Exploring second oscillation maximum at DUNE

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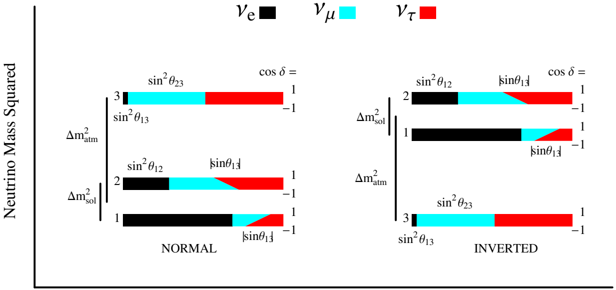
Current status and open questions in neutrino oscillation physics

Parameter	best-fit-value	3σ range	1σ uncertainty
θ_{12} [Deg.]	34.3	31.4 - 37.4	2.9%
θ_{13} (NH) [Deg.]	8.58	8.16 - 8.94	1.5%
θ_{13} (IH) [Deg.]	8.63	8.21 - 8.99	1.5%
θ_{23} (NH) [Deg.]	48.8	41.63 - 51.32	3.5%
θ_{23} (IH) [Deg.]	48.8	41.88 - 51.30	3.5%
Δ^m_{21} [eV^2]	7.5×10^{-5}	[6.94 - 8.14]$\times 10^{-5}$	2.7%
Δ^m_{31} (NH) [eV^2]	$+2.56 \times 10^{-3}$	[2.46 - 2.65] $\times 10^{-3}$	1.2%
Δ^m_{31} (IH) [eV^2]	-2.46×10^{-3}	-[2.37 - 2.55]$\times 10^{-3}$	1.2%
δ (NH) [Rad.]	-0.8π	$[-\pi, 0] \cup [0.8\pi, \pi]$	–
δ (IH) [Rad.]	-0.46π	$[-0.86\pi, -0.1\pi]$	–

Table-1: Global fit to neutrino data.

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

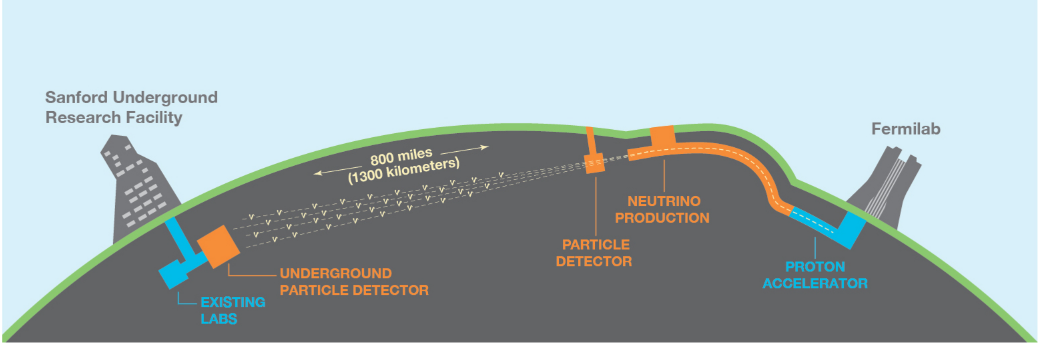


Fractional Flavor Content varying cos δ

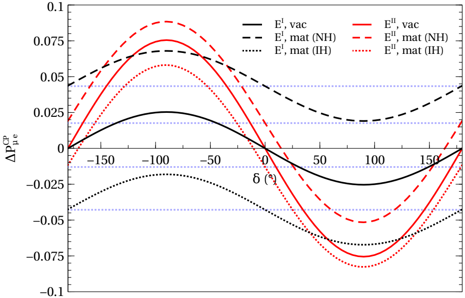
O. Mena and S. Parke, PRD69 (2004) 117301

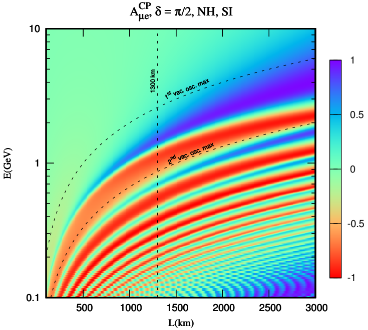
- Mixing phenomena in the leptonic sector is characterized by three angles (θ_{12}, θ_{23}, θ_{13}), two mass-squared differences (δm^2_{21}, δm^2_{31}) and one phase δ_{13} called the Dirac phase.
- Unknowns - Dirac CP phase (δ_{13}), mass hierarchy ($\Delta m^2_{31} > 0$ or < 0) and octant of θ_{23}

