Nu physics: Theory and practice

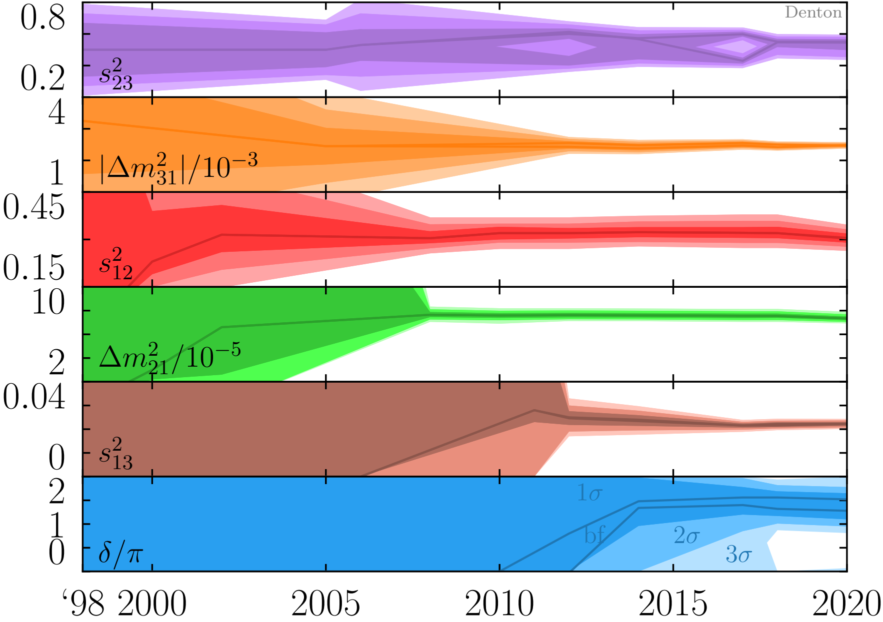
Peter B. Denton

Pheno

May 10, 2022

Brookhaven National Laboratory

Speaking from Osage land



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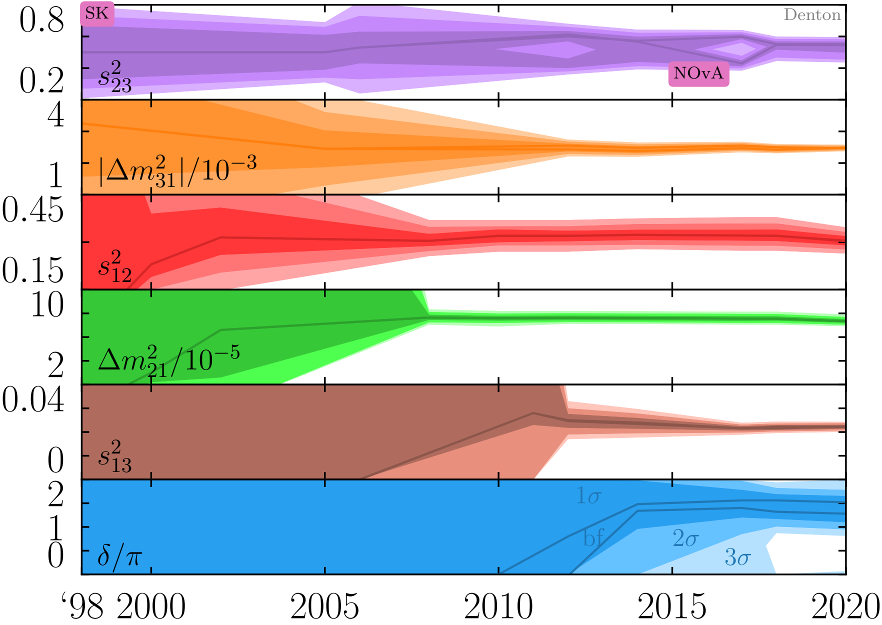
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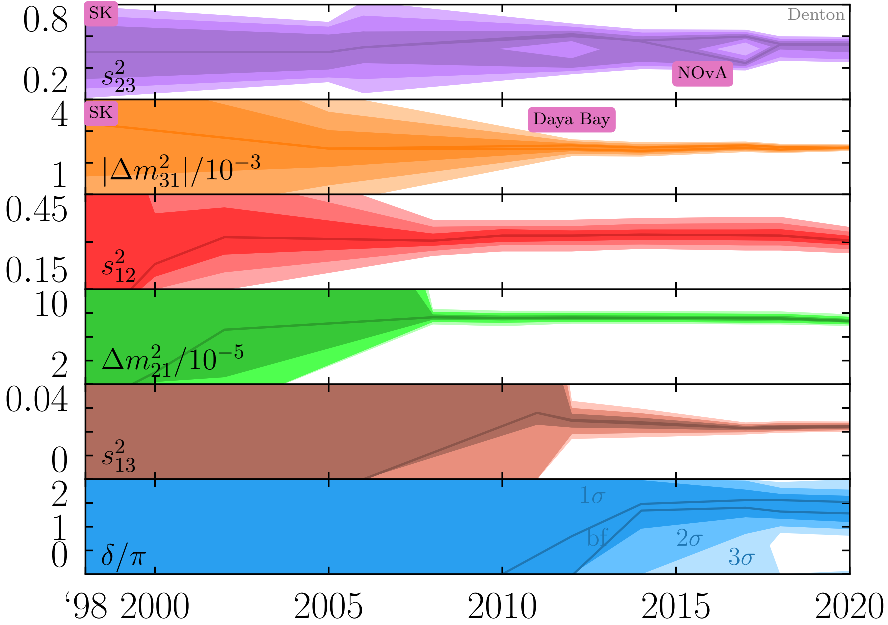

