DUNE and T2HK Complementarity: Unlocking Enhanced CP Violation Insights

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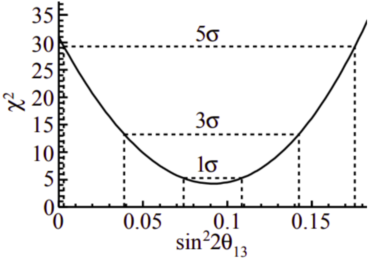
Motivation

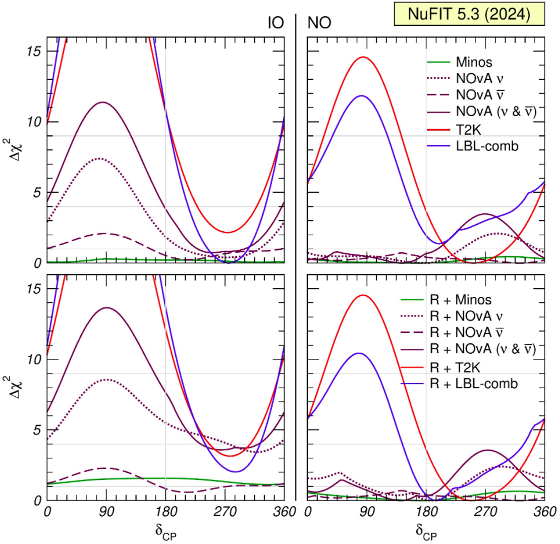


Phys.Rev.Lett. 108 (2012) 171803; Daya Bay Collaboration

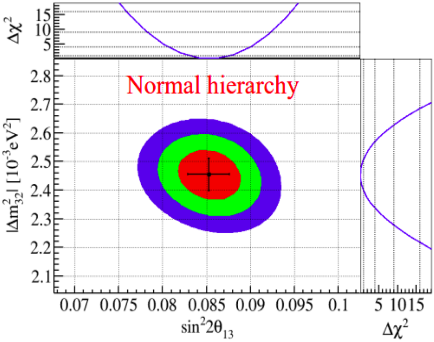
- Discovery of non-zero θ_{13} by Daya Bay led to independent source of CP violation (current precision: 2.8%)
- $J_{\rm CP} = \frac{1}{8}\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\delta_{\rm CP}$; where $J_{\rm CP}$ is Jarlskog Invariant (invariant under change of basis).
- Conditions for observing CPV-
  - non-degenerate masses
  - mixing angles $\neq 0^\circ$ & 90°
  - $\delta_{\rm CP} \neq 0^\circ$ & 180°

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4J_{CP} \times \left[\sin\left(\frac{\Delta m^2_{21}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E}L\right)\right]$$

Present Scenario



- Combined LBL disfavors π at $\sim 1\sigma\,(3\sigma)$ assuming NO (IO)
- Stronger signature towards CP violation in IO than NO in Nature



- Daya Bay has already achieved unprecedented precision in θ_{13}

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

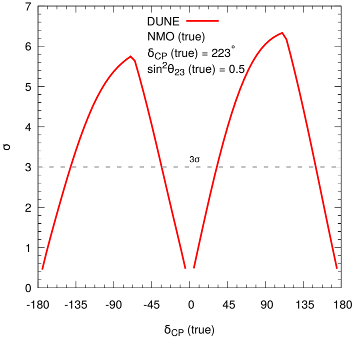
Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

(2.3% precision)

Kam-Biu Luk, Neutrino2022

This talk explores the effect of current uncertainty in θ_{23} in achieving the maximum possible CP coverage in δ_{CP} with DUNE and T2HK.

