NuMI-930

Proposal for a Five Year Run Plan for MINOS

The MINOS Collaboration

May 30, 2003

Abstract

In this document, we outline MINOS physics capabilities under three different integrated proton intensity scenarios (7.4×10^{20}, 16×10^{20} and 25×10^{20} protons on target). We propose a five year run, starting early in 2005, and show that the physics reach of the experiment is significantly enhanced as the total number of delivered protons increases. The highest intensity scenario, which appears feasible based on recent studies, will offer particularly strong oscillation measurement capabilities, including an excellent sensitivity for discovery of a small admixture of ν_μ to ν_e oscillation. The purpose of this document is to request that the laboratory prepare a specific plan of investment in proton intensity to achieve the physics goals outlined herein.

1 Introduction

Previously presented expectations for the physics sensitivity of MINOS (eg. [1, 2, 3, 4]) have been based on an expectation of a total of 7.4×10^{20} protons on target. At the time of the MINOS proposal, various program reviews, and NuMI baselining, it was assumed that this proton intensity would be delivered in approximately a two year period, beginning in October 2002. Wise advice was dispensed by one of the committees reviewing MINOS (the Baltay committee in 1998 [5]) to "maintain flexibility to new physics developments". Five years have passed since that time, and from our perspective the advice was well on the mark. Below, we summarize some of the changes in perspective in that time:

- It is now understood that atmospheric ν_μ's are disappearing as they traverse the Earth and to good approximation, this is due to oscillation of ν_μ to ν_τ [6]. A precision measurement of the nature of the oscillation is now of paramount importance.
- The existence of the atmospheric neutrino anomaly and of its interpretation as neutrino oscillations are being confirmed, with relatively lower statistics than MINOS will offer, in a very different way by the K2K experiment [7].

- The construction of the MINOS detectors continues on schedule. The far detector will be completed in June of this year. Unfortunately, the schedule for the beamline construction has resulted in a slip of at least 3 years in the planned running of MINOS with the NuMI beam. We note that in the original plan, MINOS would already now have had a result considerably more significant than that of K2K.
- The solar neutrino anomaly has been confirmed as an oscillation effect and with relatively large mixing angle and in the high Δm^2 region. [8, 9, 10]. This has very much accentuated interest in a possible small admixture of ν_μ to ν_e oscillation with the "atmospheric" Δm^2. Observation of this subdominant oscillation mode would be both a major discovery and would allow better planning for possible future studies of CP violation in the neutrino sector.
- The best-fit value of the atmospheric Δm^2 has dropped by more than a factor of 4, from > 0.01 eV^2 to 0.0025 eV^2 over the past four years. This has made it necessary for MINOS to plan to run primarily with the low energy beam option, with a corresponding reduction by a factor of 10 in the number of observed neutrino events per proton. Furthermore, if Δm^2 should be on the low end of the currently allowed region, it will be necessary to focus only on the very lowest energy neutrino events, reducing the effective flux even more.
- Recent theoretical interest in oscillations has been focussing on increasingly subtle questions: What about a small ν_e admixture? Do $\overline{\nu}$'s and ν's oscillate in exactly the same way? What are the oscillation parameters, at the few percent level? Is there any small admixture of a sterile neutrino? What is the mass hierarchy and can it be addressed using matter effects in long-baseline experiments? What about the possibility of CP violation in ν oscillations?

Over the past five years, developments in neutrino physics have made high proton intensity of key importance for the physics measurements targeted by the MINOS experiment. In fact, MINOS is far from unique in this perspective. The same is true of all accelerator based neutrino experiments. Because it is far from trivial to simply increase the number of protons per unit time at a given accelerator, all experiments which are planned to be contemporary with MINOS (OPERA, ICARUS and eventually Jaeri to Super-Kamiokande and NuMI Off-Axis) are aiming at initial runs of five year duration rather than two. This has already proven true of K2K which should now manage to complete a 5 year run before MINOS will start running with beam neutrinos. We note that the need for extended running for MINOS is already clear to Fermilab management who recently drafted a long range plan calling for four years of running for MINOS. We concur with their decision that longer running than a two year period is required and request even somewhat more than that draft plan.

Of much greater importance than five versus four years is the issue of proton intensity and the total number of protons which can/will be delivered to the NuMI target. It has always been understood that reaching the nominal goal of 7.4×10^{20} integrated protons on target would require a non-trivial investment in the accelerator complex through the Main Injector. Although some investment in this direction has indeed already occurred, it is generally clear that the main thrust of such investment has perhaps been deferred longer than is comfortable due to other pressing laboratory needs.

In order to better understand the technical issues and costs involved with increasing the proton intensity, two committees have been appointed to study the situation over the planned running period for MINOS. The first committee was formed as a joint Fermilab/MINOS group with charge coming from the Fermilab Associate Director for Accelerators and the MINOS Spokesperson. This committee was jointly chaired by Doug Michael on behalf of MINOS and Phil Martin for the Fermilab Beams Division. Its focus was directed primarily at the proton intensity issues for NuMI. The committee issued its report in August 2002 [11]. Following that report, the Fermilab Director formed a new committee in February of 2003, chaired by Dave Finley, which has been charged to review the overall proton demands through 2009 and the ability of the laboratory to meet those demands based on an investment of a "few times $10M", along with other aspects of the charge. The report from this committee is due June 1, 2003. We note that this report will only comment on how proton intensity issues can be addressed and not whether they should be addressed.

In this document, we present the physics case for an increased proton intensity for MINOS running. We request a total of 25×10^{20}, 120 GeV protons on the NuMI target in a five year run plan starting in April 2005. Of course, implicit in this request is the expectation that the NuMI beam line will be completed by December 2004, as planned, so that the first three months of 2005 can be used for low intensity commissioning. We provide a very brief outline of the year-by-year intensity and how this total might be achieved. Our main goal here is to present updated physics sensitivities for neutrino running based on a total of 7.4×10^{20}, 16×10^{20} and 25×10^{20} protons on target. (We note that running with anti-neutrinos could also be of eventual interest, be we do not address that here.) We believe that the measurement capabilities for the nature of the oscillations and the associated parameters for the ν_μ disappearance are significantly improved with the higher proton flux. Perhaps of most current interest is that the higher levels of proton intensity permit a very significant discovery potential for a small admixture of ν_μ to ν_e oscillation with the "atmospheric" Δm^2. We request that Fermilab develop a plan to meet this proton intensity level.

