

Low energy neutrino factory for large θ_{13}

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(Received 5 February 2007; published 1 May 2007)*

If the value of θ_{13} is within the reach of the upcoming generation of long-baseline experiments, T2K and NO ν A, we show that a low-energy neutrino factory, with peak energy in the few GeV range, would provide a sensitive tool to explore CP violation and the neutrino mass hierarchy. We consider baselines with the typical length 1000–1500 km. The unique performance of the low-energy neutrino factory is due to the rich neutrino oscillation pattern at energies between 1 and 4 GeV at baselines $\mathcal{O}(1000)$ km. We perform both a semianalytical study of the sensitivities and a numerical analysis to explore how well this setup can measure θ_{13} , CP violation, and determine the type of mass hierarchy and the θ_{23} octant. A *low-energy neutrino factory* provides a powerful tool to resolve ambiguities and make precise parameter determinations, for both large and fairly small values of the mixing parameter θ_{13} .

DOI: [10.1103/PhysRevD.75.093001](https://doi.org/10.1103/PhysRevD.75.093001)

PACS numbers: 14.60.Pq

I. INTRODUCTION

During the last several years our understanding of the physics of neutrinos has made remarkable progress. The experiments with solar [1–6], atmospheric [7], reactor [8], and also long-baseline accelerator [9] neutrinos have provided compelling evidence for the existence of neutrino oscillations, implying nonzero neutrino masses. The present data¹ require two large (θ_{12} and θ_{23}) and one small (θ_{13}) angles in the lepton mixing matrix [12], and at least two mass squared differences, $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$ (where m_j 's are the neutrino masses), one driving the atmospheric (Δm_{31}^2) and the other one the solar (Δm_{21}^2) neutrino oscillations. The mixing angles θ_{12} and θ_{23} control the solar and the dominant atmospheric neutrino oscillations, while θ_{13} is the angle constrained by the data from the CHOOZ and Palo Verde reactor experiments [13,14].

The Super-Kamiokande [7] and K2K [9] data are well described in terms of dominant $\nu_\mu \rightarrow \nu_\tau$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$) vacuum oscillations. The MINOS Collaboration [15] has recently reported the first neutrino oscillation results from 1.27×10^{20} protons on target [16]. The value of the oscillation parameters from MINOS are consistent with the

ones from K2K, as well as from SK data. A recent global fit [17] (see also Ref. [18]) provides the following 3σ allowed ranges for the atmospheric mixing parameters

$$\begin{aligned} |\Delta m_{31}^2| &= (1.9\text{--}3.2) \times 10^{-3} \text{ eV}^2, \\ 0.34 &< \sin^2 \theta_{23} < 0.68. \end{aligned} \quad (1.1)$$

The sign of Δm_{31}^2 , $\text{sign}(\Delta m_{31}^2)$, cannot be determined with the existing data. The two possibilities, $\Delta m_{31}^2 > 0$ or $\Delta m_{31}^2 < 0$, correspond to two different types of neutrino mass ordering: normal hierarchy and inverted hierarchy. In addition, information on the octant in which θ_{23} lies, if $\sin^2 2\theta_{23} \neq 1$, is beyond the reach of present experiments.

The 2-neutrino oscillation analysis of the solar neutrino data, including the results from the complete salt phase of the Sudbury Neutrino Observatory (SNO) experiment [6], in combination with the KamLAND spectrum data [19], shows that the solar neutrino oscillation parameters lie in the low-LMA (Large Mixing Angle) region, with best fit values [17] $\Delta m_{21}^2 = 7.9 \times 10^{-5} \text{ eV}^2$ and $\sin^2 \theta_{12} = 0.30$.

A combined 3-neutrino oscillation analysis of the solar, atmospheric, reactor and long-baseline neutrino data [17] constrains the third mixing angle to be $\sin^2 \theta_{13} < 0.041$ at the 3σ C.L. However, the bound on $\sin^2 \theta_{13}$ is dependent on the precise value of $|\Delta m_{31}^2|$, being stronger for larger values of $|\Delta m_{31}^2|$. The future goals for the study of neutrino properties in neutrino oscillation experiments is to precisely determine the already measured oscillation parameters and to obtain information on the unknown ones: namely θ_{13} , the CP -violating phase δ and the type of neutrino mass hierarchy [or equivalently $\text{sign}(\Delta m_{31}^2)$].

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¹We restrict ourselves to a three-family neutrino analysis. The unconfirmed LSND signal [10] cannot be explained within this context and might require additional light sterile neutrinos or more exotic explanations. The ongoing MiniBooNE experiment [11] is going to test the oscillation explanation of the LSND result.

In the next sections we will explore in detail the possible measurement of the two unknown parameters θ_{13} and δ with a future *neutrino factory* [20] facility as this appears to be among the most promising ways to unveil neutrino mixing and leptonic CP violation [21–35].²

A neutrino factory consists of a high intensity muon source,³ an acceleration system, and a muon storage ring with long straight sections. Muons decaying along the straight sections create high intensity neutrino beams which have a precisely-known flux, divergence, energy spectrum, and neutrino flavor content. The flavor composition of the beam depends on whether positive or negative muons are stored in the ring. Suppose, for example, that positive charged muons have been stored. Muons decaying in the straight sections will produce beams containing 50% muon-antineutrinos and 50% electron-neutrinos: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. Charged current interactions of the $\bar{\nu}_\mu$ in a distant detector will produce μ^+ (“right-sign” muons, i.e. muons of the same charge as those stored in the neutrino factory). In contrast, if the ν_e ’s oscillate to ν_μ ’s and then interact in the far detector they will produce μ^- (“wrong-sign muons” [20,21]). Thus, wrong-sign muons are an unambiguous proof of electron neutrino oscillation, in the $\nu_e \rightarrow \nu_\mu$ channel. This has been called the “golden channel” [26], and is central to the present study. A magnetized detector with excellent charge identification is necessary to exploit the golden channel.

In the following we will consider a *low-energy neutrino factory* where the stored muons have an energy of 4.12 GeV. This is motivated by recent progress in developing a viable concept for a neutrino factory detector with a threshold for reliably measuring the sign of muons with momenta down to a few hundred MeV/c [44]. We explore the impact of analyzing the “wrong-sign” and “right-sign” muon rates for several energy bins, and we consider two reference baselines: 1280 Km, the distance from Fermilab to Homestake, and 1480 Km, the distance from Fermilab to Henderson mine. Our results can be easily generalized to other baselines in the 1200–1500 km range. We find that a simultaneous fit to the energy-dependent rates provides a powerful tool to resolve ambiguities and make precise parameter determinations, for both large and fairly small values of the mixing parameter θ_{13} .

II. FORMALISM

In the present study we focus on the capabilities of a low-energy neutrino factory, if the value of θ_{13} is within reach of the upcoming generation of long-baseline experiments, T2K and NO ν A.

For neutrino energies $E \gtrsim 1$ GeV, θ_{13} within the present bounds [17,18], and baselines $L \lesssim \mathcal{O}(1000)$ km [45], the oscillation probability $\overset{(-)}{P}(L)$ can be expanded in the small parameters θ_{13} , Δ_{12}/Δ_{13} , Δ_{12}/A and $\Delta_{12}L$, where $\Delta_{12} \equiv \Delta m_{21}^2/(2E)$ and $\Delta_{13} \equiv \Delta m_{31}^2/(2E)$ [26] (see also Ref. [46]):

$$\begin{aligned} \overset{(-)}{P}(L) \simeq & \sin^2\theta_{23}\sin^22\theta_{13}\left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2\left(\frac{(A \mp \Delta_{13})L}{2}\right) \\ & + \cos\theta_{13}\sin2\theta_{13}\sin2\theta_{23}\sin2\theta_{12}\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{A \mp \Delta_{13}} \\ & \times \sin\left(\frac{AL}{2}\right)\sin\left(\frac{(A \mp \Delta_{13})L}{2}\right)\cos\left(\frac{\Delta_{13}L}{2} \mp \delta\right) \\ & + \cos^2\theta_{23}\sin^22\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right), \end{aligned} \quad (2.1)$$

where the first, second and third terms have been dubbed *atmospheric*, *interference* and *solar terms*, respectively. In the following analytical study, we use the constant density approximation for the index of refraction in matter $A \equiv \sqrt{2}G_F\bar{n}_e(L)$. Here, $\bar{n}_e(L) = 1/L \int_0^L n_e(L')dL'$ is the average electron number density, with $n_e(L)$ the electron number density along the baseline.

