Long-Baseline Neutrino Oscillation Phenomenology

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Abstract. There is a large body of phenomenological work that quantifies the physics reach of future long baseline oscillation experiments. In this article we discuss what assumptions are made about each experiment's ability to predict its far detector signal and background statistics. To understand the difficulty associated with making background predictions even with a near detector, we also examine the current experience of the MINOS experiment, and its ability to predict its far detector signal and background fractions for its electron neutrino oscillation search. Finally, we will discuss the program that is needed in order to get from the current state of the art in far detector predictions to what is required (or often simply assumed) for future generations of oscillation experiments.

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INTRODUCTION

The field of long baseline neutrino oscillations is rapidly expanding as the prospects of understanding the neutrino mass hierarchy and ultimately CP violation become better developed. The T2K experiment is in its beamline commissioning stages [1] and the NOvA experiment is ramping up to be in an accelerated detector production mode [2]. At the same time, the MINOS experiment is approaching the end of its 5th year of data-taking [3], and has far detector samples of hundreds of events, similar at least in number to the expected detector statistics of the T2K and NOvA experiments. In addition, much work is going into developing megaton-scale neutrino detectors, and megawatt scale neutrino beamlines as the next step in conventional neutrino beam programs [4,5].

While it is important to keep focus on being able to produce these next generation experiments, it is at least as important to learn what we can about the experimental techniques from the current long baseline program. This article will first review the two-detector experimental technique for measuring oscillations, including what the systematic errors are in oscillation measurements, and how they can be minimized. Next, we will discuss the expected signal and background samples for various future oscillation programs: not only the T2K and NOvA generation, but also future super-beams, beta-beams, and neutrino factory experiments. Next, we will discuss the current status of the MINOS electron neutrino appearance search, and the level of success that MINOS has had in executing the strategies described earlier. Finally, we will try to apply the techniques employed by MINOS to future programs, both with conventional and with unconventional neutrino beams.

MEASURING OSCILLATION PROBABILITIES

To measure an oscillation probability (consider for example, a conventional neutrino beam experiment) $P(\nu_\mu \to \nu_x)$, long baseline experiments use the following equation:

$$N_{far} = \phi_{\nu_\mu} \sigma_{\nu_x} P(\nu_\mu \to \nu_x) \varepsilon_x M_{far} + B_{far},$$

where N_{far} is the number of events seen in the far detector, ϕ_{ν_μ} is the muon neutrino flux at the far detector, σ_{ν_x} and ε_x are the cross section and efficiency respectively for the signal events, and M_{far} and B_{far} are the far detector mass and background. Using this notation, it is straightforward to derive the equation for the error on the measured probability:

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\phi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M_{far})^2} + (N_{far} - B_{far}) \left(\left[\frac{\delta \phi_{\nu_\mu}}{\phi_{\nu_\mu}} \right]^2 + \left(\frac{\delta \sigma_{\nu_x}}{\sigma_{\nu_x}} \right)^2 + \left(\frac{\delta \varepsilon_{\nu_x}}{\varepsilon_{\nu_x}} \right)^2 \right).$$

The two terms in this equation indicate that there are two different regimes: when the number of

background events is close to the predicted background, then the error on the background prediction dominates. However, when there is a substantial signal that is far above background, then there can be a substantial uncertainty in the probability measurement that comes from the uncertainties in the neutrino flux, cross section, and detector efficiency.

In order to best predict the numbers of signal and background events at a far detector, most experiments take advantage of a near detector. The standard justification is that if a near detector is in the same neutrino beam, then uncertainties are minimized. If the backgrounds in the near and far detector are described using the following notation,

$$B_{far} = \sum_{i=\mu,e} \phi_{\nu_i\, far}(P)\sigma_{\nu_i}\varepsilon_{ix}M_{far} \text{ and}$$

$$N_{near} = \sum_{i=\mu,e} \phi_{\nu_i\, near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}$$

