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NEUTRINO FACTORY PHYSICS STUDY [1] STATUS AND AN ENTRY LEVEL SCENARIO

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The status of an ongoing neutrino factory physics study at Fermilab is described, together with a personal view of the parameters required for an "entry–level" neutrino factory.

1 Introduction: Why study neutrino factories now ?

Recent measurements of atmospheric muon neutrino (ν_μ) fluxes from the Super–Kamiokande (SuperK) collaboration have shown an azimuth–dependent ($\rightarrow$ baseline dependent) depletion that strongly suggests neutrino oscillations of the type $\nu_\mu \rightarrow \nu_x$. Since the atmospheric ν_e flux is not similarly depleted, ν_x cannot be ν_e, and must therefore be either ν_τ, or ν_s (a sterile neutrino). These observations have inspired many theoretical papers, several neutrino oscillation experiment proposals, and much interest in the physics community. This interest is well motivated. Understanding the neutrino-mass hierarchy and the mixing matrix that drives flavor oscillations may provide clues that lead to a deeper understanding of physics at very high mass-scales and insights into the physics associated with the existence of more than one lepton flavor. Hence, there is a strong incentive to find a way of measuring the neutrino flavor mixing matrix, confirm the oscillation scheme (three–flavor mixing, four–flavor, n-flavor ?), and determine which mass eigenstate is the heaviest (and which is the lightest). This will require a further generation of accelerator based experiments beyond those currently proposed.

High energy neutrino beams are currently produced by creating a beam of charged pions that decay in a long channel pointing in the desired direction. This results in a beam of muon neutrinos ($\pi^+ \rightarrow \mu^+ + \nu_\mu$) or muon anti–neutrinos ($\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$). In the future, to adequately unravel the mixing matrix, we will need ν_e and $\overline{\nu}_e$ (as well as ν_μ and $\overline{\nu}_\mu$) beams. To illustrate this, consider neutrino oscillations within the framework of three-flavor mixing, and adopt the simplifying approximation that only the leading oscillations contribute (those driven by the largest δm^2_{ij} defined as $\delta m^2_{32} \equiv m^2_3 - m^2_2$, where m_i is the mass associated with mass eigenstate i). The probability that a neutrino of energy E (GeV) and flavor α oscillates into a neutrino of flavor β whilst traversing a distance L (km) is given by:

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \sin^2(1.267\delta m^2_{32}L/E)\,, \tag{1}$$

$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23}\ \sin^2 2\theta_{13}\ \sin^2(1.267\delta m^2_{32}L/E)\,, \tag{2}$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\ \sin^2 2\theta_{23}\ \sin^2(1.267\delta m^2_{32}L/E)\ . \tag{3}$$

Each of the oscillation probabilities depend on δm^2_{32} and two mixing angles θ_{ij}. To adequately determine all the θ_{ij} and sort out the various factors contributing to the $P(\nu_\alpha \to \nu_\beta)$ will require ν_e as well as ν_μ beams ! In addition, there is a bonus in using ν_e beams since electron neutrinos can elastically forward scatter off electrons in matter by the charged current (CC) interaction. This introduces a term in the mixing matrix corresponding to $\nu_e \to \nu_e$ transitions that is not present for neutrinos of other flavors. Hence, if electron–neutrinos travel sufficiently far through the Earth, matter effects modify the oscillation probabilities. This modification depends on the sign of δm^2_{32}, and provides a unique way of measuring which mass eigenstate is heaviest, which is lightest !

We conclude that if we can find a way of producing ν_e beams *of sufficient intensity*, we are highly motivated to do so. The obvious way to attempt to produce high energy ν_e beams is to exploit muon decays. Since muons live 100 times longer than pions, we need to avoid using a linear decay channel, which would be impractically long for high energy muons. The solution is to use a muon storage ring with long straight sections, one of which points in the desired direction. This yields a neutrino beam consisting of 50% ν_e and 50% $\overline{\nu}_\mu$ if μ^+ are stored, or 50% ν_μ and 50% $\overline{\nu}_e$ in μ^- are stored.