In order to study the sensitivity to CP violation, we introduce the weighted probability difference between the case of $\delta \neq 0$ and the one with no CP violation ($\delta = 0$)⁴:

$$\mathcal{S}(\delta) \equiv \frac{(P(L, \delta) - P(L, 0))^2}{P(L, \delta)}, \quad (2.2)$$

$$\bar{\mathcal{S}}(\delta) \equiv \frac{(\bar{P}(L, \delta) - \bar{P}(L, 0))^2}{\bar{P}(L, \delta)}. \quad (2.3)$$

The quantity $\mathcal{S}(\delta)$ ($\bar{\mathcal{S}}(\delta)$) is useful to get an estimate of the energy range, for a fixed baseline, for which the sensitivity is maximal. Using Eq. (2.1), we find that

$$\mathcal{S}(\delta)(\bar{\mathcal{S}}(\delta)) = \frac{4\cos^2\theta_{13}\sin^22\theta_{12}\cos^2\theta_{23}\left(\frac{\Delta_{12}}{\Delta_{13}}\right)^2\left(\frac{\Delta_{13}L}{2}\right)^2(\cos(\delta - \frac{\Delta_{13}L}{2}) - \cos\frac{\Delta_{13}L}{2})^2}{1 + 2\epsilon\cos(\delta - \frac{\Delta_{13}L}{2}) + \epsilon^2}, \quad (2.4)$$

where we have approximated $\cos\theta_{13} \simeq 1$. The quantity ϵ is defined as

$$\epsilon \equiv \frac{\cos\theta_{23}}{\sin\theta_{23}} \frac{\sin2\theta_{12}}{\sin2\theta_{13}} \frac{\Delta_{12}}{\Delta_{13}} \frac{\Delta_{13}L}{2} \frac{A \mp \Delta_{13}}{\Delta_{13}} \frac{1}{\sin((A \mp \Delta_{13})L/2)}, \quad (2.5)$$

²For the prospects of future measurements of these two oscillation parameters at β beam experiments [36,37], see Refs. [38–43].

³A neutrino factory muon source is an attractive stepping-stone towards a high energy muon collider.

⁴A similar analysis with similar results could be carried out for the case $\delta = \pi$. We present here the analytical study assuming that δ is within the interval $[-\pi/2, \pi/2]$. Our numerical simulations will consider the full δ range $[-\pi, \pi]$.

where $\bar{\nu}$ refers to neutrinos (antineutrinos), respectively. At leading order we can neglect A/Δ_{13} terms and ϵ is the same for neutrinos and antineutrinos.

The sensitivity to CP violation is 0 when the interference term in the oscillation probability, e.g. the second term in the right-hand side of Eq. (2.1), cancels. For the values of θ_{13} of interest, this happens at the oscillation minima:

$$(\Delta_{13} \mp A)L/2 = n\pi, \quad n = 1, 2, 3, \dots \quad (2.6)$$

Neglecting the small correction due to matter effects, we find that the minima in the sensitivity to CP violation corresponds to an energy of $E_m = 1.4(1.2)$ GeV for $L = 1480(1280)$ km, with $n = 1$. Here and in the following, we used $\Delta m_{31}^2 = 2.4 \times 10^{-3}$ eV². Matter effects modify this result by 10–20%. At smaller energies additional minima and maxima with a fast oscillatory behavior are present but we will not consider such energy range due to detector resolutions, efficiencies and thresholds. As at high energies $\mathcal{S}(\delta)$ and $\bar{\mathcal{S}}(\delta)$ drop as E^{-2} , we expect a maximum in sensitivity at an energy of few GeV. In the case of neutrinos and normal hierarchy (and, for negligible A/Δ_{13} , antineutrinos and inverted hierarchy), an additional minimum in CP -violation sensitivity is found for $\cos(\delta - \Delta_{13}L/2) = \cos(\Delta_{13}L/2)$. This equation has a solution for

$$\frac{\Delta_{13}L}{2} = \frac{\delta}{2} \quad \text{for } \delta \geq 0, \quad (2.7)$$

$$\frac{\Delta_{13}L}{2} = \pi - \frac{\delta}{2} \quad \text{for } \delta < 0. \quad (2.8)$$

For $\delta = \pi/2(-\pi/2)$, the energy of the minimum in sensitivity is at $E_m = 5.7(1.9)$ GeV for $L = 1480$ km and at $E_m = 5.0(1.7)$ GeV at $L = 1280$ km. Let us notice that, if $\delta < 0$, the two minima in Eqs. (2.6) and (2.8) are very close and the maximum in between cannot be fully exploited due to limited energy resolution. The maximum in sensitivity at higher energy is located close to the minimum in Eq. (2.6), that is in the energy range $E_M \sim (2-3)$ GeV, depending on the value of δ . For non-negative values of δ , it is possible to make full use of the maximum in sensitivity between the two minima in Eqs. (2.6) and (2.8). Again, the maximal sensitivity will be achieved at E_M of few GeV. In both cases, we can obtain a more precise estimate for E_M by neglecting ϵ and solving the equation $(\cos(\delta - \frac{\Delta_{13}L}{2}) - \cos\frac{\Delta_{13}L}{2}) + \frac{\Delta_{13}L}{2}(\sin(\delta - \frac{\Delta_{13}L}{2}) + \sin\frac{\Delta_{13}L}{2}) = 0$. Notice that this equation holds only far away from the minima. Typically, the maximum is reached in the energy range (1.6–5.2) GeV [(1.4–4.5) GeV] for $L = 1480$ km [$L = 1280$ km]. In particular, for $\delta = \pi/2(-\pi/2)$ we have $E_M \approx 1.7(3.2)$ GeV [1.5(2.6) GeV] with $L = 1480$ km [$L = 1280$ km]. Matter effects included in ϵ in the denominator modify these results by a 10–20%.

For neutrinos and inverted hierarchy, (and antineutrinos and normal hierarchy, neglecting terms of order A/Δ_{13}),

we find a similar behavior. The minimum in addition to the one in Eq. (2.6) is reached when $\cos(\delta + \Delta_{13}L/2) = \cos(\Delta_{13}L/2)$ whose solutions are

$$\frac{\Delta_{13}L}{2} = \pi - \frac{\delta}{2} \quad \text{for } \delta \geq 0, \quad (2.9)$$

$$\frac{\Delta_{13}L}{2} = \frac{\delta}{2} \quad \text{for } \delta < 0. \quad (2.10)$$

We can also estimate the position of the maximum by solving the equation $(\cos(\delta + \frac{\Delta_{13}L}{2}) - \cos\frac{\Delta_{13}L}{2}) - \frac{\Delta_{13}L}{2} \times (\sin(\delta + \frac{\Delta_{13}L}{2}) - \sin\frac{\Delta_{13}L}{2}) = 0$. The maximum is reached at approximately the same energy as for neutrinos but with opposite δ . As far as ϵ is negligible, the sensitivity does not depend on θ_{13} . Our approximated analytical results on the energy maxima hold for $\sin^2\theta_{13} \gg 10^{-3}(\Delta_{13}L/2)/\sin(\Delta_{13}L/2)$. In conclusion, our analytical study suggests that maximal sensitivity to CP violation is reached in the few GeV range. Notice that, given one type of hierarchy, neutrinos and antineutrinos have similar behavior but for opposite values of δ . The combination of the two channels allows us to reach optimal sensitivity independently of the true value of the CP -violating phase.

Similar considerations hold also for the sensitivity to the type of hierarchy. We can study a similar quantity: $(P_+ - P_-)^2/P_+$ for neutrinos and antineutrinos. We find that the dominant term is proportional to AL while CP -violating terms constitute a correction at most of 20%–30% for the highest allowed values of $\sin^2\theta_{13}$. A minimum in the sensitivity is found in correspondence to the minima of the oscillation probability as in the case of CP violation studied above. The sensitivity to the type of hierarchy depends on the value of the δ phase once the CP -violating corrections are taken into account. For $0 \leq \delta < \pi/2$, the energy for which a maximum in sensitivity is obtained, E_M will be an decreasing function of the θ_{13} mixing angle. For example, for $\delta = 0$, the maximum in sensitivity will be reached in the 3.7–2.3 GeV range for $\sin^2\theta_{13} = 0.01-0.1$. Conversely, for $\pi/2 < \delta \leq \pi$, E_M will increase with θ_{13} but typically remain in the 1.3–1.6 GeV range. We can conclude that maximal sensitivity is reached for energies around 1.3–4 GeV. For antineutrinos, a similar behavior can be found, with the exchange of δ in $\pi - \delta$.

In order to study the sensitivity to CP violation and type of hierarchy, by exploiting the number of events in a simulated experiment, the energy dependence of the cross sections and fluxes should be included. We can expect the value of the energy for which the maxima of sensitivity are reached to be shifted slightly at higher values.

From the above considerations, we can conclude that the use of a detector with a low threshold and good energy resolution and efficiency at $E \geq 1$ GeV is crucial for exploiting the potentiality of a neutrino factory with baselines in the 1000–1500 Km. In addition, a high energy neutrino

beam is not necessary and it is sufficient to use lower energies with respect to the commonly studied options for a neutrino factory with muon energies of 20 or 50 GeV.

