CP Violation and Physics beyond Standard Model

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ABSTRACT *Neutrinos are the window to probe physics beyond the standard model. In standard three neutrino physics the role of dirac CP phase is still to be determined. In this work we have quantified the impact of the new CP phase* δ_3*,coming from new physics, in imposing bounds on the "standard" three active neutrino phase* δ_{CP}*.This study is carried out for appearance channel at NOvA experiment. The new phase enters the probability equation by adding one sterile neutrino along with three active neutrinos.The effect of this new phase on standard neutrino physics is studied. Understanding regarding this phase is very crucial for neutrino physics and should be taken into account while planning the future neutrino experiments, aiming towards the measurement of* δ_{CP}*.*

KeyWords: *threeactive neutrinos, sterile neutrino, impact, new CP phase, appearance probability.*

I. INTRODUCTION

The standard phenomenon of three active neutrino oscillation can be described with the help of six parameters. These parameters can be defined as three neutrino mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$; two mass square differences $\Delta m^2_{21}, \Delta m^2_{31}$ and dirac CP phase δ_{CP}. In past few decades the neutrino oscillation experiments have explored roughly all the parameters with high accuracy except the sign of Δm^2_{31} and the value of δ_{CP}[1][2]. The next generation neutrino experiments are aiming to pin down the undetermined neutrino oscillation parameters. The NOvA and T2K experiment have given the hint of non zero value of the dirac CP phase [3]. Neutrino oscillations are firmly established beyond the standard model hence their impact need to be studied thoroughly.

The use of appearance channel is necessary to probe the presence of CP violation through neutrino oscillation experiments. To visualize the presence of CP violation at probability level in any neutrino oscillation experiment we can look at CP asymmetry which is defined as $\Delta P^{\alpha\beta}_{CP} = A^{CP}_{\alpha\beta} = P_{\alpha\beta} - P_{\overline{\alpha\beta}}$ for $\alpha \neq \beta$ where $P_{\alpha\beta}$ and $P_{\overline{\alpha\beta}}$ are oscillation probability of neutrino and antineutrino in vacuum. The mixing angles and mass square splitting of neutrino changes when neutrinos pass through matter, due to an extra matter potential felt by the electron neutrinos on their way. The change in the value of neutrino parameters in matter with respect to vacuum changes the oscillation probability and this induces fake CP violation. In long baseline neutrino oscillation experiments, matter effects play significant role and fake CP violation cannot be ignored [4][5].

In the past few decades the neutrino oscillation experiments have reported several anomalous signatures and these promote us to look for new physics. One possible way to answer these anomalies is addition of light sterile neutrinos[6] in three neutrino framework. These new neutrino states are assumed to have mass square splitting of the order of 0.1-10 eV and these neutrinos do not participate in the weak interactions. Inclusion one sterile neutrino along with three active neutrinos define the minimal parameter space[7]. The upcoming and ongoing neutrino experiments are focusing towards imposing tight bounds on CP and CPT violation in presence of sterile neutrino [8][9]. In our work we have selected 3+1 framework that is three active and one sterile neutrino framework.

II: Parametrization Scheme and Neutrino Oscillation Formalism

The parameterization scheme selected for this work is:

$$U = U_{34}(\theta_{34},0)U_{24}(\theta_{24},0)\,U_{14}(\theta_{14},0)U_{23}(\theta_{23},\delta_3)U_{13}(\theta_{13},\delta_2)U_{12}(\theta_{12},\delta_1)$$

Here$U_{ij}$are the unitary matrix which are defined in terms of mixing angles and phases.

(1)

The difference in neutrino oscillation probability for golden channel$\nu_e \rightarrow \nu_\mu$is developed by using formalism developed by Kimura, Takamura and Yokomakura [10][8]

$$\Delta P_{CP}^{\mu e} = 4c_{13}c_{14}^2c_{24}s_{13}s_{23}s_{14}s_{24}\sin(\delta_2-\delta_3)\frac{\Delta_e}{(\Delta_e-\Delta_{31})}\sin\Delta m_{31}^2\frac{L}{2E} + 4c_{13}c_{14}^2c_{24}s_{13}s_{23}\,s_{14}s_{24}\sin(\delta_2-\delta_3)\,\frac{\Delta_{31}^2}{(\Delta_e-\Delta_{31})\,\Delta_e}\sin2\Delta_e$$

(2)

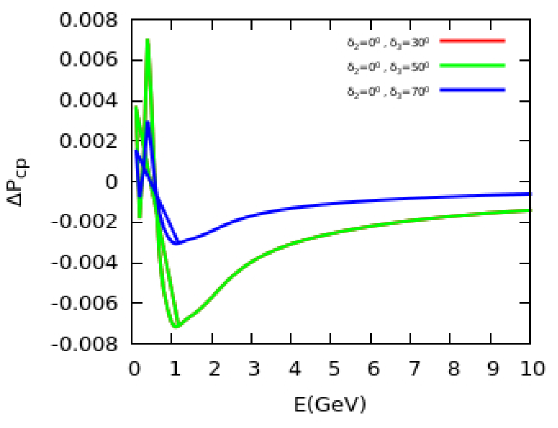
In the above probability equation $\delta_2$is standard three neutrino CP phase and $\delta_3$is CP phase due to new physics.

