

Neutrino Theory Overview

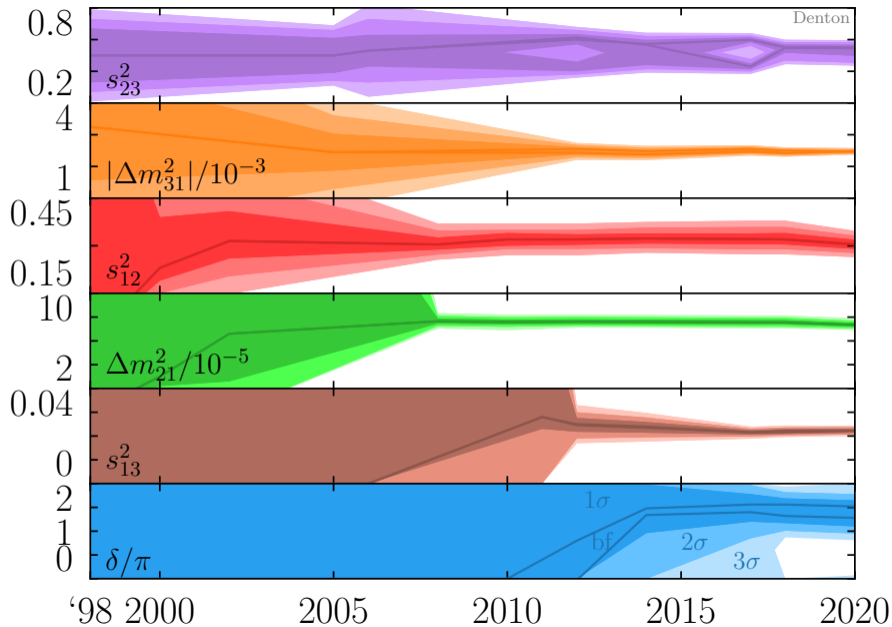
Peter B. Denton

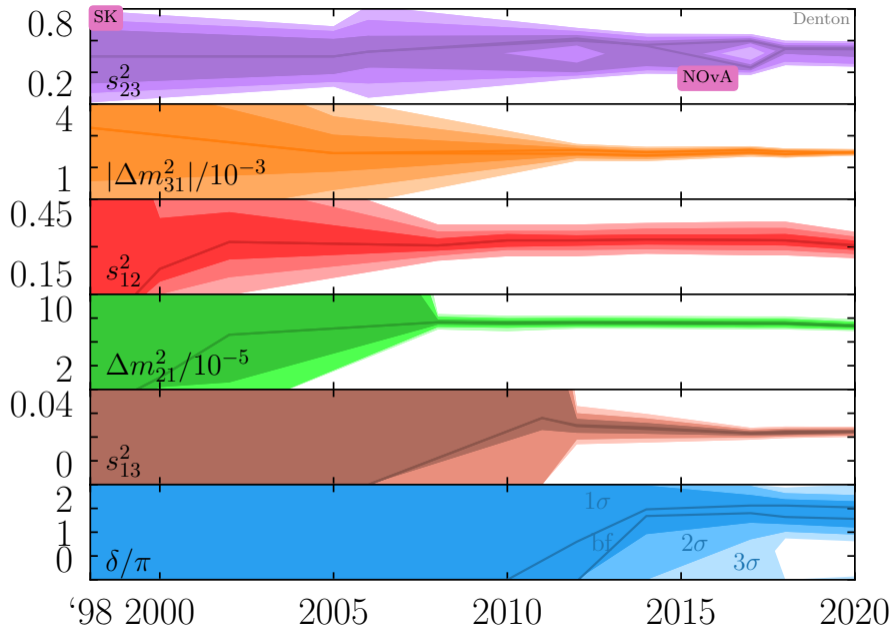
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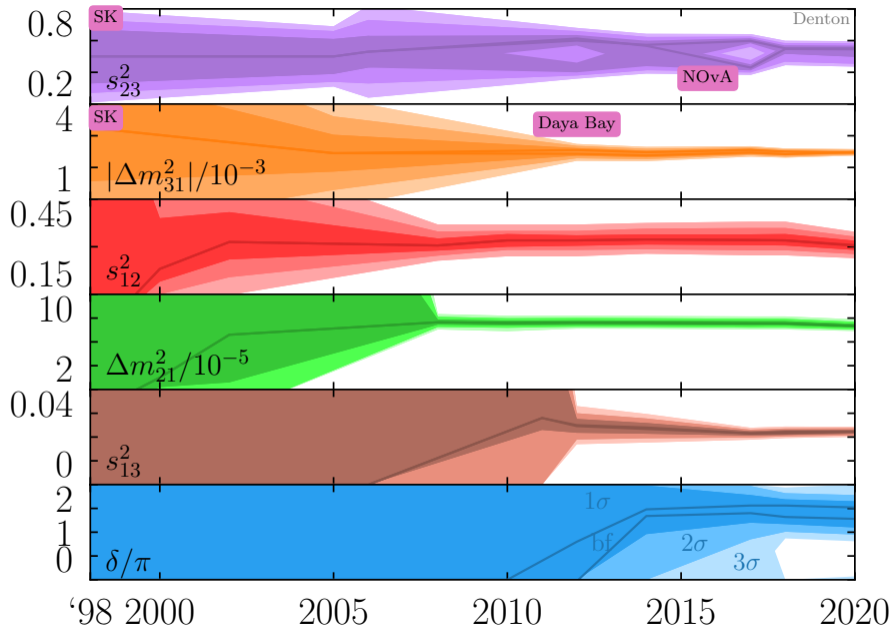
May 11, 2022

