Investigating the NuMI beam focusing uncertainties for ν_μ flux at MINERνA

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Abstract

MINERνA is an experiment at Fermilab dedicated to investigate the nature of neutrino interactions with matter. It has already made novel and important measurements and is making significant progress towards achieving its physics goals. However, the uncertainties in neutrino flux at the detectors are larger than desired. The NuMI beam produces pions from 120 GeV protons. These pions are focused, and hence, when they decay as neutrinos, there is a wealth of neutrinos traveling towards MINERνA and the other experiments set up along the beam. The systematic uncertainties in the NuMI flux arise due to a number of factors involved in creating the intense beam. By generating Monte Carlo data using a simulation program, G4NuMI, for various focusing parameters, one is able to study the effect of these parameters on the predicted neutrino flux at the detector. From this, one can ascertain the beam focusing uncertainties in neutrino flux. I investigate uncertainties in muon neutrino flux at MINERνA, producing a plot of fractional uncertainty as a function of neutrino energy for several such focusing parameters related to the focusing of the beam.

I Introduction

MINERνA (Main INjector ExpeRiment: ν-A) is an experiment at Fermilab designed to study neutrino interactions with matter. It is dedicated to learning more about the energy dependence of neutrino interactions, to examine differences in these interactions between neutrinos and anti-neutrinos, and to learn more about backgrounds related to oscillation experiments, among various other goals.[1] It sits on the NuMI (Neutrinos [Nu] at the Main Injector) beamline, upstream of the MINOS near detector, and consists of a suite of nuclear targets, an active tracking region, and electronic and hadronic calorimeters. Figure 1 shows a schematic depiction of MINERνA. The number of detecting instruments combined with a fine-grained structure provides a wealth of physics knowledge.

As the name suggests, the experiments along the NuMI beamline are fed by using protons from Fermilab's Main Injector. Protons are accelerated in the Main Injector and then diverted to serve a particular purpose. Those for MINOS, MINERνA, and the upcoming NOνA experiments are sent at a slight

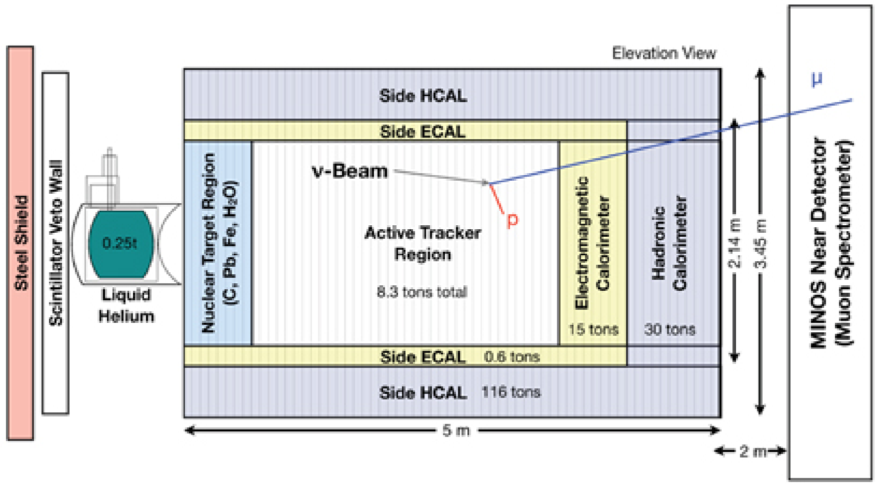

Figure 1: A drawing of the MINERνA detector.[1]

angle, three degrees downwards, and directly at a carbon target. Some of the protons will interact with the carbon target, producing a multitude of various charged secondary particles in the final states. Among them are protons, neutrons, pions, and kaons. Some of these particles will then interact further in the carbon. Eventually, some number of hadrons will leave the carbon target at varying angles and with varying energy from numerous intereactions and re-interactions. Downstream of the target, there are two aluminum horns that help focus these assorted final states; these horns carry current on their outer and inner conductors, producing a toroidal magnetic field that helps to focus the charged hadrons exiting the carbon target into a stream pointed towards the downstream detectors.[2] Some of the hadrons focused toward the detectors, namely pions and kaons, are unstable and decay on their journey. These decay mostly into muons and muon anti-neutrinos or anti-muons and muon neutrinos, depending on the charge of the hadron in question. For example, positive pions decay to anti-muons and muon neutrinos with a probability of more than 99.9 percent.[3] Several hundred meters of rock and Earth work to filter out the muons, while the neutrinos will pass through these. Downstream of these absorbers are the experiments, which are bombarded by the neutrinos produced in the pion and kaon decays. Figure 2 depicts the NuMI beam.

For MINERνA's cross-section analyses, it is important to have precise knowledge of the total flux of neutrinos at the detector. One must know the number of neutrinos at the detector to know the significance of a given number of events towards a probability. Currently, the neutrino flux uncertainties associated with MINERνA are larger than desired. Investigation of the systematics involved in the neutrino flux uncertainty could help better define these uncertainties, leading to more precise physics results from MINERνA. In the past, fast Monte Carlo

