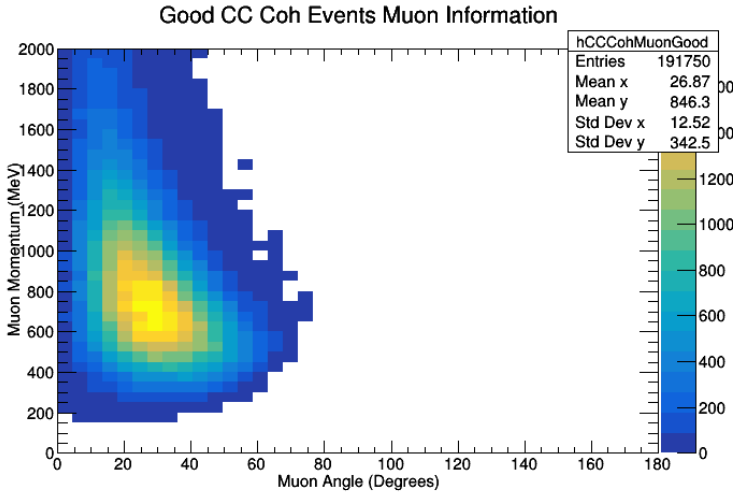

Figure 19: This is a plot right here. Nice of you to notice!

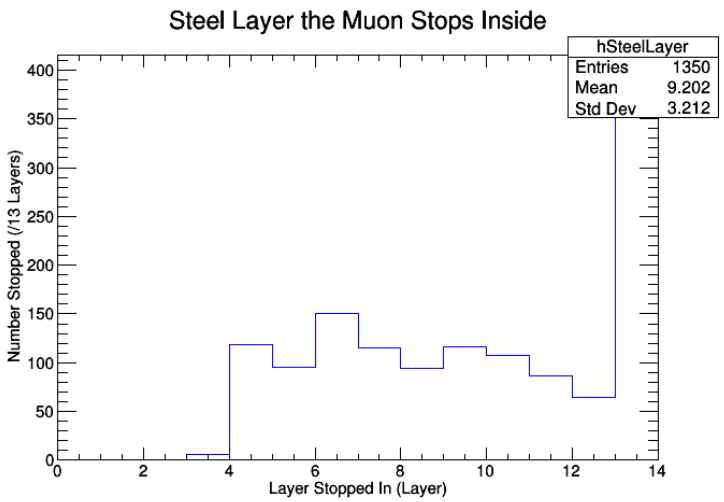

Figure 20: This is a plot right here. Nice of you to notice!

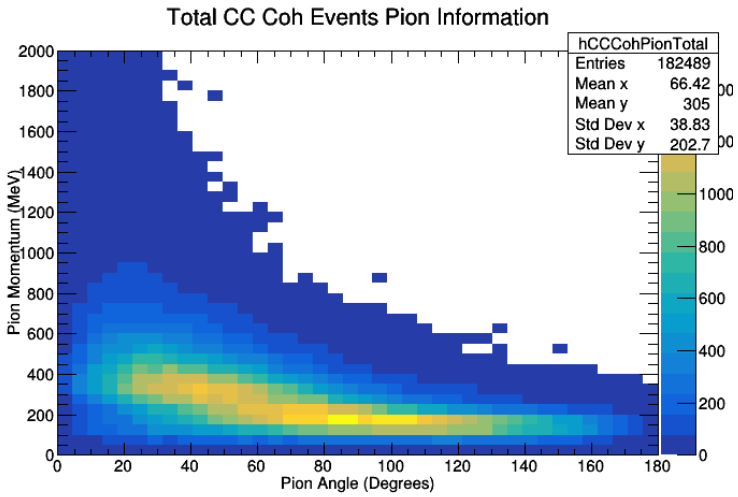

Figure 21: This is a plot right here. Nice of you to notice!

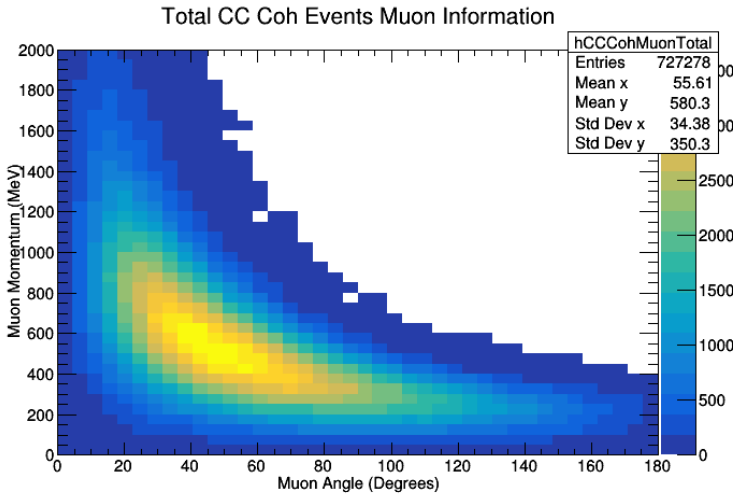

Figure 22: This is a plot right here. Nice of you to notice!

The NewNMBergerSehgal.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:

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

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:

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

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 $(MeV/c)^2$.

3.8 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).

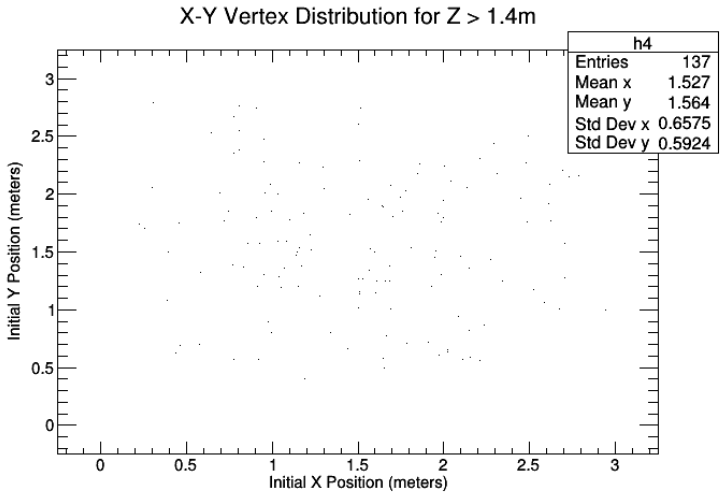

Figure 23: This is a plot right here. Nice of you to notice!

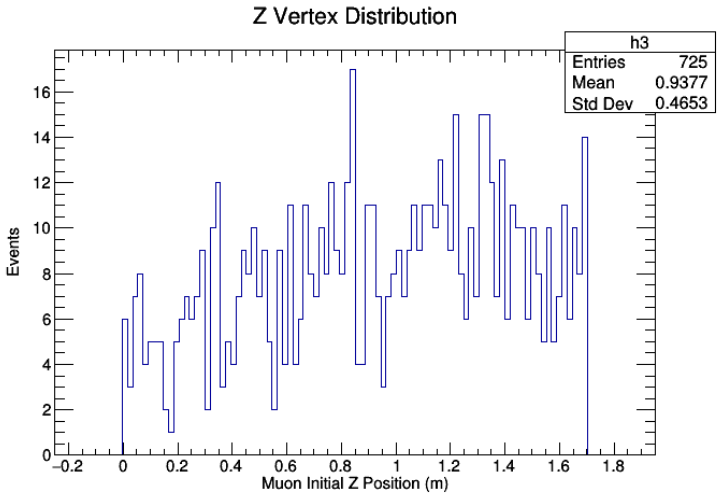

Figure 24: This is a plot right here. Nice of you to notice!

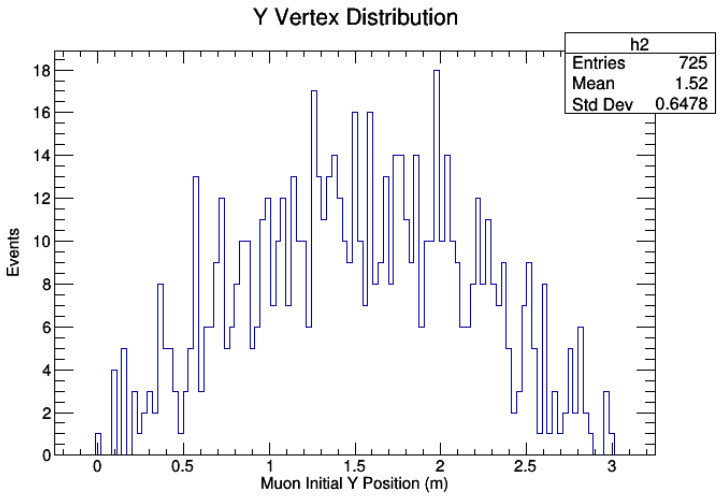

Figure 25: This is a plot right here. Nice of you to notice!

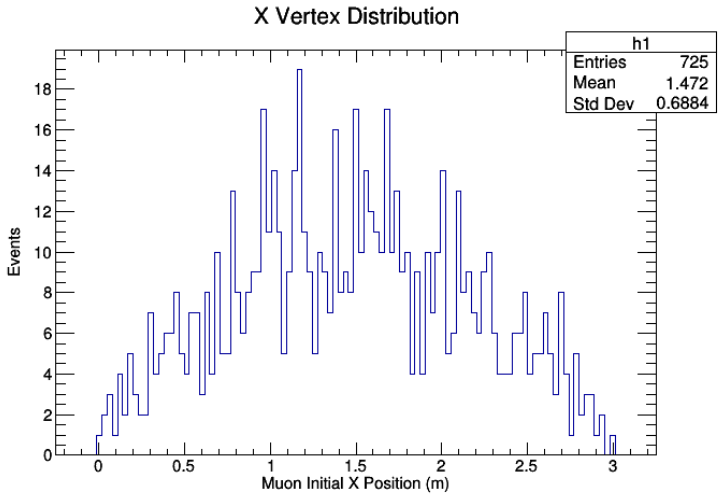

Figure 26: This is a plot right here. Nice of you to notice!

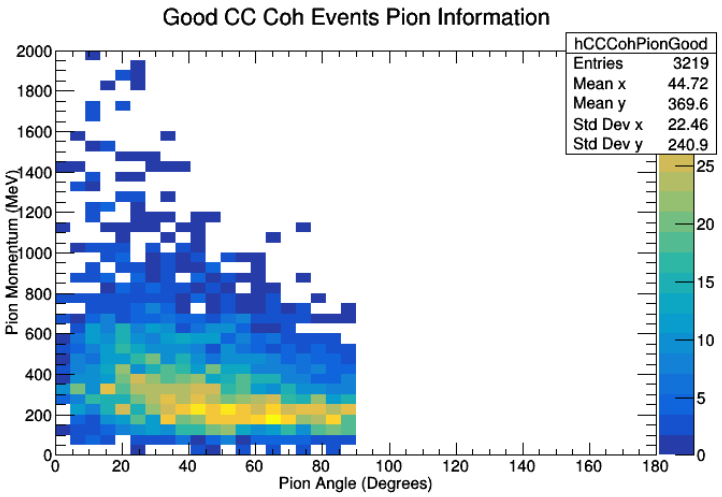

Figure 27: This is a plot right here. Nice of you to notice!

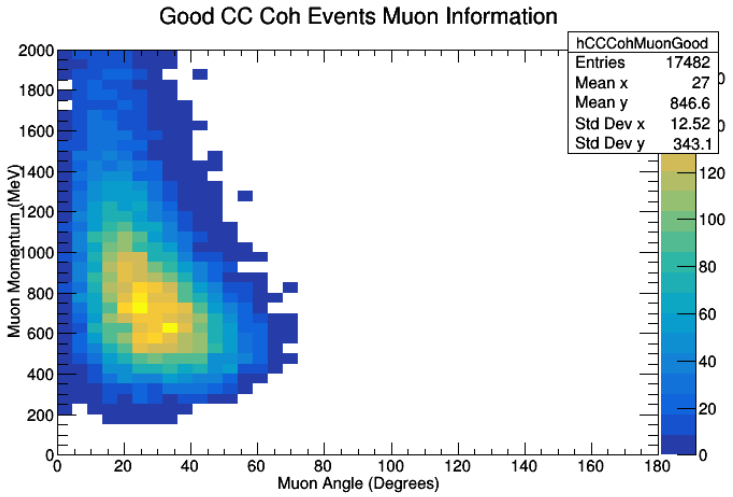

Figure 28: This is a plot right here. Nice of you to notice!

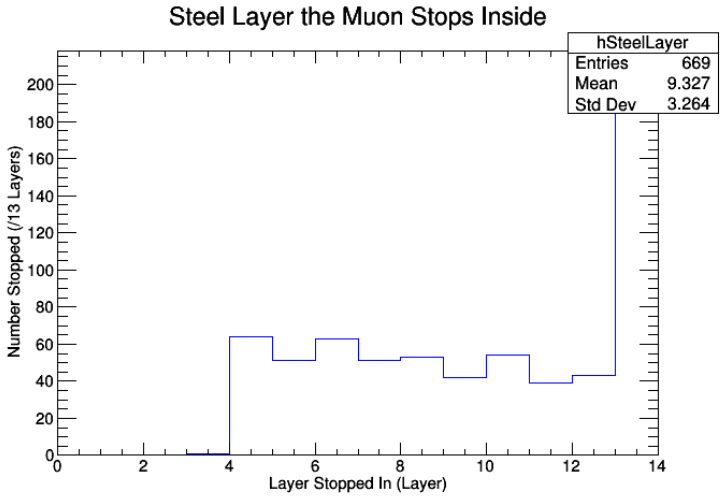

Figure 29: This is a plot right here. Nice of you to notice!

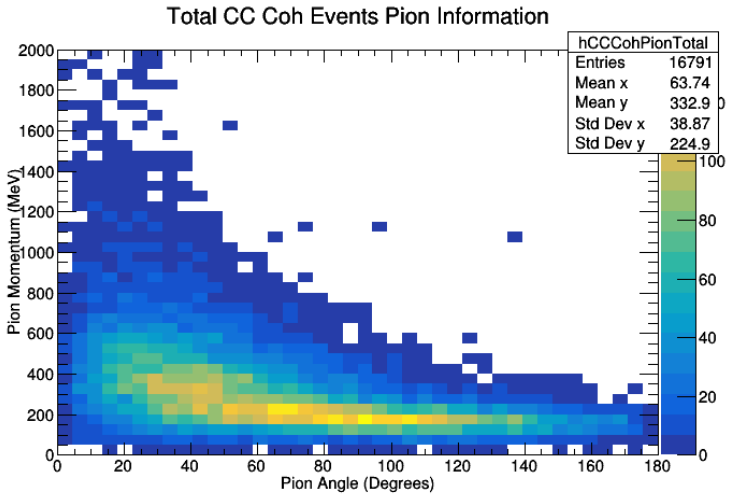

Figure 30: This is a plot right here. Nice of you to notice!

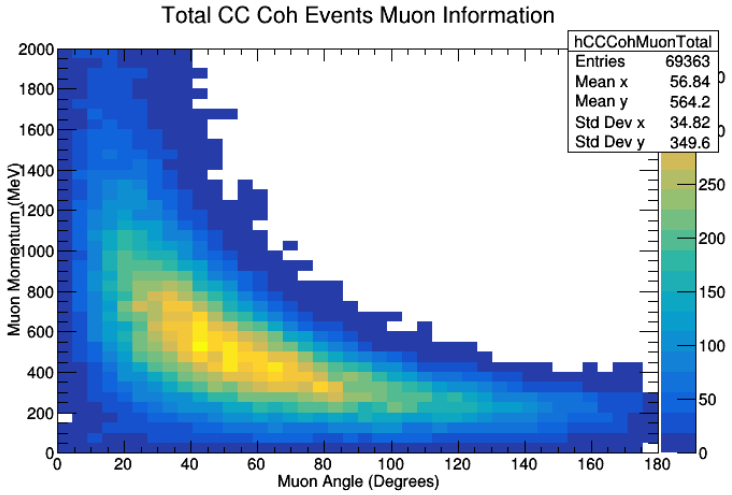

Figure 31: This is a plot right here. Nice of you to notice!

The OldNMReinSehgal.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:

$$|\vec{p}_\mu| = \sqrt{P_{\mu_x}^2 + P_{\mu_y}^2 + P_{\mu_z}^2} \tag{17}$$

$$|\vec{p}_\pi| = \sqrt{P_{\pi_x}^2 + P_{\pi_y}^2 + P_{\pi_z}^2} \tag{18}$$

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:

$$\theta_\mu = tan^{-1}(\sqrt{P_{\mu_x}^2 + P_{\mu_y}^2}/P_{\mu_z}) \tag{19}$$

$$\theta_\pi = tan^{-1}(\sqrt{P_{\pi_x}^2 + P_{\pi_y}^2}/P_{\pi_z}) \tag{20}$$

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:

$$Q^2 = |(P_{\nu_\mu} - P_\mu)^2| \tag{21}$$

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

$$Q^2 = |(P_{\nu_{\mu,x}} - P_{\mu_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E})^2| \tag{22}$$

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:

$$|t| = |(Q - P_\pi)^2| = |(P_{\nu_\mu} - P_\mu - P_\pi)^2| \tag{23}$$

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

$$|t| = |(P_{\nu_{\mu,x}} - P_{\mu_x} - P_{\pi_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y} - P_{\pi_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z} - P_{\pi_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E} - P_{\pi_E})^2| \tag{24}$$

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

3.9 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).