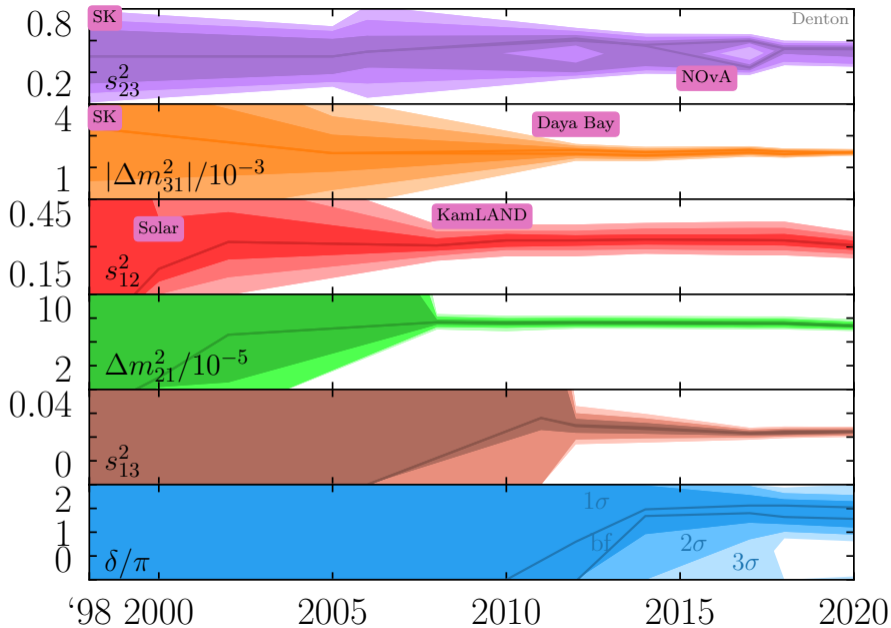


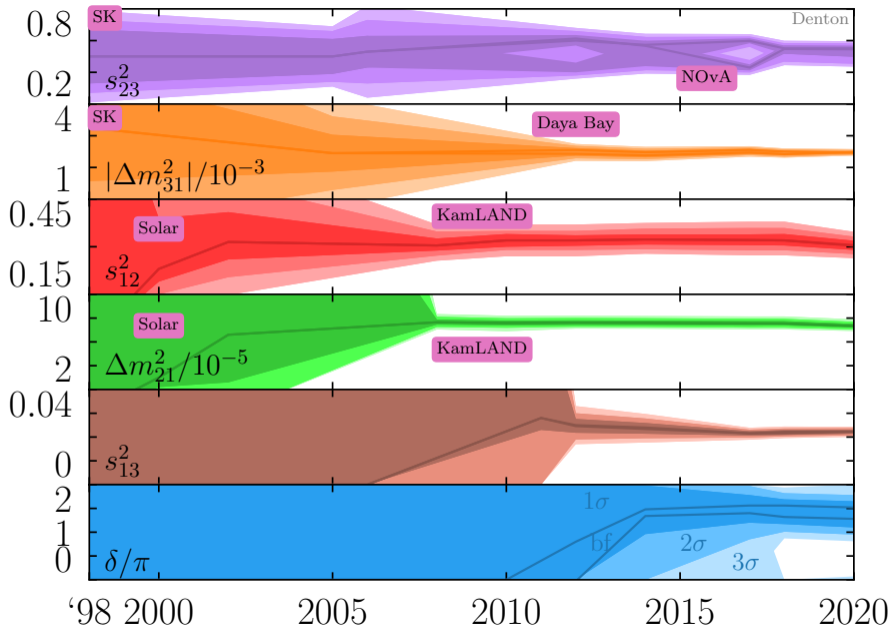
Brookhaven[™]
National Laboratory

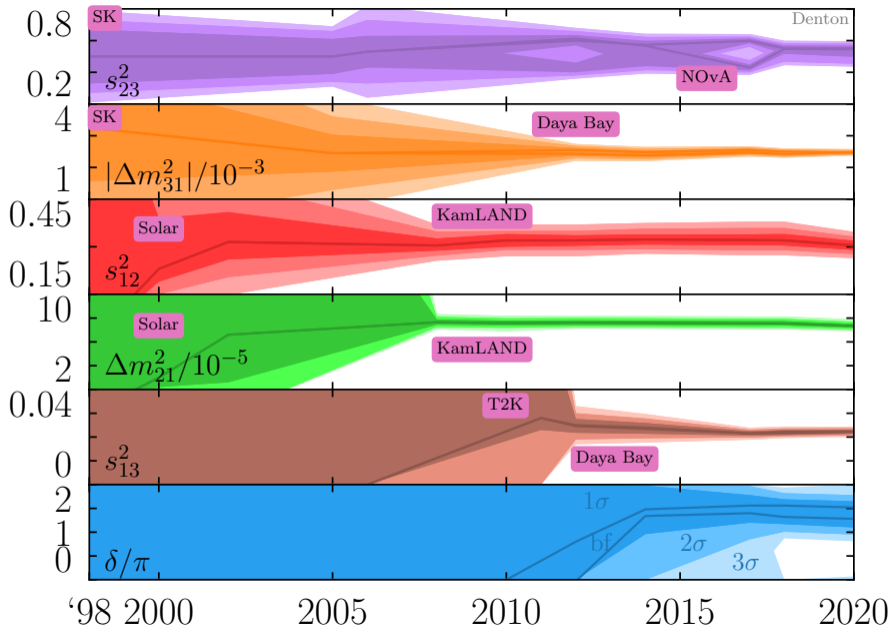


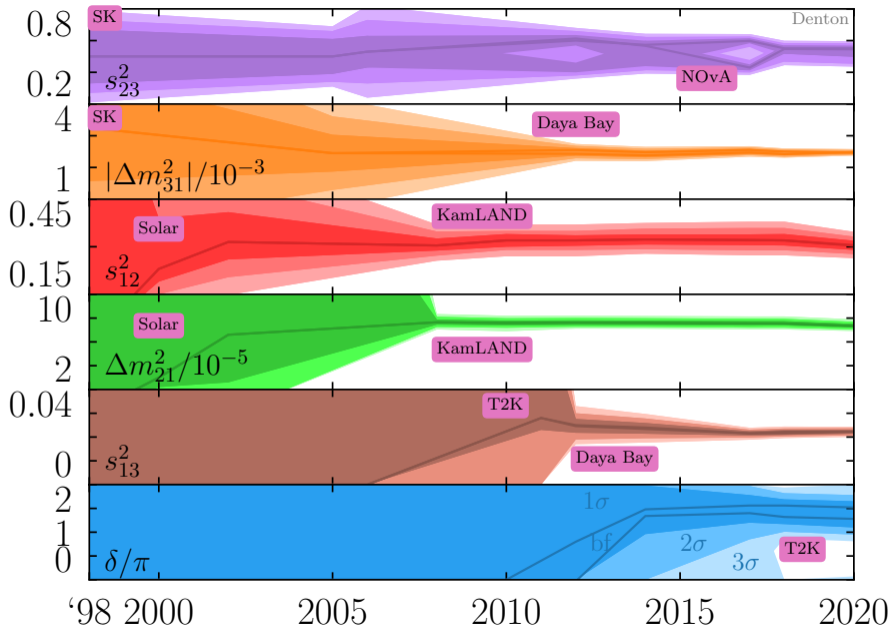












Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Cosmology, scattering, $0\nu\beta\beta$, ...

Atmospheric mass ordering

Mass ordering: what is it?

