Establishing non-maximal 2-3 mixing with DUNE in light of current neutrino oscillation data
arXiv: 2111.11748

Ritam Kundu (ritam.k@iopb.res.in),
Sanjib Kumar Agarwalla, Suprabh Prakash, Masoom Singh

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Institute of Physics, Bhubaneswar, India

Outline

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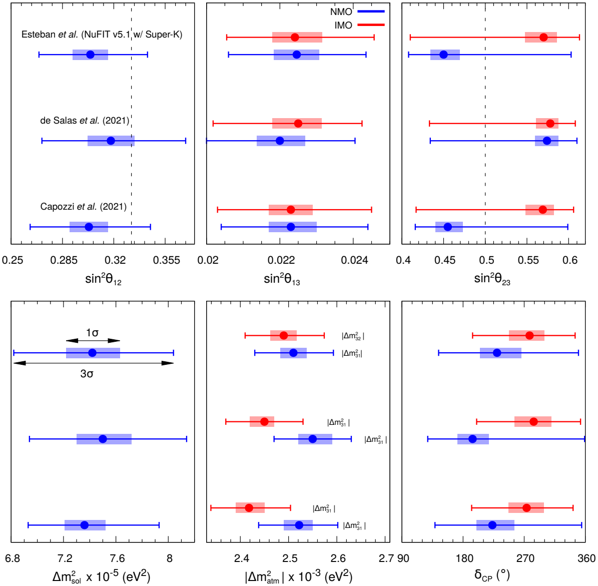
Present global-fit scenario in 3ν-paradigm

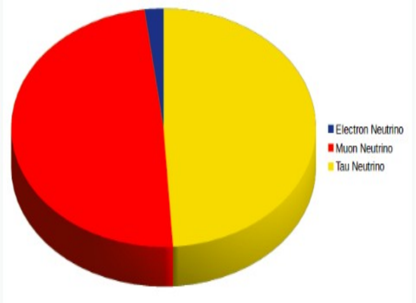


- 3σ (1σ) range of ν oscillation parameters, Esteban *et al*. www.nu-fit.org, de Salas *et al*. arXiv: 2006.11237, and Capozzi *et al*. arXiv: 2107.00532 in NMO and IMO.

Parameters	Relative 1σ error
$\sin^2\theta_{12}$	4.5%
Δm^2_{21}	2.3%
$\sin^2\theta_{23}$	6.7%
Δm^2_{31}	1.1%
$\sin^2\theta_{13}$	3%
δ_{CP}	16%

- The two most uncertain parameters are θ_{23} and δ_{CP}.
- θ_{23} is in LO (HO) for NMO (IMO) by Esteban *et al*. and Capozzi *et al*.

Deviation of θ_{23} from maximal mixing



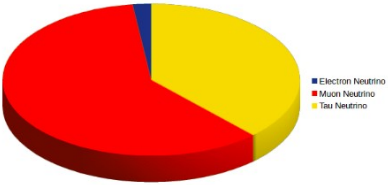
- $\mu \to \tau$ symmetry

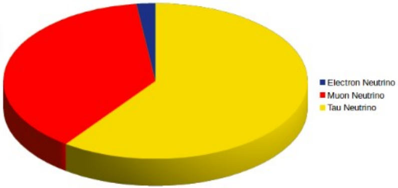
$$|\nu_2\rangle = \cos\theta_{23}\ |\nu_\mu\rangle + \sin\theta_{23}\ |\nu_\tau\rangle$$
$$|\nu_3\rangle = -\sin\theta_{23}\ |\nu_\mu\rangle + \cos\theta_{23}\ |\nu_\tau\rangle$$

- If $\theta_{23} = 45^\circ$, i.e for MM, ν_2 and ν_3 have equal contributions of ν_μ and ν_τ.

https://arxiv.org/abs/hep-ph/9604415

Deviation of θ_{23} from maximal mixing





- For LO, ν_3 mass-eigenstate has more contribution of ν_τ.
- For HO, ν_3 mass-eigenstate has more contribution of ν_μ.
- Non-maximal θ_{23} will provide crucial inputs to the therories of neutrino masses and mixings.
- Models like A_4 flavor symmetry, quark-lepton complementarity have been suggested to explain one small and two large mixing angles, precision measurement of θ_{23} will help to study the deviations from these symmetries.
- The resolution of θ_{23} octant will severely constrain the patterns of symmetry breaking.

