Complementarity among Next-generation Long-baseline Experiments

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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 $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$,

0.03 0.3

$$
\begin{aligned}
P_{\mu e} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& - \alpha \sin 2\theta_{13}\, \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha \sin 2\theta_{13}\, \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};
\end{aligned}
$$

0.09 → θ_{13} driven

Resolves octant

0.009 → CP-odd

→ CP-even

0.0009 → Solar Term

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!

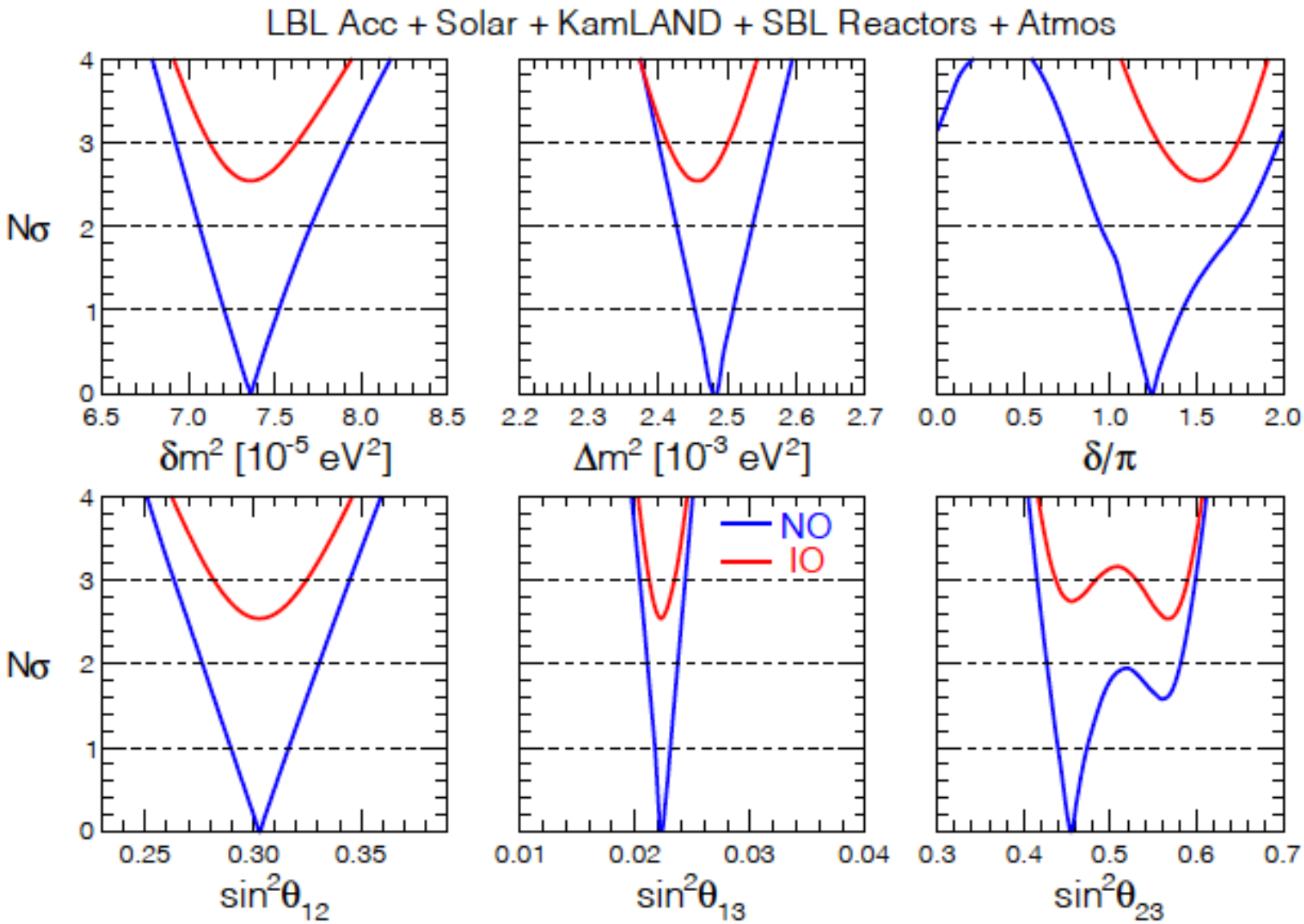
changes sign with polarity causes fake CP asymmetry!

Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071

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

Global Fit of Neutrino Oscillation Parameters Circa 2021

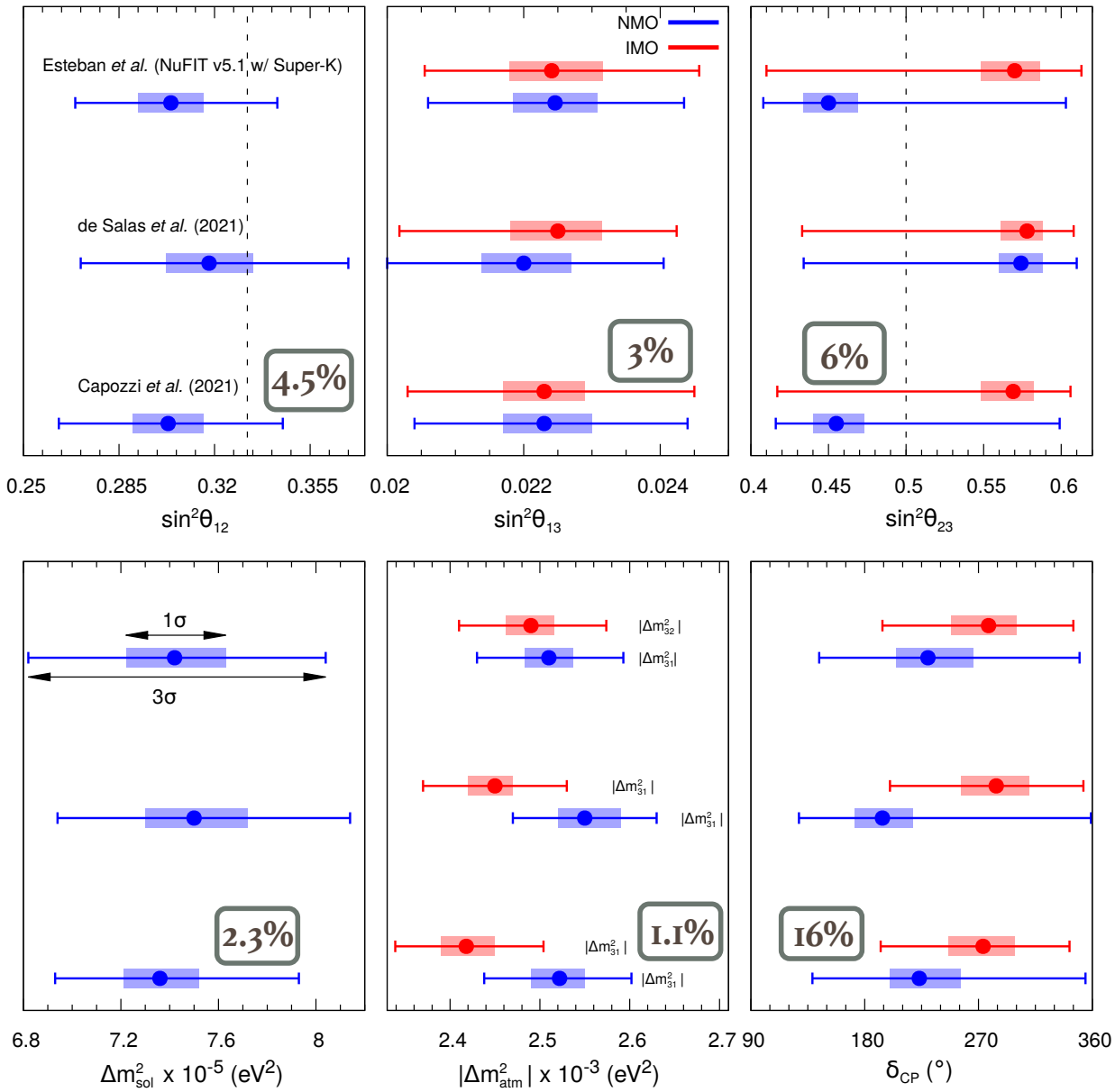
Preference for Normal Mass Ordering (~ 2.5σ), θ_{23} < 45 degree and sinδ < 0 (both at 90% C.L.)



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

Remarkable Precision on Neutrino Oscillation Parameters

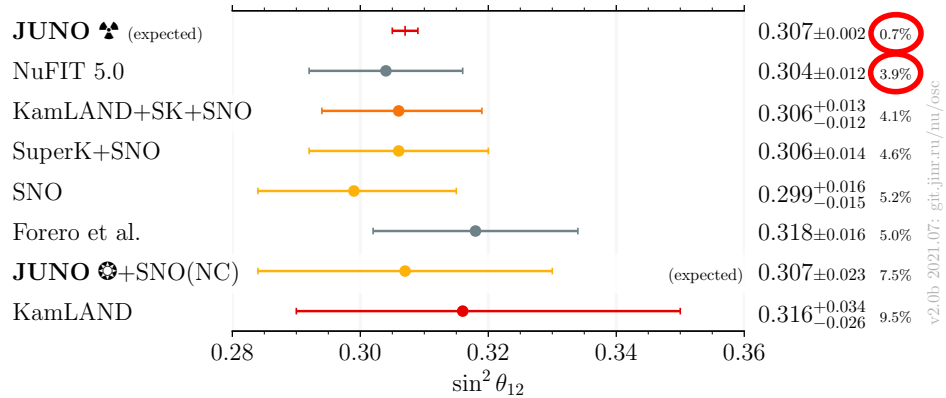
Robust three-flavor neutrino oscillation paradigm

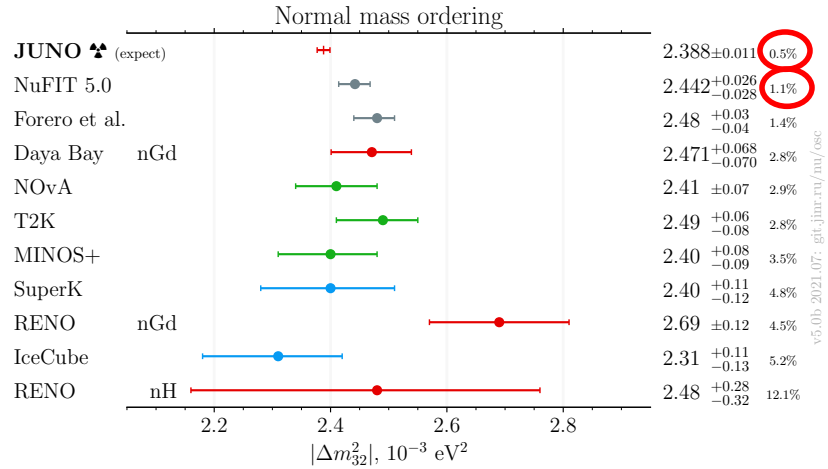


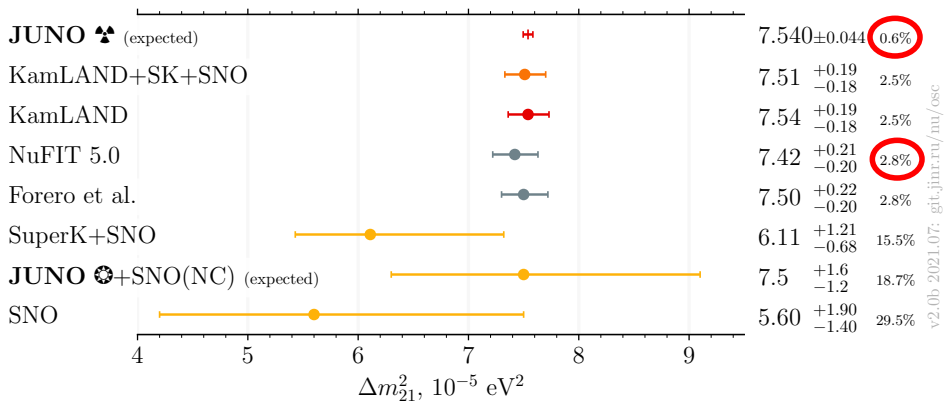
Huge boost for the discovery of NMO, CPV, and θ_{23} Octant

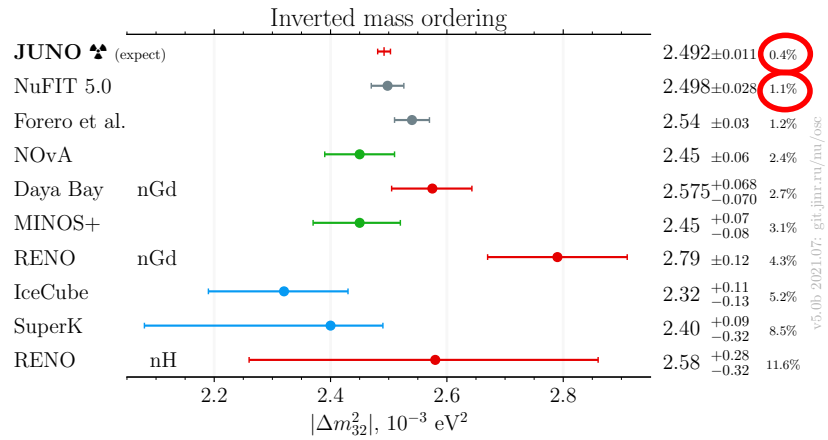
Agarwalla, Kundu, Prakash, Singh, JHEP 03 (2022) 206

