Standard PMNS oscillations and physics beyond PMNS

(a model builder point of view)

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Disclaimer

Going to present the point of view of a Model Builder

→ discussion about neutrino properties form oscillation data only

→ 1.PMNS now and in the near future

→ 2. some aspect of New Physics in the oscillation domain

What we know: flavor mixing

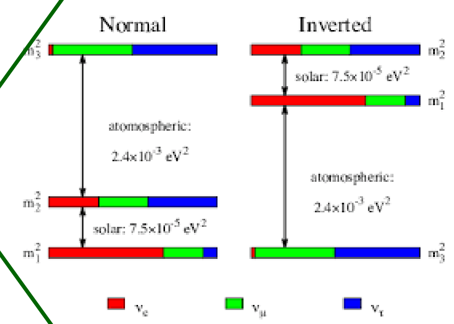
Standard Model states

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

PMNS matrix

Neutrino mass states

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} .$$



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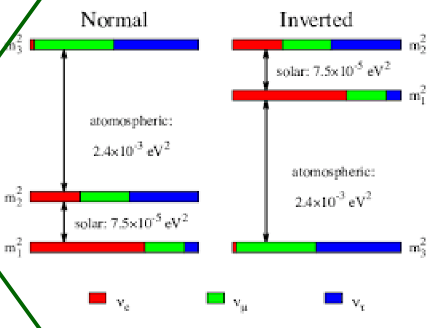

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric | reactor | solar

2 mass differences + 3 angles + 1 phase = 6 new parameters for SM

PMNS some years ago

$\tan\theta_{12} = 1/\phi$, with $\phi = (1+\sqrt{5})/2$

$$T_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Bi-maximal mixing

$$T_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Tri-Bi-maximal mixing

$$T_{GR} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ \frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

Golden Ratio

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Golden Ratio

CP conserving patterns

nice

$\tan(\theta_{12}) = 1$	$\tan(\theta_{12}) = \frac{1}{\sqrt{2}}$	$\tan(\theta_{12}) = \frac{2\sqrt{5}}{\sqrt{5+\sqrt{5}}}$

accceptable

$\tan(\theta_{23}) = 1$	$\tan(\theta_{23}) = 1$	$\tan(\theta_{23}) = 1$

bad

$\sin(\theta_{13}) = 0$	$\sin(\theta_{13}) = 0$	$\sin(\theta_{13}) = 0$

What we know: the solar sector

before 2012

solar ν_e disappearence, large θ_{12} (H/S,Ga,SK) (02)
solar ν_e are converted to $\nu_\mu+\nu_\tau$ (SNO) (02)

→ not useful for distinguishing among different patterns

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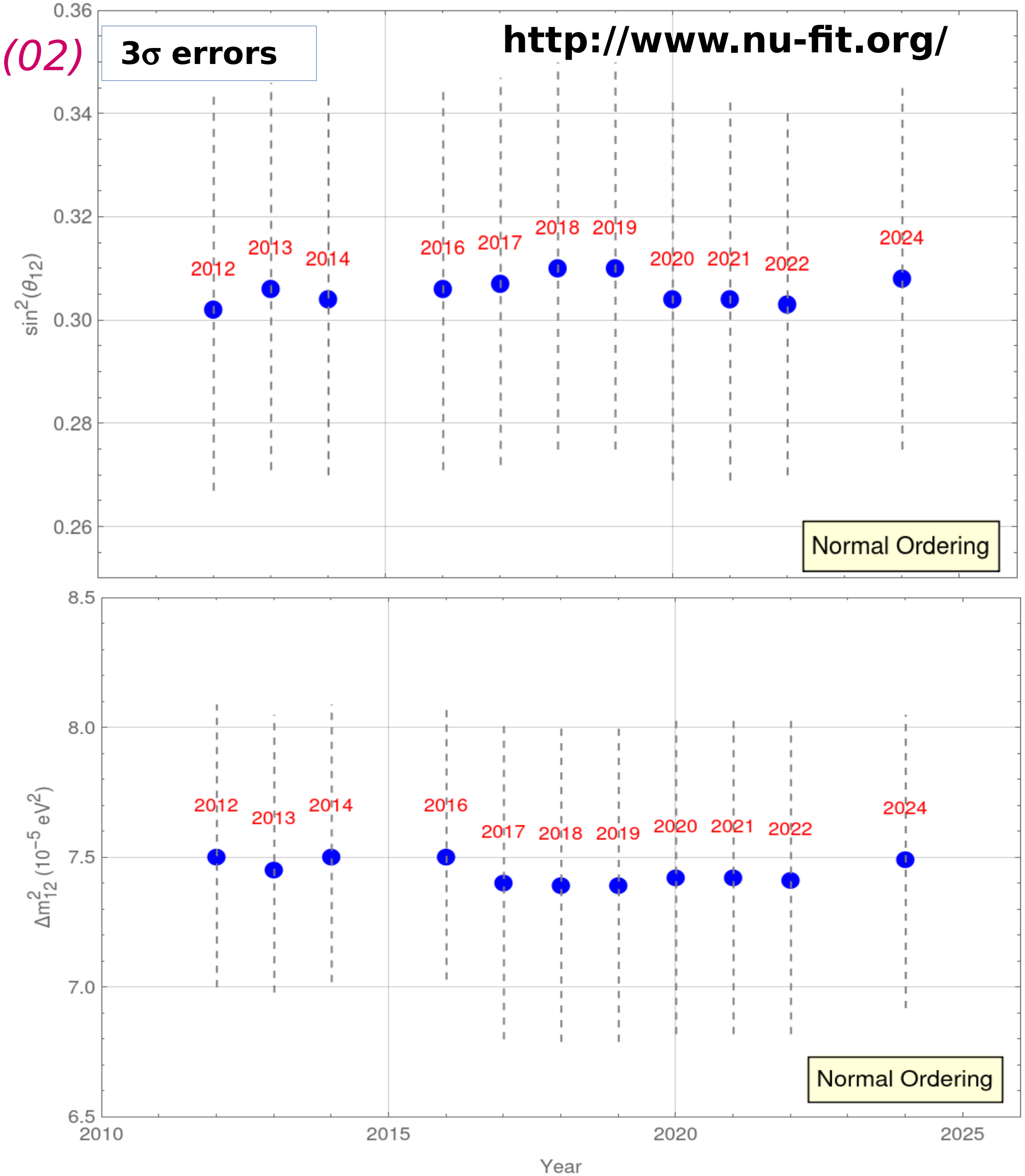
from 2012 to 2024



What we know: the solar sector

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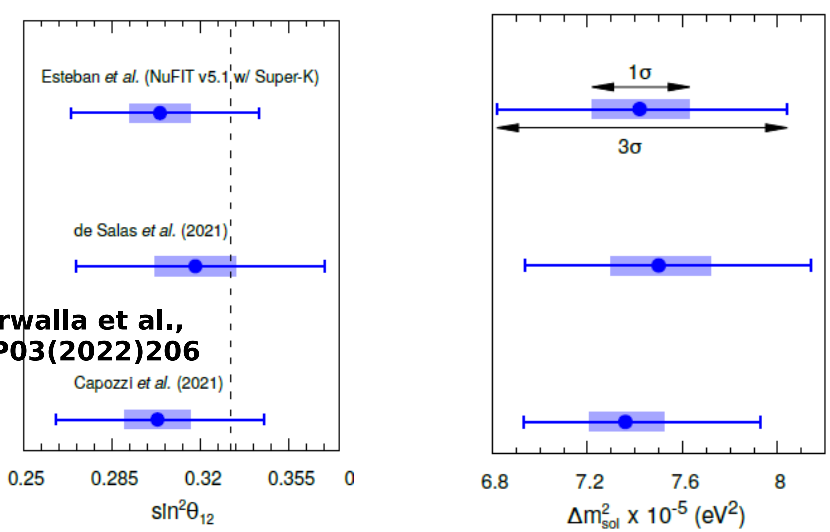
solar ν_e are converted to $\nu_\mu+\nu_\tau$ (SNO) (02)

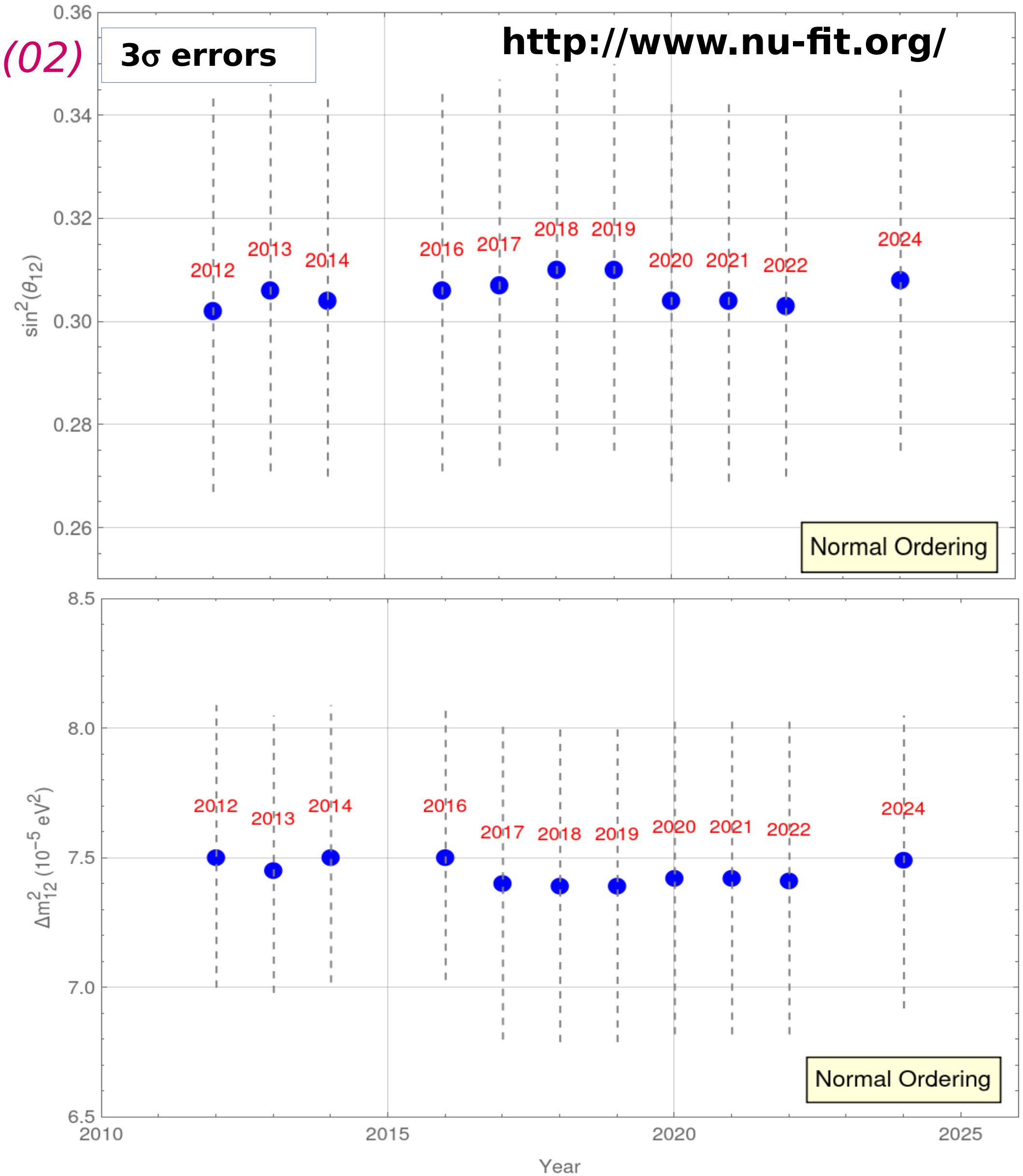
Relevant features:

- central values almost constant
- not large improvements on errors
- precisely determined by solar and KamLAND constraints
- no significant best-fit difference between the NO and IO cases.



Agarwalla et al., JHEP03(2022)206

from 2012 to 2024



What we know: the atmospheric sector

<u>before 2012</u>

atmospheric ν_μ disappear, large θ_{23} (SK) (98)
accelerator ν_μ disappear (K2K 04 , MINOS 06)
accelerator ν_μ converted to ν_τ (OPERA 10)

→ All consistent among different patterns

What we know: the atmospheric sector

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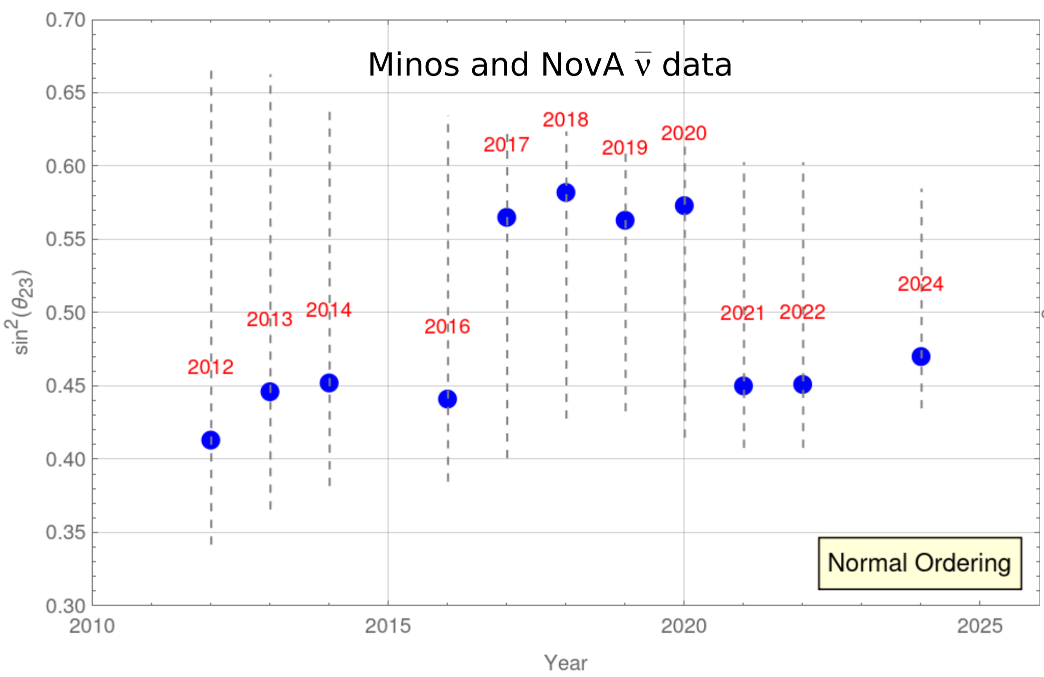
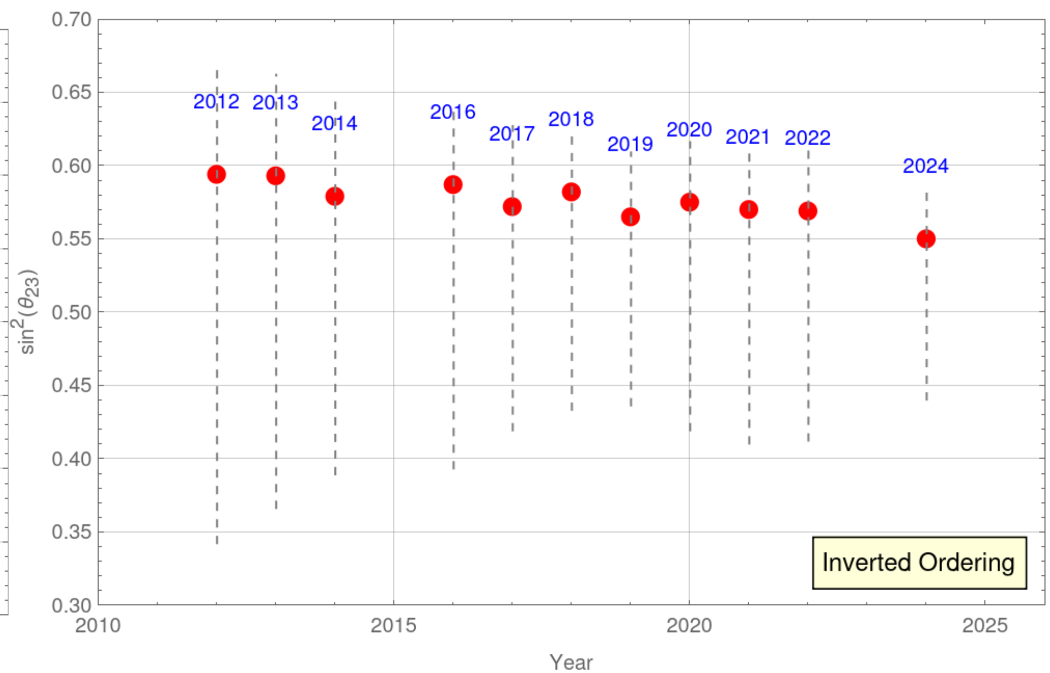
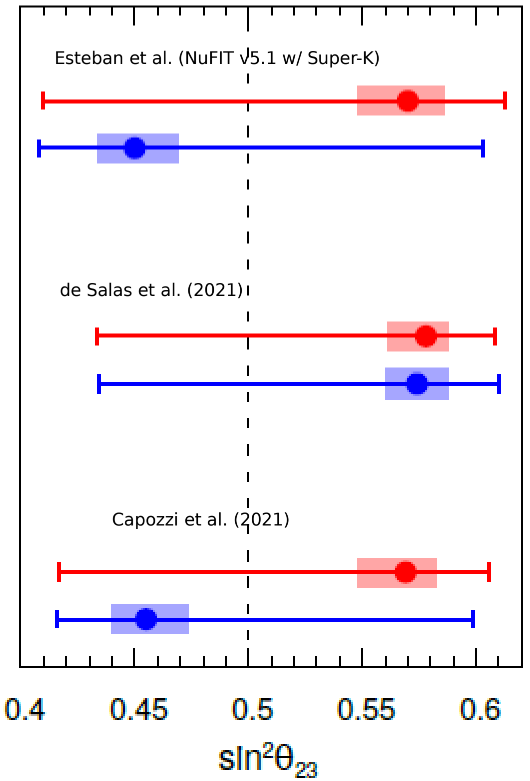




Quite a puzzling situation !

