IL NUOVO CIMENTO **47 C** (2024) 365
DOI 10.1393/ncc/i2024-24365-7

COLLOQUIA: MAYORANA 2023

# Measuring the leptonic Dirac CP phase with DUNE + $\mu$THEIA(*)

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received 6 August 2024

**Summary.** — We explore the possibility of using the recently proposed THEIA detector to measure the $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation with neutrinos from a muon decay at rest ($\mu$DAR) source to improve the leptonic CP phase measurement. Due to its intrinsic low-energy beam, this $\mu$THEIA configuration ($\mu$DAR neutrinos at THEIA) is only sensitive to the genuine leptonic CP phase $\delta_D$ and not contaminated by the matter effect. We find that the combination with the high-energy DUNE can significantly reduce the CP uncertainty, especially around the maximal CP violation case $\delta_D = \pm 90^\circ$.

## 1. – Issues of CP measurement at long-baseline accelerator neutrino experiments

After the measurement of the nonzero reactor mixing angle $\theta_r \equiv \theta_{13}$, the focus of neutrino physics is directed towards the determination of the remaining unknowns such as the Dirac CP phase $\delta_D \equiv \delta_{\text{CP}}$. The Dirac CP phase is allowed to have physical effects due to the nonzero $\theta_r$ since $\delta_D$ and $\theta_r$ always appear together as $\sin\theta_r e^{\pm i\delta_D}$ in the standard parametrization of the PMNS matrix [2]. Typically, the neutrino oscillations from the muon flavor to the electron flavor ($\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$) are used by the long-baseline (LBL) accelerator experiments to measure $\delta_D$. For the next-generation LBL DUNE experiment, the matter effect cannot be neglected due to its high neutrino energy peaking around 2.5 GeV and hence leads to the neutrino oscillation probabilities [3],

$$P_{\nu_\mu\to\nu_e,\bar{\nu}_\mu\to\bar{\nu}_e} \approx \alpha^2 \sin^2 2\theta_s c_a^2 \frac{\sin^2(A\Delta_a)}{A^2} + 4 s_r^2 s_a^2 \frac{\sin^2[(1\mp A)\Delta_a]}{(1\mp A)^2} + 2\alpha s_r \sin 2\theta_s \sin 2\theta_a \cos(\Delta_a \pm \delta_D) \times \frac{\sin(A\Delta_a)}{A}\frac{\sin[(1\mp A)\Delta_a]}{(1\mp A)}. \tag{1}$$

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(*) Please see [1], on which this conference proceeding is based, for more details.
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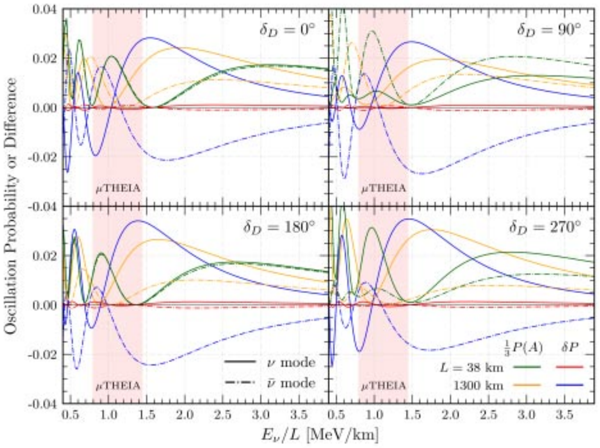

Fig. 1. – The oscillation probability and oscillation probability difference between the matter-induced and vacuum cases as a function of $E_\nu/L$.

As shown in fig. 1, the sign ± (∓) is for neutrino (the upper panel) and anti-neutrino (the lower panel), respectively. For convenience, we have used $(s_{a,r}, c_{a,r}) \equiv (\sin\theta_{a,r}, \cos\theta_{a,r})$ to denote the sine and cosine functions of the atmospheric ($\theta_a \equiv \theta_{23}$) and reactor ($\theta_r$) mixing angles while $\theta_s \equiv \theta_{12}$ is the solar mixing angle. The atmospheric oscillation phase $\Delta_a \equiv |\Delta m^2_a| L/4E_\nu$ includes the atmospheric mass squared difference $\Delta m^2_a \equiv \Delta m^2_{31}$, the neutrino energy $E_\nu$, and the oscillation baseline $L$. To maximize the event rate, the DUNE neutrino energy and baseline are matched to put the atmospheric oscillation phase at the first peak $\Delta_a \approx \pi/2$, making the oscillation probability have only $\sin\delta_D$ dependence. Moreover, the matter term $A \equiv 2E_\nu V/\Delta m^2_a$ includes the matter potential $V \equiv 2 G_F n_e$ and contributes to the matter effect on the oscillation probability.

