Abstract

In particle physics there exist two regions: the Standard Model which is fairly complete and the new physics sector which is completely unknown. Inbetween and overlapping with both of these is neutrino physics. Neutrinos exist within the Standard Model but are not explained by it due to the discovery of neutrino oscillations. In this colloquium I will discuss where we stand with neutrino oscillations, where we might go with them, and how we might learn about the nature of neutrinos.

Knowns and Unknowns in Neutrinos

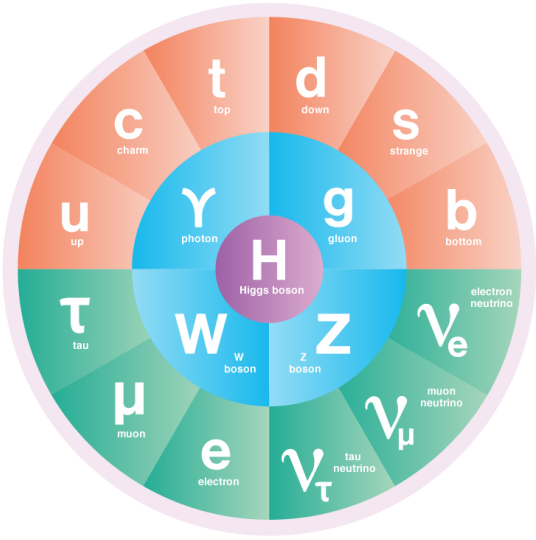
Peter B. Denton

Stony Brook

October 18, 2022

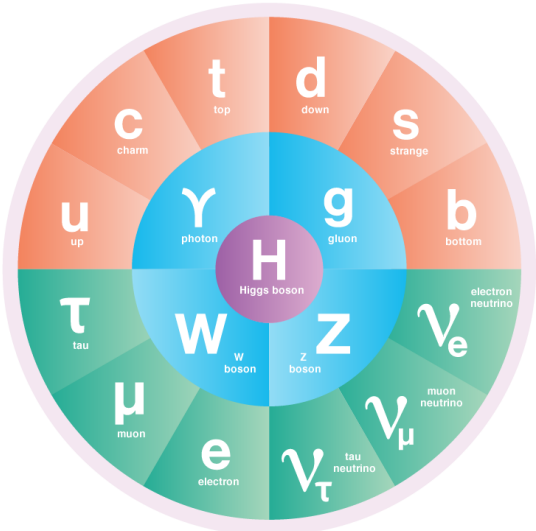
Speaking from Setauket land

Particle physics



Symmetry Magazine

Particle physics



Symmetry Magazine

Discovering/understanding particles:

- Photon: easy
- Charged leptons: easy
- Heavy quarks: hard experimentally, easy theoretically
- Light quarks: easy experimentally, harder theoretically
- W & Z: hard experimentally, easy theoretically
- Gluons: easy experimentally, harder theoretically
- Higgs boson: hard experimentally, easy theoretically
- Neutrinos: hard experimentally, hard theoretically

Approach

1. Brief pedagogical review of neutrino oscillations
2. Where we are today with oscillations
3. What kinds of other new physics might be out there

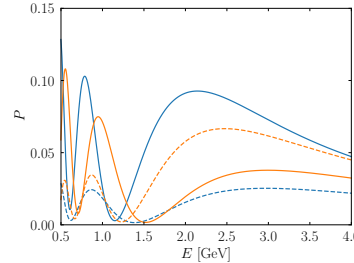
Neutrino oscillations: the basics

Do neutrinos have mass?

- Neutrinos seemed to be massless
- Direct kinematic searches have still not yielded any indication for a mass

KATRIN 2105.08533

Do neutrinos have mass?



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- Through quantum mechanical interference of entangled states, they evolve

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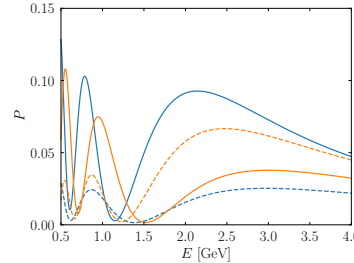

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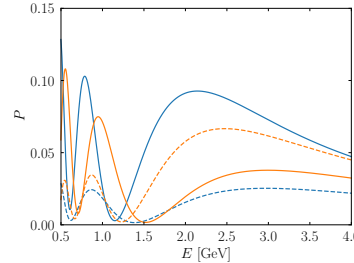

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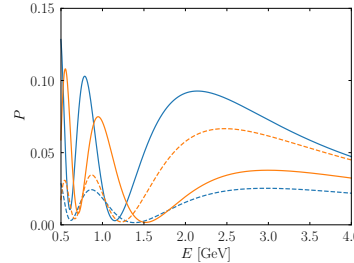

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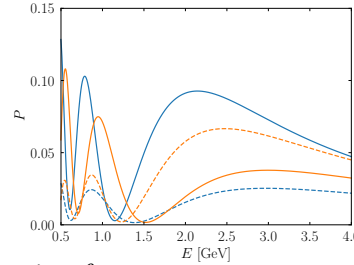

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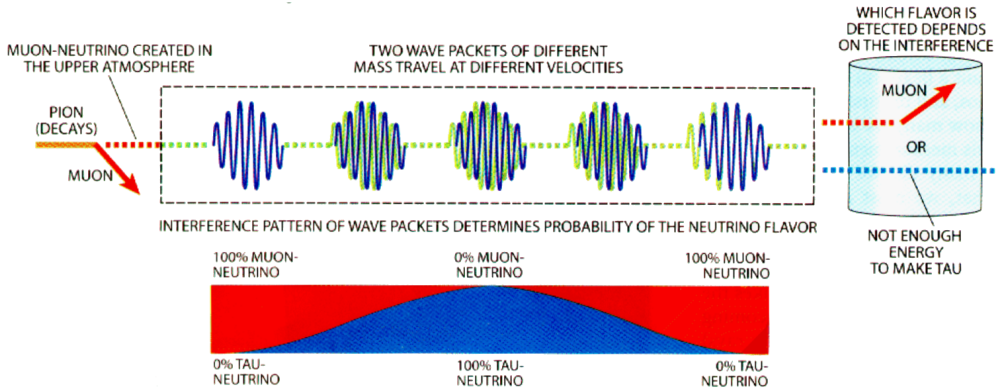
- Through quantum mechanical interference of entangled states, they evolve

Neutrinos oscillate!

- Since they act differently at different times, they must have mass
- Masses are $> 1,000,000$ times smaller than the electron
- Their masses are still unknown!
- The mechanism by which they get mass is unknown!

How does oscillation work?

A schematic for many environments:



Some neutrino oscillation theory

Quantum mechanics exercise:

$$i\frac{\partial}{\partial t}|\nu_i\rangle = H|\nu_i\rangle$$

Some neutrino oscillation theory

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$$H = \begin{pmatrix} E_1 & & \\ & E_2 & \\ & & E_3 \end{pmatrix}$$

$$|\nu_i(t)\rangle = e^{-iEt}|\nu_i(0)\rangle$$

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Subtract a common phase pt from all:

$$|\nu_i(t)\rangle = e^{-im_i^2 L/2E}|\nu_i(0)\rangle$$

Note that switching $E \simeq p$ and $x \simeq t$ is potentially problematic
Full QFT calculation gives the same answer

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Subtract a common phase pt from all:

$$|\nu_i(t)\rangle = e^{-im_i^2 L/2E}|\nu_i(0)\rangle$$

No oscillations!

Note that switching $E \simeq p$ and $x \simeq t$ is potentially problematic
Full QFT calculation gives the same answer

Production and detection

Need to produce neutrinos in a different basis

QM entanglement!

