Hierarchy and NSI study of P2O in its Optimal Configuration

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Introduction

- P2O : future proposed long baseline experiment (neutrino source at Protvino, Russia and ORCA detector in the Mediterranean sea)
- Unknowns of neutrino oscillation sector
  - Mass hierarchy of neutrinos (normal $\Delta m^2_{31} > 0$ or $\Delta m^2_{31} > 0$)
  - Octant of θ_{23} (higher $\theta_{23} > 45°$ or lower $\theta_{23} < 45°$)
  - The absolute value of δ_{CP}
- In our paper, we have explored the hierarchy sensitivity of P2O and DUNE in standard three flavor scenario and in the presence of NSI.
- Recent work by two independent groups[1] shows that the presence of NSI parameters like $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ can resolve the δ_{CP} tension between NOvA and T2K.
- In our work we study if these values ($\epsilon_{e\mu}$ and $\epsilon_{e\tau}$) can be constrained in P2O.

[1] Phys. Rev. Lett. 126 (2021), no. 5 051802, Rev. Lett. 126 (2021), no. 5 051801

Introduction

- The mass hierarchy sensitivity depends on the matter effect, therefore longer the baseline higher the sensitivity.
- DUNE has a baseline $\sim$ 1300 km and P2O has a baseline $\sim$ 2595 km, which is close to the bi-magic baseline that helps in determination of mass hierarchy by resolving the hierarchy - δ_{CP} degeneracy.
- There are 3 proposed configuration of P2O[2]
  - minimal configuration with 90 kw beam and ORCA detector
  - updated accelerator configuration with 450 kw beam with ORCA detector
  - updated accelerator of 450 kw beam with Super-ORCA detector

[2] Eur. Phys. J. C 79 (2019), no. 9 758

Simulation Details

- We have used General Long Baseline Neutrino Experiments (GLoBES) package to simulate these experiments.
- We have used minimal configuration of P2O of beam power 90 kw.
- Although P2O baseline is high compared to DUNE, its hierarchy sensitivity is low due to high background systematics error.
- For background reduction factor of 0.46 and systematics normalization factor of 4$\%$ the hierarchy sensitivity of P2O is becoming eqivalent to DUNE for $\delta_{CP} = 195°$. We named it as *Optimized P2O* in our work.
- *P2O and Optimized P2O* $(3\nu + 3\overline{\nu})$: Beam power of 90 KW corresponding to POT = 0.8×10^{20} per year.
- *DUNE* $(3.5\nu + 3.5\overline{\nu})$: Beam power of 1.2 MW corresponding to POT = 1.1×10^{21} per year.

Bi-magic property

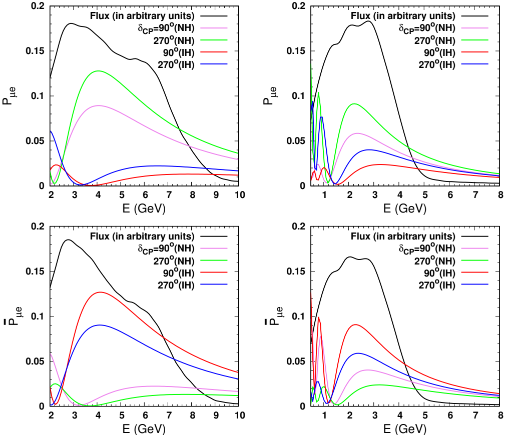

Figure 1: Appearance channel probability and flux as a function of energy. The left column is for P2O baseline and the right column is for DUNE baseline. In each column the top panel is for neutrinos and the bottom panel is for antineutrinos.

Hierarchy sensitivity in standard 3 flavor

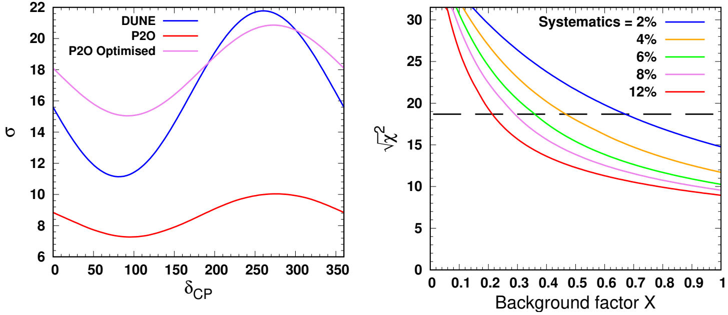

Figure 2: Hierarchy sensitivity as a function of true δ_{CP} (left panel) and as a function of background reduction factor X (right panel).

