



Can Deviation from maximal θ_{23} be Resolved in DUNE ?



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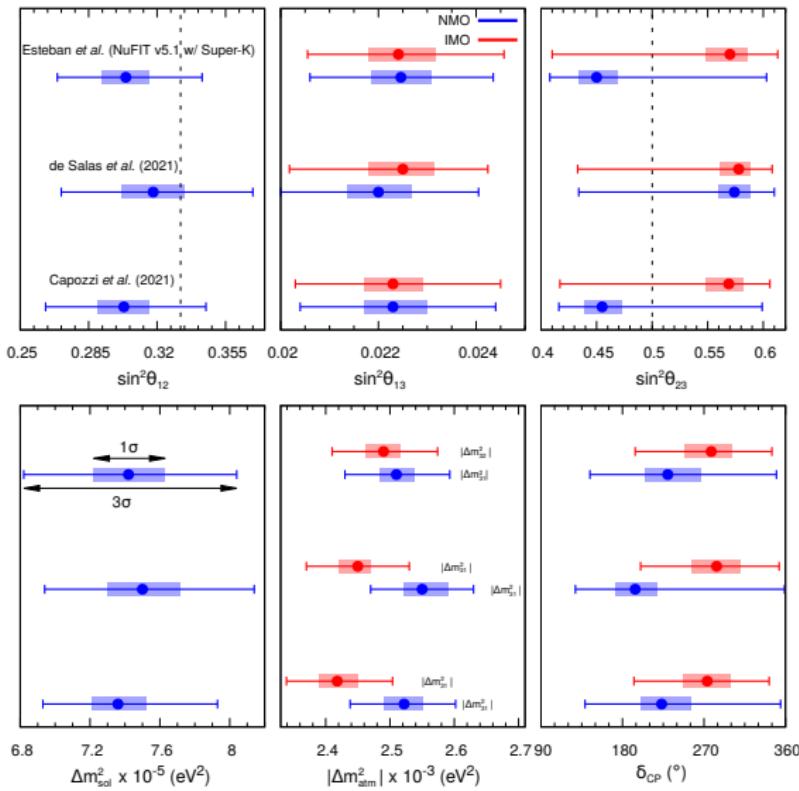
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Talk is based on published work — A close look on 2-3 mixing angle with DUNE in light of current neutrino oscillation data; [JHEP03\(2022\)206](#).

NuFACT 2022

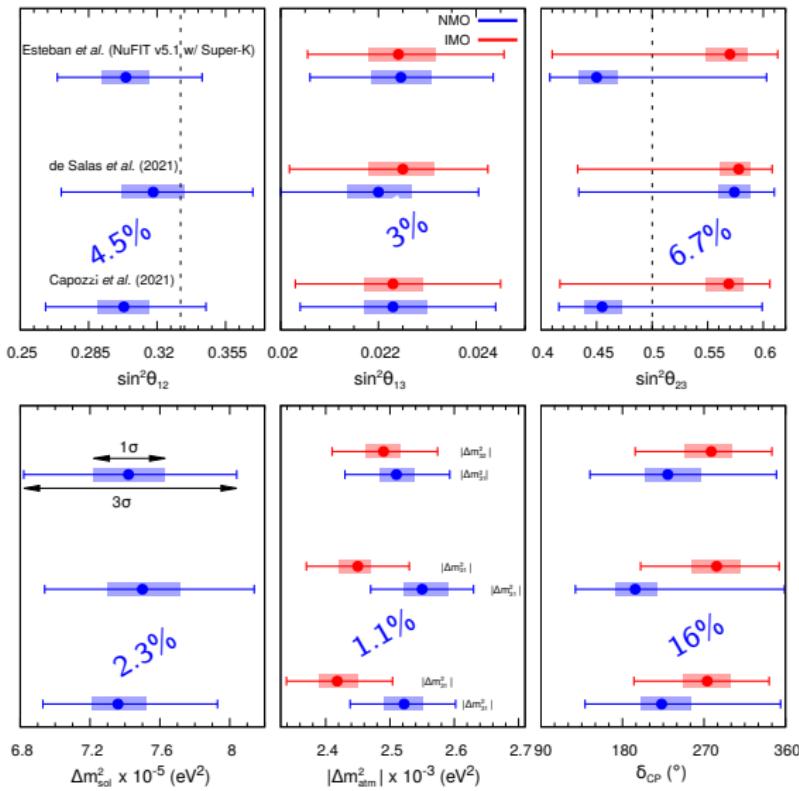
23rd International Workshop on Neutrinos from Accelerators, July 30 (Sat) to Aug 7 (Sun), 2022

Present scenario



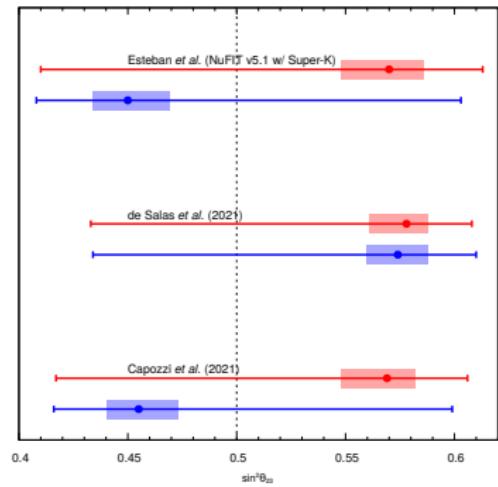
- Global oscillation data taken from:
NuFit5.1, JHEP 09 (2020) 178,
and Phys.Rev.D 104 (2021) 8,
083031
- Black-dashed line in $\sin^2 \theta_{12}$ and $\sin^2 \theta_{23}$ gives values in tribimaximal mixing scheme