In the flavor/interaction basis:

$$i\frac{\partial}{\partial t}|\nu_\alpha\rangle = H_f|\nu_\alpha\rangle$$

$$H_f = \frac{1}{2E}U_{\text{PMNS}}\begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix}U_{\text{PMNS}}^\dagger$$

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U_{PMNS} is: complex, 3×3, unitary; 4 parameters: θ_{23}, θ_{13}, θ_{12}, δ

Many different ways to parameterize matrix:
PBD, R. Pestes 2006.09384

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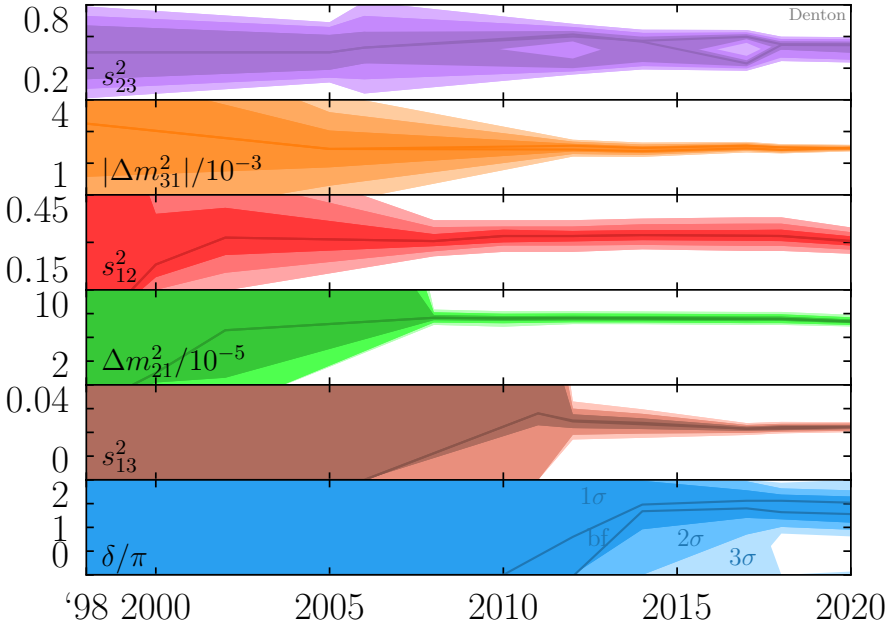
$$P(\nu_\alpha \to \nu_\beta) = \left|\sum_{i=1}^{3} U_{\alpha i}^* e^{-im_i^2 L/2E} U_{\beta i}\right|^2$$

Only $m_i^2 - m_j^2$ contribute

Oscillations!

