Contents

1 Summary

In this thesis we are attempting to analyze a particular kind of particle interaction involving anti-muon neutrinos. Neutrinos are tiny, low mass, chargeless particles that are considered the most abundant type of matter in the universe, but are very difficult to detect considering their lack of charge and mass. The interaction we are studying is called an induced resonance interaction, a type of nuclear/particle physics interaction in which a neutrino strikes a nucleon and excites it into a resonant state, which then immediately decays. This interaction is being studied because it comprises a large portion of the neutrino interactions between 1 and 8 Giga-electron volts for the future DUNE and past NOMAD experiments.

We are using data from the Neutrino Oscillation Magnetic Detector (NOMAD) for this thesis. NOMAD was an experiment at CERN meant to study neutrino oscillations, but in doing so it also gathered over 1.7 million neutrino events for study. We are using this vast amount of data to make high precision measurements of the resonance interaction.

For our study, we are looking to separate resonance interactions, referred to as signal, from other neutrino events called background. We will do so by first using the Rein-Seghal theoretical model and Monte Carlo simulation techniques to create a set of simulated interactions called MC events, from which we can obtain all the information that we would perceive if these events were real and in the NOMAD detector as well as the true type of interaction. We can then apply our method of separation to these MC events to test its effectiveness and measure our sensitivity to the resonance interaction, defined as how well we separate signal from background for this type of signal.

The separation method is done in two major steps: simple, preselection cuts and multivariable analysis. For the first, we look at the many pieces of information called variables about each event such as the momentum of each component, the charges of each particle, and the total energy. We then look at the distributions of these variables for signal and background and then place a cut at a certain level of the variable. The idea behind this is to remove events from the regions where background exists and signal does not, though we may end up cutting some signal events to remove more background. Once finished, we take the remaining events through a multi-variable analysis using an Artificial Neural Network. This analysis method takes several variables not yet used to make the simple cuts and analyzes them to try to create a mutli-variable function which can separate signal and background efficiently. This neural network then can be applied to other events to output a sort of probability value of an event being signal, which we can use to create another simple cut (for example removing all events where this output is less than 0.6) and hopefully be left with a mostly signal data set.

However, during this thesis we found that the variables we had available were not sufficient to successfully separate signal and background. Because we initially started out with about 100 times more background that signal, we were unable to reduce the background proportion to less than 4 times that of signal. This means that our sensitivity to the resonance interaction is no where near sufficient to provide a precise set of measurements on the anti-muon neutrino induced resonance interaction and thus we concluded that it was impossible with this method to study that particular interaction.

A Study of Anti-Muon-Neutrino Induced Resonance Production in NOMAD Three-track Topology

Edward Dunton
University of South Carolina

May 1, 2017

Abstract

In this study we are attempting to measure the sensitivity of our methods to anti-muon neutrino induced resonance interactions in the 3-track topology of the NOMAD experiment. We will use a set of Monte Carlo data meant to resemble the NOMAD outputs but with true event type known and then proceed by using a system of single-variable cuts and multivariable analysis through a multilayer perception neural network to distinguish events from these interactions and events from other neutrino or non-neutrino interactions. We will then produce a measurement of the sensitivity to these interactions and determine whether or not proceeding with applying this analysis method to actual NOMAD data in order to measure the anti-muon neutrino induced resonance cross section is possible.

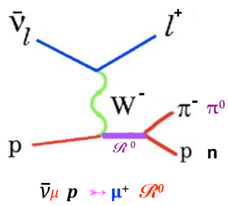
2 Introduction

In this thesis we are attempting to study neutrinos. Neutrinos are the most abundant massive particles in the universe but are not very well understood due to the difficulty of detection. As neutrinos have no charge and very little mass, they be said to interact solely through the weak nuclear force. This gives neutrinos the ability to pass through vast amounts of normal matter without being stopped or slowed by any obstacles in between.

There are a few interesting facts about neutrinos. First, neutrinos are leptons with three distinct flavors: electron neutrinos $\boldsymbol{\nu_e}$, muon neutrinos $\boldsymbol{\nu_\mu}$, and tau neutrinos $\boldsymbol{\nu_\tau}$. It is further known that antiparticles for each of the three neutrino flavors existed, called anti-neutrinos such as anti-electron neutrinos $\boldsymbol{\bar{\nu}_e}$or anti-muon neutrinos $\boldsymbol{\bar{\nu}_\mu}$. Also, neutrinos oscillate between the three flavors, allowing an experiment to produce one type and detect another from the same source.

