Unmatched Precision on Neutrino Oscillation Parameters using Complementarity between DUNE and T2HK

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Three-Flavor Neutrino Oscillation Framework: Simple & Robust

It happens because flavor (weak) eigenstates do not coincide with mass eigenstates

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} : $P(\nu_\mu \to \nu_\mu)$ by Atoms. ν and ν beam

θ_{13}: $P(\nu_e \to \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \to \nu_e)$ by Reactor and solar ν

$L/E = 500$ km/GeV $\qquad$ $L/E = 15,000$ km/GeV

$\Delta m^2_{31} \sim 2.5 \times 10^{-3}$ eV^2 $\qquad$ $P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m^2_{ij}\frac{L}{E}\right)$ $\qquad$ $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2

Three mixing angles: $\theta_{23}, \theta_{13}, \theta_{12}$ and one CP-violating (Dirac) phase δ_{CP}

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13}e^{-i\delta}$$

3 mixing angles simply related to flavor components of 3 mass eigenstates

Over a distance L, changes in the relative phases of the mass states may induce flavor change

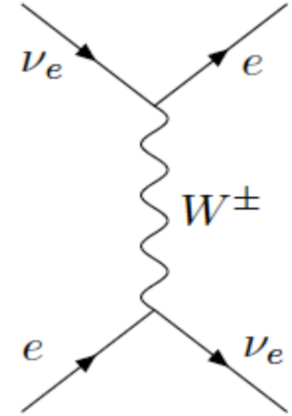
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij}.$$

$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$

$\Delta m^2_{ij} = m^2_i - m^2_j$

for antineutrinos replace δ_{CP} by $-\delta_{CP}$

Neutrino Oscillations in Matter: MSW Effect



Neutrino propagation through matter modify the oscillations significantly

Coherent forward scattering of neutrinos with matter particles

Charged current interaction of ν_e with electrons creates an extra potential for ν_e

MSW matter term: $A = \pm 2\sqrt{2} G_F N_e E$ or $A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho\ (\mathrm{g/cc}) E(\mathrm{GeV})$

N_e = electron number density , + (-) for neutrinos (antineutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino to antineutrino

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ → **even if $\delta_{CP} = 0$, causes fake CP asymmetry**

Matter term modifies oscillation probability differently depending on the sign of Δm^2

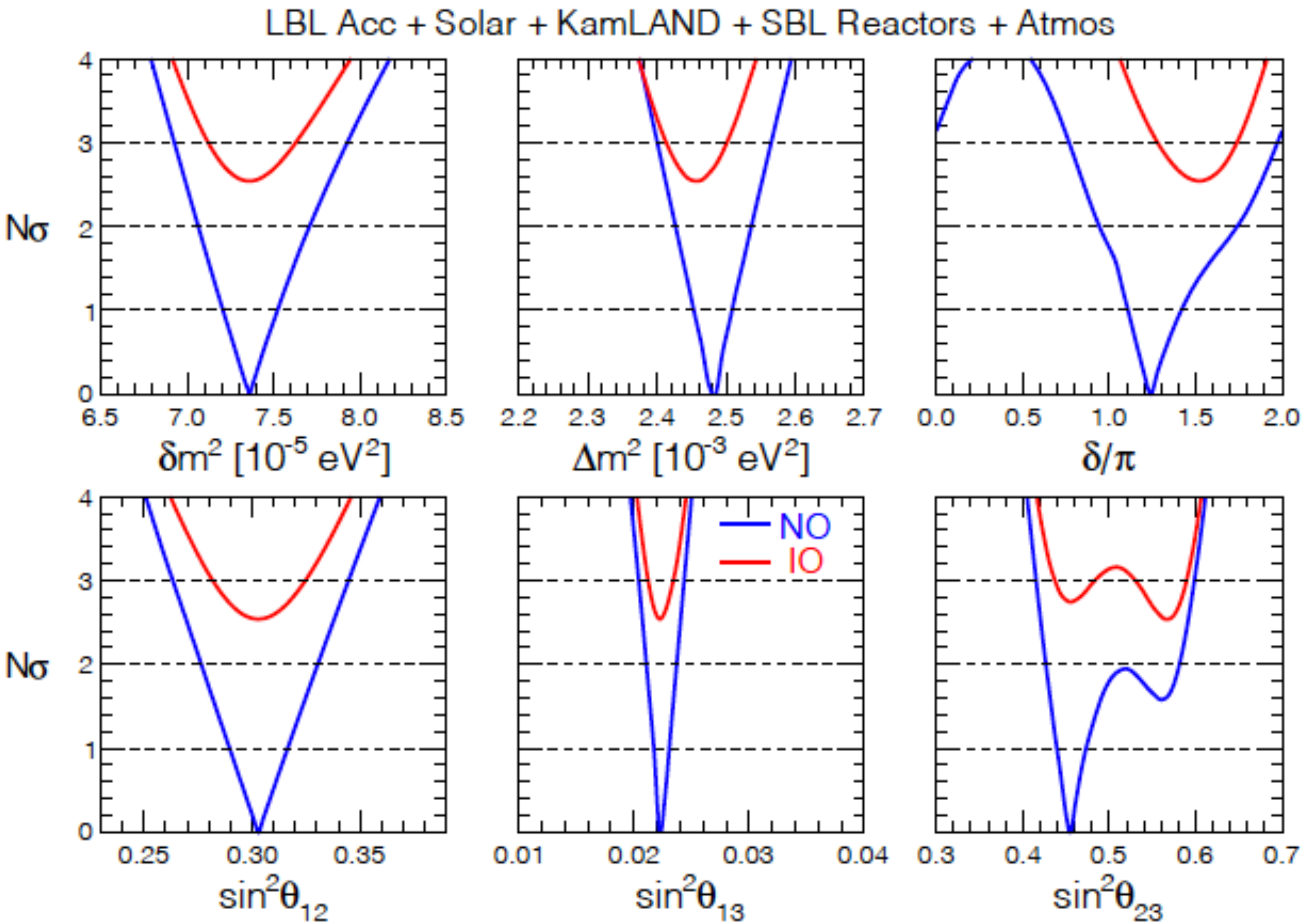
$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\rm res}^{\rm Earth} = 6 - 8\,\mathrm{GeV}$ → **Resonant conversion – Matter effect**

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ **Resonance occurs for neutrinos (antineutrinos) if Δm^2 is positive (negative)**

Global Fit of Neutrino Oscillation Parameters Circa 2022

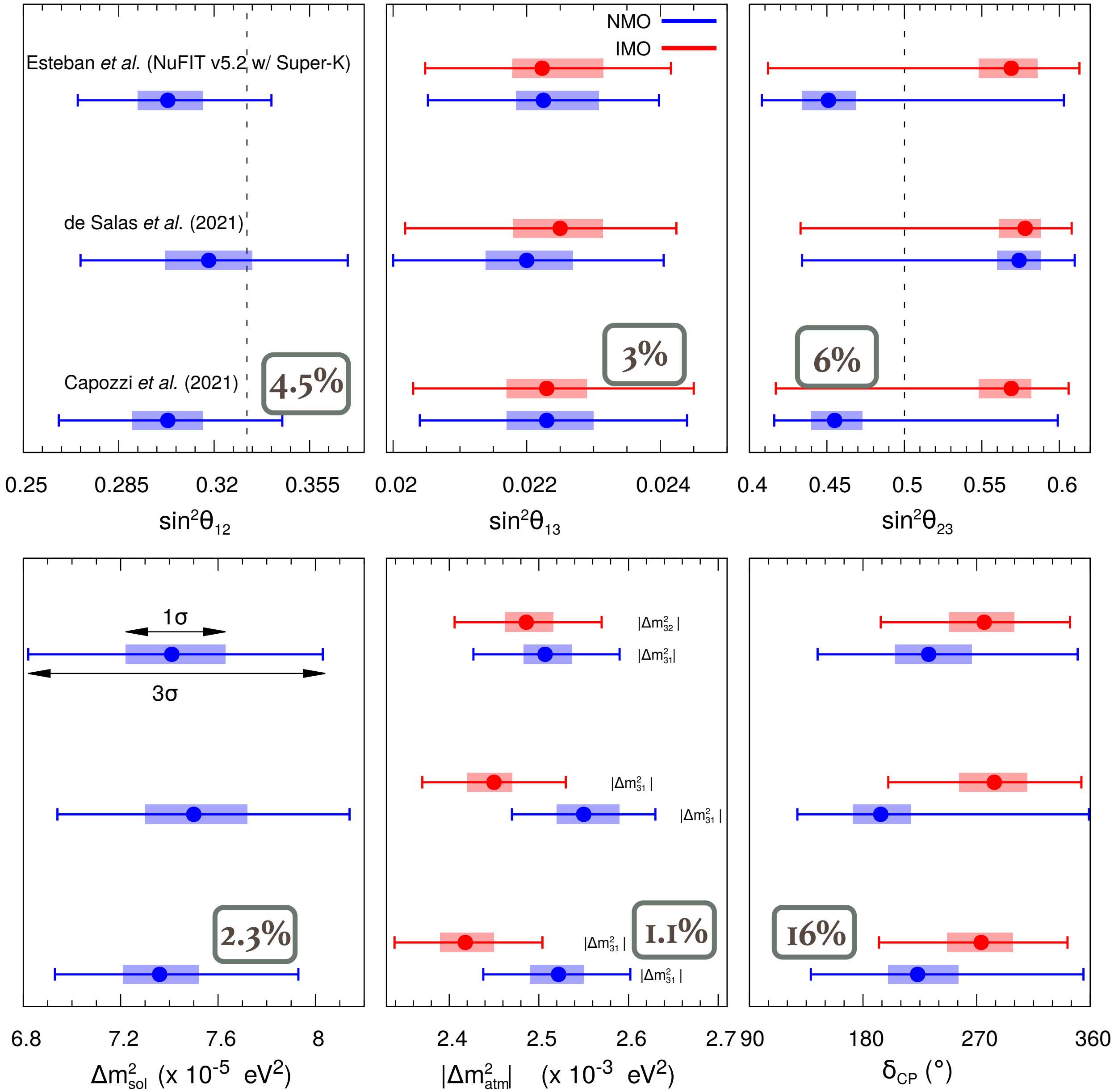
Preference for Normal Mass Ordering (~ 2.5σ), θ_{23} < 45 degree and sin$\boldsymbol{\delta}$ < 0 (both at 90% C.L.)



Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

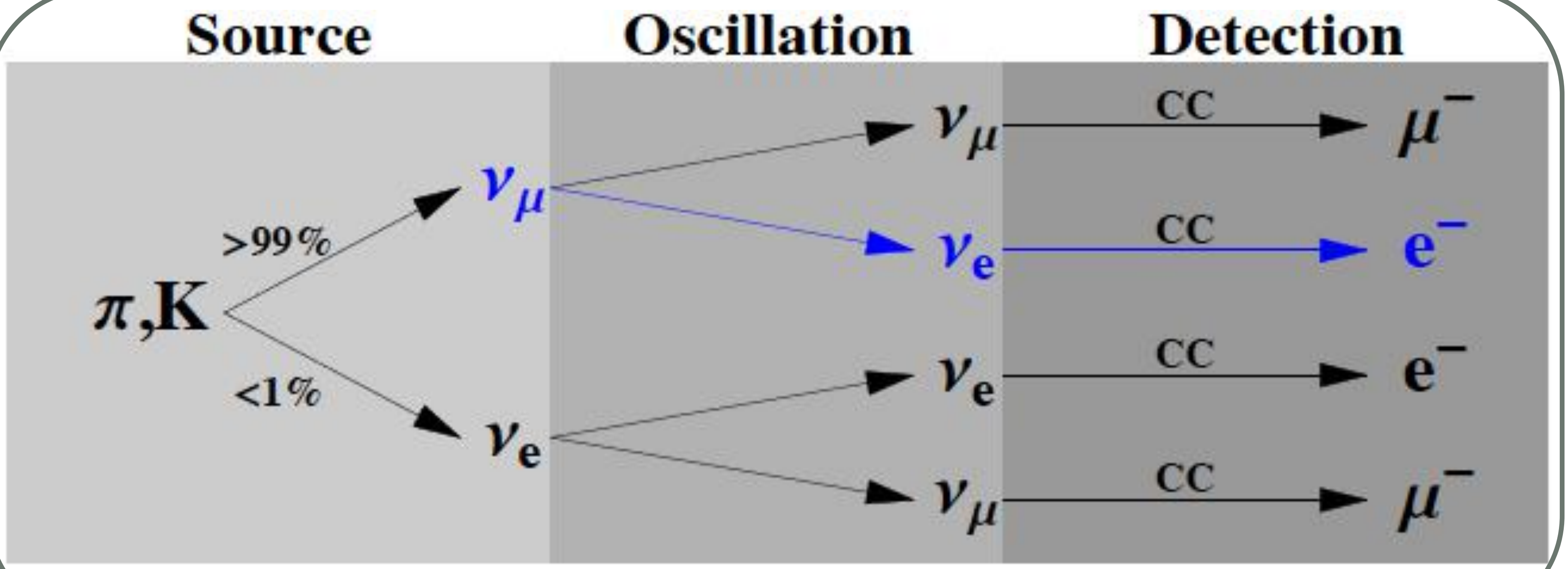
Remarkable Precision on Neutrino Oscillation Parameters

Robust three-flavor neutrino oscillation paradigm



Huge boost for the discovery of NMO, CPV, and θ_{23} Octant

Agarwalla, Kundu, Prakash, Singh, JHEP 03 (2022) 206



Traditional approach: Neutrino beam from pion decay

Three-Flavor Effects in $\nu_\mu \to \nu_e$ Oscillation Channel

The appearance probability $(\nu_\mu \to \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ (0.03) and $\sin 2\theta_{13}$ (0.3),

$$P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

→ θ_{13} driven ($\sin^2 2\theta_{13}$: 0.09)

$$- \alpha \sin 2\theta_{13} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ CP-odd ($\alpha \sin 2\theta_{13}$: 0.009)

$$+ \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

→ CP-even

$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$

→ Solar Term (α^2: 0.0009)

$\sin^2\theta_{23}$ → Resolves octant

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!

changes sign with polarity causes fake CP asymmetry!

Cervera et al., hep-ph/0002108
Freund et al., hep-ph/0105071
Agarwalla et al., e-Print: 1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracies. How can we break them?

Leptonic CP Violation: Important Open Question

Is CP violated in the neutrino sector, as in the quark sector?

Mixing can cause CPV in neutrino sector, provided $\delta_{CP} \neq 0^\circ$ and 180°

Need to measure the CP-odd asymmetries:

$$\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta;\, L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta;\, L) \quad (\alpha \neq \beta)$$

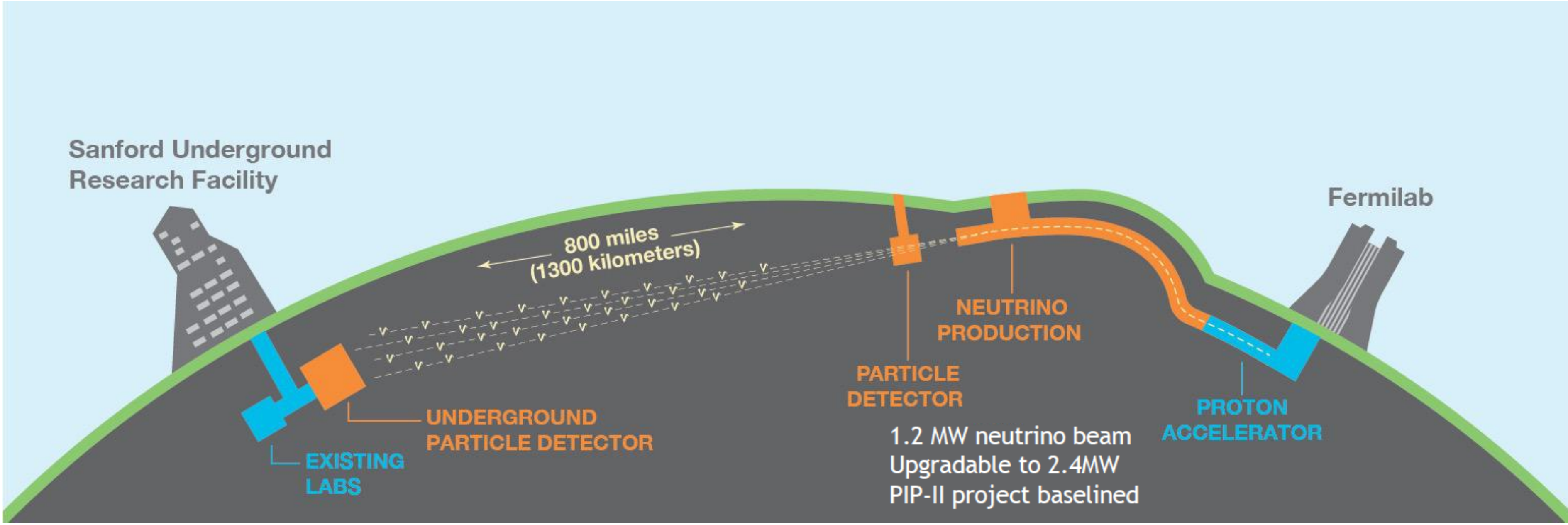
$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4 J_{CP} \times \left[\sin\left(\frac{\Delta m^2_{21}}{2E} L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E} L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E} L\right) \right]$$

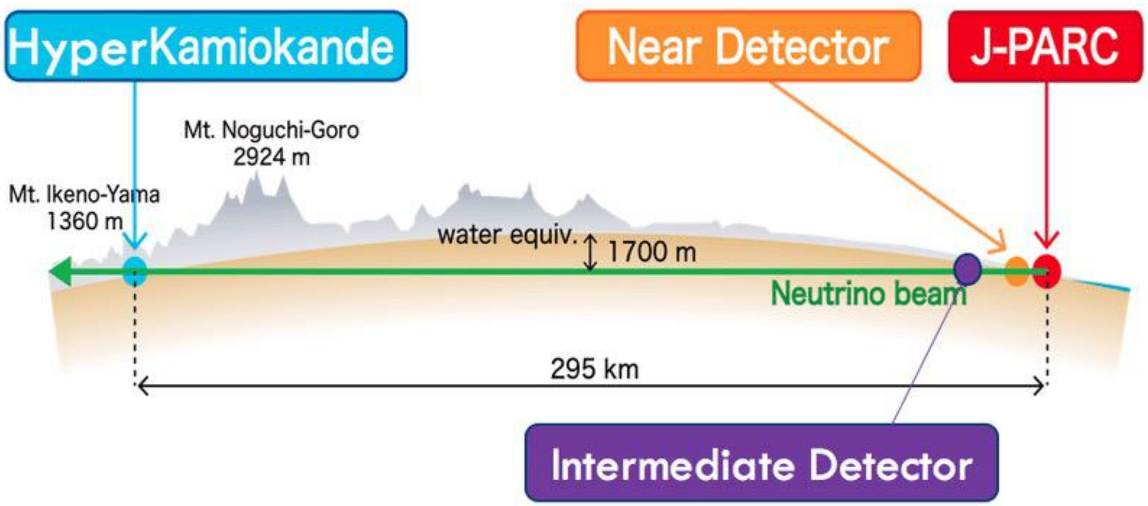
Jarlskog CP-odd Invariant → $J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta_{CP}$