CP Coverage and CP Asymmetry



CP coverage denotes the values of true $\delta_{\rm CP}$ (expressed in %) in its entire range of $[-180^\circ, 180^\circ]$, for which leptonic CP violation can be established at $\geq 3\sigma$ C.L.

$$\text{Intrinsic CP Asymmetry } \mathcal{A}_{CP}^{\mu e} = \frac{P_{\nu_\mu \to \nu_e} - \bar{P}_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e} + \bar{P}_{\bar{\nu}_\mu \to \bar{\nu}_e}}$$

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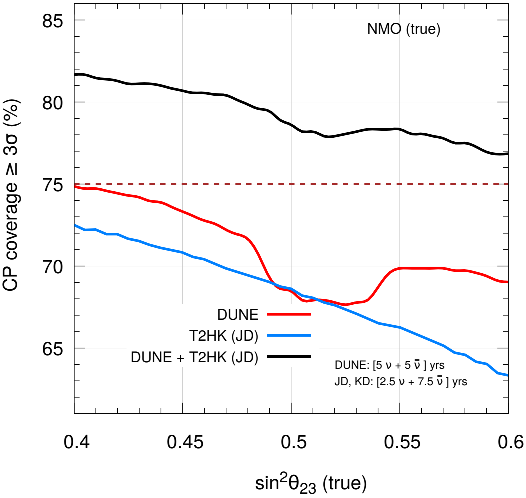
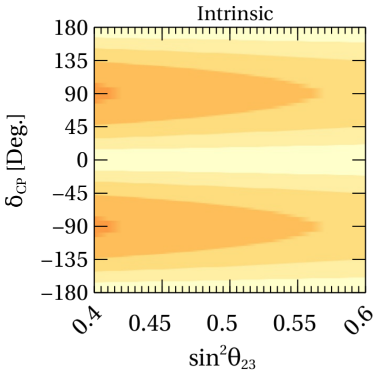
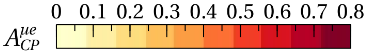


- DUNE: 480 kt·MW·years of exposure, $L = 1285$ km, $\rho_{\rm avg} = 2.848$ g/cm^3, P.O.T. of 1.1 $\times 10^{21}$ per year.
- T2HK (T2HKK): 2431 kt·MW·years of exposure, $L =$ 295 (1100) km, $\rho_{\rm avg} = 2.8$ g/cm^3, P.O.T. of 2.7 $\times 10^{22}$ per year.
- DUNE + T2HK is must to achieve leptonic CP violation at 3σ for at least 75% choices of $\delta_{\rm CP}$ irrespective of the values of θ_{23}.

$$\Delta\chi^2 = \min_{(\delta_{\rm CP}^{\rm test},\, \theta_{23})} \left[\chi^2(\delta_{\rm CP}^{\rm test} = 0^\circ \text{ and } 180^\circ) - \chi^2(\delta_{\rm CP}^{\rm true})\right]$$

Intrinsic (Genuine) CP Asymmetry





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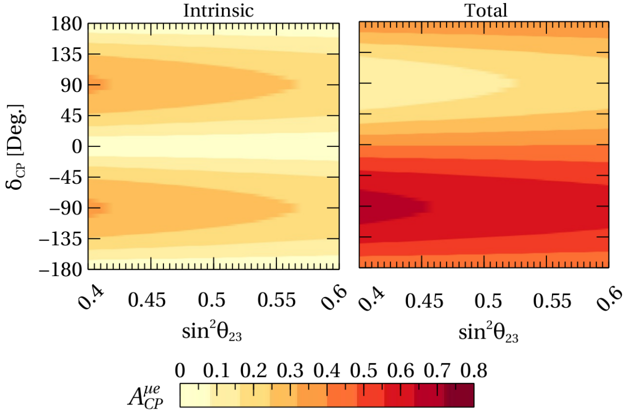
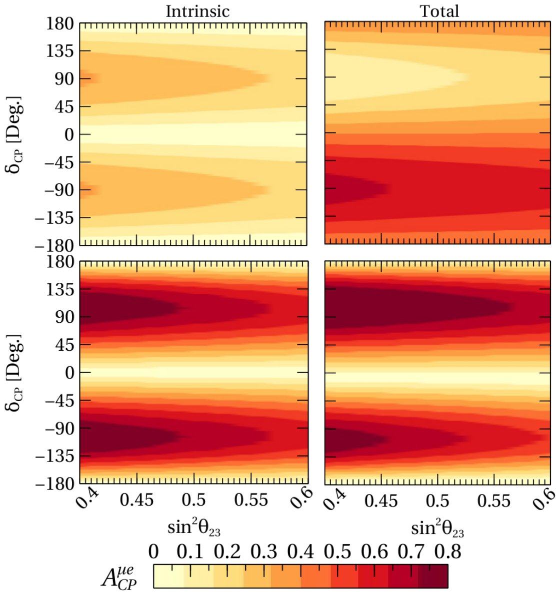
- CP asymmetry in vacuum in DUNE for first oscillation maximum ($E = 2.5$ GeV).
- $\mathcal{A}^{\mu e}_{CP} = \dfrac{P_{\nu_\mu \to \nu_e} - \bar{P}_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e} + \bar{P}_{\bar{\nu}_\mu \to \bar{\nu}_e}}$
- CP asymmetry decreases with increasing value of θ_{23}

