Flavor mixing, CP violation, and Unitarity

Peter B. Denton

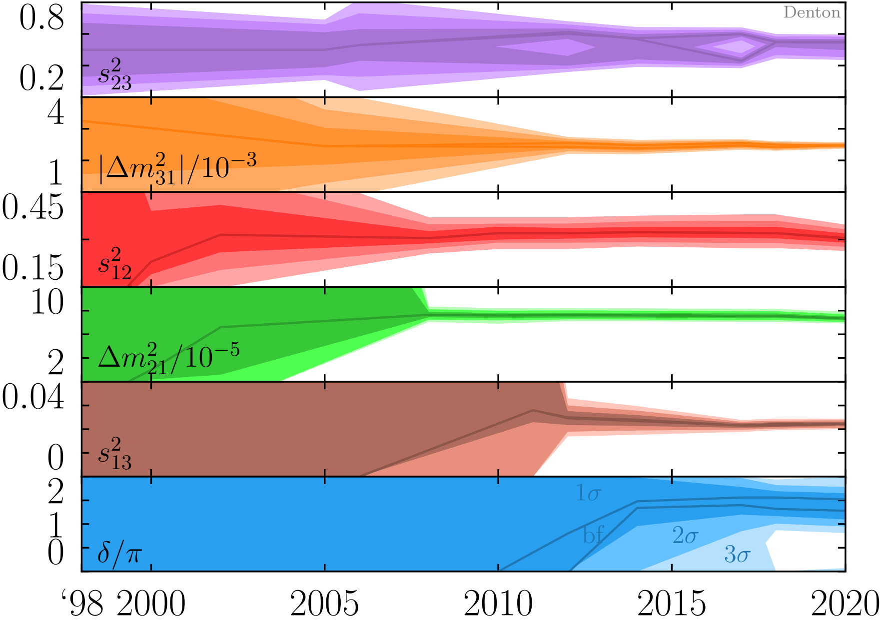
Neutrino 2022

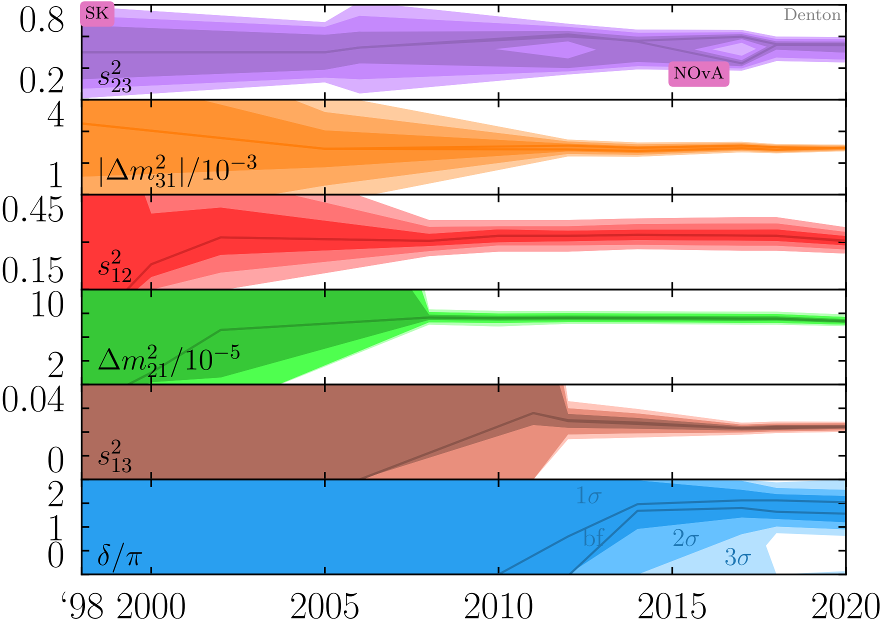
June 1/2, 2022

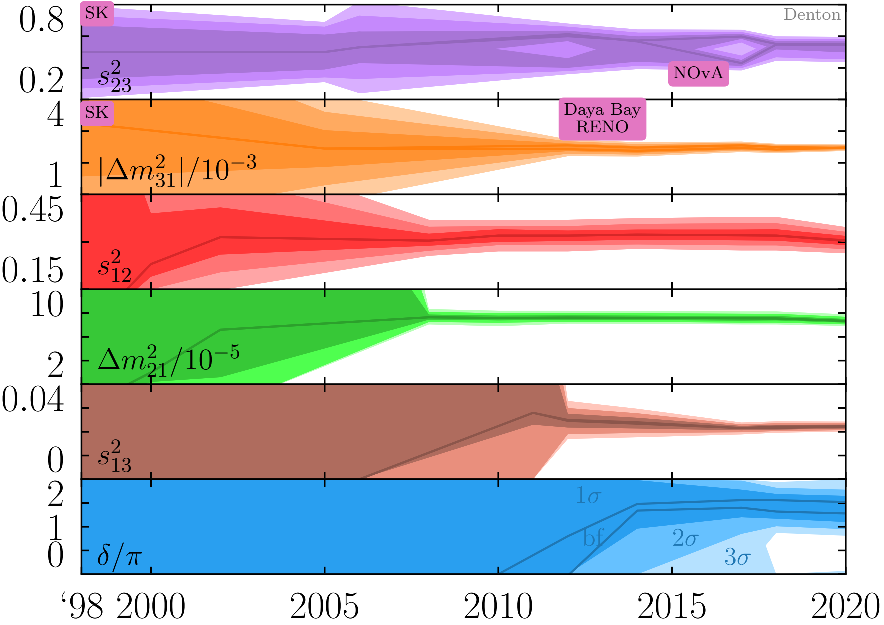
Brookhaven™
National Laboratory

Brookhaven
NDI
Neutrino Discovery Initiative

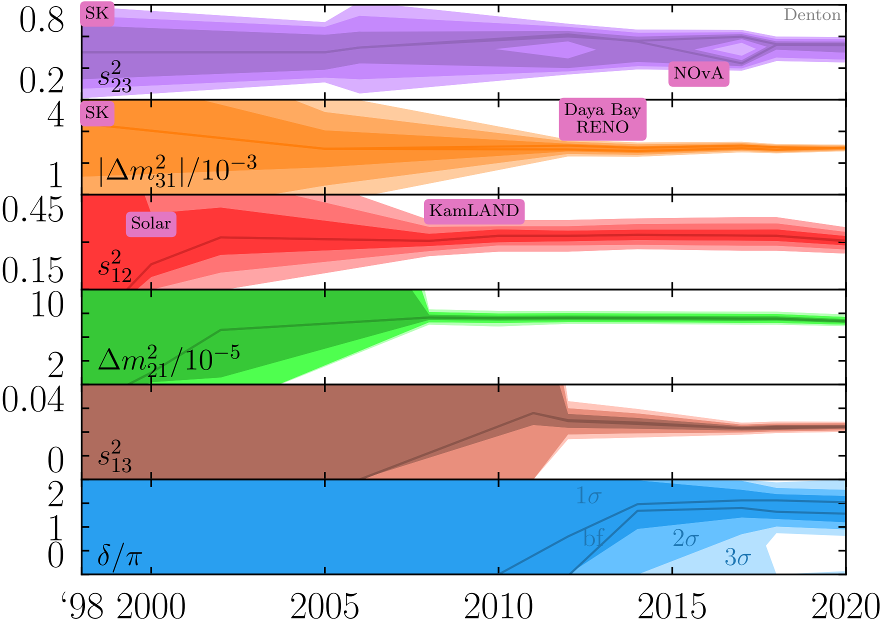
Speaking from Setauket land

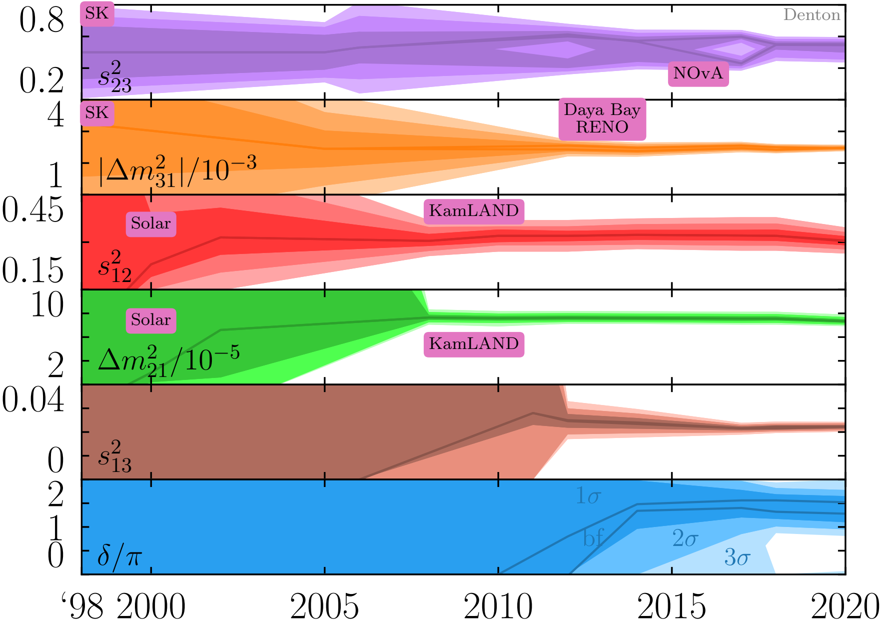