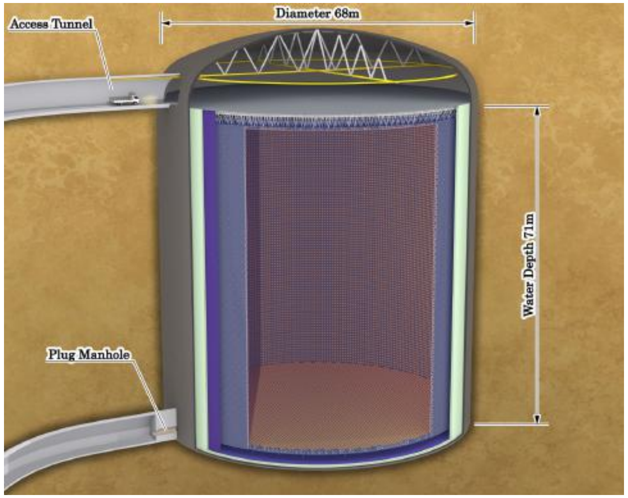
Three-flavor effects are key for CPV, need to observe interference

Conditions for observing CPV:
1) Non-degenerate masses ✔
2) Mixing angles $\neq 0^\circ$ & 90° ✔
3) $\delta_{CP} \neq 0^\circ$ and 180° (Hints)

Future Long-Baseline Experiments: DUNE, T2HK, and T2HKK







Complementarity among Next-generation Long-baseline Experiments in Enhancing Sensitivity to Leptonic CP Violation

-- Combination of DUNE & T2HK is must to establish Leptonic CP Violation at 3σ for 75% values of δ_{CP}

-- Impact of 2-3 mixing angle
-- Optimizing neutrino and antineutrino runtime
-- Impact of exposures
-- Impact of systematic uncertainties

S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, arXiv:2211.10620 [hep-ph]

Essential Features of DUNE, T2HK (JD), and T2HKK (JD+KD)

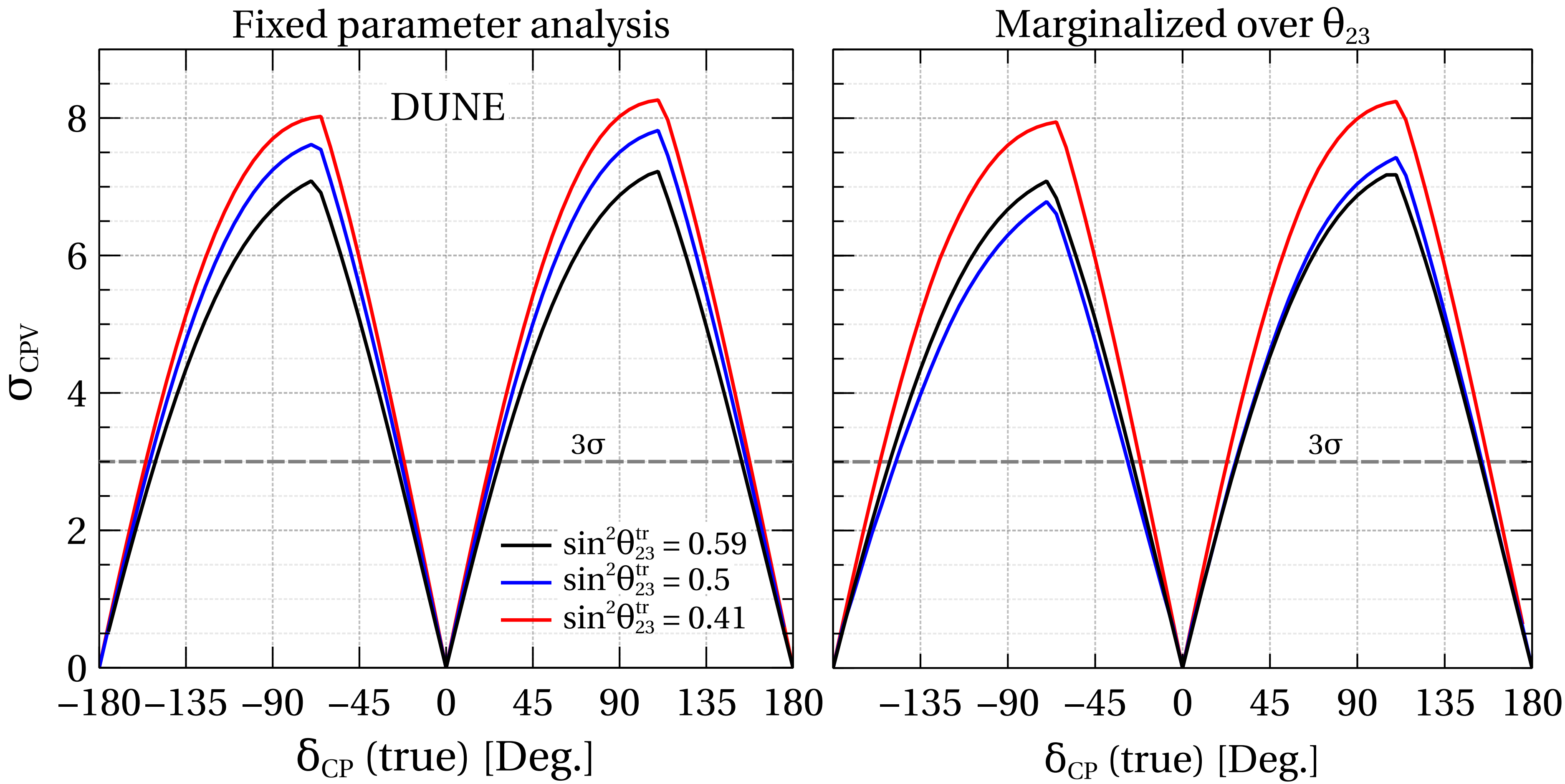
Characteristics	DUNE	JD/KD
Baseline (km)	1285	295 (1100)
ρ_{avg} (g/cm^3)	2.848	2.7 (2.8)
Beam Type	wide-band, on-axis	narrow-band, 2.5° off-axis
Beam Power	1.2 MW	1.3 MW
Proton Energy	120 GeV	30 GeV
P.O.T./year	1.1×10^{21}	2.7×10^{22}
Flux peaks at (GeV)	2.5	0.6
1^{st} (2^{nd}) oscillation maxima for appearance channel (GeV)	2.6 (0.87)	0.6 (0.2) / 1.8 (0.6)
Detector mass (kt)	40, LArTPC	187 each, water Cherenkov
Runtime ($\nu + \bar{\nu}$) yrs	5 + 5	2.5 + 7.5
Exposure (kt·MW·yrs)	480	2431
Signal Norm. Error (App.)	2%	5% (2.7%)
Signal Norm. Error (Disapp.)	5%	3.5%

Due to upgraded ND280 & a new Intermediate Water Cherenkov Detector (IWCD) ~ at 1 km

DUNE Collaboration: arXiv:2103.04797 [hep-ex]

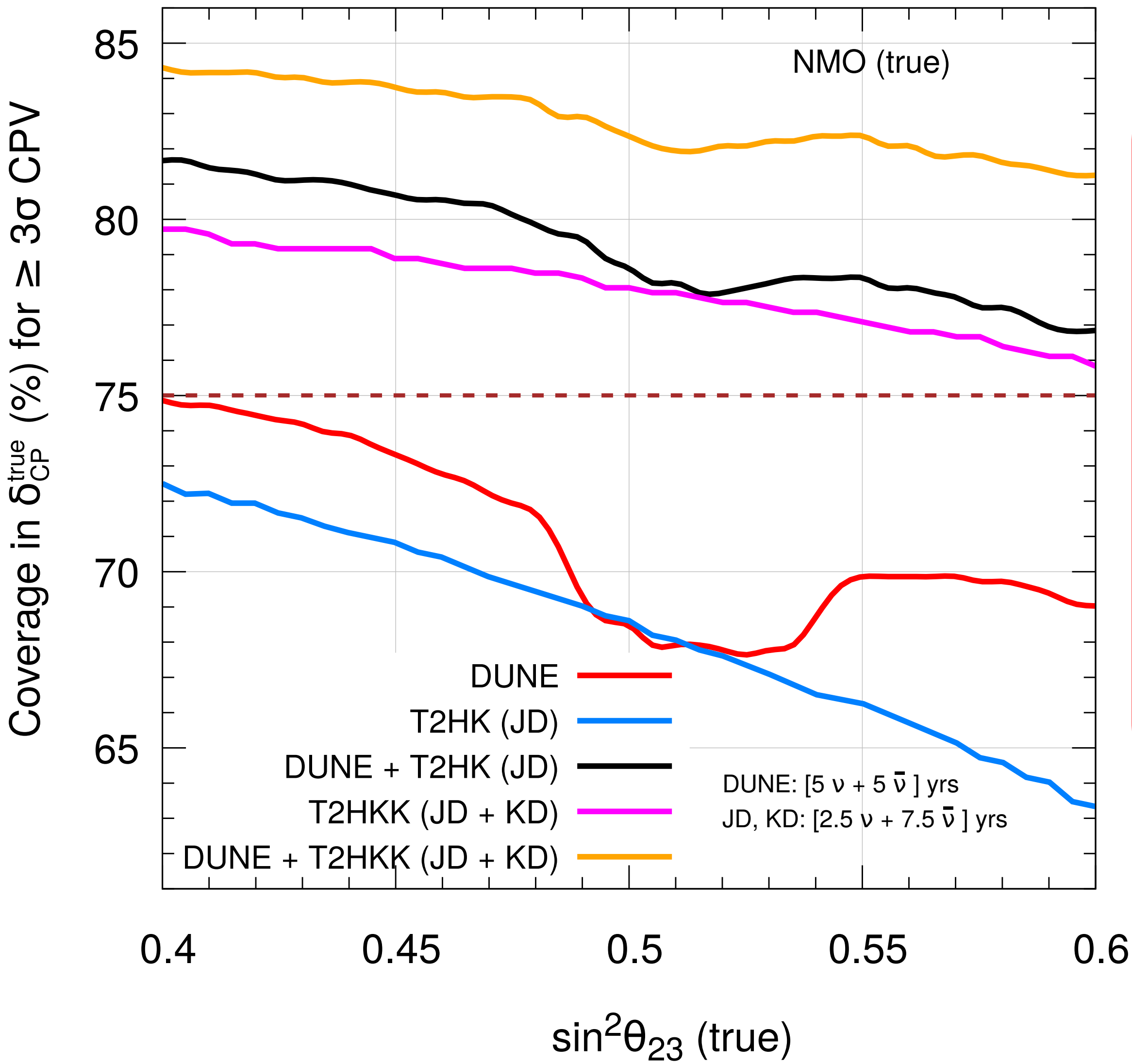
Hyper-Kamiokande Collaboration: arXiv:1611.06118 [hep-ex]

CP Violation in DUNE for three different choices of θ_{23}



CP violation sensitivity deteriorates around maximal mixing choices of true θ_{23} while minimizing over test θ_{23} in the fit. Why?

CP Coverage for Leptonic CP Violation at ≥ 3σ as a function of θ_{23}

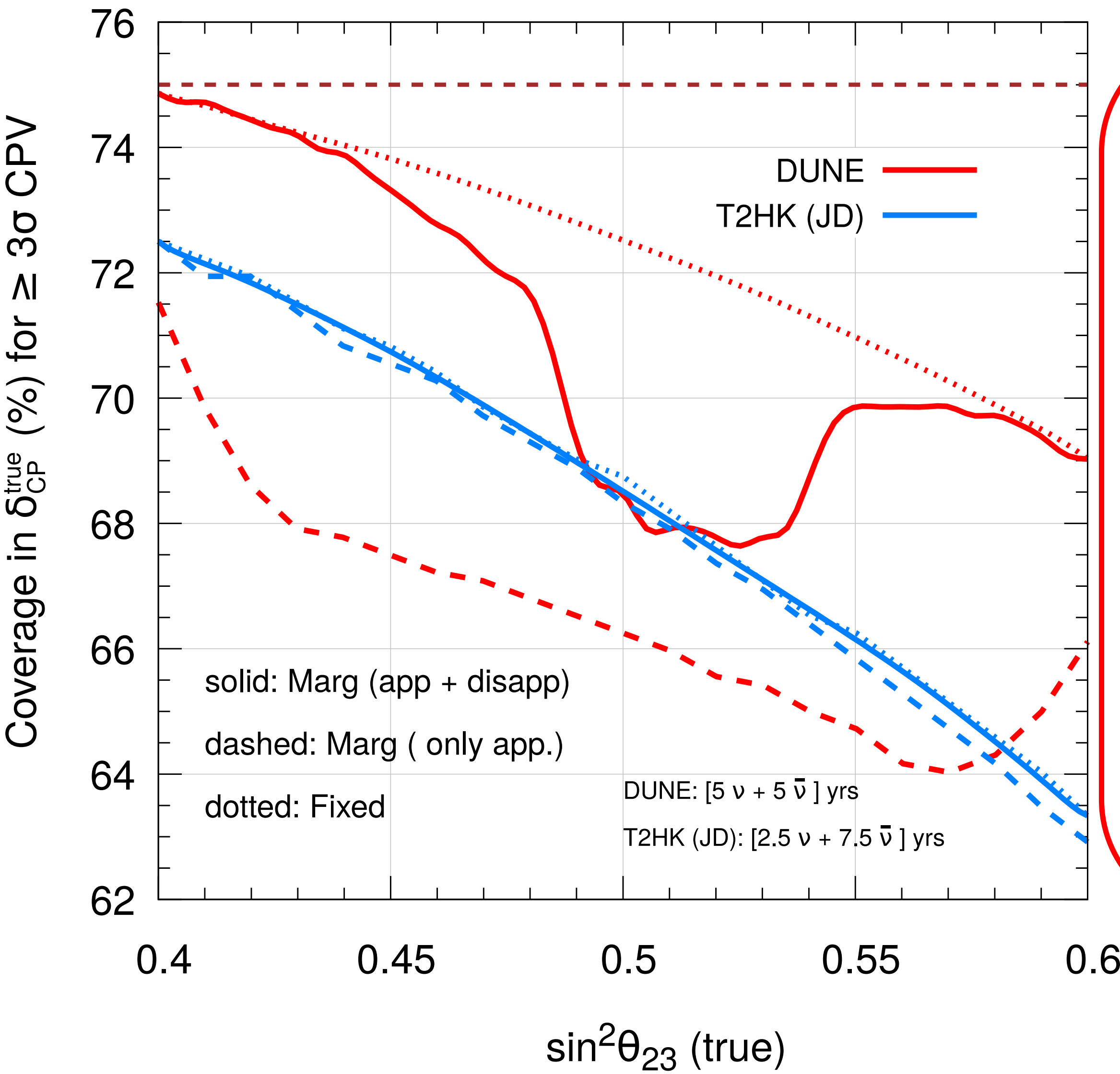


CP asymmetry decreases with increasing θ_{23} → CP coverage gets reduced as we increase θ_{23}

Around maximal mixing choices of θ_{23} → sensitivity gets deteriorated in DUNE

Combination of DUNE & T2HK is must to achieve leptonic CP violation at ≥ 3σ for at least 75% choices of δ_{CP} irrespective of θ_{23}

CP Coverage for Leptonic CP Violation at ≥ 3σ as a function of θ_{23}

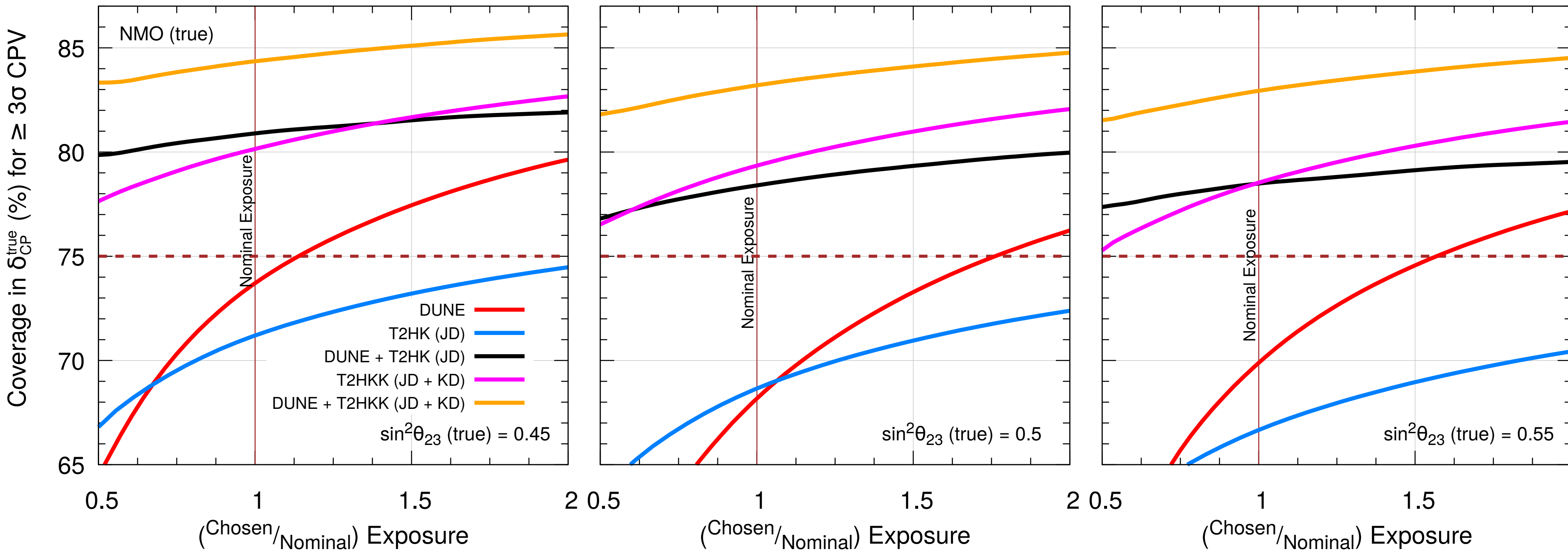


Disappearance channel reduces the impact of marginalization over θ_{23} in the fit & enhances the sensitivity in DUNE

Due to matter effect in DUNE, fake CP asymmetry is quite pronounced in disappearance channel around maximal mixing