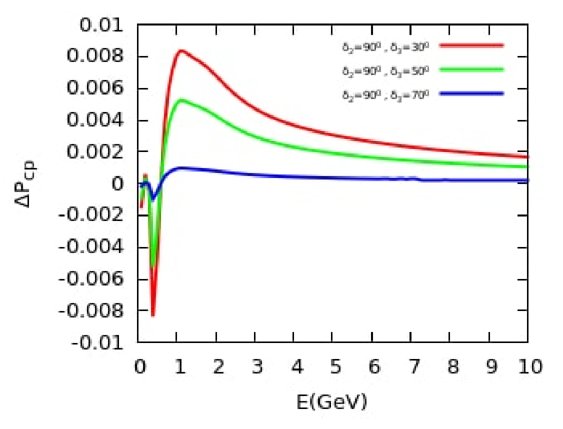
The value of oscillation parameters used in our analysis are

$$\theta_{23} = 45^0, \theta_{13} = 8^0, \theta_{12} = 34^0, \Delta m_{21}^2 = 8x10^{-5}, \Delta m_{31}^2 = 2.5x10^{-3}, \delta_2 = \pi/2\,;0^0, \theta_{14} = 6.7^0, \theta_{24} = 3.3^0,\ \theta_{34} = 6.3^0$$

The value of new phase$\delta_3$is varied between 0 to$\pi/2$.

III. Simulation tool and Result





(a) (b)

Fig. 1: The above plot shows the variation inCP asymmetry with neutrino energy. In (a) the phase is kept fixed at 0⁰ and the new phase is varied : red line $\delta_3 = 3$, green line $\delta_3 = 5$, blue line $\delta_3 = 7$while in (b) the phase is kept fixed at π,and the new phase is varied : red line $\delta_3 = 3$, green line $\delta_3 = 5$, blue line $\delta_3 = 7$

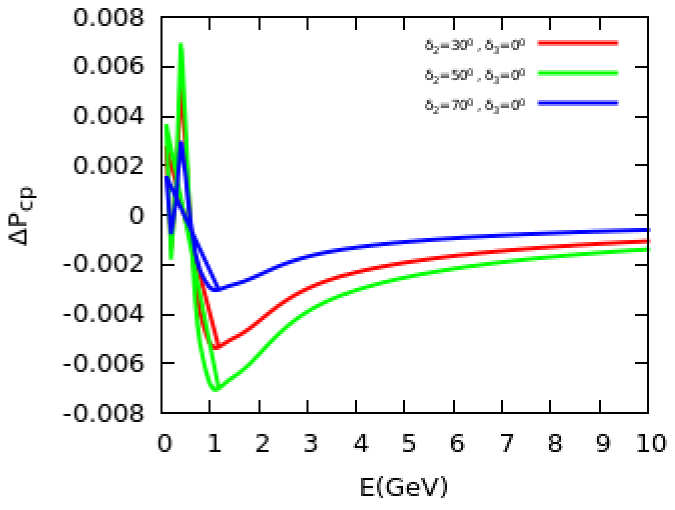


Fig. 1: The above plot shows the variation in CP asymmetry with neutrino energy. In this plot the phase is kept fixed at 0^0 and the phase is varied : red line $\delta_3 = 3$, green line $\delta_3 = 5$, blue line $\delta_3 = 7$

For this work we have used GloBES simulation package to observer and simulate long baseline neutrino oscillation experiment NOvA[11][12]. This tool contains comprehensive abstract experiment definition, which is used to define the experiment completely and accurately. C language is used to define the observables of the experiment i.e asymmetry, rate vectors and chi square.

Using GloBES software package we have observed the impact of new CP phase$\delta_3$on the measurement of three neutrino CP phaseδ_2.Using equation 2 we implement the asymmetry in GloBES and then observe the asymmetry in probability for golden channel with NOvA experiment. Here we have selected two extreme values of$\delta_2$in Fig. 1 and at these exteme values we have observed the impact of new phase$\delta_3$on neutrino oscillation studies. In (a) of Fig. 1 we can observe that in absence of CP phase$\delta_2$the new CP phase signatures are merged in the angular range 30^0- 50^0 and the new CP signatures response to different angular values at 70^0. In (b) figure of Fig. 1 we have kept the$\delta_2$as maximum and observed the effect of new CP phase in this scenario. In the figure we can see that for different angles we can see separate signatures of new phase. From these plots we can say that three neutrino phase need to be at maximum in order to predict the correct values of new CP phase. The Fig. 2 reflects the signatures of$\delta_2$in the absence of new phase. Above CP asymmetry analysis at probability level predicts that NOvA experiment can impose a bound on the new phase and it will allow us to extract three neutrino oscillation physics with better precision.

IV: conclusion

In this work we have examined the contribution of new CP phase arising due to the addition of sterile neutrino on the standard three neutrino physics [13][14][15]. Only one sterile neutrino is considered in our case and the analytical equation of probability is developed for 3+1 case. Sterile neutrinos are introduced to explain the anomalous results observed by the neutrino oscillation experiments. The extra phase introduced by sterile in the golden channel comes with matter effect terms in the probability equation hence fake CP violation should be disentangled from the CP violation in order to impose constraints on or new CP phase . The above results also depends on the present constraints on sterile angles and tight constraints on them will give better results on CP phase. The impact introduced by new phase is large enough and demands the new physics parameters to be determined accurately.

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