Appearance channel

- The appearance probability for $\nu_\mu \to \nu_e$.

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2(2\theta_{13})\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$
$$-\alpha\sin(2\theta_{13})\zeta\sin\delta_{CP}\sin(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$
$$+\alpha\sin(2\theta_{13})\zeta\cos\delta_{CP}\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$
$$+\alpha^2\cos^2\theta_{23}\sin^2(2\theta_{12})\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

where $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \approx 0.033$, $\Delta = \Delta m^2_{31}L/4E$, $\zeta = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$,
and $\hat{A} = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$

- First term is driven by $\sin^2(\theta_{23})$ and hence helps to resolve octant degeneracy.
- This channel is good for probing δ_{CP}.

Disappearance channel

- The survival probability for $\nu_\mu \to \nu_\mu$.

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(\Delta)$$
$$+ (\alpha\Delta)c_{12}^2\sin^2(2\theta_{23})\sin(2\Delta)$$
$$- 2\alpha\zeta\cos(\delta_{CP})\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(\hat{A}-1)\Delta]}{(\hat{A}-1)}$$
$$+ \frac{2}{(\hat{A}-1)}\alpha\zeta\cos(2\theta_{23})\cos(\delta_{CP})\sin(\Delta)[\hat{A}\sin(\Delta) - \frac{\sin(\hat{A}\Delta)}{\hat{A}}\cos((\hat{A}-1)\Delta)]$$

where $\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \approx 0.033$, $\Delta = \Delta m_{31}^2 L/4E$, $\zeta = \sin\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})$, $\hat{A} = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$

- Second term is driven by $\sin^2(2\theta_{23})$. It is Atmospheric Term. This is the leading term and this channel gives precision of θ_{23}. But it cannot resolve the octant degeneracy.
- This channel does not probe δ_{CP} well.

Considered values of ν oscillation parameters in our work

Parameters	Best-fit	1σ range	3σ range
$\delta m^2/10^{-5}\ eV^2$	7.36	7.21-7.52	6.93-7.93
$\sin^2\theta_{12}/10^{-1}$	3.03	2.90-3.16	2.63-3.45
$\sin^2\theta_{13}/10^{-2}$	2.23	2.17-2.30	2.04-2.44
$\sin^2\theta_{23}/10^{-1}$	4.55	4.40-4.73	4.16-5.99
$\Delta m^2_{31}/10^{-3}\ eV^2$	2.522	2.490-2.545	2.436-2.605
$\delta_{CP}/^\circ$	223	200-256	139-355

Capozzi et.al. https://arxiv.org/abs/2107.00532

Total number of events (L = 1300 km)

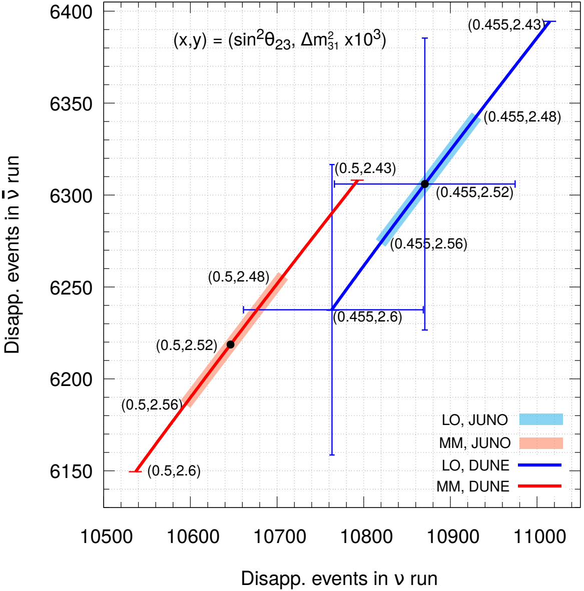
$$\begin{array}{c} \mathcal{N}(223, 2.436) \\ \uparrow \\ \mathcal{N}(139, 2.522) \leftarrow \mathcal{N}(223, 2.522) \rightarrow \mathcal{N}(355, 2.522) \\ \downarrow \\ \mathcal{N}(223, 2.605) \end{array}$$

