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Neutrino Factories: Physics Potential

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Abstract. The physics potential of low-performance and high-performance neutrino factories is briefly reviewed.

1. Introduction

The recent evidence for neutrino oscillations [1] opens a new and exciting era in neutrino physics. We now know that neutrinos of one flavor can transform themselves into neutrinos of a different flavor. The atmospheric– and solar–neutrino results from the Super-Kamiokande (Super-K) and Sudbury Neutrino Observatory (SNO) experiments suggest that all three known flavors participate in neutrino oscillations. Within the framework of three-flavor mixing, the oscillation probabilities are determined by three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), one complex phase ($\delta$), and two mass splittings (Δm^2_{32} and Δm^2_{21} where $\Delta m^2_{ij} \equiv m^2_i$ - m^2_j, the difference between the squares of the masses of the neutrino mass eigenstates). The Super-K and SNO data suggest that (i) $|\Delta m^2_{32}| \sim 2 \times 10^{-3}$ eV^2, (ii) $\sin^2 2\theta_{23} \sim 1$, and if the LMA MSW solution is confirmed, (iii) $\Delta m^2_{21} \sim 5 \times 10^{-5}$ eV^2, and (iv) $\sin^2 2\theta_{12} \sim 0.87$. In addition, the CHOOZ reactor ν_e disappearance search result implies (v) $\sin^2 2\theta_{13} < O(0.1)$. However, there is a lot we don't know:

- Does three-flavor mixing provide the right framework, or are there also contributions from additional sterile neutrinos, neutrino decay, CPT-violation ... ?
- Is $\sin^2 2\theta_{13}$ small, tiny, or zero ?
- Is δ non-zero ? Is there CP-violation in the lepton sector, and does it contribute significantly to baryogenesis via leptogenesis ?
- What is the sign of Δm^2_{32} (which determines the neutrino mass hierarchy) ?
- Is $\sin^2 2\theta_{23}$ maximal (= 1) ?

The answers to these questions may lead us towards an understanding of the origin of flavor. However, getting the answers will require the right tools, and a neutrino factory [2] appears to be the tool that we will ultimately require.

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2. Beam properties

In a neutrino factory muons are stored in a ring with long straight sections. Muon decays generate a neutrino beam downstream of each straight section. If μ^+ are stored $\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$ decays generate a beam consisting of 50% ν_e and 50% $\overline{\nu}_\mu$. If μ^- are stored the beam consists of 50% ν_μ and 50% $\overline{\nu}_e$. Design studies [3] suggest that neutrino factories can provide $O(10^{20})$ useful muon decays per year. Since the kinematics of muon decay is well known, we expect minimal systematic uncertainties on the neutrino flux and spectrum. Hence, compared to conventional neutrino beams made using a $\pi^\pm$ decay channel, neutrino factories provide ν_e and $\overline{\nu}_e$ beams in addition to ν_μ and $\overline{\nu}_\mu$ beams, with small systematic uncertainties on the beam flux and spectrum.

2.1. ν_μ beam properties

At a high performance 20 GeV neutrino factory providing 2×10^{20} useful muon decays/yr the ν_μ beam flux is about an order of magnitude larger than the anticipated future NuMI beam flux at Fermilab. Eventually superbeams (very high intensity conventional neutrino beams driven by MW-scale primary proton beams) may also be able to achieve beam fluxes that are about a factor of 10 greater than the NuMI flux. However, with higher energy neutrino factories the event rate at a distant detector increases like E^3, rapidly exceeding any corresponding rate we can imagine at a superbeam. This is not the whole story. The beam energy distributions are also different. The neutrino factory beam has a sharp cut-off at the energy of the stored muons. In a conventional neutrino beam there is an annoying high-energy tail which gives rise to backgrounds from neutral current (NC) events in which a leading π^0 is misinterpreted as an electron, faking a $\nu_\mu \rightarrow \nu_e$ signal. This background source is absent at a neutrino factory.

