Physics Potential of a 2540 Km Baseline Superbeam Experiment

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Abstract. We study the physics potential of a neutrino superbeam experiment with a 2540 km baseline. We assume a neutrino beam similar to the NuMI beam in the medium energy configuration. We consider a 100 kton totally active scintillator detector at a 7 mr off-axis location. We find that such a configuration has an outstanding hierarchy discriminating capability. In conjunction with the data from the present reactor neutrino experiments, it can determine the neutrino mass hierarchy at the 3σ level in less than 5 years, if $\sin^2 2\theta_{13} \geq 0.01$, running in the neutrino mode alone. As a stand alone experiment, with a 5 year neutrino run and a 5 year anti-neutrino run, it can determine non-zero θ_{13} at the 3σ level if $\sin^2 2\theta_{13} \geq 7\times10^{-3}$ and hierarchy at the 3σ level if $\sin^2 2\theta_{13} \geq 8\times10^{-3}$. This data can also distinguish $\delta_{CP} = \pi/2$ from the CP conserving values of 0 and π, for $\sin^2 2\theta_{13} \geq 0.02$.

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INTRODUCTION

Some of the currently unknown neutrino oscillation parameters are the sign of the larger mass-squared difference Δ_{31}, the mixing angle θ_{13} and the CP violating phase δ_{CP}. The $\nu_\mu \to \nu_e$ oscillation probability, $P_{\mu e}$ is sensitive to all these unknowns, and is hence a good candidate to measure them. Determining whether Δ_{31} is positive (normal hierarchy, or NH) or negative (inverted hierarchy, or IH) is not straightforward because of the uncertainty in δ_{CP} and θ_{13}. The $P_{\mu e}$ spectrum in energy with the correct hierarchy and one set of oscillation parameters can be mimicked by the other hierarchy with a different set of parameters, i.e. $P_{\mu e}(NH, \theta_{13}, \delta_{CP}) = P_{\mu e}(IH, \theta'_{13}, \delta'_{CP})$ [1]. Figures 1 and 2 show the hierarchy-θ_{13} degeneracy and hierarchy-δ_{CP} degeneracies for the 1300 km baseline.

Because of this problem of degeneracies, it is not possible to determine the mass hierarchy unambiguously using data from a single experiment. It has been shown [2] that even the combined results from the current experiments cannot determine the mass hierarchy for all δ_{CP}.

CALCULATION

An approximate expression for $P_{\mu e}$ in matter is given as an expansion in the small parameter $\alpha = \Delta_{21}/\Delta_{31}$. It can be written as [3]

$$P_{\mu e} = C_0 \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} + \alpha\, C_1 \frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})} \frac{\sin(\hat{A}\Delta)}{\hat{A}} + \alpha^2\, C_2 \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}, \quad (1)$$

where $\Delta = (\Delta_{31}L/4E)$ and $\hat{A} = A/\Delta_{31}$. The matter term $A\,(\text{in eV}^2) = 0.76\times10^{-4}\rho\,(\text{gm/cc})\,E\,(\text{GeV})\,\text{eV}^2$. Here, ρ is the density of matter through which the neutrino propagates. Of the coefficients C_i, only C_1 depends on δ_{CP}.

In the magic baseline proposal, the δ_{CP} dependent term is eliminated by choosing $\sin(\hat{A}\Delta) = 0$ [4]. This

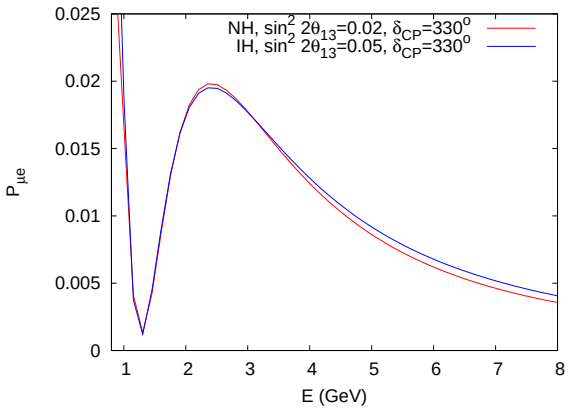

FIGURE 1. Hierarchy-θ_{13} degeneracy in $P_{\mu e}$ at 1300km. We see that $P_{\mu e}(NH, \sin^2 2\theta_{13} = 0.02; E) = P_{\mu e}(IH, \sin^2 2\theta_{13} = 0.05; E)$. The value of δ_{CP} is taken to be 330° here.