2 Proton request for the MINOS 5 year run plan

Table 1 shows our proton request for each year of MINOS running. The request for each year is from April of the listed year through March of the following year. This is done so as to make all years "full", on the assumption that the start of physics running (following the commissioning of the NuMI beamline) is in April of 2005.

In this document, it is our intent to primarily address only the physics which can

Year	2005	2006	2007	2008	2009	Total
Protons ($\times 10^{20}$)	2.5	3.8	5.0	6.5	7.2	25

Table 1: Requested protons per year of MINOS running. Note that each year runs from April of the listed year to March of the next year in order to permit full running years starting in 2005, after NuMI beamline commissioning.

be accomplished with such a request and not how such a request can be accomplished. However, we note that the MINOS Collaboration is developing an active role in the work necessary to provide an improved proton intensity. We think it is important to at least outline the basis of what we believe might make such intensities possible. Of course, it will be the responsibility of Fermilab and the managers for the accelerator complex to determine how best to deliver such intensities. The MINOS Collaboration hopes to join as an active partner with Fermilab in achieving this goal. Here, we list some assumptions which go into the MINOS request:

- 2005: Five batches of Booster protons of at least 5×10^{12} protons per batch will be accelerated to 120 GeV in the Main Injector along with two stacked batches of protons for pbar production with a Main Injector cycle time of 2.0 seconds. Additional Booster and MI stability work remains to accomplish this but we note that already the Booster is operating at near this level and the Main Injector has recently operated at about 2/3 of this level.

- 2006: In this time, some form of multi-batch stacking will start to become available in the Main Injector for protons for NuMI in addition to the slip-stacking for pbar production. We assume that the initial stacking will be slip-stacking, but it could just as easily be a first version of barrier stacking or variant thereof. At the same time, the Booster performance would continue to slowly improve. The MI cycle time is assumed to increase slightly (to 2.2 seconds) to permit enough Booster batches to be loaded into the Main Injector.

- 2007: Here we assume that there continue to be slow Booster improvements and that multi-batch stacking improvements have been made, likely switching the stacking technique over to barrier-type stacking rather than slip-stacking for both NuMI and pbar. This should permit increase in intensity for both. Some upgrades in MI RF power will start to be of interest on this timescale. Also, although it will not yet be operational, we assume that investment in reducing the MI cycle time by increasing the RF power and magnet ramp power will be started at this time.

- 2008: We assume that by spring of 2008, the MI ramp time can be reduced to 1.0 s from 1.5 s, following the necessary investment in RF and magnet power. We further assume that pbar cooling has been optimized by this time so that the cycle time can be less than 2.0 s. Hence, the MI cycle time can be reduced to 1.8 s, benefitting both the Collider program and NuMI.

- 2009: We assume this year of running is similar to the previous year but with some small, continued improvements in operation. There is an issue for program planning in this year to determine the appropriate split of MI running time for slow and fast spill operations.

We believe that there are alternate scenarios to this one for delivery of the requested number of protons, but here we only wish to illuminate some idea of the kind of improvements and investments which will be necessary. The necessary technical improvements listed here are consistent with an investment of "a few times $10M" with the cost of reducing the MI cycle time being the major contributor. We are optimistic that should such investment be undertaken, it will be possible for this number of protons to be delivered. We note that Booster operations are apparently already beyond our assumptions in this plan. Of course, various realities may reduce somewhat the intensities which we discuss here. We believe that these could be addressed with perhaps an additional year of running if necessary.

3 ν_μ Disappearance Measurements

A primary physics goal of MINOS is an unambiguous demonstration of the oscillation mechanism through measurement of the energy distribution of ν_μ CC events and a precise determination of the associated oscillation parameters. Making precise measurements of the ν_μ disappearance is more challenging as Δm^2 becomes smaller. The NuMI beamline provides an opportunity for adjusting the energy of the neutrino beam. The energy spectrum of measured far detector CC events without oscillations is shown in Figure 1 for the "low", "medium" and "high" energy NuMI beam configurations. For MINOS, our current plan calls for mostly utilizing the lowest energy tune permitted by the components which are currently in fabrication. This is because of the relatively low central value of $\Delta m^2 = 0.0025$ eV^2 which is the current best-fit value from Super-Kamiokande measurements [6]. This value is consistent with the less precise results from other atmospheric neutrino experiments and the current best value from the K2K experiment [17, 16, 7]. It is possible that a new target and horn could be built which would allow an even lower energy optimization of the NuMI beam. However, such an upgrade is substantial and would likely only be undertaken if some initial running suggests it might be necessary. Hence, we anticipate that for at least the first 2-3 years of running, MINOS will rely on the existing horn and target configuration and hence the "low energy" beam shown in figure 1 will be the lowest energy configuration available in that time.

For $\Delta m^2 = 0.0025$ eV^2, the oscillation maximum at 735 km is at $E_\nu = 1.5$ GeV. The peak energy of neutrino interactions for the NuMI "low energy" beam is 3 GeV corresponding to the oscillation maximum for $\Delta m^2 = 0.005$ eV^2. Given that the 90% CL upper bound from Super-Kamiokande is currently 0.004 eV^2, we anticipate that the measured oscillation maximum in MINOS will lie somewhere below the peak energy of the beam. Should Δm^2 lie near the lower edge of the allowed region of parameter space from

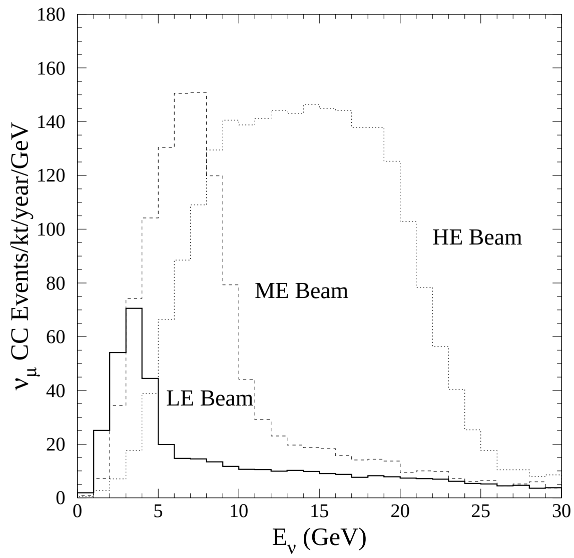

Figure 1: Spectrum of observed CC ν_μ events at the MINOS Far Detector in the absence of oscillations for the NuMI "low", "medium" and "high" energy tunes.