Intrinsic (Genuine) and Total CP Asymmetry



- CP asymmetry in vacuum (left) and in presence of matter (right) in DUNE for first oscillation maxima ($E = 2.5$ GeV).
- Due to Earth matter potential, extrinsic or fake CP asymmetry induces.
- CP asymmetry decreases with increasing value of θ_{23}



- CP asymmetry in vacuum (left) and matter (right) in DUNE for first (top, $E = 2.5$ GeV) and second (bottom, $E = 0.8$ GeV) oscillation maxima.
- Vacuum CP asymmetry is three times larger in $\Delta = 3\pi/2$ (second osc. maxima)
- At second osc. max. the size of the $\delta-$dependent interference term is a factor of ~ 3 larger than that at the first osc. max.
- CP asymmetry decreases with increasing value of θ_{23}

Intrinsic and Total CP Asymmetry

$$\mathcal{A}_{\rm CP}^{\mu e} = [\mathcal{A}_{\rm CP}^{\mu e}]_{\rm vac} + \hat{A}[\mathcal{A}_{\rm CP}^{\mu e}]_{\rm mat} + \mathcal{O}(\hat{A}^2) \quad (1)$$

Fix $\sin\theta_{13} \sim 1/7$ and $\sin\theta_{12} \sim 1/\sqrt{3}$ and expand in $\hat{A}$ up to the first order. So,

$$[\mathcal{A}_{\rm CP}^{\mu e}]_{\rm vac} = \frac{-28\alpha\Delta\cos\theta_{23}\sin\delta_{\rm CP}\sin\Delta}{3\sqrt{2}\sin\theta_{23}\sin\Delta + 28\alpha\Delta\cos\theta_{23}\cos\delta_{\rm CP}\cos\Delta} \quad (2)$$

$$[\mathcal{A}_{\rm CP}^{\mu e}]_{\rm mat} = -\sin^2\theta_{23}(\Delta\cos\Delta - \sin\Delta)\frac{126\alpha\Delta\cos\theta_{23}\cos\delta_{\rm CP}\cos\Delta + 18\sin^2\theta_{23}\sin\Delta}{(3\sin^2\theta_{23}\sin\Delta + 7\sqrt{2}\alpha\cos\delta_{\rm CP}\cos\Delta\sin^2(2\theta_{23}))^2} \quad (3)$$

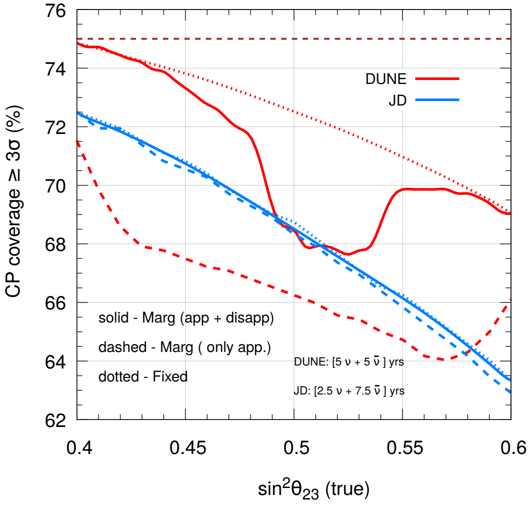
As θ_{23} decreases $\Longrightarrow$ denominator increases $\Longrightarrow$ $\mathcal{A}_{\rm CP}^{\mu e}$ becomes smaller $\Longrightarrow$ less CPV sensitivity

At first oscillation maximum, $(\Delta = 3\pi/2)$

$$\mathcal{A}_{\rm CP}^{\mu e} \approx -\frac{7}{3}\alpha\sqrt{2}\pi\cot\theta_{23}\sin\delta_{\rm CP} + 2\hat{A}\,, \quad (4)$$

where $\mathcal{A}_{\rm CP}^{\mu e}$ decreases as θ_{23} increases

- Why in DUNE there is a deterioration in CP coverage around $\sin^2\theta_{23} = 0.5$?



