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Hierarchy and NSI study of P2O in its Optimal Configuration

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We have studied the hierarchy sensitivity of Protvino to ORCA experiment in standard three flavor oscillation and in the presence of non-standard interactions. It has a baseline of 2595 km, and it is expected to have better sensitivity to mass hierarchy and non-standard interactions compared to the DUNE experiment. Despite having higher appearance events than DUNE, we noticed that it has less sensitivity to hierarchy. The hierarchy sensitivity of Protvino to ORCA experiment becomes equivalent to DUNE for $\delta_{CP} = 195^0$ for a background reduction factor of 0.46 and appearance channel background systematic normalization of 4%. We see that $\epsilon_{e\tau}$ ($\epsilon_{e\mu}$) sensitivity of this optimized configuration is better (similar) than DUNE when both $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ are considered in the analysis. We find that the change in hierarchy sensitivity of Protvino to ORCA experiment is more significant compared to DUNE in the presence of non-standard interactions. Further, the hierarchy sensitivity in this case is higher (lower) than the standard three flavor case for $\delta_{CP} = 270^0 (90^0)$.

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1. Introduction

We are currently in the precision measurement age of neutrino oscillation physics. Numerous neutrino experiments are being planned for the future, and some are even already in progress. These experiments have the potential to uncover some novel physics and are capable of detecting neutrinos oscillation parameters precisely. Three mixing angles (θ_{12}, θ_{13} and θ_{23}), two mass squared differences (Δm^2_{21} and Δm^2_{31}), and one Dirac CP phase (δ_{CP}) make up the standard three flavour oscillation parameters. Among these parameters, the following are currently unknown: (i) hierarchy of absolute neutrino masses which can be either normal i.e. $\Delta m^2_{31} > 0$ or inverted i.e. $\Delta m^2_{31} < 0$, (ii) octant of the atmospheric mixing angle which can be upper i.e. $\theta_{23} > 45^0$ or lower i.e. $\theta_{23} < 45^0$, (iii) the absolute value of CP phase δ_{CP}. Apart from these parameters, long baseline neutrino experiments can be sensitive to non-standard interactions (NSI) generated through the interaction between propagating neutrinos and matter fermions. NSIs can influence the neutrino oscillation probabilities and hence can affect sensitivity of neutrino long baseline experiments.

Protvino to ORCA (P2O) and Deep Underground Neutrino Experiment (DUNE) are proposed future long baseline experiments designed to probe earth's matter effect to measure one of the major unknowns in standard three flavor neutrino oscillation sector i.e neutrino mass hierarchy. As the mass hierarchy sensitivity depends on matter effects, the longer the baseline the better the sensitivity. DUNE has a baseline of 1300 km and P2O has a baseline of 2595 km. The baseline of P2O is very close to the bi-magic baseline. Therefore it is very sensitive to mass hierarchy by resolving hierarchy - δ_{CP} degeneracy. Additionally, because matter effect has an impact on NSI parameters, these experiments can offer extremely tight constraints on those parameters. We demonstrated that, while P2O's baseline and expected number of ν_e events are higher than DUNE's, P2O's hierarchy sensitivity is lower in the standard three flavour scenario. We determine that this is due to the extremely large background of the P2O experiment. We found an optimized configuration of P2O in terms of background and systematic errors for which hierarchy sensitivity is comparable to DUNE. We named this configuration "P2O Optimized" in our work. We have calculated its hierarchy sensitivity in standard three flavor oscillation scenario and in presence of NSI and compared it with P2O and DUNE.

2. Experimental setup and Simulation details

To simulate P2O and DUNE experiments, we have used GLoBES [1, 2] package and to incorporate NSI probability engine, we have used some additional plugins for GLoBES. There are three proposed configurations of P2O [3]. Out of which, we are considering the minimal P2O configuration for our study. In the minimal configuration of P2O the source at Protvino produces a ν_μ beam of power 90 kW corresponding to 0.8×10^{20} POT per year and the ORCA detector present in the Mediterranean sea detects these neutrinos. The detector is of total 8 Mt seawater. The baseline of this experiment is about 2595 Km. The energy resolution, particle identification and efficiencies of the ORCA detector are taken from Ref. [4]. The flux and systematic error information are taken from Ref. [3]. The systematic error for background normalization error and shape error are listed in Table 1 of our work [7]. We have taken the total run time of 6 years (3 ν + 3 $\overline{\nu}$).

We used the official GLoBES files from the DUNE technical design report [5] for DUNE. A 40 Kt liquid argon time-projection chamber detector with a power of 1.2 MW and a running time of 7 years (3.5 ν + 3.5 $\overline{\nu}$) is placed 1300 km from the source and delivers 1.1×10^{21} POT per year. The neutrino source will be located at Fermilab, USA and the detector will be located at South Dakota, USA.