Therefore, the advantage due to disappearance channel is less around $\theta_{23} \approx 45^\circ$

CP Coverage for Leptonic CPV at ≥ 3σ as a function of Exposure

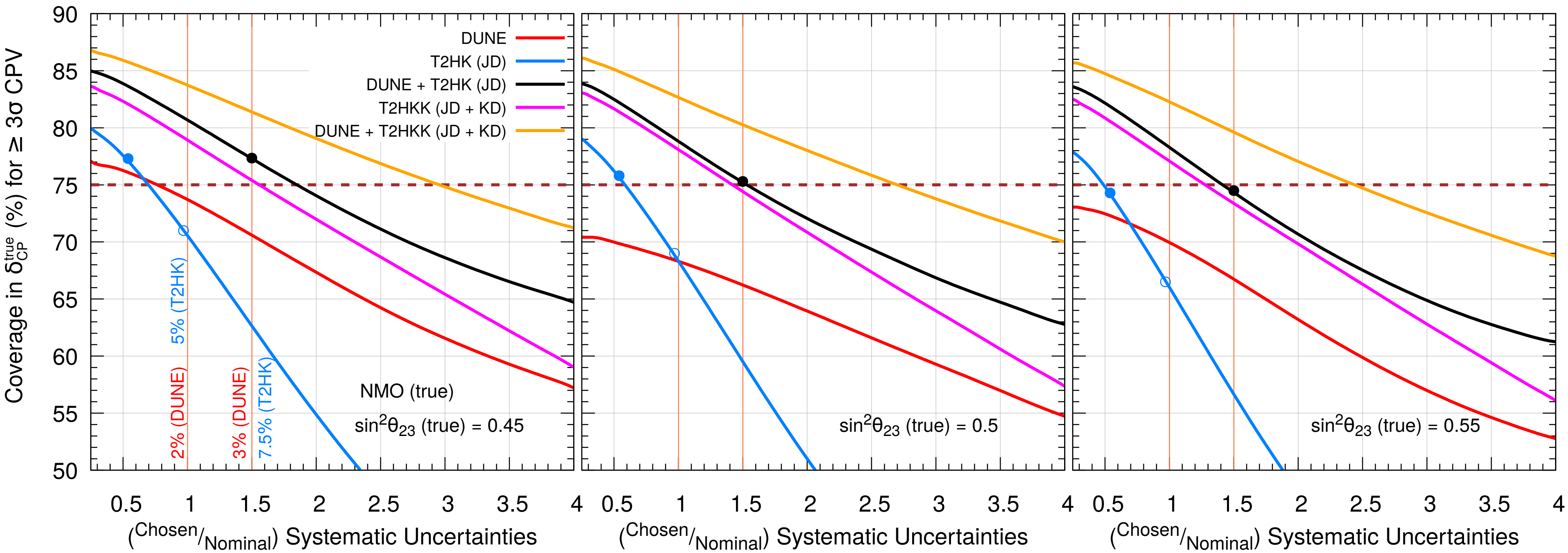


DUNE & T2HK individually <u>cannot achieve</u> leptonic CPV at ≥ 3σ for at least 75% choices of δ_{CP} with their nominal exposures & systematic uncertainties

DUNE + T2HK <u>can attain</u> the same <u>for all values</u> of θ_{23} with only <u>half of their nominal exposures</u>

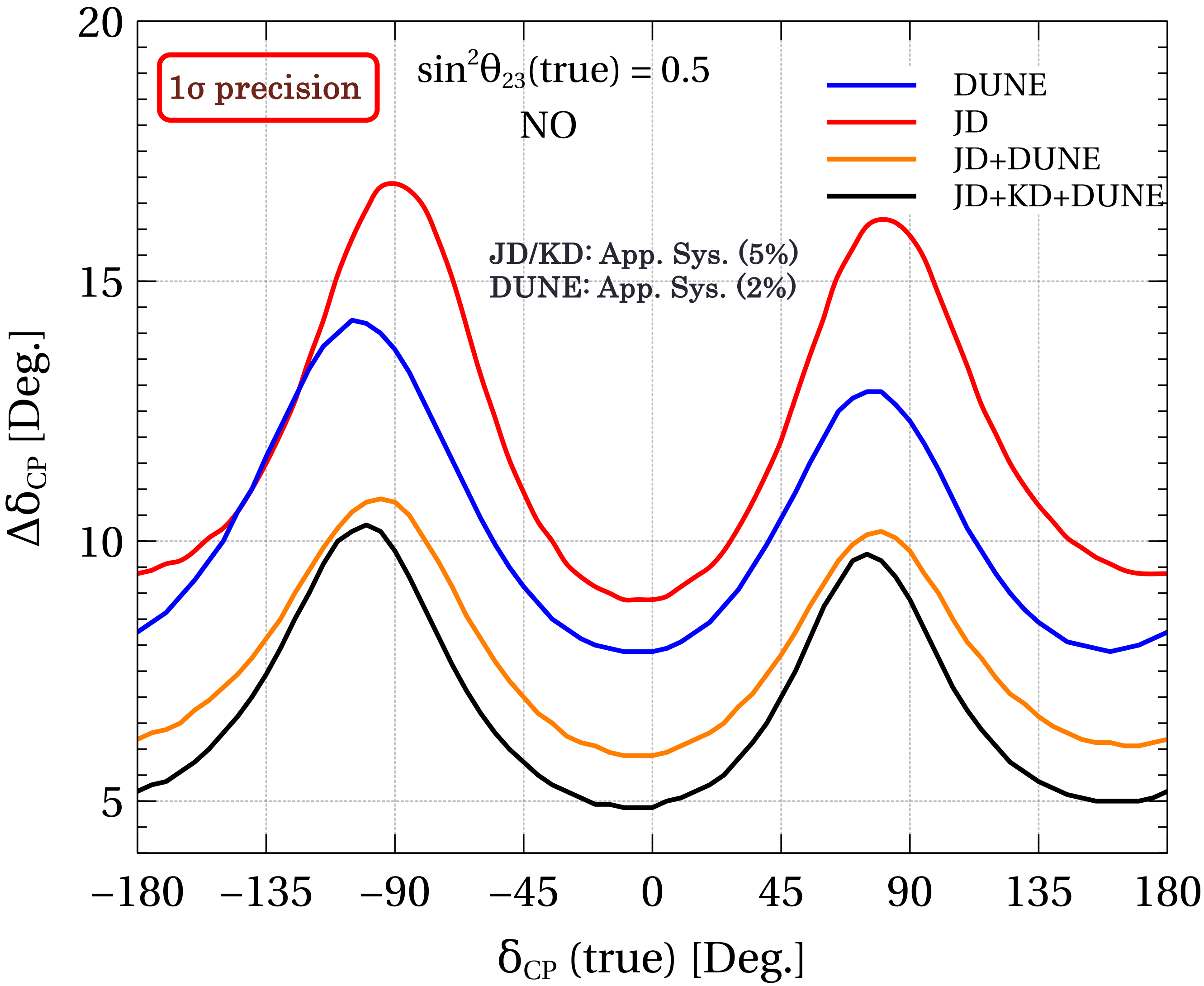
DUNE + T2HKK can further enhance the CP coverage to <u>more than 80%</u> with only <u>half of their nominal exposures</u>

CP Coverage for Leptonic CPV at ≥ 3σ as a function of Systematics



Complementarity between DUNE & T2HK may allow us to achieve <u>75% CP coverage for ≥ 3σ leptonic CP violation</u>, even in a pessimistic scenario where the <u>systematic uncertainties are 1.5 times larger than the nominal ones</u>

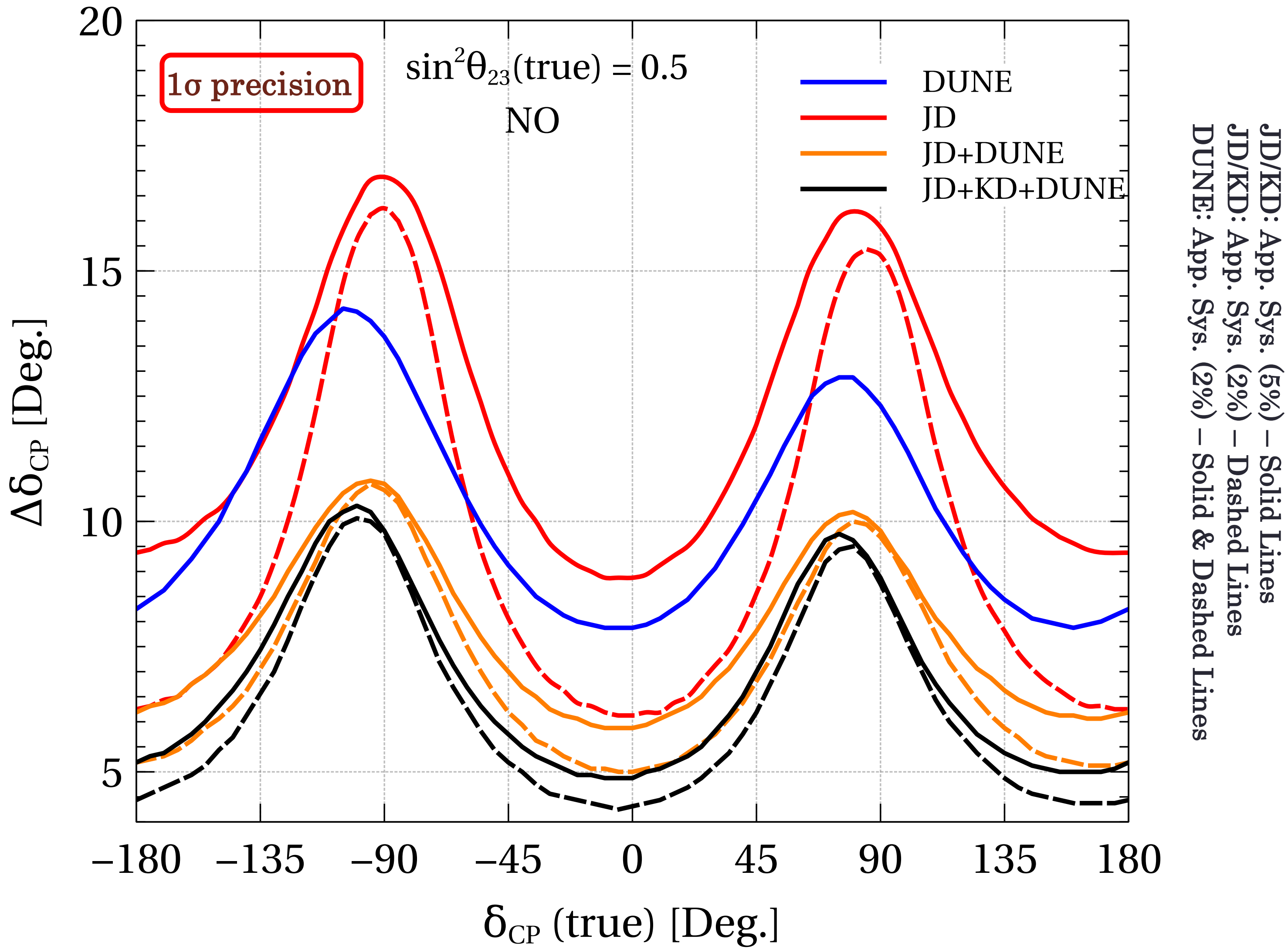
High-Precision Measurement of Dirac CP Phase



DUNE + T2HK (JD) can measure any value of δ_{CP} with a 1σ precision $\lesssim 10^\circ$

S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, in preparation

High-Precision Measurement of Dirac CP Phase



Significant improvement in precision for CP-conserving choices of δ_{CP} w/ reduced systematics

S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, in preparation

High-Precision Measurements of Atmospheric Oscillation Parameters

-- Combination of DUNE & T2HK is crucial for high-precision measurements of 2-3 oscillation parameters

-- Deviation from maximal θ_{23}
-- Resolution of Octant of θ_{23}
-- Precision on 2-3 oscillation parameters

S. K. Agarwalla, R. Kundu, S. Prakash, and M. Singh, JHEP 03 (2022) 206

S. K. Agarwalla, R. Kundu, and M. Singh, in preparation

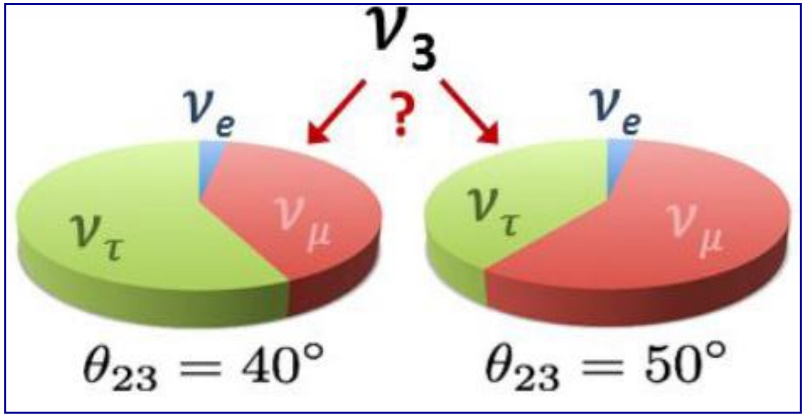
Octant of 2-3 Mixing Angle: Important Open Question

→ In ν_μ survival probability, the dominant term is mainly sensitive to $\sin^2 2\theta_{23}$

→ If $\sin^2 2\theta_{23}$ differs from 1 (recent hints), we get two solutions for θ_{23}

→ One in lower octant (LO: $\theta_{23} < 45$ degree)

→ Other in higher octant (HO: $\theta_{23} > 45$ degree)



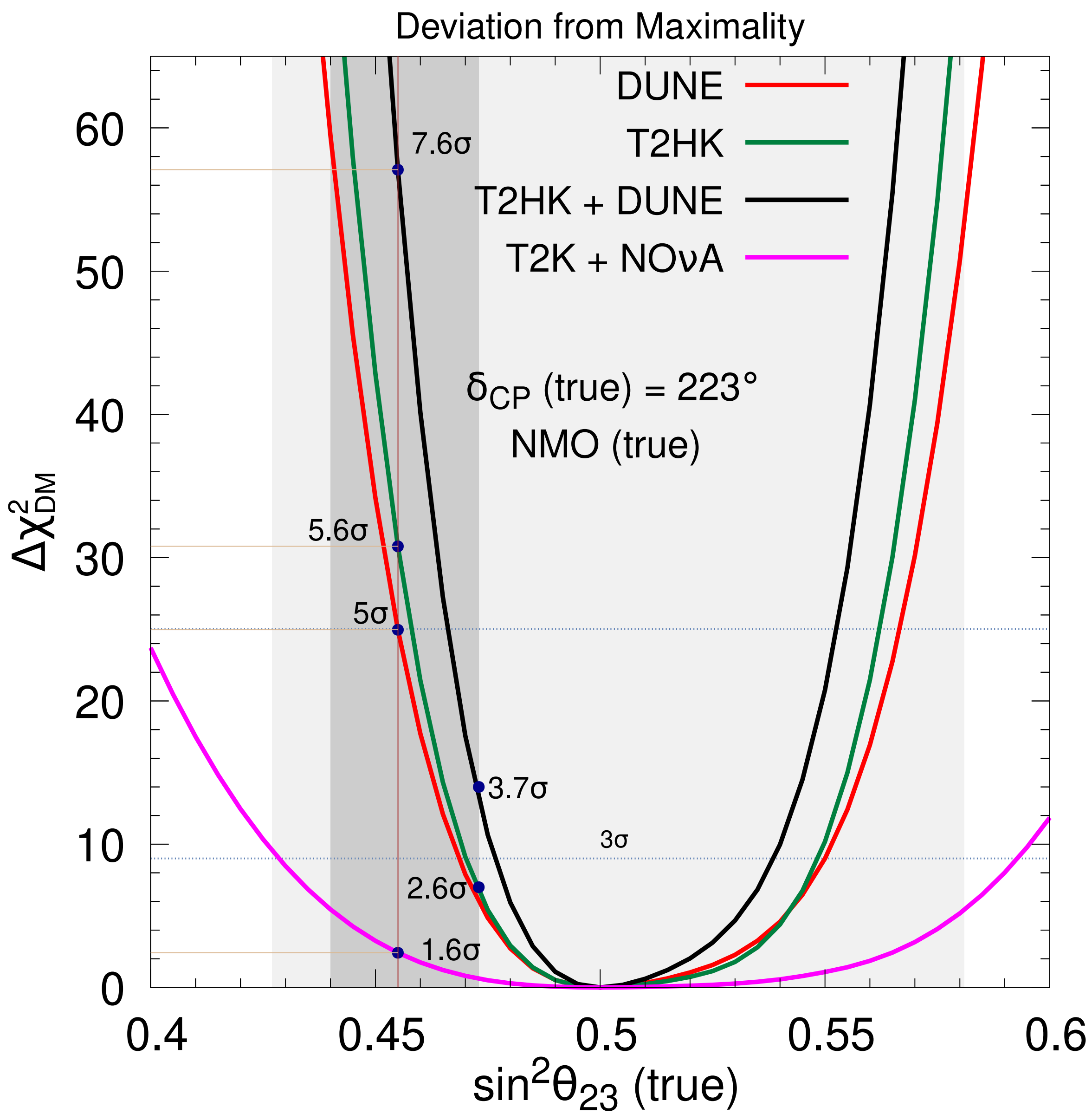
Octant ambiguity of θ_{23}

Fogli and Lisi, hep-ph/9604415

$\nu_\mu \to \nu_e$ oscillation channel can break this degeneracy

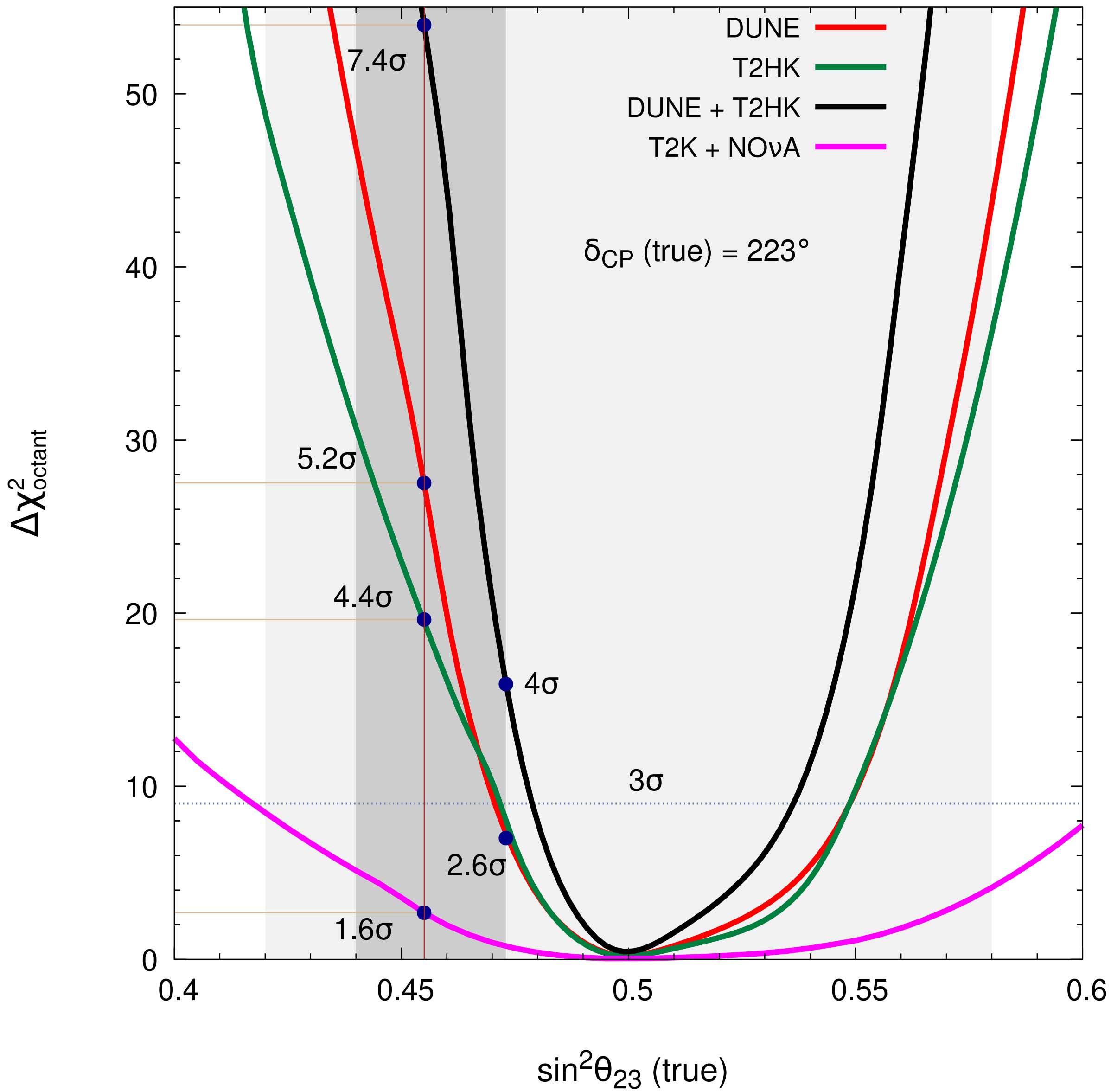
Preferred value would depend on the choice of neutrino mass ordering