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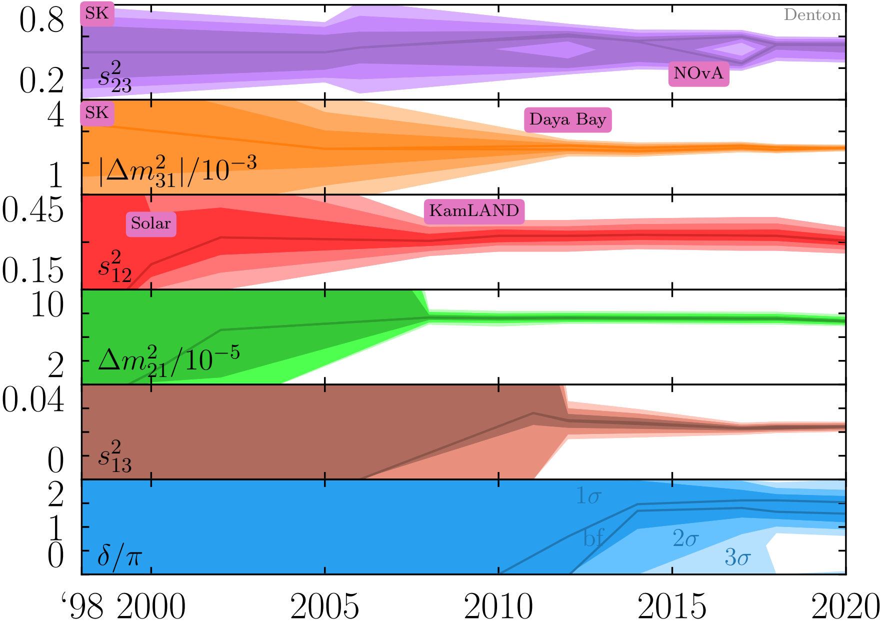

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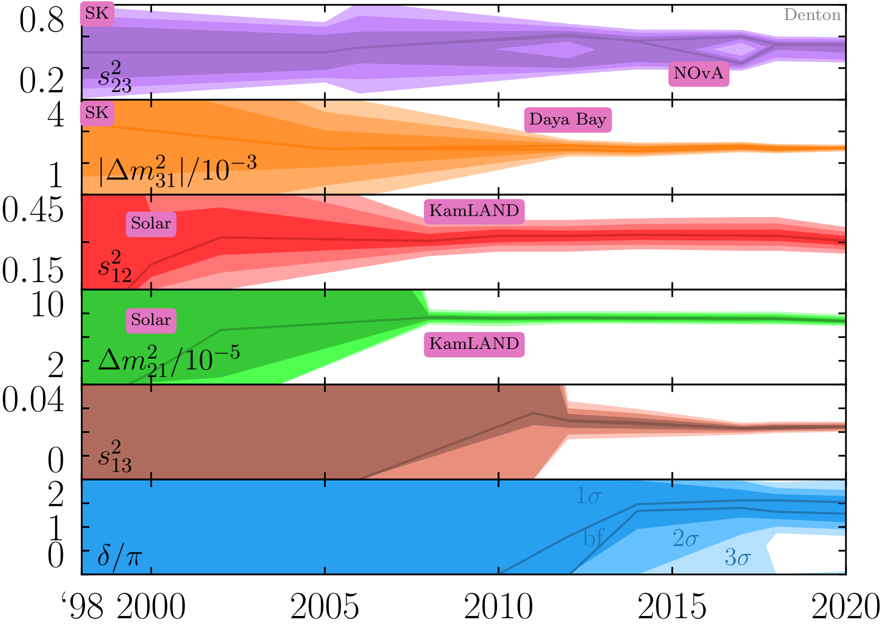
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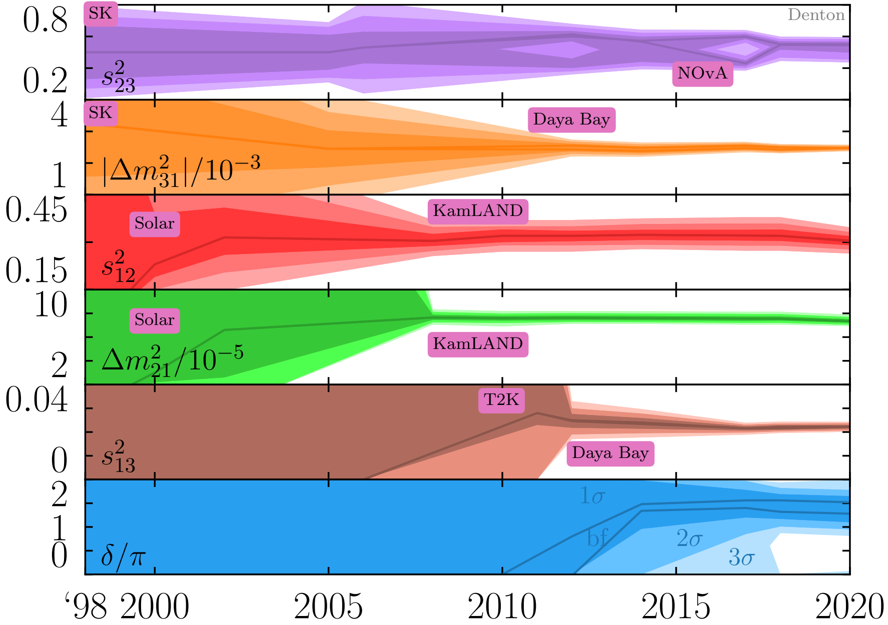

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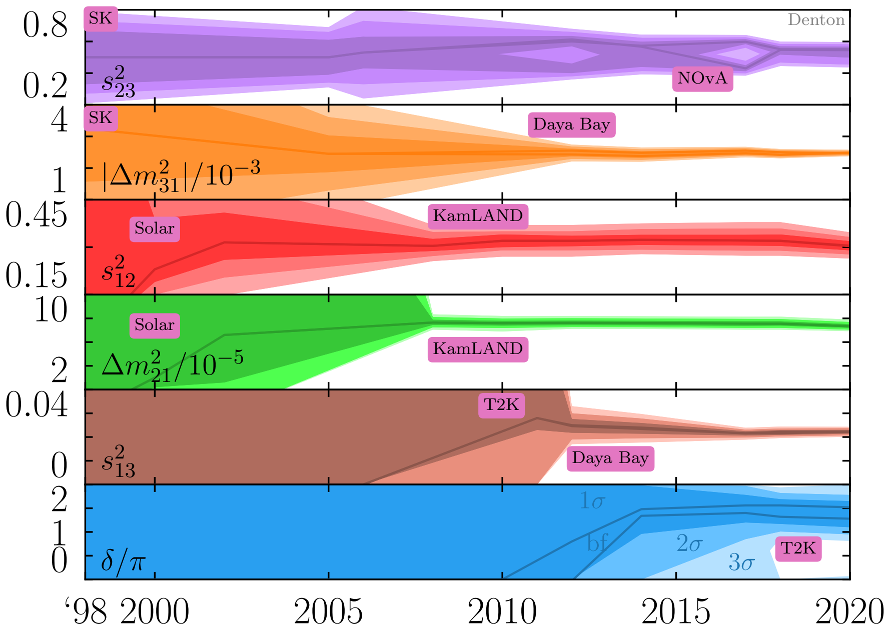
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Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Four known unknown in particle physics: all neutrinos