Using a storage ring to produce secondary beams of $\mu^\pm, e^\pm, \overline{p}$, and ν was proposed by Koshkarev [2] in 1974. The idea (also ascribed to Wojcicki [3] and Collins [4]) therefore dates back to the early days of the ISR at CERN. The key questions that need to be addressed in order to produce a viable proposal for the production of secondary beams by this method are: (i) How can enough particles be stored ? and (ii) How can their phase-space be compressed to produce sufficiently intense beams for physics ? The calculated beam fluxes using the Koshkarev scheme were too low to motivate the construction of a secondary beam storage ring. A viable solution to the key question (how to make sufficiently intense beams) was implemented at the beginning of the 1980's for antiproton production, leading directly to the CERN proton–antiproton collider and the discovery of the weak Intermediate Vector Bosons. The solution to the intensity question involved using lithium lenses to collect as many negative particles as possible, and stochastic cooling to reduce the phase-space of the $\overline{p}$ beam before acceleration. In 1980 it was suggested [5] that the negative particle collection ring (the Debuncher) at the proposed Fermilab antiproton source could be used to provide a neutrino beam downstream of one of its long straight sections. The Debuncher collects negative pions (as well as antiprotons) which decay to produce a flux of captured negative muons. The muon flux in the Debuncher was subsequently measured and found to be modest. The short baseline neutrino oscillation experiment proposal (P860 [6]) that was developed following these ideas was not approved ... the problem of intensity had not been solved !

To make progress we need a method of cooling muon beams and a way of producing more muons. Stochastic cooling cannot be used since the cooling time much longer than the muon lifetime. Ionization cooling was proposed as a possible solution (see [7]). A way of collecting more pions (that subsequently decay into muons) using a very high-field solenoid was proposed by Djilkibaev and Lobashev [8] in 1989. Thus by the end of the 1980's the conceptual ingredients required for very intense muon sources were in place, but the technical details had not been developed. Fortunately in the 1990's the desire to exploit an intense muon source to produce muon beams for a high energy muon collider motivated the formation of an R&D collaboration (*The Muon Collider Collaboration*). This has resulted in a more complete technical understanding of the design of an intense muon source [9].

In 1997 it was proposed (Geer [10]) to use a muon collider type muon source, together with a dedicated muon storage ring with long straight sections, to produce a very intense neutrino source. It was shown that this "neutrino factory" was sufficiently intense to produce thousands of events per year in a reasonably sized detector on the other side of the Earth ! The intensity problem had been solved ! In addition, it was shown that the ring could be tilted at large angles to provide beams for very long (trans–Earth) neutrino oscillation experiments, and that muon polarization could in principle be exploited to turn on/off the initial ν_e flux [10]. This proposal came at a time of increasing interest in neutrino oscillation experiments due to the SuperK results, and also at a time when the particle physics community was/is considering possible facilities needed at its laboratories in the future [11]. Thus, the neutrino factory concept quickly caught the imagination of the physics community, and the interest of its laboratory directors. This interest led to the first NUFACT workshop at Lyon in 1999, and a request from the Fermilab directorate for a 6 month technical study [12] to explore an explicit neutrino factory design and identify the associated R&D issues, together with a parallel 6 month physics study [13] to explore the physics potential of a neutrino factory as a function of its energy, intensity, and the baseline for oscillation experiments.

2 Physics study: status and results

We are, at the time of writing, half way through the Fermilab 6 months neutrino factory physics study [1]. The charge for the study is given below. Fortunately there have been many recent papers [10,11,14,16] that address the physics potential of neutrino factories and provide valuable insight that the study can draw on. However, it is too early to give comprehensive results from the ongoing study, or draw firm conclusions. Instead, I will use results from calculations done in collaboration with my colleagues [16] to anticipate some of the results that may come from the full study, and give a personal view on the parameters of what might be considered an "entry–level" neutrino factory.

2.1 Charge

The charge for the physics study is to deliver a concise report by March 31, 2000 that will explicitly include:

1. The physics motivation for a neutrino source based on a muon storage ring, operating in the era beyond the current set of neutrino oscillation experiments.

2. The physics program that could be accomplished at a neutrino factory as a function of: (a) The stored muon energy, with the maximum energy taken to be 50 GeV., (b) The number of muon decays per year in the beam-forming straight section, taken to be in the range from 10^{19} to 10^{21} decays per year., (c) The presence or absence of muon polarization within the storage ring, and for oscillation experiments, (d) The baseline length including investigations evaluating matter effects.