Deviation from Maximal θ_{23}



Agarwalla, Kundu, and Singh, in preparation

Discovery of θ_{23} Octant



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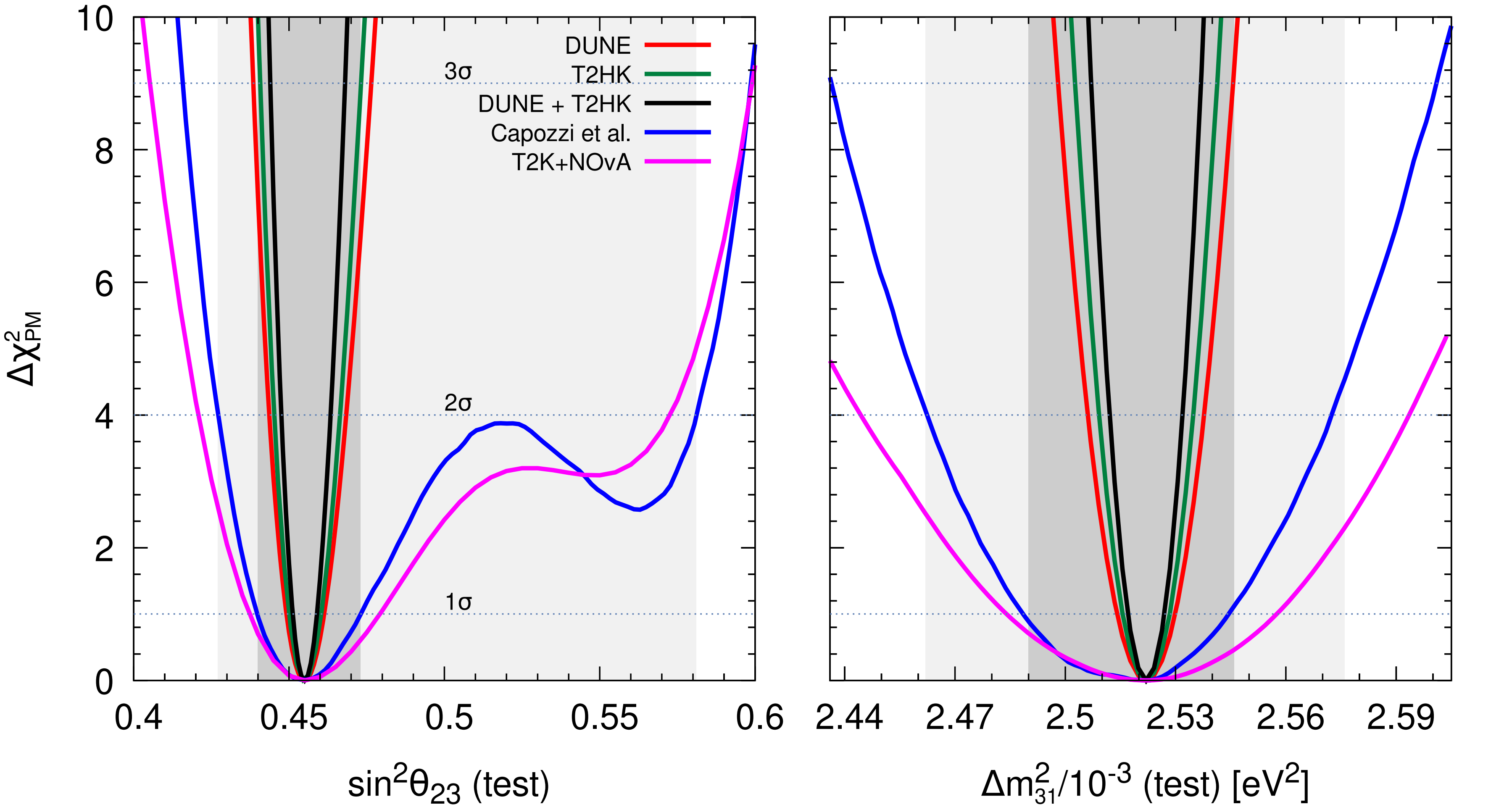
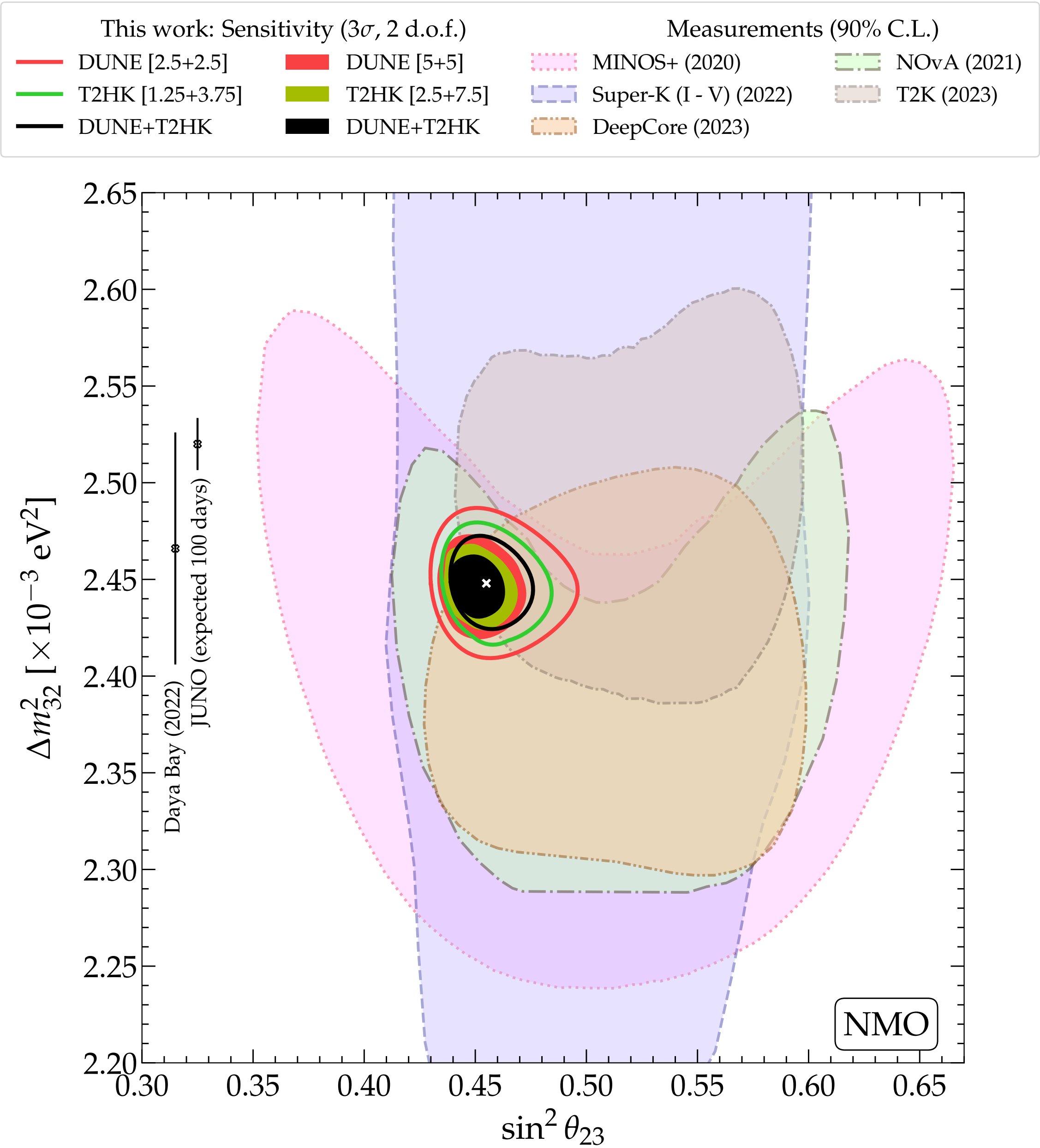
Precision Measurement of Atmospheric Oscillation Parameters



Parameter	Relative 1σ precision (%)					
	T2HK	DUNE	T2HK+DUNE	T2K+NOνA	Capozzi *et al.*	JUNO
$\sin^2\theta_{23}$	1.18	1.40	0.88	7.10	6.72	—
Δm^2_{31}	0.25	0.31	0.20	0.99	1.09	0.2

Agarwalla, Kundu, and Singh, in preparation

Precision Measurement of Atmospheric Oscillation Parameters



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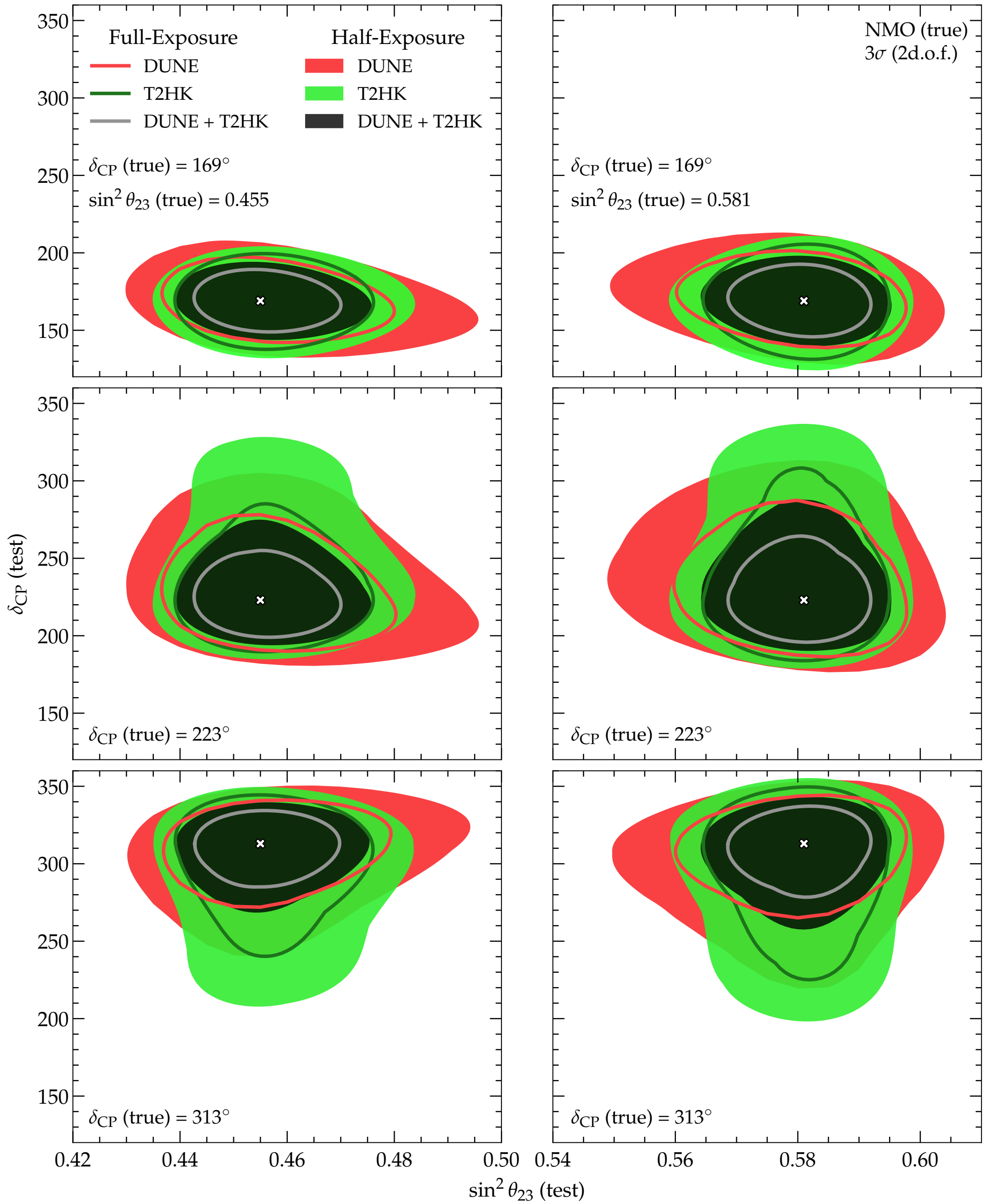
Allowed Regions in Plane ($\sin^2\theta_{23} - \delta_{CP}$) Plane



Agarwalla, Kundu, and Singh, in preparation

Concluding Remarks

Fundamental Physics with LBL Neutrino Oscillation Experiments

Exciting opportunities to address the pressing issues in three-flavour neutrino paradigm: neutrino mass ordering, leptonic CP violation, and accurate measurements of oscillation parameters

Improved precision on three-flavor oscillation parameters in the next 5 to 10 years are very crucial to set the stage for next-generation long-baseline experiments

DUNE and T2HK bring complementary information to probe the entire parameter space of mass-mixing parameters with high confidence level - Crucial to know the origin of neutrino mass, to elucidate the age-old flavor puzzle, and to explain the prevalence of matter over antimatter in the Universe!

Thank you!

CP Violation: Necessary Requirement for Matter-Antimatter Asymmetry

Five irreducible CP-Violating Phases in the ν Standard Model

In the Quark Sector:

+ The CP-odd phase in the CKM matrix – measured to be $\gamma \simeq 70^{o}$

- Governs all the CP-violating phenomena observed so far

+ The strong CP-phase θ of the QCD Vacuum

- Known to be vanishingly small $< 10^{-10}$

In the Lepton Sector:

+ The Dirac CP-odd phase δ_{CP} in the 3×3 unitary ν mixing matrix

- Can be measured in ν oscillation experiments (hints)

+ The Majorana neutrinos can have two more CP-violating phases

- No effect in ν oscillations, only affect LNV processes (unknown)

Remember

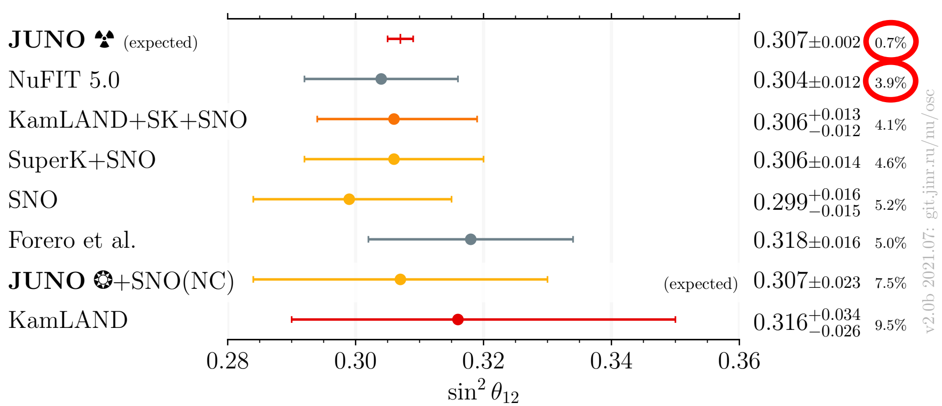
The CKM CP phase is not responsible for the baryon asymmetry of the Universe

