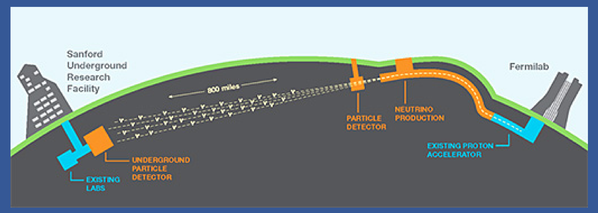

Physics prospects with the second oscillation maximum at Deep Underground Neutrino Experiment

Sheeba Shafaq[1] with Jogesh Rout[1], Mary Bishai[2] and Poonam Mehta[1]

[1]School of Physical Sciences, Jawaharlal Nehru University, New Delhi 110067
[2]Brookhaven National Laboratory, PO Box 5000 Upton, NY 11973-5000

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Idea

We elucidate the role of second oscillation maximum and contrast it with the first oscillation maximum in addressing issues pertaining to unknowns in the standard three flavour paradigm in the context of the future Deep Underground Neutrino Experiment (DUNE).

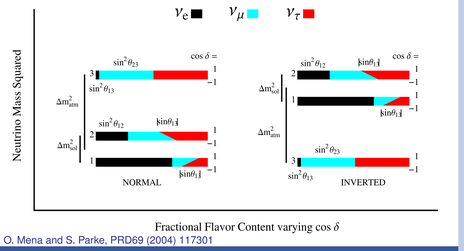
Current status of ν mass and mixing

3-flavor ν parameters accessible via oscillation experiments

- 3 angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and 1 phase ($\delta$)
- 2 mass squared differences (Δm^2_{21}, Δm^2_{31})

Current unknowns:

- Mass hierarchy - sign of Δm^2_{31}
  sign of $\Delta m^2_{31} > 0 \rightarrow$ normal hierarchy (NH)
  sign of $\Delta m^2_{31} < 0 \rightarrow$ inverted hierarchy (IH)
- CP violating phase - δ
- Octant of θ_{23}



P. F. de Salas, et. al., JHEP 02, 071 (2021), 2006.11237

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

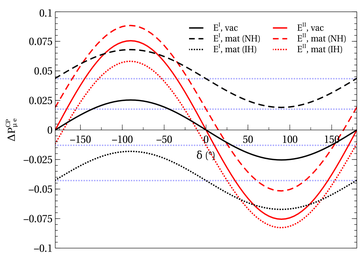
Salient features of $\nu_\mu \rightarrow \nu_e$ probability

$\nu_\mu \rightarrow \nu_e$ probability : Oscillation maxima

$$P^{vac}_{\mu e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31} + \sin\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin^2\Delta_{31}\sin(2\alpha\Delta_{31})$$
$$+ \cos\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\Delta_{31}\sin(2\alpha\Delta_{31})\cos\Delta_{31} + \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\alpha\Delta_{31})$$

Oscillation Maxima occur at $\Delta_{31} \equiv \frac{\Delta m^2_{31} L}{4E} = (2n-1)\frac{\pi}{2} \Rightarrow \frac{L}{E} \approx (2n-1)\times 500\,\frac{\text{km}}{\text{GeV}}$; n=1,2...

CP asymmetry

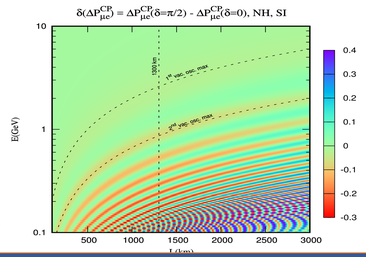


$$\Delta P^{CP}_{\mu e} = P_{\mu e}(\delta) - \bar{P}_{\mu e}(\delta) = \underbrace{16\sin\delta J_r[\sin(\Delta_{31})\sin(\alpha\Delta_{31})\sin(1-\alpha)\Delta_{31}]}_{\text{intrinsic}},$$

$$\Delta P^{CP}_{\mu e} \approx \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\Theta_+\Theta_-}_{\text{extrinsic}} + \underbrace{8\alpha J_r\frac{\sin(\hat{A}\Delta_{31})}{\hat{A}}[\cos\delta\Theta_-\cos\Delta_{31} + \sin\delta\Theta_+\sin\Delta_{31}]}_{\text{intrinsic and extrinsic}},$$

