Exploring second oscillation maximum at DUNE

**Jogesh Rout**

Jawaharlal Nehru University
New Delhi, India

With Sheeba Shafaq (JNU), Mary Bishai (BNL) and Poonam Mehta (JNU)


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Current status and open questions in neutrino oscillation physics

Parameter best-fit-value $3\sigma$ range $1\sigma$ uncertainty
\[ \begin{array}{llll}
\theta_{12} \text{ [Deg.]} & 34.3 & 31.4 - 37.4 & 2.9% \\
\theta_{13} \text{ (NH) [Deg.]} & 8.58 & 8.16 - 8.94 & 1.5% \\
\theta_{13} \text{ (IH) [Deg.]} & 8.63 & 8.21 - 8.99 & 1.5% \\
\theta_{23} \text{ (NH) [Deg.]} & 48.8 & 41.63 - 51.32 & 3.5% \\
\theta_{23} \text{ (IH) [Deg.]} & 48.8 & 41.88 - 51.30 & 3.5% \\
\Delta_{21}^m \text{ [eV$^2$]} & 7.5 \times 10^{-5} & [6.94 - 8.14] \times 10^{-5} & 2.7% \\
\Delta_{31}^m \text{ (NH) [eV$^2$]} & +2.56 \times 10^{-3} & [2.46 - 2.65] \times 10^{-3} & 1.2% \\
\Delta_{31}^m \text{ (IH) [eV$^2$]} & -2.46 \times 10^{-3} & [-2.37 - 2.55] \times 10^{-3} & 1.2% \\
\delta \text{ (NH) [Rad.]} & -0.8\pi & [-\pi, 0] \cup [0.8\pi, \pi] & - \\
\delta \text{ (IH) [Rad.]} & -0.46\pi & [-0.86\pi, -0.1\pi] & - \\
\end{array} \]

Table-1: Global fit to neutrino data.

P. de Salas, et al. (2020), 2006.11237

- Mixing phenomena in the leptonic sector is characterized by three angles ($\theta_{12}, \theta_{23}, \theta_{13}$), two mass-squared differences ($\delta m_{21}^2, \delta m_{31}^2$) and one phase $\delta_{13}$ called the Dirac phase.

- Unknowns - Dirac CP phase ($\delta_{13}$), mass hierarchy ($\Delta m_{31}^2 > 0$ or $< 0$) and octant of $\theta_{23}$

O. Mena and S. Parke, PRD69 (2004) 117301

jogesh.rout1@gmail.com  Exploring second oscillation maximum at DUNE
An international mega-science project located in the US

1300 km long accelerator experiment, World’s Most intense wide band neutrino beam

Main goal: to address the issue of CP violation, Mass hierarchy and Octant of $\theta_{23}$ more precisely in the leptonic sector
Intrinsic CP asymmetry ($\Delta P_{\mu e}^{CP} = 0.75 \sin \delta$) at 2$^{nd}$ oscillation maxima is $\sim$3 times larger than at 1$^{st}$ oscillation maxima ($\Delta P_{\mu e}^{CP} = 0.3 \sin \delta$).

Matter effects are more pronounced at 1$^{st}$ oscillation maximum than at 2$^{nd}$ oscillation maximum. So intrinsic versus extrinsic separation is better around 2$^{nd}$ maxima.

To access the second maxima at DUNE, we use a very intense neutrino beam from a multi-MW proton beam.

For precise measurement of the oscillation parameters, we consider the combination of standard CP optimized wide-band beam for CDR DUNE (2015) and the 8GeV 3MW beam (PIP-III SRF linac option) which peaks around second oscillation maxima.
Solid curve for smearing matrices obtained from a fast MC (2015) CDR, Dashed curve for improved energy reconstruction capabilities with Gaussian smearing.
Both the LE combination and LE combination with 2\textsuperscript{nd} oscillation maxima beam can discern the MH for the given amount of exposure.

MH can be deciphered better with improved energy reconstruction capabilities.
Combination of 2\textsuperscript{nd} maxima beam, LE (1.1MW) and LE (2.2MW) improves the sensitivity to $\theta_{23}$ octant degeneracy where the contribution mainly comes from the LE beams.

Variation of CP phase $\delta : [-\pi \rightarrow \pi]$ creates the band and the grey shaded region indicates the 1\textsigma bound on $\theta_{23}$ from the recent global fit to neutrino data.
Resolution of CP phase ($\delta$) and Jarlskog invariant ($J$)

\[ J = \sin \theta_{12} \cos \theta_{12} \sin \theta_{23} \cos \theta_{23} \sin \theta_{13} \cos^2 \theta_{13} \sin \delta \]
Our results can be summarized as follows

<table>
<thead>
<tr>
<th>Sensitivity to</th>
<th>Nominal case</th>
<th>Improved energy resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPV</td>
<td>76% (79%)</td>
<td>78% (81%)</td>
</tr>
<tr>
<td>MH</td>
<td>Modest improvement</td>
<td>better</td>
</tr>
<tr>
<td>Octant of $\theta_{23}$</td>
<td>Modest improvement</td>
<td>better</td>
</tr>
<tr>
<td>$\delta$ resolution</td>
<td>$6^\circ - 15^\circ$</td>
<td>$\sim 6^\circ - 10^\circ$</td>
</tr>
<tr>
<td>$J$ resolution</td>
<td>$6.6 \times 10^{-3}(J = 0.033)$</td>
<td>$3.8 \times 10^{-3}(J = 0.033)$</td>
</tr>
</tbody>
</table>
Thank You
Beamline parameters assumed for our design fluxes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LE (CPV optimized design)</th>
<th>$2^{nd}$ maxima</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam energy</td>
<td>80 GeV</td>
<td>8 GeV</td>
</tr>
<tr>
<td>Proton Beam power</td>
<td>1.1 MW (PIP-II)/2.2 MW (PIP-III)</td>
<td>3 MW (PIP-III)</td>
</tr>
<tr>
<td>Protons on target (POT) per year</td>
<td>$1.47 \times 10^{21}/2.94 \times 10^{21}$</td>
<td>$40.1 \times 10^{21}$</td>
</tr>
<tr>
<td>Focusing</td>
<td>2 horns, GA optimized for CPV sensitivity (2015)</td>
<td></td>
</tr>
<tr>
<td>Horn Current</td>
<td>$\sim 300$ kA</td>
<td>$\sim 300$ kA</td>
</tr>
<tr>
<td>Decay pipe length</td>
<td>194 m</td>
<td>200 m</td>
</tr>
<tr>
<td>Decay pipe diameter</td>
<td>4 m</td>
<td>4 m</td>
</tr>
</tbody>
</table>

GA $\rightarrow$ Genetic Algorithm

jogesh.rout1@gmail.com
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Low Energy (LE) beam peaks around 1st oscillation maxima.

2nd oscillation maxima beam peaks around 2nd oscillation maxima.

Figure: Events with migration matrices based on fast MC (left) and gaussian smearing (right)