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# Phenomenology of neutrino oscillations at the neutrino factory

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# Phenomenology of neutrino oscillations at the neutrino factory

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**Abstract.** We consider the prospects for a neutrino factory to measure mixing angles, the CP violating phase and mass-squared differences by detecting wrong-charge muons arising from the chain $\mu^+ \to \nu_e \to \nu_\mu \to \mu^-$ and the right-charge muons coming from the chain $\mu^+ \to \bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$ (similar to $\mu^-$ chains), where $\nu_e \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ are neutrino oscillation channels through a long baseline. First, we perform the baseline and energy optimization of the neutrino factory including the latest simulation results from the magnetized iron neutrino detector (MIND). Second, we study physics with near detectors and consider the treatment of systematic errors including cross section errors, flux errors, and background uncertainties. Third, the effects of one additional massive sterile neutrino are investigated in the context of near and far detector combinations.

## 1. Introduction

Neutrino oscillation experiments have provided compelling evidence that the active neutrinos are massive particles [1], calling for physics beyond the Standard Model. Given three generations of massive neutrinos, two mass-squared differences $\Delta m^2_{21}$ and $|\Delta m^2_{31}|$ are well understood while we have well-constrained mixing angles $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$ so far [2], including the new results from T2K [3] and MINOS [4] hinting at a non-zero $\theta_{13}$. There are still unknown problems in the standard scenario: whether $\Delta m^2_{31} > 0$ (normal ordering) or $\Delta m^2_{31} < 0$ (inverted ordering); the value of $\theta_{13}$, and whether there is CP violation (CPV) in the lepton sector.

An exceptional LSND measurement has implied an $\mathcal{O}(1)$ eV$^2$ mass-squared difference [5], which naturally requires an additional sterile neutrino with $|\Delta m^2_{41}| \gg |\Delta m^2_{31}|$. A global fit to experimental data, however, is not in favor to this hypothesis [6]. The recent results from MiniBooNE, however, are consistent with sterile neutrino oscillations in the antineutrino sector [7]. It becomes a crucial question whether the sterile neutrino exists or not.

A neutrino factory is able to answer questions in terms of three active neutrinos and find clues whether there are any sterile neutrinos or not. In the neutrino factory, electron neutrinos and muon neutrinos are produced by pure muon decays. Then signals are caused by wrong-charged muons arising from the chain $\mu^+ \to \nu_e \to \nu_\mu \to \mu^-$ and the right-charged muons coming from the chain $\mu^+ \to \bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$ (similar to $\mu^-$ chains), where $\nu_e \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ are neutrino oscillation channels through a long baseline. A magnetized detector, such as MIND, is proposed to fulfill the requirements of charge identifications. The baseline configurations in the International Design Study for the Neutrino Factory (IDS-NF) [8] include the beam energy at

