LEPTON FLAVOR VIOLATING ERA
OF NEUTRINO PHYSICS

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The physics agenda for future long-baseline neutrino oscillation experiments is outlined and the prospects for accomplishing those goals at future neutrino facilities are considered. Neutrino factories can deliver better reach in the mixing and mass-squared parameters but conventional super-beams with large water or liquid argon detectors can probe regions of the parameter space that could prove to be interesting.

1 Introduction

Neutrino oscillation phenomena probe the fundamental properties of neutrinos. We presently have evidence for (i) atmospheric \( \nu_\mu \) disappearance oscillations with mass-squared difference \( \delta m^2_{\text{atm}} \approx 3 \times 10^{-3} \text{eV}^2 \), (ii) solar \( \nu_e \) disappearance oscillations with \( \delta m^2_{\text{solar}} \approx 5 \times 10^{-5} \text{eV}^2 \), and (iii) and accelerator \( \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e \) and \( \nu_\mu \leftrightarrow \nu_e \) oscillations with \( \delta m^2_{\text{LSND}} \approx 1 \text{eV}^2 \). Limits from accelerator and reactor experiments place important constraints on oscillation possibilities. In particular, reactor experiments exclude large amplitude \( \bar{\nu}_e \) disappearance oscillations at \( \delta m^2 > 10^{-3} \text{eV}^2 \).

A 3-neutrino model can explain the atmospheric and solar data and provides a useful benchmark for neutrino factory studies. The mixing of 3 neutrinos can be parametrized by 3 angles \( (\theta_{23}, \theta_{12}, \theta_{13}) \) and a CP-violation phase \( (\delta) \). The angle \( \theta_{23} \) controls the atmospheric oscillation amplitude, \( \theta_{12} \) controls the solar oscillation amplitude, and \( \theta_{13} \) couples atmospheric and solar oscillations and controls the amount of \( \nu_e \) oscillations to \( \nu_\mu \) and \( \nu_\tau \) at the atmospheric scale.

What we now know from experiments is that:

(i) \( \theta_{23} \sim \pi/4 \), \( |\delta m^2_{32}| \sim 3 \times 10^{-3} \text{eV}^2 \) for atmospheric oscillations;
(ii) \( \theta_{12} \sim \pi/4 \), \( |\delta m^2_{23}| \sim 5 \times 10^{-5} \text{eV}^2 \) is favored for solar oscillations (the LAM solution) but other values are not fully excluded;
(iii) \( \theta_{13} \sim 0 \) (\( \sin^2 2\theta_{13} < 0.1 \)) from the reactor experiments.

In the limit \( \theta_{13} = 0 \), the oscillations are bimaximal.

A new round of accelerator experiments with medium baselines is underway. The K2K experiment (\( L = 250 \text{ km} \), \( \langle E_\nu \rangle \sim 1.4 \text{ GeV} \)) is finding evidence in line with the atmospheric \( \nu_\mu \) disappearance. The MINOS experiment (\( L = \ldots \))

*Talk presented at the Joint U.S./Japan Workshop on New Initiatives in Lepton Flavor Violation and Neutrino Oscillation with High Intense Muon and Neutrino Sources, Honolulu, Hawaii, Oct. 2-6, 2000
730 km, $\langle E_{\nu} \rangle \sim 10$ GeV) and the CNGS experiments ICANOE and OPERA ($L = 730$ km, $\langle E_{\nu} \rangle \sim 20$ GeV) are expected to “see” the first oscillation minimum in $\nu_\mu \leftrightarrow \nu_\mu$, measure $\sin^2 2\theta_{23}$ to 5% and $\delta m^2_{3\text{atm}}$ to 10% accuracy, and search for $\nu_\mu \rightarrow \nu_e$ down to 1% in amplitude. The short-baseline MiniBooNE experiment at Fermilab will confirm or reject the LSND effect. However, information about neutrino masses and mixing will still be incomplete. Higher intensity beams of both $\nu_\mu$ and $\nu_e$ flavors are needed.

Conventional neutrino beams based on $\pi$, $K$ decays are dominantly $\nu_\mu$ and $\bar{\nu}_\mu$. Neutrino factories would provide high intensity $\nu_\mu$ and $\bar{\nu}_\mu$ (or $\bar{\nu}_\mu$ and $\nu_e$) beams from muon decays. The $\nu_e$ and $\bar{\nu}_e$ beams would access neutrino oscillation channels that are otherwise inaccessible and are essential for eventual reconstruction of the neutrino mixing matrix.