Denton
0.8
0.2
s_{23}^2
4
1
$|\Delta m_{31}^2|/10^{-3}$
0.45
0.15
s_{12}^2
10
2
$\Delta m_{21}^2/10^{-5}$
0.04
0
s_{13}^2
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020

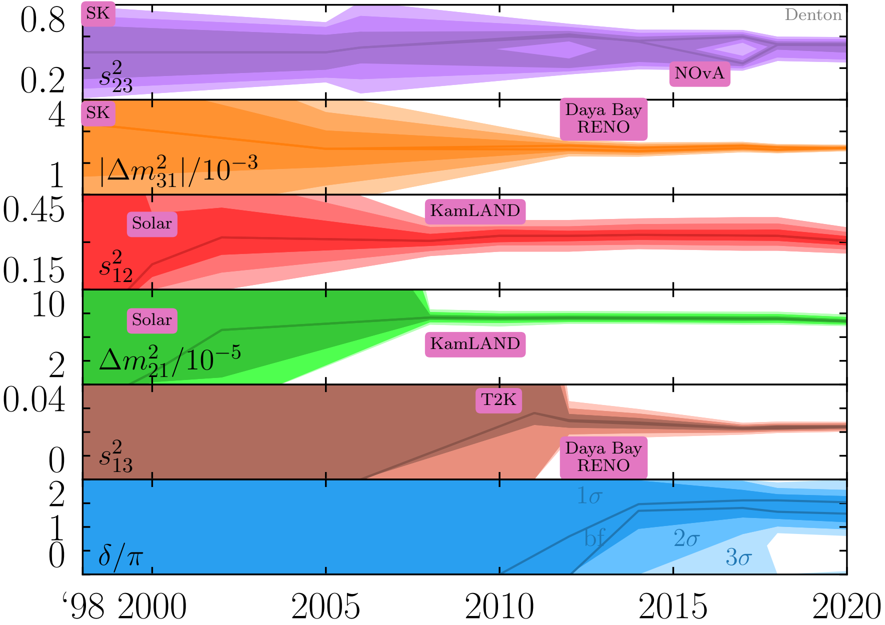

SK
Denton
0.8
0.2
s^2_{23}
NOvA
4
1
$|\Delta m^2_{31}|/10^{-3}$
0.45
0.15
s^2_{12}
10
2
$\Delta m^2_{21}/10^{-5}$
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020

