Search for CP violation in neutrino oscillations

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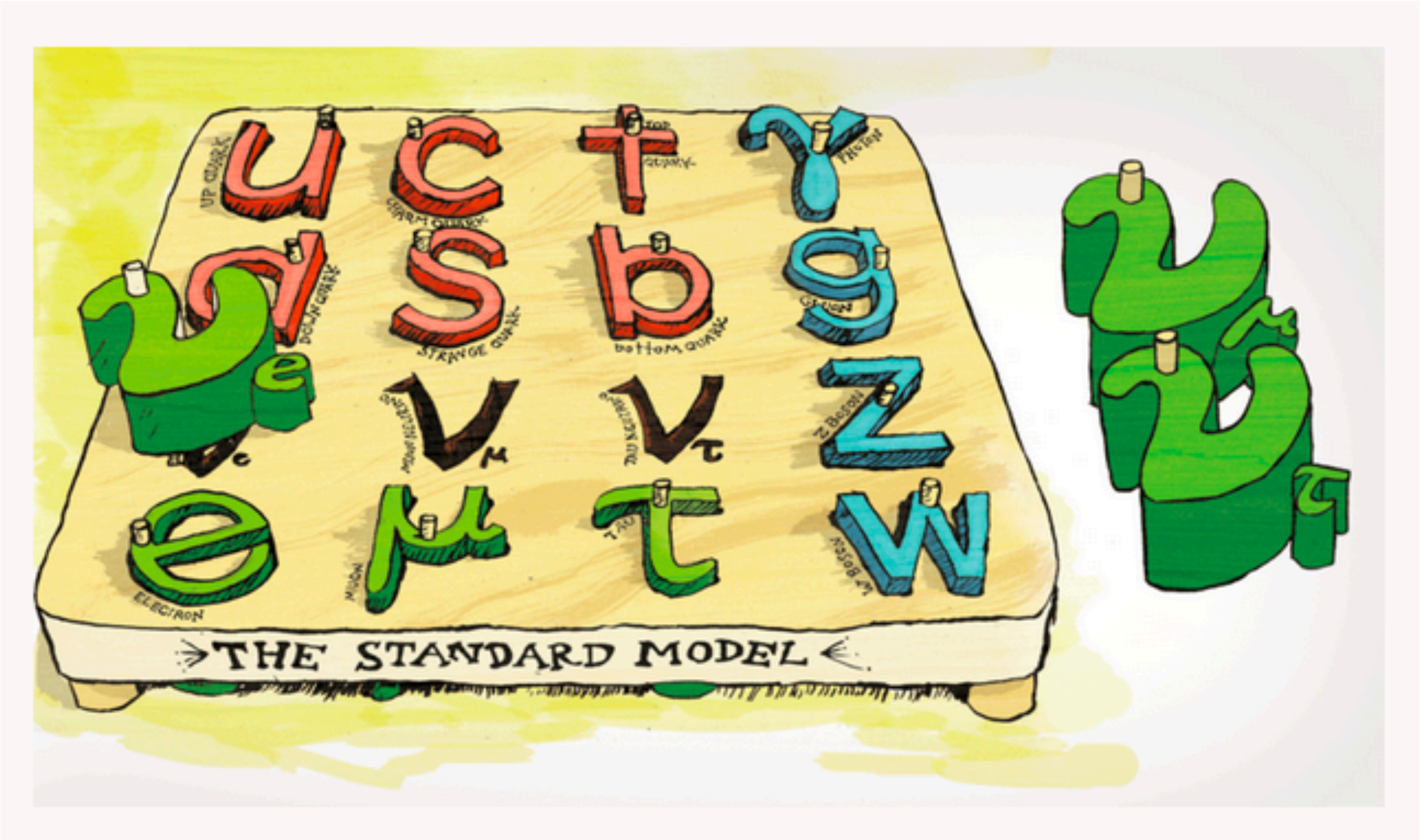
DISCRETE 2022

11th November 2022

Neutrino oscillations

Observation of neutrino oscillations:

→ Strong evidence of physics beyond the SM

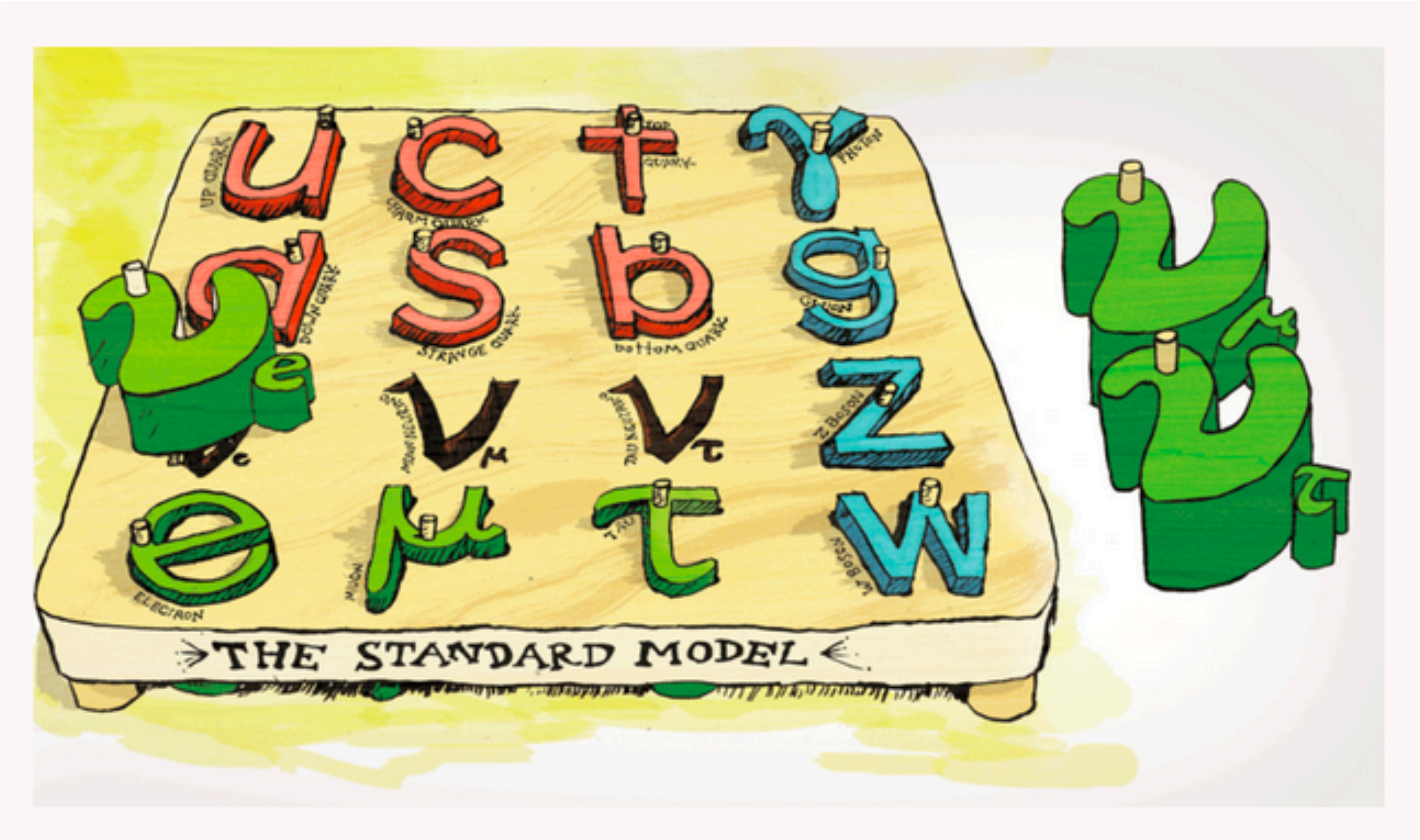


Neutrino oscillations

Observation of neutrino oscillations:

→ Strong evidence of physics beyond the SM

→ introduced more parameters to the model
(3 angles, at least one phase, 3 masses)
⇒ want to measure them



Neutrino oscillations

flavor eigenstates (of weak interaction) and mass eigenstates (of free particle Hamiltonian) not aligned for neutrinos

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

U_{PMNS}: relates flavor and mass states

Parametrized by four parameters (3 angles and at least one phase)

$$U_{\text{PMNS}} = U_{23}(\theta_{23}) U_{13}(\theta_{13}, \delta) U_{12}(\theta_{12})$$

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U_{PMNS}: relates flavor and mass states

Parametrized by four parameters (3 angles and at least one phase)

$$U_{\text{PMNS}} = U_{23}(\theta_{23}) U_{13}(\theta_{13}, \delta) U_{12}(\theta_{12}) \mathrm{diag}(\mathrm{e}^{\mathrm{i}\alpha_1/2}, \mathrm{e}^{\mathrm{i}\alpha_2/2}, 1)$$

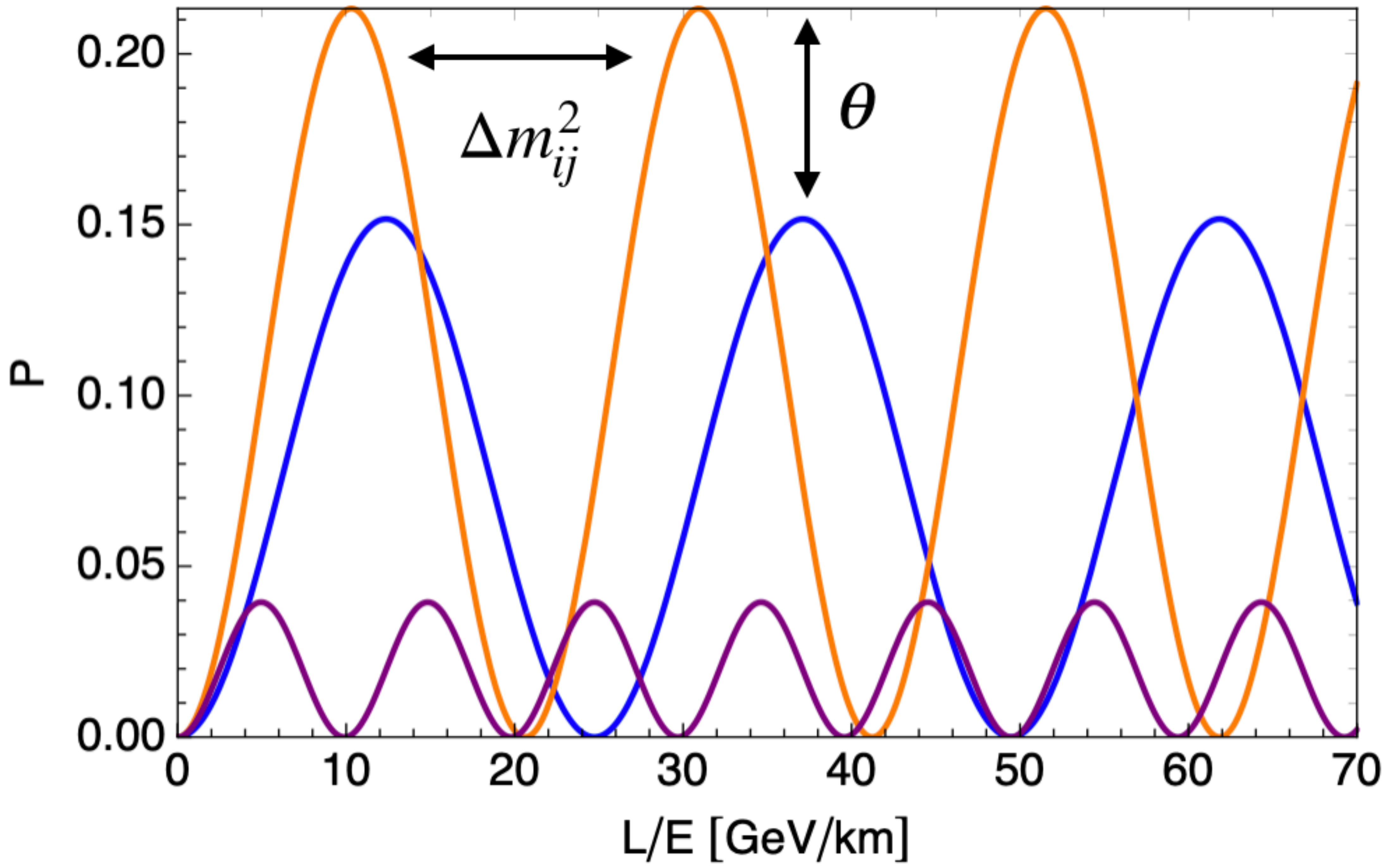
Majorana phases: only physical for Majorana neutrinos,
oscillation experiments not sensitive to them
$\rightarrow$ not going to talk about them further

Neutrino oscillation parameters

produce neutrino of flavor α with energy *E*, probability to detect neutrino with flavor β at distance *L* is

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(\Delta m_{ij}^2 L/4E), \ \Delta m_{ij}^2 = m_i^2 - m_j^2$$

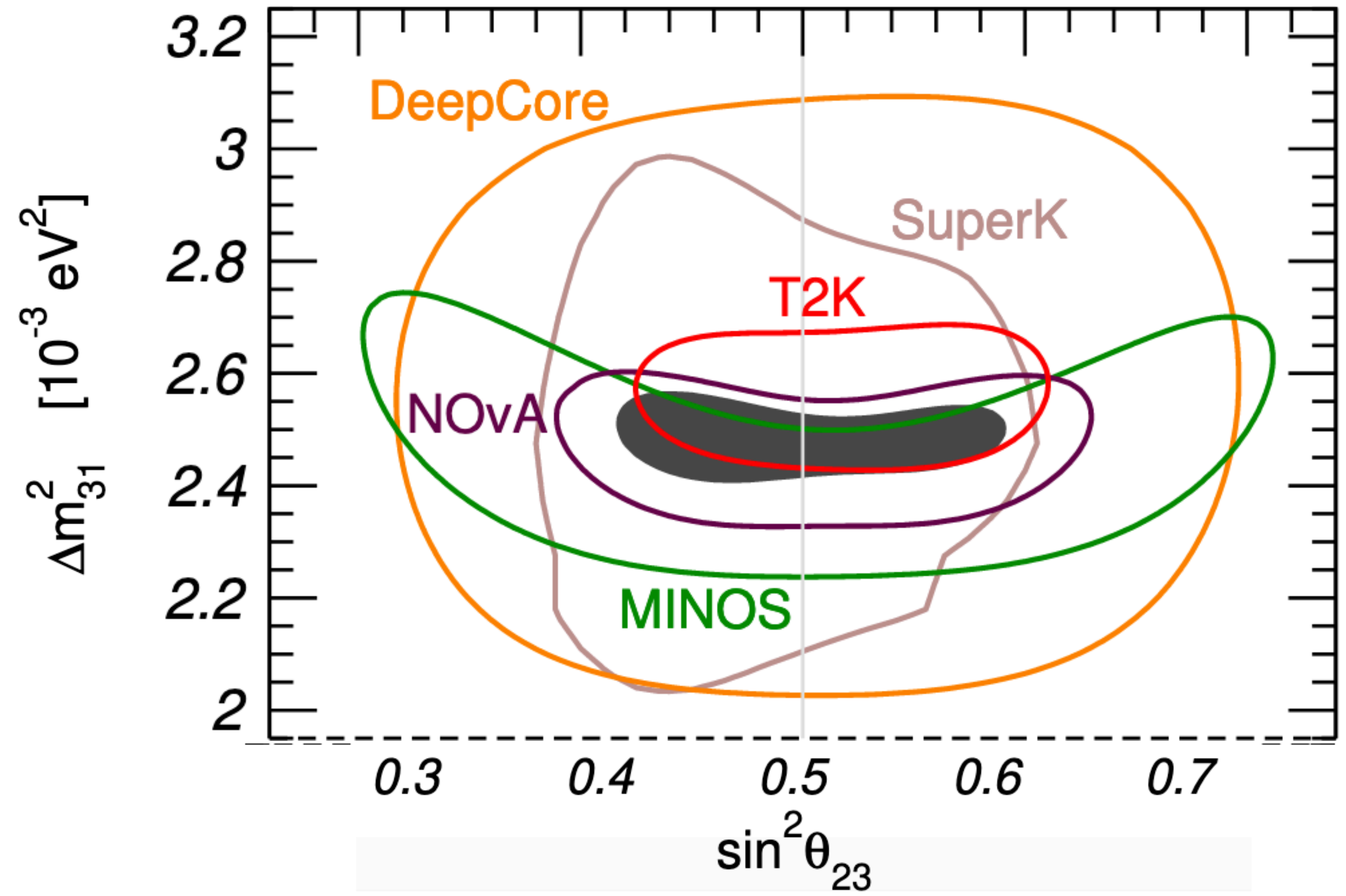
In a 2-flavor approximation



Neutrino oscillation parameters

Many experiments have measured the angles and mass splittings
→ impressive agreement between experiments