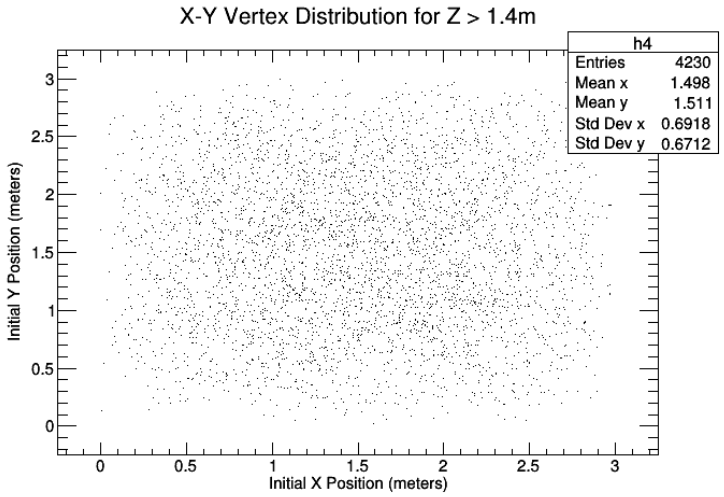

Figure 32: This is a plot right here. Nice of you to notice!

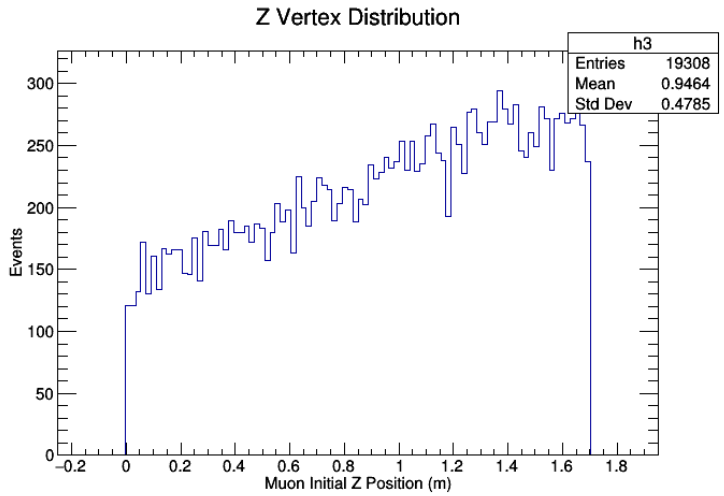

Figure 33: This is a plot right here. Nice of you to notice!

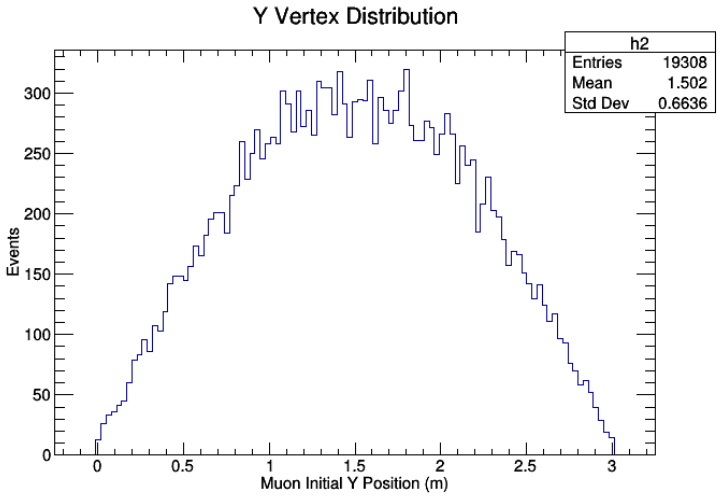

Figure 34: This is a plot right here. Nice of you to notice!

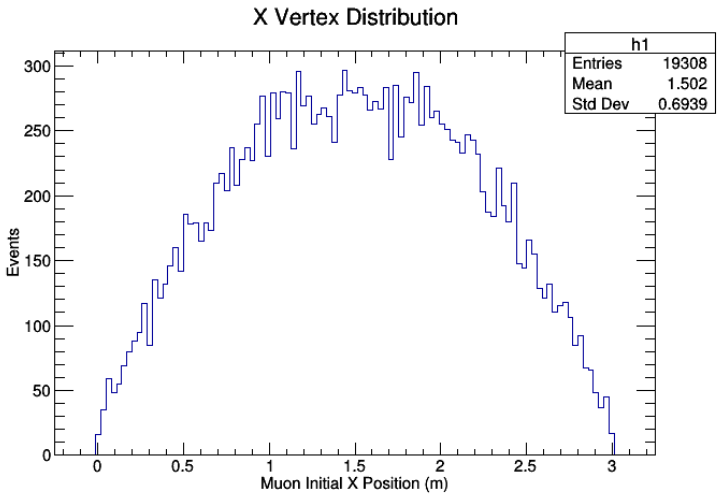

Figure 35: This is a plot right here. Nice of you to notice!

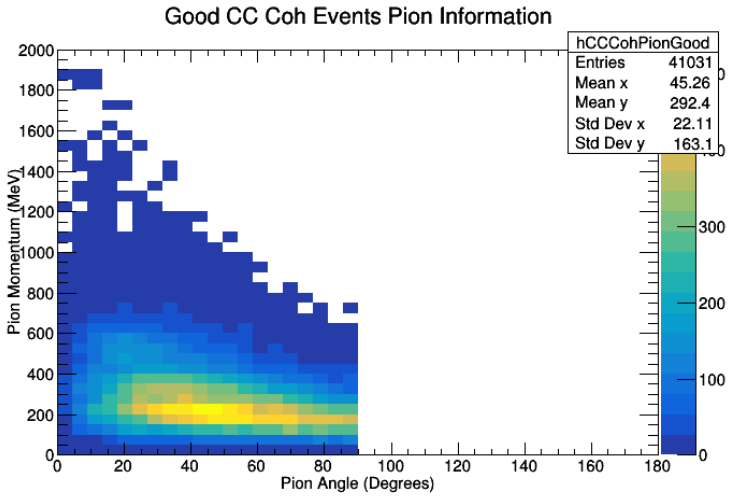

Figure 36: This is a plot right here. Nice of you to notice!

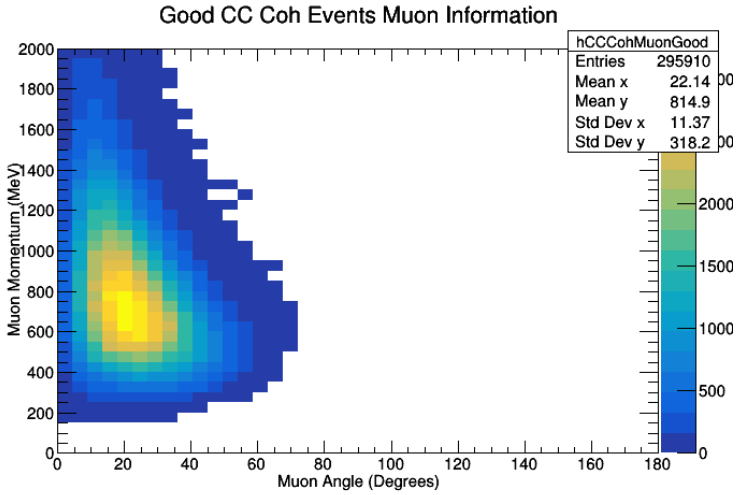

Figure 37: This is a plot right here. Nice of you to notice!

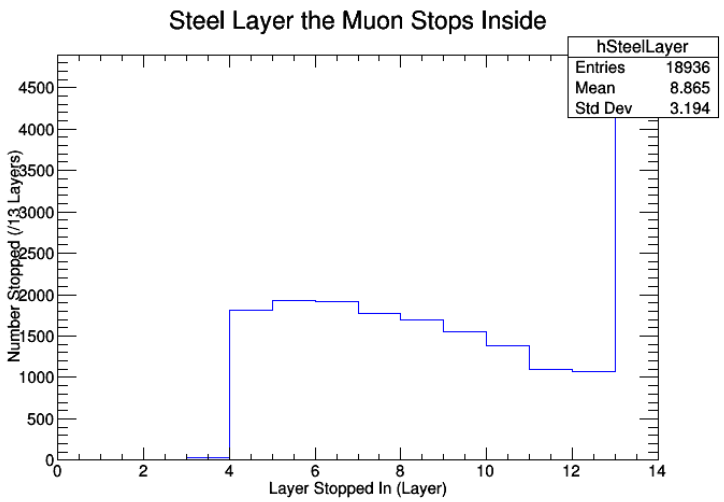

Figure 38: This is a plot right here. Nice of you to notice!

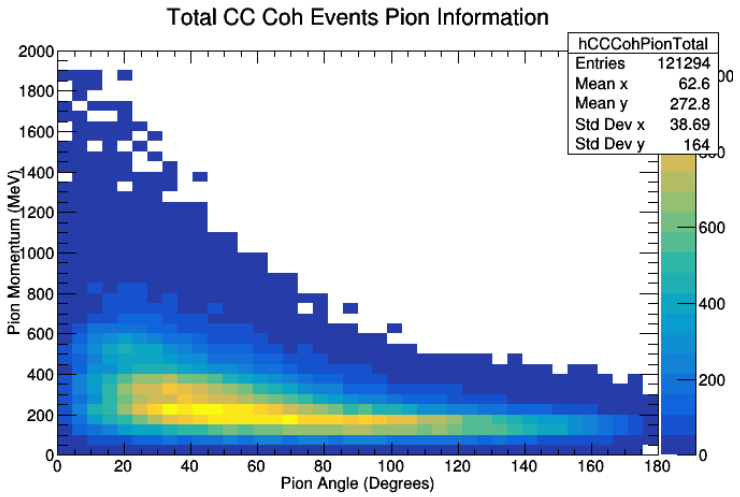

Figure 39: This is a plot right here. Nice of you to notice!

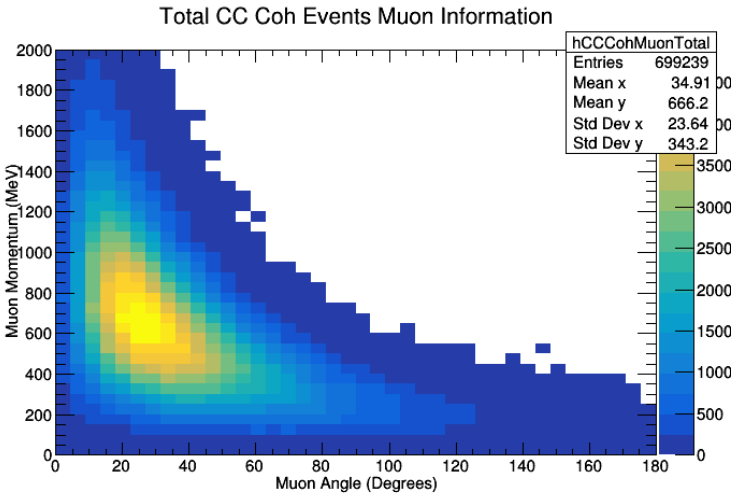

Figure 40: This is a plot right here. Nice of you to notice!

The NewANMReinSehgal.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:

$$|\vec{p}_\mu| = \sqrt{P_{\mu_x}^2 + P_{\mu_y}^2 + P_{\mu_z}^2} \tag{25}$$

$$|\vec{p}_\pi| = \sqrt{P_{\pi_x}^2 + P_{\pi_y}^2 + P_{\pi_z}^2} \tag{26}$$

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:

$$\theta_\mu = tan^{-1}(\sqrt{P_{\mu_x}^2 + P_{\mu_y}^2}/P_{\mu_z}) \tag{27}$$

$$\theta_\pi = tan^{-1}(\sqrt{P_{\pi_x}^2 + P_{\pi_y}^2}/P_{\pi_z}) \tag{28}$$

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:

$$Q^2 = |(P_{\nu_\mu} - P_\mu)^2| \tag{29}$$

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

$$Q^2 = |(P_{\nu_{\mu,x}} - P_{\mu_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E})^2| \tag{30}$$

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:

$$|t| = |(Q - P_\pi)^2| = |(P_{\nu_\mu} - P_\mu - P_\pi)^2| \tag{31}$$

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

$$|t| = |(P_{\nu_{\mu,x}} - P_{\mu_x} - P_{\pi_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y} - P_{\pi_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z} - P_{\pi_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E} - P_{\pi_E})^2| \tag{32}$$

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

3.10 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).

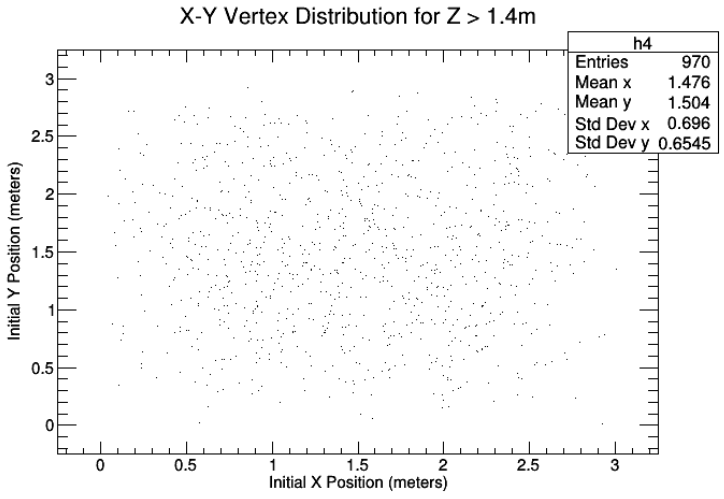

Figure 41: This is a plot right here. Nice of you to notice!

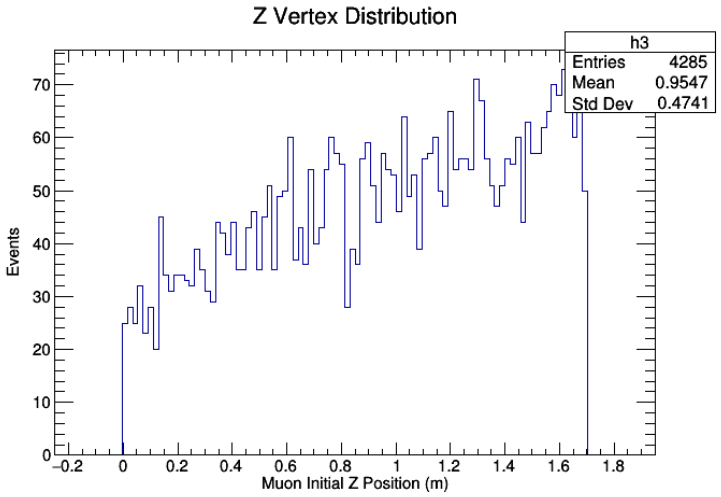

Figure 42: This is a plot right here. Nice of you to notice!

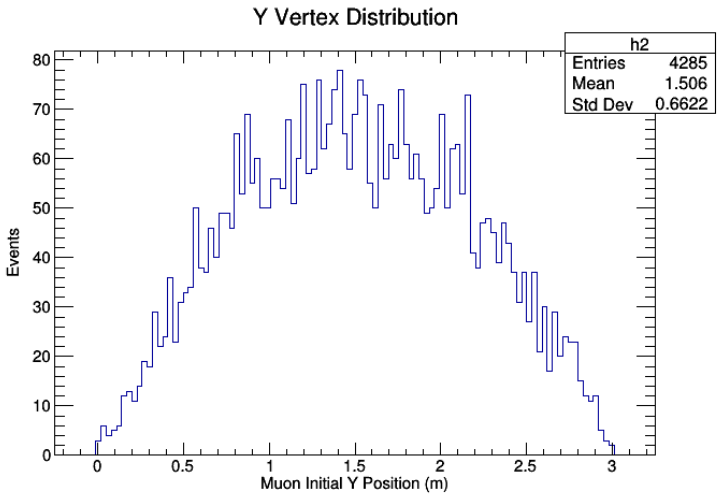

Figure 43: This is a plot right here. Nice of you to notice!

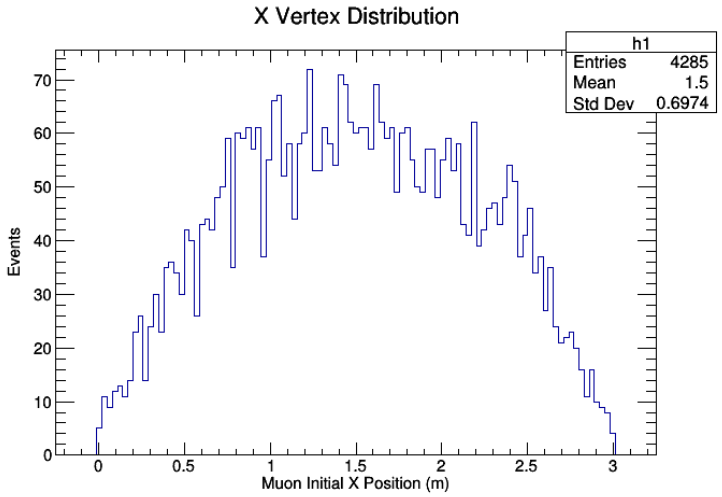

Figure 44: This is a plot right here. Nice of you to notice!

