

Flavor mixing, CP violation, and Unitarity

Peter B. Denton

Neutrino 2022

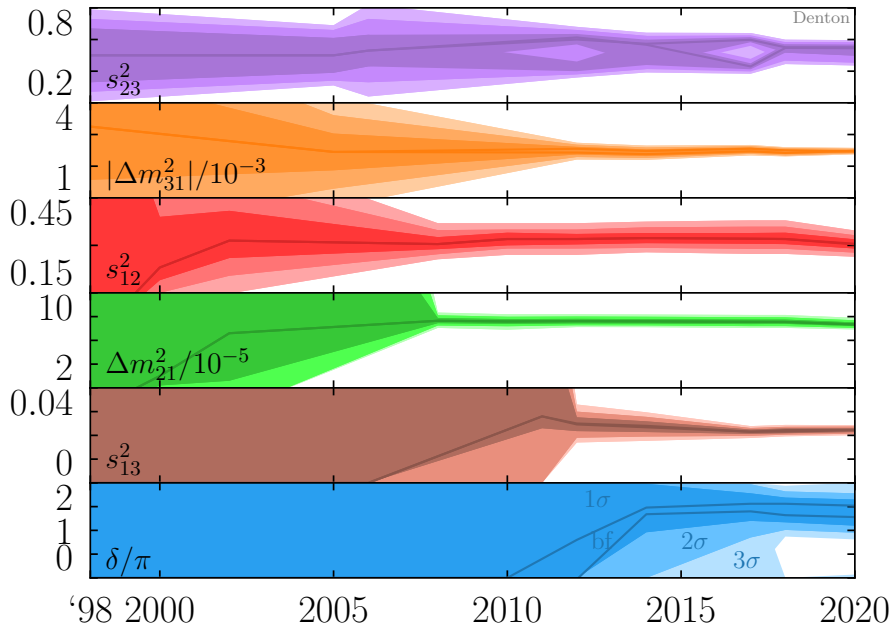
June 1/2, 2022

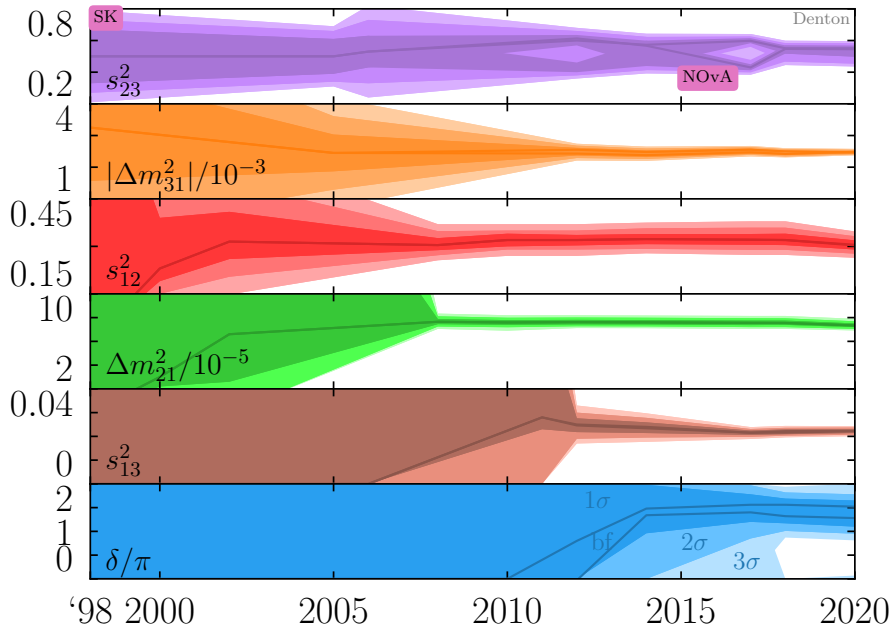


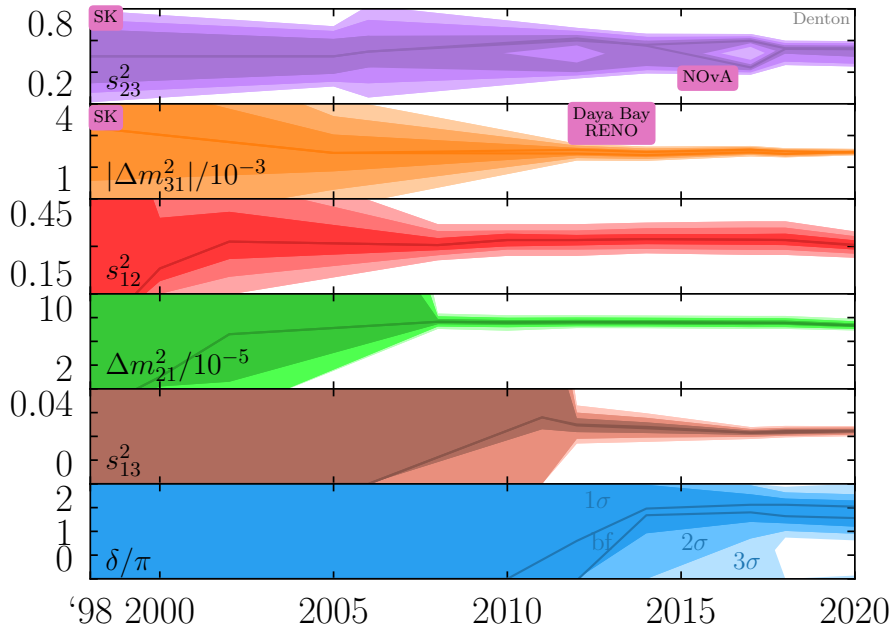
Brookhaven[™]
National Laboratory

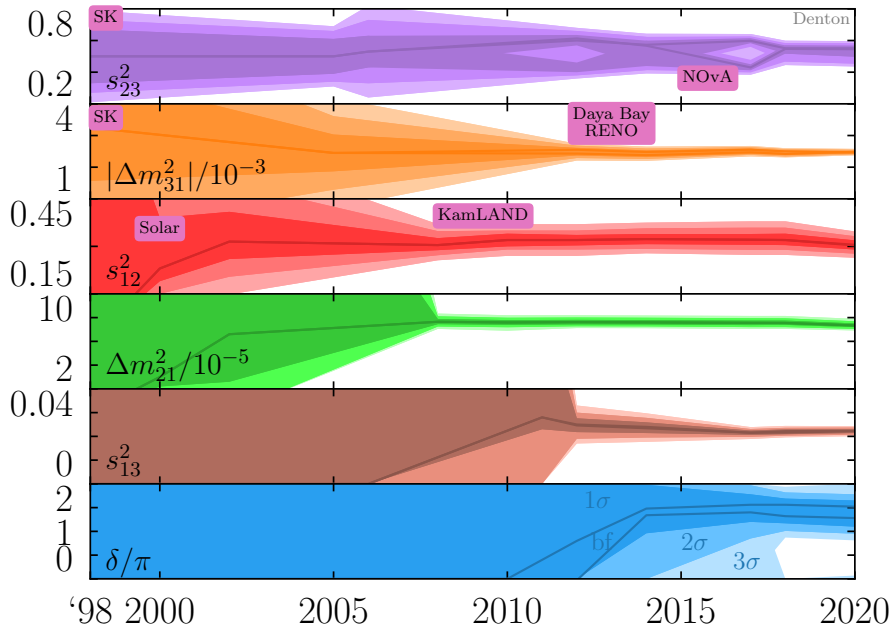


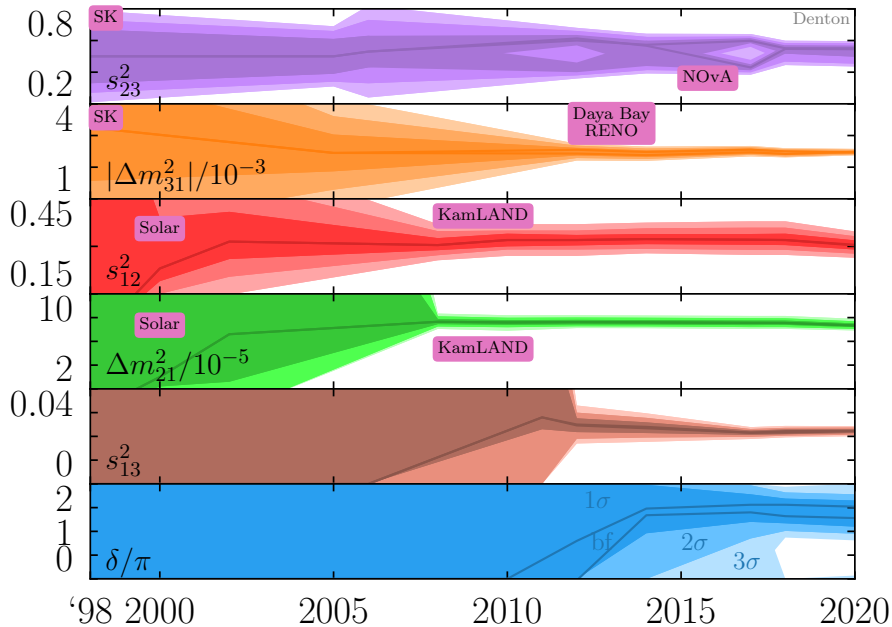
Speaking from [Setauket](#) land

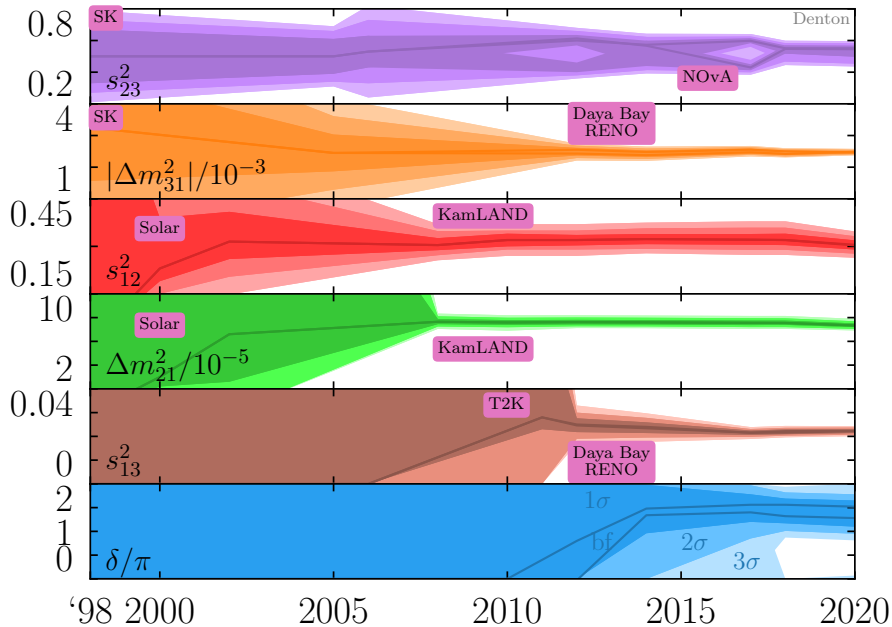


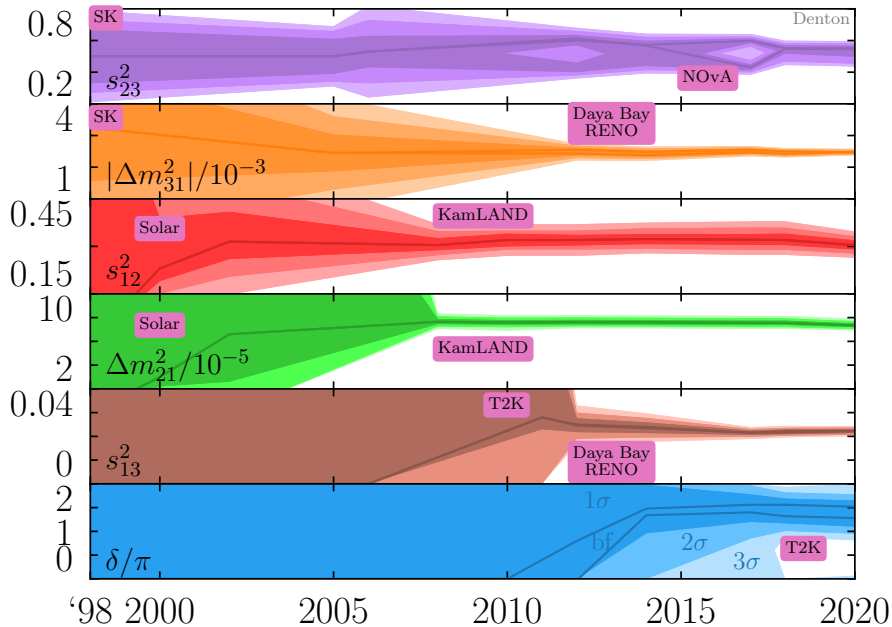












Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

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θ_{23} octant