[nufit v5.1]



Neutrino oscillation parameters

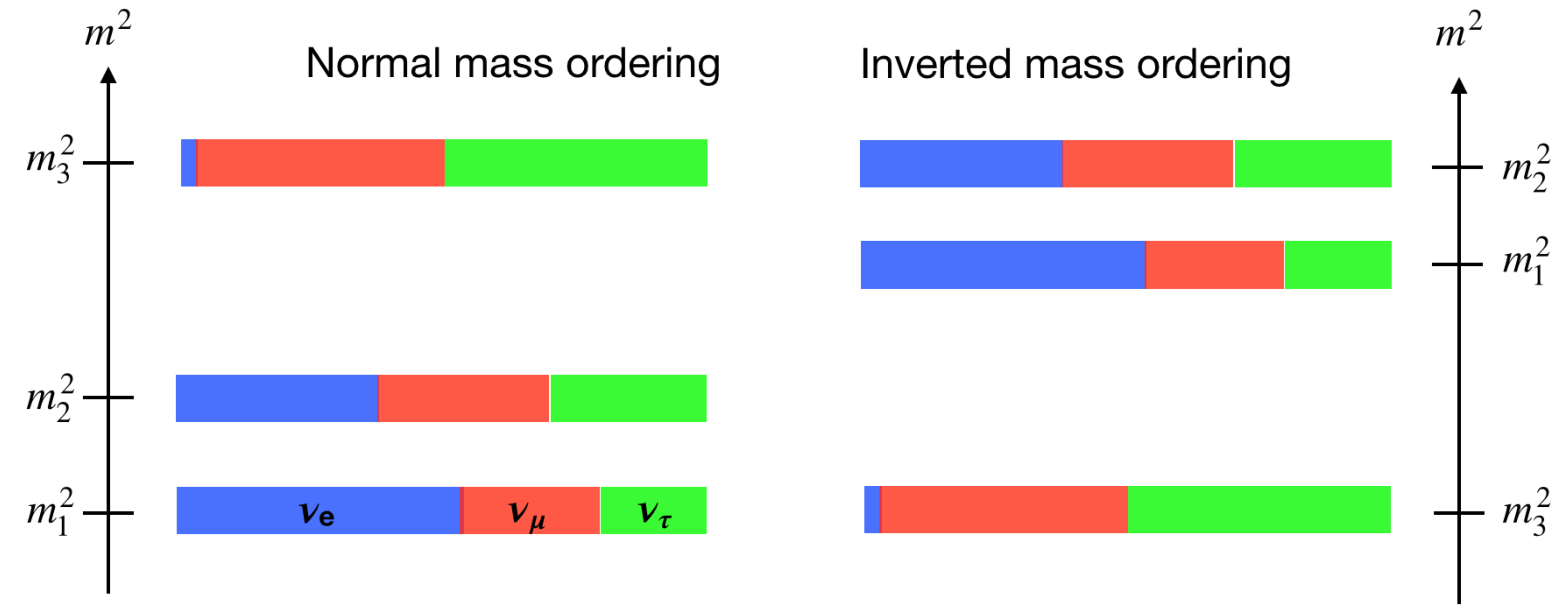
Global fits to oscillation data:

Information on mixing angles, mass splittings

mass splittings: $|\Delta m_{32}^2| = 2.5 \cdot 10^{-3}\ \mathrm{eV}^2,\ \Delta \mathrm{m}_{21}^2 = 7.4 \cdot 10^{-5}\ \mathrm{eV}^2$

[nufit v5.1]

mass ordering unknown



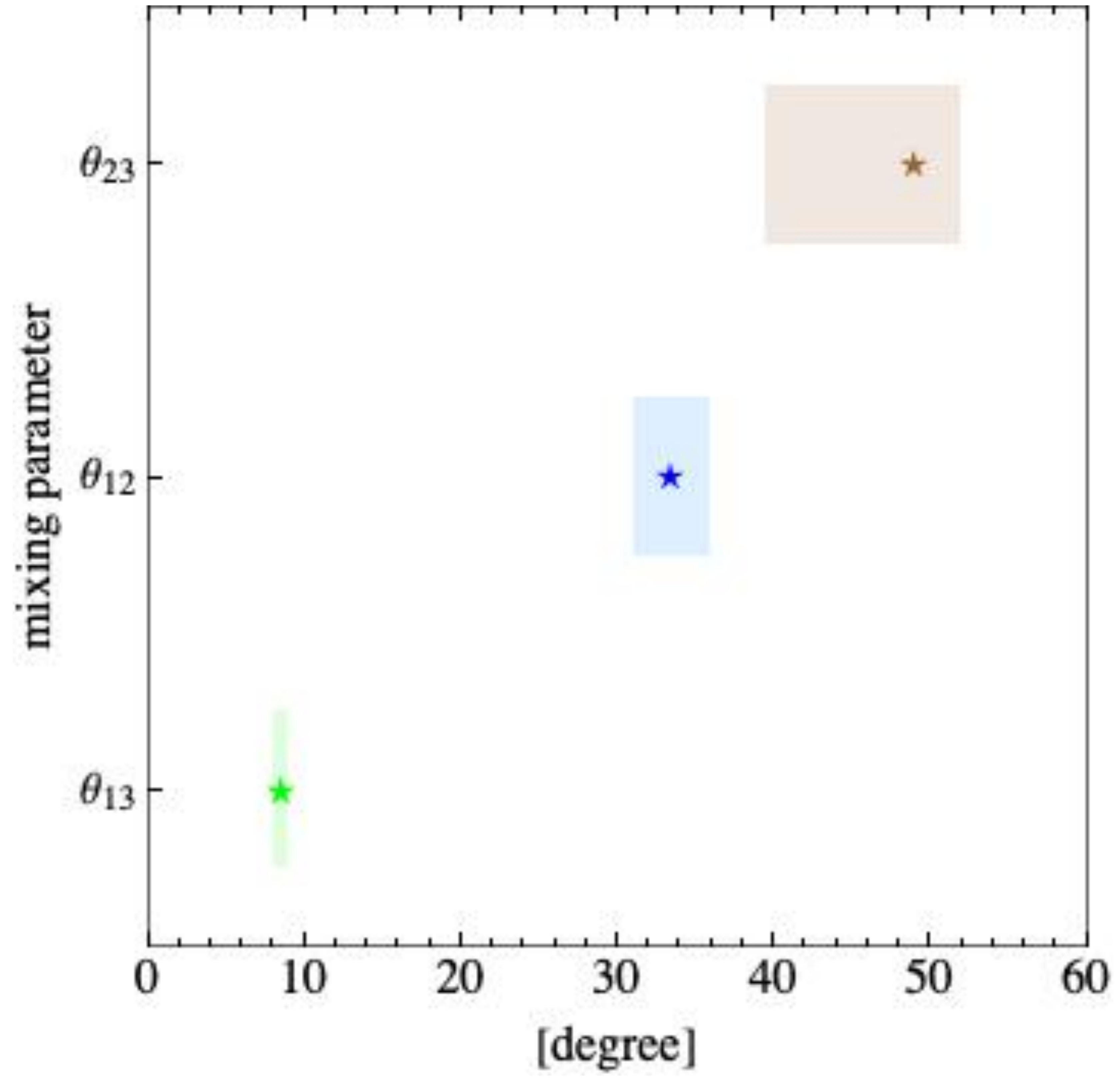
Neutrino oscillation parameters

Global fits to oscillation data:

Information on mixing angles, mass splittings

[nufit v5.1]

all three angles non-zero
mixing angles are large!



Neutrino oscillation parameters

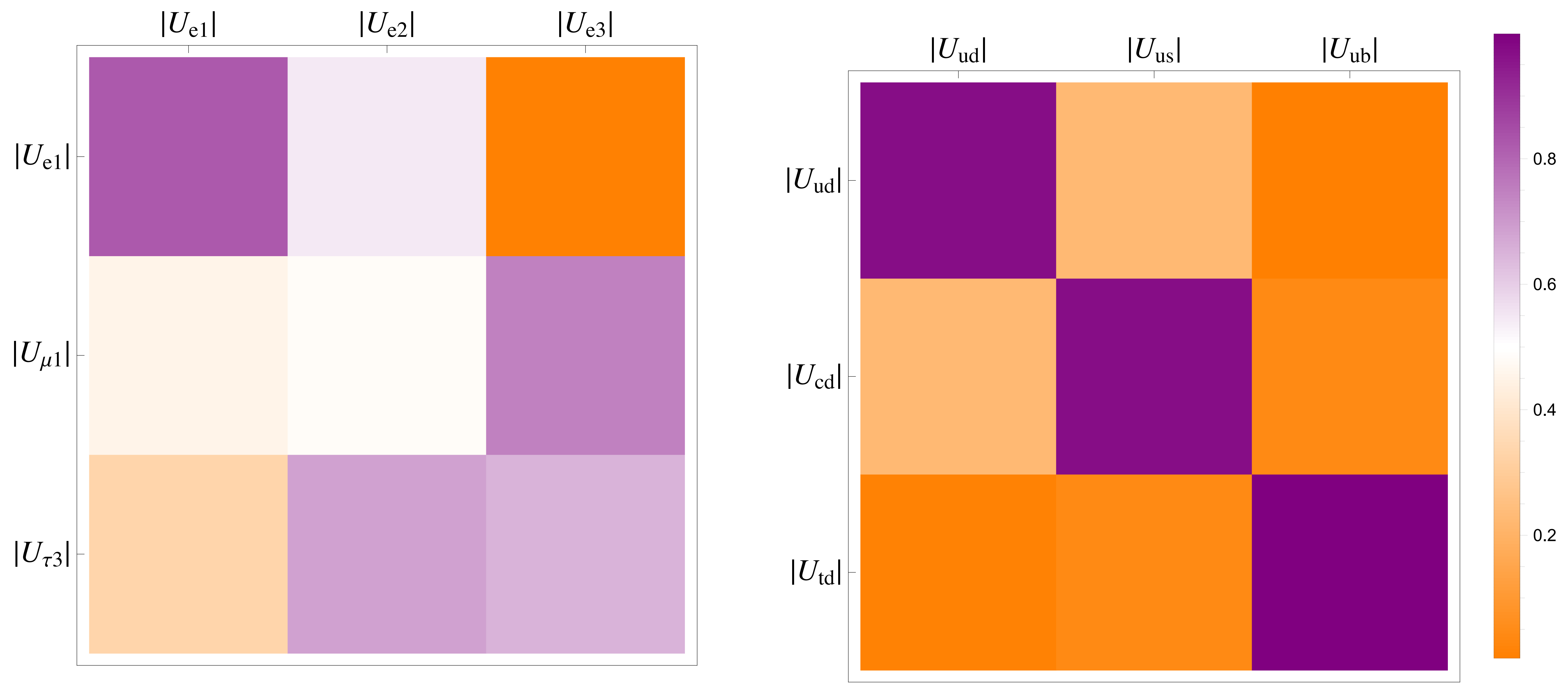
Global fits to oscillation data:

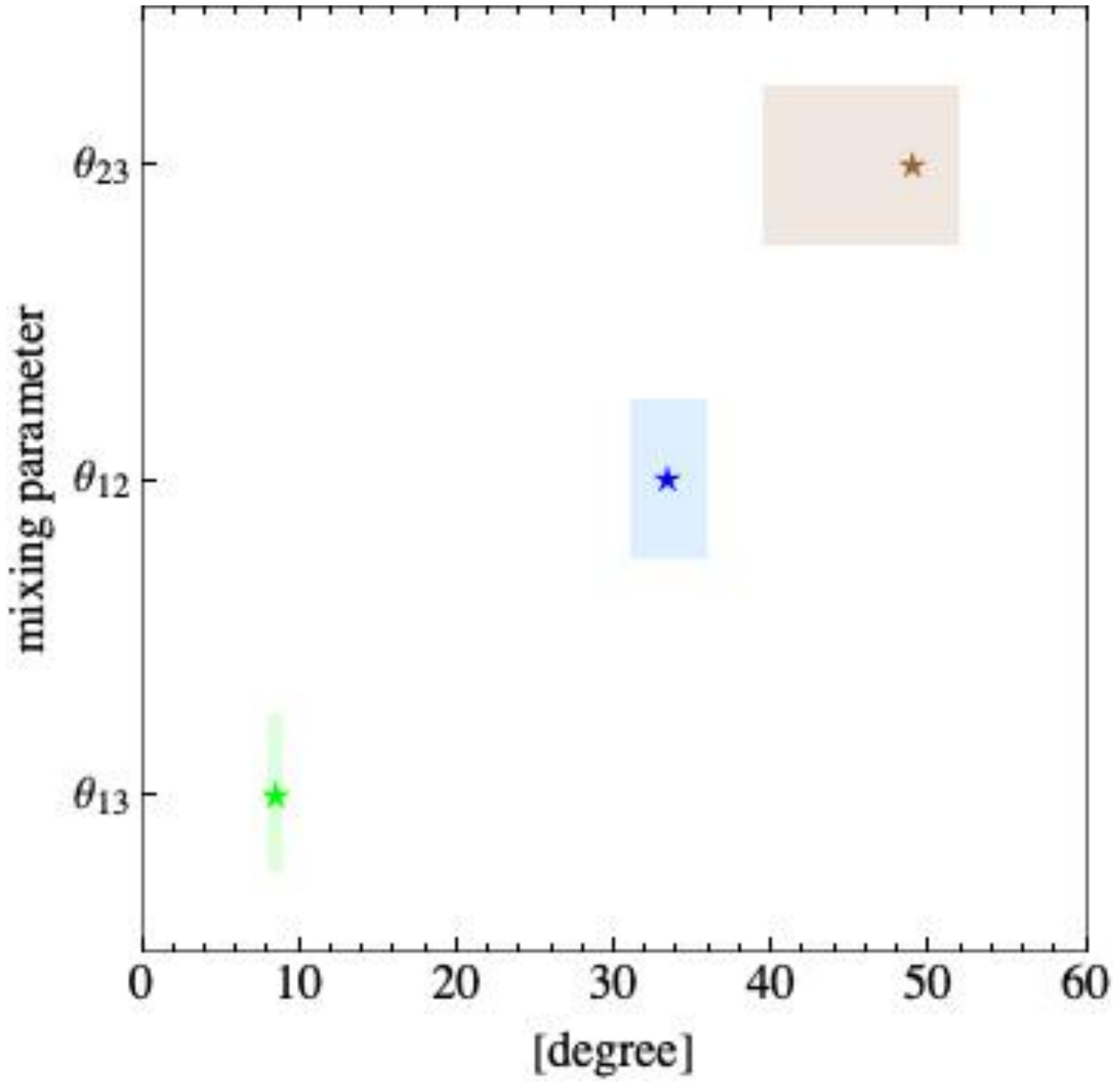
Information on mixing angles, mass splittings

[nufit v5.1]

all three angles non-zero
mixing angles are large!