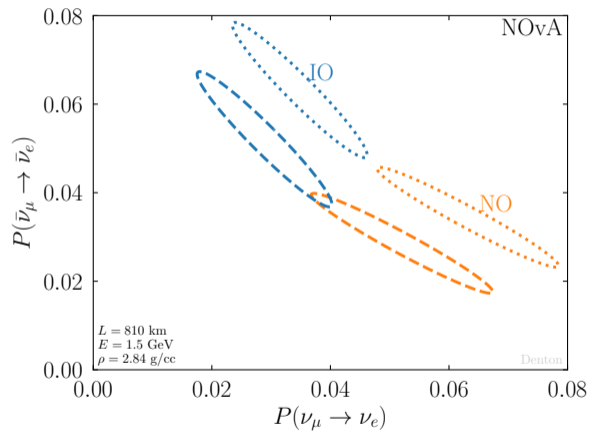
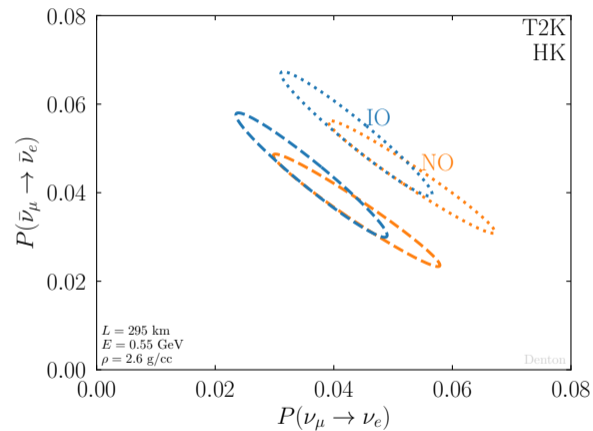
Normal



Inverted



Mass ordering: what is it really?



Mass ordering current status: oscillations

1. NOvA and T2K both prefer NO over IO
2. NOvA+T2K prefers IO over NO
3. SK still prefers NO over IO
4. NOvA+T2K+SK still prefers NO over IO
5. + Daya Bay & RENO \Rightarrow slight preference NO
6. = $2.5 - 2.7\sigma$

K. Kelly, et al. [2007.08526](#)

PBD, J. Gehrlein, R. Pestes [2008.01110](#)

I. Esteban, et al. [2007.14792](#)

F. Capozzi, et al [2107.00532](#)

P. de Salas, et al [2006.11237](#)

Mass ordering current status: all

Cosmology: $m_1 + m_2 + m_3 < 90$ meV at 95% CL

E. Valentino, S. Gariazzo, O. Mena [2106.15267](#)

→ 20 meV precision with DESI, EUCLID, ...

From oscillations:

Normal : $m_1 + m_2 + m_3 > 60$ meV

Inverted : $m_1 + m_2 + m_3 > 100$ meV

See also KATRIN [2105.08533](#)

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E. Valentino, S. Gariazzo, O. Mena [2106.15267](#)

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PRIORS?

Some claim “decisive” Bayesian evidence for normal

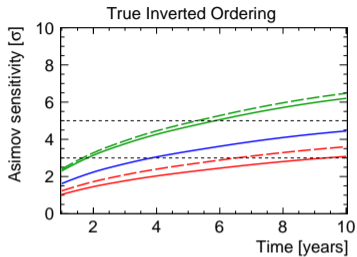
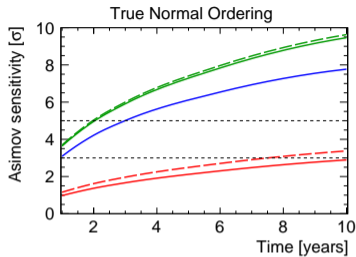
R. Jimenez, et al [2203.14247](#)

More general prior assumptions ⇒ no significant information from cosmology

S. Gariazzo, et al [1801.04946](#)

S. Gariazzo, et al [2205.02195](#)

Mass ordering: future sensitivities

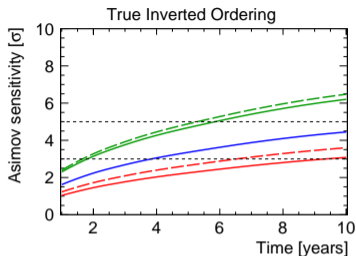
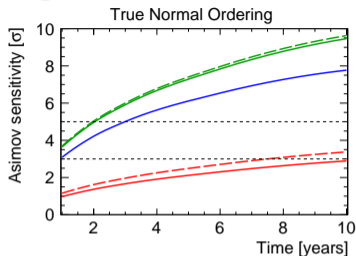


Joint
KM3NeT
JUNO

JUNO, KM3NeT [2108.06293](#)

Note: if lower octant, KM3NeT is less sensitive

Mass ordering: future sensitivities



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KM3NeT
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JUNO, KM3NeT [2108.06293](#)

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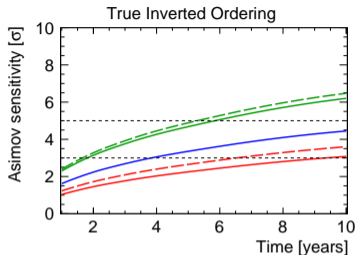
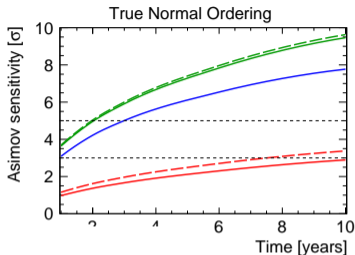
$$\Delta m_{ee}^2 = c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2$$

$$\Delta m_{\mu\mu}^2 = s_{12}^2 \Delta m_{31}^2 + c_{12}^2 \Delta m_{32}^2 + \mathcal{O}(s_{13} \Delta m_{21}^2)$$

Differ by $\pm \sim 1.5\%$ in each mass ordering

H. Nunokawa, S. Parke, R. Funchal [hep-ph/0503283](#)

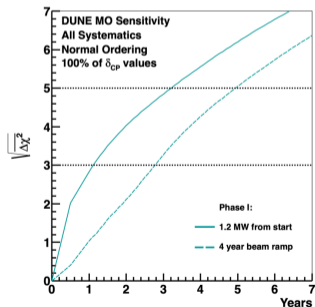
Mass ordering: future sensitivities



Joint
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JUNO, KM3NeT [2108.06293](#)

Note: if lower octant, KM3NeT is less sensitive



Matter effect \Rightarrow DUNE [2203.06100](#)

$$\Delta m_{ee}^2 = c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2$$

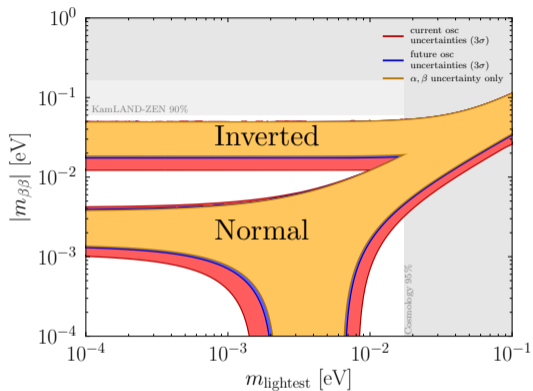
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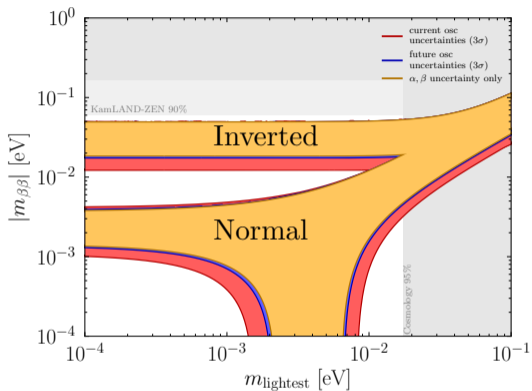
Mass ordering: broad implications