Constraining NSI parameters

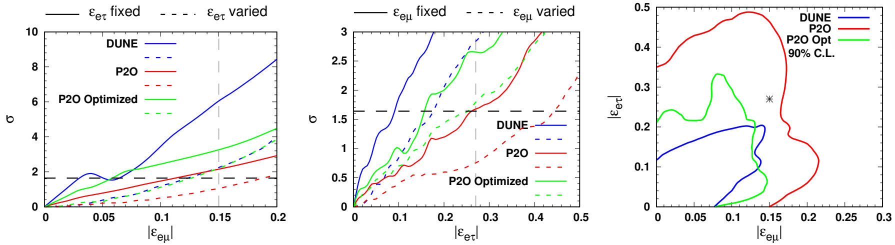

Figure 3: Capability of P2O and DUNE to constrain the NSI parameters (first two panels). The 3rd panel represents 90% contours in the $|\epsilon_{e\mu}|$ - $|\epsilon_{e\tau}|$ plane.

Bounds on NSI parameters

90% bound on the NSI parameters		
Experiments	$\|\epsilon_{e\mu}\|$	$\|\epsilon_{e\tau}\|$
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.

Hierarchy sensitivity in presence of NSI

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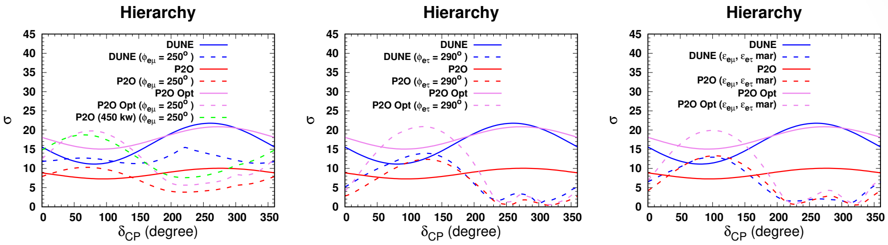

Figure 4: Hierarchy sensitivity as a function of δ_{CP} (true) in presence of NSI. The first (second) panel is for only $|\epsilon_{e\mu}|$ ($|\epsilon_{e\tau}|$). The third panel is when both $|\epsilon_{e\mu}|$ and $|\epsilon_{e\tau}|$ are included in the analysis.

Hierarchy sensitivity in presence of NSI

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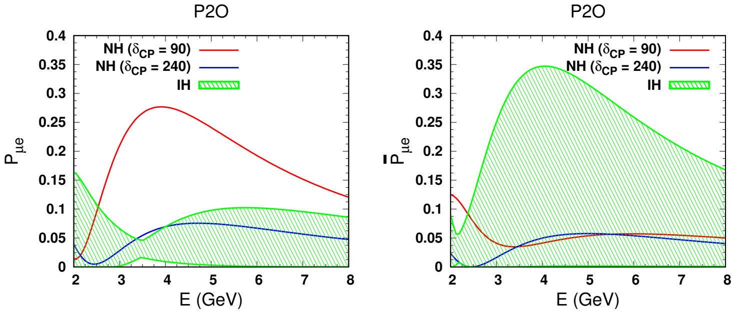

Figure 5: Appearance channel probability for neutrinos (left panel) and antineutrinos (right panel) in the presence of NSI parameter $|\epsilon_{e\tau}|$ = 0.27. The NH curves are generated for $|\phi_{e\tau}|$ = $290°$, and δ_{CP} = $90°$ and $240°$. In IH these phases are varied.

Hierarchy sensitivity in presence of NSI

The appearance channel formula for neutrinos in presence of $\epsilon_{e\tau}$ takes the following form:

$$\begin{aligned} P_{\mu e} &= x^2 f^2 + 2xyfg\cos(\Delta + \delta_{\rm CP}) + y^2 g^2 \\ &+ 4\hat{A}\epsilon_{e\tau} s_{23} c_{23} \{xf[f\cos(\phi_{e\tau} + \delta_{\rm CP}) - g\cos(\Delta + \delta_{\rm CP} + \phi_{e\tau})] \\ &- yg[g\cos\phi_{e\tau} - f\cos(\Delta - \phi_{e\tau})]\} + 4\hat{A}^2 g^2 c_{23}^2 s_{23}^2 \epsilon_{e\tau}^2 \\ &+ 4\hat{A}^2 f^2 s_{23}^2 c_{23}^2 \epsilon_{e\tau}^2 - 8\hat{A}^2 fg s_{23}^2 c_{23}^2 \epsilon_{e\tau}^2 \cos\Delta \, , \end{aligned} \tag{1}$$

where,

$$\begin{aligned} x &\equiv 2s_{13}s_{23} \, , \quad y \equiv 2\alpha s_{12}c_{12}c_{23} \, , \\ f &\equiv \frac{\sin[\Delta(1-\hat{A})]}{(1-\hat{A})} \, , \quad g \equiv \frac{\sin(\hat{A}\Delta)}{\hat{A}} \, . \end{aligned} \tag{2}$$