Present scenario



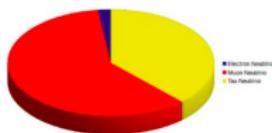
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Motivation

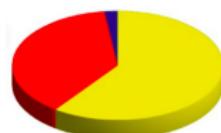


- Current 3 σ allowed range in $\sin^2 \theta_{23} \sim [0.4 : 0.6]$
- $\sin^2 \theta_{23} = 0.5$ (MM) still allowed
- Present global best-fit is far from MM, either in LO or HO
- Must exclude deviation from MM (maximality) with high C.L. before addressing issue of octant

$\theta_{23} > 45^\circ$ (HO)

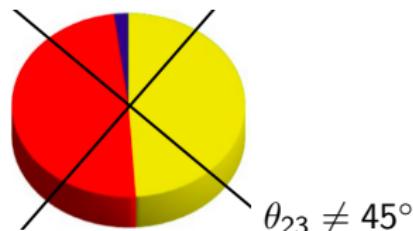


$\theta_{23} < 45^\circ$ (LO)



Before addressing Octant Ambiguity

Fogli and Lisi, hep-ph/9604415



Deviation from MM needs to be established with high significance

Disappearance Channel

$$P_{\mu\mu} \approx 1 - \underbrace{M \sin^2 2\theta_{23}}_{\text{Leading}} - N \sin^2 \theta_{23} - R \sin 2\theta_{23} + T \sin 4\theta_{23}, \quad (1)$$

where,

$$M = \sin^2 \Delta - \alpha \cos^2 \theta_{12} \Delta \sin 2\Delta + \frac{2}{\hat{A}-1} \sin^2 \theta_{13} \left(\sin \Delta \cos \hat{A} \Delta \frac{\sin(\hat{A}-1)\Delta}{\hat{A}-1} - \frac{\hat{A}}{2} \Delta \sin 2\Delta \right),$$

$$N = 4 \sin^2 \theta_{13} \frac{\sin^2(\hat{A}-1)\Delta}{(\hat{A}-1)^2},$$

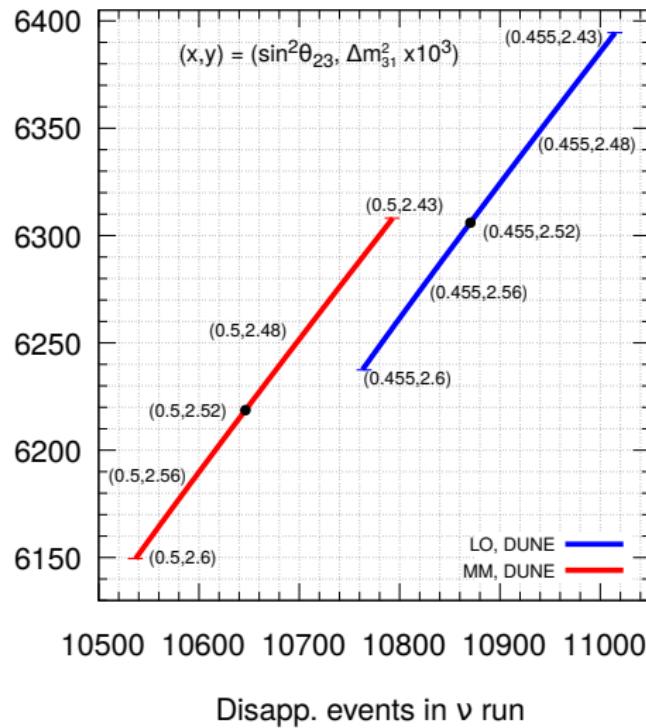
$$R = 2\alpha \sin \theta_{13} \sin 2\theta_{12} \cos \delta_{\text{CP}} \cos \Delta \frac{\sin \hat{A} \Delta}{\hat{A}} \frac{\sin(\hat{A}-1)\Delta}{\hat{A}-1}, \text{ and}$$

$$T = \frac{1}{\hat{A}-1} \alpha \sin \theta_{13} \sin 2\theta_{12} \cos \delta_{\text{CP}} \sin \Delta \left(\hat{A} \sin \Delta - \frac{\sin \hat{A} \Delta}{\hat{A}} \cos(\hat{A}-1)\Delta \right).$$

- Here, $\Delta \equiv \Delta m_{31}^2 L / 4E$ and $\hat{A} \equiv A / \Delta m_{31}^2 \equiv 2\sqrt{2} G_F N_e E$.
- $\sin^2 \theta_{13} \approx 0.02$, $\alpha \sin \theta_{13} \approx 0.004$
- Leading term depends on Δ