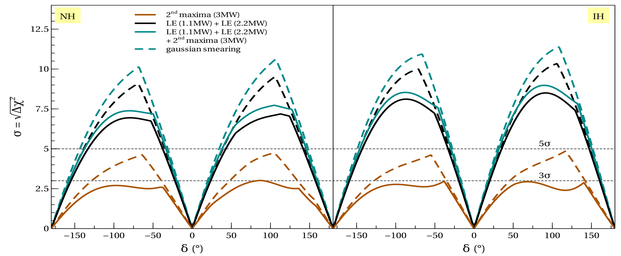
$J = \sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\theta_{13}\cos^2\theta_{13}\sin\delta = J_r\sin\delta$ is the Jarlskog factor, $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\hat{A} = 2\sqrt{2}G_F n_e E/\Delta m^2_{31}$ where G_F is Fermi constant, n_e is the electron density in matter and $\Theta_\pm = \sin[(\hat{A}-1)\Delta_{31}]/(\hat{A}-1) \pm \sin[(\hat{A}+1)\Delta_{31}]/(\hat{A}+1)$

- The intrinsic CP component can be extracted better at second maxima.
- The largest difference occurs around $\delta = \pm 90^\circ$ where, in vacuum, $\Delta P^{CP}_{\mu e}$ at second maxima ($E^{II} = 0.8$ GeV) is thrice as much as at the first maxima ($E^I = 2.6$ GeV) for DUNE (L = 1300km).

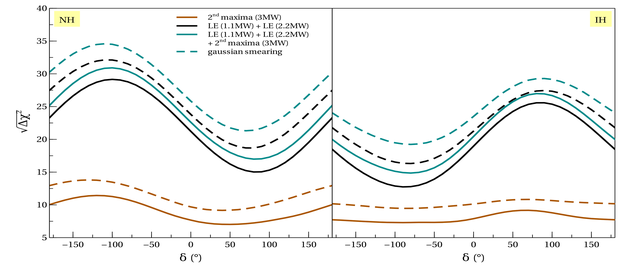


Results

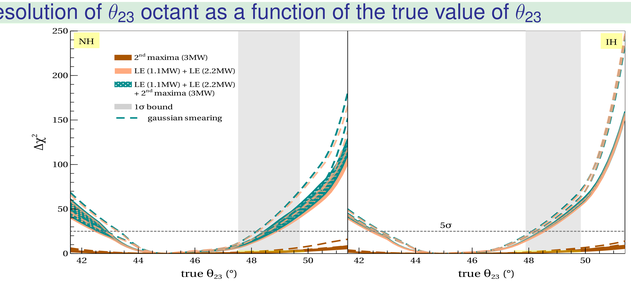
Senstivity to CP violation as a function of δ



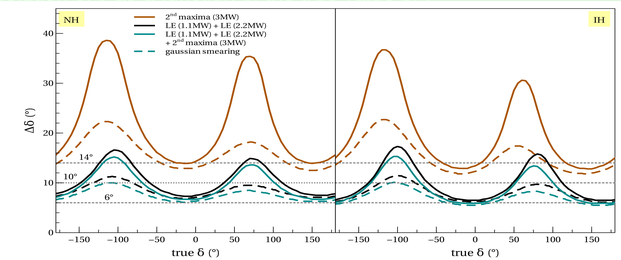
Senstivity to the neutrino mass hierarchy as a function of δ