- ▶ Affects cosmology
- ▶ Affects $0\nu\beta\beta$
- ▶ Affects end point measurements
- ▶ Affects $C\nu B$

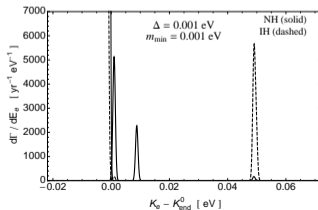
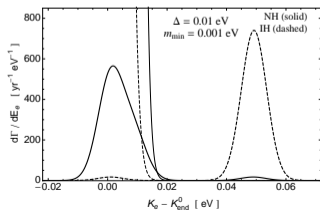


Mass ordering: broad implications

- ▶ Affects cosmology
- ▶ Affects $0\nu\beta\beta$
- ▶ Affects end point measurements
- ▶ Affects $C\nu B$



A. Long, C. Lunardini, E. Sabancilar [1405.7654](#)



Mass ordering: new physics degeneracies

In the presence of new physics such as NSI we have:

$$[\text{NO}] + [\epsilon = 0] \equiv [\text{IO}] + [\epsilon_{ee} = -2]$$

$$[\text{IO}] + [\epsilon = 0] \equiv [\text{NO}] + [\epsilon_{ee} = -2]$$

Equivalences hold even if all oscillation probabilities are *perfectly* measured

P. Bakhti, Y. Farzan [1403.0744](#)

P. Coloma, T. Schwetz [1604.05772](#)

[PBD](#), S. Parke [2106.12436](#)

[PBD](#), J. Gehrlein [2204.09060](#)



This is known as the **LMA-Dark** solution

Is the mass ordering robust?

Need **scattering** to break



CHARM and NuTeV for $M_{Z'} \gtrsim 10$ GeV

PBD, et al [1701.04828](#)

COHERENT for $M_{Z'} \gtrsim 50$ MeV and cosmology for $M_{Z'} \lesssim 5$ MeV

PBD, Y. Farzan, I. Shoemaker [1804.03660](#)

Dresden-II for any mediator mass

PBD, J. Gehrlein [2204.09060](#)

Can still evade with $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$ or certain u / d combinations

θ_{23} octant

θ_{23} octant: what is it?

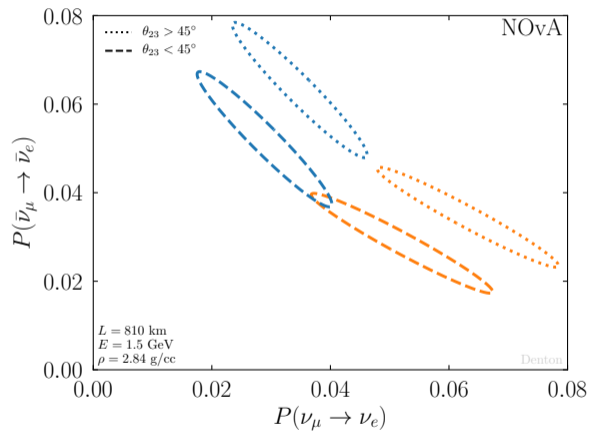
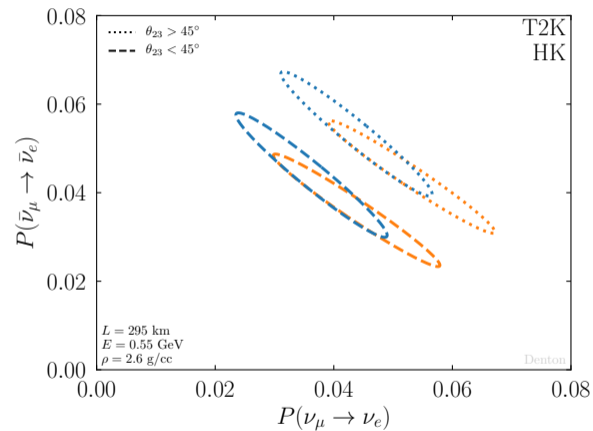
Normal



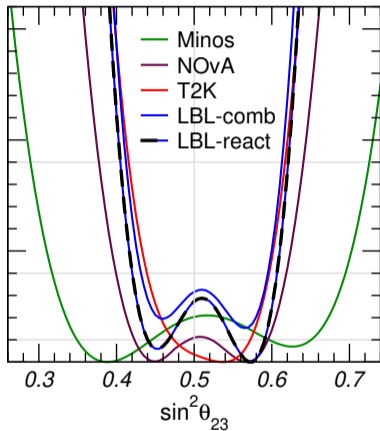
Inverted



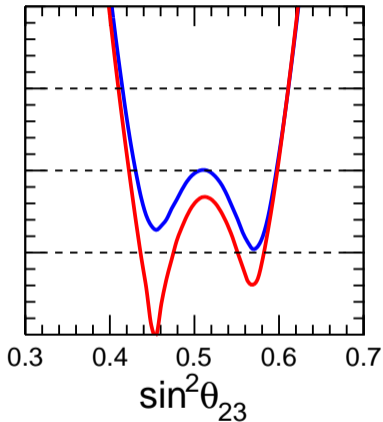
θ_{23} octant: what is it really?



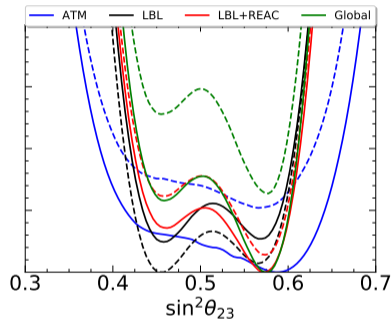
θ_{23} octant: current status



I. Esteban, et al [2007.14792](#)

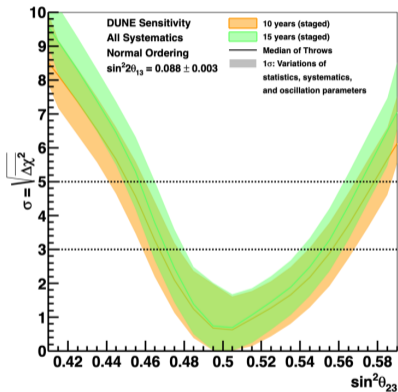


F. Capozzi, et al [2107.00532](#)

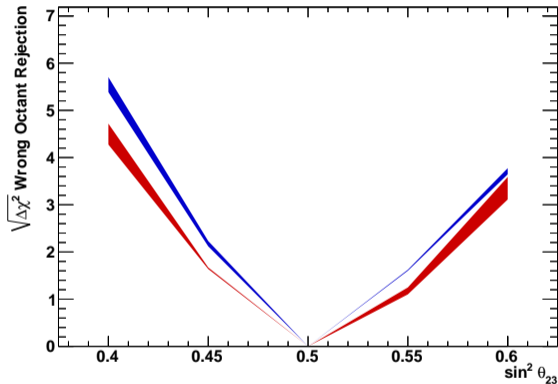


P. de Salas, et al [2006.11237](#)

θ_{23} octant: future sensitivities



DUNE 2002.03005



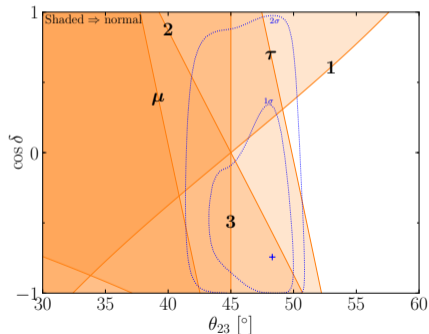
HK 1805.04163

θ_{23} : broader implications

Normalcy

Is the heaviest neutrino mostly ν_τ ?