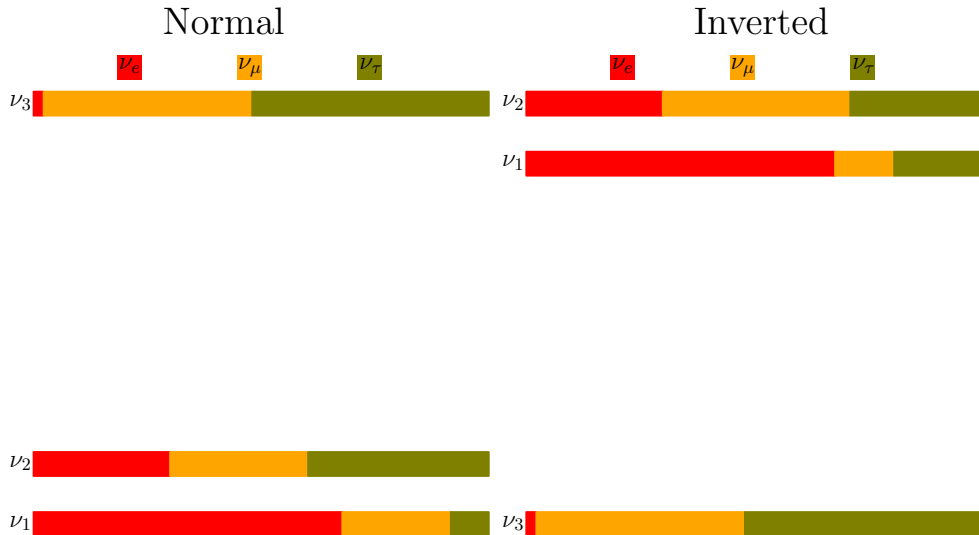
Complex phase

Absolute mass scale

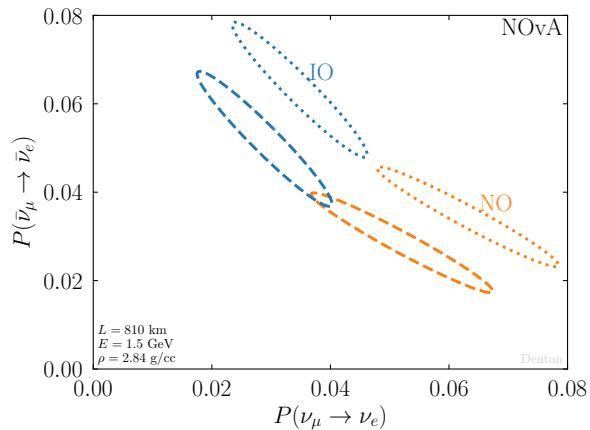
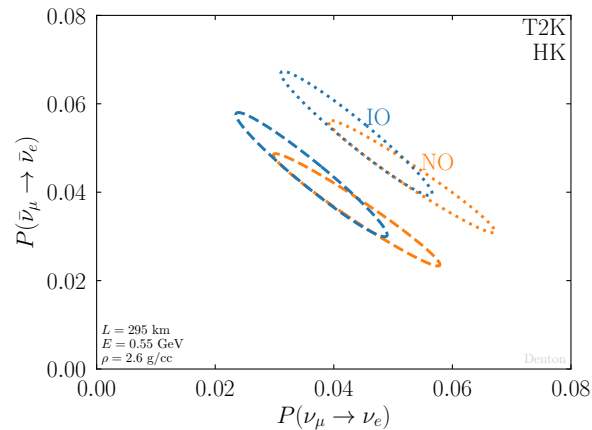
Cosmology, scattering, $0\nu\beta\beta$, ...

Atmospheric mass ordering

Mass ordering: what is it?



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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PRIORS?

Some claim “decisive” Bayesian evidence for normal

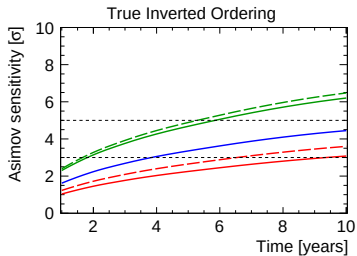
R. Jimenez, et al. [2203.14247](#)

More general prior assumptions $\Rightarrow$ no significant information from cosmology