Super-Kamiokande (90% CL at $\Delta m^2 = 0.0016$ eV^2), the primary way to get a sufficient number of events to clearly resolve the dip in the spectrum will simply be to increase the total number of neutrino events, through longer running, more protons or both. If nature is kind, Δm^2 may lie on the high side of the Super-Kamiokande best-fit parameter in which case measurements for MINOS will be relatively robust with modest statistics. But for planning purposes we believe it is important not to assume that this will be the case.

The selection of ν_μ CC events in MINOS depends primarily on identification of an event which contains a relatively clean and long track which is consistent with a muon. This is relatively straight-forward at high energies where most muons in such events travel sufficiently far as to standout clearly beyond the "shower region" of the interaction. At lower energies, more events are quasi-elastic and these events are generally easy to identify as CC events. However, some NC events where a single pion is produced or carries most of the momentum of the final state can appear somewhat similar. Hence, it is important to use a realistic event simulation and pattern recognition algorithm to accurately predict the physics sensitivity from measurement of the the low energy neutrino events.

For the analyses presented here, we have used events which have been fully simulated in the MINOS Far Detector using NeuGen and GEANT3 with Gheisha as the hadron interaction package. The simulation includes a full simulation of the MINOS detector response. Although work on our reconstruction package is still on-going, we have used

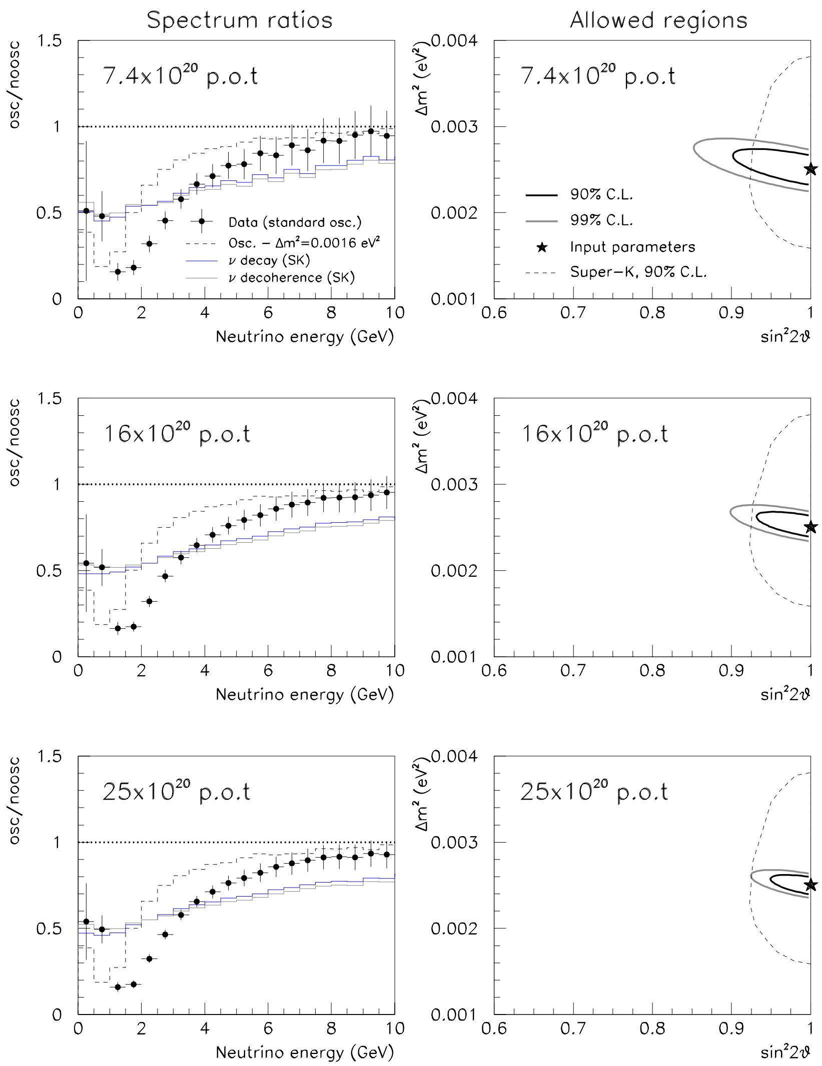

Figure 2: Oscillation measurement for different numbers of protons on target which MINOS can make with the actual values of the oscillation parameters being $\Delta m^2 = 0.0025$ eV^2 and $\sin^2 2\theta = 1.0$. The plots on the left show the expected measured ratio of oscillated far detector data to the no-oscillation prediction while the plots on the right show the resulting CL regions on the measurement of the oscillation parameters. The points with error bars in the energy distribution plots are the expected MINOS data. Also shown are histograms for the expected ratio if Δm^2 were 0.0016 eV^2 instead, or for neutrino decay or decoherence. The parameter space plots also show the current 90% CL measurement contours for Super-Kamiokande based on atmospheric neutrino measurements. The current uncertainty in the K2K value of Δm^2 is comparable to that from the Super-K analysis.

the latest version of our pattern recognition and track reconstruction software to identify whether events contain a muon track. This track reconstruction software has been shown to be $> 90\%$ efficient at identifying events which contain a muon with at least 1 GeV/c of momentum. The probability of a NC event being mis-identified as a CC event depends strongly on the apparent momentum of a muon. Below 1 GeV/c "muon" momentum, roughly half of the identified "CC" events are in fact NC background. Above 1 GeV/c muon momentum, the background is less than 10%. Hence, it is important to understand this background at low energies and develop reliable background subtraction based on near detector measurements. An important recent development is that we have made measurements with our calibration detector of how likely it is that charged pions can look like muons and we have found a result which is consistent with the GEANT Gheisha prediction. In the results presented here, we have made a conservative assumption of a 20% systematic uncertainty in the background subtraction of the NC events in the CC sample. Further, we have applied a 2% normalization uncertainty and an additional 2% bin-to-bin systematic uncertainty per 1 GeV bin on the ability to properly predict the unoscillated number of CC events at the far detector based on the near detector measurements. These uncertainties are estimated based on previous understanding of the beam and near detector analyses.