Is the lightest neutrino least ν_τ ?



Quarks easily satisfy normalcy [PBD 2003.04319](#)

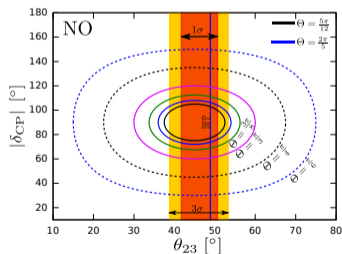
μ - τ interchange/reflection symmetry

$$\nu_\mu \leftrightarrow \nu_\tau$$

$$M_\nu = X M_\nu X^{(*)} \quad X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$M_\nu \equiv U D_\nu U^\dagger$$

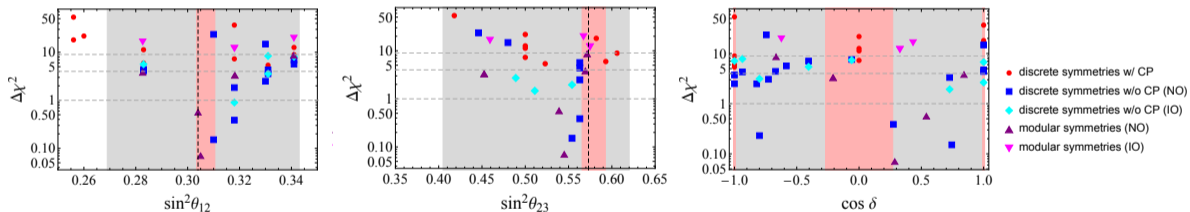
Predicts: $\theta_{23} = 45^\circ$, often $\theta_{13} = 0$



P. Chen, et al [1512.01551](#)

Parameter interplay

Models predict specific correlations among the parameters



Complex phase

δ and CP violation

$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin \delta$$

C. Jarlskog [PRL 55, 1039 \(1985\)](#)



δ and CP violation



$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin \delta$$

C. Jarlskog [PRL 55, 1039 \(1985\)](#)

1. Strong interaction: no observed EDM \Rightarrow CP (nearly) **conserved**

$$\frac{\bar{\theta}}{2\pi} < 10^{-11}$$

J. Pendlebury, et al. [1509.04411](#)

2. Quark mass matrix: non-zero but **small** CP violation

$$\frac{|J_{CKM}|}{J_{\max}} = 3 \times 10^{-4}$$

CKMfitter [1501.05013](#)

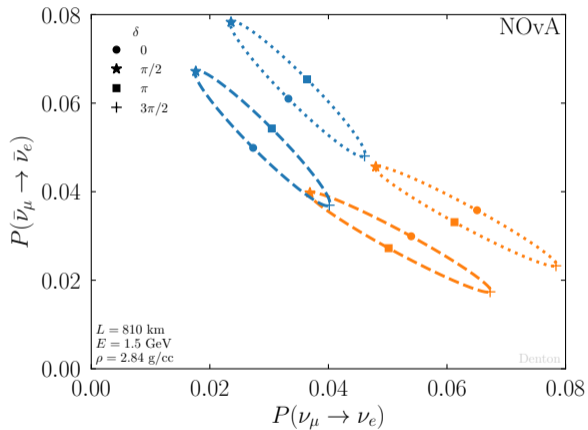
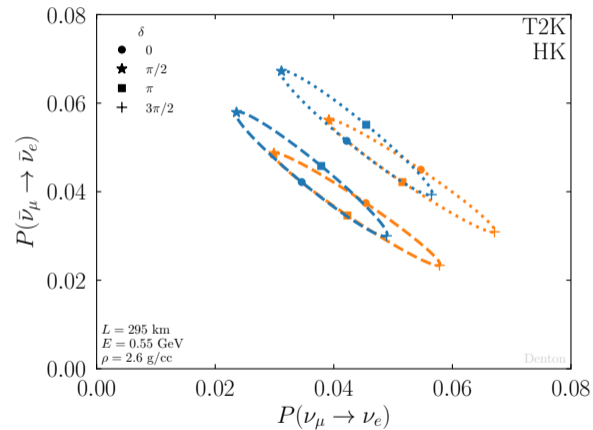
3. Lepton mass matrix: ?

$$\frac{|J_{PMNS}|}{J_{\max}} < 0.34$$

[PBD](#), J. Gehrlein, R. Pestes [2008.01110](#)

$$J_{\max} = \frac{1}{6\sqrt{3}} \approx 0.096$$

δ : what is it really?



δ : what is it not?

$\delta \not\Rightarrow$ Baryogenesis

The amount of leptogenesis is a function of:

1. the heavy mass scale
2. δ
3. α, β (Majorana phases)
4. CP phases in the RH neutrinos
5. ...

C. Hagedorn, et al [1711.02866](#)

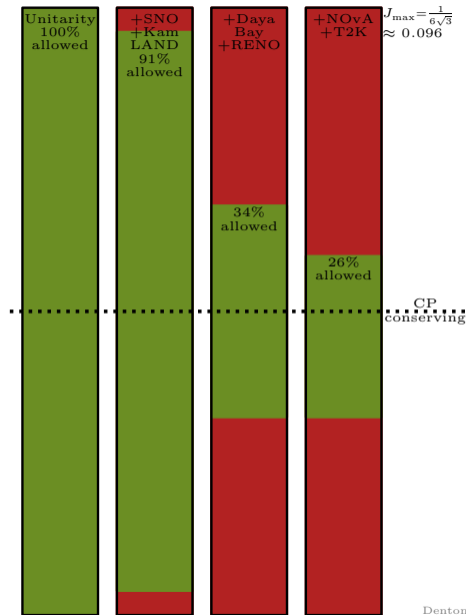
K. Moffat, et al [1809.08251](#)

Measuring $\delta = 0, \pi$	$\not\Rightarrow$	no Baryogenesis
Measuring $\delta \neq 0, \pi$	$\not\Rightarrow$	Baryogenesis

δ, J : current status

Maximal CP violation is already ruled out:

1. $\theta_{12} \neq 45^\circ$ at $\sim 15\sigma$
2. $\theta_{13} \neq \tan^{-1} \frac{1}{\sqrt{2}} \approx 35^\circ$ at many (100) σ
3. $\theta_{23} = 45^\circ$ allowed at $\sim 1\sigma$
4. $|\sin \delta| = 1$ allowed



When δ and when J ?