2.2 Neutrino oscillations: points in parameter space

To fulfill the charge, we are proceeding by defining [15] a handful of representative points in oscillation parameter space, and studying, for each of these points, the physics reach as a function of the neutrino factory parameters. So far three points (1A, 1B, 1C) have been defined within the framework of three–flavor mixing, and one point (2A) has been defined within the framework of four–flavor mixing (one sterile neutrino flavor):

Point 1A: Three-flavor oscillations, with δm^2_{ATM} and $\sin^2 2\theta_{ATM}$ corresponding to the central value favored by the current SuperK data, δm^2_{SUN} and $\sin^2 2\theta_{SUN}$ corresponding to the LMA MSW solution. Explicitly, $\delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2/c^4, $\delta m^2_{21} = 5.0 \times 10^{-5}$ eV^2/c^4, $\sin^2 2\theta_{12} = 0.8$, $\sin^2 2\theta_{23} = 1.0$, $\sin^2 2\theta_{31} = 0.04$, $\delta = 0$.

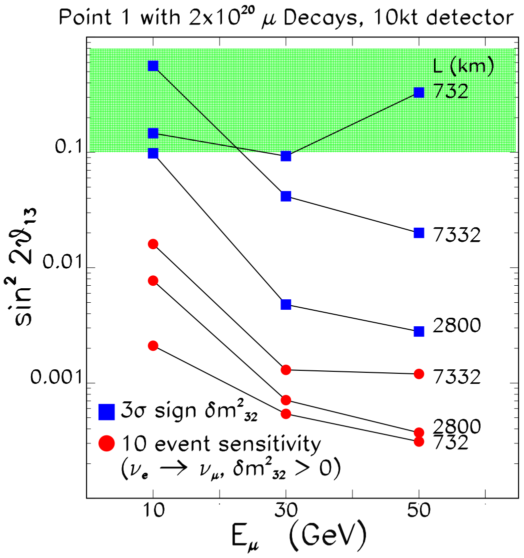

Figure 1: The value of $\sin^2 2\theta_{13}$ that yields, in a 10 kt detector (a) 10 events per $2 \times 10^{20}\mu^+$ decays (boxes), and (b) a three standard deviation determination of the sign of δm^2_{32} when the wrong-sign muon event rates for $2 \times 10^{20}\mu^+$ decays are compared with the corresponding rates for $2 \times 10^{20}\mu^-$decays (circles). The $\sin^2 2\theta_{13}$ sensitivity is shown versus E_μ and L (as labeled). The calculations assume values for δm^2_{32}, $\delta m^2_{12}, s_{23}, s_{12}$, δ corresponding to parameter point 1A (see text). The shaded region is excluded by the existing data.

Point 1B: Three-flavor oscillations, with δm^2_{ATM} and $\sin^2 2\theta_{ATM}$ corresponding to the central value favored by the current SuperK data, δm^2_{SUN} and $\sin^2 2\theta_{SUN}$ corresponding to the SMA MSW solution. Explicitly, $\delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2/c^4, $\delta m^2_{21} = 6.0 \times 10^{-6}$ eV^2/c^4, $\sin^2 2\theta_{12} = 0.006$, $\sin^2 2\theta_{23} = 1.0$, $\sin^2 2\theta_{31} = 0.04$, $\delta = 0$.

Point 1C: Three-flavor oscillations, with δm^2_{ATM} and $\sin^2 2\theta_{ATM}$ corresponding to the central value favored by the current SuperK data, δm^2_{SUN} and $\sin^2 2\theta_{SUN}$ corresponding to the low mass MSW solution. Explicitly, $\delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2/c^4, $\delta m^2_{21} = 1.0 \times 10^{-7}$ eV^2/c^4, $\sin^2 2\theta_{12} = 0.9$, $\sin^2 2\theta_{23} = 1.0$, $\sin^2 2\theta_{31} = 0.04$, $\delta = 0$.

Point 2A: Four-flavor oscillations with one sterile neutrino flavor. Explicitly: $\delta m^2_{34} = 3.5 \times 10^{-3}$ eV^2/c^4, $\delta m^2_{12} = 5.0 \times 10^{-5}$ eV^2/c^4, $\delta m^2_{13} = 0.3$ eV^2/c^4, $\sin^2 2\theta_{34} = 1.0$, $\sin^2 2\theta_{12} = 0.8$, $\sin^2 2\theta_{14} = \sin^2 2\theta_{13} = \sin^2 2\theta_{24} = \sin^2 2\theta_{23} = 0.03$, $\delta_1 = \delta_2 = \delta_3 = 0$.