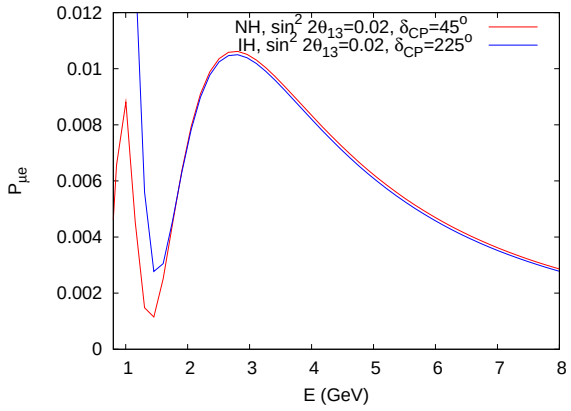

FIGURE 2. Hierarchy-δ_{CP} degeneracy in $P_{\mu e}$ at 1300km. We see that $P_{\mu e}(NH, \delta_{CP} = 45°; E) = P_{\mu e}(IH, \delta_{CP} = 225°; E)$ for $E > 1.5$ GeV. The value of $\sin^2 2\theta_{13}$ is taken to be 0.02 here.

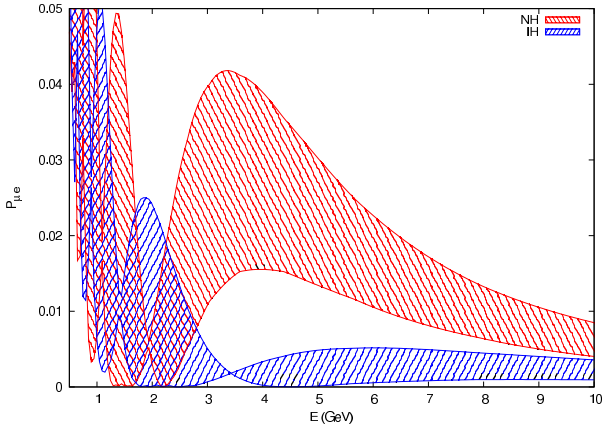

FIGURE 3. $P_{\mu e}$ as a function of E for $L = 2540$ Km and $\sin^2 2\theta_{13} = 0.02$. $P_{\mu e}$ is plotted for both NH and IH, each for the full range of values of δ_{CP}.

condition can be satisfied simultaneously for both hierarchies, and is independent of energy. Solving it gives a baseline of 7500 km. At this baseline, $P_{\mu e}$ becomes independent of δ_{CP}. Thus, an experiment at the magic baseline should be able to distinguish between the two hierarchies, independently of δ_{CP}. However, an experiment with such a long baseline requires a very intense source, due to the inverse distance-squared fall in flux. The technology for such a source is futuristic by current standards. Moreover, the δ_{CP} independence of $P_{\mu e}$ at this baseline means that such an experiment cannot make any prediction about δ_{CP}.

In our proposal, we manipulate the $(1-\hat{A})\Delta$ term [5], which depends on the hierarchy and energy as well. For IH, we demand δ_{CP} independence, by imposing $(1-\hat{A})\Delta = -\pi$, which also makes $P_{\mu e}$ very small. For good hierarchy discrimination, we demand that $P_{\mu e}(NH)$ be maximum, i.e. $(1-\hat{A})\Delta = \pi/2$. Solving these two conditions simultaneously gives a baseline of 2540 km and an energy of 3.3 GeV. The $P_{\mu e}$ oscillation probability for 2540 km is shown in figure 3 for $\sin^2 2\theta_{13} = 0.02$.

RESULTS

The NuMI beam in the medium energy option has an unoscillated event spectrum that peaks around 3.5 GeV for locations 7 mr off-axis [6]. Therefore, we chose a NuMI-like beam as the source, and a 100 kton liquid scintillator detector placed 2540 km away and 7 mr off the beam axis. We scaled up the beam power of our source so as to give 10×10^{20} POT/yr instead of the current 7.3×10^{20} POT/yr for NuMI. This tenfold increase in exposure as compared to NOνA gives our setup the same statistical weight as NOνA, since the NOνA flux is ten times higher due to its shorter baseline. We have used GLoBES [7] for our calculations. We considered systematic effects as well as backgrounds arising from the intrinsic beam ν_e, neutral current events and misidentified ν_μ events.

