PROCEEDINGS OF SCIENCE

# Leptonic CP Violation in Neutrino Oscillations

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One of the main goals of the ongoing and forthcoming neutrino oscillation experiments is to determine the leptonic Dirac CP-violating phase $\delta$, which is one of the fundamental constants in Nature. We first examine the radiative corrections to $\delta$, which should be taken into account when one confronts the theoretical prediction at a high-energy scale with the experimental observations at the low-energy scale. Then, the CP-violating effects in neutrino oscillations in Earth matter are discussed by using neutrino oscillograms. New working observables have been proposed to characterize the intrinsic leptonic CP violation and to optimize the experimental setups.

*The European Physical Society Conference on High Energy Physics -EPS-HEP2013*
*18-24 July 2013*
*Stockholm, Sweden*

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PoS(EPS-HEP 2013)538

## 1. Introduction

Recent years have seen great progress in neutrino physics [1]. In particular, the smallest leptonic mixing angle $\theta_{13}$ has recently been measured in the Daya Bay and RENO reactor neutrino experiments to be relatively large, i.e., $\theta_{13} \sim 9^\circ$, which is well consistent with the latest measurements from the Double Chooz experiment, and the $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ appearance results from the accelerator-based neutrino experiments MINOS and T2K. This opens up the possibility to determine neutrino mass hierarchy (i.e., the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$) in the ongoing long-baseline accelerator-based neutrino experiment NO$\nu$A, in the future medium-baseline reactor neutrino experiments (e.g., JUNO and RENO-50), and in the huge atmospheric neutrino experiments (e.g., Hyper-Kamiokande, PINGU and ORCA). The future long-baseline neutrino oscillation experiments (e.g., LAGUNA-LBNO and LBNE) and a neutrino factory will greatly improve the sensitivity to the neutrino mass hierarchy, and even to determine the leptonic CP-violating phase $\delta$.

It is interesting to notice that the latest global-fit analyses of solar, atmospheric, accelerator and reactor neutrino oscillation experiments have shown a weak hint on the leptonic CP-violating phase $\delta = (1.08^{+0.28}_{-0.31})\pi$ and $\delta = (1.67^{+0.37}_{-0.77})\pi$ from Refs. [2] and [3], respectively, although the $1\sigma$ errors are still quite large. From Ref. [4], the best-fit value is $\delta = 0.08\pi$ in the case of normal mass hierarchy (NH), and $\delta = -0.03\pi$ in the case of inverted mass hierarchy (IH). On the other hand, a lot of neutrino mass models based on discrete flavor symmetries or phenomenological assumptions have recently been proposed to describe the observed leptonic mixing pattern, in particular a relatively large $\theta_{13}$. At the same time, they predict specific values of $\delta$. The flavor models are usually constructed at superhigh-energy scales. Therefore, we are concerned with how the theoretical predictions or the observed value of $\delta$ will be modified by radiative corrections when running from a low-energy scale to a superhigh-energy scale. Furthermore, we will also study how to describe the intrinsic leptonic CP violation in neutrino oscillations, and to extract $\delta$ from observations.

## 2. Running CP-violating Phase

In order to accommodate tiny neutrino masses, one can extend the Standard Model (SM) by the Weinberg operator $\mathscr{O} = -(\overline{\ell_{\rm L}}H)\kappa(H^T\ell^{\rm C}_{\rm L})/2 + {\rm h.c.}$ [5], where $\ell_{\rm L}$ and $H$ stand for the lepton and Higgs doublet fields, respectively, and $\kappa$ is a symmetric and complex matrix of inverse mass dimension. After electroweak symmetry breaking, the mass matrix of the three light Majorana neutrinos is given by $M_\nu = \kappa v^2$ with $v = \langle H \rangle = 174$ GeV being the vacuum expectation value of the SM Higgs field, or by $M_\nu = \kappa(v\sin\beta)^2$ with $\tan\beta$ being the ratio of the vacuum expectation values of the two Higgs doublets in the Minimal Supersymmetric Standard Model (MSSM). Note that we are working within an effective theory, and consider the running of neutrino mixing parameters below a cutoff scale $\Lambda$ where new physics takes effect. At one-loop order, the evolution of $\kappa$ is governed by [6]

$$16\pi^2 \frac{{\rm d}\kappa}{{\rm d}t} = \alpha_\kappa + C_\kappa \left[ \left( Y_l Y_l^\dagger \right) \kappa + \kappa \left( Y_l Y_l^\dagger \right)^{\rm T} \right] , \tag{2.1}$$

where $t \equiv \ln(\mu/\Lambda_{\rm EW})$ with $\mu$ being an arbitrary renormalization scale between the electroweak scale $\Lambda_{\rm EW} \approx 100$ GeV and the cutoff scale $\Lambda$, and $Y_l$ is the Yukawa coupling matrix of the charged