Once events are identified as containing a muon, the neutrino energy is calculated from the sum of the muon energy and the shower energy in the event. Because at this time we are still working on some of the details of our reconstruction code for these features, we have used smeared true energies for this purpose based on our measured resolutions from the calibration detector ($\sigma_{E_\mu}/E_\mu = 0.10$, $\sigma_{E_{\rm had}}/E_{\rm had} = 0.55/\sqrt{E_{\rm had}}$, $\sigma_{E_{\rm EM}}/E_{\rm EM} = 0.22/\sqrt{E_{\rm EM}}$). We anticipate that use of this particular approximation will have a negligible bias compared to the real algorithm which we will eventually use. Note however that all of the critical pattern recognition steps make use only of fully simulated and reconstructed MC data.

Figure 2 shows several plots associated with the measurements which MINOS can make with the actual values of the oscillation parameters being $\Delta m^2 = 0.0025$ eV^2 and $\sin^2 2\theta = 1.0$. There are three pairs of plots for a total of 7.4×10^{20}, 16×10^{20} and 25×10^{20} protons on target. The left plot in each pair shows the expected measured ratio of oscillated far detector data to the no-oscillation prediction while the right plot shows the resulting CL regions on the measurement of the oscillation parameters. The energy distribution plots also show histograms for the expected ratio if Δm^2 were 0.0016 eV^2 instead, or for neutrino decay or decoherence [13, 12]. The parameter space plots also show the current 90% CL measurement contours for Super-Kamiokande based on atmospheric neutrino measurements. For these values of the oscillation parameters, MINOS will be able to resolve the dip in the oscillation spectrum at all levels of proton intensity, though at the lower total number of protons on target the significance of the rise is modest. In all cases, MINOS will improve the measurement of Δm^2 by more than a factor of 5 over the current best measurement. However, only at the higher total numbers of protons on target will MINOS be able to improve on the measurement of $\sin^2 2\theta$. For the highest level of protons, MINOS will be able to improve this measurement by about a factor of 2. The MINOS measurement of Δm^2 will also improve by about a factor of 2 for the higher number of protons compared to the lower number. We believe that this measurement would constitute a clear improvement in our understanding of both parameters and offers the very interesting possibility of significantly better constraining the mixing angle than any existing measurements.

Figure 3 shows the same situation as Figure 2 but for $\Delta m^2 = 0.0016$ eV^2. In this case, the data points show the expected MINOS measurements and a histogram curve is shown for $\Delta m^2 = 0.0025$ eV^2. This figure illustrates how it is more difficult to precisely measure the nature of the oscillations and oscillation parameters as Δm^2 gets smaller. Here, only with the higher numbers of protons on target will any statistically significant measure be made of the rise in neutrino flux at the lower energies. The reason for this is simply the low rate of neutrino events at these energies. Although the oscillation parameters are measured less well as Δm^2 becomes lower, the most difficult problem is the ability to resolve the rise in the flux of low energy neutrinos where the oscillation probability is less than maximal. The reason is that the entire curve contributes significantly to the measure of the oscillation parameters as is clearly illustrated by the difference of the curve for $\Delta m^2 = 0.0025$ eV^2 and the data which follow the curve for 0.0016 eV^2.

In fact, the data presented in both Figures 2 and 3 represent a somewhat idealized situation. The data points shown in the energy distribution in these figures show the correct error bars but perfectly follow the expected distribution given the oscillation parameters. Of course, in our real measurements the data points will fluctuate in a manner consistent with the statistical errors. Figure 4 shows the energy distribution from three different "real" experiments based on 7.4×10^{20} protons on target (where we simply let data points fluctuate accordingly). No effort has been made to select these experiments; they are just three at random. However, they help to give some intuitive feeling for how difficult it will be to make a convincing demonstration of the nature of the oscillations with a lower number of protons should Δm^2 be in the low range of the currently allowed 90% CL region.

In order to make a complete measurement of the nature of the oscillation, we need to measure an energy dependence of the oscillation which follows the expected $\sin^2 1/E_\nu$ behavior, including a rise in the oscillated neutrino flux in lowest energy bins. Table 2 shows the significance of the dip in the energy spectrum and the rise compared to the dip at the lowest energies for the different number of protons on target. The dip significance is taken as the number of sigma that the lowest bin (0.5 GeV wide) differs from the no oscillation expectation. The rise significance is calculated by comparing the average number of events per bin in all bins with energy lower than that which contains the fewest measured events, the "dip bin". The significance is the σ of the difference between the average number of events per bin in the lower energy bins and the number of events in the dip bin. In general, the dip significance is always large but the significance of