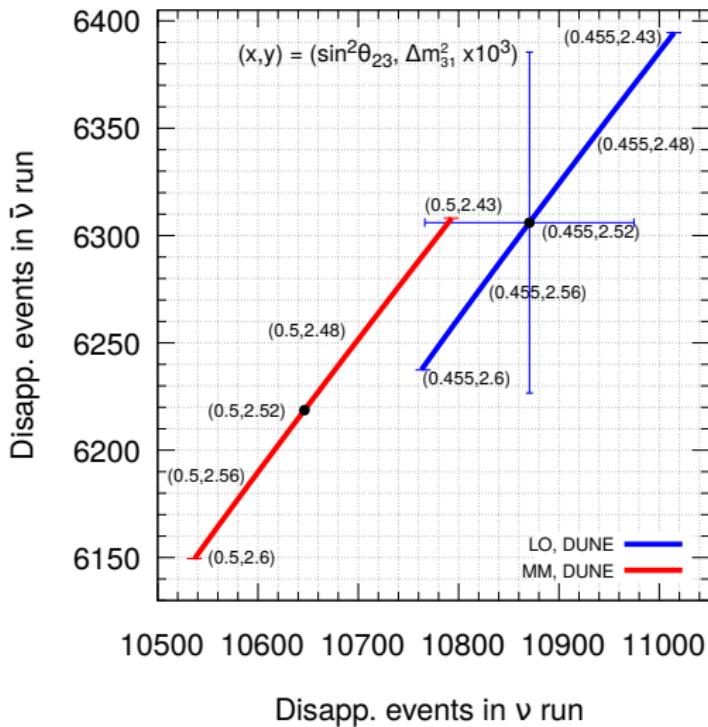
Bi-events in the $(\Delta m_{31}^2 - \sin^2 \theta_{23})$ plane

Disapp. events in $\bar{\nu}$ run



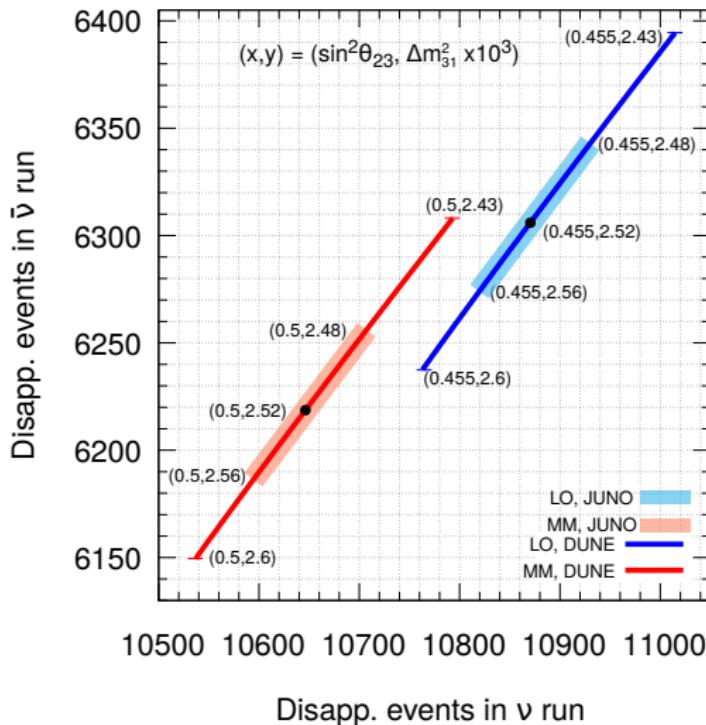
- Total Disapp. event rates in $\nu-\bar{\nu}$ plane.
 - 3σ uncertain range in Δm_{31}^2 $[2.436 : 2.605] \times 10^{-3} \text{ eV}^2$
- [Phys.Rev.D 104 \(2021\) 8, 083031](#)
- $\sin^2 \theta_{23} = 0.455$ (blue), 0.5 (red)

Bi-events in the $(\Delta m_{31}^2 - \sin^2 \theta_{23})$ plane



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[Phys.Rev.D 104 \(2021\) 8, 083031](#)
- $\sin^2 \theta_{23} = 0.455$ (blue), 0.5 (red)
- 1σ statistical uncertainty shows degeneracy

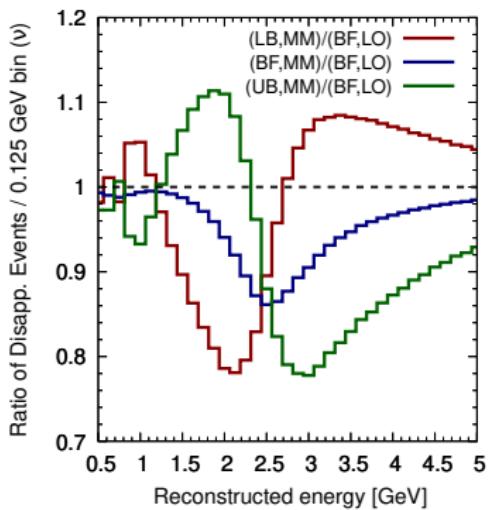
Bi-events in the $(\Delta m_{31}^2 - \sin^2 \theta_{23})$ plane



- Total Disapp. event rates in ν - $\bar{\nu}$ plane.
- 3σ uncertain range in Δm_{31}^2 $[2.436 : 2.605] \times 10^{-3} \text{ eV}^2$
[Phys.Rev.D 104 \(2021\) 8, 083031](#)
- $\sin^2 \theta_{23} = 0.455$ (blue), 0.5 (red)
- Expected 3σ uncertainty from JUNO in rectangular regions