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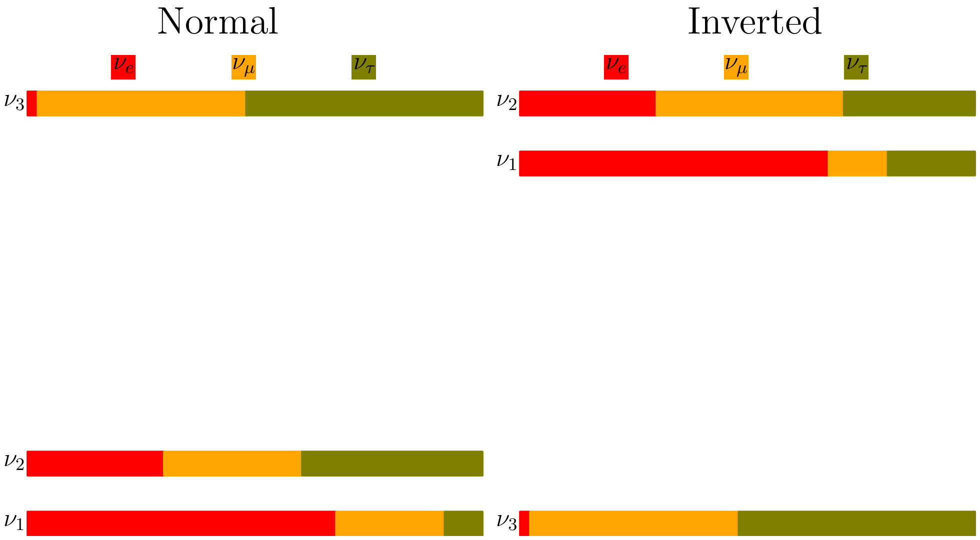
Complex phase

Absolute mass scale

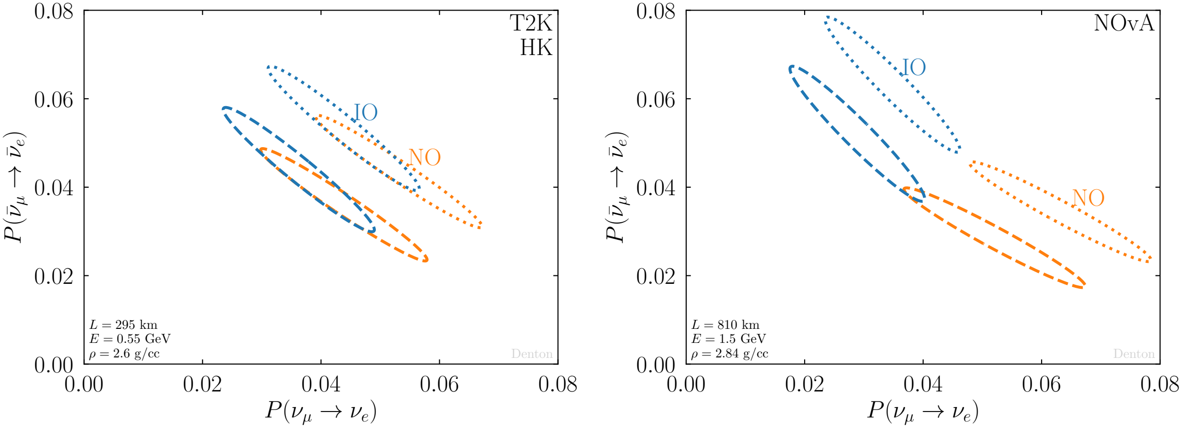
Cosmology, scattering, $0\nu\beta\beta$, ...

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

$\to$ 20 meV precision with DESI, EUCLID, ...

From oscillations:

$$\text{Normal}: \quad m_1 + m_2 + m_3 > 60 \text{ meV} \qquad \text{Inverted}: \quad m_1 + m_2 + m_3 > 100 \text{ meV}$$

See also KATRIN 2105.08533

Mass ordering current status: all

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E. Valentino, S. Gariazzo, O. Mena 2106.15267

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See also KATRIN 2105.08533

PRIORS?

Some claim "decisive" Bayesian evidence for normal

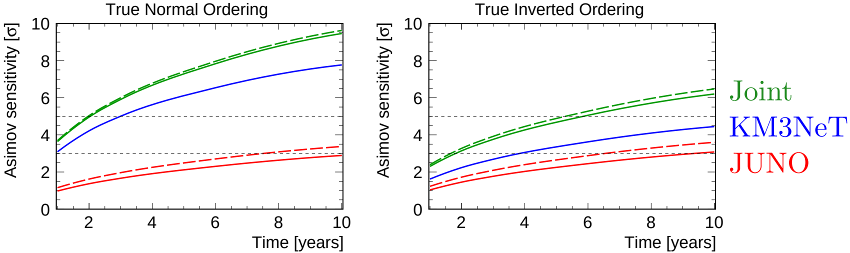
R. Jimenez, et al 2203.14247

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

S. Gariazzo, et al 1801.04946

S. Gariazzo, et al 2205.02195

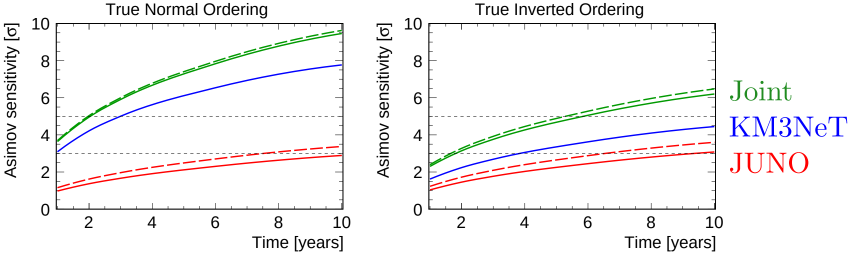
Mass ordering: future sensitivities



JUNO, KM3NeT 2108.06293

Note: if lower octant, KM3NeT is less sensitive

Mass ordering: future sensitivities



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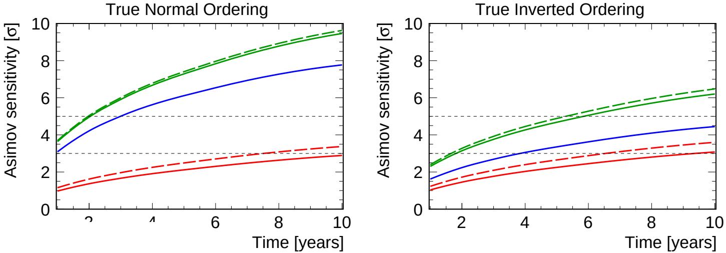
Note: if lower octant, KM3NeT is less sensitive