2.2. ν_e beam properties

Although the ν_μ beam properties are interesting, the main reason for wanting a neutrino factory is that it would also provide ν_e and $\overline{\nu}_e$ beams, enabling very sensitive searches for $\nu_e \rightarrow \nu_\mu$ oscillations. The resulting ν_μ component can interact in the far detector via the charged current (CC) interaction to produce a muon with a charge of opposite sign to that of the muons stored in the neutrino factory. The experimental signature is therefore the appearance of a wrong-sign muon, for which backgrounds are expected to be at the 10^{-4} level or lower. In contrast to this, the equivalent $\nu_\mu \rightarrow \nu_e$ oscillation search using a superbeam suffers from background levels that are at about the 10^{-2} level. To compare signal and background rates it is useful to consider some explicit examples [4] corresponding to entry-level and high-performance neutrino facilities:

- Entry-Level Superbeam (JHF → Super-K). Running period = 5 years, detector mass = 22.5 kt, proton beam power = 0.75 MW.
- High-Performance Superbeam (Super-JHF → Hyper-K). Running period = 8 years, detector mass = 1000 kt, proton beam power = 4 MW.

Table 1. Superbeam and neutrino factory event rates from ref. [4]. The event numbers correspond to the scenarios described in the text, with $|\Delta \mathrm{m}^2_{32}| = 3 \times 10^{-3}$ eV^2, $\Delta \mathrm{m}^2_{21} = 3.7 \times 10^{-5}$ eV^2 $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{12} = 0.8$, $\sin^2 2\theta_{13} = 0.1$, and $\delta = 0$.

	JHF-SK	JHF-HK	NUFACT I	NUFACT II
Signal	140	13000	1500	65000
Background	23	2200	4.2	180
S/B	6	6	360	360

- Entry-Level Neutrino Factory (NUFACT I): 1×10^{19} useful muon decays / year at 50 GeV. Running period = 5 years, detector mass = 100 kt.
- High-Performance Neutrino Factory (NUFACT II): 2.6×10^{20} useful muon decays / year at 50 GeV. Running period = 8 years, detector mass = 100 kt.

For these four examples, the signal and background rates are compared in Table 1. Based on the signal to background (S/B) ratios we might expect that the sensitivity at a neutrino factory will ultimately be about two orders of magnitude better than at a high-performance superbeam. More detailed studies [4] suggest that this naive conclusion is not far from the truth although the full story is much more complicated.

3. Physics reach

Neutrino factory data can be separated into 6 subsamples with events tagged by the appearance of (i) a right-sign muon, (ii) a wrong-sign muon, (iii) an e^+ or e^-, (iv) a τ^+, (v) a τ^-, or (vi) the absence of a lepton. Measurements can be made with μ^+ and then with μ^- stored in the ring. Hence there are 12 event energy distributions that can be simultaneously fit to obtain the oscillation parameters. Since neutrino factories provide intense high energy beams, oscillation baselines can be long, or very long (thousands of km). With multiple experiments, measurements can be checked with a wide range of baselines. Recent studies have suggested that this wealth of information will be necessary to pin down the oscillation parameters and provide sufficient redundancy to ensure we have the right oscillation framework. To better understand this it is instructive to expand the expressions for the oscillation probabilities in terms of small quantities, keeping just the leading order terms. We already know that $\sin^2 2\theta_{13}$ is small. We can construct a second small quantity $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$. Defining $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$, to leading order in $\sin^2 2\theta_{13}$ and α, the oscillation probabilities in vacuum are given by:

$$\begin{aligned}
P_{\mu\mu} &= 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta + 2\alpha\cos^2\theta_{13}\cos^2\theta_{12}\sin^2 2\theta_{23}\Delta\cos\Delta \\
P_{e\mu} &= \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\Delta + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta \\
&\quad \mp \alpha\sin^2 2\theta_{13}\sin\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin^3\Delta \\
&\quad - \alpha\sin^2 2\theta_{13}\cos\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\Delta\sin^2\Delta
\end{aligned}$$

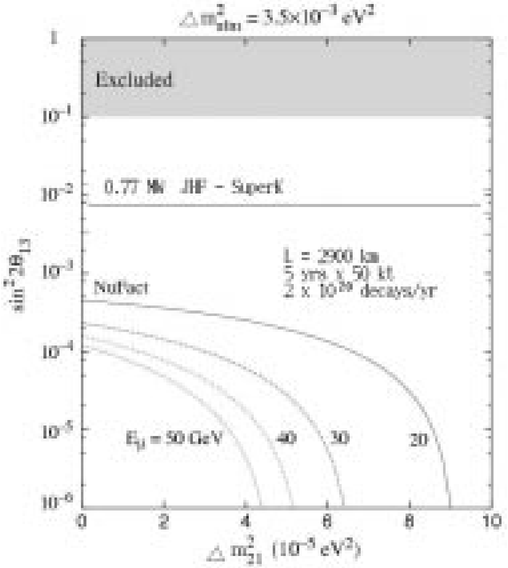

Figure 1. Minimum value of $\sin^2 2\theta_{13}$ for which a $\nu_e \leftrightarrow \nu_\mu$ would be observed, shown as a function of Δm^2_{21} for superbeam and neutrino factory experiments. Figure based on calculations described in ref. 6.

