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

University of Wisconsin

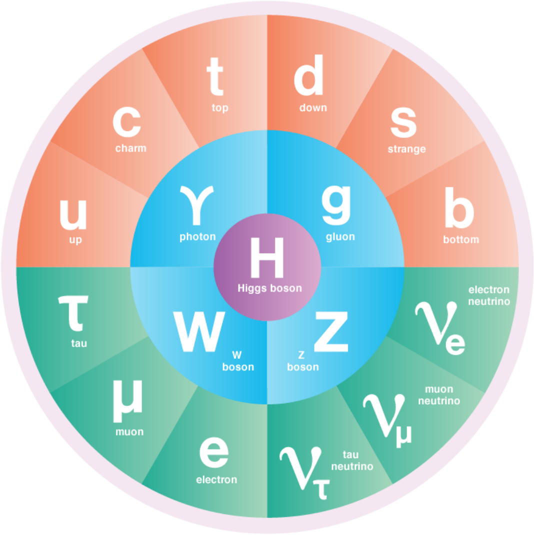
April 14, 2023

Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

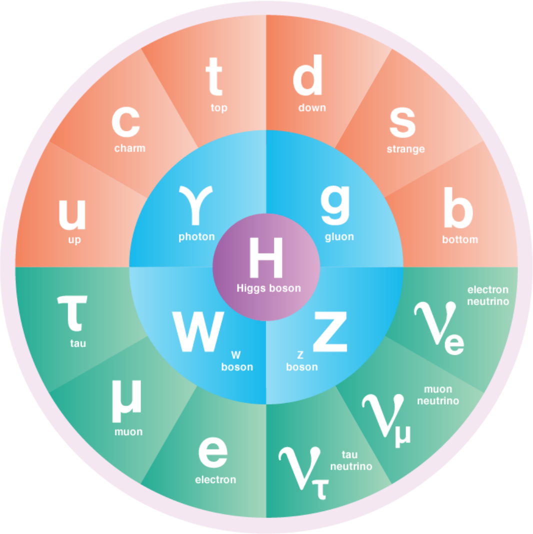
Speaking from Peoria land

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

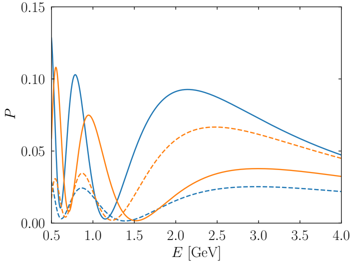
Neutrino oscillations: the basics

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

Neutrinos oscillate!

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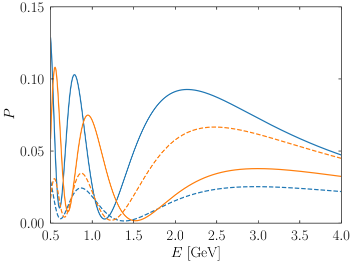

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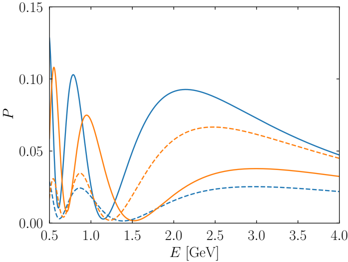

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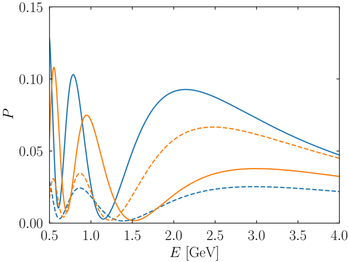

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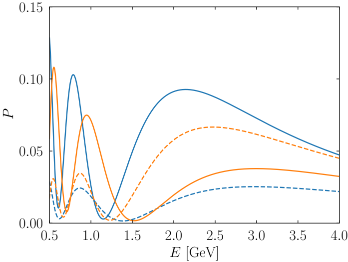

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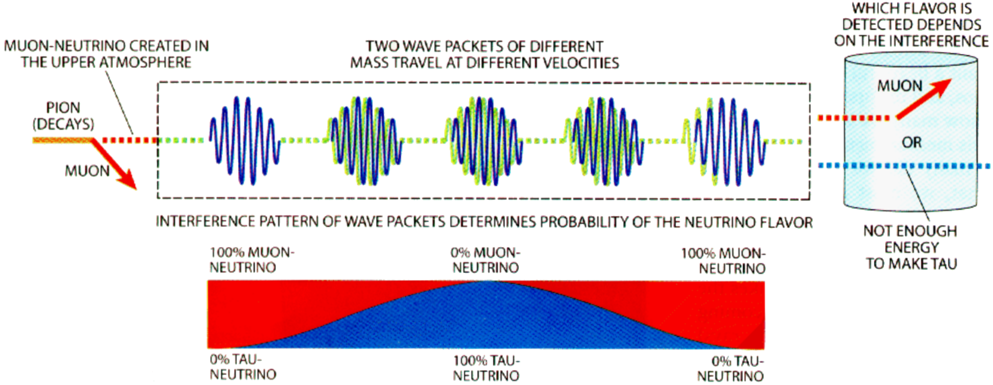
Neutrinos oscillate!

- 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:

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

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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:

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

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

Some neutrino oscillation theory

Quantum mechanics exercise:

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Subtract a common phase pt from all:

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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

QM entanglement!

Need to produce neutrinos in a different basis

In the flavor/interaction basis:

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

$\alpha = e, \mu, \tau$

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

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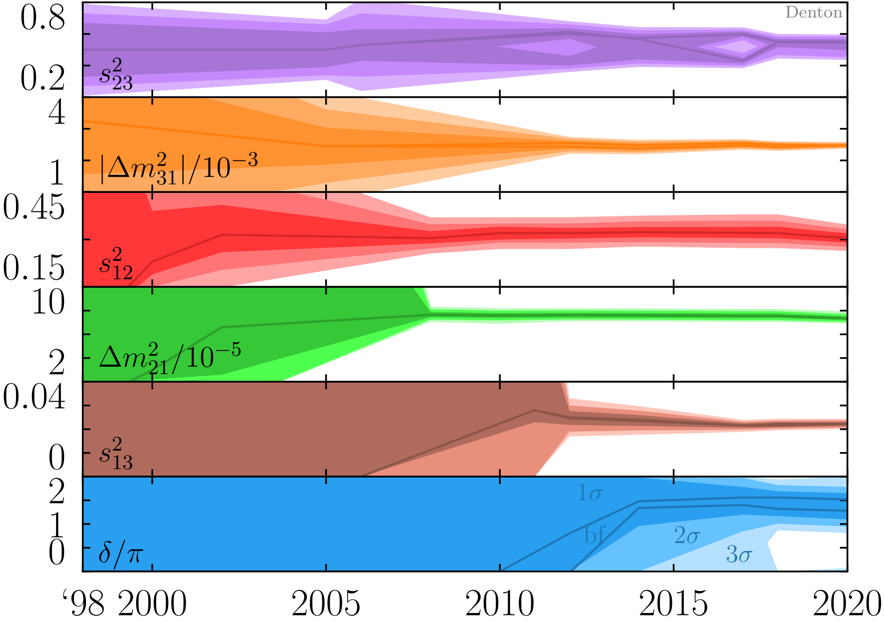
$$P(\nu_\alpha\to\nu_\beta) = \left|\sum_{i=1}^{3} U_{\alpha i}^* e^{-im_i^2L/2E}U_{\beta i}\right|^2$$

Only $m_i^2 - m_j^2$ contribute

Oscillations!