Neutrino oscillations: today


Denton
0.8
0.2
s^2_{23}
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0.45
0.15
s^2_{12}
10
2
$\Delta m^2_{21}/10^{-5}$
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0
s^2_{13}
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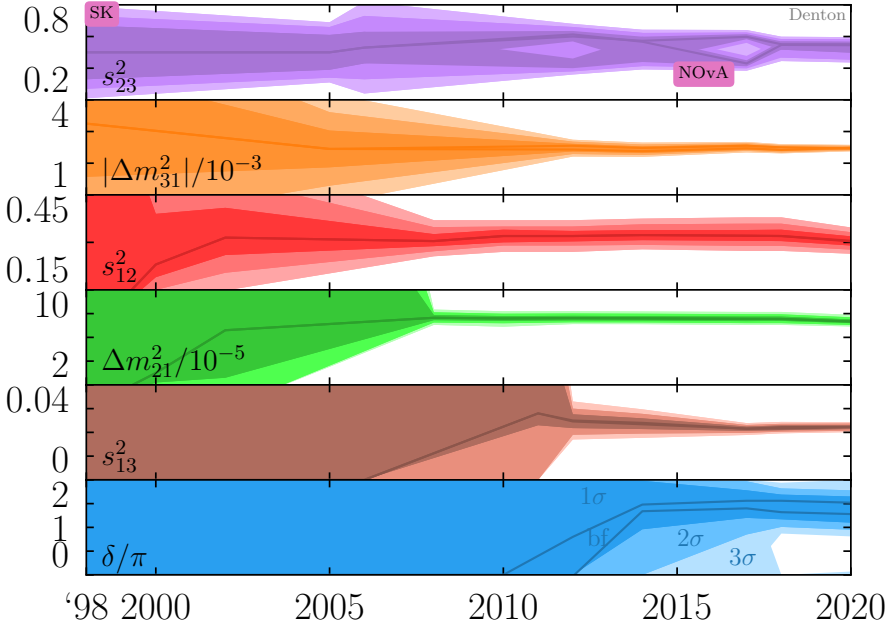
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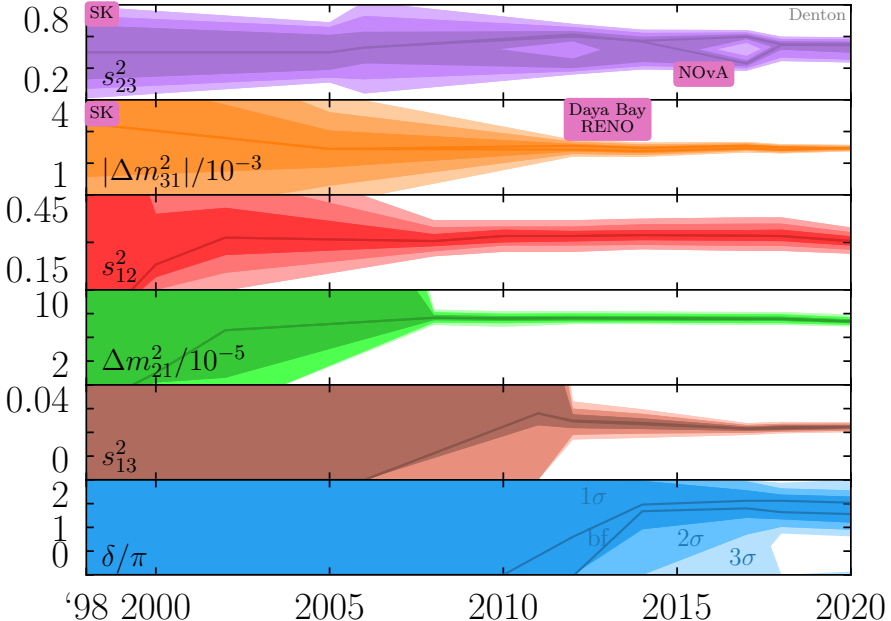
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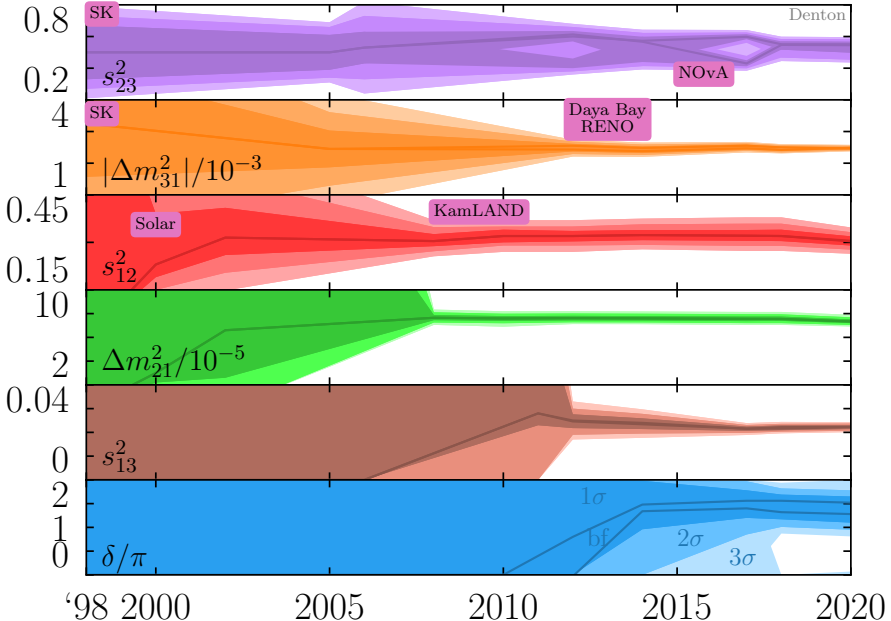
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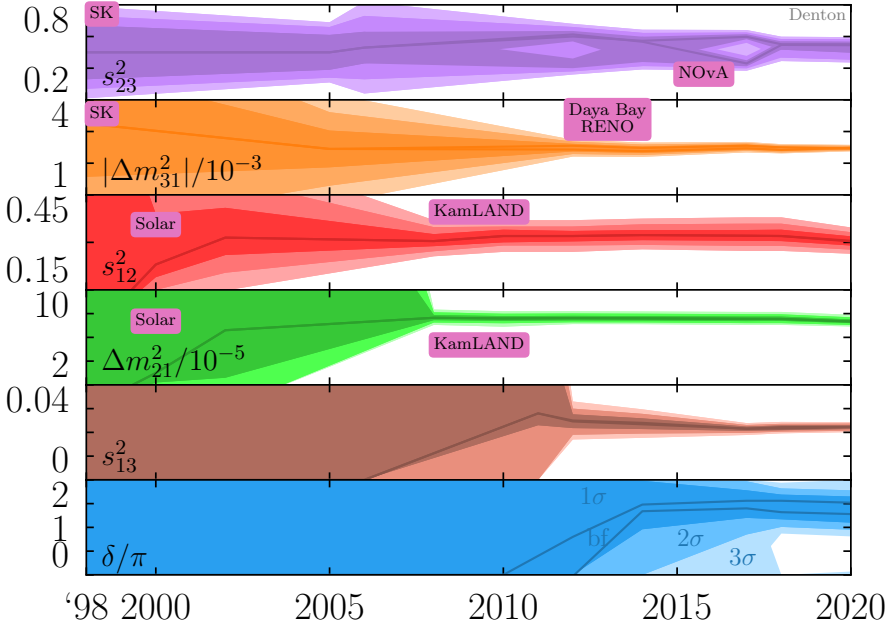
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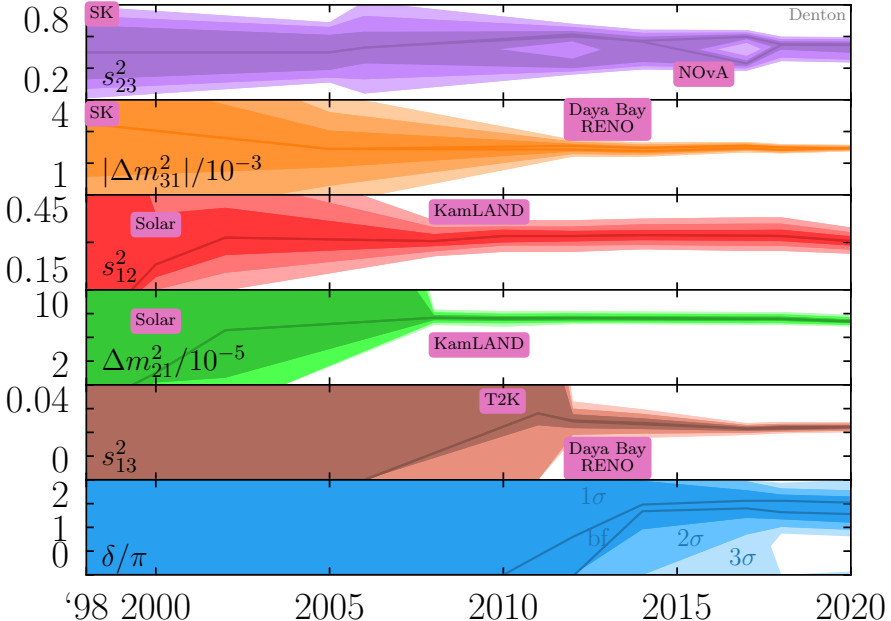
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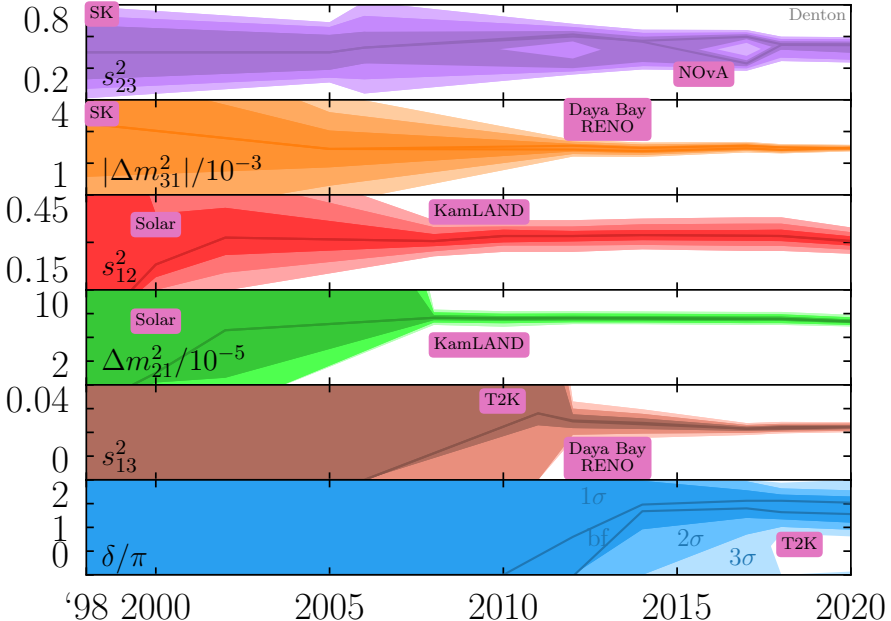
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Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

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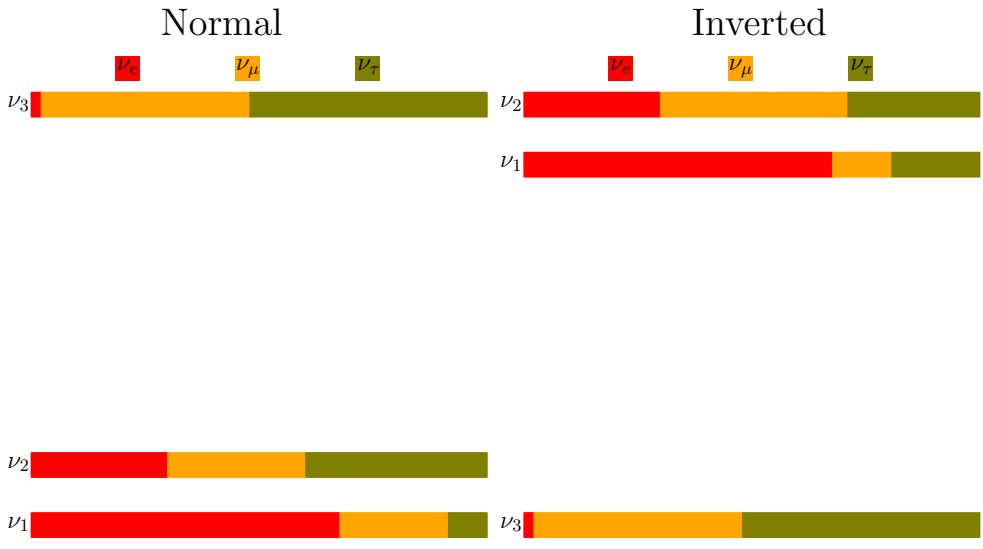
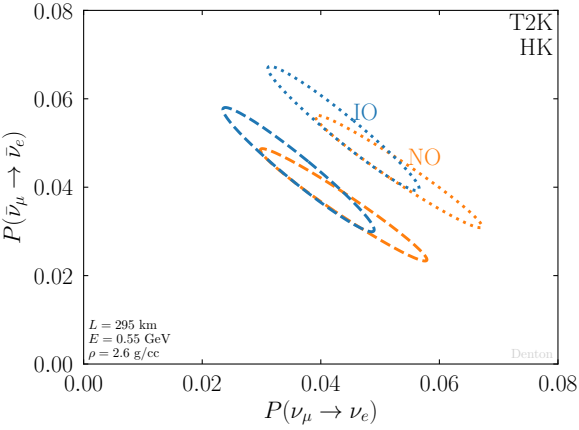
Cosmology, scattering, $0\nu\beta\beta$, ...