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

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

	DUNE	JD/KD
Detector Mass	40 kt LArTPC	187 kt WC (each)
Baseline	1300 km	295/1100 km
Proton Energy	120 GeV	80 GeV
Beam type	Wide-band, on-axis	Narrow-band, off-axis (2.5°)
Beam power	1.2 MW	1.3 MW
P.O.T./year	1.1×10^{21}	2.7×10^{21}
Oscillation Maxima	1st (2.6 GeV) & 2nd (0.9 GeV)	1st (0.6 GeV) & 2nd (0.6 GeV)
Run time ($\nu + \bar{\nu}$)	3.5 yrs + 3.5 yrs / 5 yrs + 5 yrs	2.5 yrs + 7.5 yrs
Sig. Norm. Err. (App.)	2%	5%
Sig. Norm. Err. (Disapp.)	5%	3.5%

DUNE Collaboration: e-Print: 1606.09550 [physics.ins-det]

DUNE Collaboration: e-Print: 2103.04797 [hep-ex]

Hyper-Kamiokande Collaboration: e-Print: 1611.06118 [hep-ex]

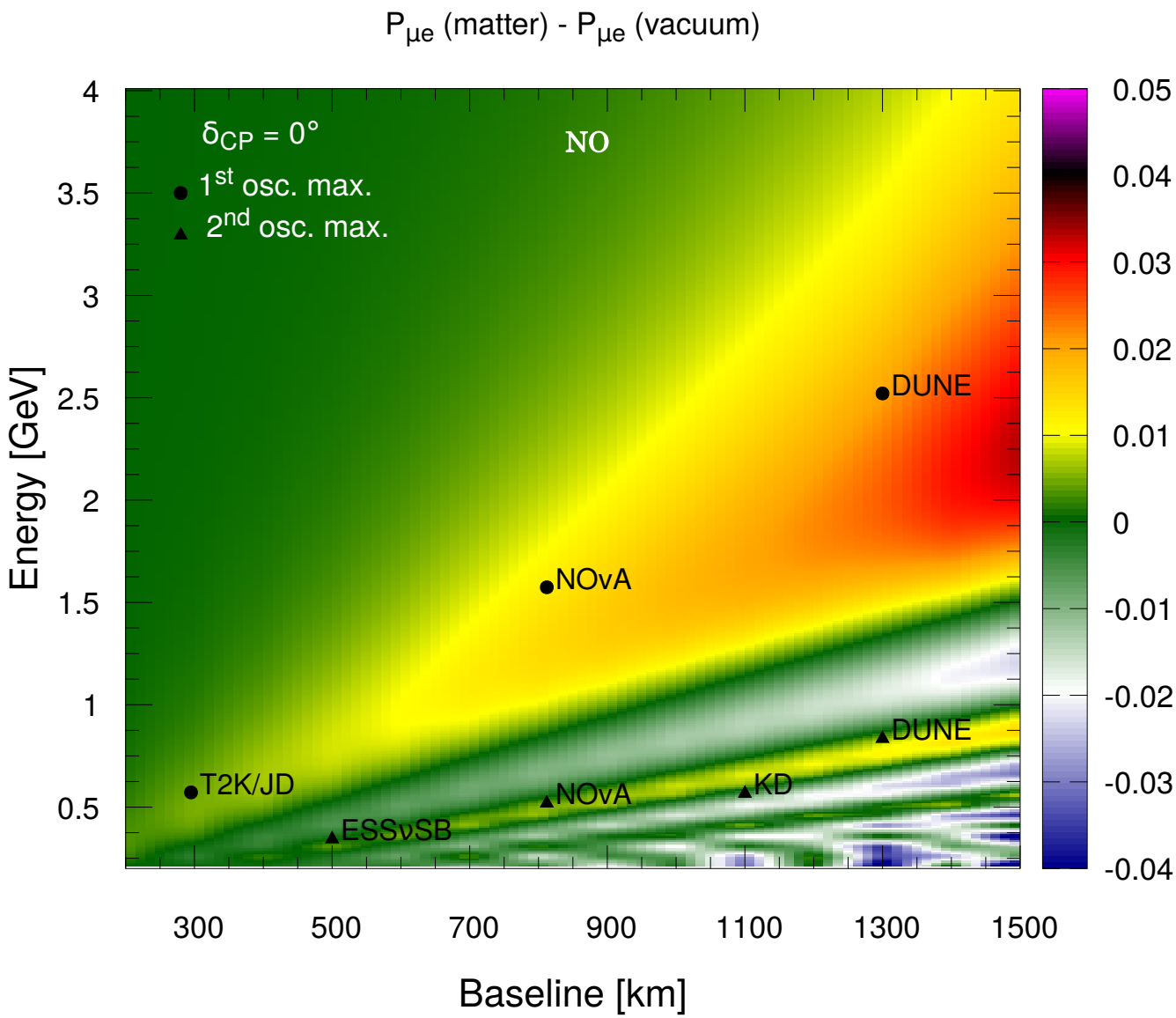
Establishing Matter Effect and Exploring (ρ_{avg} - δ_{CP}) and (ρ_{avg} – $\sin^2\theta_{23}$) Degeneracies in Next-generation Long-baseline Experiments

-- A Striking Complementarity between DUNE and T2HK (JD) / T2HKK (JD+KD)

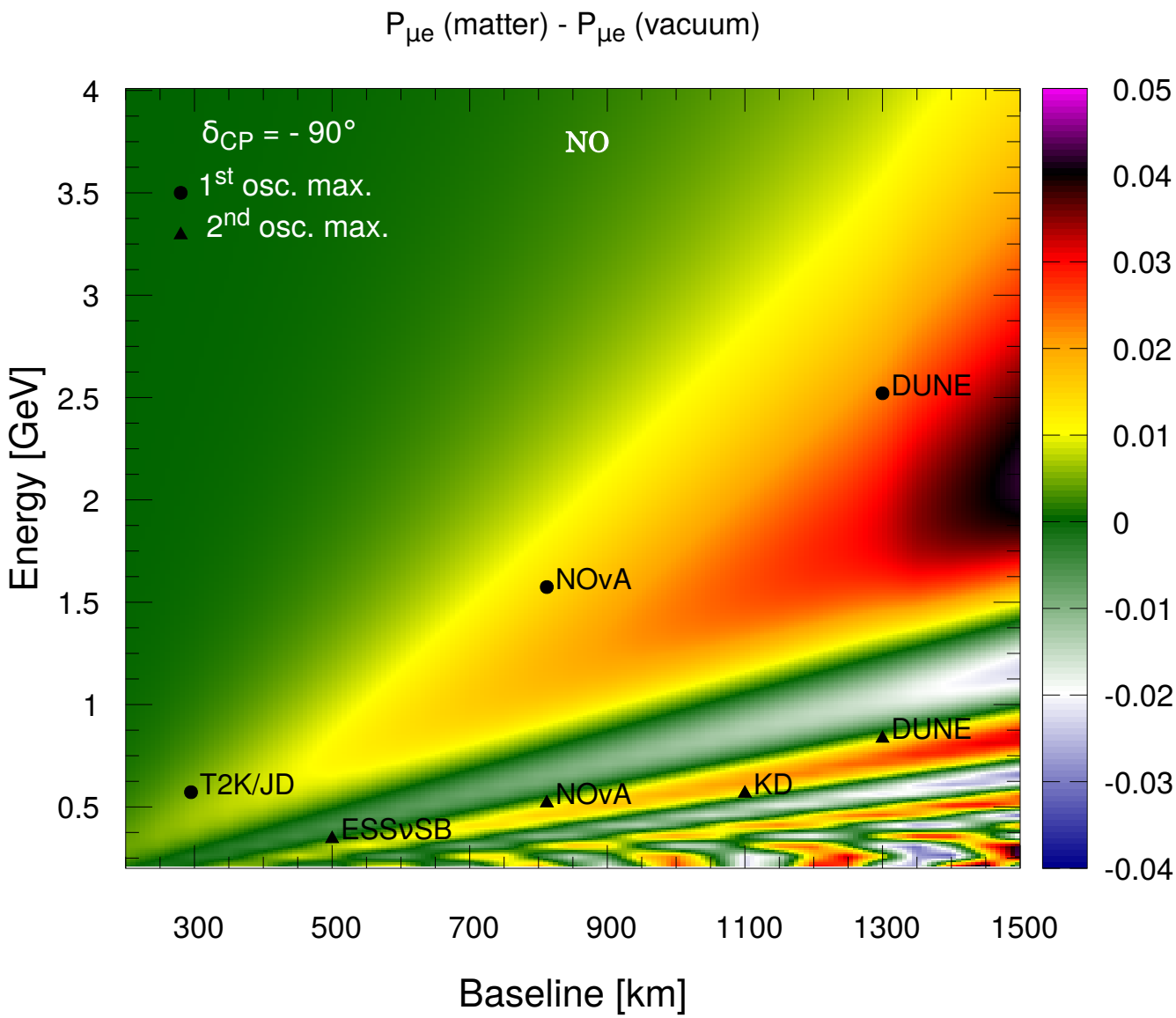
Masoom Singh and Sanjib Kumar Agarwalla, PoS (EPS-HEP2021) 191

Masoom Singh, Soumya C., and Sanjib Kumar Agarwalla, in preparation

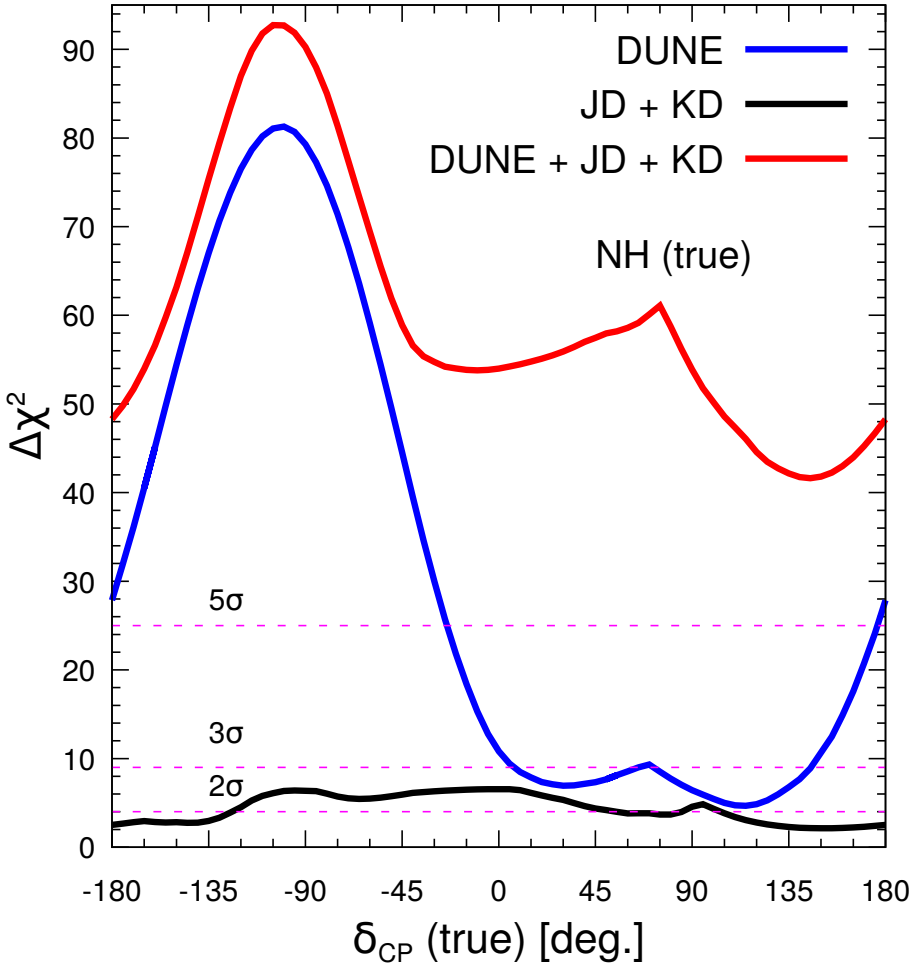
Matter Effect in Long-Baseline Experiments