For the estimation of the sensitivity we use the Poisson log-likelihood and assume that it is χ^2-distributed

$$\chi^2_{\text{stat}} = 2 \sum_{i=1}^{n} \left[N_i^{\text{test}} - N_i^{\text{true}} - N_i^{\text{true}} \log \left(\frac{N_i^{\text{test}}}{N_i^{\text{true}}} \right) \right], \tag{1}$$

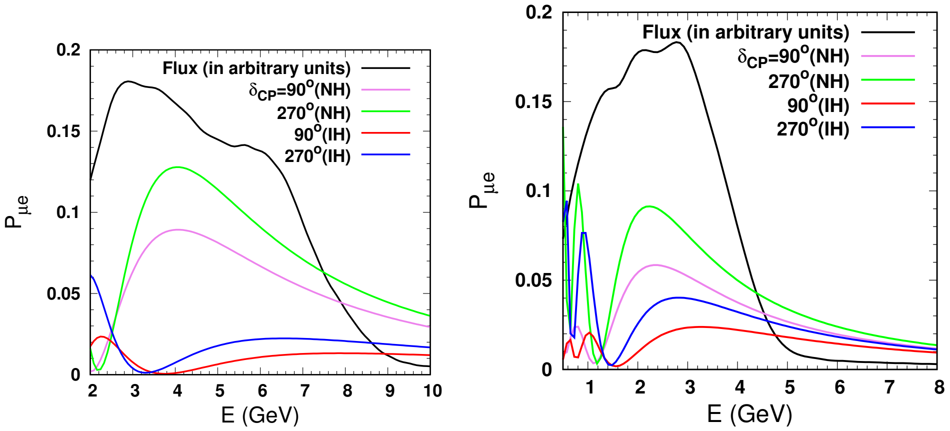

Figure 1: Neutrinos appearance channel probability and flux as a function of energy. The left column is for P2O baseline and the right column is for DUNE baseline.

where N^{test} is the number of events in the test spectrum, N^{true} is the number of events in the true spectrum and i is the number of energy bins. The systematic is incorporated by the method of pull. The best-fit values of the oscillation parameters and the 3σ values of θ_{23} are adopted from NuFIT [6].

3. Bi-magic baseline

It has been demonstrated that there is no CP dependence in IH for L ~ 2540 km and that there is also a probability maximum in NH at 3.3 GeV. The bi-magic baseline is referred to as such. This bi-magic characteristic may also be shown in Fig. 1 because the baseline of P2O is about 2595 km. A detailed discussion about this property of P2O has been done in our article [7]. The hierarchy sensitivity of an experiment is determined by the separation of the appearance channel probabilities in normal hierarchy and inverted hierarchy. We have displayed the appearance channel probability with neutrino energy in Fig. 1. The left column is for P2O and the right column is for DUNE. Green, purple, blue, and red curves are the (δ_{CP}, hierarchy) combinations of (270^0, NH), (90^0, NH), (270^0, IH), and (90^0, IH) in each panel, respectively. The black curves represent the fluxes from the P2O and DUNE experiments. As a result of the stronger matter effect of the P2O baseline relative to the DUNE baseline, it is clear from these panels that the gap between the NH and IH curves is greater for the former.

We can see from the top left panel that the blue and red curves meet at a single point at about 3.5 GeV. This suggests that for different values of δ_{CP}, the appearance channel probability becomes equal for inverted hierarchy. In other words, the appearance channel probability in the inverted hierarchy becomes independent of δ_{CP} at this energy level. However, the fluctuation of the probability with respect to δ_{CP} reaches its maximum for NH at E = 3.5 GeV. The opposite is true for antineutrinos. Because of this, the gap between the probabilities in the normal hierarchy and the inverted hierarchy is at its widest at this moment. We don't see these characteristics in the DUNE oscillation probability.

4. Hierarchy sensitivity

In fig. 2 the left panel represents hierarchy sensitivity of DUNE and P2O w.r.t δ_{CP}. The blue, red and magenta curve represents the hierarchy sensitivity of DUNE, P2O and Optimized P2O, respectively. The sensitivity of the red curve is inferior to the blue curve even though P2O has roughly double the baseline length compared to DUNE. This is due to the fact that P2O has very high systematic and background errors.