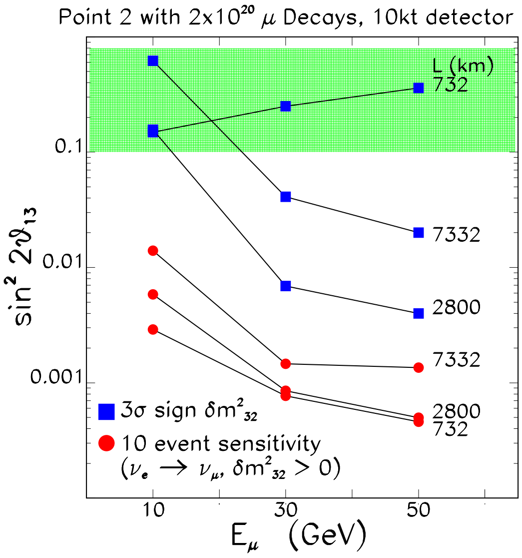

Figure 2: As figure 1, but for parameter point 1C (see text).

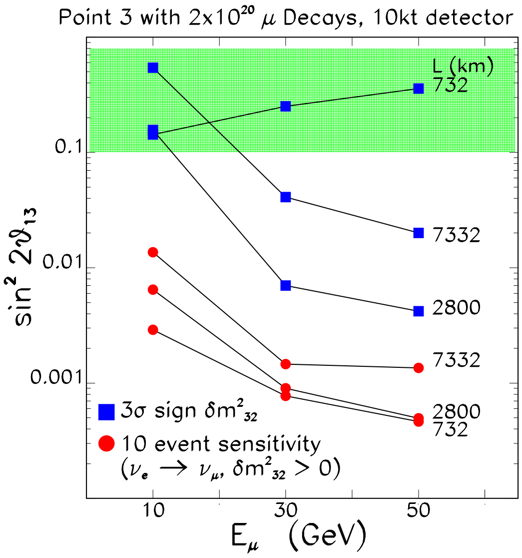

Figure 3: As figure 1, but for parameter point 1C (see text).

2.3 Neutrino oscillations: wrong-sign muons

The most important oscillation channels to be explored at a neutrino factory seem to be $\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu$. In addition to providing a first observation of these transitions and a measurement of the mixing angle θ_{13}, a comparison of the two oscillation modes would also enable a measurement of matter effects, a determination of whether $m_3 > m_2$ or $m_3 < m_2$, and provide knowledge of (limits on) the CP–phase δ. Armed with this information the consistency of the oscillation scenario (three–flavor, four–flavor, ...) could be checked.

The transitions $\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu$ result in CC interactions producing "wrong–sign" muons. If positive (negative) muons are stored in the neutrino factory, oscillated neutrinos undergoing CC interactions produce negative (positive) muons in the detector at the far site. In the leading oscillation approximation, the oscillation probability $P(\nu_e \to \nu_\mu)$ is proportional to $\sin^2 2\theta_{13}$ (see Eq. 1). The experimental sensitivity of the $\nu_e \to \nu_\mu$ measurements therefore decreases with decreasing $\sin^2 2\theta_{13}$. For a given oscillation and neutrino factory scenario we can ask (i) What value of $\sin^2 2\theta_{13}$ would yield 10 wrong–sign muon events per year ? (ii) What value of $\sin^2 2\theta_{13}$ would enable the sign of δm^2_{32} to be determined with a statistical precision of 3 standard deviations ? The answers to these questions have recently been explored by Barger et al. [16] for parameters that correspond to the LMA MSW solar solution (parameter point 1A) as a function of the energy of the stored muons (E_μ), and for three baselines ($L = 732, 2800$, and 7332 km). The results from this study are shown in Fig. 1. The 10 event level "reach" in $\sin^2 2\theta_{13}$–space improves with increasing E_μ and decreasing L. However, 732 km is too short to obtain significant matter effects. Hence, to obtain reasonable sensitivity to the sign of δm^2_{32} longer baselines (for example $L = 2800$ km) are preferred. As an example, choosing $E_\mu = 30$ GeV and $L = 2800$ km we find that with 2×10^{20} muon decays we would expect to observe > 10 wrong–sign muon events in a 10 kt detector provided $\sin^2 2\theta_{13} > 0.0007$, and make a 3σ determination of the sign of δm^2_{32} provided $\sin^2 2\theta_{13} > 0.005$. Extending the study to points 1B and 1C in oscillation parameter space (Figs. 2 and 3), we obtain similar sensitivities. These results are encouraging, but do not yet take account of experimental backgrounds or systematic effects. These possible experimental limitations are under study [17]. Finally, it has been noted [16] that the measured $\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu$ CC interaction energy distributions, as well as the rates, are sensitive to the magnitude and sign of δm^2_{32}. Thus, a fit to these distributions would be expected to enhance the sensitivity to the oscillation parameters. This deserves further study.