What we know: the atmospheric sector

Agarwalla et al., JHEP03(2022)206

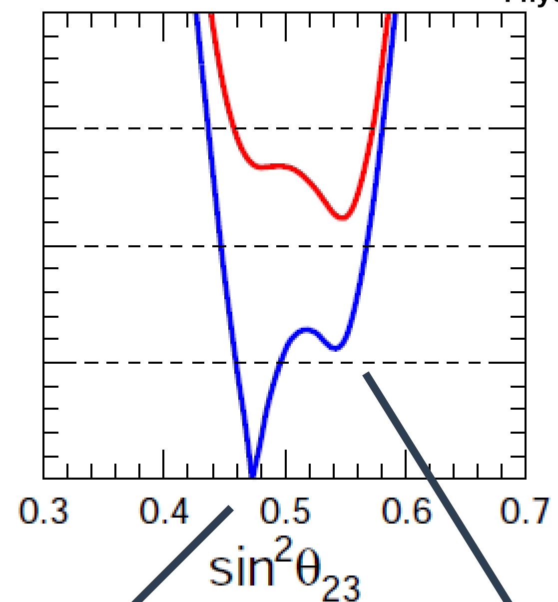


Octant degeneracy problem:

θ_{23} smaller or larger than 45°

$$P_{\mu\mu} \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Capozzi et al. Phys.Rev.D111 (2025) no.9, 093006



lower octant

higher octant

What we know: the atmospheric sector

All patterns predict maximal mixing

$$T_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Corrections must be added to describe the correct octant, once found...

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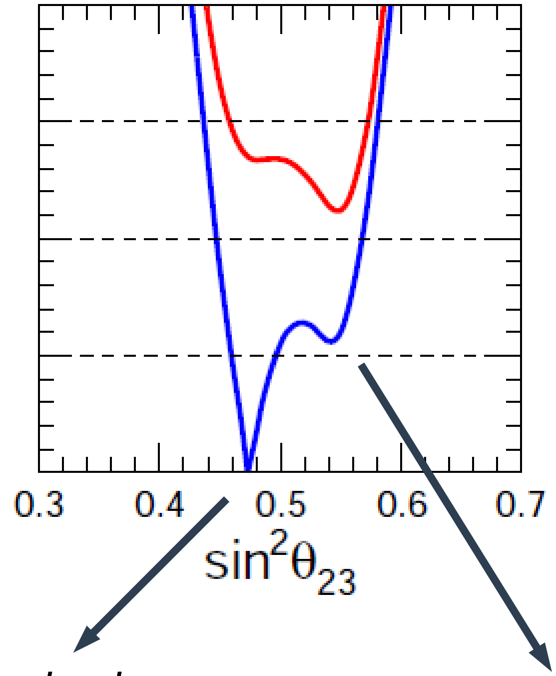

lower octant

higher octant

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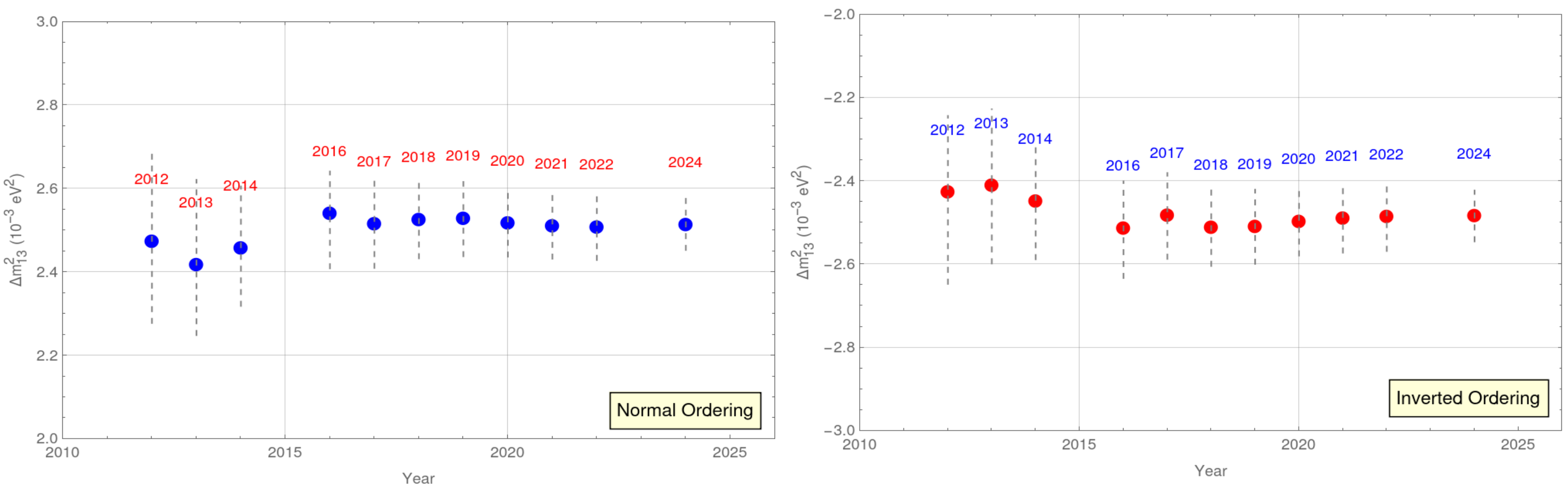
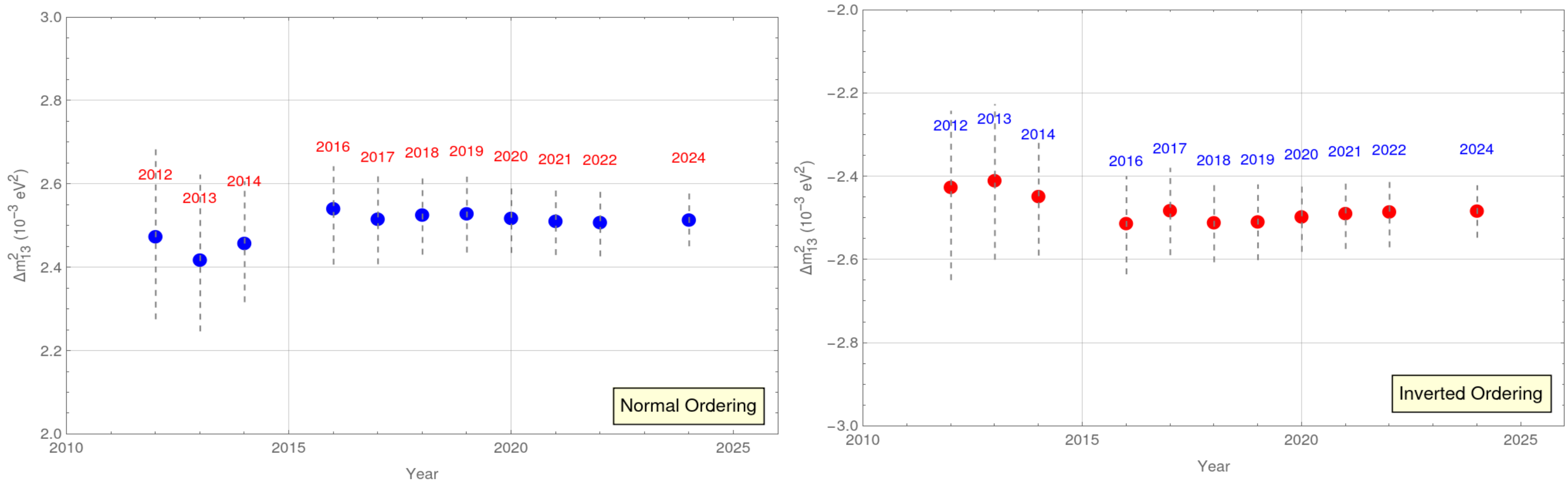


What we know: the atmospheric sector



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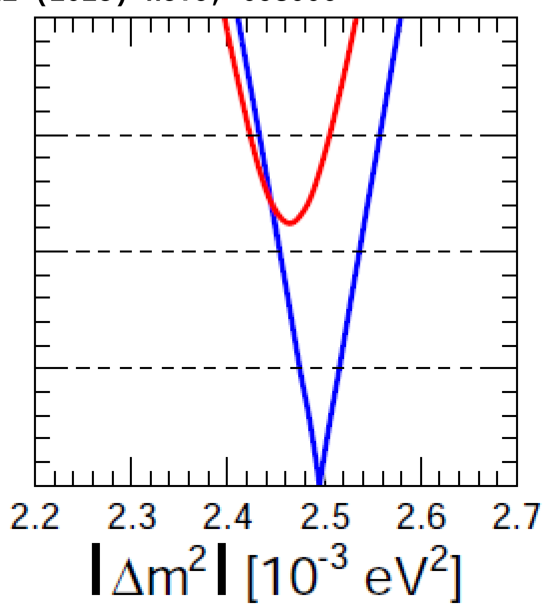


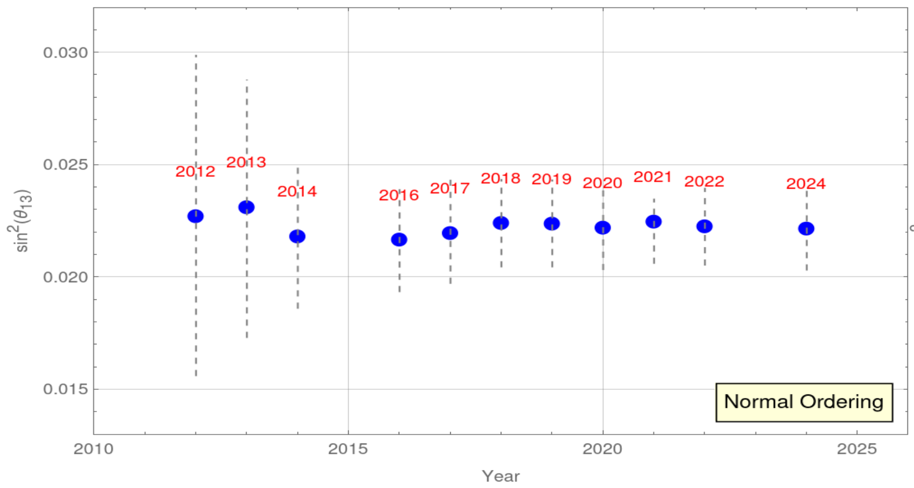
Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475 – 2.515	2.454 – 2.536	2.433 – 2.558	0.8
	IO	2.465	2.444 – 2.485	2.423 – 2.506	2.403 – 2.527	0.8

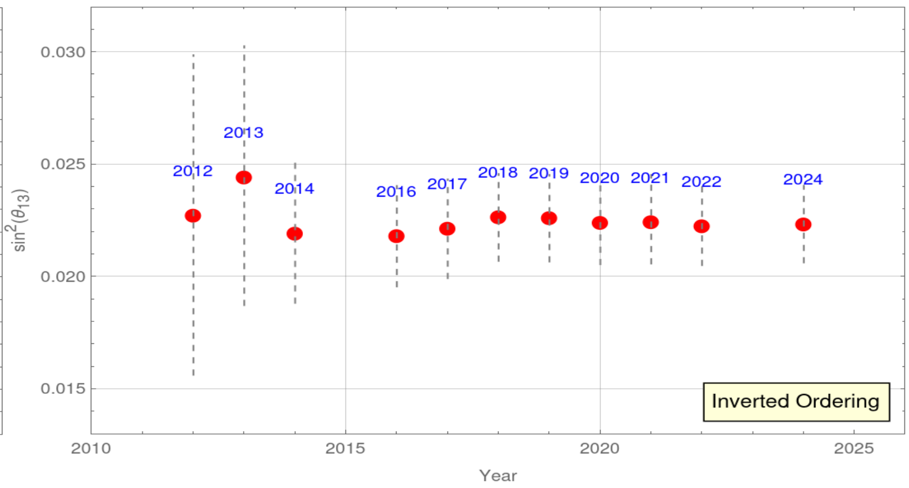
- Δm^2_{atm} entering the <u>subpercent precision era</u>

- NO favoured at 2.2 sigma (2.5 in 2021)

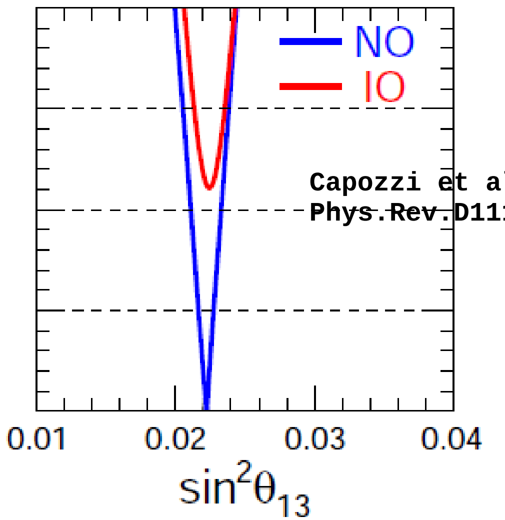
(preference for IO by combined LBL accelerator data first reduced by SBL reactor data and then flipped to NO by atmospheric data)

What we know: the reactor sector





Very clear situation:
converging hints about nonzero values from the global analysis of solar, KamLAND, atmospheric and LBL accelerator data that consistently reached a cumulative statistical above 3sigma before its discovery and precise measurement by SBL reactor experiments



Capozzi et al.
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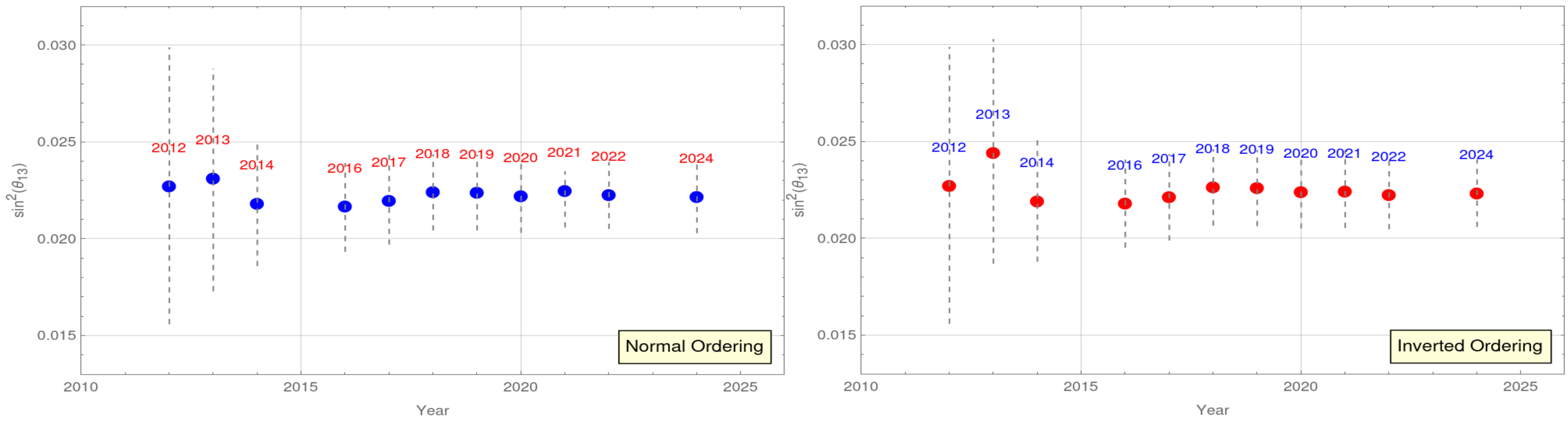
1 sigma error at the level of 4-5%

$$\sin(\theta_{13}) = (2.23 \pm 0.06)\, 10^{-2}$$

What we know: the reactor sector



Major breakthrough in the model building industry

Corrections are needed from charged lepton diagonalization

$$U^{PMNS} = U_{cl}^{+} \cdot T_{BM} \qquad U_{cl} \sim \begin{pmatrix} 1 & \lambda_C & \lambda_C \\ \lambda_C & 1 & 0 \\ \lambda_C & 0 & 1 \end{pmatrix}$$

