

Optimized Neutrino Factory for small and large θ_{13}

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Abstract. Recent results from long baseline neutrino oscillation experiments point towards a non-zero value of θ_{13} at around 3σ confidence level. In the coming years, further ratification of this result with high significance will have crucial impact on the planning of the future long baseline Neutrino Factory setup aimed to explore leptonic CP violation and the neutrino mass ordering. In this talk, we discuss the baseline and energy optimization of the Neutrino Factory including the latest simulation results on the magnetized iron neutrino detector (MIND) in the light of both small and large θ_{13} . We find that in case of small θ_{13} , baselines of about 2500 to 5000 km is the optimal choice for the CP violation measurement with E_μ as low as 12 GeV can be considered. However, for large θ_{13} , we show that the lower threshold and the backgrounds reconstructed at lower energies allow in fact for muon energies as low as 5 to 8 GeV at considerably shorter baselines, such as Fermilab to Homestake. This suggests that with the latest MIND simulation, low- and high-energy versions of the Neutrino Factory are just two different forms of the same experiment optimized for different regions of the parameter space.

1. Introduction and Motivation

The performance of future long baseline neutrino oscillation experiments to unravel leptonic CP violation (CPV) and the neutrino mass hierarchy (MH) is crucially dependent on the achievable event rates and hence strongly on the size of θ_{13} [1–4]. Recent T2K [5] and MINOS [6] data have provided new information on θ_{13} , indicating that $0.01 \lesssim \sin^2 2\theta_{13} \lesssim 0.1$ at 2σ confidence level with a best-fit value of 0.051 (0.063) for normal (inverted) mass ordering [7]. It is expected that in the next few years, this hint will be validated with high significance with more informations coming from the T2K, MINOS and upcoming reactor and $\text{NO}\nu\text{A}$ experiments, opening up the possibility of observing CPV in the lepton sector if the Dirac CP phase, δ_{CP} , is not equal to 0° or 180° .

The prospects of the present generation long baseline experiments, T2K and $\text{NO}\nu\text{A}$ in probing CPV and the mass ordering are very limited even if θ_{13} is large [8]. The experiment class, which can ultimately address these unsolved issues with unprecedented sensitivity for both small and large θ_{13} , is the Neutrino Factory [1,3]. In a Neutrino Factory, the neutrino beam is created from the decay of muons in flight in the straight sections of a storage ring. The International Neutrino Factory and Superbeam Scoping Study [1,9,10] has laid the foundations for the currently ongoing Design Study for the Neutrino Factory (IDS-NF) [11] which has come up with a first-version baseline setup of a high energy neutrino factory (HENF) with $E_\mu = 25$ GeV and two baselines $L_1 \simeq 3\,000 - 5\,000$ km and $L_2 \simeq 7\,500$ km served by two racetrack-shaped storage rings [12].