$\mathcal{N}(x, y)$ where $\mathcal{N}$: total number of events, x: $\delta_{\rm CP}$ in degrees, y: Δm^2_{31} in 10^{-3} eV^2

Channel		LO ($\sin^2\theta_{23} = 0.455$)	MM ($\sin^2\theta_{23} = 0.5$)	HO ($\sin^2\theta_{23} = 0.599$)
Appearance	ν	1104 ↑ 820 ←1121→ 969 ↓ 1135	1193 ↑ 908 ←1211→ 1058 ↓ 1226	1383 ↑ 1107 ←1403→ 1254 ↓ 1421
	$\bar{\nu}$	206 ↑ 267 ←208→ 258 ↓ 210	227 ↑ 289 ←230→ 280 ↓ 232	277 ↑ 338 ←279→ 329 ↓ 281
Disappearance	ν	11018 ↑ 10870 ←10870→ 10896 ↓ 10758	10797 ↑ 10646 ←10646→ 10663 ↓ 10532	11249 ↑ 11100 ←11100→ 11095 ↓ 10986
	$\bar{\nu}$	6397 ↑ 6306 ←6306→ 6280 ↓ 6234	6310 ↑ 6219 ←6219→ 6193 ↓ 6146	6565 ↑ 6477 ←6477→ 6452 ↓ 6406

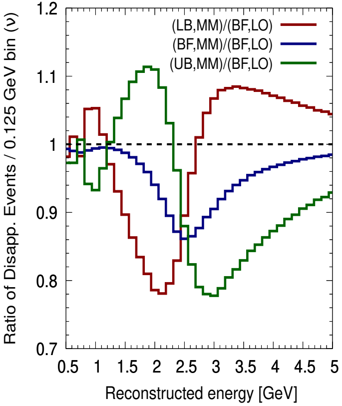
- On varying $\delta_{\rm CP}$, degeneracies in LO and MM with ν App.
- On varying Δm^2_{31}, degeneracies in LO and MM with ν Disapp.
- Degeneracies may be lifted if App. and Disapp. are combined.

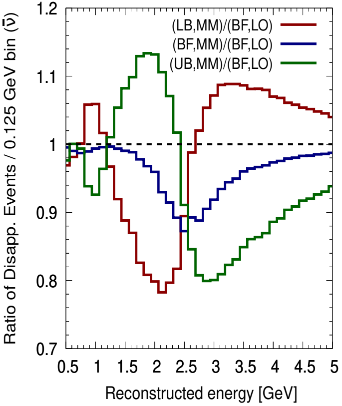
Bi-events in disappearance channel



- MM events overlappig with relative 1σ fluctuation in LO, for best-fit Δm^2_{31} in both ν and $\bar{\nu}$ modes.
- At total rate level, degeneracies exist.
- Overlapping regions get reduced on considering 3σ range of Δm^2_{31} from JUNO .

Ratio of events in disappearance channel





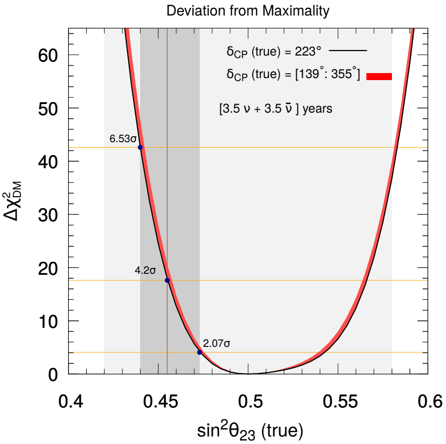
- All the lines converge towards 1 at lower energy bin but deviate at higher energy bin. This deviation is signature of deviation from maximal θ_{23}.
- All the lines flip their direction with respect to the 1st oscillation minimum (2.5 GeV).