Talk by M.Gonchar in EPS-HEP 2021

Spectral Analysis

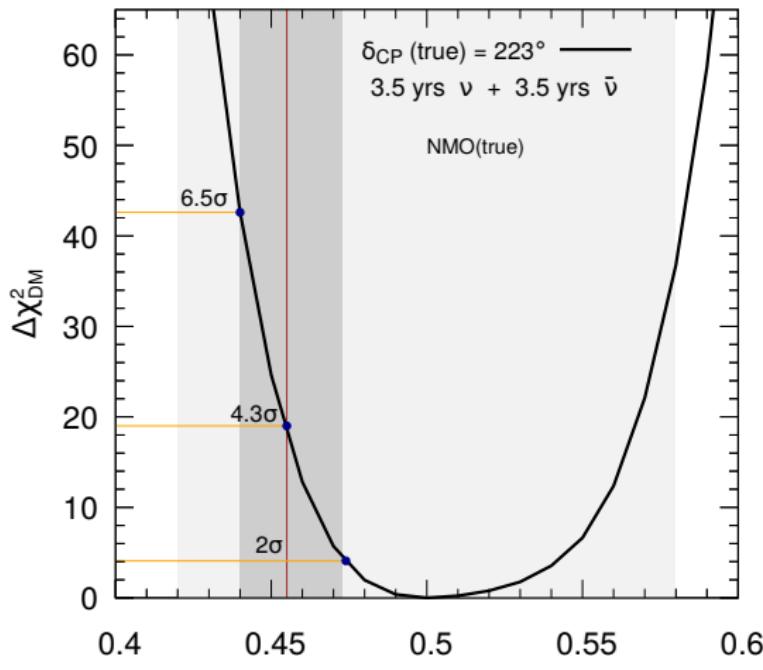


- Ratio of ν disappearance events in each energy bin as a function of reconstructed E_ν assuming 3.5 years of ν run in DUNE.
- N : events for $(\Delta m_{31}^2 = 2.522 \times 10^{-3} \text{ eV}^2, \sin^2 \theta_{23} = 0.455)$,
- N_1 : $(\Delta m_{31}^2 = 2.436 \times 10^{-3} \text{ eV}^2, \sin^2 \theta_{23} = 0.5)$,
- N_2 : $(\Delta m_{31}^2 = 2.522 \times 10^{-3} \text{ eV}^2, \sin^2 \theta_{23} = 0.5)$,
- N_3 : $(\Delta m_{31}^2 = 2.605 \times 10^{-3} \text{ eV}^2, \sin^2 \theta_{23} = 0.5)$.
- Curves behave oppositely on the either side of $P_{\nu_\mu \nu_\mu}$ osc. minima ($E = 2.5 \text{ GeV}$)
- Converging for lower E_ν (sensitivity to deviation from MM lower), diverging for higher E_ν (sensitivity to deviation from MM higher).
- Spectral informations expected to break $(\Delta m_{31}^2 - \sin^2 \theta_{23})$ degeneracy.

Deviation from maximality

$$\Delta\chi^2_{\text{DM}} = \min_{(\lambda, \kappa_s, \kappa_b)} \left\{ \chi^2 (\sin^2 \theta_{23}^{\text{true}} \in [0.4, 0.6]) - \chi^2 (\sin^2 \theta_{23}^{\text{test}} = 0.5) \right\}$$

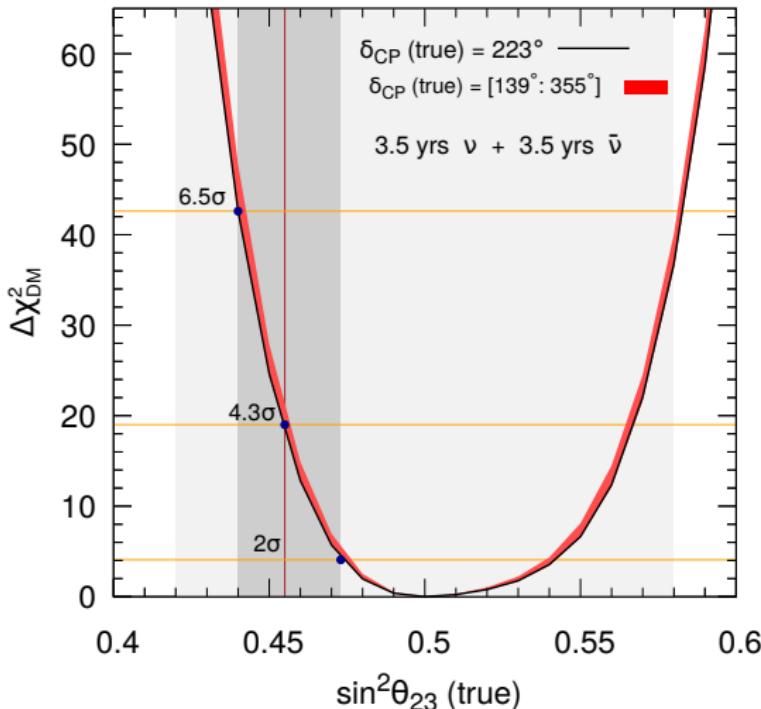
where $\lambda = \delta_{\text{CP}} \in [139^\circ : 355^\circ]$, $\Delta m_{31}^2 \in [2.436 : 2.605] \times 10^{-3}$ and κ_s and κ_b are the pull parameters on signal and background, respectively



- Following present best-fit, DUNE establishes deviation from MM at 4.3σ C.L. for $[3.5\nu + 3.5\bar{\nu}]$ yrs, assuming NMO.
- Total P.O.T of 1.1×10^{21} per year

