Using Near Detector Data to Make Far Detector Predictions in an On-Axis Long-Baseline Experiment

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Abstract. Various techniques have been developed in long-baseline neutrino oscillation experiments to leverage near detector data to form predictions for the far detector spectrum and backgrounds. I will review the techniques used in MINOS, an on-axis long-baseline neutrino experiment that uses Fermilab's NuMI beam. The extrapolation methods used in the MINOS muon neutrino and anti-neutrino disappearance measurements and electron neutrino appearance search will be covered.

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INTRODUCTION

In long-baseline neutrino oscillation experiments, oscillations are observed by measuring the event rate in the far detector, which depends on the oscillation probability. With an identical near detector, one can instead look at the relative event rates between the detectors. The neutrino flux, cross section, and detection efficiency cancel in the far to near event rate ratio. In addition, the uncertainties associated with the flux and cross section, which can be large, mostly cancel in the ratio, allowing for more precise measurements of the oscillation parameters. Both the K2K experiment (1999-2004) and the MINOS experiment (2005-present) are on-axis long-baseline neutrino oscillation experiments with near and far neutrino detectors. The Long-Baseline Neutrino Experiment (LBNE) is a future project that will have a similar setup. This document will focus on MINOS.

The MINOS experiment uses the NuMI beam at Fermilab. The secondary particles produced when 120 GeV protons hit a target are focused by magnetic horns and enter a decay pipe where they decay to neutrinos or anti-neutrinos, depending on the polarity of the horns. The neutrino spectrum can be tuned by changing the position of the target relative to the horns and by changing the horn current. The Near Detector (ND) is located at Fermilab, and the Far Detector (FD) is located at a baseline of 735 km. Both detectors are magnetized tracking calorimeters made of steel planes and scintillator strips.

MINOS uses near detector data in oscillation studies to tune the beam simulation, predict the unoscillated ν_μ or $\overline{\nu}_\mu$ charged-current (CC) spectrum at the FD, predict the background to ν_e appearance at the FD, and predict the neutral current (NC) spectrum in the FD. The near detector is additionally used to measure neutrino cross sections and to observe atmospheric neutrinos.

BEAM SIMULATION TUNING

Data taken in several different beam configurations is used to constrain the neutrino flux calculation [1]. The production yield of pions off the target can be parameterized as a function of the transverse (p_T) and longitudinal (p_z) momentum of the pions. Then the data is fit by tuning the production in the beam Monte Carlo (MC). Data from different beam configurations sample different regions of p_T and p_z.

NEUTRINO OR ANTI-NEUTRINO DISAPPEARANCE MEASUREMENT

In the neutrino and anti-neutrino disappearance analyses, ND data is used to predict the spectrum of ν_μ and $\overline{\nu}_\mu$ CC events at the FD assuming no oscillations. Oscillations will cause a deficit in the observed rate relative to the prediction.

In order to make the FD prediction based on ND data, the expected difference in the neutrino flux between the near and far detector must be understood. The complicated energy dependence of the far to near flux ratio is due to the fact that the FD essentially sees a point source of neutrinos while the ND sees an extended source. Figure 1 shows the far to near ratio of the flux, comparing the ratio for NuMI beam with the simpler cases of a point source or a line source of neutrinos. Neutrinos with a given energy in the ND come from parent pions which would yield neutrinos covering a range of energies in the FD. To account for this, the beam simulation is used to

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create a matrix that transports the near spectrum to the far [1].

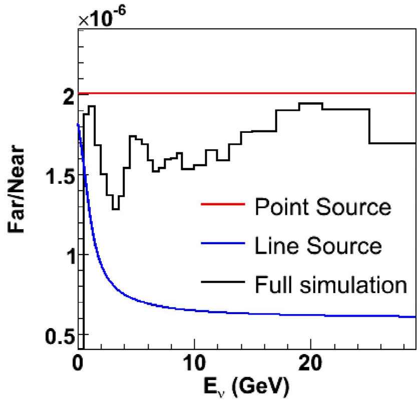

FIGURE 1. The far to near flux ratio in MINOS as a function of neutrino energy. Shown on the same plot is a horizontal line, showing the ratio for the case of a point source. Also shown is the case of a line source, where the ratio is the exponential curve.