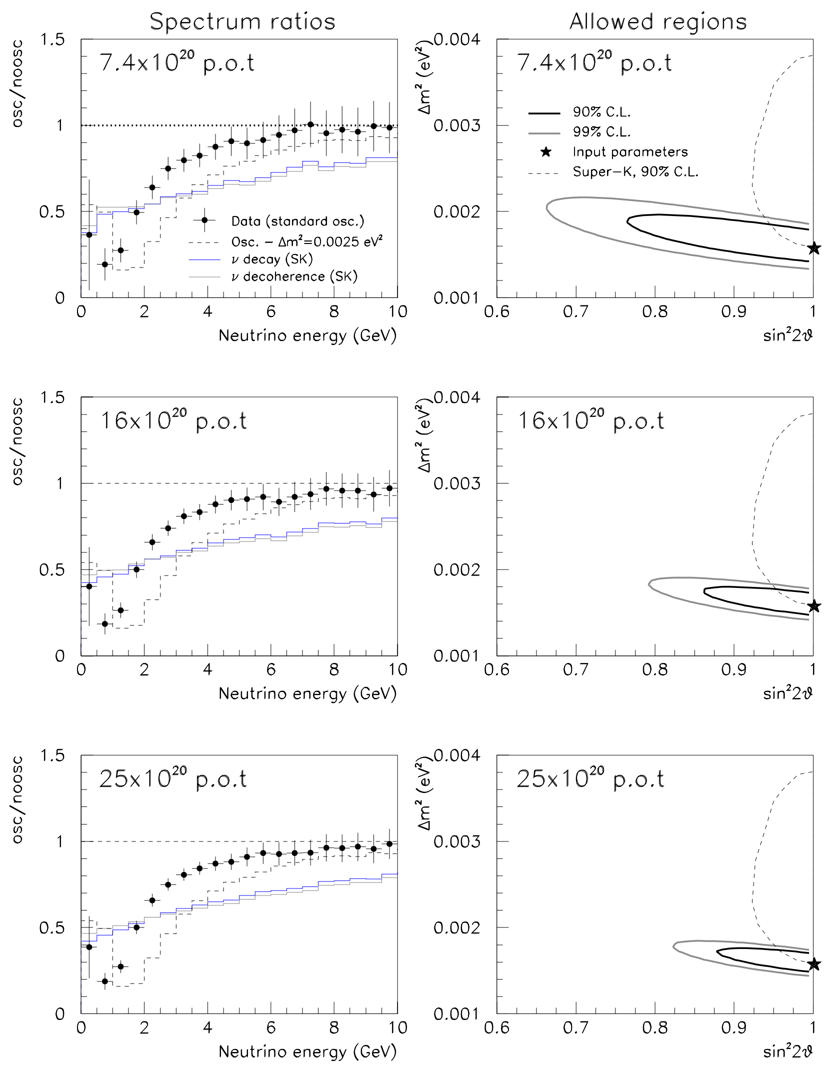

Figure 3: Oscillation measurement for different numbers of protons on target which MINOS can make with the actual values of the oscillation parameters being $\Delta m^2 = 0.0016$ eV^2 and $\sin^2 2\theta = 1.0$. The plots on the left show the expected measured ratio of oscillated far detector data to the no-oscillation prediction while the plots on the right show the resulting CL regions on the measurement of the oscillation parameters. The energy distribution plots also show histograms for the expected ratio if Δm^2 were 0.0025 eV^2 instead, or for neutrino decay or decoherence. The parameter space plots also show the current 90% CL measurement contours for Super-Kamiokande based on atmospheric neutrino measurements.

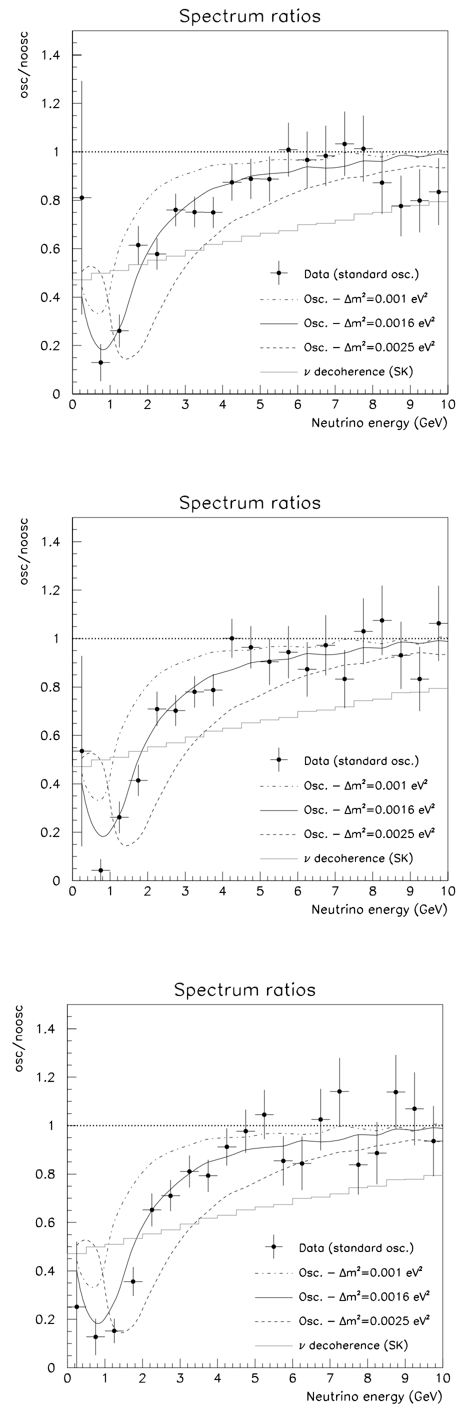

Figure 4: The energy distribution of the ratio of the observed far detector events to the no oscillation expectation for three random experiments with $\Delta m^2 = 0.0016\,\mathrm{eV}^2$ and with 7.4×10^{20} protons on target.