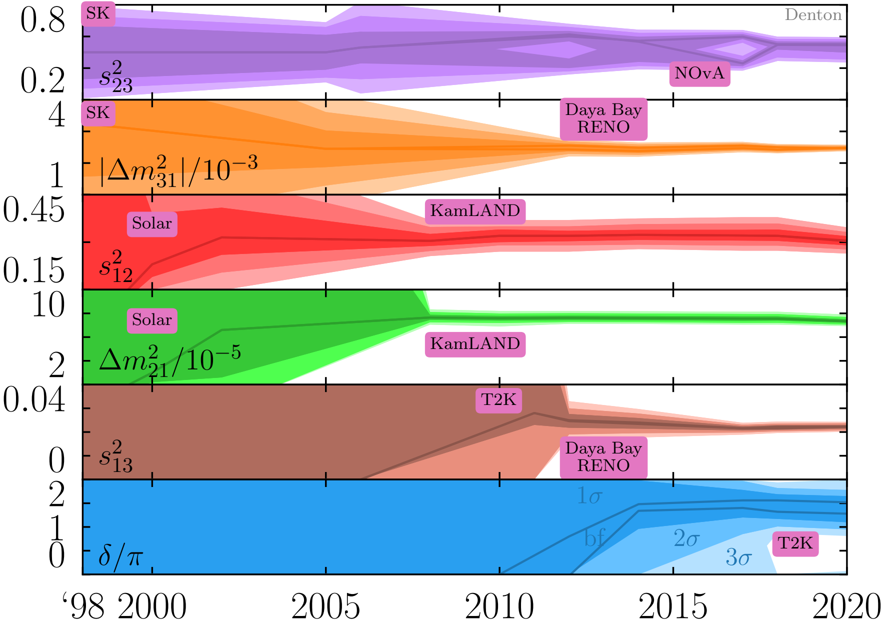


SK
Denton
0.8
0.2
s_{23}^2
NOvA
SK
Daya Bay
RENO
4
1
$|\Delta m_{31}^2|/10^{-3}$
0.45
0.15
s_{12}^2
10
2
$\Delta m_{21}^2/10^{-5}$
0.04
0
s_{13}^2
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020


Denton
SK
NOvA
s^2_{23}
0.8
0.2
SK
Daya Bay
RENO
$|\Delta m^2_{31}|/10^{-3}$
4
1
Solar
KamLAND
s^2_{12}
0.45
0.15
$\Delta m^2_{21}/10^{-5}$
10
2
s^2_{13}
0.04
0
δ/π
2
1
0
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020


0.8
0.2
s^2_{23}
SK
NOvA
Denton
4
1
$|\Delta m^2_{31}|/10^{-3}$
SK
Daya Bay
RENO
0.45
0.15
s^2_{12}
Solar
KamLAND
10
2
$\Delta m^2_{21}/10^{-5}$
Solar
KamLAND
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020


Denton
SK
NOvA
s^2_{23}
0.8
0.2
SK
Daya Bay RENO
$|\Delta m^2_{31}|/10^{-3}$
4
1
Solar
KamLAND
s^2_{12}
0.45
0.15
Solar
KamLAND
$\Delta m^2_{21}/10^{-5}$
10
2
T2K
Daya Bay RENO
s^2_{13}
0.04
0
δ/π
2
1
0
1σ
bf
2σ
3σ
'98 2000
2005
2010
2015
2020



0.8
0.2
s_{23}^2
SK
NOvA
Denton
4
1
$|\Delta m_{31}^2|/10^{-3}$
SK
Daya Bay RENO
0.45
0.15
s_{12}^2
Solar
KamLAND
10
2
$\Delta m_{21}^2/10^{-5}$
Solar
KamLAND
0.04
0
s_{13}^2
T2K
Daya Bay RENO
2
1
0
δ/π
1σ
bf
2σ
3σ
T2K
'98
2000
2005
2010
2015
2020

