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CP violation in T2HK and DUNE with non-standard interaction

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CP violation in the quark sector has been established, which is described by the CKM phenomenon, and we are entering the precision era as far as Flavor physics is concerned. Accumulation of more data from the LHCb and Belle II experiments will, hopefully, guide us to the pathways to physics beyond the standard model. Unfortunately, the tiny CP asymmetry observed in the quark sector cannot explain the overserved baryon asymmetry of the Universe. In this context, it is widely believed that leptonic CP violation could be the salvage. Interestingly, the measured non-zero value of θ_{13} has opened the door of optimism. Needless to mention, the determination of CP violating phase δ_{CP} is the prime target of most of the current and upcoming neutrino experiments. Unfortunately, non-standard interactions can be a spoiler for the clean determination of the CP phase. We explore, the effect of non-standard interaction and study the prospects of its effect in the future experiments DUNE and T2HK, taking inputs from the currently running long baseline experiments, i.e., T2K and NOvA. Considering non-standard interaction effects from $e-\mu$ and $e-\tau$ sectors, we find interesting results concerning the probabilities, the octant of the θ_{23}, and the CP sensitivities, and therefore, a better understanding of the effects will be crucial for the cleaner determination of δ_{CP}.

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1. Introduction

The existence of new physics beyond the standard model will help us in understanding the origin of neutrino mass, the question of dark matter, and dark energy. The nature of new physics is yet unknown. An ideal ground to probe new physics could be neutrino oscillation. It plays an important role in examining neutrino masses and mixing angles. The ongoing long-baseline neutrino experiments, i.e., T2K and NOvA, are addressing the important questions of neutrino mass ordering, octant degeneracy, and leptonic CP violation. The presence of matter effect and non-standard interaction (NSI) hinder the clean determination of the neutrino oscillation parameters. Wolfenstein introduced non-standard interaction (NSI) [1–4] besides the neutrino mass matrix.

The observed baryon asymmetry of the Universe (BAU) can not be explained by the CP violation in the quark sector. Recent results from T2K and NOvA show that in the case of the inverted mass ordering, the neutrino parameter i.e., δ_{CP} from both T2K and NOvA look consistent with each other, but for the normal mass ordering, there appears to be tension (T2K points to the δ_{CP} about 1.5π whereas NOνA suggests the same parameter to be around 0.8π). In the attempt to link the difference in δ_{CP}, observed in T2K and NOνA, we discuss the possibility of new physics in the form of non-standard interaction (NSI) [5]. Here, we investigate the CP violation and possible implications for the neutrino mass ordering, taking into account the results from T2K and NOνA. Furthermore, in this analysis, we attempt to understand the effect of non-standard interaction on the CP asymmetry parameter in the DUNE and T2HK experimental setup.

2. Formalism

Non-standard interactions can be expressed using six-dimensional four-fermion (ff) operators of the form:

$$\mathcal{L}_{NSI} = 2\sqrt{2} G_F \epsilon^{fC}_{\alpha\beta} [\overline{\nu_\alpha}\gamma^\rho P_L \nu_\beta][\overline{f}\gamma_\rho P_C f] + h.c. \tag{1}$$

where neutrino flavors are given by $\alpha, \beta = e, \mu, \tau$, the chirality of superscript $C = L, R$ refers to the chirality of ff current, $f = u, d, e$ indicates the matter fermions and $\epsilon^{fC}_{\alpha\beta}$ are dimensionless parameters that measure the new interaction's strength in relation to the SM. The neutrino propagation Hamiltonian in the presence of matter, NSI, can be expressed as:

$$H_{Eff} = \frac{1}{2E}\left[U_{PMNS}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{bmatrix} U^\dagger_{PMNS} + V\right]$$

where U_{PMNS} is the unitary Potecorvo-Maki-Nakagawa-Sakata mixing matrix, E is the neutrino energy and $\Delta m^2_{21} \equiv m^2_2 - m^2_1$, $\Delta m^2_{31} \equiv m^2_3 - m^2_1$. m_1, m_2 and m_3 are the different mass eigenstates. V is written as:

$$V = 2\sqrt{2} G_F N_e E \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{\mu e} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{\tau e} e^{-i\phi_{e\tau}} & \epsilon_{\tau\mu} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau}. \end{bmatrix}$$

