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POSITION PAPER ON THE BEAM FLUX

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I. INTRODUCTION

The present memo attempts to summarize the status of the Monte Carlo simulation of the NuMI beam flux, especially as it pertains to the CC analysis. While the MINOS near detector (ND) flux can be measured directly, the beam Monte Carlo is the only unbiased mechanism we have to describe the non-oscillated flux of neutrinos at the far detector (FD) due to the anticipated differences in neutrino flux at the ND and FD. As such, the beam MC plays a role in the calculation of the denominator of a ν_μ disappearance measurement.

If the energy spectrum of neutrinos at the ND and FD are identical, then the ND flux would be a direct measure of the expected FD flux, to be scaled by the relative solid angles:

$$\phi^i_{far} = \left(\frac{z_{near}}{z_{far}} \right)^2 \phi^i_{near}$$

where ϕ_i is the flux of neutrinos in an energy bin i and z_{near}=1040 m is the distance of the ND from the NuMI target and z_{far}=735,000 m.

Three effects modify the above approximation, requiring Monte Carlo simulation to provide a more accurate prediction of the FD spectrum. These are pictured schematically in Figure 1:

1. The ND distance of z_{near}=1000 m is comparable to the mean decay length of pions, ($\gamma\beta c\tau$ ~ 560 m for a 10 GeV pion). This means that soft pions will decay significantly upstream of the ND, while fast pions will decay right in front of it exaggerating their flux contribution to the ND by nearly a factor of two.
2. Soft pions are typically under-focused by the horns, so have a larger divergence as they enter the decay pipe. Fast pions, because of their boost, are at smaller entrance angles.
3. The energy of neutrino reaching the detectors is a non-trivial function of the parent π/K energy and the angle of the neutrino with respect to the π/K direction:

$$E_\nu = \left(1 - \frac{m^2_\mu}{m^2_{\pi,K}} \right) \frac{E_{\pi,K}}{1 + (\gamma\theta)^2} \qquad (1)$$

where γ is the boost of the parent hadron and θ is the decay angle. This effect, on average, reduces the neutrino energy seen by the ND compared to the FD.

The competing effects above lead to systematic distortions between the ND and FD flux at the 20-30% level. If such accuracy is sufficient for the FD flux, one may perform the analysis using the ND spectrum as the FD predictor, weighted by $(z_{near}/z_{far})^2 = 1.85\times10^{-6}$.

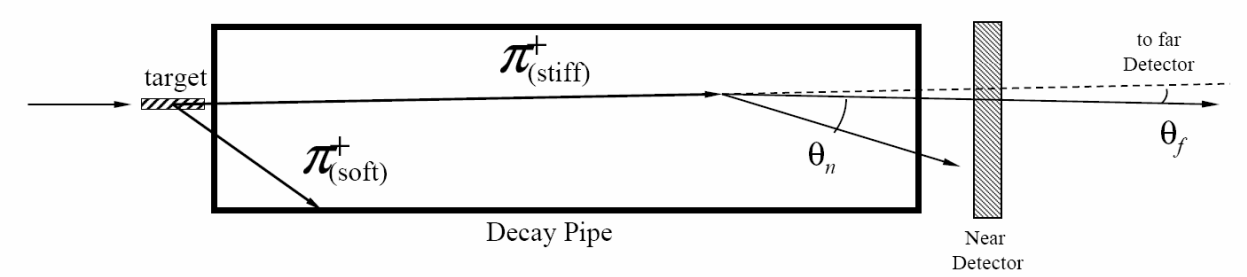


Figure 1: Schematic view of pion decay leading to neutrinos that reach the ND or FD. On average, the ND sees a different (broader) decay angle θ_n than does the FD, which sees an angle θ_f. Furthermore, fast pions decay right in front of the ND, exaggerating their importance to the ND flux as compared to the FD flux.

The different neutrino spectra seen by the two detectors due to these kinematic and acceptance effects can be well modeled by the beam MC. The beam MC relies on input data for the yield of particles from the NuMI target as a function of x_F and p_T. The beam MC tracks these particles through the magnetic field of the two focusing horns and allows them to decay with appropriate weight according to their lifetime. Along the paths of these particles, a reasonably correct description of the beam line geometry is in place so that interactions and scatterings of the particles can be appropriately simulated which have the effect of lowering their energy or increasing their divergence with respect to the beam axis. Particle re-interactions are responsible for 20-30% of the neutrino flux. The output of the beam MC is an ntuple of particles which have decayed along the Decay Pipe which includes their decay location, energy, direction, probability to propagate to and decay at the given location, and particle species. Using this ntuple, the user can calculate the additional weighting probability for the particle's daughter neutrino to hit the near or far detector and also calculate the resulting neutrino energy at that location using equation (1). In this way, an energy spectrum at either location is obtained (note that in the ND the energy spectrum actually changes across the face of the detector).

The beam MC readily permits systematic study of the inputs to the beam MC (particle yield from the target, focusing properties of the horns, *etc*.). This can be performed by tweaking these inputs to the beam MC and observing what effects are observed in the output ntuples of decayed pions and kaons. As the same parent mesons are decayed to either the ND or FD location, these 'tweaked ntuples' will properly generate the distorted neutrino spectra at both detectors. An analysis of 'toy data' generated under distorted conditions can be performed to understand the effects of systematic uncertainties on oscillation fits or limits to the experiments sensitivity. How the experiment will exploit this correlation information in the near→far extrapolation is a separate matter, and is commented on in Section V.