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

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

Mass ordering: future sensitivities



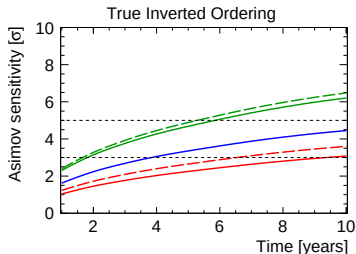
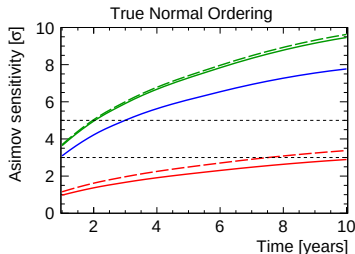
Joint
KM3NeT
JUNO

JUNO, KM3NeT [2108.06293](#)

JUNO, IceCube [1911.06745](#)

Note: if lower octant, KM3NeT is less sensitive

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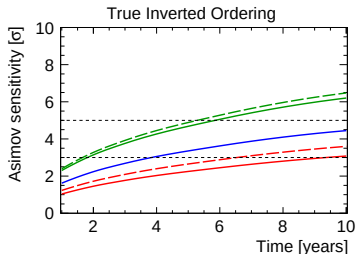
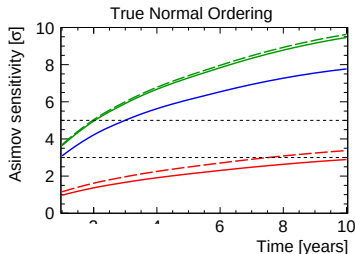
$$\Delta m_{ee}^2 = c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2$$