where the $\mp$ sign in the expression for $P_{e\mu}$ corresponds to neutrino/antineutrino oscillations. Examining the leading order oscillation expressions we note that:

i) We can replace Δm^2_{31} with $-\Delta m^2_{31}$ without changing $P_{e\mu}$ since vacuum oscillations do not depend upon the sign of Δ. For sufficiently long (neutrino factory) baselines within the Earth this degeneracy is broken by matter effects.

ii) For non-maximal mixing we can replace θ_{23} with $\pi/2 - \theta_{23}$ and compensate the change in the predicted oscillation probabilities by changing $\sin^2 2\theta_{13}$.

iii) We expect a strong correlation between the fitted values for δ and $\sin^2 2\theta_{13}$. In many cases the best fit combination (δ, θ_{13}) is accompanied by another pair (δ', θ'_{13}) that yields the same predicted leading order oscillation probabilities.

Hence, we can expect strong correlations between the values of the oscillation parameters extracted from fits to the data. In addition we can expect degenerate solutions (alternative regions in parameter space that are consistent with the data). To understand the physics capabilities of neutrino factories (or superbeams) we must take into account the impact of these correlations and degeneracies.

3.1. $\sin^2 2\theta_{13}$

Consider first the smallest value of $\sin^2 2\theta_{13}$ that will yield a $\nu_\mu \leftrightarrow \nu_e$ signal. We will begin by ignoring effects of the all important correlations and degeneracies. The value of $\sin^2 2\theta_{13}$ that will yield a significant appearance signal is shown as a function of Δm^2_{21} in Fig. 1 for the JHF → Super-K superbeam and for neutrino factories with energies between 20 GeV and 50 GeV. Superbeams can probe values of $\sin^2 2\theta_{13}$ an order of

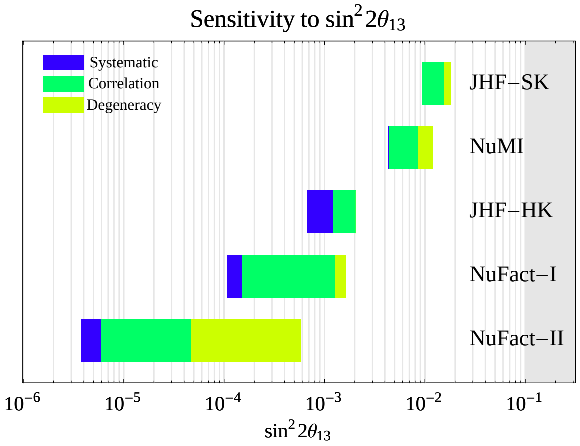

Figure 2. Impact of systematics, correlations, and degeneracies on the minimum value of $\sin^2 2\theta_{13}$ probed by superbeam experiments (as indicated) and neutrino factory experiments with L = 3000 km. Figure from ref. 4.

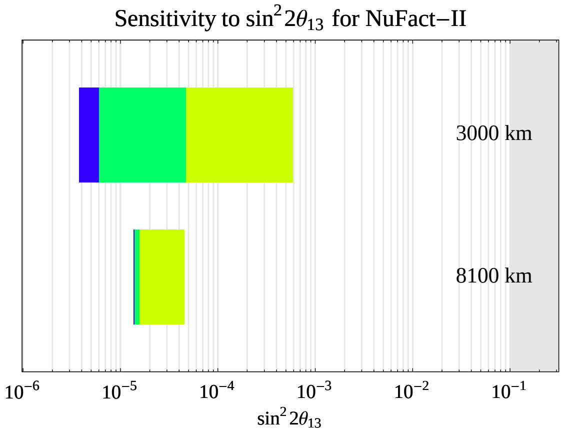

Figure 3. Impact of systematics, correlations, and degeneracies on the minimum value of $\sin^2 2\theta_{13}$ probed by neutrino factory experiments with baselines of 3000 km and 8100 km. Figure from ref. 4

magnitude below the present limit. If Δm^2_{21} is very small, so that the sub-leading scale does not contribute to the appearance signal, a high-performance neutrino factory would improve on the superbeam sensitivity by more than another order of magnitude. If Δm^2_{21} is in the upper half of the presently allowed region (spanned by the figure) then neutrino factory experiments will measure an appearance signal even if $\sin^2 2\theta_{13} = 0$, enabling oscillations generated by the sub-leading scale to be directly measured.