ν_e APPEARANCE SEARCH

MINOS has searched for $\nu_\mu \to \nu_e$ oscillations [2]. The signal is a small excess of ν_e CC-like interactions at the FD over the expected background. The ν_e selection criteria are applied to ND data to predict the background at the FD. An irreducible background comes ν_e CC interactions due to the small ν_e component intrinsic to the beam. Other background is due to NC interactions or ν_μ CC interactions with a low energy muon, particularly when a π^0 is produced as part of the recoil system. Some factors that affect the extrapolation from the ND to the FD are different for each background component. For example, beam geometry effects are different for ν_μ's and beam ν_e's and the ν_μ CC component is altered by oscillations. For these reasons, the ND ν_e-like sample must be broken down into the different background components before extrapolation to the FD.

The background separation is performed using ND data taken in three different beam configurations: standard, horn-off, and high-energy. The neutrino energy spectrum for each configuration is shown in Figure 2. The horn-off sample is taken with the magnetic focusing horns turned off. The high-energy sample is taken with the target position changed to create a higher energy beam. ν_e-like events are selected in each data set. Compared to the standard configuration, both the horn-off and high-energy configurations produce a ν_e-selected sample with an enhanced NC component, due to reduced contamination from low-energy ν_μ CC interactions. Using the total measured rate of ν_e-like interactions in each configuration and horn-off to standard and high-energy to standard ratios from the MC for each background component to relate the data between configurations, a fit is performed to determine the background components in the standard sample. The fit indicates that (64±5)% of the ND ν_e-like events in the standard sample are NC interactions, (23±5)% are ν_μ CC interactions, and (13±3)% are beam ν_e CC interactions. The quoted uncertainties include statistical and systematic effects.

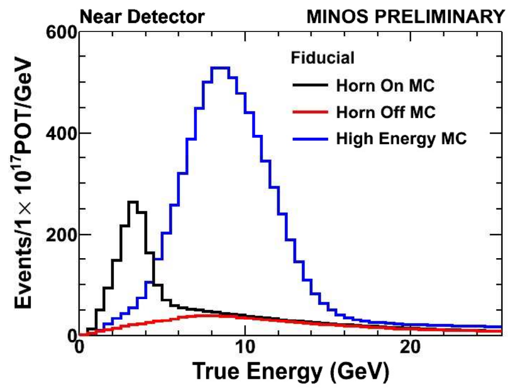

FIGURE 2. The true neutrino energy spectrum at the ND from MC simulation for the the three beam configurations used to do the background separation for the ν_e appearance analysis. In the standard configuration, the peak is at about 3 GeV, while in the high energy configuration, the peak is at around 9 GeV. In the horn off configuration, the peak disappears because there is no focusing of the parent pions.

The background prediction is then made using far to near ratios from the MC simulation for each background component. The ratios take into account all far/near differences, including flux and detector effects.

The far to near ratio method is also used to predict the NC rate in the FD in the search for oscillations to sterile neutrinos [3].

SUMMARY

MINOS uses ND data to tune the neutrino beam simulation and to form FD predictions for both neutrino disappearance and appearance measurements. The capability to run the NuMI beam in different configurations has been key to getting the most of the near detector data.

REFERENCES

1. P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. D **77**, 072002 (2008) [arXiv:0711.0769 [hep-ex]].
2. P. Adamson *et al.* [The MINOS Collaboration], Phys. Rev. D **82**, 051102 (2010) [arXiv:1006.0996 [hep-ex]].
3. P. Adamson *et al.* [The MINOS Collaboration], Phys. Rev. D **81**, 052004 (2010) [arXiv:1001.0336 [hep-ex]].