2.1 Resonance Interaction

One of the few ways in which neutrinos interact with matter is the neutrino induced resonance interaction. A neutrino or anti-neutrino ($\boldsymbol{\overline{\nu}}$) can in-elastically scatter off a target nucleon via a charged current interaction (CC), exciting the



(a) $\bar{\nu}_\mu$-p Induced Resonance Interaction

Figure 1: Feynman Diagram of $\bar{\nu}_\mu$ induced proton Resonance interactions.

nucleon into a short-lived resonant state ($\mathcal{R}$) which instantaneously (10^{-27}s) decays into a nucleon and a pion. The resonant states are predominately Δ-type resonances, specifically Δ^0 and Δ^- for $\bar{\nu}_\mu$-induced resonance interactions as in our study. These are not true Δ states, and as such they will be indicated by the $\mathcal{R}$ symbol instead of the Δ symbol. The first interactions under study are $\bar{\nu}_\mu$-induced proton resonances:

$$\bar{\nu}_\mu + p \longrightarrow \mu^+ + \mathcal{R}^0 \longrightarrow \mu^+ + p + \pi^-,$$
$$\bar{\nu}_\mu + p \longrightarrow \mu^+ + \mathcal{R}^0 \longrightarrow \mu^+ + n + \pi^0$$

These interactions are pictured in Figure 1. The NOMAD detector primarily is designed to detect charged particles, including $\mu^+, p,$ and π^- from the first interaction or channel. Thus that channel appears to show three distinct tracks in the detector event display, termed a 3-Track topology. This topology is the focus of our analysis, and most resonance events within that topology are of this form. The second channel creates three particles as well $\mu^+, n,$ and π^0, but only μ^+ has charge and can be detected. Thus this interaction mostly appears as a 1-Track topology in our event display. Our sensitivity in this topology is very poor, thus we do not consider it in our analysis.

The corresponding $\bar{\nu}_\mu$-induced neutron resonance is described by:

$$\bar{\nu}_\mu + n \longrightarrow \mu^+ + \mathcal{R}^- \longrightarrow \mu^+ + n + \pi^-.$$

Which is pictured in Figure 2. The final state comprises μ^+, n, π^- which manifests primarily as a 2-Track topology in our detector. While our sensitivity to this interaction is acceptable for analysis, we did not consider the 2-track topology in our study.

In summary, this research will focus on the $\bar{\nu}_\mu$-induced resonance interactions using the 3-Track topology. While most of the Resonance modes for this topology will come from the $p \rightarrow \mathcal{R}^0$ type interaction, there will be some overlap from the other modes. It is conceivable that a neutral particle could decay into a pair of charged and thus detectable particles, as in a π^0 decaying into e^-, e^+, and conversely it is possible for us to not detect a charged particle from a three-track event turning it into a 2-track topology. It is therefore important to note that the topology we see does not directly convert into a specific interaction channel.

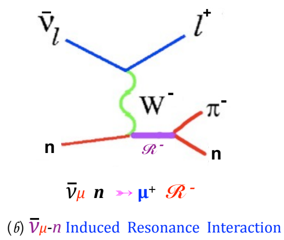


Figure 2: Feynman Diagram of $\bar{\nu}_\mu$ induced neutron Resonance interactions.

2.2 NOMAD Experiment

The **N**eutrino **O**scillation **MA**gnetic **D**etector (NOMAD, WA-96) was designed to search for ν_μ to ν_τ oscillations in the CERN SPS wide band neutrino beam. The neutrino beam is produced by 450 GeV protons from the Super Proton Synchrotron (SPS) incident on a beryllium target. The positively charged secondary π and K mesons are focused by two magnetic horns into a 290 m evacuated decay pipe where they then decayed, producing neutrinos.

The NOMAD detector is composed of several sub-detectors. The target consists of 132 planes of $3 \times 3m^2$ drift chamber (DC), with a 2.7 ton fiducial mass. The average density of $0.1gm/cm^3$ is similar to that of liquid hydrogen, and the effective atomic number of 12.8 is similar to carbon. Following the drift chambers are a Transition Radiation Detector (TRD), a pre-shower detector (PRS) and a lead-glass electromagnetic calorimeter (ECAL). The ensemble of DC, TRD, and PRS/ECAL is placed within a dipole magnet providing a 0.4 T magnetic field orthogonal to the neutrino beam line, which enables high precision momentum measurement of charged particles.

During its run, the NOMAD experiment recorded over 1.7 million neutrino interactions in its active drift-chamber target. This high resolution neutrino data sample offers an unprecedented opportunity to study a large number of neutrino and anti-neutrino interactions in addition to the neutrino oscillation search.

3 Method

In this study we are attempting to find the sensitivity of the NOMAD data to Resonance interactions in the three track topology. We wish to discover whether or not our methods and the available data are sufficient to cleanly separate three track resonance interactions from other forms of background.

3.1 Background vs. Signal

In our study we define two type of event: signal and background. Signal refers to events of the interaction type, or mode, we desire to study; in this case they