(where notice that the backgrounds in the far detector may depend on other oscillation probabilities such as ν_μ to ν_τ oscillations), then the expression for the far detector background simply becomes

$$B_{far} = N_{near}\frac{\sum_{i=\mu,e} \phi_{\nu_i\, far}(P)\sigma_{\nu_i}\varepsilon_{ix}M_{far}}{\sum_{i=\mu,e} \phi_{\nu_i\, near}\sigma_{\nu_i}\varepsilon_{ix}M_{near}},$$

and the uncertainties in the flux, cross sections, and efficiency are said to cancel in the ratio. However, a more complete description of this equation must include the fact that the detector measures simply a number of events as a function of neutrino energy, and if the near detector is "functionally identical" to the far detector, then the separation between signal and background is the same for a given energy, but the incoming energy distributions may be very different:

$$\left(\frac{\delta P}{P}\right)^2 = \frac{(N_{far} + (\delta B_{far})^2)}{(\phi_{\nu_\mu}\sigma_{\nu_x}\varepsilon_x M_{far})^2} + (N_{far} - B_{far})\left(\left[\frac{\delta\phi_{\nu_\mu}}{\phi_{\nu_\mu}}\right]^2 + \left(\frac{\delta\sigma_{\nu_x}}{\sigma_{\nu_x}}\right)^2 + \left(\frac{\delta\varepsilon_{\nu_x}}{\varepsilon_{\nu_x}}\right)^2\right).$$

Of course, in a conventional neutrino beam of muon neutrinos there is a small contamination of signal electron neutrinos, so in principle a near detector can see both backgrounds from mis-identification, as well as the backgrounds from real electron neutrinos. The challenge there is that if the near detector is no better than the far at distinguishing signal from background, the extrapolation from the near to far detector samples brings some uncertainty with it, since the different background samples all extrapolate very differently from near to far. For example, the background from electron neutrinos in the beam won't change in the same way as the background from mis-identified muon neutrinos, since that flux will oscillate to tau neutrinos by the time it reaches the far detector.

For beta beams [6], which are completely either electron neutrino or electron antineutrino beams, or neutrino factory beams [7], which are (for example) a combination of electron neutrino and muon antineutrino beams, however, there is no intrinsic background in the near detector. While this means that the statistical precision at the far detector is not diluted by having to subtract off this background, it does mean that the near detector cannot probe the signal process as in the far detector—it is simply a measure of the unoscillated neutrino event rate, and the backgrounds that come from misidentified processes.

To understand what kinds of systematic uncertainties will be required to see the mass hierarchy and CP violation, it is helpful to look at the asymmetry, defined as the difference over the sum for a given neutrino and antineutrino oscillation probability (for one baseline and one energy). This

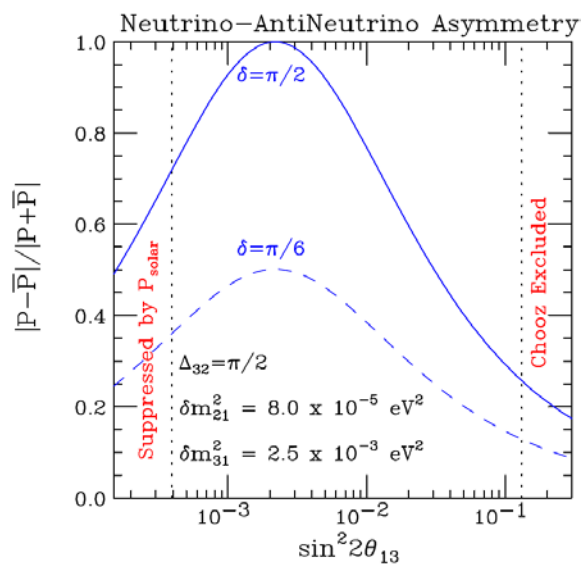

FIGURE 1. The asymmetry for neutrino oscillations as a function of the mixing angle $\sin^2 2\theta_{13}$, taken from ref. 8.

plot (Fig. 1) shows that although the asymmetry could be large for very small θ_{13}, if θ_{13} is large enough to be discovered by T2K or NOvA then the next generation of experiments will need to be ready to measure oscillation differences that are 20% or less. For a three sigma discovery, that implies total oscillation systematic uncertainties at the few per cent level.