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

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

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

Mass ordering: future sensitivities



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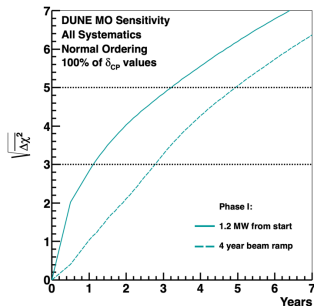
JUNO, IceCube [1911.06745](#)

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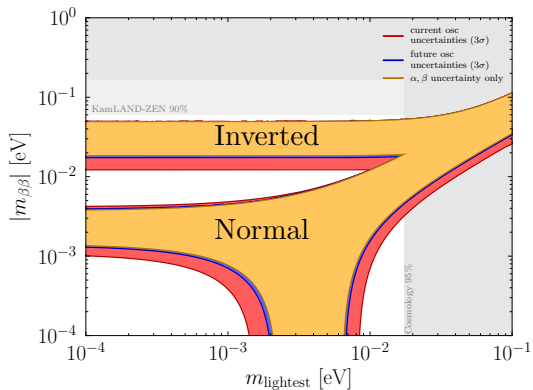


Matter effect $\Rightarrow$ DUNE [2203.06100](#)

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

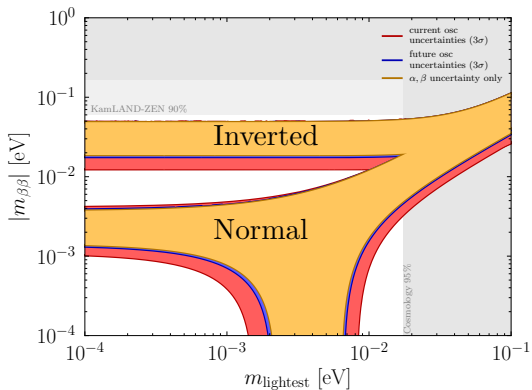
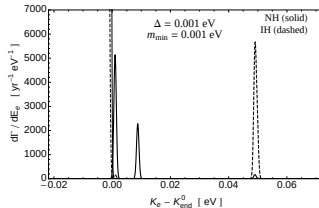
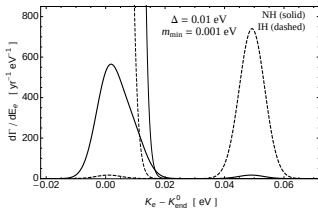
Mass ordering: broad implications

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



Mass ordering: broad implications

- Affects cosmology
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- 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 NSI¹ we have:

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

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

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

¹See Yasaman Farzan's talk on Friday, June 3!



Is the mass ordering robust?

Need **scattering** to break



Can probe same NC $\epsilon = -2$ process in scattering, but...

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

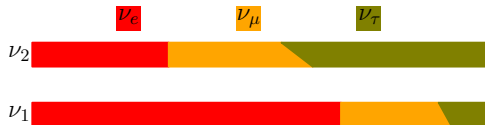
θ_{23} octant

θ_{23} octant: what is it?

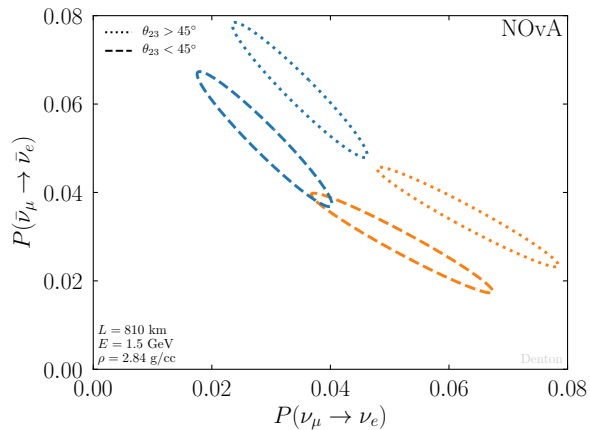
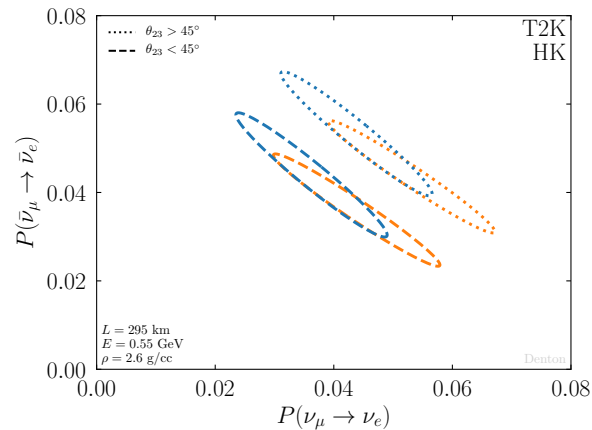
Normal



Inverted

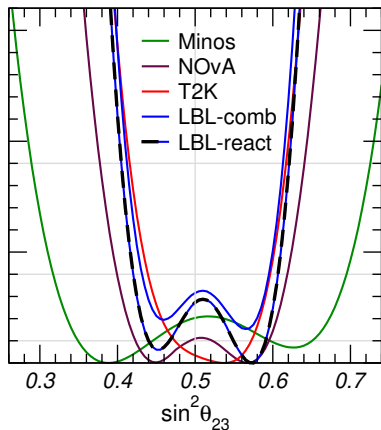


θ_{23} octant: what is it really?



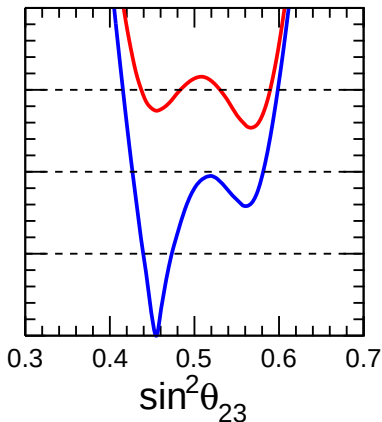
Lower octant more “normal” than upper octant

θ_{23} octant: current status



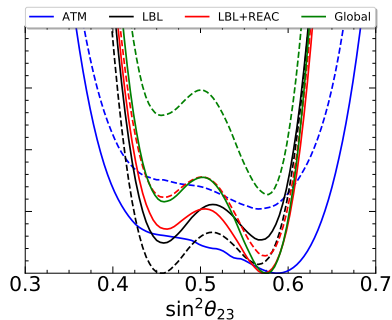
I. Esteban, et al. [2007.14792](#)