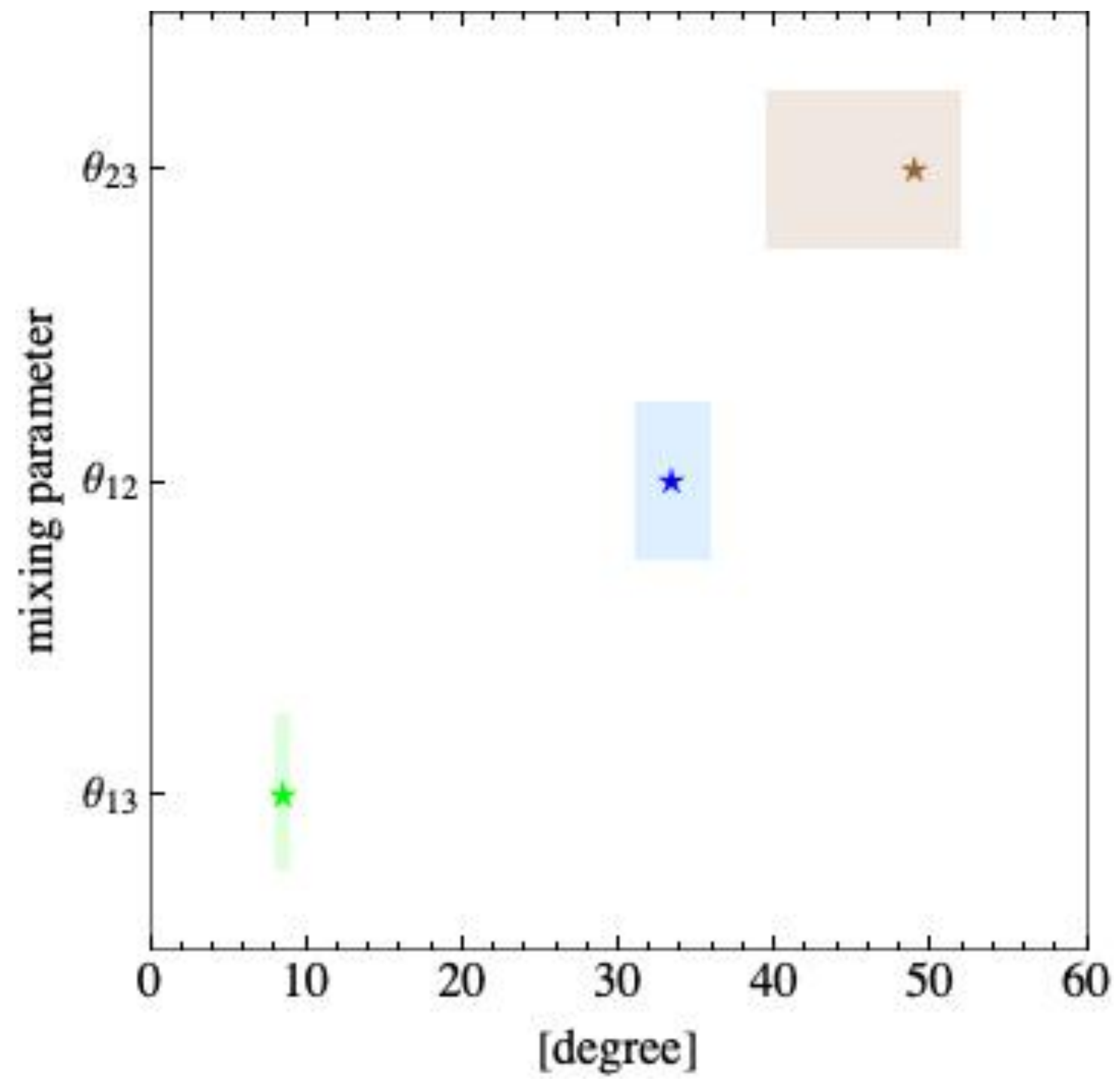
surprising if compared to small quark mixing





Neutrino oscillation parameters

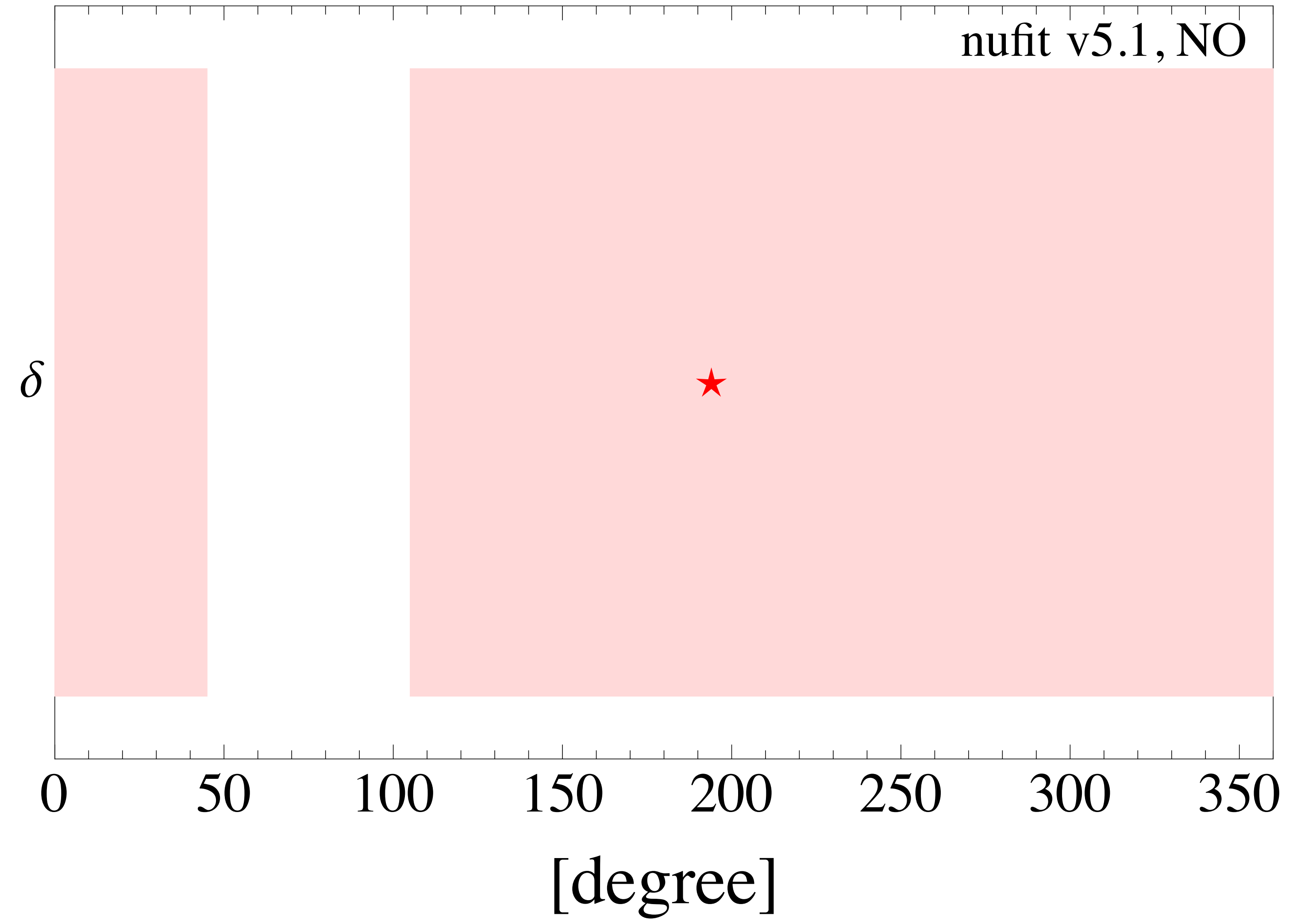
Global fits to oscillation data:
Information on mixing angles, mass splittings



all three mixing angles are non-zero
→ possibility for CPV in lepton sector

currently least known parameter is δ which governs CPV in lepton sector

⇒ Want to measure δ!



[nufit v5.1]

CP violation in SM

weak interaction: CP maximally violated [Cronin, Fitch ’64]

strong interaction: no observed EDM → CP conserved (?) (→ strong CP problem)

Lepton sector?

CP violation in SM

CPV in mass matrices quantified via basis invariant

$$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta$$ [Jarlskog '85]

All mixing angles play a role!

$$J_{CP}^{max} = 1/(6\sqrt{3}) \approx 0.096$$

quark mixing matrix: non-zero δ_{CKM} but CPV is small $|J_{\mathrm{CKM}}|/J_{CP}^{\max} = 3 \cdot 10^{-4}$ [PDG]

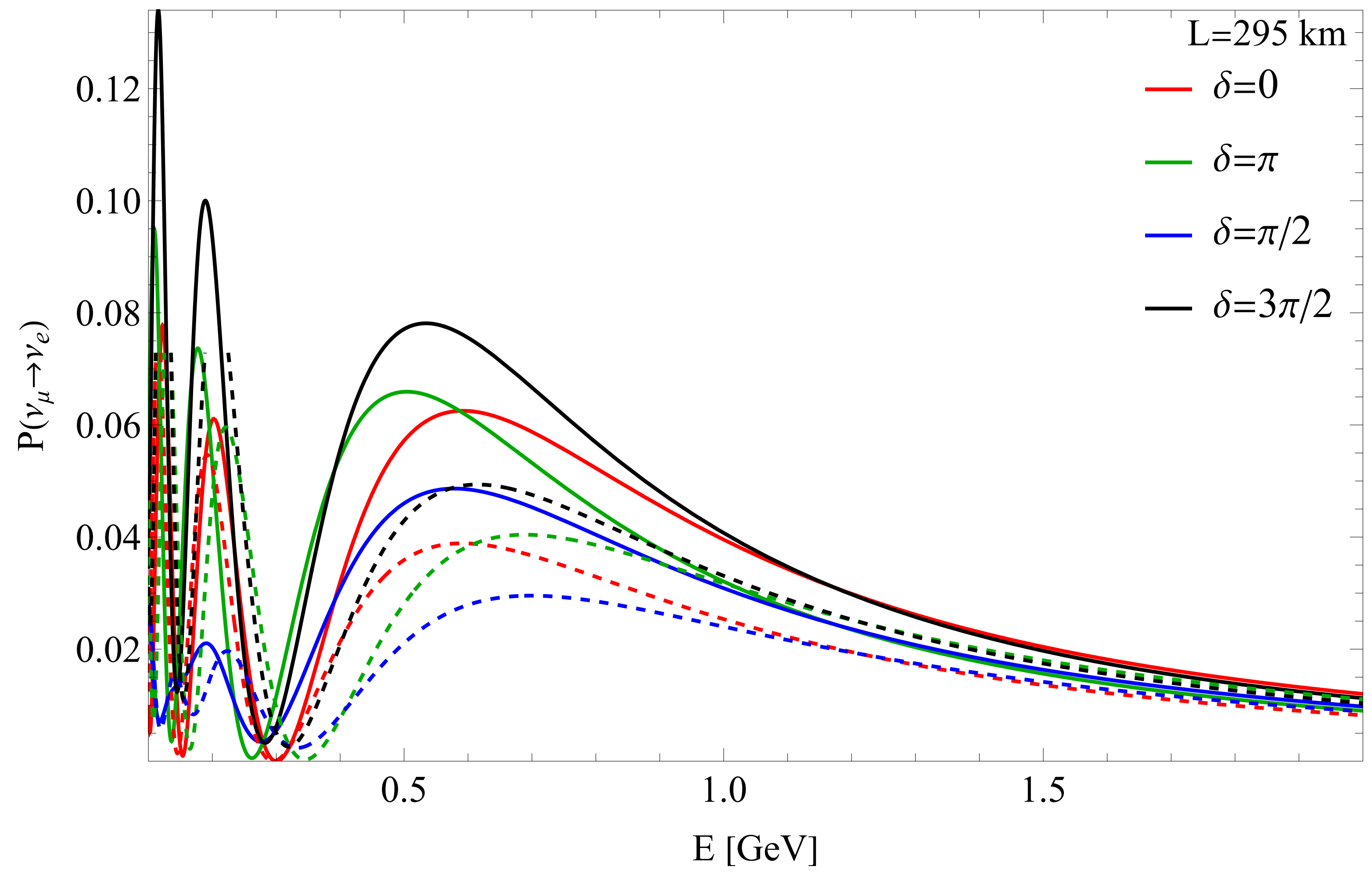
Is CP violated in the lepton sector? $|J_{\mathrm{PMNS}}|/J_{CP}^{\max} < 0.34$

CP violation in lepton sector

How to measure CPV?

- CPV can only take place in appearance experiments $P(\nu_\alpha \to \nu_\beta)$
- need a channel where all three flavors play a role (need interference of two contributions to the oscillation probability given by the two mass splittings)
- compare neutrino with anti neutrino oscillation probability
- $\Rightarrow$ use $P(\nu_\mu \to \nu_e)$ as oscillation channel!

due to matter effects this channel is also sensitive to the mass ordering



CP violation in lepton sector

Current experiments

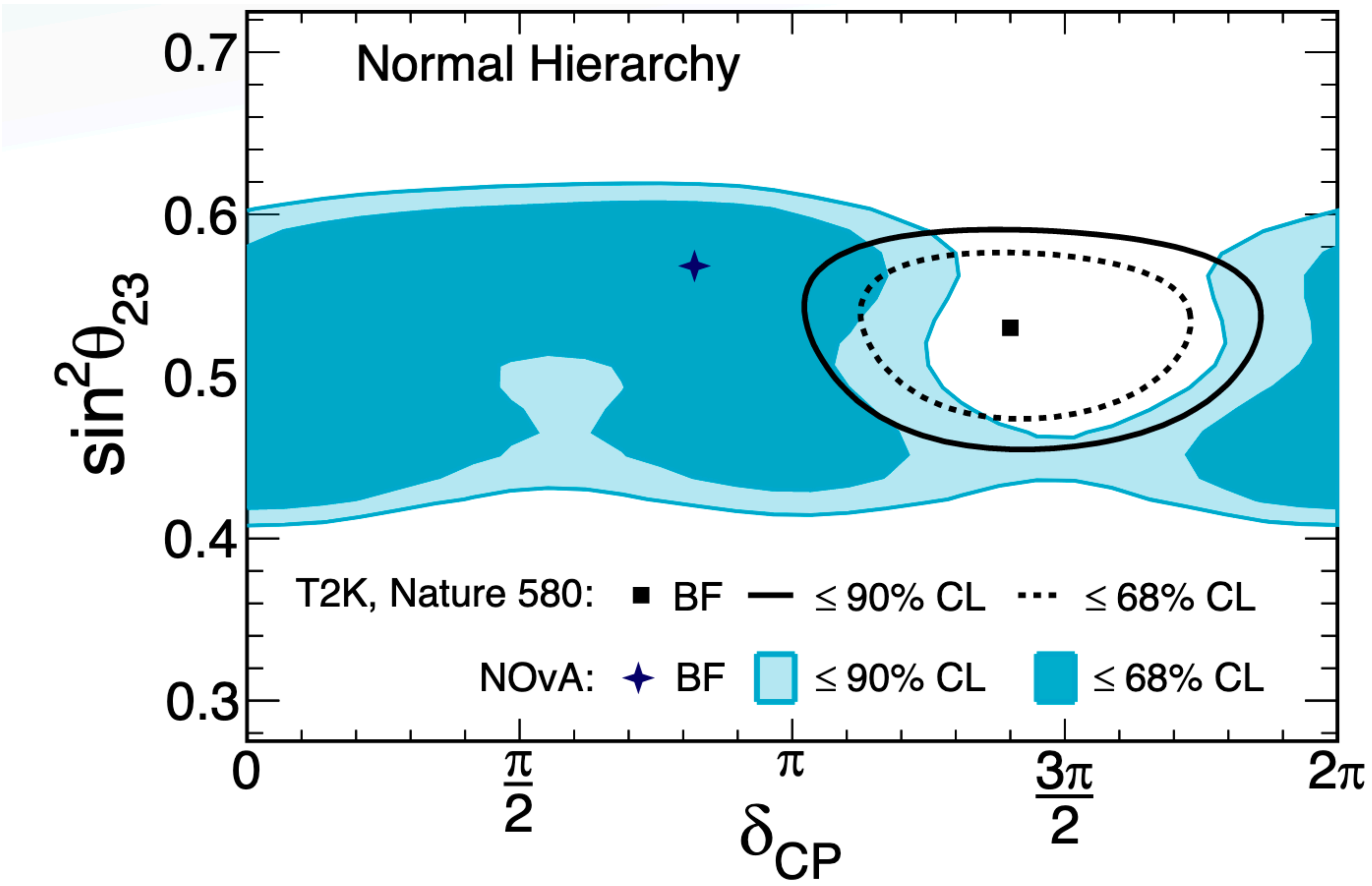
Future experiments

All mixing angles play a role:
precise measurements of
θ_{ij}, Δm_{ij}, mass ordering important

