CP-Violation in 3- and 4-family at the Neutrino Factory

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The leptonic CP-violating phase δ can be measured with a Neutrino Factory with 2×10^{20} useful muons per year, if the solar neutrino problem is solved by the LMA-MSW solution, with $\Delta m^2_{12} \geq 2 \times 10^{-5}$ eV^2 (in this analysis a 40 kT magnetized iron detector is considered, taking into account its efficiencies and backgrounds). If LSND is confirmed, CP-violating phenomena in four-family scenarios can be most easily addressed with a small 1 kT detector at $L = \mathcal{O}(10)$ km (no detailed analysis of the detector efficiencies and backgrounds has been performed in this case).

1. Introduction

Indications in favour of neutrino oscillations have been obtained both in solar [1] and atmospheric [2] neutrino experiments. The atmospheric data require $\Delta m^2_{atm} \sim (2-5) \times 10^{-3}$ eV^2 [3] whereas the solar data prefer $\Delta m^2_{sun} \sim 10^{-10} - 10^{-4}$ eV^2 , depending on the particular solution to the solar neutrino deficit. LSND data [4] would indicate a $\nu_\mu \to \nu_e$ oscillation with a third mass difference, $\Delta m^2_{LSND} \sim 1$ eV^2 . Depending on MiniBooNE results [5], the chance to observe a non-zero CP-violating phase in the leptonic sector of the Standard Model is completely different. If LSND is not confirmed, the experimental results are well described by three-family neutrino oscillation. We have a 3×3 mixing matrix with three angles, θ_{12}, θ_{13} and θ_{23}, and one phase, δ. The CP-violating oscillation probability is [6]

$$P_{\not{CP}} = \pm 2J \left(\sin\Delta_{12} + \sin\Delta_{23} - \sin\Delta_{13}\right) \qquad (1)$$

with $J = c_{12}s_{12}c^2_{13}s_{13}c_{23}s_{23}\sin\delta$ the Jarlskog factor and $\Delta_{ij} = \Delta m^2_{ij} L/2E_\nu$ (the $\pm$ sign refers to neutrinos/antineutrinos). If $\Delta_{12} \ll \Delta_{23}$, $P_{\not{CP}}$ is negligible. Therefore, for three-family neutrino mixing the size of the CP-violating oscillation probability depends on the range of Δm^2_{12}. In [7,8] it has been shown that a maximal phase, $|\delta| = 90°$, can be measured at 90% CL if the LMA-MSW solution with $\Delta m^2_{12} \geq 2 \times 10^{-5}$ eV^2 is considered. For smaller values of the solar mass difference, it seems impossible to measure δ with the foreseeable beams. If LSND is confirmed, a fourth light sterile neutrino [9] is needed to accommodate the experimental results. We have in this case a 4×4 mixing matrix with six angles and three phases. In contrast with the three-family case, we can consider CP-violating observables that do not depend on the solar mass difference. Moreover, to maximize $P_{\not{CP}}$ the baseline is $\mathcal{O}(10)$ km, and the matter effects are negligible. In this case, the phases δ_i could be measured with a small, near detector with τ-detection capability [10,11].

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2. Three-Family

In ten years from now, we will know θ_{23} and Δm^2_{23} at the 10% level and at most one of the solutions to the solar neutrino problem will still be viable (with θ_{12} and Δm^2_{12} known within large errors). However, the present bounds on $\sin^2 2\theta_{13}$ will go down to 10^{-2}, at most. The Neutrino Factory [12] is a facility especially helpful for the measure of the by then (probably) unknown parameters of the MNS mixing matrix, θ_{13} and δ. It provides high energy and intense $\nu_e(\bar{\nu}_e)$ beams coming from positive (negative) muons which decay in the straight sections of a muon storage ring