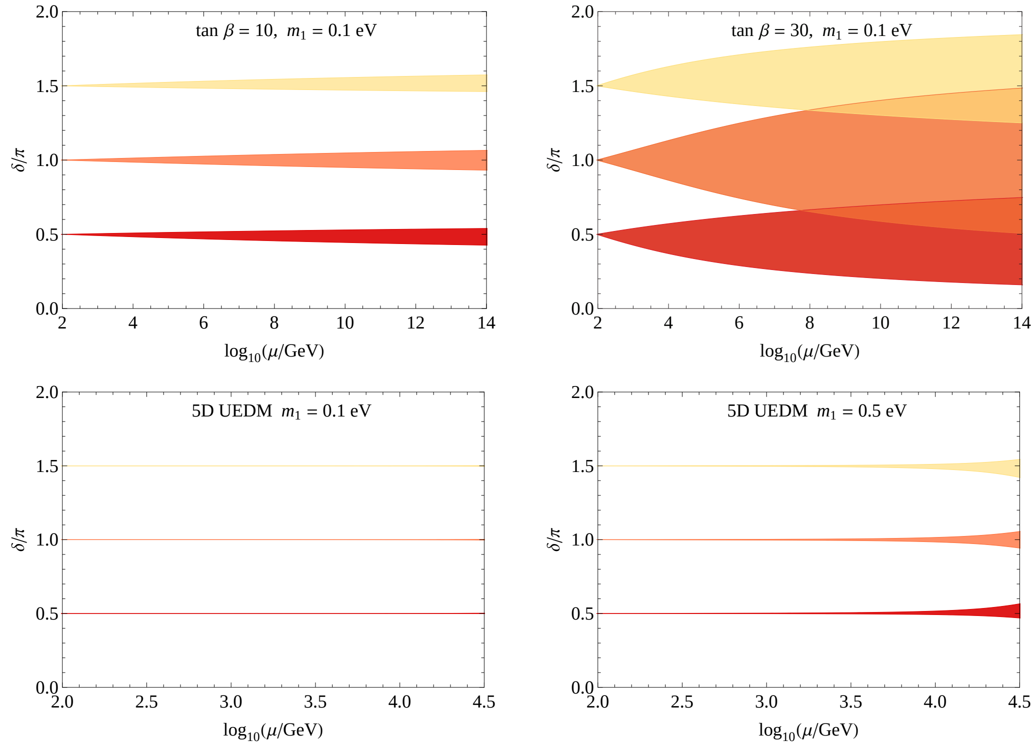


**Figure 1:** Evolution of $\delta$ for Majorana neutrinos in the MSSM (upper plots) and in the UEDM (lower plots). The initial values $\delta = \pi/2$, $\delta = \pi$, and $\delta = 3\pi/2$ are assumed, while the Majorana CP-violating phases $\rho$ and $\sigma$ are marginalized. The values of $\theta_{12}$, $\theta_{13}$, $\theta_{23}$, $\Delta m^2_{21}$, $\Delta m^2_{31}$ in the $1\sigma$ ranges from the global-fit analysis (for $\Delta m^2_{31} > 0$) have been used as input [3].

leptons. The coefficients $\alpha_\kappa$ and $C_\kappa$ are flavor universal, and have been explicitly given in Appendix A of Ref. [7] for the SM, the MSSM, and the Universal Extra-Dimensional Model (UEDM).

