

Exploring Earth's Matter Effect in High-Precision Long-Baseline Experiments

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The Earth's matter effect is going to play a crucial role in measuring the unknown three-flavor neutrino oscillation parameters at high confidence level in future high-precision long-baseline experiments. We observe that owing to the new degeneracies among the most uncertain oscillation parameters (δ_{CP} , θ_{23}) and the average Earth's matter density (ρ_{avg}) for the 1300 km baseline, the sensitivity of the upcoming Deep Underground Neutrino Experiment (DUNE) to establish Earth's matter effect reaches only about 2σ C.L. for all possible choices of oscillation parameters. We notice that the current uncertainty in δ_{CP} degrades the measurement of ρ_{avg} more as compared to θ_{23} . To lift these degeneracies, we explore the possible complementarity between DUNE and Tokai to Hyper-Kamiokande (T2HK/JD) facility with a second detector in Korea, popularly known as T2HKK or JD+KD setup. While DUNE uses a wide-band beam with an on-axis detector, T2HKK setup plans to use a narrow-band beam with two off-axis detectors: one in Japan and other in Korea. We exhibit how the high-precision measurement of δ_{CP} in JD+KD setup and the information on ρ_{avg} coming from DUNE can reduce the impact of these degeneracies in both $(\rho_{avg} - \delta_{CP})$ and $(\rho_{avg} - \theta_{23})$ planes. We show that the combined data from DUNE and JD+KD setups can establish Earth's matter effect at more than 6σ C.L. irrespective of both the choices of mass hierarchy: normal (NH) and inverted (IH), δ_{CP} , and θ_{23} . With the help of this combined data set, we can measure the average matter density (ρ_{avg}) with a relative 1σ precision of around 11.2% (9.4%) assuming true NH (IH) and $\delta_{CP} = -90^\circ/90^\circ$.

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1. Complementarity between DUNE and T2HKK (JD+KD) Setups

In this work, we explore the interesting complementarity between the two next generation high-precision long-baseline experiments DUNE and T2HKK (JD+KD) in establishing the Earth's matter effect [1] by rejecting the vacuum oscillation. The DUNE far detector (a 40 kt LArTPC) will receive an on-axis, high-intensity, wide-band neutrino beam covering both first and second oscillation maxima with a baseline of 1300 km [2]. On the other hand, the T2HKK setup plans to house its first far detector (187 kt, water Cherenkov detector) in Japan (JD) at a distance of 295 km from J-PARC and to deploy an another 187 kt, water Cherenkov detector in Korea (JD+KD) at a baseline of 1100 km [3]. The Japanese (Korean) detector will observe an off-axis (2.5°), narrow-band beam covering the first (second) oscillation maximum. We expect a high-precision measurement of δ_{CP} and a conclusive evidence for leptonic CP violation from this JD+KD setup, which has much less matter effect. On the other hand, DUNE feels a substantial matter effect due to its larger baseline and energies as compared to the JD+KD setup. Therefore, the combined data from DUNE and JD+KD may establish the Earth's matter effect at high C.L. by reducing the impact of possible degeneracies among the oscillation parameters (δ_{CP} , θ_{23}) and the average Earth's matter density (ρ_{avg}). In this work, we discuss several interesting issues along this direction.

2. Establishing Earth's matter effect

We perform our simulations using the GLOBES software [4]. We generate the prospective data with the following choices of oscillation parameters: $\sin^2 \theta_{23} = [0.44, 0.5, 0.56]$, $\sin^2 2\theta_{13} = 0.085$, $\sin^2 \theta_{12} = 0.307$, δ_{CP} in the range -180° to 180° , $\Delta m_{31}^2 = 2.5(-2.4) \times 10^{-3} \text{ eV}^2$ for NH (IH), $\Delta m_{21}^2 = 7.4 \times 10^{-5} \text{ eV}^2$, and the average matter density (ρ_{avg}) = 2.86 g/cm^3 for all the three (JD, KD, and DUNE) baselines. The statistical significance of the long-baseline experiments to establish the