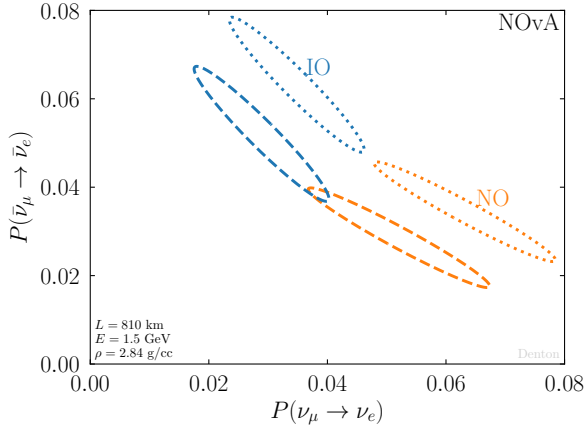
Atmospheric mass ordering

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

$\rightarrow$ 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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See also KATRIN 2105.08533

PRIORS?

Some claim "decisive" Bayesian evidence for normal

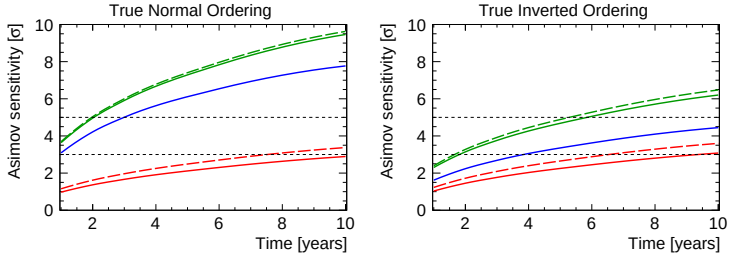
R. Jimenez, et al. 2203.14247

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

JUNO, IceCube 1911.06745

Note: if lower octant, KM3NeT is less sensitive

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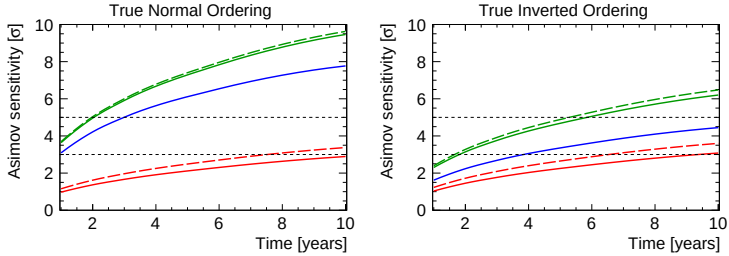

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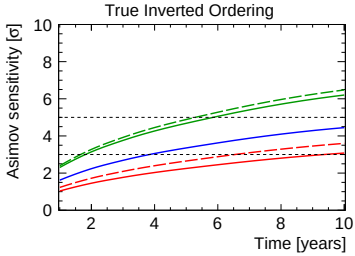
$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$

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

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

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

Mass ordering: future sensitivities



Joint
KM3NeT
JUNO

JUNO, KM3NeT 2108.06293

JUNO, IceCube 1911.06745

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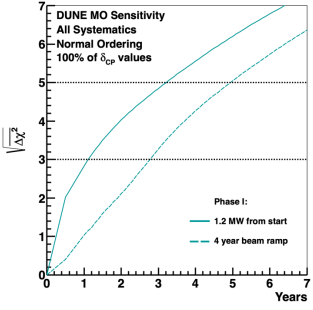

Matter effect ⇒ DUNE 2203.06100

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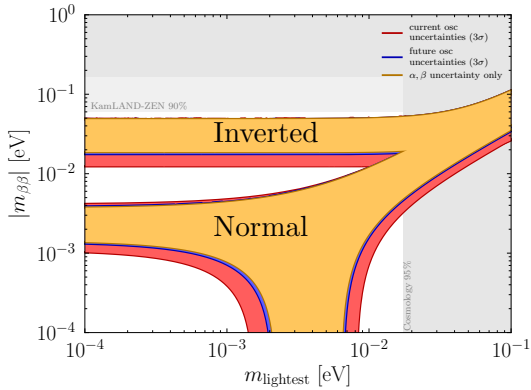
Differ by $\pm \sim 1.5\%$ in each mass ordering

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 CνB



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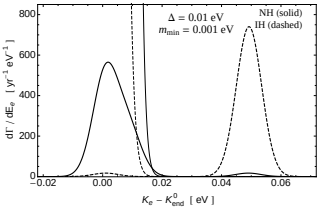
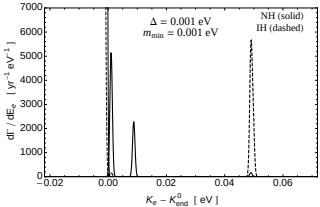
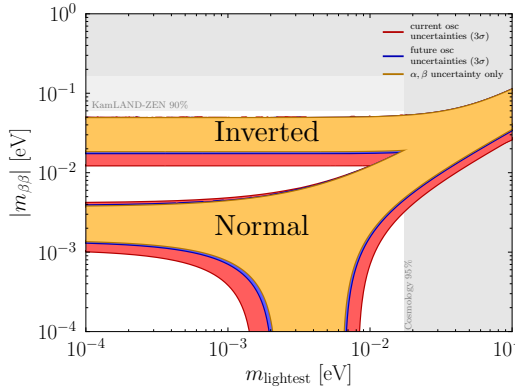






