Optimization of leptonic CP violation search using baseline configurations

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Introduction

Conventionally, we employ a single far detector (FD) for oscillation analysis to address the unknowns *viz.* CP violation, mass ordering, and θ_{23} precision. What if we can place multiple detectors as array of FDs, can it enhance the physics potential of an experiment to above questions? In this study, we utilize this technique to optimize CPV search in LBNEs.

Oscillation Probability:

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \sum_{k>j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m^2_{kj} L}{2E}}}$$

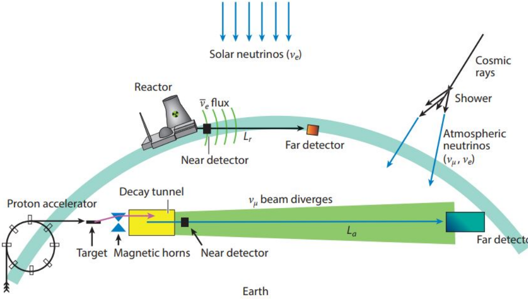
CP Asymmetry:

$$\boxed{A^{\alpha\beta}_{CP} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$$

In conventional accelerator LBLs:

$$\boxed{A^{\mu e}_{CP} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$\boxed{A^{\mu e}_{CP}(\mathrm{E}_{reco}) = \mathrm{N}_{\nu_e}(\mathrm{E}_{reco}) - \mathrm{N}_{\bar{\nu}_e}(\mathrm{E}_{reco})}$$



$$\boxed{N_{\nu_\beta} \propto \overbrace{\Phi_\alpha(E)}^{Production} \times \underbrace{\frac{1}{L^2} P_{(\nu_\alpha \to \nu_\beta)}(E, L, \rho; \theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{21}, \Delta m^2_{31}, \delta_{CP})}_{Propagation} \times \overbrace{\sigma(E)}^{Interaction} \times \underbrace{\epsilon}_{Detection}}$$

Image Courtesy: Annual Review of Nuclear and Particle Science, 66, (2016)

Experiments' Specifications

	T2HK^a	DUNE^b	ESSνSB^c
Baseline:	295 km	1284.9 km	360 km
Beam Power	1.3 MW	1.2 MW	5 MW
Det. Target	Water Cherenkov	Liquid Argon-TPC	Water Cherenkov
Det. Vol.:	187 kton	40 (20) kton	538 kton
Runtime:	$(2.5+7.5)^\dagger$ years	$(5+5)^\dagger$ years	$(5+5)^\dagger$ years

Parameter	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2_{21} (10^{-5})	$\Delta m^2_{32}(10^{-3})$
Best Fit	0.303	0.02203	0.572	7.41 eV^2	2.511 eV^2

Table: Oscillation parameters used for the sensitivity analysis (Ref. νFit 5.2).

$^\dagger(\nu+\bar{\nu})$ runtime. [a]PTEP 2018 (2018) 6, 063C01. [b]DUNE Collaboration (2021), e-Print: 2103.04797[hep-ex]. [c]Eur.Phys.J.ST 231 (2022) 21, 3779-3955.

(Thank you Dr. M. Ghosh of ESSνSB Collab. for sharing the GLoBES-AEDL file.)

CPV sensitivity as a function of baseline

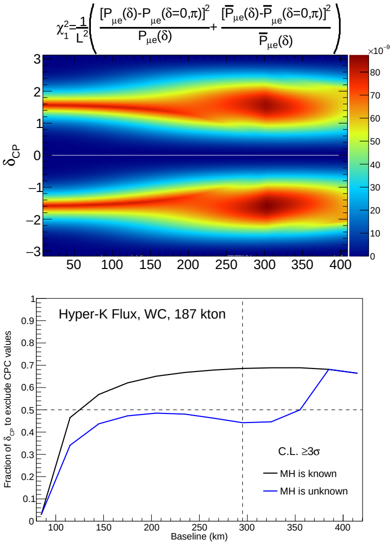
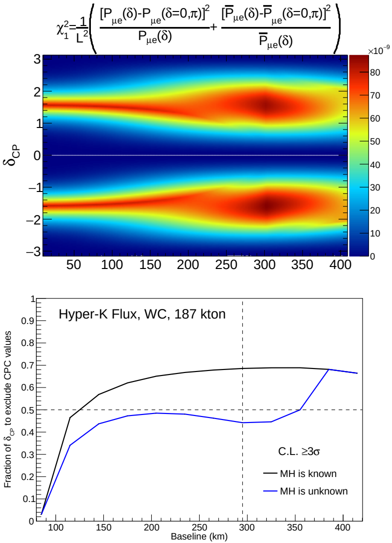


Fig.: Fraction of true δ_{CP} that can be explored with atleast 3σ C.L. to exclude CPC values, as a function of baseline (in km), using HK FD flux is shown in the bottom plot. The top plot show the equivalent χ^2 sensitivity in terms of probability picture.