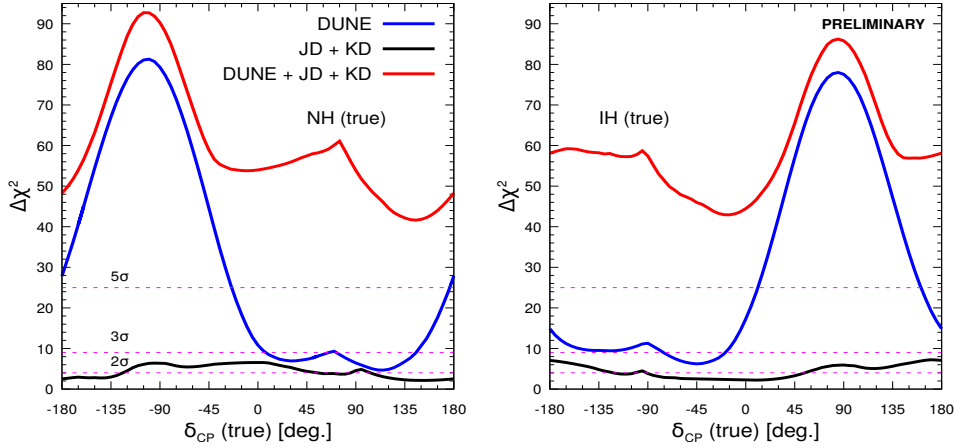


Figure 1: The sensitivity of JD+KD (black curves), DUNE (blue curves), and the combined DUNE+JD+KD setup (red curves) in establishing the Earth's matter effect as a function of true δ_{CP} assuming true NH (IH) in the left (right) panel. We consider $\sin^2 \theta_{23}$ (true) = 0.5 and marginalize over $\sin^2 \theta_{23} = [0.4 : 0.6]$, $\delta_{CP} = [-180^\circ : 180^\circ]$, and $\Delta m_{31}^2 = \pm [2.36 : 2.64] \times 10^{-3}$ in the fit.

Earth's matter effect by refuting the vacuum oscillation is defined as follows

$$\Delta\chi^2 = \min_{(\vec{\gamma}, \lambda_1, \lambda_2)} \{ \chi^2(\rho_{avg}^{true} \neq 0) - \chi^2(\rho_{avg}^{test} = 0) \}, \quad (1)$$

where $\vec{\gamma} = \{\theta_{23}, \delta_{\text{CP}}, \Delta m_{31}^2\}$ is the set of oscillation parameters on which marginalization is performed and λ_1, λ_2 are the systematic pulls [5] on signal and background, respectively. In Fig. 1 we observe that DUNE (blue lines) itself can establish the matter effect for about 45% choices of true δ_{CP} at 5σ C.L. for both true NH and IH. On the other hand, the JD+KD setup (black lines) alone has much less sensitivity towards the Earth's matter effect. When we combine the performance of DUNE and JD+KD, we observe a significant enhancement in the sensitivity and Earth's matter effect can be established with more than 6σ C.L. (red lines) for all possible choices of true δ_{CP} and for both NH and IH. We see this improvement in the sensitivity for the unfavorable choices of true δ_{CP} (around 0° to 180° for true NH and -180° to 0° for true IH) because the data from JD+KD setup reduces the impact of marginalization over test δ_{CP} while analyzing the data from DUNE.

3. Precision measurement of ρ_{avg}

The statistical significance to measure ρ_{avg} in a given experiment is defined as

$$\Delta\chi_{\text{PM}}^2(\rho_{\text{avg}}) = \chi^2(\rho_{\text{avg}}) - \chi_0^2, \quad (2)$$

where we obtain $\chi^2(\rho_{\text{avg}})$ by performing a fit to the prospective data with $\rho_{\text{avg}} = 2.86 \text{ g/cm}^3$ and χ_0^2 is the minimum value of $\chi^2(\rho_{\text{avg}})$ considering ρ_{avg} in the range of 1.5 to 4 g/cm^3 . Fig. 2 shows

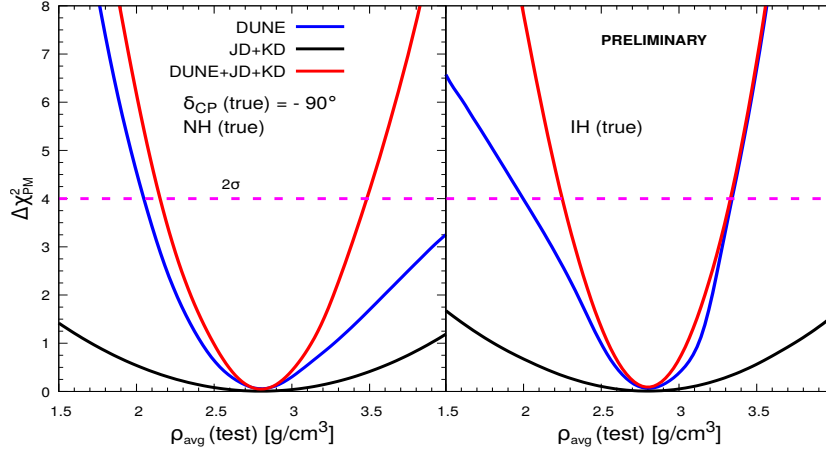


Figure 2: Left (Right) panel shows the achievable precision in the measurement of ρ_{avg} for JD + KD (black lines), DUNE (blue lines), and DUNE+JD+KD (red lines) assuming true NH (IH). Here, we consider true $\delta_{\text{CP}} = -90^\circ$ and $\sin^2 \theta_{23} = 0.5$. In the fit, we marginalize over $\sin^2 \theta_{23}$, δ_{CP} , and Δm_{31}^2 (see Fig. 1 caption).

that the JD+KD setup alone offers a relative 1σ precision in ρ_{avg} of around 40% (35%) for true NH (IH) assuming $\delta_{\text{CP}}(\text{true}) = -90^\circ$ and $\sin^2 \theta_{23}(\text{true}) = 0.5$. The same quantity for DUNE setup alone is around 15% (12%). Interestingly, when we combine the data from these two high-precision experiments, the achievable precision in ρ_{avg} reaches to 11.2% (9.4%).