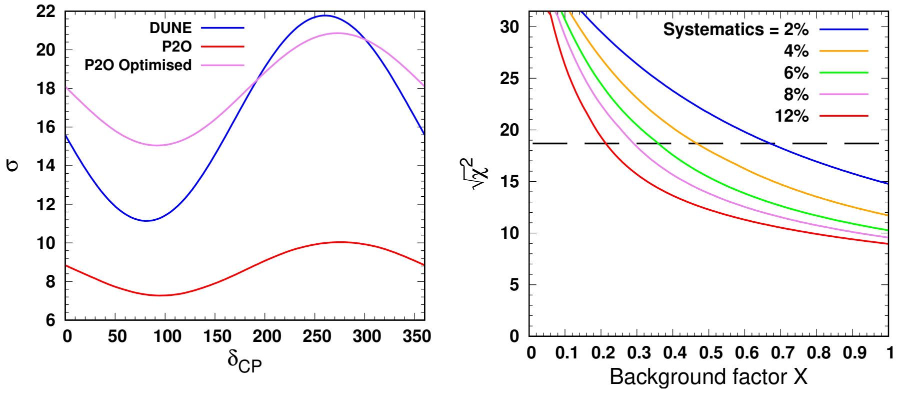

Figure 2: Hierarchy sensitivity as a function of true δ_{CP} (left panel) and as a function of background reduction factor X (right panel).

The right panel plot shows the variation of hierarchy sensitivity of P2O w.r.t the background reduction factor X. Factor X is multiplied by the background efficiencies to modify the overall background efficiencies. The different color curves represent the different values of systematic errors. The horizontal black dashed line represents the hierarchy sensitivity of DUNE at $\delta_{CP} = 195^0$. Where the colored curves intersect with the black dashed line, for that value of X the hierarchy sensitivity of P2O becomes equal to that of DUNE for a particular value of systematic error. One particular observation demonstrates that the sensitivity of P2O becomes similar to DUNE at X = 0.46 and a systematic error of 4%. We are calling this setup of P2O as Optimized P2O in our paper. This configuration is also shown in the left panel plot. We can see evidence of similar hierarchy sensitivity from this plot where blue and magenta lines intersect each other.

5. NSI sensitivity

For our analysis we have considered two off diagonal NSI parameters $\epsilon_{e\mu} = |\epsilon_{e\mu}|e^{i\phi_{e\mu}}$ and $\epsilon_{e\tau} = |\epsilon_{e\tau}|e^{i\phi_{e\tau}}$. Recently, it was demonstrated in Refs. [8, 9] that the NSI parameters $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ can be introduced to resolve the disagreement between the δ_{CP} measurements in the experiments T2K and NOvA. Taking one-parameter at a time, the discrepancy was resolved for the values of $|\epsilon_{e\mu}| = 0.15$ (0.19), $\phi_{e\mu} = 250°$ (270°) and $|\epsilon_{e\tau}| = 0.27$ (0.28), $\phi_{e\tau} = 290°$ (288°) in Ref. [8] ([9]). Therefore, in this work, we will investigate the sensitivity of P2O and DUNE in the presence of the NSI parameters $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$.

5.1 Constraining NSI parameters

In fig. 3, the first two panels represent one-dimensional sensitivity of DUNE, P2O and Optimized P2O to constrain $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$. The participation of one (two) NSI parameter is indicated by the solid lines (dashed lines). The horizontal black dashed line represents the value of σ corresponding to 90% C.L. The grey dashed vertical line shows the values of $|\epsilon_{e\mu}| = 0.15$ (first panel) and $|\epsilon_{e\tau}| = 0.27$ (second panel), which are the best-fit values of the NSI parameters as determined in Ref. [8]. This point is shown as a star in the third panel. The third panel shows the 90% contours in $|\epsilon_{e\mu}| - |\epsilon_{e\tau}|$ plane. All these plots are generated by assuming that there is no NSI in nature and we have marginalized the NSI parameters in the test. As seen in the first two panels, the sensitivity increases when we take into account just one NSI parameter as opposed to when both NSI values are taken into account for the analysis. The bounds on these NSI parameters are listed in table 1. The structure for DUNE in the first panel has been discussed in our paper [7]. In the third panel, we can notice that all the experiments exclude the point $|\epsilon_{e\mu}| = 0.15$, $|\epsilon_{e\tau}| = 0.27$ regardless of the value of $\phi_{e\mu}$ and $\phi_{e\tau}$ except P2O.