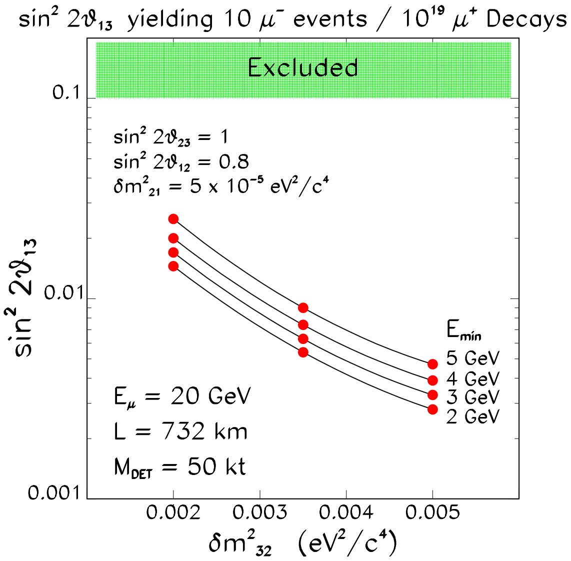

Figure 4: Values of $\sin^2 2\theta_{13}$ that yield, as a function of $|\delta m^2_{32}|$, 10 wrong–sign muon events in a 50 kt detector with $1 \times 10^{19} \mu^+$ decays in the beam forming section of a 20 GeV neutrino factory with $L = 732$ km. The calculations assume δm^2_{12}, $\sin^2 2\theta_{23}$, and $\sin^2 2\theta_{13}$ as listed. The four curves correspond to four thresholds for muon detection (as labeled). The shaded region is excluded by the existing data.

2.4 Other measurements

The interest in neutrino factories is primarily motivated by the need for high energy ν_e and $\overline{\nu}_e$ beams to enable measurements of $\nu_e \to \nu_\mu$, $\overline{\nu}_e \to \overline{\nu}_\mu$, and possibly $\nu_e \to \nu_\tau$, and $\overline{\nu}_e \to \overline{\nu}_\tau$ oscillations. In addition to these fundamentally important measurements there are a variety of other interesting physics topics that could be pursued at a neutrino factory. These "bread and butter" physics measurements include precision oscillation measurements that exploit the ν_μ and $\overline{\nu}_\mu$ neutrino–beam components. It has been shown [16] that at a neutrino factory it may be possible to improve the statistical precision of the measured values of δm^2_{32} and $\sin^2 2\theta_{23}$ by an order of magnitude beyond the precision that will be achieved by the next generation of long–baseline experiments. Finally, the non–oscillation physics topics include unique measurements of structure functions (including spin structure functions), charm production, $D - \overline{D}$ mixing, B physics, a more precise measurement of the weak mixing angle, and searches for exotic processes (multiplicative lepton number violation, radiative neutrino decays, ...). The scope of this physics program is under study [18].

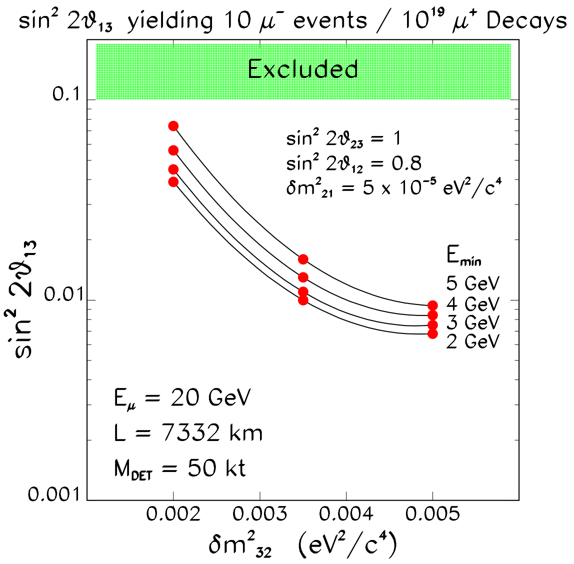

Figure 5: As figure 4, but for baseline $L = 7332$ km.