4. Degeneracies in test $(\rho_{\text{avg}} - \delta_{\text{CP}})$ and test $(\rho_{\text{avg}} - \theta_{23})$ Planes

The black curves in left (right) panel of Fig. 3 shows that the JD+KD setup alone can measure δ_{CP} (θ_{23}) quite precisely while having almost no sensitivity towards ρ_{avg} due to their shorter

baselines. Whereas the DUNE setup alone can constrain the allowed ranges in ρ_{avg} and can provide reasonable measurements of δ_{CP} and θ_{23} (blue curves). When we combine the data from

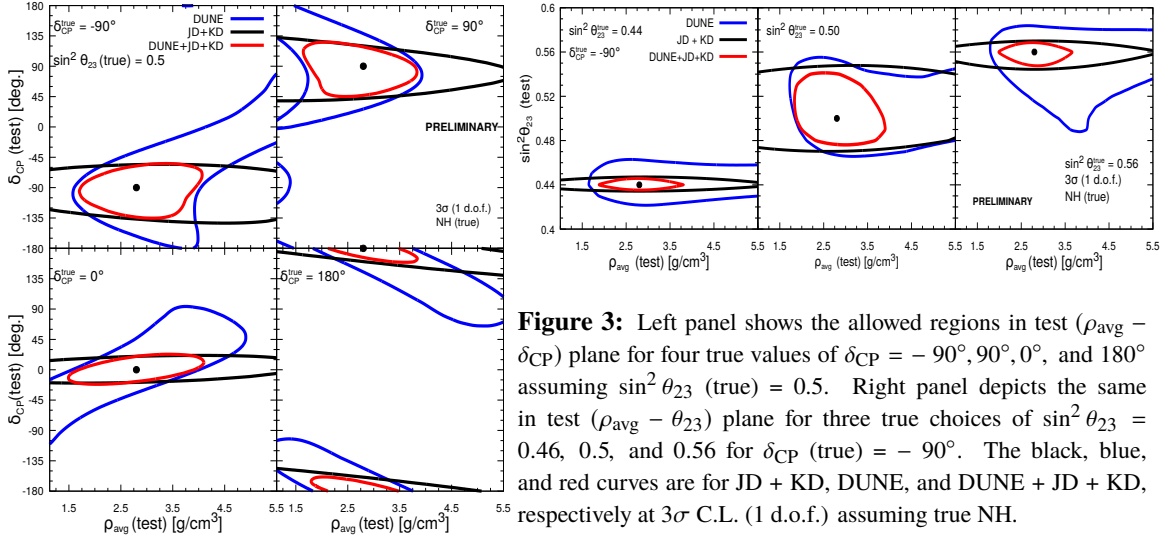


Figure 3: Left panel shows the allowed regions in test ($\rho_{\text{avg}} - \delta_{\text{CP}}$) plane for four true values of $\delta_{\text{CP}} = -90^\circ, 90^\circ, 0^\circ,$ and 180° assuming $\sin^2 \theta_{23} (\text{true}) = 0.5$. Right panel depicts the same in test ($\rho_{\text{avg}} - \theta_{23}$) plane for three true choices of $\sin^2 \theta_{23} = 0.46, 0.5,$ and 0.56 for $\delta_{\text{CP}} (\text{true}) = -90^\circ$. The black, blue, and red curves are for JD + KD, DUNE, and DUNE + JD + KD, respectively at 3σ C.L. (1 d.o.f.) assuming true NH.

these two setups, we see a considerable reduction in the allowed ranges in both ($\rho_{\text{avg}} - \delta_{\text{CP}}$) and ($\rho_{\text{avg}} - \theta_{23}$) planes (red curves) due to the complementary information from these two experiments.

5. Conclusion

DUNE with 1300 km baseline has significant matter effect and can measure δ_{CP} and θ_{23} with reasonable precision exploiting the information on oscillation pattern at several L/E values. On the other hand, with a relatively shorter baseline and high statistics JD offers an unmatched sensitivity to the δ_{CP} free from matter effect. KD with a roughly four times baseline than JD has some sensitivity to Earth's matter effect and provides crucial information on δ_{CP} around the second oscillation maxima. In this work, for the first time, we show how the complementary features between DUNE and JD+KD setups can play an important role to establish the Earth's matter effect at more than 6σ C.L. for any values of oscillation parameters. The complementary informations coming from DUNE and JD+KD setups also play an important role to provide a high-precision measurement of ρ_{avg} and to reduce the allowed regions in ($\rho_{\text{avg}} - \delta_{\text{CP}}$) and ($\rho_{\text{avg}} - \theta_{23}$) planes considerably.

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