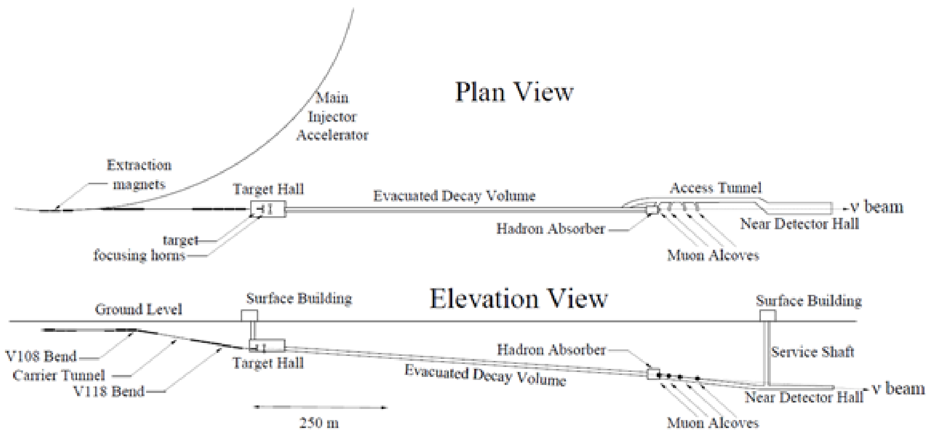

Figure 2: A depiction of the NuMI beam.[2] MINERνA is located in the (MINOS) near detector hall.

simulations have been used to study such flux uncertainties for MINOS,[2] but a dedicated full Monte Carlo of the NuMI beamline geometry such as G4NuMI[2] should provide more precision. The nominal operating conditions of delivering neutrinos to the experiments would lead to a particular flux spectrum of muon neutrinos at the detector. However, there is an uncertainty in that nominal value, and different values of the contributing parameters will lead to a different flux at the detector. This uncertainty in the muon neutrino flux received at MINERνA is a systematic associated with any measurement in MINERνA. Beam focusing parameters are part of what leads to such uncertainty, and some of these paramters include those relating to the spatial setup of the surrounding materials and horns, the extent of focusing of charged particles by the horns, the density of the target, scraping of the protective baffle by protons, and the hadron production within the NuMI target.[2] The uncertainties in beam focusing parameters found in past studies (with fast Monte Carlo) lead to noteworthy uncertainties in ν_μ flux. They are shown in the table in Figure 3, ignoring hadron production.

Figures four and five offer a better depiction of the focusing horns. Figure 4 shows a sketch of the horn 1, its shape and features, drawn by the author in Mathematica, using a set of NuMI data.[4] The gap in the drawing's outline is an artifact of drawing and is not physical. Figure 5 depicts horn focusing in more detail than the prior figure of the NuMI beam. As mentioned before, the horns focus particles by carrying current in an outer and inner conductor, creating a toroidal magnetic field. This field is such that the courses of particles traveling down the middle, or neck, of the horn are not altered by the field, while particles traveling between the inner and outer conductors are given a longitudinal boost by the field such that they travel forward, towards the detectors, as in

Source	Uncertainty
Number of protons on target	2.0 %
Horn transverse misalignment	1.0 mm
Horn tilt	0.2 mrad
Horn current miscalibration	1.0 %
Horn current distribution	$\delta = 6$ mm/$\delta = \infty$
Baffle scraping	0.25 %
Misalignment of shielding blocks	1.0 cm
Target density	2 %

Figure 3: The uncertainties in important NuMI beam hardware.[2]

Figure 5.[2] The field goes as $B = \frac{\mu_0 I}{2\pi R}$, where R is the distance from center of the horn, and the kick received by a particle traveling through the horn is approximately $J = \frac{a\mu_0 IR}{2\pi}$, where a is a constant related to the curve of the inner conductor.[2] Multiple horn parameters affect the extent of their focusing, and thus the overall predicted flux: a few such parameters are horn current amplitude, horn misalignment transverse to the beam, and horn rotation relative to the beam.

II Methodology

GEANT4 is a software specializing in simulating particles passing through matter.[5] This naturally makes it useful for experimental setups such as those involved in the NuMI beam, as particles pass through various objects in traveling toward MINERνA: the protons hitting the target, charged secondaries going through the horns, etc. GEANT4 has been tuned and adapted to look use the geometry of the NuMI beamline. This is the Monte Carlo simulation called G4NuMI. It simulates a given number of protons on target (POT) using a very long list of parameters governing the particles and experimental setup (the G4NuMI source files directory contains more than four dozen files). The output is stored in a set of ntuples—a list of values—for the events leading to neutrinos in the final state. Among other important simulation data, the G4NuMI ntuples contain information such as the neutrino's parent states, the momentum and positions of all states, the neutrino energy at various locations relating to NuMI beam experiments, etc. A sample piece of a G4NuMI ntuple is shown in Figure 6. By installing G4NuMI and manipulating its source files, one is able to simulate events in the NuMI beam for almost any condition and configuration. This ntuple generation is performed by executing a Perl script that submits jobs to the Fermilab computing grid, allowing for hundreds of millions of protons on target to be run in chunks simultaneously (for example 100 jobs of 1 million POT each, as opposed to 100 million POT in one file). This and changes made to the G4NuMI source code to allow easier customization drastically cuts back on the time and effort involved in generating these data for a full MC, allowing one to