Neutrino oscillations: today


Denton
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0.15
s_{12}^2
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2
$\Delta m_{21}^2/10^{-5}$
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s_{13}^2
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2σ
3σ
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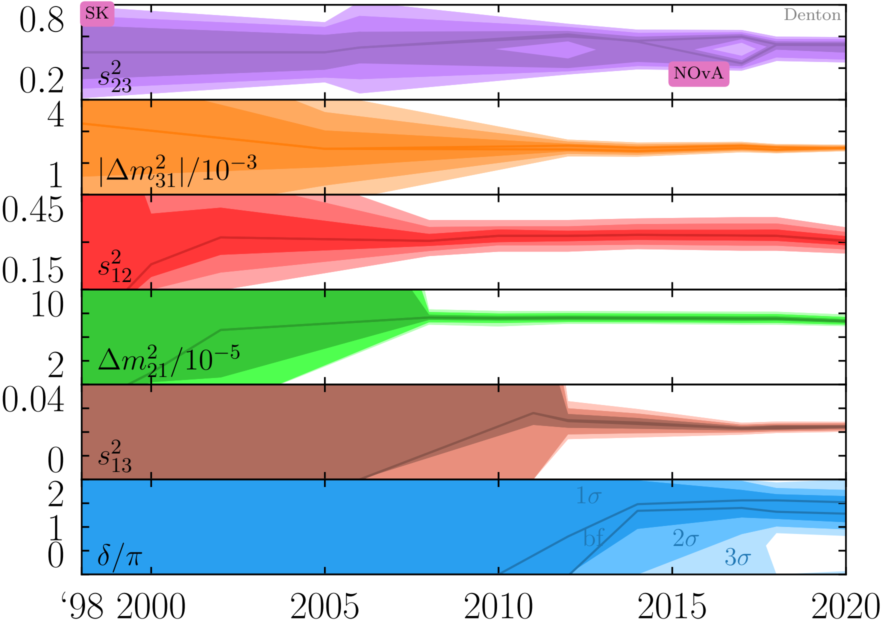