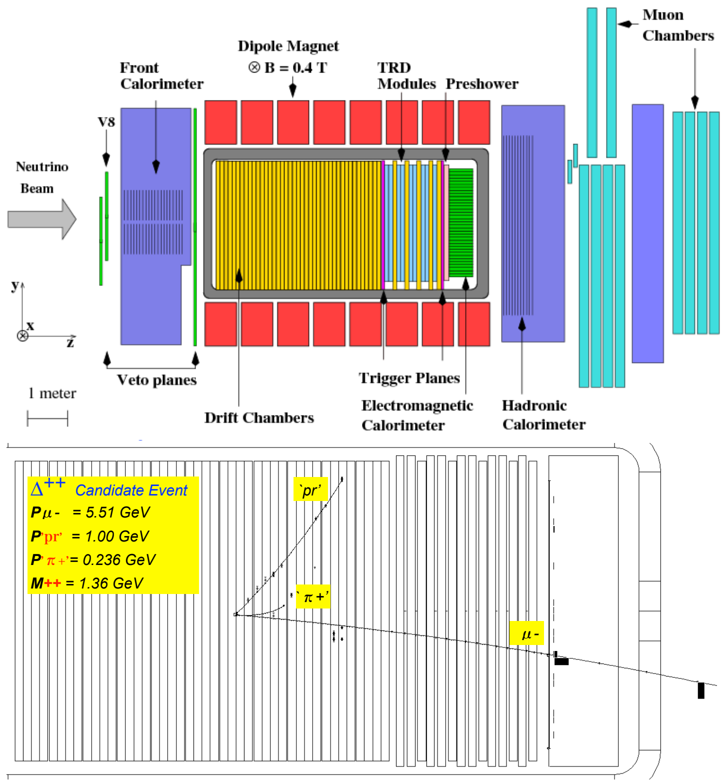


Figure 3: The NOMAD detector (top) and a candidate 3-track CC-Res event where a $\mathbf{\Delta}^{++}$ decays into a proton and $\boldsymbol{\pi}^{+}$ (bottom).

are $\bar{\nu}_\mu$-induced Resonance interactions. Background, therefore, refers to any other sort of neutrino interaction which presents itself in 3-track topology. A benefit of using this topology is that there is only one such mode: Charged current Deep inelastic scattering (CC-DIS).

Resonance events are mostly distinguished from CC-DIS by the fact that they have low energy transfers to the nucleus (Q^2) and therefore low hadron energies (E_{had}) in the resultant events. CC-DIS events are characterized by the opposite: high Q^2 energy transfers and high E_{had}. However, the cross section of CC-DIS events is almost 100 times greater than that of Resonance, so even the extreme ends of the tail which overlap the Resonance events in terms of Q^2 and E_{had} can be large compared to the signal events.

We also consider other processes such as coherent pion and Quasi-elastic interactions for rigor, but we find that they to not provide enough overlap with the signal characteristics in this topology to impact our sensitivity measurement.

3.2 Phenomenology

Resonance interactions are described by the Rein-Seghal (RS) model [1]. This model describes nucleons as 3-quark systems in relativistic harmonic oscillator potentials, considering all resonance states to have invariant-mass, W, < 2 GeV. A non-resonance, non-interfering background is added in the model for our analysis. Another error is that the original RS model for resonance assumes zero lepton mass. Thus it shows some disagreement with pion production data, especially in the low Q^2 region. Therefore the non-zero lepton mass effect is included in our analysis.

3.3 Simulation

In order to make a sensitivity measurement we must know how effectively our method separates signal and background. We cannot use real experimental data for this method, as the entire purpose of the study is separate the data using a method developed and tested through a evaluable process. For this purpose we use Monte Carlo simulated events following the theory from the RS model described above for induced resonance interactions. We then use other similar models to simulate events of all possible modes with the GENIE neutrino simulator, obtaining a set of Monte Carlo (MC) events which can be run through our reconstruction software to obtain MC NOMAD events which can be used to test our methods. We will assume we are using these MC events unless specified otherwise.

These MC events are then normalized to the characteristics of the beam. This process entails defining the relative cross sections of each interaction type according to the best guess provided by available data and beam characteristics, allowing us to approximate the levels of signal and background from our data in our simulation and thus provide a more accurate representation of our sensitivity.

3.4 Pre-selection Cuts

Prior to attempting the analysis which is meant to distinguish signal from background we perform a set of pre-selection cuts which are meant to limit the data we are entering into our multivariable analysis to events which can be analyzed successfully. We also intend to use such simple kinematic events to remove background events which vary widely from signal characteristics, which refines our analyzed sample to those events which truly resemble signal. These cuts are:

1. Fermi momentum (Pfermi): We cut any events where the Fermi momentum is greater than 1 because that is not physically possible.
2. Total relativistic mass (W2s): We limit the total relativistic mass of DIS events to above 1.96 GeV.
3. Fiducial Volume (FV/cut): We cut any events where the primary vertex, and thus the majority of the event, is outside of the detector volume and thus the event is not identifiable.
4. Phase 2: We limit our events to only those that are Phase 2 interactions.
5. Number of Muons (Nmu): we are interested only in events where a muon is present, thus we cut any events with no identifiable muon.
6. Veto/tube cuts: These cuts remove any events initiated by charged particles such as muons or electrons created outside the detector.
7. Muon momentum (|Pmu|): We obtain the best quality of results with muons of momentum $\boldsymbol{> 1.5}$ GeV, thus we cut any events with lower muon momentum than that.
8. Charge confirmation (antimu): Because we are searching for anti-muon neutrino events, only anti-muon particles (positively charged) should pass this cut.
9. Relative change in momentum (DeltaP/P): we confirm that this is less than **20** percent according to our model of resonance interactions.
10. Visible Energy (Evis): We limit the total visible energy to less than 300 GeV.
11. Hadron momentum (Phad): We limit the total hadron momentum to less than 300 GeV.
12. Track count (ncand): We confirm that we are dealing with 3-track events only, as other topologies are not of interest to this study.
13. Total charge conservation (+-): we ensure that the total charge of the particles in the detector is 0, as determined by charge conservation.
14. neutral vertex cut (!nv0): We use this cut to remove any events that show a neutral vertex other than the initial, which would indicate a $\boldsymbol{\pi^0}$ from a DIS event.
15. neutral cluster cut (—nclu): we use this cut to remove any events which show clustered particles, again an indication of $\boldsymbol{\pi^0}$ from a DIS event.
16. Total angle limits (thetaCut): We use this cut to ensure that total angular momentum is conserved in the event.