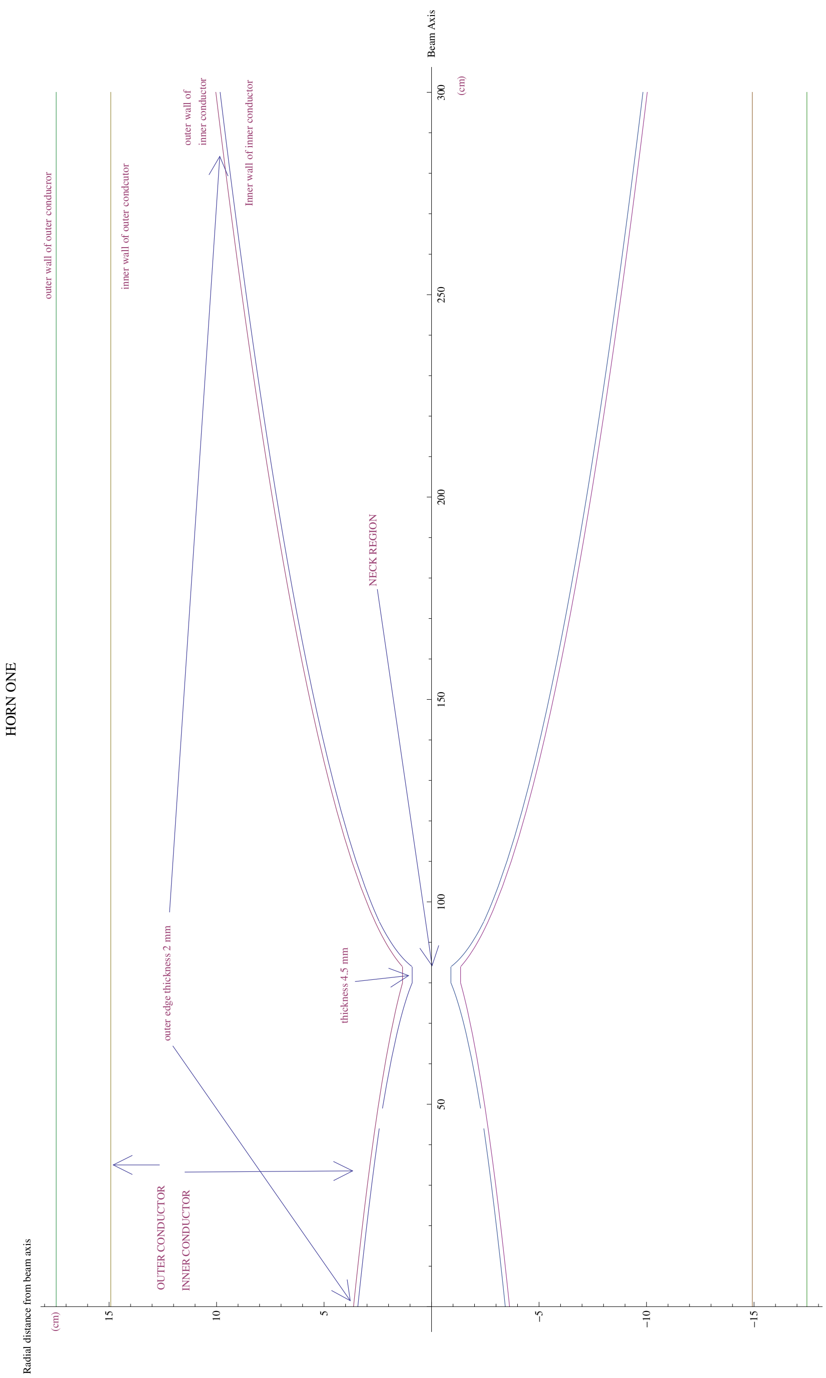

Figure 4: A sketch of the NuMI horn shapes based on data from the NuMI Technical Design Handbook.[4]

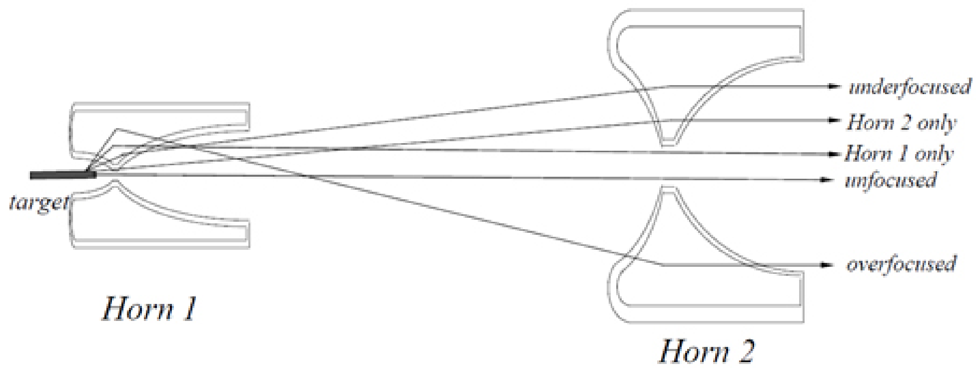

Figure 5: A drawing of charged particles being focused towards the detector.[2]

generate a large data set with less hassle. This is important because using a full MC simulation such as G4NuMI will provide more precise information but takes much longer to simulate. As aforementioned, prior studies of flux uncertainties have used fast MC simulations; one such simulation is PBEAM.[2]

Since these generated ntuples contain information on the simulated neutrinos for a given set of parameters, one can use these ntuples to calculate the corresponding neutrino flux as a function of energy. To perform this calculation, analysis software written in C++/ROOT pulls in the ntuples and sorts them based on neutrino type and energy. For this study, which is concerned with muon neutrinos, the muon neutrinos are recorded in a histogram of flux versus neutrino energy. The histogram is weighted, too, for statistical considerations performed by G4NuMI. Further C++/ROOT analysis is performed on these fluxes to determine the fractional flux uncertainties for ν_μ at MINERνA.

III Analysis

Due to time constraints, it was not possible to reach the desired POT for each of the three considered parameters. For this reason, the analysis for simulations for each value of horn 1 and 2 transverse misalignments were run with POT of the order of tens of millions and the simulations for each horn current value with hundreds of millions of POT (399.2 million POT).