III. THE LOW-ENERGY NEUTRINO FACTORY CONCEPT

A neutrino factory consists of (i) an intense low-energy muon source, (ii) a muon beam manipulation and cooling system to maximize the number of muons within a useful acceptance, (iii) a "preaccelerator" to accelerate the muons from low kinetic energies (typically 100–200 MeV) to about 1 GeV, (iv) a system of one or more accelerators to further accelerate the muons to the desired final energy, and (v) a muon storage ring with long straight sections. Design studies [47–49] have shown that, for a 20 GeV neutrino factory, the 1–20 GeV acceleration systems are expected to account for about 26% of the estimated cost. Hence, if the physics goals can be met using muons with energies much lower than 20 GeV, there is a significant cost advantage. In the following, we first discuss the performance of the far detector (which places a lower limit on the desired neutrino factory muon energy), and then discuss the low-energy neutrino factory and its performance. The primary neutrino oscillation channel at a neutrino factory requires identification of wrong-sign muons, and hence a detector with excellent muon charge identification. To obtain the required event rates, the far detector fiducial mass needs to be at least $O(10 \text{ Kt})$, and therefore we require a very large magnetized detector. Early studies [32] based on a MINOS-like segmented magnetized detector suggested that, to reduce the charge misidentification rate to the 10^{-4} level while retaining a reasonable muon reconstruction efficiency, the detected muon needs to have a minimum momentum of 5 GeV. The analysis obtained a 50% reconstruction efficiency for CC neutrino interactions exceeding $\sim 20 \text{ GeV}$. This effectively places a lower limit of about 20 GeV on the desired energy of the muons stored in the neutrino factory. However, a more recent analysis [44] has shown that, with more sophisticated selection criteria, high efficiencies ($> 80\%$) can be obtained for neutrino interactions exceeding $\sim 10 \text{ GeV}$, with efficiencies dropping to $\sim 50\%$ by 5 GeV. The new analysis suggests a MINOS-like detector could be used at a neutrino factory with energy less than 20 GeV, but probably not less than 10 GeV. If we wish to consider lower energy Neutrino Factories, we will need a finer grained detector that enables reliable sign-determination of lower energy muons with good efficiency. One way to achieve this would be to use a totally active magnetized segmented detector, for example, a $\text{NO}\nu\text{A}$ -like detector [50] within a large magnetic volume. Initial studies [44] show that, for this technology, the muon reconstruction efficiency is expected to approach unity for momenta exceeding $\sim 200 \text{ MeV}/c$, with a charge misiden-

tification lower than 10^{-4} (10^{-3}) for momenta exceeding approximately 400 MeV/c (300 MeV/c).

Further studies are needed to fully understand the efficiency and misidentification as a function of neutrino energy, but there is hope that a neutrino factory detector might be designed with good wrong-sign muon identification and high efficiency for neutrino energies as low as 1 GeV, or perhaps a little lower. Given these recent developments, in our analysis we will assume that a massive magnetized detector can be designed to identify wrong-sign muons with full efficiency for neutrino interactions above 0.8 GeV, and zero efficiency below this energy. We will see that the excellent physics capability of a low-energy neutrino factory motivates striving for a detector that can achieve this demanding performance.

With a magnetized far detector concept that makes plausible precision measurements of neutrino interactions down to about 0.8 GeV, we are motivated to consider Neutrino Factories with stored muon energies of a few GeV. In present designs for a 20 GeV neutrino factory [49], there are at least two acceleration stages that accelerate the muons from about 1 GeV to 20 GeV. Depending on the design, these accelerators consist either of recirculating linear accelerators (RLAs) or fixed field alternating gradient accelerators (FFAGs). A few GeV neutrino factory would require only one of these acceleration stages. Note that the RLAs have long straight acceleration sections which, if pointing in a suitable direction, could provide a neutrino beam with a time-dependent energy that varies from 200 MeV up to the final energy. This might facilitate a tunable-energy neutrino factory. To illustrate this, Table I shows, for 7.5×10^{20} positive muons (per year) injected into an 1–5.8 GeV RLA, the number of muon decays in a given straight section at each intermediate energy. Only 7% of the injected muons decay during the acceleration, and hence 93% (7×10^{20}) are available to be injected into a dedicated fixed-energy neutrino factory. If the neutrino factory straight section length is 30% of the ring circumference, this would provide an additional 2×10^{20} useful muon decays per year at 5.8 GeV. Note that using the RLA to provide a neutrino beam would provide flexibility in choosing the desired neutrino energy spectrum. The acceleration cycle could, in principle, be varied to keep the

TABLE I. Useful positive muon decays in one straight section of an RLA designed to accelerate from 1 GeV to 5.8 GeV in 5 turns. The straight section and arc lengths are, respectively, 100 m and 30 m. The numbers tabulated correspond to 7.5×10^{20} injected muons, or roughly one years operation.

Turn number	1	2	3	4	5
Initial energy (GeV)	1.0	1.96	2.92	3.88	4.84
Final energy (GeV)	1.48	2.44	3.40	4.36	5.32
$f_{\text{decay}} = 100m/\gamma c\tau$ (%)	1.30	0.73	0.51	0.39	0.32
N_{decay} per year ($\times 10^{18}$)	9.8	5.5	3.8	2.9	2.4

muons for as long as desired at any intermediate energy. Hence, the 2×10^{20} useful muon decays could be redistributed amongst the intermediate energies, as needed. However, the flexibility of using the RLA to provide a low-energy neutrino beam comes at the cost of a more complicated design for the accelerator. In particular, the angular divergence of the beam within the straight section needs to be small compared to the angular spread of the neutrinos generated in muon decay. If designs that achieve this prove to be impractical or expensive, flexibility could also be achieved by designing the RLA so that the muons could be extracted on any given turn and injected into one of several fixed-energy neutrino factory storage rings (note that the cost of the storage rings is believed to be small compared to the cost of the RLA).

In the following we will show that a low-energy neutrino factory with a fixed energy of 4.12 GeV would provide a sensitive tool for exploring neutrino oscillations if θ_{13} is “large.” This energy would require about 4 turns in a single RLA. Note that the sensitivity of a neutrino factory experiment depends upon the event statistics, and hence upon the product of the detector fiducial mass, the length of the data taking period, and the number of muons per unit time decaying in the appropriate neutrino factory straight section. Initial studies have considered, as reasonable, a totally active magnetized detector with a fiducial mass of about 20 Kt. Present neutrino factory studies suggest that it would be reasonable to expect, for a neutrino factory with (without) a muon cooling channel before the preaccelerator, about 5×10^{20} (3×10^{20}) useful positive muon decays per year and 5×10^{20} (3×10^{20}) useful negative muon decays per year in a given neutrino factory straight section. Hence, a conservative estimate of the sensitivity of a neutrino factory experiment might be based upon 5 years data taking with 3×10^{20} useful muon decays of each sign per year in the storage ring, and a detector fiducial mass of 20 Kt, corresponding to 3×10^{22} Kt decays for each muon sign. A more aggressive estimate might be based upon 10 years of data taking with 5×10^{20} useful muon decays of each sign per year in the storage ring, and a detector fiducial mass of 20 Kt, corresponding to 1×10^{23} Kt decays for each muon sign.

IV. NUMERICAL ANALYSIS: DEGENERATE SOLUTIONS

We can ask ourselves whether it is possible to unambiguously determine δ and θ_{13} by measuring the transition probabilities $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ at fixed neutrino energy and at just one neutrino factory baseline. The answer is no. It has been shown [29] that, by exploring the full (allowed) range of the δ and θ_{13} parameters, that is, $-180^\circ < \delta < 180^\circ$ and $0^\circ < \theta_{13} < 10^\circ$, one finds, at fixed neutrino energy and at fixed baseline, the existence of degenerate solutions (θ'_{13}, δ') , that have been labeled in the literature *intrinsic degeneracies*, which give the same

oscillation probabilities as the set (θ_{13}, δ) chosen by nature. More explicitly, if (θ_{13}, δ) are the correct values, the conditions

$$P_{\nu_e \nu_\mu}(\theta'_{13}, \delta') = P_{\nu_e \nu_\mu}(\theta_{13}, \delta)$$

$$P_{\bar{\nu}_e \bar{\nu}_\mu}(\theta'_{13}, \delta') = P_{\bar{\nu}_e \bar{\nu}_\mu}(\theta_{13}, \delta)$$

can be generically satisfied by another set (θ'_{13}, δ') .

Additional solutions might appear from unresolved degeneracies in two other oscillation parameters:

- (1) At the time of the future neutrino factory, the sign of the atmospheric mass difference Δm_{31}^2 may remain unknown, that is, we would not know if the hierarchy of the neutrino mass spectrum is normal or inverted. In this particular case, $P(\theta'_{13}, \delta', -\Delta m_{31}^2) = P(\theta_{13}, \delta, \Delta m_{31}^2)$.
- (2) Disappearance experiments only give us information on $\sin^2 2\theta_{23}$: is θ_{23} in the first octant, or is it in the second one, $(\pi/2 - \theta_{23})$? In terms of the probabilities, $P(\theta'_{13}, \delta', \frac{\pi}{2} - \theta_{23}) = P(\theta_{13}, \delta, \theta_{23})$.

This problem is known as the problem of degeneracies in the neutrino parameter space [29,30,45,51–53]. All these ambiguities complicate the experimental determination of δ and θ_{13} . Many strategies have been advocated to resolve this issue which in general involve another detector [29,31,54–59] or the combination with another experiment [34,35,60–68].

In the present study we show that, if the value of θ_{13} turns out to be not very small, a *low-energy neutrino factory* provides the ideal scenario for the extraction of the unknown parameters as well as for resolving the discrete degeneracies. The reason is simple: at distances of $\mathcal{O}(1000)$ km the neutrino oscillation pattern is extremely rich at neutrino energies below 4 GeV. We have thus explored a single decaying muon energy scenario $E_\mu = 4.12$ GeV.

By exploiting the energy dependence of the signal, it is possible to disentangle θ_{13} and δ and to eliminate the additional solutions arising from the discrete ambiguities. We have divided the signal in four energy bins. The energy binning of the signal has been chosen accordingly to the analytical study. The energy range of these four energy bins is $[0, 0.8]$, $[0.8, 1.5]$, $[1.5, 3.5]$, and $[3.5, 4.12]$ GeV. We will show the physics potential of the chosen energy binning here in the next subsection. The detection efficiencies are considered as perfect (100%) above the first bin, as described in the previous section.