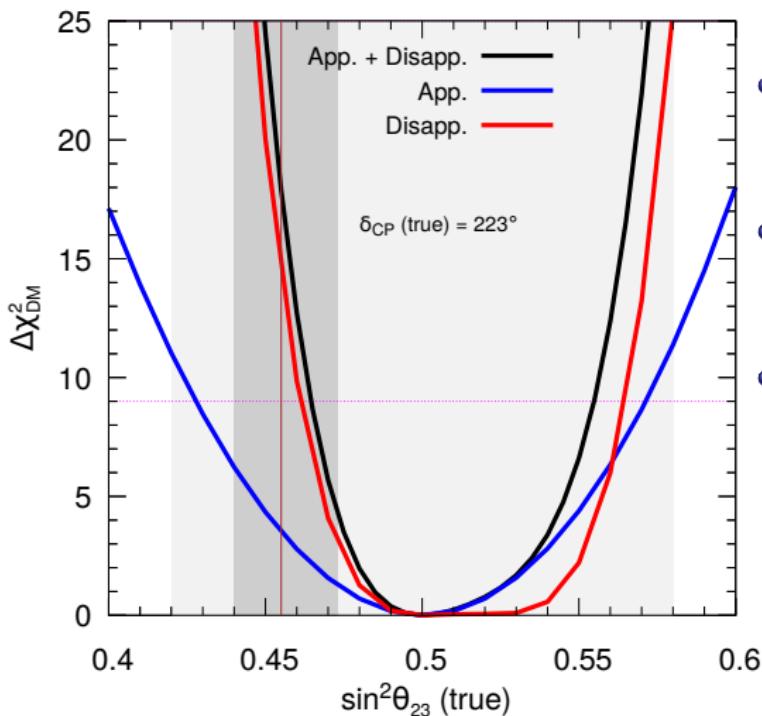
Deviation from maximality

$$\Delta\chi^2_{\text{DM}} = \min_{(\lambda, \kappa_s, \kappa_b)} \left\{ \chi^2 (\sin^2 \theta_{23}^{\text{true}} \in [0.4, 0.6]) - \chi^2 (\sin^2 \theta_{23}^{\text{test}} = 0.5) \right\}$$



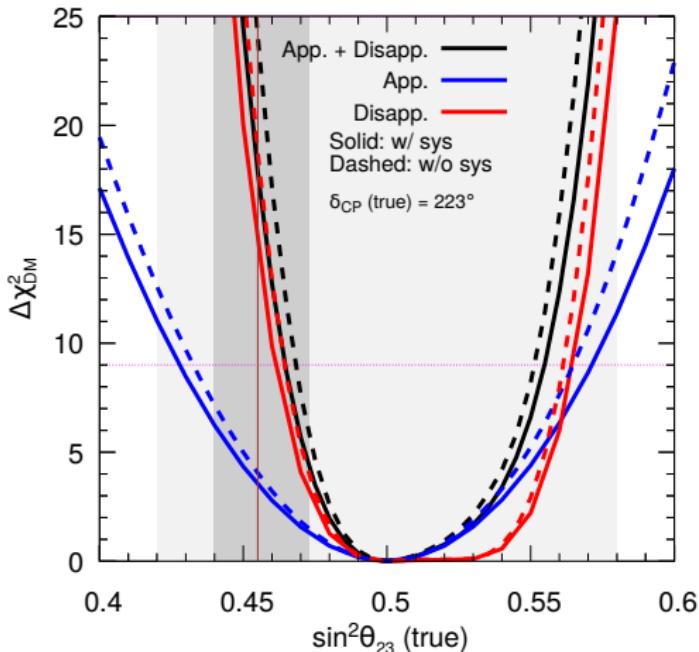
- Following present best-fit, DUNE establishes deviation from MM at 4.3σ C.L. for $[3.5\nu + 3.5\bar{\nu}]$ yrs, assuming NMO.
- Total P.O.T of 1.1×10^{21} per year
- Uncertainty in δ_{CP} does not affect our results (red filled curves).

Effect of App. and Disapp.



- Contribution of App. and Disapp. in establishing deviation from maximality
- Disapp. contribution dominates for most of the region in $\sin^2\theta_{23}$
- App. dominates for $\sin^2\theta_{23}$ (true) = [0.5 : 0.56]

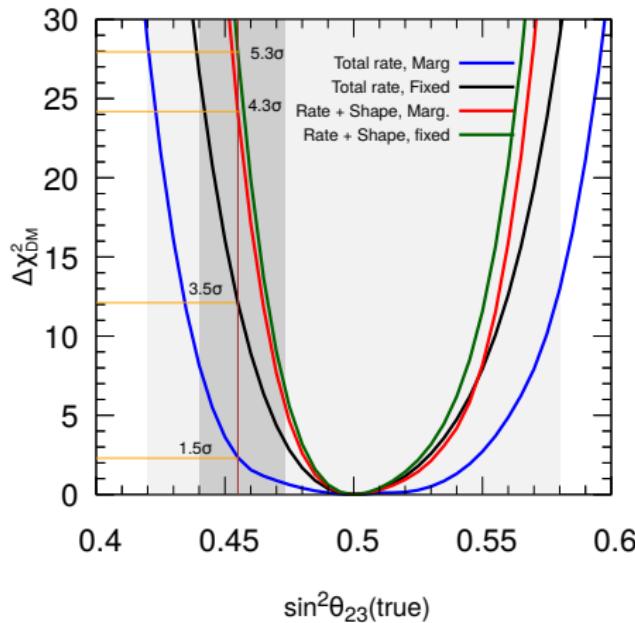
Effect of Systematics



- Both App. and Disapp. are affected under nominal systematic uncertainties: 2% in App, 5% in Disapp.
- Not much effect on Disapp. from the table below.