The feature of $\sin\delta_D$ dependence and non-negligible matter effect causes several intrinsic problems. First, the CP sensitivity is closely related to the variation of the oscillation probabilities with the CP phase $\delta_D$. With $\sin\delta_D$ dependence, the variation has $\cos\delta_D$ dependence, $|\partial P/\partial\delta_D| \propto |\cos\delta_D|$, which goes to zero for the maximal CP phase. The CP uncertainty is inversely proportional to the variation, $|1/\cos\delta_D|$ which is intrinsically large for maximal CP $\delta_D \approx -\pi/2$. Secondly, since the essential observable for CP measurement is the difference between the neutrino and anti-neutrino oscillation probabilities, $P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e} \propto \sin\Delta_a \sin\delta_D$, a realistic measurement has sign differences in not just the Dirac CP phase $\delta_D$ but also the matter term $A$. In this sense, the matter potential can fake the genuine CP violation. Hence at a single long-baseline neutrino oscillation experiment, there is only one independent CP observable but two parameters ($A$ and $\delta_D$). The uncertainty from the matter effect can reduce the sensitivity of $\delta_D$.

## 2. – CP measurement at DUNE + $\mu$THEIA

We propose to use low-energy $\mu$DAR neutrinos to supplement the original DUNE high-energy neutrinos in order to resolve these issues. The $\mu$DAR neutrinos are produced by a cyclotron complex. For example, a typical 800 MeV proton beam hits a thick target to first generate pions. Although both $\pi^\pm$ can be produced, $\pi^-$ is mostly absorbed by the positively charged nuclei while $\pi^+$ decays at rest via $\pi^+ \to \mu^+ + \nu_\mu$. The decay product $\mu^+$ also loses its energy and decays at rest via $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$. During this process, three neutrinos ($\nu_\mu$, $\nu_e$, and $\bar{\nu}_\mu$) are produced. Of them, $\bar{\nu}_\mu$ experiences the $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation that is of interest to CP measurement. Since $\mu^+$ decays at rest, $\bar{\nu}_\mu$ has a wide and well-understood spectrum with the maximum energy of 53 MeV. Note that it is impossible to simply add a $\mu$DAR source and share the same liquid Argon detectors of DUNE. This is because there are no free protons to provide inverse beta decay (IBD) for unique probe of the electron anti-neutrino and hence the $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation. Besides, the $\bar{\nu}_e$-Ar cross section is too small to detect the $\mu$DAR flux at DUNE. Fortunately, a new THEIA detector at the same site of SURF with a new technique of water-based liquid scintillator (WbLS) was recently proposed. It is possible to use both scintillation and Cherenkov lights which opens the possibility of detecting the low-energy $\mu$DAR neutrino oscillation to supplement the high- energy mode at DUNE. For convenience, we call the combination of $\mu$DAR and THEIA as $\mu$THEIA.

With $\mathcal{O}(10)$ km baseline, the oscillation phase term, $L/E$, is much wider than the one at DUNE. Consequently, there is no way to hide the $\cos\delta_D$ term. In other words, introducing a $\mu$DAR component to DUNE can significantly reduce the CP uncertainty around the maximal CP value. Moreover, the difference between the oscillation probabilities with and without matter potential, $\delta P_{\mu e} \equiv P_{\mu e}(A) - P_{\mu e}(A = 0)$, in fig. 1 shows explicitly the matter effect at the DUNE and $\mu$THEIA configurations. The matter effect at DUNE is at the same order as the genuine CP effect. In contrast, the matter effect at $\mu$THEIA is negligibly small. Being essentially insensitive to the matter potential, $\mu$THEIA can focus on the genuine CP phase while DUNE probes both. Their combination can significantly improve the CP sensitivity.