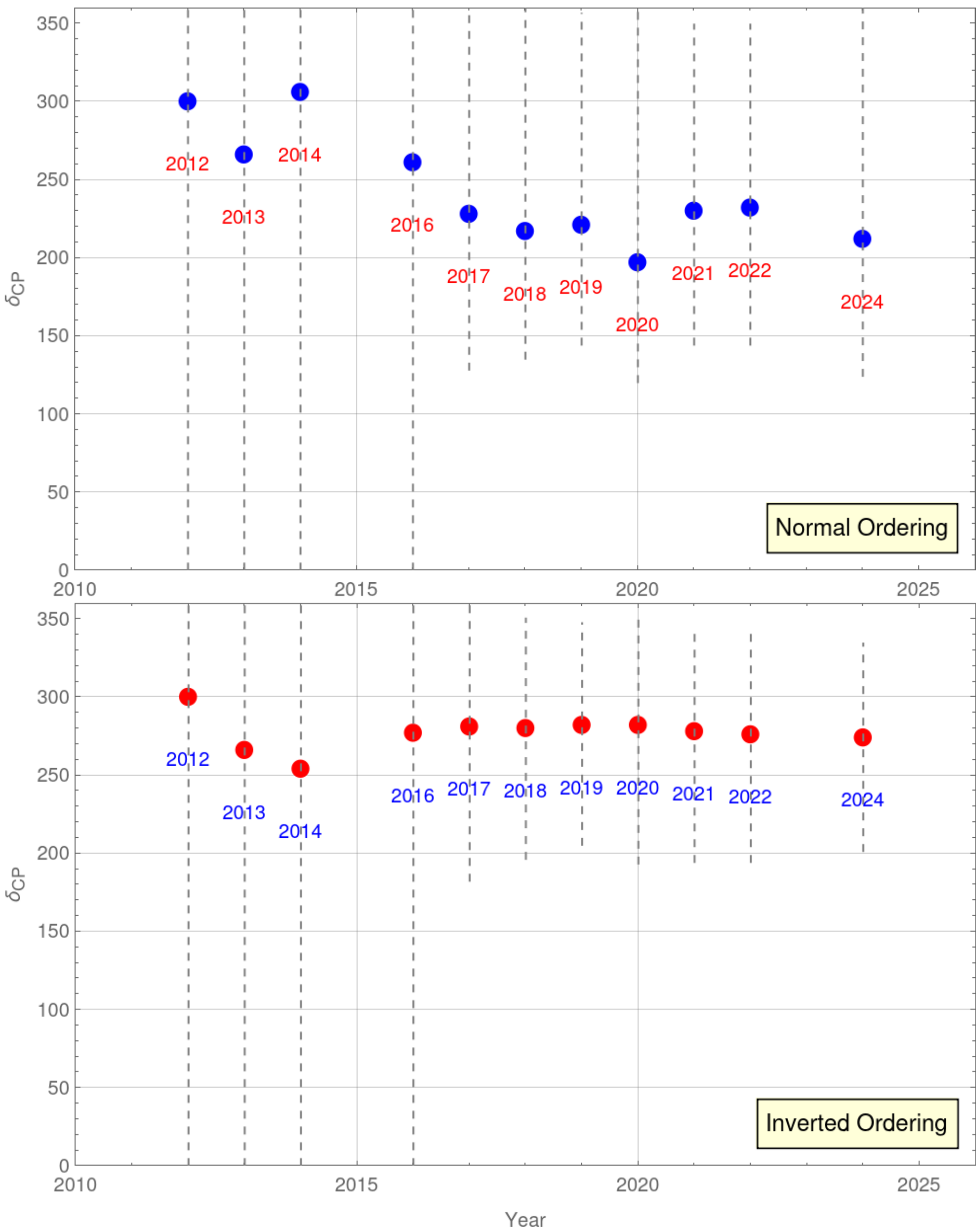
Altarelli et al., 0903.1940

good results:

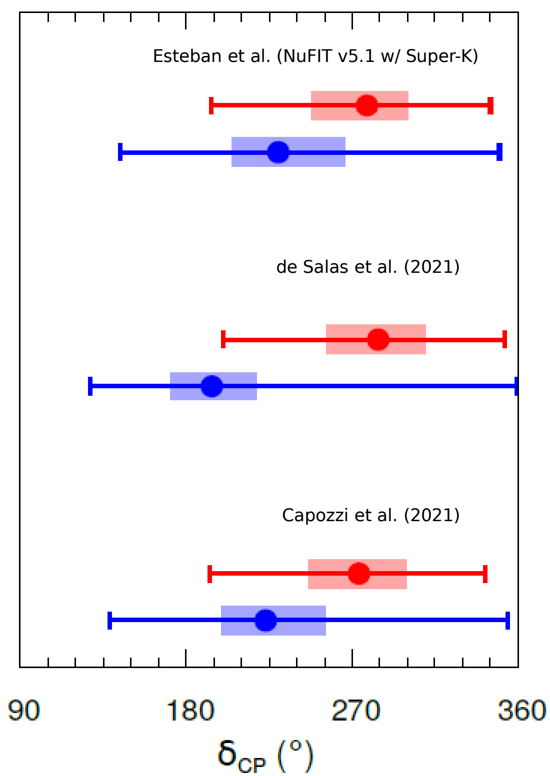
$$\begin{cases} \sin^2\theta_{12} = \frac{1}{2} - O(\lambda_C) \\ \sin^2\theta_{23} = \frac{1}{2} \\ \sin\theta_{13} = \frac{1}{\sqrt{2}} O(\lambda_C) \end{cases}$$

$$[\,\theta_{13}^{PMNS} = O(1) \cdot \theta_{12}^{CKM}\,]$$

What we know: δ_{CP}



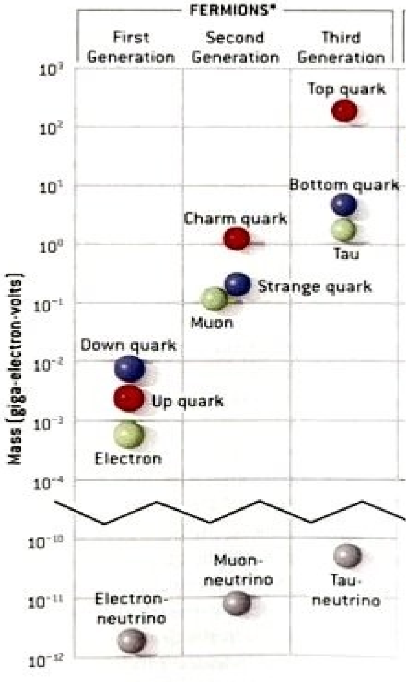
$$P_{\alpha\beta}^{CPV} \sim \sin(\theta_{13}) \left(\frac{\Delta m_{sol}^2}{\Delta m_{atm}^2} \right) \sin \delta_{CP}$$



- weak indications:
IO ***seems*** to prefer maximal CP violation while NO a CP conserving solution

The Flavor Problem (I)

Mass hierarchies



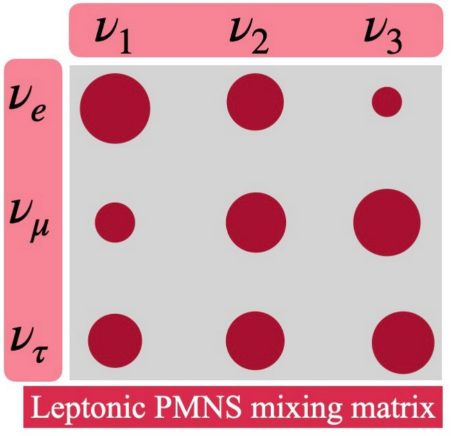
$$m_d \ll m_s \ll m_b\,, \quad \frac{m_d}{m_s} = 5.02 \times 10^{-2}\,,$$

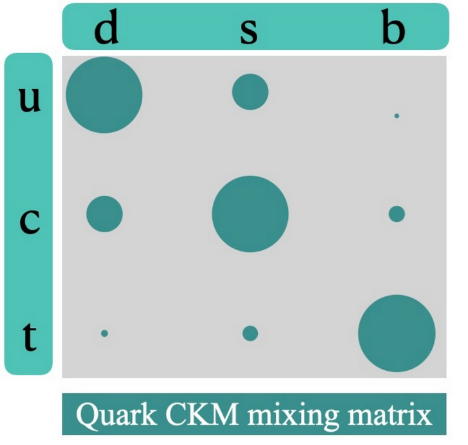
$$m_u \ll m_c \ll m_t\,, \quad \frac{m_u}{m_c} = 1.7 \times 10^{-3}\,,$$

$$\frac{m_s}{m_b} = 2.22 \times 10^{-2}\,, \quad m_b = 4.18 \text{ GeV};$$

$$\frac{m_c}{m_t} = 7.3 \times 10^{-3}\,, \quad m_t = 172.9 \text{ GeV};$$

Fermion mixing





all mixing are large but the 13 element

almost a diagonal matrix

Why are they so different?

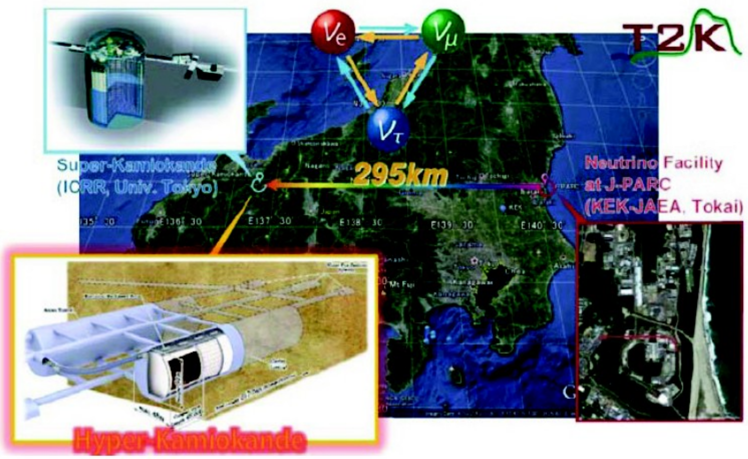
my personal perspective

Approach	Advantages	Disadvantages
Discrete Non-Abelian Symmetries	Flexibility: Wide choice of groups (e.g., A_4, S_4) and representations to fit data. Established Precedents: Well-studied and widely applied Intuitive Structure: Directly imposes order on mass matrices via group invariants.	Complexity: Requires additional scalar fields and non-trivial vacuum alignment. Free Parameters: Many degrees of freedom (flavon VEVs, coupling constants) reduce predictivity. Ad Hoc: Phenomenologically motivated, less tied to fundamental theories.
Modular Forms	Elegance: Reduces the number of fields (only τ as a 'flavon-like' field), simplifying the model. Predictivity: Yukawa couplings constrained by modular forms, with fewer free parameters. Theoretical Foundation: Naturally arises from string theory or extra-dimensional geometries.	τ Stabilization: Determining the modulus τ's value is challenging. Limited Flexibility: The form of couplings is fixed by modular weight and level. Mathematical Complexity: Requires familiarity with modular forms and the $SL(2,\mathbb{Z})$ group.

Future measurements can help in discarding some approaches to the flavor problem

Future perspectives

T2HK

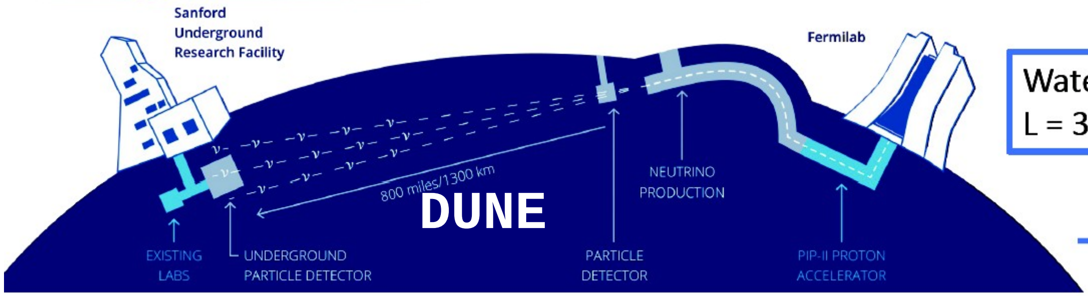


WC 374 kt
295 km

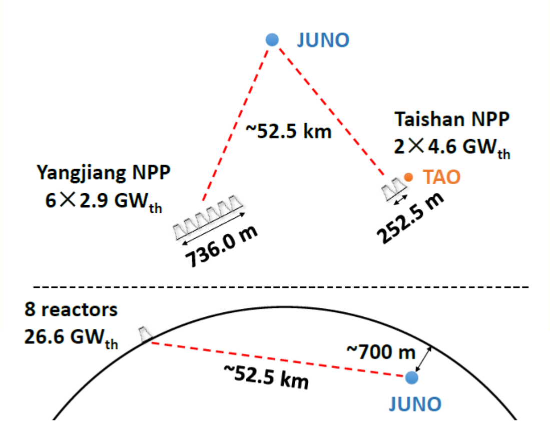
ESSnuSB – talk by Eric Baussan

Image Credit – Monojit Ghosh

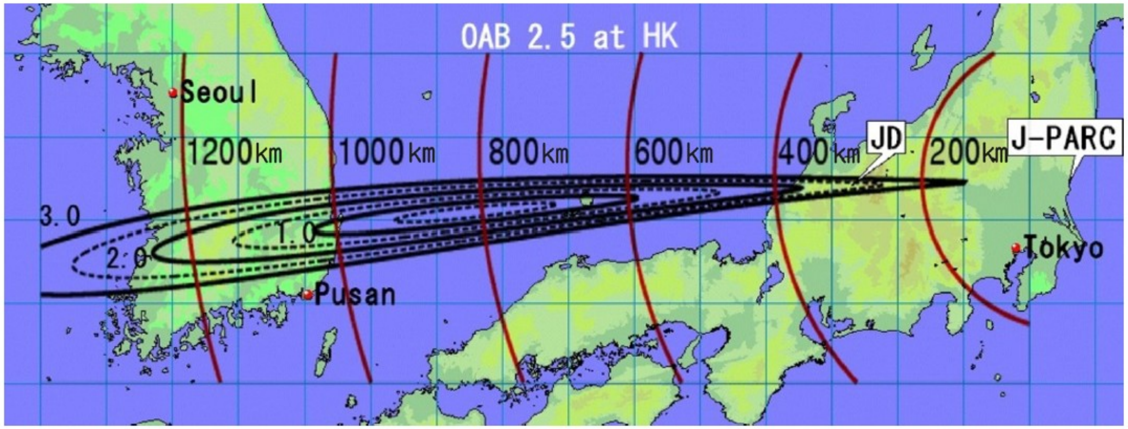
Water Cerenkov (WC) Far detector of 540 kt
L = 360 km



Liquid argon TPC of 40 kt
L = 1300 km

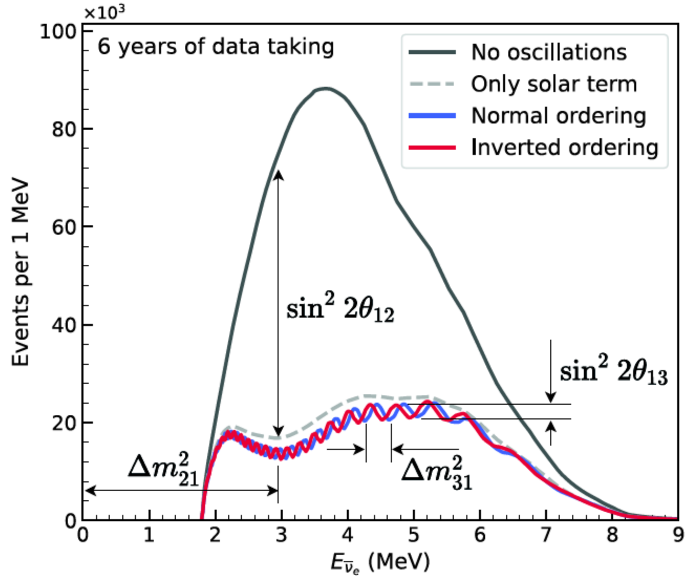


KNO

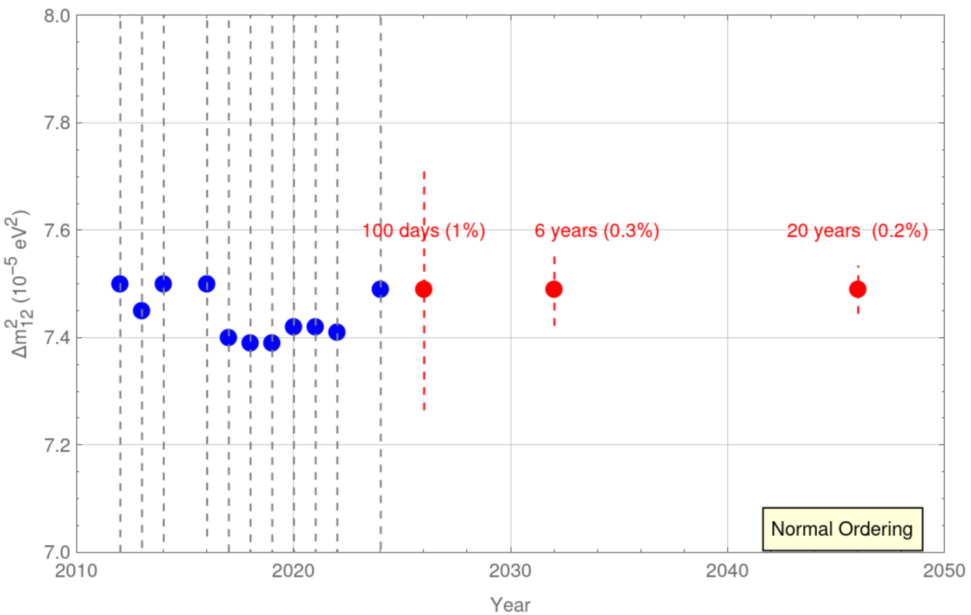


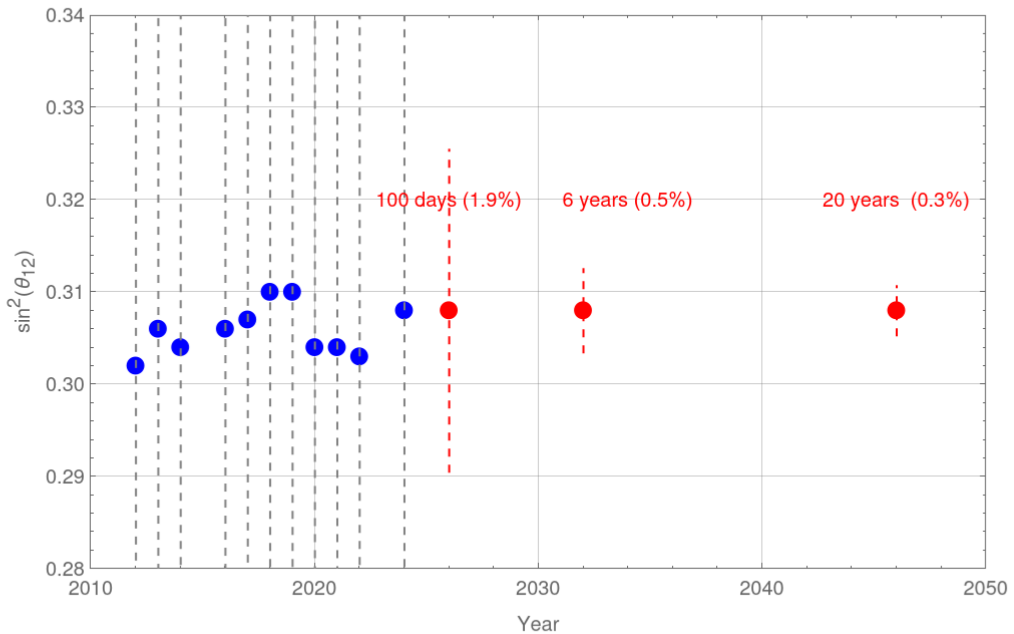
Better determination of solar parameters