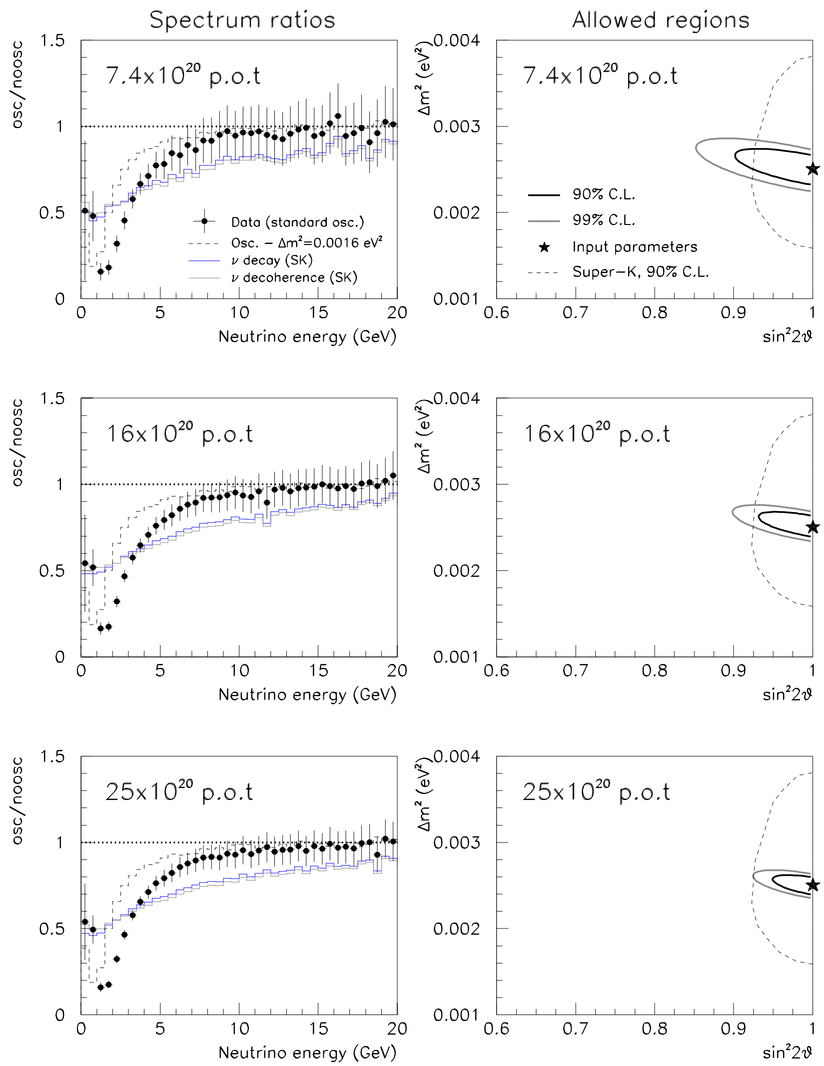

Figure 5: The same as Figure 2 but showing data up to 20 GeV.

$\Delta m^2 = 0.0025$ eV^2	$\sin^2 2\theta = 1.0$	
P.O.T.	$\sigma_{\rm dip}$	$\sigma_{\rm rise}$
7.4×10^{20}	17	2.3
16×10^{20}	23	3.4
25×10^{20}	30	4.2
$\Delta m^2 = 0.0016$ eV^2	$\sin^2 2\theta = 1.0$	
P.O.T.	$\sigma_{\rm dip}$	$\sigma_{\rm rise}$
7.4×10^{20}	8.6	0.5
16×10^{20}	13	0.9
25×10^{20}	17	1.1

Table 2: The significance of the dip and of the rise of the neutrino flux at low energies for three different levels of protons on target for the oscillation parameters shown. A good measurement of the rise requires the higher number of protons and if Δm^2 is very low may also require a modified low-energy beam.

the rise at low energy requires the higher number of protons to be meaningful. We see that for $\Delta m^2 = 0.0016$ eV^2, we will be very interested in some means of improving the beam focus conditions in order to increase the number of lowest energy neutrino events. Work is already underway to understand how to make such improvements, but we do not anticipate that such improvements will actually be proposed until we have some evidence that Δm^2 in fact appears to be quite low. We anticipate that sufficient evidence, one way or the other, will start to become available to us by about 2006.

Finally, all of the above figures show only the data with observed energy below 10 GeV for clarity in the low energy region. In Figure 5 we show the data up to 20 GeV for completeness. The data in this region is interesting both as a normalization for the low energy data and for an ability to search for any deviations from the expected flux which may be indicative of any exotic effects, even relatively subtle ones. Should any anomalies be observed in this region running with the low energy beam, it would be relatively easy for us to increase running with one of the higher energy configurations to relatively quickly address such an effect. One example of a model which this higher energy data can contribute to addressing is neutrino decoherence [12]. Figure 6 shows the sensitivity of MINOS to the decoherence parameter μ compared to Super-Kamiokande and Super-Kamiokande combined with K2K. It is evident that the relatively high statistics and better resolution on L and E in MINOS will offer significantly better measurements of this kind of effect, even at relatively low levels of protons on target. In this case, the higher levels of protons on target will make it possible to set increasingly tight limits on any non-standard effects in addition to the expected oscillation. Should any non-standard effect be observed, the higher level of proton intensity will offer much better data to allow a convincing discovery.

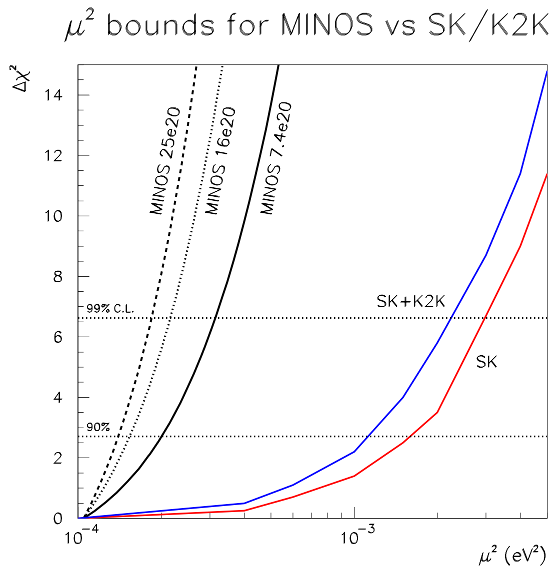

Figure 6: The sensitivity of MINOS (based on the deviation in the energy distribution expected for standard oscillations and the decoherence effect) to the exotic neutrino decoherence parameter μ. The $\Delta\chi^2$ for MINOS at three levels of proton intensity is shown versus μ. Also shown are the sensitivity for Super-Kamiokande and Super-Kamiokande plus K2K as calculated in reference [12].

4 ν_e Appearance Measurements

An important physics goal for MINOS has always been a search for a possible small oscillation probability for ν_μ to ν_e. Results on solar and reactor neutrinos in the last few years, suggesting a relatively large Δm^2 and mixing angle for those oscillations, has heightened interest in such an admixture associated with the atmospheric Δm^2. Although there is no firm theoretical prediction, there are several theoretical suggestions that having this final oscillation parameter (U_{e3}) very much smaller than the other angles would be difficult/unnatural.