2 Neutrino Factory

Collimated high-intensity neutrino beams can be obtained from decays of muons stored in an oval ring with straight sections. For $\mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e$ decays, the oscillation channels $\nu_\mu \rightarrow \nu_\mu$ (disappearance), $\nu_\mu \rightarrow \nu_e$ (appearance), and $\nu_\mu \rightarrow \nu_\tau$ (appearance) give “right-sign” leptons $\mu^-$, $e^-$, and $\tau^-$, respectively, whereas the oscillation channels $\nu_e \rightarrow \nu_e$ (disappearance), $\nu_e \rightarrow \nu_\mu$ (appearance), and $\nu_e \rightarrow \nu_\tau$ (appearance) give “wrong-sign” leptons $e^+$, $\mu^+$, and $\tau^+$, respectively. The oscillation signals are relatively background free. The charge-conjugate channels can be studied in $\mu^+$ decays.

With stored muon energies $E_\mu \gg m_\mu$, the neutrino beam is highly collimated and its flux is $\Phi \simeq N (E_\nu/m_\mu)^2/(\pi L^2)$, where $N$ is the number of useful muon decays and $L$ is the baseline. The $\nu N$ cross section rises linearly with $E_\nu$ and hence with $E_\mu$. The event rate is proportional to $(E_\mu)^3$. The $\bar{\nu}N$ cross section is about 1/2 of the $\nu N$ cross section. The charged-current cross section for $\nu_\tau N$ suffers from kinematic suppression at low neutrino energies.

Muons are the easiest to detect. The sign of the muon needs to be measured to distinguish $\nu_\mu \rightarrow \nu_\mu$ (right-sign $\mu$) and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ (wrong-sign $\mu$). The backgrounds to the wrong-sign signal are expected to be small if the energy of the detected $\mu$ is $\gtrsim 4$ GeV, which requires stored muon energies $E_\mu \gtrsim 20$ GeV. The sign of electrons is more difficult to determine. It might only be possible to measure the combined $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_e \rightarrow \bar{\nu}_e$ events. Tau-leptons can be detected kinematically or by kinks. The $\tau$-production threshold of $E_\nu = 3.5$ GeV requires higher energy neutrino beams.

The critical parameters of neutrino factory experiments are the number of useful muon decays $N$, the baseline $L$, and the data sample size (kt-years), where the latter is defined as the product of the detector fiducial mass, the
efficiency of the signal selection requirements, and the number of years of
data taking. An entry-level machine may have \( N = 6 \times 10^{19} \) and \( E_\mu = 
20 \) GeV, while a high-performance machine may have \( N = 6 \times 10^{20} \) and \( E_\mu = 
35–70 \) GeV. The average neutrino beam energies are related to the stored
muon energies by \( \langle E_{\nu_\mu} \rangle = 0.7 E_\mu \) and \( \langle E_{\nu_e} \rangle = 0.6 E_\mu \). Baseline distances from
730 km to 10,000 km are under consideration. For an iron scintillator target a
detector mass of 10–50 kt may be employed. With these factories, thousands
of neutrino events per year could be realized in a 10 kt detector anywhere on
Earth. A number of recent studies have addressed the potential of long-baseline
experiments to determine the neutrino masses and mixing parameters\(^6–14\).

3 Physics Agenda (PA)

There is a well-defined set of physics goals for long-baseline neutrino experi-
ments, as follows.

**PA1**: The measurement of \( \theta_{13} \) is a primary goal. A nonzero value of \( \theta_{13} \)
is essential for CP violation and for matter effects with electron-neutrinos. The
flavor-changing vacuum probabilities in the leading-oscillation approximation
are

\[
P(\nu_e \to \nu_\mu) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right),
\]

(1)

\[
P(\nu_e \to \nu_\tau) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right),
\]

(2)

\[
P(\nu_\mu \to \nu_\tau) \simeq \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left( \frac{\delta m_{\text{atm}}^2 L}{4E} \right).
\]

(3)

The \( \nu_e \to \nu_\mu \) and \( \nu_e \to \nu_\tau \) appearance channels provide good sensitivity to \( \theta_{13} \); including the disappearance channels improves the sensitivity. All baselines
are okay for a \( \theta_{13} \) measurement.