A.Abusleme et al. [JUNO], Chin.Phys.C46 (2022)no.12,123001

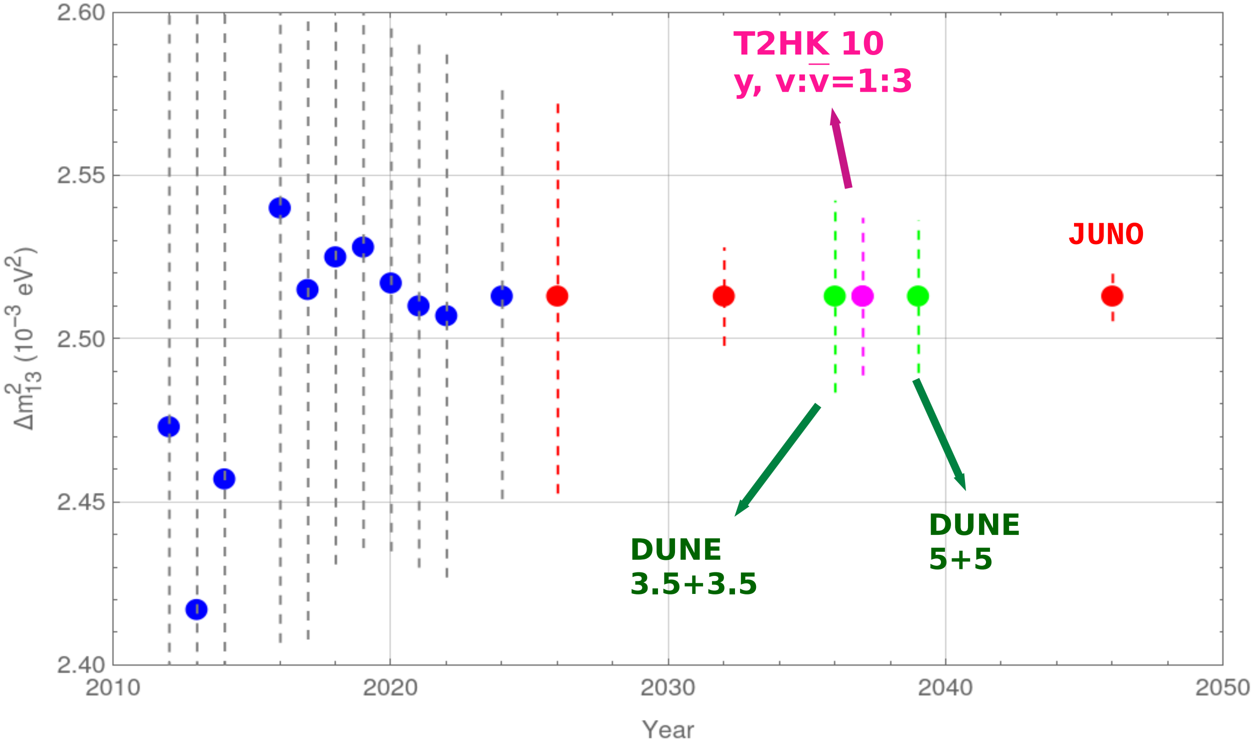


sensitive to both solar and atmospheric oscillations





Atmospheric mass precision & ordering

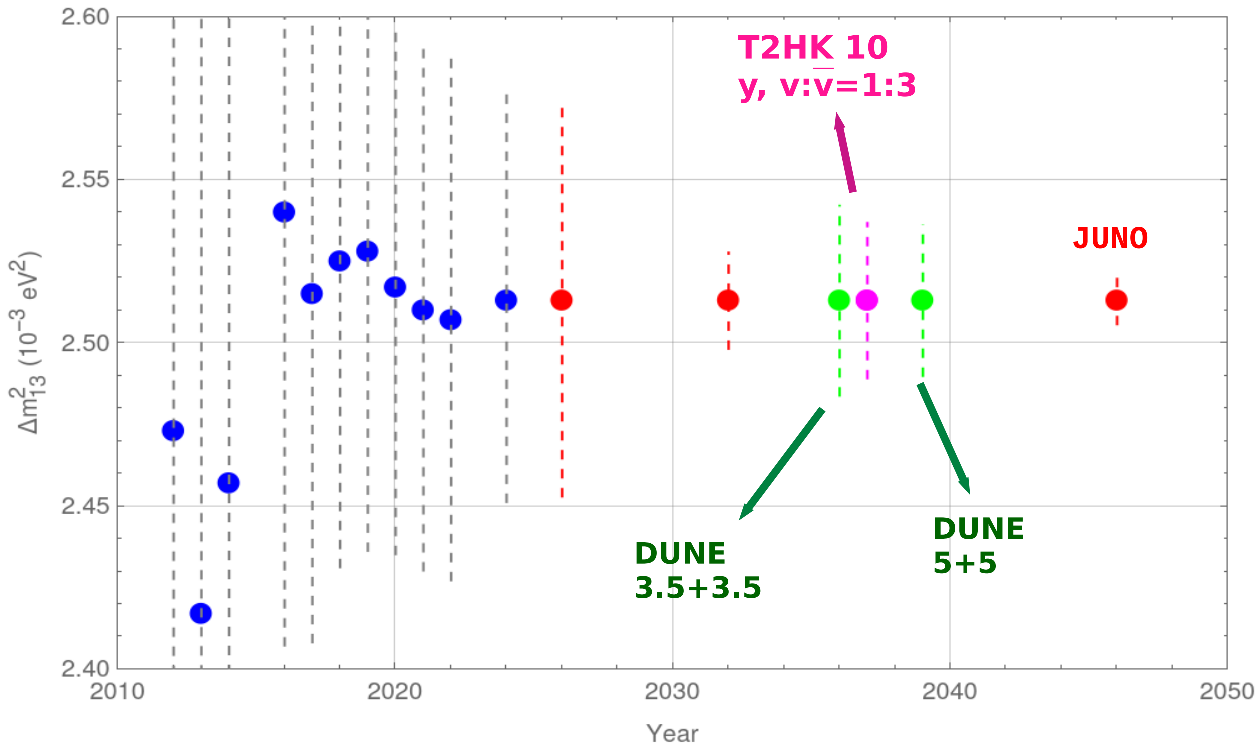


Jeanne Wilson, T2HK, NOW24

Marshall, DUNE, Neutrino24
Agarwalla et at., JHEP03(2022)206

A.Abusleme et al. [JUNO],
Chin.Phys.C46 (2022)no.12,123001

Atmospheric mass precision & ordering



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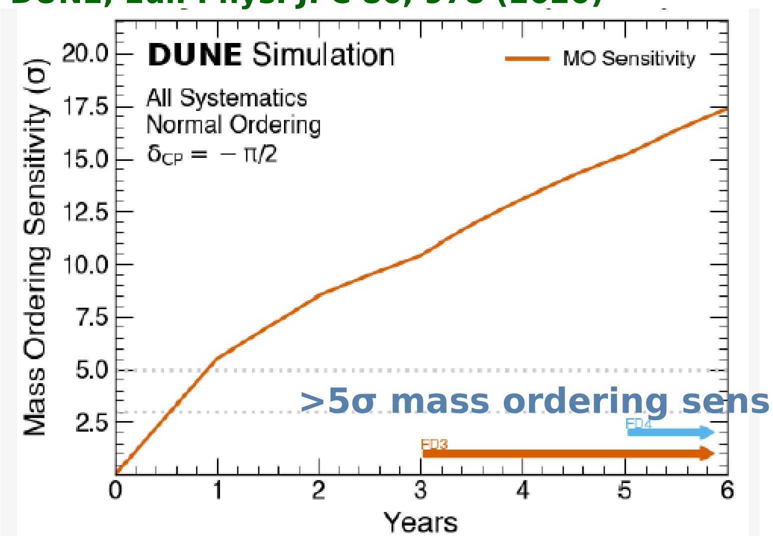
DUNE, Eur. Phys. J. C 80, 978 (2020)

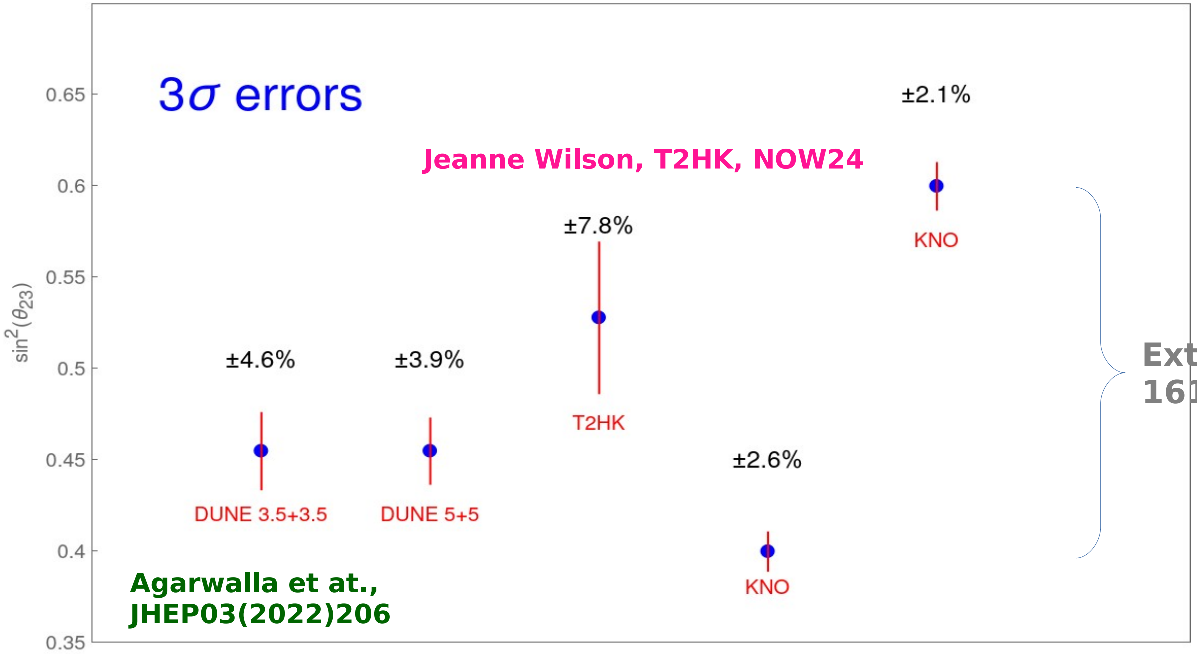


>5σ mass ordering sensitivity in 1 year

Snowmass: NF01 Topical Group Report

		Atmospheric Mass Ordering
JUNO	Optimistic	2030: 3σ
	Conservative	2030: 2.5σ
DUNE	Optimistic	2030: 5σ
	Conservative	2032: 5σ
HK	Optimistic	2033: 5σ
	Conservative	2032: 3σ

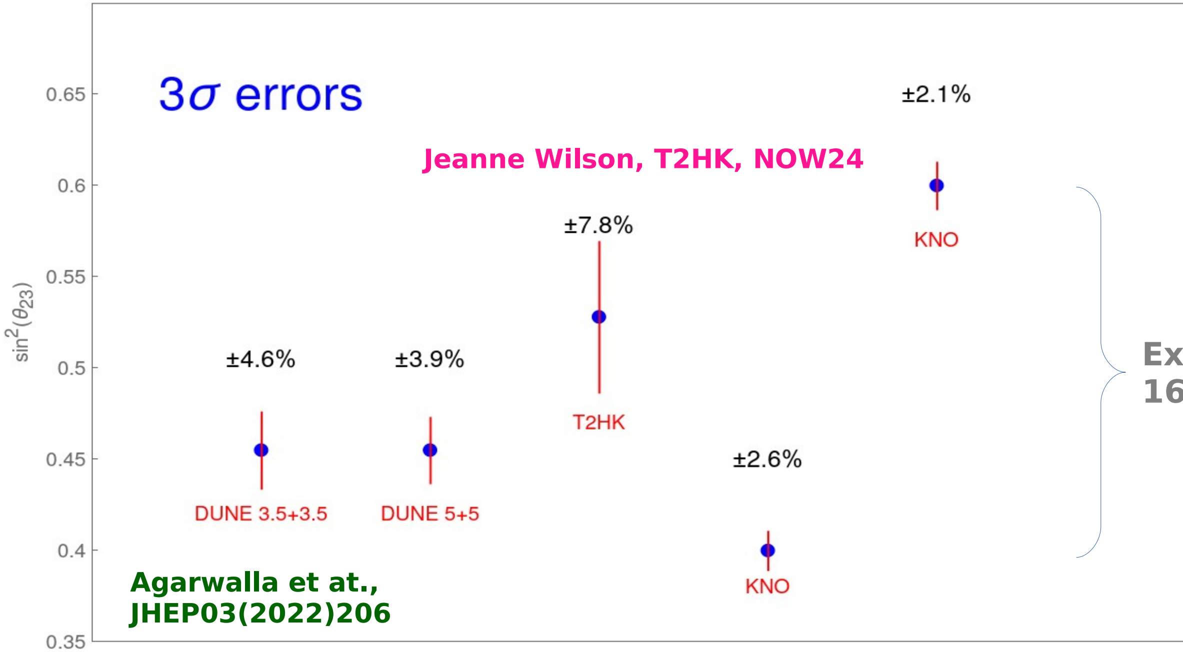
Atmospheric angle precision & octant degeneracy



Extrapolated from 1611.06118v3 [hep-ex]

some representative points for different true octants

Atmospheric angle precision & octant degeneracy

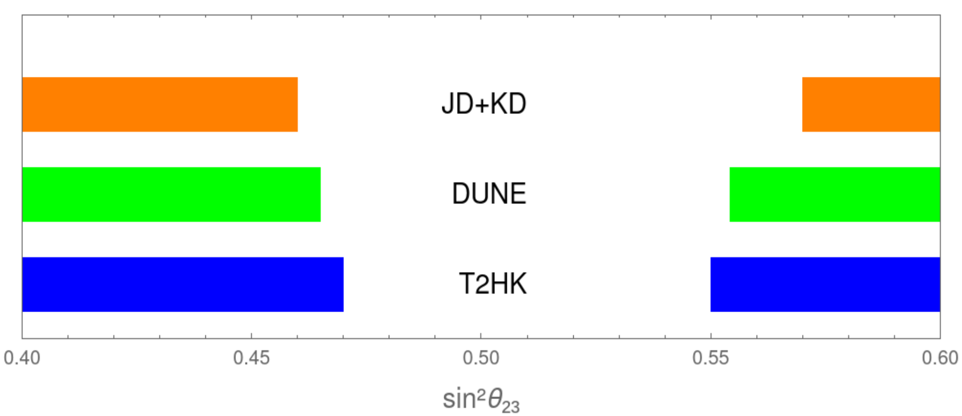


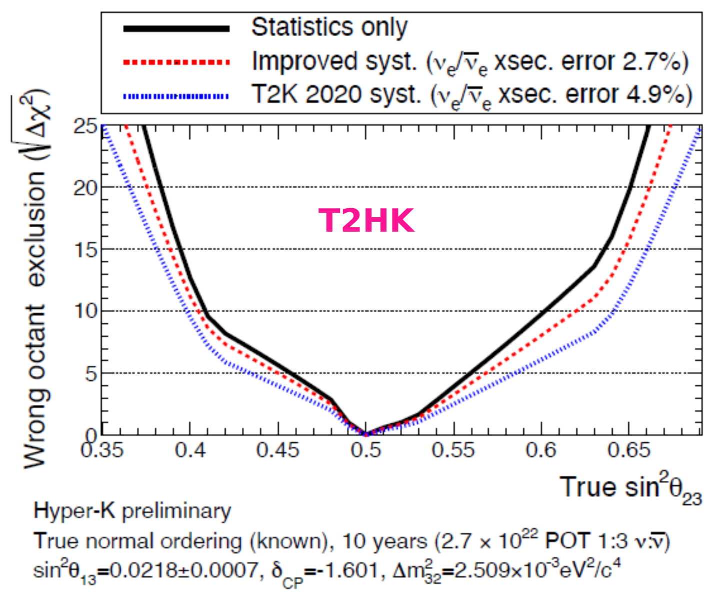
some representative points for different true octants

Extrapolated from 1611.06118v3 [hep-ex]

EPJ Web of Conferences 312, 02005 (2024)

excluding the wrong octant at 3σ





Discovery of CP violation

Personal point of view: delta CP is the most important Standard Model parameter to be determined.

flavor models

- many fits both NO and IO
- many fits both octant of theta23
- many models are CP violanting **OR** CP conserving