Figure 7 shows a few such calculations of flux overlayed, one for a run at the nominal 185kA (which is actually 182.1 kA) and the other for a negative 3sigma shift, or 176.637 kA, where sigma is the parameter's uncertainty, as shown in Figure 3. Additionally, Figure 8 shows the same type of plot, but for a different shift in NuMI run conditions, this one for nominal settings and shifts in the transverse position of the first horn relative to the beam by 2 mm and 4 mm. Note that in Figure 8, in the focusing peak (the energy values where most of

```
protonX          = -1.59694
protonY          = 0.620618
protonZ          = -4100
protonPx         = 0
protonPy         = 0
protonPz         = 120000
nuTarZ           = -450
hornCurrent      = 182.1
Ndxdz            = 0.00610391
Ndydz            = -0.0465298
Npz              = 0.575557
Nenergy          = 0.576191
NdxdzNear[11]    = 0.000192682 , 0.000204263 , 0.0153025 , 0.0248308 , 0.0328637 ,
                    0.0428495 , 0.0615526 , 0.000237585 , 0.110696 , 0.00465562 ,
                    -0.00441251

NdydzNear[11]    = -0.000311746 , -0.00634126 , -0.0111289 , -0.011552 , -0.014367 ,
                    -0.00961686 , -0.000719961 , 0.165077 , 0.333918 , 0.00322858 ,
                    -0.00396492

NenergyN[11]     = 1.74019 , 3.07338 , 1.87173 , 0.897251 , 0.552057 ,
                    0.326057 , 0.154178 , 0.0189507 , 0.00495134 , 1.25971 ,
                    2.17511

NWtNear[11]      = 0.00304688 , 0.0106802 , 0.00457982 , 0.00113352 , 0.000465618 ,
                    0.00027595 , 0.000127081 , 5.34807e-07 , 1.11886e-07 , 0.00154764 ,
                    0.00491298

NdxdzFar[2]      = 1.38802e-07 , 3.56578e-05

NdydzFar[2]      = -2.24572e-07 , 0.000100171

NenergyF[2]      = 1.6907 , 1.67619

NWtFar[2]        = 1.49247e-09 , 1.20357e-09
```


Figure 6: A piece of an example ntuple. The printed data includes horn current, neutrino energies that would be measured at different places, etc. and comes from one event in the Monte Carlo simulation. This particular ntulple was generated at nominal horn current settings.

the neutrino events are), transverse misalignments in horn 1 cause a decrease in flux. However, these small transverse misalignments cause an increase in flux in the falling edge of the neutrino spectrum (around 4-5 GeV).

One can then examine the ratios of the fluxes, as this reveals the effects of the shifts on the flux as a function of energy.[2] There are two ways to examine such ratios, each of which has useful physics. The first method is taking the simple ratio of Flux(shifted)/Flux(nominal) as a function of neutrino energy. This will show in clear terms how shifts in a particular parameter affect the flux at different neutrino energies, and an example is given in Figure 9. Figure ten is a zoomed in version of this plot, to the region surrounding the focusing peak, where uncertainties are small due to larger statistics. This plot for the flux ratio of horn 1 transverse misalignment of 2 mm to nominal provides a further depiction of the trend mentioned above about Figure 8. The second method is more useful in the calculation of the fractional flux uncertainties. This ratio is ΔFlux/Flux(nominal), where the choice of ΔFlux=Flux(shifted)-Flux(nominal) or ΔFlux=Flux(nominal)-Flux(shifted) is a personal one. In this study, the first is chosen, so that the ratio from a shift leading to an increase in flux is positive. In the interest of brevity, this type of plot will be referred to as a delta ratio or delta ratio plot.

Once one has the delta ratios for each shift in a given parameter, the fractional flux uncertainty due to that parameter can be ascertained. These uncertainties will be different for neutrinos of different energies, so one must consider

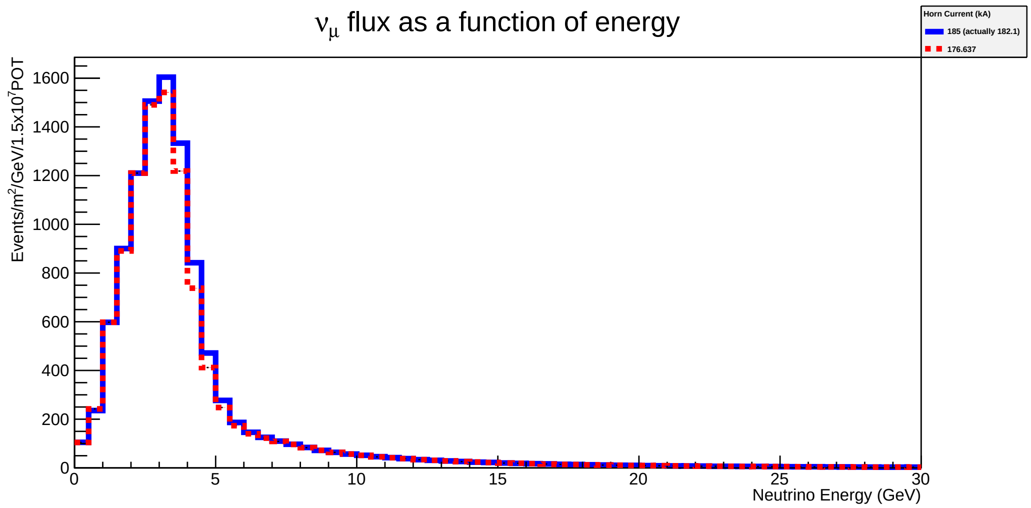

Figure 7: Flux vs. neutrino energy for two horn current amplitude settings.