Section II summarizes our current beam MC and differences with repect to previous versions. Section III summarizes the results of other studies on our attempts to translate uncertainties on the inputs to the beam MC into uncertainties on the neutrino flux, as well as comment on possible systematics not yet studied. Section IV describes available cross checks of the beam MC. Section V comments on possible mechanisms for using the beam MC to perform the Near→Far extrapolation. Section VI discusses a one such method, advocated by the K2K collaboration, of treating the problem of extrapolating Near→Far which permits simultaneous handling of other errors from cross sections reconstruction, backgrounds, *etc*. Section VII discusses criteria for 'opening the box' in January. Section VIII concludes.

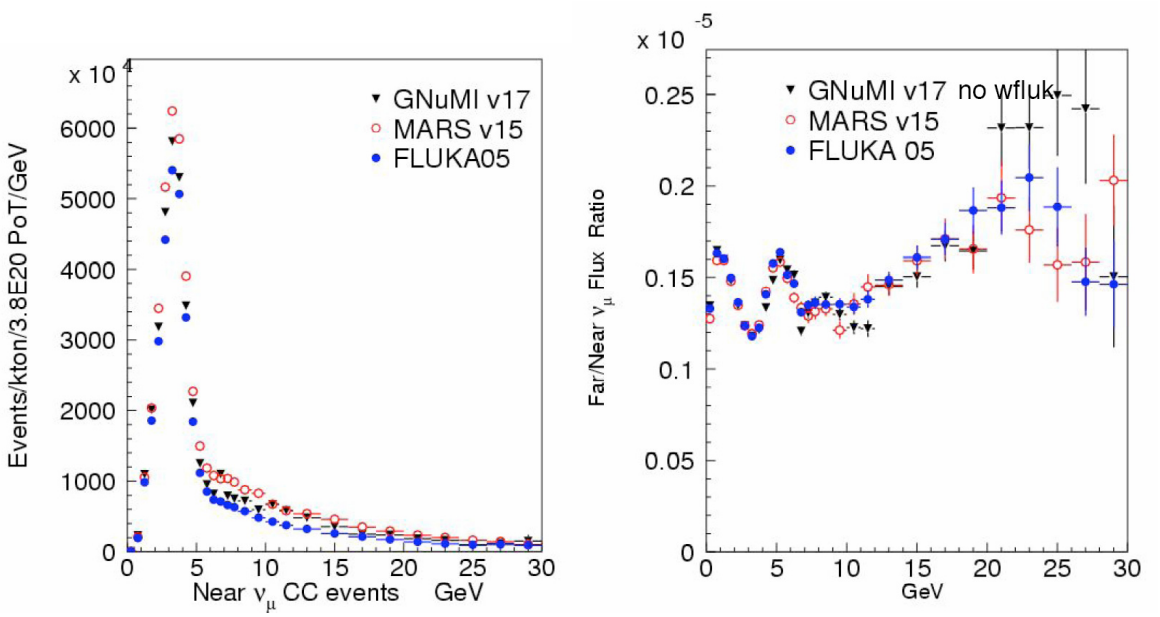


Figure 2: (left) Expected event rate in the ND. (right) Calculated FD/ND ratio in the absence of oscillations. The calculation of GNuMI v.17 is compared to two variants of GNuMI v.18: the first variant uses target particles produced by the MARS model and the second by the FLUKA2005 model. For the F/N ratio above wfluk.F was omitted in calculating the v.17 F/N ratio, since it had a bug. For the Fall 2005 analyses, the beam MC group has recommended use of FLUKA2005.

II. CURRENT FLUX CALCULATION: GNUMI – V. 18

The version of the beam flux in use by the MINOS collaboration for the Fall 2005 analyses is v.18. This effort is documented on the Beam MC web page [1]. The ND flux and F/N ratio are shown in Figure 2. With respect to the preceding version, the changes in this flux calculation are as follows:

- Particles created in the target are simulated using a separate Monte Carlo model. These particles are simulated in the FLUKA 2005 code and fed as inputs into the horn tracking software of GNuMI. This procedure replaces an approximate reweighting routine (wfluk.F) utilized in GNuMI v.17 to approximately derive the FLUKA fluxes as a reweighting of GFLUKA simulations. The effect of this improvement over the old reweighing calculation is (2-3)% in the focusing peak (see Figure 3).
- The model of the target was made more realistic, including Budal fin, more accurate descriptions of the cooling tubes and supports, the Beryllium window of the target canister, etc. Furthermore, the proton beam spot size was set to a realistic value of 1.1×1.2 mm^2. The effect of this improved geometry is ~(2-3)% [2] (see Figure 3).
- The decay pipe was filled with air at 0.4 Torr. The effect of this was «1%.
- The horn current was multiplied by 0.984, reflecting a calibration by J. Hylen. Such has a ~5% effect on the neutrino flux near the focusing peak edges, as is discussed in [3].

The sum of all these effects, as shown in Figure 2, turns out to be ~7% in the focusing peak. Such is in accordance with expectations from the earlier studies reproduced in Figure 3.