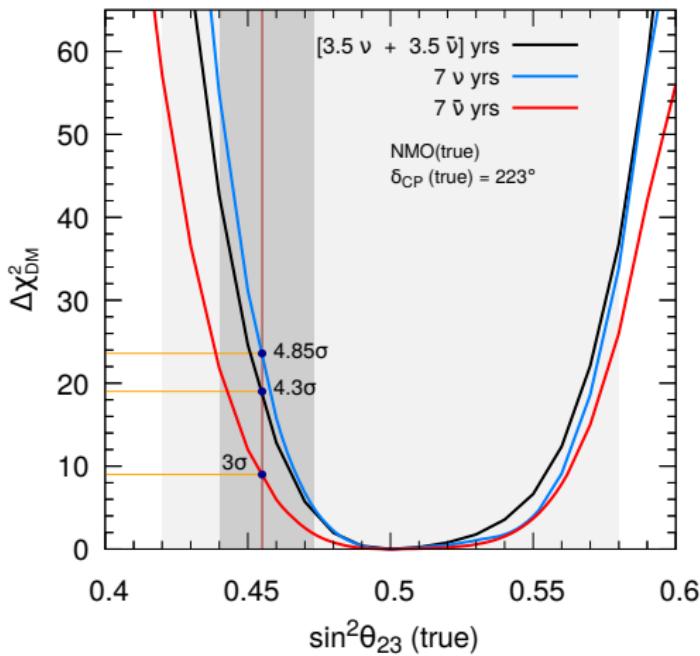
$\Delta\chi^2_{DM}$ for $\sin^2 \theta_{23}$ (true)	Channels	2%, 5%	5%, 5%	10%, 10%
0.455	App.	3.5	2.3	1
	Disapp.	14.3	14.3	14.1
	App. + Disapp.	17.6	16.8	15.4
0.473	App.	1.2	0.8	0.3
	Disapp.	2.9	2.9	2.9
	App. + Disapp.	4.2	3.8	3.4

Spectral Analyses and Marginalization



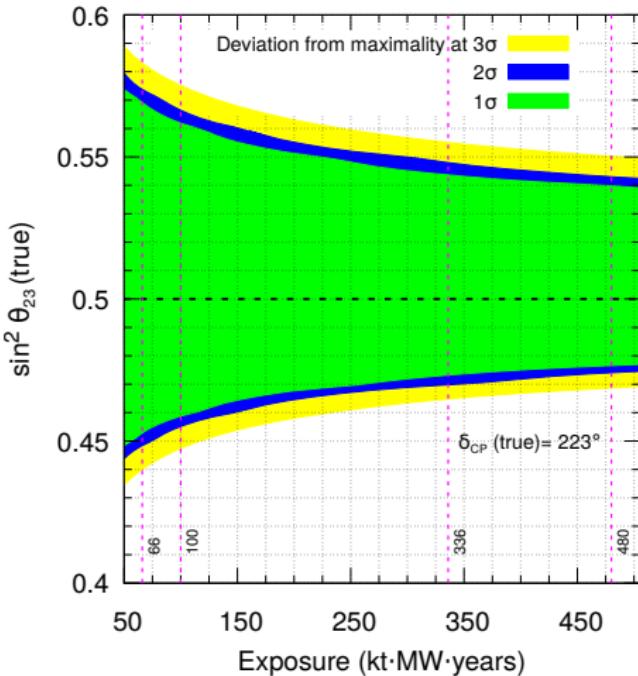
- At Rate level, effect of marginalization over Δm_{31}^2 is much more visible than in Rate + Shape.
- Adding spectral information reduces effect of Δm_{31}^2 uncertainty.
- Rate + Shape improves sensitivity in $\Delta\chi^2_{DM}$ manifold.

Impact of ν and $\bar{\nu}$ modes

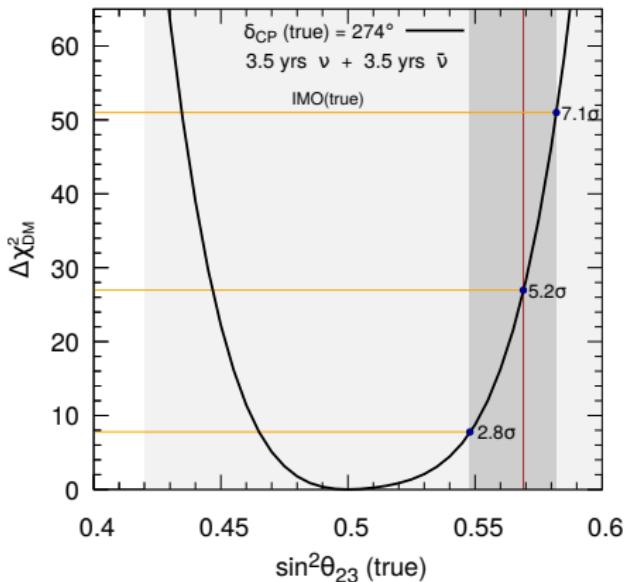
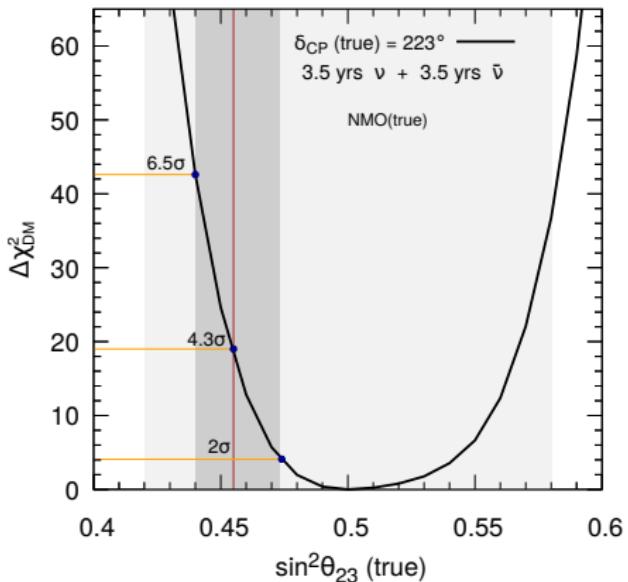


- Only ν run for 7 years achieve better sensitivity towards $\Delta\chi^2_{DM}$ if in Nature $\sin^2\theta_{23}$ is in LO.
- Balanced run: $[3.5 \nu + 3.5 \bar{\nu}]$ achieves better sensitivity for almost all the $\sin^2\theta_{23}$ in Nature
- Only $\bar{\nu}$ run establishes least sensitivity

Effect of Exposure



- Benchmark exposure - 336 kt·MW·years
- After 336 kt·MW·years, $\Delta\chi^2_{\text{DM}}$ marginally increases, suggests NOT statistics limited afterwards.