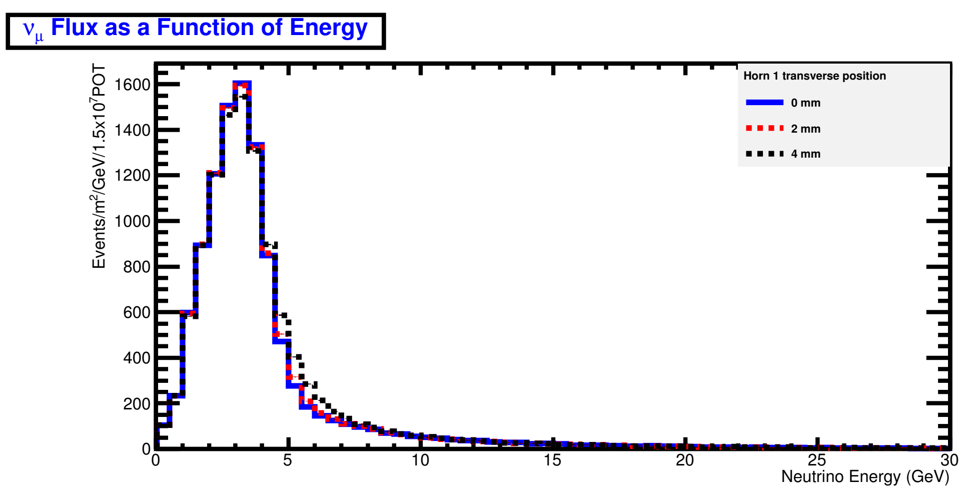

Figure 8: Flux vs. neutrino energy for three horn one transverse misalignment settings.

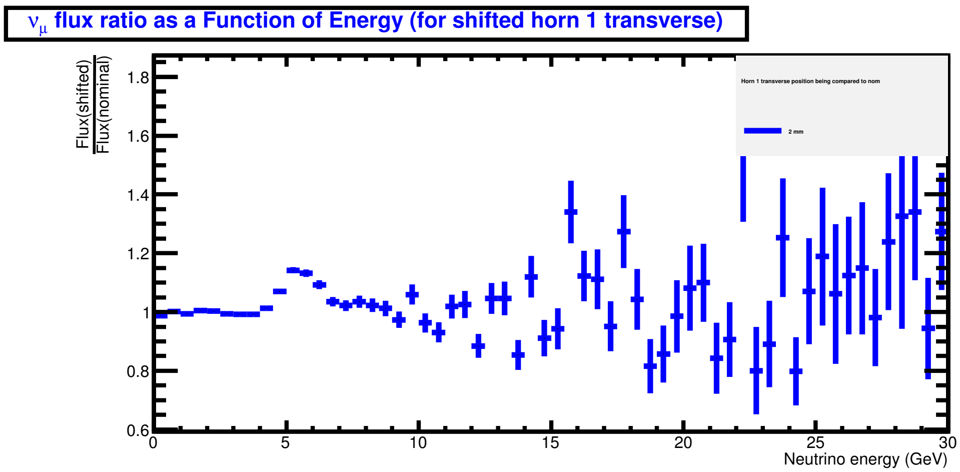

Figure 9: This shows the result of plotting the ratio of the flux with horn 1 shifted transversely to the beamline by 2 mm to the flux with it not shifted, as a function of neutrino energy.

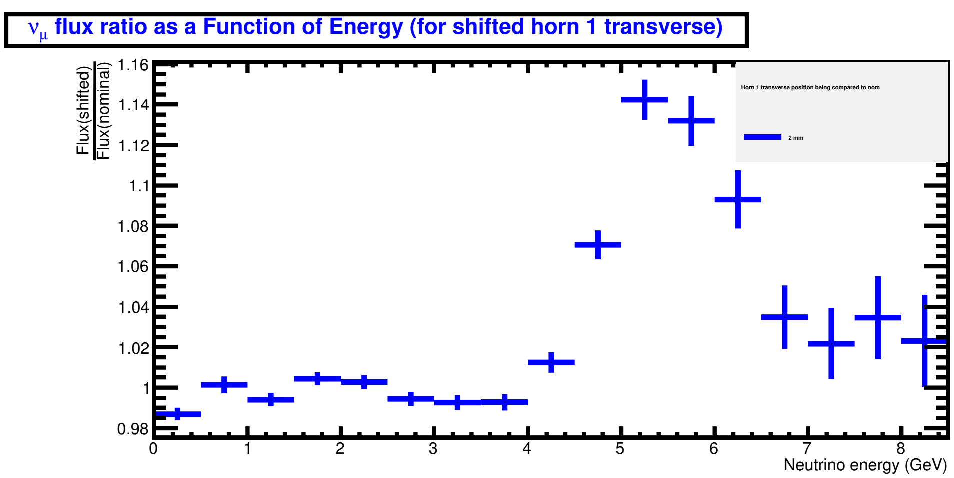

Figure 10: The same as Figure 9, but showing a smaller range of neutrino energy near the focusing peak and hence less dominated by statistical fluctuations.

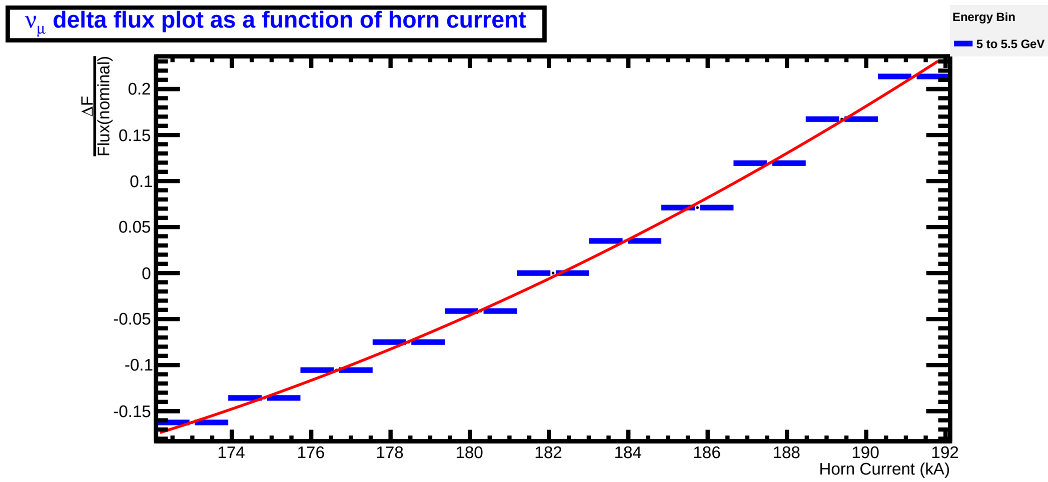

Figure 11: The fitted sensitivity plot for 5-5.5 GeV neutrinos with various horn current amplitudes. It is from this plot that the fractional uncertainty in flux for this energy range of neutrinos due to horn current variations is derived.