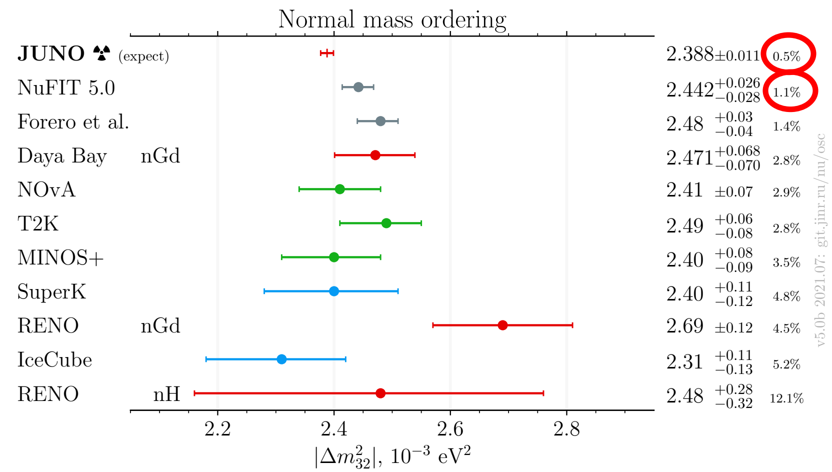
The PMNS CP phase is the only hope

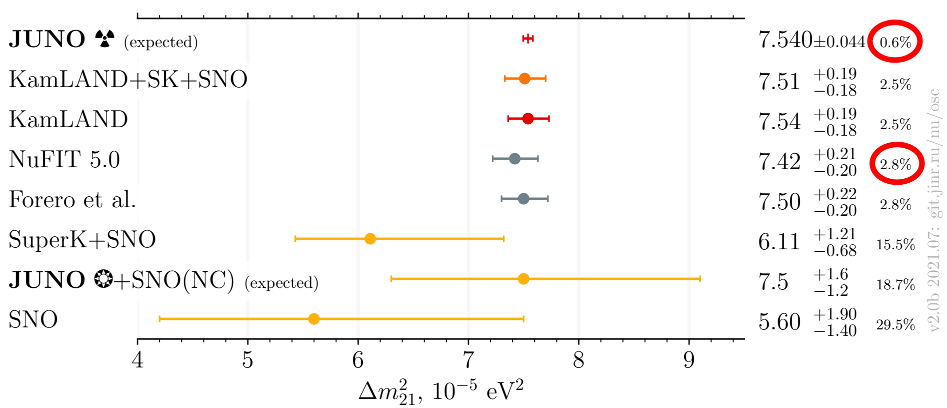
The discovery of non-zero CP-violating phase δ_{CP} in neutrino oscillation experiments would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry of the Universe

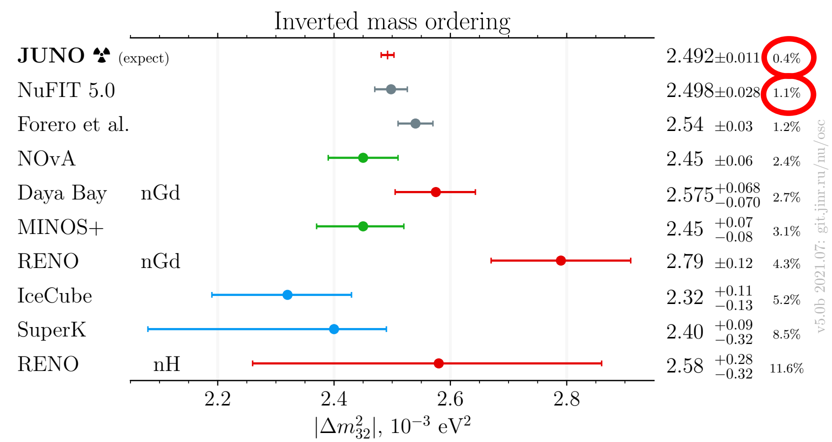
The determination of CP violation requires the full interplay of 3-flavor effects in neutrino oscillations

Very Bright Future Ahead: Triumph of JUNO









Maxim Gonchar (JUNO Collaboration) EPS-HEP 2021, July 26

JUNO will improve significantly our knowledge on neutrino oscillation parameters. These developments are crucial to probe sub-leading three-flavor effects in next-generation long-baseline experiments for the discovery of NMO, leptonic CPV, and Octant of 2-3 mixing angle

Quark Mixing vs. Neutrino Mixing

$$|V_{\rm CKM}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$

PDG 20222

$$|U|^{\text{with SK-atm}}_{3\sigma\ \text{PMNS}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.144 \to 0.156 \\ 0.244 \to 0.499 & 0.505 \to 0.693 & 0.631 \to 0.768 \\ 0.272 \to 0.518 & 0.471 \to 0.669 & 0.623 \to 0.761 \end{pmatrix}$$

NuFIT 5.1 (2021)

The goal is to achieve the CKM level precision for the PMNS
A Long Journey Ahead! But the precision is improving rapidly for PMNS

Good News: There may be large CPV in neutrino sector than quark sector

$$J_{CP} = \frac{1}{8} \cos\theta_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{23}\ \sin 2\theta_{12}\ \sin\delta_{CP}$$

$J_{\rm CKM} \sim 3 \times 10^{-5}$, whereas $J_{\rm PMNS}$ can be as large as 3×10^{-2}

Accelerator Long-Baseline Neutrino Experiments

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: Appearance Channel

$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$: Disappearance Channel

T2K (Japan) & NOvA (USA) [running, off-axis]

FD: 295 km
1st Osc. Max. ~ 0.6 GeV

FD: 810 km
1st Osc. Max. ~ 1.6 GeV

narrow-band beam

DUNE (USA) [upcoming, on-axis]

FD: 1285 km
1st Osc. Max. ~ 2.6 GeV

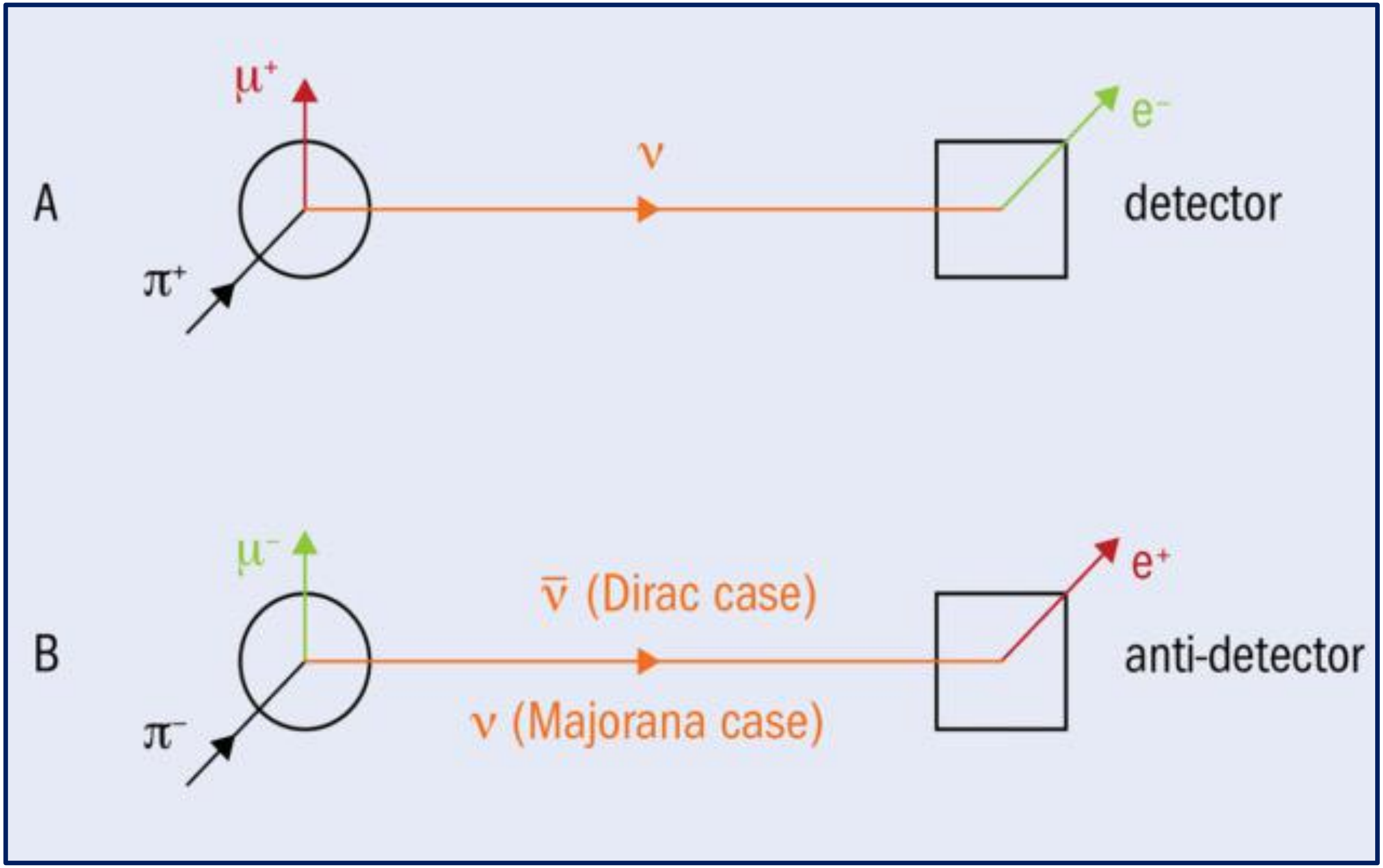
wide-band beam

T2HK (Japan) [upcoming, off-axis]

FD: 295 km
1st Osc. Max. ~ 0.6 GeV

narrow-band beam

The Pursuit of Leptonic CPV in LBL Experiments



The whole idea is based on comparing the rates of two CP-mirror-image processes

Above experimental approach is a perfectly valid probe of leptonic CPV regardless of whether neutrinos are Dirac or Majorana particles

Current Long-Baseline Experiments: T2K and NOvA

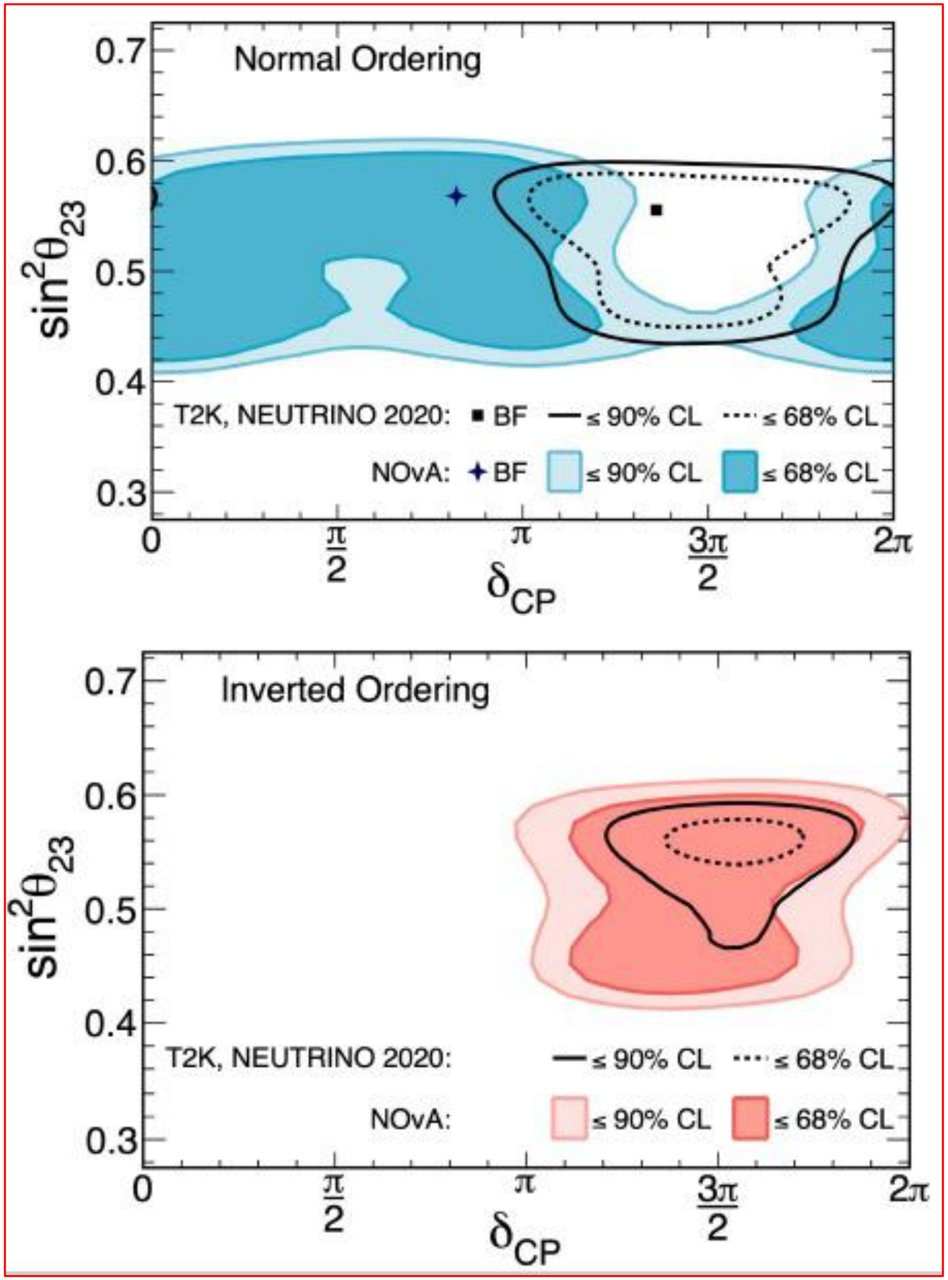
T2K & NOvA operate at different energies and baselines

Complement each other & help to remove degeneracies among various oscillation parameters

Probe multiple oscillation maxima

Compare neutrino and antineutrino oscillation probabilities

Latest CP Measurements from T2K and NOvA



Complementarity between T2K & NOvA

Both T2K & NOvA individually show a slight preference for NMO

NMO: T2K excludes large regions of the NOvA constraints at 90% C.L., & NOvA excludes parts of T2K's 90% C.L. region

IMO: Both the experiments consistently favour the $\pi < \delta_{CP} < 2\pi$ region, with a weak preference for the upper octant

Both the experiments need more data (at present statistically limited) to have better measurements

Joint oscillation analyses between T2K, Super-K, & NOvA would be very helpful

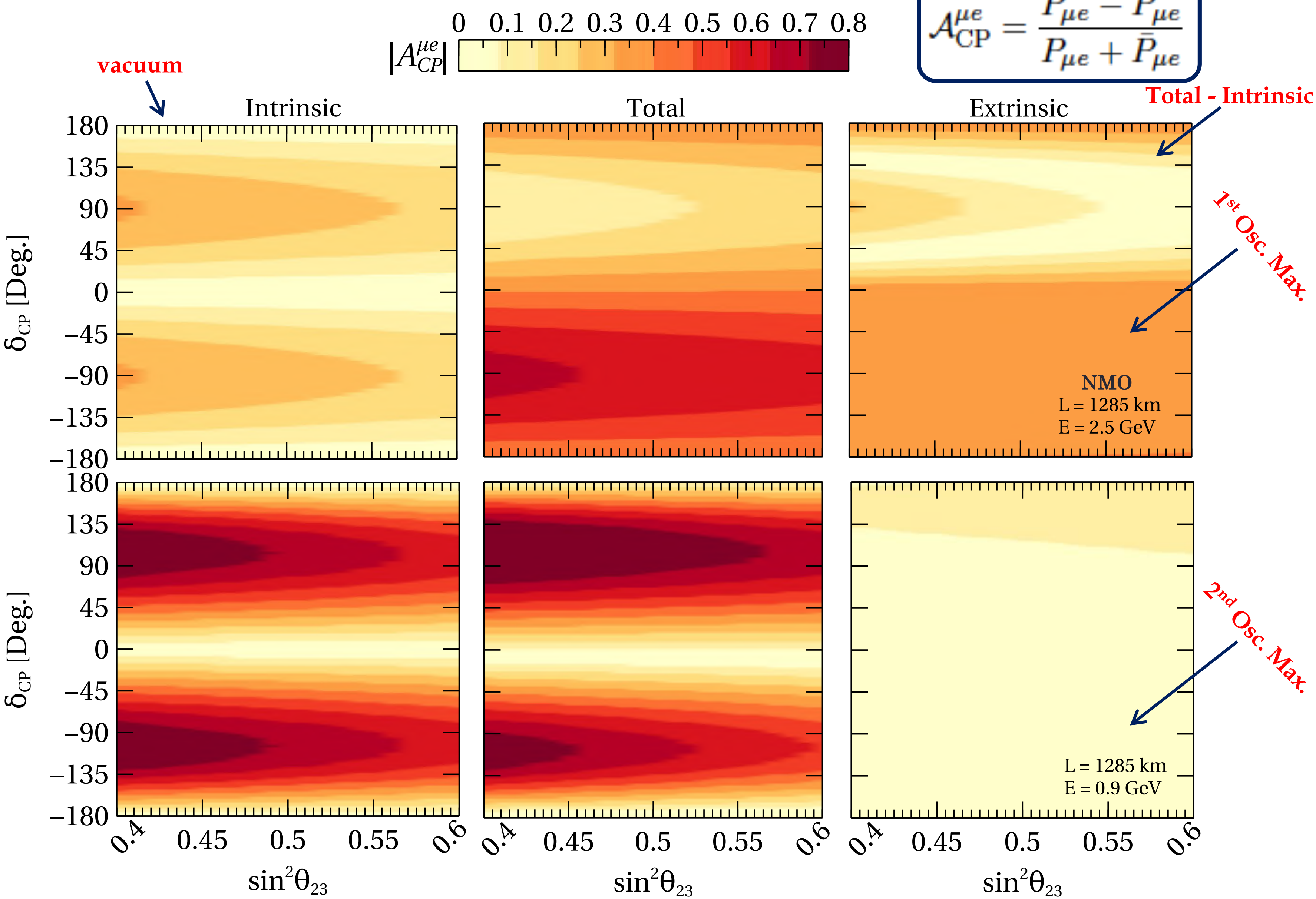
T2K: arXiv:2303.03222 [hep-ex]
NOvA: arXiv: 2108.08219 [hep-ex]

Intrinsic (Genuine), Extrinsic (Fake), and total CP Asymmetries in Appearance Channel

S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, arXiv:2211.10620 [hep-ph]