CP violation in lepton sector

Current status of CPV in lepton sector

[Himmel ’20]



CP violation in lepton sector

Current status of CPV in lepton sector

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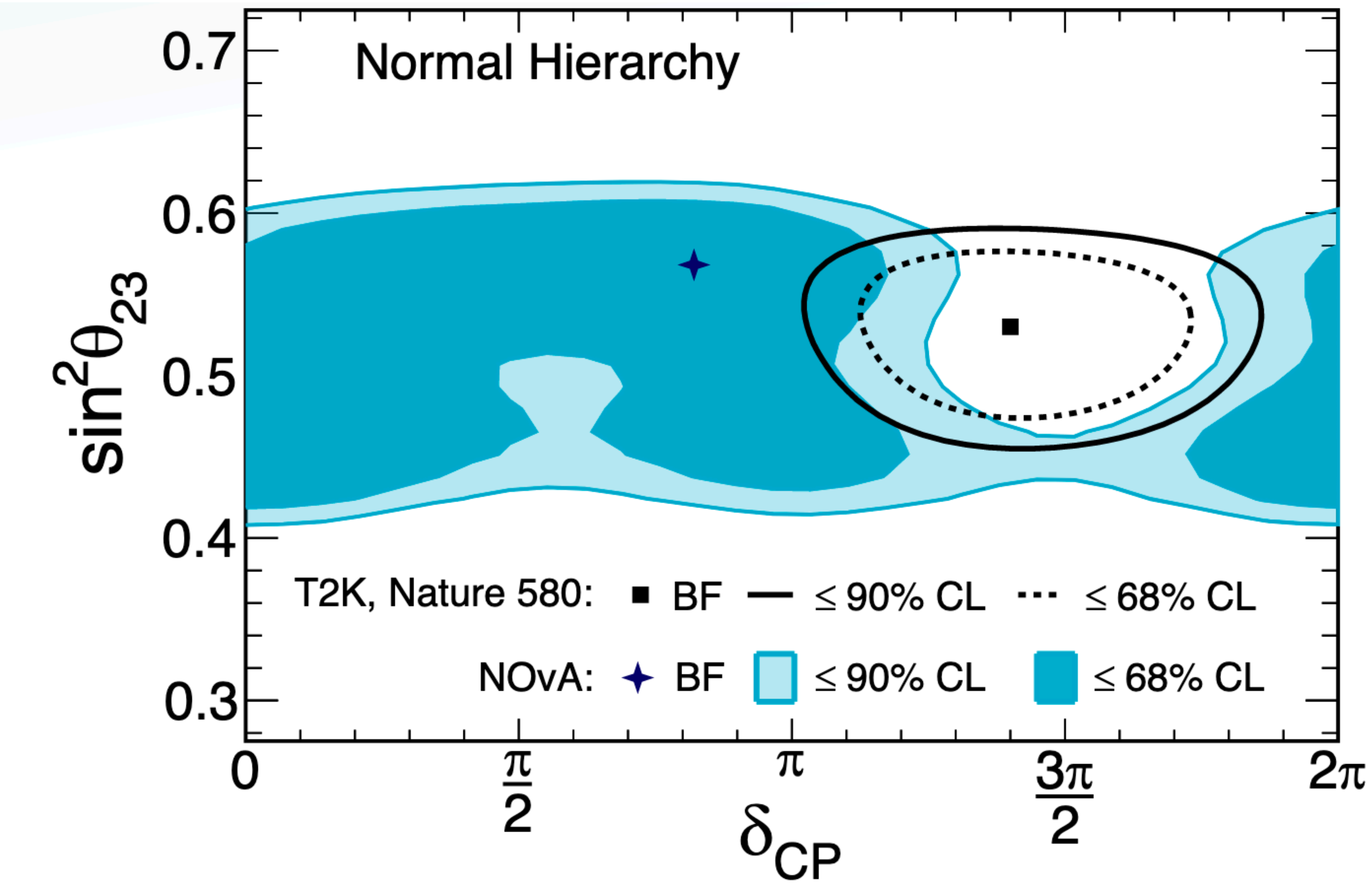


both experiments prefer NO

no strong preference for NOvA, generally around $\delta \approx \pi$,

T2K prefers $\delta \approx 3\pi/2$

$\Rightarrow$ slight disagreement at $\sim 2\sigma$

Neutrino 2022 update:
similar results of T2K and NOvA using different statistical framework

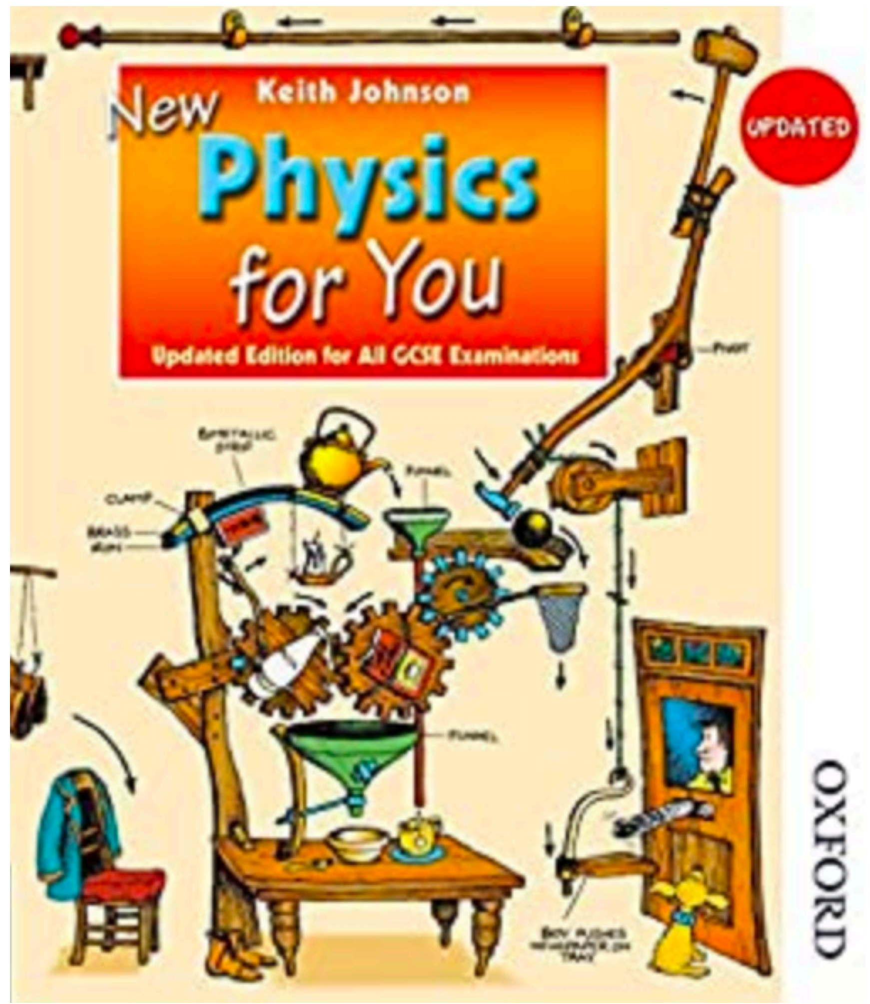
CP violation in lepton sector

Can new physics alleviate this slight discrepancy?

difference between NOvA and T2K is the baselines and the matter density
→ neutrinos at NOvA experience stronger matter effects

new physics solution could be related to this difference

introduce new matter interactions for neutrinos
⇒ neutrino non-standard interactions



CP violation in lepton sector

Can new physics alleviate this slight discrepancy?

$\Rightarrow$ neutrino non-standard interactions [Wolfenstein '78]

New forward scattering with matter

$$\mathscr{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \epsilon^f_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f}\gamma_\mu f)$$

Affect neutrino oscillations as a new matter effect

$$H = \frac{1}{2E}\left[U^\dagger M^2 U + a \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right]$$

Matter potential $a \propto G_F \rho E$

CP violation in lepton sector

Can new physics alleviate this slight discrepancy?

[Wolfenstein ’78]

⇒ neutrino non-standard interactions

New forward scattering with matter

$$\mathscr{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \epsilon^f_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f}\gamma_\mu f)$$

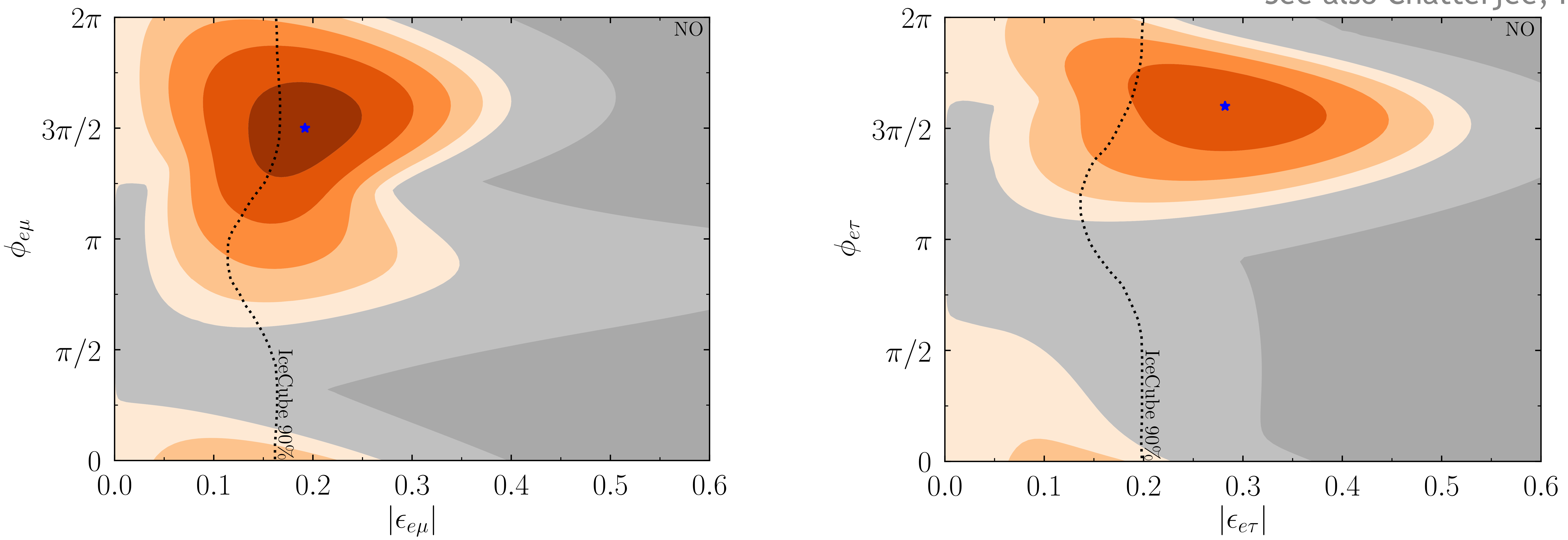
Affect neutrino oscillations as a new matter effect

Focus on off-diagonal NSI parameters $\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}| \mathrm{e}^{\mathrm{i}\phi_{\alpha\beta}}$

Derive analytically and numerically values of
complex off-diagonal NSI parameters which can resolve the tension

CP violation in lepton sector

[Denton, Gehrlein, Pestes, 2008.01110,
See also Chatterjee, Palazzo, 2008.04161]



orange preferred over SM at integer values of $\Delta\chi^2$, dark gray disfavored at $\Delta\chi^2 = 4.61$

constraints from atmospheric neutrinos at IceCube and neutrino scattering experiments

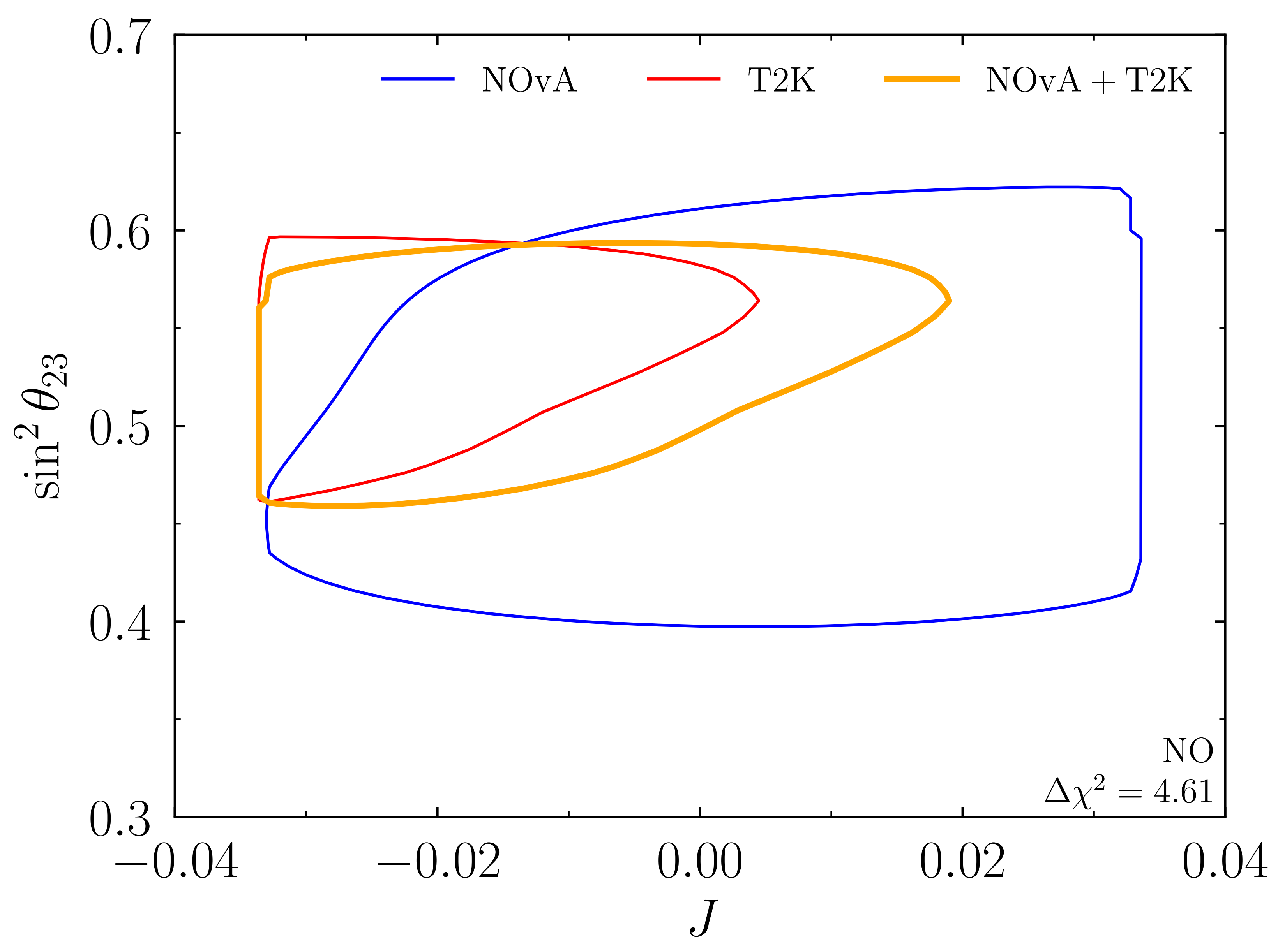
Complex NSI with $|\epsilon| \approx 0.2$, $\phi \approx 3\pi/2$, $\delta \approx 3\pi/2$, NO can fully resolve the tension