A. Long, C. Lunardini, E. Sabancilar 1405.7654

Mass ordering: new physics degeneracies

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

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

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

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

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

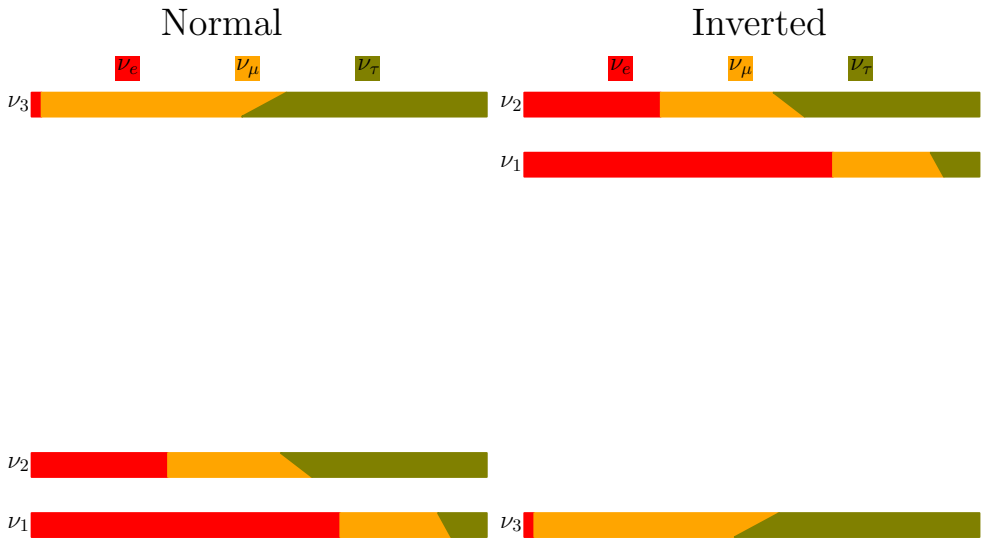
Dresden-II for any mediator mass

PBD, J. Gehrlein 2204.09060

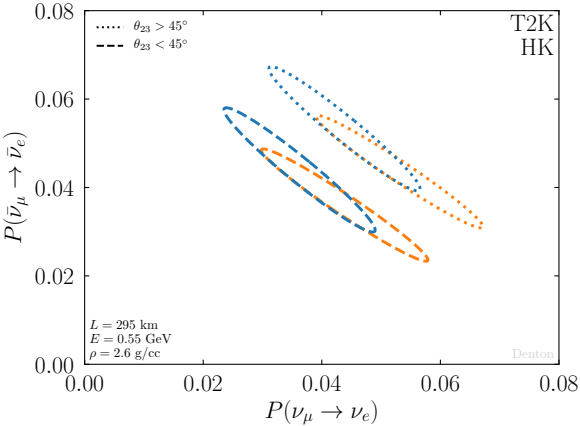
Can still evade with $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$ or certain u / d combinations

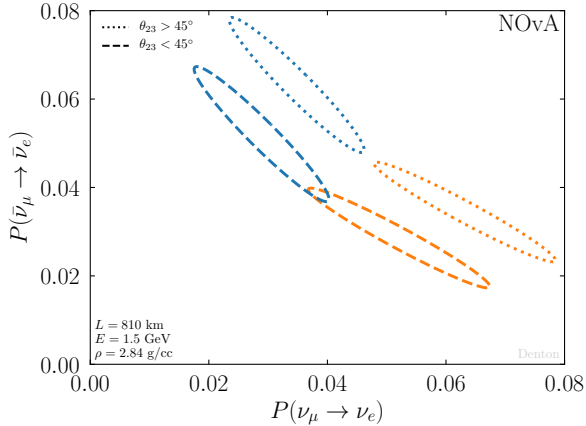
θ_{23} octant

θ_{23} octant: what is it?



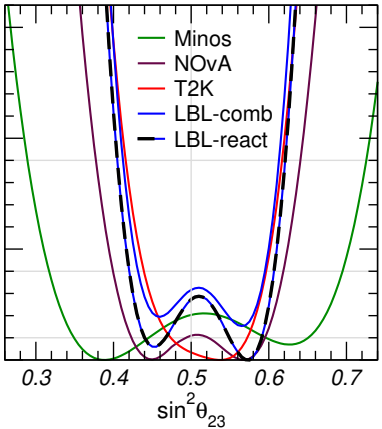
θ_{23} octant: what is it really?





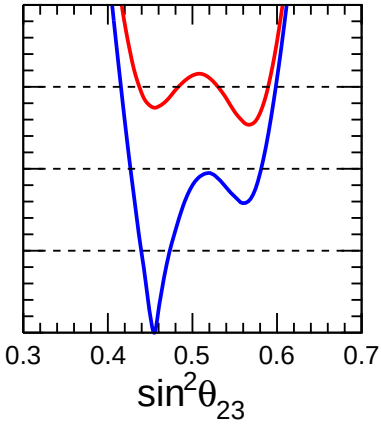
Lower octant more “normal” than upper octant

θ_{23} octant: current status



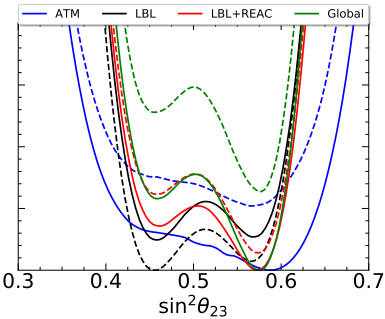
I. Esteban, et al. 2007.14792

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



F. Capozzi, et al. 2107.00532

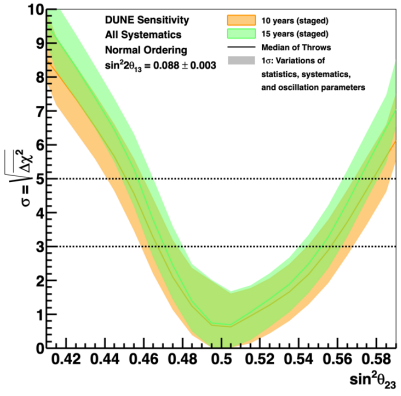
Prefers **lower** at $\sim 1.5\sigma$



P. de Salas, et al. 2006.11237

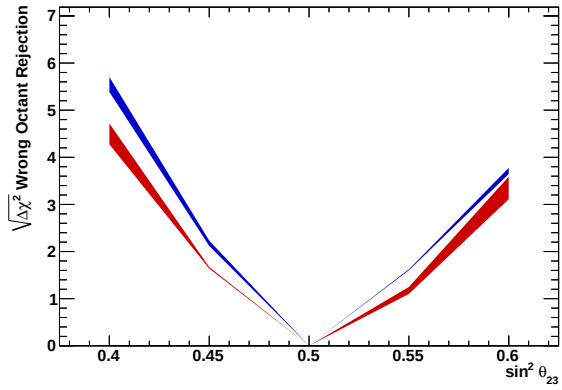
Prefers **upper** at $> 2\sigma$

θ_{23} octant: future sensitivities



$\sim 3-5\sigma$

DUNE 2002.03005



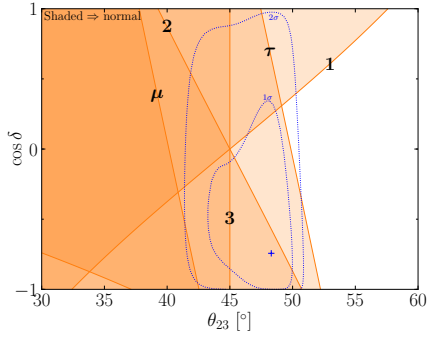
Beam+Atm$\Rightarrow \sim 3-6\sigma$

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

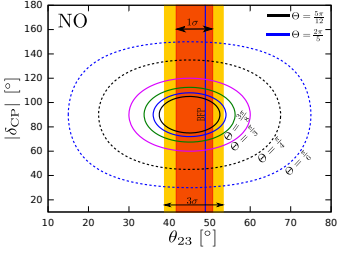
μ-τ interchange/reflection symmetry

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

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

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

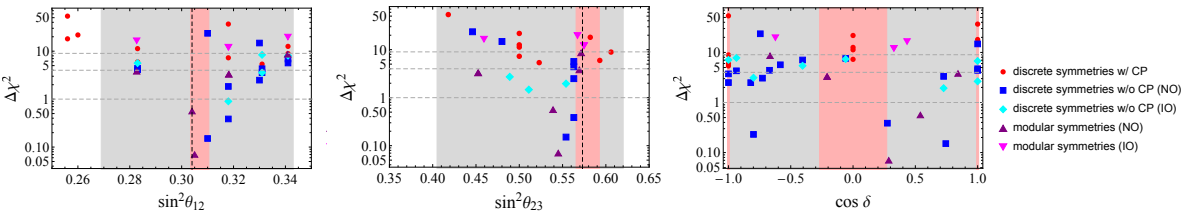
Predicts: $\theta_{23} = 45°$, often $\theta_{13} = 0$