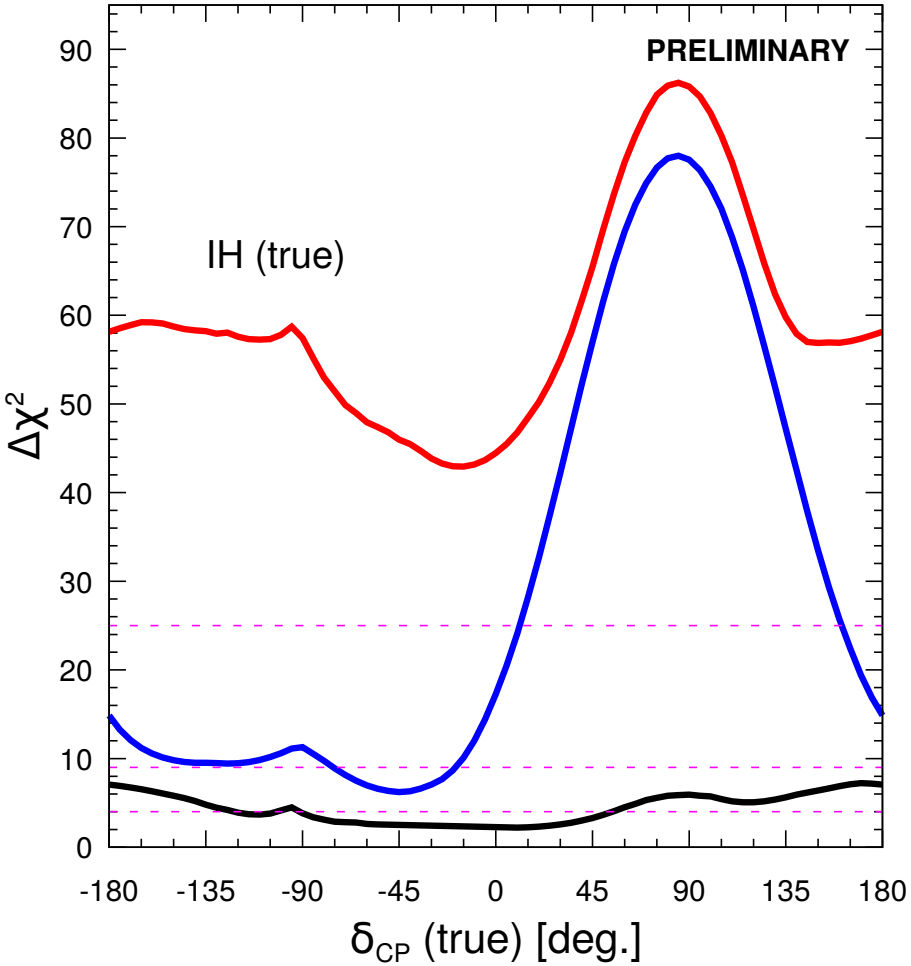


Matter Effect in Long-Baseline Experiments



Establishing Matter Effect in Long-Baseline Experiments



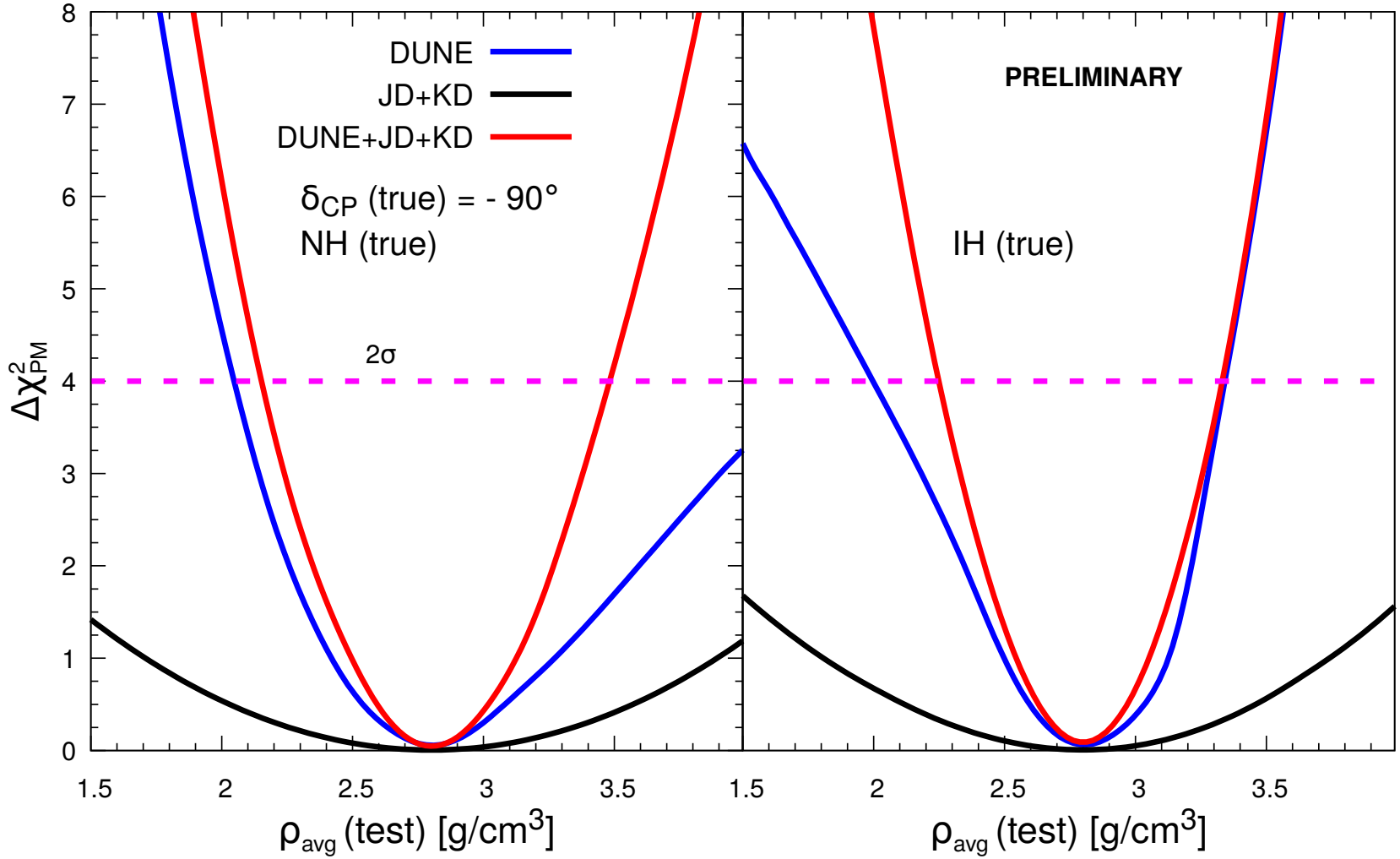


Interesting complementarity between DUNE and T2HKK (JD+KD)

DUNE + T2HKK can establish matter effect > 6σ C.L. irrespective of the choices of NMO, δ_{CP}, & θ_{23}

DUNE + T2HK can establish matter effect > 5σ C.L. irrespective of the choices of NMO, δ_{CP}, & θ_{23}

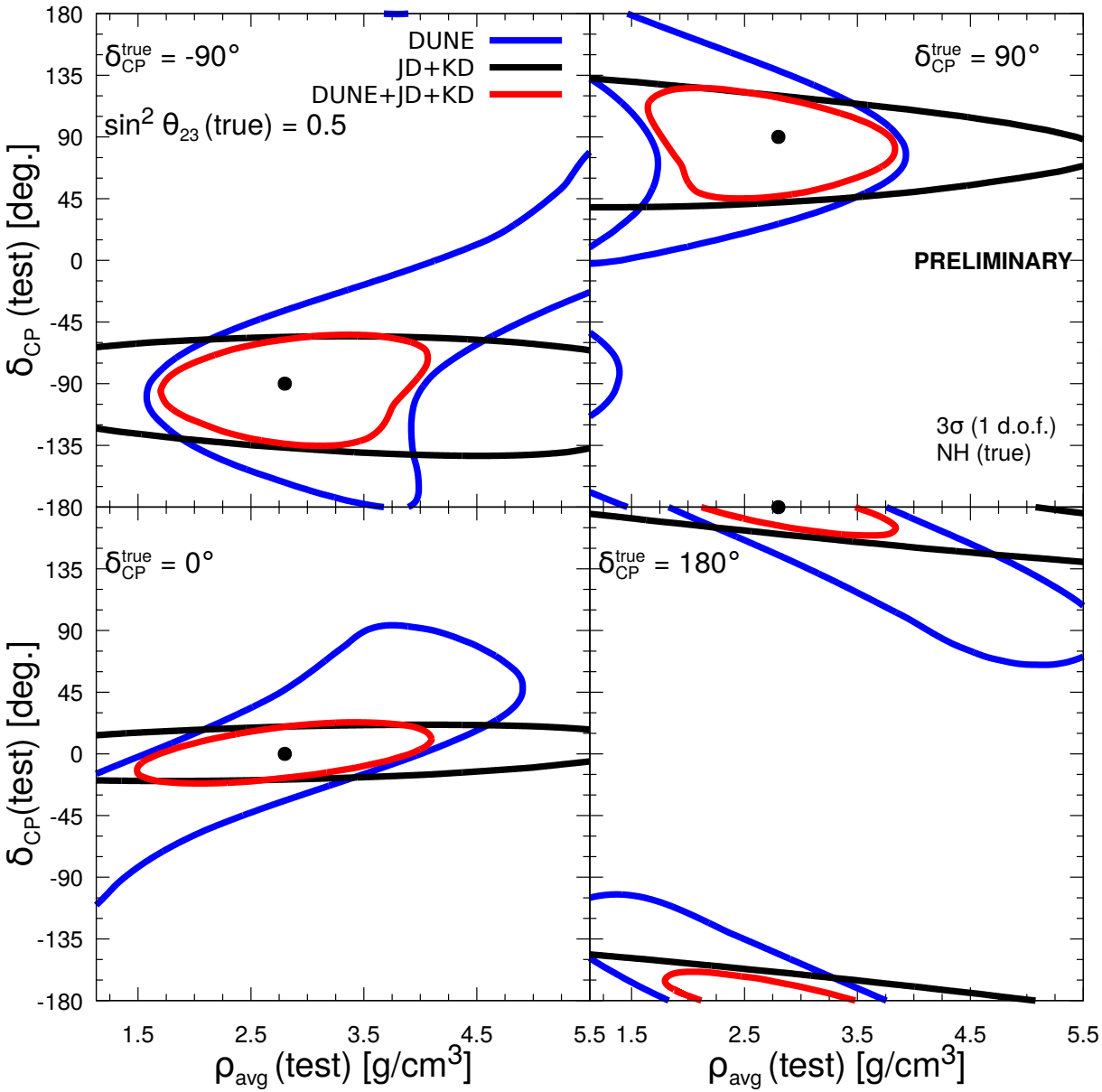
Precision Measurement of Average Matter Density



Rel. 1σ precision on ρ_{avg} for NH : JD+KD (40%), DUNE (15%), and DUNE + JD + KD (11.2%)

Rel. 1σ precision on ρ_{avg} for IH : JD+KD (35%), DUNE (12%), and DUNE + JD + KD (9.4%)

Degeneracies between Average Matter Density and CP Phase



JD + KD has no sensitivity towards ρ_{avg}, but it can constrain the allowed range of δ_{CP}.

DUNE has sensitivity towards both ρ_{avg} and δ_{CP}.

DUNE + JD + KD can significantly reduce the allowed region in ($\rho_{avg} - \delta_{CP}$) plane.

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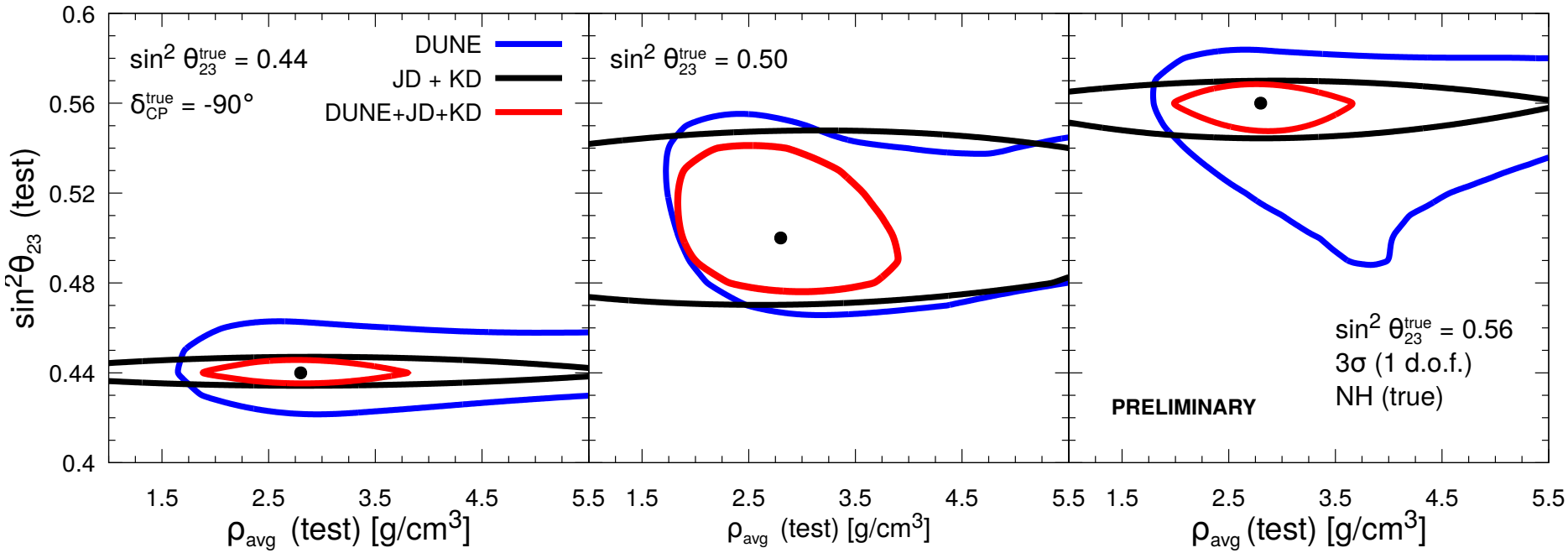
Degeneracies between Average Matter Density and θ_{23}