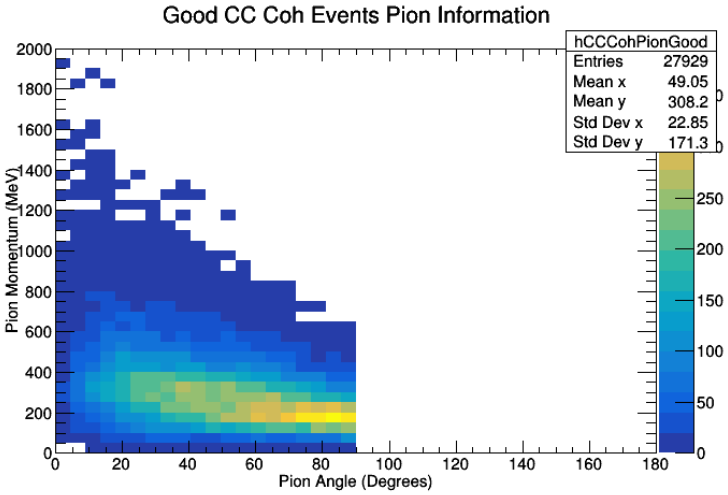

Figure 45: This is a plot right here. Nice of you to notice!

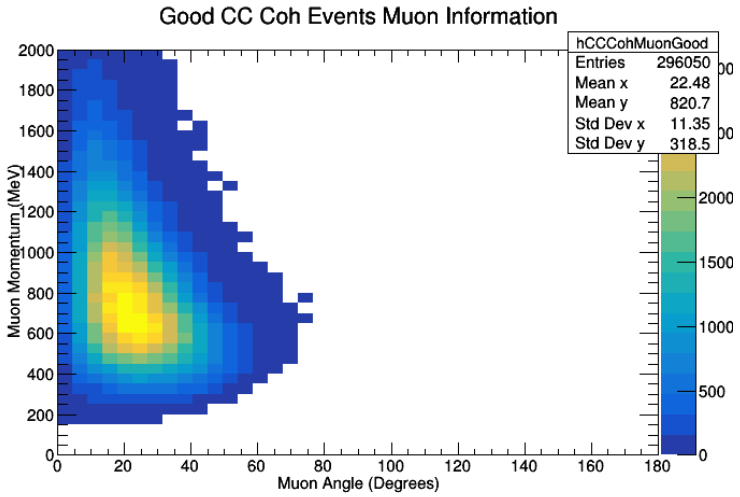

Figure 46: This is a plot right here. Nice of you to notice!

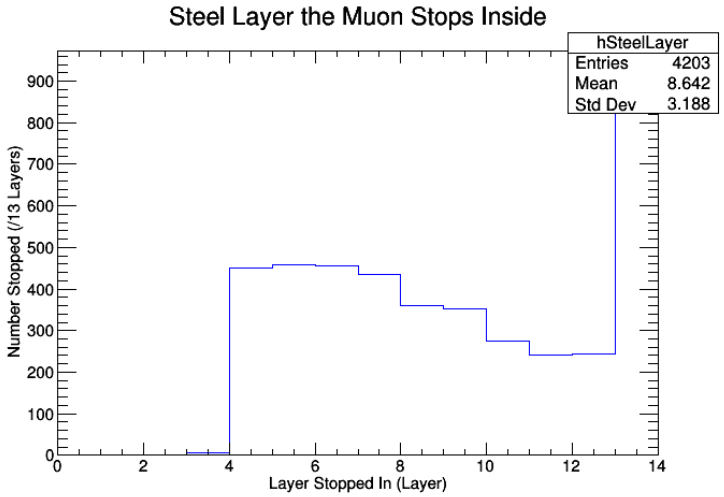

Figure 47: This is a plot right here. Nice of you to notice!

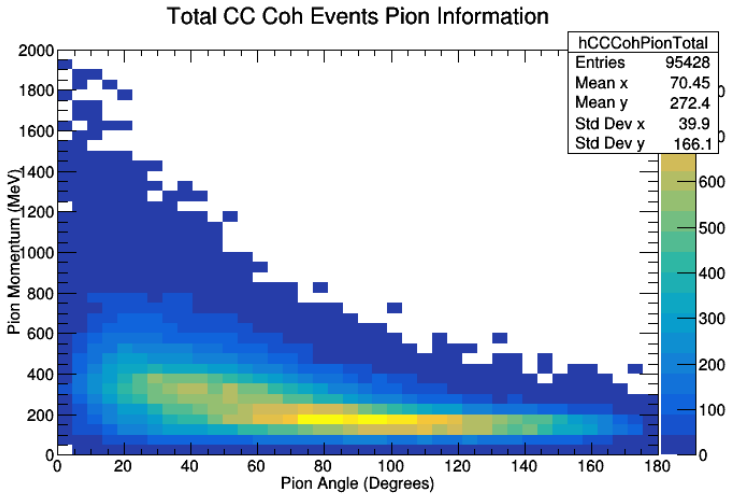

Figure 48: This is a plot right here. Nice of you to notice!

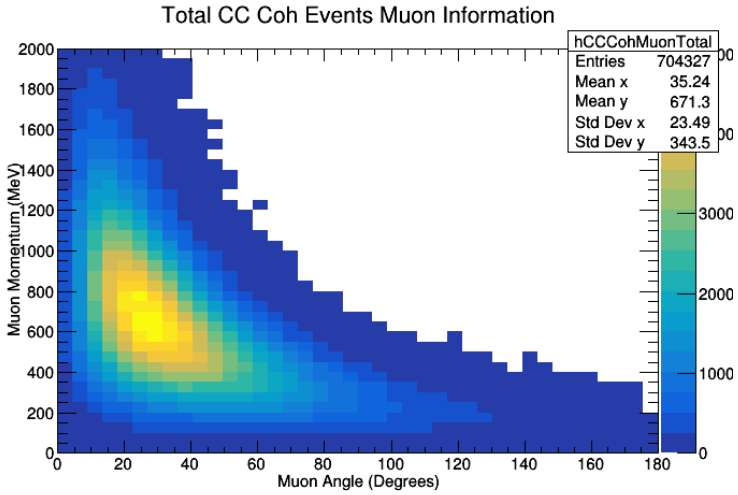

Figure 49: This is a plot right here. Nice of you to notice!

The NewANMBergerSehgal.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:

$$|\vec{p}_\mu| = \sqrt{P_{\mu_x}^2 + P_{\mu_y}^2 + P_{\mu_z}^2} \tag{33}$$

$$|\vec{p}_\pi| = \sqrt{P_{\pi_x}^2 + P_{\pi_y}^2 + P_{\pi_z}^2} \tag{34}$$

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:

$$\theta_\mu = tan^{-1}(\sqrt{P_{\mu_x}^2 + P_{\mu_y}^2}/P_{\mu_z}) \tag{35}$$

$$\theta_\pi = tan^{-1}(\sqrt{P_{\pi_x}^2 + P_{\pi_y}^2}/P_{\pi_z}) \tag{36}$$

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:

$$Q^2 = |(P_{\nu_\mu} - P_\mu)^2| \tag{37}$$

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

$$Q^2 = |(P_{\nu_{\mu,x}} - P_{\mu_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E})^2| \tag{38}$$

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:

$$|t| = |(Q - P_\pi)^2| = |(P_{\nu_\mu} - P_\mu - P_\pi)^2| \tag{39}$$

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

$$|t| = |(P_{\nu_{\mu,x}} - P_{\mu_x} - P_{\pi_x})^2 + (P_{\nu_{\mu,y}} - P_{\mu_y} - P_{\pi_y})^2 + (P_{\nu_{\mu,z}} - P_{\mu_z} - P_{\pi_z})^2 + (P_{\nu_{\mu,E}} - P_{\mu_E} - P_{\pi_E})^2| \tag{40}$$

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

3.11 NMCombinedPlots.C

I need to come back and insert all of my images here.

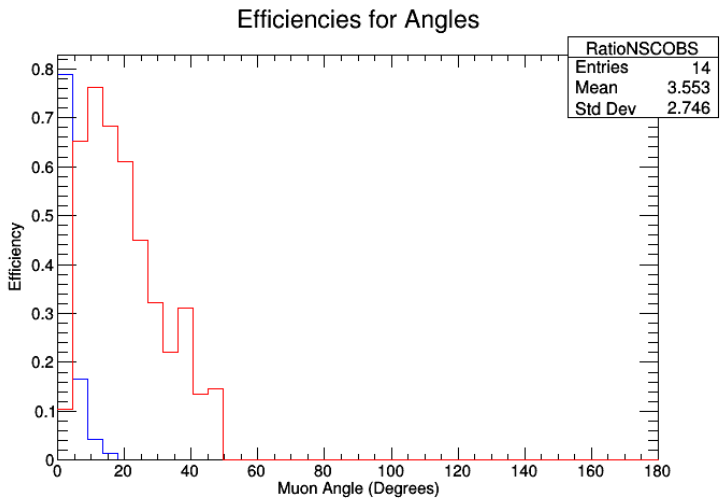

Figure 50: This is a plot right here. Nice of you to notice!

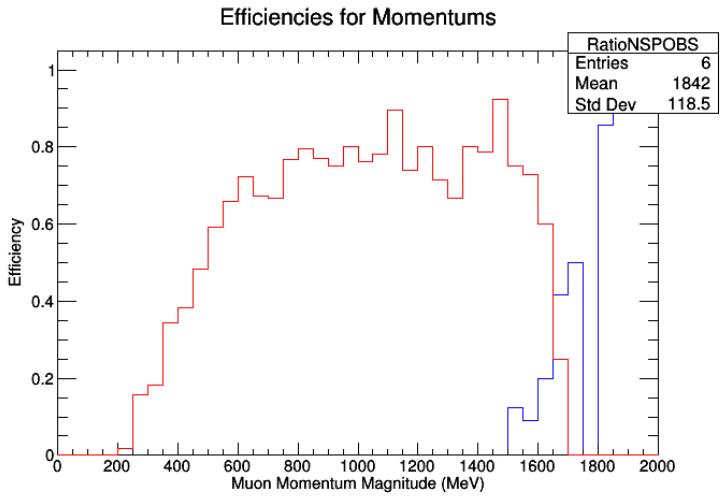

Figure 51: This is a plot right here. Nice of you to notice!

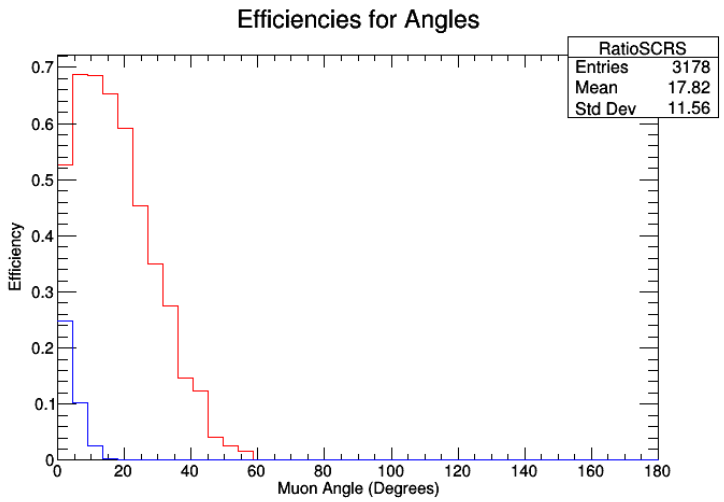

Figure 52: This is a plot right here. Nice of you to notice!

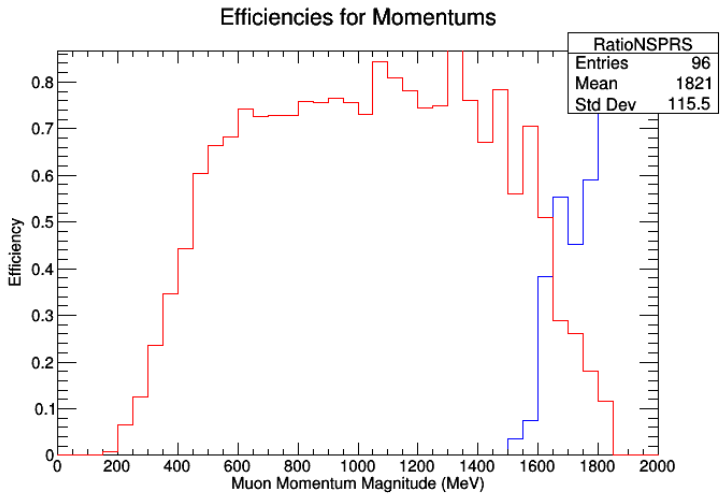

Figure 53: This is a plot right here. Nice of you to notice!

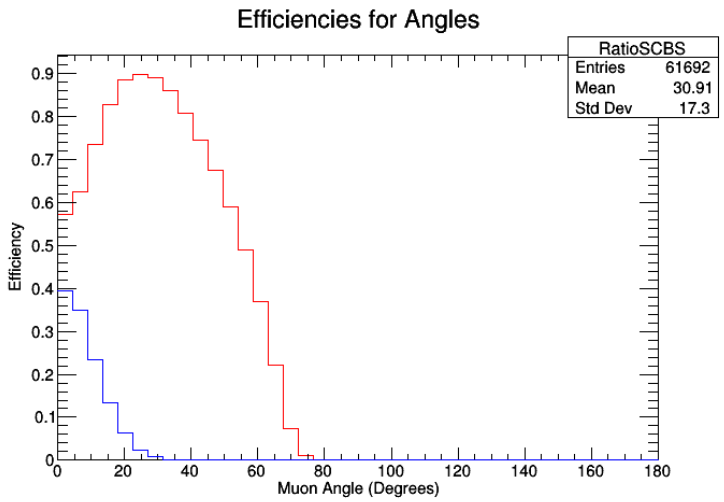

Figure 54: This is a plot right here. Nice of you to notice!

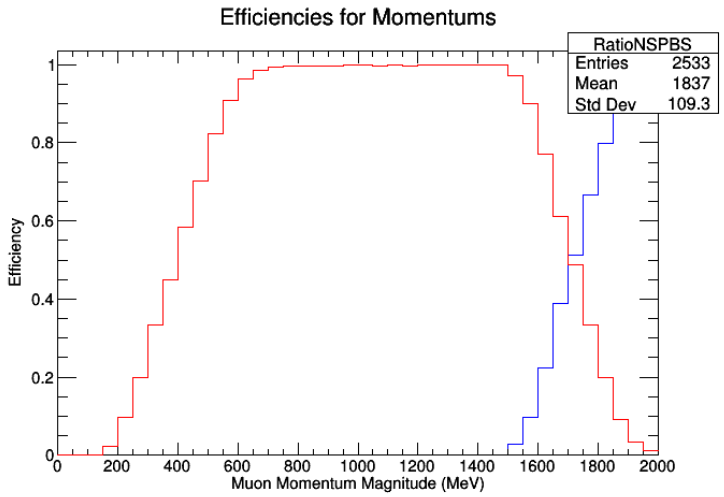

Figure 55: This is a plot right here. Nice of you to notice!

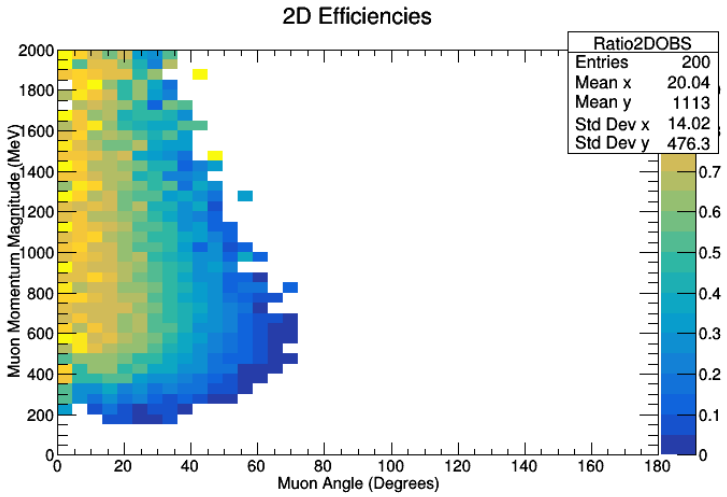

Figure 56: This is a plot right here. Nice of you to notice!

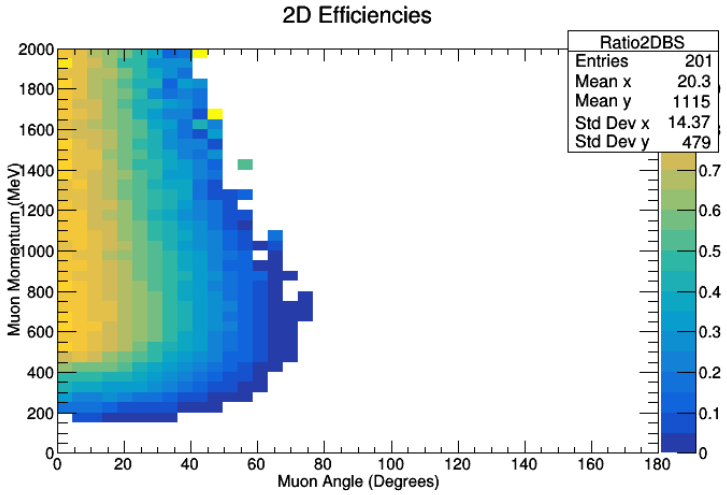

Figure 57: This is a plot right here. Nice of you to notice!

