Hadron production uncertainties at NuMI

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Abstract. An improved approach for the extrapolation of the neutrino spectrum from the near to the far site is described. The method exploits the strong correlation between neutrino spectra at two arbitrary detector locations, provided that they come from the same parent hadron beam. The accuracy of the method was extensively studied on the particular example of hadron production uncertainties. The neutrino flux at the far on-axis site can be predicted more accurately than in the Far/Near ratio method. In an off-axis experiment, the integrated neutrino flux can be known to 1-2%, even using only the on-axis near detector information. The off-axis intrinsic ν_e flux can be estimated to 5% by correlating it to the ν_μ and $\bar{\nu}_\mu$ flux measured in an on-axis detector.

1. The Near-to-Far correlation matrix

Prediction of the far detector spectrum in the absence of oscillations is of primary importance in a neutrino oscillation experiment. In MINOS, this is done by an extrapolation from a near detector via a nominal Far/Near ratio, the latter being defined mainly by beamline geometry. It has been shown [1] that this method allows MINOS to control their systematic errors from hadron production to below 10% in the whole energy spectrum and to around 2% in the peak region, even though absolute flux predictions for either the near or the far detector (without anticipating the future E907 results on low-p_T pion production on a beryllium target) are up to 25% uncertain.

The Far/Near ratio method is approximative in character in that it assumes that each neutrino observed in the near detector implies some flux of *same energy* neutrinos in the far detector. From the well known kinematical relation between angle and neutrino energy, basis of the off-axis concept [2], it follows that this strictly holds only for two aligned detectors (e.g. on-axis) and a perfectly focused parent pion beam. However, from the same relation it also follows that, for a given pion decay (which in the point-like near detector approximation is fully characterized by four quantities: pion momentum, pion angle and two coordinates of decay point), the corresponding near and far neutrino energies are unambiguous and strictly calculable in the most general case of unequal angles, which includes off-axis. Also strictly calculable are the probabilities of a neutrino produced in a given pion decay reaching the near and far detectors, respectively. Consequently, measurement of a near spectrum will always yield a prediction of the far spectrum once the full pion decay distribution inside the decay pipe is known, regardless of the position of the two detectors. The actual recipe

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to convert the near into the far spectrum is a generalization of the Far/Near ratio method and is defined primarily by the beamline geometry.

In finite energy bins, neutrino flux extrapolation is done by means of a Near-to-Far correlation matrix whose elements tell us how many neutrinos in the far detector at a particular energy interval correspond to one neutrino in the near detector in the given energy interval. A detailed description of matrix element calculation can be found in [3]. In the on-axis case with perfect beam focusing, the matrix is diagonal and its effects are identical to those of the Far/Near ratio. In a realistic experiment, like MINOS, departures from diagonality are found especially in the high energy tail, where we can notice the effects of imperfect focusing of pions outside the central energy range. More importantly, the correlation matrix method can be used to predict a far off-axis spectrum from a near on-axis spectrum, with a similar accuracy as does the Far/Near ratio in an on-axis experiment.

2. Prediction of the ν_μ flux at a far site

As shown in [3], in the energy range of good pion focusing, the matrix method yields identical results as the Far/Near ratio. In the high energy tail, noticeable reduction of various systematic errors for MINOS is found compared to the standard method. In particular, the present hadron production uncertainties are kept below 5% at any point of the spectrum, in either the low or the medium beam energy configuration.

Absolute predictions for the far off-axis neutrino flux differ from each other by up to 25% in the different hadron production models. In a NuMI-based off-axis experiment, we can nontheless significantly profit from the MINOS on-axis near detector. The residual hadron production uncertainty, after applying various correlation matrices derived within each model to the spectrum measured in the MINOS near detector, is depicted in figure 1 (left). The total number of events in the 1-3 GeV energy region is found stable to 2% in the low energy configuration and to around 1% in the medium energy configuration.