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

Atmospheric mass ordering

θ_{23} octant

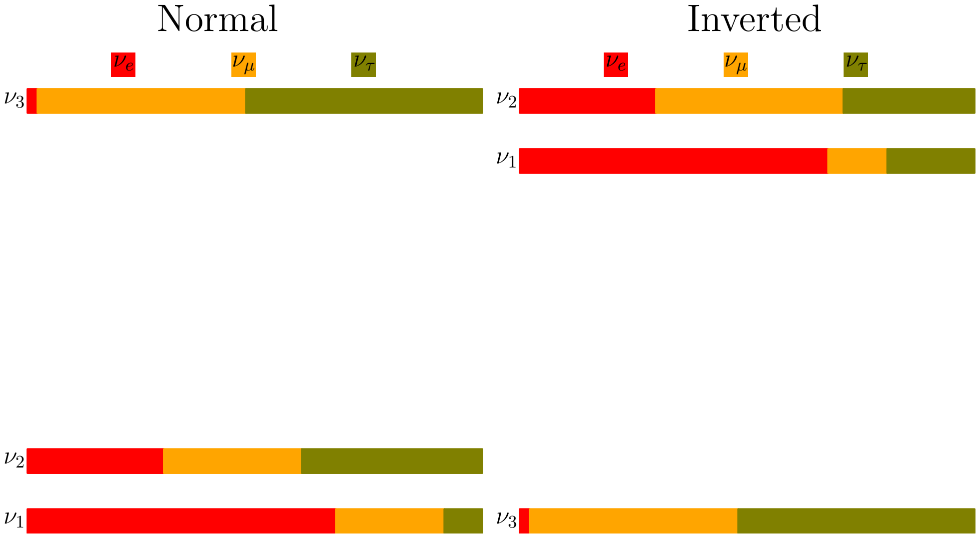
Complex phase

Absolute mass scale

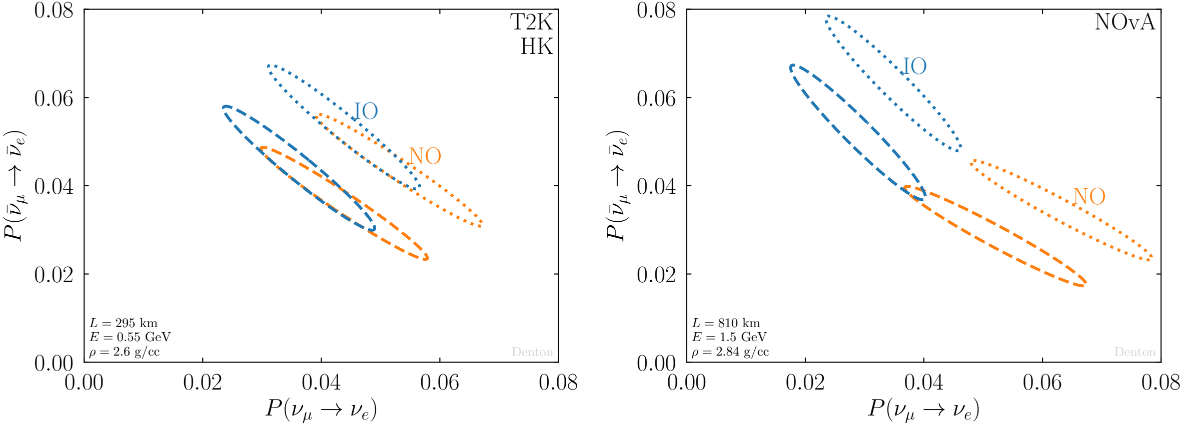
Cosmology, scattering, $0\nu\beta\beta$, . . .

Atmospheric mass ordering

Mass ordering: what is it?



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 ⇒ 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:

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

See also KATRIN `2105.08533`

Mass ordering current status: all

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:

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

See also KATRIN 2105.08533

PRIORS?

Some claim "decisive" Bayesian evidence for normal

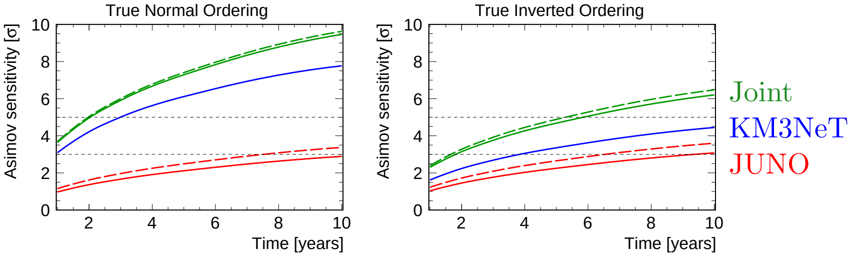
R. Jimenez, et al. 2203.14247

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

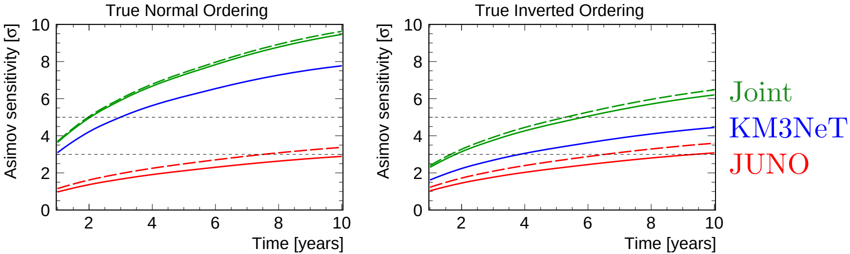


JUNO, KM3NeT `2108.06293`

JUNO, IceCube `1911.06745`

Note: if lower octant, KM3NeT is less sensitive

Mass ordering: future sensitivities



JUNO, KM3NeT 2108.06293

JUNO, IceCube 1911.06745

Note: if lower octant, KM3NeT is less sensitive

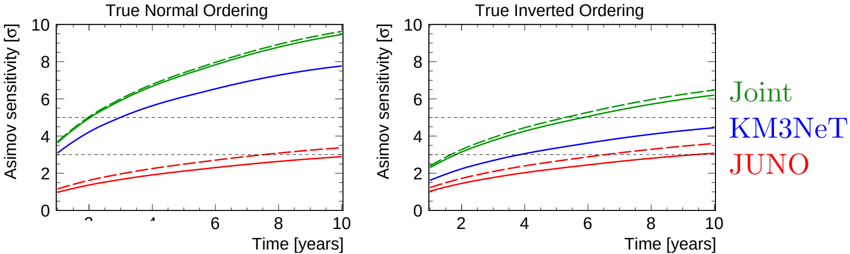
$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$

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

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

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

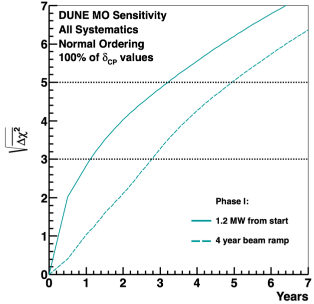
Mass ordering: future sensitivities



JUNO, KM3NeT 2108.06293

JUNO, IceCube 1911.06745

Note: if lower octant, KM3NeT is less sensitive



Matter effect ⇒ DUNE 2203.06100

$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$

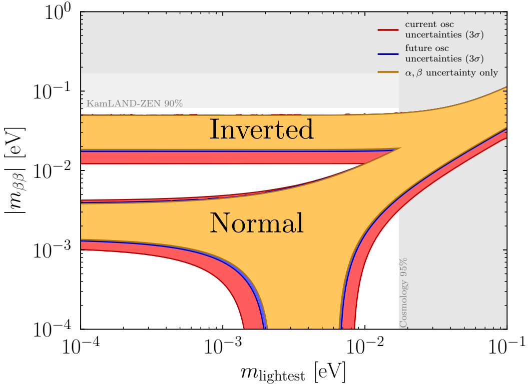
$$\Delta m^2_{\mu\mu} = s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + \mathcal{O}(s_{13}\Delta m^2_{21})$$