Two possible baselines have been carefully explored: 1280 Km, the distance from Fermilab to Homestake, and 1480 Km, the distance from Fermilab to Henderson mine. The results are presented for the two possible scenarios described in the previous section, in order to quantify the benefits of increased exposure times and muon intensities: a conservative scenario of 3×10^{22} Kton decays and a more ambitious one with 1×10^{23} Kton decays.

All numerical results simulated in the next subsections here have been obtained with the exact formulae for the oscillation probabilities. Unless specified otherwise, we take the following central values for the remaining oscillation parameters: $\sin^2\theta_{12} = 0.29$, $\Delta m_{21}^2 = 8 \times 10^{-5} \text{ eV}^2$, $|\Delta m_{31}^2| = 2.5 \times 10^{-3} \text{ eV}^2$, and $\theta_{23} = 40^\circ$. The χ^2 for a fixed baseline λ is defined as

$$\chi_\lambda^2 = \sum_{i,j} \sum_{p,p'} (n_{i,p}^\lambda - N_{i,p}^\lambda) C_{i,p:,j,p'}^{-1} (n_{j,p'}^\lambda - N_{j,p'}^\lambda), \quad (4.1)$$

where $N_{i,\pm}^\lambda$ is the predicted number of muons for a certain oscillation hypothesis, $n_{i,p}^\lambda$ are the simulated ‘‘data’’ from a Gaussian or Poisson smearing and C is the $2N_{\text{bin}} \times 2N_{\text{bin}}$ covariance matrix given by

$$C_{i,p:,j,p'}^{-1} \equiv \delta_{ij} \delta_{pp'} (\delta n_{i,p})^2, \quad (4.2)$$

where $(\delta n_{i,p}) = \sqrt{n_{i,p} + (f_{\text{sys}} \cdot n_{i,p})^2}$ contains both statistical and a 2% overall systematic error ($f_{\text{sys}} = 0.02$). All the contour plots presented in the following in a two parameter space have been performed assuming 2 d.o.f. statistics.

A. Optimizing the energy binning

In this subsection we provide an explanation for the energy binning chosen here, crucial to resolve the additional solutions (degeneracies). As first noticed in Ref. [60], the location of the degeneracies is E, L dependent. For large θ_{13} , the location of the *intrinsic* degeneracies is given by

$$\delta' \simeq \pi - \delta,$$

$$\theta'_{13} \simeq \theta_{13} + \cos\delta \sin 2\theta_{12} \frac{\Delta m_{21}^2 L}{4E} \cot\theta_{23} \cot\left(\frac{\Delta m_{31}^2 L}{4E}\right). \quad (4.3)$$

Notice that the shift $\theta'_{13} - \theta_{13}$ depends on the energy and the baseline through the function $\cot(\frac{\Delta m_{31}^2 L}{4E})$. If the function $\cot(\frac{\Delta m_{31}^2 L}{4E})$ changes sign from one energy bin to another, the degenerate solutions will appear in different regions of the parameter space. Consequently, the combination of fits to the various energy bins can eliminate the *intrinsic* degeneracies.

To illustrate this, Fig. 1(a) depicts results from fitting the simulated data for each of the energy bins. The simulation is for $L = 1480 \text{ km}$, $\theta_{13} = 3^\circ$, $\delta = 0^\circ$, normal mass hierarchy, and $\theta_{23} = 40^\circ$. The fit results shown in the figure correspond to the correct hierarchy and θ_{23} (the impact of including the discrete degeneracies will be discussed later). The 90%, 95%, and 99% C.L. contours resulting from the fits are shown for the second energy bin (blue), third energy bin (cyan) and fourth energy bin (magenta). Notice that in addition to the correct solution, there are also fake solutions for which $\delta' \simeq \pi$, as indicated by Eq. (4.3). However, the fake solutions from the fit to the third energy bin get opposite displacements $\theta'_{13} - \theta_{13}$ from those from the fits to the second and fourth energy bins. The relative displacement (positive or negative) is given by the sign of the trigonometric function $\cot(\frac{\Delta m_{31}^2 L}{4\langle E \rangle})$, where $\langle E \rangle$ is the medium energy for a fixed bin. A combination of fits to the second, third and fourth energy bins will therefore help in resolving the *intrinsic* degeneracies.

A similar exercise to the one described above can be done for the discrete degeneracies. For instance, the

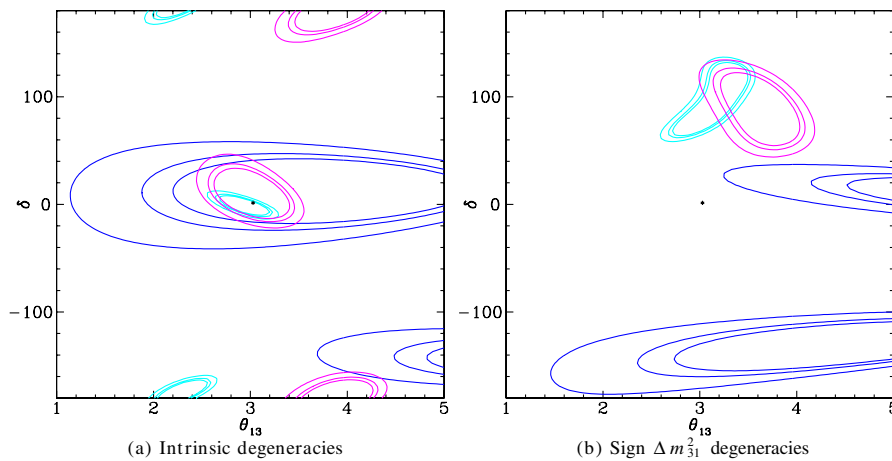


FIG. 1 (color online). 90%, 95%, and 99% (2 d.o.f.) contours resulting from fits to simulated data for $L = 1480 \text{ km}$, $\theta_{13} = 3^\circ$, and $\delta = 0^\circ$ (position in parameter space denoted by a star). The black (blue), light grey (cyan), and dark grey (magenta) contours represent the results from fits to the second, third and fourth energy bins, respectively. In the left panel, we have neglected the impact of the discrete degeneracies. In the right panel, the fit assumes incorrectly that the sign of the atmospheric mass difference is negative. The atmospheric mixing angle is fixed to $\theta_{23} = 40^\circ$.

wrong-sign(Δm_{31}^2) additional solutions will be located in different regions of the parameter space for each energy bin, see Fig. 1(b), and therefore fits to the combination of the energy bins will result in a resolution of the *sign* degeneracies. The location of the fake solutions for the second energy bin is different from those for the third and fourth energy bins, since at lower energies matter effects are less important.

Resolving the additional θ_{23} -octant degeneracy is, in general, very difficult. As shown in Ref. [60], for large θ_{13} , the location of the θ_{23} degeneracies is given by

$$\sin\delta' \simeq \cot\theta_{23} \sin\delta,$$

$$\theta'_{13} \simeq \tan\theta_{23}\theta_{13} + \frac{\sin 2\theta_{12} \frac{\Delta m_{21}^2 L}{4E}}{2 \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)} \left(\cos\left(\delta - \frac{\Delta m_{31}^2 L}{4E}\right) - \tan\theta_{23} \cos\left(\delta' - \frac{\Delta m_{31}^2 L}{4E}\right) \right). \quad (4.4)$$

This system describes two solutions. For one of them, the L and E dependent terms in Eq. (4.4) tend to cancel for $\theta_{23} \rightarrow \pi/4$, resulting in $\theta'_{13} = \theta_{13}$ and $\delta' = \delta$ in this limit. The second solution coincides in this limit with the intrinsic degeneracy, Eq. (4.3). Notice that no fake solutions are expected for $|\cot\theta_{23} \sin\delta| > 1$. Figure 2 illustrates the equivalent exercise to those performed above for the *intrinsic* and for the wrong-sign(Δm_{31}^2) degeneracies. The simulated data is for the θ_{23} in the first octant, i.e. $\theta_{23} = 40^\circ$, while the fit is performed incorrectly assuming the second octant, i.e. $\theta_{23} = 50^\circ$. Notice from the results depicted in Fig. 2(a) that there are two sets of degenerate solutions, as previously discussed: those which resemble the correct values and those which are related to the intrinsic solution. While the location of the former is E ,

L independent, the location of the latter will depend on E , L , and therefore the combined fits to the various energy bins will help in resolving these degeneracies. Note that the degeneracies which are closer to the correct values are extremely difficult to resolve. The information in the second bin is crucial: if the detector efficiency in the second bin ($[0.8, 1.5]$ GeV) is sufficiently high (we are assuming 100%), the combination of fits to the various energy bins will resolve the additional solutions related to the wrong choice of the atmospheric mixing angle octant. Since the second bin is the lower energy bin, it turns out that for these lower energies the solar term, see Eq. (2.1), is the dominant one for $\theta_{13} \leq 3^\circ$, larger than both the atmospheric and the interference terms. The solar term goes as $\cos^2\theta_{23}$, while the atmospheric term goes as $\sin^2\theta_{23}$, therefore, exploiting this low-energy bin is crucial to resolve the θ_{23} degeneracy. The resulting fit, after the combination of the data in the three energy bins considered here, is degeneracy free down to very small values of $\theta_{13} \simeq 1^\circ$ [see Fig. 2(b)], since the additional solutions from fits to the second bin lie on different locations in parameter space than those for the third and fourth energy bins.