Expected Statistics of Future Long Baseline Experiments

According to the most recent projections, the T2K experiment expects to see roughly 103 signal events on a background of 23 events, in neutrino running after a 5 year run, if $\sin^2 2\theta_{13}$ is equal to 0.10 [1]. Similarly, the NOvA experiment, after a nominal exposure in neutrino and antineutrino beams both, would see 75 and 29 events, over a background of 14.4 and 7.6 events, respectively [2]. The statistical level of precision that is afforded by these event samples is roughly 10% for T2K, and 12-15% or so for NOvA. Therefore, the systematic precision that is demanded by these statistics is on the level of 10% or better, to get the most out of the statistical reach.

Next Generation Super-Beams

The next generation of oscillation experiments seeks to upgrade not only the detector mass, but also the beam power and the baseline of the experiment. The net effect in terms of detector event statistics is a net increase in the signal events of roughly a factor of five to ten in statistics, and for very different energy spectra. In the LBNE proposal, which uses a broad band neutrino beam that is sent from Fermilab to Homestake and may use a water Cherenkov detector, the signal for electron neutrino appearance is some 353 events predicted on an intrinsic electron neutrino background of 55 events [4]. For the T2KK proposal which uses the T2K beamline but with an off axis detector in Korea, and also a water Cherenkov device, the event samples are at the 1300 event level on a total background of roughly 740 events (this background includes non-quasielastic electron neutrino charged current events) [3]. For these experiments, a systematic uncertainty of 5% or better is assumed (and required) in order to get the full reach of these programs' statistics.

Beta-Beams

There is recent work that looks at the physics reach of a green-field beta beam experiment. In this experiment, there is either a pure electron neutrino or electron anti-neutrino beam, and the baseline assumed is the magic baseline where the matter effects are largest and the CP-violating effects are small [9]. This baseline can provide the most statistically accurate measure of the mixing angle itself, while also providing a definitive determination of the mass hierarchy, even for small values of θ_{13}. The background uncertainties assumed for these studies are 5%, and the signal uncertainties assumed are 2.5%. This will be particularly challenging to achieve, since there will be no intrinsic signal events in the near detector.

Neutrino Factories

Recent work on neutrino factories examines a coordinated approach: what is the statistical reach of a neutrino factory that can provide measurements of all six transitions (using four possible initial state neutrino beams, and all six possible final state neutrino beams). An example of the event samples expected is given in Table 1, taken from ref. 7, where different polarizations of the muons are assumed, and the statistics of all final state leptons is given. Note that in some cases there are thousands of events expected in the far detectors, and the statistical uncertainties assumed vary from two to five per cent.

TABLE 1. This table shows the number of events expected in several different sample neutrino factory experiment samples, as a function of muon beam polarization, as described in ref. 7. Note that all disappearance and appearance channels are included.

$\mathcal{P}_{\mu^-}$	$N_{\mu^-}/10^4$	$N_{e^+}/10^4$	N_{μ^+}	N_{e^-}	N_{τ^+}	$N_{\tau^-}/10^2$
0	172	75	107	186	80.7	89.9
0.3	150	97.5	140	174	105	81.7
1	97.5	150	215	147	161	64.6
$\mathcal{P}_{\mu^+}$	$N_{\mu^+}/10^4$	$N_{e^-}/10^4$	N_{μ^-}	N_{e^+}	N_{τ^-}	$N_{\tau^+}/10^2$
0	87.4	148	244	99	151	45.2
−0.3	76.1	192	317	93.4	196	41.5
−1	49.5	295	487	79.3	302	32.8

CASE STUDY: MINOS

The MINOS experiment has been taking data for almost 5 years [10] and in the past year has released the first results of its search for electron neutrino appearance in a muon neutrino beam [11]. Although the experiment was not optimized to look for this mode, they have set the stage for the efforts required to understand systematic uncertainties in these future oscillation experiments.