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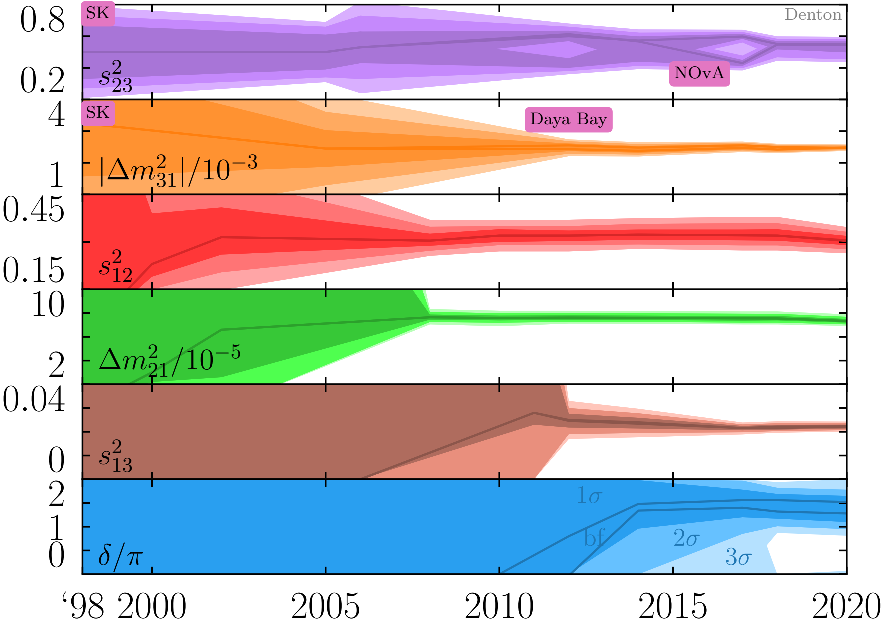
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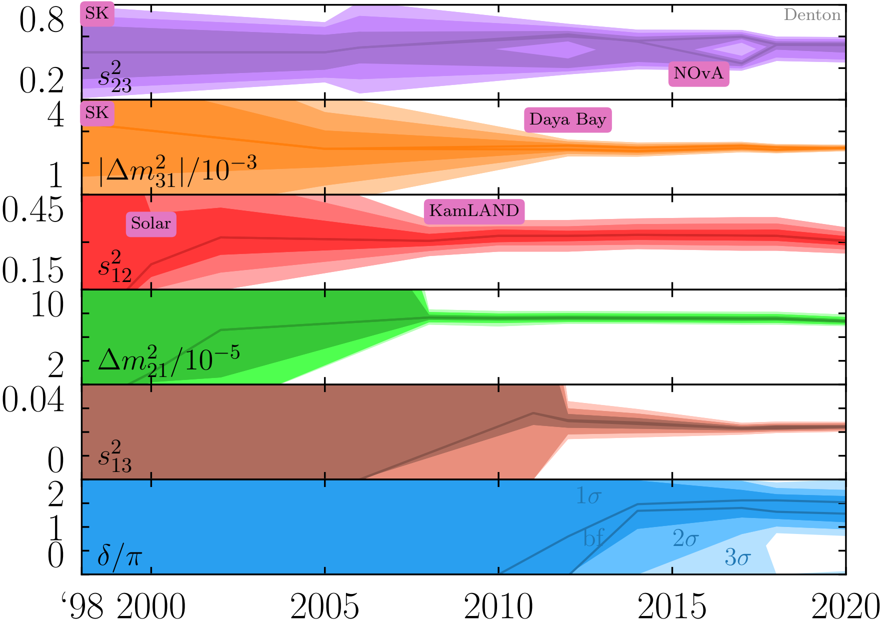
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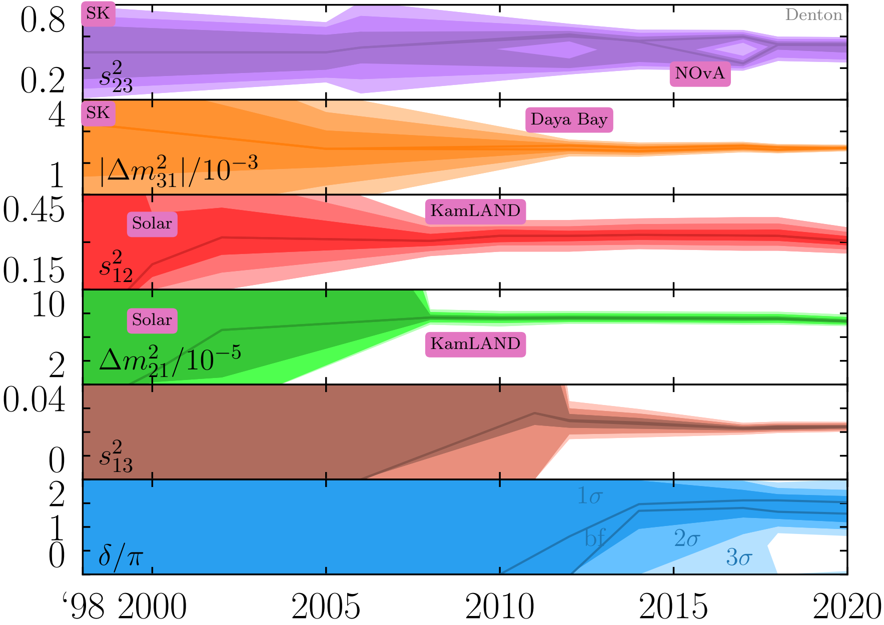
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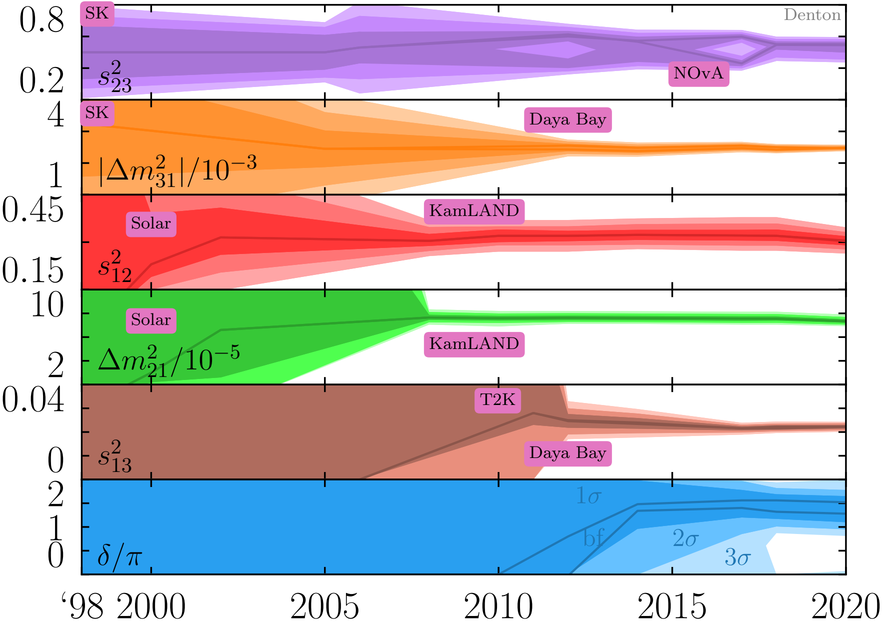
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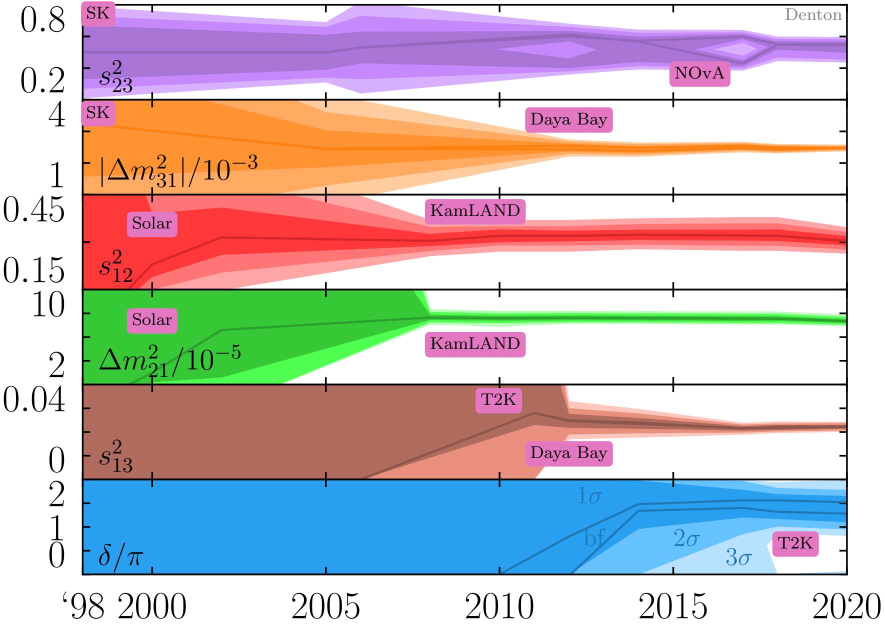
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Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Four known unknown in particle physics: all neutrinos

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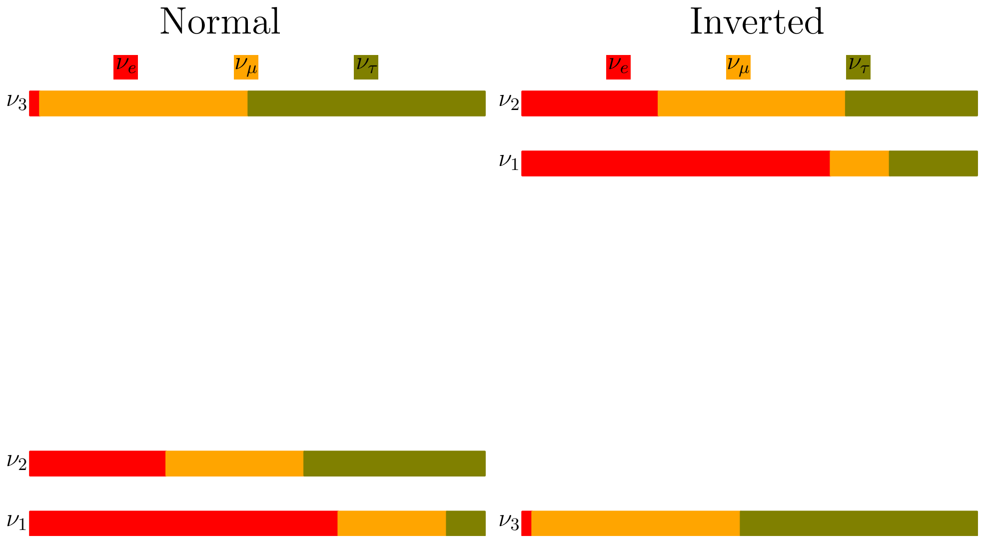
Absolute mass scale

