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Exploring Matter Effect and Associated Degeneracies at DUNE

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Matter effect plays a pivotal role in the upcoming Deep Underground Neutrino Experiment (DUNE) to address pressing fundamental issues such as leptonic CP violation, neutrino mass hierarchy, and precision measurements of the oscillation parameters in the precision era. In this paper, for the first time, we explore in detail the capability of DUNE to establish the matter oscillation as a function of $\delta_{\rm CP}$ and θ_{23} by excluding the vacuum oscillation. With the optimized neutrino beam design and using an exposure of 300 kt·MW·years, DUNE can confirm the presence of Earth's matter effect at 2σ C.L. irrespective of the choices of hierarchy, $\delta_{\rm CP}$, and θ_{23}. Moreover, DUNE can rule out the vacuum oscillation at 3σ (5σ) significance with a $\delta_{\rm CP}$ coverage of 64% (46%) for normal hierarchy and maximal θ_{23}, whereas for inverted hierarchy, the $\delta_{\rm CP}$ coverage is 82% (43%). The relative 1σ precision in the measurement of line-averaged constant Earth matter density (ρ_{avg}) for maximal CP-violating choices of $\delta_{\rm CP}$ is around 10% to 15% depending on the choice of neutrino mass hierarchy. The same for CP-conserving values of $\delta_{\rm CP}$ is around 25% to 30%. We find that if $\delta_{\rm CP}$ turns out to be around -90° or 90°, the precision in measuring ρ_{avg} in DUNE is better than that one can achieve using the atmospheric data from Super-Kamiokande, combined data from Solar and KamLand, and from the full exposure of T2K and NOνA. We also identify new degeneracies in ($\rho_{avg} - \delta_{\rm CP}$) and ($\rho_{avg} - \sin^2\theta_{23}$) planes and notice that the uncertainty in $\delta_{\rm CP}$ affects the measurement of ρ_{avg} more than that of θ_{23}. A detailed understanding of these degeneracies are essential to correctly assess the outcome of DUNE.

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1. Introduction

With the determination of reactor mixing angle θ_{13}, the focus of Neutrino Physics is directed towards the precision measurement of oscillation parameters and the determination of the unknowns such as CP-violating phase $\delta_{\rm CP}$, neutrino mass hierarchy, and the octant of atmospheric mixing angle. Matter effect [1] plays significant role in the determination of unknowns as it affect neutrino oscillation probability differently for neutrinos and antineutrinos, normal hierarchy and inverted hierarchy, and lower octant and higher octant. Therefore, it is of great important to confirm that the long baseline experiments like Deep Underground Neutrino Experiment (DUNE) must have seen enough matter effect before addressing the fundamental questions regarding the current unknowns in neutrino sector. As a result, we study the cabability of DUNE in establishing the matter effect by excluding vacuum oscillation. We also obtain the precision of matter density parameters at DUNE.

2. Matter vs vacuum oscillation

In order to quantify the capability of an experiment to establish matter oscillation, we define a quantity ΔP as the difference in the oscillation probabilities in matter and in vacuum, i.e.,

$$\begin{aligned}\Delta P =& \ P^{\rm mat}_{\nu_\mu\longrightarrow\nu_e} - P^{\rm vac}_{\nu_\mu\longrightarrow\nu_e}\\ =& \ \frac{1}{2}\sin^2\theta_{23}\sin^2 2\theta_{13}\left[(X-1)+\cos[(2n+1)\pi\hat{A}]\,(X+1)\right] \quad \text{(at oscillation maxima)},\end{aligned}$$

where $X = 3\hat{A}^2{+}2\hat{A}$, $\hat{A} = A/\Delta{\rm m}^2_{31}$ with $A = 0.76{\times}10^{-4}({\rm eV}^2){\times}\left(\frac{\rho_{\rm avg}}{\rm g/cm^3}\right){\times}\left(\frac{\rm E}{\rm GeV}\right)$, $\Delta = 1.27\Delta{\rm m}^2_{31}L/E$, $\Delta m^2_{ij} = m^2_i - m^2_j$, L is the baseline, $\rho_{\rm avg}$ is Earth's matter density, n=0 first and n=1 for second oscillation maxima, and E is the energy. It should be noted from the above equation that ΔP depends on the mixing angles (θ_{13} and θ_{23}). Further, the matter potential comes in the oscillation maxima with a cosine term. ΔP as a function of various baseline and energy is given in Fig.1. We use following benchmark value of oscillation parameters in our analysis unless otherwise mentioned:

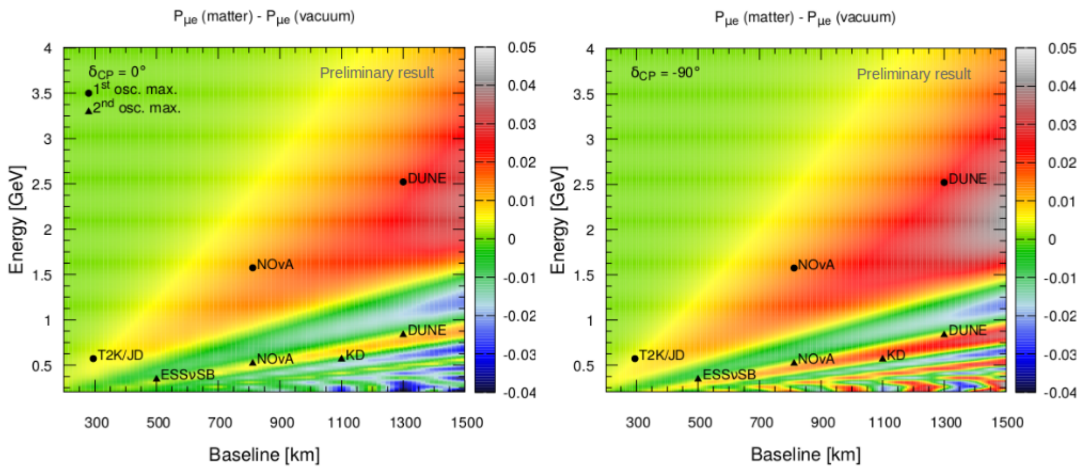

Figure 1: ΔP distribution for various combination of baseline and energy.

$\sin^2\theta_{12} = 0.307$, $\sin^2 2\theta_{13} = 0.085$, $\sin^2\theta_{23} = 0.5$, $\delta_{\rm CP} = [-180^0 : 180^0]$, $\Delta m^2_{21} = 7.4\times10^{-5}{\rm eV}^2$, and $\Delta m^2_{31} = 2.5(-2.4)\times10^{-3}{\rm eV}^2$ for NH (IH). From the figure, it can be seen that long baseline experiments have non-zero contribution for ΔP and so they are capable of distinguishing matter oscillation from vacuum oscillation.

3. Simulation details

In this work, we consider a total of 300 kt·MW·years of exposure for DUNE which is equally divided in both neutrino and antineutrino beam modes. The neutrino beam is generated from a proton beam power of about 1.07 MW with energy 80 GeV as given in [2]. We use the latest flux files from [3]. We use GLoBES [4, 5] package for our analysis by considering the reconstructed energy range from 0.1 GeV - 20 GeV. Further we used identical systematics for both neutrino and anti-neutrino mode.

4. Results and Conclusions

To show the new degeneracies among the oscillation parameters, the bi-event curves for DUNE is given in the left panel of the Fig.2. It can be seen from the figure that the solid and dashed ellipses are overlapping with each other. In the overlapped region, one cannot distinguish between the matter or vacuum oscillation parameters which results in new types of degeneracy among the oscillation parameters so-called $\rho_{\rm avg} - \delta_{\rm CP} - \theta_{23}$ degeneracy. The precision measurement of $\rho_{\rm avg}$ for various experiments is given in the right panel of Fig.2. From the figure, one can see that the precision in the measurement of $\rho_{\rm avg}$ is better for DUNE compared to all other experiments. The capability of DUNE in establishing matter oscillation as a function of true values of $\delta_{\rm CP}$ is given in Fig.3. From the figure, it can be seen that DUNE can exclude vacuum oscillation at 2σ C.L.