17. Normalization: we perform this process to ensure that the overall shape of the MC data set matches that of the signal set, which theoretically ensures that the proportions of signal and background are also the same.

This results in a cut table as shown in Table 1 in the Data section.

3.5 Multi-variable Analysis

While the pre-selection cuts manage to eliminate the majority of non-DIS background, they do not manage to separate DIS background from signal. Thus we next use an Artificial Neural Network (ANN) on these two event types in an effort to obtain a more reliable separation. The ANN we are using is a multilayer perception with one input layer, 2 hidden layers, and 1 output layer. All the layers are made up of interconnected neurons. Those in the input layer receive and normalize the inputs, which are next forwarded to the hidden layers in some combinations and then processed into a function of those inputs. In our process these function outputs are processed again in new combinations and finally forwarded to the output layer, which computes a linear combination of those inputs and uses them to sort the signal and background into two different sets.

The neural network undergoes three processes during use: learning, testing, and analysis. During learning, the neural network is given MC data with known neutrino interaction modes and uses fitting functions to try and match the combinations of input variables given with each event to the type of event they are. Once it completes this process, it then is given another set of MC data for testing. This data is then processed by the neural network which outputs a value for each event, theoretically between 0 and 1, representing the likelihood of the even being signal. 0 is defined as background-like, while 1 is extremely signal-like. We can then apply another cut by finding where on this scale the majority of events are signal and the majority of the events are data.

An output of one such neural network program is shown in Figure 4, displaying correlations strength of used variables, the variables used and their neural connections to the hidden and output layers, and a potential test result for a different set of signal and data. We used a number of different sets of variables and connections in our multivariable analysis, among which this was one of the more successful.

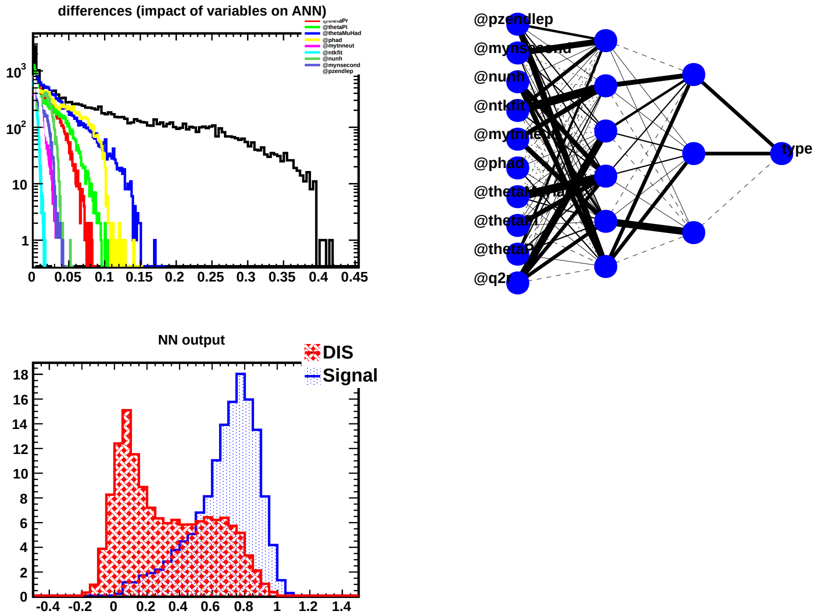


Figure 4: An output of the Multi-variable analysis using 10 input variables, 9 hidden synapses, and 1 output. From this we determine the optimal cut-off of the NN output variable is approximately 0.6 for this version.

4 Data

cut	cutinfo	Res	QE	CCDIS	Coh	NuMu	NC	Bkg	MC	Data
0	Total	1339.15	718.26	36043.74	394.96	13781.09	13049.02	63987.07	65326.21	189609
1	Pfermi<1.0	1330.93	713.75	35740.11	394.96	13666.38	12939.01	63454.21	64785.14	189609
2	W2s>1.96(CCDIS)	1330.93	713.75	31147.93	394.96	12891.61	12862.00	58010.23	59341.16	189609
3	FV/cut	1197.43	643.20	27745.68	353.93	11866.69	11651.07	52260.56	53457.99	137286
4	Phase2>0	1183.58	638.44	25841.30	326.37	10254.36	341.02	37401.50	38585.08	48963
5	Nmu=1	1183.58	638.44	25750.81	325.84	10212.01	291.13	37218.23	38401.81	48586
6	veto/tube	1170.27	635.41	25591.85	323.87	10168.47	289.53	37009.14	38179.40	45755
7	—Pmu—>2.5	1169.14	634.71	25485.61	320.49	10098.26	278.24	36817.31	37986.45	45484
8	antimu	1169.04	634.69	25391.66	319.63	134.47	149.31	26629.76	27798.80	33590
9	DeltaP/P<=0.2	1167.55	634.06	25309.64	317.93	129.54	145.06	26536.22	27703.77	33316
10	Evis<300GeV	1167.44	633.97	25308.35	317.85	129.51	145.05	26534.73	27702.16	33150
11	phad<300GeV	1167.44	633.97	25308.32	317.85	129.51	145.05	26534.70	27702.14	33150
12	ncand=3	176.12	1.97	6005.53	4.75	13.33	17.96	6043.54	6219.66	6177
13	+-	155.44	1.39	5123.83	1.63	6.72	14.30	5147.87	5303.31	5099
14	!nv0	154.16	1.39	4410.12	1.45	4.91	10.30	4428.17	4582.33	4230
15	!nclu	143.88	1.33	2440.99	0.94	0.83	2.83	2446.91	2590.79	1762
16	thetaCut	141.92	1.27	2384.92	0.72	0.66	2.28	2389.85	2531.77	1693
17	normalization	141.92	1.27	1879.03	0.72	0.66	2.28	1883.96	2025.87	1693
18	NN>0.6	105.67	0.93	448.32	0.25	0.04	0.17	449.71	555.38	309