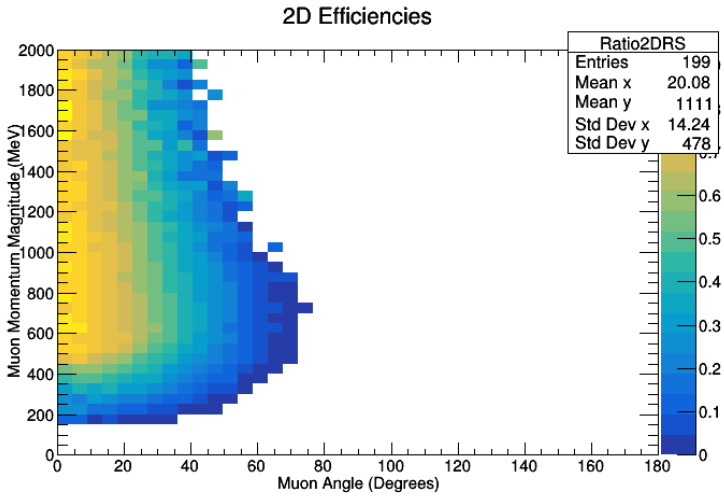

Figure 58: This is a plot right here. Nice of you to notice!

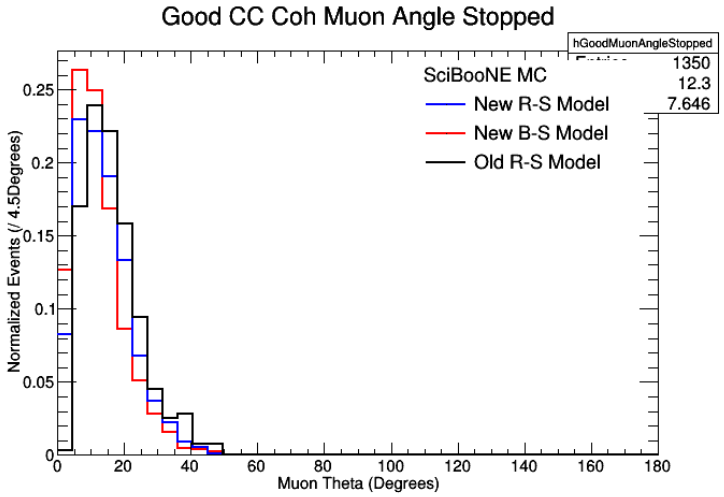

Figure 59: This is a plot right here. Nice of you to notice!

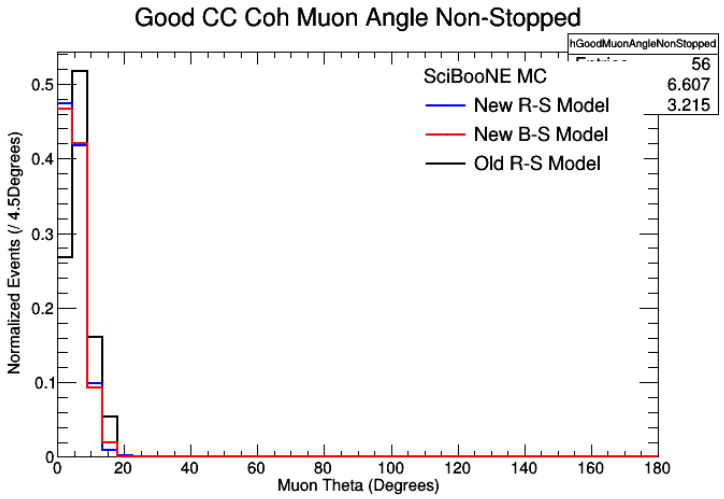

Figure 60: This is a plot right here. Nice of you to notice!

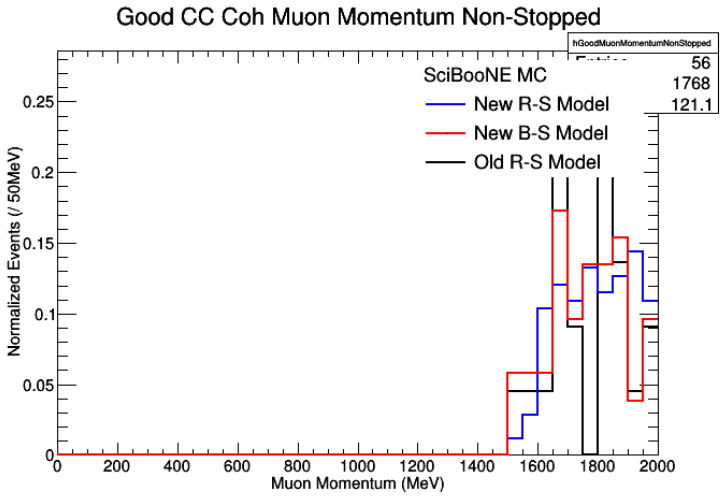

Figure 61: This is a plot right here. Nice of you to notice!

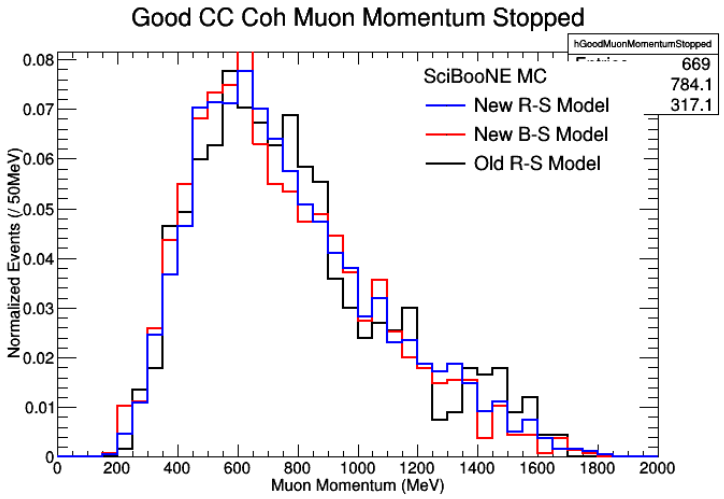

Figure 62: This is a plot right here. Nice of you to notice!

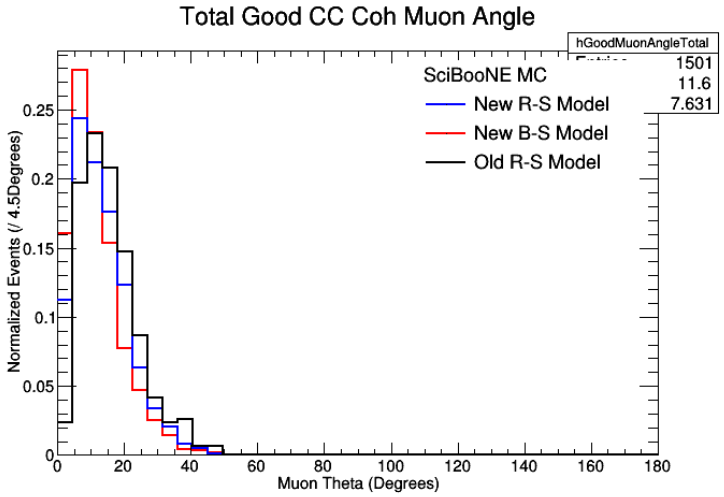

Figure 63: This is a plot right here. Nice of you to notice!

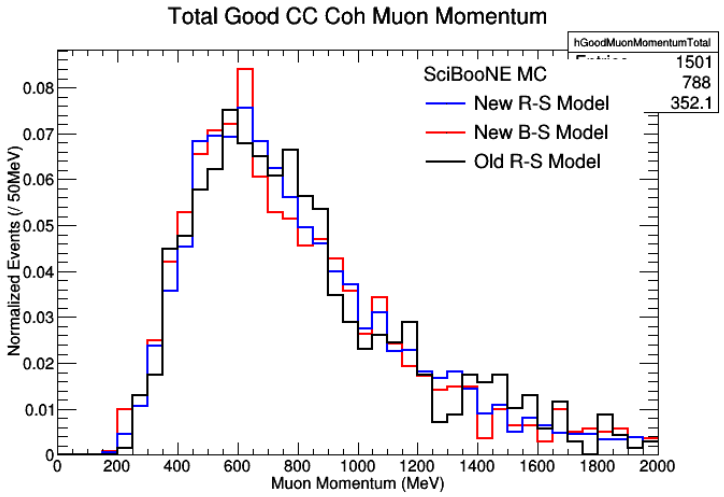

Figure 64: This is a plot right here. Nice of you to notice!

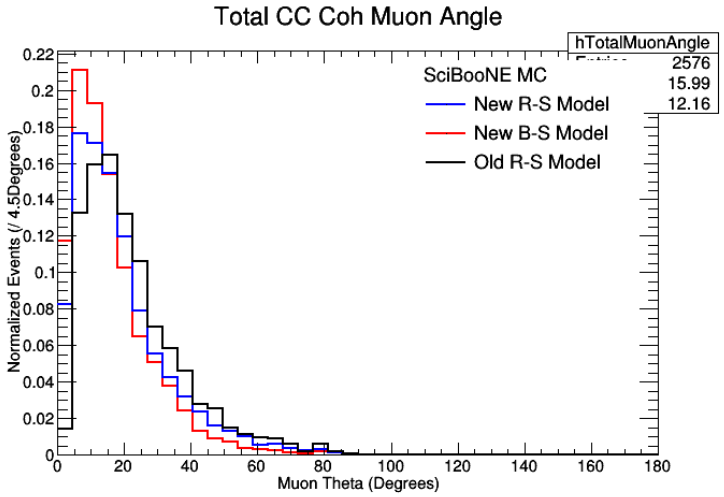

Figure 65: This is a plot right here. Nice of you to notice!

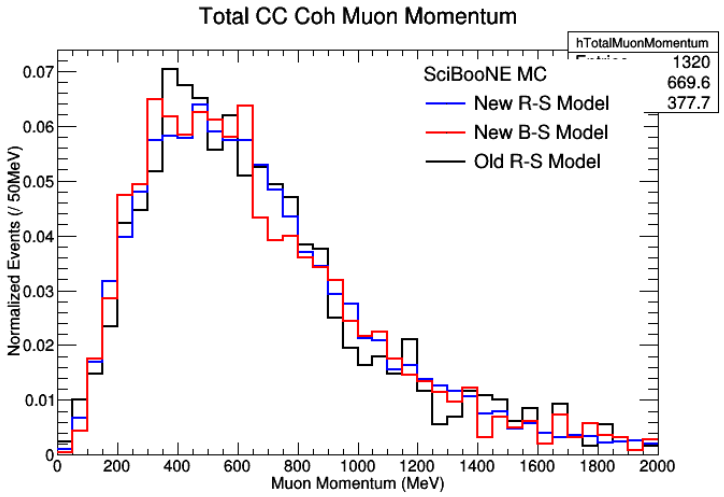

Figure 66: This is a plot right here. Nice of you to notice!

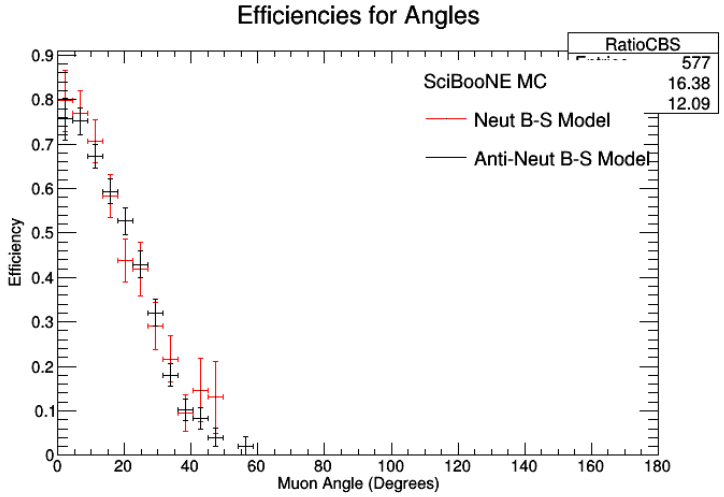

Figure 67: This is a plot right here. Nice of you to notice!

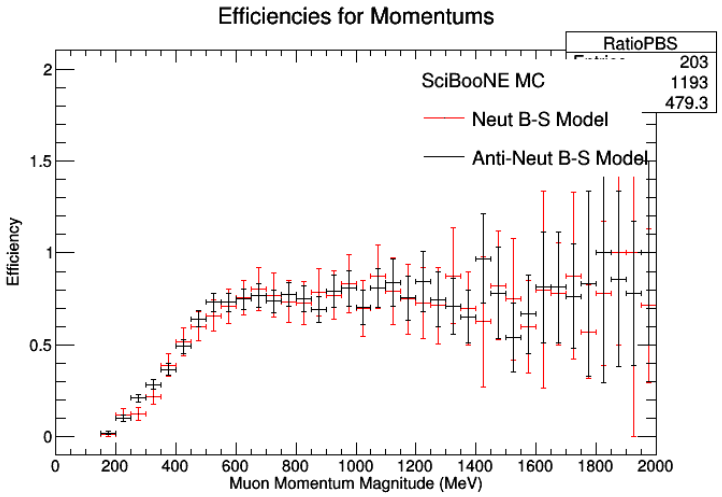

Figure 68: This is a plot right here. Nice of you to notice!

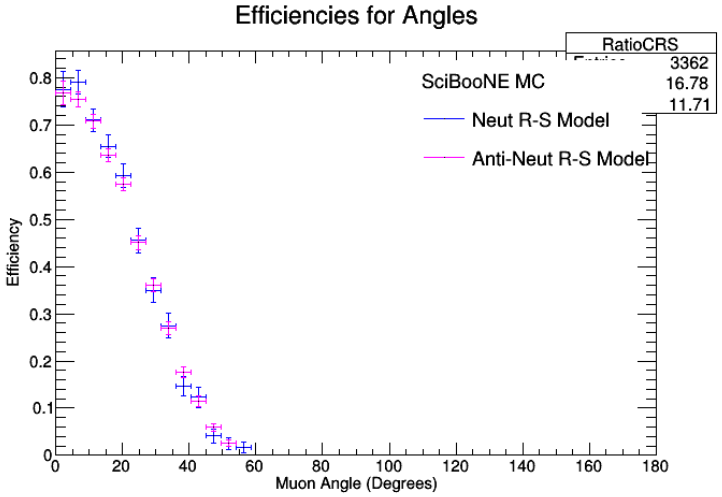

Figure 69: This is a plot right here. Nice of you to notice!

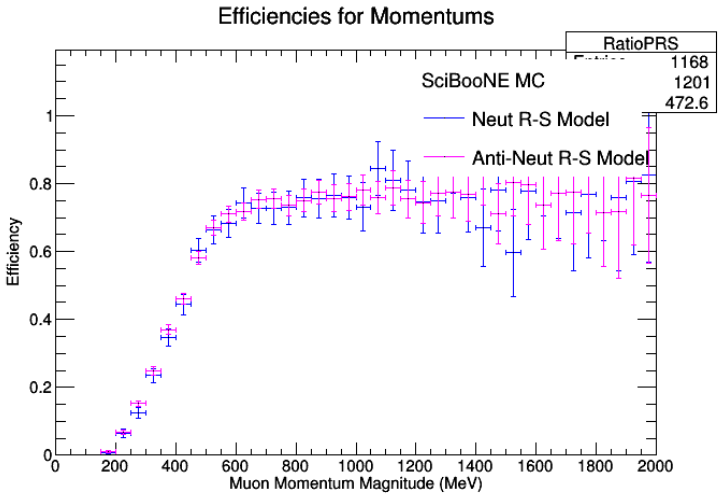

Figure 70: This is a plot right here. Nice of you to notice!

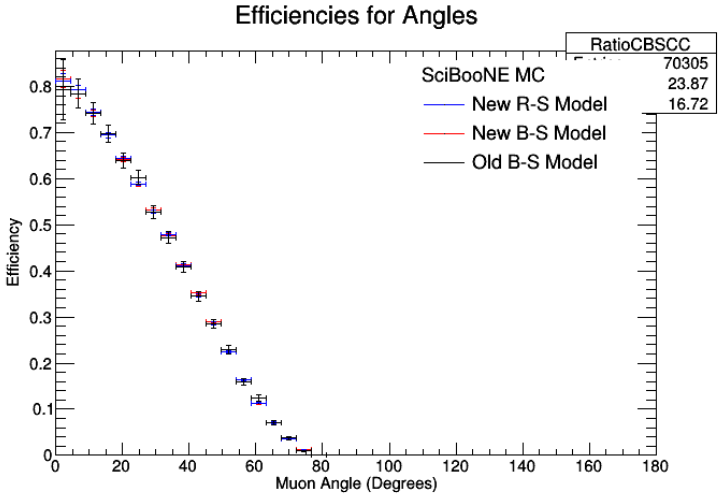

Figure 71: This is a plot right here. Nice of you to notice!