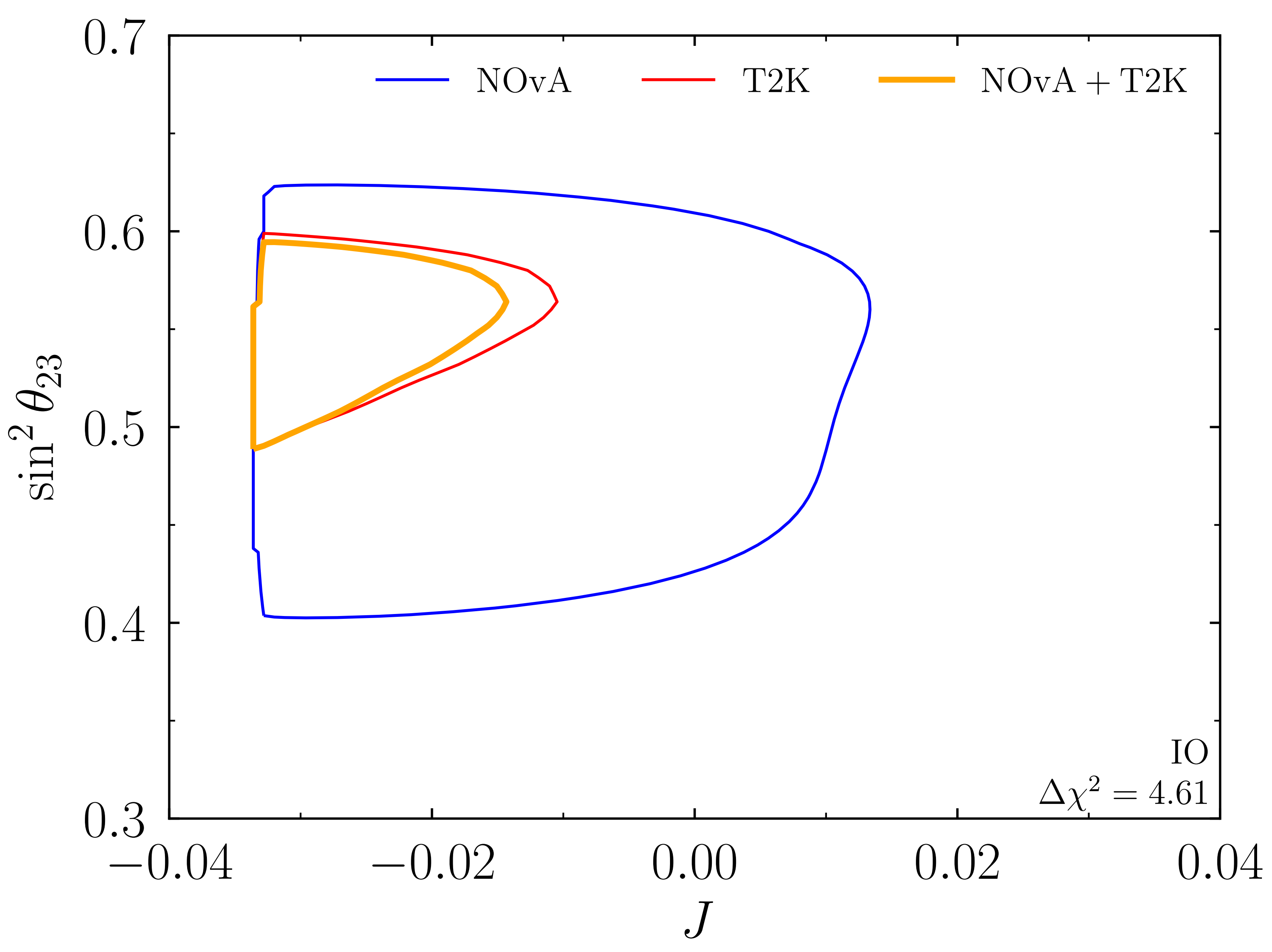
CP violation in lepton sector

[Denton, Gehrlein, Pestes, 2008.01110, See also Chatterjee, Palazzo, 2008.0416, Kelly et al, 2007.08526, Esteban et al 2007.14792]

discrepancy slightly resolved by swapping the mass ordering

1. NOvA and T2K both prefer NO over IO
2. NOvA+T2K prefers IO over NO (at $\Delta\chi^2 = 2.3$)
3. SK still prefers NO over IO
4. NOvA+T2K+SK still prefers NO over IO
5. near future reactor experiments provide information in the future



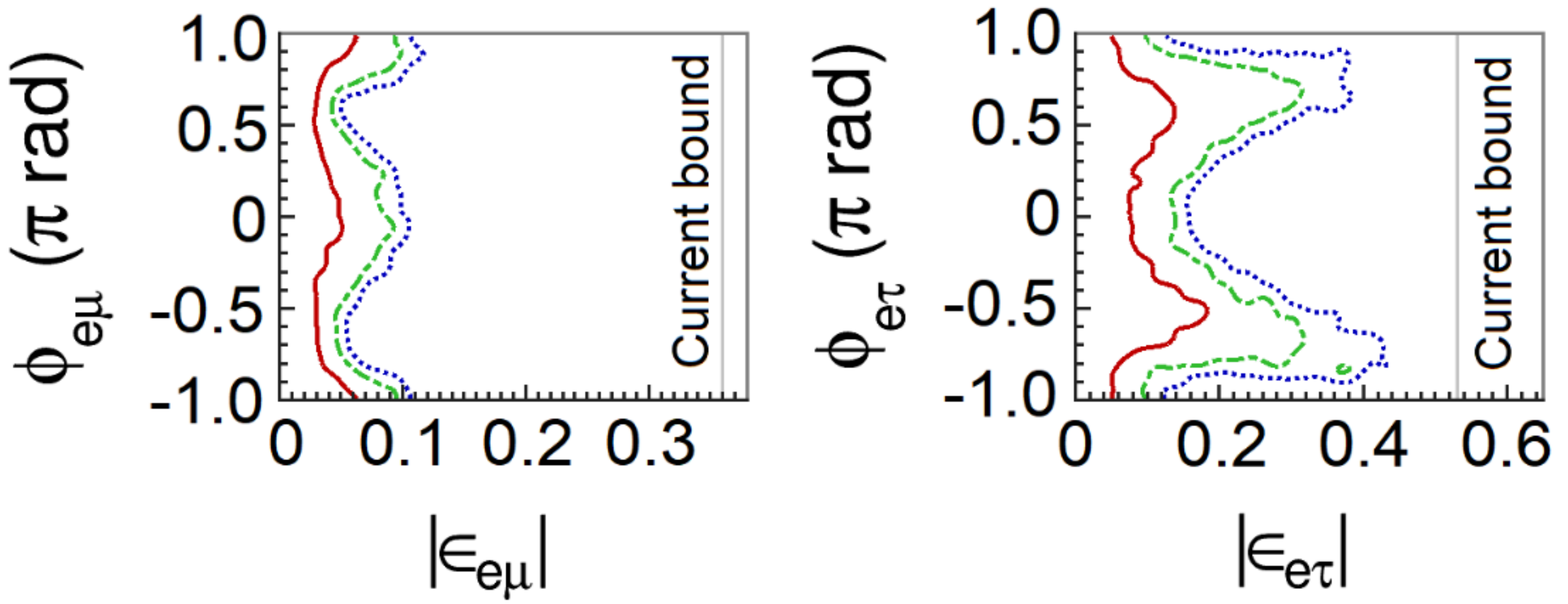


CP violation in lepton sector

Future of CP violation searches

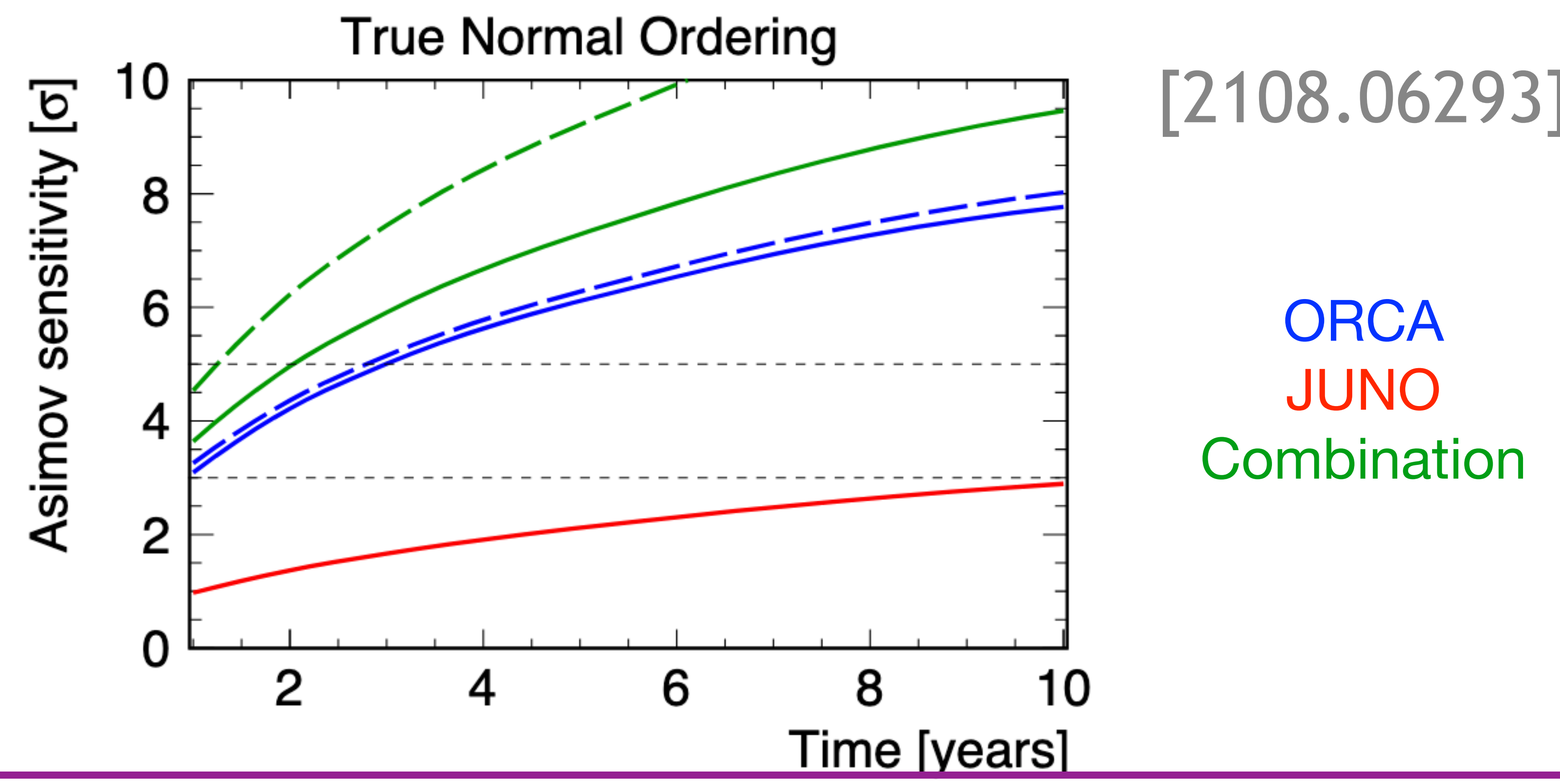
- NOvA & T2K continue to take data
  Ongoing joint experimental analysis between collaborations

[DUNE TDR ’20]



- Complex NSI solution can be probed in future with DUNE, HK

- SM solution: swap of mass ordering from NO to IO can be probed with future reactor experiment JUNO+atmospheric neutrinos



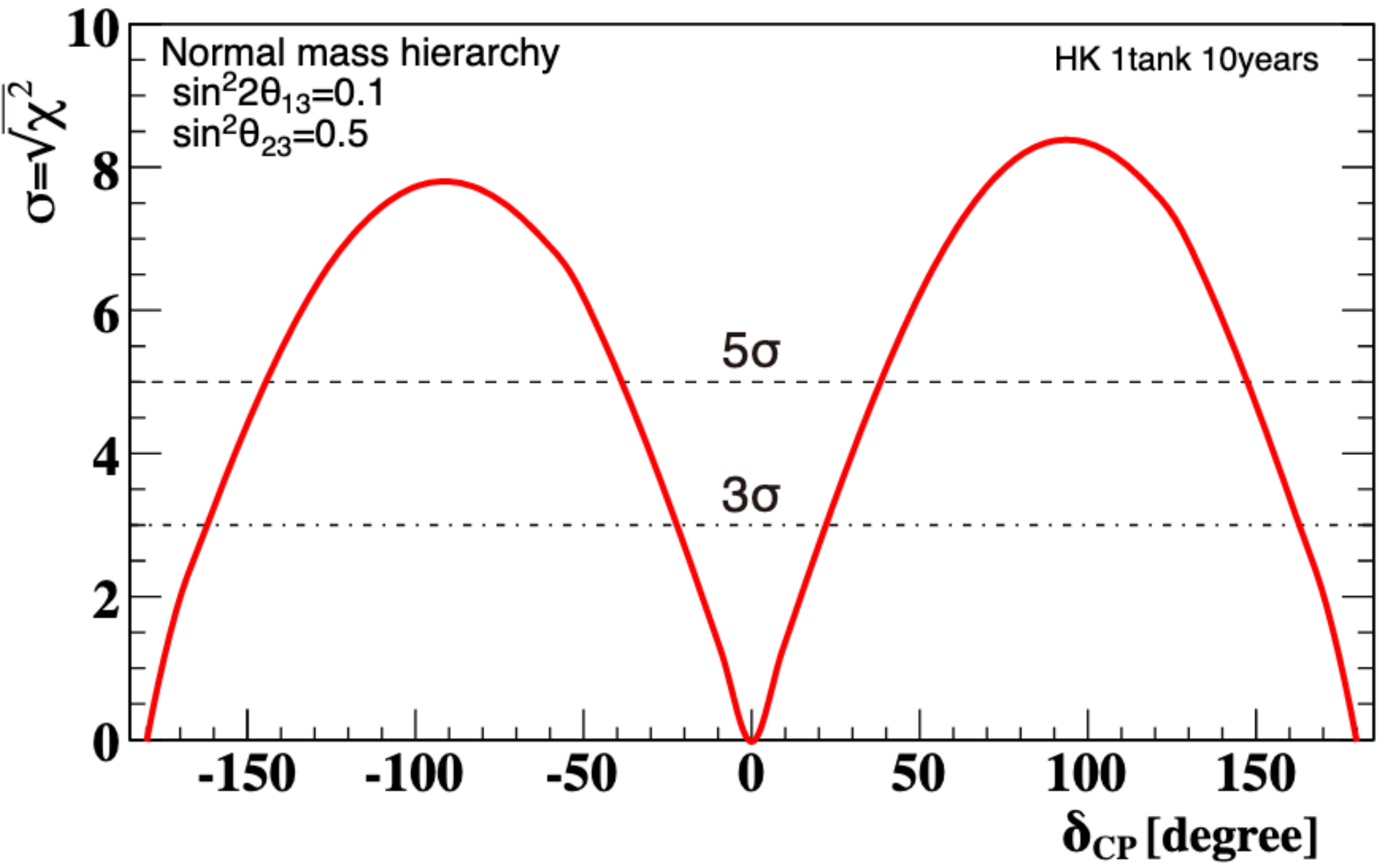
[2108.06293]