Resolution of θ_{23} octant as a function of the true value of θ_{23}



Resolution of δ as a function of the true value of δ



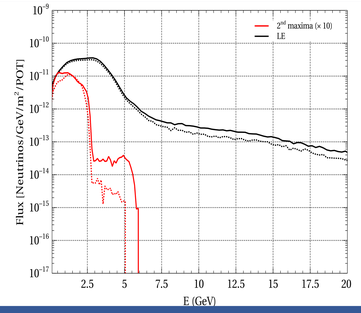
Beamtune Options

- (a) a runtime of 5 yr in LE, 1.1 MW and 5 yr in LE, 2.2 MW
- (b) a runtime of 5 yr in LE, 1.1 MW, 5 yr in LE, 2.2 MW and 5 yr with 2nd maxima, 3 MW
- (c) a runtime of 5 yr with 2nd maxima, 3 MW.

The LE (low energy)flux $\rightarrow$ CP optimized 80 GeV beam

2nd maxima flux $\rightarrow$ PIP-III SRF linac option

Proton Improvement Plan III (2015), URL https://pip3.fnal.gov/



Summary

Sensitivity to	(a) LE, 1.1 MW + LE, 2.2 MW		(b) LE, 1.1 MW + LE, 2.2 MW + 2nd maxima, 3 MW	
	NH	IH	NH	IH
(i) CP violation $[\sigma]$ at $\delta = \pi/2$	6.9 (8.9)	8.5 (9.9)	7.6 (9.9)	9.0 (10.8)
(ii) CP fraction $f(\geq 3\sigma)$	0.74 (0.75)	0.78 (0.79)	0.77 (0.78)	0.80 (0.81)
$f(\geq 5\sigma)$	0.54 (0.58)	0.61 (0.64)	0.59 (0.63)	0.65 (0.68)
(iii) MH $[\sqrt{\Delta\chi^2}]$ at $\delta = \pi/2$	15.0 (18.9)	25.6 (27.5)	17.0 (21.7)	26.9 (29.3)
(iv) Octant of θ_{23} $[\Delta\chi^2]$ at $\theta_{23} = 48.8^\circ$	30.8 (39.3)	31.8 (39.0)	33.2 (40.8)	32.8 (40.3)
(v) δ resolution $[^\circ]$ at $\delta = 0$	7.5 (7.1)	6.5 (6.3)	6.7 (6.3)	5.9 (5.5)
$[^\circ]$ at $\delta = \pi/2$	13.3 (9)	14.9 (9.6)	11.8 (8)	11.9 (8)
(vi) J resolution $[\times 10^{-3}]$ at $J = 0$	4.3 (4.1)	3.7 (3.6)	3.9 (3.6)	3.4 (3.2)
$[\times 10^{-3}]$ at $J = 0.033$	4.0 (2.7)	4.5 (2.8)	3.6 (2.4)	3.6 (2.4)

Key Observations

- Sensitivity to CP violation, Mass Hierarchy and the octant of $\theta_{23} \rightarrow$
  - *modest* improvement
- Resolution of CP phase (δ) $\rightarrow$
  - The standard DUNE wide-band beam when coupled with excellent detector resolution capabilities is sufficient to resolve δ to better than $\sim 12^\circ$ for all values of δ in a decade of running.
  - For second maxima (8 GeV 3MW) beam running concurrently with the standard wide-band (80 GeV 2.2 MW) beam for 5 of the 10 years, it is found that δ can be further resolved better than $\sim 10^\circ$ for all values of δ.
  - At $\delta = 0$, $\Delta\delta \sim 5.9 - 7.9^\circ (5.5 - 7.1^\circ)$ with nominal (improved) detector resolution.
- The 1σ contours from a two-dimensional fit to θ_{23} and δ with external constraint on $\theta_{13} \rightarrow$
  - shrinking of the contours with improved energy reconstruction.

Email: sheebakhawaja7@gmail.com