3 An entry–level Neutrino Factory: a tentative proposal

What is the minimum neutrino factory energy and beam intensity required to provide a cutting–edge oscillation physics program ? To try to address this question, consider first a 20 GeV neutrino factory pointing at a 50 kt detector with a baseline of 732 km. We will assume that our goal is to make the first observation of $\nu_e \rightarrow \nu_\mu$ oscillations and the first (low precision) measurements of $\sin^2 2\theta_{13}$. The signal event rate will depend on δm^2_{32}, which we must allow to vary over the favored SuperK range. Fig. 4 shows as a function of δm^2_{32} the value of $\sin^2 2\theta_{13}$ that would yield 10 wrong–sign muon events if 10^{19} muons decay in the beam–forming section of the neutrino factory. The expected event rates depend upon the threshold energy for detecting the wrong–sign muon, and the figure therefore shows the variation of the $\sin^2 2\theta_{13}$ "reach" with the threshold energy E_{min}. We note that if the value of δm^2_{32} is in the upper half of the favored SuperK parameter space, then a 20 GeV neutrino factory delivering 10^{19} muons decays per year would enable us to achieve out goals provided $\sin^2 2\theta_{13}$ was not less than about an order of magnitude below the currently excluded region. We expect to know soon from the K2K measurements whether the upper half of the δm^2_{32} region is favored. If this is the case, then a 20 GeV factory with 10^{19} decays per year and $L = 732$ km would seem a candidate entry–level scenario.

Let us now consider other candidate entry–level scenarios. Can we reduce the neutrino factory energy further ? Note that the sensitivities shown in Fig 4 vary with E_{min} by about a factor of 2 over the range of E_{min} considered. It will be important to try to minimize E_{min} to obtain good sensitivity and minimize the bias a high threshold introduces into measured energy distributions. At present E_{min} values of 3–4 GeV are being considered as plausible. If E_{min} cannot be further reduced in a realistic very massive detector then it would seem unwise to reduce the neutrino factory energy significantly below 20 GeV. Hence we adopt 20 GeV for our entry–level scenario. Next consider changing the baseline. The signal event rate increases with decreasing L. However, at $L = 732$ km our entry–level scenario yields a total CC rate of O(10^5) events per year in our 50 kt detector. Hence we require the backgrounds to be at or below the 1 event per 10^5 CC events level. It is believed that backgrounds are likely to be close to this level (or perhaps a little higher). Hence we would not want to decrease L, and may in fact want to go to a larger L to further reduce the background rate. How about a longer baseline ? Figure 5 shows as a function of δm^2_{32} the value of $\sin^2 2\theta_{13}$ that would yield 10 wrong–sign muon events if $L = 7332$ km. The $\sin^2 2\theta_{13}$ reach has been reduced by only a factor of $2 - 3$. On the other hand the total event rate (and hence backgrounds) are reduced by a factor of O(100) ! In addition, should a first observation of wrong–sign muon events be made, higher statistics measurements (an intensity upgrade) would then enable matter effects to be measured and the sign of δm^2_{32} determined. Hence the very–long baseline entry–level scenario has some advantages.

Let us assume there are no sterile neutrinos. We are now ready to propose a candidate entry–level scenario, which we take to be a 20 GeV storage ring with the product of the number of muon decays per year and the detector mass being 5×10^{20} kt. A fairly long baseline is desirable ($L \geq 2000$ km) to minimize background rates and enable the eventual measurement of matter effects. It should be noted that if the MiniBooNE experiment confirms the LSND oscillation results and we will need to rethink our entry–level scenario to address the exciting prospect of a relatively large leading δm^2 and the possibility of one or more sterile neutrino–types participating in the oscillations.

4 Summary

Given the recent SuperK results, neutrino factories have understandably caught the attention of the high energy physics community, and its laboratory directors. A Fermilab directorate initiated study of the physics potential of neutrino factories is in progress. This study is expected to deepen our understanding of the desired neutrino factory parameters. I believe that the real question to be addressed now is not so much “What physics can be done with a *Cadillac* neutrino factory ?” but rather “What is the entry–level neutrino factory scenario that would enable this new type of physics facility to be developed and built in principle on a relatively short time-scale ?” What do we need to get the show on the road and start climbing the learning curve ?

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