**PA2**: The sign of \( \delta m_{32}^2 \) determines the pattern of neutrino masses (i.e., whether the
closely spaced mass-eigenstates that give \( \delta m_{\text{solar}}^2 \) lie above or below the
third mass-eigenstate). The coherent scattering of electron neutrinos in matter
gives a probability difference \( P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) \) that is positive for
\( \delta m_{32}^2 > 0 \) and negative for \( \delta m_{32}^2 < 0 \). At baselines of about 2000 km or longer,
a proof in principle has been given that the sign of \( \delta m_{32}^2 \) can be determined
in this way at energies \( E_\nu \sim 15 \) GeV or higher\(^6\). A complicating factor is that
fake CP violation from matter effects must be distinguished from intrinsic CP
violation due to the phase \( \delta \).

In the presence of matter the \( \nu_e \to \nu_\mu \) probability at small \( \theta_{13} \) is approxi-
\[ \langle P(\nu_e \rightarrow \nu_\mu) \rangle \simeq \frac{\sin^2 2\theta_{13}}{1 - \frac{\langle A \rangle}{\delta m^2_{32}}} \sin^2 \left\{ 1.27 \frac{\delta m^2_{32} L}{\langle E_{\nu} \rangle} \left| 1 - \frac{\langle A \rangle}{\delta m^2_{32}} \right| \right\} , \tag{4} \]

where \( \langle A \rangle = 2\sqrt{2} G_F \langle N_e \rangle \langle E_{\nu} \rangle \). The sign of \( A \) is reversed for \( \bar{\nu}_e \rightarrow \bar{\nu}_\mu \). Matter effects can enhance appearance rates by an order of magnitude at long baselines. One appearance channel is enhanced and the other suppressed so the separation of the \( \nu_e \rightarrow \nu_\mu \) and \( \bar{\nu}_e \rightarrow \bar{\nu}_\mu \) probabilities turns on as \( L \) increases.

**PA3:** Precision measurements of the leading-oscillation parameters at the few percent level are important for testing theoretical models of masses and mixing. The magnitude of \( \delta m^2_{32} \) affects the shape of the oscillation suppression and \( \sin^2 2\theta_{23} \) affects the amount of suppression, so both can be well measured by neutrino factories.

**PA4:** The subleading \( \delta m^2_{\text{solar}} \) solar oscillation can be probed if the currently favored large-angle mixing (LAM) solution to the solar neutrino problem proves correct. The KAMLAND reactor \( \bar{\nu}_e \) experiment should also accurately measure the subleading-oscillation parameters of the LAM solution.

**PA5:** An important goal of neutrino factories is to detect intrinsic CP violation, \( P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \). This is only possible if the solar solution is LAM. Sensitivity to intrinsic CP violation is best for baselines \( L = 2000\text{–}4000 \) km. Intrinsic CP violation at a neutrino factory dominates matter effects for small \( \theta_{13} \) (\( \sim 10^{-4} \)), whereas matter effects dominate intrinsic CP for large \( \theta_{13} \) (\( \sim 10^{-1} \)).

## 4 Conventional Neutrino SuperBeams

Conventional neutrino beams are produced from decays of charged pions. These beams of muon-neutrinos have small components of electron-neutrinos. Possible upgrades of existing proton drivers to megawatt (MW) scale are being considered to produce conventional neutrino superbeams. An upgrade to 4 MW of the 0.77 MW beam at the 50 GeV proton synchrotron of the proposed Japan Hadron Facility (JHF) would give an intense neutrino superbeam (SuperJHF) of energy \( E_\nu \sim 1 \) GeV. An upgrade of the 0.4 MW proton driver at Fermilab would increase the intensity of the NuMI beam by a factor of four (SuperNuMI) with three options for the peak neutrino energy \( [E_\nu(\text{peak}) \sim 3 \text{ GeV (LE)}, 7 \text{ GeV (ME)}, \text{ and } 15 \text{ GeV (HE)}] \). The capabilities of these conventional superbeams to accomplish parts of the neutrino oscillation physics agenda are currently being explored. Very large water detectors or smaller liquid argon detectors with excellent background rejection would be used in conjunction with the superbeams.
5 Physics Reach

The results in this section summarize a recent comparative study of superbeam and neutrino-factory physics capabilities in future medium- and long-baseline experiments. The reach of various superbeam and neutrino factory options are compared in Table 1. In these results 3 years of neutrino running followed by 6 years of anti-neutrino running is assumed. For superbeams the argon detector (A) has 30 kt fiducial mass and the water detector (W) a 220 kt fiducial mass, a factor of 10 larger than SuperKamiokande; signal efficiency and estimated detector backgrounds are taken into account. For neutrino factories a 50 kt iron scintillator detector is assumed.