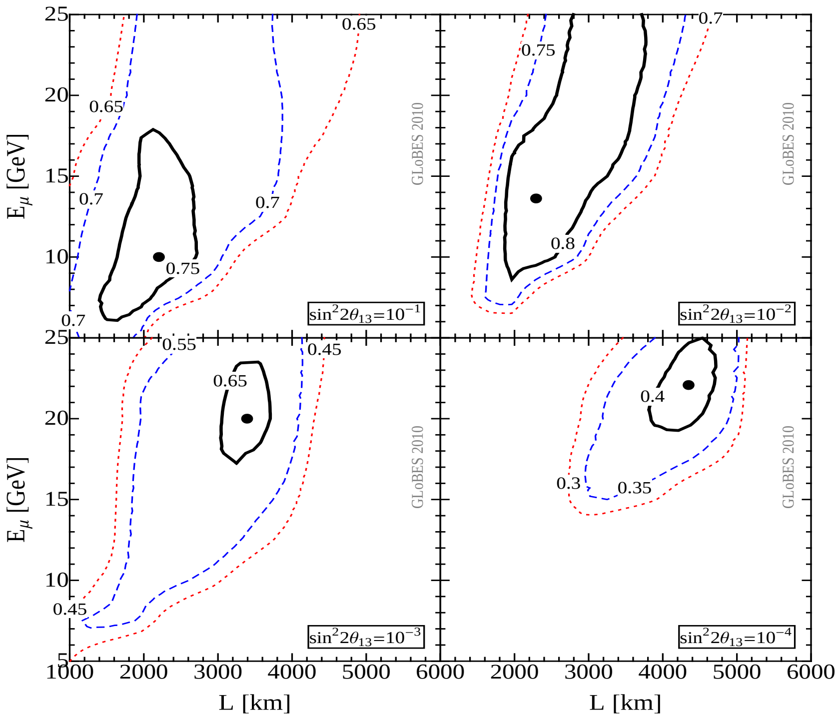


**Figure 1.** The discovery reach of CP violations (at $3\sigma$ C.L.) as a function of the baseline $L$ and the beam energy $E_\mu$ for the single baseline neutrino factory with 50 kt detector. The contours are the fraction of CP violating $\delta_{\rm CP}$. The optimal performance is marked by a dot: $(2200, 10.00)$, $(2288, 13.62)$, $(3390, 20.00)$ and $(4345, 22.08)$ with regard to their best reaches of the fraction of $\delta_{\rm CP}$ at: 0.77, 0.84, 0.67 and 0.42. The figure is taken from the reference [10].

$E_\mu = 25\,\text{GeV}$ and two MINDs located at $L_1 \simeq 3\,000 - 5\,000\,\text{km}$ and $L_2 \simeq 7\,500\,\text{km}$ (the "magic" baseline [9]), respectively. In addition, there are no Near Detectors (NDs) in the IDS-NF.

## 2. Update of optimization of the neutrino factory

Recently more refined detector simulations have become available [11, 12] and $\nu_e(\nu_\mu) \to \nu_\tau \to \tau \to \mu$ (similar to the other polarity) has been ignored for a long time [13, 14]. There is a strong request for an re-optimization of the beam energy and baseline at the neutrino factory in light of new migration matrices for MINDs including the oscillated-$\nu_\tau$ related backgrounds. We consider the so-called migration matrices bridging between the incident and reconstructed neutrino energies. It can also apply to tau related backgrounds. We update the optimization of the beam energy and baselines for the neutrino factory. From Fig. 1, we can read that the low-energy and high-energy neutrino factory are two versions of the same experiment optimized for different parameter space. For large $\sin^2 2\theta_{13} \simeq 10^{-1}$, shorter baselines and lower energies are preferred. Compared to earlier analyses without background migrations, too high $E_\mu$ are in fact disfavored in the large $\sin^2 2\theta_{13}$ case. As for a traditional high-energy neutrino factory with $E_\mu \simeq 20 - 25$ GeV, the baseline between 4 000 and 5 000 km is still preferred.

## 3. Oscillation physics by active neutrinos with near detectors

The previous IDS-NF setup usually assumes the systematic errors coming from signal and background normalization errors uncorrelated among all channels and detectors. It is similar to the uncertainties for cross sections as well. We can take the $\nu_\mu \to \nu_\mu$ channel as an example to

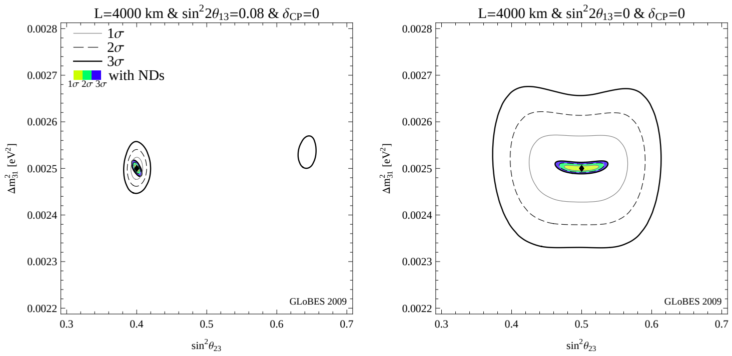


**Figure 2.** A comparison of the precision measurement at the $\sin^2\theta_{23}$–$\Delta m^2_{31}$ plane for the 4000 km baseline neutrino factory with or without NDs. The best fit points are marked by diamonds. The figures are adapted from [15].

explain how near detectors cancel systematic uncertainties. We have the events for near detector (ND) and far detector (FD):

$$n^{\rm ND}_{\nu_\mu} = \frac{N_{\rm ND}}{L^2_{\rm ND}}\Phi_{\nu_\mu}\sigma_{\nu_\mu}\epsilon_{\nu_\mu} \tag{1}$$

$$n^{\rm FD}_{\nu_\mu} = \frac{N_{\rm FD}}{L^2_{\rm FD}}\Phi_{\nu_\mu}P(\nu_\mu\to\nu_\mu)\sigma_{\nu_\mu}\epsilon_{\nu_\mu} \tag{2}$$

