

# Discovery reach of CP violation in neutrino oscillation experiments with standard and non-standard interactions

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**Abstract.** Considering the value of mixing angle  $\theta_{13}$  as obtained in recent Daya Bay and MINOS experiments we have explored the discovery reach of CP violation in the leptonic sector due to complex  $\delta$  phase in neutrino oscillation experiments with superbeam. We have considered two experimental set-up corresponding to two baselines of 130 Km and 2300 Km respectively. Considering numerical simulation we have shown how the discovery reach of CP violation will change due to the presence of various non-standard interactions (NSIs). Although it is known that short baseline is better choice for CP violation study for Standard Model (SM) interactions of neutrinos with matter but in presence of NSI we find that sometimes better discovery reach is possible in relatively longer baselines.

## 1. Introduction

Among the various neutrino oscillation parameters the values of two mixing angles  $\theta_{12}$  and  $\theta_{23}$  have been provided by experiments with certain accuracy. Regarding the third mixing angle  $\theta_{13}$ , recently the Daya Bay experiment [1] and MINOS [2] has found non-zero large value of  $\sin^2 2\theta_{13}$ . The magnitude of the mass squared differences  $|\Delta m_{31}^2|$  and  $\Delta m_{21}^2$  are also known but the sign of  $\Delta m_{31}^2$  (hierarchy) and the CP violating phase  $\delta$  are still unknown. In this work we try to explore CP violation due to  $\delta$  in the light of recent experimental findings of large value of  $\theta_{13}$  and non-standard interactions(NSIs) [3, 4]. For this we have considered a superbeam source and two different baselines one of length 2300 Km and another of 130 Km length.

## 2. NSI and its effect in neutrino oscillation probabilities for different baselines

In addition to the Standard Model (SM) Lagrangian density we consider the following non-standard fermion-neutrino interaction in matter defined by the Lagrangian:

$$\mathcal{L}_{NSI}^M = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fP}[\bar{f}\gamma_\mu Pf][\bar{\nu}_\beta\gamma^\mu L\nu_\alpha] \quad (1)$$

where  $P \in (L, R)$ ,  $L = (1 - \gamma^5)/2$ ,  $R = (1 + \gamma^5)/2$ ,  $f = e, u, d$  and  $\varepsilon_{\alpha\beta}^{fP}$  denotes the non-standard interactions(NSIs) [5, 6]. These NSI parameters can be reduced to the effective parameters as  $\varepsilon_{\alpha\beta} = \sum_{f,P} \varepsilon_{\alpha\beta}^{fP} \frac{n_f}{n_e}$ , where  $n_f$  is the fermion number density and  $n_e$  is the electron number density. These NSIs can modify the interaction of neutrinos with matter and thus change the oscillation probability of different flavor of neutrinos. In section 4 in presenting results of our



numerical analysis considering NSI effect during propagation of neutrinos only, we consider the constraints on the NSIs as  $|\varepsilon_{ee}| \leq 0.75$  [7],  $|\varepsilon_{e\mu}| \leq 3.8 \times 10^{-4}$  [7],  $|\varepsilon_{e\tau}| \leq 0.25$  [7],  $|\varepsilon_{\mu\mu}| \leq 3 \times 10^{-2}$  [8],  $|\varepsilon_{\mu\tau}| \leq 6 \times 10^{-3}$  [8] and  $|\varepsilon_{\tau\tau}| \leq 3 \times 10^{-2}$  [8].

### 2.1. Oscillation Probability

For understanding qualitatively the NSI effect in finding the discovery reach of CP violation we consider the oscillation probability  $P_{\nu_e \rightarrow \nu_\mu}$  given in equations (8.3) and (8.4) of ref [9] as  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillation channels are particularly sensitive to CP violation. We can obtain  $P_{\nu_\mu \rightarrow \nu_e}$  from  $P_{\nu_e \rightarrow \nu_\mu}$  by replacing  $\delta$  by  $-\delta$ .

To estimate the order of magnitude of different terms in the above mentioned oscillation probabilities we shall consider the average earth matter density of 0.0263 gm/cc and 3.314 gm/cc for a short baseline of 130 Km and a relatively longer baseline of 2300 Km respectively and as such  $A < \alpha$  for 130 Km baseline for  $E \sim 0.3$  GeV and  $A \sim 0.5$  for 2300 Km baseline for  $E \sim 5$  GeV near the peak of the oscillation probability. Here,  $A = 2E\sqrt{2}G_F n_e / (\Delta m_{31}^2)$  and  $\alpha = \Delta m_{21}^2 / (\Delta m_{31}^2)$  where  $\Delta m_{ij}^2 = m_i^2 - m_j^2$ ,  $m_i$  denotes the mass of the  $i$ -th neutrino,  $G_F$  is the Fermi constant and  $n_e$  is the electron number density of matter.  $A$  is due to the interaction of neutrinos with matter in SM. For only SM interactions, (i.e  $\varepsilon_{\alpha\beta} \rightarrow 0$ ) in equations(8.3)and (8.4) of ref [9], one finds that for both the baselines the  $\delta$  dependence occurs at order of  $\alpha^{3/2}$ . However, for large values of  $A$  for longer baseline the matter effect is more in the  $\delta$  independent part. For this reason the discovery reach of CP violation is better in short baseline.