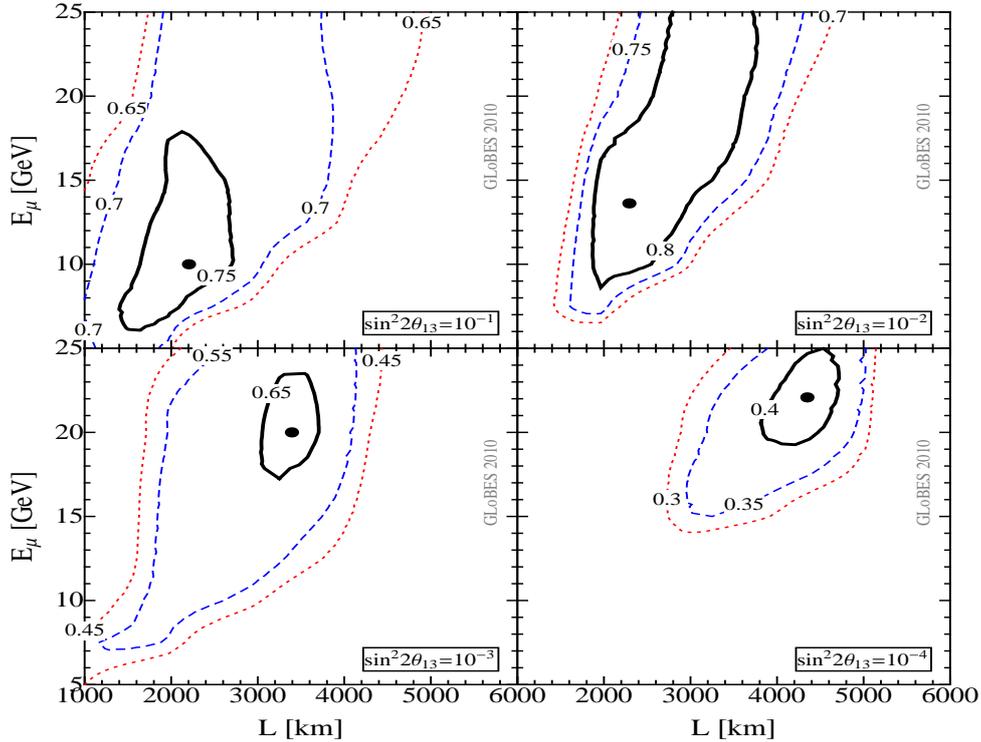


Figure 1. Fraction of $\delta_{\text{CP}}(\text{true})$ for which CPV will be discovered at 3σ C.L. as a function of L and E_μ for the single baseline Neutrino Factory. The different panels correspond to different true values of $\sin^2 2\theta_{13}$, as given there. Here we consider 5×10^{21} useful muon decays in total with a 50 kt detector. 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 $\delta_{\text{CP}}(\text{true})$ at: 0.77, 0.84, 0.67 and 0.42.

The most promising avenue to explore CPV and $\text{sgn}(\Delta m_{31}^2)$ at a Neutrino Factory is the subdominant $\nu_e \rightarrow \nu_\mu$ oscillation channel which produces muons of the opposite charge (wrong-sign muons) to those stored in the storage ring and these can be detected with the help of the charge identification capability of a magnetized iron neutrino detector (MIND) [13]. As the design of the Neutrino Factory matures, more realistic detector simulation and analysis technique have been developed which improves the efficiency of MIND at low energies and also lowers the threshold [14, 15]. These new simulations provide the full response matrices for all the signal and background channels. In the most recent analysis [15], low energy neutrino signal events down to 1 GeV were selected with an efficiency plateau of $\sim 60\%$ for ν_μ and $\sim 80\%$ for $\bar{\nu}_\mu$ events starting at ~ 5 GeV, while maintaining the background level at or below 10^{-4} . For the neutral current background, the impact of migration is non-negligible and it is peaked at lower energies. This feed-down is the strongest effect of migration and thus has potential impact on the energy optimization, since it penalizes neutrino flux at high energies, where there is little oscillation but a large increase in feed-down background. Now we discuss the simultaneous optimization of baseline and muon energy in a green-field Neutrino Factory scenario [3] using the new migration matrices for MIND detector [15].

2. Optimization of a green-field Neutrino Factory setup with new MIND detector

Here we are interested to optimize L and E_μ for the single baseline Neutrino Factory to have CPV discovery at 3σ C.L. for different fractions of true values of δ_{CP} assuming that the true

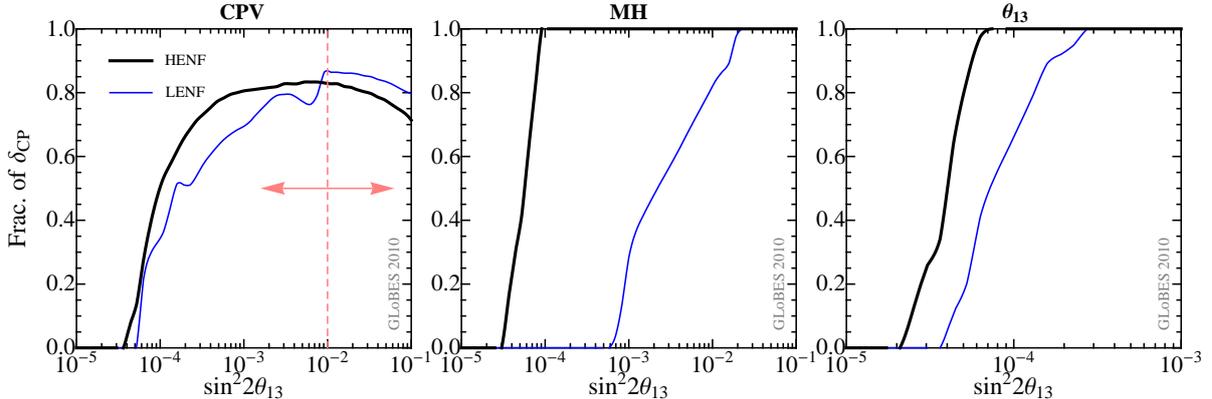


Figure 2. CP fractions for which a discovery at 3σ confidence level is possible as a function of true $\sin^2 2\theta_{13}$. From left to right for CPV, MH and θ_{13} . Here we compare the performances of a single baseline LENS with $E_\mu = 10$ GeV, $L = 2000$ km, and a 50 kt MIND detector, and a two baseline HENF with $E_\mu = 25$ GeV and a 50 kt MIND detector at each baseline, and $L_1 = 4000$ km, and $L_2 = 7500$ km.