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

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

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

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

CKMfitter 1501.05013

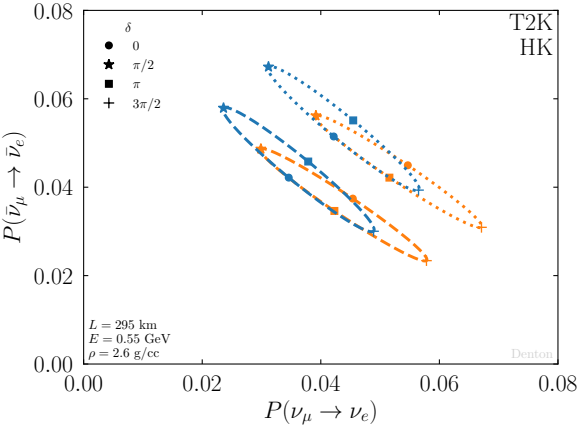
3. Lepton mass matrix: **?**

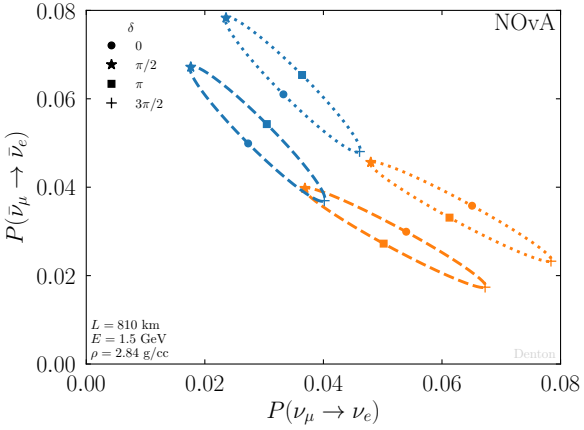
$$\frac{|J_{\rm PMNS}|}{J_{\rm max}} < 0.34$$

PBD, J. Gehrlein, R. Pestes 2008.01110

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

δ: what is it really?





$\delta \not\Rightarrow$ Baryogenesis

The amount of leptogenesis is a function of:

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

C. Hagedorn, et al. 1711.02866

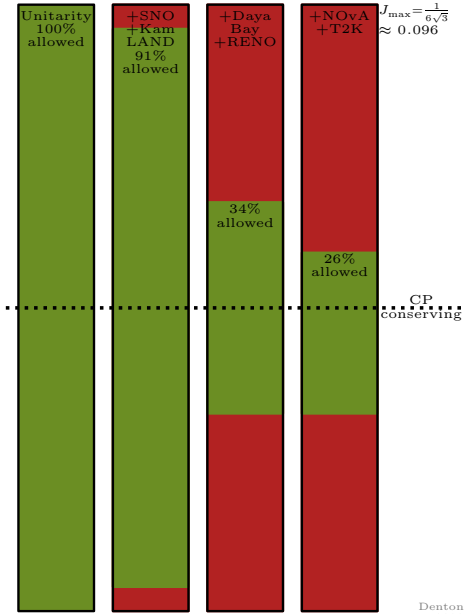
K. Moffat, et al. 1809.08251

$$\begin{aligned} \text{Measuring } \delta = 0, \pi \quad &\not\Rightarrow \quad \text{no leptogenesis} \\ \text{Measuring } \delta \neq 0, \pi \quad &\not\Rightarrow \quad \text{leptogenesis} \end{aligned}$$

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



Denton
2020

Neutrinos: more new physics?

Lots of interesting new physics scenarios

1. Sterile neutrinos
2. Non-standard neutrino interactions (NSI)
   with any Lorentz structure: SPVAT
3. Non-standard neutrino SELF interactions
4. Neutrino decay
   with visible or invisible final states
5. Unitarity violation
6. Neutrino – dark matter interactions
7. Decoherence
8. Lorentz invariance or CPT violation

Lots of interesting new physics scenarios

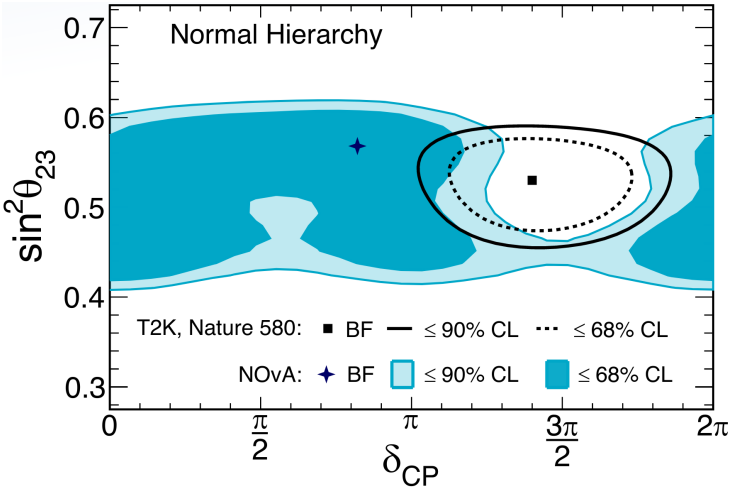
1. Sterile neutrinos — PBD, Y. Farzan, I. Shoemaker 1811.01310; PBD 2111.05793
2. Non-standard neutrino interactions (NSI)
   with any Lorentz structure: SPVAT — PBD, J. Gehrlein, R. Pestes 2008.01110; P. Coloma, PBD, M. Gonzalez-Garcia, M. Maltoni, T. Schwetz 1701.04828; PBD, J. Gehrlein 2008.06062, 2204.09060; PBD, A. Giarnetti, D. Meloni 2210.00109
3. Non-standard neutrino SELF interactions — G. Barenboim, PBD, I. Oldengott 1903.02036
4. Neutrino decay
   with visible or invisible final states — PBD, I. Tamborra 1805.05950; PBD, A. Abdullahi 2005.07200; PBD 2109.14576
5. Unitarity violation — PBD, J. Gehrlein 2109.14575
6. Neutrino – dark matter interactions — A. Dev, et al. 2205.06821; C. Boehm, P. Fayet, R. Schaeffer astro-ph/0012504
7. Decoherence — T. Stuttard, M. Jensen 2007.00068; A. Gouvêa, V. Romeri, C. Ternes 2104.05806
8. Lorentz invariance or CPT violation — S. Ge, H. Murayama 1904.02518

Two BSM scenarios:

Non-standard neutrino interactions (NSI)
Unitarity violation (UV)

CP violation at NOvA and T2K?

Excitement at Neutrino2020!