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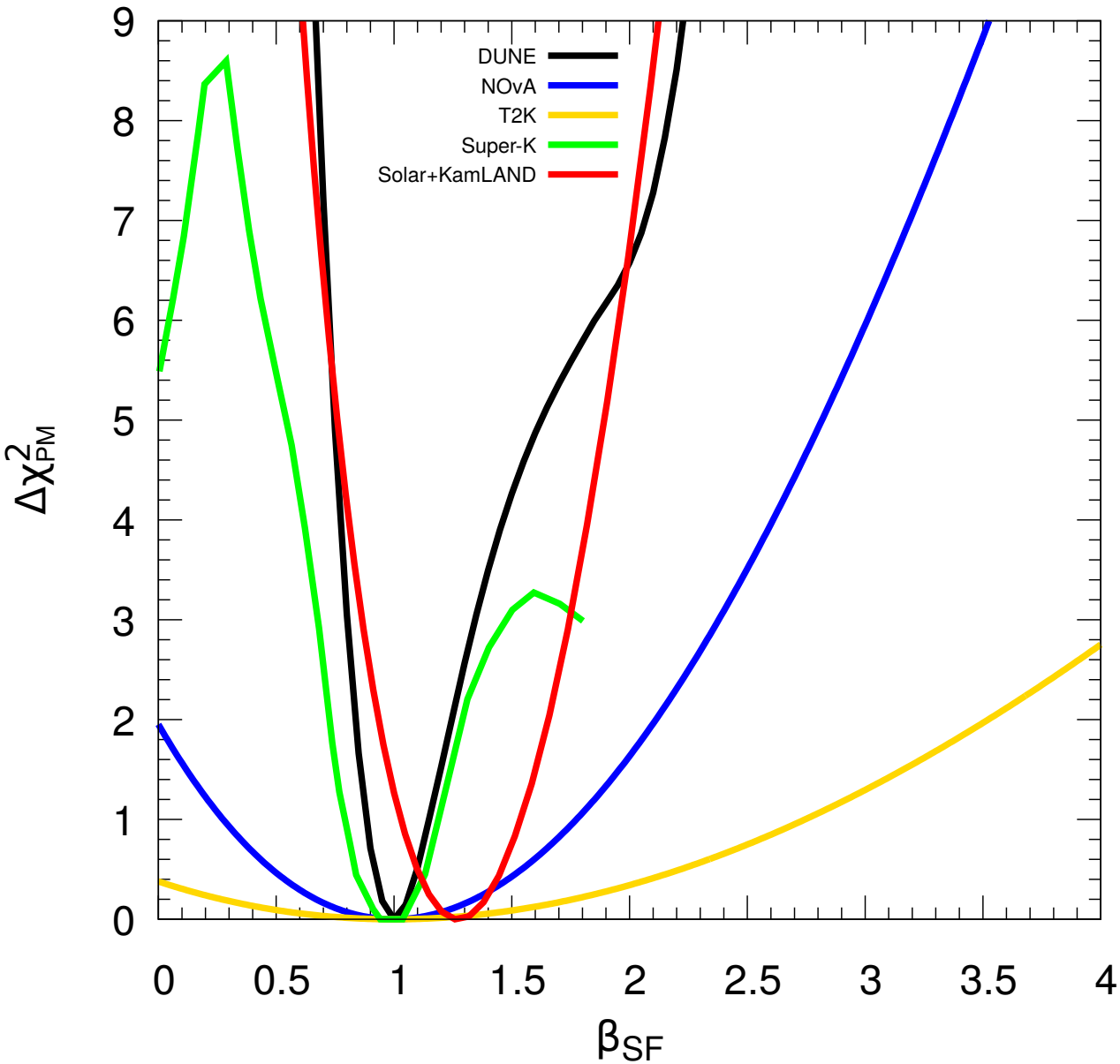
JD + KD has no sensitivity towards ρ_{avg} , but it can constrain the allowed range of θ_{23} quite precisely.

DUNE has sensitivity towards both ρ_{avg} and θ_{23}.

DUNE + JD + KD can significantly reduce the allowed region in ($\rho_{avg} - \theta_{23}$) plane.

Comparison among Various Expt. for Precision Measurement of ρ_{avg}



Masoom Singh, Soumya C., and Sanjib Kumar Agarwalla, in preparation

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)

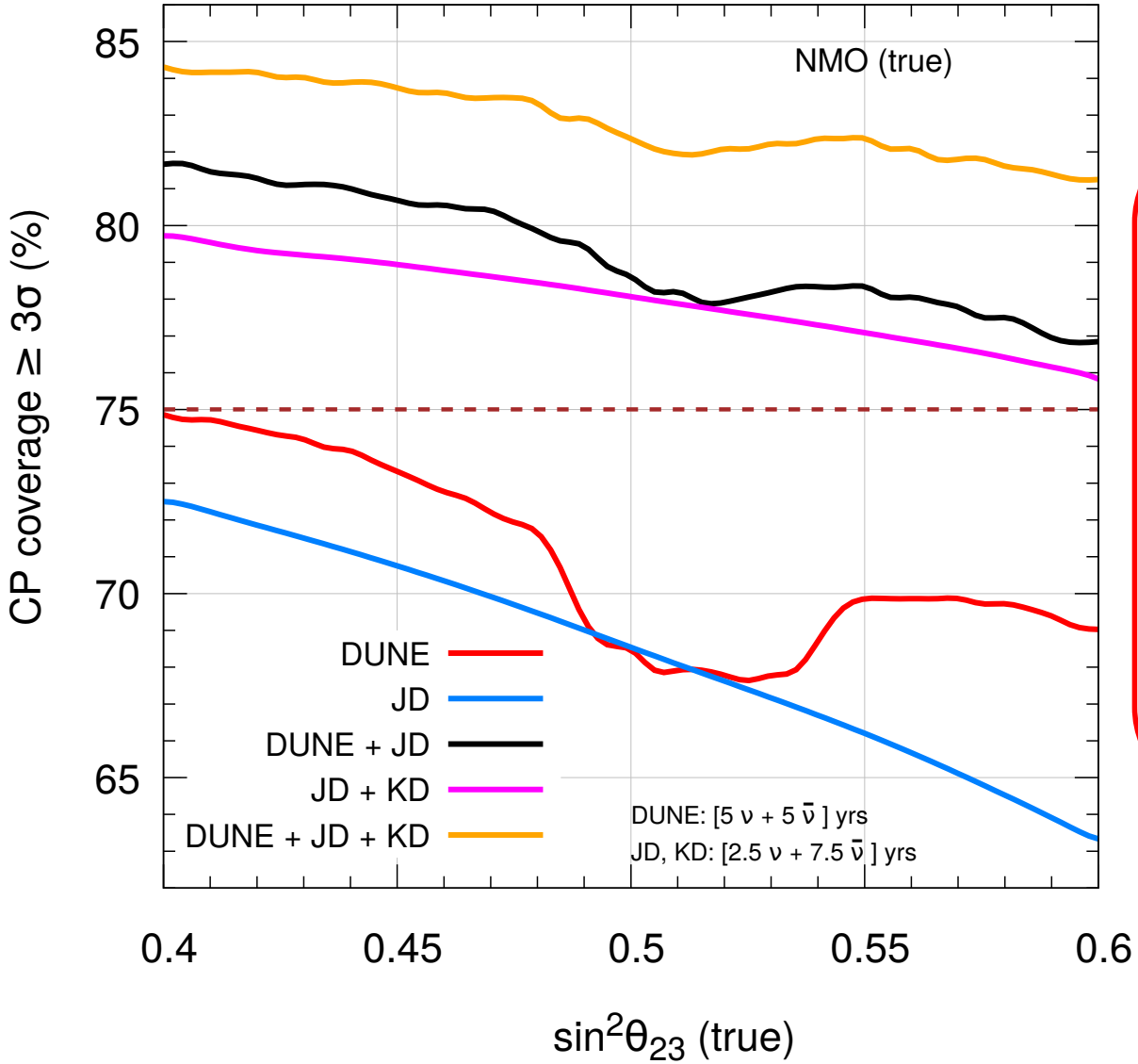
Complementarity among Next-generation Long-baseline Experiments in Searching Leptonic CP Violation

-- 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
-- Impact of neutrino and antineutrino runtime
-- Impact of exposure
-- Impact of systematic uncertainties

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

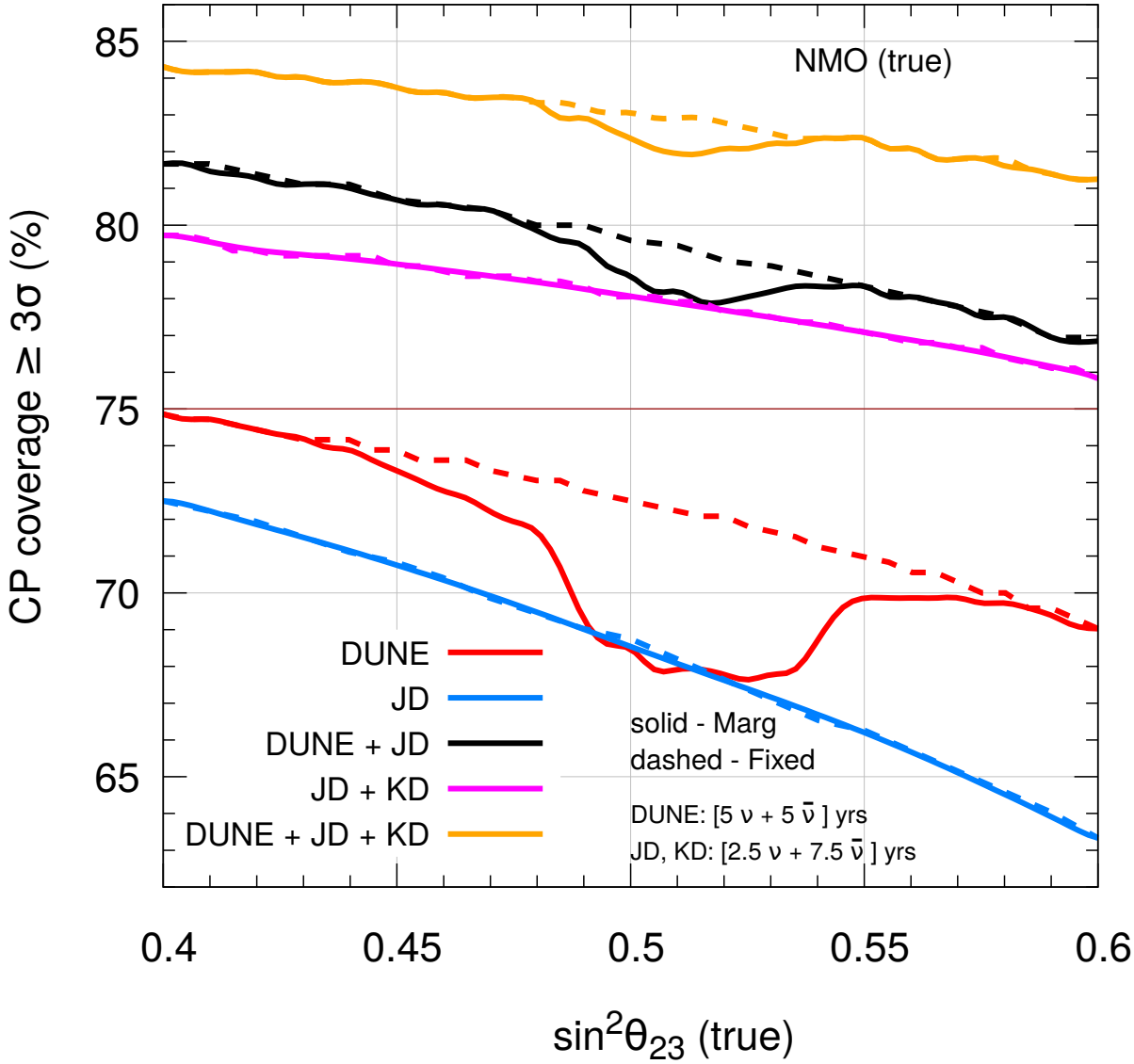
CP Coverage for Leptonic CP Violation at ≥ 3σ as a function of θ_{23}



CP asymmetry decreases with increasing value of θ_{23} and therefore, CP coverage gets reduced for higher values of θ_{23}

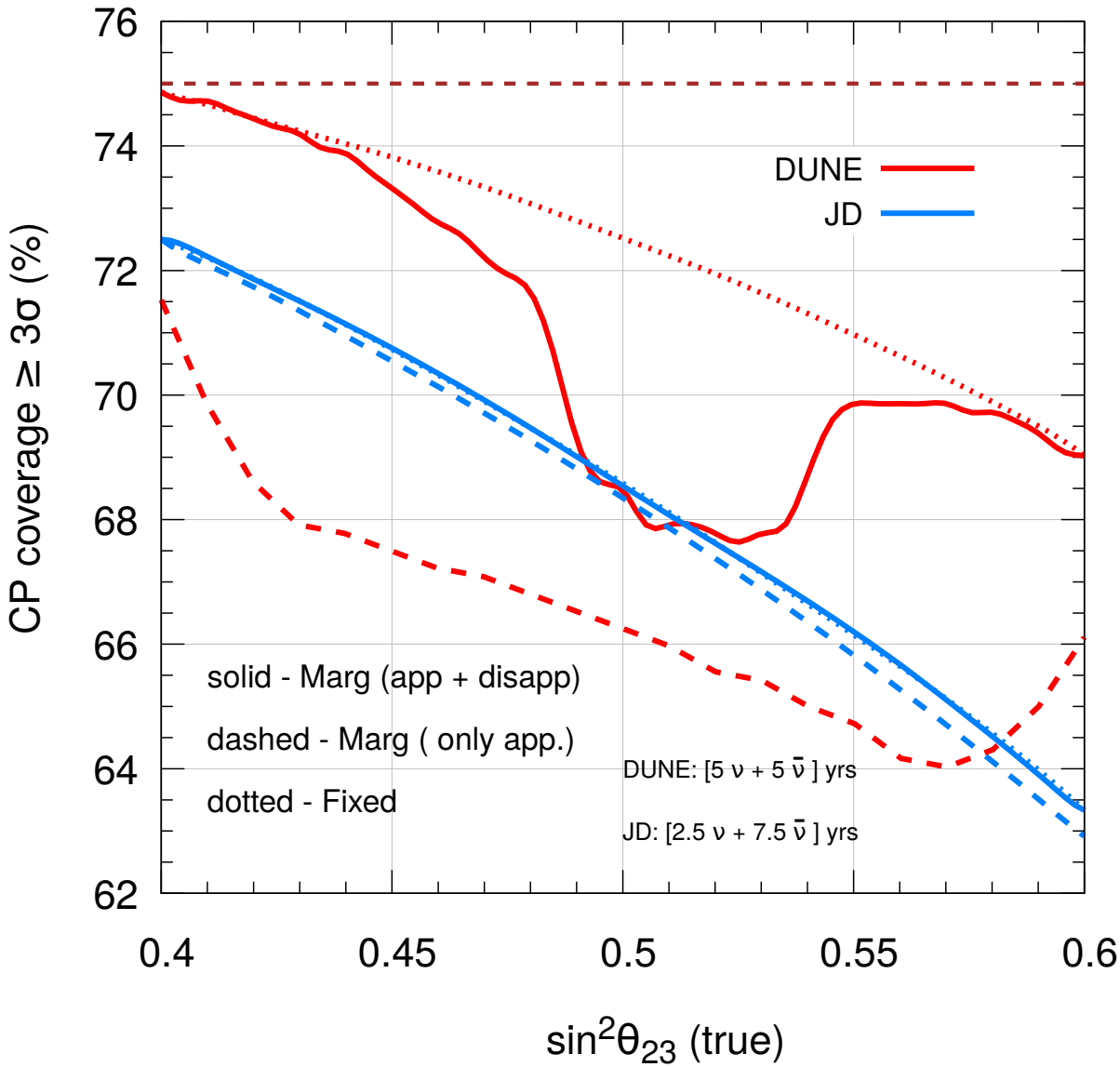
Combination of DUNE and T2HK (JD) is must to achieve leptonic CP violation at 3σ for at least 75% choices of δ_{CP}