**2·1.** *Neutrino detection of the low-energy mode* . – The "low-energy mode" is defined as the $\mu$DAR beam detected by the THEIA detector. With the equipment of both Cherenkov and scintillation light detections at THEIA, the IBD signal is quite distinctive and all backgrounds can be suppressed to a small amount as shown in fig. 2.

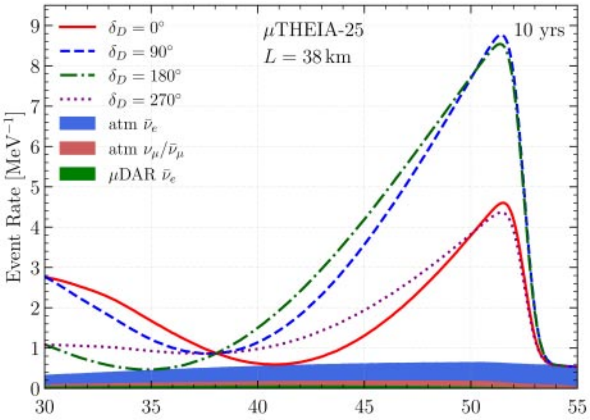

Fig. 2. – The neutrino event spectra of $\mu$DAR source at THEIA detector.

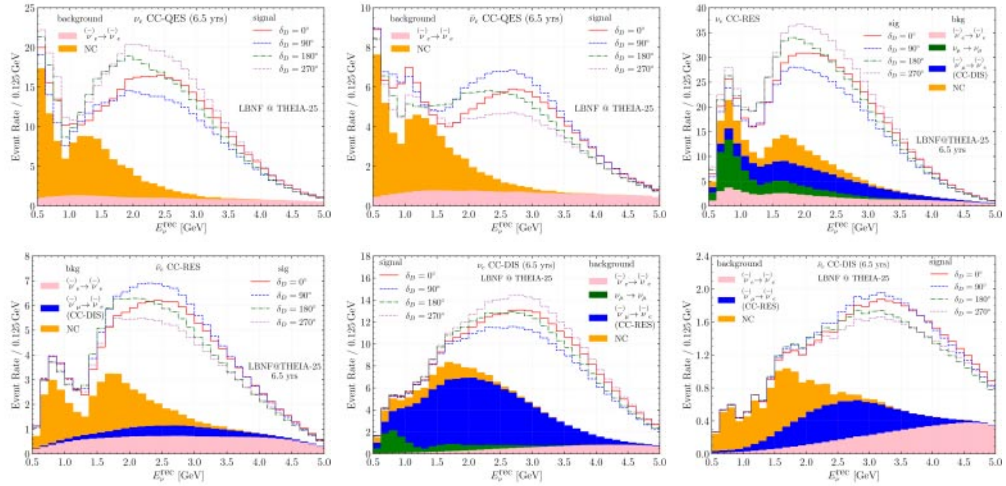

Fig. 3. – The neutrino event spectra of LBNF source at THEIA detector.

$\mathbf{2}$·2. *Neutrino detection of the high-energy mode* . – The "high-energy mode" is defined as the original LBNF beam detected by both the DUNE and THEIA detectors. With a broad energy range of LBNF neutrinos, several types of CC scatterings with a target nuclei $N$ can happen. In order to make better neutrino reconstruction, it is desirable to distinguish these different CC scattering events, CC-QE, CC-RES, and CC-DIS, as shown in fig. 3.

## 3. – CP sensitivities at DUNE + $\mu$THEIA

$\mathbf{3}$·1. *Baseline options of $\mu$THEIA*. – The baseline between the $\mu$DAR source and the THEIA detector can significantly affect the CP uncertainty $\Delta\delta_D$ which is defined as the half-width of the $\Delta\chi^2 = \chi^2(\delta_D) - \chi^2_{\rm min} = 1$ band with $\chi^2_{\rm min}$ being the best-fit value of the CP phase. Figure 4 shows $\Delta\delta_D$ as a function of the $\mu$THEIA baseline $L$. Since