[13]. The $\nu_e(\bar{\nu}_e)$ can oscillate to $\nu_\mu(\bar{\nu}_\mu)$, resulting in "wrong-sign" muons in the detector [14]. We consider a Neutrino Factory with very intense and energetic muon beam ($E_\mu = 50$ GeV , 2×10^{20} useful muons per year, 5 years of running with both polarities) and for definiteness the 40 kT magnetized iron detector described in [15]; three reference baselines have been considered, $L = 732, 3500, 7332$ km. In the LMA-MSW range, the dependence of the oscillation probabilities on the solar parameters θ_{12} and Δm^2_{12} and on the phase δ is sizeable at terrestrial distances. For this reason it is necessary to perform the simultaneous measurements of the two unknowns: θ_{13} and δ. The matter effects must be properly taken into account: if on one side they can be positively used to extract the sign of Δm^2_{23}, on the other hand the fake CP-violating asymmetry they induce complicates the measurement of the phase δ. To reduce the impact of the matter effects, naively a "short" ($L \leq 1000$ km) baseline should be best suited for a CP-violation measurement. However, it has been shown in [7] that an intermediate baseline is more appropriate (see also [16]), due to the detector efficiency and background (decreasing very fast with the distance) and to the correlation between θ_{13} and δ at short distance. At $L = 3500$ km, with the considered beam-detector setup (and the following parameter set: $\Delta m^2_{23} = 2.8 \times 10^{-3}$ eV^2 , $\Delta m^2_{12} = 1 \times 10^{-4}$ eV^2 , $\sin^2 2\theta_{23} = 1, \sin^2 2\theta_{12} = 0.5$) a precision of a few tenths of degree and of a few tens of degrees is attained for θ_{13} and δ, respectively. For $\Delta m^2_{12} \sim 5 \times 10^{-5}$ eV^2 the phase δ can still be measured, but for the lower part of the LMA-MSW solution, $\Delta m^2_{12} \sim 1 \times 10^{-5}$ eV^2 the sensitivity to CP-violation is lost (the detector mass or the intensity of the muon beam should be unrealistically increased). The error induced in the measurement of θ_{13} by the uncertainty on Δm^2_{12} and θ_{12} can be quite large. How this could affect the measurement of δ must be carefully studied. On the contrary, the Neutrino Factory should reduce the uncertainty on θ_{23} and Δm^2_{23} down to 1% through disappearance experiments [17]. This level of uncertainty is not expected to affect significantly our results.

We have quantified what is the minimum value of Δm^2_{12} for which a maximal phase, $|\delta| = 90°$, can be distinguished at 99% CL from $\delta = 0$. The result is shown in Fig. 1 for different muon beam intensity. For 2×10^{20} useful muons per year and 5 year of running with both polarities, a maximal phase can be measured for $\Delta m^2_{12} > 2 \times 10^{-5}$ eV^2, with very small dependence on θ_{13} in the range considered (for $\sin^2\theta_{13}$ down to 1×10^{-3}).

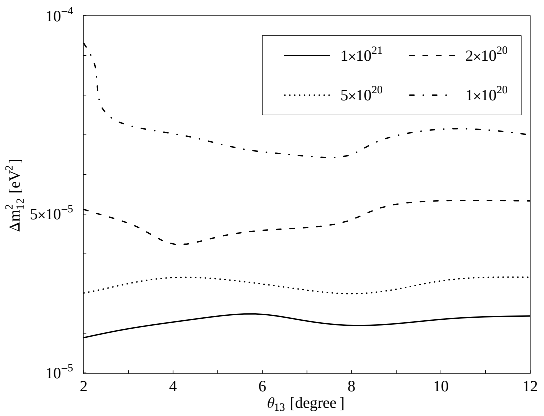

Figure 1. *Lower limit in Δm^2_{12} at which a maximal phase ($|\delta| = 90°$) can be distinguished from a vanishing phase at 99% CL, as a function of θ_{13} at L = 3500 km and for different numbers of useful muons per year (5 year of running at both polarities). Background errors and efficiencies are included.*

Recently, it has been proposed to measure δ with a low-energy, $E_\nu < 1$ GeV , conventional [18] or neutrino-factory-like [19] beam and a near detector, $L = \mathcal{O}(100)$ km. This should reduce the fake CP-asymmetry induced by matter effects whilst enhancing the CP-violating oscillation probability. However, in this case no detailed analysis taking into account the characteristics of a specific detector has been performed. Finally, the reach of a medium-high energy ($E_\nu \geq 1$ GeV) conventional "superbeam" with different detector-types (including backgrounds) has been studied in [20]. Their results show that is very unlikely that δ can be measured with these facilities, except for a small region of parameter space with $\Delta m_{12}^2 \geq 1 \times 10^{-4}$ and $\sin^2\theta_{13} \geq 2 \times 10^{-2}$ where a maximal phase can be distinguished at 99% CL from $\delta = 0, \pi$ with a JHF-like beam on a supermassive water Cherenkov at $L = 295$ km.