each energy bin separately. The general procedure involves making sensitivity plots showing how the flux responds to shifts in the parameter, using the delta ratios for shifts ranging from -5 sigma to 5 sigma, for each energy bin. Thus, these plots definitely show the effects of a shift in parameter on neutrino flux. These plots are then fitted with a second-order polynomial, as perhaps not every parameter will yield linear results. This was a choice made by Žarko Pavlović in a prior study for MINOS,[2] and I concur with this choice. The value of this fit at 1 sigma then represents the fractional change in the flux with changes to the parameter at that point. This extracted value of the fit at 1 sigma is the fractional flux uncertainty for that energy of neutrino for that specific NuMI parameter. Figures 11 to 14 show a few of the fitted sensitivity plots. The uncertainties from each energy are then plotted, to create the histogram displaying fractional uncertainty in flux vs. neutrino energy. Figure 15 shows an overlay of all studied uncertainties. In the plot, the total uncertainty arising from these parameters is also shown, defined to be the sum of component uncertainties added in quadrature.[2]

IV Discussion

The fits are expected to get better with simulations run at even higher POT, and this analysis is ongoing. One important feature is that the shapes of the uncertainties in Figure 15 are pretty closely matched to those found in previous

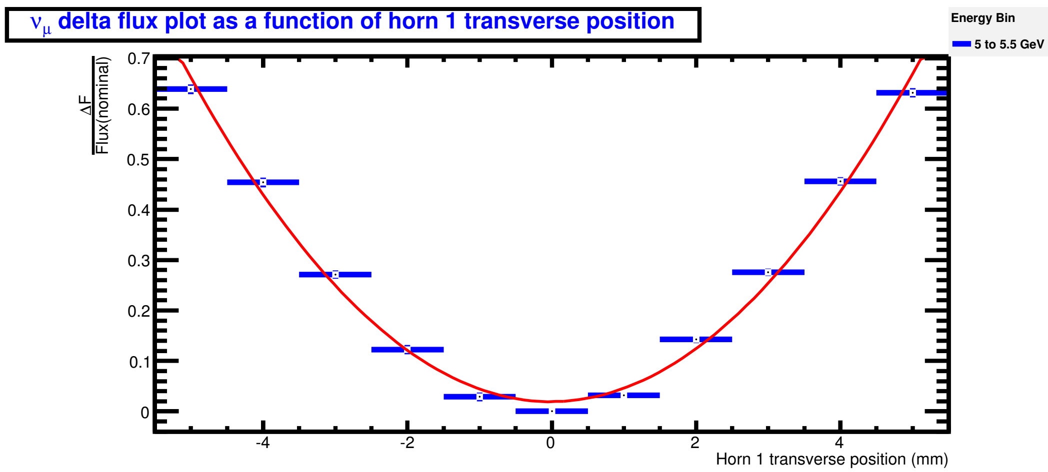

Figure 12: The fitted sensitivty plot for 5-5.5 GeV neutrinos with various horn one transverse positions. This shows the increase in flux that comes with shifts in this energy range.

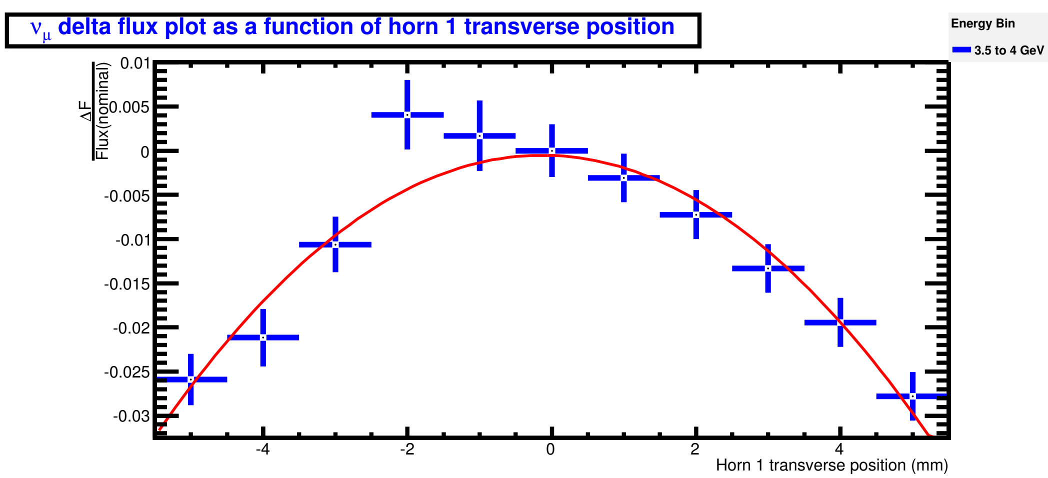

Figure 13: The fitted sensitivty plot for 3.5-4 GeV neutrinos with various horn one transverse positions. This shows the decrease in flux that comes with shifts in this energy range.