TABLE 1. Exposure time in years required for 3σ hierarchy discrimination.

$\sin^2 2\theta_{13}$ (true)	Exposure time (NH)(years)	Exposure time (IH)(years)
0.10	0.022	0.048
0.07	0.040	0.082
0.05	0.070	0.137
0.03	0.180	0.420
0.01	2.950	4.800

First, we calculated the exposure time (in years) required to get a 3σ distinction between the two hierarchies, as a function of θ_{13}. This calculation was done assuming a neutrino run alone. Since the effect of the value of θ_{13} on our results is significant, we did this calculation by combining the results of our setup with those expected from T2K, NOνA, Double Chooz and Daya Bay [8]. Some results of this calculation are shown in the table. The full results with discussions are given in [9].

Next, we have calculated the sensitivity of our setup combined with the above mentioned experiments in the $\theta_{13} - \delta_{CP}$ plane. For this, we have assumed a 5 year neutrino and a 5 year anti-neutrino run, to constrain δ_{CP}. Figure 4 shows the 1σ and 2σ contours for fifteen different sets of true values.

We have determined the capability of our setup as a stand-alone experiment to measure non-zero θ_{13}, determine the mass hierarchy and discover CP violation for

$\sin^2 2\theta_{13}$ as small as 10^{-4}. For this, we again considered a 5 year neutrino and a 5 year anti-neutrino run. The θ_{13} discovery reach for this setup is similar to that for determining the mass hierarchy, as shown in figure 5. Figure 6 shows the CP violation discovery potential.

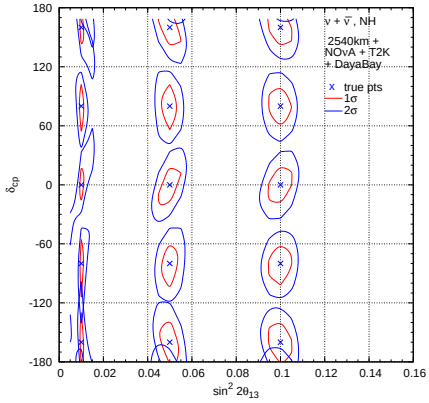

FIGURE 4. 1σ and 2σ contours for sensitivity in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane.

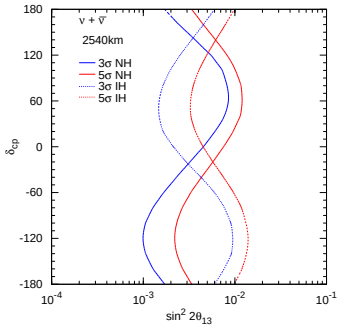

FIGURE 5. 3σ and 5σ contours in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane for excluding the 'wrong' hierarchy.

CONCLUSIONS

We see that a superbeam experiment at 2540 km using modest technology in terms of detector capabilities and beam power can determine the neutrino mass hierarchy unambiguously for all values of δ_{CP}. For this, it is sufficient to run the experiment in neutrino mode alone for less than 5 years.

The proposed setup can measure a non-zero value for θ_{13} for values as small as $\sin^2 2\theta_{13} = 7 \times 10^{-3}$. Determination of the mass hierarchy is possible for $\sin^2 2\theta_{13} \geq 8 \times 10^{-3}$. The maximal CP violating cases $\delta_{CP} = \pi/2, 3\pi/2$ can be distinguished from the CP conserving $\delta_{CP} = 0, \pi$ for $\sin^2 2\theta_{13} \geq 0.01$. The capabilities of an experiment at 2540 km using a neutrino factory have also been studied recently in [10].

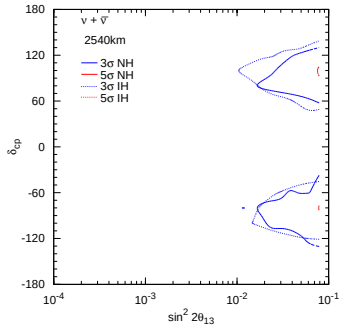

FIGURE 6. 3σ and 5σ contours in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane for excluding CP conservation.

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