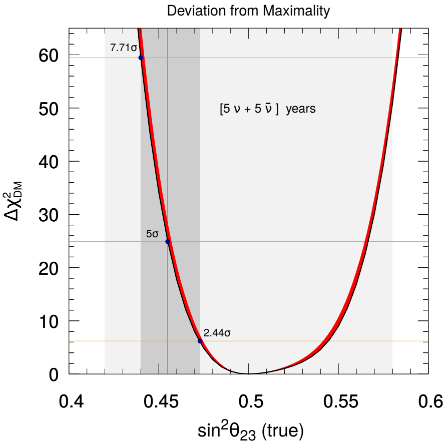
Definition of $\Delta\chi^2_{\mathsf{DM}}$

$$\Delta\chi^2_{\mathsf{DM}} = \min_{(\vec{\lambda},\ \vec{\kappa}_1,\vec{\kappa}_2)} \left\{\chi^2\left(\sin^2\theta_{23}^{\rm true} = [0.4, 0.6]\right) - \chi^2\left(\sin^2\theta_{23}^{\rm test} = 0.5\right)\right\},$$

where, $\lambda = \delta_{\rm CP}$, Δm^2_{31} is the marginalised parameters and κ_1, κ_2 are systematic errors in signal and background respectively.

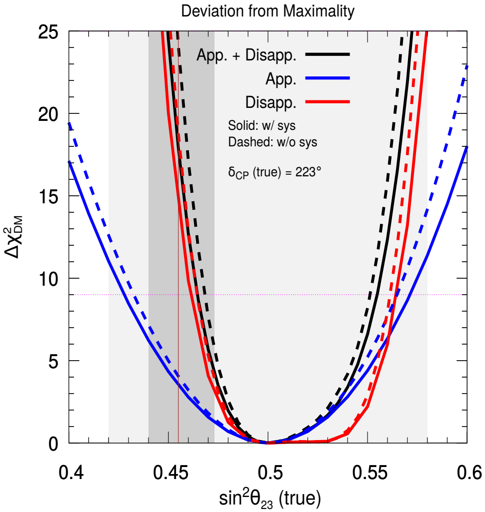
Deviation from maximal θ_{23}





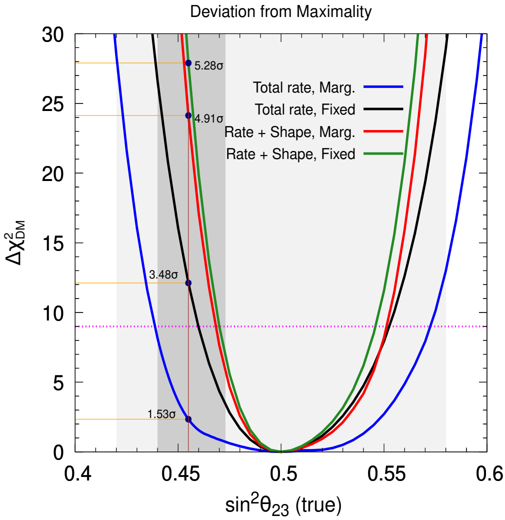
- For 7 (10) years run-time, DUNE can establish the deviation from MM at the best-fit $\sin^2\theta_{23}$ with 4.2σ (5σ) C.L.
- Deviation from MM gets improved with upper bound of 1σ range of $\sin^2\theta_{23}$ (true).

Role of App. and Disapp. channels and Systematics



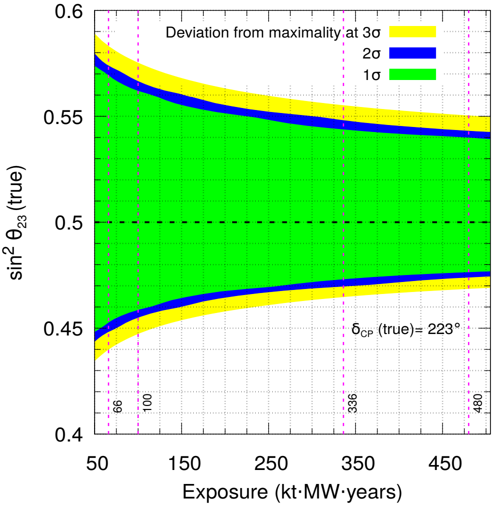
- Combination of App. and Disapp. gives more sensitivity than the individual channels.
- Sensitivity of App. is more than Disapp. for $\sin^2\theta_{23} \gtrsim 0.57$.
- Effect of systematics is lesser in disappearance channel than the appearance channel.