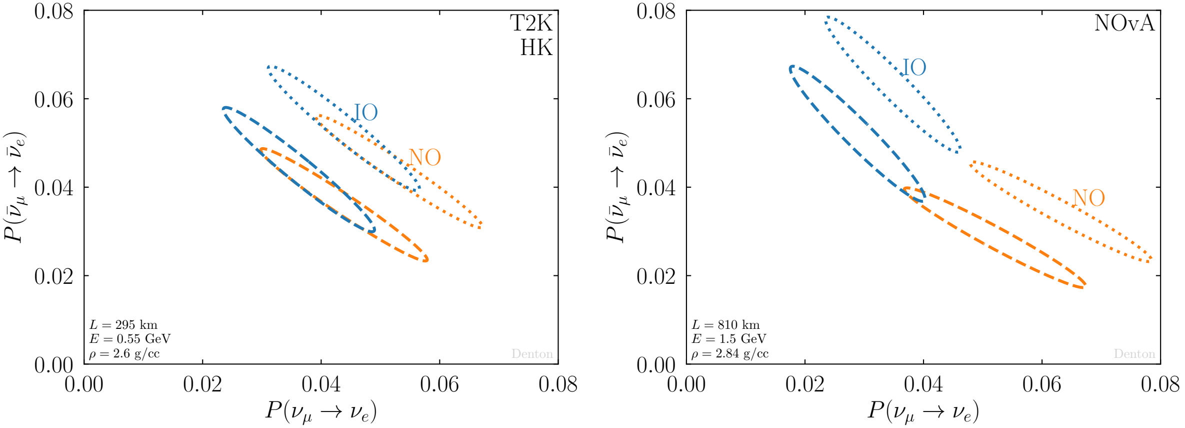
Cosmology, scattering, $0\nu\beta\beta$, ...

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`

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See also KATRIN 2105.08533

PRIORS?

Some claim "decisive" Bayesian evidence for normal

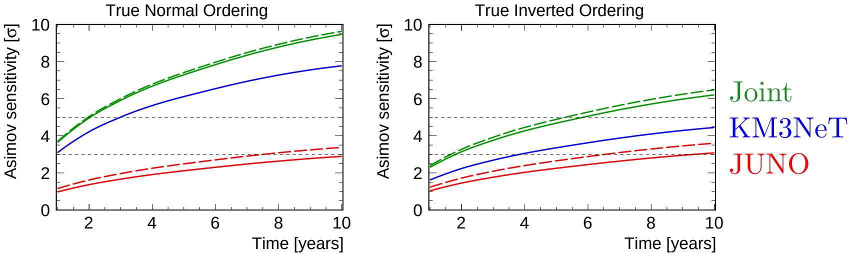
R. Jimenez, et al. 2203.14247

More general prior assumptions ⇒ 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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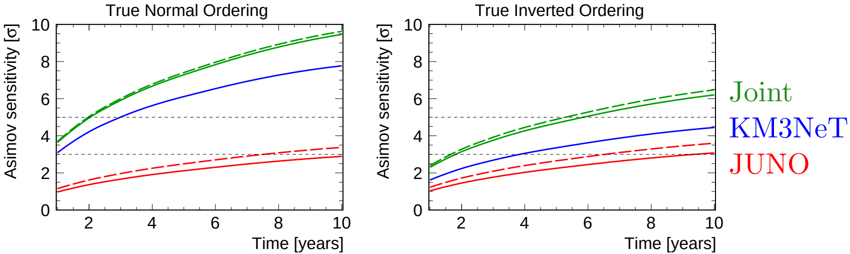

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Differ by $\pm\sim 1.1\%$ in each mass ordering

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

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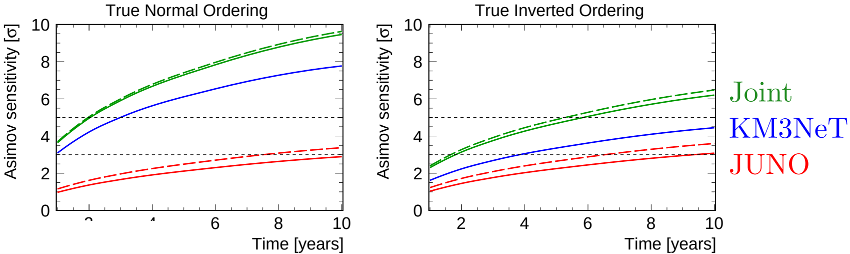

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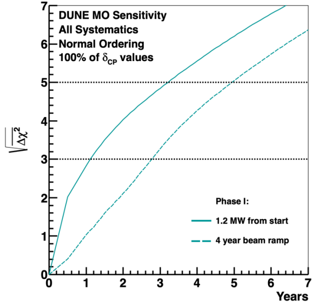
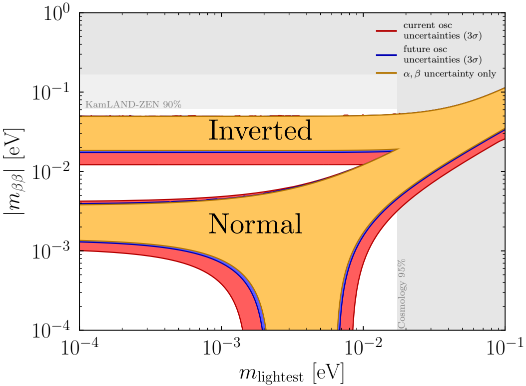


Matter effect ⇒ DUNE 2203.06100

Mass ordering: broad implications

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



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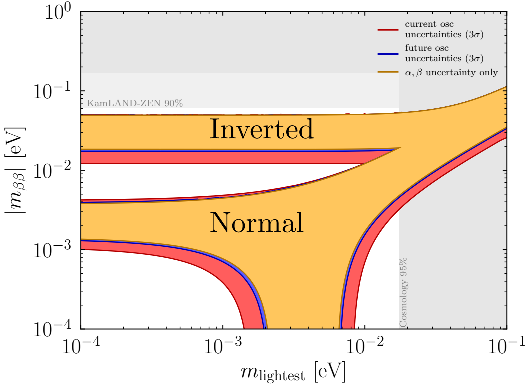
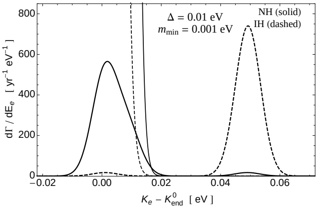
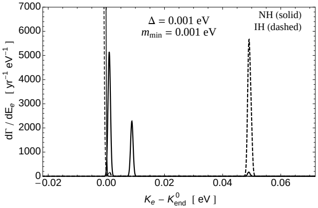