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



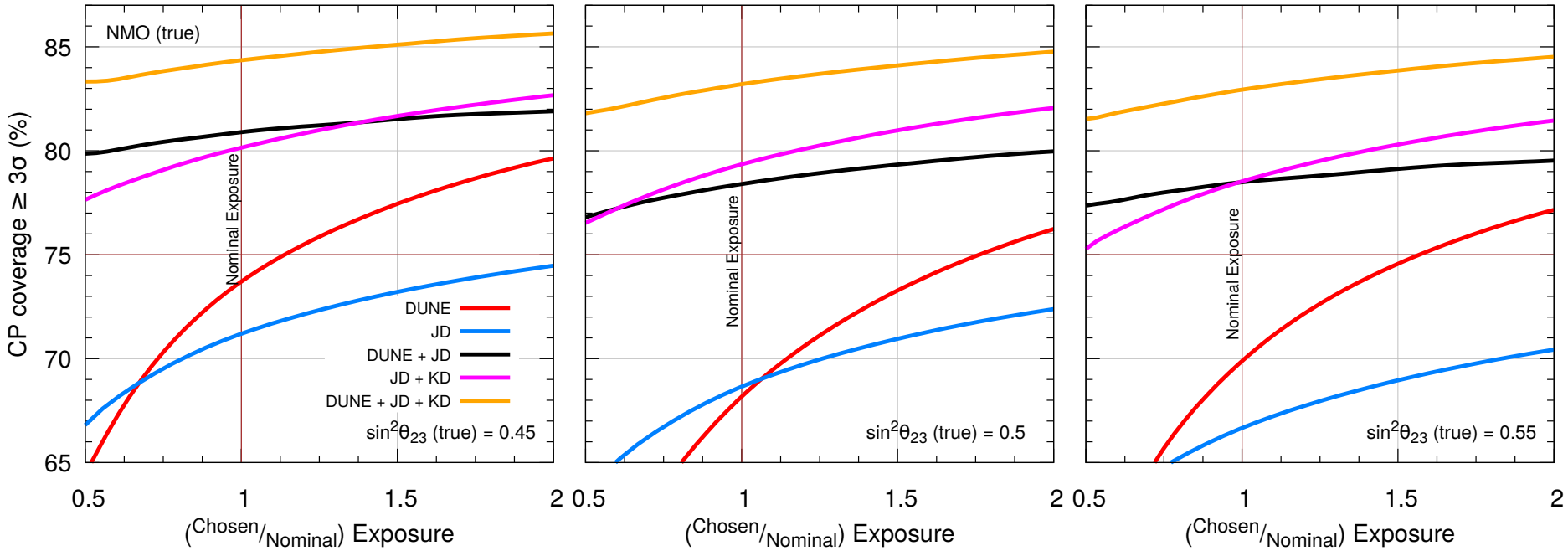
$\theta_{23} - \delta_{CP}$ degeneracies affect the CP coverage for leptonic CP violation in DUNE for θ_{23} values close to maximal mixing

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

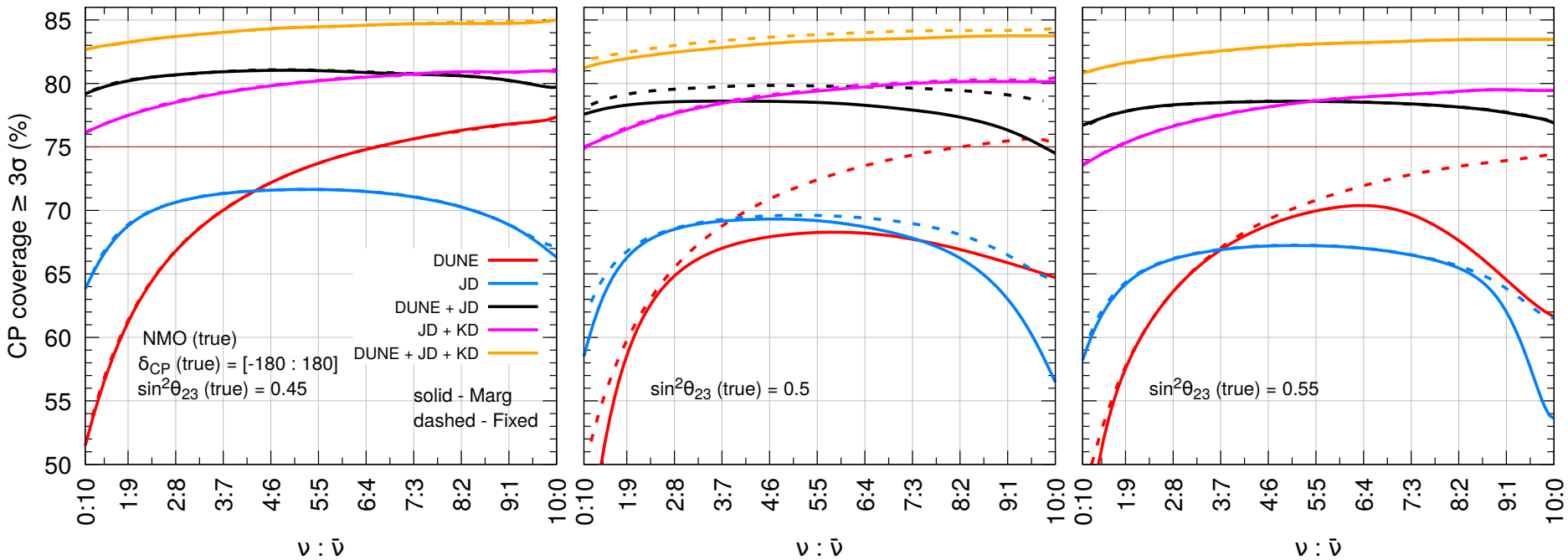


Disappearance channel plays an important role in DUNE to enhance the CP coverage for leptonic CP violation for all θ_{23}

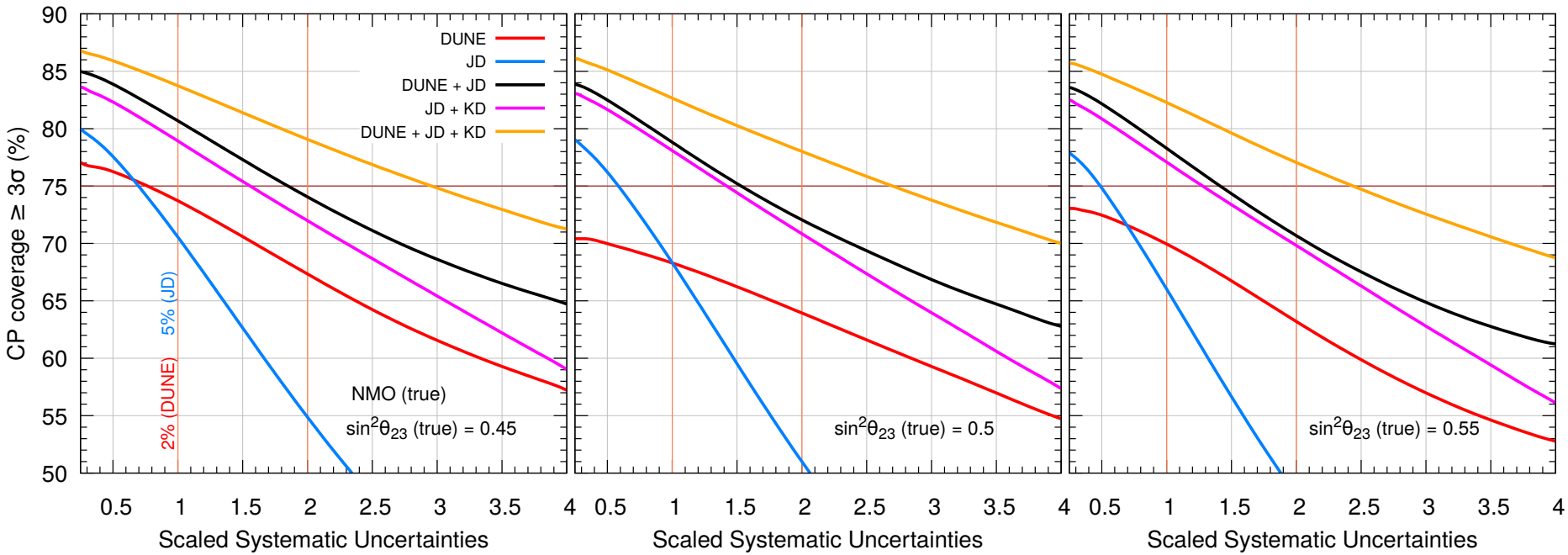
CP Coverage for Leptonic CPV at ≥ 3σ as a function of Exposure



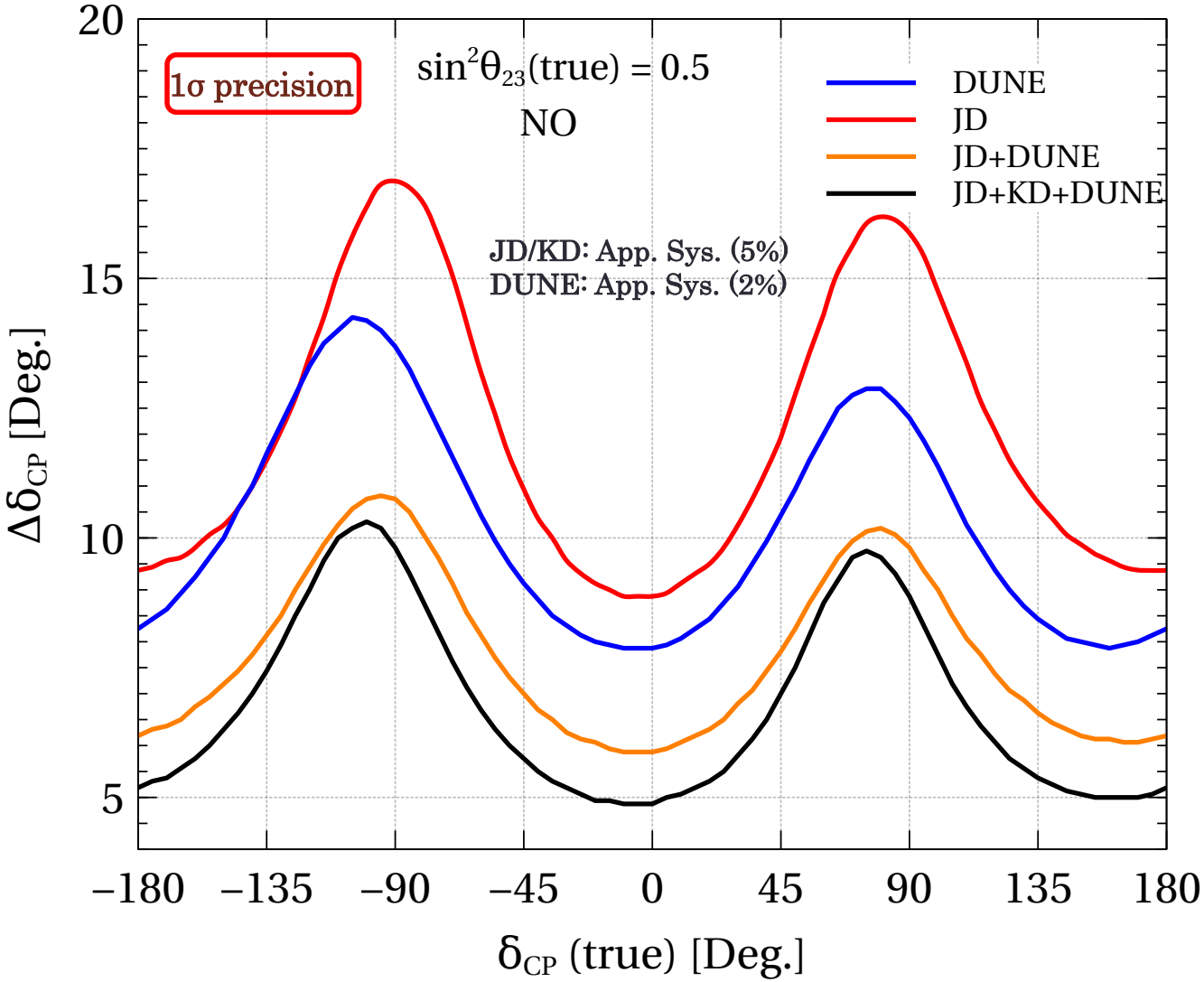
CP Coverage for Leptonic CPV at ≥ 3σ as a function of Runtime