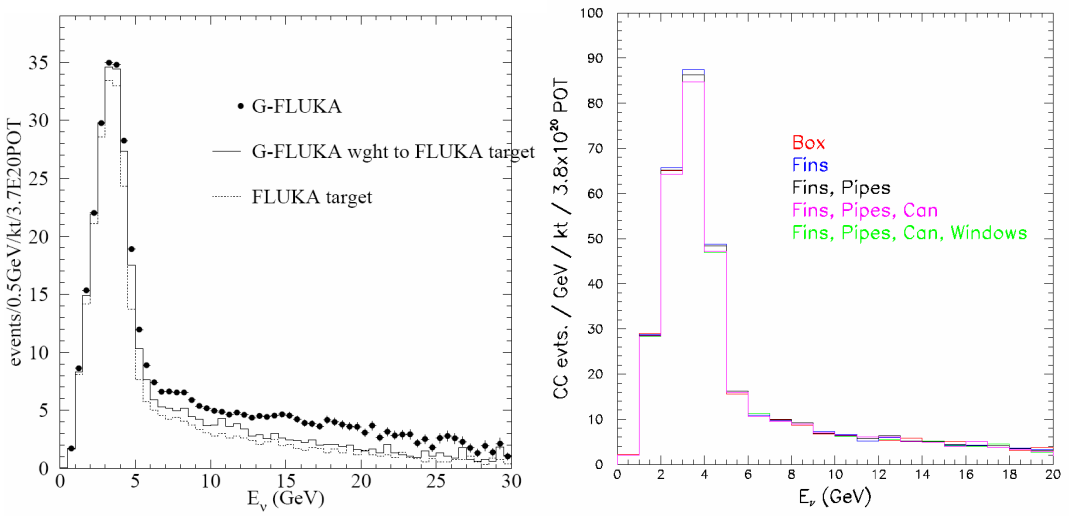


Figure 3: (left) Comparison of FD neutrino spectrum calculated with target particles simulated in GFLUKA (used in GNUMI v.16), FLUKA used in GNUMI v.18), and a reweighted sample of GFLUKA particles reweighted to the FLUKA yields (v.17). (right) Study of the effect of target geometry on the neutrino flux from [2]: to a box target is added fin geometry, water cooling tubes, vacuum canister, and Beryllium windows.

It is our expectation that the v.17 fluxes would have been mostly OK in the Fall, 2005 analyses in so far as they would not introduce a bias into the oscillation analysis. The one exception to that statement is the fact that the Near→Far extrapolation was slightly off in the lowest few bins of GNuMI v.17 due to statistical flucuations in wfluk.F (part of the v.17 package).

III. SYSTEMATIC UNCERTAINTIES

A review of the expected systematic uncertainties on the ND neutrino flux and on the Near→Far extrapolation has been written [3]. Therefore, only a brief summary pertaining to our confidence in these calculations is warranted here.

Owing to the efforts of many, the NuMI beam has been designed with an impressively tight 'error budget' and instrumented to the level necessary to demonstrate the attainment of these errors. To date, beam conditions have been quite stable with only minor variations have occurred. We therefore benefit from a level of luxury not available in many past experiments or even in the currently-running MiniBooNE experiment.

The NuMI beam instrumentation has allowed us to apply fairly tight constraints on several parameters which can distort the neutrino spectrum. Some examples: (1) To the extent there are proton beam targeting variations, or halo missing the target, or halo hitting the upstream collimating baffle, these are reasonably well measured by the primary beam instrumentation and the effects of such proton beam variations can be confirmed in the muon monitors (which directly tell us that there is a an effect on the neutrino flux in accordance with our expectations). (2) The horn current and magnetic field have been directly measured *in situ*, as has our beam toroid which counts protons on target. (3) Alignment of the target and both horns has been performed *in situ* using the proton beam to "X-ray" the target hall [4].

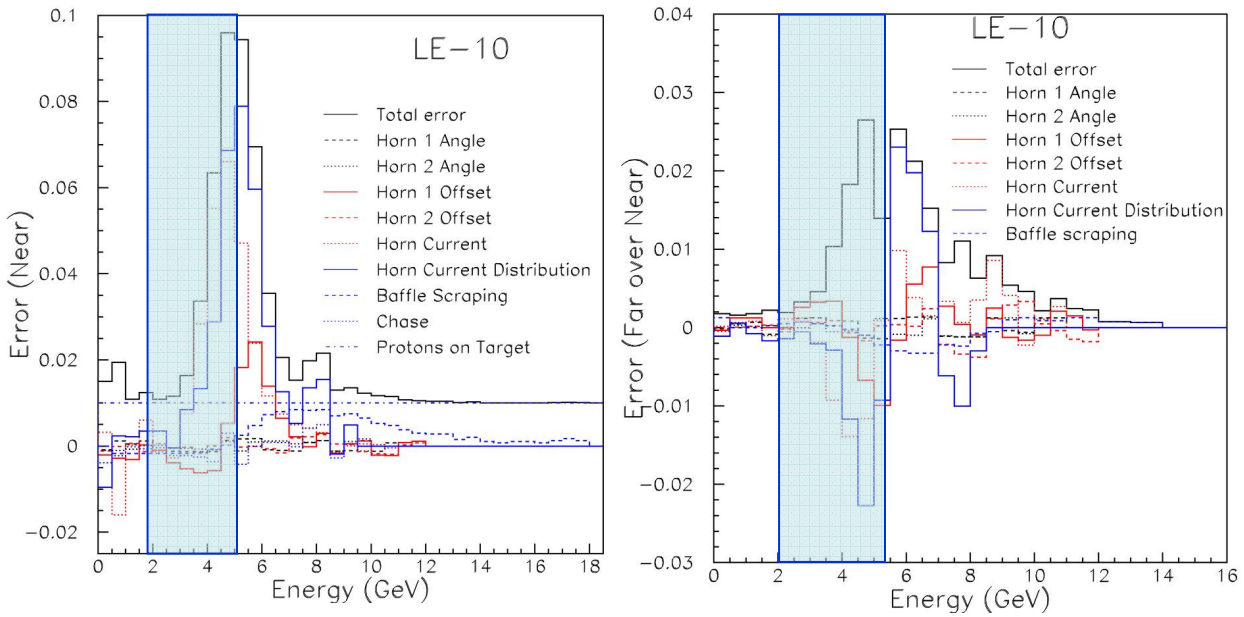


Figure 4: (left) Expected (relative) uncertainty on the ND flux in the LE(10) beam. (right) Expected (relative) uncertainty in the F/N ratio in the LE(10) beam. All uncertainty contributions except hadron production are included. Taken from [3]. The energy band of the LE(10) focusing peak is indicated by the shaded area.