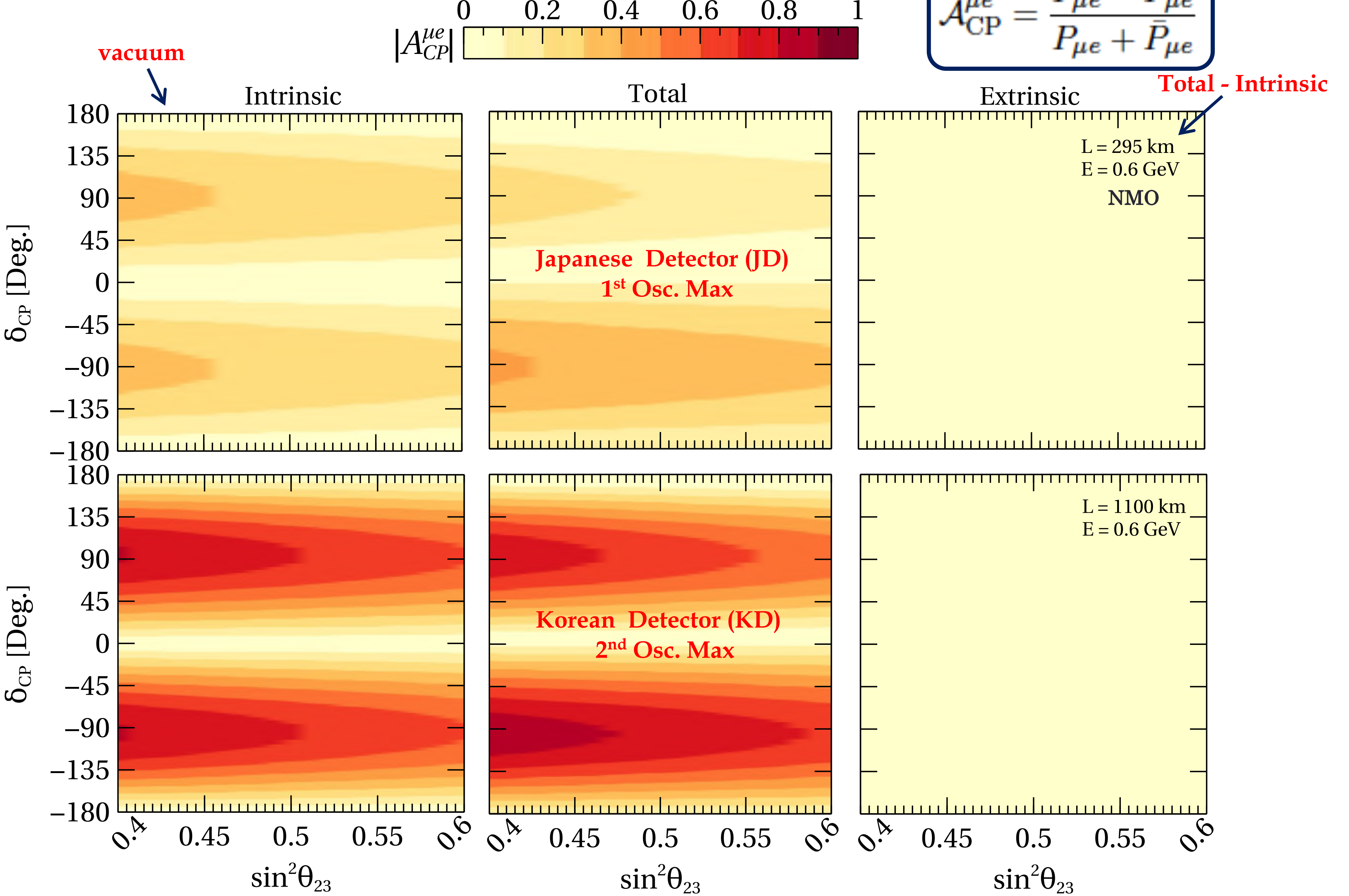
Absolute CP Asymmetry in DUNE at 1st and 2nd Oscillation Maxima

$$\mathcal{A}_{\rm CP}^{\mu e} = \frac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}}$$



Absolute CP Asymmetry in JD (1st Osc. Max.)/KD (2nd Osc. Max.)

$$\mathcal{A}_{\rm CP}^{\mu e} = \frac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}}$$



Analytical Expressions for CP Asymmetries in Appearance Channel

$$P_{\mu e} \approx N \sin^2\theta_{23} + O \sin 2\theta_{23} \cos(\Delta + \delta_{\rm CP})$$

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

$$O = 2\alpha \sin\theta_{13} \sin 2\theta_{12} \frac{\sin \hat{A}\Delta}{\hat{A}} \frac{\sin[(\hat{A}-1)\Delta]}{\hat{A}-1}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$

$$\Delta = \Delta m^2_{31} L/4E$$

$$A = 2\sqrt{2} G_F N_e E$$

$$\hat{A} = A/\Delta m^2_{31}$$

$$\mathcal{A}^{\mu e}_{\rm CP} = \frac{P_{\mu e} - \bar{P}_{\mu e}}{P_{\mu e} + \bar{P}_{\mu e}}$$

$$\sin\theta_{13} \sim 1/7$$

$$\sin\theta_{12} \sim 1/\sqrt{3}$$

Expand in Â up to the first order

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

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

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

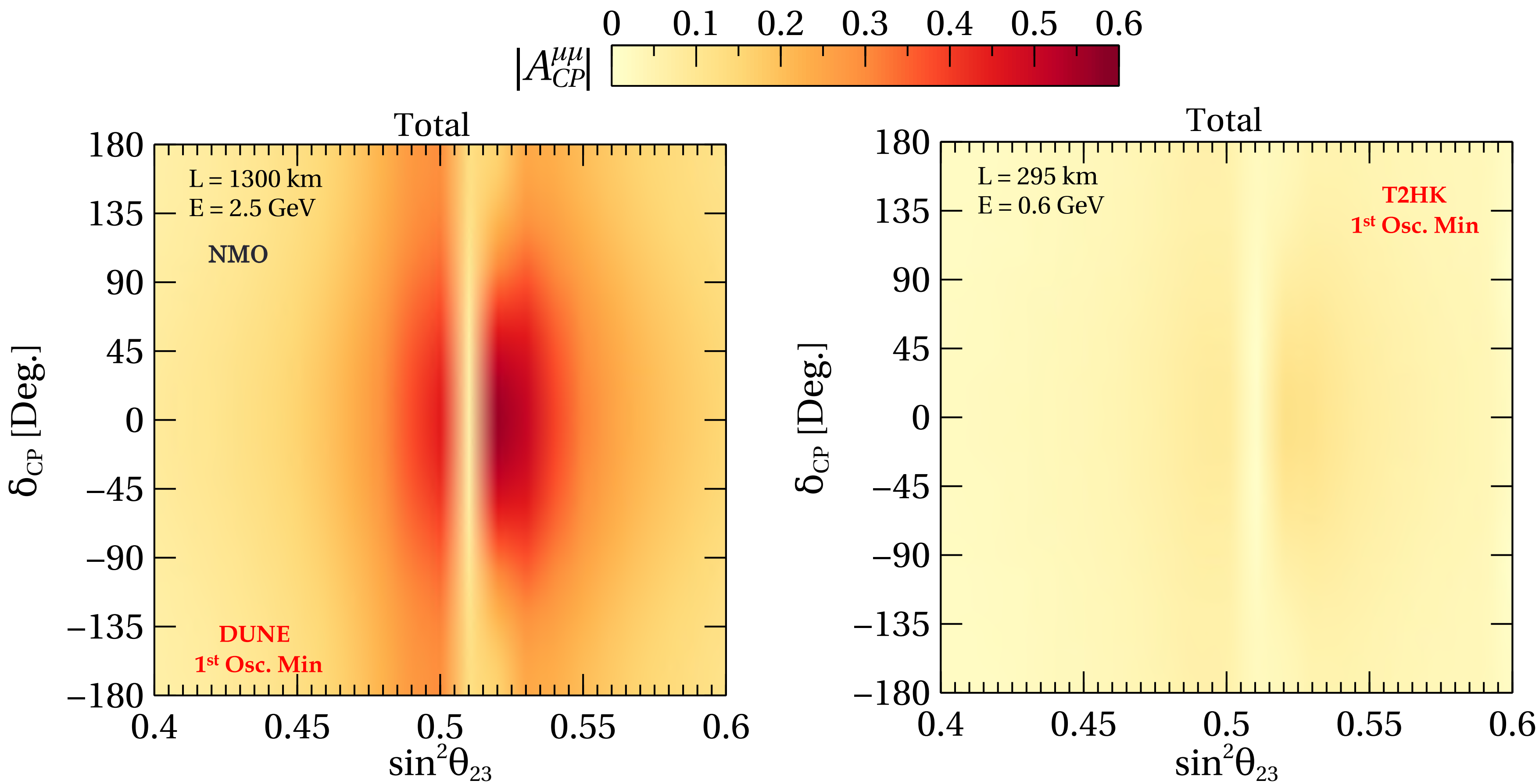
$$\mathcal{A}^{\mu e}_{\rm CP} \approx -\frac{7}{3}\alpha\sqrt{2}\pi\cot\theta_{23}\sin\delta_{\rm CP} + 2\hat{A} \longrightarrow$$

At 1^{st} Osc. Max.
$\Delta = \pi/2$

Extrinsic (Fake) CP Asymmetries in Disappearance Channel

S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, arXiv:2211.10620 [hep-ph]

Extrinsic/Fake CP Asymmetry in Disappearance Channel



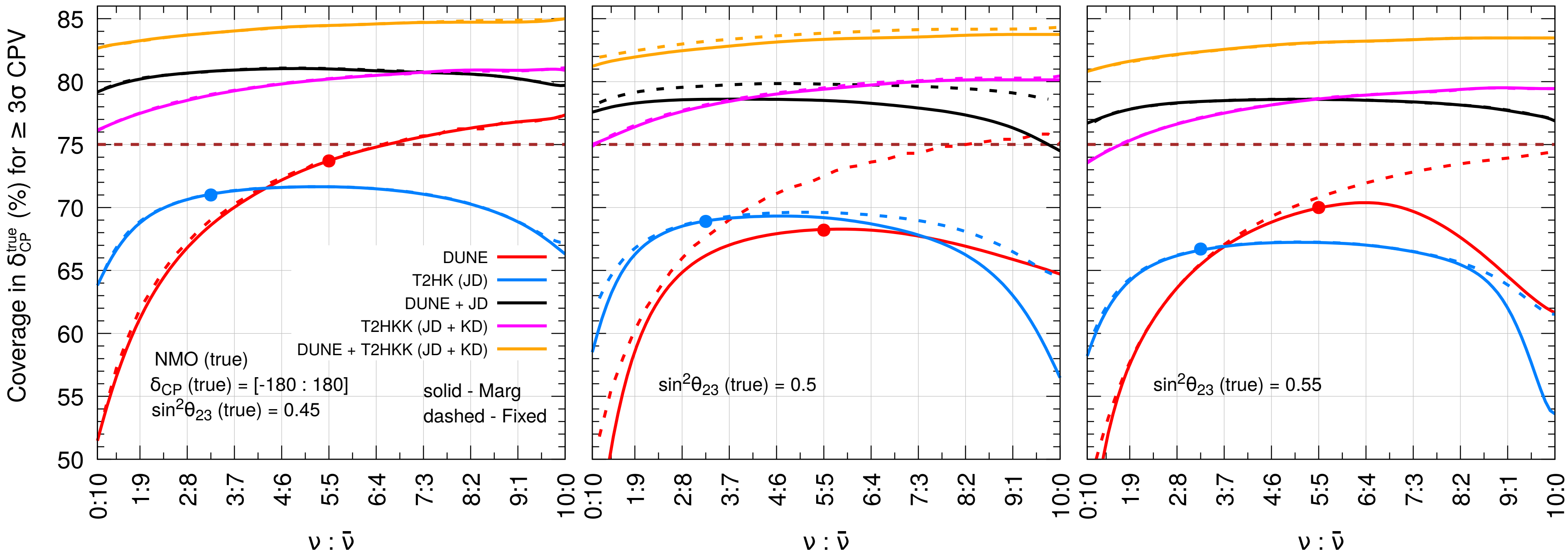
At 1st Osc. Max. $\Delta = \pi/2$

$$\mathcal{A}_{\rm CP}^{\mu\mu} = \frac{P_{\mu\mu} - \bar{P}_{\mu\mu}}{P_{\mu\mu} + \bar{P}_{\mu\mu}} \qquad \mathcal{A}_{\rm CP}^{\mu\mu} \approx \hat{A}\,\frac{24\sin^2\theta_{23} + 7\sqrt{2}(\pi^2 - 4)\alpha\cos\delta_{\rm CP}\sin 2\theta_{23}}{6 + 141\cos 2\theta_{23}}$$

Above expansion breaks at $\sin^2\theta_{23} \approx 0.52$

Due to matter effect in DUNE, fake CP asymmetry is quite pronounced around maximal mixing

CP Coverage for Leptonic CPV at ≥ 3σ as a function of Runtime

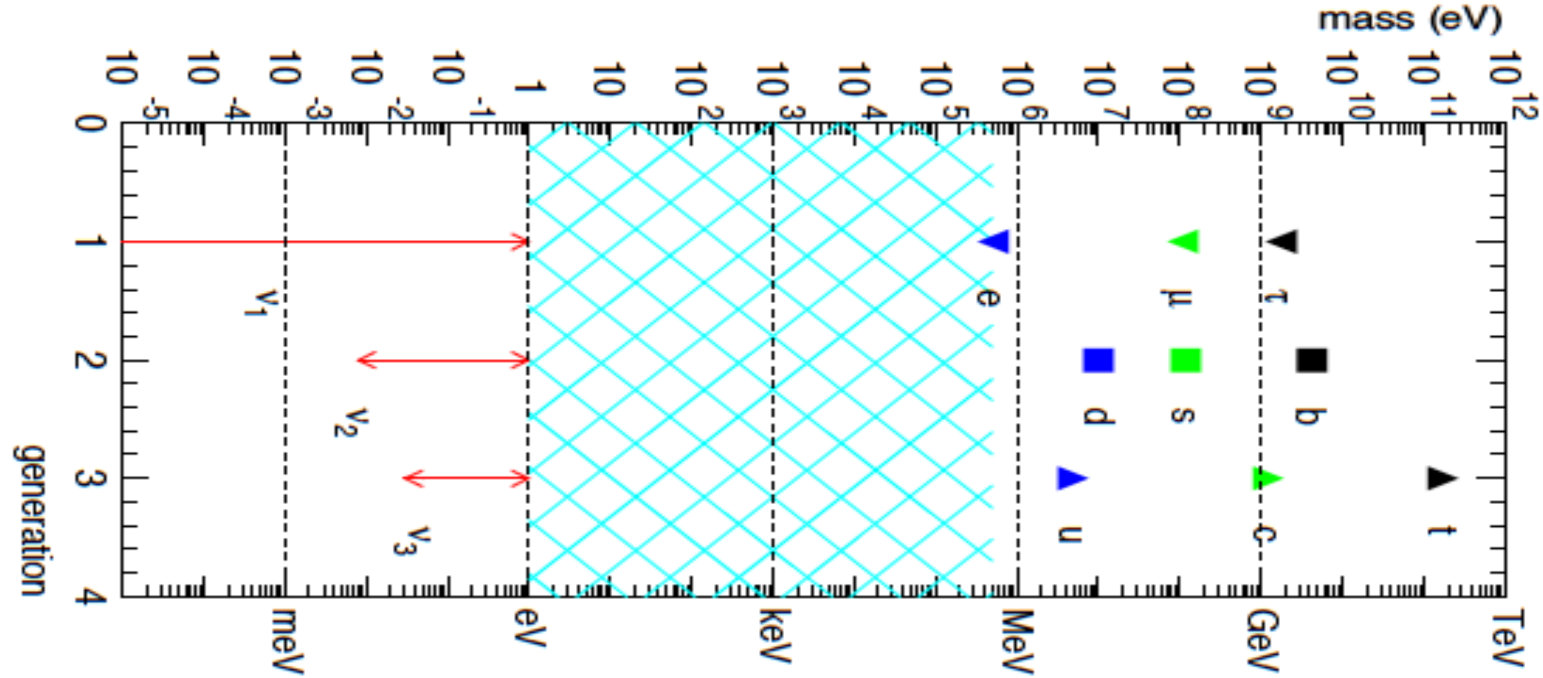


Depending upon the value of θ_{23}, different ratios of runtime in neutrino & antineutrino modes are needed in DUNE & T2HK to have better CP coverage

T2HK always prefers a ratio of neutrino & antineutrino runtimes for which the no. of appearance events in neutrino & antineutrino modes are almost similar irrespective of the choice of θ_{23}

If $\theta_{23} < 45^\circ$, then the expected no. of appearance events in DUNE becomes very less and therefore, it prefers to have more run in the neutrino mode

The Two Fundamental Questions



Why are neutrinos so light? The origin of Neutrino Mass!

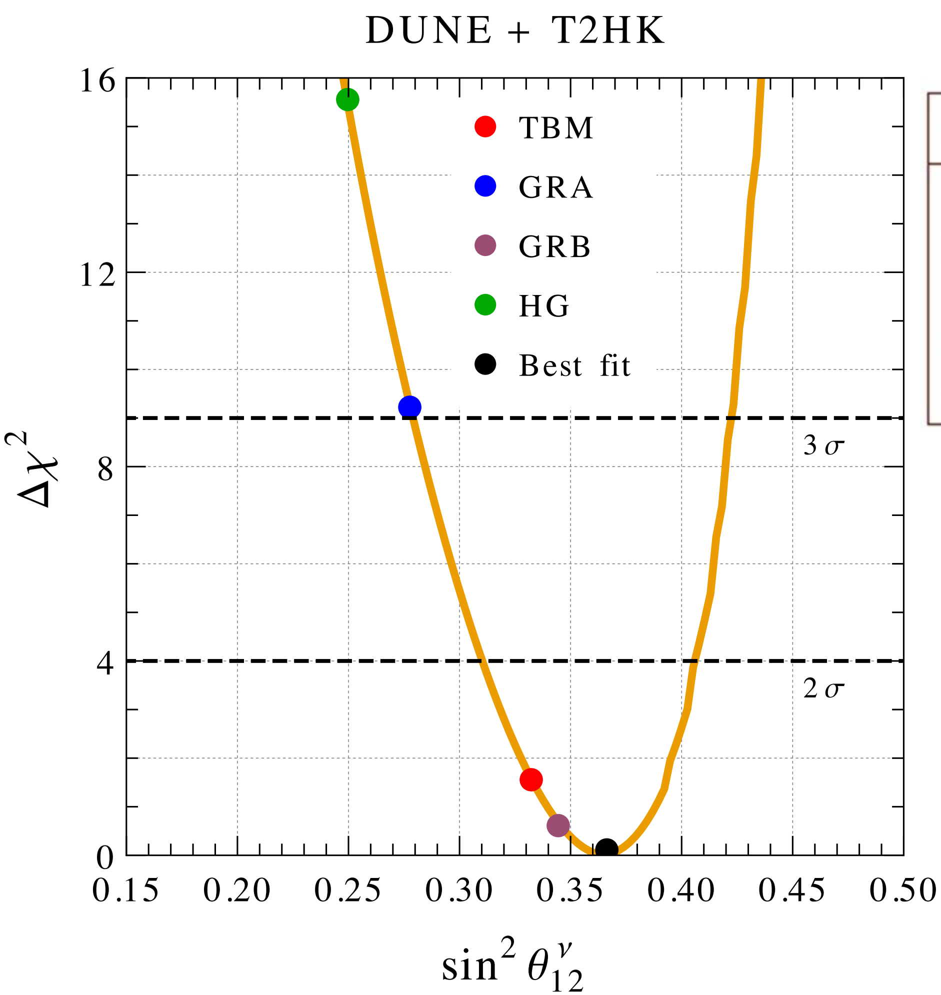
	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45^\circ$	8.5°	34°	?
Quarks	2.4°	0.20°	13°	69°

Why are lepton mixings so different from quark mixings?