We must now consider the impact of correlations and degeneracies. The calculated $\sin^2 2\theta_{13}$ sensitivities (90% CL) from ref. [4] are shown in Fig. 2 for the superbeam and neutrino factory scenarios listed in Section 2.2. The leftmost end of the bars indicate the sensitivities in the absence of correlations, degeneracies, and systematic uncertainties. The impact of each of these effects on the sensitivity is indicated by the shaded sub-bars. Systematic uncertainties degrade the sensitivity by a modest amount. With

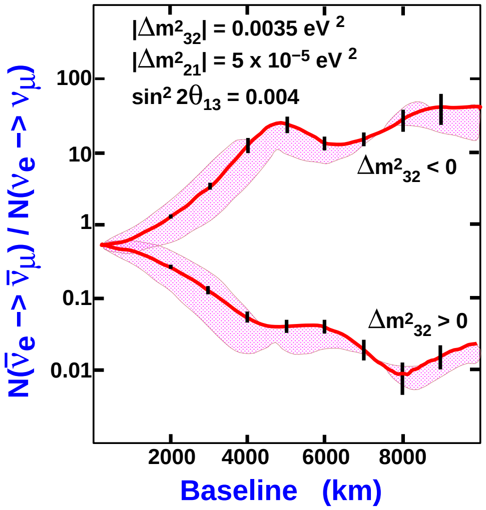

Figure 4. Predicted ratios of wrong-sign muon event rates when μ^+ and μ^- are stored in a 20 GeV neutrino factory, shown versus baseline. The two bands correspond to the two signs of Δm^2_{32}. The widths of the bands show the variation as the CP phase δ changes from $-\pi/2$ to $+\pi/2$. The thick lines are for $\delta = 0$. The statistical errors correspond to a neutrino factory providing 10^{21} muon decays with a 50 kt detector. The figure is from ref. 6.

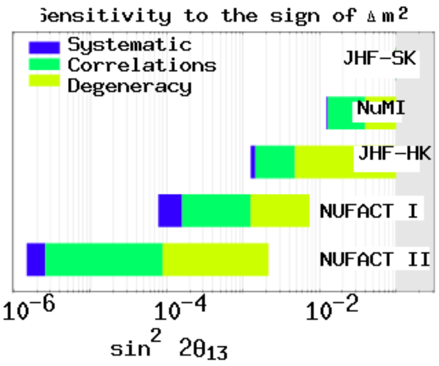

Figure 5. Impact of systematics, correlations, and degeneracies on the minimum value of $\sin^2 2\theta_{13}$ for which the sign of Δm^2_{32} could be determined by superbeam and neutrino factory experiments. Figure from ref. 4.

a baseline of 3000 km, the impact of correlations and degeneracies limits the high-performance neutrino factory $\sin^2 2\theta_{13}$ sensitivity to $O(10^{-3})$. We can fight correlations and degeneracies by using a longer baseline, or multiple baselines. In fact with a baseline of $\sim$ 8000 km the sensitivity is expected to have improved to a few $\times 10^{-5}$ (Fig. 3).