Figure 4 shows a summary of all the systematic uncertainties investigated with the exception of the hadron production uncertainties. To be clear, the curves in Figure 4 show the ratios of spectra simulated under some error scenario and that simulated under the nominal condition. Thus, the 'error' due to horn alignment is the ratio of neutrino fluxes calculated with a misaligned horn to that with the horn aligned in the MC. The level of error condition simulated has been constrained using the beam instrumentation or alignment numbers from [4]. Similar error bands, calculated for the LE, pME, and pHE beams, are available in [3].

It should be emphasized that the F/N ratio is not recommended as our analysis technique for the Fall 2005 analyses. The errors are thus quoted only for purpose of demonstration that the FD flux uncertainty, derived from the ND and the Near→Far extrapolation, is smaller than the dead reckoning of the ND flux.

To be conservative, we often took the error source as the full uncertainty. For example, horn 1 was found to be 1.0±0.2 mm out of alignment, so we took 1.0 mm as the horn alignment uncertainty. Likewise, the horn current was found to be off by (1.6±0.5)%, so we took the horn current uncertainty to be 1.6%. The fraction of beam on the baffle was found to be (0.5±0.2)%, so we calculated the flux uncertainty from 0.5% beam scraping.

By far the largest uncertainty in either the ND flux or the Near→Far extrapolation is the yield of secondary pions and kaons off the target as a function of x_F and p_T [5]. The spread of BMPT, MARS, FLUKA, and GFLUKA models for secondary particle production yields a variation in absolute neutrino flux of approximately ~8% in the focusing peak of the LE beam, and upwards of 40% in the high energy tail. However, the larger spread in the high energy tail is likely exaggerated by the bug in the GFLUKA Monte Carlo known to be present at high x_F. Therefore, we have estimated a smaller model spread in the neutrino event spectra of ~8% in the focusing

peak and 16% in the high energy tail. These numbers are found to be quite similar in the pME and pHE beams [1]. For the F/N ratios, these uncertainties are about a factor of 2-3 smaller (see [3]). To be sure, correlations amongst the models exist, and it would be desirable to perform an independent analysis of the source data quality to assess a true 'uncertainty' due to hadron production. Such has not been done.

Another systematic effect which has not been studied is the 'thick target' effect of pions reinteracting in the target and thereby becoming lower-energy pions. Such reinteraction occurs less and high energy pions are more likely to escape if the proton beam strikes near the edge of the target edge. Thus, changes in the proton beam position on target, or changes in the proton beam spot size, are expected to slightly modify the neutrino spectrum. The direct effect of the spot size variation can be seen in Figure 5. Similar results have been found in the muon monitor data when the proton beam is scanned across the target. Over the range of proton beam spot sizes relevant in our data set, the muon monitor rates are changing by ~1% (dropping in Alcove 1 while rising in Alcove 2, indicating a stiffening of the neutrino spectrum). While study of the effect in the beam MC is yet to be completed, the anticipation is that this effect is amplified by a factor of 2-3 the ND rate (in the focusing peak) and probably not observable in the Near→Far extrapolation. It will be larger in the ND rate in the focusing peak than in the muon monitors because the muon monitors are not sensitive to the low end of the neutrino spectrum.

To date, the errors for the ND spectra or the Near→Far extrapolation have been provided as overall error bands, not as *correlated errors*, which recognize that a misalignment producing a flux enhancement at 6 GeV neutrino energy in the LE(10) beam also produces a depletion at 4 GeV (notable in the error bands of Figure 4). A more mature plan is discussed in Section VI

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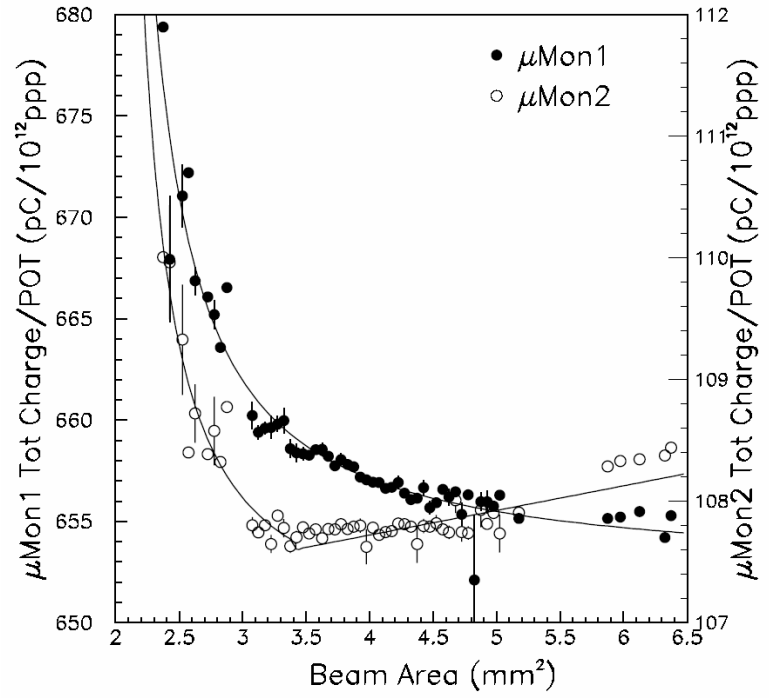


Figure 5: Signal in the muon monitors (alcoves 1 and 2) as a function of the proton beam spot size at the NuMI target. Note the suppressed zero. The vast majority of the data fall between (3.5-5.0)mm^2.