In a conventional neutrino beam based on pion and kaon decays, there are several backgrounds to an electron neutrino appearance search. As was described earlier, there are intrinsic electron neutrinos in the beam that come from three-body muon and kaon decays. These backgrounds are larger in on-axis beams but will also be important in the T2K and NOvA experiments. The next largest background comes from

neutral current interactions that are mis-identified in the detector as electron neutrino events, because of the pions that are produced in those interactions. Finally, there are also muon neutrino charged current events that are mis-identified just as the neutral current events are, because the muon is too low in energy to be seen, and a produced neutral pion is mis-identified as an electron. Finally, a small background which must still be quantified is that coming from tau neutrino charged current events, where the produced tau decays to an electron and therefore appears as an electron neutrino charged current event. In the MINOS experiment, the neutral current background is by far the largest, followed by the muon neutrino charged current background.

When MINOS first examined its near detector electron neutrino candidate sample, there was a substantial disagreement between the data and the prediction. Depending on which combination of backgrounds contributed to that discrepancy, the far detector background prediction would change dramatically. In order to determine the true composition of the near detector background sample, two different cross-checks were done with the data samples.

By running for a short time without focusing the pions and kaons after production in the target, the MINOS experiment was able to significantly alter the muon neutrino spectrum, as well as the expected composition of electron neutrino background events. The next generation of neutrino superbeams can resort to the same technique to change the incoming neutrino spectrum to do near detector studies.

One other flexibility that the MINOS experiment has now but which will not be available to future generations of superbeams is the ability to move the production target farther away from or closer to the focusing system. This has the effect of raising or lowering the peak muon neutrino energy, and the MINOS experiment took advantage of this feature in the beamline to tune their neutrino production spectrum to best match the data.

It is worth mentioning that as a result of the special runs to do this tuning, the MINOS experiment modified the peak energy spectrum by about 10 per cent, and modified the flux prediction for the high energy tail by about 30 per cent. The final uncertainty on the extrapolated flux is quoted as a function of energy, but is several per cent at the peak and over 10% in the high energy tail [10]. Both T2K [1] and NOvA [2] quote statistical errors on the disappearance probability parameters at the per cent level—achieving this level of systematic uncertainty will clearly require special running configurations and special near detector studies.

For a beta beam experiment or a neutrino factory experiment, one can alter the neutrino energy by altering the parent particle energy in the storage ring, but generally this is not an easy task for large energy changes, since the ring optics are tuned and optimized for a narrow energy range. Another beamline characteristic that could be changed is the divergence of the parent particle beam, but this too would probably only be able to be done for small changes in the divergence. So although the backgrounds expected at these future facilities are significantly lower, it is still important to consider ways to significantly alter the neutrino spectrum for short running periods, in order to do near detector studies.

Another study that was done by MINOS for the electron neutrino search was to study the composition of identified hadron showers by looking at muon neutrino charged current events in the near detector after removing the energy deposition identified with the muon in each event. The electron neutrino analysis cuts were then performed on those identified hadron showers, and compared between data and Monte Carlo, where in the Monte Carlo the muon energy depositions were also removed. A correction factor, defined as the ratio between the “muon removed” data and Monte Carlo as a function of visible energy, was applied to the near detector electron neutrino candidate sample (after correcting for the expected near detector electron neutrino sample). The resulting corrected near detector data then matched the corrected near detector background Monte Carlo prediction [11].

Future superbeam experiments are expected to have significantly lower backgrounds from neutral current events because they are at lower neutrino energies. However, because the neutrino energies are lower, the difference between the hadronic remnant for a charged current event and a neutral current event will be larger: these superbeams are right at the threshold for Δ production, and the differences between Δ^+ and Δ^0 decays are likely to be larger than the difference between charged and neutral current hadron showers at 3 GeV and above.