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

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

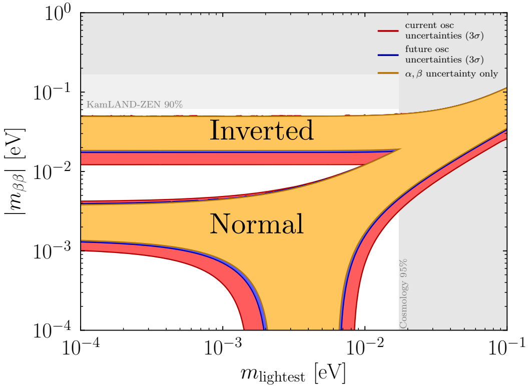
Mass ordering: broad implications

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

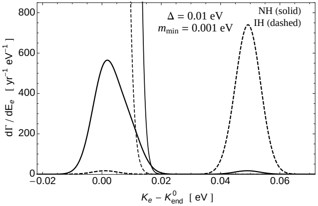


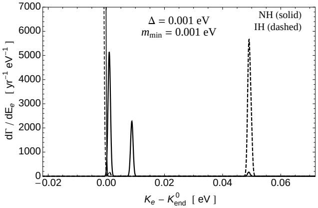
Mass ordering: broad implications

- Affects cosmology
- 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[1] 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

---

[1] See 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`

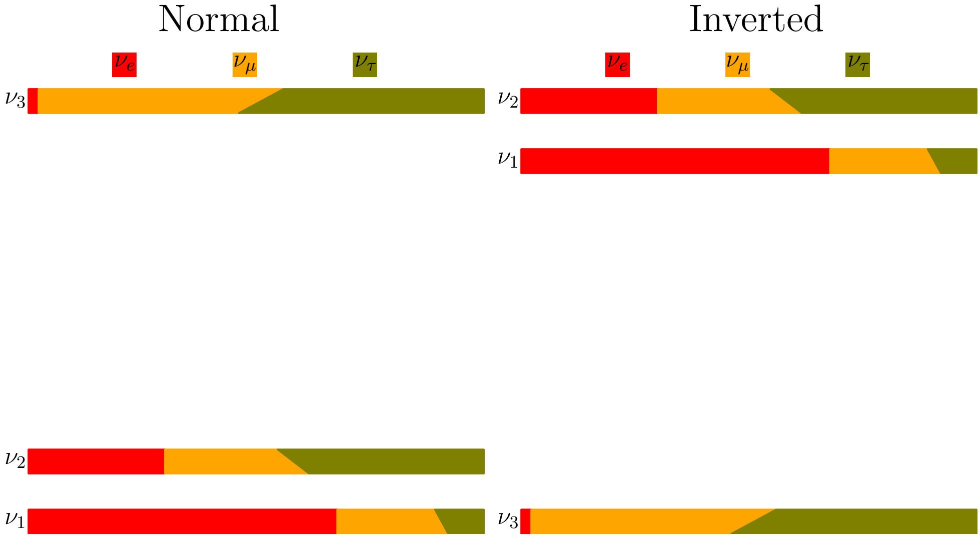
Dresden-II for any mediator mass

PBD, J. Gehrlein `2204.09060`

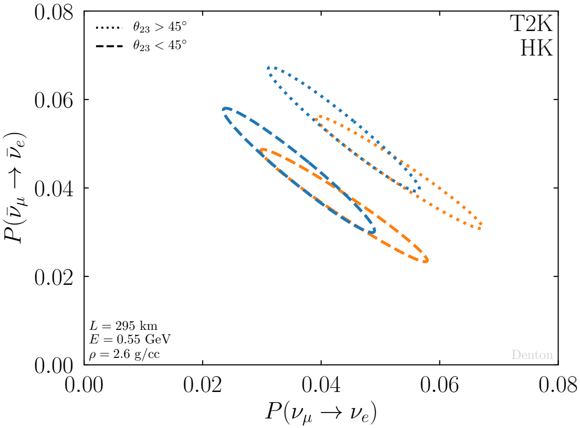
Can still evade with $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$ or certain u / d combinations

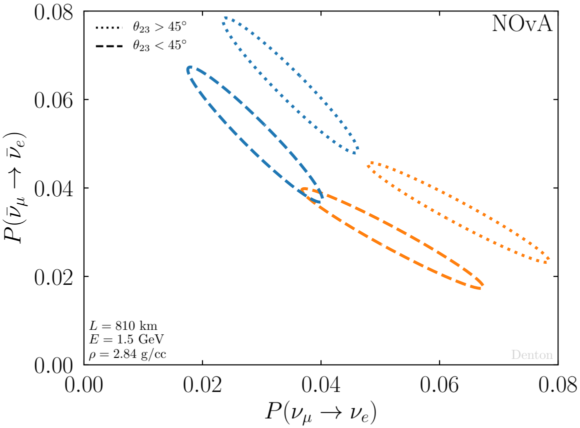
θ_{23} octant

θ_{23} octant: what is it?



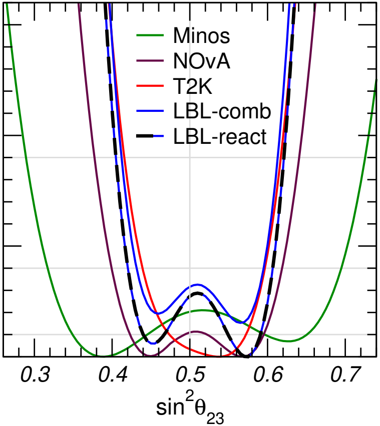
θ_{23} octant: what is it really?