However, when NSIs are also taken into account one can see that for longer baseline further  $\delta$  dependence in  $P_{\nu_\mu \rightarrow \nu_e}$  could occur at the order of  $\alpha^{3/2}$  through terms in equations (8.3) and (8.4) containing NSIs -  $\varepsilon_{e\mu}$  and  $\varepsilon_{e\tau}$  of the order of  $\alpha$ . We have checked that for slightly higher NSIs of the order of  $\sqrt{\alpha}$  the same  $\delta$  dependent terms in  $P_{\nu_\mu \rightarrow \nu_e}$  appears with NSIs -  $\varepsilon_{e\mu}$  and  $\varepsilon_{e\tau}$  in the oscillation probability for long baseline making these terms at the order of  $\alpha$  which could compete with the  $\delta$  independent but matter dependent part in  $P_{\nu_\mu \rightarrow \nu_e}$  as that is also at the order of  $\alpha$ . This improvement of  $\delta$  dependent part over independent part for long baseline does not happen for short baseline as  $\delta$  dependent terms containing NSIs are small for short baseline due to small value of  $A$ . So presence of NSIs -  $\varepsilon_{e\mu}$  and  $\varepsilon_{e\tau}$  in  $\delta$  dependent terms improves the discovery reach of CP violation for longer baseline. It is expected that in presence of these NSIs i.e.  $\varepsilon_{e\mu}$  and  $\varepsilon_{e\tau}$  the long baseline could provide a better discovery reach for CP violation. However, as the upper bound of  $\varepsilon_{e\mu}$  is somewhat smaller one may expect  $\varepsilon_{e\tau}$  will have significant effect in the discovery reach of CP violation. In fact, our numerical analysis also shows this feature.

### 3. Experimental setup, systematic uncertainties and errors of various parameters

In this work for the numerical simulation we consider two set-ups: (a) A superbeam setup which originates in CERN and reaches a 100 kt Liquid Argon detector placed at a distance of 2300 Km at Pyhäsalmi (Finland) (b) A Superbeam setup originating in CERN and reaching a 500 Kt Water Cherenkov detector [10] placed at a distance of 130 Km at Fréjus (France).

For both the set-ups the true values of the neutrino oscillation and the errors on these parameters are considered as in ref [11]. In doing the whole analysis we have used GLOBES software [12,13].

For set-up (a), in doing the numerical analysis to study the response of the detector we have followed ref [11]. The time period has been taken to be 5 years each for neutrinos and anti-neutrinos. The correlation between the visible energy of background NC events and the neutrino energy is implemented by migration matrices which has been provided by L. Whitehead [14].

The flux considered for set-up (b) has mean energy  $\sim 0.3$  GeV, for 3.5 GeV protons and  $10^{23}$  protons on target per year. The beam power has been considered of about 4 MW per year and the time period has been taken to be 2 years for neutrinos and 4 years for anti-neutrinos.

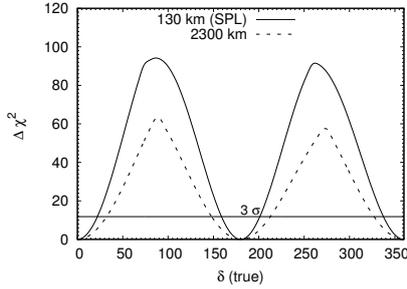


Figure 1: Discovery reach of CP violation due to  $\delta$  for two different baselines 130 Km and 2300 Km considering only SM interactions and NH at  $3\sigma$ .