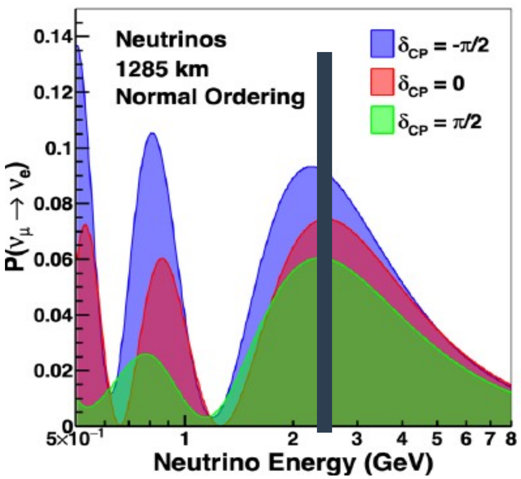
↓

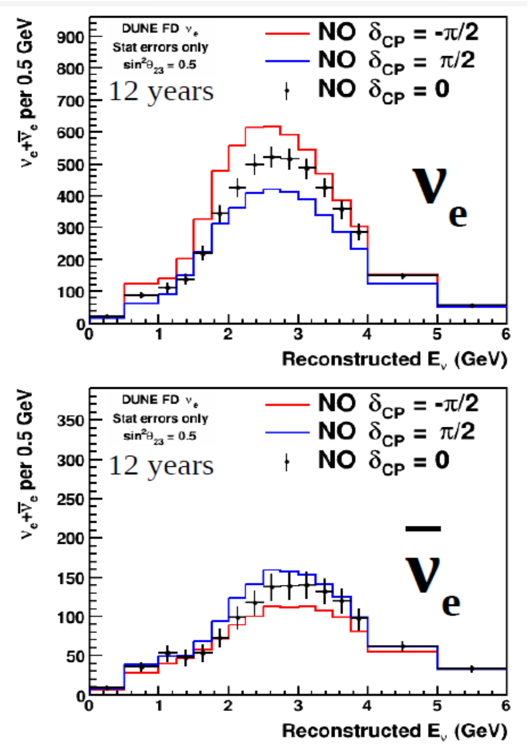
huge discriminant

let us focus on ability to discriminate $\delta=0,\pi$ vs $\delta=\pi/2, 3/2\pi$

Discovery of CP violation: DUNE and T2HK

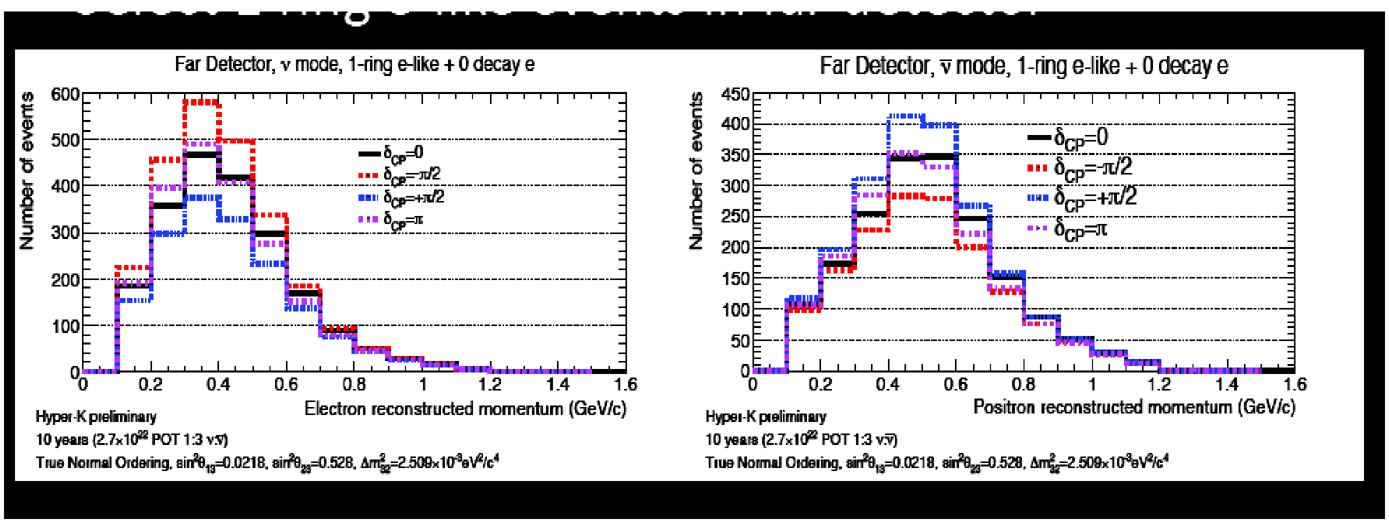
DUNE





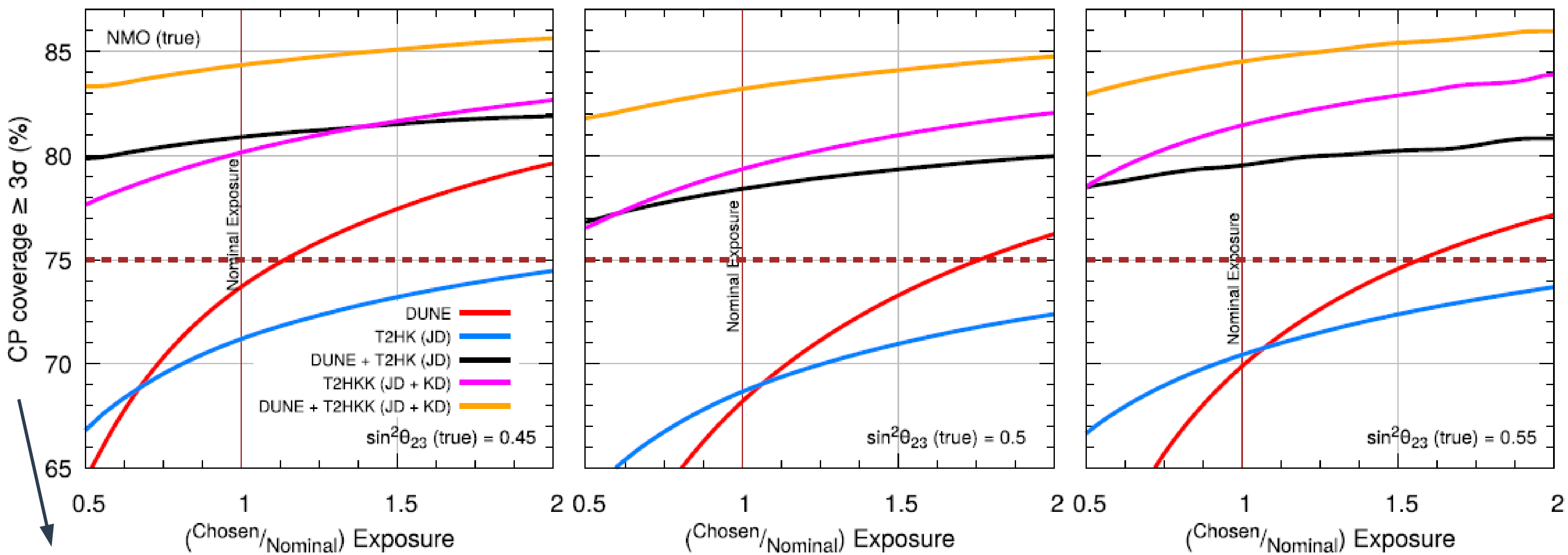
$|\delta|$=+-$\pi/2$ **max changes in ν_e appearance**

T2HK



Discovery of CP violation: DUNE, T2HK and KNO

Agarwalla et al. Eur. Phys. J. C (2023) 83:694



denotes the values of true dCP (in %) in its entire range for which leptonic CPV can be established at ≥ 3σ confidence level.

differences among panels given by δ-θ_{23} degeneracy

Relevant feature: at nominal exposure KNO always exceeds DUNE and T2HK

Discovery of CP violation: ESSνSB

atmospheric term — solar term

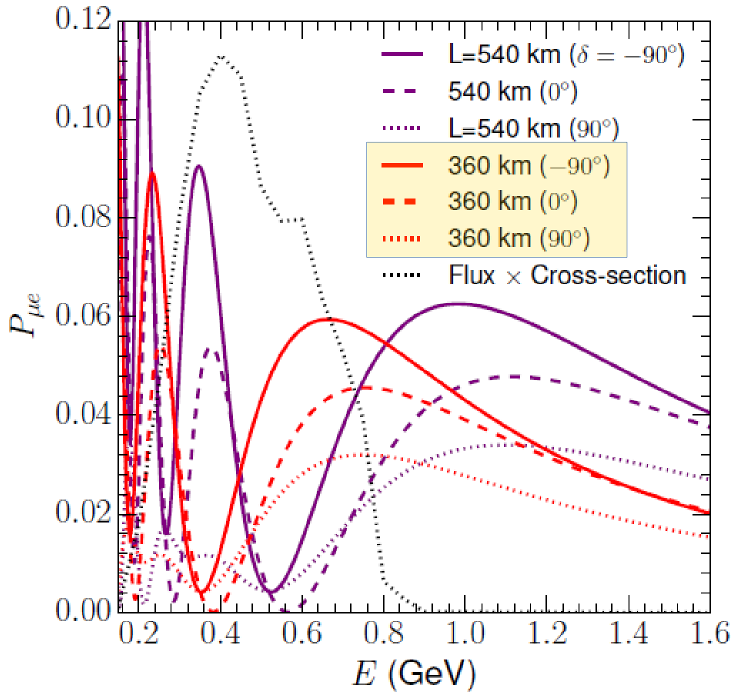
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$

$$+ \tilde{J}\frac{\Delta_{21}}{A}\frac{\Delta_{31}}{\tilde{B}_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\frac{\Delta_{31}L}{2} \pm \delta\right),$$

$$\tilde{B}_\mp = |A \mp \Delta_{13}|$$

First oscillation peak: $\Delta_{12}L/2 \sim 0.05$ and the “atmospheric” term tends to dominate

Second oscillation maximum: $\Delta_{12}L/2 \sim 0.14$ and the dependence on δ is much more important



Discovery of CP violation: ESSνSB

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$$+ \tilde{J}\frac{\Delta_{21}}{A}\frac{\Delta_{31}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta\right),$$

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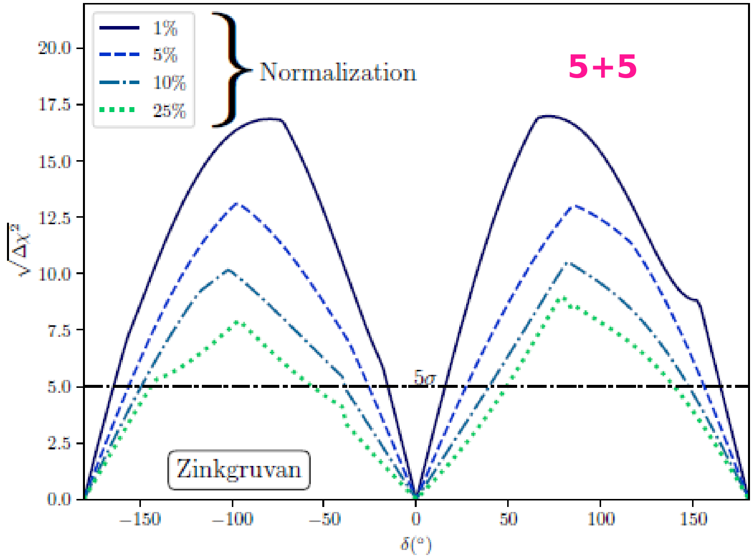
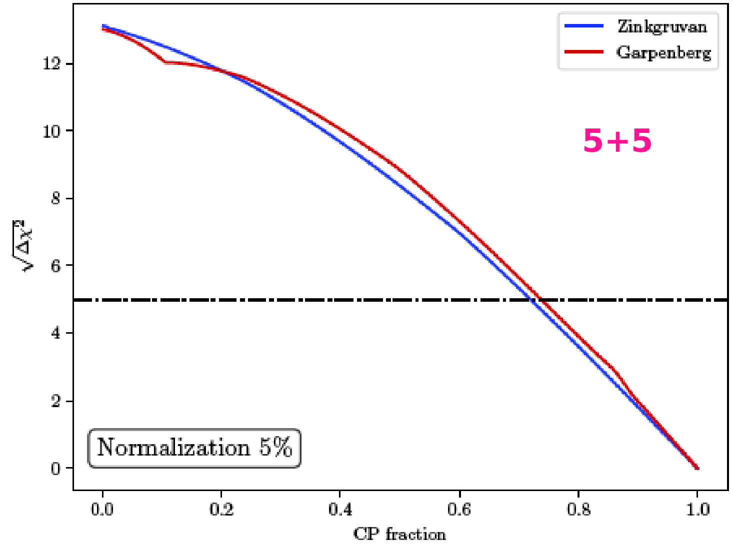
First oscillation peak: $\Delta_{12}L/2 \sim 0.05$ and the "atmospheric" term tends to dominate
Second oscillation maximum: $\Delta_{12}L/2 \sim 0.14$ and the dependence on δ is much more important

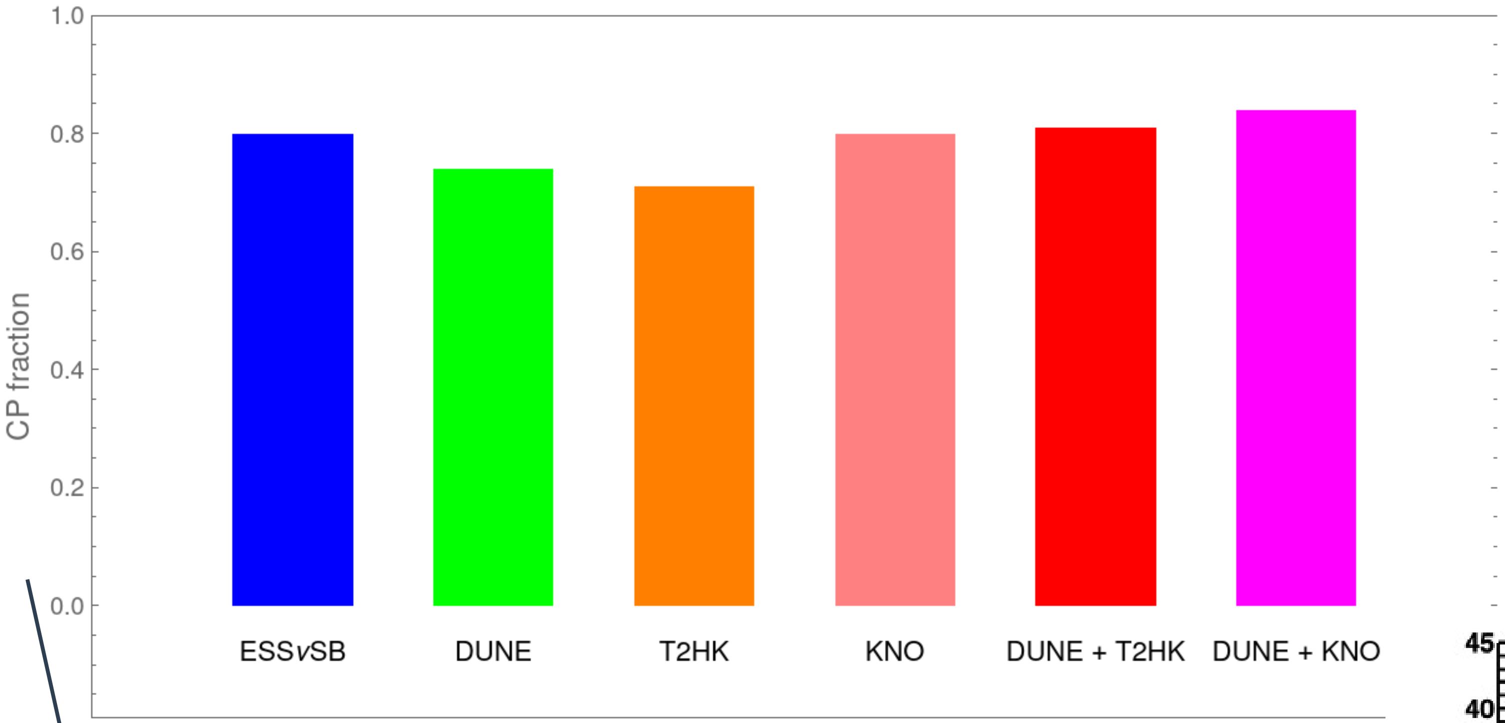
significance with which ESSnuSB would be able to disfavour CP-conservation



Significance with which CP violation could be established as a function of the fraction of values for which it would be possible.