Prefers **upper** at $< 1\sigma$



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

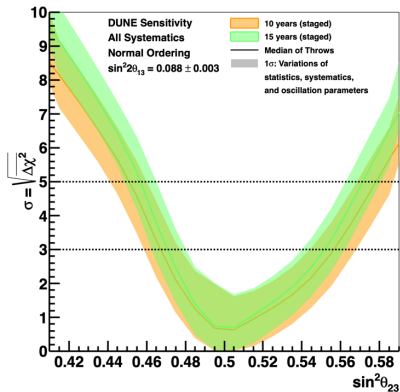
Prefers **lower** at $\sim 1.5\sigma$



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

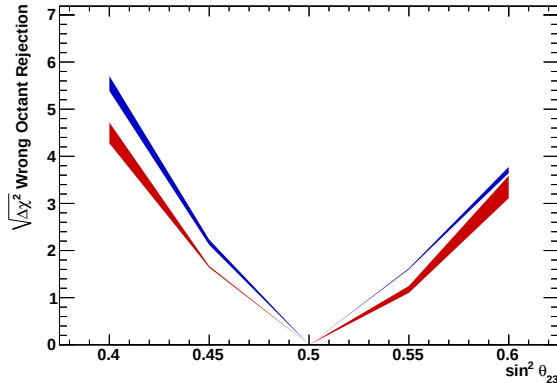
Prefers **upper** at $> 2\sigma$

θ_{23} octant: future sensitivities



$\sim 3 - 5\sigma$

DUNE 2002.03005



Beam+Atm $\Rightarrow \sim 3 - 6\sigma$

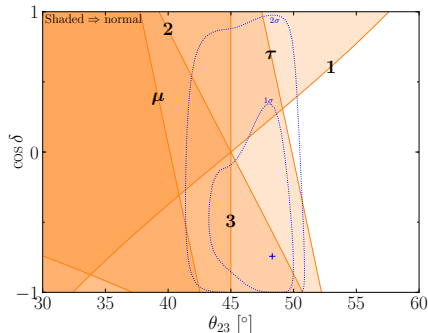
HK 1805.04163

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](#)

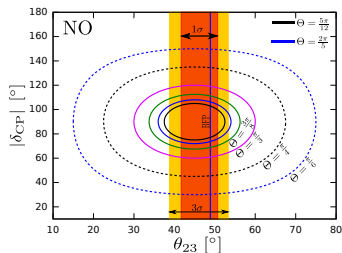
μ - τ interchange/reflection symmetry

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

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

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

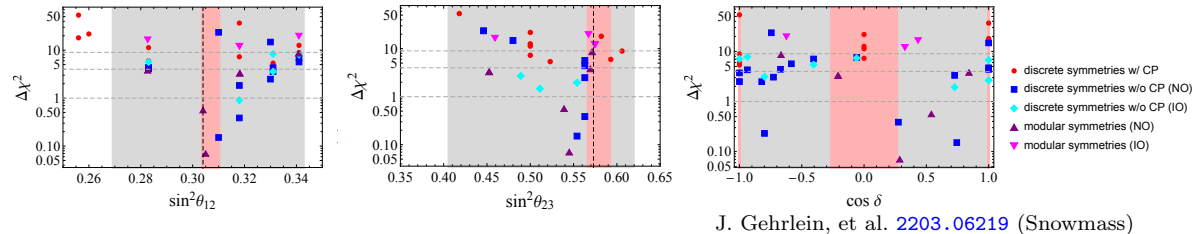
Predicts: $\theta_{23} = 45^\circ$, often $\theta_{13} = 0$



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](#)

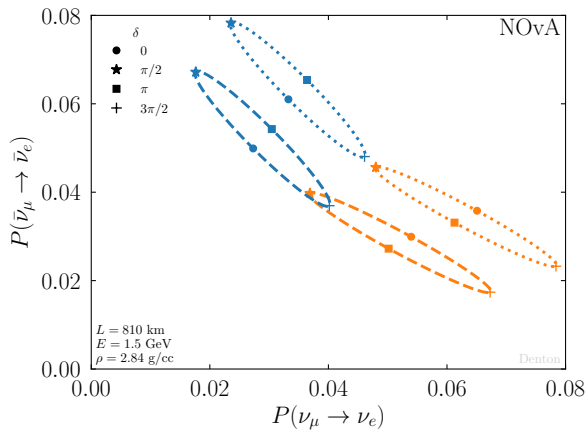
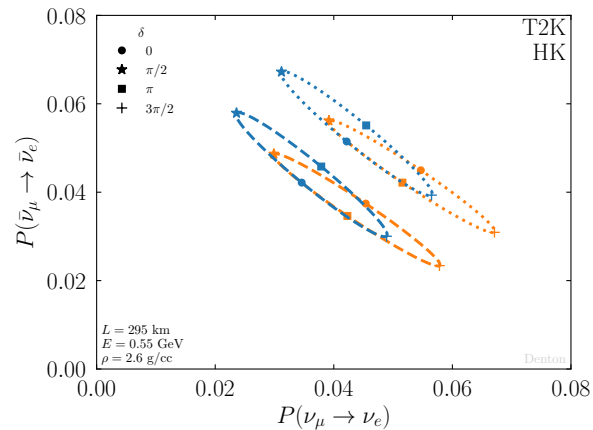
3. Lepton mass matrix: ?

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

[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](#)

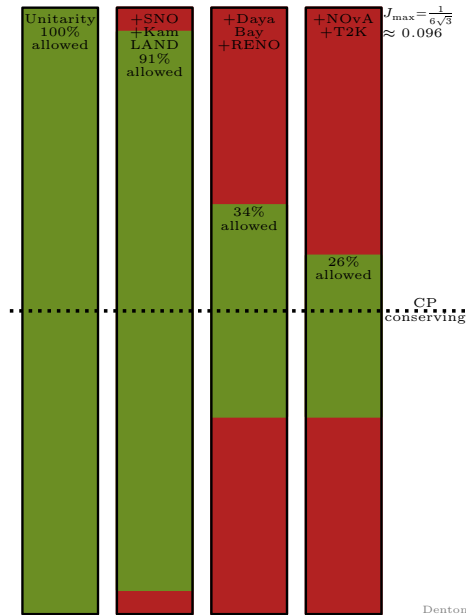
K. Moffat, et al. [1809.08251](#)

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

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

T2K does this now!