In the region of the atmospheric neutrino Δm^2, the current most sensitive constraint comes from the CHOOZ experiment [14]. This experiment measured both the reactor $\overline{\nu}_e$ total flux as well as the expected energy distribution. This resulted in a strong constraint in the parameter U_{e3}. Additional constraints, though not quite as restrictive, come from Super-Kamiokande [6] and Soudan 2 [16], based on the fact that they measure the expected flux of atmospheric ν_e events, from another reactor experiment, Palo-Verde [15] and from Super-Kamiokande [6] and MACRO [17] based on the fact that the upgoing muon distribution shows no oscillation suppression effect through the core of the earth

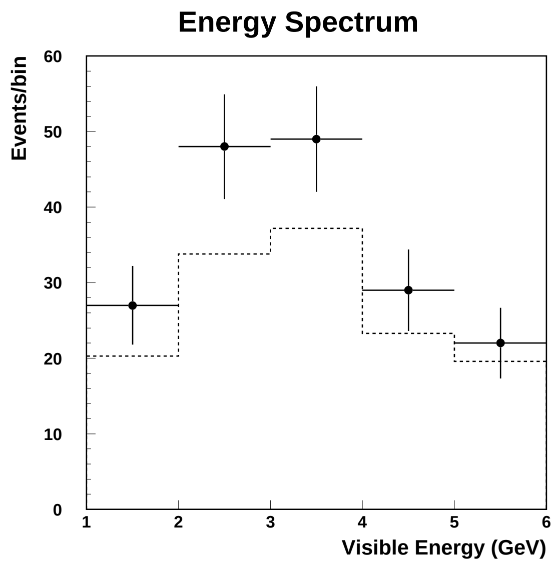

Figure 7: The energy distribution of the ν_e candidate events in the MINOS far detector given parameters of $\Delta m^2 = 0.0025$ eV^2 and $\sin^2 2\theta = 0.067$ for ν_μ to ν_e oscillations (data points with error bars) compared to the expected background with no ν_μ to ν_e oscillation (dashed histogram).

which would result from ν_μ to ν_e oscillations.

We have recently evaluated more closely the discovery potential which MINOS can offer for this very interesting measurement. We believe that the discovery potential is in fact quite interesting given the number of protons on target which we request herein, and it is this discovery potential which is one of our primary bases for establishing the request.

The MINOS ν_e appearance signature depends on the selection of events which are dominated by a single EM shower with energy consistent with the region of ν_μ disappearance. The primary background comes from neutral current events where a single π^0 carries most of the momentum of the final state. Additional, though less important, backgrounds come from mis-identified CC events and intrinsic ν_e's resulting from K^+ and μ^+ decays. A final, though yet smaller, source of background comes from ν_τ CC events where the produced τ^- decays to an electron. The absolute background rate varies depending on the specific analysis applied and ranges from about 0.5%-3.0% of the rate of ν_μ CC events without oscillations. In all analyses, a background subtraction is made in observed far detector events, based on nearly identical high-statistics measurements in the near detector. The resulting sensitivities are dominated by the statistical fluctuation of the backgrounds in the far detector. Hence, to good approximation the sensitivity will improve as the square-root of the total exposure. However, it is possible that some

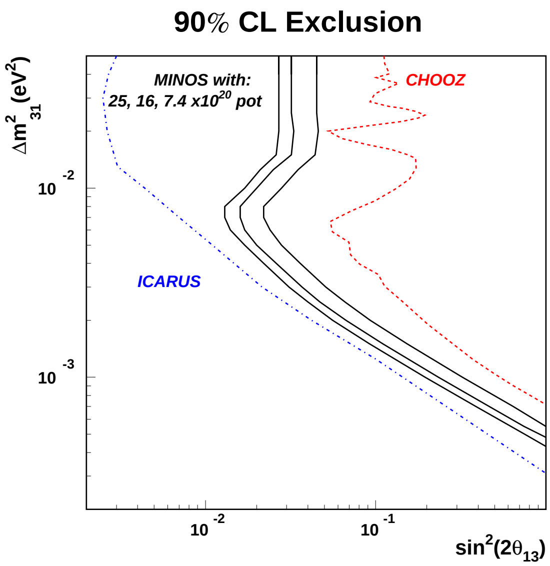

Figure 8: The 90% CL exclusion limits for ν_μ to ν_e oscillation for MINOS with 7.4×10^{20}, 16×10^{20} and 25×10^{20} protons on target. Also shown are the limits already published for CHOOZ and those expected for five years of running for 3 kT ICARUS.

modifications to the beam configuration could offer improved sensitivity, due to relatively lower backgrounds, and we are actively studying such possibilities.

The results presented here have been calculated using fully simulated and reconstructed Monte Carlo data. Two different methods of reconstruction and pattern recognition were used to calculate the efficiency for true ν_e events and the probability of background. One method used a neural network while the other used a likelihood analysis based on shower shape parameters and requiring identified events to have measured energies consistent with having oscillated from ν_μ's in the main peak of the beam spectrum.

Figure 7 shows the number of ν_e selected events versus the observed energy in MINOS based on 25×10^{20} protons on target (clearly, the number of events will simply scale at lower numbers of protons). The figure shows a dashed histogram which are the events expected with no ν_μ to ν_e oscillation and points with error bars which result from an example of oscillation parameters for which MINOS can make a 3σ discovery, $\Delta m^2 = 0.0025$ eV^2 and $\sin^2 2\theta = 0.067$. We note that oscillations with these parameters would have induced a modulation in the CHOOZ energy spectrum which is several times smaller than the reported statistical error bars. Hence, even a hint of such an oscillation would not yet have been observed.

Figure 8 shows the 90% CL exclusion limits which MINOS will be able to make with 7.4×10^{20}, 16×10^{20} and 25×10^{20} protons on target. Also shown are the limits already

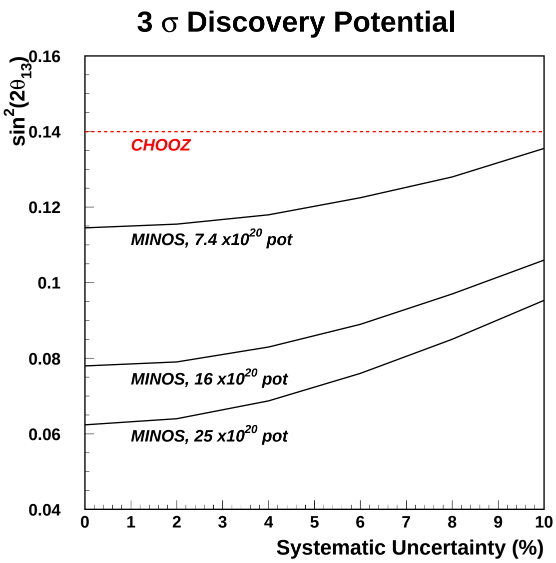

Figure 9: The 3σ discovery contours for $\sin^2 2\theta$ versus the systematic error in background subtraction for MINOS with $\Delta m^2 = 0.0025$ eV^2 for ν_μ to ν_e oscillation with 7.4×10^{20}, 16×10^{20} and 25×10^{20} protons on target. We estimate that the systematic uncertainty will be 5% or less. The current CHOOZ limit is also shown. We would like to point out that the relative sensitivity between MINOS and CHOOZ are roughly independent of Δm^2 in the region of interest.

published for CHOOZ and those expected for five years of running for ICARUS (complete in 2011 in the CERN plan). This limit assumes a 5% systematic uncertainty in the statistical background subtraction for MINOS, due to small, unavoidable differences in the near detector backgrounds compared to those at the far detector (the main issue being that the ν_μ's oscillate away and hence their CC events no longer appear as much as background in the far detector). Figure 9 shows the 3σ discovery contour for MINOS with three total numbers of protons on target versus the systematic uncertainty in the background subtraction. Figure 10 shows how the 3σ contours vary in the two-dimensional oscillation parameter space assuming that Δm^2 is known from the ν_μ disappearance measurement and the systematic uncertainty on the background subtraction is 5%.