Table 1: Cut Table

4.1 Selected variables

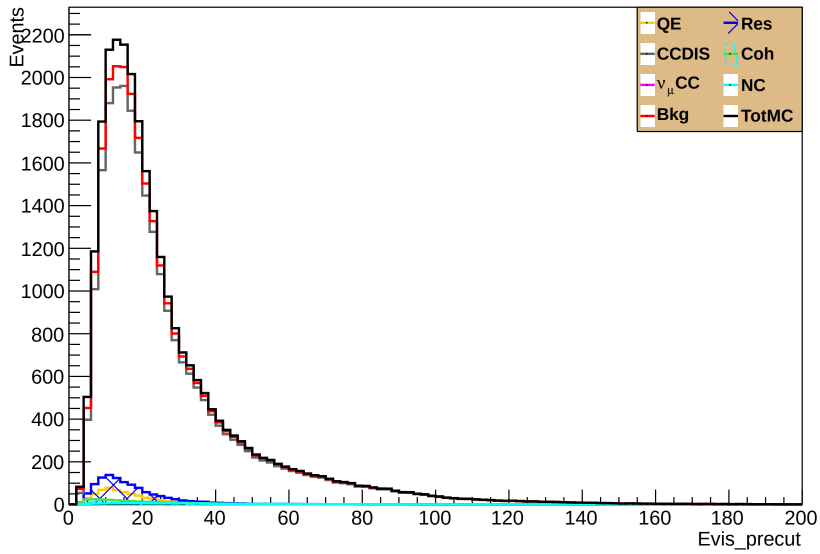


Figure 5: This graph shows the Visible energy (Evis) distribution among all event modes prior to any sort of selection or analysis process. It can be seen that background processes, specifically CC-DIS, overwhelm the Resonance signal by a factor of at least 10, but few other details are visible.

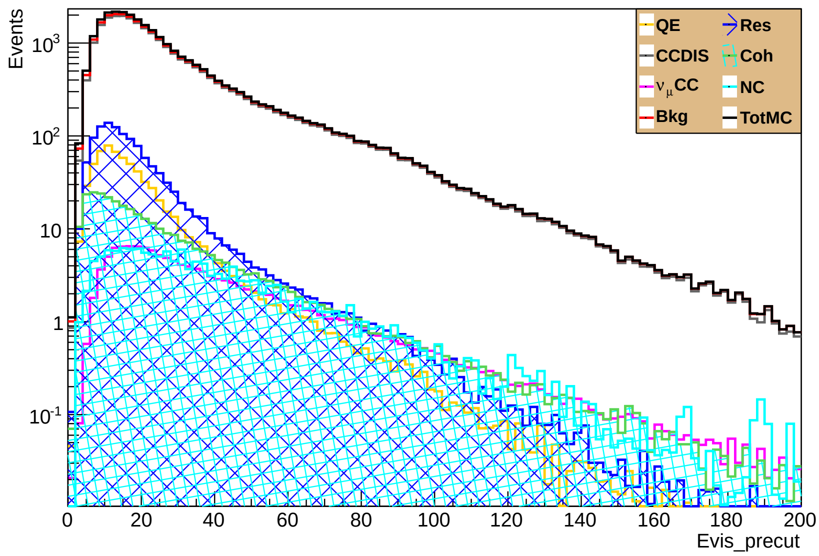


Figure 6: This is a log-y version of the previous graph (Evis all modes pre-cuts) in order to visualize details of the less common modes than CC-DIS.

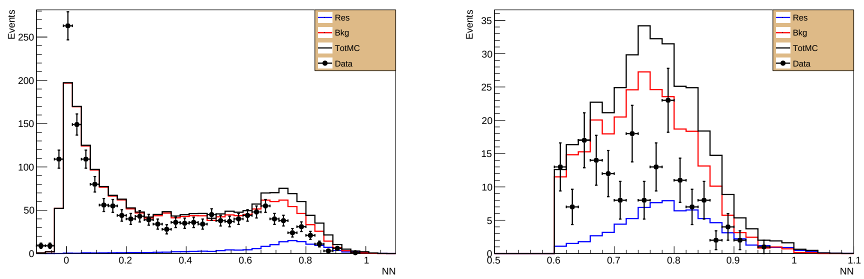


Figure 7: This is the before (left) and after (right) distribution of the Neural network output variable (NN) around the NN>0.6 cut. While it is clear that many background events were removed by the cut, we also note that in the post-cut distribution signal is still overwhelmed by background at every location. This indicates that we need some other variable or factor with which to separate the remaining events.