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



High-Precision Measurement of Dirac CP Phase



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

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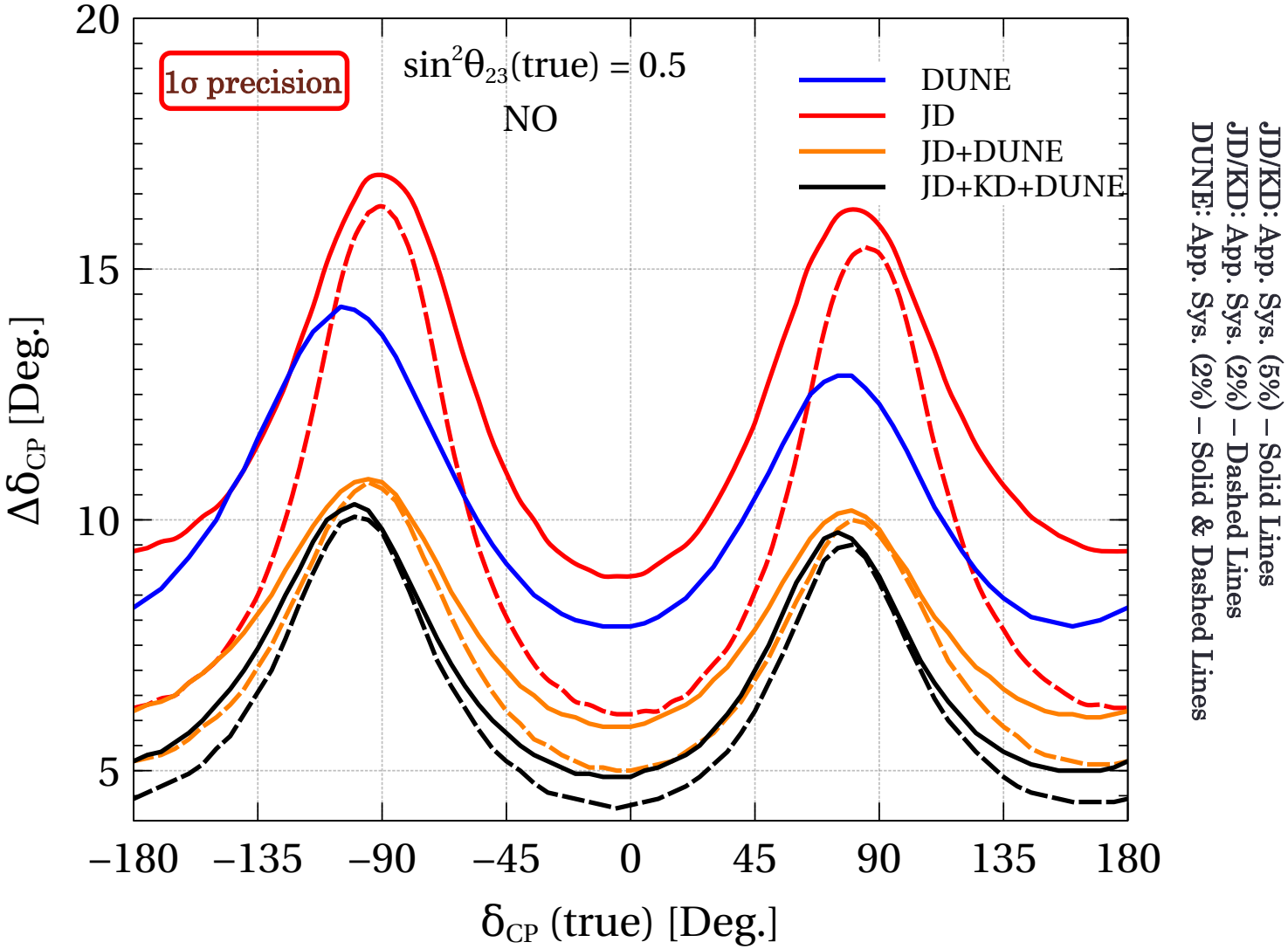
High-Precision Measurement of Dirac CP Phase



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

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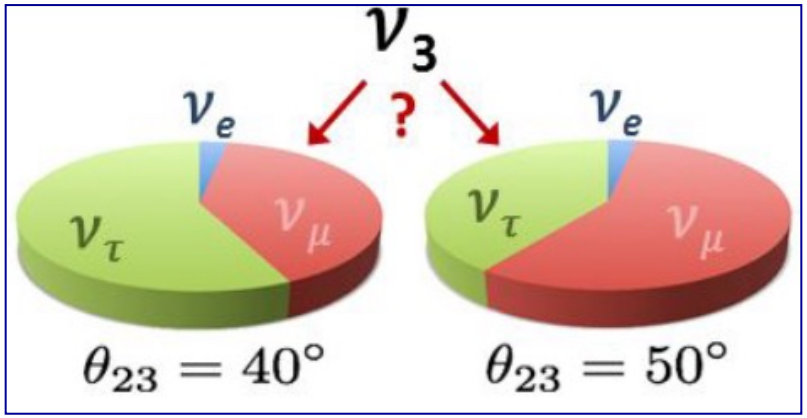
Octant of 2-3 Mixing Angle: Important Open Question

→ 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

$\nu_\mu \rightarrow \nu_e$ oscillation channel can break this degeneracy.
Preferred value would depend on the choice of neutrino mass ordering.

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

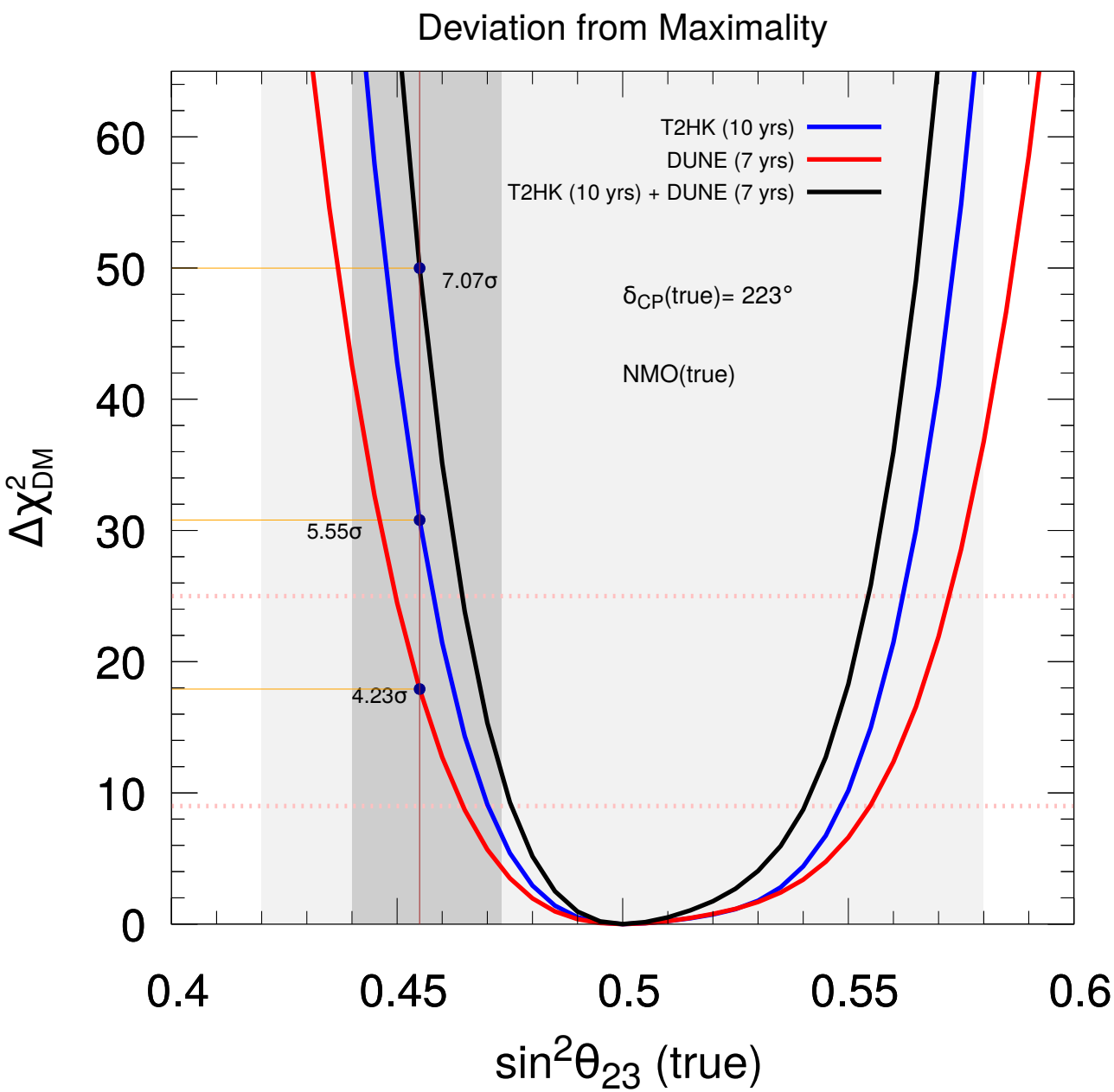
S. K. Agarwalla, R. Kundu, and M. Singh, in preparation

Parameter	Best fit	3σ range	Relative 1σ (%)
$\Delta m^2_{21}/10^{-5}\ \mathrm{eV}^2$	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
$\lvert\Delta m^2_{31}\rvert/10^{-3}\mathrm{eV}^2$	2.522	2.436 - 2.605	1.1
$\delta_{CP}/^\circ$	223	139 - 355	16

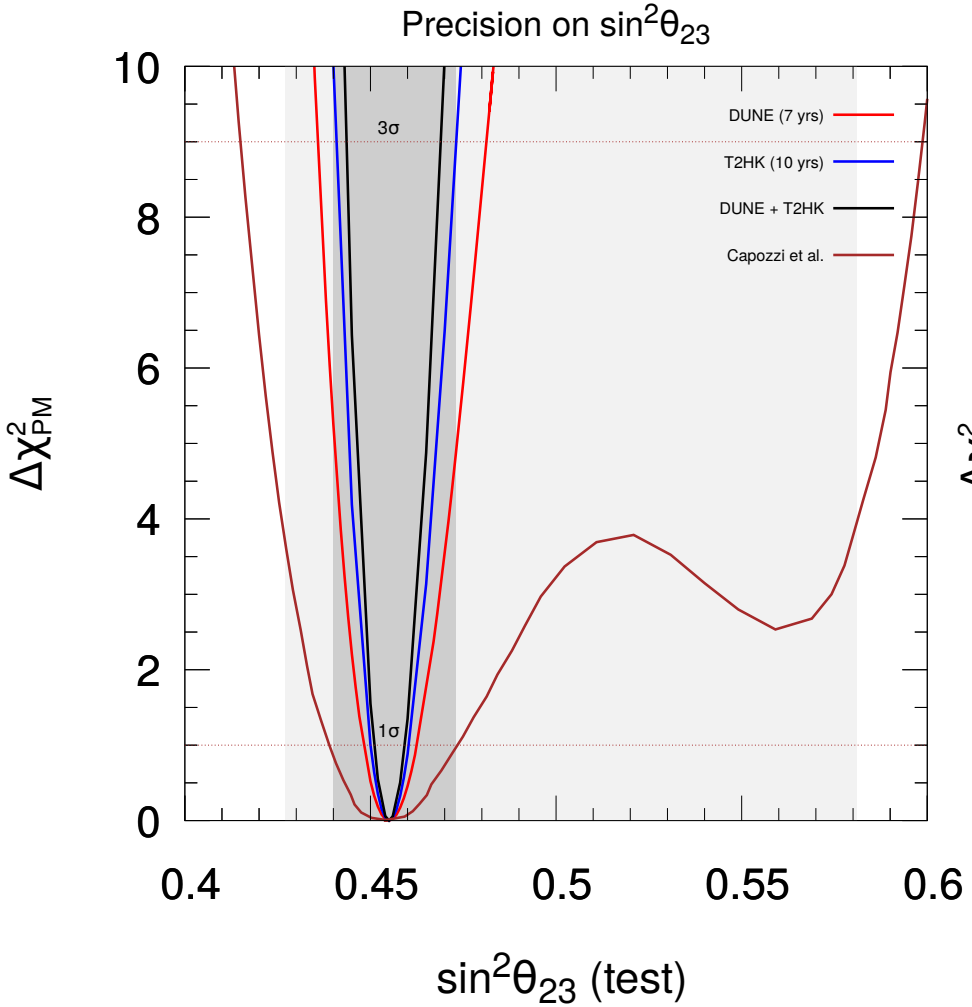
Best-fit values of the oscillation parameters, their corresponding 3σ allowed ranges, and relative 1σ precision on the oscillation parameters assuming normal mass ordering

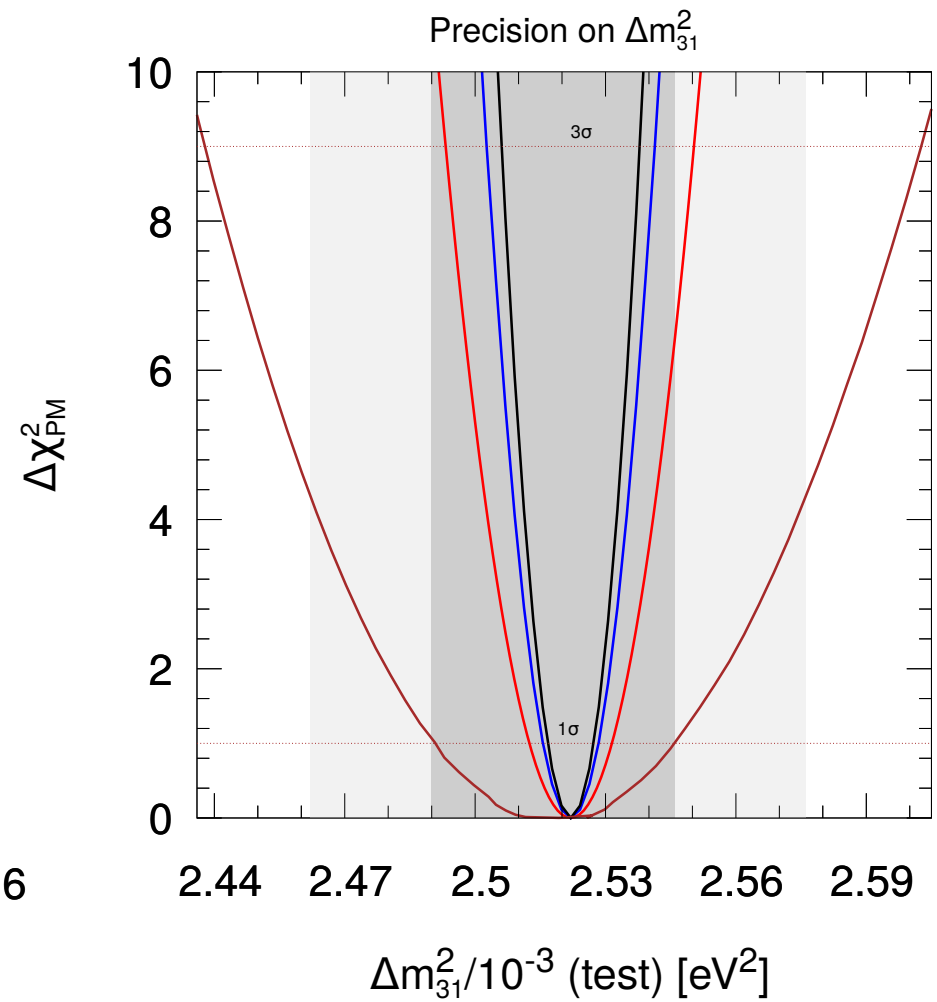
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