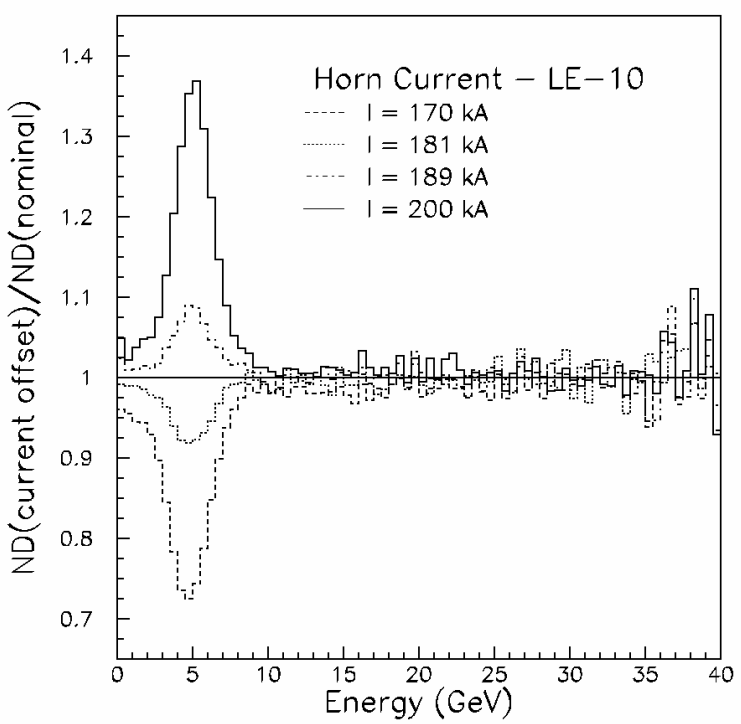


Figure 6: Ratio of spectra in the ND with the horn pulsed at 200, 189, 171, and 170 kA to that when the horn is pulsed at 185 kA. All spectra calculated with the target in the LE(10) position. Note that, for this plot, the horizontal axis is smeared neutrino energy, not true neutrino energy. (PLACEHOLDER PLOT AWAITING NEW DATA/MC COMPARISON).

IV. CROSS-CHECKS OF THE FLUX

In addition to the LE/pME/pHE energy scan performed in the Spring, an important cross-check was performed this summer when we ran the horn at 170 kA and 200 kA for periods of $\sim 1.5\times10^{18}$ POT each, keeping the target in the LE(10) position. The data from this study period were investigated by P. Vahle, but no MC was yet available. It would be useful to see that this data compares well with the beam MC once the new round of data/MC processing is concluded. For reference, Figure 6 (calculated with PBEAM) shows our expectation for the effect of these off-current runs on the ND spectrum.

The point of this study (and of the energy scan performed in March-May) is that by varying the beam in a controlled way, we may be able to factorize some of the effects which go into the ND rate and also affect the Near→Far extrapolation. For example, if the ND spectra in the various special runs is incorrect in various neutrino energy bins (*eg*: is high relative to the beam MC and is high for all the beams – LE, pME, pHE, …), this indicates either a neutrino cross section error or a hadron production error. If the former, then the factor should be consistent amongst all the beams. If the factor of data/MC is not consistent at a given neutrino energy for the various beams, then the error could arise from hadron production (*ie*: the beam flux).

If the beam flux is responsible for a discrepancy between data and MC in the ND, then the relative sampling of pion x_F and p_T must be compared amongst the various beams. In June we tried to understand the ND-MC discrepancies by adjusting the pion p_T distribution from

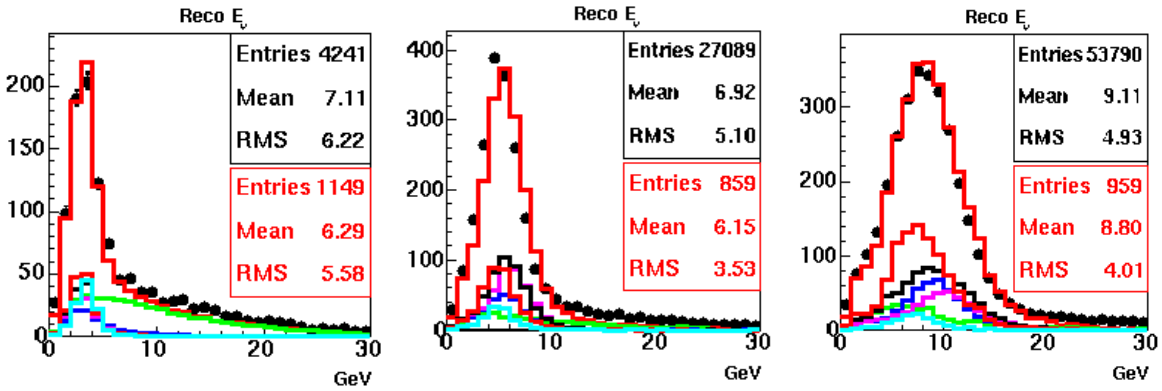


Figure 7: Study of ND data and beam MC fed through GMINOS dating from June (left to right: LE, pME, pHE). The pion p_T in the MC has been adjusted by 70 MeV to attempt a forced agreement between data and MC. No tuning was able to simultaneously describe all three beams. Figure courtesy P. Vahle.