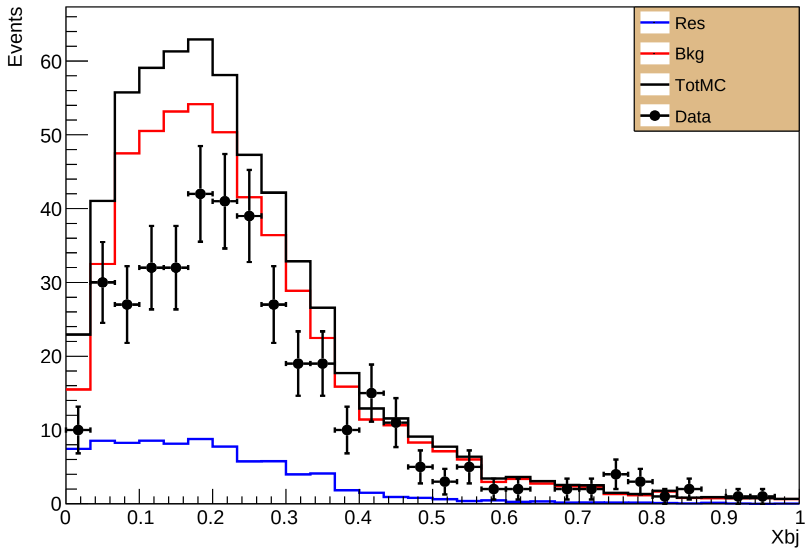


Figure 8: This is the pre-multivariable analysis X Bjorken variable (Xbj) distribution for all remaining events.

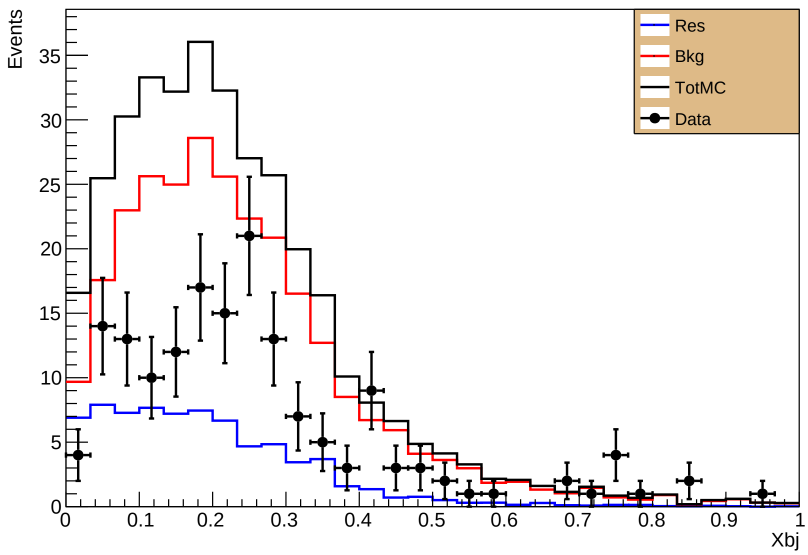


Figure 9: This is the post-analysis X Bjorken variable (Xbj) distribution for all remaining events. As compare to figure 8, Signal is a much larger portion of the distribution but still overwhelmed by background.

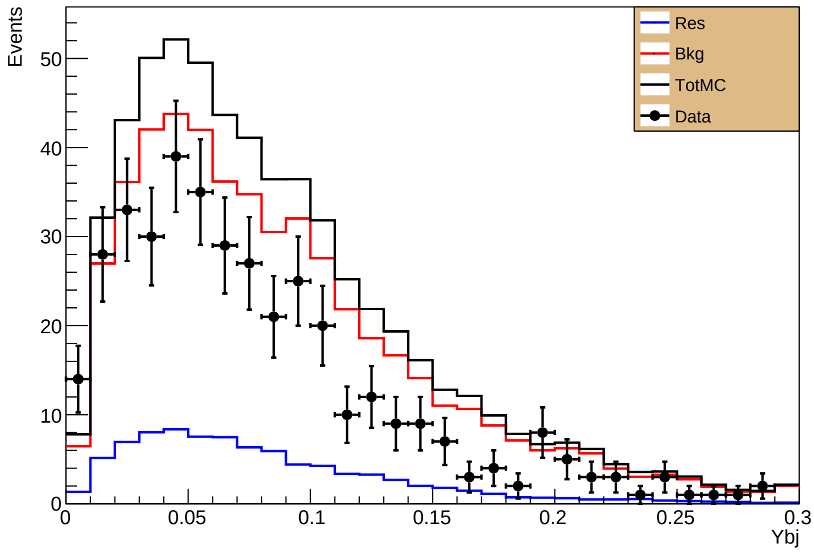


Figure 10: This is the pre-analysis Y Bjorken variable (Ybj) distribution for all remaining events.

