A discussion of CPV sensitivity in presence of NSI at DUNE and other long baseline experiments

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Based on arXiv:1603.01380 (MM, P. Mehta)
**Motivation**

**CP violation in appearance channel\(\text{@DUNE}\)**

\[
P_{\mu e} = P_{\text{atm}} + P_{\text{int}}(\delta) + P_{\text{sol}}
\]

\[
\theta_{13}^2 \quad \theta_{13} \quad \theta_{13} - \text{indep}
\]

\[
P(\nu_e \rightarrow \nu_e) = 4 \frac{(\Delta m_{31}^2)^2}{(\Delta m_{31}^2 - a)^2} s_{23}^2 s_{13}^2 \sin^2 \left( \frac{(\Delta m_{31}^2 - a)L}{4E} \right)
\]

\[
+ 8J_{\nu} \frac{\Delta m_{31}^2 \Delta m_{21}^2}{a(\Delta m_{31}^2 - a)} \sin \left( \frac{aL}{4E} \right) \sin \left( \frac{(\Delta m_{31}^2 - a)L}{4E} \right) \cos \left( \frac{\delta - \Delta m_{31}^2 L}{4E} \right)
\]

\[
+ 4 \left( \frac{\Delta m_{21}^2}{a} \right)^2 c_{12}^2 s_{12}^2 c_{23}^2 \sin^2 \left( \frac{aL}{4E} \right).
\]

\[
\frac{L(\text{km})}{E_{\nu}(\text{GeV})} = (2n - 1) \frac{\pi}{2} \times 1.27 \times \frac{1}{\Delta m_{31}^2(\text{eV}^2)}
\]

\[
\approx (2n - 1) \times 510 \text{ km/GeV}
\]

For \(E=2.5\) GeV, we get \(L=1300\) km

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Ref: M. Masud, A. Chatterjee, P. Mehta, 1510.08261 ;
M. Masud and P. Mehta, 1603.01389
What is DUNE (Deep Underground Neutrino Experiment)?

- A proposed long baseline experiment (the erstwhile LBNE)
- 1300 km baseline
- Underground Far detector possibly augmented with a near detector

DUNE collaboration: 1512.06148
New physics (Non-standard neutrino interaction)

- \( H = H_{\text{vac}} + H_{\text{SI}} + H_{\text{NSI}} \)

\[
\frac{\text{i} \, \text{d}}{\text{d}t} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}
\]

\[
|\epsilon_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.3 & 0.5 \\ 0.3 & 0.068 & 0.04 \\ 0.5 & 0.04 & 0.15 \end{pmatrix}
\]

1209.2710, 0907.0097, SK+MINOS collaboration
Effect of NSI phase variation: Probability level

\[ P_{\mu e} = a_{\mu e} + b_{\mu e} \sin \delta + c_{\mu e} \cos \delta \]
\[ P_{\mu\mu} \simeq a_{\mu\mu} + c_{\mu\mu} \cos \delta \]
Simulation details

- **DUNE**: 1MW proton beam; (5+5) yrs of $\nu + \bar{\nu}$ beam; 35 kt FD, 1300 km
- **NOvA**: 700 kW proton beam, 14 kt FD, 800 km, (3+3) yrs of $\nu + \bar{\nu}$ beam
- **T2K**: 770 kW proton beam, 22.5 kt FD, 295 km, (3+3) yrs of $\nu + \bar{\nu}$ beam
- **HK**: 7.5 MW proton beam, 560 kt FD, 295 km, (1+3) yrs of $\nu + \bar{\nu}$ beam
Individual NSI: Impact on events at DUNE

Substantial overlapping regions: can come from SI or NSI-SI interplay
**Effect of individual NSI on CPV sensitivity at DUNE**

- $\chi^2$ measures the contrast between:
  a) the dataset containing $\delta_{\text{true}} \in [-\pi: \pi]$  
  b) dataset containing the CP conserving cases $(0, \pi)$