- fixed-parameter case does not have any $\theta_{23} - \delta_{\rm CP}$ degeneracy, so no deterioration.
- Marginalization over uncertainty in θ_{23} leads to $\theta_{23} - \delta_{\rm CP}$ degeneracy in DUNE due to considerable matter effect.
- Disappearance channel is crucial in DUNE.
- In T2HK, negligible matter effect ensures **no** $\theta_{23} - \delta_{\rm CP}$ degeneracy.

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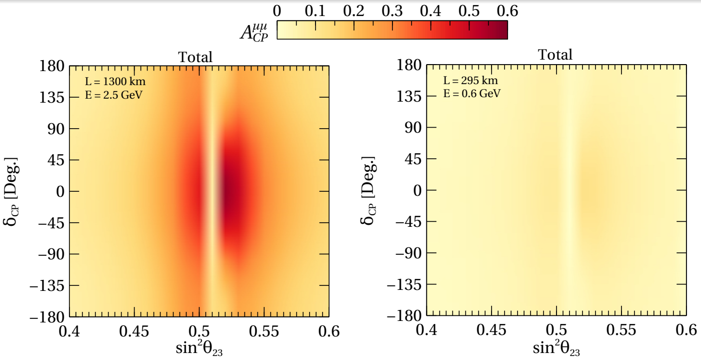

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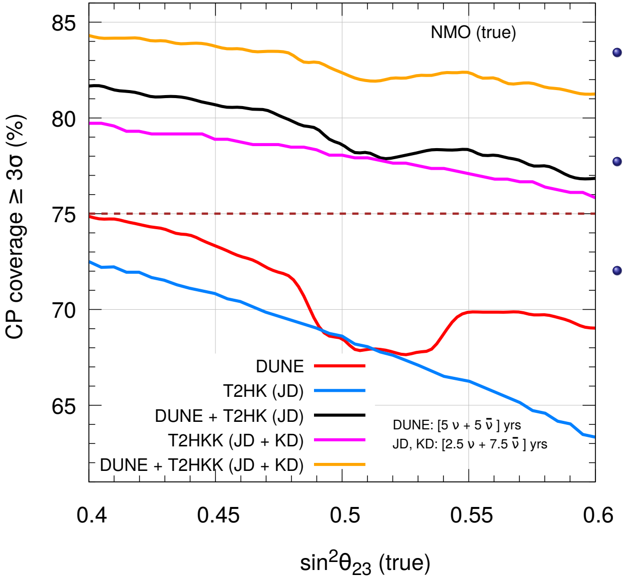
- $\mathcal{A}_{CP}^{\mu\mu} = \dfrac{P_{\nu_\mu\to\nu_\mu} - \bar{P}_{\bar{\nu}_\mu\to\bar{\nu}_\mu}}{P_{\nu_\mu\to\nu_\mu} + \bar{P}_{\bar{\nu}_\mu\to\bar{\nu}_\mu}} \Rightarrow \mathcal{A}_{\mathrm{CP}}^{\mu\mu} \approx \hat{A}\,\frac{24\sin^2\theta_{23}+7\sqrt{2}(\pi^2-4)\alpha\cos\delta_{\mathrm{CP}}\sin 2\theta_{23}}{6+141\cos 2\theta_{23}}$
- $\mathcal{A}_{CP}^{\mu\mu}$ increases, with increasing θ_{23}, until expansion breaks at $\cos 2\theta_{23} =$ - 6/141.
- Earth matter potential (V_{CC}) interacts oppositely with ν and $\bar{\nu}$ leading to fake CP asymmetry.
- Disapp. is able to fix θ_{23} in δ_{CP} independent manner far from $\sin^2\theta_{23} = 0.5$.
- Around $\sin^2\theta_{23} = 0.5$, disapp. faces $(\theta_{23} - \delta_{\mathrm{CP}})$ degeneracy.