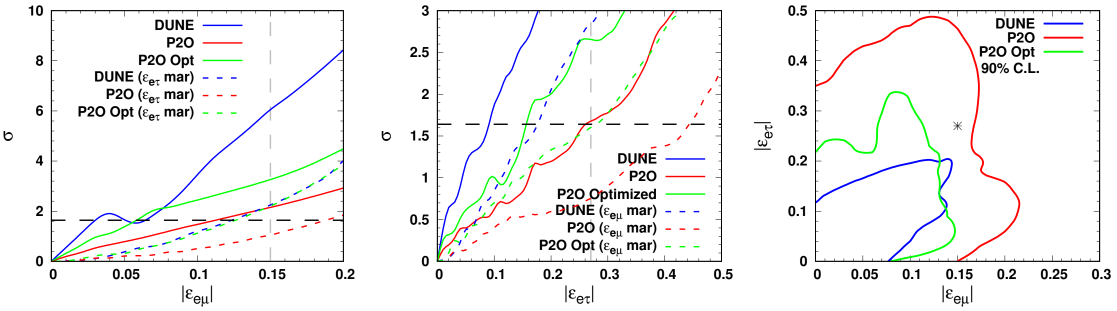

Figure 3: Capability of P2O and DUNE to constrain the NSI parameters. In the first (second) panel we present the one-dimensional sensitivity curves for $|\epsilon_{e\mu}|$ ($|\epsilon_{e\tau}|$). In the third panel we present 90% contours in the $|\epsilon_{e\mu}|$ - $|\epsilon_{e\tau}|$ plane.

90% bound on the NSI parameters		
Experiments	$\lvert\epsilon_{e\mu}\rvert$	$\lvert\epsilon_{e\tau}\rvert$
P2O	0.112 (0.188)	0.26 (0.444)
Optimized P2O	0.058 (0.126)	0.157 (0.28)
DUNE	0.065 (0.123)	0.09 (0.176)

Table 1: 90% bound on the NSI parameters. The numbers in the parenthesis corresponds to the case when both $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ are included in the analysis.

5.2 Effect of NSI on hierarchy sensitivity

In fig. 4, the first two panels represent hierarchy sensitivity of DUNE, P2O and Optimized P2O in the presence of single NSI parameter $|\epsilon_{e\mu}|$ (first panel) and $|\epsilon_{e\tau}|$ (second panel). Both the NSI parameters are used for generating the plot in the third panel. The solid and dashed lines represent the hierarchy sensitivity in the standard three flavor case and in the presence NSI, respectively. The blue/red/purple curves correspond to DUNE/P2O/optimized P2O. We see quite the opposite nature of hierarchy sensitivity for the standard three flavor case and in the presence of NSI for $\delta_{CP} = 90^0$ and $\delta_{CP} = 270^0$. For all three experiments, we can see that the hierarchy sensitivity decreases to nearly nothing around $\delta_{CP} = 240^0$ when NSI is present. This is because of a hierarchy degeneracy that occurs between $\delta_{\rm CP} = 240°$ in NH and ($\delta_{\rm CP}$, $\phi_{e\tau}$) in IH for neutrinos. The existence of NSI causes this degeneracy, which wasn't present in the case of the standard three flavour scenario. The dashed green curve in the first panel displays the hierarchy sensitivity for a 450 KW beam (upgraded P2O) when NSI is present. We deduce from this panel that the 450 KW beam's sensitivity is similar to our optimized P2O arrangement.

6. Conclusion

In conclusion, we can say that the sensitivity of the optimized P2O is similar to the sensitivity of P2O with the upgraded beam. However, the best sensitivity of P2O can be achieved with an upgraded beam and Super-ORCA configuration. The findings of this study are significant because they demonstrate the sensitivity of P2O to NSI as well as the impact of background and systematic errors on the calculation of mass hierarchy.

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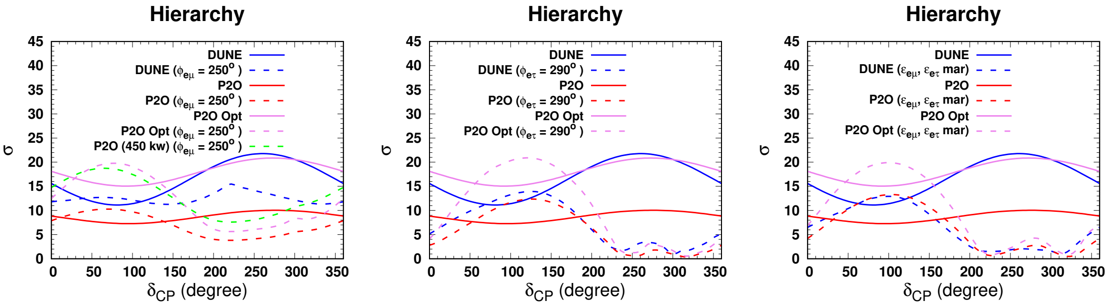

Figure 4: Hierarchy sensitivity as a function of δ_{CP} (true) in presence of NSI. The first (second) panel is for only $\epsilon_{e\mu}$ ($\epsilon_{e\tau}$). The third panel is when both $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ are included in the analysis.

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