$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$
$$\Delta m^2_{\mu\mu} = s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + \mathcal{O}(s_{13}\Delta m^2_{21})$$

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

H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283

Mass ordering: future sensitivities



JUNO, KM3NeT 2108.06293

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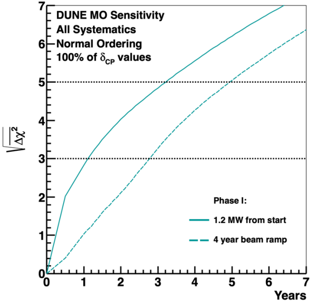

Matter effect ⇒ DUNE 2203.06100

$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$
$$\Delta m^2_{\mu\mu} = s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + \mathcal{O}(s_{13}\Delta m^2_{21})$$

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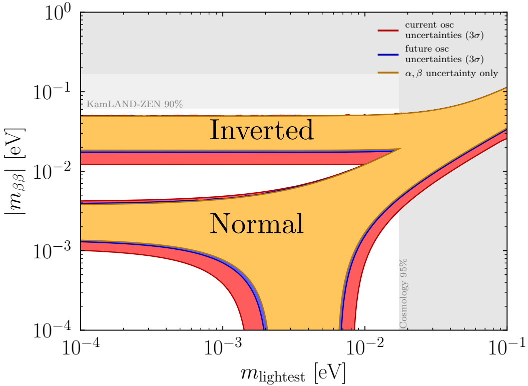
Mass ordering: broad implications

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



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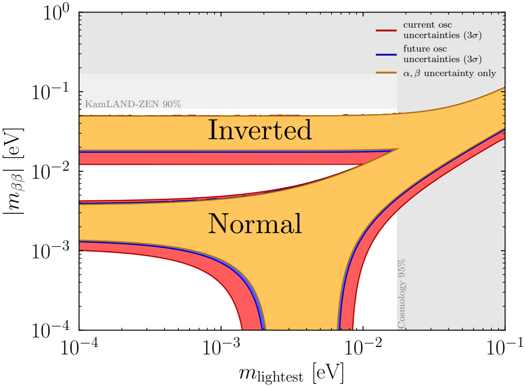
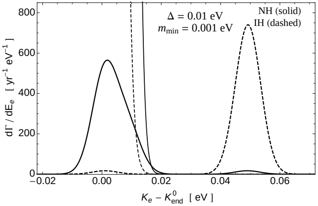
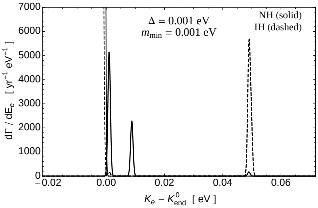


A. Long, C. Lunardini, E. Sabancilar 1405.7654





Mass ordering: new physics degeneracies

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

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

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

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

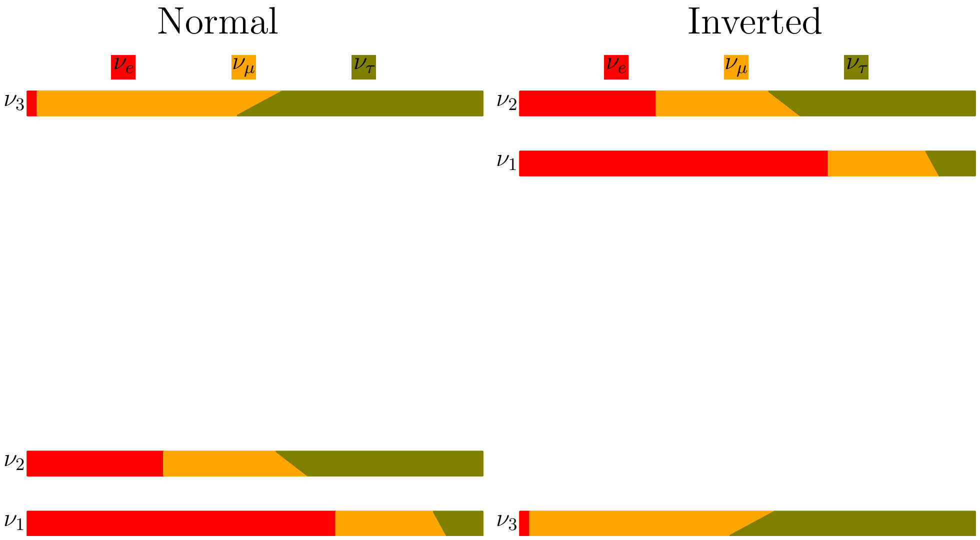
Dresden-II for any mediator mass

PBD, J. Gehrlein 2204.09060

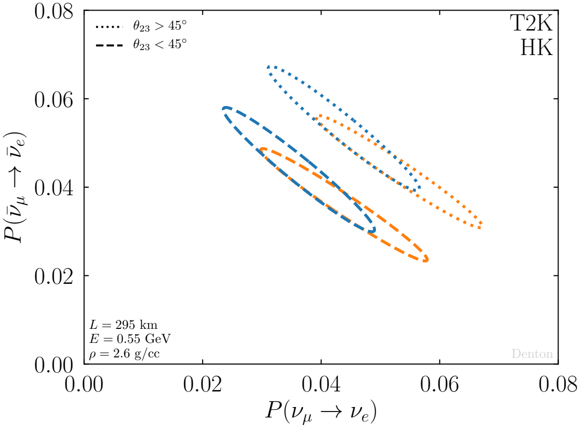
Can still evade with $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$ or certain u / d combinations