CP violation in lepton sector

Future of CP violation searches

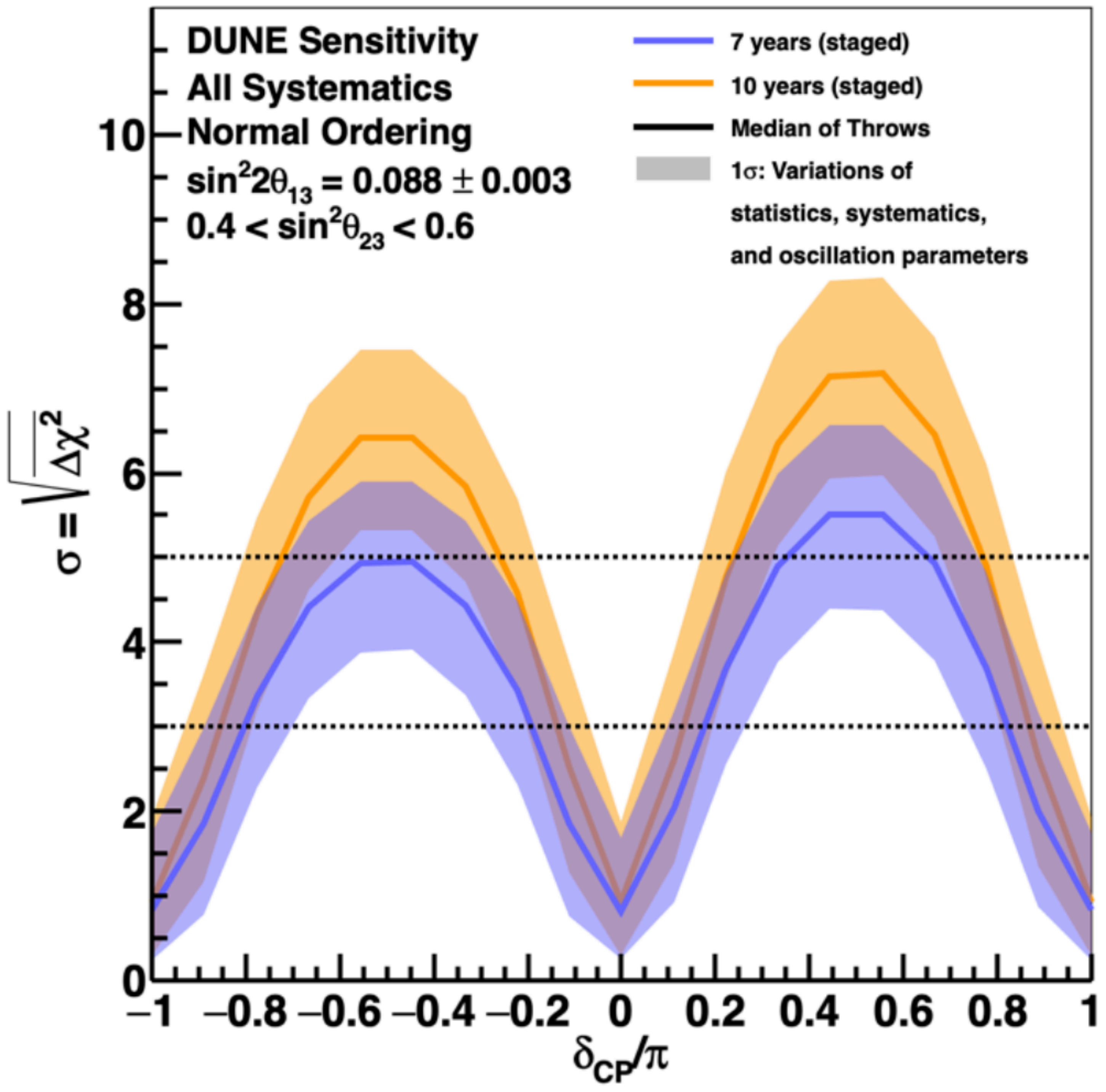
Hyper-Kamiokande sensitivity

[HK DR ’18]



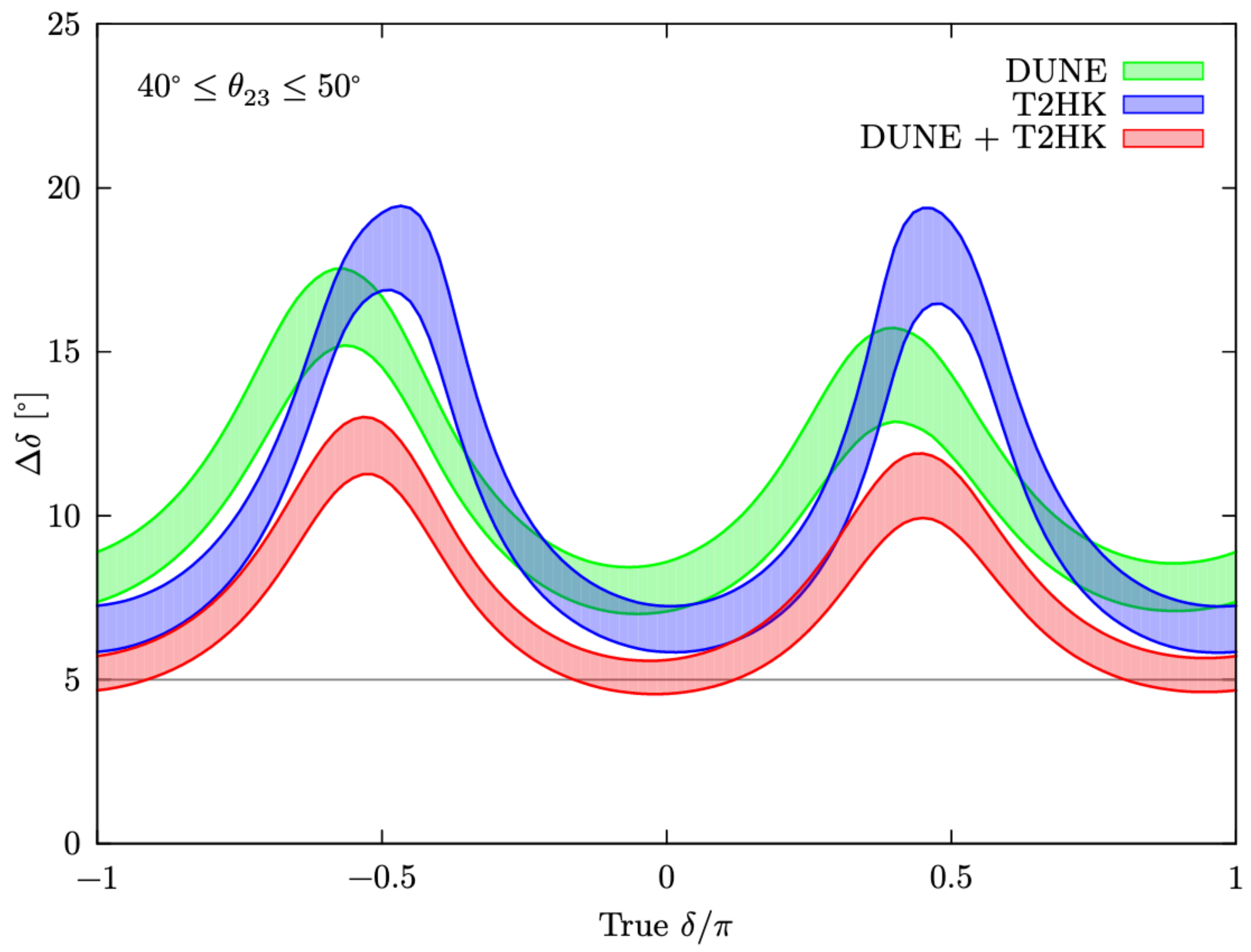
DUNE sensitivity

[DUNE TDR ’20]



DUNE & HK combination

[Ballett et al, 1612.07275]

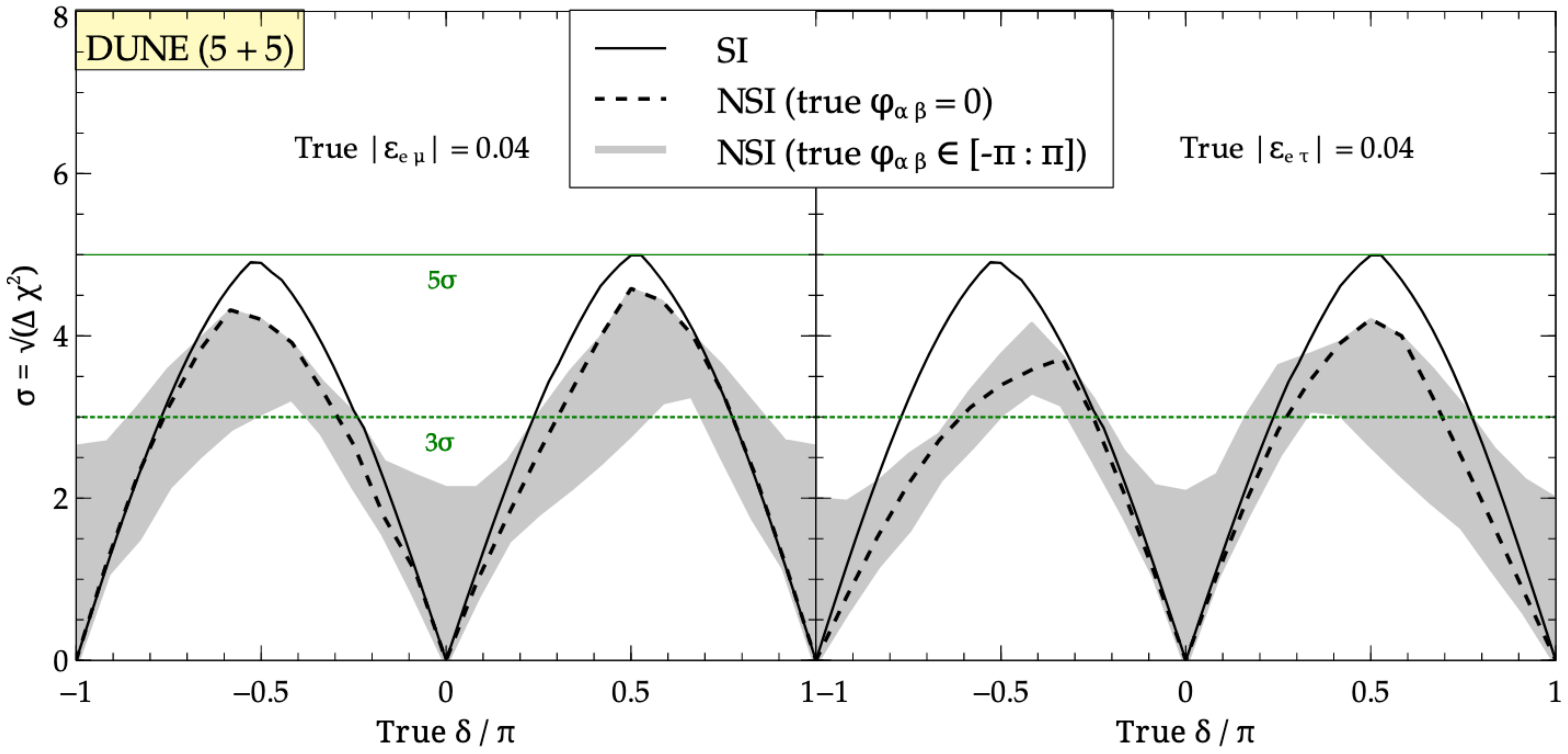


CP violation in lepton sector

Future of CP violation searches with BSM

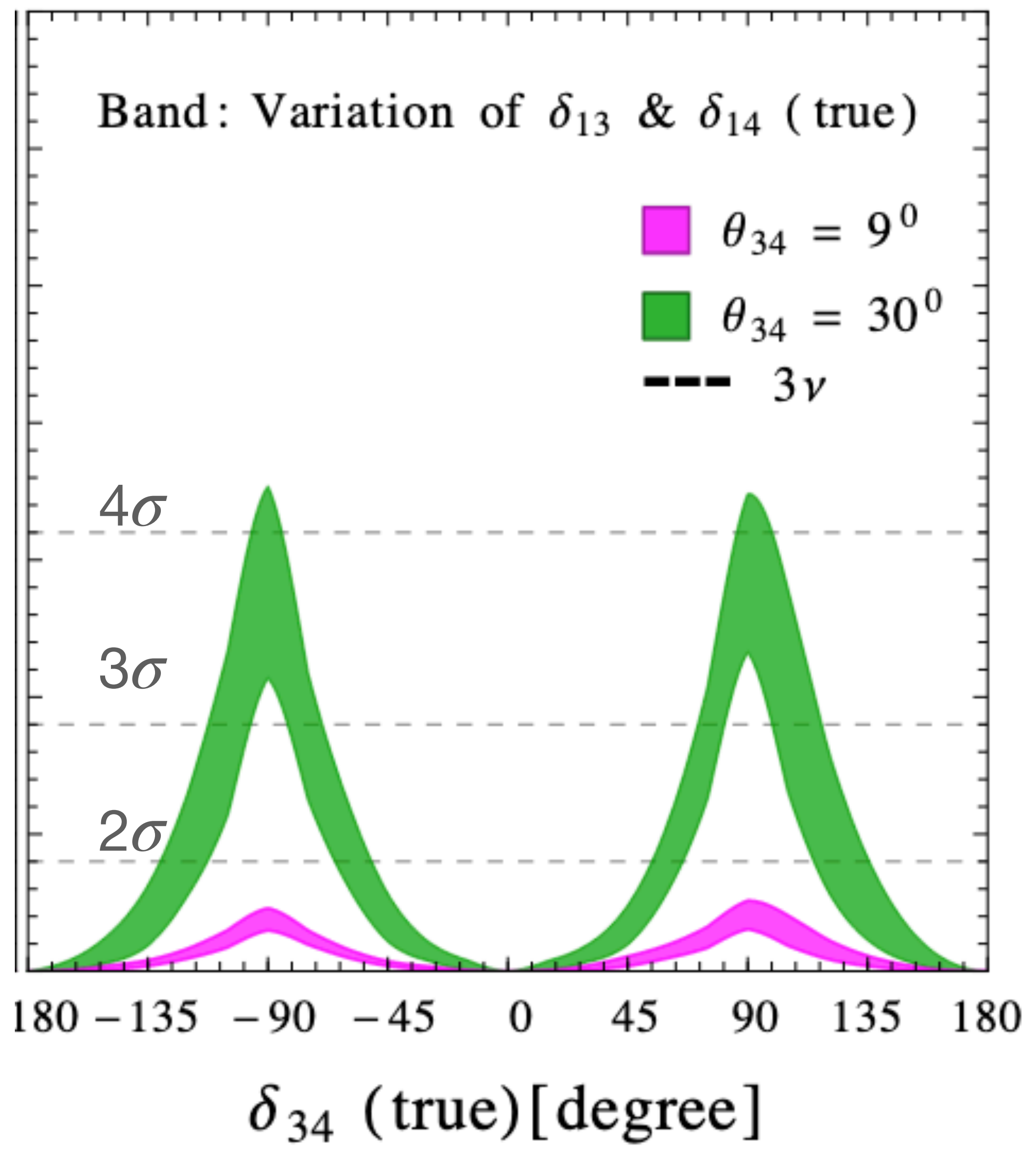
DUNE sensitivity with NSI

[Masud, Chatterjee, Metha, 1510.08261]