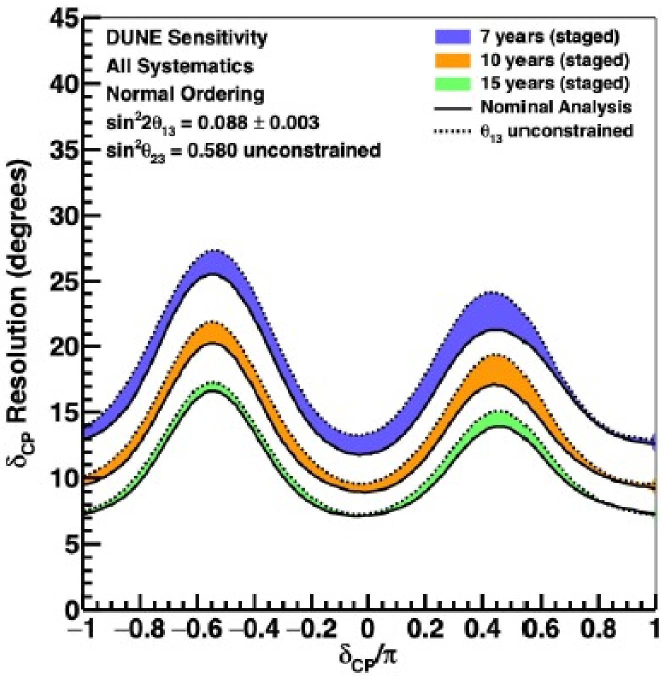


Discovery of CP violation: a summary



Significance with which CP violation could be established as a function of the fraction of values for which it would be possible.

tipical error of δ measurement >= 10°



New Physics

plethora of NP signatures at future Long Baseline Experiments → not going to revise them

- Non-Standard Interactions
- Neutrino Self-Interactions
- Neutrino Decay
- Decoherence
- Unitarity Violation
- Large Extra Dimensions
- CPT Violation
- Lorentz Invariance Violation

} many of them have new sources of CP violation

↓

how to get info on them

New sources of CP violation

main ingredient:
Asymmetries

A.Giarnetti, D.Meloni,
Universe 7 (2021) no.7, 240

G.Altarelli, D.Meloni
Nucl. Phys. B809 (2009), 158-182

$$A_{\alpha\beta} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$$

$$A_{\mu e}^{SM_0} = -\frac{12}{f_1}\, r\, \alpha \Delta_{31} \sin\delta \sin^2\Delta_{31}$$

vacuum case

$$A_{\mu\tau}^{SM_0} = \frac{4}{3} r \alpha \Delta_{31} \sin\delta$$

$s_{13} = \frac{r}{\sqrt{2}}$,
$\alpha = \Delta m^2_{21} / \Delta m^2_{31}$

New sources of CP violation

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$$s_{13} = \frac{r}{\sqrt{2}}, \quad \alpha = \Delta m_{21}^2 / \Delta m_{31}^2$$

matter case

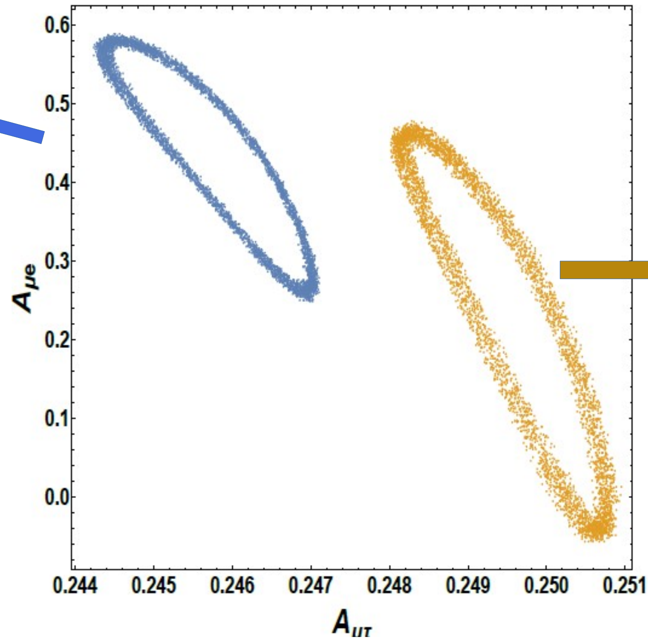
$$A_{\alpha\beta} = A_{\alpha\beta}^{SM_0} + V_{CC}\, A_{\alpha\beta}^{SM_1}$$

$$\begin{aligned} A_{\mu e}^{SM_1} &= -\frac{6}{f_1} r(\Delta_{31}\cos\Delta_{31} - \sin\Delta_{31})[2\alpha\Delta_{31}\cos\delta\cos\Delta_{31} + 3r\sin\Delta_{31} + \\ &- \frac{24}{f_1} r\alpha^2 \sin^2\delta\,\Delta_{31}^2 \sin^3\Delta_{31}\Big], \\ A_{\mu\tau}^{SM_1} &= -2r^2(1 - \Delta_{31}\cot\Delta_{31}) + \frac{8}{27}\alpha^2\Delta_{31}^3 \cot\Delta_{31}, \\ A_{\mu\mu}^{SM_1} &= \frac{4}{3} r\alpha\Delta_{31}\cos\delta(\Delta_{31} - \tan\Delta_{31}) - \frac{8}{27}\alpha^2\Delta_{31}^3\tan\Delta_{31}. \end{aligned}$$

See also:
J.Kopp et al., Phys.Rev.D77:013007,2008, T.Kikuchi et al.,JHEP 0903:114,2009, D.Meloni et al,.JHEP0904:033,2009, J.Liao et al., Phys.Rev.D93,093016(2016), P.Coloma, JHEP03(2016)016

New sources of CP violation

NH



IH

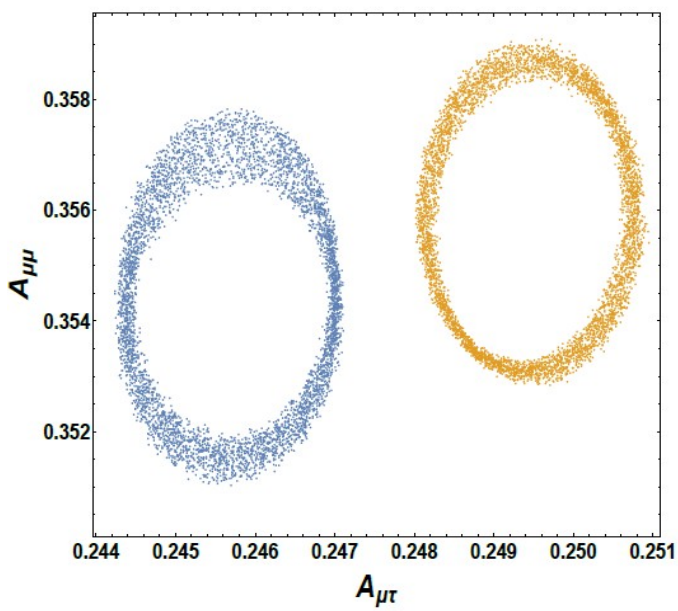
a single sources of CP violation: closed curves

Spread due to experimental uncertainties

matter case

$$A_{\alpha\beta} = A_{\alpha\beta}^{SM_0} + V_{CC}\, A_{\alpha\beta}^{SM_1}$$

Largest variation on $A_{\mu e}$



very small variation on $A_{\mu\mu}$ driven by matter effects

New sources of CP violation in NSI

modified matter potential

$$A_{CC}\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

3 more CP phases: $\varepsilon_{\mu\tau}$, $\varepsilon_{e\tau}$, $\varepsilon_{e\mu}$

$$A_{\alpha\beta} = A^{SM_0}_{\alpha\beta} + V_{CC}(A^{SM_1}_{\alpha\beta} + A^{NSI}_{\alpha\beta})$$

leading contribution from $\varepsilon_{\mu\tau}$

New sources of CP violation in NSI

modified matter potential

$$A_{CC}\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^{*} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^{*} & \varepsilon_{\mu\tau}^{*} & \varepsilon_{\tau\tau} \end{pmatrix}$$

3 more CP phases: $\varepsilon_{\mu\tau}$, $\varepsilon_{e\tau}$, $\varepsilon_{e\mu}$

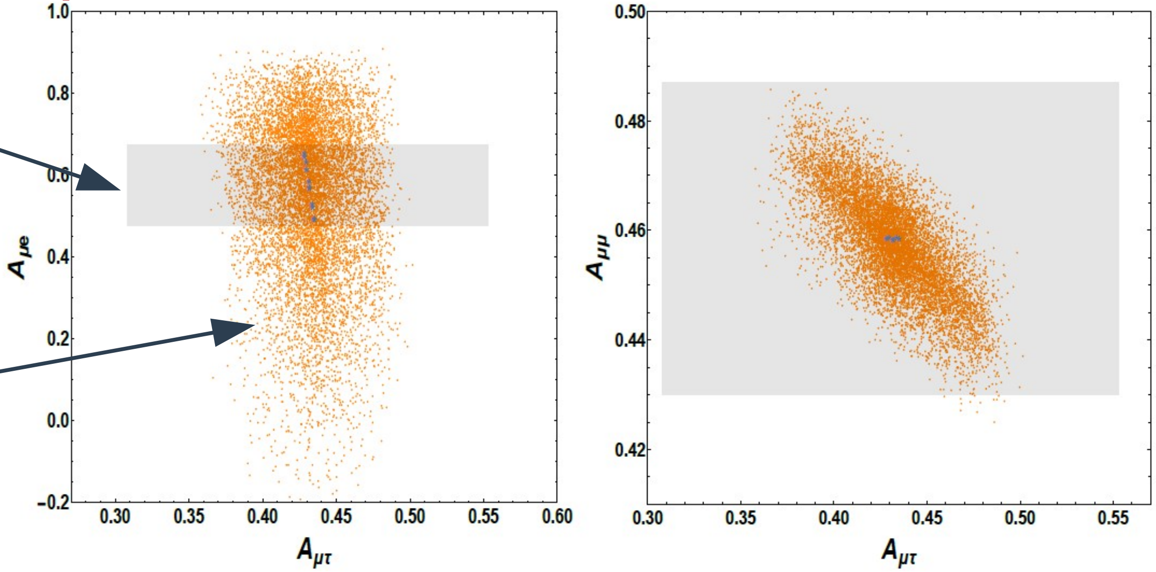
$$A_{\alpha\beta} = A_{\alpha\beta}^{SM_0} + V_{CC}(A_{\alpha\beta}^{SM_1} + A_{\alpha\beta}^{NSI})$$

leading contribution from $\varepsilon_{\mu\tau}$

Now using integrated asymmetries in DUNE
(optimized flux)

statistical errors on SM asy.

values in the NSI scenario



$A_{\mu e}$ is the most promising

and

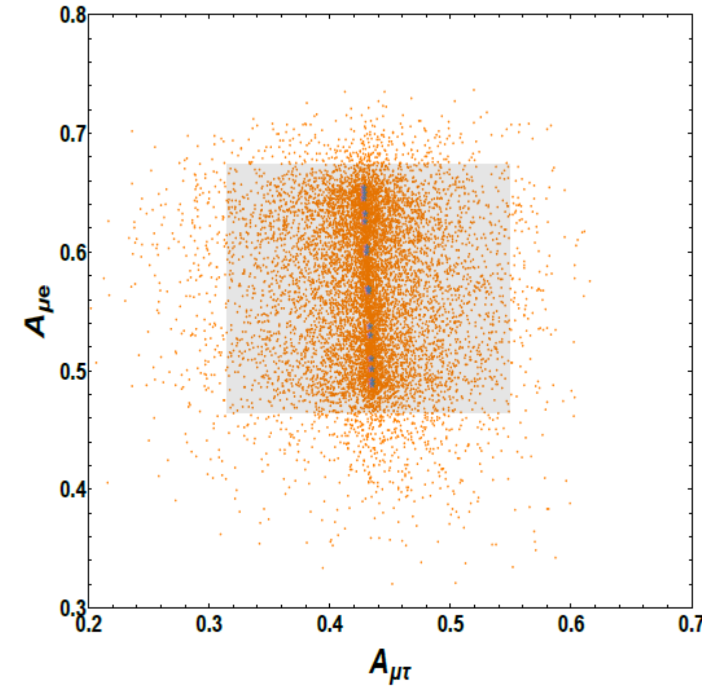
more resolution on tau detection

New sources of CP violation in 3+1 scheme

$$U = R(\theta_{34})R(\theta_{24})R(\theta_{23},\delta_3)R(\theta_{14})R(\theta_{13},\delta_2)R(\theta_{12},\delta_1)$$

two new sources of CP violation

$$\begin{aligned}
A^{3+1}_{\mu e} &\sim \frac{s_{14}s_{24}}{f_1}\{-6[2\alpha\Delta_{31}\sin\delta_1 + 3r\cos\Delta_{31}\sin(\delta_2-\delta_3)\sin\Delta_{31}]\} + \\
&\quad \frac{s_{14}s_{24}}{f_1^2}\{216r^2\alpha\Delta_{31}\cos(\delta_2-\ \delta_3)\sin(\delta_1-\delta_2+\delta_3)\ \sin^4\Delta_{31}\}\,, \\
A^{3+1}_{\mu\tau} &= 2s_{24}s_{34}\cot\Delta_{31}(\sin\delta_3 - 2V_{NC}\Delta_{31}\cos\delta_3)\,, \\
A^{3+1}_{\mu\mu} &= 4s_{24}s_{34}V_{NC}\Delta_{31}\cos\delta_3\tan\Delta_{31}\,.
\end{aligned}$$

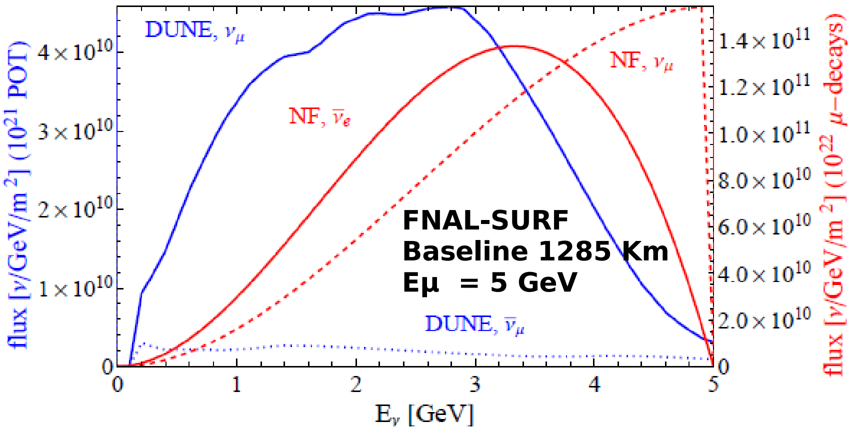


$A_{\mu e}$ and $A_{\mu\tau}$ are good candidates

Neutrino Factory & NSI

Denton et al.,
Nucl. Phys. B 1018 (2025), 117040

Nucl. Phys. B 1012 (2025), 116818



$$\mu^- \longrightarrow \nu_\mu e^- \bar{\nu}_e$$

$$\mu^+ \longrightarrow \bar{\nu}_\mu e^+ \nu_e$$

- neutrino energies reach higher energies than a fixed target
- spectrum is different with part of it rising to the maximum
- the composition and the expected energy of the neutrino beam is a 3 body decay
- no ντ get produced in the source, allowing for cleaner searches for ντ appearance

Neutrino Factory & NSI

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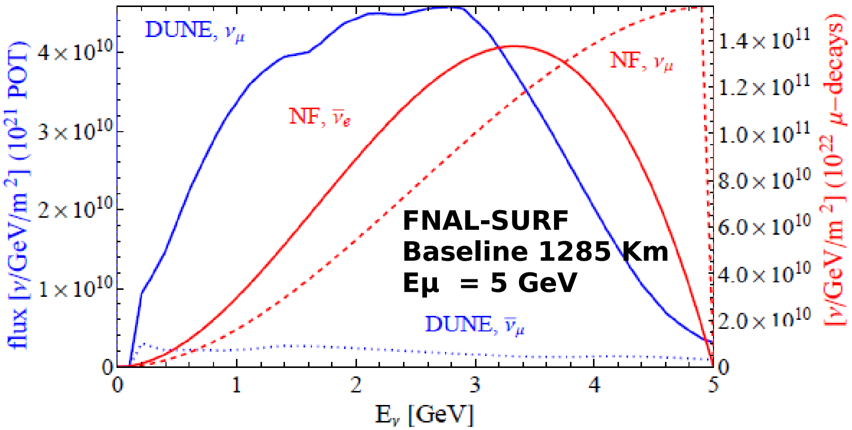
$\mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e$ $\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e$