N_e is the number density of electrons and for neutrino propagation in the Earth, G_F is Fermi coupling constant,

$$\epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \equiv \sum_{f,C} \epsilon^{fC}_{\alpha\beta} \frac{N_f}{N_e} \equiv \sum_{f=e,u,d} (\epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}) \frac{N_f}{N_e} \tag{2}$$

N_f being the number density of f fermion. The $\epsilon_{\alpha\beta}$ are real and $\phi_{\alpha\beta} = 0$ for $\alpha = \beta$. We concentrate on flavour non-diagonal NSI ($\epsilon_{\alpha\beta}$'s with $\alpha \neq \beta$). Here, we consider single NSI parameter $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$ (one at a time) to examine the conversion probability of $\nu_\mu \to \nu_e$ for the LBL studies which can be stated as the sum of three (plus higher order; cubic and beyond) terms in the presence of NSI [6, 7]:

$$P_{\mu e} = P_0 + P_1 + P_2 + h.o. \tag{3}$$

the above Eq.(2), similar to ref [8] takes the following form:

$$P_0 = 4s_{13}^2 s_{23}^2 f^2 + 8s_{13}s_{23}s_{12}c_{12}c_{23}rfg\cos(\Delta + \delta_{CP}) + 4r^2 s_{12}^2 c_{12}^2 c_{23}^2 g^2$$

$$P_1 = 8\hat{A}\epsilon_{e\mu}[s_{13}s_{23}[s_{23}^2 f^2\cos(\Psi_{e\mu}) + c_{23}^2 fg\cos(\Delta + \Psi_{e\mu})] + 8rs_{12}c_{12}c_{23}[c_{23}^2 g^2\cos\Psi_{e\mu} + s_{23}^2 g\cos(\Delta - \phi_{e\mu})]]$$

and:

$$P_2 = 8\hat{A}\epsilon_{e\tau}[s_{13}c_{23}[s_{23}^2 f^2\cos(\Psi_{e\tau}) - s_{23}^2 fg\cos(\Delta + \Psi_{e\tau})] - 8rs_{12}c_{12}s_{23}[c_{23}^2 g^2\cos\Psi_{e\tau} - c_{23}^2 g\cos(\Delta - \phi_{e\tau})]]$$

where:

- $f \equiv \frac{\sin[(1-\hat{A})\Delta]}{1-\hat{A}}$, $g \equiv \frac{\sin\hat{A}\Delta}{\hat{A}}$, $\Delta = \frac{\Delta m_{31}^2 L}{4E}$, $\hat{A} = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$, $r = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$
- $\Psi_{e\mu} = \phi_{e\mu} + \delta_{CP}$, $\Psi_{e\tau} = \phi_{e\tau} + \delta_{CP}$

3. Analysis Details

We employed the GLoBES software [9, 10] and its additional public tool, which can implement NSI, in our analysis. The standard model parameters' best-fit values and associated uncertainties are obtained from nuFIT v5.1 [11]. As an illustration, the parameters used (for normal ordering) are given in table 1. We combined the datasets from T2K and NOvA using GLoBES. We address

Table 1: The standards model parameters used are summarized below:

SM Parameters	bfp ± 1σ NO
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$
$\delta_{CP}/°$	230^{+36}_{-25}
$\frac{\Delta m_{21}^2}{10^{-5}eV^2}$	$7.42^{+0.21}_{-0.20}$
$\frac{\Delta m_{3l}^2}{10^{-3}eV^2}$	$+2.510^{+0.027}_{-0.027}$

the sensitivity and oscillation probability for the two next-generation LBL experiments, DUNE and T2HK, using the obtained NSI constraints. For simulating experiments like T2HK and DUNE

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operating for 3.5 years and 3 years in ν mode and similarly 3.5 years and 4 years in $\bar{\nu}$ mode, respectively, we used the AEDL (a complete abstract experiment definition language) available in GLoBES.