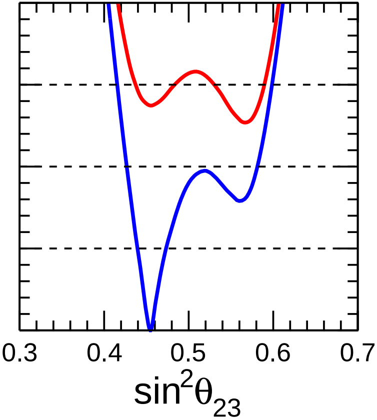


Lower octant more “normal” than upper octant

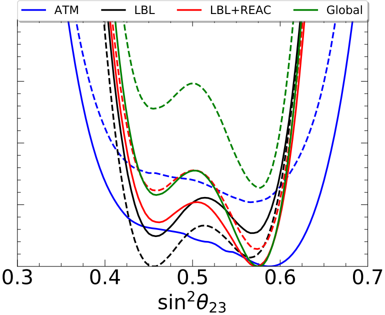
θ_{23} octant: current status



I. Esteban, et al. 2007.14792



F. Capozzi, et al. 2107.00532



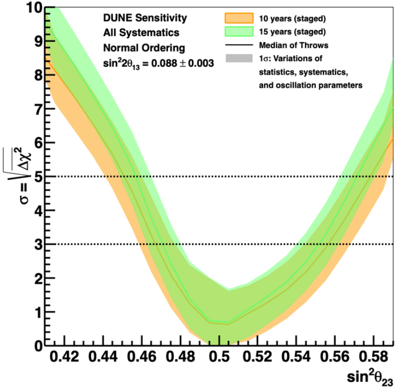
P. de Salas, et al. 2006.11237

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

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

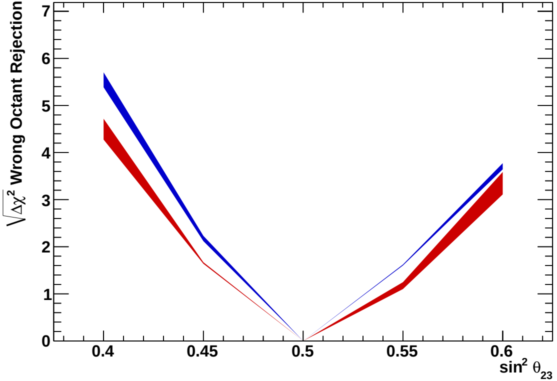
Prefers **upper** at $> 2\sigma$

θ_{23} octant: future sensitivities



$\sim 3-5\sigma$

DUNE 2002.03005



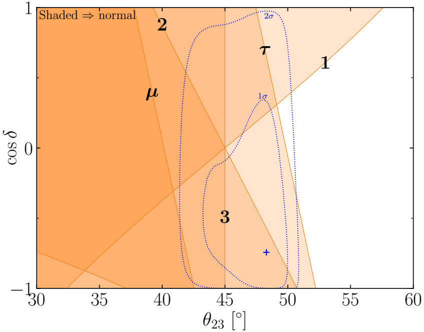
Beam+Atm$\Rightarrow\sim 3-6\sigma$

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

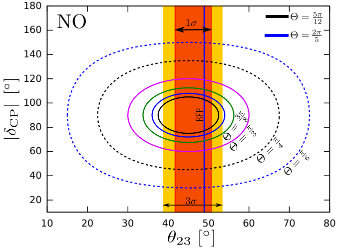
μ-τ interchange/reflection symmetry

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

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

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

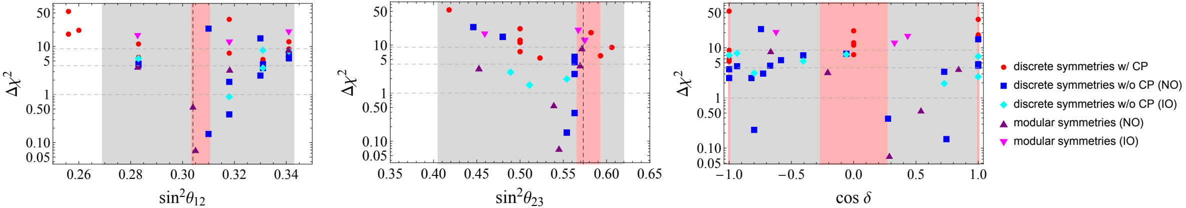
Predicts: $\theta_{23} = 45°$, often $\theta_{13} = 0$



P. Chen, et al. 1512.01551

Parameter interplay

Models predict specific correlations among the parameters



J. Gehrlein, et al. 2203.06219 (Snowmass)

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

$$\frac{|J_{\rm CKM}|}{J_{\rm max}}=3\times10^{-4}$$

CKMfitter `1501.05013`

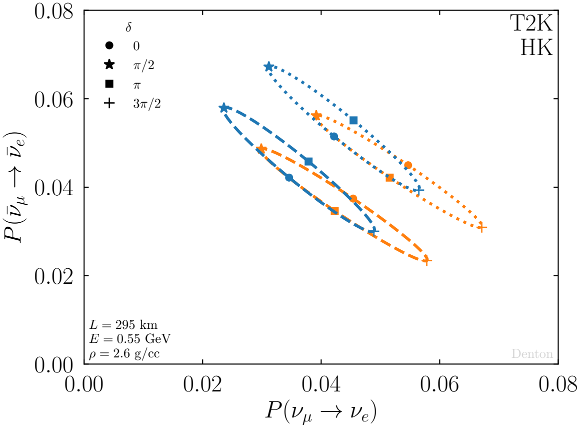
3. Lepton mass matrix: **?**

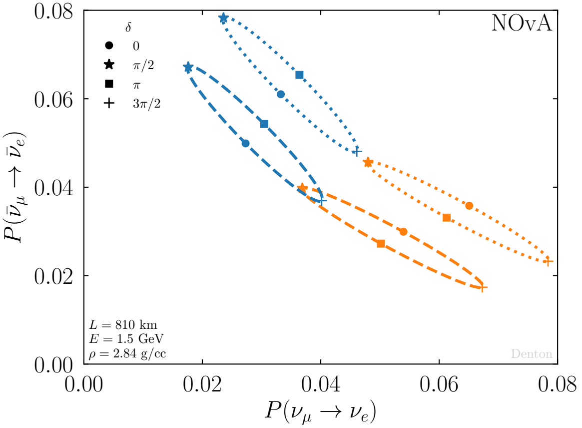
$$\frac{|J_{\rm PMNS}|}{J_{\rm max}}<0.34$$

PBD, J. Gehrlein, R. Pestes `2008.01110`

$J_{\rm max}=\frac{1}{6\sqrt3}\approx0.096$

δ: what is it really?