- neutrino energies reach higher energies than a fixed target
- spectrum is different with part of it rising to the maximum
- the composition and the expected energy of the neutrino beam is a 3 body decay
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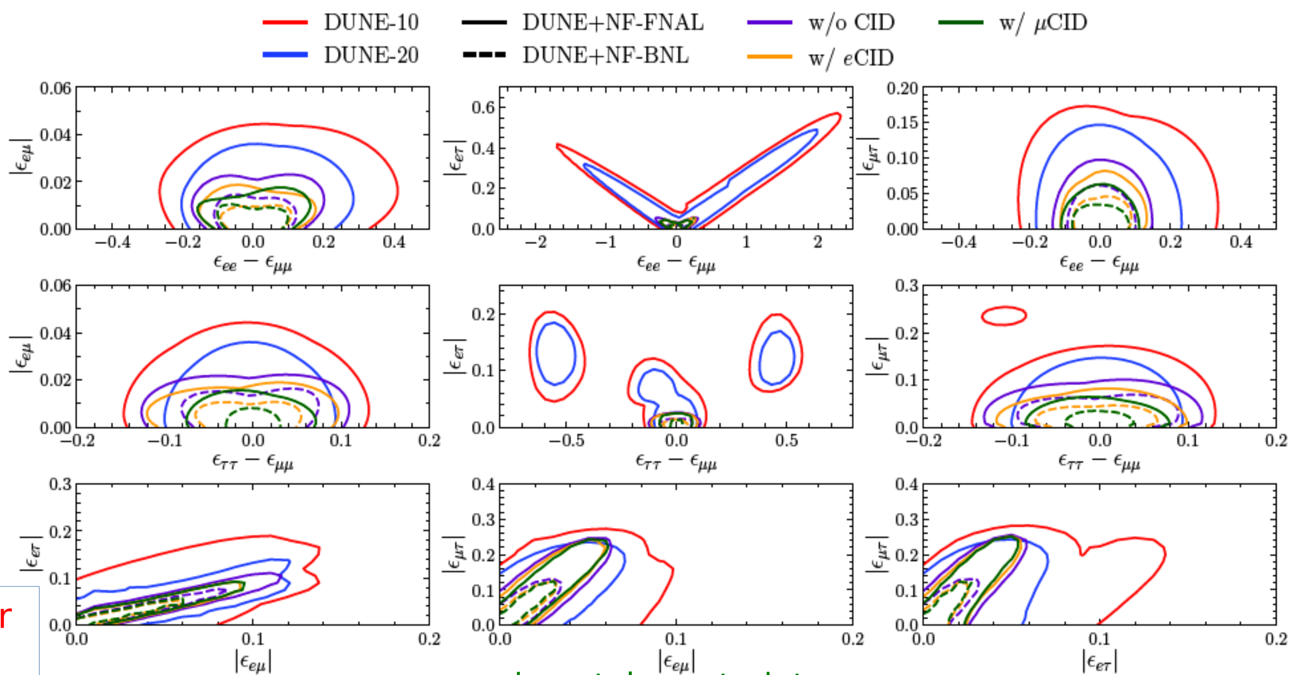
10^{21} muon (or anti-muon) decays per year

far detector is a LArTPC configuration with a total fiducial target mass of 40 kT



the sensitivity can be improved by a factor of ~ 2 compared to DUNE with 20 years running time

experimental constraint on different combinations of two NSI

Distinguishing New Physics models at DUNE

Strategy: assume that one of the benchmark new physics points represents reality and then attempt to reconstruct it in a different new physics scenario

scalar NSI

sterile

$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
$\varepsilon_{e\mu}$ NO	200	140	140	170	/	180	160	80
$\varepsilon_{e\tau}$ NO	60	48	50	45	50	/	50	40
$\varepsilon_{\mu\tau}$ NO	200	180	170	180	160	180	/	80
$\varepsilon_{e\mu}$ IO	170	80	75	90	/	10	13	3
$\varepsilon_{e\tau}$ IO	70	50	50	45	45	/	60	20
$\varepsilon_{\mu\tau}$ IO	500	400	400	400	300	350	/	160

data could not be well fit with a different New Physics model

Reality: vector NSI from Nova and T2K

Denton,Giarnetti,Meloni JHEP02(2023)210

Distinguishing New Physics models at DUNE

Strategy: assume that one of the benchmark new physics points represents reality and then attempt to reconstruct it in a different new physics scenario

vector NSI

sterile

$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
$\eta_{e\mu}$ NO	0.14	/	0.005	0.088	0.071	0.033	0.055	0.02
$\eta_{e\tau}$ NO	0.08	0.003	/	0.041	SM	SM	SM	0.01
$\eta_{\mu\tau}$ NO	0.60	0.48	0.48	/	SM	SM	SM	0.02
$\eta_{e\mu}$ IO	100	/	4.7	6.3	80	70	90	21
$\eta_{e\tau}$ IO	60	1.0	/	1.5	44	38	50	11
$\eta_{\mu\tau}$ IO	30	4.6	4.8	/	23	20	29	12

there is some confusions for particular choices

Reality: scalar NSI from Nova and T2K

Denton,Giarnetti,Meloni
JHEP02(2023)210

Conclusions

- about the “current” PMNS
  parameters known with sufficient precision but the theta23&CP phase

- about the “future” PMNS
  improvements on the measure of CP phase crucial for model building

- about “new physics”
  in 20 years from now, either we discern small variations from the standard picture or the SM is likely to be valid up to the Planck scale

Neutrino Factory & CPT violation

Denton et al.,
Nucl. Phys. B 1018 (2025), 117040

neutrinos are described by $x \in \left\{\theta_{ij}, \delta_{CP}, \Delta m^2_{ij}\right\}$

anti-neutrinos are associated with $\bar{x} \in \left\{\overline{\theta}_{ij}, \overline{\delta}_{CP}, \Delta\overline{m}^2_{ij}\right\}$

CPT conserved → all parameters are the same but a“-” sign on the phase

limits on CPT violation are obtained by evaluating

$$\chi^2(|\Delta x|) = \chi^2(|x - \overline{x}|) = \chi^2_{\nu}(x) + \chi^2_{\overline{\nu}}(\overline{x})$$

Neutrino Factory & CPT violation

Denton et al.,
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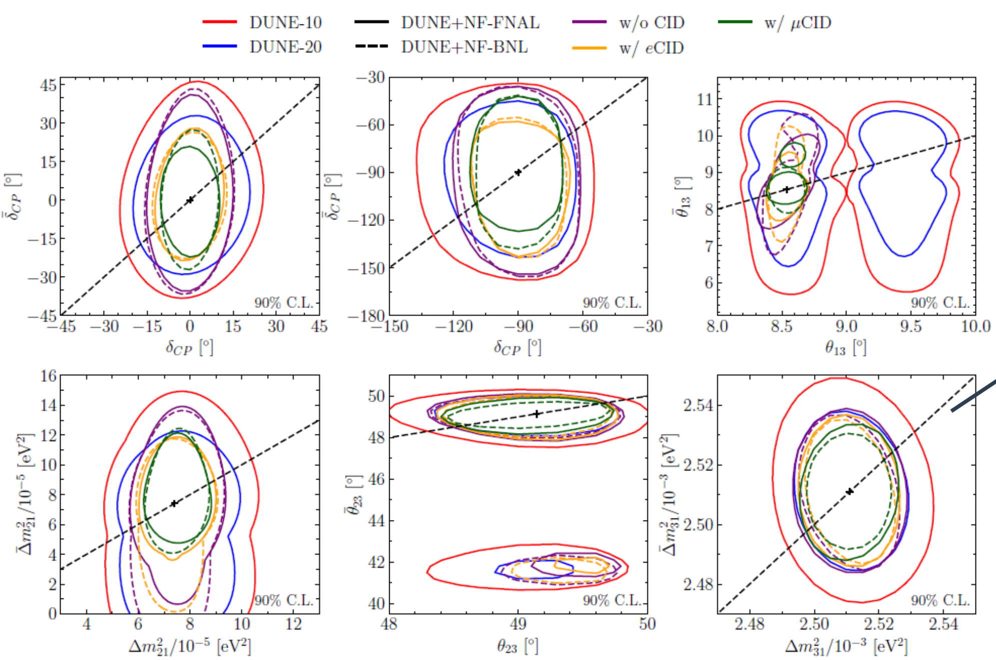


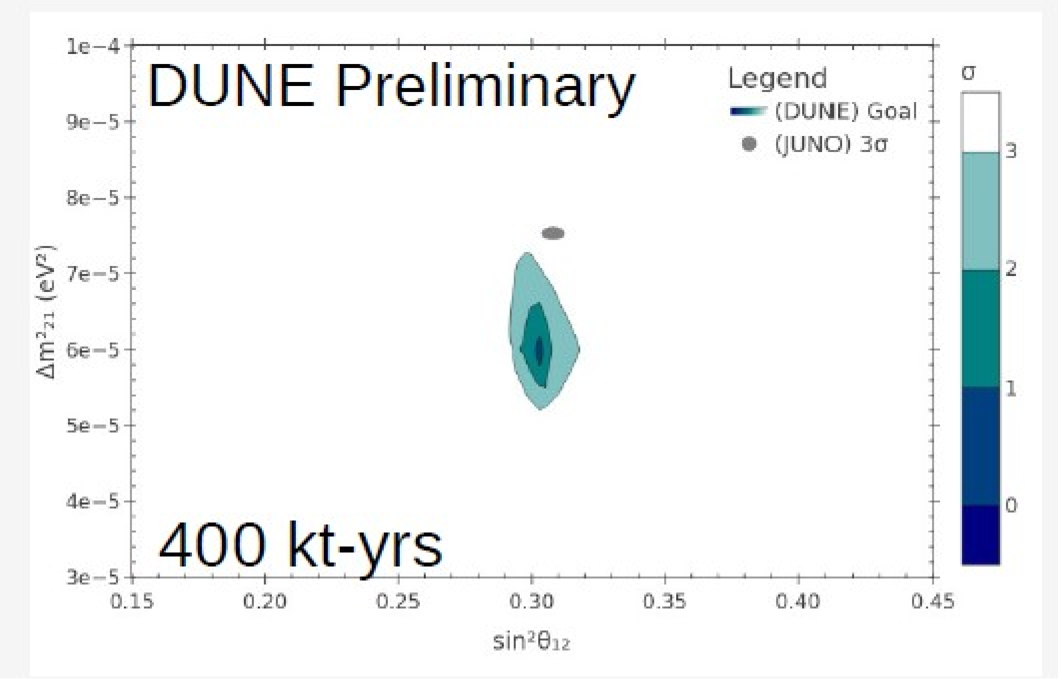
experimental sensitivity to the difference between the oscillation parameters for neutrino and anti neutrinos

CPT conserving line

the addition of a NF to DUNE improves the precision on the oscillation parameters for neutrinos and antineutrinos simultaneously

Dune & solar neutrinos

DUNE sensitivity to solar neutrinos



Some experimental setup

Agarwalla et al. Eur. Phys. J. C (2023) 83:694

Table 2 Essential experimental features of various long-baseline experiments considered in our analysis. The first column characterizes DUNE, while the second column depicts aspects of JD and KD

Characteristics	DUNE	JD/KD
Baseline (km)	1285	295 (1100)
ρ_{avg} (g/cm^3)	2.848	2.7 (2.8)
Beam	LBNF [16]	J-PARC [57]
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
1st (2nd) 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%
Signal norm. error (Disapp.)	5%	3.5%
Binned-events matched with	[19]	[23]

Table 3 Total appearance event rates (signal + background) in neutrino, antineutrino modes, and $\mathcal{N}_{CP}^{\mu e}$ for DUNE (JD) corresponding to different sets of δ_{CP} : 0°, 90°, −90° and θ_{23} : 40°, 45°, and 50° are shown in the second (third) set of rows, respectively

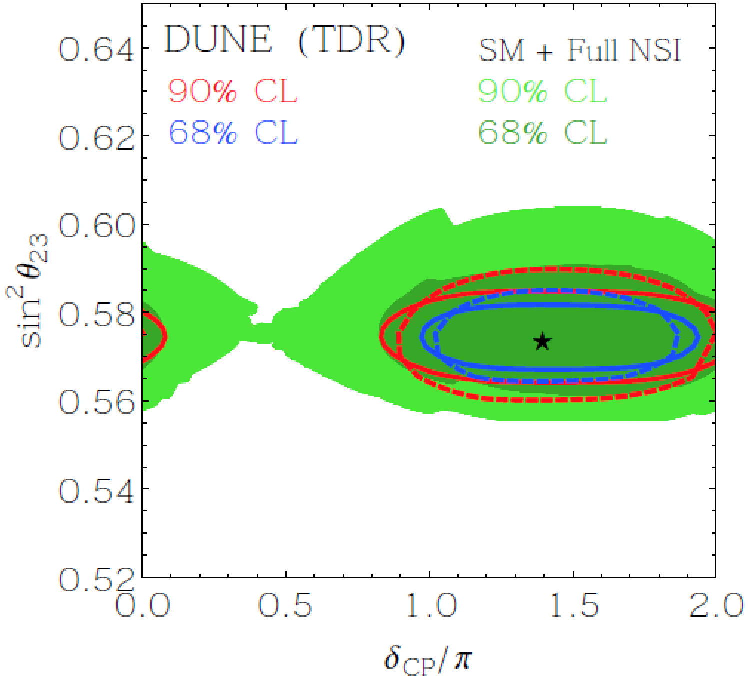
Experiment	Parameter			
	θ_{23}	δ_{CP}= 0° ($\nu_e, \bar{\nu}_e, \mathcal{N}_{CP}^{\mu e}$)	δ_{CP} = 90° ($\nu_e, \bar{\nu}_e, \mathcal{N}_{CP}^{\mu e}$)	δ_{CP} = −90° ($\nu_e, \bar{\nu}_e, \mathcal{N}_{CP}^{\mu e}$)
DUNE	40°	1965, 812, *0.41*	1657, 857, *0.31*	2303, 728, *0.52*
	45°	2215, 875, *0.43*	1902, 920, *0.34*	2558, 790, *0.53*
	50°	2470, 938, *0.45*	2161, 982, *0.37*	2807, 854, *0.53*
JD	40°	1644, 1420, *0.074*	1277, 1687, *− 0.14*	2024, 1113, *0.29*
	45°	1890,1594, *0.085*	1517, 1868, *− 0.1*	2276, 1286, *0.28*
	50°	2137, 1770, *0.093*	1770, 2041, *− 0.07*	2518, 1476, *0.26*

Limits on NC NSI and correlation with the SM

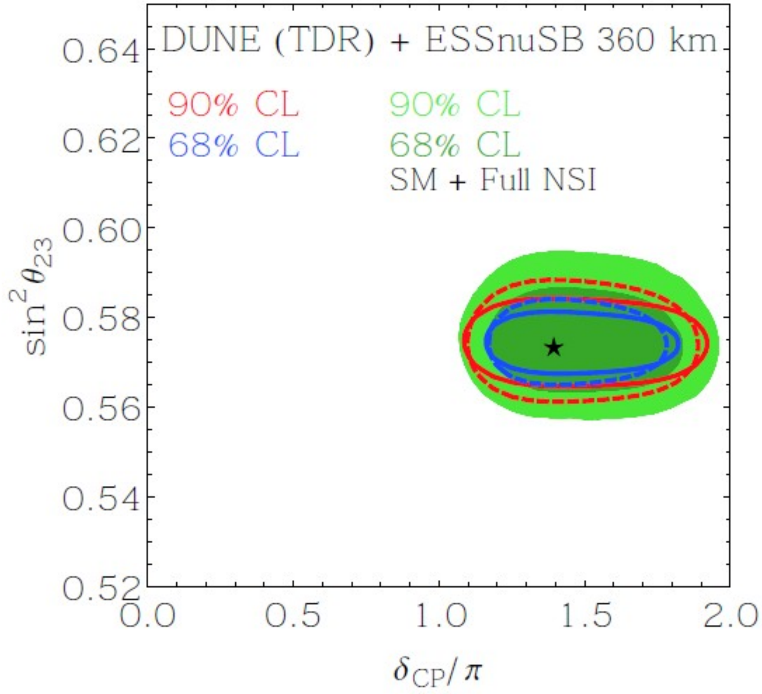
Singha et al. 2112.04876

$$\begin{pmatrix} |\epsilon_{ee}| < 4\times 10^{0} & |\epsilon_{e\mu}| < 3\times 10^{-1} & |\epsilon_{e\tau}| < 3\times 10^{0} \\ & |\epsilon_{\mu\mu}| < 7\times 10^{-2} & |\epsilon_{\mu\tau}| < 3\times 10^{-1} \\ & & |\epsilon_{\tau\tau}| < 2\times 10^{1} \end{pmatrix}$$

L.A. Delgadillo and O.G.Miranda
PRD108 (095024)