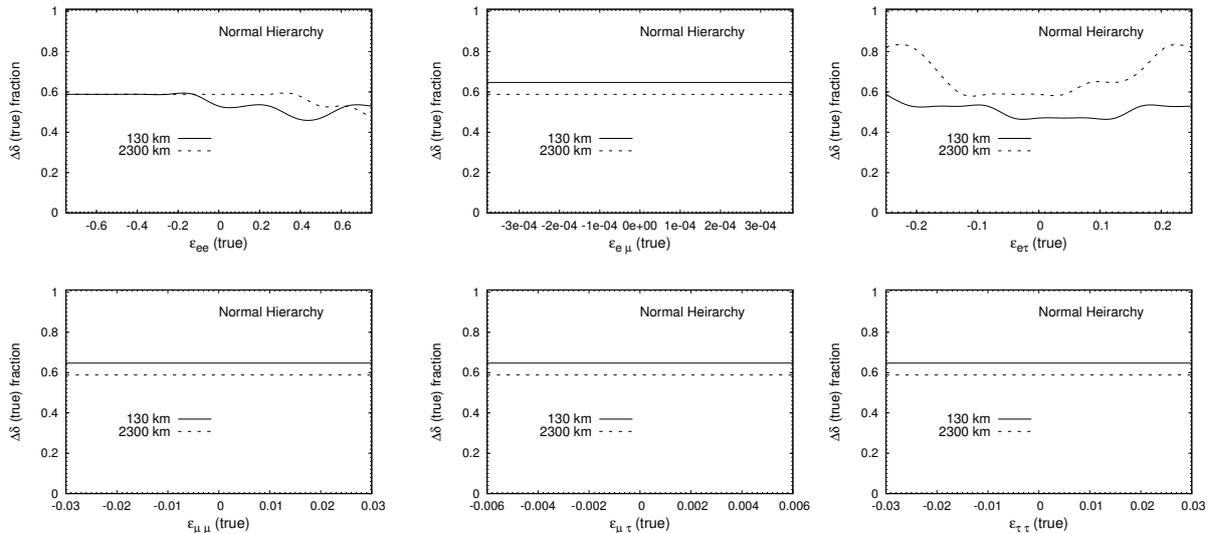


Figure 2: Fraction of  $\delta$  for CP violation discovery ( $\Delta\delta$  fraction) for two different baselines 130 Km and 2300 Km at  $3\sigma$  considering NSIs for NH.

We consider the same flux as in [15, 16]. The efficiencies for the signal and background are included in the migration matrices based on [10] except for the channels  $\nu_\mu$  disappearance,  $\bar{\nu}_\mu$  disappearance and  $\nu_\mu$  (NC) which are 64%, 81% and 11.7% efficiencies respectively. We have considered systematic uncertainties of 2% on signal and background channels.

#### 4. Discovery reach of CP violation due to $\delta$ for real NSIs'

In this work we have done a comparative study for the two experimental set-ups (a) and (b) in finding the discovery reach of the CP violation due to phase  $\delta$  depending on different NSI parameters (true values) and for true hierarchies.

In figure 1 we have shown the the discovery reach of CP violation for SM interactions of neutrinos with matter. Particularly at  $3\sigma$  confidence level for normal hierarchy(NH) the CP violation could be discovered over about 78% of the possible  $\delta$  values for 130 Km and 65% for 2300 Km baselines. The discovery reach for 2300 Km was shown earlier by Coloma *et al* [11]. So with only SM the short baseline like 130 Km seems to give better discovery reach of CP violation. This was observed earlier by different authors [17–21]. However, the short baseline may not be always better in presence of NSI which we discuss below.

In figure 2 we have compared the discovery reach of CP violation for 130 Km baseline and 2300 Km baseline in presence of NSIs at  $3\sigma$  confidence level for NH considering only one NSI at a time. Here we define  $\Delta\delta$  fraction as the ratio of sum of all ranges of  $\delta$  (true) values for which

CP violation could be discovered divided by total allowed range of  $\delta$  (true) between 0 to  $2\pi$ . This fraction corresponds to discovery reach of CP violation.

For  $\varepsilon_{ee}$  in the range about -0.2 to 0.6 the discovery reach of CP violation due to  $\delta$  is found to be better for 2300 Km baseline.. However for  $\varepsilon_{e\tau}$  in its almost entire allowed range for 2300 Km baseline there is better discovery reach. In presence of NSIs —  $\varepsilon_{e\mu}$ ,  $\varepsilon_{\mu\mu}$ ,  $\varepsilon_{\mu\tau}$  and  $\varepsilon_{\tau\tau}$  we see for the entire allowed range of these NSI parameters there is better discovery reach for 130 Km baseline. We have checked the discovery of CP violation for inverted hierarchy(IH) also and we find similar results with NH.

One may note that the effect of the NSI —  $\varepsilon_{e\mu}$ ,  $\varepsilon_{\mu\mu}$ ,  $\varepsilon_{\mu\tau}$  and  $\varepsilon_{\tau\tau}$  on the CP violation discovery is negligible due to their relatively smaller values. However, statistically due to the inclusion of extra NSI parameter the degree of freedom has increased thus making the discovery reach fraction little bit lesser in comparison to the case with only SM interaction. The straight line in the figures 2 corresponding to those NSIs' indicates this negligible effect.

## 5. Conclusion

Considering the large value of  $\theta_{13}$  provided by the Daya Bay experiment we have tried to study the CP violation discovery reach using a short baseline of length 130 Km and a relatively longer baseline of 2300 Km. It is found that in the presence of only SM interaction shorter baseline is better and if NSIs' are considered longer baselines also could give better discovery reach of CP violation. Considering the possibility of the presence of NSIs in nature it seems both short and long baseline should be considered particularly for discovery of CP violation in the leptonic sector through neutrino oscillation experiment.

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