If the goal is **CP violation** the Jarlskog invariant should be used

however

If the goal is **measuring the parameters** one must use δ

Given θ_{12} , θ_{13} , θ_{23} , and J , I can't determine the sign of $\cos \delta$ which is physical

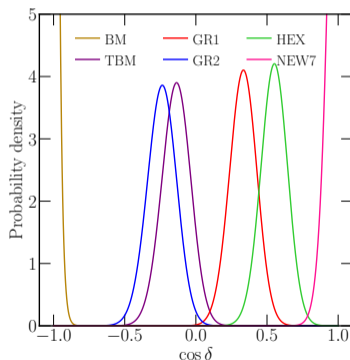
e.g. $P(\nu_\mu \rightarrow \nu_\mu)$ depends on $\cos \delta$ a tiny bit

- ▶ T2K/HK are mostly sensitivity to $\sin \delta$; they should focus on J
- ▶ NOvA/DUNE has modest $\cos \delta$ sensitivity; both J and δ should be reported

The importance of $\cos \delta$

- ▶ If only $\sin \delta$ is measured \Rightarrow sign degeneracy: $\cos \delta = \pm \sqrt{1 - \sin^2 \delta}$
- ▶ Most flavor models predict $\cos \delta$

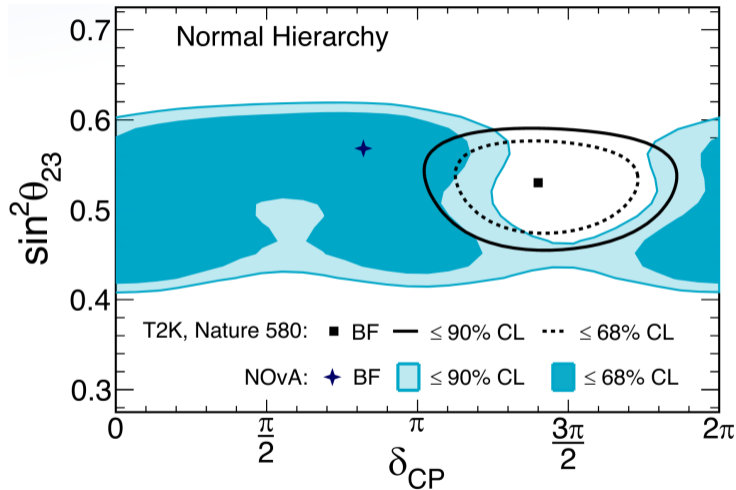
J. Gehrlein, et al [2203.06219](#)



L. Everett, et al [1912.10139](#)

δ : new physics hints?

Excitement at Neutrino2020!



A. Himmel for NOvA [10.5281/zenodo.3959581](https://zenodo.org/record/3959581)

Estimate size of new physics

$$|\epsilon_{e\beta}| \approx \frac{s_{12}c_{12}c_{23}\pi\Delta m_{21}^2}{2s_{23}w_\beta} \left| \frac{\sin\delta_{\text{T2K}} - \sin\delta_{\text{NOvA}}}{a_{\text{NOvA}} - a_{\text{T2K}}} \right| \approx \begin{cases} 0.22 & \text{for } \beta = \mu \\ 0.24 & \text{for } \beta = \tau \end{cases}$$

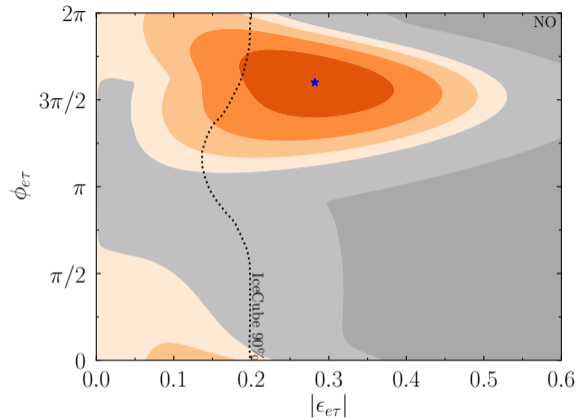
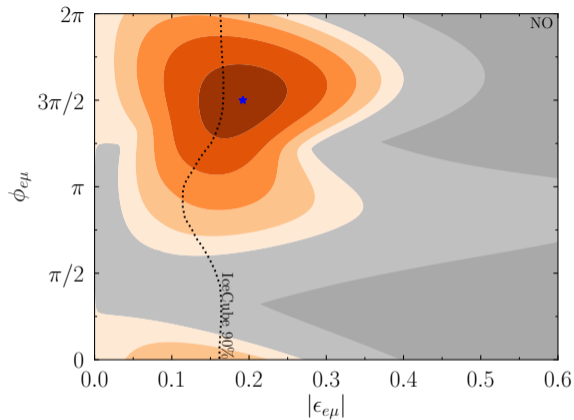
$$w_\beta = s_{23}, c_{23} \text{ for } \beta = \mu, \tau$$

Assumed upper octant $\theta_{23} > 45^\circ$

Consistency checks:

- ▶ $\sin\delta_{\text{NOvA}} = \sin\delta_{\text{T2K}} \Rightarrow |\epsilon| = 0$
- ▶ $\sin\delta_{\text{NOvA}} \neq \sin\delta_{\text{T2K}}$ and $a_{\text{NOvA}} = a_{\text{T2K}} \Rightarrow |\epsilon| \rightarrow \infty$
- ▶ Octant:
 1. LBL is governed by ν_3
 2. Upper octant $\Rightarrow \nu_3$ is more ν_μ
 3. More $\nu_\mu \Rightarrow$ need less new physics coupling to ν_μ to produce a given effect

NSI parameters



Orange is preferred over SM, dark gray is disfavored

PBD, J. Gehrlein, R. Pestes [2008.01110](#)

T. Ehrhardt, IceCube [PPNT \(2019\)](#)

$\epsilon_{\mu\tau}$, IO in backups

Neutrino oscillation summary

- ▶ Four known unknowns in particle physics: all neutrinos
- ▶ Mass ordering will be measured
- ▶ θ_{23} octant is important for flavor models
- ▶ δ could shed light on CP violation
- ▶ Hints for new physics are testable

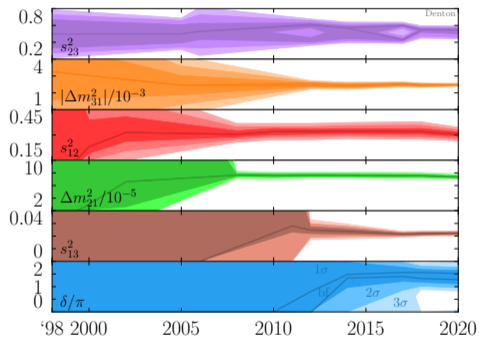
Robustness?

Precision is coming to neutrinos!