In the case of DUNE [12], a 40-kiloton liquid argon detector will be used to produce neutrino and antineutrino beams from in-flight pion decays using a 1.2 MW proton beam. The proton beam will start, 1300 kilometers upstream at Fermilab. The energy ranges of the neutrinos will be between 0.5 to 20 GeV, with a flux peak around 2.6 GeV. The T2HK experiment will use a water Cherenkov detector with a 225 kt capacity. Its detector will be located 295 kilometers from the source and will use an enhanced 30 GeV J-PARC beam with a power of 1.3 MW.

In Figure 1, we have shown the allowed region plots for $\epsilon_{e\mu}$ versus standard model CP phase δ_{CP} in the left plane and $\epsilon_{e\mu}$ versus non-standard phase $\phi_{e\mu}$ in the left plane. The results of this analysis are obtained using the combination of T2K and NOvA. The red and blue contours show the regions allowed at 68% (1σ) and 95% (2σ) confidence levels for two degrees of freedom. In the left panel, non-standard CP-phase $\phi_{e\mu}$, θ_{13}, and θ_{23} are marginalized away whereas in the right panel plot θ_{13}, θ_{23}, and δ_{CP} are marginalized. A similar exercise is also done for the IO scenario as well as for $\epsilon_{e\tau}$ sector. The best-fit values are given in table 2.

Table 2: The best-fit points are picked up corresponding to the minimum χ^2 value.

Mass ordering	NSI	$\lvert\epsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	χ^2
Normal Ordering (NO)	$\epsilon_{e\mu}$	0.1	0.2	0.52
	$\epsilon_{e\tau}$	0.1	1.47	0.39
Inverted Ordering (IO)	$\epsilon_{e\mu}$	0.01	1.67	0.53
	$\epsilon_{e\tau}$	0.13	0.8	1.67

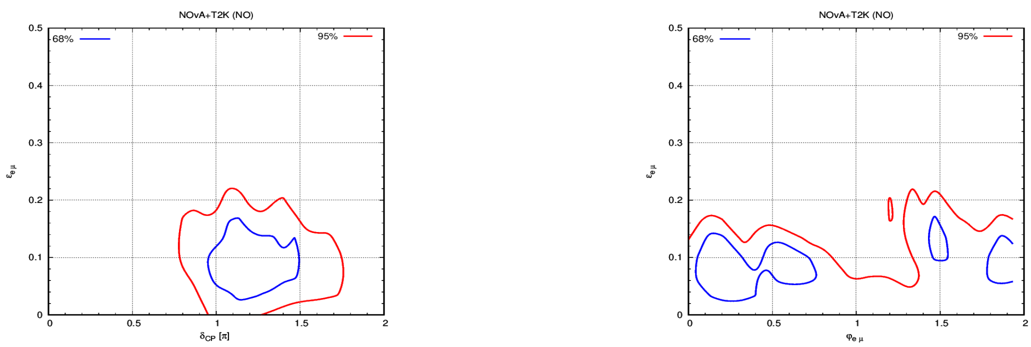

Figure 1: Allowed regions for $\epsilon_{e\mu}$ and the CP phase (left); $\epsilon_{e\mu}$ and phase $\phi_{e\mu}$(right) determined by the combination of T2K and NOvA for NO. The contours are drawn at the 68%, and 90% C.L. for 2 d.o.f

4. CP Violation Sensitivity

The precision measurement of the CP phase δ_{CP} is one of the important objectives of the current and future LBL neutrino experiments. In the standard three neutrino oscillations framework, we discuss CP violation sensitivity:

$$\Delta\chi^2_{CPV} = Min[\Delta\chi^2_{CP}(\delta^{test}_{CP} = 0), \Delta\chi^2_{CP}(\delta^{test}_{CP} = \pi)]$$

In Figure 2, we have CP discovery potential for both T2HK and DUNE. In order to study the sensitivity, we have utilized the obtained NSI constraints. There is an appreciable difference in the sensitivities for the case of SM with the inclusion of NSI in comparison to SM prediction. In the case of the DUNE, there appears to be better sensitivity to NSI than T2HK.