After the two different analyses described above were performed, the far detector background prediction agreed within errors. It is worth noting though that although there were millions of near detector events collected, the uncertainty in the far detector background prediction was evaluated to be 7.3%. The statistical error on the electron neutrino sample is much greater, at 23%, but clearly for future long baseline experiments that will have to predict background samples of a few hundred events, the strategies will have to improve to reduce these uncertainties.

PLANNING FOR THE FUTURE

Planning for the future oscillation measurements means more than figuring out how to achieve the required statistics with high power beamlines and high mass detectors. The field must also plan for strategies to measure all the components of the produced neutrino fluxes, and strategies to measure the cross sections that comprise both the signal and background processes. Whatever the near detectors at these future facilities look like, the populations of near detector background events and far detector background events will be different. For conventional beams, the near detector backgrounds will have a larger fraction of muon neutrino charged current events in them, because in the far detector those backgrounds will have oscillated away. In beta beam experiments, the near detector events will consist solely of electron neutrino events which are mis-identified as muon neutrinos, and there will be no way to measure muon neutrino cross sections and efficiencies in the near detector. Finally, in a neutrino factory experiment, the near detector background events will come from muon antineutrino charged current and neutral current events that are charge misidentified, and again the charged current muon neutrino backgrounds will be significantly altered by muon neutrino disappearance in the far detector. Again in the neutrino factory, this complete lack of signal events to which to normalize could pose a problem when looking for probability differences on the order of a few per cent.

There are cross-section experiments planned in the near future which are planning to provide some of these much needed measurements of both signal and background processes. The MINERvA experiment will start running between now and the next NuFact conference, and that experiment is designed to do exclusive final state measurements with fine grained solid scintillator [12]. The experiment is currently planned to run with four different nuclear targets, and will collect data in time for results on the highest statistics MINOS measurements, and also the NOvA and T2K data sets. The T2K experiment is currently commissioning a 280 m off axis near detector that will focus on exclusive neutral pion measurements and some exclusive states in a water target [13]. The NOvA near detector will first operate above ground and look at a very high off axis angle muon neutrino beam of 2 GeV from kaon decays, and may also provide some information on 2 GeV neutrinos on carbon [2].

It is not enough to prepare for the future by measuring fluxes and cross-sections. New tests must also be done of these new detector technologies to prove that the background rejection expected can in fact be achieved. There is currently an R&D effort for putting a totally active scintillator tracking detector in a magnetic field to study its applicability to neutrino factory experiments [14]. Also, the MicroBooNE experiment proposes to benchmark the Liquid Argon detector technology in the 1 GeV neutrino energy regime, while also studying the MiniBooNE low energy excess [15].

CONCLUSIONS

There are many ideas in the literature for how to achieve the statistical precision required for definitive measurements of the neutrino mass hierarchy and CP violation. Those ideas all involve programs that accumulate hundreds if not thousands of far detector signal events. In order to get the full experimental precision implied from these statistics, there are many challenges that must be met to keep the systematic errors low.

Accelerator physicists must design in the ability to cross-check the neutrino flux that is coming from the complex. Experiments at conventional neutrino beams can take advantage of precision muon monitoring programs and a variable focusing system that comes from changing horn currents. Hadron production experiments can also provide important constraints [16]. However, different strategies will have to be used for neutrino factories or beta beams. An idea that has been examined for its far detector implications is varying the polarization in a muon storage ring [17]; this should be examined for its near detector implications.

Theoretical physicists must improve the modeling of neutrino interactions in the few GeV regime. There has been much effort on the quasi-elastic cross section, but the future experiments such as NOvA or the longer baseline programs will have most events in the resonance or deep inelastic scattering regime. To understand both signal and background processes, the cross sections must be better modeled, but also the secondary particle production spectra must be better modeled.

Experimental particle physicists must understand cross sections and in particular, the way hadronic showers in their detectors can be measured (or cross-checked) in the data. Understanding the detector response to neutrinos for a reasonable scale prototype before building a 100 kton device is also prudent. Finally, test beam programs with prototype detector elements provide key cross-checks of the detector simulations.

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