We can immediately identify the dependence of $\sigma_{\nu_\mu}\epsilon_{\nu_\mu}$ cancels between near and far detectors after a combination of them:

$$n^{\rm FD}_{\nu_\mu} = n^{\rm ND}_{\nu_e}\frac{N_{\rm FD}}{N_{\rm ND}}\frac{L^2_{\rm ND}}{L^2_{\rm FD}}P(\nu_\mu\to\nu_\mu) \tag{3}$$

It implies that the uncertainties of cross sections and the detection efficiency will not take any effects assuming the same technology for ideal NDs and FDs. A refined treatment of systematic uncertainties including all channels is given in the reference [15]. As shown in Fig. 2, we make a comparison of the precision measurement in the $\sin^2\theta_{23}$–$\Delta m^2_{31}$ plane for the 4000 km baseline neutrino factory with or without NDs. We find a significant improvement of sensitivity once we include NDs.

## 4. Combine near and far detectors to search for sterile neutrinos

While earlier studies have focused on sterile neutrinos with a LSND-like mass splitting $\mathcal{O}(\mathrm{eV}^2)$ (see the references [1, 6, 17]), we cannot rely on constraints from the atmospheric and solar experiments, which need to be re-analyzed in a global fit for the presence of very light sterile neutrinos in a self-consistent way. Therefore, we combine both near and far detectors to search for arbitrarily massive sterile neutrinos in a self-consistent treatment. In terms of one additional sterile neutrino, there are four different scenarios corresponding to $\Delta m^2_{31}>0$, $\Delta m^2_{41}>0$ (A), $\Delta m^2_{31}>0$, $\Delta m^2_{41}<0$ (B), $\Delta m^2_{31}<0$, $\Delta m^2_{41}>0$ (C), and $\Delta m^2_{31}<0$, $\Delta m^2_{41}<0$ (D). They are shown in the caption of Fig. 3. We consider the following configurations: two near detectors – each with a mass of 32 t, and each with a distance of $d=2$ km from the end of the straight section in the muon storage ring, combined with two far MINDs with one at 4000 km and the other at 7500 km. As shown in Fig. 3, the upper peak hardly depends on the mass ordering. The lower (long-baseline) peak, which is only present in the middle and right panels, depends on the mass ordering. There are two qualitatively different cases: for the schemes A and D, the sensitivity is destroyed just at the value of $\Delta m^2_{31}$ while the exclusion limits for the schemes B and C remain unchanged.

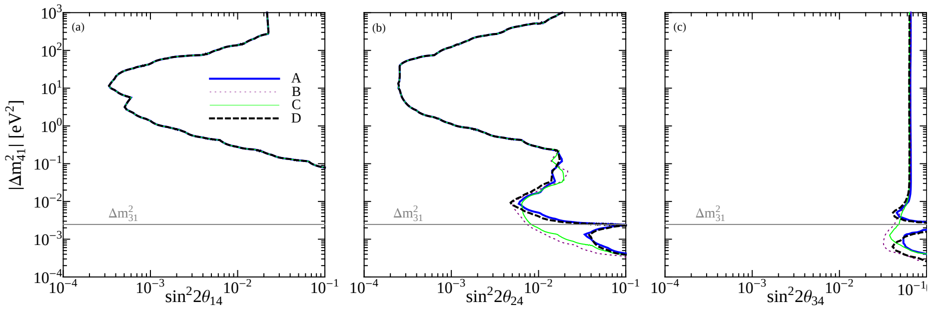


**Figure 3.** The exclusion limit of $\sin^2 2\theta_{i4}$–$\Delta m^2_{41}$ $(i = 1, 2, 3)$ in terms of arbitrarily massive sterile neutrinos. Four different mass orderings are taken into account such as $\Delta m^2_{31} > 0$, $\Delta m^2_{41} > 0$ (A), $\Delta m^2_{31} > 0$, $\Delta m^2_{41} < 0$ (B), $\Delta m^2_{31} < 0$, $\Delta m^2_{41} > 0$ (C), and $\Delta m^2_{31} < 0$, $\Delta m^2_{41} < 0$ (D). The figure is taken from [16].

## 5. Conclusions

The neutrino factory is one of the most powerful machine towards neutrino oscillation physics. We have revisited the optimization of the beam energy and the baselines in light of the latest information. We have found that the low-energy and high-energy neutrino factory are just two versions of the same experiment optimized for a different parameter space. In addition, we have discussed how to adopt NDs to cancel systematic uncertainties. We have shown the impact on NDs at the precision measurement of $\theta_{23}$ and $\Delta m^2_{31}$. Finally, we have investigated the search for sterile neutrinos by combining NDs and FDs at the neutrino factory. A substantial difference of four different mass orderings has been presented.

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