3. Four-Family

As in the standard three-family scenario, to observe CP-odd effects in oscillations it is necessary to have both physical CP-odd phases and at least two non-vanishing mass differences. In contrast with the three-neutrino case, the solar suppression is now replaced by a less severe atmospheric suppression. CP-violating effects are expected to be at least one order of magnitude larger than in the standard case, because they are not suppressed by the solar mass difference, Δm_{12}^2.

We consider the same Neutrino Factory as for the three-family case, but with only one year of running for both polarities. For illustration we consider in what follows a generic 1 kT detector located at $O(10)$ km distance from the neutrino source with τ-detection capability [10].

In a four-family scenario, the mixing matrix is a 4×4 unitary matrix with six angles and three phases. In the "two mass scale dominance" scheme, we neglect the solar mass difference and end up with a reduced parameter space, consisting of five angles and two phases. We consider the 2+2 scenario (two light neutrinos with solar mass difference and two heavy neutrinos with atmospheric mass difference, and $\mathcal{O}(1)$ eV^2 LSND separation between the two pairs), with the "conservative" assumption of small cross-gap angles $\theta_{13}, \theta_{14}, \theta_{23}, \theta_{24}$. For definiteness, the chosen parameter set is Set 2 of [10,11]: $\theta_{34} = 45^\circ$, $\theta_{ij} = 2^\circ$ and $\Delta m_{atm}^2 = 2.8 \times 10^{-3}$ eV^2 for $\Delta m_{LSND}^2 = 1$ eV^2 .

We define as in [14,7] the neutrino-energy integrated asymmetry:

$$A_{\mu\tau}^{CP}(\delta) = \frac{\{N[\tau^+]/N_o[\mu^+]\} - \{N[\tau^-]/N_o[\mu^-]\}}{\{N[\tau^+]/N_o[\mu^+]\} + \{N[\tau^-]/N_o[\mu^-]\}}, \quad (2)$$

with $N[\tau^\pm]$ the measured number of taus, and $N_o[\mu^\pm]$ the expected number of muons charged current interactions in the absence of oscillations. In order to quantify the significance of the signal, we compare the value of the integrated asymmetry with its error, in which we include the statistical error and a conservative background estimate at the level of 10^{-5}. The size of the signal-over-noise ratio is very different for μ- and τ-appearance channels, the difference following the fact that the CP-even transition probability $P_{CP}\,(\nu_\mu \to \nu_\tau)$ is smaller than $P_{CP}\,(\nu_e \to \nu_\mu)$, due to a stronger suppression in small mixing angles. Notice that the opposite happens in the three-family case, where the preferred channel to measure CP-violation is $\nu_e \to \nu_\mu$.

In Fig. 2 we show the signal-over-noise ratio in $\nu_\mu \to \nu_\tau$ versus $\bar{\nu}_\mu \to \bar{\nu}_\tau$ oscillations as a function of the distance. Matter effects, although negligible, have been included, as well as the exact formulae for the probabilities. For the scenario and distances discussed here, the scaling laws are analogous to those derived for three neutrino species in vacuum. The maxima of the curves move towards larger distances when the energy of the muon beam is increased, or the assumed LSND mass difference is decreased. Increasing the energy enhances the significance of the effect at the maximum. At $E_\mu = 50$ GeV, 30 standard deviation (sd) signals are attainable at $L \simeq 40$ km, levelling off at larger distances and finally diminishing when E_ν/L approaches the atmospheric range.

4. Conclusions

If LSND is not confirmed, it is possible to measure a maximal phase $|\delta| = 90^\circ$ at a very intense high-energy ($E_\mu = 50$ GeV) Neutrino Factory, if the solar neutrino problem is found to be solved by the LMA-MSW and $\Delta m_{12}^2 \geq 2 \times 10^{-5}$, for $\sin^2\theta_{13}$ as low as 1×10^{-3}. These results have been obtained carefully taking into account the backgrounds and efficiencies of a magnetized iron detector, finding that the optimal baseline for a simultaneous measurement of θ_{13} and δ is $L \sim 3000$ km. Medium-high–energy ($E_\nu \geq 1$ GeV) conventional "super-beam" can possibly measure a maximal phase if $\sin^2\theta_{13} \geq 2 \times 10^{-2}$ and $\Delta m_{12}^2 \geq 1 \times 10^{-4}$ with a supermassive water Cherenkov detector and a