The $\sin^2 2\theta_{13}$ reach at neutrino factories depends on the subleading scale $\delta m_{21}^2$. This dependence is illustrated in Fig. 1 for stored muon energies of 20, 30, 40 and 50 GeV.

![Figure 1: Limiting $\sin^2 2\theta_{13}$ sensitivity for the observation of $\nu_\mu \rightarrow \nu_e$ oscillations expected with superbeams and neutrino factories versus the subleading scale $\delta m_{21}^2$. (Adapted from the study in Ref. [17]).](image)

The $\text{sign}(\delta m_{32}^2)$ and CP sensitivities are illustrated in Figures 2–5 for var-
Table 1: Summary of the $\sin^2 2\theta_{13}$ reach (in units of $10^{-3}$) for various combinations of neutrino beam, distance, and detector for (i) a 3σ $\nu_\mu \rightarrow \nu_e$ appearance with $\delta m_{21}^2 = 10^{-5}$ eV$^2$, (ii) an unambiguous 3σ determination of the sign of $\delta m_{32}^2$ with $\delta m_{21}^2 = 5 \times 10^{-5}$ eV$^2$, and (iii) a 3σ discovery of CP violation for $\delta m_{21}^2 = 5 \times 10^{-4}, 1 \times 10^{-4}$, and $2 \times 10^{-4}$ eV$^2$, from left to right respectively. Dashes in the sign of $\delta m_{32}^2$ column indicate that the sign is not always determinable. Dashes in the CPV columns indicate CPV cannot be established for $\sin^2 2\theta_{13} \leq 0.1$, the current experimental upper limit, for any values of the other parameters. The CPV entries are calculated assuming the value of $\delta$ that gives the maximal disparity of $N(e^+)$ and $N(e^-)$; for other values of $\delta$, CP violation may not be measurable.

| Beam       | $L$ (km) | Detector | $\sin^2 2\theta_{13}$ reach (in units of $10^{-3}$) | (i) | (ii) | (iii) |
|------------|----------|----------|-----------------------------------------------|-----|-----|-----|
| JHF        | 295      | A        | 25                                           | −   | −   | −   | 25 |
|            |          | W        | 17                                           | −   | −   | 40  | 8  |
| SJHF       | 295      | A        | 8                                            | −   | −   | 5   | 3  |
|            |          | W        | 15                                           | −   | 100 | 20  | 5  |
| SNUMI LE   | 730      | A        | 7                                            | −   | 100 | 20  | 4  |
|            |          | W        | 30                                           | −   | −   | −   | 40 |
| SNUMI ME   | 2900     | A        | 3                                            | 6   | −   | −   | 100|
|            |          | W        | 8                                            | 15  | −   | −   | −  |
|            | 7300     | A        | 6                                            | 6   | −   | −   | −  |
|            |          | W        | 3                                            | 3   | −   | −   | −  |
| SNUMI HE   | 2900     | A        | 3                                            | 7   | −   | 100 | 20 |
|            |          | W        | 10                                           | 15  | −   | −   | −  |
|            | 7300     | A        | 4                                            | 4   | −   | −   | −  |
|            |          | W        | 3                                            | 3   | −   | −   | −  |
| 20 GeV NuF| 2900     | 50 kt    | $0.5$                                        | 2.5 | −   | 2   | 1.5|
| $1.8 \times 10^{20} \mu^+$ | 7300     |          | $0.5$                                        | 0.3 | −   | −   | −  |
| 20 GeV NuF| 2900     | 50 kt    | $0.1$                                        | 1.2 | 0.6 | 0.4 | 0.6|
| $1.8 \times 10^{21} \mu^+$ | 7300     |          | $0.07$                                       | 0.1 | −   | −   | −  |

ious neutrino beam and detector choices:

(i) neutrino factory with $E_\mu = 20$ GeV and $L = 2900$ km (Fig. 2);
(ii) SJHF with a water Cherenkov detector at $L = 295$ km (Fig. 3);
(iii) SNUMI with an $E_\nu$(peak) $\sim 3$ GeV beam and a liquid argon detector at $L = 730$ km (Fig. 4);
(iv) SNUMI with an $E_\nu$(peak) $\sim 15$ GeV beam and a liquid argon detector at $L = 2900$ km (Fig. 5).
In these SNUMI examples, the CP sensitivity is better in (iii) and the sign($\delta m_{32}^2$) sensitivity is better in (iv).