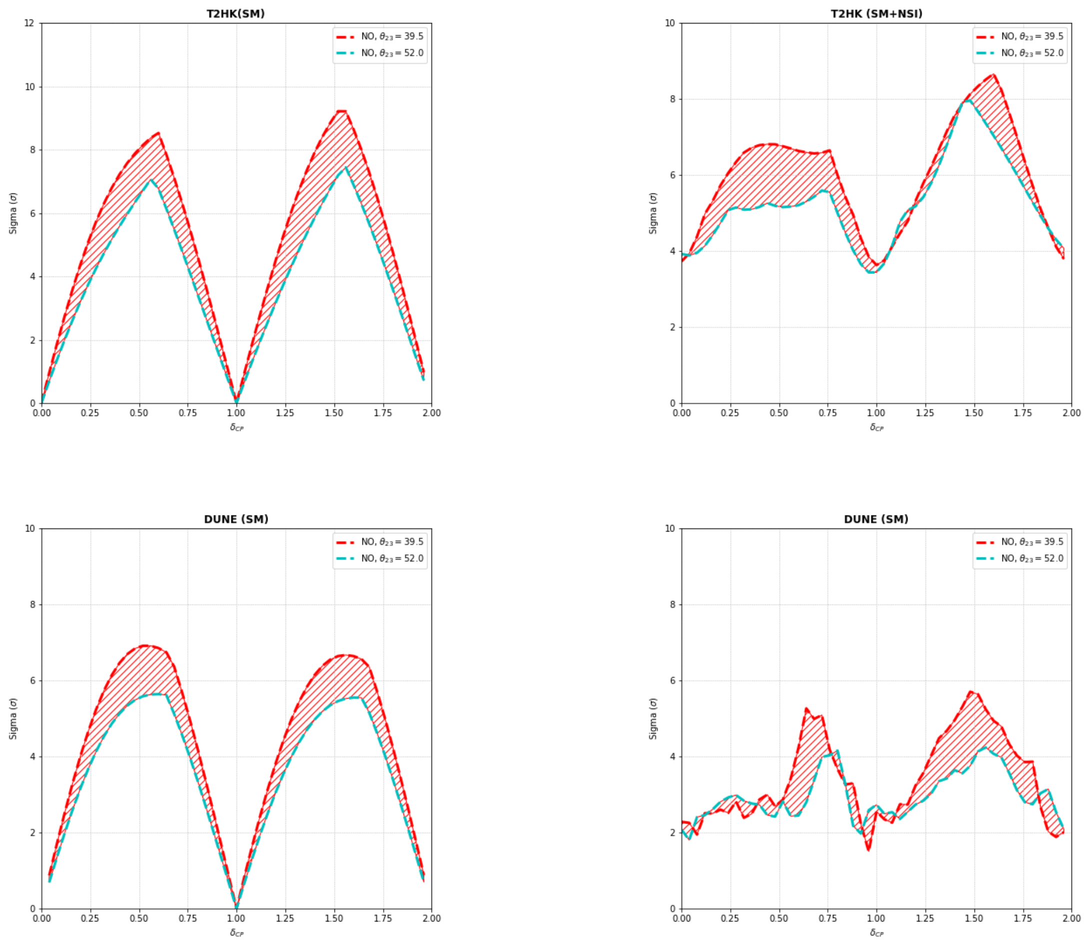

Figure 2: CP discovery potential for T2HK (top panel) and DUNE (bottom panel) for the true value of the leptonic CP phase for NO in SM scenario(left panel) and SM+NSI scenario (right panel).