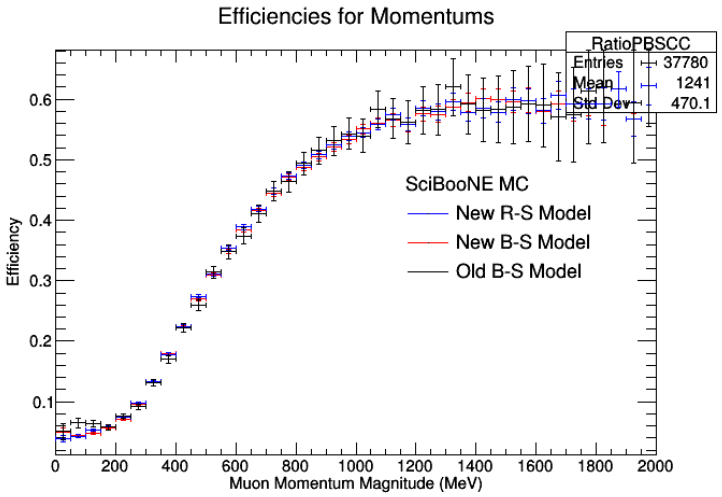

Figure 72: This is a plot right here. Nice of you to notice!

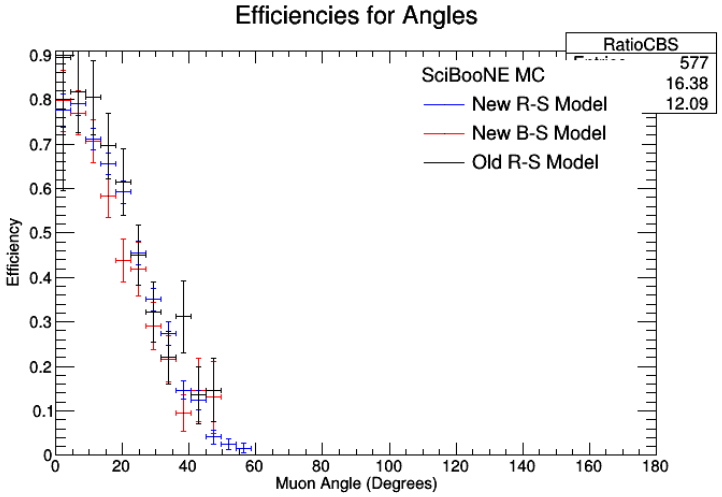

Figure 73: This is a plot right here. Nice of you to notice!

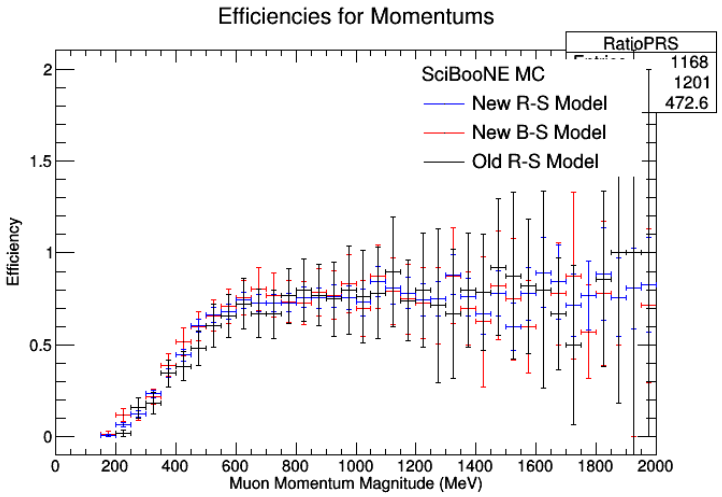

Figure 74: This is a plot right here. Nice of you to notice!

3.12 NMPionPlotting.C

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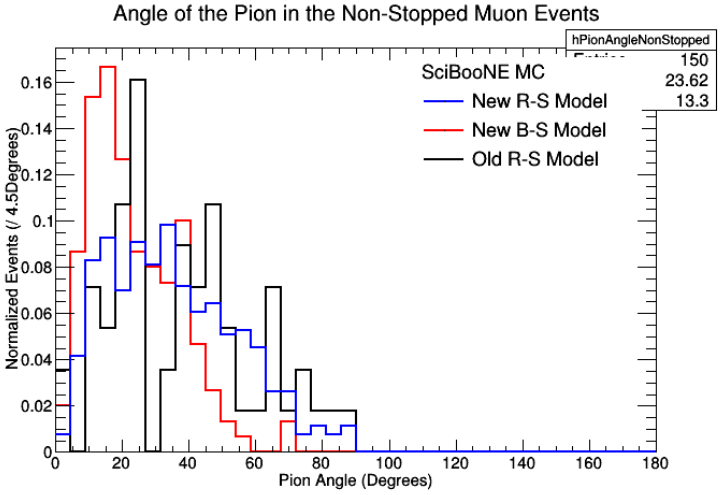

Figure 75: This is a plot right here. Nice of you to notice!

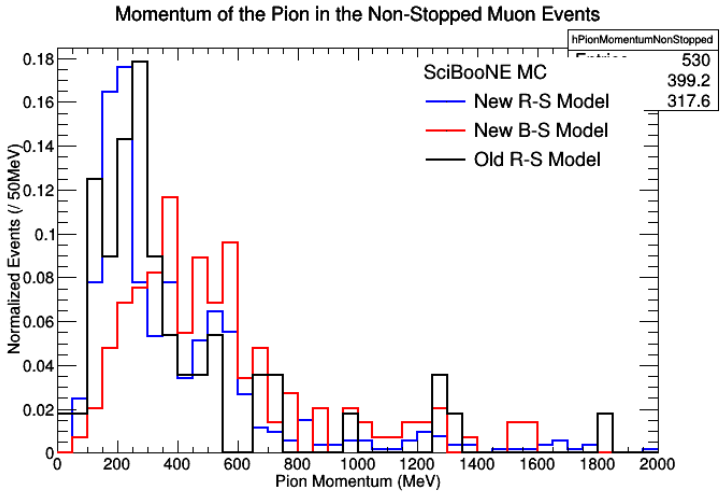

Figure 76: This is a plot right here. Nice of you to notice!

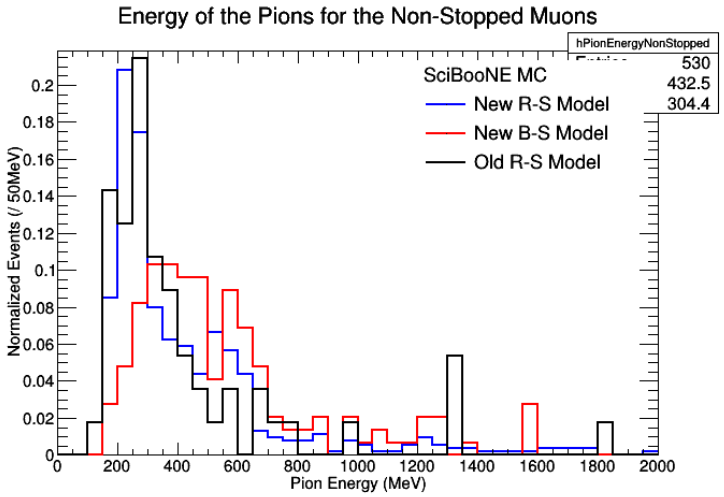

Figure 77: This is a plot right here. Nice of you to notice!

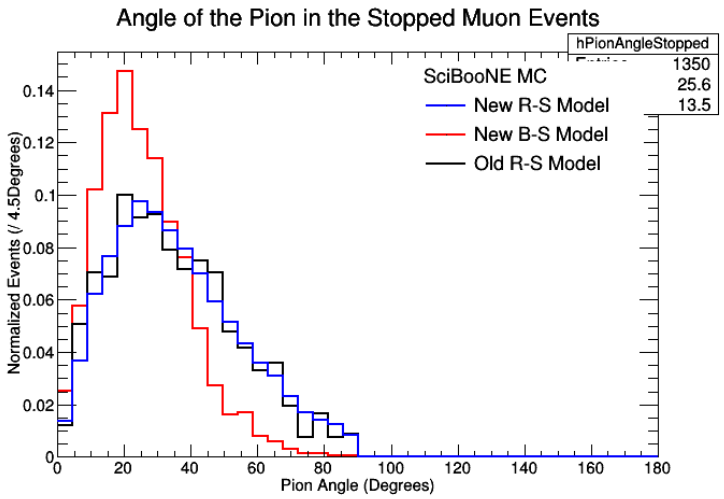

Figure 78: This is a plot right here. Nice of you to notice!

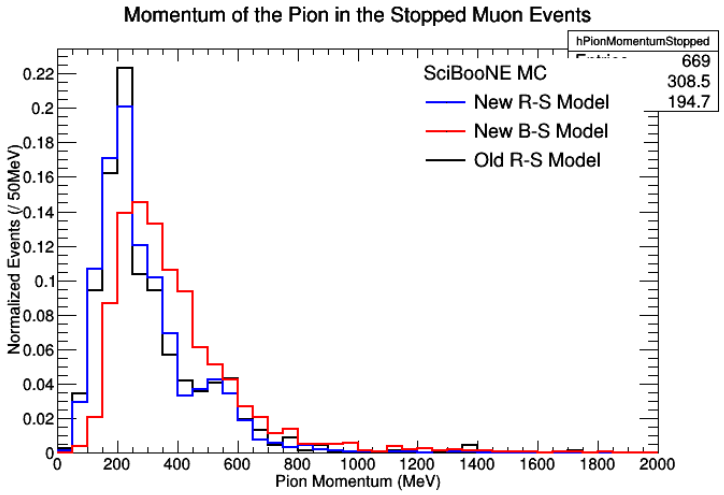

Figure 79: This is a plot right here. Nice of you to notice!

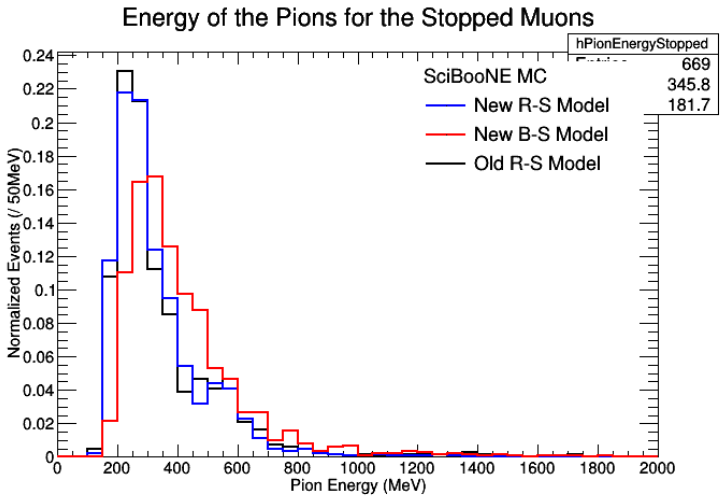

Figure 80: This is a plot right here. Nice of you to notice!

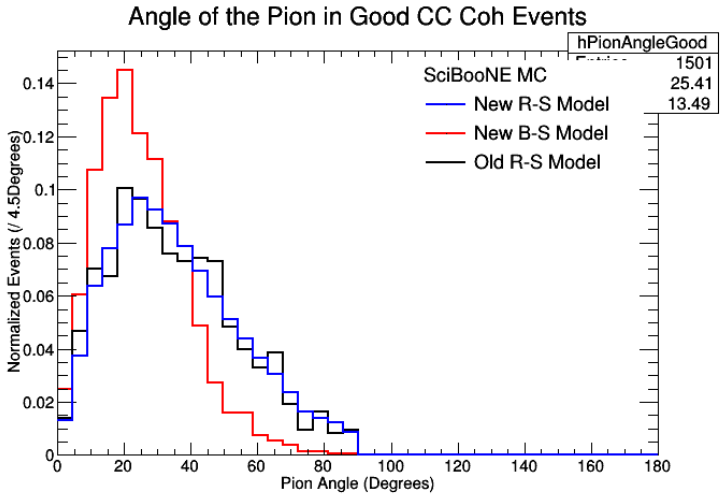

Figure 81: This is a plot right here. Nice of you to notice!

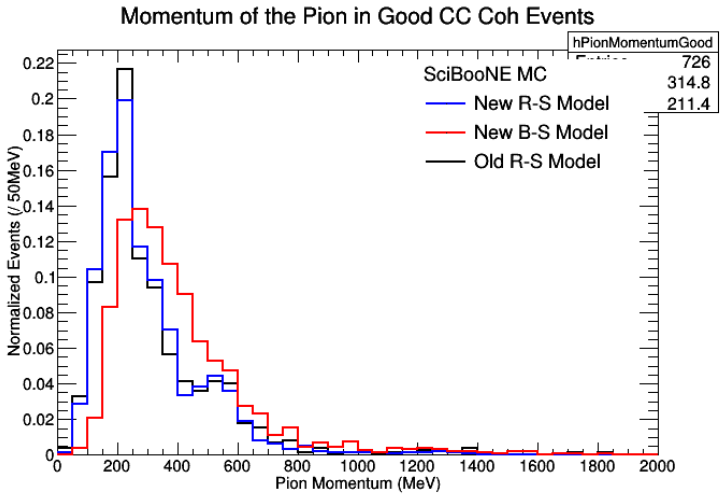

Figure 82: This is a plot right here. Nice of you to notice!

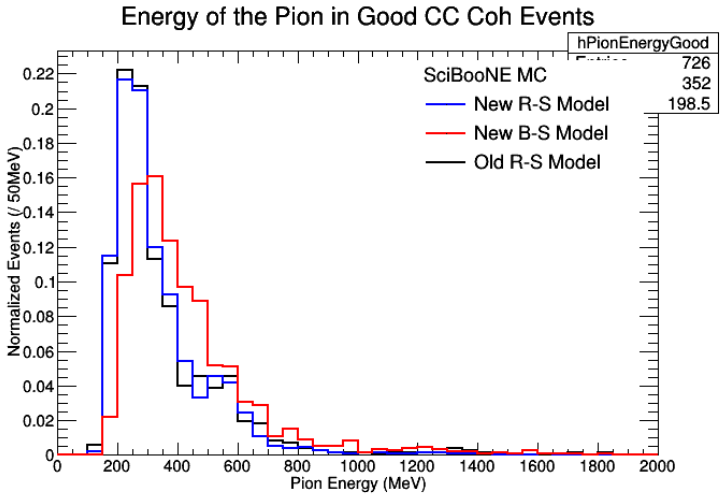

Figure 83: This is a plot right here. Nice of you to notice!

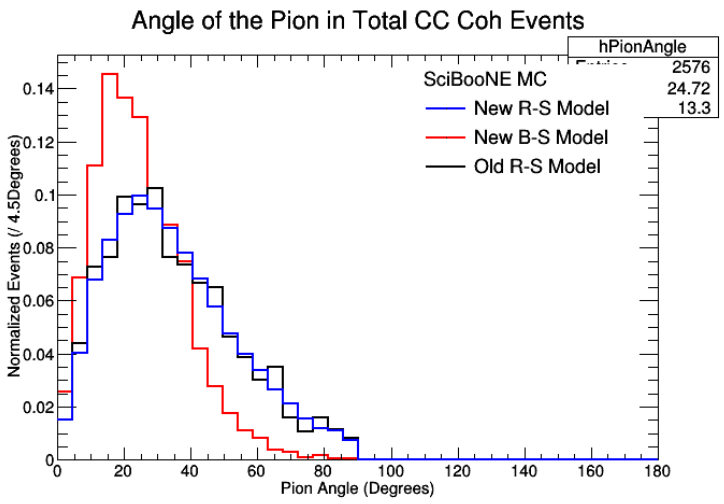

Figure 84: This is a plot right here. Nice of you to notice!

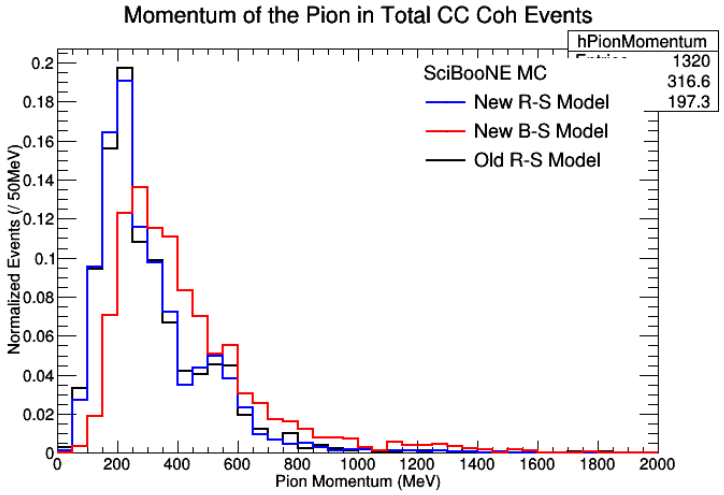

Figure 85: This is a plot right here. Nice of you to notice!

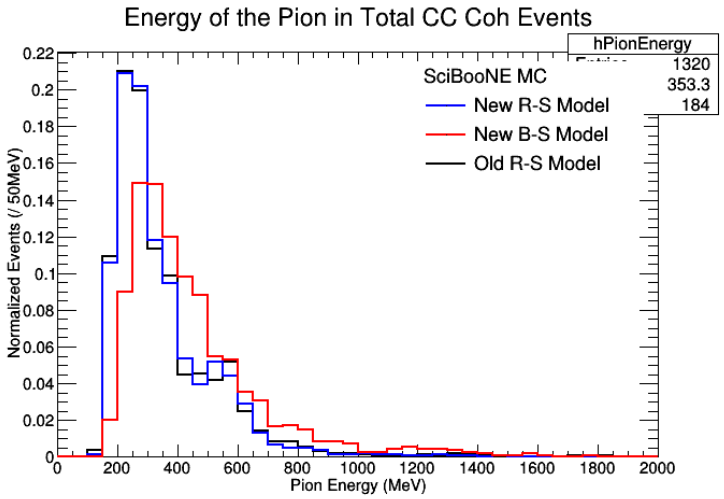

Figure 86: This is a plot right here. Nice of you to notice!