Backups

References



SK [hep-ex/9807003](#)

M. Gonzalez-Garcia, et al. [hep-ph/0009350](#)

M. Maltoni, et al. [hep-ph/0207227](#)

SK [hep-ex/0501064](#)

SK [hep-ex/0604011](#)

T. Schwetz, M. Tortola, J. Valle [0808.2016](#)

M. Gonzalez-Garcia, M. Maltoni, J. Salvado [1001.4524](#)

T2K [1106.2822](#)

D. Forero, M. Tortola, J. Valle [1205.4018](#)

D. Forero, M. Tortola, J. Valle [1405.7540](#)

P. de Salas, et al. [1708.01186](#)

F. Capozzi et al. [2003.08511](#)

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta) (\bar{f} \gamma_\mu f)$$

Models with large NSIs consistent with CLFV:

Y. Farzan, I. Shoemaker [1512.09147](#) Y. Farzan, J. Heeck [1607.07616](#) D. Forero and W. Huang [1608.04719](#)
 K. Babu, A. Friedland, P. Machado, I. Mocioiu [1705.01822](#) [PBD](#), Y. Farzan, I. Shoemaker [1804.03660](#)
 U. Dey, N. Nath, S. Sadhukhan [1804.05808](#) Y. Farzan [1912.09408](#)

Affects oscillations via new matter effect

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

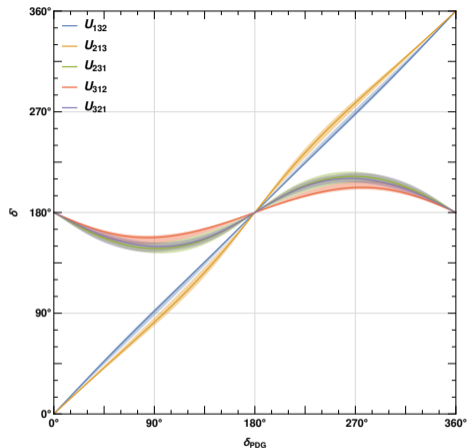
Matter potential $a \propto G_F \rho E$

B. Dev, K. Babu, [PBD](#), P. Machado, et al. [1907.00991](#)

Complex phase in different parameterizations

- ▶ Can relate the complex phase in one parameterization to that in another
- ▶ U_{132} and U_{213} similar to U_{123}
- ▶ δ constrained to $\sim [150^\circ, 210^\circ]$ in $U_{231}, U_{312}, U_{321}$
- ▶ Bands indicate 3σ uncertainty on $\theta_{12}, \theta_{13}, \theta_{23}$
- ▶ “50% of possible values of δ ”
⇒ parameterization dependent

DUNE TDR II [2002.03005](#)



Repeated rotations in backups

Quark mixing

From the PDG, V_{CKM} in the V_{123} parameterization is

$$\theta_{12} = 13.09^\circ \quad \theta_{13} = 0.2068^\circ \quad \theta_{23} = 2.323^\circ \quad \delta_{\text{PDG}} = 68.53^\circ$$

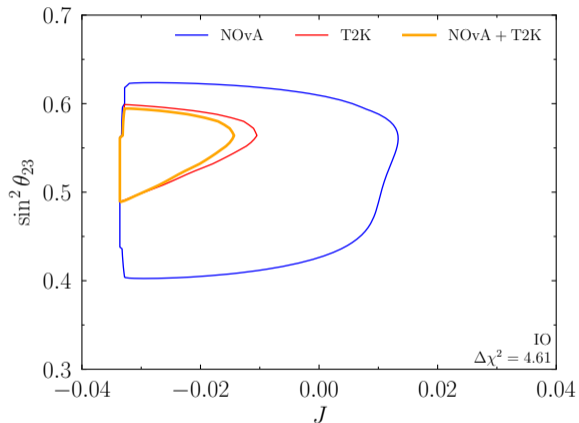
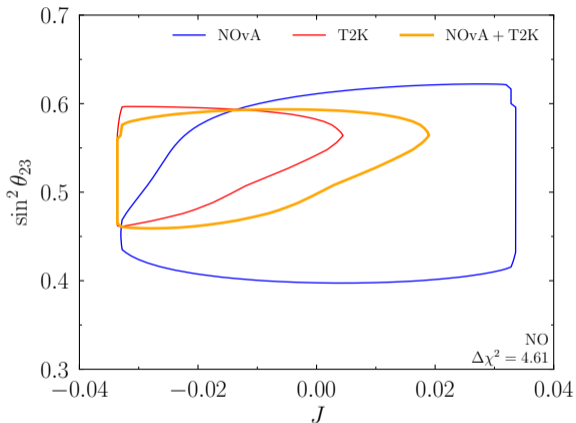
Looks like “large” CPV:

$$\sin \delta_{\text{PDG}} = 0.93 \sim 1$$

yet $J_{\text{CKM}}/J_{\text{max}} = 3 \times 10^{-4}$.

Switch to V_{212} parameterization, $\Rightarrow \delta' = 1^\circ$ and $\sin \delta' = 0.02$.

Standard oscillation parameters



Can see that the combination doesn't like the NO while it does like the IO
IO preferred over NO at $\Delta\chi^2 = 2.3$

CP violation in oscillations

In vacuum at first maximum:

$$P_{\mu e} - \bar{P}_{\mu e} \approx 8\pi J \frac{\Delta m_{21}^2}{\Delta m_{32}^2}$$

$$J \equiv s_{12}c_{12}s_{13}c_{13}^2s_{23}c_{23} \sin \delta$$

C. Jarlskog [PRL 55, 1039 \(1985\)](#)

- ▶ Extracting δ from data requires every other oscillation parameter
- ▶ J requires only Δm_{21}^2 (up to matter effects)

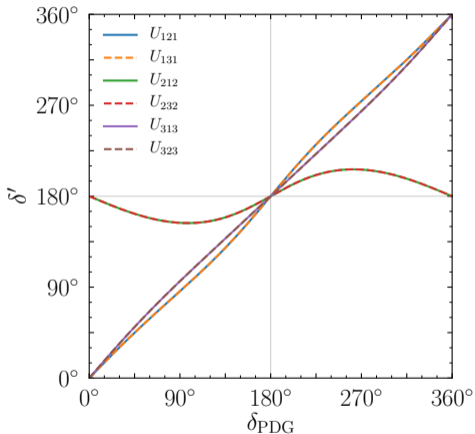
Matter effects are easily accounted for

$$\hat{J} \simeq \frac{J}{\sqrt{(c_{212} - c_{13}^2 a / \Delta m_{21}^2)^2 + s_{212}^2} \sqrt{(c_{213} - a / \Delta m_{ee}^2)^2 + s_{213}^2}}$$

[PBD](#), S. Parke [1902.07185](#)

[PBD](#), H. Minakata, S. Parke [1604.08167](#)