5. CP Asymmetry

We extend our work to focus on CP asymmetry studies. The CP asymmetry is the difference between the quantity of matter and anti-matter present in the universe. The CP asymmetry observable can be used to assess CP violation since it measures the change in oscillation probabilities when the sign of the CP phase changes. CP-asymmetry is defined as:

$$A_{CP} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)},$$

In Figure 3, we have CP asymmetry versus δ_{CP} plots for T2HK (top) and DUNE (bottom), in SM case as well as SM with the inclusion of non-standard interactions arising from $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$. Here, we consider different values of $|\epsilon_{e\mu}|$ (left) and $|\epsilon_{e\tau}|$ (right).

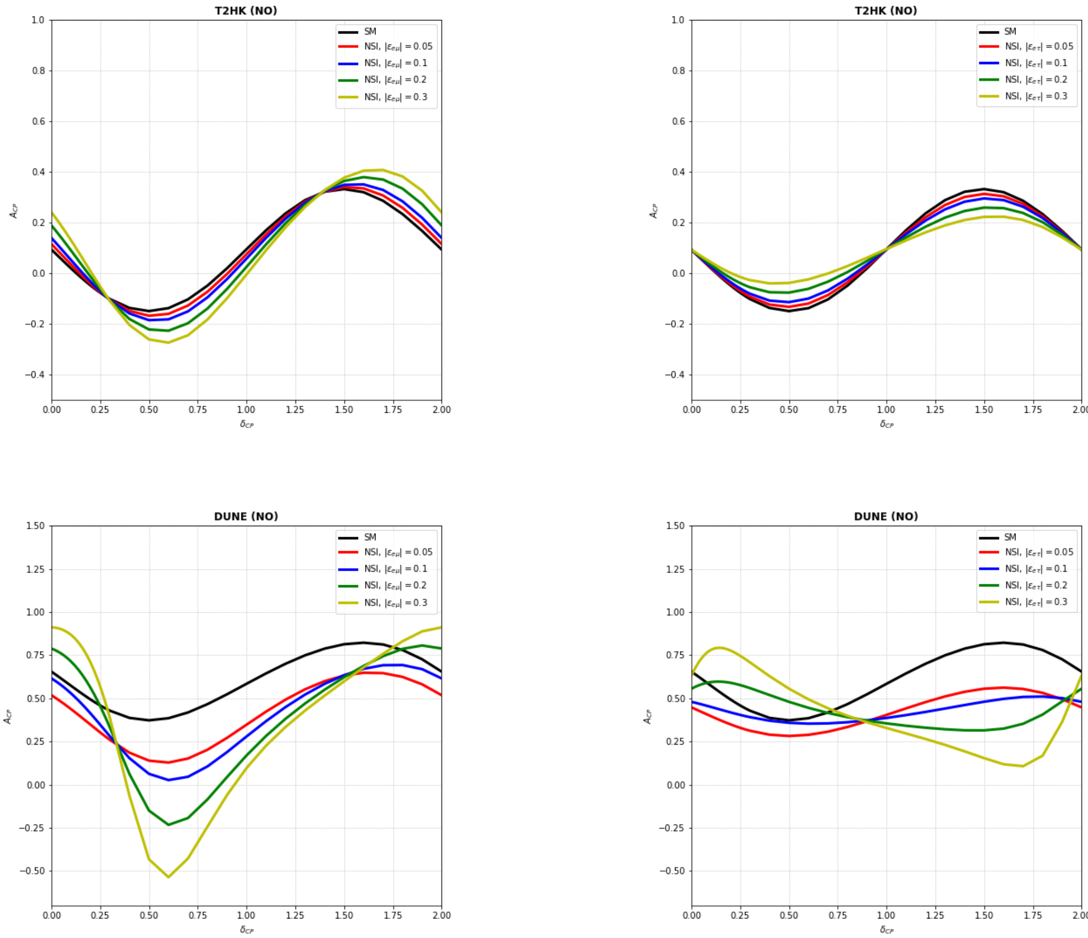

Figure 3: CP asymmetry plots for T2HK (top panel) and DUNE (bottom panel) for SM and SM in addition to non-standard interactions with different values of $|\epsilon_{e\mu}|$ (left) and $|\epsilon_{e\tau}|$ (right)