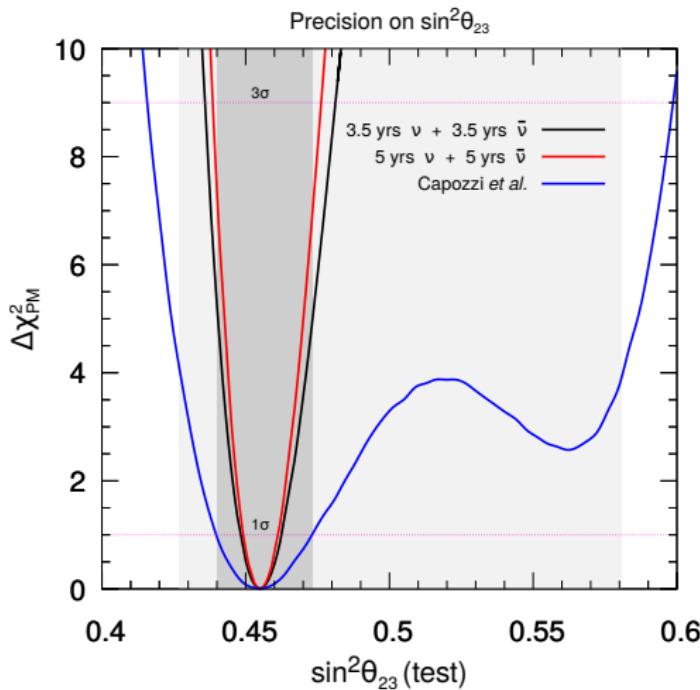


- Best-fit values are taken from [Phys.Rev.D 104 \(2021\) 8, 083031](#)
- IMO (true) has better sensitivity than NMO (true) for the current best-fit scenario.

Precision in $\sin^2 \theta_{23}$

$$\Delta\chi^2_{\text{PM}} = \min_{(\lambda, \kappa_s, \kappa_b)} \{ \chi^2 (\sin^2 \theta_{23}^{\text{true}} = 0.455) - \chi^2 (\sin^2 \theta_{23}^{\text{test}} \in [0.41 : 0.59]) \} \quad \text{where}$$

$\lambda = \delta_{\text{CP}} \in [139^\circ : 355^\circ]$ and κ_s and κ_b are the pull parameters on signal and background, respectively



- Relative 1σ precision from Phys.Rev.D 104 (2021) 8, 083031 (blue colored curve) is 6.72%
- Relative 1σ precision around $\sin^2 \theta_{23} = 0.455$ is 1.53% for $[3.5 \nu + 3.5 \bar{\nu}]$.
- Precision increases to 1.3% for $[5 \nu + 5 \bar{\nu}]$

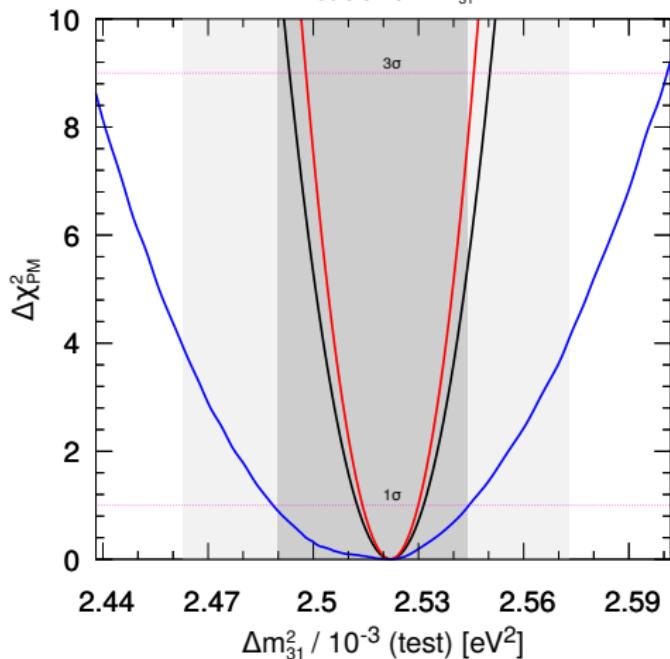
Precision in Δm_{31}^2

$$\Delta\chi_{\text{PM}}^2 =$$

$$\min_{(\vec{\lambda}, \kappa_s, \kappa_b)} \left\{ \chi^2 (\sin^2 \theta_{23}^{\text{true}} = 2.522 \times 10^{-3}) - \chi^2 (\sin^2 \theta_{23}^{\text{test}} \in [2.436 : 2.605] \times 10^{-3}) \right\}$$