Effect of Shape analysis and Marginalization



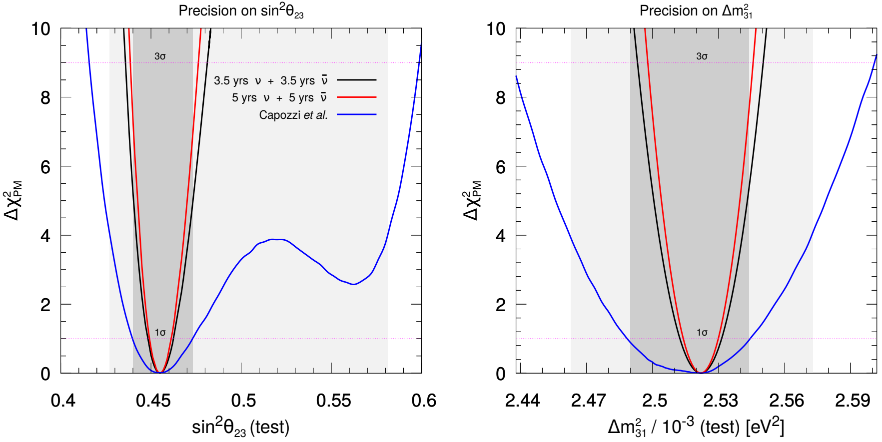
- Marginalization over Δm^2_{31} is lesser in rate + shape analysis than total rate analysis in [3.5 yrs. ν + 3.5 yrs. $\bar{\nu}$].
- Rate + shape analysis establish deviation from maximal θ_{23} with higher C.L. than total rate analysis at best-fit $\sin^2\theta_{23}$.
- High energy resolution for LArTPC detector in DUNE.
- Systematic uncertainties are not considered.

Potential of DUNE with varying Exposures



- With increasing the exposure from 50 kt.MW.years to 100 kt.MW.years, significant improvement in the establishment of non-maximal θ_{23} is seen.
- From 100 kt.MW.years to 336 kt.MW.years (benchmark choice), marginal improvement is seen.
- Beyond 336 kt.MW.years, statistics is not an issue for improvement of establishing non-maximal θ_{23}.

Precision measurement of $\sin^2\theta_{23}$ and Δm^2_{31}



- DUNE can precisely measure $\sin^2\theta_{23}$ and Δm^2_{31} better than achieved by Capozzi *et al*. with better precision.
- These precisions improve for higher run-time.

Relative 1σ precision

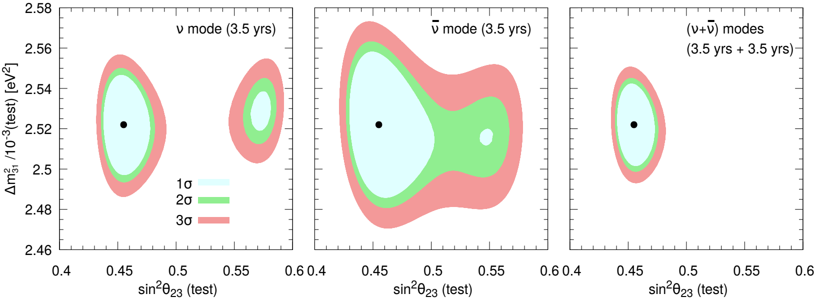
The relative 1σ precision in the measurement of oscillation parameters ζ is estimated as follows:

$$p(\zeta) = \frac{\zeta^{\max} - \zeta^{\min}}{6.0 \times \zeta^{\text{true}}} \times 100\%$$

$\zeta^{\max}$ and $\zeta^{\min}$ are the allowed 3σ upper and lower bounds, respectively.

Parameter	Relative 1σ precision (%)			
	DUNE $(3.5\ \nu + 3.5\ \bar{\nu})$ yrs	DUNE $(5\ \nu + 5\ \bar{\nu})$ yrs	Capozzi *et al.*	JUNO
$\sin^2\theta_{23}$	1.53	1.31	6.72	—
Δm^2_{31}	0.39	0.31	1.09	0.50

Allowed regions in $\sin^2\theta_{23} - \Delta m^2_{31}$ plane



- Neither ν nor $\bar{\nu}$ modes can exclude wrong octant solution even at 1σ C.L. in test $\Delta m^2_{31} - \sin^2\theta_{23}$ plane.