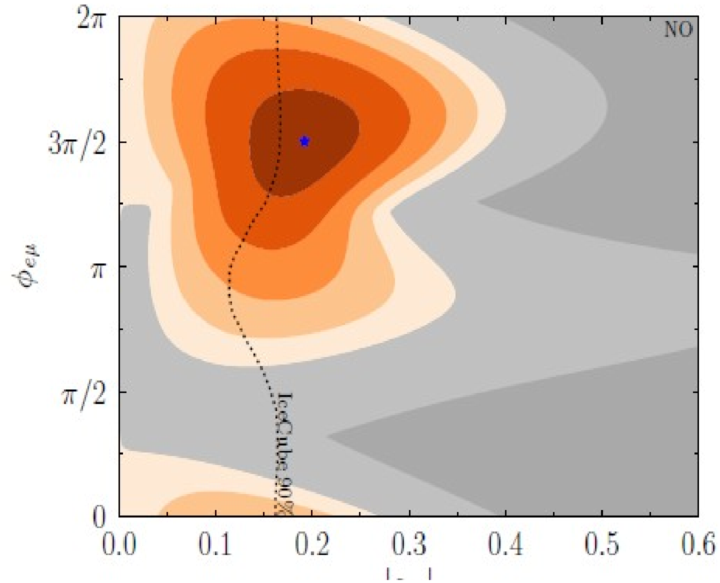


synergy



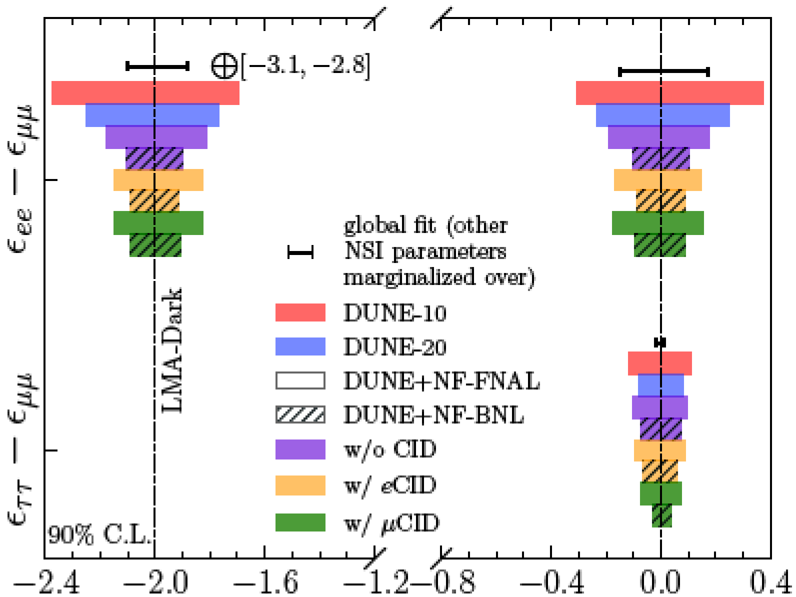
NoVA-T2K tension on delta CP

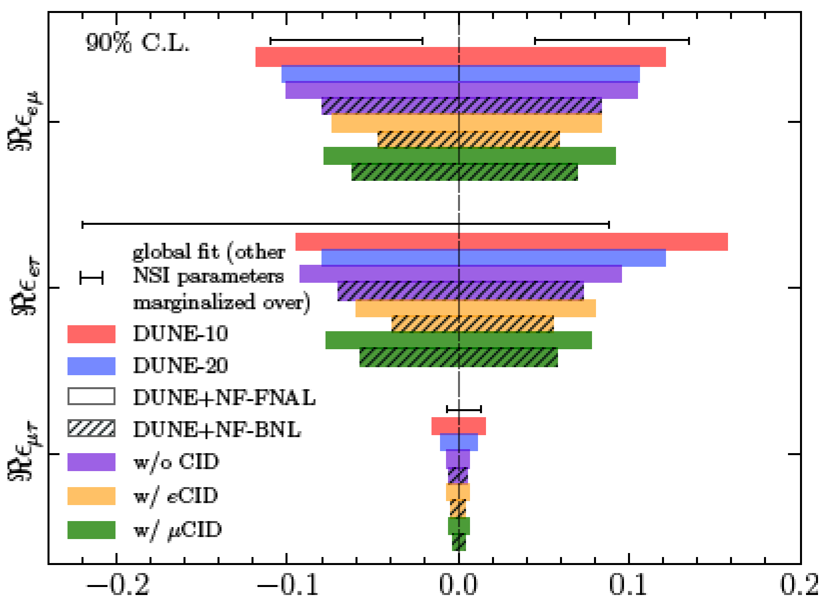
Denton et al., PhysRevLett.126.051801



tension in the recent NOvA and T2K data solved by complex NSI

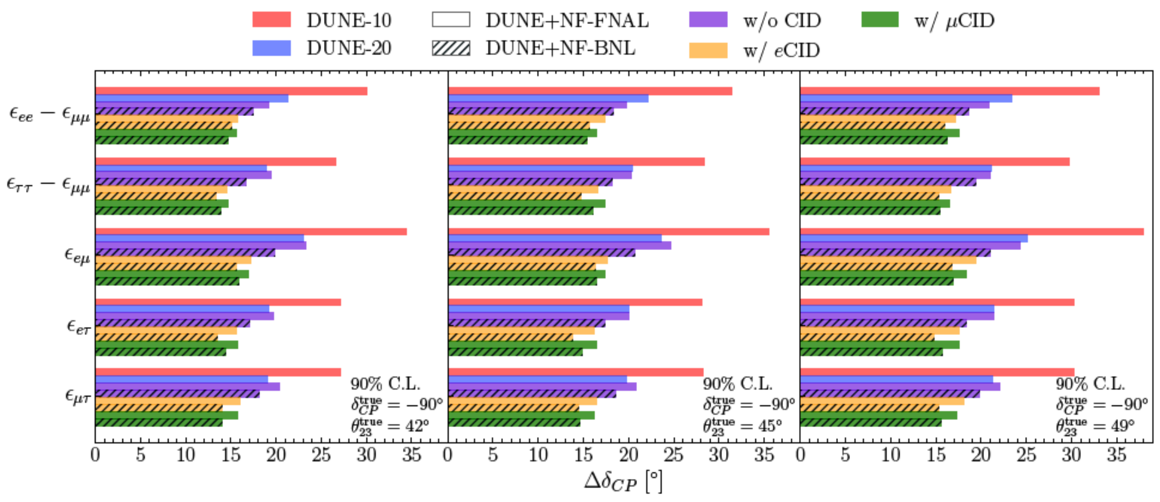
Denton et al.,2502.14027, NSI at NuFact



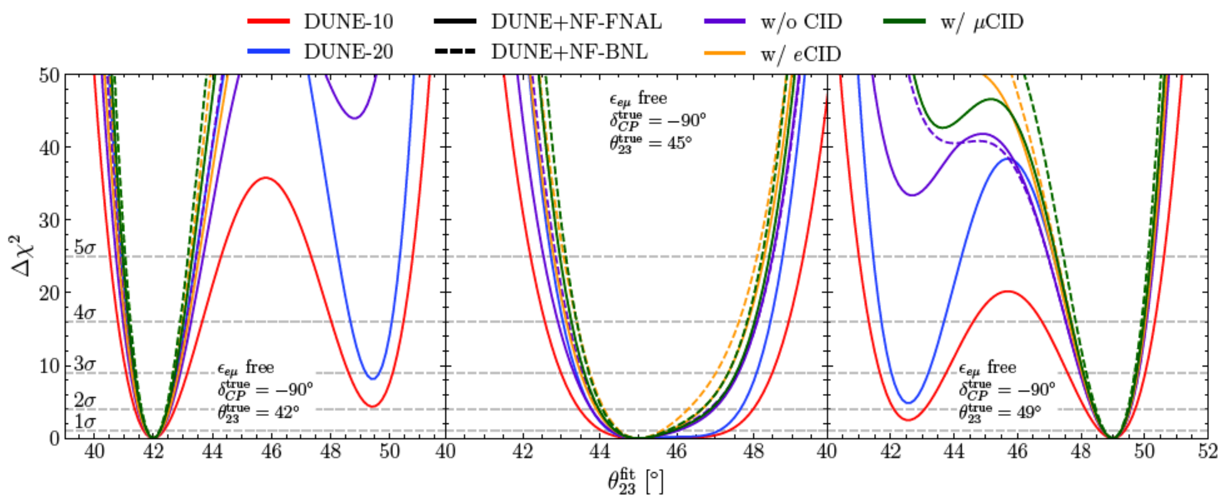


Effects of NSI on delta CP measurement

Denton et al.,2502.14027,
NSI at NuFact

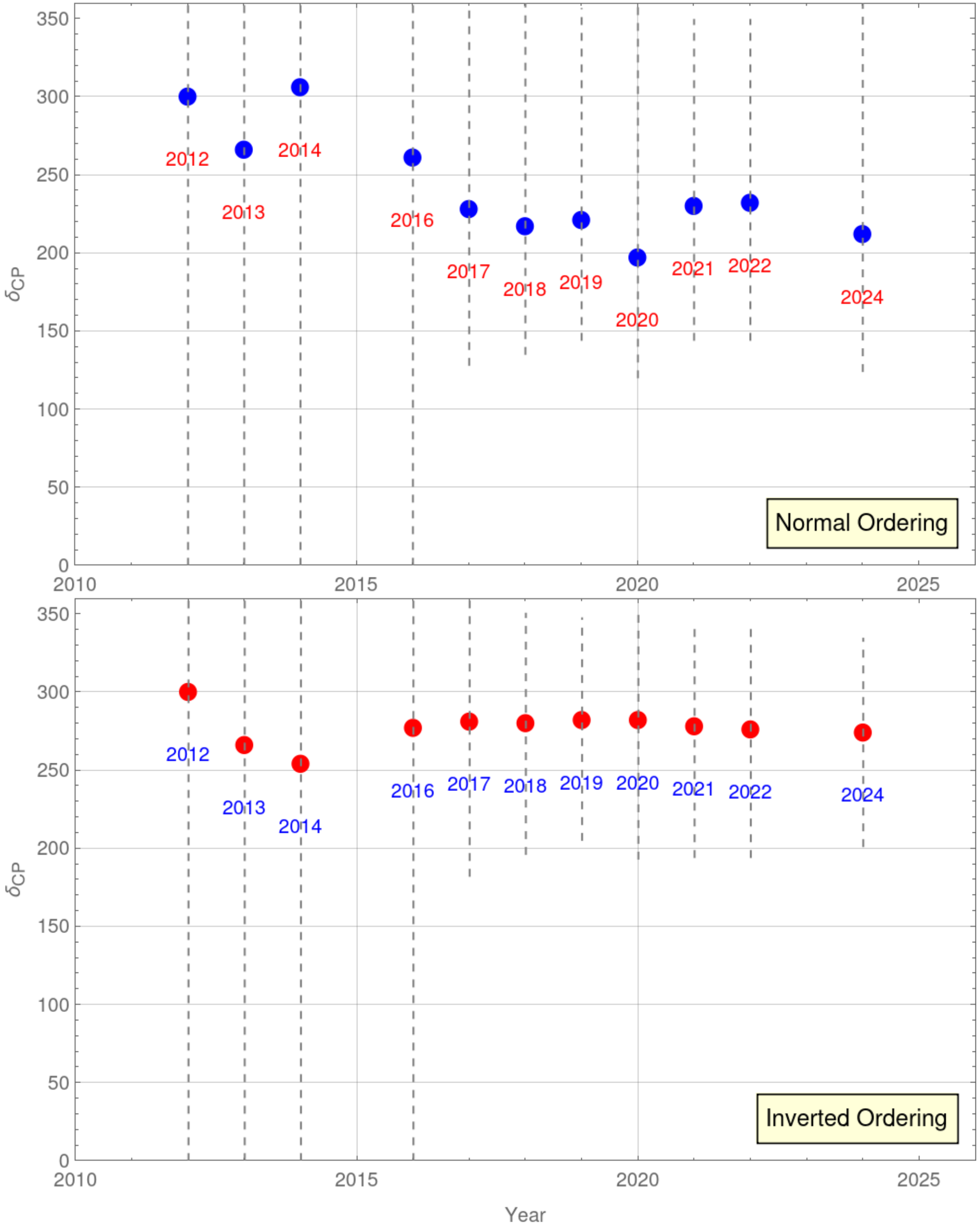


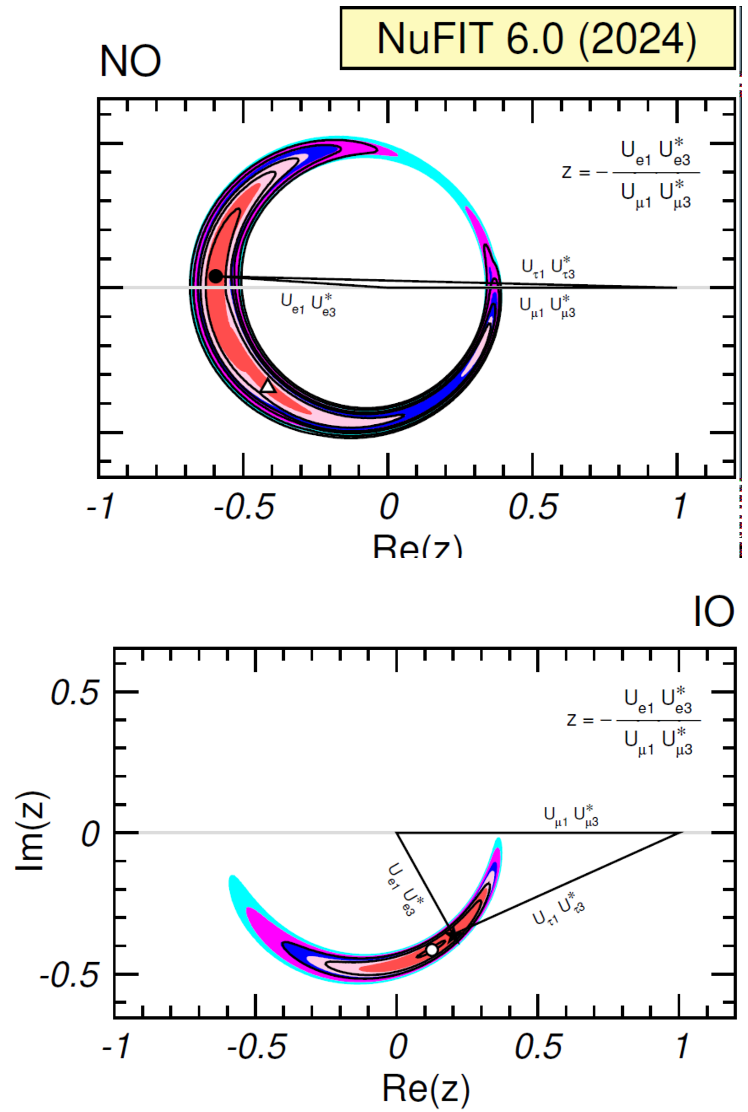
Expected sensitivity
on deltaCP



experimental
sensitivity to theta23

What we know: δ_{CP}

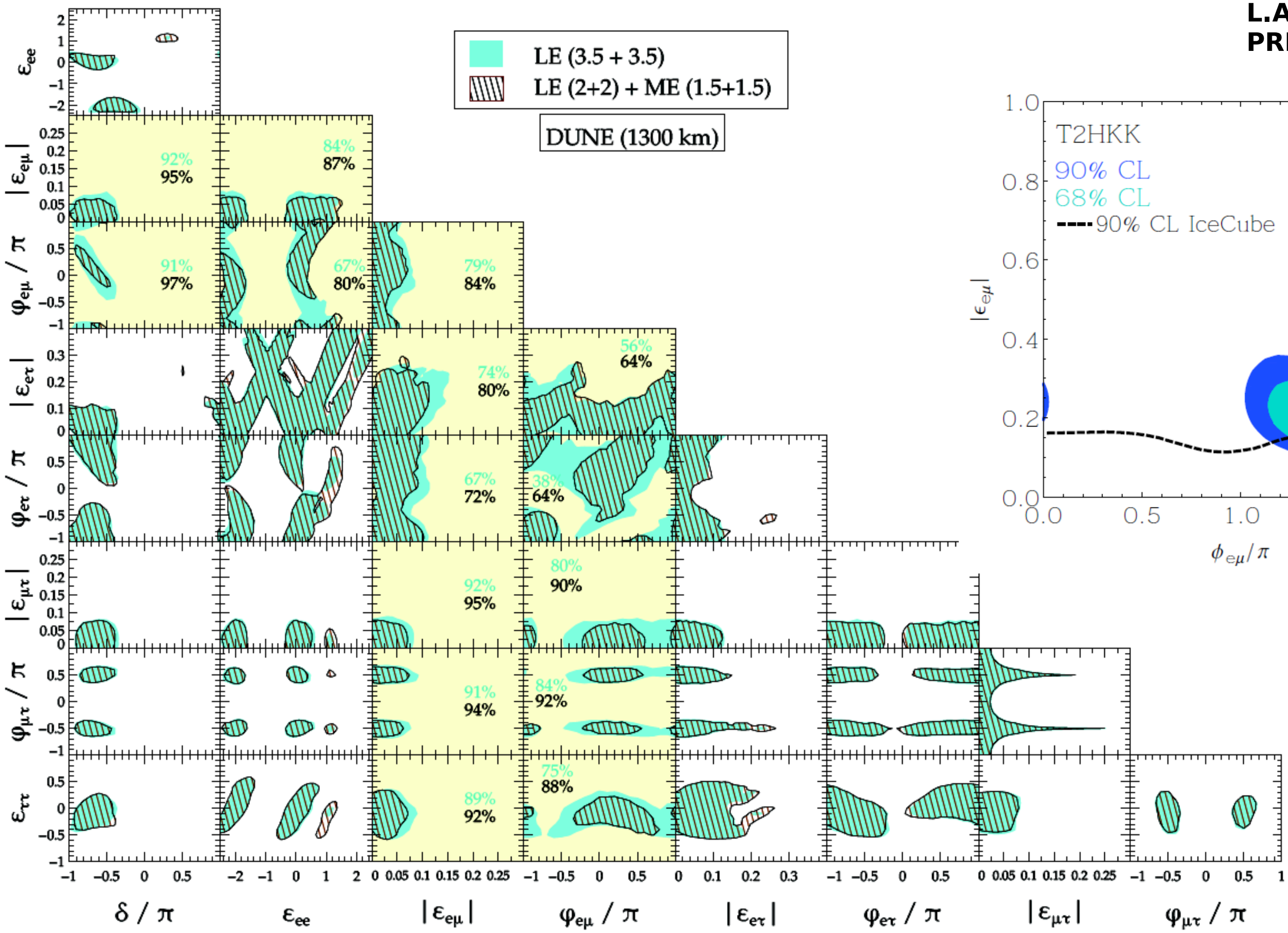




- weak indications:
IO seems to prefer maximal CP violation while NO a CP conserving solution

New sources of CP violation in NSI

M.Masud, S.Roy and P.Mehta,
Phys. Rev. D99 (2019) no.11, 115032



L.A. Delgadillo and O.G.Miranda
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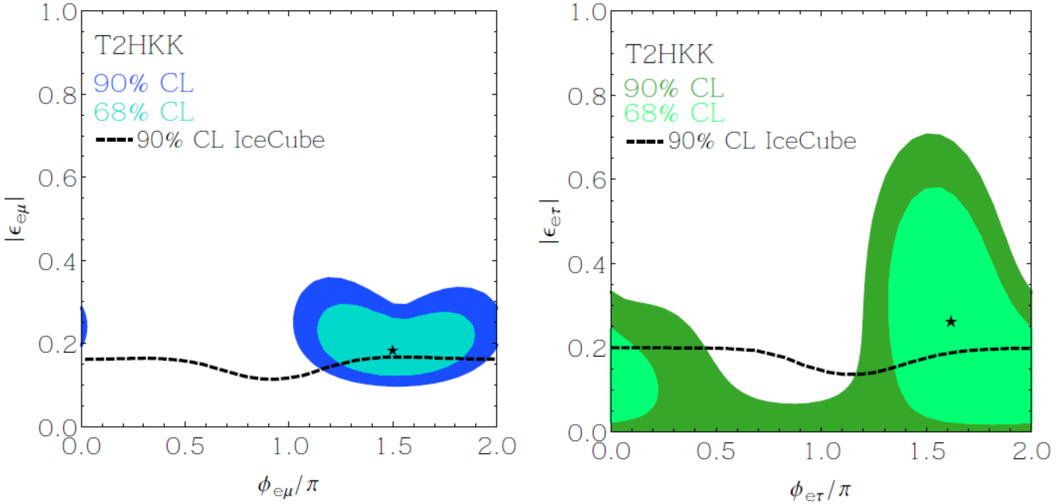

difficult to strongly constrain CP phases