CPV sensitivity as a function of baseline



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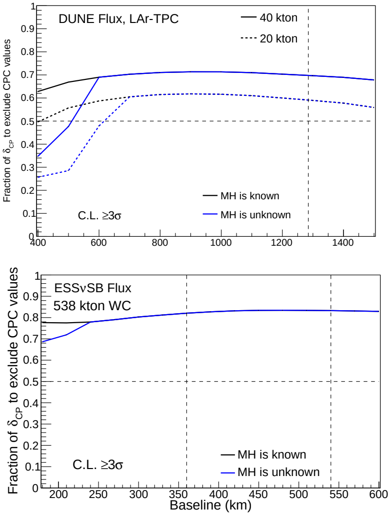

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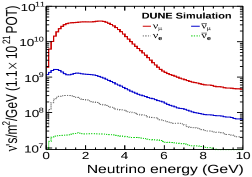
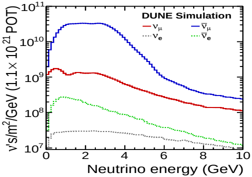
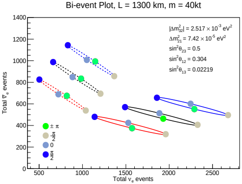
Optimizing CPV search using array of far detectors: Motivation







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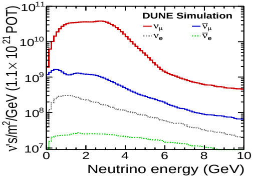
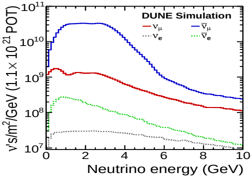
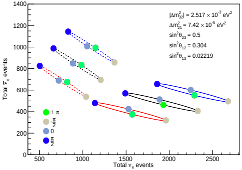
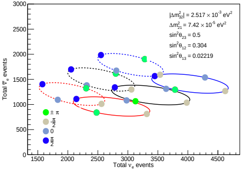


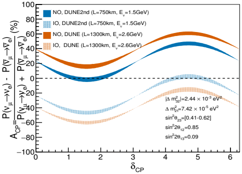


Bi-event Plot, L = 1300 km, m = 40kt



Bi-event Plot, L = 750 km, m = 40kt





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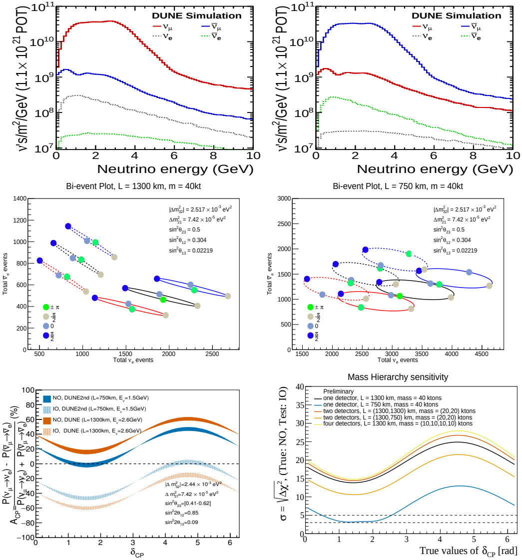

Top: Unoscillated FD flux profiles. ***Middle:*** Bi-event rates for L= 1300 km (750 km) in the left (right) plot. Solid (dashed) ellipses represents NO (IO). ***Bottom:*** CP Asymmetry (left) and MH sensitivity (right) as function of δ_{CP}.

Table: True neutrino Energy of 1st and 2nd oscillation maxima.

Baseline	E_1 (GeV)	E_1 (GeV)
1300 km	2.60	0.87
1000 km	2.00	0.67
750 km	1.50	0.50

Optimizing CPV search using array of far detectors: Motivation

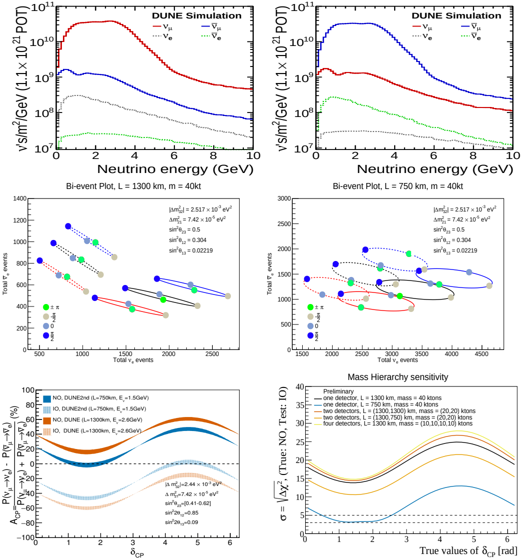

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Table: DUNE, HK and ESSνSB FDs array: Baseline and mass distribution