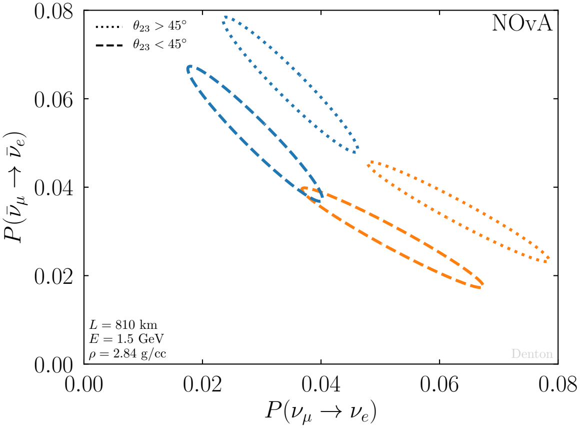
θ_{23} octant

θ_{23} octant: what is it?

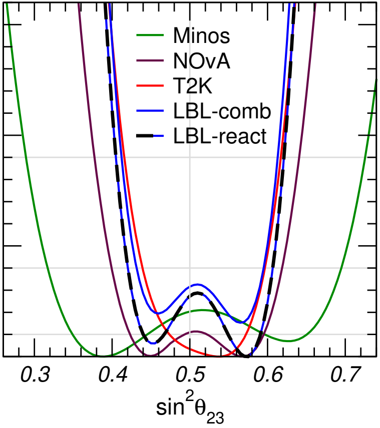


θ_{23} octant: what is it really?

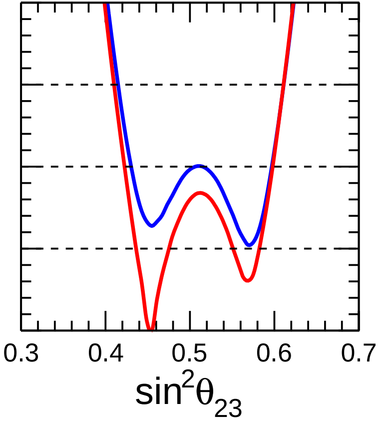




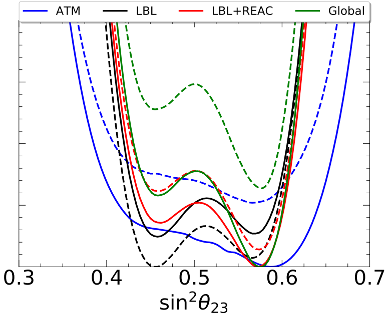
θ_{23} octant: current status



I. Esteban, et al 2007.14792

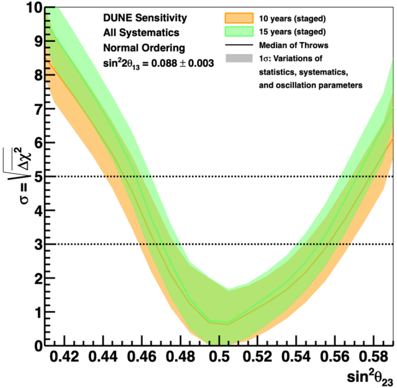


F. Capozzi, et al 2107.00532

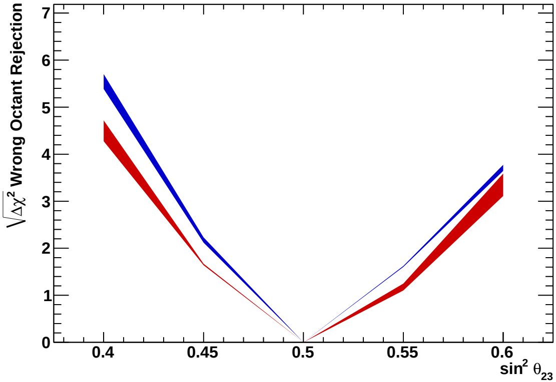


P. de Salas, et al 2006.11237

θ_{23} octant: future sensitivities



DUNE 2002.03005

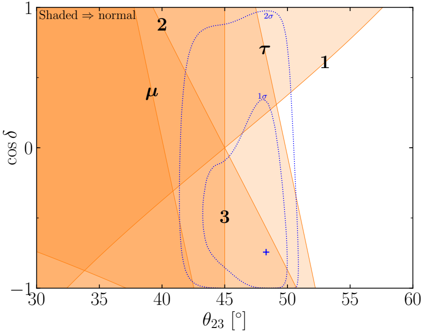


HK 1805.04163

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

See Marina Artuso's talk

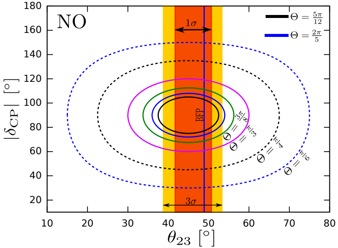
μ-τ interchange/reflection symmetry

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

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

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

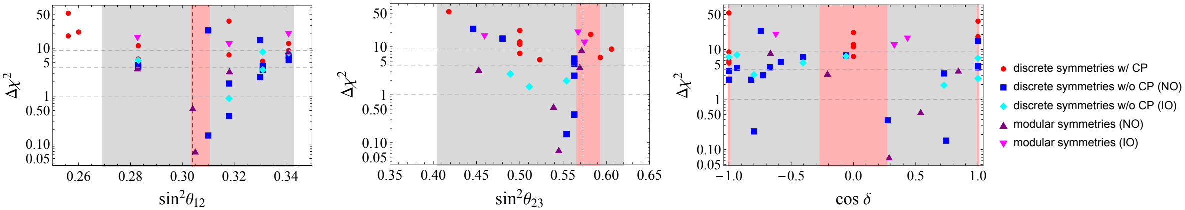
Predicts: $\theta_{23} = 45^\circ$, often $\theta_{13} = 0$