B. Exploring the disappearance channel

We explore here the measurement of the atmospheric neutrino oscillation parameters, θ_{23} and Δm_{31}^2 making use of the ν_μ disappearance channel. We study as well the impact of this channel regarding the θ_{23} -octant degeneracy. The disappearance channel at the neutrino factory has been already considered in the literature [24,69] and it has been widely and carefully explored in Ref. [70]. The vacuum $\nu_\mu \rightarrow \nu_\mu$ oscillation probability expanded to the second order in the small parameters θ_{13} and $(\Delta_{12}L/E)$ reads [46]

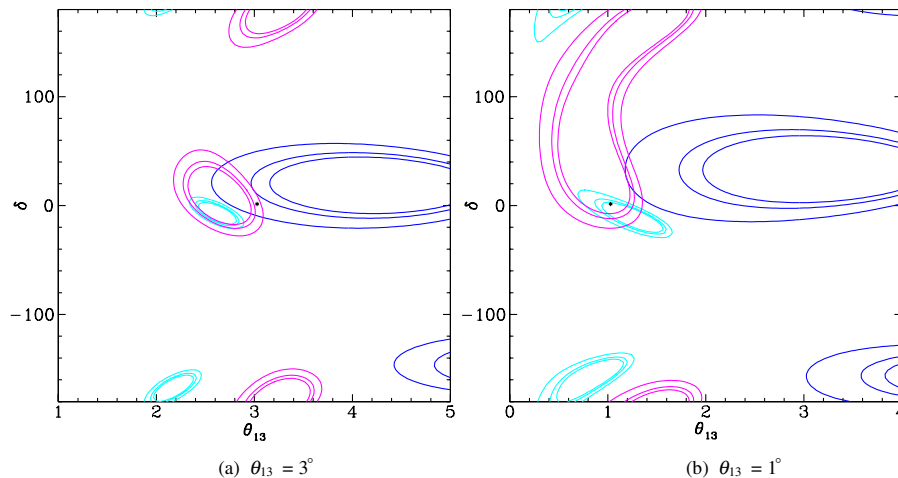


FIG. 2 (color online). (a) 90%, 95%, and 99% (2 d.o.f.) contours resulting from the fits to the data at $L = 1480$ km, assuming that the nature solution is $\theta_{13} = 3^\circ$ and $\delta = 0^\circ$ (denoted by a star). The black (blue), light grey (cyan), and dark grey (magenta) contours represent the results with the second, third and fourth energy bin data, respectively. We assume that the true value of the atmospheric mixing angle is $\theta_{23} = 40^\circ$ (first octant) but the data is fitted to $\theta_{23} = 50^\circ$ (second octant). (b) Same than in (a) but assuming that the nature solution is $\theta_{13} = 1^\circ$ and $\delta = 0^\circ$ (denoted by a star). The statistics considered for both simulations corresponds to 3×10^{22} Kton decays.

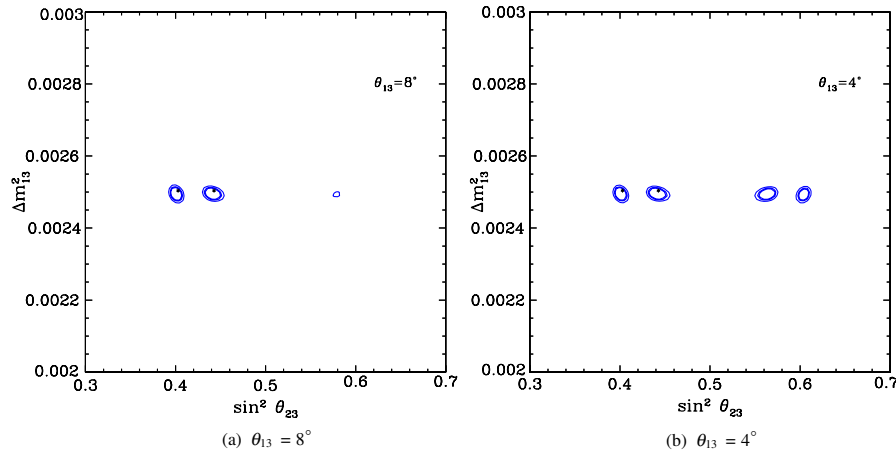


FIG. 3 (color online). 90%, 95% and 99% (2 d.o.f.) C.L. contours resulting from the fits at $L = 1480$ km assuming two central values for $\sin^2\theta_{23} = 0.4$ and 0.44 and $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV². In the right (left) panel, $\theta_{13} = 8^\circ$ (4°). A larger value of θ_{13} introduces a larger asymmetry and the four-fold degeneracy in the atmospheric neutrino parameters is solved. The statistics considered for both simulations corresponds to 3×10^{22} Kton decays. Only disappearance data have been used to perform these plots.

$P(\nu_\mu \rightarrow \nu_\mu)$

$$\begin{aligned}
 &= 1 - [\sin^2 2\theta_{23} - s_{23}^2 \sin^2 2\theta_{13} \cos 2\theta_{23}] \sin^2 \left(\frac{\Delta_{23} L}{2} \right) \\
 &\quad - \left(\frac{\Delta_{12} L}{2} \right) [s_{12}^2 \sin^2 2\theta_{23} + \tilde{J} s_{23}^2 \cos \delta] \sin(\Delta_{23} L) \\
 &\quad - \left(\frac{\Delta_{12} L}{2} \right)^2 [c_{23}^4 \sin^2 2\theta_{12} + s_{12}^2 \sin^2 2\theta_{23} \cos(\Delta_{23} L)],
 \end{aligned} \tag{4.5}$$

where $\tilde{J} = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$ and $\Delta_{23} = \Delta m^2_{32}/2E$, $\Delta_{12} = \Delta m^2_{21}/2E$. The first term in the first parenthesis is the dominant one and is symmetric under $\theta_{23} \rightarrow \pi/2 - \theta_{23}$. However, when a rather large nonvanishing θ_{13} is switched on, a θ_{23} -asymmetry appears in Eq. (4.5) and the octant in which θ_{23} lies can be extracted from disappearance data, as will be shown in our numerical results. We assume here the same detection efficiencies⁵ and energy binning than those which will be considered for the golden $\nu_e \rightarrow \nu_\mu$ transition. A global 2% systematic error has been included in the χ^2 fits to the atmospheric neutrino parameters. We present our results in the $(\sin^2\theta_{23}, \Delta m^2_{31})$ plane in Figs. 3 for two simulated values of θ_{13} , and two simulated values for $\sin^2\theta_{23}$: $\sin^2\theta_{23} = 0.4$ and $\sin^2\theta_{23} = 0.44$. The detector is located at the Henderson mine at a baseline of $L = 1480$ km (similar results are obtained for the Homestake detector location). The CP violating phase δ has been set to zero. Notice that this channel is able to reduce atmospheric parameter uncertainties to an unprecedented level: the resolution in $\sin^2\theta_{23}$ is astonishing, maximal mixing can be excluded

⁵We believe this is conservative since less aggressive cuts are required to reduce backgrounds for the disappearance channel than those required for the appearance channel.

at 99% C.L. if $\sin^2\theta_{23} < 0.48$ ($\theta_{23} < 43.8^\circ$), independently of the value of θ_{13} . In addition, for a relatively large value of $\theta_{13} > 8^\circ$, the θ_{23} -octant degeneracy will not be present at the 99% C.L. for $\sin^2\theta_{23} < 0.44$ ($\theta_{23} < 41.5^\circ$), if θ_{13} is treated as a fixed parameter. We have explored as well the situation in which the simulated value of θ_{23} lies in the second octant, see Figs. 4 for $\sin^2\theta_{23} = 0.6$ and $\sin^2\theta_{23} = 0.56$. If the atmospheric mixing angle lies in the second octant, the θ_{23} -octant degeneracy will not be present at the 99% C.L. for $\sin^2\theta_{23} > 0.6$ ($\theta_{23} > 50.6^\circ$), if θ_{13} is treated as a fixed parameter and $\theta_{13} > 8^\circ$.

These results have been obtained for the more conservative neutrino factory scenario described above, a scenario with 3×10^{22} Kton decays for each muon sign. Since the statistics and the size of the expected signal are both large in disappearance measurements, the error on the parameters will be dominated by the systematic error and a more ambitious scenario with higher statistics (with 1×10^{24} Kton decays) will not improve much these results.