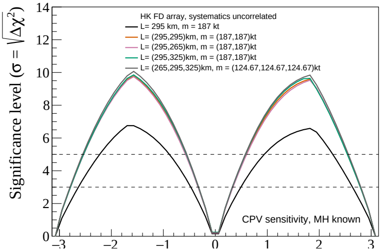
FD Set-up	Detector Mass
DUNE (1300 km)	40 ktons
(1300,1000) km	(20,20) ktons
(1300,750) km	(20,20) ktons
(1300,1000,750)	(13.3,13.3,13.3) ktons

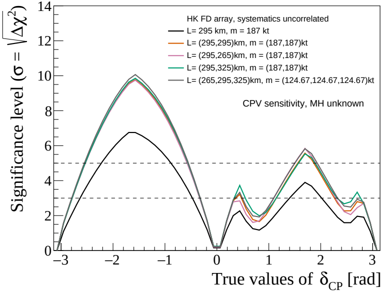
FD Set-up	Detector Mass
HK (295 km)	187 ktons
(295,265) km	(187,187) ktons
(295,325) km	(187,187) ktons
(295,265,325)	(124.7,124.7,124.7) ktons

FD Set-up	Detector Mass
ESS (360 km)	538 ktons
(360,450) km	(269,269) ktons
(360,540) km	(269,269) ktons
(360,450,540)	(179.3,179.3,179.3) ktons

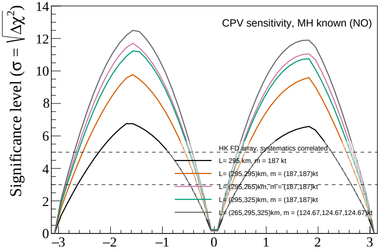
CPV sensitivity using arrays of HK FDs

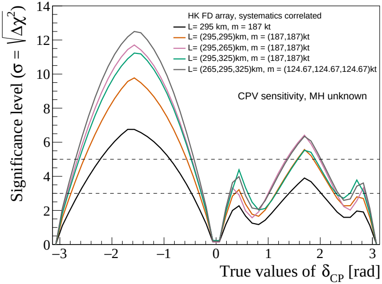
Uncorrelated Systematics





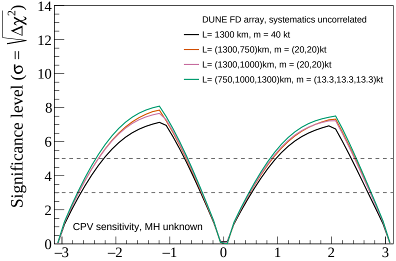
Correlated Systematics

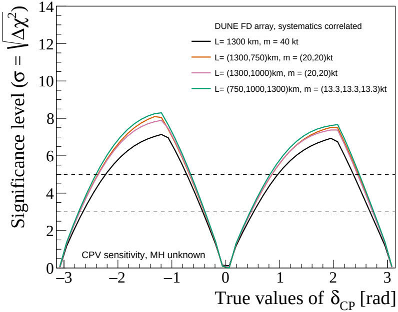




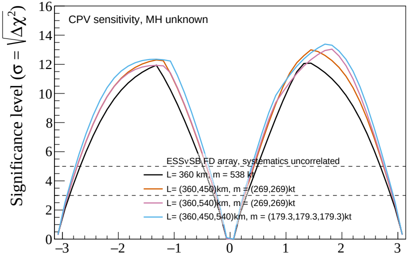
CPV sensitivity using arrays of DUNE and ESSνSB FDs

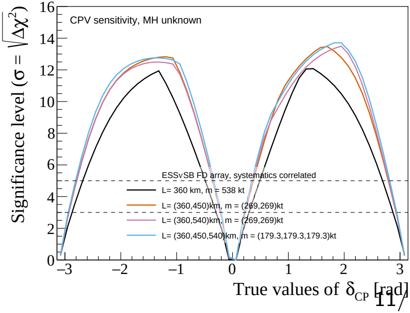
DUNE





ESSνSB





Fraction of true δ_{CP} coverrage using arrays of FDs

Table: Fractional region of true δ_{CP} (in %) that can be explored with 5σ or higher significance when the *mass hierarchy is known (NO)*, using arrays of Hyper-Kamiokande FDs, DUNE FDs and ESSνSB FDs.