Deviation from Maximal θ_{23}



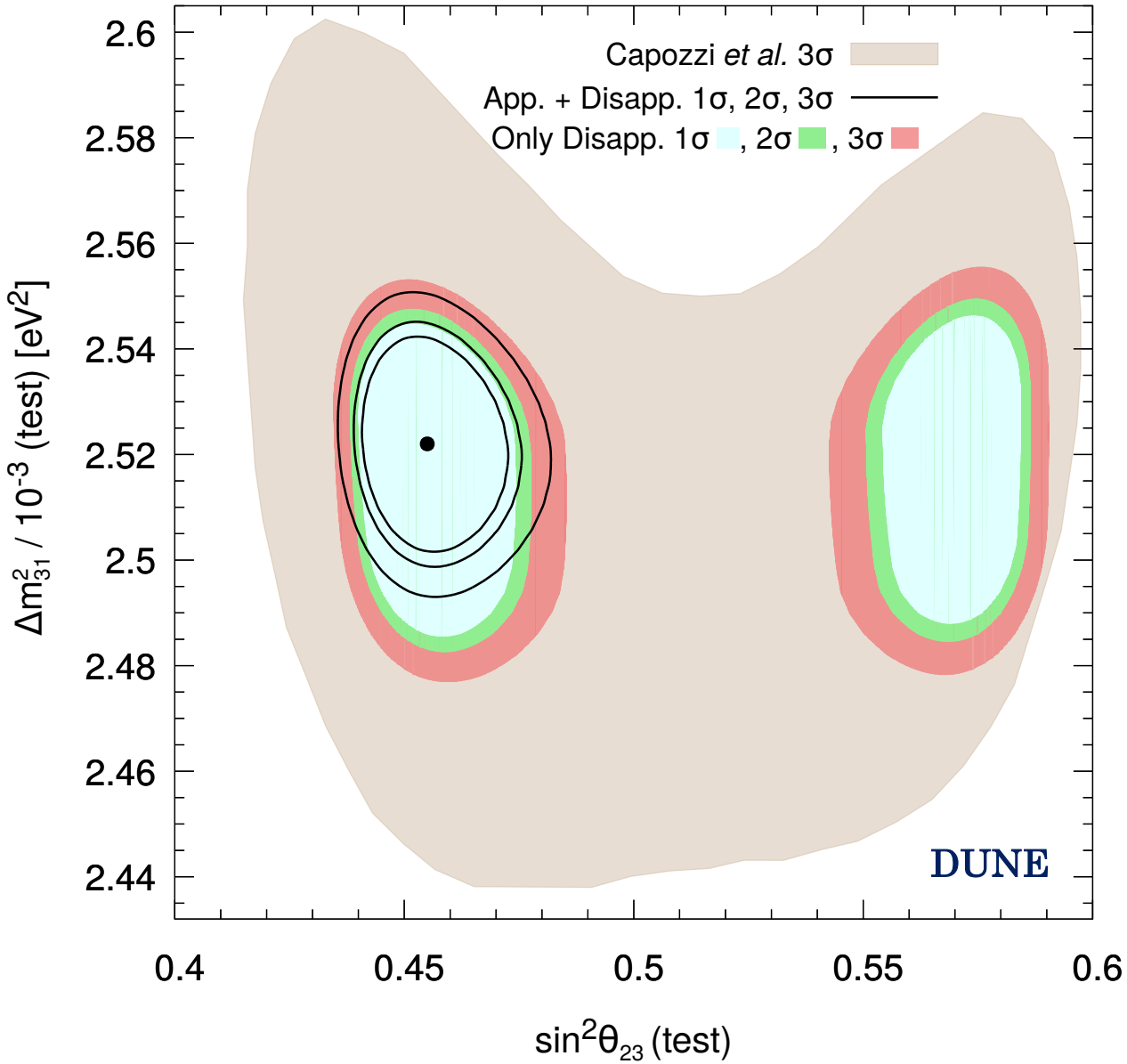
Precision Measurement of Atmospheric Oscillation Parameters





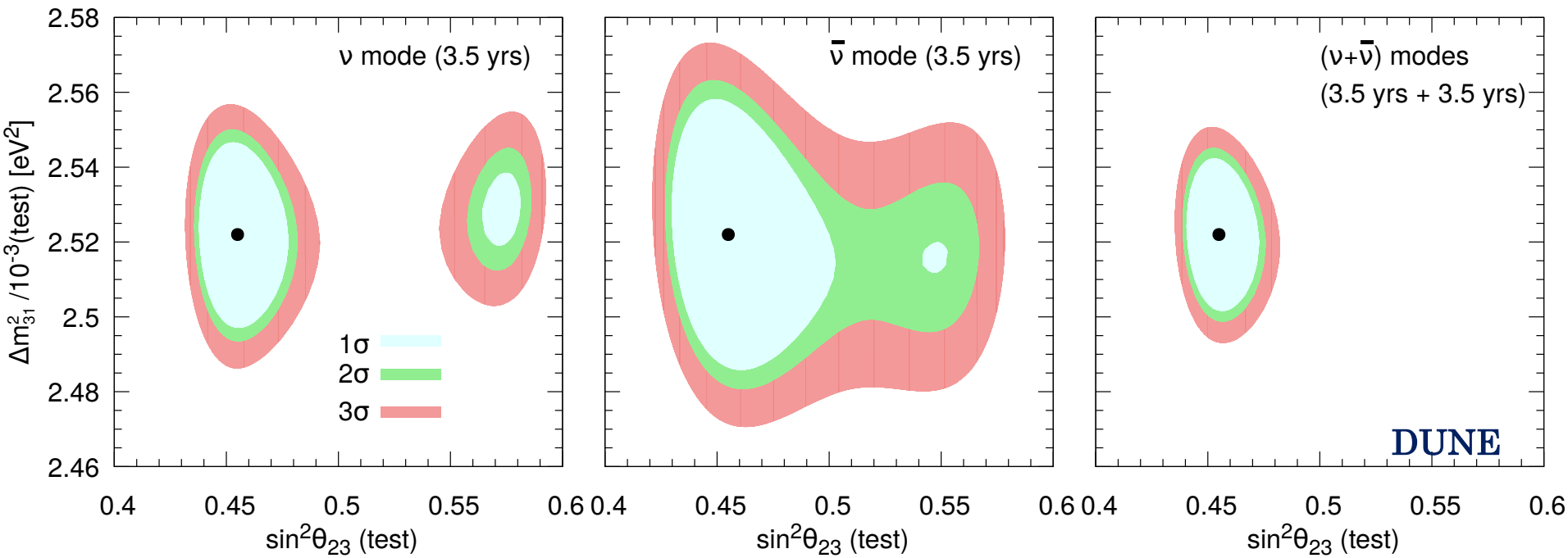
Parameter	Relative 1σ precision (%)				
	JD ($2.5\ \nu + 7.5\ \bar{\nu}$) yrs	DUNE ($3.5\ \nu + 3.5\ \bar{\nu}$) yrs	JD+DUNE	Capozzi *et al.*	JUNO
$\sin^2\theta_{23}$	1.18	1.53	0.93	6.72	—
Δm^2_{31}	0.25	0.39	0.21	1.09	0.50

Precision Measurement of Atmospheric Oscillation Parameters



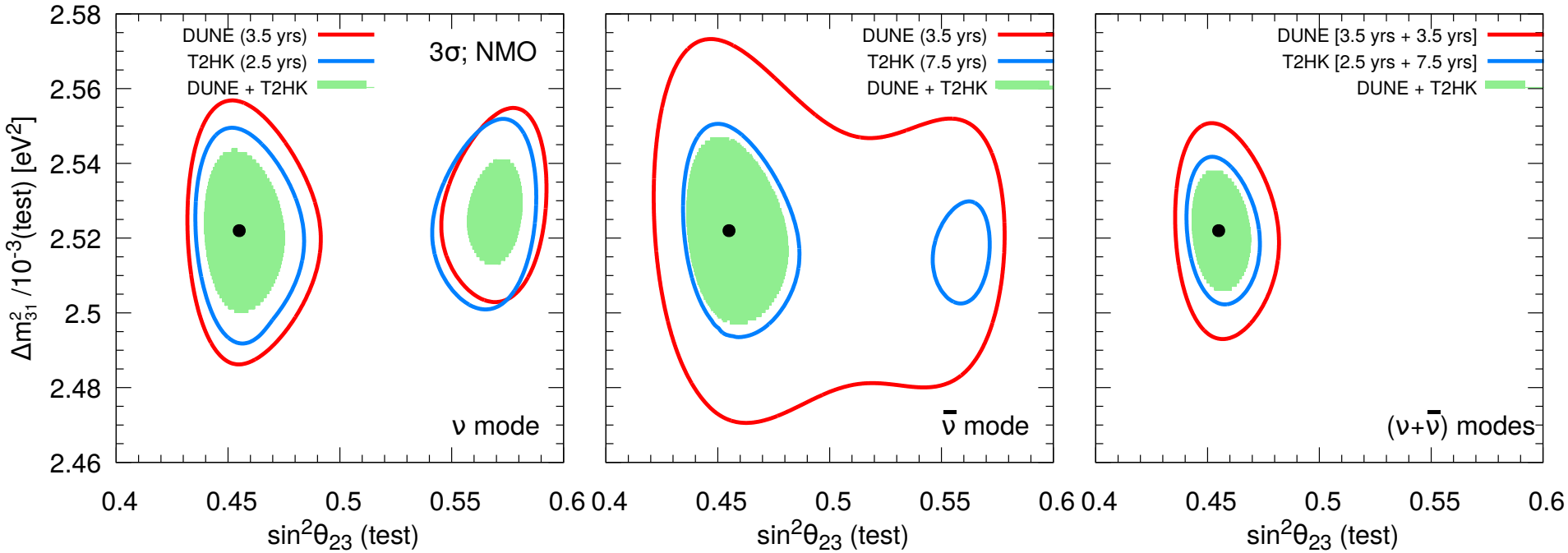
Contributions from both appearance and disappearance channels are important

Precision Measurement of Atmospheric Oscillation Parameters

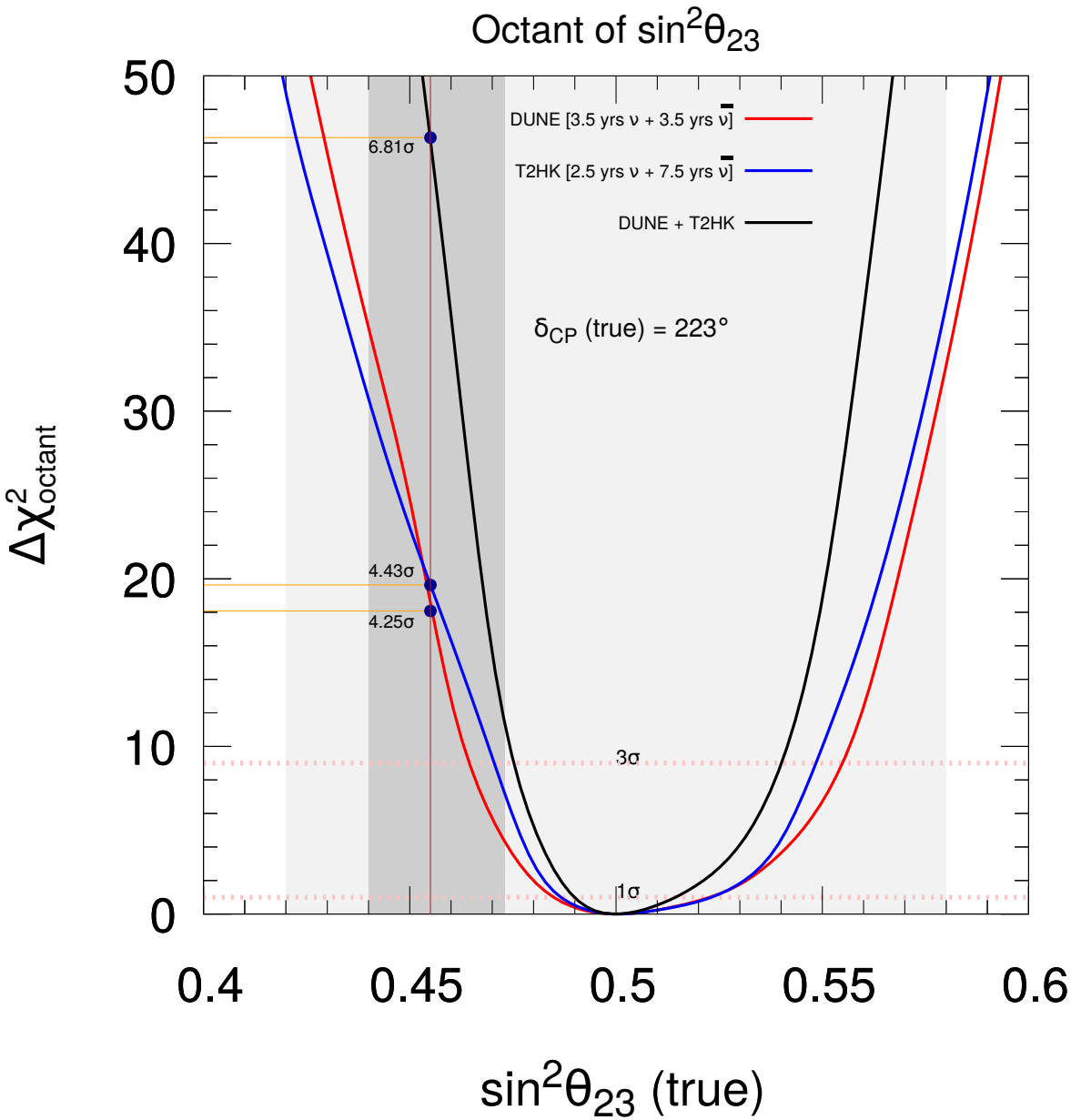


Contributions from both neutrino and antineutrino modes are crucial

Precision Measurement of Atmospheric Oscillation Parameters



Discovery of θ_{23} Octant



Concluding Remarks

Fundamental Physics with Long-Baseline 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