- $\chi^2_{\text{tot}} = \min\left[\chi^2_{\text{app}} + \bar{\chi}^2_{\text{app}} + \chi^2_{\text{dis}} + \bar{\chi}^2_{\text{dis}}\right]$
  
  $\propto \min_{0, \pi} \left\{ [b_{\mu e} \sin \delta_{\text{true}} + c_{\mu e} \cos \delta_{\text{true}} - c_{\mu e} \cos \delta|_{0, \pi}]^2 
  + [c_{\mu \mu} \cos \delta_{\text{true}} - c_{\mu \mu} \cos \delta|_{0, \pi}]^2 + [\bar{\nu} \text{ terms}] \right\}$

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**Figure:**

- Legend: **SI**, **NSI (true $\phi_{e, \mu} = 0$)**, **NSI (true $\phi_{e, \mu} \in [-\pi: \pi]$)**
- Axes: True $\delta / \pi$
- Curves: $|\varepsilon_{e, \mu}| = 0.01$, app, $5\sigma$, $3\sigma$
- Curves: $|\varepsilon_{e, \mu}| = 0.01$, dis
- Curves: $|\varepsilon_{e, \mu}| = 0.01$, com
$\epsilon_{ee}$ has reasonable effect while $\epsilon_{\mu\mu}, \epsilon_{\tau\tau}$ have very small impacts (because of tight constraints)
Effect of collective NSI on CPV sensitivity at DUNE

Significant change in sensitivity in the NSI scenario.

Can give misleading high sensitivity even for the CP conserving value \((0, \pi)\). Conversely, the introduction of NSI may also give \(\lesssim 3\sigma\) sensitivity for the maximally CP violating values.
Effect of collective NSI on CP sensitivity at NOvA, T2K

- Effect of NSI decreases as the baseline decreases
The information from NOvA, T2K can serve in increasing the CP sensitivity at DUNE for the standard case.

The effect of NSI is grossly similar to that of DUNE even in the combined case.
Effect of NSI on CPV sensitivity at HK

- 560 kt fiducial mass and 7.5 MW proton beam
- Although comparable to DUNE, the effect of NSI is much less due to shorter baseline
Different choices of true $\theta_{23}$ has small effect
Different true values of $\Delta m_{31}^2$ practically do not affect the CPV sensitivity
CP fraction and NSI

- In standard case, CP cannot be resolved above $3\sigma$ for about $\sim 55\%$ of the $\delta$ parameter space because the $\chi^2$ is close to 0 at the CP conserving values $(0, \pm \pi)$.

- NSI can drastically change this fraction.

- In particular, a very small CP fraction even for a sufficiently large exposure ($\sim 250 \text{ kt.MW.yr}$) is an indication of new physics.
Impact of NSI on baseline optimization

Choice of baseline is significantly impacted by NSI!

<table>
<thead>
<tr>
<th>NSI term</th>
<th>Nominal systematics (green)</th>
<th>Optimal systematics (magenta)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NSI</td>
<td>SI</td>
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<tr>
<td></td>
<td>$L_{\text{opt}}$ km</td>
<td>$L_{\text{opt}}$ km</td>
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<td>$</td>
<td>\varepsilon_{ee}</td>
<td>= 0.04$</td>
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<td>800 – 1300</td>
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<td>$</td>
<td>\varepsilon_{e\mu}</td>
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<td>$</td>
<td>\varepsilon_{e\tau}</td>
<td>= 0.04$</td>
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<td>$\varepsilon_{ee} = 0.04$</td>
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Introduction of NSI can significantly impact CPV sensitivity at long baselines and may even create confusion between CPV and CPC cases.

The effect of NSI increases with baseline and the impact also depends on the choice of detector.

The CP fraction serves as a useful quantity to probe new physics effects.

Finally, the optimized choice of baseline (~1300 km) for DUNE can significantly change if NSI is present.