value of $\sin^2 2\theta_{13}$ is known. The different panels of Fig. 1 depict the same for four different true values of $\sin^2 2\theta_{13}$. As expected, this figure clearly shows that the optimization strongly depends on the true value of $\sin^2 2\theta_{13}$ chosen. In case of large $\sin^2 2\theta_{13} \simeq 10^{-1}$, shorter baselines and lower energies are preferred. Even E_μ as low as 5 to 8 GeV at the Fermilab-Homestake baseline of about 1300 km is quite close to the optimal choice, which means that the MIND detector approaches the magnetized totally active scintillator detector performance of the low energy Neutrino Factory (LENF) [16]. Note that compared to earlier analyses without feed-down effect due to background migration, now too high E_μ are in fact disfavored in the large $\sin^2 2\theta_{13}$ case. For the other extreme, $\sin^2 2\theta_{13} \simeq 10^{-4}$, baselines between 4000 and 5000 km are preferred with $E_\mu \simeq 20 - 25$ GeV, which corresponds more to the choice of L_1 for HENF, such as the IDS-NF baseline. Including the other two panels, the optimal region within each panel moves from the lower left on the plots to the upper right as the true value of $\sin^2 2\theta_{13}$ decreases. This means that, depending on the choice of true $\sin^2 2\theta_{13}$, the optimization results in the LENS, the HENF, or an intermediate scenario, and that the low and high energy Neutrino Factories are just two versions of the same experiment optimized for different parts of the parameter space. Note that, all the figures presented in this talk have been taken from [3] and all the simulations have been performed using the GLOBES software [17, 18].

3. Summary and conclusions

In this talk, we have discussed the optimization of the Neutrino Factory based on the most up-to-date analysis of the MIND detector using response matrices for all the signal and background channels. The lower threshold and higher efficiencies compared to earlier simulations indicate that the MIND detector characteristics are getting more similar to the characteristics of the detectors proposed for the LENS (e.g., a magnetized TASD). For large $\sin^2 2\theta_{13}$, a single baseline Neutrino Factory with E_μ as low as 5 to 8 GeV and a baseline as short as Fermilab to Homestake (about 1300 km) might be sufficient. In the case of small $\sin^2 2\theta_{13} < 10^{-2}$, however, a two baseline Neutrino Factory with one baseline between about 2500 km and 5000 km, the other one at about the magic baseline 7500 km is ideal. The additional information coming from the second baseline which is at the magic distance (insensitive to δ_{CP}) helps to remove the degeneracies and it enhances the fraction of δ_{CP} for which CPV discovery is possible. Fig. 2 nicely depicts this message where we compare the performance of the optimal single baseline LENS with the optimal two baseline HENF for the same MIND detector. It is quite evident from this figure

that for $\sin^2 2\theta_{13} \gtrsim 10^{-2}$ the low energy version can perform all of the required measurements, whereas for smaller values the HENF is clearly better. It suggests that this different optimization would be sufficient to compensate for the relative deterioration of performance at large $\sin^2 2\theta_{13}$ observed in the traditional HENF.

We conclude that the features of the new detector simulation that the backgrounds are typically reconstructed at lower energies and that the threshold is lower have significant impact on the optimization of E_μ . The recent simulation results for the MIND have reduced the performance margin between T ASD and MIND considerably. Therefore, we suggest that the low- and high-energy Neutrino Factory should not be regarded as separate options and they merely correspond to two extreme corners of a common parameter space.

Acknowledgments

I am grateful to the conference organizers for the invitation. I would like to thank Patrick Huber, Jian Tang and Walter Winter for their collaboration. I would also like to thank Paul Soler for insightful discussions during NUFACT11. I acknowledge the support from the European Union under the European Commission Framework Programme 07 Design Study EUROnu, Project 212372 and the project Consolider-Ingenio CUP.

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