- DUNE faces $\theta_{23} - \delta_{\mathrm{CP}}$) degeneracy; T2HK has high appearance systematic uncertainties (5%).
- **DUNE + T2HK is must to achieve leptonic CP violation at 3σ for at least 75% choices of $\delta_{\mathbf{CP}}$.**
- Lower appearance systematic uncertainties in DUNE (2%) and negligible matter effect in T2HK complements each other in achieving better CP coverage.

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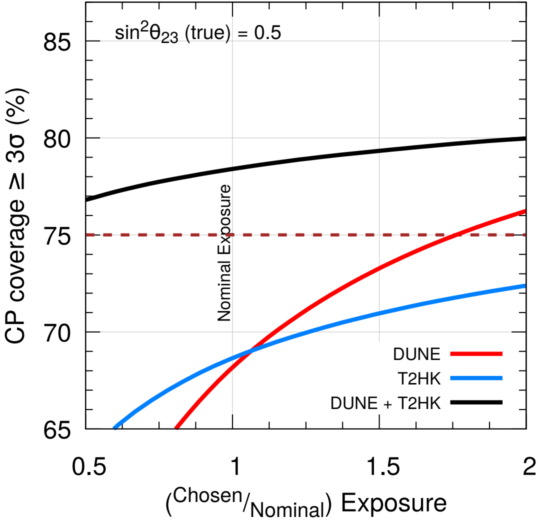
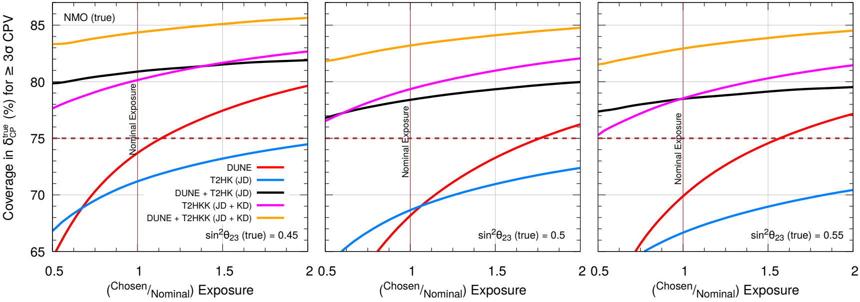


- **DUNE + T2HK can achieve more than 75% CP coverage even with half of their individual exposures.**

CP Coverage as a function of Exposure



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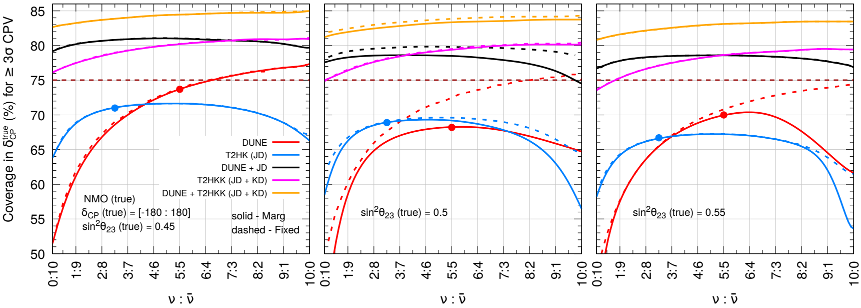
DUNE + T2HK can achieve more than 75% CP coverage even with half of their individual exposures in all the three scenarios.