$\langle p_T \rangle$=0.44 GeV by an amount ±70 MeV, which is at the extreme of the allowed range from hadron production models (see Figure 7). It was not possible to satisfactorily describe all 3 beams in the energy scan simultaneously (*ie*: we had to selectively tune pion p_T for each beam configuration in the energy scan); the inability to tune the beam was a strong indicator that the beam flux was not solely responsible for ND-beamMC discrepancies. Those who fear that the ND only measures the product of {cross section × flux} neglect the fact that the beam flux has demonstrable dependencies on the focusing, and furthermore the focusing has been selectively varied to provide useful tests to reveal the discrepancies.

V. NEAR→FAR EXTRAPOLATION OF THE FLUX IN THE CC ANALYSIS

It is clear that in a two detector neutrino disappearance experiment that we would like to use the ND flux as a measure of the FD flux. Such lessens the need to 'dead reckon' the flux at the FD using beam MC as the denominator of an $\{FD_{observed}/FD_{non\text{-}oscillated}\}$ ratio.

One method to extrapolate the flux is to use the ND distribution, along with the conventional F/N ratio to establish a prediction of the FD flux, bin by bin in neutrino energy. The effect of (residual) systematic uncertainties from the beam in such a method were explored in [6]. This method tends to overstate the uncertainty on the FD flux, since it ignores the kinematical correlation between the ND and FD fluxes. Even with this caveat the residual beam systematic uncertainties do not (a) lessen the experiment's sensitivity at low Δm^2 appreciably, (b) significantly worsen our resolution in Δm^2 or $\sin^2 2\theta$ in the event of a positive signal, or (c) give rise to a false positive in the absence of a signal. In fact, statistical uncertainties would dominate.

Another method, which I shall call the "K2K method" [7] calls on us to vary our inputs to the beam MC within some range so as to maintain some reasonable "one-sigma" agreement with the ND data, and in so doing observe the range of possible spread in FD flux measurements. In point of fact, a 20% discrepancy between ND data and beam MC does *not* lead to a 20% flux uncertainty in the FD spectrum, because one will ultimately use the ND data to pin down the beam MC predictor of the FD flux. Nor does an uncertainty of 20% in one's ability to dead-reckon the ND yield a 20% uncertainty in the FD flux. The FD uncertainty one quotes in this

method is only that "2nd order" residual uncertainty similar to that in the F/N ratio method, except in this case the use of the beam MC in lieu of the F/N ratio allows one to make use of the known kinematical relation between a ND neutrino and a FD neutrino. This is the method previously advocated by the NuMI Beam MC Group [8]. The advantage of this method is that it simultaneously can be used to handle a variety of input uncertainties in a consistent manner.

Another method [9] calls on us to use a matrix to evaluate the kinematic correlations. This method is very similar to that of ref. [7], but evaluates the spectral differences in a binned fashion using a matrix: bins i in the ND contribute with weight M_{ij} to bin j in the FD. Such a method is also fine, so long as the same demonstrations (a)-(c) above that were done in ref. [6] can be repeated in the matrix method. Of particular importance is to show that the matrix method can handle a variety of uncertainties, not only from the beam, but from detector reconstruction effects, *etc*., as was done in [7]. For example, backgrounds (from NC events) must first be subtracted off the ND spectrum in this matrix method, and then the matrix applied to obtain the FD spectrum. Since the NC background has its own matrix between the ND and FD, and since this matrix is coupled to the matrix for the CC events (the NC's come from the same flux but have different visible energy), the matrix method has several corrections, large in several bins, that must be applied *ad hoc*. Similar arguments may be applied for other effects such as reconstruction effects, efficiencies, …

VI. Discussion of the K2K Method

The advantage of the K2K method because it is (a) simple to understand and because (b) treatment of our beam systematic uncertainties can be readily handled in a single framework along with other uncertainties which come from detector effects. In this section, we outline this method further. This discussion obviously does not serve as a demonstration, only an outline of the method to be studied for MINOS.

First, let us understand the variety of possible distortions that can happen in the ND. There are several main categories, but each has numerous individual effects which can be studied:

1. Beam: This category includes many individual effects, such as hadron production from the target, the current in the horn, the target or horn alignments, beam scraping on the baffle, *etc*.
2. Background: this is presumably NC's showing up at the low end of the visible energy spectrum.
3. Event Reconstruction: Looking at the results of ND Data-MC comparisons from ANN, PDF, or straight cuts selections that there are different levels of agreement with the beam MC. A variety of effects from reconstruction, detector effects, late light, …, can account for these different levels of discrepancy.

For each of the effects above (there can be 40, 50, …), we may make a prediction of what this would do to the ND spectrum. Using the beam MC, we may also calculate what would happen to the FD spectrum. This is shown in cartoon fashion in Figure 8.