A. Long, C. Lunardini, E. Sabancilar 1405.7654

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

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

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

   PBD, et al. `1701.04828`

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

   PBD, Y. Farzan, I. Shoemaker `1804.03660`

3. Dresden-II for any mediator mass

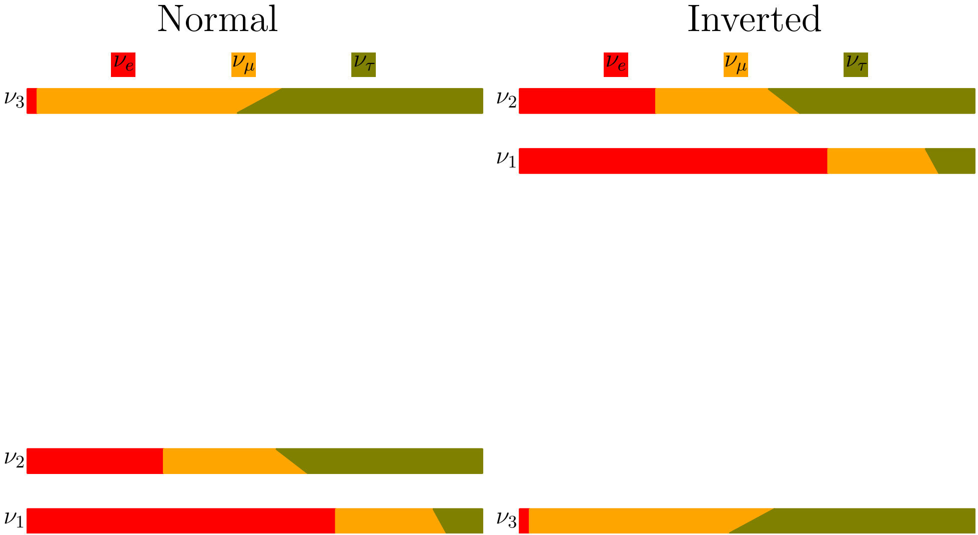
   PBD, J. Gehrlein `2204.09060`

4. Can still evade with specific flavor structures

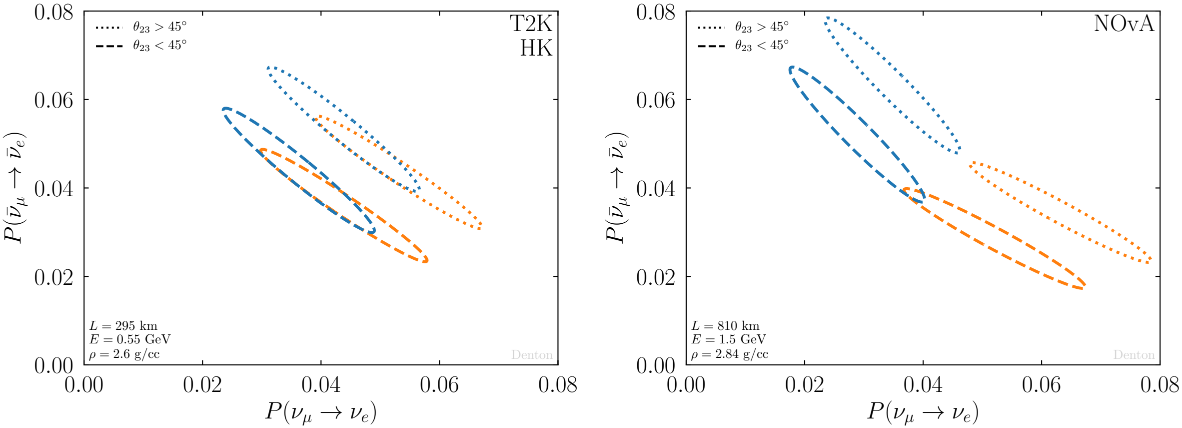
   $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$ or certain u / d combinations

θ_{23} octant

θ_{23} octant: what is it?

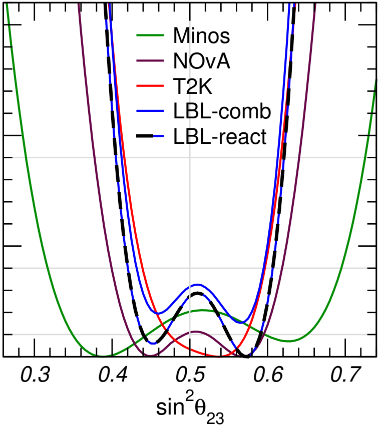


θ_{23} octant: what is it really?



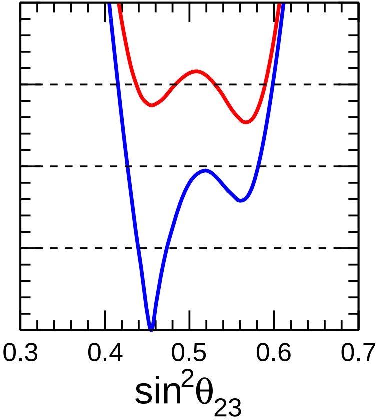
Lower octant more “normal” than upper octant