HK array (km)	**(295,295)**	(295,265)	(265, 295)	(265, 295, 325)
Uncorrelated	**62.4**	62.1	62.7	63.5
Correlated		69.5	67.9	72.2

DUNE array (km)	**1300**	(1300,1000)	(1300, 750)	(750, 1000, 1300)
Uncorrelated	**46**	50.4	50.6	52.7
Correlated		52.4	52.5	54.3

ESSνSB array (km)	**360**	(360,450)	(360, 540)	(360, 450, 540)
Uncorrelated	**69.9**	73.6	74.0	75.9
Correlated		77.2	77.4	78.7

Discussion and Direction

- Using arrays of far detectors (FDs), instead of the conventional one FD set-up enhances the coverage of the allowed true δ_{CP} regions to exclude the CPC values.
- CPV sensitivity shows a great boost when we consider/mimick correlation among the signal events of the different FDs.
- Although the results are preliminiary, they are significant. This concept can be helpful while constructing upcoming accelerator-based experiments to arrange an array of FDs instead of just one.
- More realistic approach to establish the correlation among the flux profiles, event rates of signal and background of the FDs is required. This can be either implemented by building user-defined χ^2 function to include the relevant systematics, or by using covariance matrices to incorporate the systematic parameters.

Systematics and significance of CPV sensitivity

We use,

$$\chi^2 = Min_{\zeta_s,\zeta_b}\left[2\sum_{i=1}^{n}(N_i^{test} - N_i^{true} - N_i^{true}\ln\frac{N_i^{test}}{N_i^{true}}) + \zeta_s^2 + \zeta_b^2\right]$$

ζ_s and ζ_b are the "pulls" due to the systematics errors on the signal and backgrounds respectively, such that $\zeta_j^2 \propto \frac{1}{s_j^2}$ $(j = s, b)$.

The systematic errors on the signal (s_s) and background events (s_b) for the considered experiments are given below.

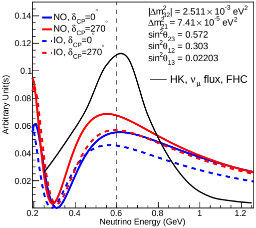
Experiments	Energy	window (GeV)	Signal	errors	Background	errors
	App	*Dis*	*App*	*Dis*	*App*	*Dis*
T2HK	0.1-2.0	0.2-3.0	$\sim 4.5\%$	$\sim 4\%$	10%	10%
DUNE	0.5-18	0.5-18	2%	5%	5%	5%
ESSνSB	0.1-1.0	0.1-1.0	5%	5%	5%	5%

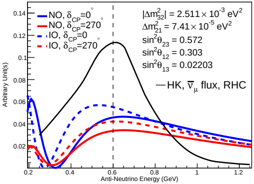
The statisctical significance to exclude CP conserving values $(0, \pm\pi)$ for value value of true δ_{CP} is:

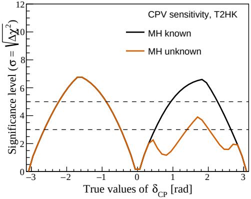
$$\Delta\chi^2(\delta_{true}) \sim \min\left(\chi^2_{total}(\delta_{true}) - \chi^2_{total}(\delta_{test} = 0, \pm\pi)\right)$$

For the minimization of χ^2 over the MH options, we consider two cases:
(i) MH is known and normal, or (ii) MH is unknown.

$P_{\mu e}$ and CPV sensitivities for T2HK, DUNE & ESSνSB (*left to right*)







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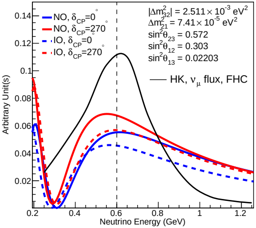

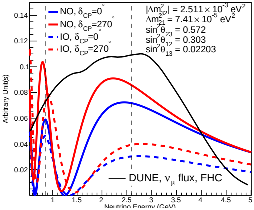

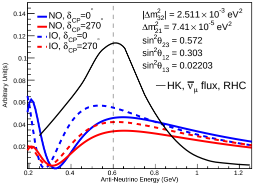

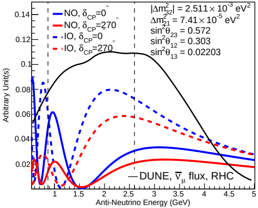

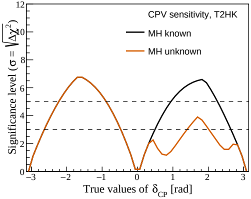

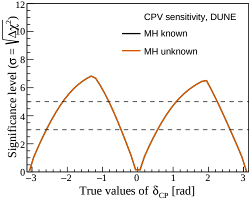

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