In the flavor basis where the charged-lepton Yukawa matrix is diagonal $Y_l = \mathrm{diag}(y_e, y_\mu, y_\tau)$ and in the limit of $y_e \ll y_\mu \ll y_\tau$, the renormalization-group equation of $\delta$ approximates to [7]

$$\dot{\delta} \approx -\frac{C_\kappa y_\tau^2}{8\pi^2} \frac{m_1^2}{\Delta m^2_{21}} \left\{ s^2_{23} s_{2(\rho-\sigma)} + \frac{2 s_{23} c_{23}}{s_{12} c_{12} s_{13}} \left[ s^2_{13} c_{(\delta+\rho-\sigma)} + \frac{\Delta m^2_{21}}{\Delta m^2_{31}} s^2_{12} c^2_{12} c_{(\delta+\rho+\sigma)} s_{(\rho-\sigma)} \right] \right\} , \quad (2.2)$$

where $\dot{\delta} \equiv \mathrm{d}\delta/\mathrm{d}t$, $s_x \equiv \sin x$, and $c_x \equiv \cos x$ have been defined, and $m_1$ is the absolute neutrino mass. Some comments on Eq. (2.2) are in order: (a) The running of $\delta$ is dominated by the tau-lepton Yukawa coupling; (b) The enhancement may arise from the factor $m_1^2/\Delta m^2_{21}$, implying that the running effect will be significant for a nearly-degenerate neutrino mass spectrum; (c) The running behavior depends crucially on the difference between two Majorana-type CP-violating phases.

In Fig. 1, the running behavior of $\delta$ has been illustrated in the MSSM and the 5-dimensional UEDM. In the former case, we have $C_\kappa^{\rm MSSM} = 1$ and $y_\tau^2 = m_\tau^2 (1 + \tan^2\beta)/v^2$, different from the SM values $C_\kappa^{\rm SM} = -3/2$ and $y_\tau^2 = m_\tau^2/v^2$. As shown in the first row of Fig. 1, the running effect can be significantly large for $\tan\beta = 30$ and $m_1 = 0.1$ eV, where the Majorana phases $\rho$ and $\sigma$ are allowed to freely vary in $[0, 2\pi)$. In the latter case, we have $C_\kappa^{\rm UEDM} = C_\kappa^{\rm SM}(1+s)$, where $s = \lfloor \mu/\mu_0 \rfloor$ stands for the number of excited Klein-Kaluza modes and $\mu_0 = R^{-1}$ with $R$ being the radius of the extra

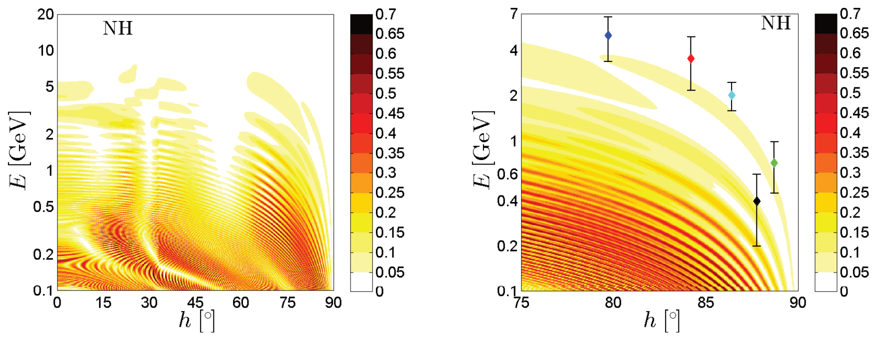


**Figure 2:** Numerical results of $\Delta A^{\rm m}_{\mu e}$ for normal neutrino mass hierarchy, where the best-fit values of the fundamental neutrino parameters are used [2]. In the right plot, we have zoomed in the parameter region that is relevant for the long-baseline neutrino oscillation experiments T2K (green, at $h = 88.7^\circ$), NO$\nu$A (cyan, at $h = 86.4^\circ$), LBNE (red, at $h = 84.1^\circ$), LAGUNA-LBNO (blue, $h = 79.7^\circ$), and ESS (black, at $h = 87.8^\circ$).

spatial dimension. It is worthwhile to note that the UEDM is cut off around $\mu = 3\times 10^4$ GeV, where the Landau pole for the $U(1)$ gauge coupling is encountered [8]. One can observe from the second row of Fig. 1 that even for $m_1 = 0.5$ eV the running effect is insignificant. Therefore, except for a large value of $\tan\beta$ in the MSSM, the running effect of $\delta$ is not substantial and the experimental constraint on $\delta$ directly applies to the flavor model at a high-energy scale. However, an important point should be noticed that even if $\delta = 0$ or $\pi$ at a high-energy scale, a nonzero $\delta$ can in principle be generated radiatively at the low-energy scale [9, 10].