P. Chen, et al 1512.01551

Parameter interplay

Models predict specific correlations among the parameters



Complex phase

δ and CP violation

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

C. Jarlskog PRL 55, 1039 (1985)

δ and CP violation

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

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

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

CKMfitter 1501.05013

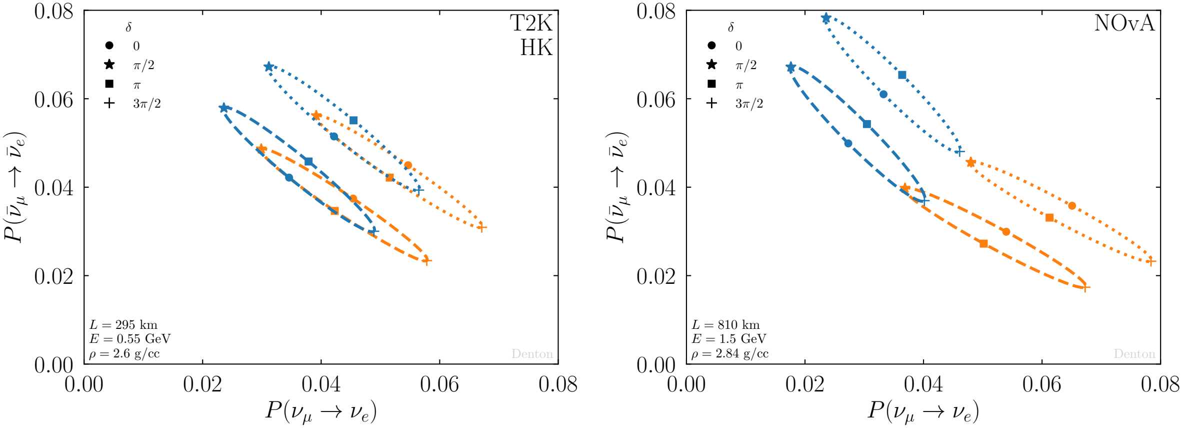
3. Lepton mass matrix: **?**

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

PBD, J. Gehrlein, R. Pestes 2008.01110

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

δ: what is it really?



δ: what is it not?

$$\delta \not\Rightarrow \text{Baryogenesis}$$

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

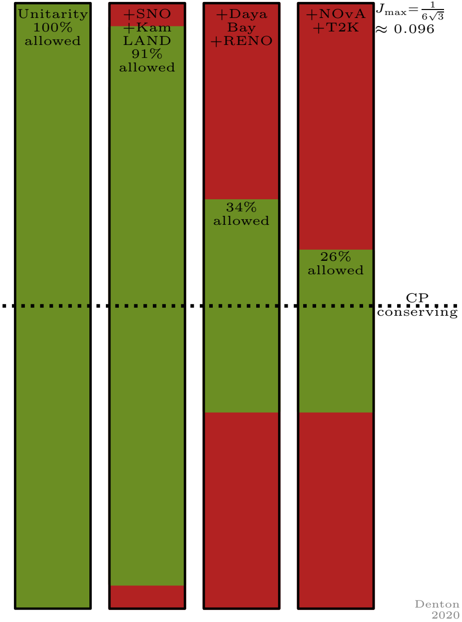
K. Moffat, et al 1809.08251

$$\boxed{\begin{array}{lcl} \text{Measuring } \delta = 0, \pi & \not\Rightarrow & \text{no Baryogenesis} \\ \text{Measuring } \delta \neq 0, \pi & \not\Rightarrow & \text{Baryogenesis} \end{array}}$$

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

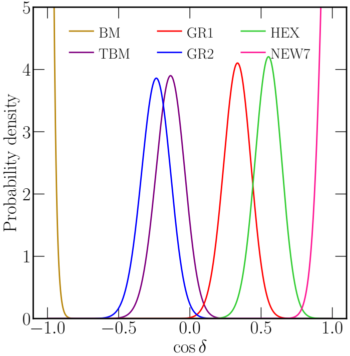
e.g. $P(\nu_\mu \to \nu_\mu)$ depends on $\cos\delta$ a tiny bit

- 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 $\cos\delta$

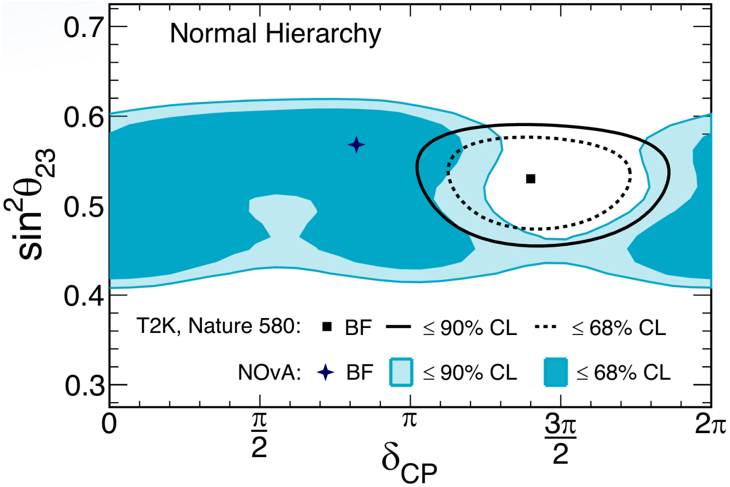
J. Gehrlein, et al 2203.06219



L. Everett, et al 1912.10139

δ: new physics hints?

Excitement at Neutrino2020!



A. Himmel for NOvA 10.5281/zenodo.3959581

Estimate size of new physics

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

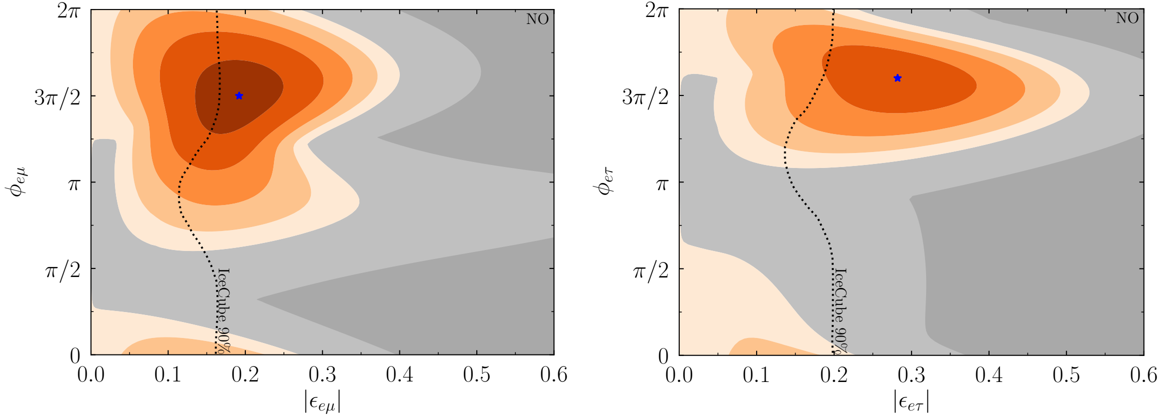
$w_\beta = s_{23},\ c_{23}$ for $\beta=\mu,\tau$