C. Simultaneous fits to θ_{13} and δ

In this subsection we exploit the *golden channel*, i.e. the $\nu_e(\bar{\nu}_e) \rightarrow \nu_\mu(\bar{\nu}_\mu)$ transitions to extract the unknown parameters θ_{13} and δ . We start exploring the more conservative neutrino factory scenario with 3×10^{22} Kton decays. We present in Figs. 5 the 90%, 95%, and 99% C.L. contours for a fit to the simulated data from a future low-energy neutrino factory with the detector located at Homestake, at a baseline $L = 1280$ km (left panel) and at Henderson, at a baseline $L = 1480$ km (right panel). The “true” parameter values that we have chosen for these examples are depicted in the figures with a star: we have explored four different values of $\delta = 0^\circ, 90^\circ, -90^\circ$ and 180° and $\theta_{13} = 8^\circ$. The simulations are for the normal mass hierarchy and θ_{23} in the first octant ($\sin^2\theta_{23} = 0.41$

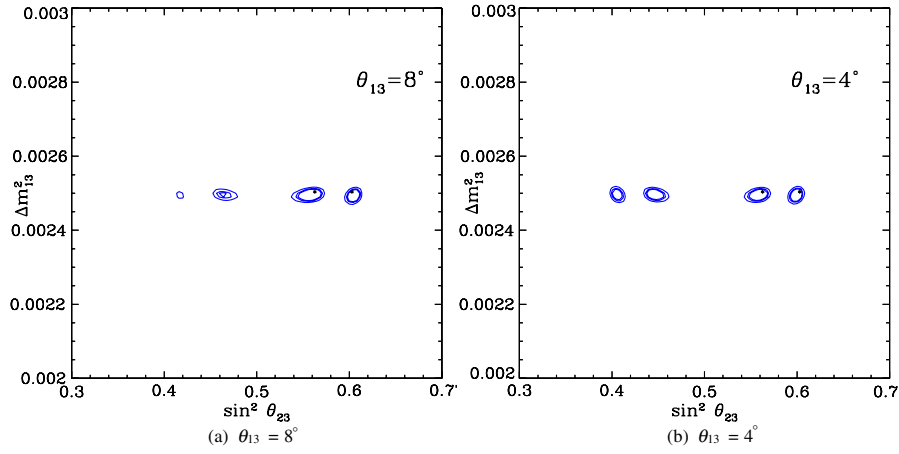


FIG. 4 (color online). The same as in Figs. 3 for $\sin^2 \theta_{23} = 0.6$ and 0.56 and $\Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2$.

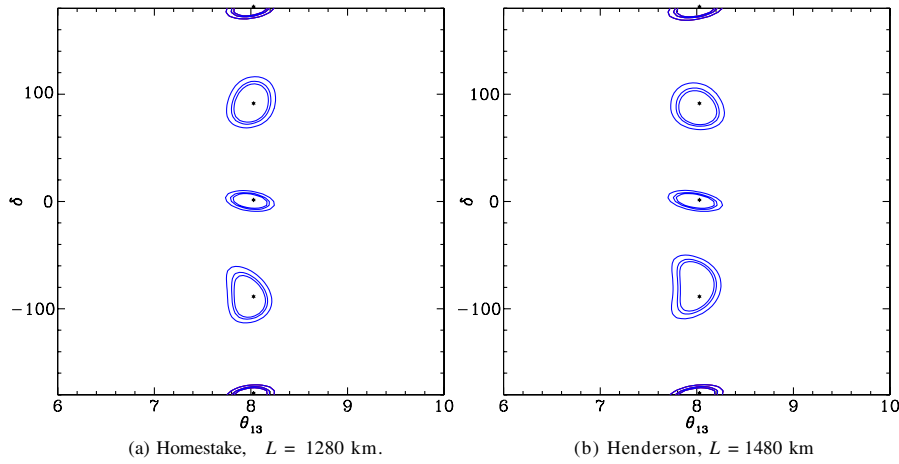


FIG. 5 (color online). 90%, 95% and 99% (2 d.o.f.) C.L. contours resulting from the fits at $L = 1280 \text{ km}$ (left panel) and $L = 1480 \text{ km}$ (right panel) assuming four central values for $\delta = 0^\circ, 90^\circ, -90^\circ$ and 180° and $\theta_{13} = 8^\circ$. The statistics considered for both simulations corresponds to 3×10^{22} Kton decays.

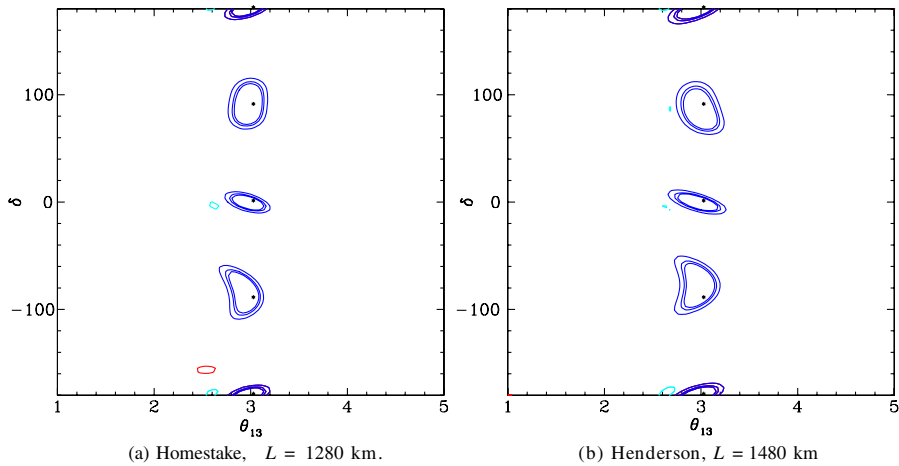


FIG. 6 (color online). The same as Figs. 5 but for $\theta_{13} = 3^\circ$. The additional solution (only at the 99% C.L.) associated to the wrong choice of the neutrino mass ordering is depicted in dark grey (red). The additional solutions (only at the 99% C.L.) arising from the wrong choice of the θ_{23} octant are depicted in light grey (cyan). The statistics considered for both simulations corresponds to 3×10^{22} Kton decays.

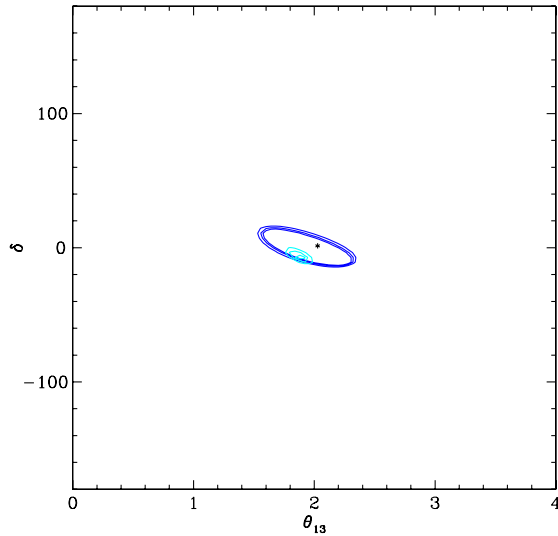


FIG. 7 (color online). 99% (2 d.o.f.) C.L. contours resulting from the fits at $L = 1480$ km assuming $\delta = 0^\circ$ and $\theta_{13} = 2^\circ$. The additional solutions arising from the wrong choice of the θ_{23} octant are depicted in light grey (cyan). The three different contours correspond to three different values of the systematic error: 2%, 4%, and 6%. The statistics considered for the simulation corresponds to 3×10^{22} Kton decays.

which corresponds to $\theta_{23} = 40^\circ$). Our analysis includes the study of the discrete degeneracies. That is, we have fitted the data assuming both the wrong hierarchy and the wrong choice for the θ_{23} octant (i.e. negative hierarchy and $\sin^2 \theta_{23} = 0.59$, which corresponds to $\theta_{23} = 50^\circ$) and the additional solutions (if present) will be shown in red and in cyan, respectively. Notice that in Figs. 5 the sign ambiguity is solved at the 99% C.L. The additional solutions associated to the wrong choice of the θ_{23} octant are not present at

the same C.L. due to the information extracted from the disappearance channel.

Similar results are obtained for smaller values of θ_{13} , see Figs. 6. Notice that the performance of the *low-energy neutrino factory* is unique: the sign(Δm_{31}^2) can be determined at the 99% if $\theta_{13} > 2^\circ$ independent of the value of the CP phase δ . Regarding the θ_{23} -octant ambiguity, it can be removed at the 99% C.L. down roughly to $\theta_{13} > 1^\circ$ for a nature's choice of $\sin^2 \theta_{23} = 0.41$, independent of the value of δ , provided that the conservative estimate of 3×10^{22} Kt decays for each muon sign are feasible. The θ_{23} octant degeneracy is solved with the information contained in the second energy bin data, which is sensitive to the solar term, as mentioned before.

The impact of a larger systematical error is depicted in Fig. 7, where we present the 99% C.L. contours for a fit to the simulated data from a future low-energy neutrino factory with the detector located at Henderson, choosing as the true parameter values $\delta = 0^\circ$ and $\theta_{13} = 2^\circ$. The three different contours correspond to three different values of the systematic error used in the analysis: 2%, 4%, and 6%. The additional solutions (only at the 99% C.L.) arising from the wrong choice of the θ_{23} octant are depicted in cyan. The degeneracies associated to the wrong hierarchy are solved. Notice from the figure that a slightly larger systematical error does not affect the main results presented previously.