## 3. Measures of Leptonic CP Violation

Another important question is how to extract $\delta$ from experimental observations, and to describe the experimental sensitivity to it. Unlike the CP asymmetry $A^{\rm CP}_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \propto \sin\delta$ for neutrino oscillations in vacuum, that for neutrino oscillations in matter does not vanish even for $\delta = 0$ or $\pi$. The reason is simply that the earth matter itself is CP asymmetric, and the Mikheyev-Smirnov-Wolfenstein matter effect [11] is very important for the long-baseline neutrino oscillation experiments. Take $\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$ for example. One can write the oscillation probabilities as $P(\nu_\mu \to \nu_e) = a\cos\delta + b\sin\delta + c$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e) = \overline{a}\cos\delta + \overline{b}\sin\delta + \overline{c}$, where the coefficients $\{a, b, c\}$ and $\{\overline{a}, \overline{b}, \overline{c}\}$ are independent of $\delta$ [12]. Thus, the CP asymmetry becomes $A^{\rm CP}_{\mu e}(\delta) = \Delta a\cos\delta + \Delta b\sin\delta + \Delta c$, where $\Delta a \equiv a - \overline{a}$ and likewise for $\Delta b$ and $\Delta c$. Now it is clear that $A^{\rm CP}_{\mu e}(\delta)$ is in general nonzero for $\delta = 0$ or $\pi$. For a constant matter density, we can expand the oscillation probabilities in terms of $s^2_{13}$ and $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$. More explicitly, we have [13]

$$\begin{aligned}
\Delta a &\approx +8\alpha s_{12}c_{12}s_{23}c_{23}s_{13}\Theta_- \frac{\sin A\Delta}{A}\cos\Delta\,, \\
\Delta b &\approx -8\alpha s_{12}c_{12}s_{23}c_{23}s_{13}\Theta_+ \frac{\sin A\Delta}{A}\sin\Delta\,, \\
\Delta c &\approx 4 s^2_{13}s^2_{23}\Theta_+\Theta_-\,,
\end{aligned} \tag{3.1}$$

where $\Delta \equiv \Delta m^2_{31}L/4E$ with $L$ being the distance between the source and detector, $A \equiv 2EV/\Delta m^2_{31}$ with $V$ being the matter potential, and $\Theta_\pm \equiv \sin[(A-1)\Delta]/(A-1) \pm \sin[(A+1)\Delta]/(A+1)$. Note that Eq. (3.1) is valid as long as $\alpha\Delta \ll 1$, i.e., when the distance $L$ and energy $E$ are far away from the region where the $\Delta m^2_{21}$-driven oscillations become dominant. This condition is satisfied in all the ongoing and upcoming long-baseline experiments.

To describe the intrinsic CP violation and remove the fake CP effects induced by matter, we define $\Delta A^{\rm CP}_{\mu e}(\delta) \equiv A^{\rm CP}_{\mu e}(\delta) - A^{\rm CP}_{\mu e}(0)$, which obviously vanishes for $\delta = 0$. In addition, another working observable $A^{\rm m}_{\mu e} \equiv \max\{A^{\rm CP}_{\mu e}(\delta)\} - \min\{A^{\rm CP}_{\mu e}(\delta)\}$ can be introduced to measure the experimental sensitivity to $\delta$, where the maximum and minimum have been found by varying $\delta$ in $[0, 2\pi)$. The former can be used to extract $\delta$ from experimental data, while the latter to optimize the experimental setups. In Fig. 2, we calculate $A^{\rm m}_{\mu e}$ in the NH case by using the PREM model of the earth matter density [13]. In the left plot, one can observe that the large values appear in the region of low neutrino energies. Furthermore, we zoom in the area with nadir angles from 75° and 90°, corresponding to the baselines relevant for the present and future long-baseline neutrino oscillation experiments. It is interesting to note that the NO$\nu$A, T2K, LAGUNA-LBNO, and LBNE experiments are lying on the band of $\Delta A^{\rm m}_{\mu e} \sim 10$ %, while the ESS setup is better with $\Delta A^{\rm m}_{\mu e} \sim 15$ %.

## 4. Summary

We have examined the renormalization-group running of the leptonic Dirac CP-violating phase in the MSSM and 5-dimensional UEDM, which should be taken into account when confronting theoretical predictions with experimental values. It turns out that the running effects are insignificant except for a large $\tan\beta$ in the MSSM. Moreover, two working observables $\Delta A^{\rm CP}_{\mu e}(\delta)$ and $A^{\rm m}_{\mu e}$ have been used to characterize the intrinsic CP violation and optimize the experimental setups.

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PoS(EPS-HEP 2013)538