δ: what is it not?

$\delta \nRightarrow$ 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

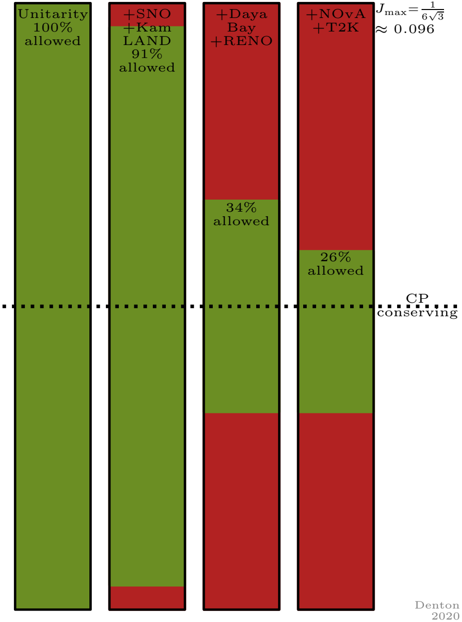
K. Moffat, et al. 1809.08251

Measuring $\delta = 0, \pi \quad \nRightarrow \quad$ no leptogenesis
Measuring $\delta \neq 0, \pi \quad \nRightarrow \quad$ 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. $P(\nu_\mu \to \nu_\mu)$ 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?

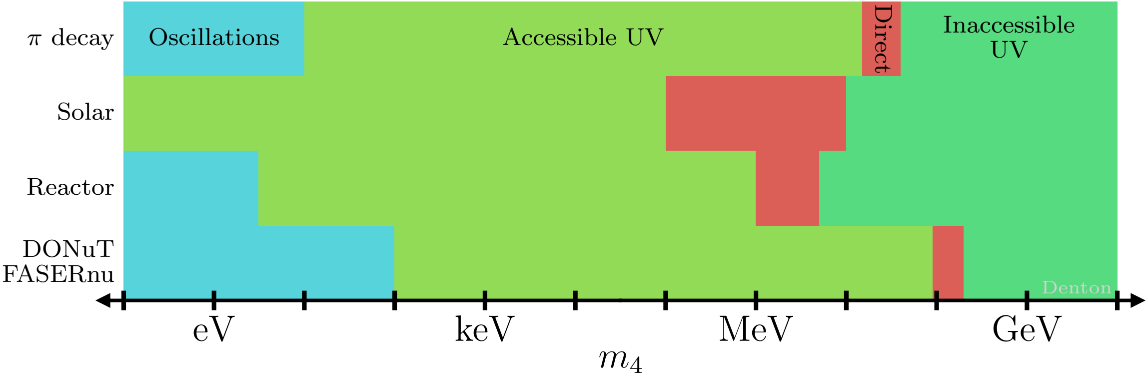
and/or

Searches for unitarity violation?

Not the same!

Lots of models to test standard three-flavor picture:
Sterile, unitarity violation, NSI, neutrino decay, decoherence, …

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:

$$U_3U_3^\dagger \neq \mathbb{1}$$

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

$$U \to \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\ U_{a1} & U_{a2} & U_{a3} & U_{a4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Unitarity Violation ⇒

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:

$$\sin^2 \frac{\Delta m^2_{41} L}{4E} \to \frac{1}{2}$$

$$\sin \frac{\Delta m^2_{41} L}{4E} \to 0$$

3. No matter effect:

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

Unitarity violation: how to calculate

Kinematically **accessible** states

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

$$\sin^2\frac{\Delta m^2_{41}L}{4E} \to \frac{1}{2}$$

$$\sin\frac{\Delta m^2_{41}L}{4E} \to 0$$

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 ⇒ 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

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

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. Antush, 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

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

Vastly different mixing angle hierarchy

$\Rightarrow$

Like comparing apples and hairstyles

Unitarity violation: tau row

Leptons: tau row is the weakest

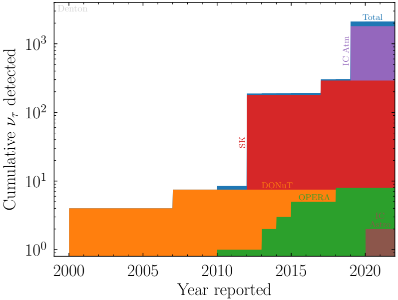
1. Existing global analyses use OPERA and SNO
2. More data from atmospheric ν_τ appearance!

PBD 2109.14576

Also astrophysical ν_τ appearance; weak but distinct!

PBD, J. Gehrlein 2109.14575

Atmospheric works because τ is in direct region



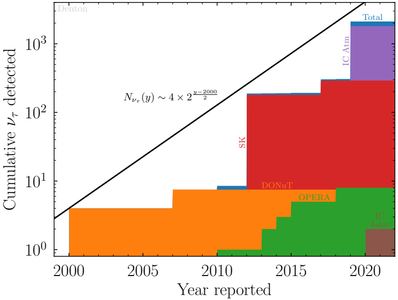
PBD, et al. 2203.05591 (whitepaper)

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

Atmospheric 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

Robustness?

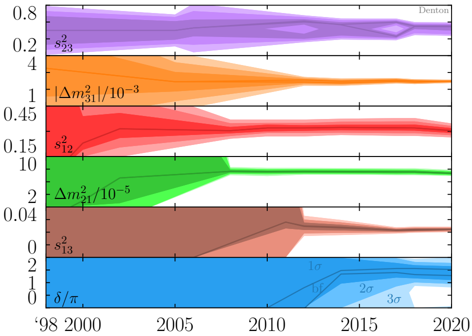
- θ_{23} octant is important for flavor models
- δ could shed light on CP violation
- Unitarity violation is phenomenologically very rich
- Lots of existing tau information to be utilized!