θ_{23} octant: current status



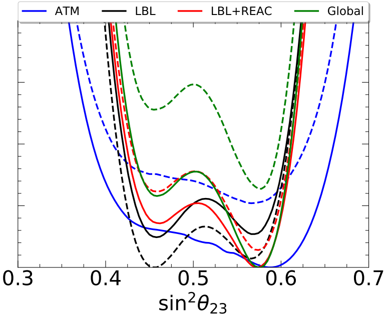
I. Esteban, et al. 2007.14792

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



F. Capozzi, et al. 2107.00532

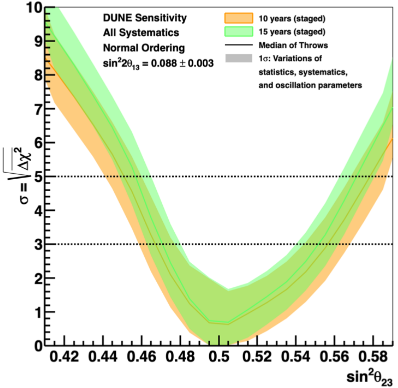
Prefers **lower** at $\sim 1.5\sigma$



P. de Salas, et al. 2006.11237

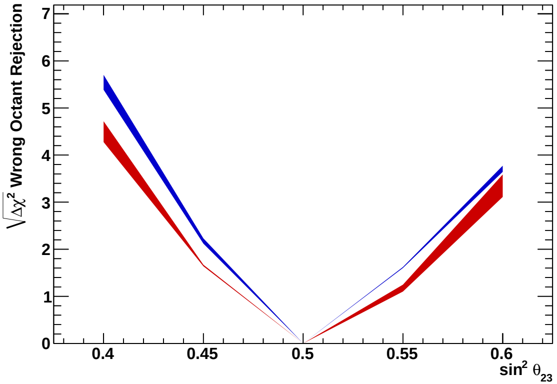
Prefers **upper** at $> 2\sigma$

θ_{23} octant: future sensitivities



$\sim 3-5\sigma$

DUNE 2002.03005



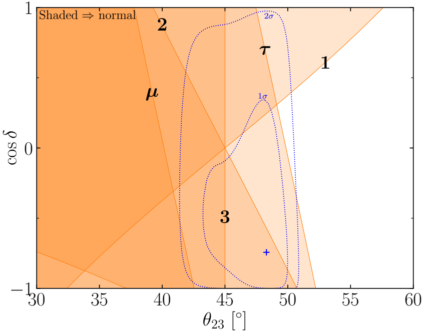
Beam+Atm$\Rightarrow\sim 3-6\sigma$

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

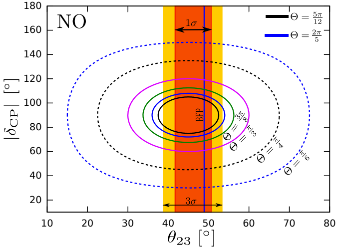
μ-τ interchange/reflection symmetry

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

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

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

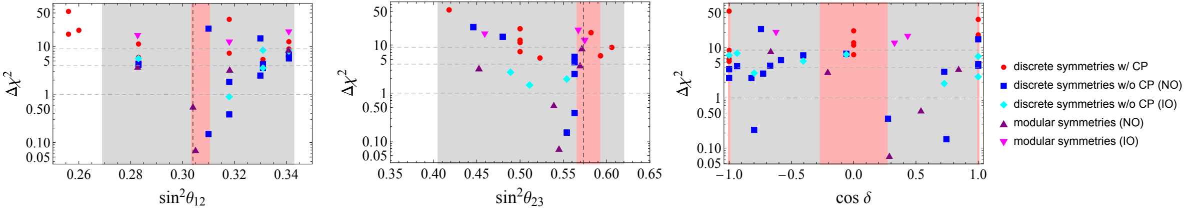
Predicts: $\theta_{23} = 45°$, often $\theta_{13} = 0$



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

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

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 ⇒ 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`

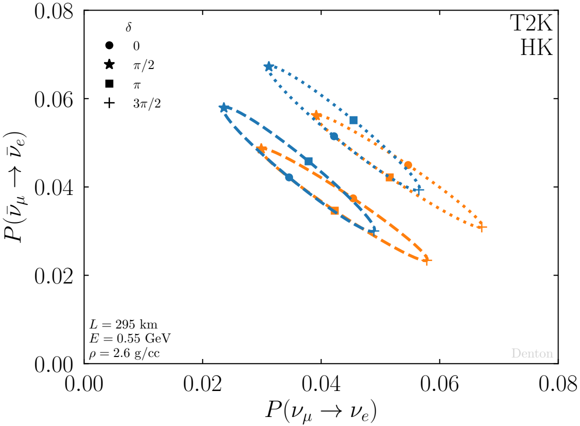
3. Lepton mass matrix: **?**

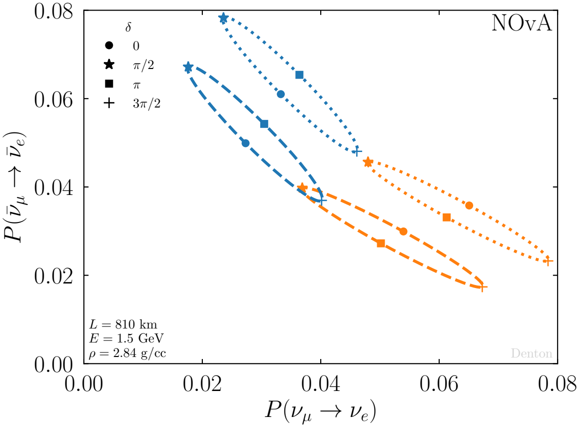
$$\frac{|J_{\rm PMNS}|}{J_{\rm max}} < 0.34$$

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

$J_{\rm max} = \frac{1}{6\sqrt3} \approx 0.096$

δ: what is it really?





δ: what is it not?

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

The amount of leptogenesis is a function of:

1. 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

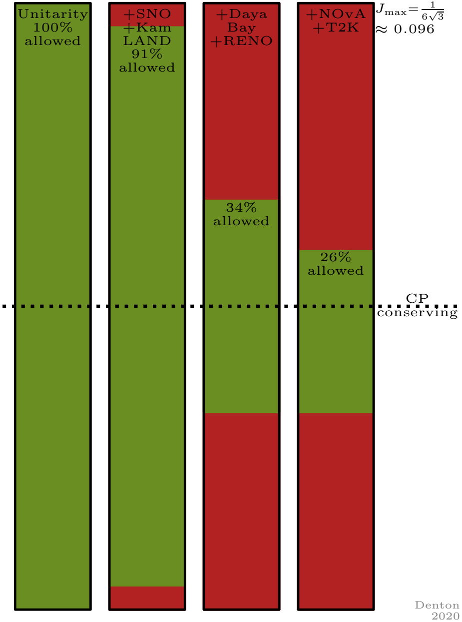
K. Moffat, et al. 1809.08251

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

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



Neutrinos: more new physics?

Lots of interesting new physics scenarios in oscillations

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 in oscillations

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

5. Unitarity violation

   PBD 2109.14576
   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

Three BSM scenarios:

Non-standard neutrino interactions (NSI)
Light sterile neutrinos
Unitarity violation (UV)

Three BSM scenarios:

Non-standard neutrino interactions (NSI)

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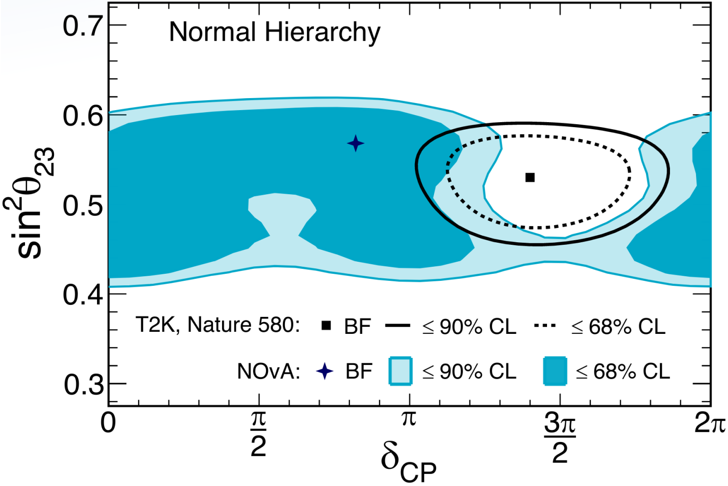
CP violation at NOvA and T2K?