Assumed upper octant $\theta_{23} > 45°$

Consistency checks:

- $\sin\delta_{\rm NOvA} = \sin\delta_{\rm T2K} \Rightarrow |\epsilon| = 0$
- $\sin\delta_{\rm NOvA} \neq \sin\delta_{\rm T2K}$ and $a_{\rm NOvA} = a_{\rm T2K} \Rightarrow |\epsilon| \to \infty$
- 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

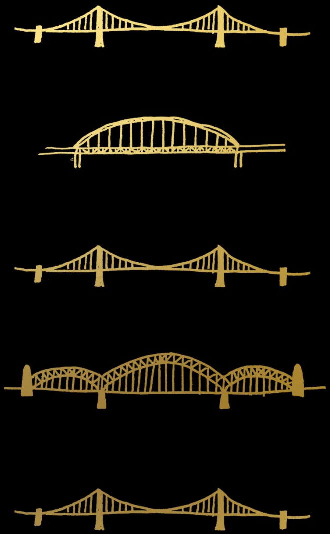
Neutrino oscillation summary

- Four known unknowns in particle physics: all neutrinos
- Mass ordering will be measured

Robustness?

- θ_{23} octant is important for flavor models
- δ could shed light on CP violation
- Hints for new physics are testable

Precision is coming to neutrinos!

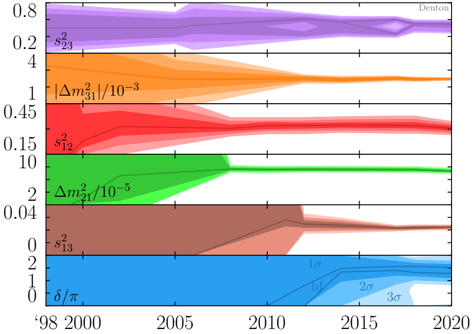


THE CITY OF BRIDGES
PITTSBURGH, PENNA.

Peter B. Denton

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

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

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

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

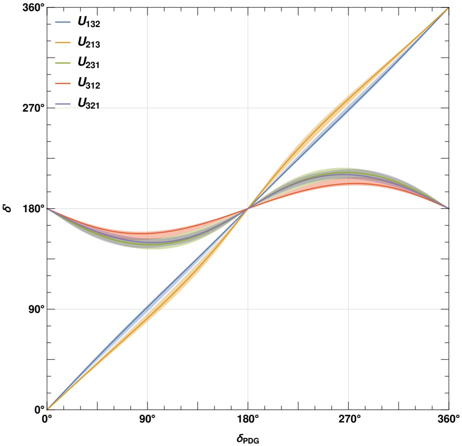
Matter potential $a \propto G_F\rho E$

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 $\sim [150°, 210°]$ in U_{231}, U_{312}, U_{321}
- Bands indicate 3σ uncertainty on θ_{12}, θ_{13}, θ_{23}
- "50% of possible values of δ"
  $\Rightarrow$ parameterization dependent

DUNE TDR II 2002.03005



Repeated rotations in backups

Quark mixing

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

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

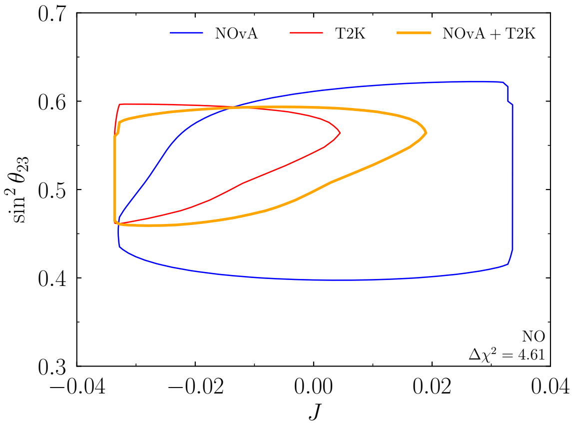
Looks like "large" CPV:

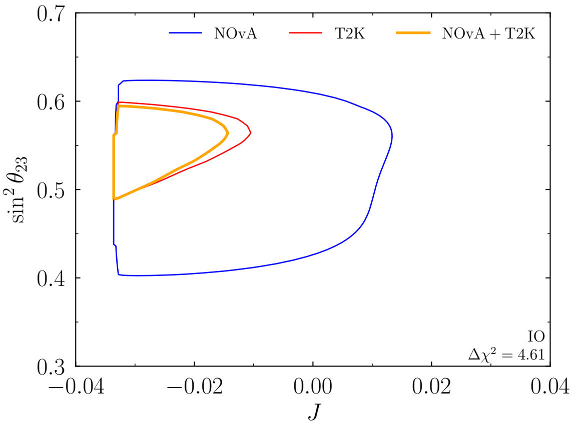
$$\sin\delta_{\rm PDG} = 0.93 \sim 1$$

yet $J_{\rm CKM}/J_{\rm max} = 3\times10^{-4}$.