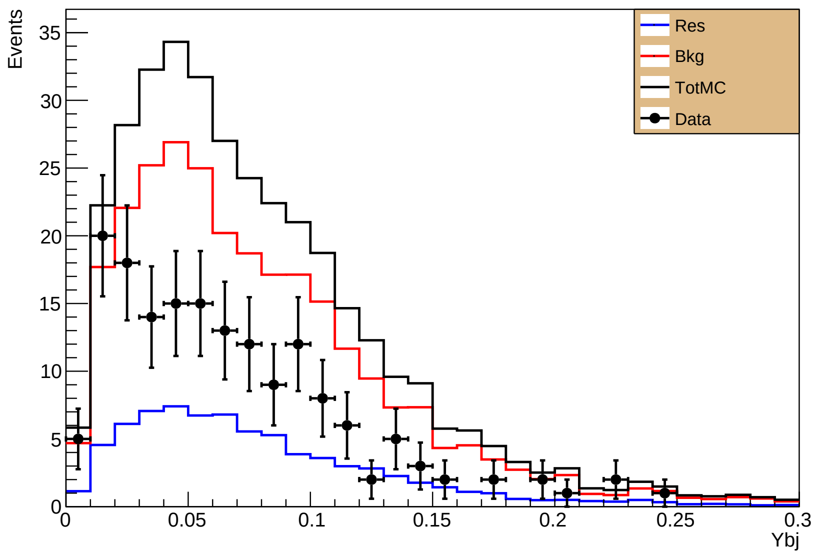


Figure 11: This is the post-analysis Y Bjorken variable (Ybj) distribution for all remaining events.

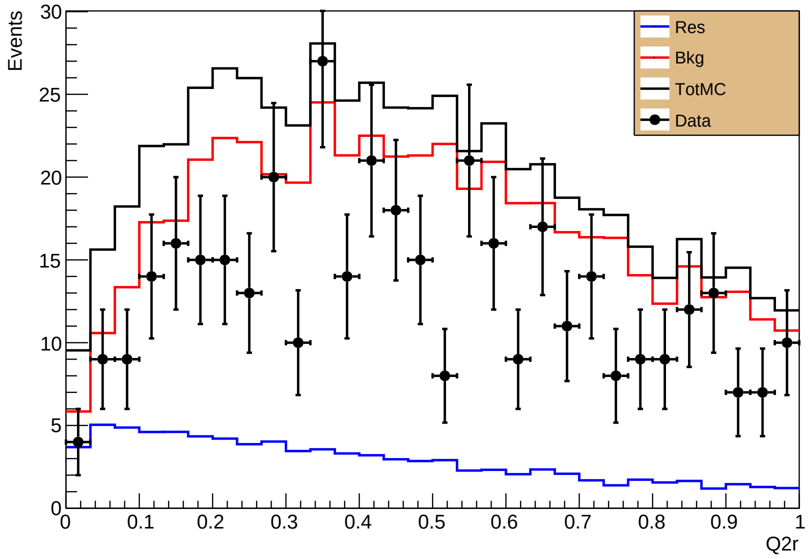


Figure 12: This is the total momentum transfer (Q2r) distribution for all remaining events before the NN cut.

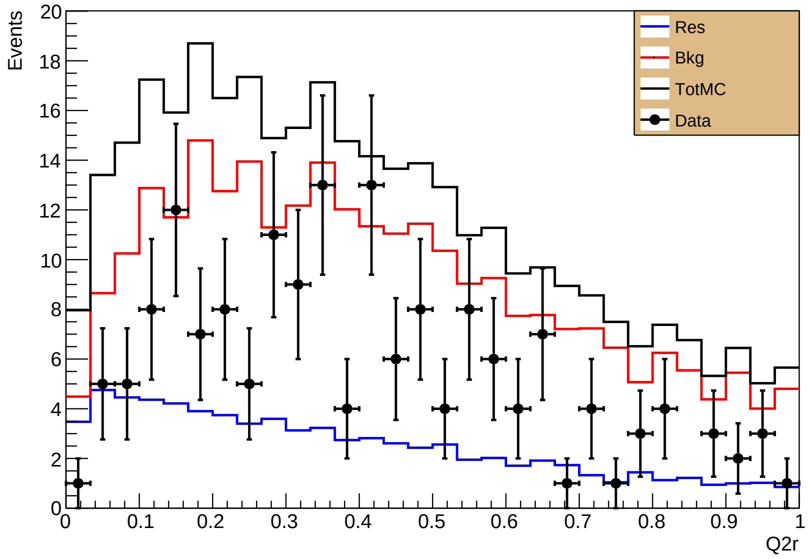


Figure 13: This is the total momentum transfer (Q2r) distribution for all remaining events after the NN cut.

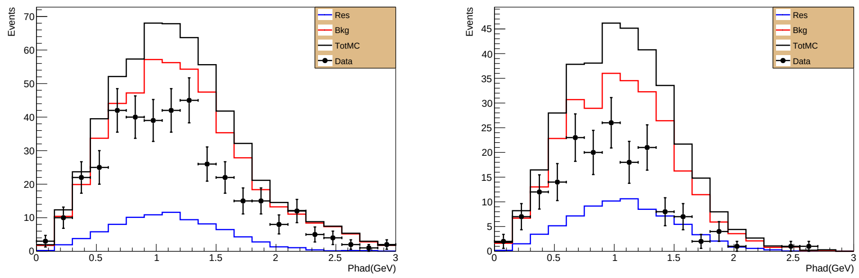


Figure 14: This is the pre- and post-NN analysis hadron momentum (Phad) distribution for all remaining events, once again with before on the left and after on the right.