A. Himmel for NOvA 10.5281/zenodo.3959581

NSI review

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

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

Estimate size of effect: magnitude

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

$a \propto \rho E$

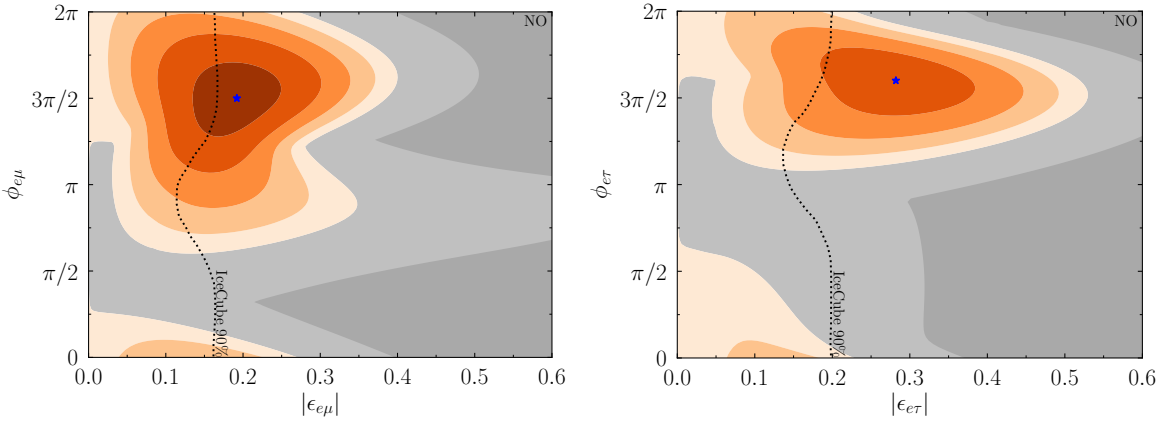
$w_\beta = s_{23},\ c_{23}$ for $\beta = \mu, \tau$

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

Consistency checks:

- $\sin\delta_{\text{NOvA}} = \sin\delta_{\text{T2K}} \Rightarrow |\epsilon| = 0$
- $\sin\delta_{\text{NOvA}} \neq \sin\delta_{\text{T2K}}$ and $a_{\text{NOvA}} = a_{\text{T2K}} \Rightarrow |\epsilon| \to \infty$
- 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 at integer values of $\Delta\chi^2$, dark gray is disfavored at 4.61

T. Ehrhardt, IceCube PPNT (2019)

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

Other CP violating NSI constraints

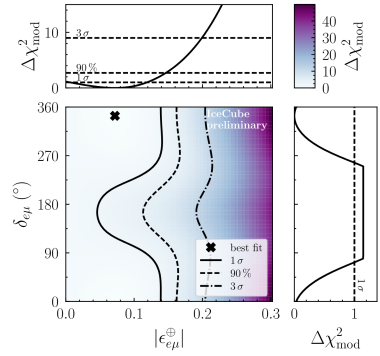
NSI effects grow with energy, density, and distance

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

Unitarity violation

Consistency of the three-flavor oscillation picture?

and/or

Searches for unitarity violation?

Unitarity violation

Consistency of the three-flavor oscillation picture?

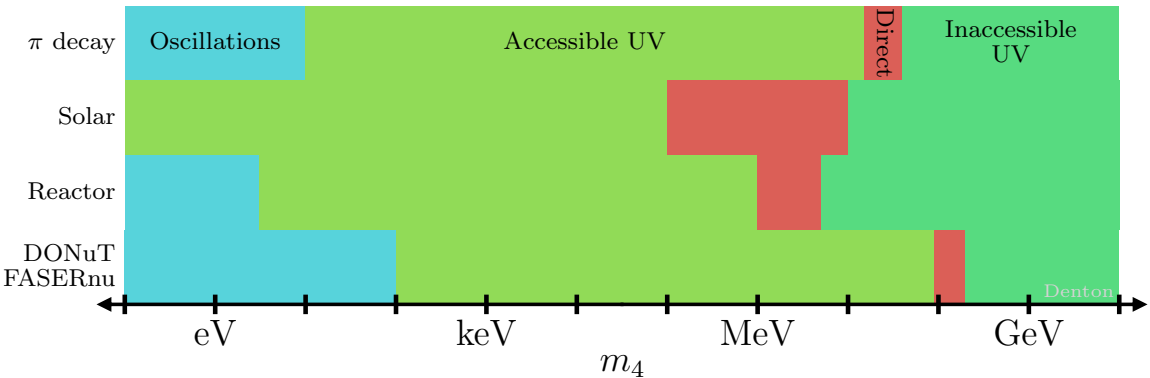
and/or

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:

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

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

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

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:

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

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

3. No matter effect:

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

Unitarity violation: how to calculate

Kinematically **accessible** states

1. Unitary calculation of full $n \times n$ matrix
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$$\sin^2 \frac{\Delta m^2_{41} L}{4E} \to \frac{1}{2}$$

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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 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

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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	-	

Vastly different mixing angle hierarchy

$\Rightarrow$

Like comparing apples and hairstyles

Lepton constraints don't include anomalies

Care is required

S. Ellis, K. Kelly, S. Li 2008.01088

Z. Hu, et al. 2008.09730

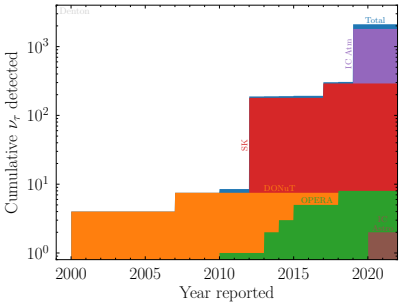
S. Parke, M. Ross-Lonergan 1508.05095

PDG

Unitarity violation: 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, et al. 2203.05591 (whitepaper)

PBD 2109.14576

Also astrophysical ν_τ appearance; weak but distinct!

PBD, J. Gehrlein 2109.14575

Atmospheric works because τ is in direct region

Unitarity violation: tau row

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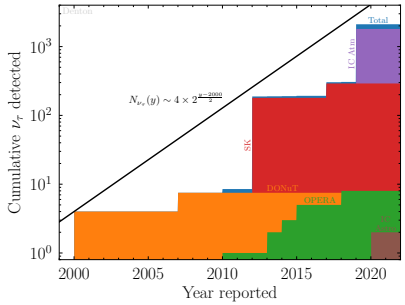

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PBD 2109.14576

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!

Neutrino oscillation summary

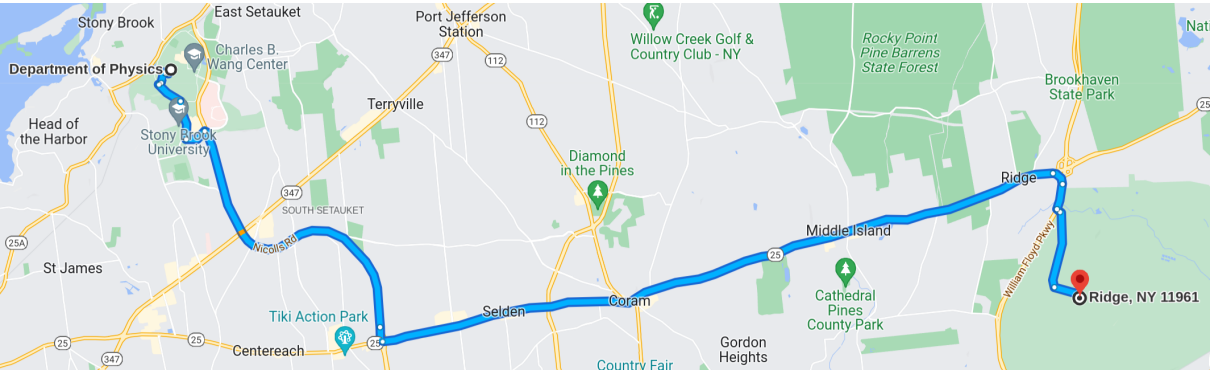
- Four known unknowns in particle physics: all neutrinos
- Mass ordering will be measured

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 neutrino information to be utilized!