It is not necessary to 'dead reckon' the ND spectrum. In the K2K method, one uses the ND data to fix or pin down the MC. One fits the ND data to a variety of inputs, each of which may

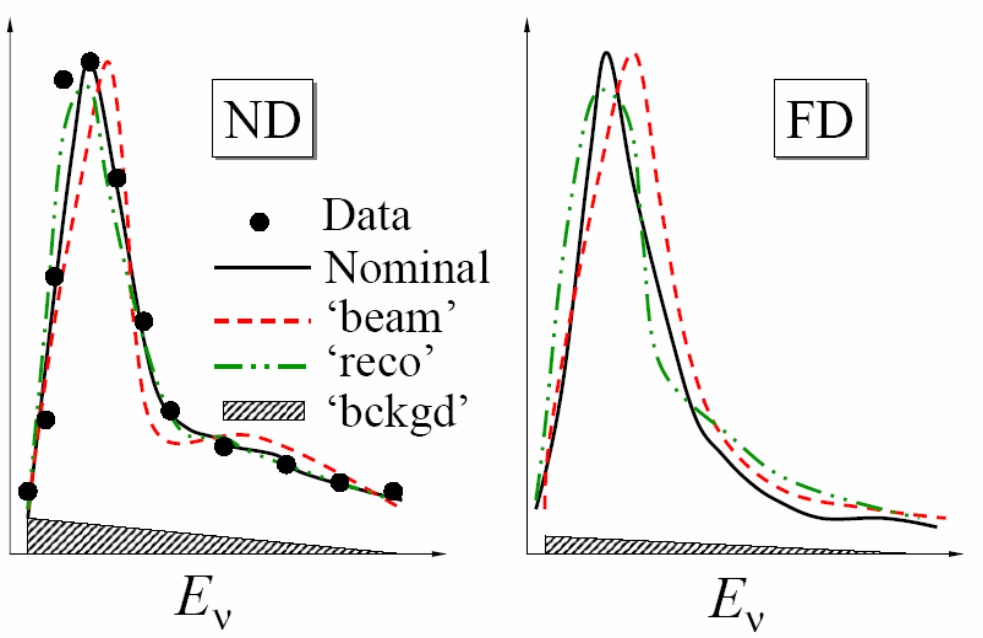


Figure 8: Cartoon demonstration of some of the inputs to the "K2K method" of beam extrapolation near→far. There is a family of curves for the neutrino spectrum in the ND which correspond to known systematic effects, such as the beam flux, event reconstruction (or cross sections, or efficiencies, or …), backgrounds (eg from NC's). For each such curve in the ND there is a separate curve in the FD which is calculated using the beam MC to extrapolate. The data in the ND is fit to the various components in this family to determine a weighting up or down of the components, and this weighting is used to reweight the FD prediction.

predict a different distortion in the ND. The fits should be performed simultaneously for the ND data from the LE, ME, HE beams as well as other special 170/200kA runs. Because there are a large number of effects to be considered, there will be a very large degeneracy in the fit: one can force agreement through a variety of tweaks to the MC. The degeneracy in the fit is not a drawback, and in fact the width of the χ^2 minimum gives a measure of the overall uncertainty in the flux. The fact that there are so many knobs to turn would make it unlikely that a satisfactory fit cannot be obtained (indeed, if no satisfactory fit results, then this might be cause for alarm).

The fit gives a set of reweighting factors for each of these beam, reconstruction, backgrounds, *etc*, effects. To use these reweighting factors in the FD, one uses the fact that the beam MC can make a separate prediction for the FD for each of these effects (which in shape may be quite different from the ND spectrum), and then one applies the reweighting factors derived in the ND to tweak the FD distributions. The uncertainty in the FD spectrum comes from the allowed spread of tweak parameters obtained from the ND fit.

To implement this method, one needs a set of functions to accomplish the ND fits. We propose to develop a set of functions which describe the warpings of the ND and FD spectra from the various effects to be considered. These functions are given as a function of true neutrino energy, and have a set of inputs:

$$f(\, I_{det},\, I_{beam},\text{Effect},n_\sigma,\, E_\nu)$$

where the inputs are

I_{det} = 1 (2) for the ND (FD)

I_{beam} = 1, 2, 3, 4 for the LE, LE10, pME, pHE beams

Effect is an integer designating the effect to be studied (horn current, hadron production, neutrino cross section, …

n_σ = 0, ±1, ±2, … is an input integer which ask that the 0, 1, 2 'sigma' warping be returned by the function.

E_ν is the true neutrino energy

An example of some of these functions (for "+1σ") for the ND and the LE10 beam are shown in the left plot of Figure 4 for the various beam effects. For each of these functions, FD functions have already been calculated. It remains only to write a simple user interface to call these functions, and to develop a similar set of functions for other non-beam (detector) effects.

The relevant strengths of this method is that

(a) the kinematic correlations noted in the matrix method [11] are properly exploited, since the beam MC is used to calculate both the ND and FD spectrum.

(b) there is no need to 'dead reckon' the ND, and in fact the ND is used to fix the MC. By fitting the ND data from a variety of beam tunes, we exploit the large amount of information present in these spectra.

(c) The method gives a single approach to handling the systematic uncertainties from all effects. The fit returns the magnitude of the flux uncertainty from the steepness or shallowness of the χ^2 minimum in the ND fit.

VII. CRITERIA FOR OPENING THE BOX

Given the discussion above, the beam group recommends the criteria below for 'opening of the box' in January. Some of these criteria have already been met.

(1) The beam MC used should be GNUMI-v.18 which represents our best understanding of the beam flux.

(2) A similar set of correlated systematic errors derived from data or MC, be developed for detector, reconstruction, neutrino cross section, *etc*, effects such has been done for the beam model and will be required for accurate extrapolation to the FD flux.