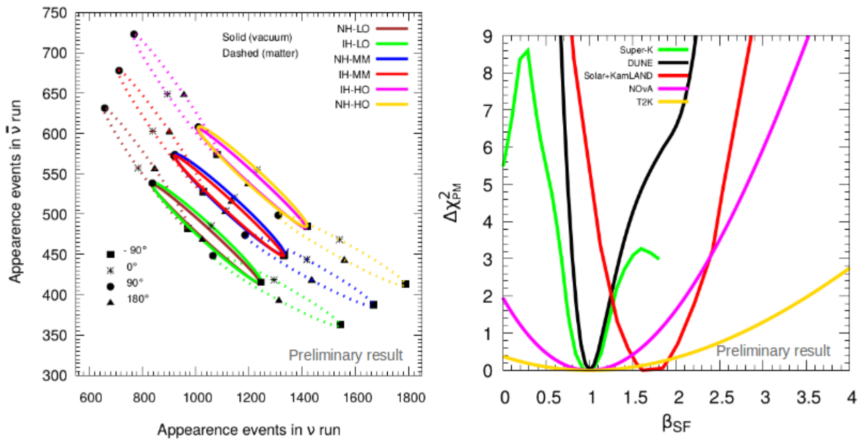

Figure 2: The bi-event curves for DUNE is in left panel. The ellipses are obtained by varying $\delta_{\rm CP}$ in in the range [-180^0:180^0]. The dashed (solid) curve corresponds to bi-event curve in matter (vacuum). The three sets are generated for three different values of $\sin^2\theta_{23} = 0.44$, 0.5, and 0.56 respectively for LO, MM, and HO for both NH and IH. The precision in the measurement of $\rho_{\rm avg}$ in terms of scaling parameter β_{SF} for different neutrino oscillation experiments is given in the right panel.

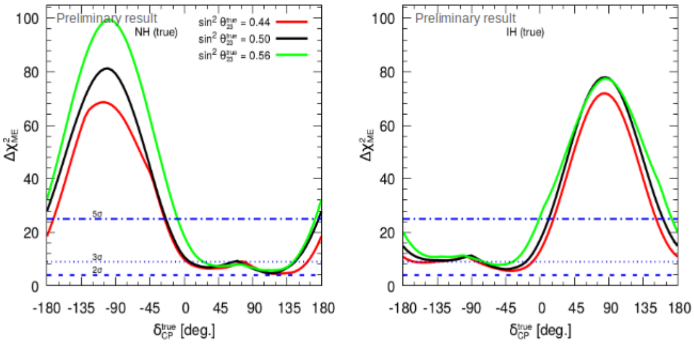

Figure 3: The vacuum oscillation exclusion sensitivity as a function of $\delta_{\rm CP}^{true}$ for DUNE.

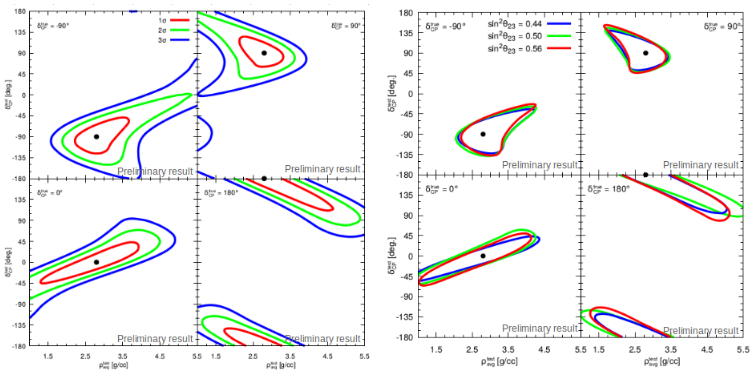

Figure 4: Allowed region in ($\rho_{\rm avg} - \delta_{\rm CP}$) and ($\rho_{\rm avg} - \sin^2\theta_{23}$) planes.

irrespective of the choices of hierarchy, $\delta_{\rm CP}$, and θ_{23}. In addition to this, DUNE can rule out the vacuum oscillation at 3σ (5σ) significance with a $\delta_{\rm CP}$ coverage of 64% (46%) for normal hierarchy and maximal θ_{23}, whereas for inverted hierarchy, the $\delta_{\rm CP}$ coverage is 82% (43%). The allowed region in ($\rho_{\rm avg} - \delta_{\rm CP}$) and ($\rho_{\rm avg} - \sin^2\theta_{23}$) planes are shown in Fig.4. It can be inferred from the figure that the uncertainty in $\rho_{\rm avg}$ can be improved if one precisely measures the value of $\delta_{\rm CP}$, as the uncertainty of $\rho_{\rm avg}$ is not much dependent on $\sin^2\theta_{23}$.

References

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