- ▶ NOvA/DUNE has modest $\cos \delta$ sensitivity; both J and δ should be reported

Unitarity violation

Consistency of the three-flavor oscillation picture?

and/or

Searches for unitarity violation?

Unitarity violation

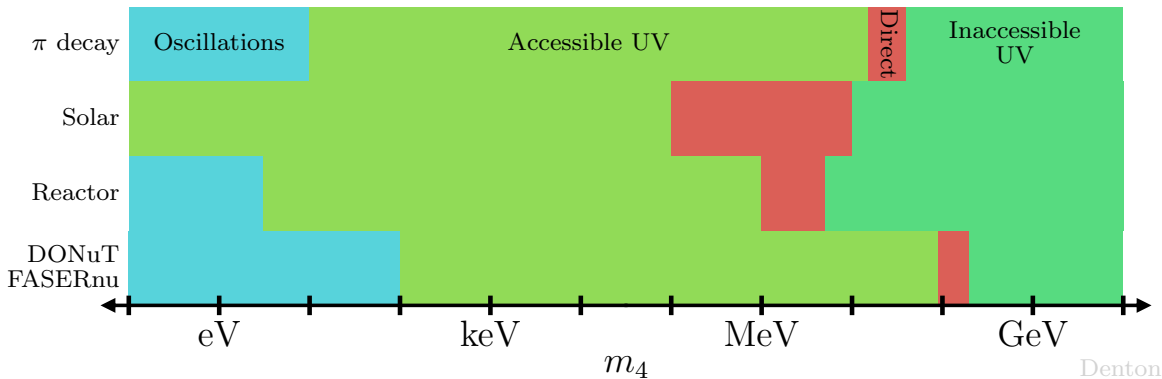
Consistency of the three-flavor oscillation picture?

and/or

Searches for unitarity violation?

Not the same!

Unitarity violation: a tale of two regimes



*Details depends on the specific experiment/channel

Unitarity violation: what is it?

Our 3×3 matrix isn't unitary:

$$U_3 U_3^\dagger \neq \mathbb{1}$$

Addition of new flavor states $\nu_a, \nu_b, \nu_c, \dots$ and new mass states ν_4, ν_5, ν_6

$$U \rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{a1} & U_{a2} & U_{a3} & U_{a4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Unitarity Violation $\Rightarrow$

New mass states not directly accessible by oscillations or decay

Thus check if U_3 is what it should be

Unitarity violation: how to calculate

Kinematically **accessible** states

1. Unitary calculation of full $n \times n$ matrix
2. Oscillation averaged:

$$\sin^2 \frac{\Delta m_{41}^2 L}{4E} \rightarrow \frac{1}{2}$$

$$\sin \frac{\Delta m_{41}^2 L}{4E} \rightarrow 0$$

3. No matter effect:

$$H^{\text{mat}} = \text{diag}(V_{\text{CC}} + V_{\text{NC}}, V_{\text{NC}}, V_{\text{NC}}, 0, \dots)$$

Unitarity violation: how to calculate

Kinematically **accessible** states

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2. Oscillation averaged:

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3. No matter effect:

$$H^{\text{mat}} = \text{diag}(V_{\text{CC}} + V_{\text{NC}}, V_{\text{NC}}, V_{\text{NC}}, 0, \dots)$$

Kinematically **inaccessible** states

1. Nonunitary calculation of $m \times m$ matrix
 m = number of kinematically accessible states
2. Rescale probability:

$$P_{\alpha\beta} = \frac{|\sum_{i=1}^{\text{acc}} U_{\alpha i}^* e^{iP_i L} U_{\beta i}|}{(\sum_{i=1}^{\text{acc}} U_{\alpha i}^* U_{\alpha i})(\sum_{i=1}^{\text{acc}} U_{\beta i}^* U_{\beta i})}$$

3. Cannot subtract multiples of $\mathbb{1}$
4. Rescale cross section/flux as appropriate
5. Rescale G_F in matter effect

Unitarity violation

- ▶ Could conceivably differentiate: 2 new states from 1, but not 3 from 2
- ▶ Zero distance effect $\Rightarrow$ near detector **with flux prediction**

E.g. RAA, Gallium

- ▶ Numerous parameterizations: α matrix, η matrix, submatrix & Cauchy-Schwartz

All apply to the inaccessible cases only

- ▶ There is an approximate correspondence to sterile and NSI

$$\alpha_{ee} \approx \frac{1}{2}(s_{14}^2 + s_{15}^2 + s_{16}^2) \approx -\epsilon_{ee}, \quad \dots$$

M. Blennow, et al. [1609.08637](#)

Applies one experiment at a time

- ▶ Additional EW precision information: W, Z, π , μ , τ decays

Care is required

S. Antusch, et al. [hep-ph/0607020](#)

S. Antusch, O. Fischer [1407.6607](#)

Unitarity violation status from oscillations

3σ maximal deviations from unitarity

	Leptons	
	Hu+	Ellis+
ν_e row	0.003	0.05
ν_μ row	0.02	0.04
ν_τ row	0.2	0.82
ν_1 col	0.06	0.22
ν_2 col	0.09	0.27
ν_3 col	0.12	0.40

	Quarks	
u row	0.0015	$\sim 3\sigma$ tension
c row	0.06	
t row	-	
d col	0.005	
s col	0.06	
b col	-	

Lepton constraints don't include anomalies

Care is required

S. Ellis, K. Kelly, S. Li [2008.01088](#)

Z. Hu, et al. [2008.09730](#)

S. Parke, M. Ross-Lonergan [1508.05095](#)

PDG

Unitarity violation status from oscillations

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Lepton constraints don't include anomalies

Care is required

S. Ellis, K. Kelly, S. Li [2008.01088](#)

Z. Hu, et al. [2008.09730](#)

S. Parke, M. Ross-Lonergan [1508.05095](#)

PDG

Vastly different mixing angle hierarchy

$\Rightarrow$

Like comparing apples and hairstyles

Unitarity violation: tau row

Leptons: tau row is the weakest

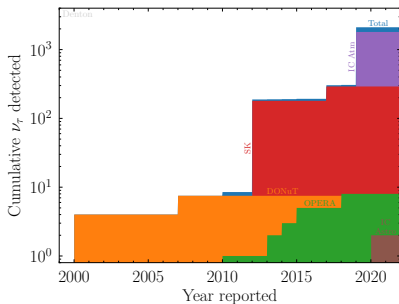
1. Existing global analyses use OPERA and SNO
2. More data from atmospheric ν_τ appearance!