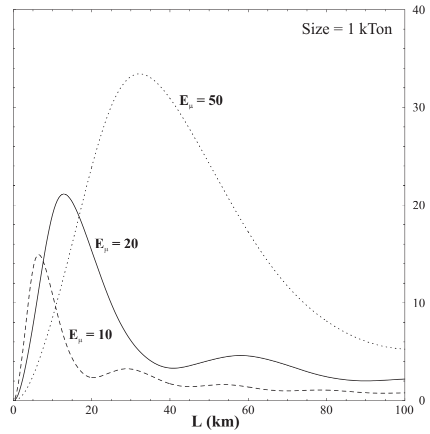

Figure 2. *Signal over statistical uncertainty for CP violation,* $|A_{\mu\tau}^{CP}(\pi/2) - A_{\mu\tau}^{CP}(0)|/\Delta A^{CP}$, *in the* $\nu_\mu \to \nu_\tau$ *channel, for the set of parameter in the text. We consider a 1 kT detector and* 2×10^{20} *useful muons per year.*

short baseline, $L \sim 300$ km. Low–energy conventional or neutrino-factory–like beams capability deserve better study with particular attention to the details of a specific detector, including background and efficiency.

If LSND is confirmed by MiniBooNE, a not-so-intense high–energy Neutrino Factory can most likely measure a maximal phase, regardless of the solar neutrino problem solution, with a small, $\mathcal{O}(1)$ kT, near detector, $L = \mathcal{O}(10)$ km, with good τ-identification capability.

REFERENCES

1. B. T. Cleveland *et al.*, Astrophys. J. **496** (1998) 505; Y. Fukuda *et al.*, Phys. Rev. Lett. **77** (1996) 1683; W. Hampel *et al.*, Phys. Lett. **B447** (1999) 127; J. N. Abdurashitov *et al.*, Phys. Rev. **C60** (1999) 055801; Y. Suzuki, Nucl. Phys. Proc. Suppl. **77** (1999) 35.
2. Y. Fukuda *et al.*, Phys. Lett. **B335** (1994) 237; R. Becker-Szendy *et al.*, Nucl. Phys. Proc. Suppl. **38** (1995) 331; Y. Fukuda *et al.*, Phys. Rev. Lett. **82** (1999) 2644; W. W. Allison *et al.*, Phys. Lett. **B449** (1999) 137; M. Ambrosio *et al.*, Phys. Lett. **B434** (1998) 451.
3. Y. Suzuki and H. Sobel, talk at Neutrino 2000, 16-21 June 2000, Sudbury, Canada.
4. C. Athanassopoulos *et al.*, Phys. Rev. Lett. **81** (1998) 1774.
5. A. Bazarko, talk at Neutrino 2000, 16-21 June 2000, Sudbury, Canada.
6. P. I. Krastev and S. T. Petcov, Phys. Lett. **B205** (1988) 84.
7. A. Cervera *et al.*, Nucl. Phys. **B579** (2000) 17.
8. A. Cervera *et al.*, hep-ph/0007281.
9. B. Pontecorvo, Sov. Phys. JETP **26** (1968) 984.
10. A. Donini *et al.*, Nucl. Phys. **574** (2000) 23.
11. A. Donini *et al.*, Nucl. Instrum. Meth. **A451** (2000) 58 and hep-ph/0007283.
12. C. Albright *et al.*, hep-ex/0008064.
13. C. M. Ankenbrandt *et al.* (Muon Collider Collaboration), Phys. Rev. ST Accel. Beams **2**, (1999) 081001; B. Autin *et al.*, CERN-SPSC/98-30, SPSC/M 617 (October 1998); S. Geer, C. Johnstone and D. Neuffer, FERMILAB-PUB-99-121.
14. A. De Rujula, M. B. Gavela and P. Hernandez, Nucl. Phys. **B547** (1999) 21.
15. A. Cervera, F. Dydak and J.J. Gomez-Cadenas, NuFact'99 and NuFact'00 Workshop.
16. K. Dick *et al.* Nucl. Phys. **B562** (1999) 29; A. Bueno, M. Campanelli and A. Rubbia, Nucl. Phys. **B589** (2000) 577; V. Barger, S. Geer and K. Whisnant, Phys. Rev. **D61** (2000) 053004; M. Freund *et al.*, Nucl. Phys. **B578** (2000) 27.
17. V. Barger *et al.*, Phys. Rev. **D62** (2000) 013004.
18. H. Minakata and H. Nunokawa, hep-ph/0004114 and hep-ph/0009091; J. Sato, hep-ph/0008056.
19. J. Sato, hep-ph/0006127.
20. V. Barger *et al.*, hep-ph/0012017.