The Flavor Puzzle!

Oscillation Data and Neutrino Mixing Schemes

Sum Rule: $$\cos\delta_{CP} = \frac{\tan\theta_{23}}{\sin 2\theta_{12}\sin\theta_{13}}\left[\cos 2\theta^{\nu}_{12} + \left(\sin^2\theta_{12} - \cos^2\theta^{\nu}_{12}\right)\left(1 - \cot^2\theta_{23}\sin^2\theta_{13}\right)\right]$$



Symmetry form	θ^{ν}_{12} [°]	$\cos\delta_{CP}$	δ_{CP} [°]
BM	45	unphysical	unphysical
TBM	$\arcsin(1/\sqrt{3}) \approx 35$	−0.16	99 ∨ 261
GRA	$\arctan(1/\phi) \approx 32$	0.21	78 ∨ 282
GRB	$\arccos(\phi/2) = 36$	−0.24	104 ∨ 256
HG	30	0.39	67 ∨ 293

$U_{PMNS} = U_e^{\dagger} U_{\nu}$ golden ratio: $\phi = (1+\sqrt{5})/2$

black dot: current best-fit value of $\delta_{CP} = 248^{\circ}$ which means

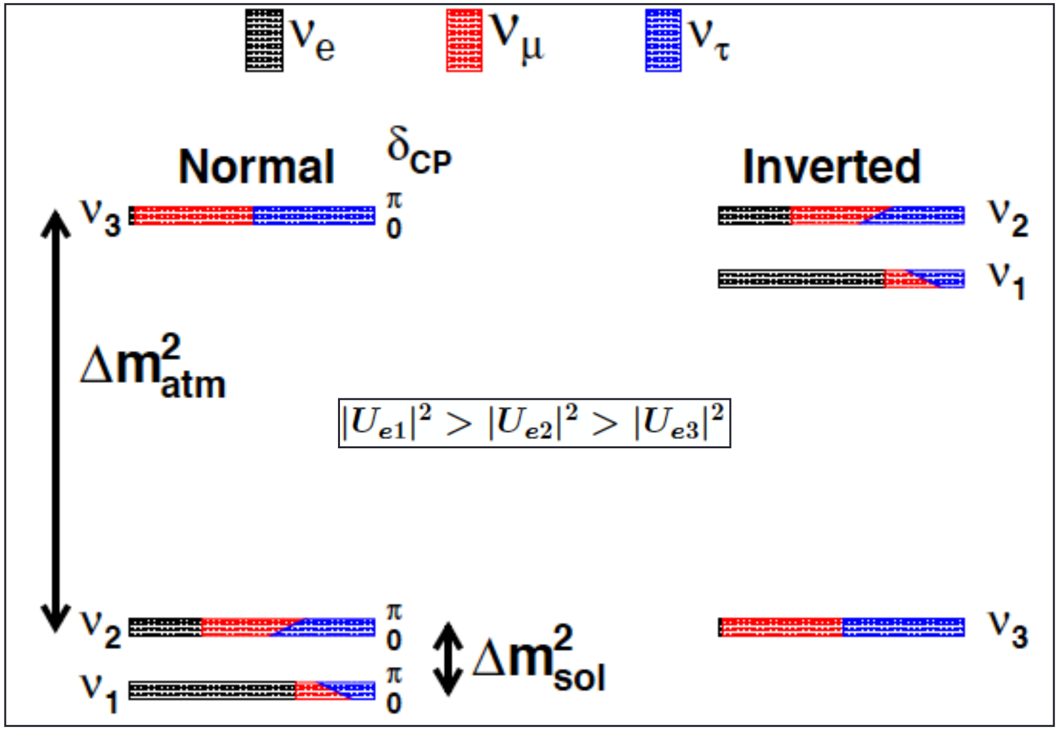
$\sin^2\theta^{\nu}_{12} = 0.364$ $(\Delta\chi^2 = 0)$

Agarwalla, Chatterjee, Petcov, Titov, arXiv:1711.02107

the coloured dots corresponding to the values of $\sin^2\theta^{\nu}_{12}$ which characterise the GRB (violet), TBM (red), GRA (blue) and HG (green) symmetry forms.

Neutrino Mass Ordering: Important Open Question

- The sign of Δm^2_{31} $(m^2_3 - m^2_1)$ is not known



ν_e component of ν_1 > ν_e component of ν_2 > ν_e component of ν_3

Neutrino mass spectrum can be normal or inverted ordered

We only have a lower bound on the mass of the heaviest neutrino

$$\sqrt{2.5 \cdot 10^{-3} \text{eV}^2} \sim 0.05 \text{ eV}$$

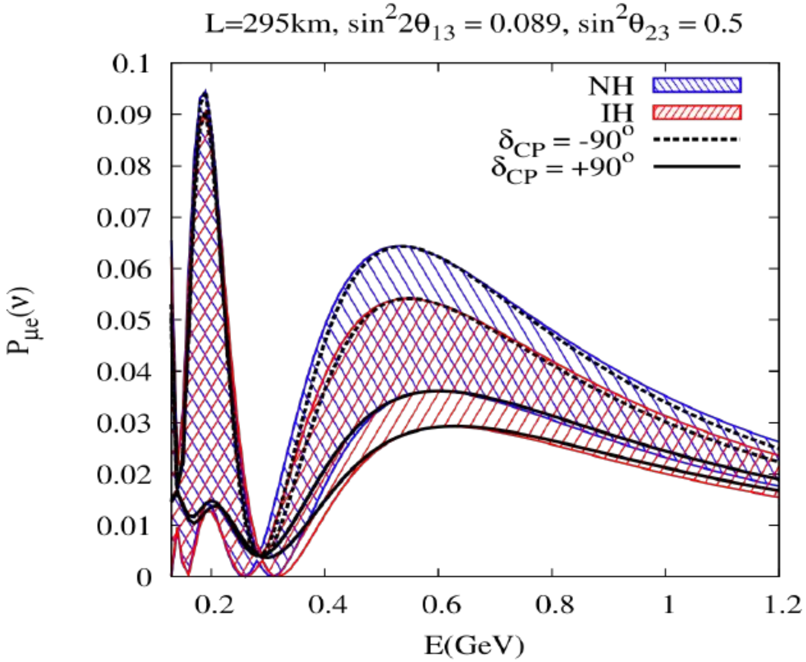
We currently do not know which neutrino is the heaviest

Matter effect inside the Sun played an important role to fix the ordering between m_2 & m_1

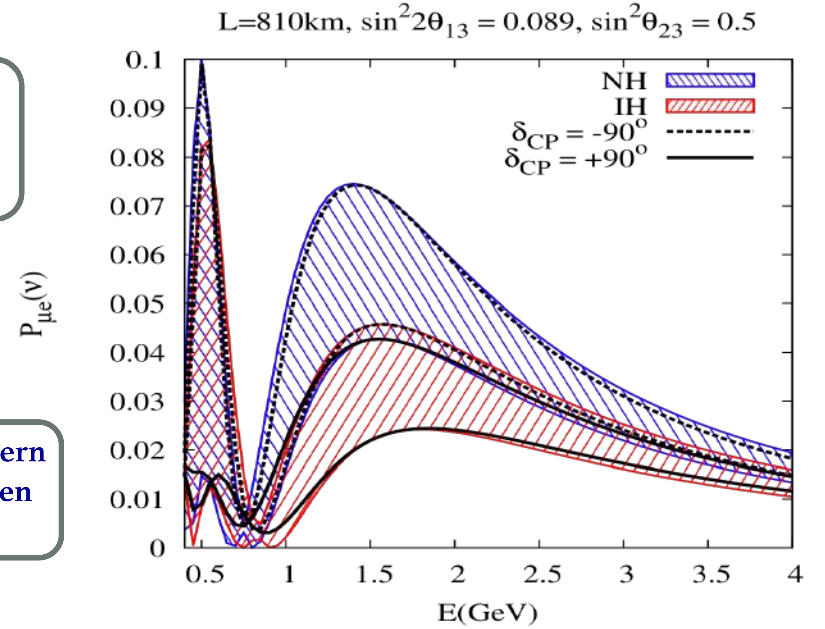
Matter effect inside the Earth will play a crucial role to fix the ordering between m_3 & m_1

Mass Ordering Discrimination : A Binary yes-or-no type question

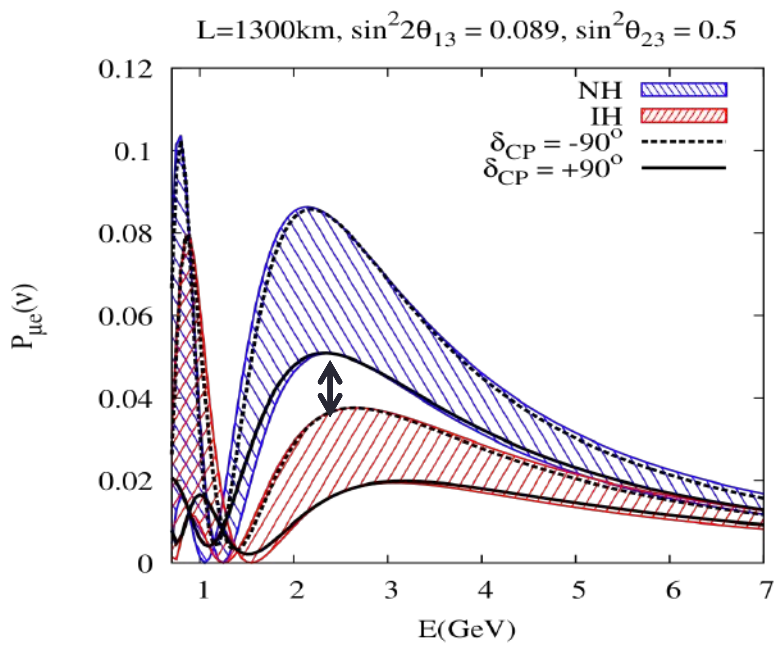
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



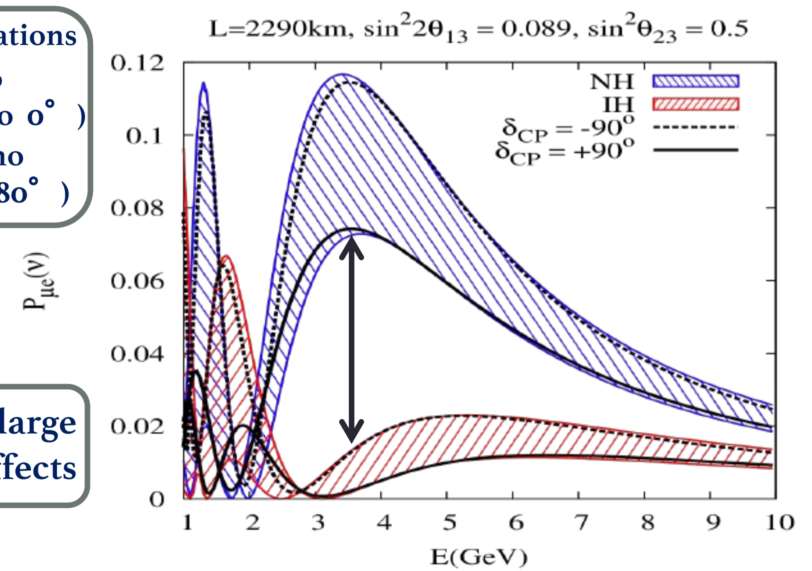
For ν:
Max: NH, -90°
Min: IH, 90°



Degeneracy pattern different between T2K & NOνA



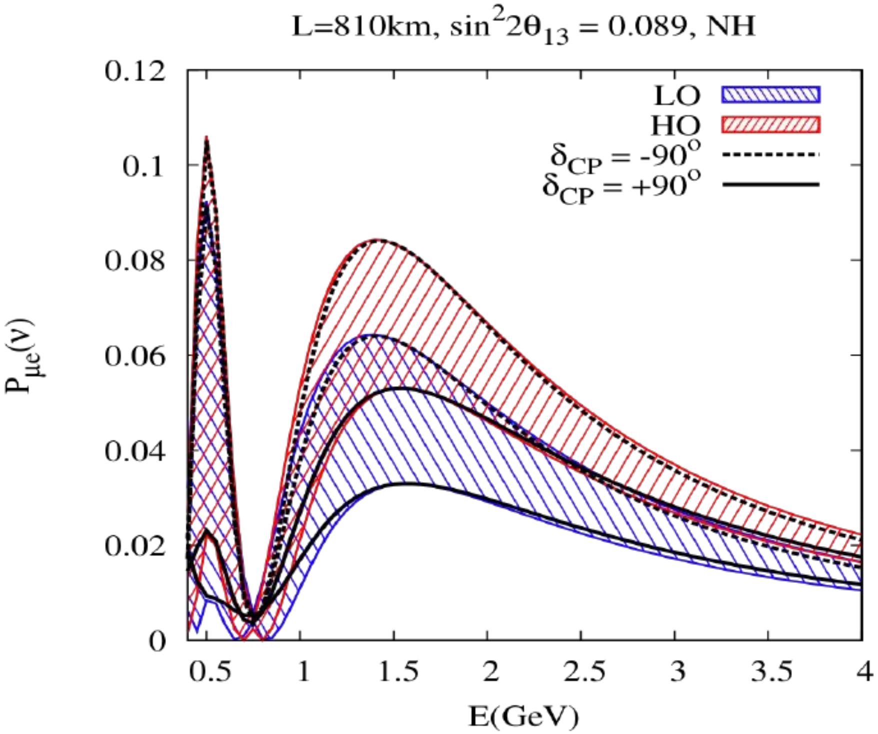
Favorable combinations
For neutrino
NH, LHP (-180° to 0°)
For antineutrino
IH, UHP (0° to 180°)

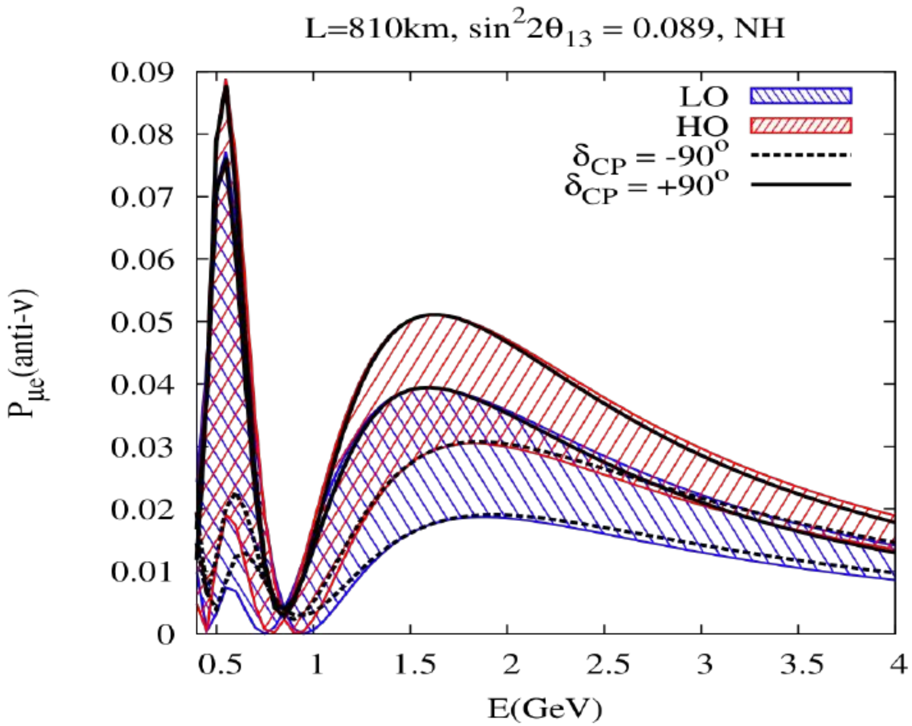


Large θ_{13} causes large Earth matter effects

Agarwalla, Prakash, Raut, Sankar, 2012-2013

Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel





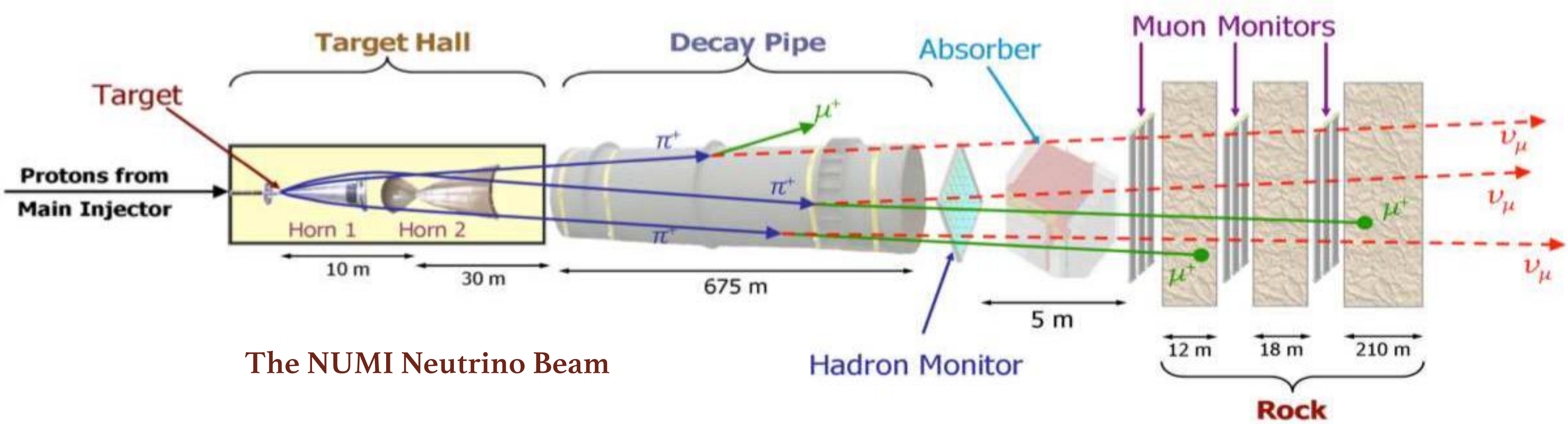
For neutrino:
Maximum: HO, -90°
Minimum: LO, 90°