(3) The energy spectrum of ν_μ CC candidates need *not* be dead reckoned by the beam MC. However, it must be demonstrated that the ND flux can be tweaked in such a way as to bring the MC and data into agreement, using the systematic error functions from the beam flux, detector effects, *etc*. noted in (2).

(4) The ND fitting to the beam MC must be achievable for all 5 beam configurations: the LE, pME, and pHE beams, and the LE/170kA and LE/200kA. The fit should be achievable in a manner that is internally consistent amongst the five beams (a tweak upward in background in on beam must be accommodated in the other beams as well, for example).

(5) Plots showing the ND visible energy in CC events from these 5 beam configurations, compared to the beam MC, should form a central part of the analysis, both as a criterion to open the box and a demonstration of our understanding of the beam.

(6) An method of extrapolating the ND flux to the FD must demonstrate what its systematic error on the FD flux is given the entire suite of known errors possible in the ND.

Considering individual error sources one at a time has the potential to mask how multiple errors may extrapolate in different fashions to the FD. In the event that the collaboration adopts multiple techniques for the extrapolation, they should be shown to provide consistent FD fluxes.

VIII. CONCLUSIONS

An extensive effort was conducted to update our flux calculation to include geometry details in the target and more recent particle production yields from the target [1]. A fairly complete work was completed to understand uncertainties in the Near→Far extrapolation [3].

Furthermore, special data runs were taken which should allow the collaboration to limit the effect of beam and other systematic effects by using the ND data in a way that is demonstrable to the outside world. It is worth noting that beam uncertainties in predicting the ND flux are approximately a factor of two smaller for predicting the FD flux when the observed ND spectrum is used along with the beam MC extrapolation to derive the FD flux.

The figures and calculations in this note were the effort of many and compiled by the author, who is responsible for any errors.

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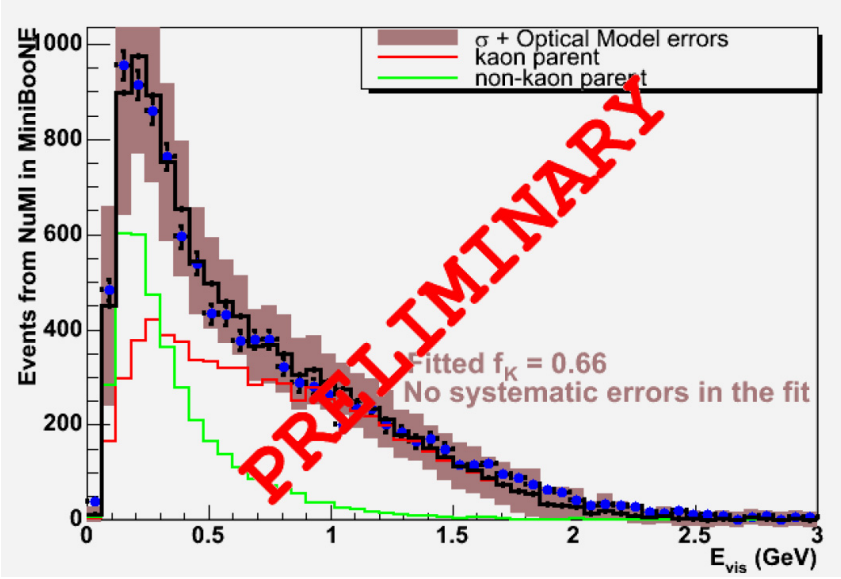


Figure 9: CC visible energy spectrum reconstructed in MiniBooNE detecting NuMI neutrinos. The off-axis flux at MiniBooNE permits separation of the neutrino flux from pion and kaon decay. The curves are obtained from the GNUMI v.17 MC, as described in the text. Taken from [10].

APPENDIX A: FUTURE CROSS-CHECKS OF THE FLUX

Some check of the secondary particle yields from the NuMI target, and in particular of the relative yield of pions and kaons, has been afforded by the MiniBooNE detector [10]. The off-axis angle to MiniBooNE is ~110mradian, resulting in pion decays-in-flight in the Decay Pipe yielding ~0.25 GeV neutrinos at MiniBooNE, while kaon decays-in-flight will give ~2.0 GeV. Thus, the two fluxes may be separated and constrained using MiniBooNE data. As is shown in Ref. [11], analysis of the MiniBooNE data has the benefit that systematic uncertainties from horn alignment, field modeling in the horn, scraping on the baffle, *etc*, which are very large effects for the NuMI on-axis flux, are actually small for modeling the off-axis flux. Furthermore, the analysis is relatively insensitive to the initial energy spectrum of the pions/kaons, since all hadrons yield approximately the same energy neutrino at the off-axis location.

Figure 9 shows MiniBooNE CC ν_μ events compared to the GNUMI v.17 flux fed into the MiniBooNE detector simulation. The red curve is the GNUMI v.17 prediction for the neutrino flux from kaon decays, the green curve is the GNUMI v.17 prediction for the neutrino flux from pion decays, and the black curve is the sum of the red and green. The kaon and pion components have been scaled separately to fit the data. Such fitting yields a fraction (0.66±0.02±0.06) of neutrinos at MiniBooNE predicted to come from kaon decays, where the first uncertainty is from the fit and the second is the systematic uncertainty from MiniBooNE's detector model and cross section unceratainties. The GNUMI v.17 prediction without scaling indicates a detected kaon fraction 0.62, which is lower than but consistent with this measurement. If the beam MC is indeed low in kaon content, this would indicate that the GNuMI v.17 flux in the high energy tail (where kaons dominate) might be a little low.

We do not expect this analysis will come to fruition in time for the opening of the January box.