We note that the area of parameter space where MINOS can make a discovery, beyond the existing 90% CL bound from CHOOZ, is significantly improved with the higher proton intensity levels. This discovery potential is made possible by use of the appearance technique in MINOS combined with our high precision measurements on the unoscillated beam offered by the MINOS near detector. Because of this, we anticipate that at any reasonable level of proton intensity that the MINOS sensitivity will be limited by statistics rather than systematic uncertainty. We think that this discovery potential offers a strong

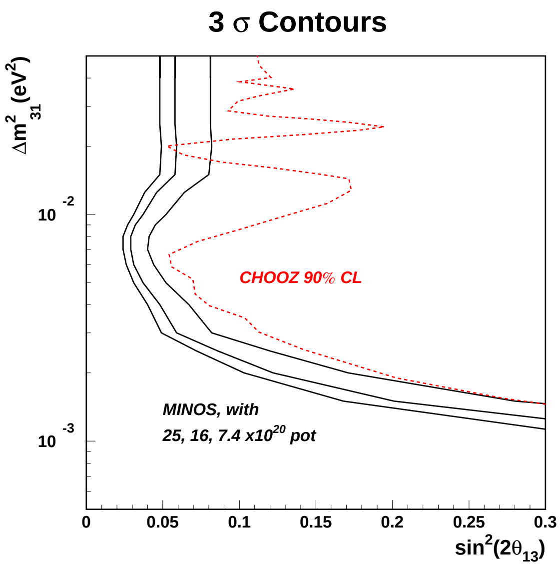

Figure 10: The 3σ discovery contours assuming that Δm^2 is known from the ν_μ disappearance and that the systematic uncertainty on background subtraction is 5%. Also shown are the existing 90% CL limits from CHOOZ.

argument for investment in proton intensity at Fermilab.

5 Summary

We have presented the expected physics sensitivity for MINOS with three levels of total protons on target. We believe that the extended capabilities which 25×10^{20} protons offer presents an exciting opportunity for MINOS and Fermilab. In particular, the discovery potential for ν_e appearance, beyond the existing experimental limits, is very significant. The ability to convincingly demonstrate the mechanism of the oscillations, and precisely measure the associated parameters is significantly enhanced. This level of protons will make it possible for MINOS to measure $\sin^2 2\theta_{23}$ significantly better than any other experiment in this time scale. This physics program requires investment in the proton intensity capabilities of the accelerator complex. We urge Fermilab to develop a plan to undertake the necessary investment to accomplish the full intensity request. The MINOS Collaboration is ready to work together with Fermilab in the development and execution of such a plan.

References

[1] The MINOS Collaboration, "P875: A Long-baseline Neutrino Oscillation Experiment at Fermilab", February 1995, Fermilab report NuMI-L-63.

[2] The MINOS Collaboration, "Addendum to P-875, A Long-baseline Neutrino Oscillation Experiment at Fermilab", April 1995, Fermilab report NuMI-L-79.

[3] The MINOS Collaboration, "MINOS Answers to HEPAP Subpanel Questions", June 1995, Fermilab report NuMI-L-96. "Fermilab Answers to HEPAP Subpanel Supplemental Questions", July 1995, Fermilab report NuMI-L-100.

[4] The MINOS Collaboration, "Neutrino Oscillation Physics at Fermilab: The NuMI-MINOS Project", May 1998, Fermilab report NuMI-L-375.

[5] C. Baltay et al., "Report of the MINOS Subcommittee of the Fermilab Physics Advisory Committee, May 1998, Fermilab report NuMI-L-389.

[6] M. Shiozawa for the Super-Kamiokande Collaboration, Presented at Neutrino 2002, Munich.

[7] K2K Collaboration, M.H.Ahn, et al.,"Indications of neutrino oscillation in a 250 km long-baseline experiment", Phys.Rev.Lett.90:041801, 2003. Also hep-ex/0212007.

[8] The Super-Kamiokande Collaboration, S. Fukuda et al., Phys.Rev.Lett.86:5656-5660,2001. Also hep-ex/0103033.

[9] The SNO Collaboration, Q.R. Ahmad, et al,"Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory", Phys.Rev.Lett.89:011301,2002. Also nucl-ex/0204008.

[10] The KamLAND Collaboration, K. Eguchi et al., Phys.Rev.Lett.90:021802,2003., Also hep-ex/0212021.

[11] B. Choudhary, et al., "Accelerator improvement options for NuMI proton intensity", August 2002, NuMI note 0863, publicly available at http://hep.caltech.edu/~michael/numipiwg/numipiwg.ps.

[12] G.L. Fogli, E. Lisi, A. Marrone and D. Montanino, "Status of atmospheric ν_μ to ν_τ oscillations and decoherence after the first K2K spectral data", hep-ph/0303064, Mar. 2003.

[13] C. Yanagisawa, Presented at NOON '03, Kanazawa, Japan www-sk.icrr.u-tokyo.ac.jp/noon2003, Feb. 2003.

[14] The CHOOZ Collaboration, M. Apollonio, et al., Eur.Phys.J.C27:331-374, 2003. Also hep-ex/0301017.

[15] The Palo Verde Collaboration, F. Boehm, et al., Phys.Rev.D64:112001,2001. Also hep-ex/0107009.

[16] M. Goodman, Presented at Neutrino 2002, Munich, Germany, July 2002.

[17] The MACRO Collaboration, M. Ambrosio et al., Phys.Lett.B517:59-66,2001.