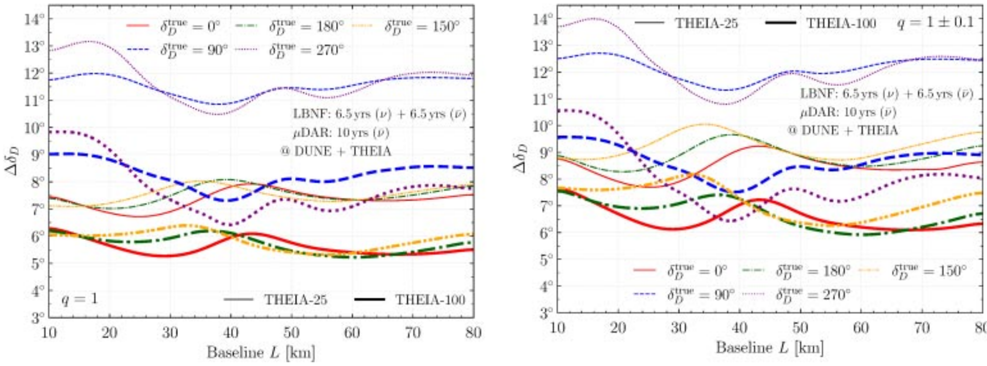

Fig. 4. – The CP phase uncertainty, $\Delta\delta_D$, for the combination of DUNE and THEIA as a function of the $\mu$THEIA baseline $L$.

the matter effect is a natural source of fake CP, we take its uncertainty by including a parameter $q$ to scale its average value, $A \to qA$. To see the impact of matter effect on the optimal baseline, the left panel of fig. 4 is obtained by fixing $q = 1$ while the right one takes $q = 1 \pm 0.1$. For both cases, the result shows two local minima in the CP uncertainty for maximal CP violation. One is around $L = 38\,\text{km}$ and the other one is around $L = 55\,\text{km}$. The longer one, $L = 55\,\text{km}$, is a local optimal option for $\delta_D = 270^\circ$ that is preferred by the T2K measurement. Although the true local minimum for vanishing CP violation cases $\delta_D = 0^\circ$ and $180^\circ$ actually happens with $L > 65\,\text{km}$, the difference in $\chi^2$ is not significant while the maximal CP violation cases $\delta_D = 90^\circ$ and $270^\circ$ (or equivalently $-90^\circ$) become much worse. Since the data-driven $\delta_D = -90^\circ$ is of larger interest, $L = 55\,\text{km}$ is preferred than the longer $65\,\text{km}$. For the shorter one, the choice is more difficult. The global minimum around $L \approx 38\,\text{km}$ for $\delta_D = \pm 90^\circ$ is very close to the global maximum for the vanishing CP violation cases. So choosing $L = 38\,\text{km}$ needs to pay too much price and we take $L = 30\,\text{km}$ to balance among various CP values. Our simulation takes these three baselines $L = 30\,\text{km}$, $38\,\text{km}$, and $55\,\text{km}$ as possible options.

**3**˙2. *CP sensitivity*. – As emphasized in earlier discussions, the CP sensitivity suffers from the matter effect contamination. The DUNE + $\mu$THEIA configuration we propose can overcome this issue to provide a clean measurement of the Dirac CP phase $\delta_D$. Figure 5 shows the CP uncertainty $\Delta\delta_D$ as a function of the true value $\delta_D^{\text{true}}$ for three $\mu$THEIA benchmark baselines, L = 30 km, 38 km, and 55 km.

To further illustrate the advantages of the DUNE + $\mu$THEIA combination, we compare with other existing experiments or designs in fig. 6. Although the $\mu$THEIA-25 can only use a fiducial volume of 17 kt, the CP uncertainty $11^\circ$ ($10^\circ$) at DUNE + $\mu$THEIA-25 is already better than TNT2HK [4]. With 70 kt fiducial volume at $\mu$THEIA-100, the CP uncertainty further reduces to only $7^\circ \sim 8^\circ$. This clearly shows the advantages of supplementing DUNE with $\mu$THEIA-25 or $\mu$THEIA-100.

## 4. – Conclusion and outlook

The leptonic CP phase measurement at accelerator-based neutrino oscillation experiments suffers from the contamination of matter effect. The higher neutrino energy, the severer contamination. To overcome this problem, we put forward a possible combination of intrinsically low-energy $\mu$DAR neutrinos and the recently proposed THEIA detector.