CP Coverage as a function of Runtime



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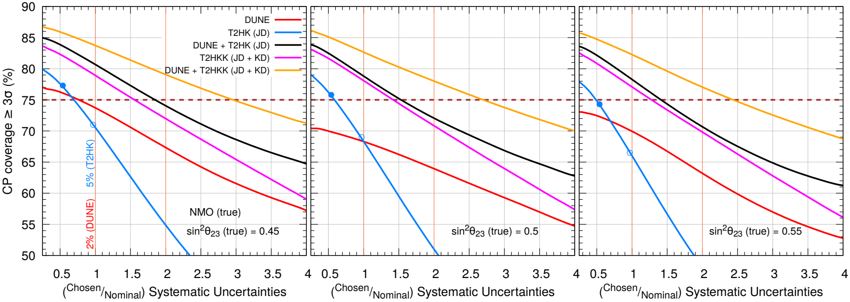
- LO
  - T2HK - choice of [2.5ν, $7.5\bar{\nu}$] is best
  - DUNE - only ν mode works best. $\delta_{\rm CP}$ independent measurements of $\sin^2\theta_{23}$ by disapp.
- MM
  - T2HK - choice of [2.5ν, $7.5\bar{\nu}$] is best
  - DUNE - Balanced runtime necessary as disapp. doesn't help
- HO
  - T2HK - choice of [2.5ν, $7.5\bar{\nu}$] is best
  - DUNE - [6.5ν, $3.5\bar{\nu}$] is best; disapp. helps but not sufficient

CP Coverage as a function of Systematics



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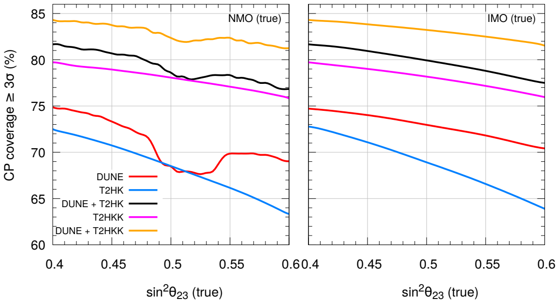
- Given improved appearance systematic uncertainties in T2HK (2.7%), T2HK outperforms DUNE (2%) in all the three scenarios.
- If in Nature, both experiments end up achieving $\sim$ 1.5 times higher app. syst. uncert. then DUNE + T2HK remains the only solution to achieve 75% of CP coverage.

Key Takeaways

- **Complementarity in DUNE + T2HK can achieve 75% CP coverage, irrespective of mass ordering and θ_{23} in Nature.**
- **DUNE + T2HK can achieve 75% CP coverage even with half of their individual exposures.**
- In DUNE, $(\theta_{23} - \delta_{\mathrm{CP}})$ degeneracy is responsible for lowering the sensitivity, because of large matter effect.
- In T2HK, higher appearance systematic uncertainties leads to lowering of sensitivity.
- Better appearance systematic uncertainties and wide-band in DUNE; low matter effect and better measurement of intrinsic CP phase in T2HK – plays a complementary role in establishing better CP coverage in DUNE + T2HK.

Backup-1



- Under IMO (true), in DUNE, no specific deterioration in sensitivity around $\sin^2\theta_{23} = 0.5$.

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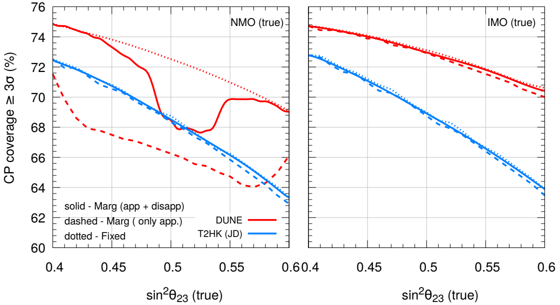
Backup-2



- Mild $(\theta_{23} - \delta_{\mathrm{CP}})$ degeneracy under IMO assumption.
- Appearance event rates are sufficient enough to establish CP violation at a good C.L.

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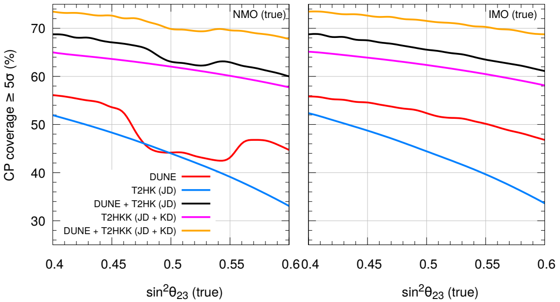
Backup-3



- Projected 5σ discovery of CP violation is achievable for $\sim$ 60% CP phase, irrespective of the MO, octant of θ_{23}, under DUNE + T2HK.

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