Improving CP Measurement with Muon Decay At Rest

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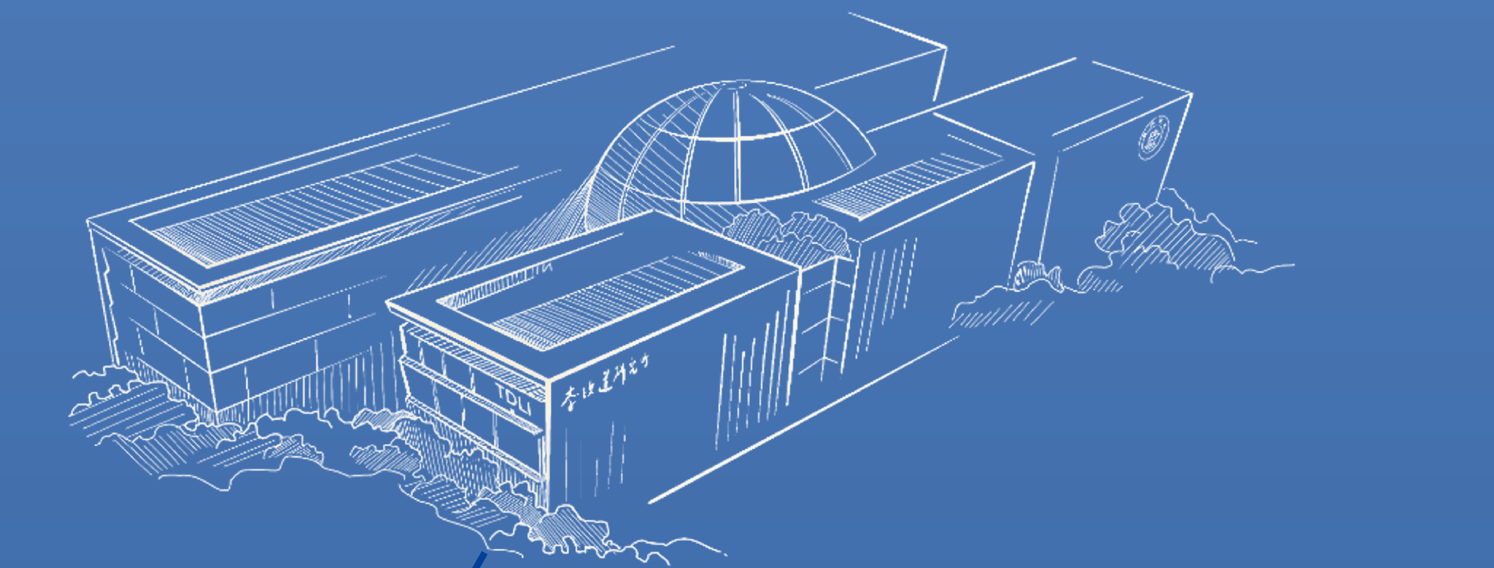

Abstract

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 (μDAR) source to improve the leptonic CP phase measurement. Due to its intrinsic low-energy beam, this μTHEIA configuration (μDAR neutrinos at THEIA) is only sensitive to the genuine leptonic CP phase δ_D and not contaminated by the matter effect. With detailed study of neutrino energy reconstruction and backgrounds at the THEIA detector, we find that the combination with the high-energy DUNE can significantly reduce the CP uncertainty, especially around the maximal CP violation cases $\delta_D = \pm 90°$. Both the μTHEIA-25 with 17 kt and μTHEIA-100 with 70 kt fiducial volumes are considered. For DUNE + μTHEIA-100, the CP uncertainty can be better than 8°.

1. Introduction

The current long-baseline experiments T2K and NOνA are approaching the discovery threshold. The 2019 T2K result with $\delta_D = 252°^{+40°}_{-33°}$ and $281°^{+28°}_{-31°}$ for the normal and inverted orderings (NO and IO), respectively, has excluded almost half of the parameter space except $[165°, 358°]$ and $[-214°, 342°]$ at 3σ confidence level (C.L.). It is interesting to see that the maximal CP phase $\delta_D = -90°$ is around the best-fit point. However, the 2019 NOνA result is $\delta_D = 0°^{+74°}_{-23°}$ for NO with best-fit value at vanishing CP phase, $\delta_D = 0°$. In 2021, T2K and NOνA updated their results with the best-fit value from T2K remaining the same, $\delta_D = 252°^{+40°}_{-33°}$ (NO) and $281°^{+28°}_{-31°}$ (IO) while the NOνA best fit changes to $\delta_D = 148°^{+49°}_{-157°}$ for NO.

Even if the current tension between T2K and NOνA measurements vanishes with more data, correct interpretation of CP measurements still faces intrinsic issues including event rate inefficiency, $\delta_D \leftrightarrow \pi - \delta_D$ degeneracy, and large CP uncertainty around the maximal values. These issues still remain for the next-generation experiments like T2HK and DUNE. Although its wide spectrum can help to reduce the δ_D degeneracy, DUNE has much larger matter effect than T2K and NOνA due to higher energy peaking around 2.5 GeV . At long-baseline experiments, the genuine CP effect can be faked by the ubiquitous matter effect, reducing the experimental sensitivity to δ_D. In addition, the uncertainties in the matter effect can also reduce the CP sensitivity at DUNE.