3. Evaluation of the intrinsic ν_e flux at a far site

Given its insufficient NC background rejection capabilities, the MINOS near detector data will not give directly a good measure of the intrinsic ν_e component of the beam. Starting, however, from the same parent pion beam, the actual spectra of ν_μ and ν_e are strongly related via well known parameters. An on-axis measurement of the ν_μ flux provides strong constraints on the off-axis ν_e flux. Figure 1 (right) shows the expected on-axis ν_μ and off-axis ν_e fluxes in different hadron production models, and their ratio. From the latter, the ν_e flux can already be estimated to $\sim$7%; this takes into account a 10% contribution from kaon decays to the number of ν_μ in the MINOS near detector. The precision should be further improved upon calculation of the corresponding full Near-to-Far correlation matrix that will precisely relate the number of ν_μ and ν_e in finite energy bins. An independent estimate can be obtained by measuring the flux of $\bar{\nu}_\mu$ in the near detector, for which the correlation with ν_e is even stronger. Ultimately, knowledge of the number of intrinsic ν_e in the signal region to 5% seems attainable.

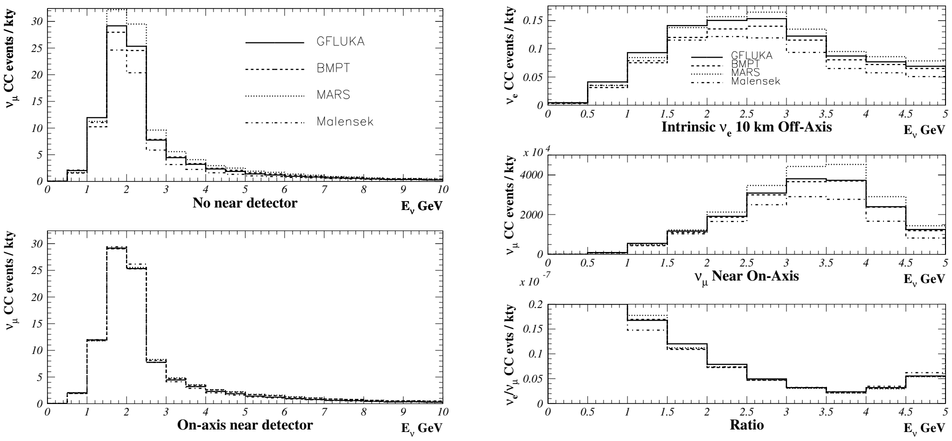

Figure 1. Left: predictions for a 10 km off-axis ν_μ spectrum at 735 km away from source, in different hadron production models: on absence of near detector (upper plot), with an on-axis near detector and using the correlation matrix method (lower plot). **Right:** predictions for the 10 km off-axis intrinsic ν_e spectrum at 735 km away from source, in different hadron production models (top), for ν_μ in an on-axis near detector (middle), and the ratio of the two plots (bottom).

4. Outlook

While hadron production at the NuMI target is going to be precisely measured by E907, and is unlikely to be an issue for either MINOS or NuMI Off-Axis at the time of data analysis, other sources of systematics in the prediction of the neutrino fluxes at the far detector will still require control to a manageable level. Studies have been carried on to determine the sensitivity of the predictions to the details of the focusing system within the correlation matrix method. It is found that a 2 mm horn displacement or a 20% horn current variation is tolerable to ensure a spectrum prediction accurate to 5% in the total number of ν_μ in the energy range of 1-3 GeV, even if such distortions were never discovered. Such precision is negligible compared to any possible statistical uncertainty in a ν_e appearance search and, naturally, online beam monitoring will significantly improve the situation.

These results clearly minimize the need of a dedicated off-axis near detector to predict neutrino fluxes in an off-axis experiment, once the MINOS on-axis near detector is in place. Based on this analysis, the motivation for an off-axis near detector for measurements of the intrinsic nue backgrounds or expected ν_μ rates is much weaker than for measurements of the neutrino cross sections and neutral current background rejection. This conclusion, however, may not hold if a precision measurement of ν_μ disppearance in an off-axis experiment is considered.

References

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