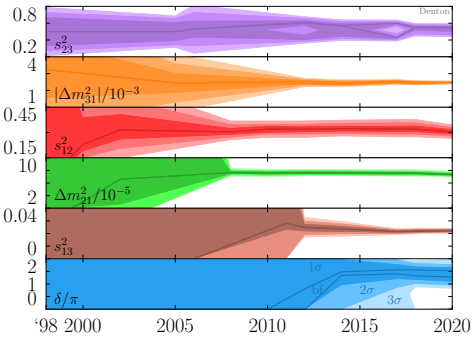
Precision is coming to neutrinos!

Thanks!


Stony Brook
East Setauket
Port Jefferson Station
Charles B. Wang Center
Department of Physics
Willow Creek Golf & Country Club - NY
Rocky Point Pine Barrens State Forest
Brookhaven State Park
Terryville
Head of the Harbor
Stony Brook University
Diamond in the Pines
Ridge
SOUTH SETAUKET
Nicolls Rd
Middle Island
St James
Cathedral Pines County Park
William Floyd Pkwy
Ridge, NY 11961
Tiki Action Park
Selden
Coram
Centereach
Gordon Heights
Country Fair

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

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

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

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

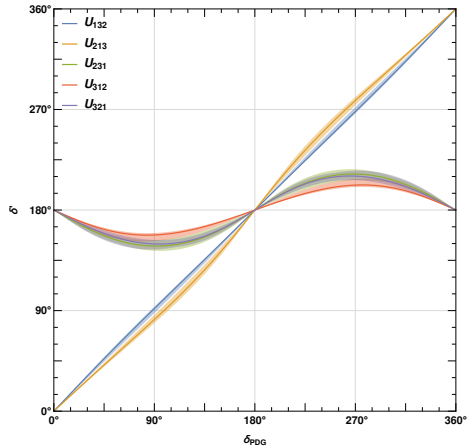
Matter potential $a \propto G_F \rho E$

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

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

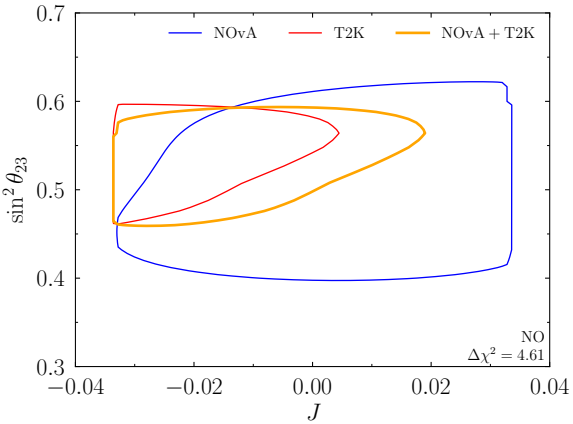
Looks like "large" CPV:

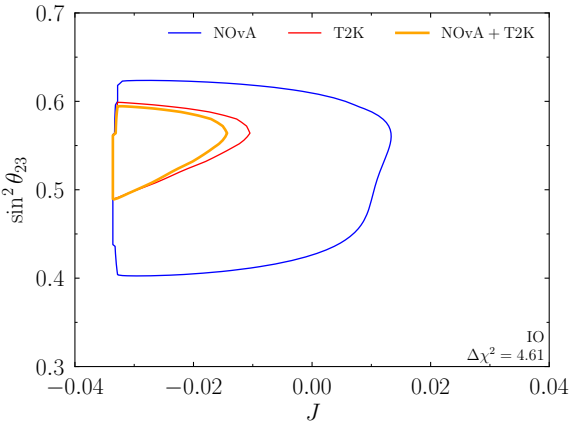
$$\sin\delta_{\rm PDG} = 0.93 \sim 1$$

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

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:

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

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

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

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

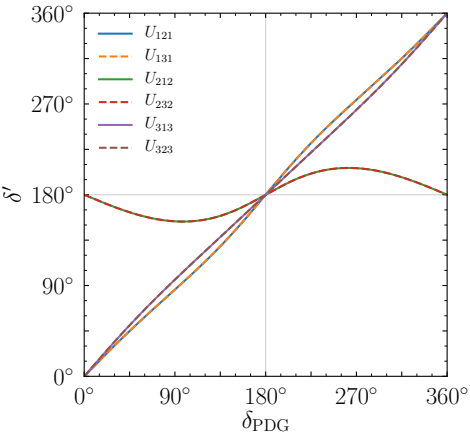
Given θ_{12}, θ_{13}, θ_{23}, and J, I can't determine the sign of $\cos\delta$ which is physical

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

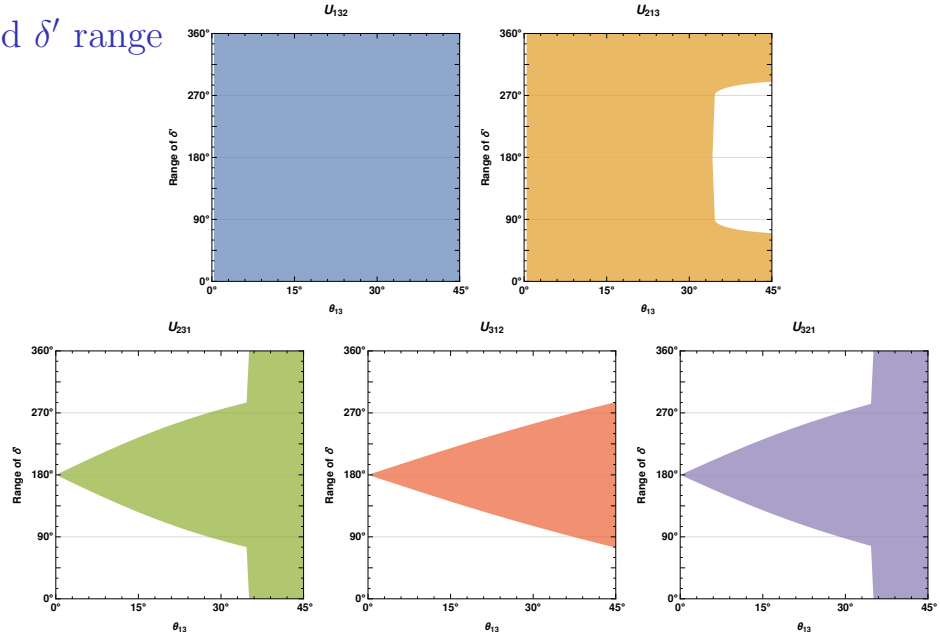
Repeated rotations



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

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

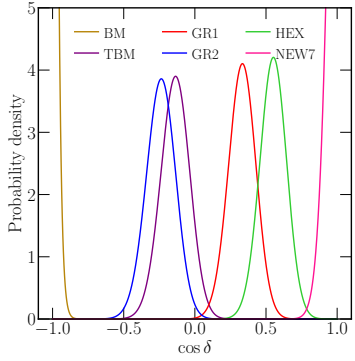
Allowed δ' range



The importance of $\cos\delta$

- If only $\sin\delta$ is measured $\Rightarrow$ 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

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

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

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: 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	$\in [100\text{ eV}, 90\text{ MeV}]$	$\gtrsim 200$ MeV
LBL ν_τ appearance (OPERA)	$\in [1\text{ eV}, 15\text{ MeV}]$	$\gtrsim 40$ MeV
LBL ν_τ appearance (DUNE)	$\in [0.1\text{ eV}, 15\text{ MeV}]$	$\gtrsim 40$ MeV
LBL ν_μ disappearance (DUNE)	$\in [0.1\text{ eV}, 15\text{ MeV}]$	$\gtrsim 40$ MeV
CEvNS	$\in [10\text{ eV}, 15\text{ MeV}]$	$\gtrsim 40$ MeV

PBD, J. Gehrlein 2109.14575