In this paper, we propose μTHEIA as combination of the THEIA detector and a μDAR neutrino flux to improve the Dirac leptonic CP phase measurement together with DUNE.

2. Improving CP Measurement with Multiple Baselines and Beam Energies

To make the CP and matter effect explicit, we perform a series expansion of the $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) oscillation probability in terms of the ratio between the two mass squared differences α ($\equiv \Delta m_s^2/\Delta m_a^2 \approx 3\%$) and the reactor mixing angle s_r ($\equiv \sin\theta_r \approx 0.15$),

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

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 matter term $A \equiv 2E_\nu V/\Delta m_a^2$ appears in two combinations, $\sin(A\Delta_a)/A$ and $\sin[(1\mp A)\Delta_a]/(1\mp A)$. In the limit of tiny matter effect, $A \to 0$, the two combinations reduce to approximately Δ_a and $\sin\Delta_a$, respectively.

At a single long-baseline neutrino oscillation experiment, there is only one independent CP observable but two parameters (A and δ_D). To disentangle the matter contamination (A) from the genuine CP effect (δ_D), a combination of two different baselines is a promising choice.

A better way is significantly reducing the matter effect with low-energy neutrino beam to make $A \ll 1$ and one possibility is using the muon decay at rest.

3. μDAR at THEIA

It is impossible to simply add a μDAR 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 μDAR flux at DUNE.

A new THEIA detector at the same site of SURF was recently proposed. With a new technique of water-based liquid scintillator (WbLS), it is possible to use both scintillation and Cherenkov lights. This opens the possibility of detecting the low-energy μDAR neutrino oscillation to supplement the high-energy mode at DUNE. For convenience, we call the combination of μDAR and THEIA as μTHEIA.

The matter effect at μTHEIA is negligibly small. Being essentially insensitive to the matter potential, μTHEIA can focus on the genuine CP phase while DUNE probes both. Their combination can significantly improve the CP sensitivity.

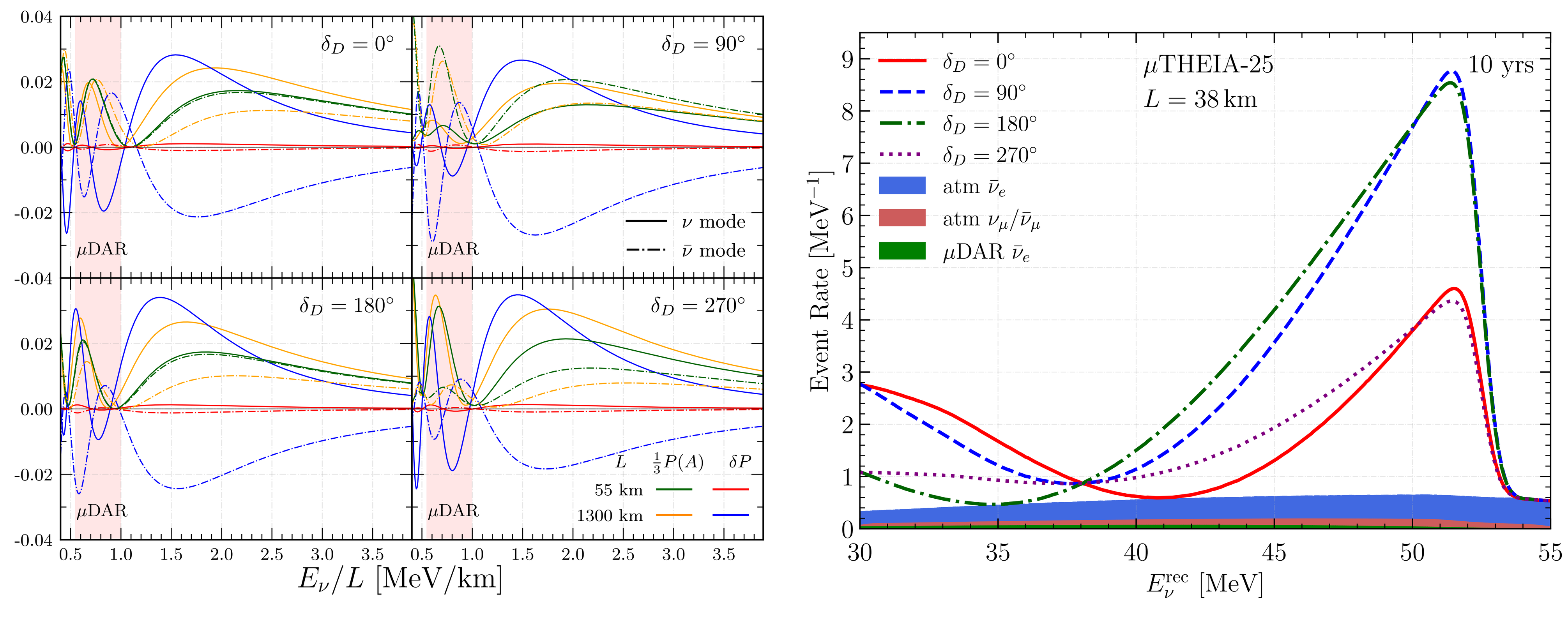

Fig. 1: Left: the oscillation probability plot. Right: Event rate at μTHEIA.