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

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

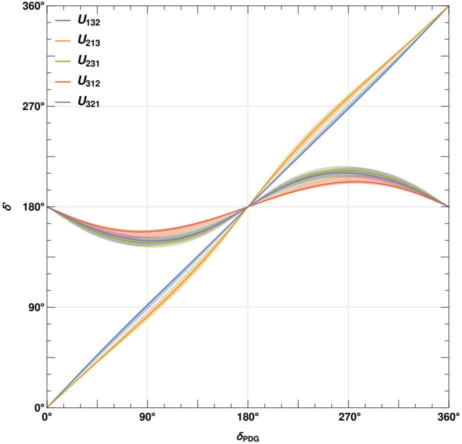
Matter potential $a \propto G_F \rho E$

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 $\sim [150°, 210°]$ 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



Quark mixing

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

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

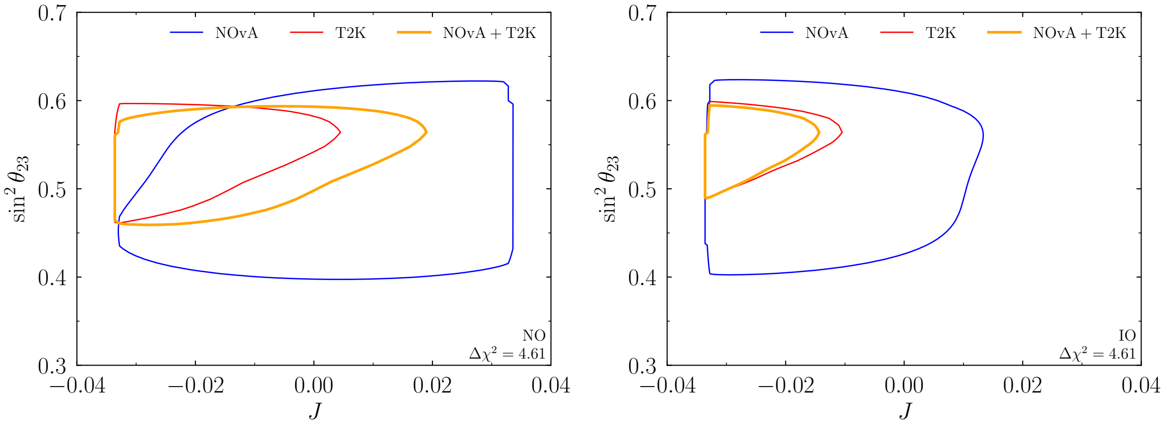
Looks like “large” CPV:

$$\sin\delta_{\rm PDG}=0.93\sim1$$

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)

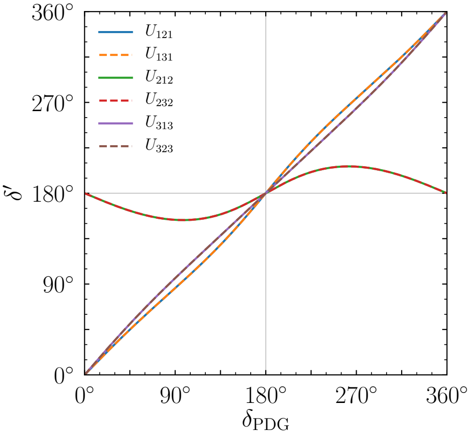
Matter effects are easily accounted for

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

PBD, S. Parke `1902.07185`

PBD, H. Minakata, S. Parke `1604.08167`

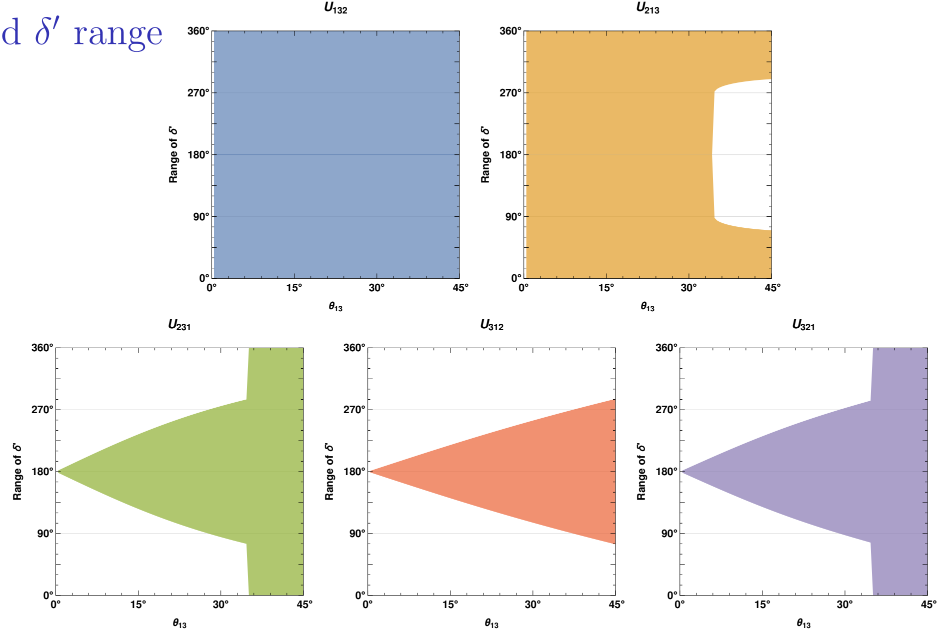
Repeated rotations



	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

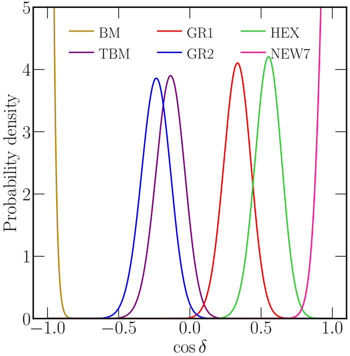
Allowed δ' range



The importance of $\cos\delta$

- If only $\sin\delta$ is measured ⇒ 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

Unitarity violation: mass ranges for tau neutrinos

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

PBD, J. Gehrlein 2109.14575