Hierarchy sensitivity in presence of NSI

For neutrinos,

$$P_{\mu e}(\delta_{\rm CP} = 90^\circ) - P_{\mu e}(\delta_{\rm CP} = 270^\circ) = 4xf(2\hat{A}\epsilon_{e\tau}s_{23}c_{23}f - yg)\,. \quad (3)$$

For anti-neutrinos

$$\overline{P}_{\mu e}(\delta_{\rm CP} = 90^\circ) - \overline{P}_{\mu e}(\delta_{\rm CP} = 270^\circ) = -4xf(2\hat{A}\epsilon_{e\tau}s_{23}c_{23}f - yg)\,. \quad (4)$$

- $yg < 2\hat{A}\epsilon_{e\tau}s_{23}c_{23}f$ always
- $P_{\mu e}(\delta_{\rm CP} = 90^\circ) > P_{\mu e}(\delta_{\rm CP} = 270^\circ)$ (opposite for antineutrinos)
- $f(neutrinos) > f(antineutrinos)$: blue and red are well separated for neutrinos but not for antineutrinos
- results are independent of baseline

Results

- P2O has very high background systematics.
- The hierarchy sensitivity in presence of NSI is lower than sensitivity in the standard three flavour scenario for $\delta_{CP} = 270°$ and higher than the sensitivity in the standard three flavour scenario for $\delta_{CP} = 90°$.
- There is degeneracy between NH and ($\delta_{CP} = 270°$, $\phi_{e\tau} = 270°$) with IH in presence of $\epsilon_{e\tau}$ in the neutrino probabilities.
- For antineutrino probabilities, both $\delta_{CP} \sim 270°$ and $\delta_{CP} \sim 90°$ in NH are degenerate with IH. This degeneracy is independent of the baseline length. Because of this, the hierarchy sensitivity became almost zero for $\delta_{CP} \sim 270°$ and non-zero for $\delta_{CP} \sim 90°$.
- The hierarchy sensitivity of updated P2O with a 450 kw beam is equivalent to out optimized P2O configuration.
- The best sensitivity of P2O can be achieved with a upgraded beam and Super-ORCA configuration.

Thanks

Backup Slides

bi-magic

$$P_{\mu e} = 4s_{13}^2 s_{23}^2 \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} + \alpha^2 \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\hat{A}\Delta}{\hat{A}^2} + \alpha s_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\Delta+\delta_{\mathrm{CP}})\frac{\sin\hat{A}\Delta}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}, \quad (5)$$

Here $\Delta = \Delta m_{31}^2 L/4E$, $\hat{A} = 2\sqrt{2}G_F n_e E/\Delta m_{31}^2$, G_F

L $\sim$ 2540 km, δ_{CP} independent in IH, probability maximum in NH at 3.3 GeV

$(1+\hat{A})\Delta = n\pi$ for $n > 0$,
$(1-\hat{A})\Delta = (m-1/2)\pi$ for $m > 0$.

Event tables

ν_e events		
Experiments	NH	IH
P2O	2404	528
DUNE	1380	702

Table 2: Total number of ν_e events for P2O and DUNE. These events corresponds to 3 years running of P2O and 3.5 year running of DUNE.

Background Events (NH) (for appearance channel)			
Experiments	ν_μ	NC	ν_τ
P2O	2166	1235	873
DUNE	24	87	45

Table 3: Total number of background events for the ν_e channel for P2O and DUNE. These events corresponds to 3 years running of P2O and 3.5 year running of DUNE.

Degeneracy in DUNE for $\epsilon_{e\mu}$

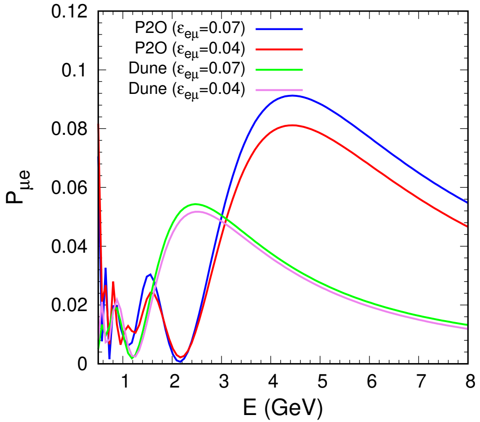

Figure 6: Appearance channel probability for neutrinos considering two sets of parameters in P2O and DUNE baselines. The sets of parameters are: $|\epsilon_{e\mu} = 0.04|$, $\sin^2\theta_{23}^2 = 0.46$, $\phi_{e\mu} = 210°$, $\delta_{\rm CP} = 60°$ and $|\epsilon_{e\mu}| = 0.07, \sin^2\theta_{23}^2 = 0.45, \phi_{e\mu} = 195°, \delta_{\rm CP} = 75°$.