For anti-neutrino:
Maximum: HO, 90°
Minimum: LO, -90°

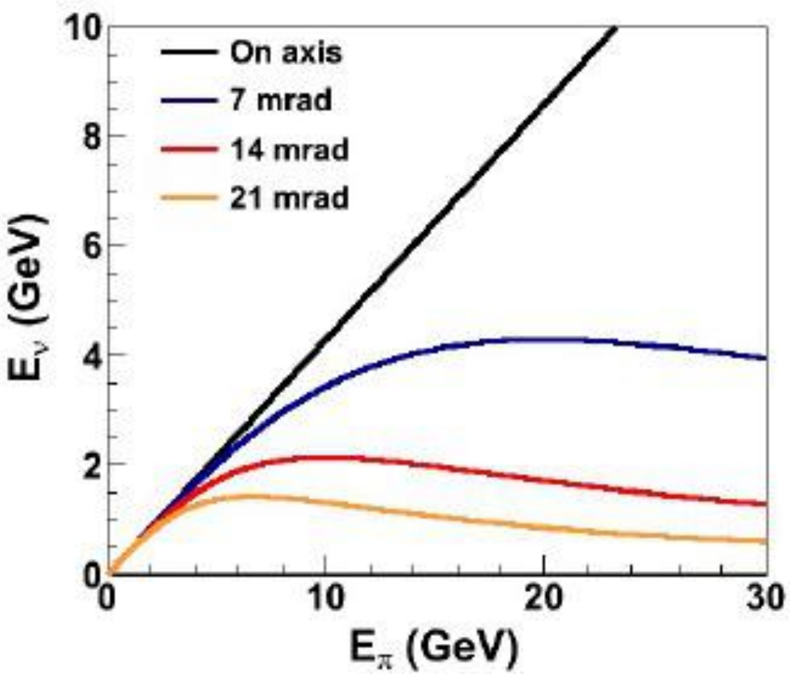
Unfavorable CP values for neutrino are favorable for antineutrino & vice-versa

Agarwalla, Prakash, Sankar, arXiv: 1301.2574

Producing Neutrino Beam



The NUMI Neutrino Beam



Two-body decay of pion: $E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$

- NOvA is 14 mrad off-axis
- Narrow-band beam peaks at 2 GeV
- Close to 1st oscillation maximum
- Reduces high-energy NC backgrounds

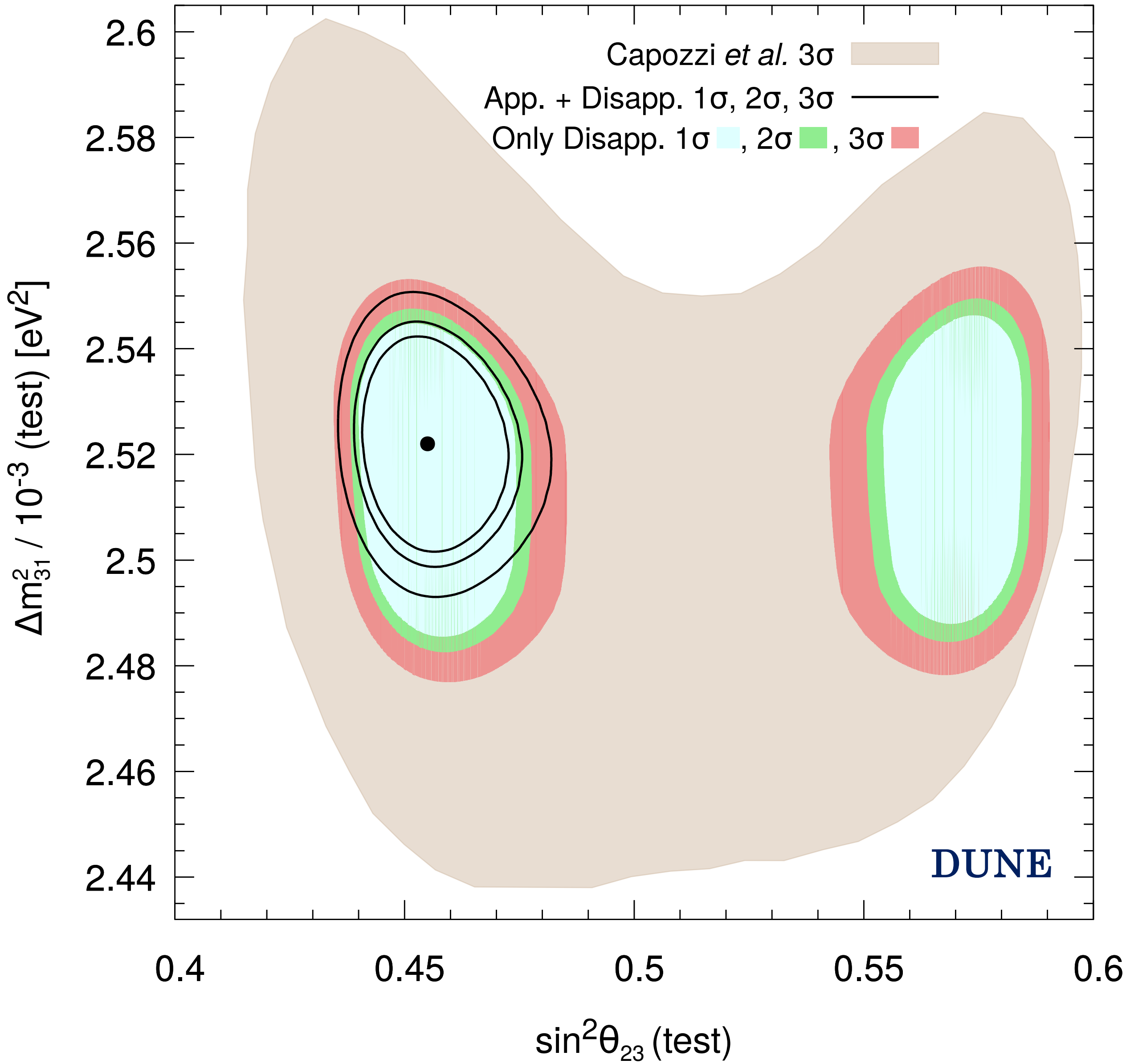
- T2K is at 2.5 degree (43.6 mrad) off-axis
- Narrow-band beam peaks at 0.6 GeV

Parameter	Best fit	3σ range	Relative 1σ (%)
$\Delta m^2_{21}/10^{-5}$ eV^2	7.36	6.93 - 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	3.03	2.63 - 3.45	4.5
$\sin^2\theta_{13}/10^{-2}$	2.23	2.04 - 2.44	3.0
$\sin^2\theta_{23}/10^{-1}$	4.55	4.16 - 5.99	6.7
$\lvert\Delta m^2_{31}\rvert/10^{-3}$eV^2	2.522	2.436 - 2.605	1.1
$\delta_{CP}/°$	223	139 - 355	16

Best-fit values of the oscillation parameters, their corresponding 3σ allowed ranges, and relative 1σ precision on the oscillation parameters assuming normal mass ordering

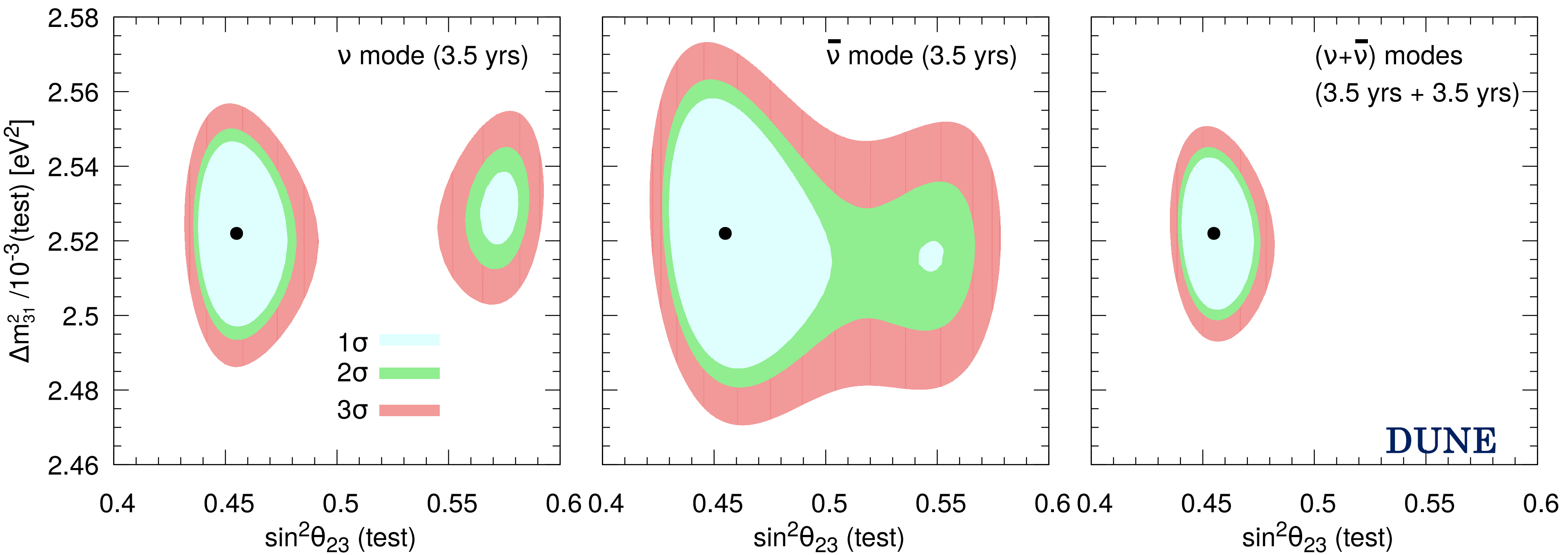
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

Precision Measurement of Atmospheric Oscillation Parameters



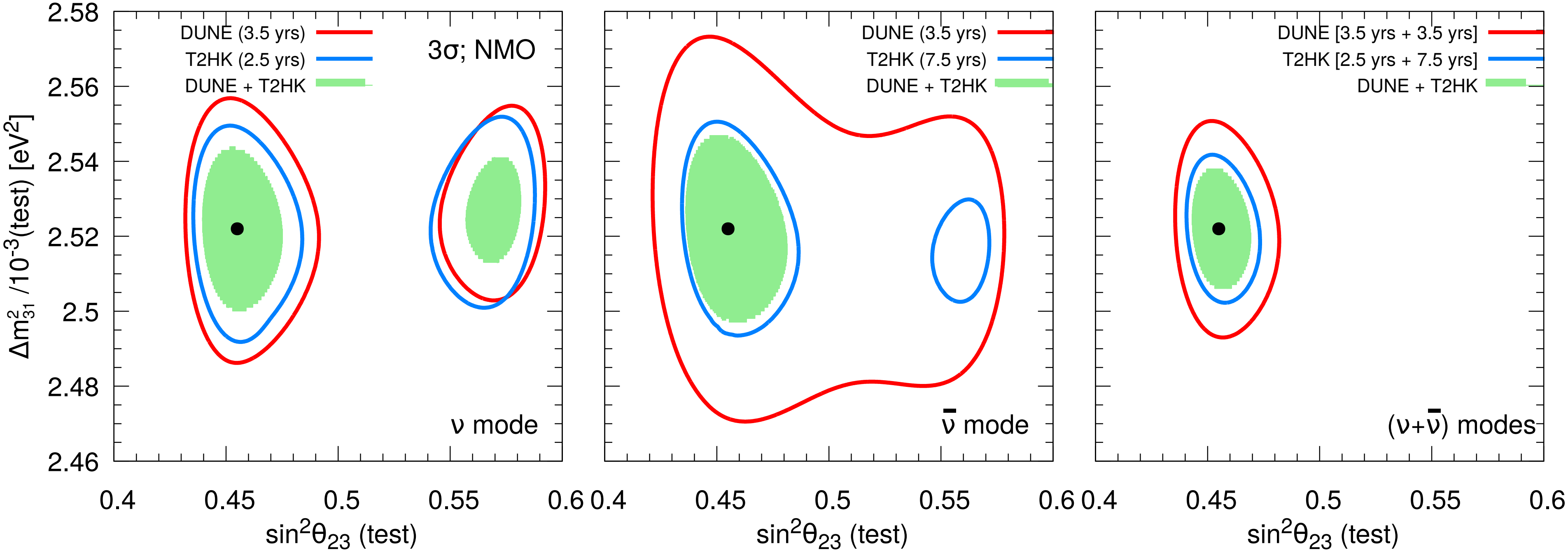
Contributions from both appearance and disappearance channels are important

Precision Measurement of Atmospheric Oscillation Parameters



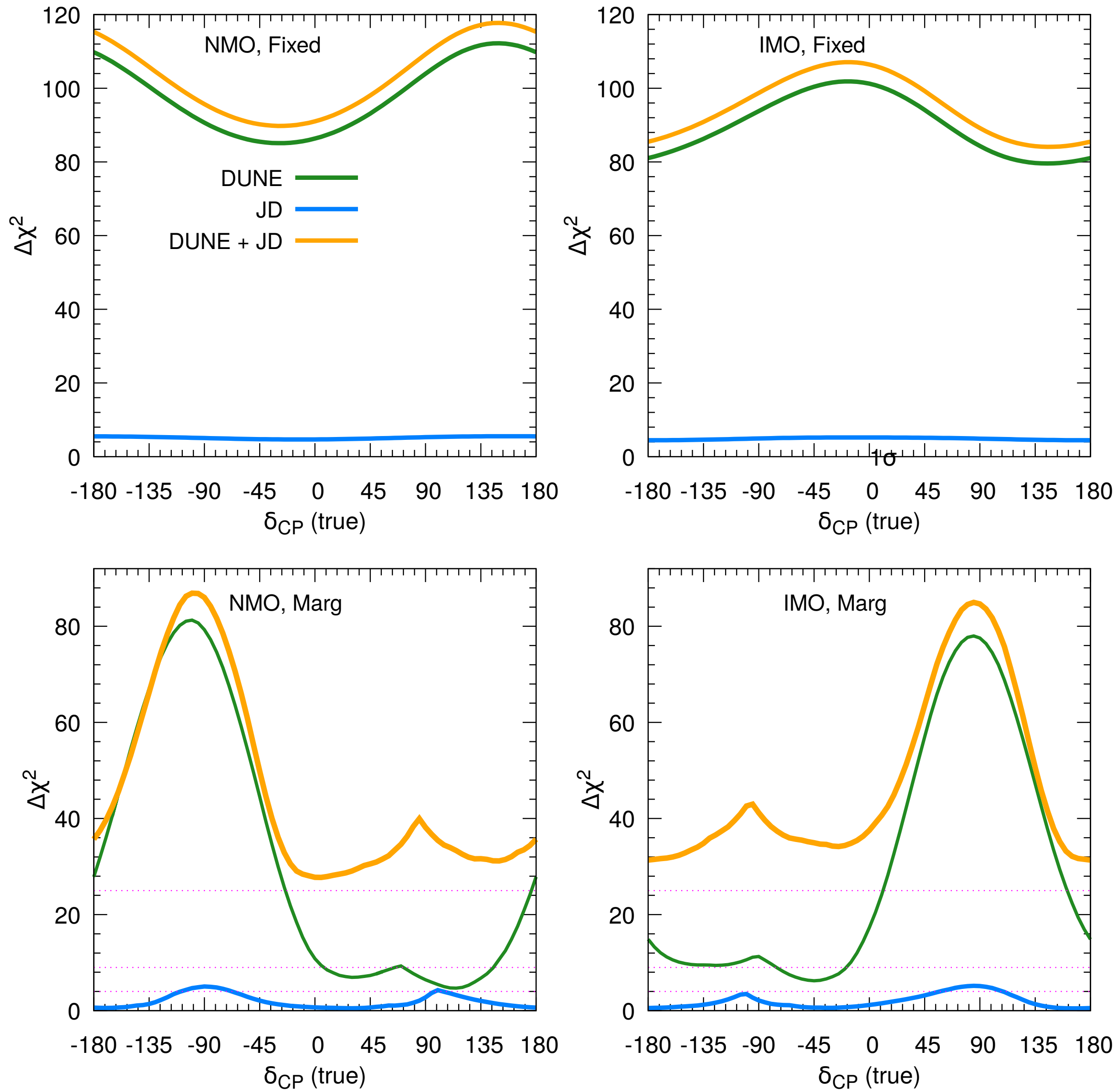
Contributions from both neutrino and antineutrino modes are crucial

Precision Measurement of Atmospheric Oscillation Parameters



Agarwalla, Kundu, and Singh, in preparation

Establishing Matter Effect in Long-Baseline Experiments



S. K. Agarwalla, M. Singh, in preparation

Present Status of Neutrino Oscillation Parameters Circa 2021

Preference for Normal Mass Ordering (~ 2.5σ), θ_{23} < 45 degree and sin**δ** < 0 (both at 90% C.L.)

Parameter	Ordering	Best fit	3σ range	"1σ" (%)
$\delta m^2/10^{-5}\ \mathrm{eV}^2$	NO, IO	7.36	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}\ \mathrm{eV}^2$	NO	2.485	2.401 – 2.565	1.1
	IO	2.455	2.376 – 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.04 – 2.44	3.0
	IO	2.23	2.03 – 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.16 – 5.99	6.7
	IO	5.69	4.17 – 6.06	5.5
δ/π	NO	1.24	0.77 – 1.97	16
	IO	1.52	1.07 – 1.90	9
$\Delta\chi^2_{\mathrm{IO-NO}}$	IO−NO	+6.5		

Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

See also, Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792v1 [hep-ph], NuFIT v5.1 w/SK

See also, de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortolla, Valle, arXiv:2006.11237v2 [hep-ph]

The Role of the *CP*-Violating CKM Phase

- If the SM extensions do not violate *CP* (this would be rather unnatural), **could the CKM phase generate the observed baryogenesis ?**

- KM *CP*-violating asymmetries, d_{CP}, must be proportional to the Jarlskog invariant J :

$$d_{CP} = J \cdot \tilde{F}_U \cdot \tilde{F}_D$$

where: $J = \mathrm{Im}\left(V_{ud} V_{cs} V_{us}^* V_{cd}^*\right) \simeq A^2 \lambda^6 \eta$, and: $\tilde{F}_U = \left(m_t^2 - m_c^2\right) \cdot \left(m_t^2 - m_u^2\right) \cdot \left(m_c^2 - m_u^2\right)$

$= \left(3.1 \pm 0.2\right) \times 10^{-5}$ $\qquad \tilde{F}_D = \left(m_b^2 - m_s^2\right) \cdot \left(m_b^2 - m_d^2\right) \cdot \left(m_s^2 - m_d^2\right)$

- Since (some) non-zero quark masses are required, *CP* symmetry can only be broken where the Higgs field has already condensed to $v_T \neq 0$ (i.e., electroweak symmetry is broken)

- To make d_{CP} dimensionless, we divide by dimensioned parameter $D = T_c$ at the EW scale ($T_c = T_{\mathrm{EW}} \sim 100$ GeV), with $[D] = \mathrm{GeV}^{12}$

$$\hat{d}_{CP} = \frac{d_{CP}}{D^{12}} \approx 10^{-19} \ll \eta \approx O\left(10^{-10}\right)$$

→ KM *CP* violation seems to be *irrelevant* for baryogenesis !