The conclusions from our comparative study of neutrino factories and conventional superbeams are as follows:

(i) A neutrino factory can deliver between one and two orders of magnitude better reach in $\sin^2 2\theta_{13}$ for $\nu_e \to \nu_\mu$ appearance, the sign of $\delta m_{32}^2$, and CP violation. At an $L = 3000$ km baseline there is excellent sensitivity to all three observables. The $\sin^2 2\theta_{13}$ reach is below $10^{-4}$. The sign of $\delta m_{32}^2$ can be determined and a detection of maximal CP violation made if $\sin^2 2\theta_{13}$ is larger than $10^{-3}$.

(ii) Superbeams with a sufficiently ambitious detector can probe $\sin^2 2\theta_{13}$ down to a few $\times 10^{-3}$. Maximal CP violation may be detected with a
JHF or SJHF beam \((E_\nu \sim 1 \text{ GeV})\) at short baselines, but these facilities will have little sensitivity to \(\text{sign}(\delta m_{32}^2)\). Higher-energy superbeams could determine \(\text{sign}(\delta m_{32}^2)\) but have little sensitivity to CP violation.

6 Short Baselines

If the LSND effect in \(\nu_\mu \rightarrow \nu_e\) and \(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\) oscillations is confirmed by Mini-BooNE, then an optimal baseline for future CP-violation studies with a neutrino factory would be

\[
L \approx 45 \text{ km} \left( \frac{0.3 \text{ eV}^2}{\delta m_{LSND}^2} \right) \left( \frac{E_\mu}{20 \text{ GeV}} \right). \tag{5}
\]

The distance from Fermilab to Argonne is 30 km, for example. In four-neutrino oscillations, which would be indicated if the LSND, atmospheric, and solar effects are all due to neutrino oscillations, there are 3 CP-violating phases.
The size of CP-violating effects in $\nu_e \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ may be enhanced or reduced relative to three-neutrino oscillations.

7 Overview

We briefly sum up our conclusions regarding future neutrino factory and conventional superbeam studies of neutrino oscillations:

- Three-neutrino mixing and $\delta m^2$ parameters can be measured at neutrino factories.
- The amplitude $\sin^2 2\theta_{13}$ is the most crucial parameter. It can be measured down to $10^{-4}$ at a neutrino factory or to $3 \times 10^{-3}$ with superbeams.
- A baseline $L \sim 3000$ km is ideal for neutrino factory measurements of $\text{sign}(\delta m^2_{32})$, CP violation, and the subleading $\delta m^2_{21}$ oscillations.
Figure 5: 3σ error ellipses in the \( [N(e^+), N(e^-)] \) plane, shown for the liquid argon detector scenario at \( L = 2900 \) km with the upgraded HE SNeMI beam. The contours are for \( \delta m^2_{21} = 10^{-4} \text{eV}^2 \). The solid and long-dashed curves correspond to the CP-conserving cases \( \delta = 0^\circ \) and \( 180^\circ \), respectively, and the short-dashed and dotted curves correspond to two other cases that give the largest deviation from the CP-conserving curves; along these curves \( \sin^2 2\theta_{13} \) varies from 0.001 to 0.1, as indicated. (From Ref. 17.)

- A longer baseline, \( L \sim 7300 \) km, is best for precision on \( \delta m^2_{32} \) and \( \sin^2 2\theta_{32} \) at a neutrino factory; for superbeam measurements of \( \sin^2 2\theta_{13} \) baselines of 3000–7000 km do equally well.
- Measurements at two baselines would provide complementary advantages (2800 and 7300 for neutrino factories or 295 km and 3000-7000 km for superbeams).
- With the LAM solar solution, intrinsic CP-violating effects could be observable at SuperJHF and at a neutrino factory. The false CP-violation from matter is a serious but manageable complication at long baselines. Further studies are needed to determine the range of \( \delta \) for which CP-violating effects are measurable.
- For four-neutrino oscillations, short baselines (\( L \sim 5–50 \) km) are also important. With four neutrinos, CP violation occurs at the \( \delta m^2_{\text{atm}} \) scale and large effects may be seen.
• Superbeams may be a reasonable next step in exploration of the neutrino sector. However, neutrino factories will eventually be needed for a complete understanding of the neutrino flavor-changing transitions.

Acknowledgments

I thank K. Whisnant for comments and S. Geer, R. Raja, and K. Whisnant for collaboration on this study. This research was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-95ER40896 and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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