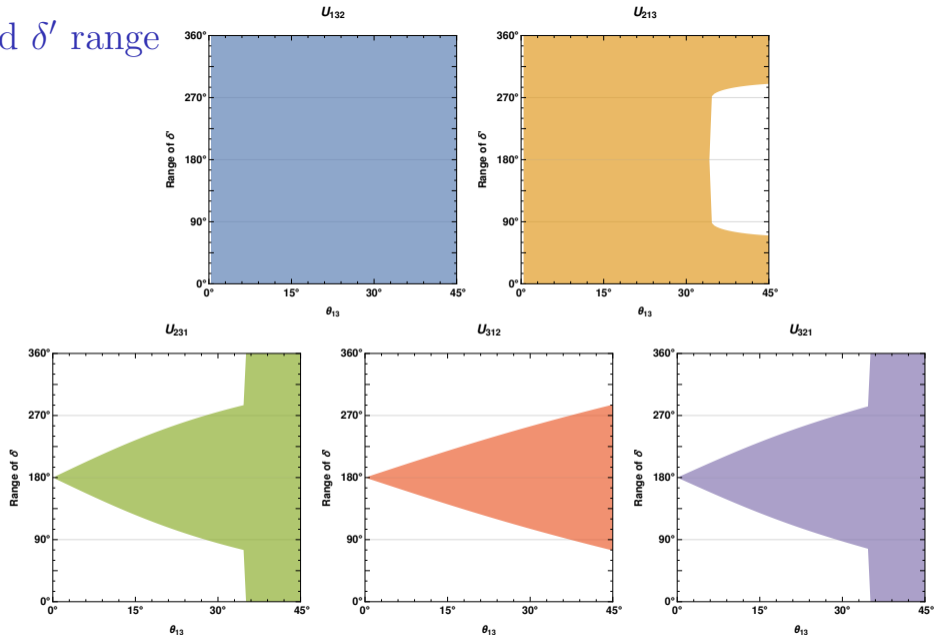
Repeated rotations



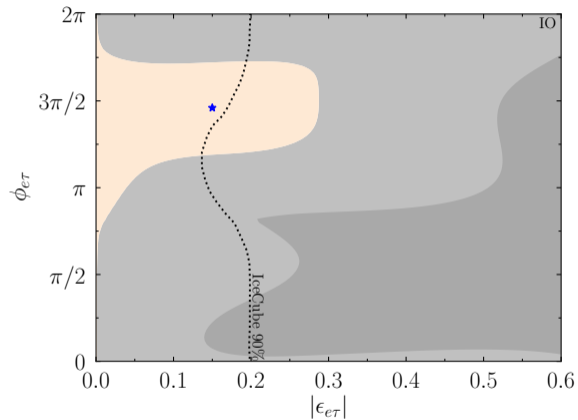
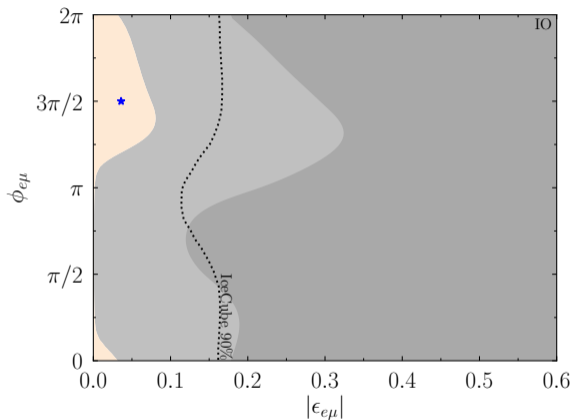
	U_{121}	U_{131}	U_{212}	U_{232}	U_{313}	U_{323}
$ U_{e2} $	✓	✓	✓	✓	✗	✗
$ U_{e3} $	✓	✓	✗	✗	✓	✓
$ U_{\mu 3} $	✗	✗	✓	✓	✓	✓

Note that $e^{i\delta}$ must be on first or third rotation

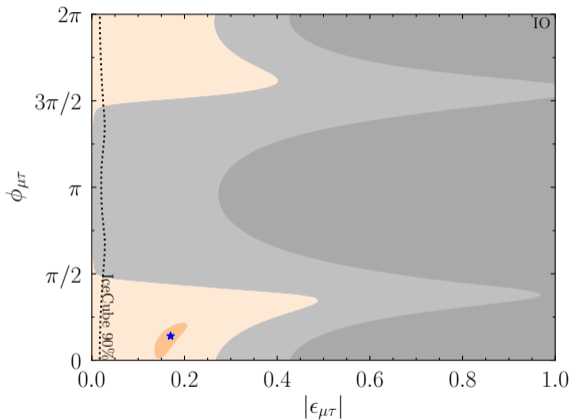
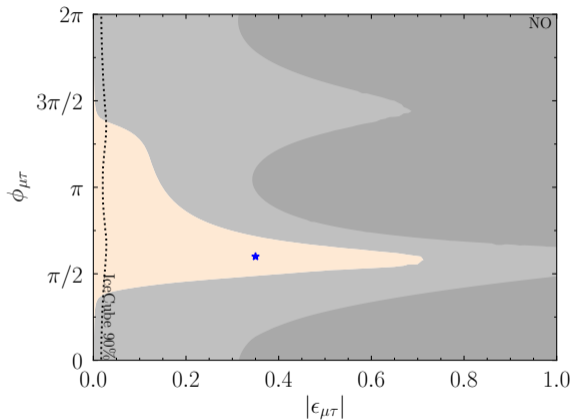
Allowed δ' range



NSI parameters: IO



NSI parameters: $\epsilon_{\mu\tau}$



Other CP violating NSI constraints

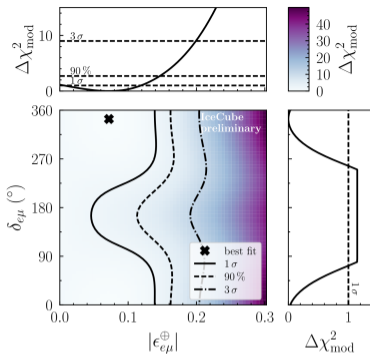
NSI effects grow with energy, density, and distance

Best probes:

- ▶ $\epsilon_{\mu\tau}$: atmospheric
- ▶ $\epsilon_{e\mu}, \epsilon_{e\tau}$: LBL appearance, atmospheric
- ▶ IceCube
 - ▶ Constraint is at LBL best fit with 3 yrs
10 yrs of data in the bank
 - ▶ Prefers non-zero $|\epsilon_{e\mu}|$ at $\sim 1\sigma$

- ▶ Super-K
 - ▶ Only consider real NSI
 - ▶ Comparable sensitivity as IceCube

- ▶ COHERENT
 - ▶ Only applies to NSI models with $M_{Z'} \gtrsim 10$ MeV
 - ▶ NSI u, d, e configuration matters
 - ▶ Comparable constraints



T. Ehrhardt, IceCube [PPNT \(2019\)](#)

Super-K [1109.1889](#)

COHERENT [1708.01294](#)

[PBD](#), Y. Farzan, I. Shoemaker [1804.03660](#)

[PBD](#), J. Gehrlein [2008.06062](#)