3.2. CP Violation and the neutrino mass hierarchy

If present, CP violation (CPV) and matter effects will modify the measured $\nu_e \leftrightarrow \nu_\mu$ oscillation probabilities. These modifications are different for neutrinos and antineutrinos. The predicted ratio of events $N(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)/N(\nu_e \rightarrow \nu_\mu)$ at a neutrino factory experiment with equal μ^+ and μ^- running is shown as a function of baseline in Fig. 4. With no CPV and no matter effects (L = 0) the ratio is 0.5, reflecting the different neutrino and antineutrino cross-sections. As L increases the ratio is enhanced (suppressed) by matter effects if the sign of Δm^2_{32} is negative (positive). At sufficiently long baselines the matter effects are much larger than effects due to possible CPV (indicated by the bands in the figure). The sign of Δm^2_{32} and the CP phase δ can therefore be determined by precise measurements of $N(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)$ and $N(\nu_e \rightarrow \nu_\mu)$. However, in this simple picture we have fixed the values of $|\Delta m^2_{32}|$, Δm^2_{21}, and $\sin^2 2\theta_{13}$. If we now allow all of these parameters to vary in our fit to the data we must deal will the resulting correlations and ambiguities. The impact of these complications on the sensitivities of neutrino factory and superbeam experiments can be seen in Fig. 5, which shows the minimum values of $\sin^2 2\theta_{13}$ for which the sign of Δm^2_{32}, and hence the neutrino mass hierarchy, can be determined. With a single experiment at one baseline, correlations and degeneracies can degrade the expected sensitivities by orders of magnitude. It is believed that at a high-performance neutrino factory, with two experiments having very different baselines, the sign can probably be determined provided $\sin^2 2\theta_{13}$ exceeds $\mathrm{O}(10^{-4})$ or perhaps a few $\times 10^{-5}$. Further study is needed to understand this better, and to understand how the picture is improved by combining superbeam and neutrino factory measurements. The sensitivity to CPV has also been studied and found to be very dependent on Δm^2_{21}. If $\Delta m^2_{21} \sim 4 \times 10^{-5}$ eV^2, in the center of the presently favored LMA parameter space, maximal CPV would be observed at a high performance neutrino factory if $\sin^2 2\theta_{13}$ exceeds a few $\times 10^{-4}$. In the next few years KamLAND is expected to improve our knowledge of Δm^2_{21}, allowing us to sharpen our understanding of the CPV capabilities of superbeams and neutrino factories.

3.3. If LSND is confirmed

If the LSND oscillation result is confirmed, the simple three-flavor mixing framework will need to be modified to include, for example, additional light neutrinos that are sterile and/or CPT violation. We will already have some knowledge of $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations. It seems likely that there will be a premium on searching for and measuring $\nu_e \rightarrow \nu_\tau$ oscillations, a program unique to neutrino factories. It has been shown [5] that there are viable regions of four-neutrino mixing parameter space in which both CPV and thousands of $\nu_e \rightarrow \nu_\tau$ events could be seen at a neutrino factory delivering only $\mathrm{O}(10^{18})$ decays/yr. Hence, if the LSND result is confirmed, a very low intensity neutrino factory might provide a well motivated first (fast and cheap ?) step towards the high-performance facility we will ultimately want.

3.4. Non-oscillation physics

Finally, we must not forget the extensive non-oscillation physics program at a neutrino factory facility. A high-performance 50 GeV neutrino factory can provide 10^6 –

10^7 neutrino events per kg per year, enabling highly instrumented detectors to obtain data samples of unprecedented magnitude. Experiments that might benefit from these intense beams include (i) precise neutrino cross-section measurements, (ii) structure function measurements (with no nuclear corrections), in which individual quark-flavor parton distributions can be extracted, (iii) precise α_S measurements from non-singlet structure functions, (iv) studies of nuclear effects (e.g. shadowing) separately for valence and sea quarks, (v) spin structure functions, (vi) tagged single charm meson and baryon production (a 1 ton detector could yield 10^8 flavor-tagged charm hadrons / yr), (vii) electroweak tests ($\sin^2\theta_W$ and $\sigma(\nu - e)$), (viii) exotic interaction searches, (ix) neutral heavy lepton searches, and (x) searches for anomalous neutrino interactions in EM fields. This is only a representative list, to which would be added the possible physics programs that exploit very intense cold muon beams and the very intense primary proton beams that would also be available at a neutrino factory complex.

4. Summary

Neutrino factories seem to offer a way to probe $\sin^2\theta_{13}$ and determine the sign of Δm^2_{32} provided $\sin^2\theta_{13}$ exceeds a few $\times 10^{-5}$. Neutrino factories would also enable $\nu_e \to \nu_\tau$ oscillation searches. No other candidate future facility has these capabilities. Should the LMA solar neutrino solution be confirmed, sensitive CPV searches would also be possible. This would either extend the reach that would already have been obtained at superbeams, or possibly follow up an initial indication of CPV with a precise measurement of the phase δ. In addition, an extensive non-oscillation physics program would enable neutrino factories to serve a broad community.

Acknowledgements

Our understanding of the physics capabilities of neutrino factories is based on the work of many groups over several years. This brief summary is indebted to all those that have contributed. I am particularly indebted to M. Lindner for Figs. 2,3, and 5.

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