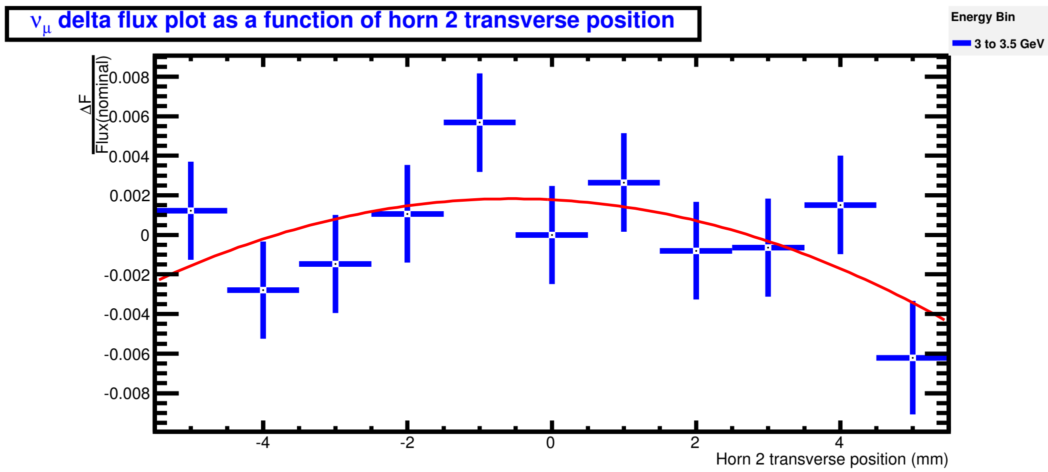

Figure 14: The fitted sensitivity plot for 3-3.5 GeV neutrinos with various horn two transverse positions. This shows that the flux is less sensitive to horn 2 transverse positions, at least at this energy, as the fluctuations are tiny. The flux is less sensitive to uncertainties in horn two transverse position.

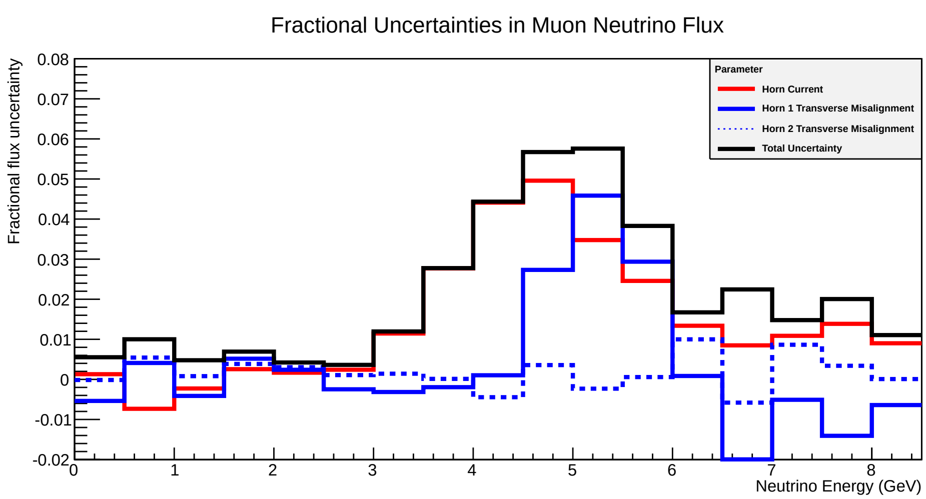

Figure 15: The fractional uncertainties as a function of energy for each parameter considered in the nominal configuration of le010z185i [Low Energy, 10 cm target placement upstream, 185 kA nominal horn current (which is actually 182.1 kA)]. The black shows the total uncertainty, which is the component uncertainties added in quadrature.

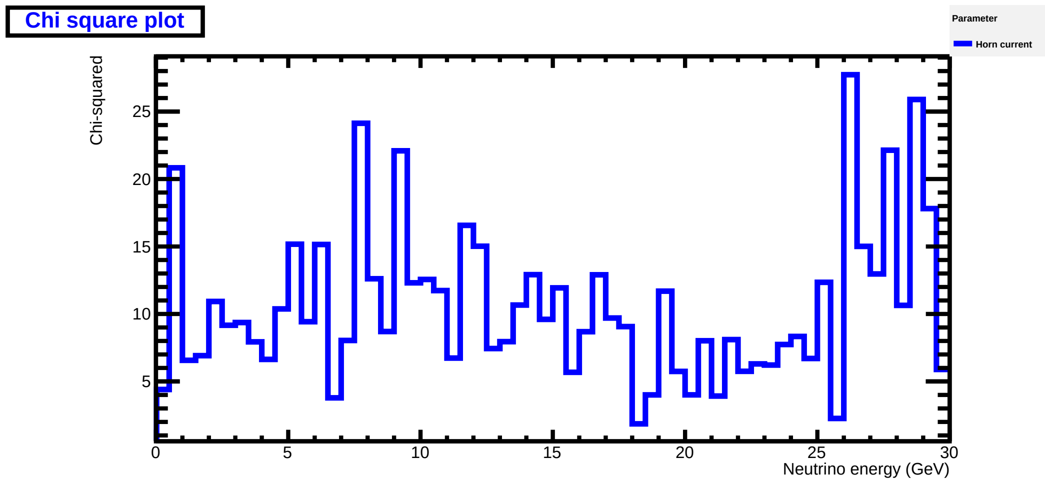

Figure 16: A plot of the χ^2 of the fit for each energy bin, for horn current variations.

study.[2] In fact, for horn current, the peak flux uncertainty occurs at the same energy but with a lower value than the prior study, and this was the study run at hundreds of millions of POT per parameter value.[2] On the other hand, the shown fractional uncertainty in horn 1 transverse position is a bit larger at its peak than in prior study.[2] However, the plots below, in Figures 16 and 17 show that the χ^2 of the fits to the sensitivity plots for horn current are much better at this POT count than those for the horn 1 transverse position. This result is preliminary but provides hope that further studies with a higher number of POT will lead to further reductions in uncertainty, leading to a better-understood flux. For general purposes, the χ^2 for horn 2 transverese misalignment is also included.