DUNE@FNAL- Deep Underground Neutrino Experiment at Fermilab



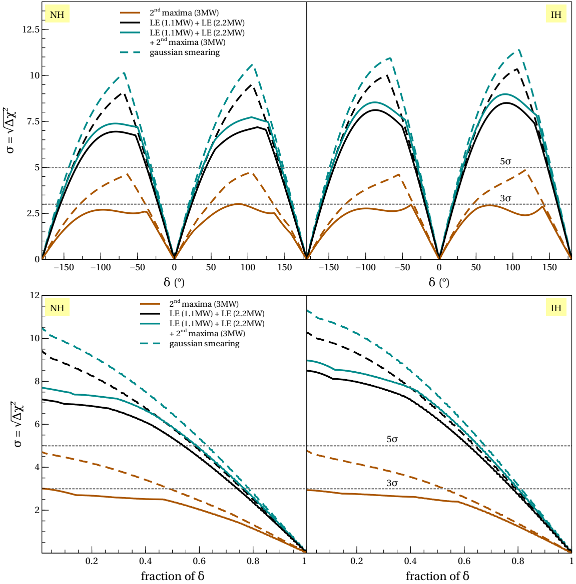
- An international mega-science project located in the US
- 1300 km long accelerator experiment, World's Most intense wide band neutrino beam
- Main goal: to address the issue of CP violation, Mass hierarchy and Octant of θ_{23} more precisely in the leptonic sector





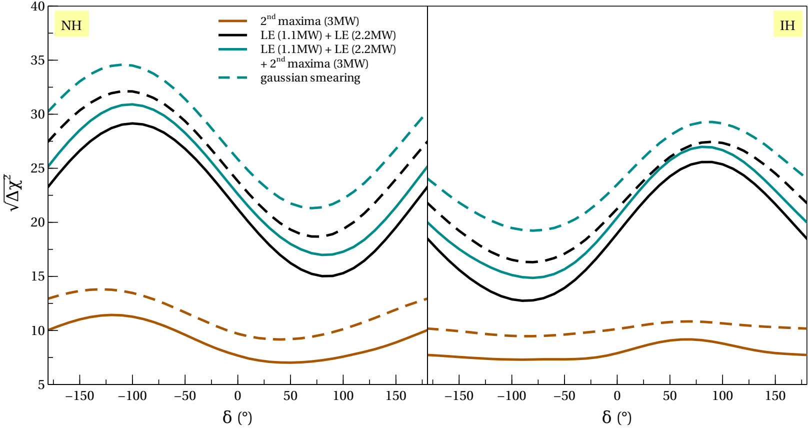
- Intrinsic CP asymmetry ($\Delta P^{CP}_{\mu e} = 0.75\ \sin\delta$) at 2^{nd} oscillation maxima is ∼3 times larger than at 1^{st} oscillation maxima ($\Delta P^{CP}_{\mu e} = 0.3\ \sin\delta$).
- Matter effects are more pronounced at 1^{st} oscillation maximum than at 2^{nd} oscillation maximum. So 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.

CP violation sensitivity

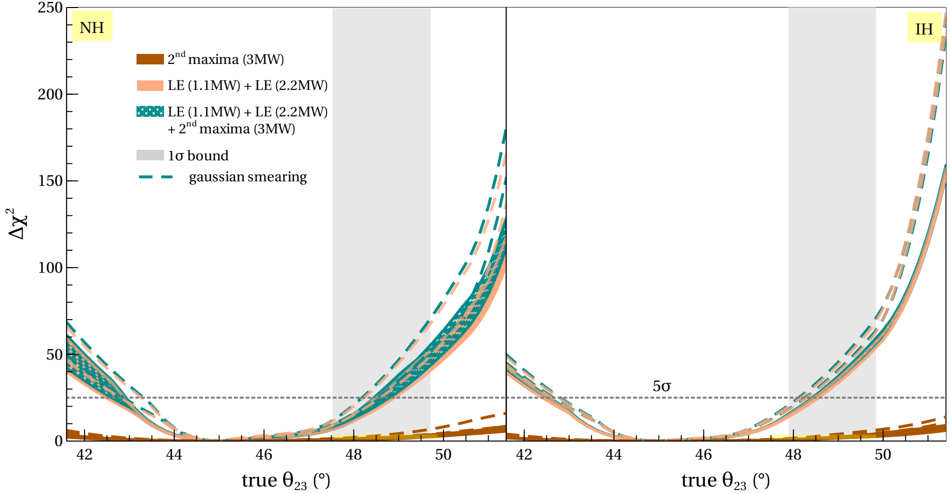


- Solid curve for smearing matrices obtained from a fast MC (2015) CDR, Dashed curve for improved energy reconstruction capabilities with Gaussian smearing