3.13 NMFourSquaredPlotting.C

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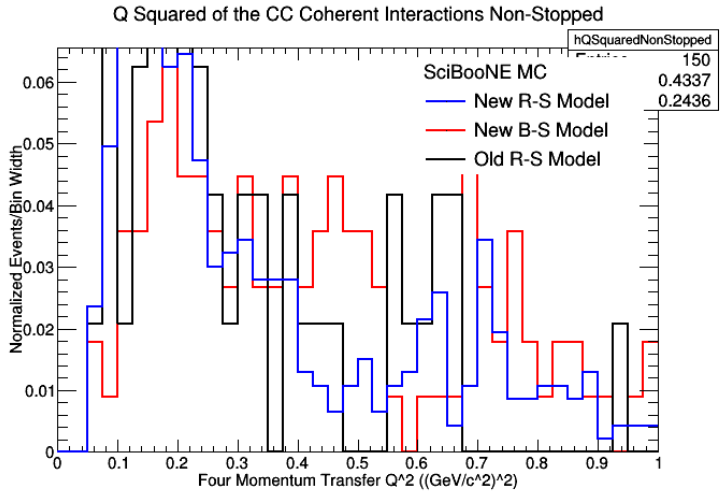

Figure 87: This is a plot right here. Nice of you to notice!

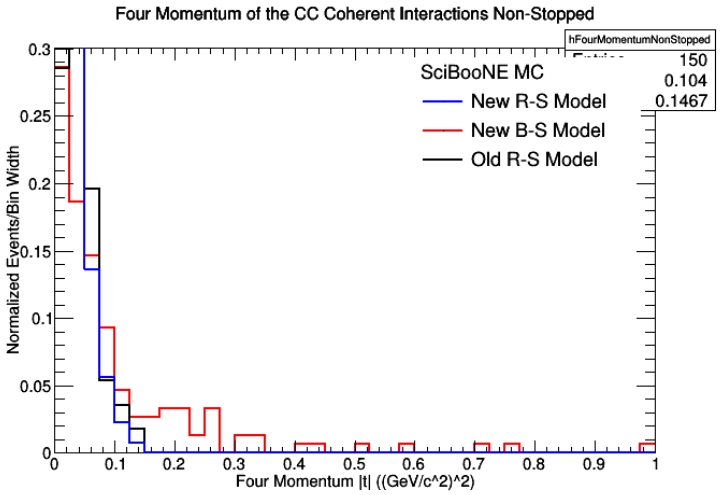

Figure 88: This is a plot right here. Nice of you to notice!

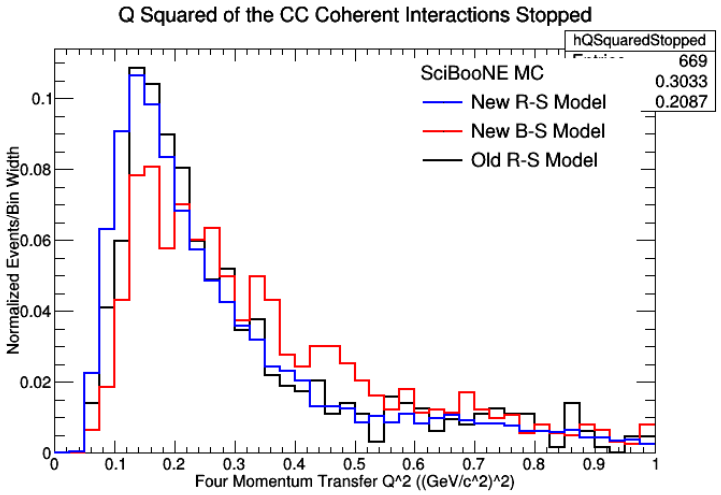

Figure 89: This is a plot right here. Nice of you to notice!

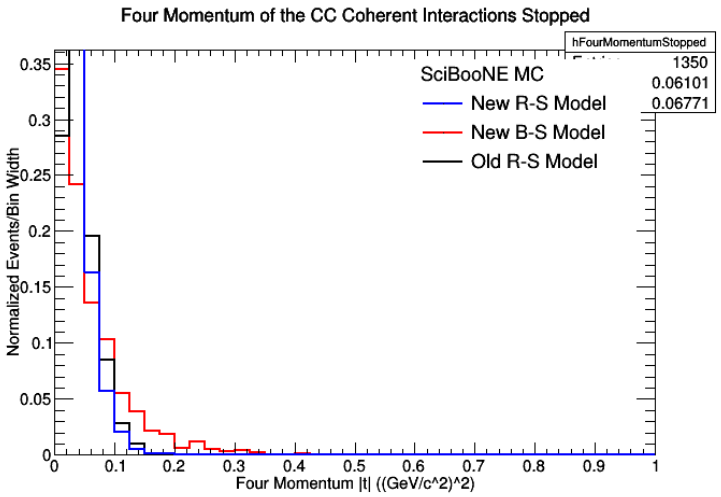

Figure 90: This is a plot right here. Nice of you to notice!

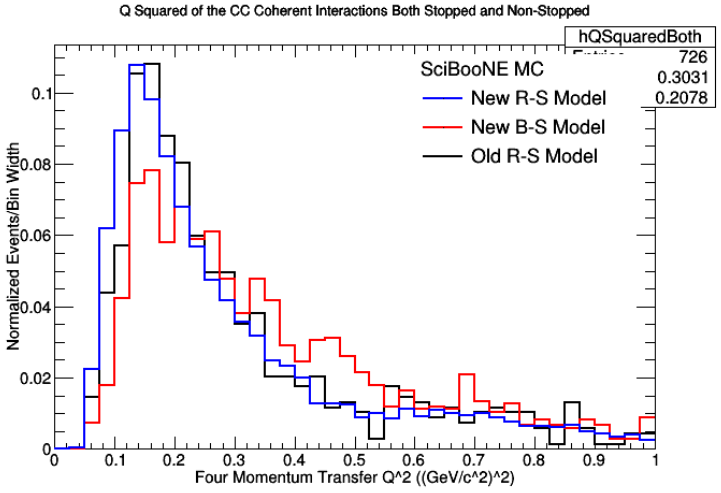

Figure 91: This is a plot right here. Nice of you to notice!

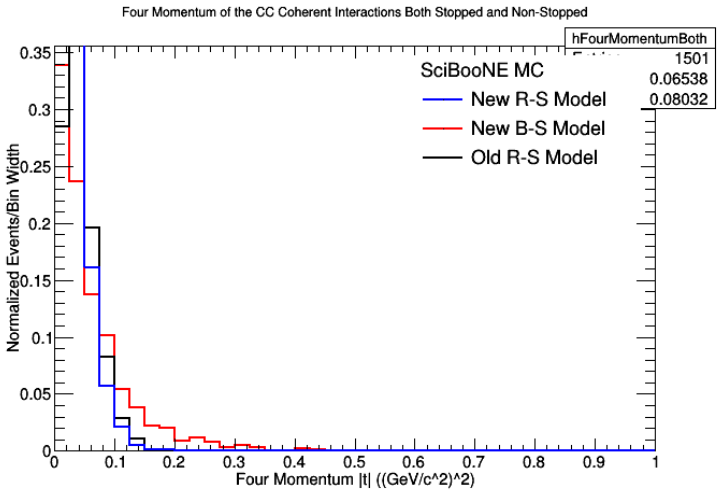

Figure 92: This is a plot right here. Nice of you to notice!

3.14 ANMCombinedPlots.C

I need to come back and insert all of my images here.

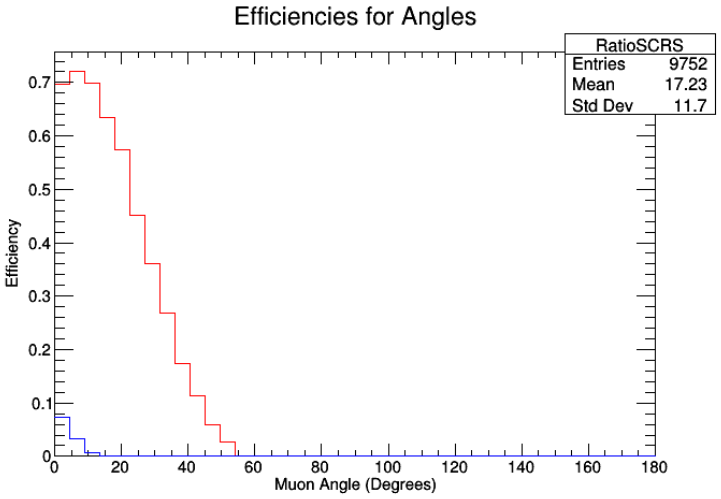

Figure 93: This is a plot right here. Nice of you to notice!

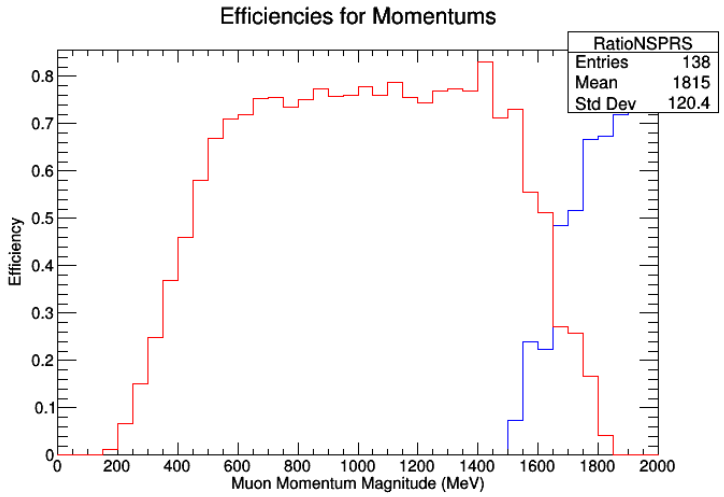

Figure 94: This is a plot right here. Nice of you to notice!

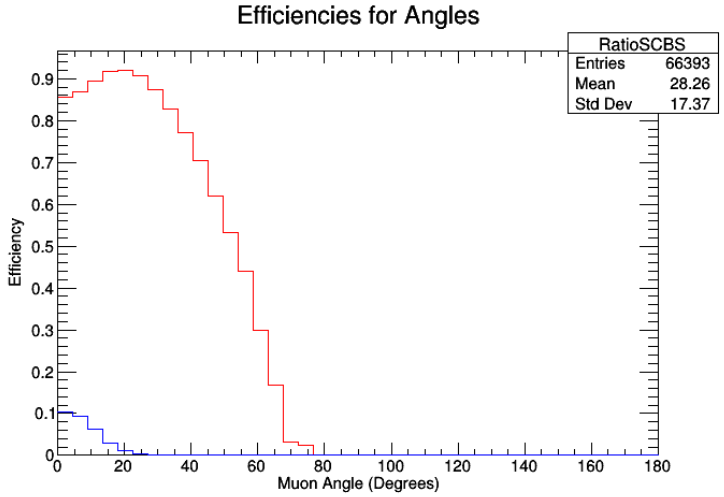

Figure 95: This is a plot right here. Nice of you to notice!

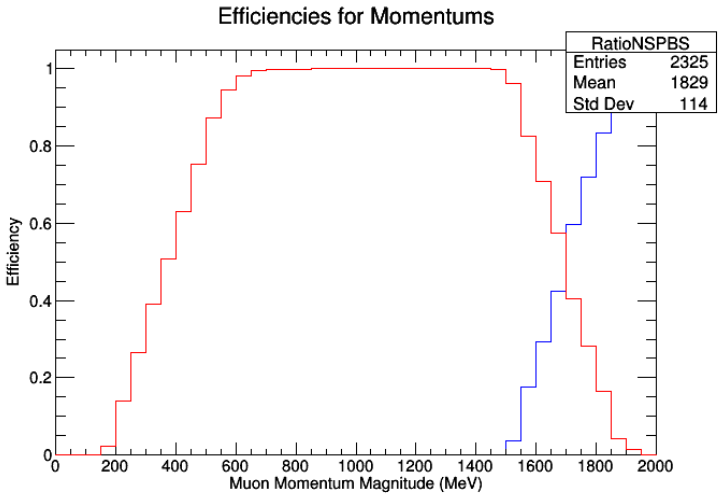

Figure 96: This is a plot right here. Nice of you to notice!

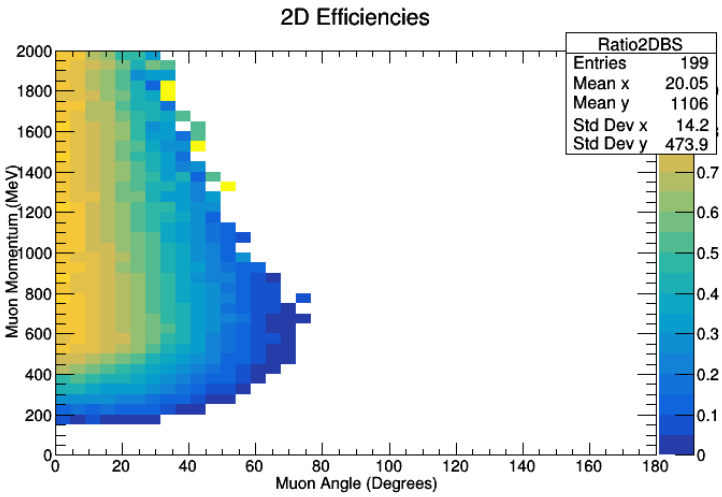

Figure 97: This is a plot right here. Nice of you to notice!

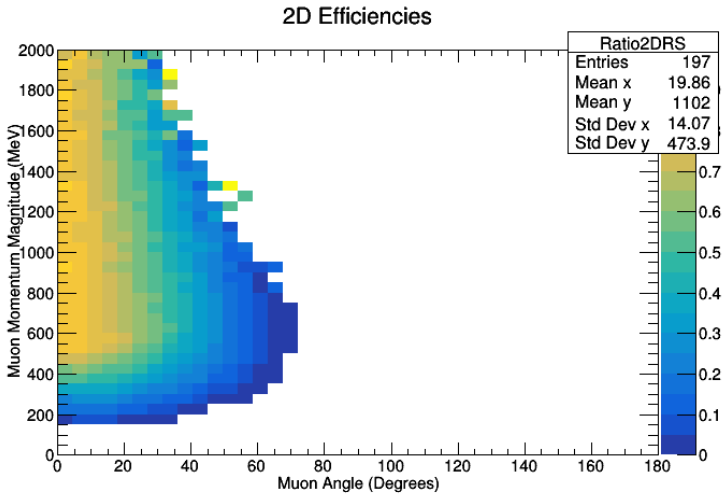

Figure 98: This is a plot right here. Nice of you to notice!

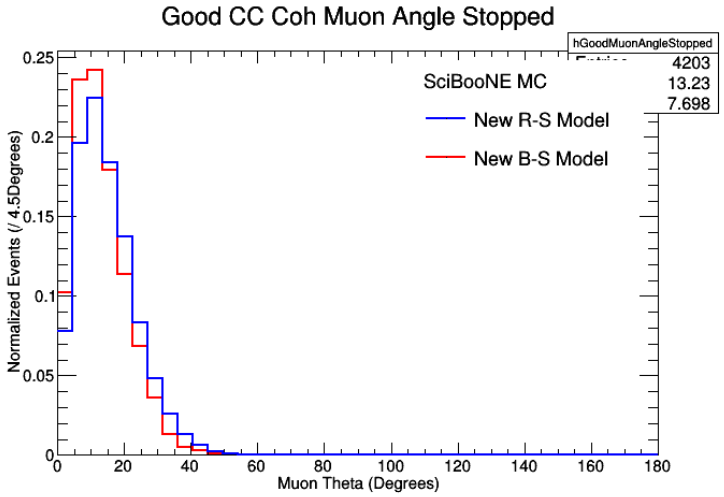

Figure 99: This is a plot right here. Nice of you to notice!

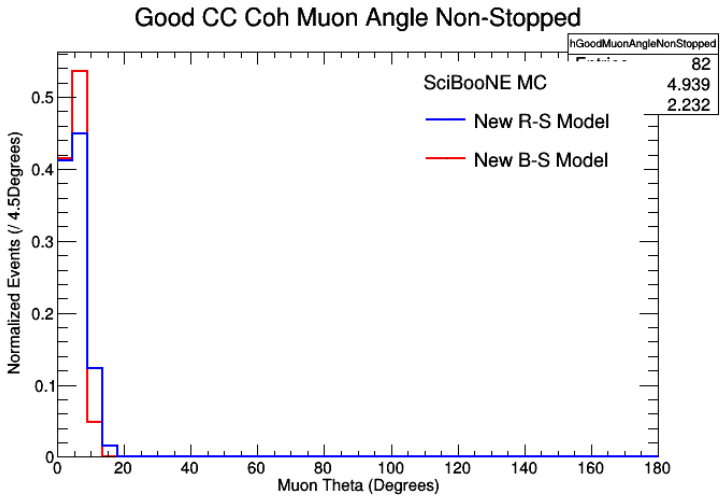

Figure 100: This is a plot right here. Nice of you to notice!