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:

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

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

C. Jarlskog PRL 55, 1039 (1985)

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

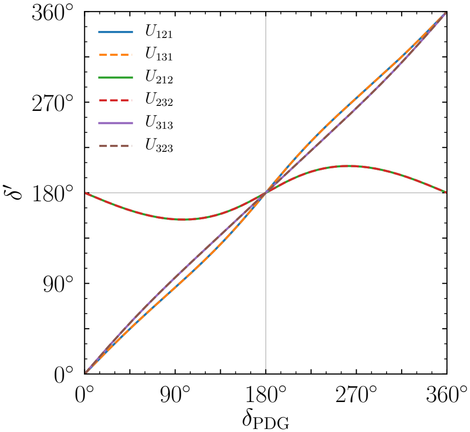
Matter effects are easily accounted for

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

PBD, S. Parke 1902.07185

PBD, H. Minakata, S. Parke 1604.08167

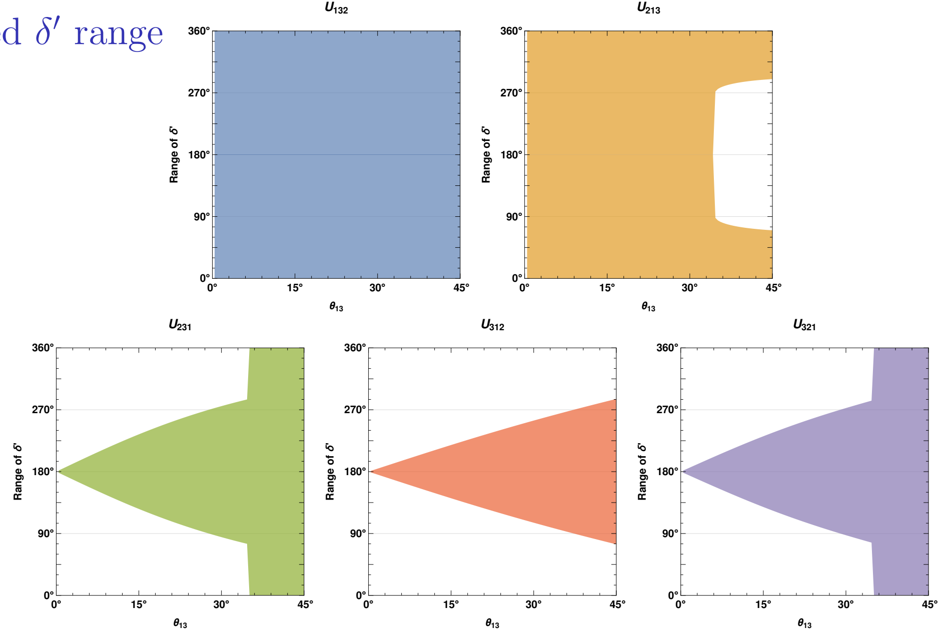
Repeated rotations



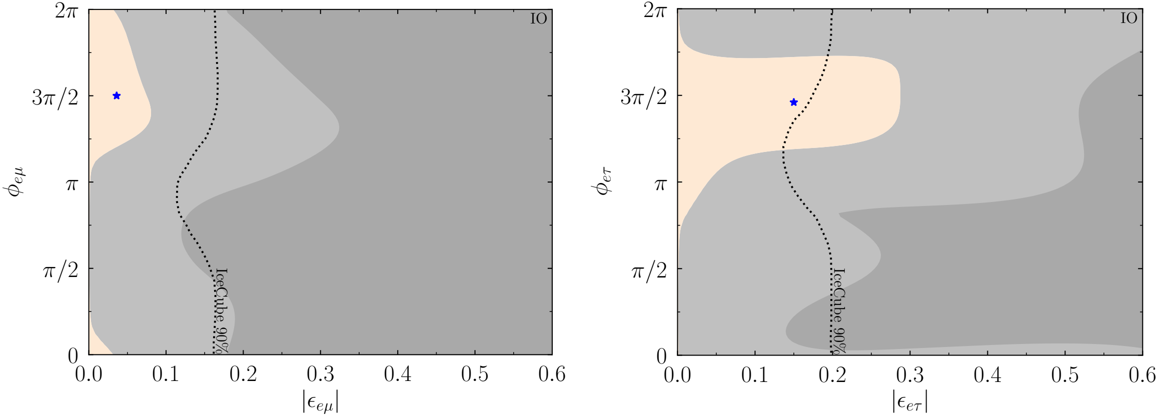
	U_{121}	U_{131}	U_{212}	U_{232}	U_{313}	U_{323}
$\lvert U_{e2}\rvert$	✓	✓	✓	✓	✗	✗
$\lvert U_{e3}\rvert$	✓	✓	✗	✗	✓	✓
$\lvert U_{\mu3}\rvert$	✗	✗	✓	✓	✓	✓

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

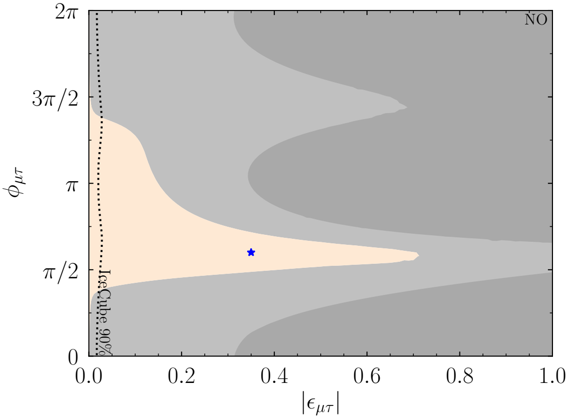
Allowed δ' range

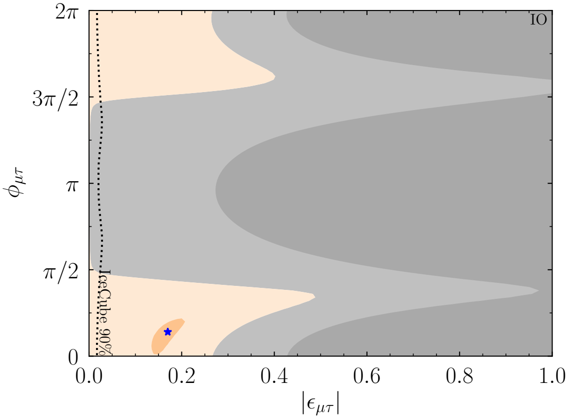


NSI parameters: IO



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





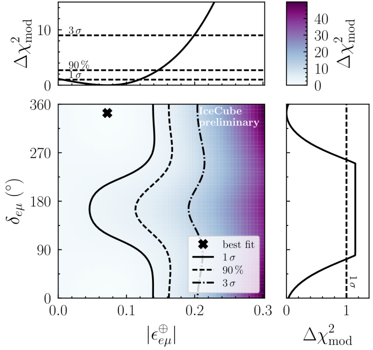
Other CP violating NSI constraints

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 $\sim 1\sigma$



T. Ehrhardt, IceCube PPNT (2019)

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

Super-K 1109.1889

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

COHERENT 1708.01294
PBD, Y. Farzan, I. Shoemaker 1804.03660
PBD, J. Gehrlein 2008.06062