Mass Hierachy (MH) sensitivity

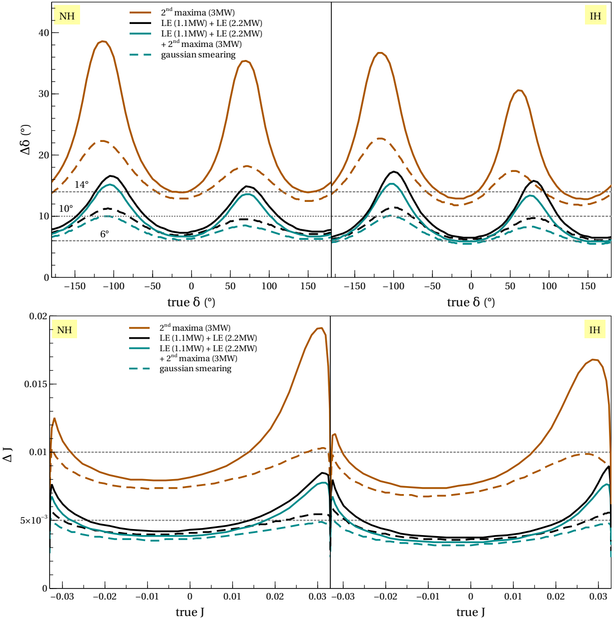


- Both the LE combination and LE combination with 2^{nd} oscillation maxima beam can discern the MH for the given amount of exposure.
- MH can be deciphered better with improved energy reconstruction capabilities.



- Combination of 2^{nd} maxima beam, LE (1.1MW) and LE (2.2MW) improves the sensitivity to θ_{23} octant degeneracy where the contribution mainly comes from the LE beams.
- Variation of CP phase δ : $[-\pi \to \pi]$ creates the band and the grey shaded region indicates the 1σ bound on θ_{23} from the recent global fit to neutrino data.

Resolution of CP phase (δ) and Jarlskog invariant (J)



$$J = \sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\theta_{13}\cos^2\theta_{13}\sin\delta$$

Summary

- Our results can be summarized as follows

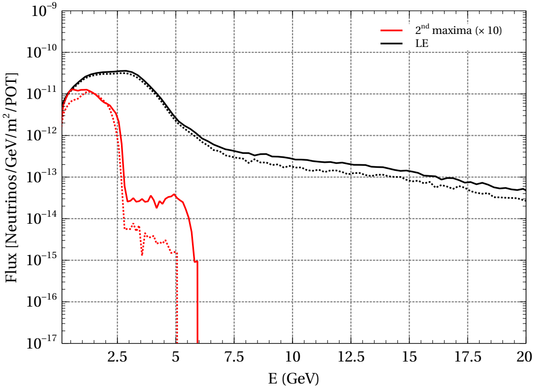
Sensitivity to	Nominal case	Improved energy resolution
CPV	76% (79%)	78% (81%)
MH	Modest improvement	better
Octant of θ_{23}	Modest improvement	better
δ resolution	6° - 15°	$\sim 6^\circ$ - 10°
J resolution	$6.6 \times 10^{-3} (J = 0.033)$	$3.8 \times 10^{-3} (J = 0.033)$

Thank You

Beamline parameters assumed for our design fluxes

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

Beam tunes



R. Acciarri et al. (DUNE) (2015), Dune fluxes (2017), Proton improvement plan III (2015)

- Low Energy (LE) beam peaks around 1^{st} oscillation maxima .
- 2^{nd} oscillation maxima beam peaks around 2^{nd} oscillation maxima.

Event Spectra

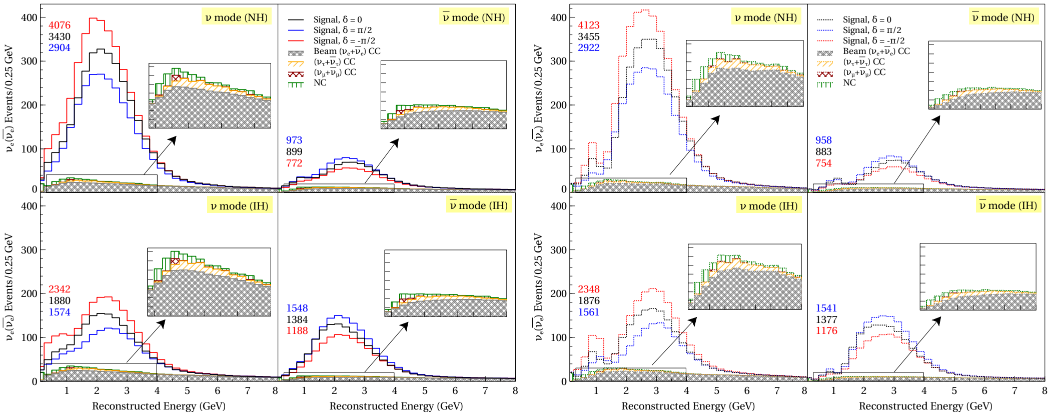


Figure: Events with migration matrices based on fast MC (left) and gaussian smearing (right)