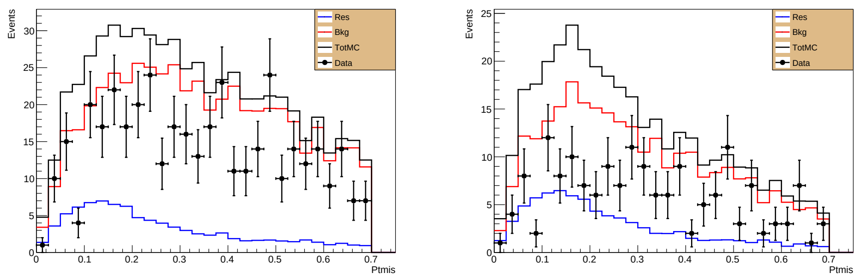


Figure 15: This is the missing transverse momentum (Ptmis) distribution for pre- and post-NN analysis for all remaining events.

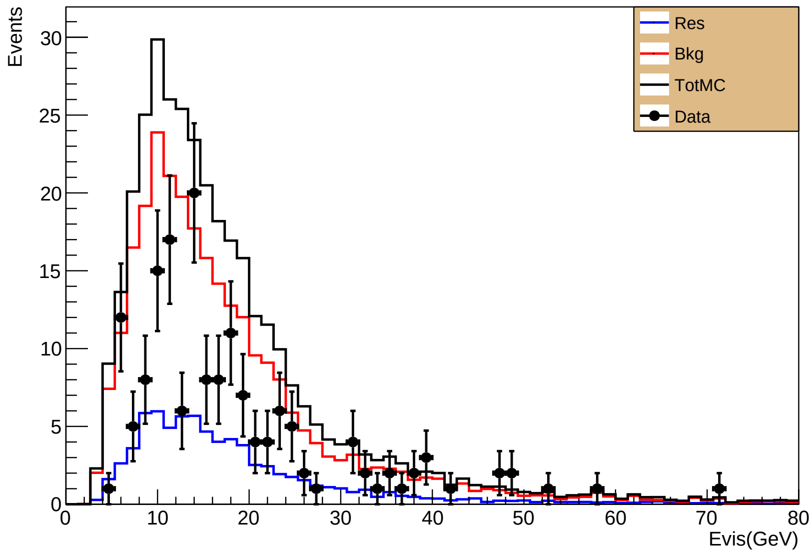


Figure 16: This is the final visible energy distribution for post analysis events. It can be seen that progress has been made bringing the numbers of signal and background closer, but also that background still dominates the signal at every energy.

4.2 Results

While vast improvement was made in distinguishing background from signal as seen from the change between Figure 5 and Figure 16, It can also be seen that fully successful separation has not occurred. We also displayed a number of possible separation variables such as X Bjorken in Figures 8 and 9, Y Bjorken in Figure 11, and missing transverse momentum in Figure 15 but in every case the shape of the background and signal distributions almost matches, with background outnumbering signal at every value of each parameter.

Sensitivity for this analysis is defined as

$$\boldsymbol{Sensitivity} = \frac{\boldsymbol{N^{c-s}}}{\sqrt{\boldsymbol{N^{c-s}} + \boldsymbol{N^{n-b}}}} \tag{1}$$

where $\boldsymbol{N^{c-s}}$ is the number of retained signal events and $\boldsymbol{N^{n-b}}$ is the number of non-removed background events. Calculating this for our remaining event totals of 75.78 signal and 274.53 background, we obtain 4.049 as our sensitivity for this measurement. This is well below any desirable value for sensitivity, which usually range between 15 and 20 for acceptable results. Thus we find that our method was insufficient to identify resonance events in the NOMAD three-track topology.

5 Conclusion

With such a low sensitivity result for our analysis, we find it is not possible to proceed with an analysis of our data set using this method. While it is desirable to study the anti-muon neutrino cross section from the resonance interaction for future experiments such as DUNE, we find that our method is simply not efficient enough to distinguish signal and background in the NOMAD three-track topology, and that as such it is impossible to provide an analysis of the anti-muon neutrino induced resonance interaction at this time. However, there is a vast amount of data on the NOMAD events and it is conceivable that there could be some variable (or set of variables) which does provide a clear distinction between Resonance and CC-DIS events in the three-track topology. Therefore we will continue to study this interaction and hopefully eventually manage to provide a cross section analysis of the anti-muon neutrino induced Resonance interaction for the NOMAD data.

References

[1] Rein D and Sehgal L M 1983 *Nucl. Phys. B* **223** 29
*

[2] G. T. Jones *et al.* [WA21 and Birmingham-CERN-Imperial-Coll-Munich-Oxford-University Coll Collaborations], Z. Phys. C **43**, 527 (1989).

[3] C. Andreopoulos, C. Barry, S. Dytman, H. Gallagher, T. Golan, R. Hatcher, G. Perdue and J. Yarba, arXiv:1510.05494 [hep-ph].