PBD 2109.14576

Also astrophysical ν_τ appearance; weak but distinct!

PBD, J. Gehrlein 2109.14575

Works because τ is in **direct** region



PBD, et al. 2203.05591 (whitepaper)

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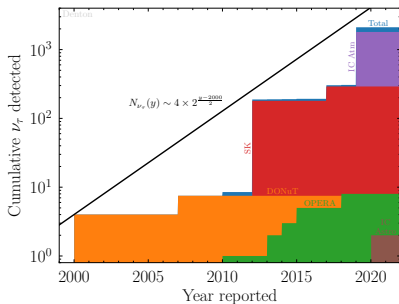
PBD 2109.14576

Also astrophysical ν_τ appearance; weak but distinct!

PBD, J. Gehrlein 2109.14575

Works because τ is in **direct** region

Tau neutrino data set doubles every two years!



PBD, et al. 2203.05591 (whitepaper)

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
- ▶ Unitarity violation is phenomenologically very rich
- ▶ Lots of existing tau information to be utilized!

Robustness?

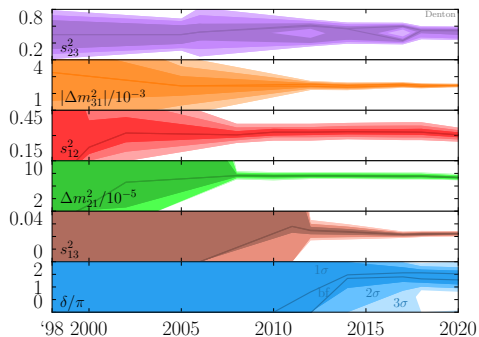
Precision is coming to neutrinos!

Thanks!



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](#)

NSI review

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

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

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

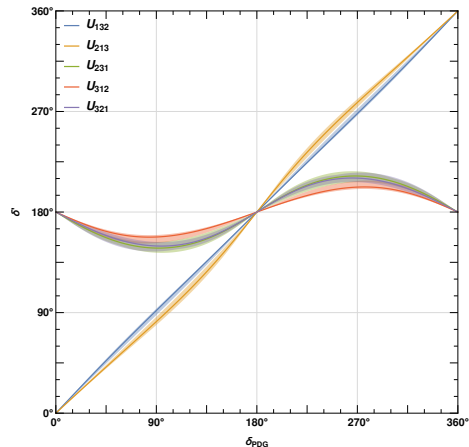
Matter potential $a \propto G_F \rho E$

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 ”
 $\Rightarrow$ parameterization dependent

DUNE TDR II [2002.03005](#)



Quark mixing

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

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

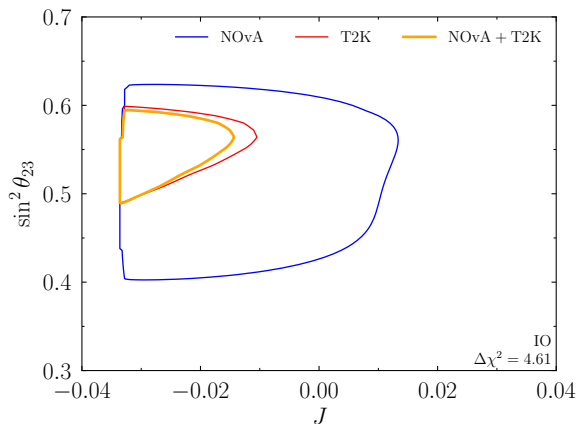
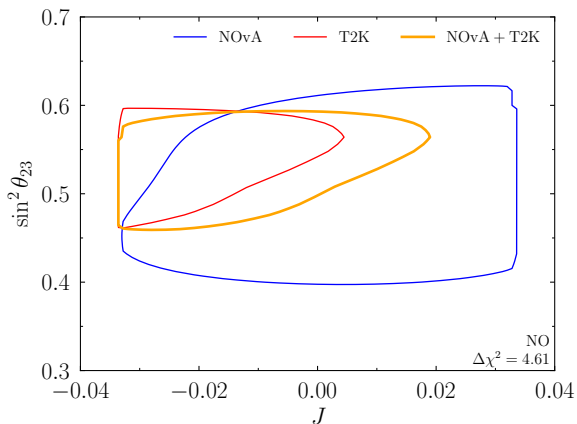
Looks like “large” CPV:

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

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)