In Figure 4, the top panel shows CP asymmetry versus energy in the presence of NSI arising from the $\epsilon_{e\mu}$ sector for the DUNE (left) and T2HK (right) experimental setup. In the case of the DUNE, the flux peak at 2.6 GeV. Similarly, for T2HK, the flux peak at 0.6 GeV. We have restricted ourselves to the energy range around the peak neutrino beam for the sake of illustration. In the case of DUNE, we note that the normal mass ordering (NO) scenario displays a positive A_{CP} value of 76%, whereas the inverted mass ordering (IO) scenario prefers a negative A_{CP} value of 21%. Here, we take into account $\delta_{CP} = 278°$ for the IO case and $\delta_{CP} = 230°$ for the NO case. In contrast, both normal and inverted mass ordering exhibit positive A_{CP} values of 36% and 16% in the T2HK energy window, respectively.

In the bottom panel, we show A_{CP} versus SM parameter δ_{CP} varying from 0 to 2π. On the left panel, we see SM as well as SM along with NSI arising from the $\epsilon_{e\mu}$ sector plots for both NO and IO in the case of DUNE, whereas on the right side, along with SM, we have included NSI arising from same $\epsilon_{e\mu}$ but now for T2HK.

In order to obtain the A_{CP} versus SM parameter δ_{CP}, we have included the non-standard phases arising from $e - \mu$ and $e - \tau$ sector in our GLoBES analysis from table 1. Hereafter, all the mentioned values of A_{CP} are obtained at the best-fit values of δ_{CP} (1.3π for NO and 1.5π for IO) for both the ordering scenarios as given in the figure. In the case of DUNE, the A_{CP} parameter indicates a positive value of 63% for NO and a negative value of 21% for IO in the SM case. With the inclusion of NSI from $\epsilon_{e\mu}$, the A_{CP} parameter value indicates a positive value of 53% for NO and a negative value of 18% for IO. For T2HK, the A_{CP} parameter indicates a positive value of 34% for NO and 15% for IO in the SM case. With the inclusion of NSI from $\epsilon_{e\mu}$, the A_{CP} parameter value now gives a positive value of 32% for NO and 16% for IO.

6. Conclusions

The comprehension of the universe's matter and anti-matter asymmetry depends on the study of CP violation. One of the key objectives of the ongoing and upcoming neutrino experiments is to provide proof of the presence of CP violation in the neutrino sector. In this work, we looked into the CP violation as well as CP asymmetries related to the T2HK and DUNE using $\epsilon_{e\mu}$ constraints obtained from the combination of NOvA and T2K. Our study reveals that the mass hierarchies for the DUNE experiment will be clearly differentiated by the A_{CP} values, in contrast to T2HK. Furthermore, we discover that the mass ordering will clearly be impacted by the contribution from the NSI coupling $\epsilon_{e\mu}$. A possible novel physics effect and the topic of neutrino mass ordering in the neutrino sector may both be understood through measurements of CP violation asymmetries. The conclusion of the mass ordering conundrum and the identification of CP violations will be made possible by the next LBL experiments.

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References

[1] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).

[2] Y. Grossman, Phys. Lett. B **359** (1995), 141-147

[3] Y. Farzan and M. Tortola, Front. in Phys. **6** (2018), 10

[4] P. S. Bhupal Dev *et al.* SciPost Phys. Proc. **2**, 001 (2019) doi:10.21468/SciPostPhysProc.2.001 [arXiv:1907.00991 [hep-ph]].

[5] B. Brahma, A. Giri, Eur. Phys. J. C **82**, 1145 (2022)