DUNE sensitivity with 1 eV sterile neutrino

[Agarwalla, Chatterjee, Palazzo, 1603.03759]



Other neutrino parameters to be measured soon:
Mass ordering, absolute neutrino mass scale

CP violation in lepton sector

Impact of CP measurement

- Measurement of one of the last unknown parameters of SM
- a precise measurement of $\cos\delta$ can probe existence of flavor models and disentangle them

Sum rules in flavor models:
Relate different oscillation parameters

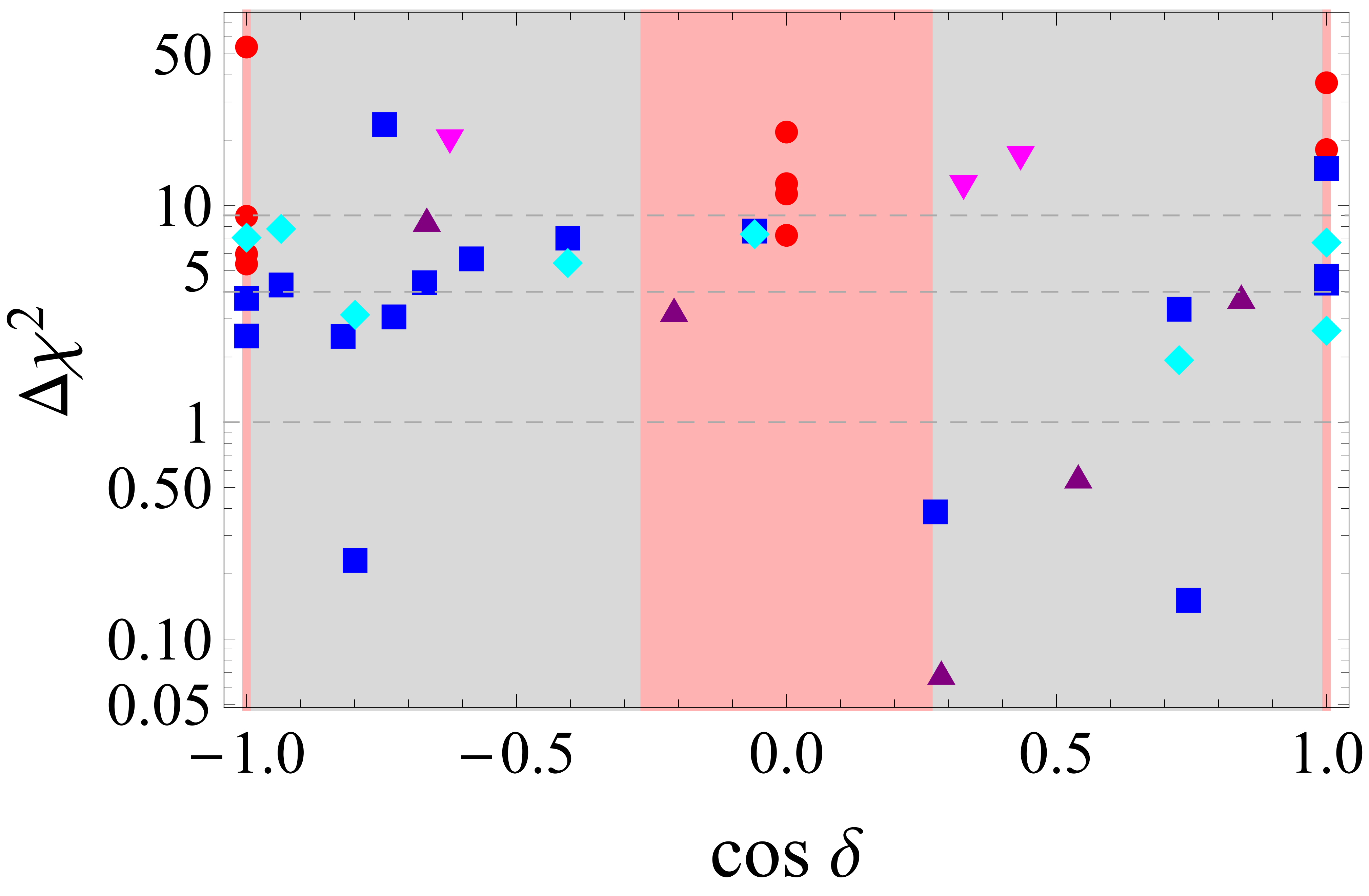
$$\theta_{12} - \theta_{12}^{\nu} \approx \theta_{13} \cos\delta$$

Predicted in models

CP violation in lepton sector

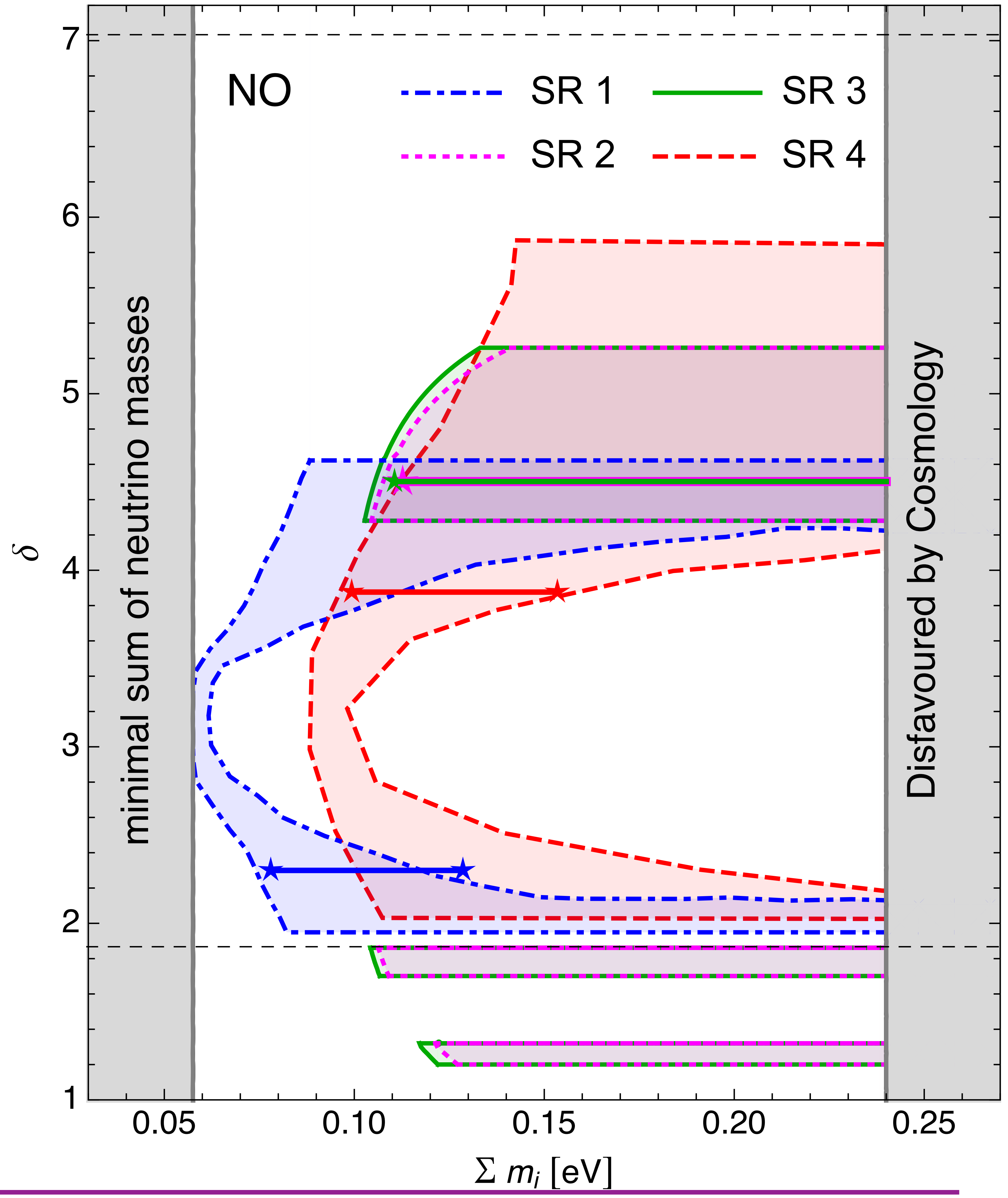
Impact of CP measurement

[Gehrlein, Spinrath, 2012.04131]



[Gehrlein, Petcov, Spinrath, Titov, 2203.06219]

- discrete symmetries w/ CP
- discrete symmetries w/o CP (NO)
- discrete symmetries w/o CP (IO)
- modular symmetries (NO)
- modular symmetries (IO)



CP violation in lepton sector

Summary & Conclusion

- open question of CPV in lepton sector
- slight tension between NOvA and T2K
- can be fully resolved with neutrino non-standard interactions!
- Solution predicts maximal CP violation in PMNS matrix and for new physics
- Future oscillation experiments will measure CP violating quantity
- Leptonic CP measurement will tell us more about symmetries of nature

Thanks for your attention!

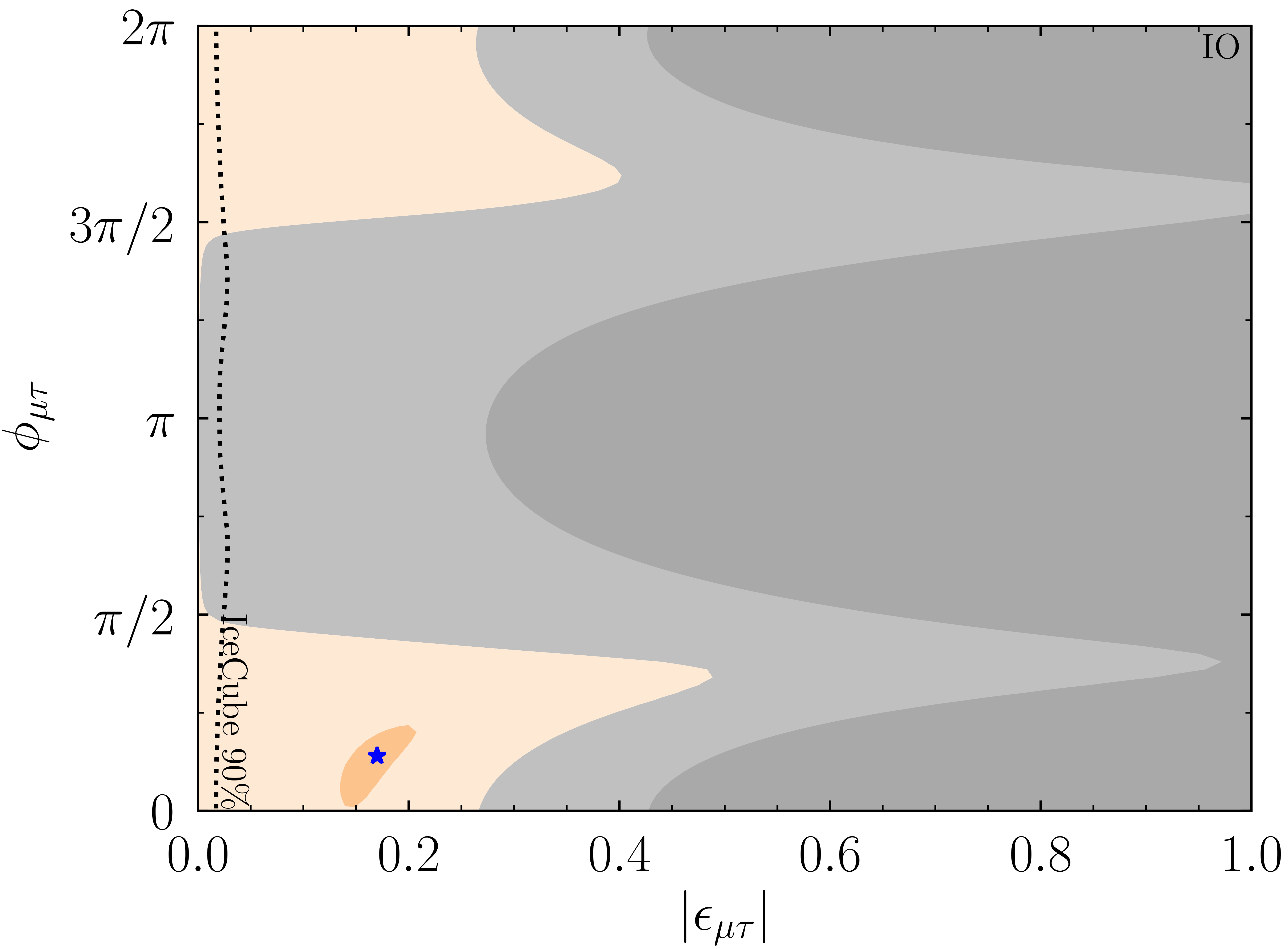
Appendix: NSI models

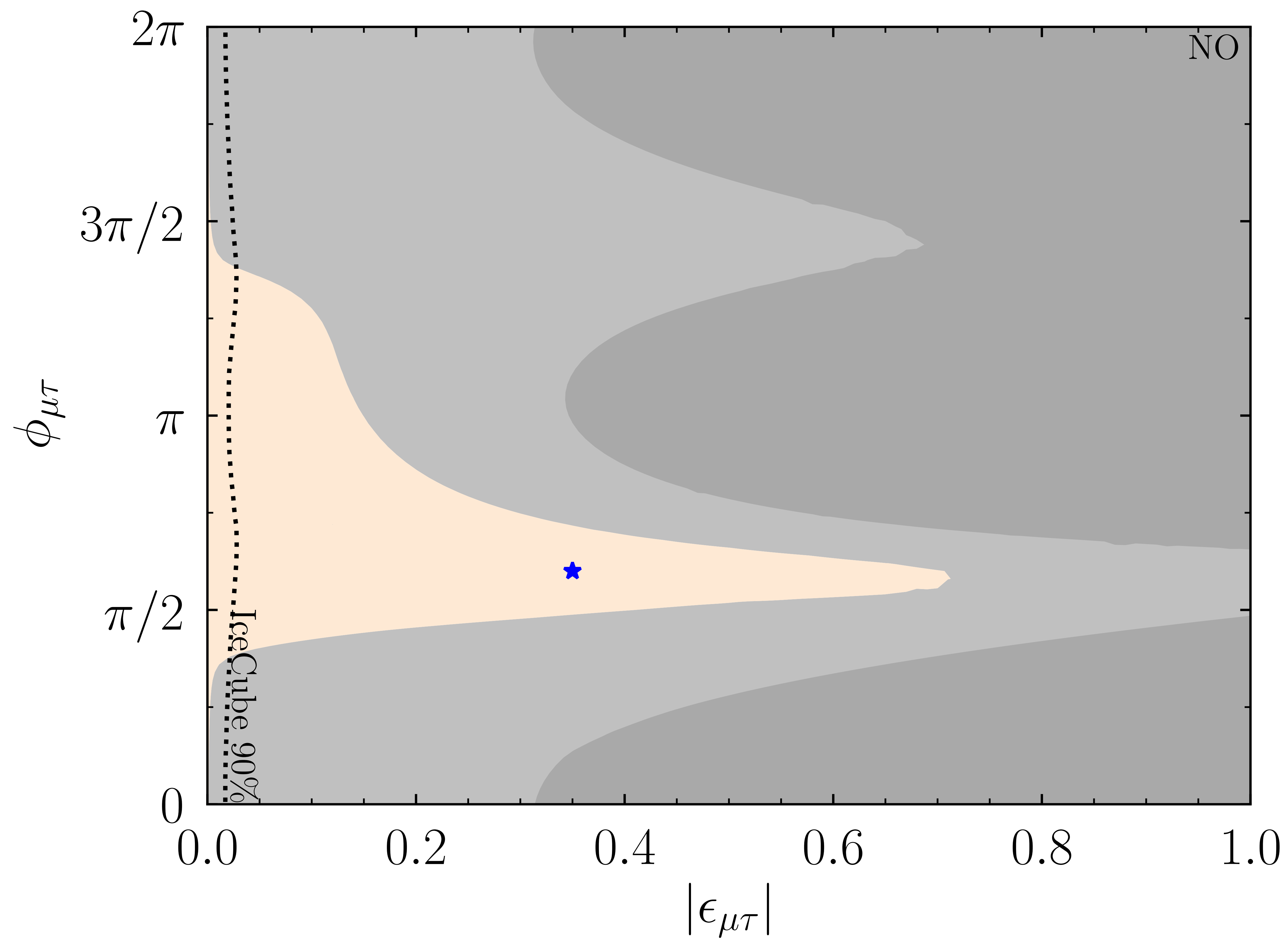
NSI models

general idea to allow for sizable NSI: constraining the direct coupling of the NSI mediator to the heavier generations or to sterile neutrinos that mix with the active ones

- D. V. Forero and W.-C. Huang, JHEP 03, 018 (2017), arXiv:1608.04719 [hep-ph].
- P. B. Denton, Y. Farzan, and I. M. Shoemaker, Phys. Rev. D 99, 035003 (2019), arXiv:1811.01310 [hep-ph
- U. K. Dey, N. Nath, and S. Sadhukhan, Phys. Rev. D 98, 055004 (2018), arXiv:1804.05808 [hep-ph].
- K. Babu, A. Friedland, P. Machado, and I. Mocioiu, JHEP 12, 096 (2017), arXiv:1705.01822 [hep-ph].
- Y. Farzan and J. Heeck, Phys. Rev. D 94, 053010 (2016), arXiv:1607.07616 [hep-ph].
- Y. Farzan and I. M. Shoemaker, JHEP 07, 033 (2016), arXiv:1512.09147 [hep-ph].
- Y. Farzan, Phys. Lett. B 748, 311 (2015), arXiv:1505.06906 [hep-ph].
- K. Babu, P. B. Dev, S. Jana, and A. Thapa, JHEP 03, 006 (2020), arXiv:1907.09498 [hep-ph].