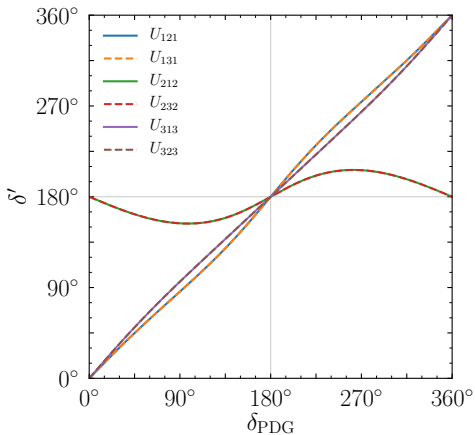
Matter effects are easily accounted for

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

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

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

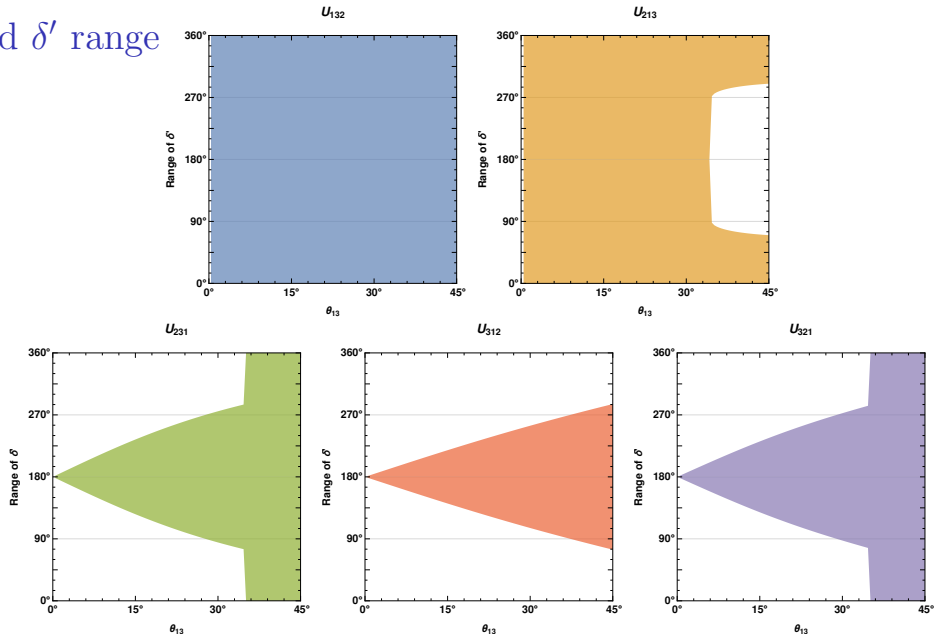
Repeated rotations



	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

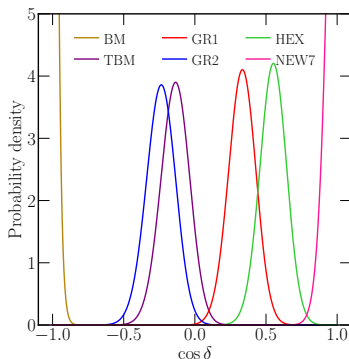
Allowed δ' range



The importance of $\cos \delta$

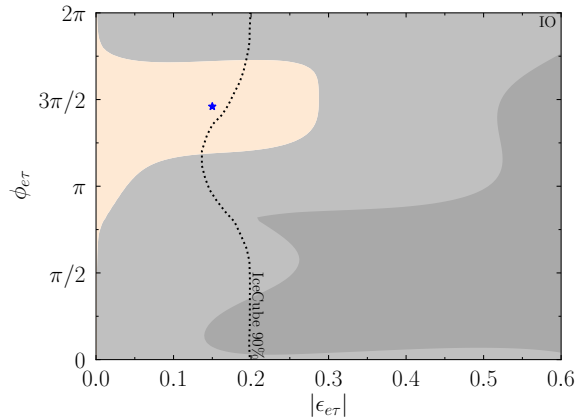
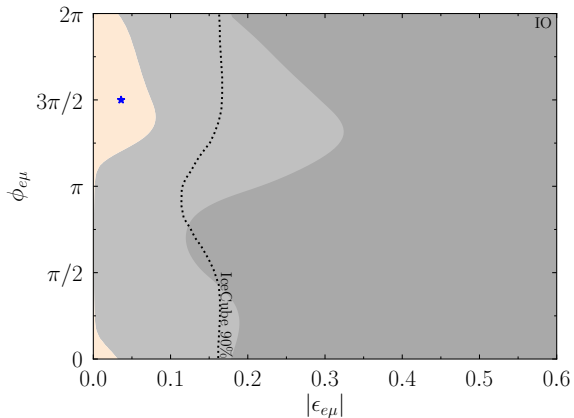
- ▶ If only $\sin \delta$ is measured $\Rightarrow$ sign degeneracy: $\cos \delta = \pm \sqrt{1 - \sin^2 \delta}$
- ▶ Most flavor models predict $\cos \delta$

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

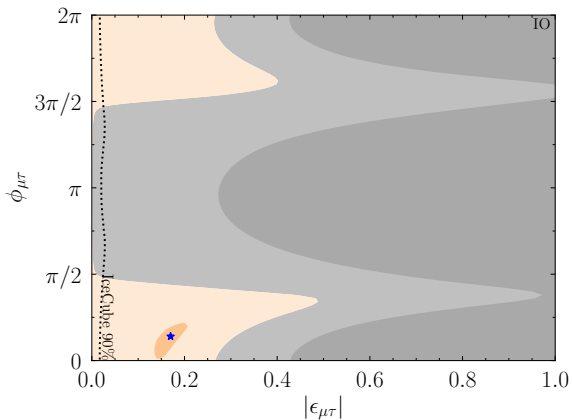
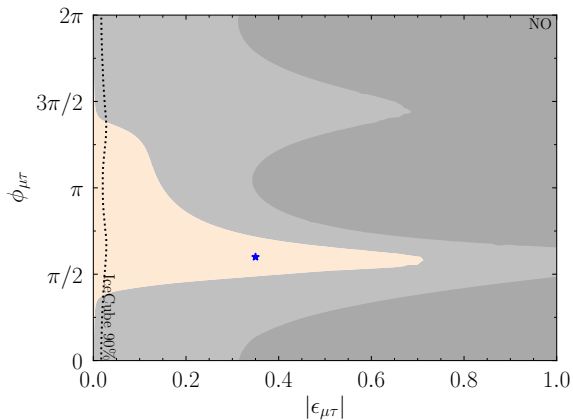


L. Everett, et al. [1912.10139](#)

NSI parameters: IO



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



Other CP violating NSI constraints

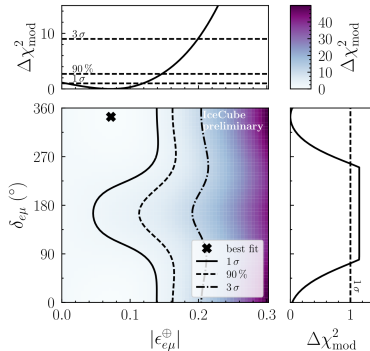
NSI effects grow with energy, density, and distance

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](#)

Unitarity violation: mass ranges for tau neutrinos

experiment	(4,4) (m_4)	(5,3) (m_4)
atmospheric ν_μ disappearance	$\in [10 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
atmospheric ν_τ appearance	$\in [10 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
astrophysical ν_τ appearance	$\lesssim 15 \text{ MeV}$	$\gtrsim 40 \text{ MeV}$
solar ^8B	$\lesssim 5 \text{ MeV}$	$\gtrsim 20 \text{ MeV}$
DONuT/FASERnu	$\in [100 \text{ eV}, 90 \text{ MeV}]$	$\gtrsim 200 \text{ MeV}$
LBL ν_τ appearance (OPERA)	$\in [1 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
LBL ν_τ appearance (DUNE)	$\in [0.1 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
LBL ν_μ disappearance (DUNE)	$\in [0.1 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$
CEvNS	$\in [10 \text{ eV}, 15 \text{ MeV}]$	$\gtrsim 40 \text{ MeV}$

PBD, J. Gehrlein [2109.14575](#)