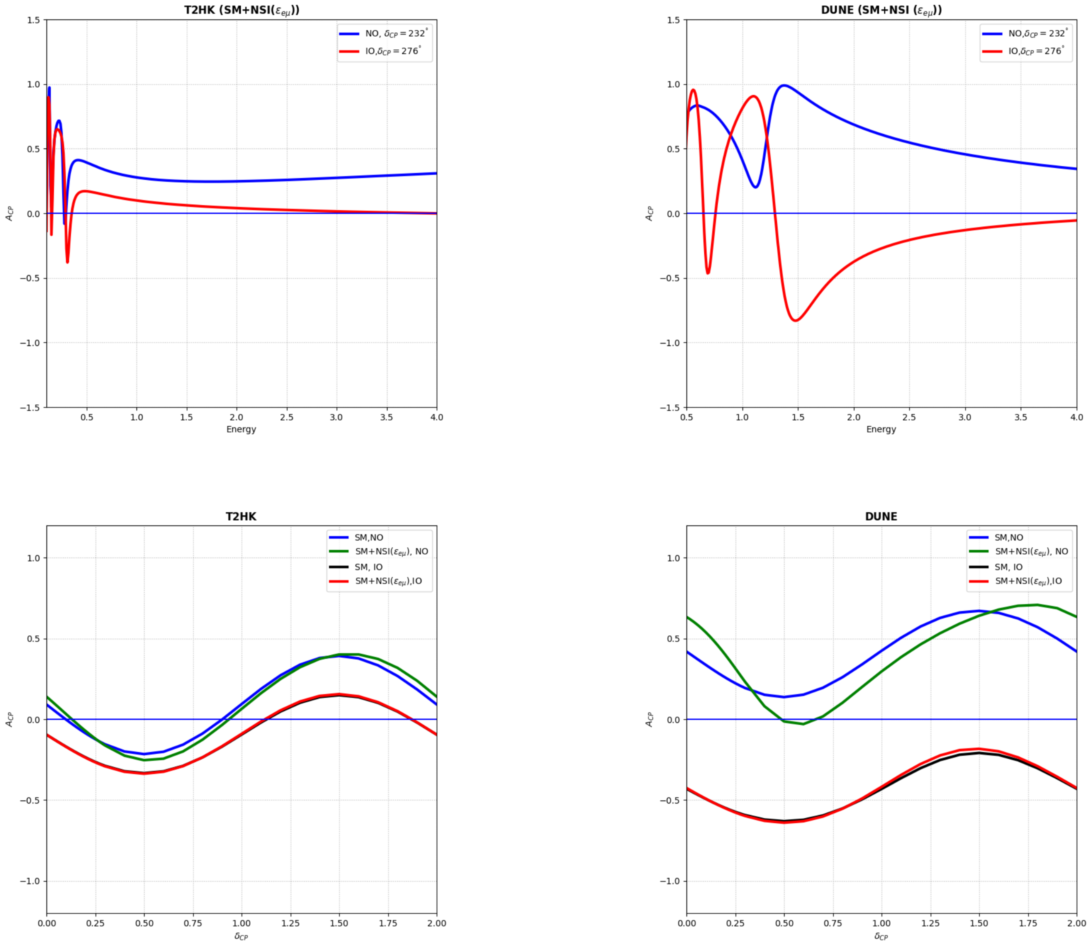

Figure 4: CP asymmetry A_{CP} versus energy [in GeV] (top panel) and A_{CP} versus δ_{CP} in the presence of NSI arising from the $\epsilon_{e\mu}$ in the case of T2HK (left) and DUNE (right) experimental setup.

[6] D. Meloni, T. Ohlsson and H. Zhang, JHEP **04** (2009), 033 doi:10.1088/1126-6708/2009/04/033 [arXiv:0901.1784 [hep-ph]].

[7] J. Kopp, M. Lindner, T. Ota and J. Sato, Phys. Rev. D **77** (2008), 013007 doi:10.1103/PhysRevD.77.013007 [arXiv:0708.0152 [hep-ph]].

[8] J. Liao, D. Marfatia and K. Whisnant, Phys. Rev. D **93** (2016) no.9, 093016 doi:10.1103/PhysRevD.93.093016 [arXiv:1601.00927 [hep-ph]].

[9] P. Huber, M. Lindner, and W. Winter, Comput. Phys. Commun. **167**, 195 (2005)

[10] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, Comput. Phys. Commun. **177**, 432 (2007)

[11] http://www.nufit.org/.

[12] B. Abi *et al.* [DUNE], [arXiv:2002.03005 [hep-ex]].