Since the results are very similar for the two baselines explored here, the physics reach with the more aggressive estimate of 1×10^{23} Kt decays for each muon sign is illustrated for only one baseline, $L = 1480$ km (Henderson mine site) and for smaller values of θ_{13} . Figure 8 shows fit results for two simulated values of θ_{13} (2° and 1°). The mass hierarchy can be determined at the 99% C.L. if $\theta_{13} > 1^\circ$ independent of the value of the CP

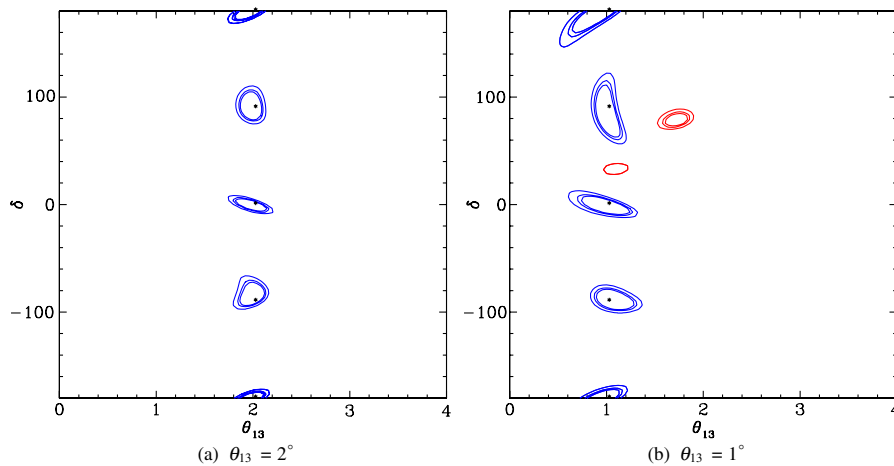


FIG. 8 (color online). 90%, 95%, and 99% (2 d.o.f.) C.L. contours resulting from the fits at $L = 1480$ km assuming four central values for $\delta = 0^\circ, 90^\circ, -90^\circ$, and 180° and $\theta_{13} = 2^\circ$ in the left panel ($\theta_{13} = 1^\circ$ in the right panel). The additional solutions associated to the wrong choice of the neutrino mass ordering are depicted in dark grey (red). The statistics considered for both simulations corresponds to 1×10^{23} Kton decays.

phase δ . In addition, for our example with $\sin^2\theta_{23} = 0.41$, the θ_{23} octant ambiguity can be resolved at 99% C.L. for all values of the CP phase δ provided $\theta_{13} > 0.6^\circ$.

We summarize the reach of the low-energy neutrino factory with two exclusion plots which illustrate the performance of the experiment explored here. We have taken into account the impact of both the intrinsic and discrete degeneracies to depict the excluded regions. For both exclusion plots we have assumed that the detector is located at the Henderson mine at $L = 1480$ km. The results for the closer baseline ($L = 1280$ km) are very similar.

Figure 9 depicts the region in the $\sin^2 2\theta_{13}$, fraction of δ plane for which the hierarchy can be resolved at the 95% C.L. assuming 2 d.o.f. statistics, for both scenarios, the more conservative one, in which the exposure is 3×10^{22} Kton decays, and the more aggressive scenario in which the exposure is 1×10^{23} Kton decays. Notice that the hierarchy could be determined in both scenarios if $\sin^2 2\theta_{13} > 0.01$ (i.e. $\theta_{13} > 3^\circ$) regardless of the value of the CP violating phase δ .

Figure 10 depicts the region in the $(\sin^2 2\theta_{13}, \delta)$ plane for which a given (nonzero) value of the CP violating phase can be distinguished at the 95% C.L. from the CP conserving case, i.e. $\delta = 0, \pm 180^\circ$ (assuming 2 d.o.f. statistics). This exercise is illustrated for the two scenarios considered in this study, the more conservative one, in which the exposure is 3×10^{22} Kton decays, and the more aggressive scenario in which the exposure is 1×10^{23} Kton decays. Notice that the CP violating phase δ could be measured with a 95% C.L. error lower than 20° in both scenarios if $\sin^2 2\theta_{13} > 0.01$ (i.e. $\theta_{13} > 3^\circ$), reaching an unprecedented precision for larger values of θ_{13} . For smaller values, $0.001 < \sin^2 2\theta_{13} < 0.01$, and in the more conservative scenario, the presence of the sign-degeneracy compromises the extraction of the CP violating phase δ . On the other hand, in the more aggressive scenario, a CP violating effect could be established at the 95% C.L. if $\sin^2 2\theta_{13} \geq 0.001$ for $20^\circ < \delta < 160^\circ$ ($-160^\circ < \delta < -20^\circ$).

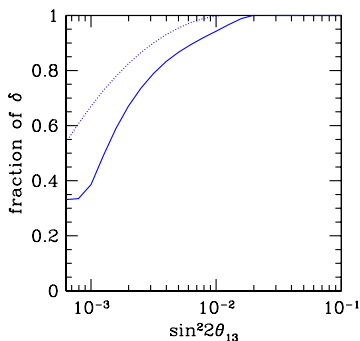


FIG. 9 (color online). 95% C.L. hierarchy resolution (2 d.o.f.) assuming that the far detector is located at a distance of 1480 km at the Henderson mine. The solid (dotted) curves depict the results assuming 3×10^{22} Kton decays (1×10^{23} Kton decays).

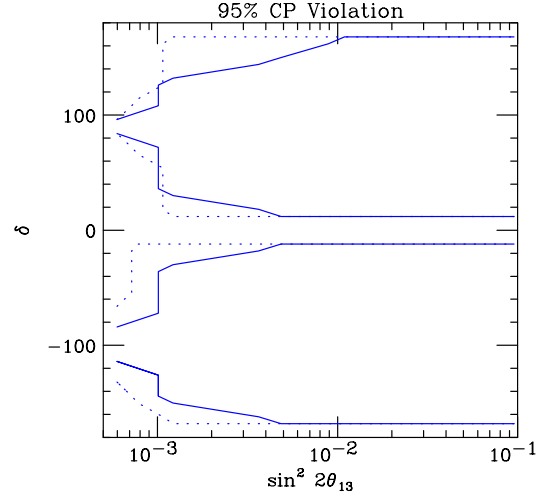


FIG. 10 (color online). 95% C.L. CP Violation extraction (2 d.o.f.) assuming that the far detector is located at a distance of 1480 km at the Henderson mine. The solid (dotted) curves depict the results assuming 3×10^{22} Kton decays (1×10^{23} Kton decays).

V. CONCLUSIONS

We have shown here the enormous physics reach of a novel neutrino factory concept, a *low-energy neutrino factory*, in which the stored muons have an energy of 4.12 GeV.

We have exploited both the disappearance ($\nu_\mu \rightarrow \nu_\mu$) and the *golden* ($\nu_e \rightarrow \nu_\mu$) channels by measuring the “right-sign” and the “wrong-sign” muons at two possible baselines: 1280 Km, the distance from Fermilab to Homestake, and 1480 Km, the distance from Fermilab to Henderson mine. The results presented here can be easily generalized to other baselines in the 1200–1500 km range.

We illustrate the results of the analysis of the energy binned signal for a facility with (a) 3×10^{22} Kt decays for each muon sign and (b) 1×10^{23} Kt decays for each muon sign. The novel setup presented here could extract the θ_{13} angle, the neutrino mass hierarchy and the leptonic CP violating phase δ with unprecedented precision.

The unique performance of the *low-energy neutrino factory* (when compared to the common 20–50 GeV neutrino factory) is due to the rich neutrino oscillation pattern at energies between 1 and 4 GeV at baselines $\mathcal{O}(1000)$ km. Recent studies have shown that it could be possible to build a neutrino factory detector with good wrong-sign muon identification and high efficiency for neutrino energies as low as 1 GeV, or perhaps a little lower. Therefore, to evaluate the physics potential of a low-energy neutrino factory, we have assumed 100% efficiency above a threshold energy of 0.8 GeV, and zero efficiency below this threshold. This naïve model for the detector performance will need to be updated once further work has been done to

better understand the expected detector energy-dependent efficiency.

With this caveat we find that maximal atmospheric neutrino mixing can be excluded at 99% C.L. if $\sin^2\theta_{23} < 0.48$ ($\theta_{23} < 43.8^\circ$). If the atmospheric mixing angle is not maximal, for a nature's choice of $\sin^2\theta_{23} = 0.4$, the octant in which θ_{23} lies could be extracted at the 99% C.L. if $\theta_{13} > 1^\circ$ ($\theta_{13} > 0.6^\circ$) with an exposure of 3×10^{22} Kt decays (1×10^{23} Kt decays) for each muon sign, independently of the value of the CP violating phase δ . The neutrino mass hierarchy could be determined at the 95% C.L., and the CP violating phase δ could be measured with a 95% C.L. error lower than 20° , if $\sin^2 2\theta_{13} > 0.01$ (i.e. $\theta_{13} > 3^\circ$) assuming the more conservative exposure scenario. All the sensitivities quoted here are computed assuming the 2 d.o.f. statistical approach, and in our analysis

we have included statistical and a 2% overall systematic error.

In summary, the *low-energy neutrino factory* scenario could provide the ideal laboratory for precision lepton physics if the mixing angle $\theta_{13} > 2^\circ$.

ACKNOWLEDGMENTS

We thank Stephen Parke for stimulating ideas. O. M. would like to thank D. Meloni for comments on the manuscript. This work was supported in part by the European Programme "The Quest for Unification" Contract No. MRTN-CT-2004-503369, and by the Fermi National Accelerator Laboratory, which is operated by the Fermi Research Association, under Contract No. DE-AC02-76CH03000 with the U.S. Department of Energy.