With essentially a background-free measurement, the enhancement on CP sensitivity

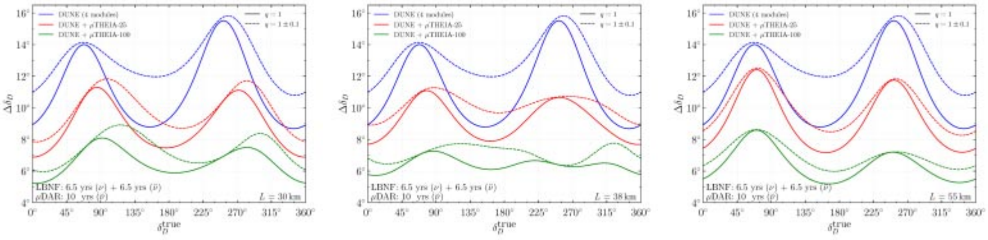

Fig. 5. – The CP phase uncertainty $\Delta\delta_D$ as a function of the true CP value $\delta_D^{\text{true}}$. For illustration, the three $\mu$THEIA baseline options $L = 30\,\text{km}$, $38\,\text{km}$, and $55\,\text{km}$ are shown separately.

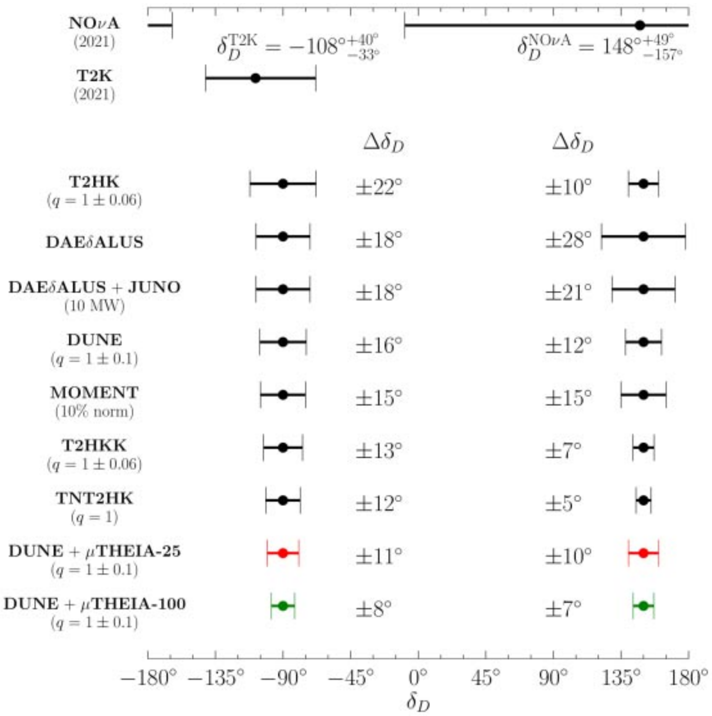

Fig. 6. – The projected CP sensitivities at various current and planned experiments are sorted by the size of CP uncertainty.

from $\mu$THEIA is significant. The CP uncertainty around the maximal CP violation $\delta_D = \pm 90^\circ$ reduces up to 20% (40%) when compared to the standard DUNE configuration. Especially, the CP uncertainty is controlled to be below 8° and the best case can be as good as 6° for the baseline $L = 38\,\text{km}$. In addition, the dependence of CP uncertainty on the true CP phase value is largely mitigated. If realized, either the DUNE + $\mu$THEIA-25 or DUNE + $\mu$THEIA-100 configuration can bring the CP measurement into a precision era.

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The authors are supported by the National Natural Science Foundation of China (12375101, 12090060 and 12090064) and the SJTU Double First Class start-up fund (WF220442604). SFG is also an affiliate member of Kavli IPMU, University of Tokyo. PSP is also supported by the Grant-in-Aid for Innovative Areas No. 19H05810.

## REFERENCES

[1] Ge S. F., Kong C. F. and Pasquini P., *Eur. Phys. J. C*, **82** (2022) 572.
[2] Particle Data Group (Workman R. L. *et al.*), *Prog. Theor. Exp. Phys.*, **2022** (2022) 083C01.
[3] Akhmedov E. K., Johansson R., Lindner M., Ohlsso T. and Schwetz T., *J. High Energy Phys.*, **04** (2004) 078.
[4] Evslin J., Ge S. F. and Hagiwara K., *J. High Energy Phys.*, **02** (2016) 137.