Appendix: Details of NOvA & T2K analysis





Appendix: Details of NOvA & T2K analysis

analytical estimates: $|\epsilon_{\alpha\beta}| \approx 0.2$, $\phi_{\alpha\beta} \approx 3\pi/2$, $\delta_{\text{true}} \approx 3\pi/2$

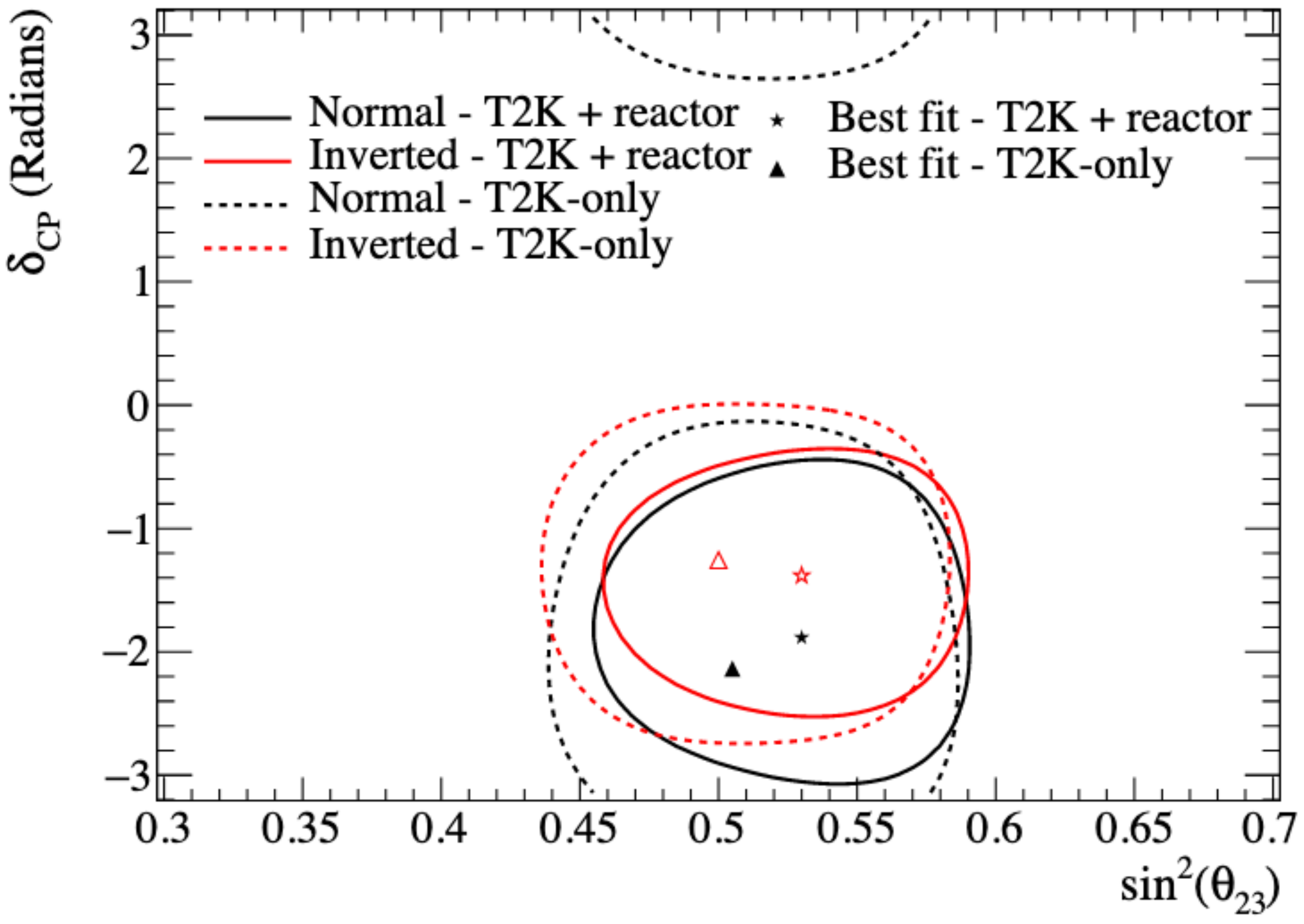
MO	NSI	$\lvert\epsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	δ/π	$\Delta\chi^2$
NO	$\epsilon_{e\mu}$	0.19	1.50	1.46	4.44
	$\epsilon_{e\tau}$	0.28	1.60	1.46	3.65
	$\epsilon_{\mu\tau}$	0.35	0.60	1.83	0.90
IO	$\epsilon_{e\mu}$	0.04	1.50	1.52	0.23
	$\epsilon_{e\tau}$	0.15	1.46	1.59	0.69
	$\epsilon_{\mu\tau}$	0.17	0.14	1.51	1.03

$\Delta\chi^2 = \chi^2_{\text{SM}} - \chi^2_{\text{NSI}}$ for a fixed MO, $\chi^2_{\text{NO}} - \chi^2_{\text{IO}} = 2.3$

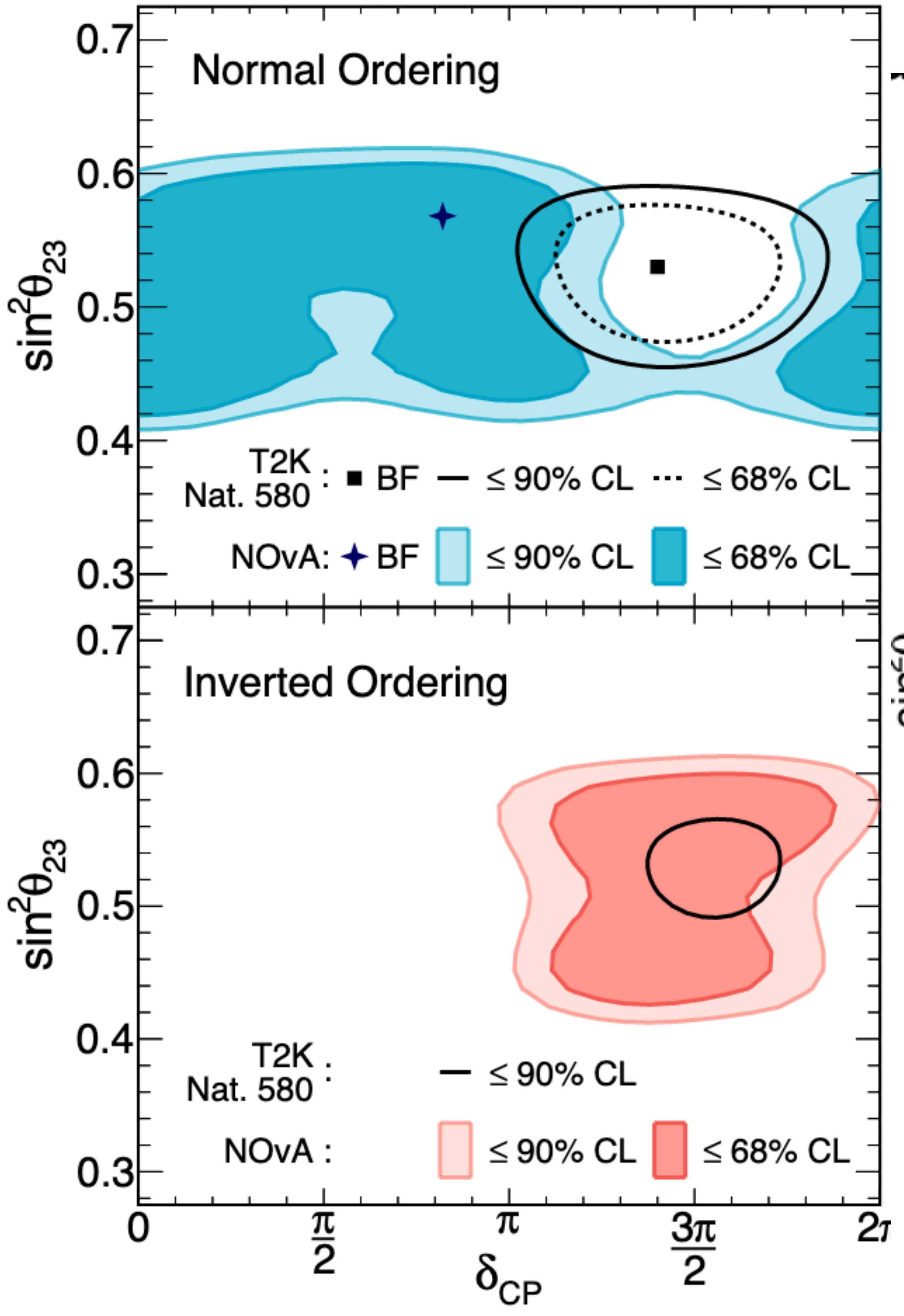
Appendix: Details of NOvA & T2K analysis

Most recent T2K results

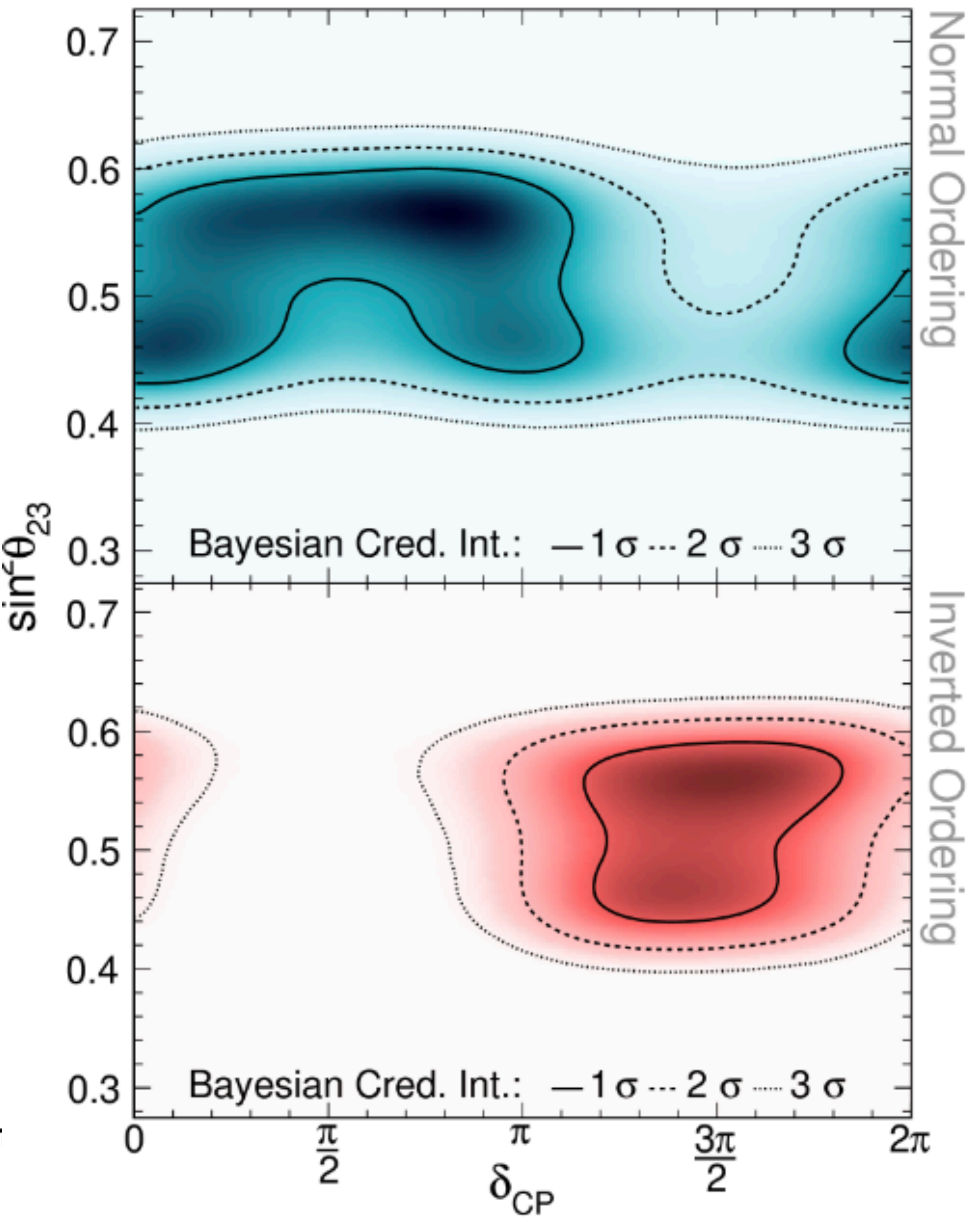
[2101.03779]



[2108.08219] Most recent NOvA results



[Harnell, Neutrino 2022]



Appendix: Details of NOvA & T2K analysis

IceCube constraints

[2106.07755]

Appendix: Details of flavor models

new approach to model building and flavor symmetries [Feruglio '17]

minimal amount of parameters $\leftrightarrow$ maximal amount of correlations

4 mixing parameters described by 2 free parameters
example: [Novichkov, Petcov, Tanimoto '18, JG, Spinrath '20]

$$\sin^2\theta_{12}(\theta) = \frac{1}{3-2\sin^2\theta}\,,$$

$$\sin^2\theta_{13}(\theta) = \frac{2}{3}\sin^2\theta\,,$$

$$\sin^2\theta_{23}(\theta,\phi) = \frac{1}{2} + \frac{\sin\theta_{13}(\theta)}{2}\,\frac{\sqrt{2-3\sin^2\theta_{13}(\theta)}}{1-\sin^2\theta_{13}(\theta)}\cos\phi\,,$$

$$\delta(\theta,\phi) = \arcsin\left(-\frac{\sin\phi}{\sin 2\theta_{23}(\theta,\phi)}\right)$$

sum rules depend on the specific models however the dependencies are the same