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- [1] B. T. Cleveland *et al.*, *Astrophys. J.* **496**, 505 (1998); Y. Fukuda *et al.* (Kamiokande Collaboration), *Phys. Rev. Lett.* **77**, 1683 (1996); J. N. Abdurashitov *et al.* (SAGE Collaboration), *J. Exp. Theor. Phys.* **95**, 181 (2002); W. Hampel *et al.* (GALLEX Collaboration), *Phys. Lett. B* **447**, 127 (1999); T. A. Kirsten (GNO Collaboration), *Nucl. Phys. B, Proc. Suppl.* **118**, 33 (2003).
- [2] S. Fukuda *et al.* (Super-Kamiokande Collaboration), *Phys. Lett. B* **539**, 179 (2002).
- [3] Q. R. Ahmad *et al.* (SNO Collaboration), *Phys. Rev. Lett.* **87**, 071301 (2001).
- [4] Q. R. Ahmad *et al.* (SNO Collaboration), *Phys. Rev. Lett.* **89**, 011301 (2002); **89**, 011302 (2002).
- [5] S. N. Ahmed *et al.* (SNO Collaboration), *Phys. Rev. Lett.* **92**, 181301 (2004).
- [6] B. Aharmim *et al.* (SNO Collaboration), *Phys. Rev. C* **72**, 055502 (2005).
- [7] Y. Ashie *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. D* **71**, 112005 (2005).
- [8] K. Eguchi *et al.* (KamLAND Collaboration), *Phys. Rev. Lett.* **90**, 021802 (2003).
- [9] M. H. Ahn (K2K Collaboration), *Phys. Rev. D* **74**, 072003 (2006).
- [10] A. Aguilar *et al.* (LSND Collaboration), *Phys. Rev. D* **64**, 112007 (2001).
- [11] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), The MiniBooNE Run Plan, available at <http://www-boone.fnal.gov/publicpages/runplan.ps.gz>
- [12] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.* **33**, 549 (1957) [*Sov. Phys. JETP* **6**, 429 (1957)]; **7**, 172 (1958); **34**, 247 (1958); Z. Maki, M. Nakagawa, and S. Sakata, *Prog. Theor. Phys.* **28**, 870 (1962).
- [13] M. Apollonio *et al.* (CHOOZ Collaboration), *Phys. Lett. B* **466**, 415 (1999).
- [14] F. Boehm *et al.*, *Phys. Rev. Lett.* **84**, 3764 (2000); *Phys. Rev. D* **62**, 072002 (2000).
- [15] E. Ables *et al.* (MINOS Collaboration), Report No. FERMILAB-PROPOSAL-0875.
- [16] D. G. Michael *et al.* (MINOS Collaboration), *Phys. Rev. Lett.* **97**, 191801 (2006).
- [17] T. Schwetz, *Phys. Scr.* **T127**, 1 (2006).
- [18] G. L. Fogli *et al.*, *Phys. Rev. D* **75**, 053001 (2007).
- [19] T. Araki *et al.* (KamLAND Collaboration), *Phys. Rev. Lett.* **94**, 081801 (2005).
- [20] S. Geer, *Phys. Rev. D* **57**, 6989 (1998); **59**, 039903(E) (1999).
- [21] A. De Rujula, M. B. Gavela, and P. Hernandez, *Nucl. Phys.* **B547**, 21 (1999).
- [22] V. D. Barger, S. Geer, and K. Whisnant, *Phys. Rev. D* **61**, 053004 (2000).
- [23] A. Donini *et al.*, *Nucl. Phys.* **B574**, 23 (2000).
- [24] V. D. Barger *et al.*, *Phys. Rev. D* **62**, 013004 (2000).
- [25] V. D. Barger *et al.*, *Phys. Rev. D* **62**, 073002 (2000).
- [26] A. Cervera *et al.*, *Nucl. Phys.* **B579**, 17 (2000); **B593**, 731(E) (2001).
- [27] M. Freund, P. Huber, and M. Lindner, *Nucl. Phys.* **B585**, 105 (2000).
- [28] V. D. Barger *et al.*, *Phys. Lett. B* **485**, 379 (2000).
- [29] J. Burguet-Castell *et al.*, *Nucl. Phys.* **B608**, 301 (2001).
- [30] M. Freund, P. Huber, and M. Lindner, *Nucl. Phys.* **B615**, 331 (2001).
- [31] A. Donini, D. Meloni, and P. Migliozzi, *Nucl. Phys.* **B646**, 321 (2002); D. Autiero *et al.*, *Eur. Phys. J. C* **33**, 243 (2004).
- [32] C. Albright *et al.*, hep-ex/0008064.
- [33] A. Blondel *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **451**, 102 (2000); M. Apollonio *et al.*, hep-ph/0210192; C. Albright *et al.* (Neutrino Factory/Muon Collider Collaboration), physics/0411123.
- [34] O. Mena, *Mod. Phys. Lett. A* **20**, 1 (2005).
- [35] P. Huber, M. Lindner, M. Rolinec, and W. Winter, *Phys. Rev. D* **74**, 073003 (2006).
- [36] P. Zucchelli, *Phys. Lett. B* **532**, 166 (2002).
- [37] M. Mezzetto, *J. Phys. G* **29**, 1781 (2003); **29**, 1771 (2003).

- [38] J. Burguet-Castell *et al.*, Nucl. Phys. **B695**, 217 (2004).
 [39] A. Donini *et al.*, Nucl. Phys. **B710**, 402 (2005).
 [40] J. Burguet-Castell *et al.*, Nucl. Phys. **B725**, 306 (2005).
 [41] P. Huber *et al.*, Phys. Rev. D **73**, 053002 (2006).
 [42] A. Donini and E. Fernandez-Martinez, Phys. Lett. B **641**, 432 (2006).
 [43] A. Donini *et al.*, Eur. Phys. J. C **48**, 787 (2006).
 [44] M. Ellis, in *Proceedings of the 8th International Workshop on Neutrino Factories, Superbeams and Betabeams (NUFACT06)*, UC Irvine, 2006, <http://nufact06.physics.uci.edu/Default.aspx>.
 [45] V.D. Barger, S. Geer, R. Raja, and K. Whisnant, Phys. Rev. D **63**, 113011 (2001).
 [46] E. K. Akhmedov *et al.*, J. High Energy Phys. 04 (2004) 078.
 [47] N. Holtkamp and D. Finley, Fermilab Report No. FERMILAB-PUB-00/108-E.
 [48] S. Ozaki *et al.*, Report No. BNL-52623.
 [49] S. Geer and M. Zisman, Report No. BNL-72369-2004; Report No. FERMILAB-TM-2259; Report No. LBNL-55478; S. Geer and M.S. Zisman, Fermilab Report No. FERMILAB-PUB-06-454-E.
 [50] D. Ayres *et al.*, hep-ex/0503053.
 [51] G.L. Fogli and E. Lisi, Phys. Rev. D **54**, 3667 (1996).
 [52] H. Minakata and H. Nunokawa, J. High Energy Phys. 10 (2001) 001.
 [53] T. Kajita, H. Minakata, and H. Nunokawa, Phys. Lett. B **528**, 245 (2002); H. Minakata, H. Nunokawa, and S.J. Parke, Phys. Rev. D **66**, 093012 (2002); P. Huber, M. Lindner, and W. Winter, Nucl. Phys. **B645**, 3 (2002); A. Donini, D. Meloni, and S. Rigolin, J. High Energy Phys. 06 (2004) 011; M. Aoki, K. Hagiwara, and N. Okamura, Phys. Lett. B **606**, 371 (2005); O. Yasuda, New J. Phys. **6**, 83 (2004); O. Mena and S.J. Parke, Phys. Rev. D **72**, 053003 (2005).
 [54] H. Minakata and H. Nunokawa, Phys. Lett. B **413**, 369 (1997).
 [55] V. Barger, D. Marfatia, and K. Whisnant, Phys. Rev. D **66**, 053007 (2002).
 [56] O. Mena Requejo, S. Palomares-Ruiz, and S. Pascoli, Phys. Rev. D **72**, 053002 (2005).
 [57] M. Ishitsuka *et al.*, Phys. Rev. D **72**, 033003 (2005); K. Hagiwara, N. Okamura, and K. i. Senda, Phys. Lett. B **637**, 266 (2006).
 [58] O. Mena, S. Palomares-Ruiz, and S. Pascoli, Phys. Rev. D **73**, 073007 (2006).
 [59] T. Kajita *et al.*, Phys. Rev. D **75**, 013006 (2007).
 [60] J. Burguet-Castell *et al.*, Nucl. Phys. **B646**, 301 (2002).
 [61] P. Huber, M. Lindner, and W. Winter, Nucl. Phys. **B654**, 3 (2003).
 [62] H. Minakata, H. Nunokawa, and S.J. Parke, Phys. Rev. D **68**, 013010 (2003).
 [63] V. Barger, D. Marfatia, and K. Whisnant, Phys. Lett. B **560**, 75 (2003).
 [64] K. Whisnant, J.M. Yang, and B.L. Young, Phys. Rev. D **67**, 013004 (2003); P. Huber *et al.*, Nucl. Phys. **B665**, 487 (2003); Phys. Rev. D **70**, 073014 (2004); A. Donini, E. Fernández-Martínez, and S. Rigolin, Phys. Lett. B **621**, 276 (2005).
 [65] O. Mena and S.J. Parke, Phys. Rev. D **70**, 093011 (2004).
 [66] P. Huber, M. Maltoni, and T. Schwetz, Phys. Rev. D **71**, 053006 (2005).
 [67] A. Blondel *et al.*, Acta Phys. Pol. **B37**, 2077 (2006).
 [68] O. Mena, H. Nunokawa, and S.J. Parke, Phys. Rev. D **75**, 033002 (2007); O. Mena, hep-ph/0609031.
 [69] A. Bueno, M. Campanelli, and A. Rubbia, Nucl. Phys. **B589**, 577 (2000).
 [70] A. Donini *et al.*, Nucl. Phys. **B743**, 41 (2006).