4. Results

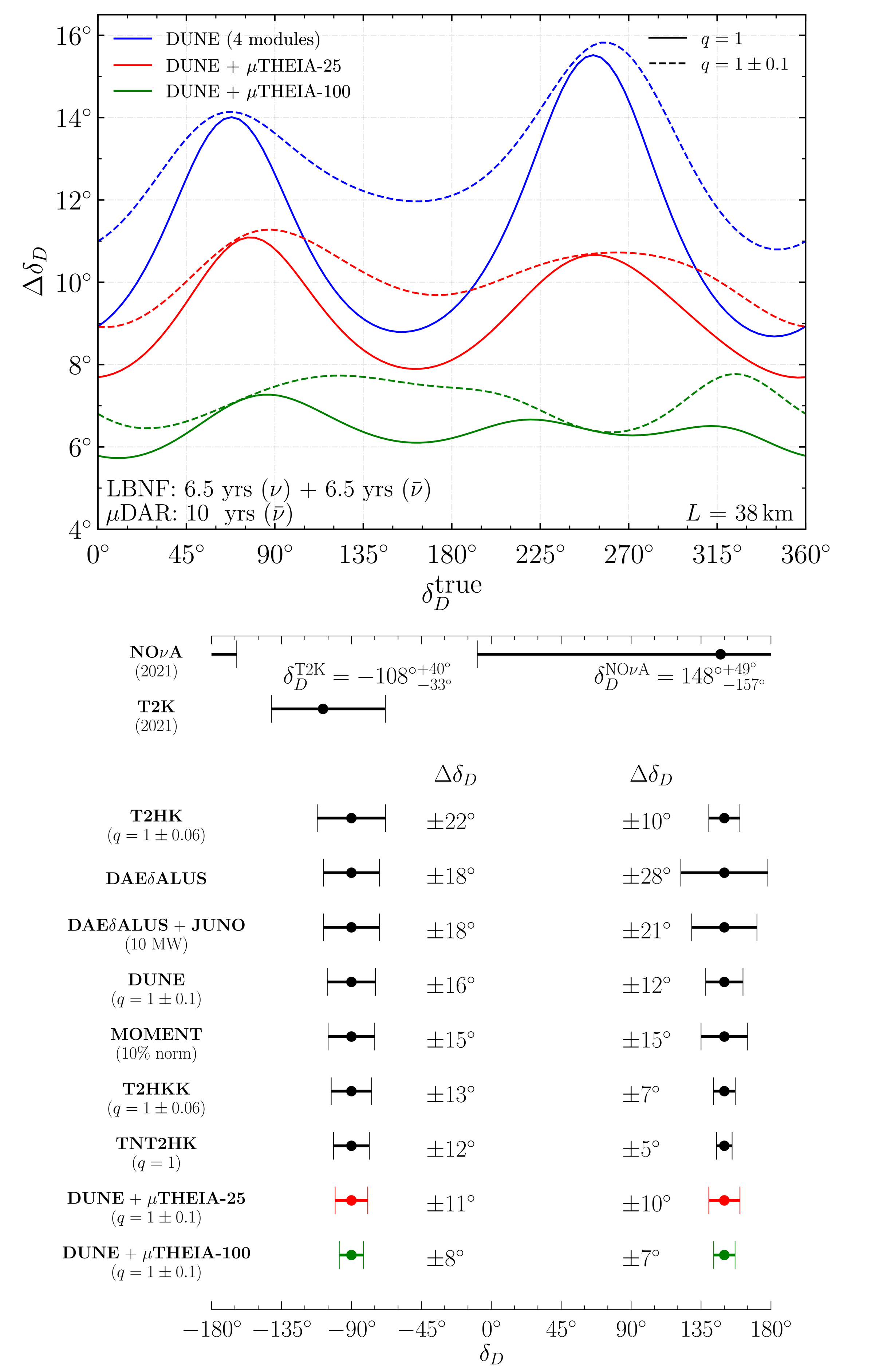

Fig. 2: Top: CP sensitivity plot. Bottom: Compare with other (proposed) experiments' results.

5. Conclusions

1. Currently, there is still a long way to go for measuring CP

2. CP sensitivity will be reduced due to the matter effect at DUNE

3. An additional low-energy μDAR neutrino beam can resolve the degeneracy and enhance CP sensitivity significantly

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