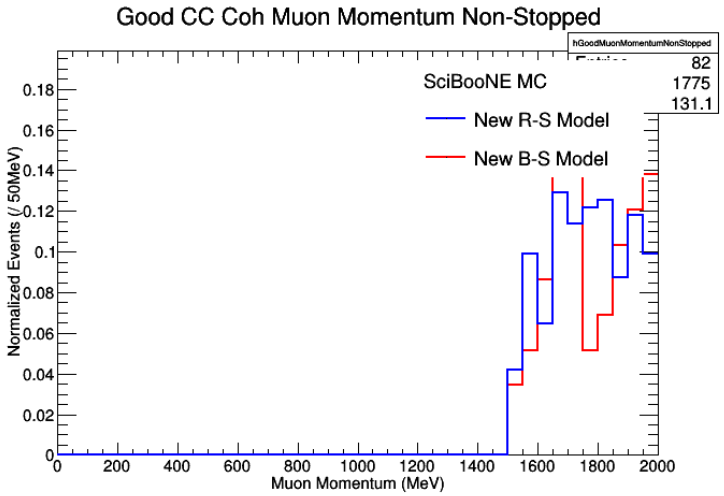

Figure 101: This is a plot right here. Nice of you to notice!

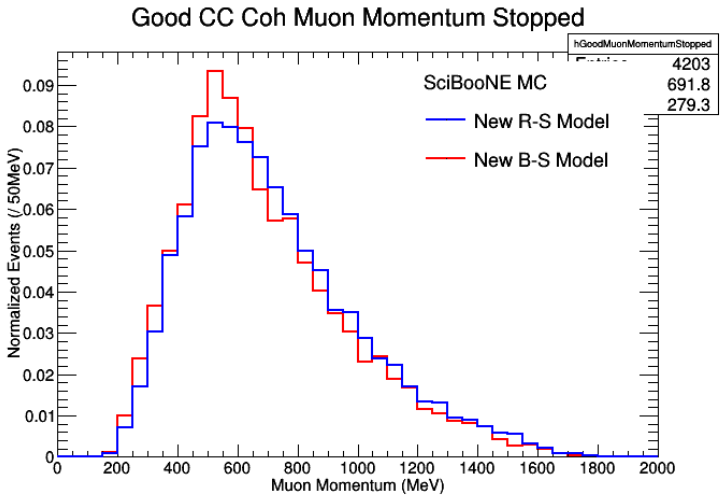

Figure 102: This is a plot right here. Nice of you to notice!

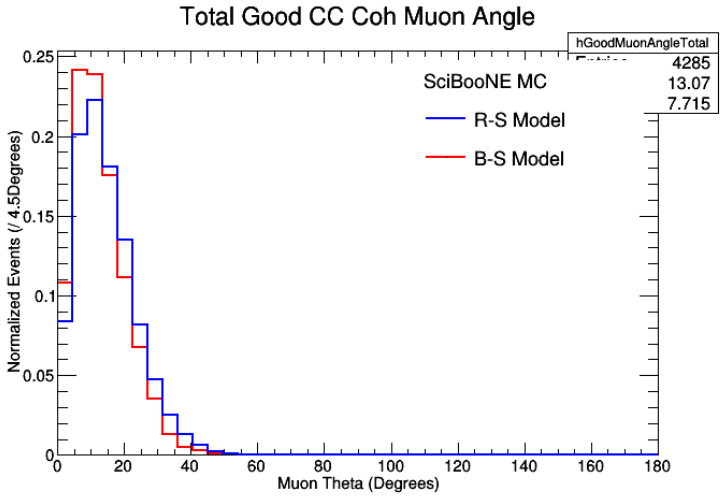

Figure 103: This is a plot right here. Nice of you to notice!

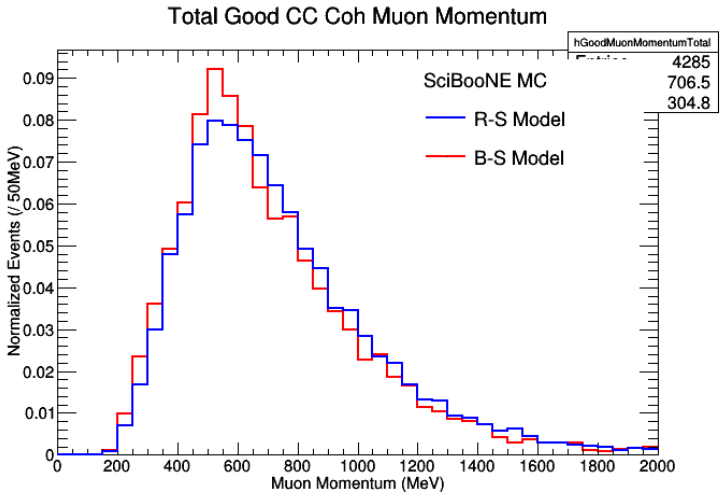

Figure 104: This is a plot right here. Nice of you to notice!

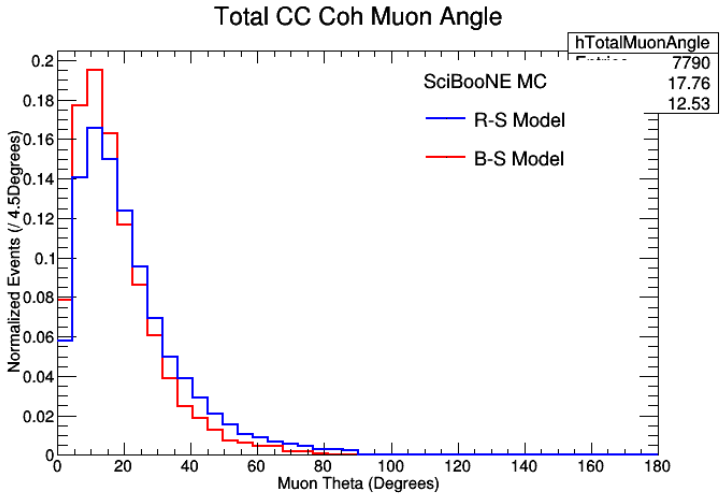

Figure 105: This is a plot right here. Nice of you to notice!

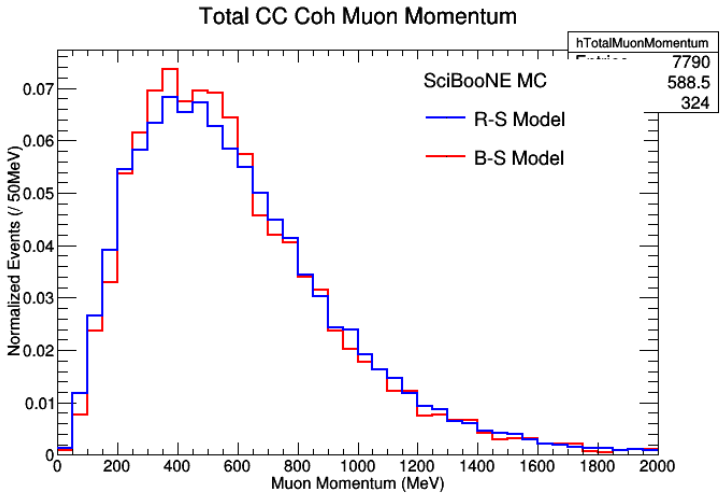

Figure 106: This is a plot right here. Nice of you to notice!

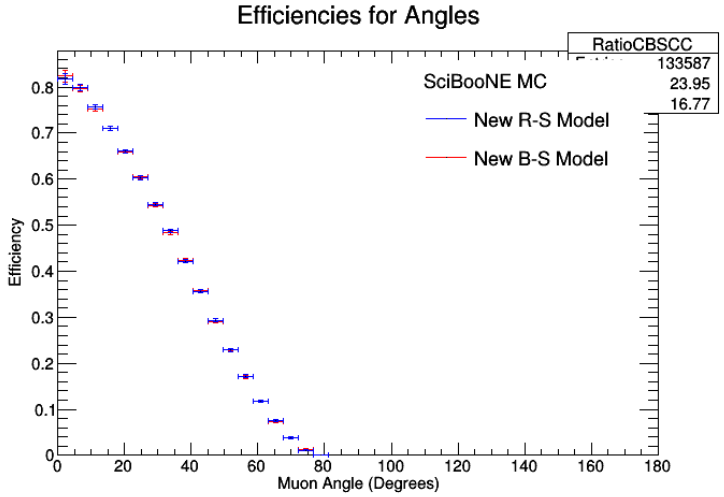

Figure 107: This is a plot right here. Nice of you to notice!

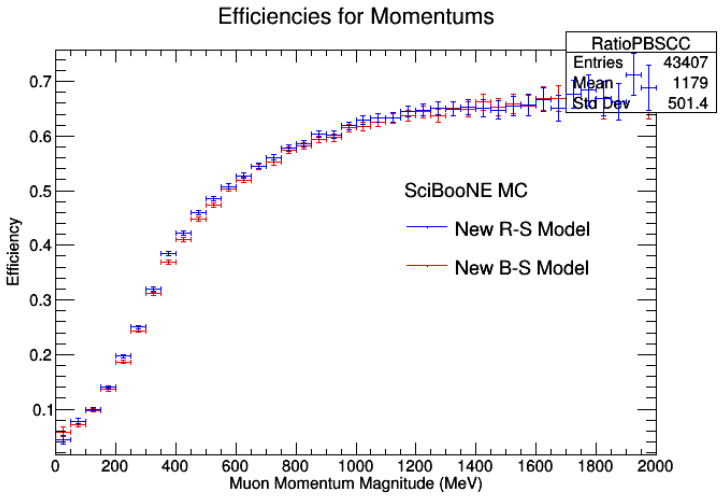

Figure 108: This is a plot right here. Nice of you to notice!

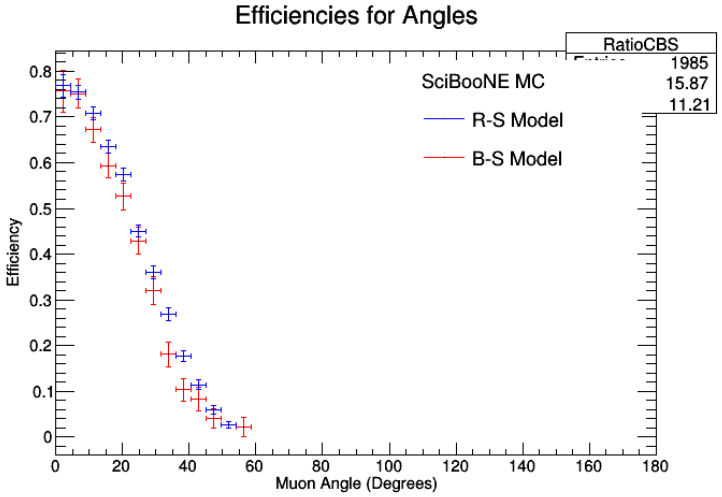

Figure 109: This is a plot right here. Nice of you to notice!

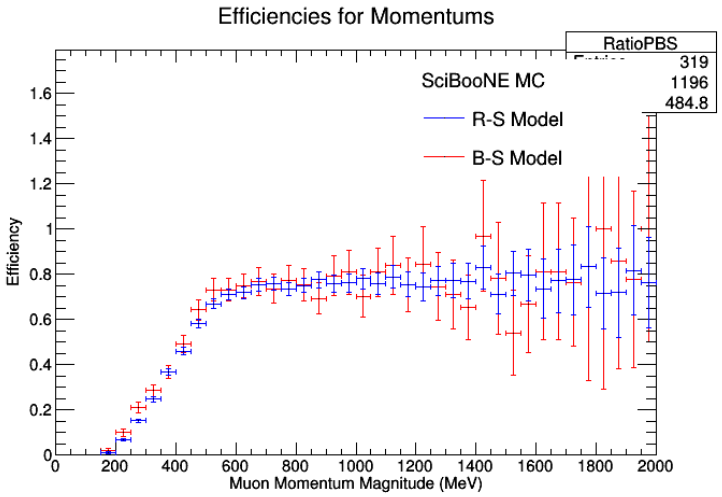

Figure 110: This is a plot right here. Nice of you to notice!

3.15 ANMPionPlotting.C

I need to come back and insert all of my images here.

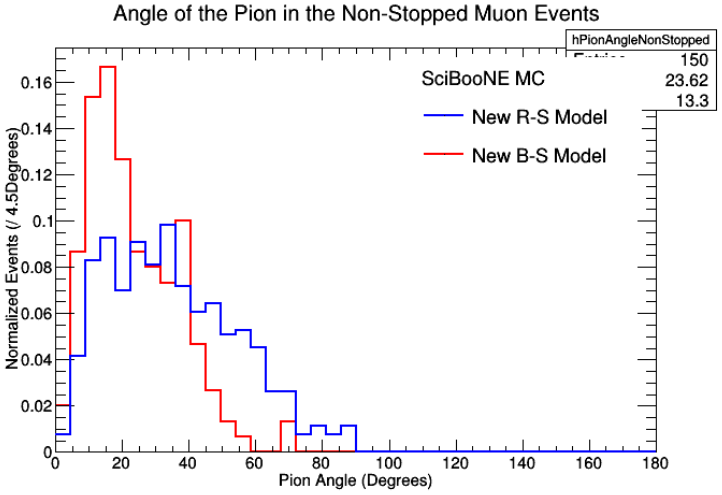

Figure 111: This is a plot right here. Nice of you to notice!

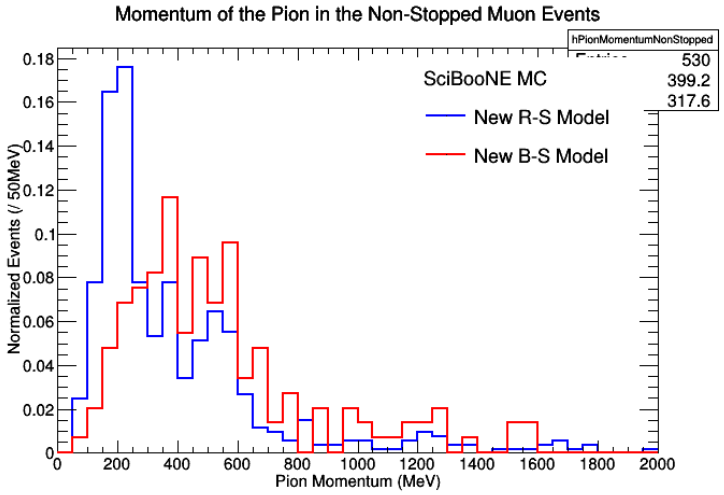

Figure 112: This is a plot right here. Nice of you to notice!

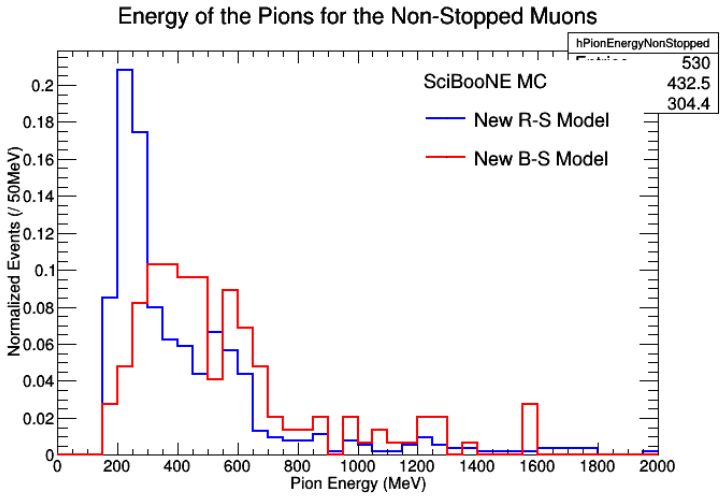

Figure 113: This is a plot right here. Nice of you to notice!

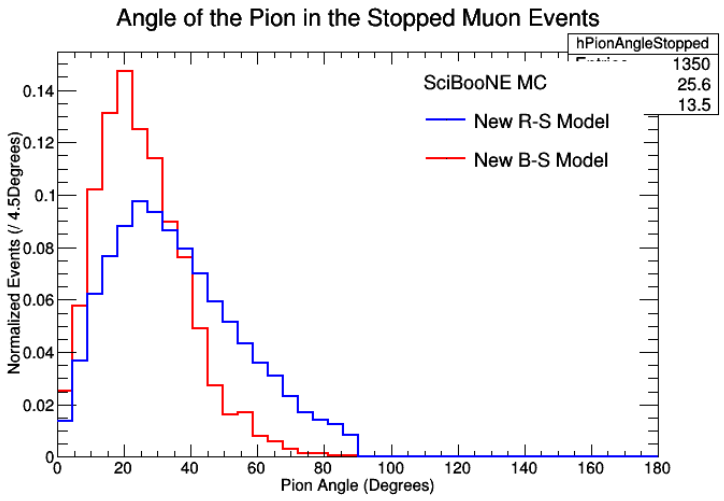

Figure 114: This is a plot right here. Nice of you to notice!