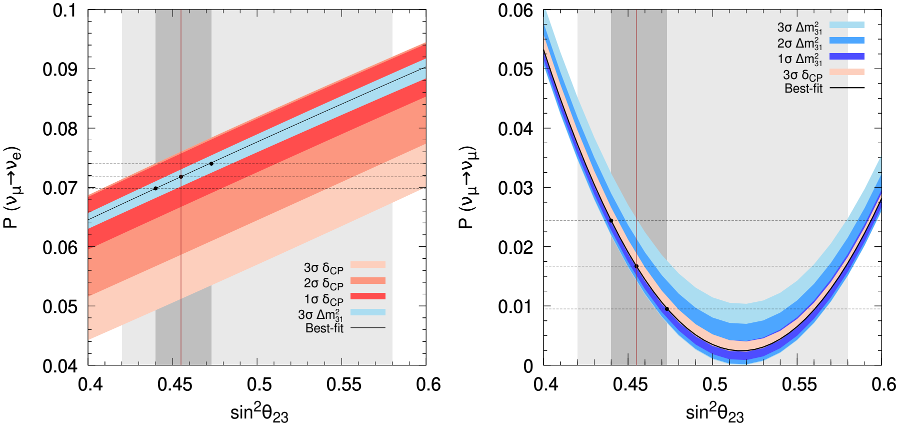
- HO can be ruled out when both ν and $\bar{\nu}$ modes are considered together.

Summary

- Ongoing long-baseline experiments strongly suggest deviation from MM of θ_{23}.
- We observe that a 3σ (5σ) determination of non-maximal θ_{23} is possible in DUNE with an exposure of 336 kt.MW.years if true $\sin^2\theta_{23} \lesssim 0.465$ (0.450) or $\sin^2\theta_{23} \gtrsim 0.554$ (0.572) for any value of δ_{CP} in present 3σ range and true NMO.
- DUNE can resolve the octant of θ_{23} at 4.2σ (5σ) using 336 (480) kt.MW.years of exposure assuming best-fit $\sin^2\theta_{23}$ (0.455) and δ_{CP} (223°) in NMO.
- DUNE can improve the current relative 1σ precision on $\sin^2\theta_{23}$ (Δm^2_{31}) by a factor of 4.4 (2.8) using 336 kt.MW.years of exposure.

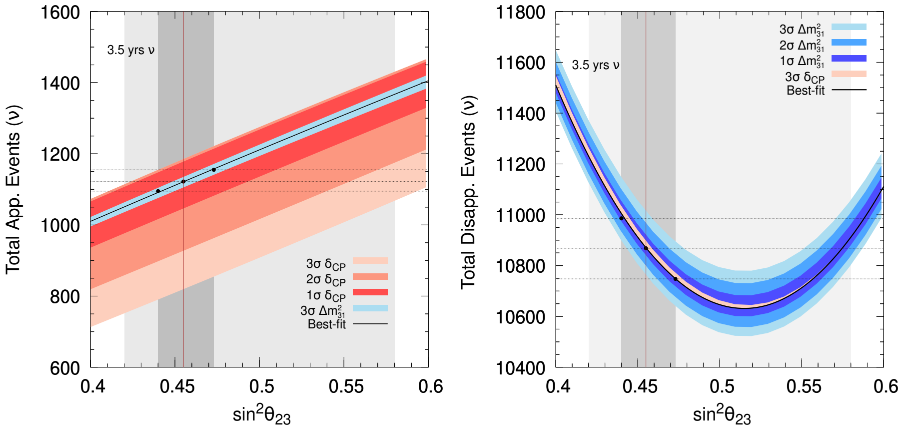

Thank you!

App. and Disapp. probabilities



- Disapp. probabilities (right) are very slowly changing from true $\sin^2\theta_{23} = 0.5$ to 0.56, after that it is incrasing faster than App. channel.

Total Events



- In Disapp. (right), total events are slowly changing from true $\sin^2\theta_{23} = 0.5$ to 0.56, after that it is incrasing faster than App. channel.

Effect of systematics in sensitivity

True $\sin^2\theta_{23}$	Channels	2%, 5%	0%, 0%	5%, 5%	5%, 10%	10%
0.455 (Best-fit)	App.+Disapp.	17.64	24.13	16.88	16.74	1
	App.	3.52	4.05	2.33	2.33	
	Disapp.	14.31	18.79	14.31	14.16	1
0.473 (1σ upper bound)	App.+Disapp.	4.28	5.72	3.88	3.84	
	App.	1.27	1.47	0.84	0.84	
	Disapp.	2.99	3.88	2.99	2.97	