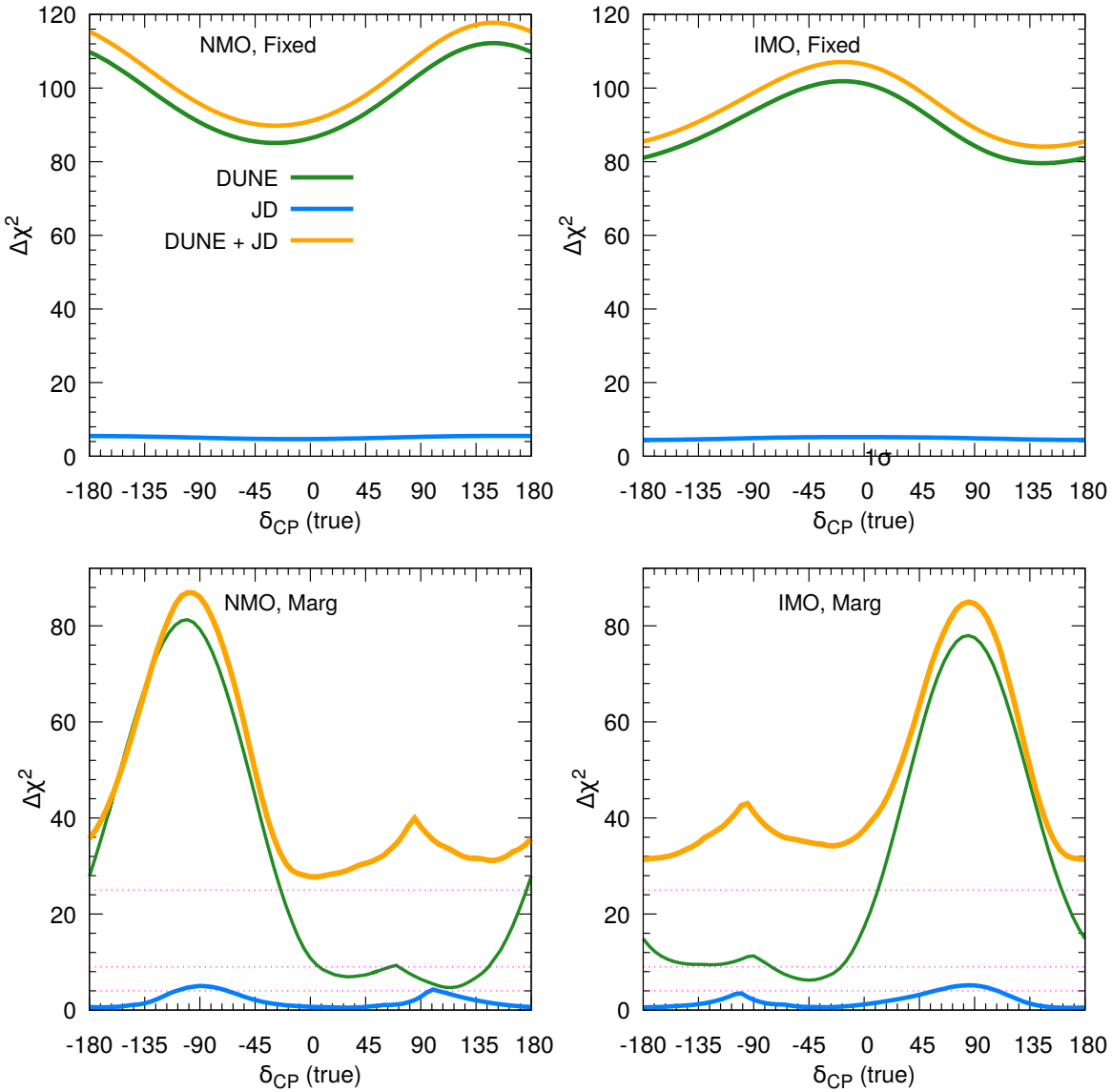
DUNE and T2HK bring complementary information to probe the entire parameter space with high confidence level

Present is very exciting! Future is very bright!

Stay Tuned!

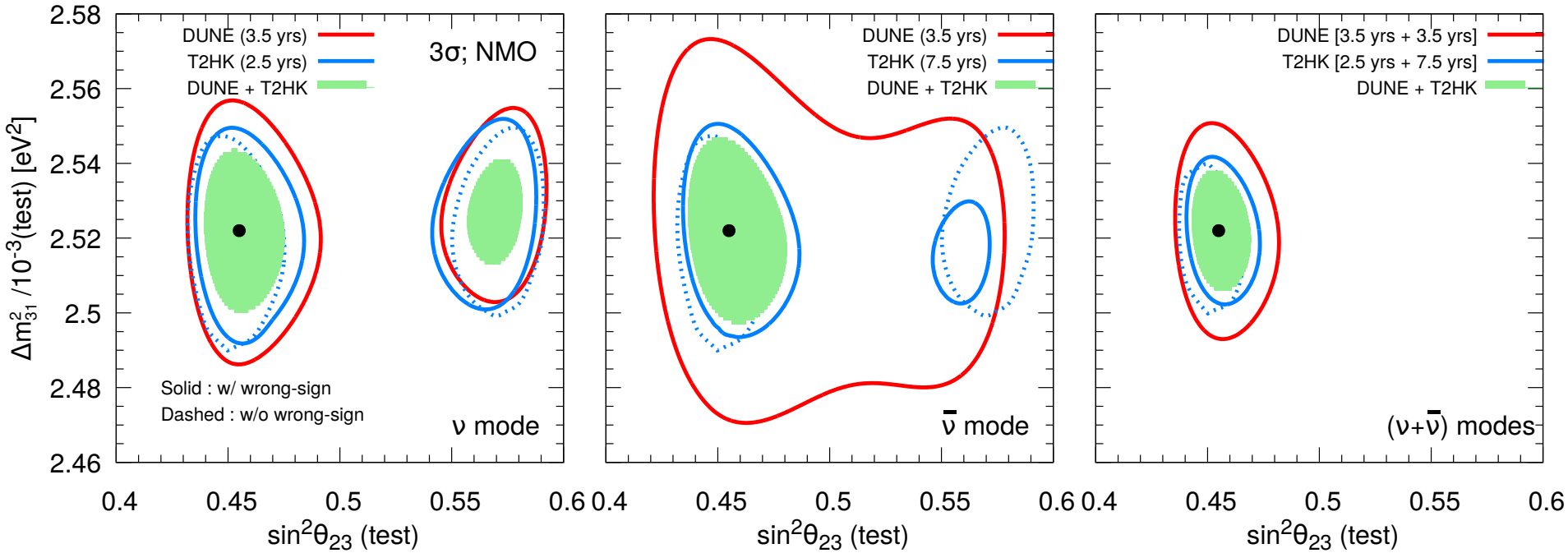
Thank you!

Establishing Matter Effect in Long-Baseline Experiments



Masoom Singh, Sanjib Kumar Agarwalla, in preparation

Precision Measurement of Atmospheric Oscillation Parameters



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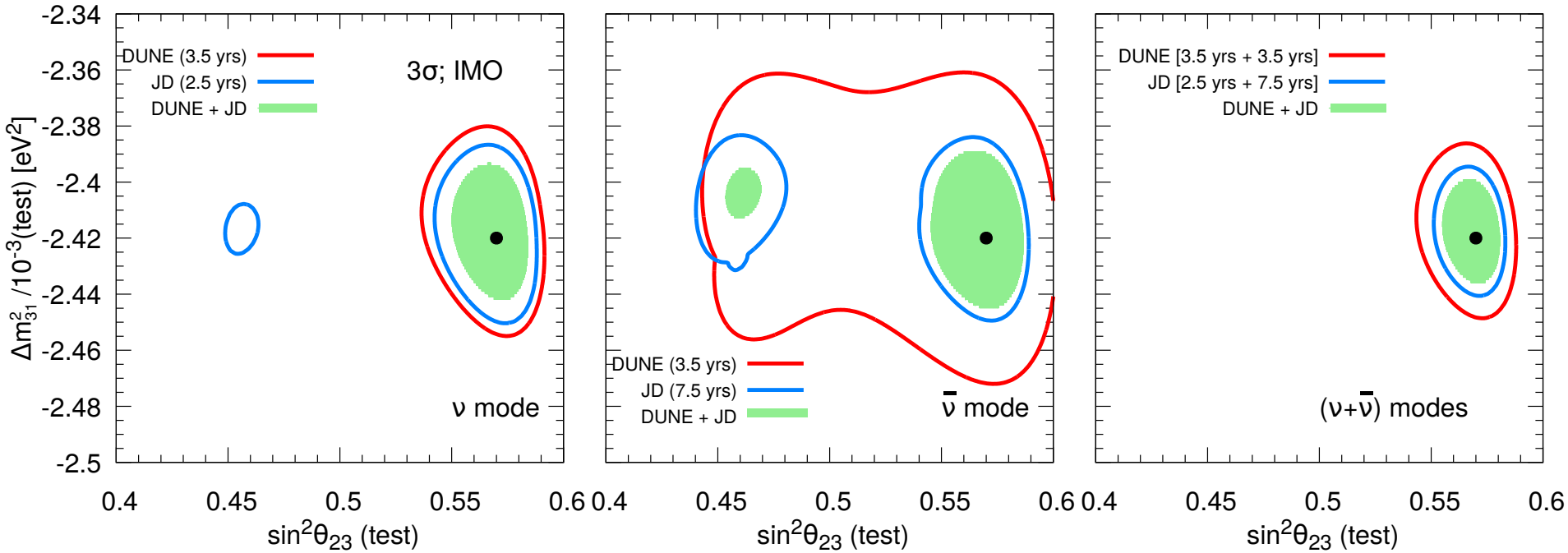


Present Status of Neutrino Oscillation Parameters Circa 2021

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

Parameter	Ordering	Best fit	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ 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
$\lvert\Delta m^2\rvert/10^{-3}$ 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		

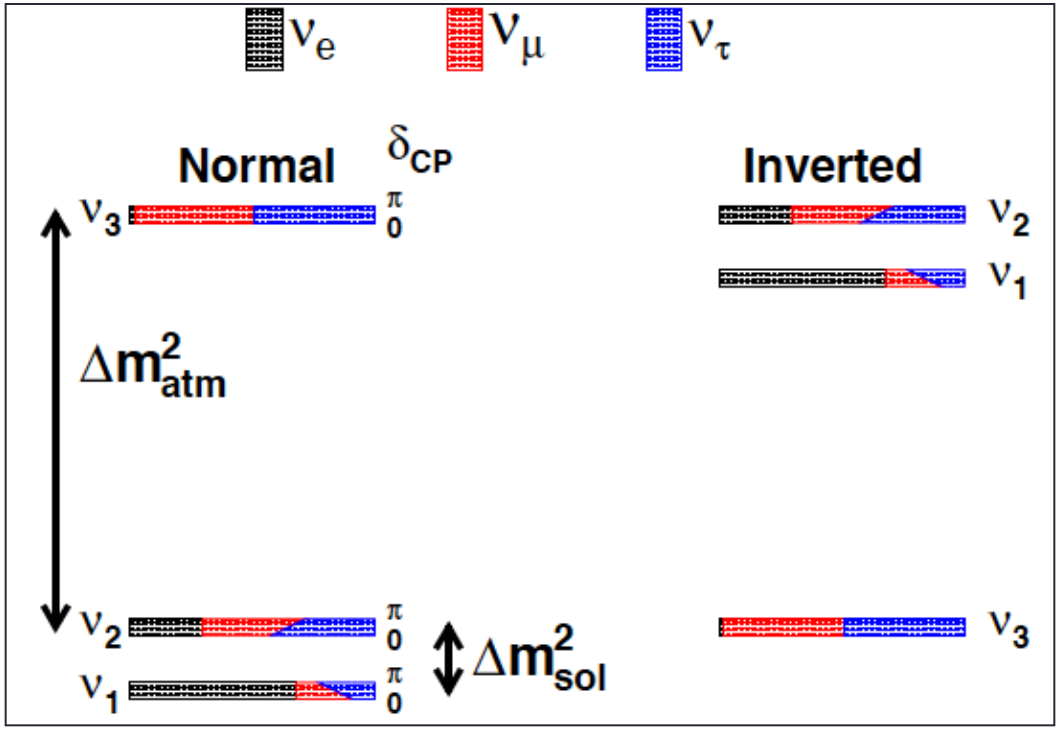
Capozzi, Valentino, Lisi, Marrone, Melchiorri, Palazzo, arXiv:2107.00532v2 [hep-ph]

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]

Neutrino Mass Ordering: Important Open Question

The sign of Δm^2_{31} $(m_3^2 - m_1^2)$ is not known



Neutrino mass spectrum can be normal or inverted ordered

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

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

We currently do not know which neutrino is the heaviest

$$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$$

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

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