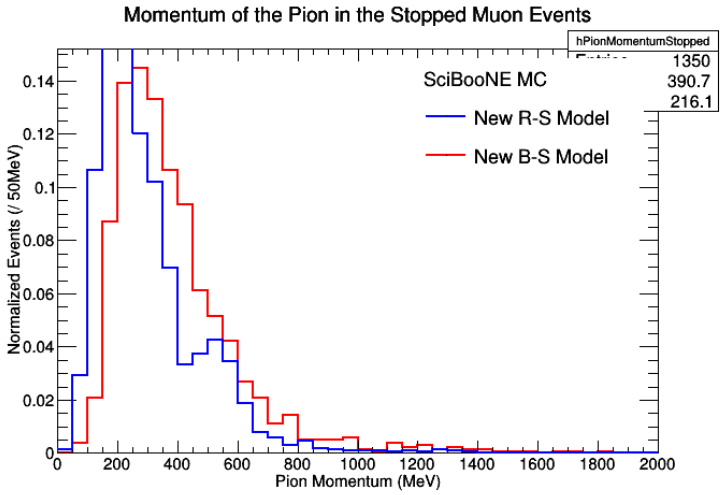

Figure 115: This is a plot right here. Nice of you to notice!

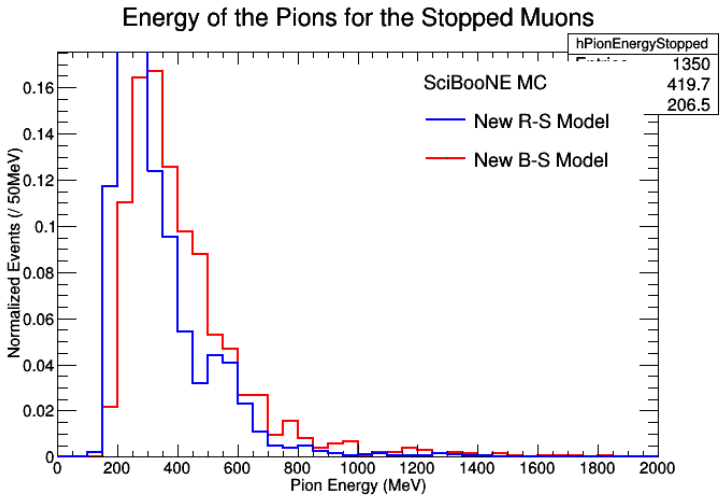

Figure 116: This is a plot right here. Nice of you to notice!

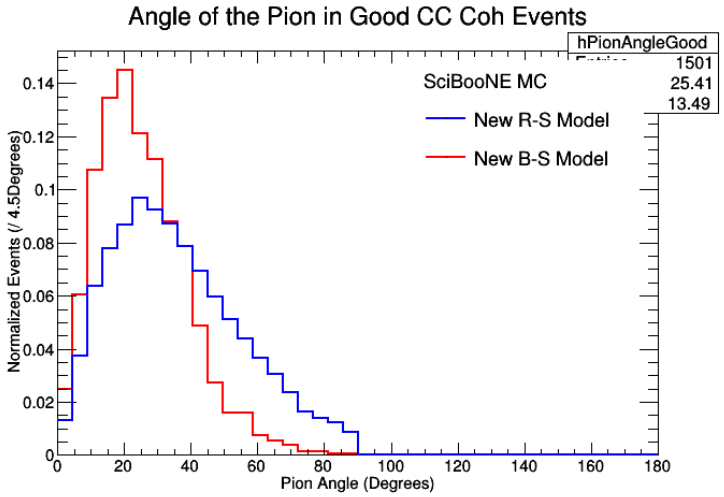

Figure 117: This is a plot right here. Nice of you to notice!

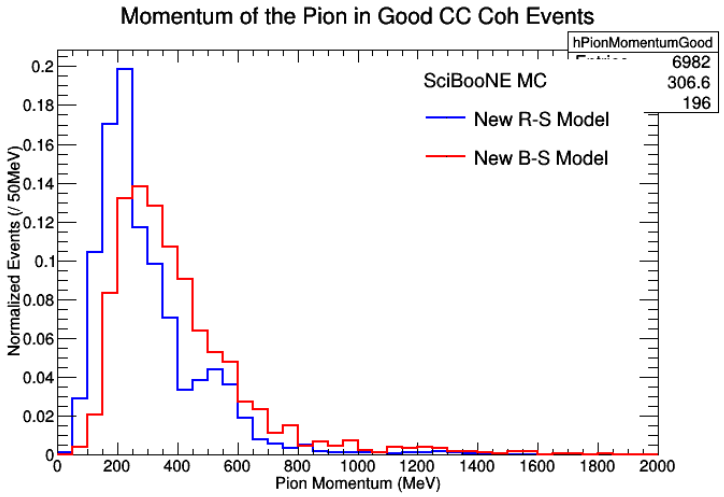

Figure 118: This is a plot right here. Nice of you to notice!

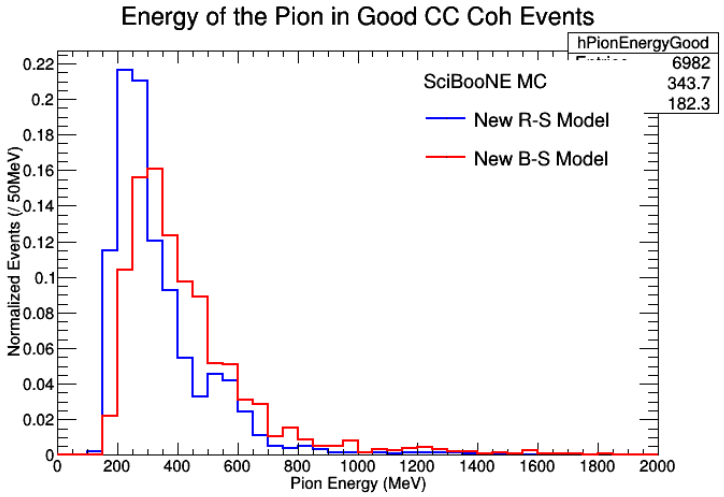

Figure 119: This is a plot right here. Nice of you to notice!

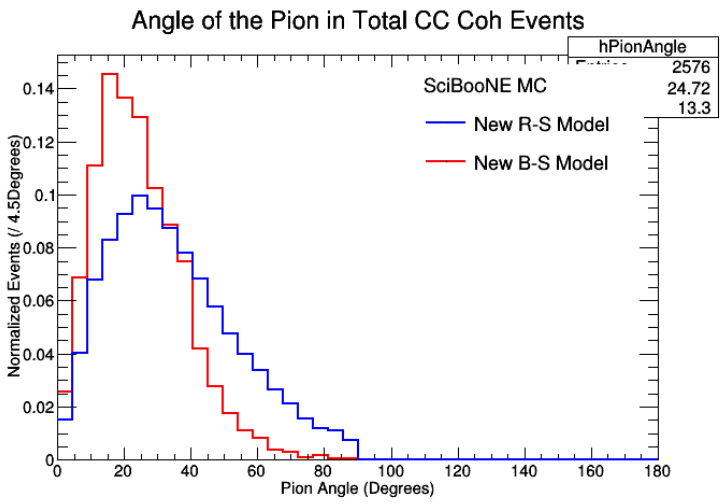

Figure 120: This is a plot right here. Nice of you to notice!

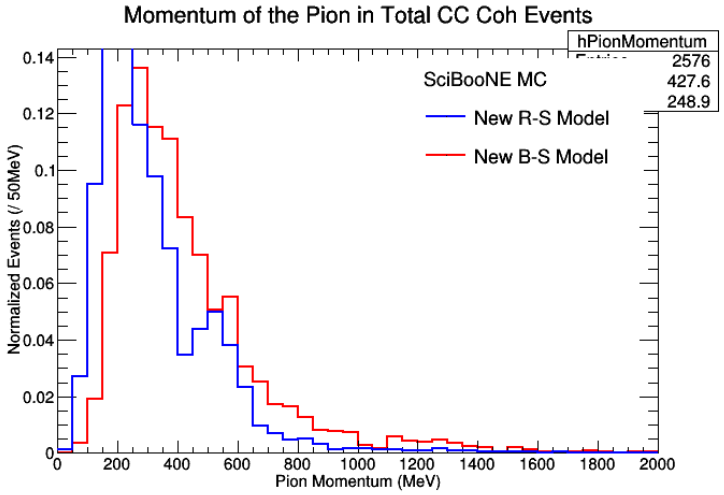

Figure 121: This is a plot right here. Nice of you to notice!

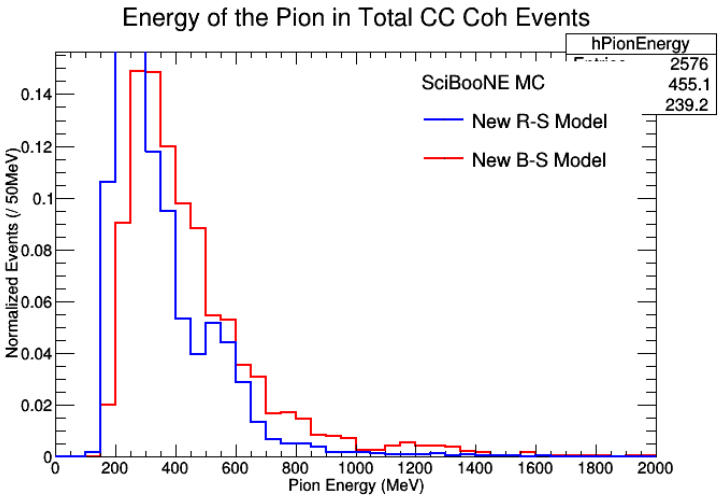

Figure 122: This is a plot right here. Nice of you to notice!

3.16 ANMFourSquaredPlotting.C

I need to come back and insert all of my images here.

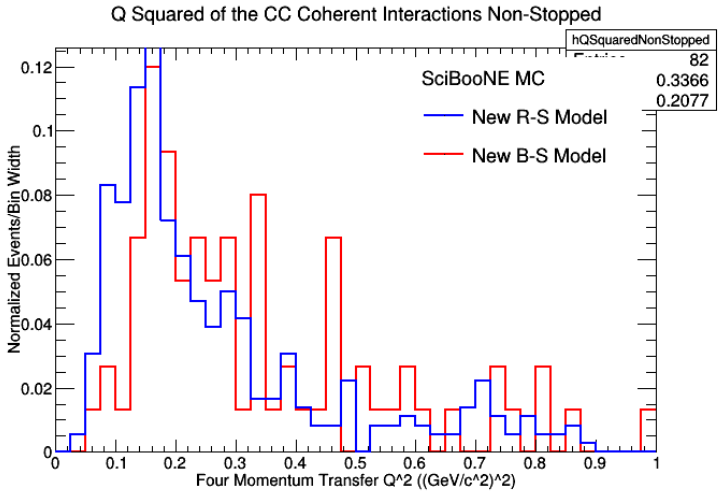

Figure 123: This is a plot right here. Nice of you to notice!

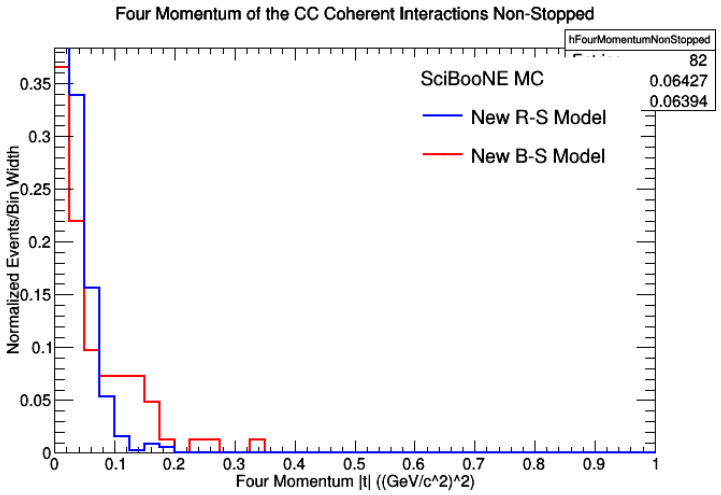

Figure 124: This is a plot right here. Nice of you to notice!

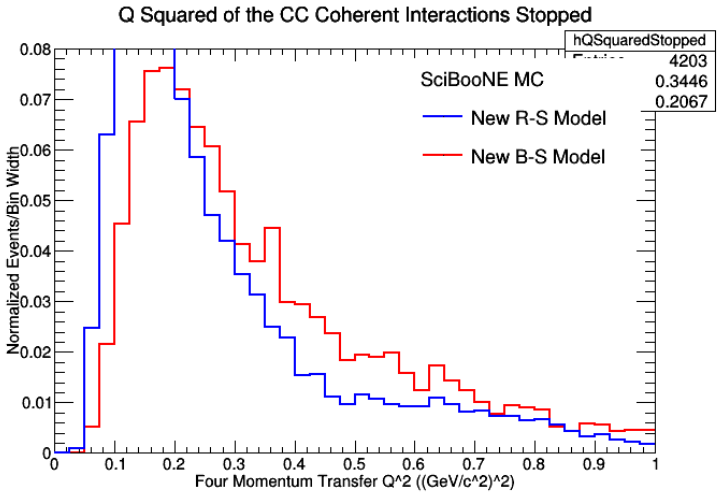

Figure 125: This is a plot right here. Nice of you to notice!

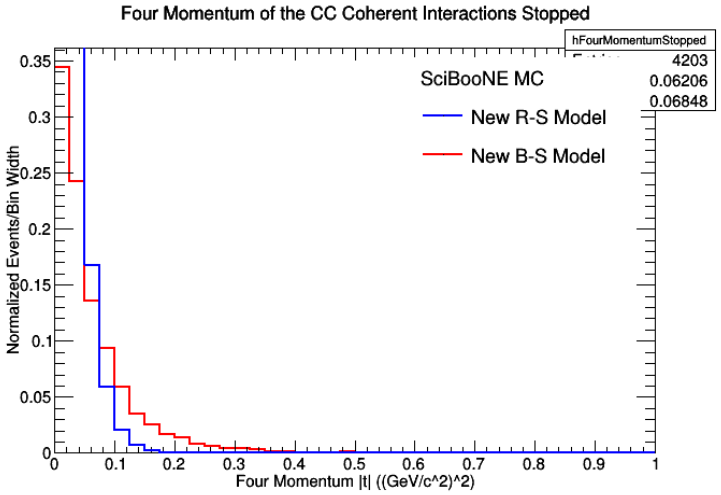

Figure 126: This is a plot right here. Nice of you to notice!

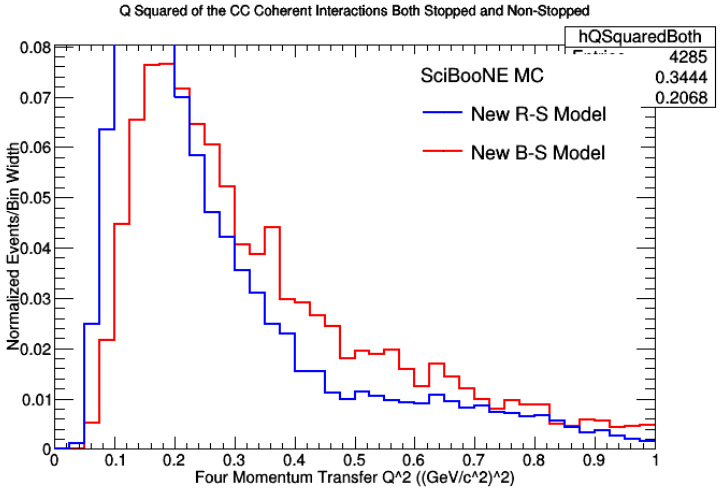

Figure 127: This is a plot right here. Nice of you to notice!

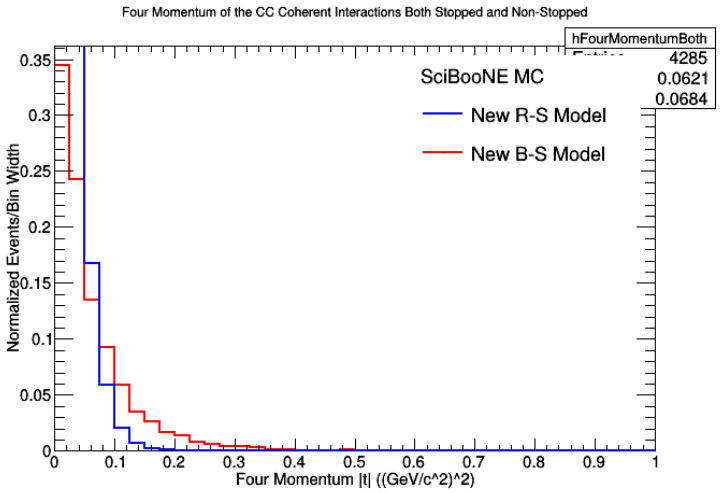

Figure 128: This is a plot right here. Nice of you to notice!

4 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.)

5 Closing Remarks and Cautions

These are just a few cautionary suggestions for potential issues that might be encountered while trying to use this code. This will also be where and further closing remarks can be made.

6 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...)

7 Appendix

7.1 List of Figures

There will eventually be a huge list of figures here.

7.2 List of Tables

There will eventually be the event reduction tables and 2D histogram tables here.

8 Yo Momma So Ugly

She really is! Believe me! I'm a scientist. I know these things.