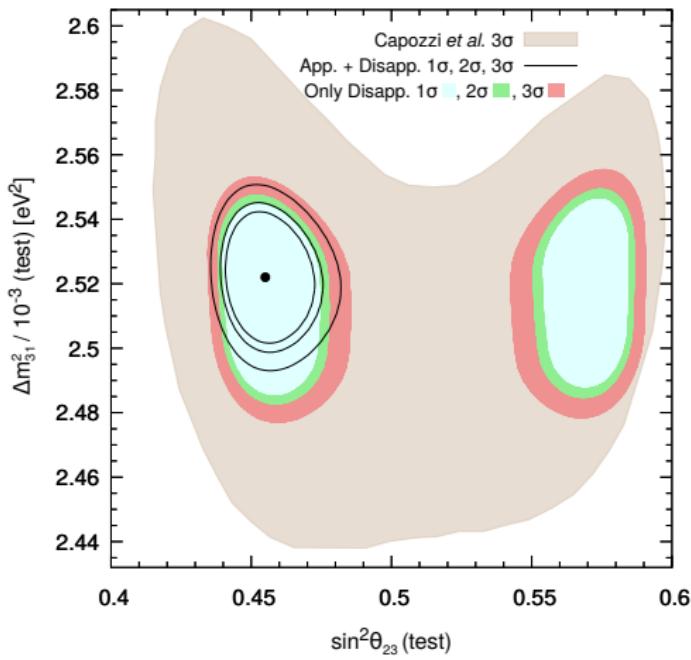
where $\lambda = \delta_{\text{CP}} \in [139^\circ : 355^\circ]$ and κ_s and κ_b are the pull parameters on signal and background, respectively

Precision on Δm_{31}^2



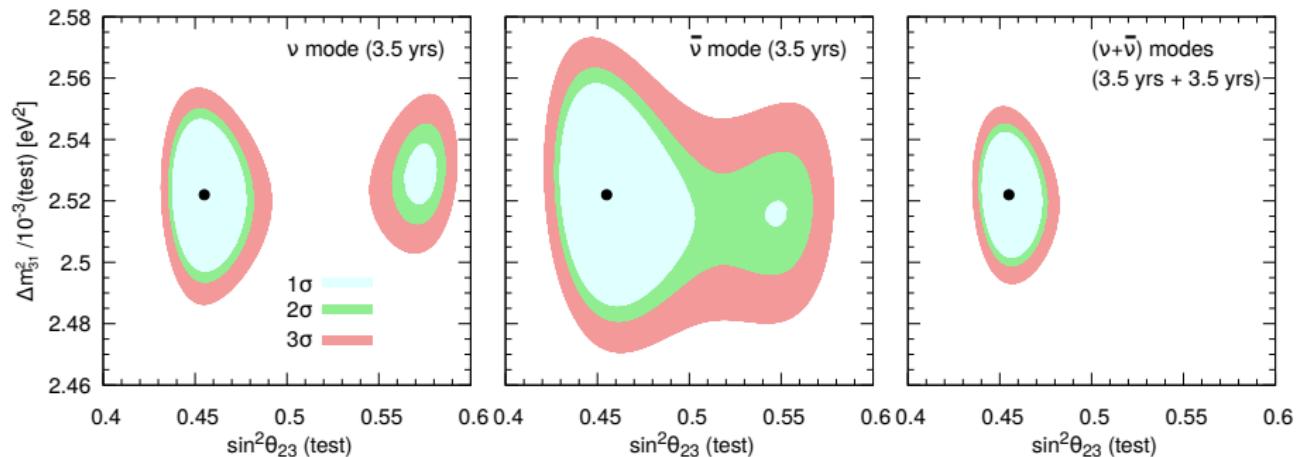
- Relative 1σ precision from Phys.Rev.D 104 (2021) 8, 083031 (blue colored curve) is 1.09%
- Relative 1σ precision around $\Delta m_{31}^2 = 2.522 \times 10^{-3}$ is 0.39% for $[3.5 \nu + 3.5 \bar{\nu}]$.
- Precision increases to 0.31% for $[5 \nu + 5 \bar{\nu}]$
- Relative 1σ precision from JUNO is 0.5% Talk by M.Gonchar in EPS-HEP 2021

Effect of channels



- Capozzi *et.al.* is taken from Phys.Rev.D 104 (2021) 8, 083031
- Leading term in $\text{disapp.} \propto \sin^2 2\theta_{23}$, helps in constraining θ_{23} in both octants
- Leading term in $\text{app.} \propto \sin^2 \theta_{23}$, helps in resolving octant degeneracy
- Complementarity between app. + disapp. rules out wrong octant solutions
- App. + Disapp. improves precision in both $\sin^2 \theta_{23}$ and Δm_{31}^2

Contribution from ν and $\bar{\nu}$ modes



- Data from both ν and $\bar{\nu}$ is necessary in ruling out wrong octant solutions and better precision measurements in both $\sin^2 \theta_{23}$ and Δm_{31}^2 .

Key Takeaways

- With current best-fit parameters DUNE ($3.5 \nu + 3.5 \bar{\nu}$) can establish deviation from maximality at 4.3σ (5.2σ) C.L. assuming true NMO (IMO)
- A 3σ $\Delta\chi^2_{\text{DM}}$ with exposure of $336 \text{ kt}\cdot\text{MW}\cdot\text{years}$ in DUNE is possible if $\sin^2 \theta_{23} \leq 0.465$ and $\sin^2 \theta_{23} \geq 0.554$ in Nature, irrespective of δ_{CP} assuming true NMO.
- Spectral informations are necessary to resolve $(\Delta m^2_{31} - \sin^2 \theta_{23})$ degeneracy
- Disappearance dominates in $\Delta\chi^2_{\text{DM}}$ sensitivity
- High $\Delta\chi^2_{\text{PM}}$ in $\sin^2 \theta_{23}$ and Δm^2_{31} necessitates –
 - both ν and $\bar{\nu}$ run
 - both app. + disapp. channels