The most tangible outcome of this investigation is achieving an estimate from a full Monte Carlo simulation for the ν_μ uncertainty at MINERνA as a result of multiple NuMI focusing parameters. As aforementioned, prior studies have used less precise fast Monte Carlo simulations. In addition to this physical result, other benefits arise as a result of this line of study. For one, to perform this study, G4NuMI source code had to be edited on the author's work space. In the process, many data inputs that would previously require compilation of code with every edit was automated to allow fast and easy changes, without the need for compilation to run in a different mode. This code will be stored and can be used by future researchers who may need this feature. Additionally, the analysis machinery put in place to study ν_μ flux can be utilized in the analysis for other flux studies as well, as will be discussed below.

In the future, several lines of study remain. Larger statistic runs will allow

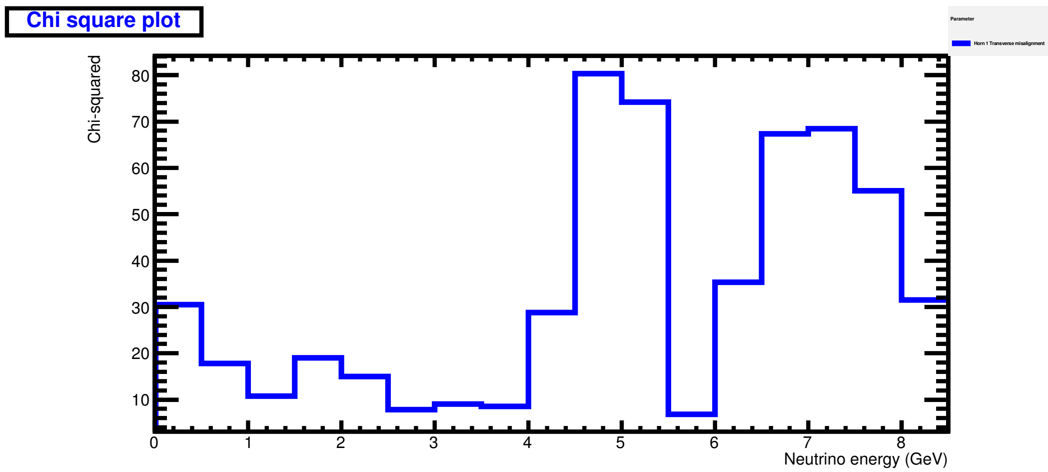

Figure 17: A plot of the χ^2 of the fit for each energy bin, for horn one transverse position variations.

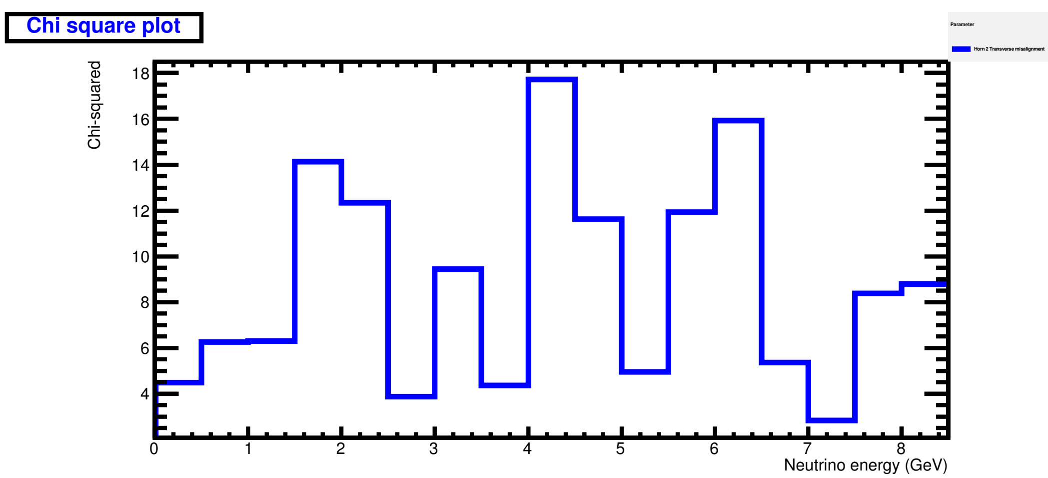

Figure 18: A plot of the χ^2 of the fit for each energy bin, for horn two transverse position variations.

for better uncertainty calculations, as mentioned above. Furthermore, other parameters of the NuMI beam not studied in this particular investigation will be included in future iterations of this study. Some such parameters are not included in the MC simulation but can be added and investigated. Additionally, the horn current distribution plays a role in the flux uncertainty. An ideal conductor of the types that appear in an undergraduate electricity and magnetism course would have charges spread over the outer edge of the conductor, however in the real, oddly-shaped inner conductors, some of the current penetrates into the conductor itself, leading to a current distribution.[2] The properties of this current distribution lead to changes in horn focusing, and thus to changes in neutrino flux. Beyond muon neutrinos, it is important to investigate the flux uncertainties arising in the electron neutrino spectrum as well. An estimation of flux uncertainties for electron neutrinos would benefit electron neutrino analyses on MINERνA. Then, beyond these aforementioned low-energy considerations, the beam will soon be operating at medium energy in the NOνA era. These runs will entail a somewhat different set of parameters, leading to the need for a new investigation.

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