Excitement at Neutrino2020!



A. Himmel for NOvA 10.5281/zenodo.3959581

NSI review

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

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

Estimate size of effect: magnitude

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

$a \propto \rho E$

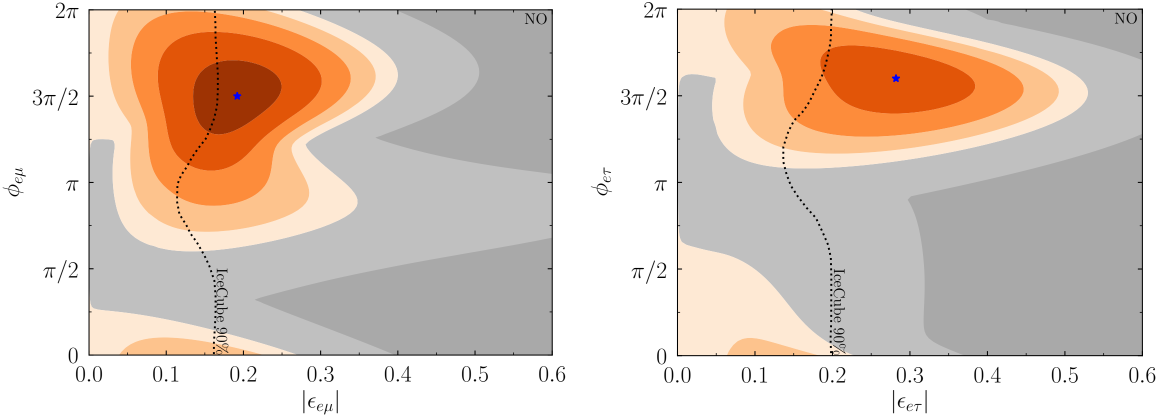
$w_\beta = s_{23}$, c_{23} for $\beta = \mu, \tau$

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

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 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

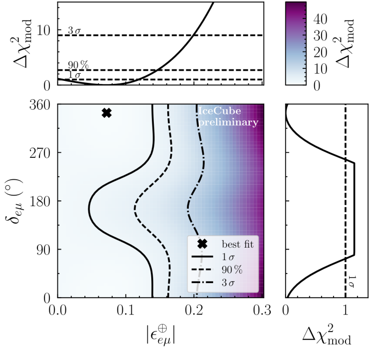
NSI effects grow with energy, density, and distance

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

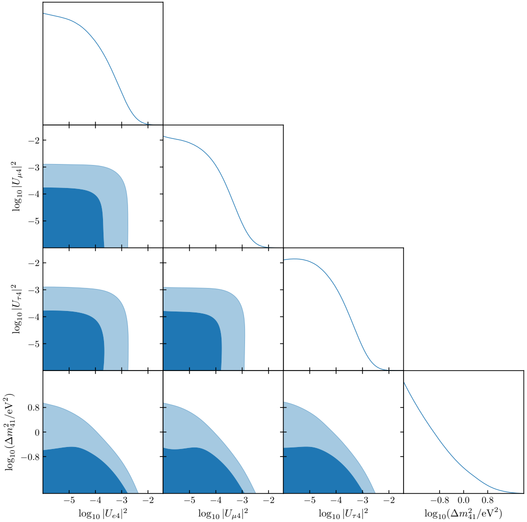
Three BSM scenarios:

Non-standard neutrino interactions (NSI)
Light sterile neutrinos
Unitarity violation (UV)

Light sterile neutrinos

- Sterile neutrinos are a generic prediction of most neutrino mass models
- Sterile neutrinos at $m_4 \sim$ keV could be dark matter
- Nobody asked for steriles at $m_4 \sim 1$ eV
- Would lead to new oscillations
- Lots of hints pointing to $m_4 \sim 1$ eV
- Cosmology?

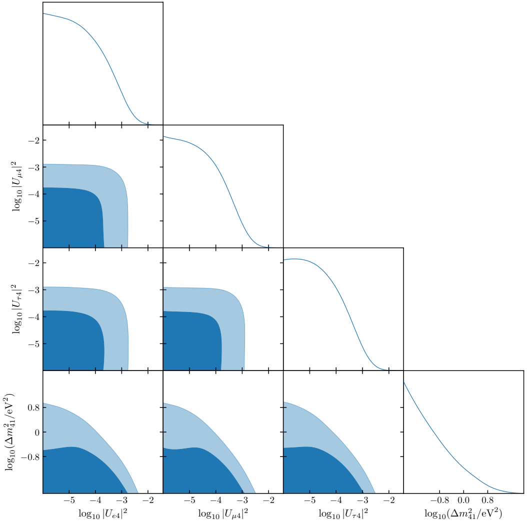
Cosmological bounds



1σ, 2σ S. Hagstotz, et al. 2003.02289

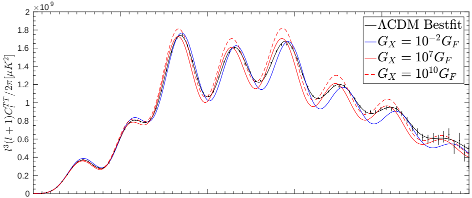
- Includes CMB temperature, polarization, and lensing, and BAO
- No local H_0 constraint
- Bounds independent of flavor
- To be consistent with data must have small mixing **and** small mass

Cosmological bounds



1σ, 2σ S. Hagstotz, et al. 2003.02289

- Includes CMB temperature, polarization, and lensing, and BAO
- No local H_0 constraint
- Bounds independent of flavor
- To be consistent with data must have small mixing **and** small mass
- Much more than just $N_{\rm eff}$ and $\sum m_\nu$
- Just adding a new interaction is not straightforward



N. Song, M. Gonzalez-Garcia, J. Salvado 1805.08218

Gallium experiments

- Low energy solar neutrino experiments measure the *pp* flux
    - Consistent with KamLAND

SAGE 0901.2200

GALLEX 1001.2731

- Callibrate detectors with intense radioactive sources
- See fewer ν_e than expected:

3.0σ: C. Giunti, M. Laveder 1006.3244

2.3σ: J. Kostensalo, et al. 1906.10980

$> 4\sigma$: BEST 2109.11482

- Cannot be easily explained with SM physics

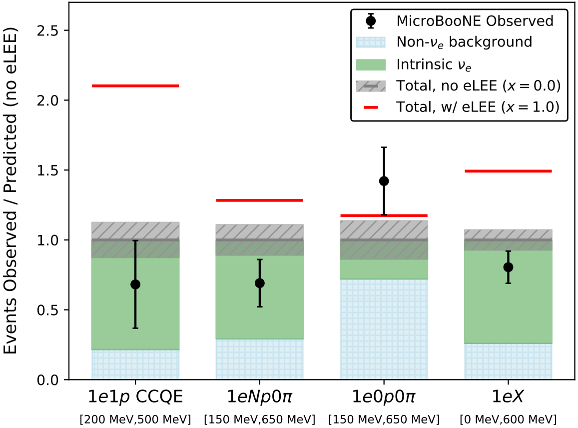
C. Giunti, et al. 2212.09722

V. Brdar, J. Gehrlein, J. Kopp 2303.05528

W. Haxton, et al. 2303.13623

- Prefers:
    - $\Delta m^2_{41} \gtrsim 0.5 \text{ eV}^2$
    - $\sin^2 2\theta_{ee} = 4|U_{e4}|^2(1-|U_{e4}|^2) \sim 0.4$

MicroBooNE

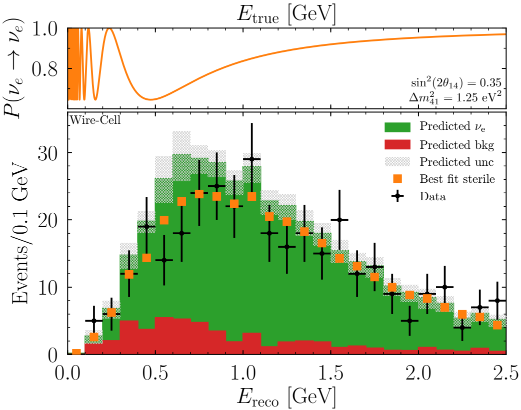


- Three analysis teams:
  1. Wire-Cell
  2. Deep Learning
  3. Pandora
     - With 0 protons
     - With 1+ protons
- Underfluctuation compared to no-oscillations
- Disfavors MiniBooNE's best fit LEE hypothesis at 3.75σ

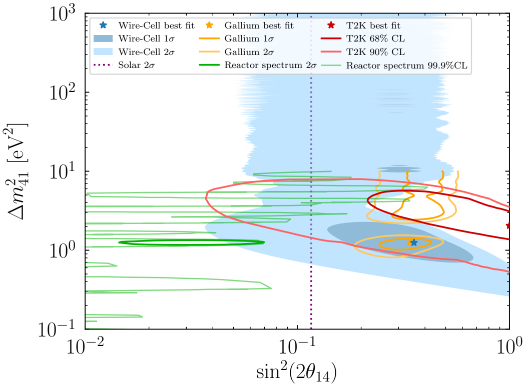
MicroBooNE `2110.14054`

Dip hunting

- 4 analysis channels
  - Wire cell has most statistics
  - Analyses not fully independent
- Dip appears in multiple analyses



Global ν_e disappearance picture



- MicroBooNE and gallium regions agree
- Constraints from solar and reactor
- Cosmology disfavors entire plane!

Shape-shifting sterile neutrinos

How to evade constraints?

Shape-shifting sterile neutrinos

How to evade constraints?

Suppose:

1. Sterile neutrinos talk to dark matter

DM is ultralight boson

2. Dark matter talks to baryons

Then:

1. Sterile neutrinos aren't abundantly produced in the early universe
2. Mixing angle in the Sun is suppressed
3. Reactor constraints still exist

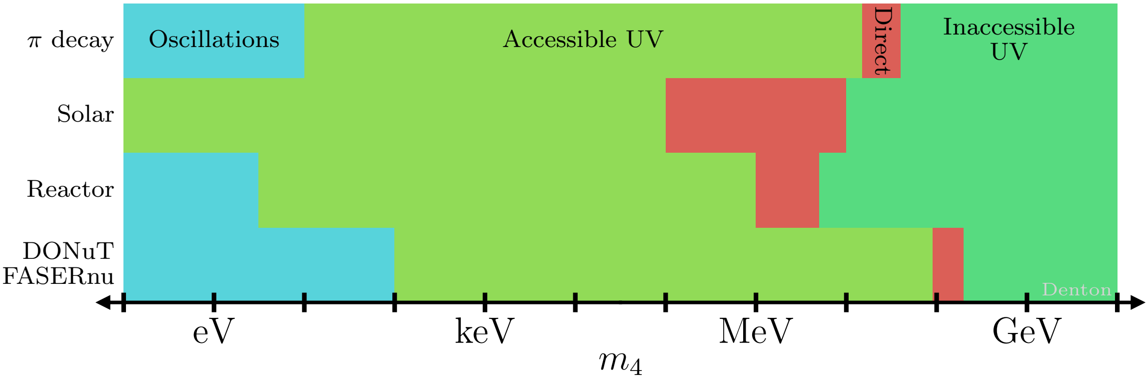
H. Davoudiasl, PBD 2301.09651

PBD 2301.11106

Three BSM scenarios:

Non-standard neutrino interactions (NSI)
Light sterile neutrinos
Unitarity violation (UV)

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

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

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

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2. Oscillation averaged:

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

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3. No matter effect:

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

Kinematically **inaccessible** states

1. Nonunitary calculation of $m \times m$ matrix

m = number of kinematically accessible states

2. Rescale probability:

$$P_{\alpha\beta}=\frac{|\sum_{i=1}^{\rm acc}U^*_{\alpha i}e^{iP_iL}U_{\beta i}|}{(\sum_{i=1}^{\rm acc}U^*_{\alpha i}U_{\alpha i})(\sum_{i=1}^{\rm acc}U^*_{\beta i}U_{\beta i})}$$

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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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 steak

Unitarity violation: tau row

Leptons: tau row is the weakest

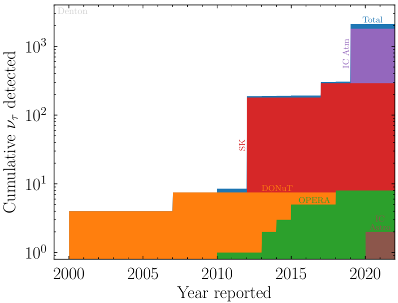
1. Existing global analyses use OPERA and SNO
2. More data from atmospheric ν_τ appearance!

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

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PBD 2109.14576

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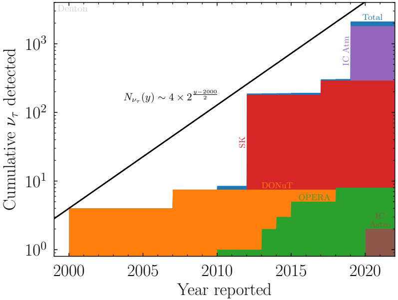
PBD, J. Gehrlein 2109.14575



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

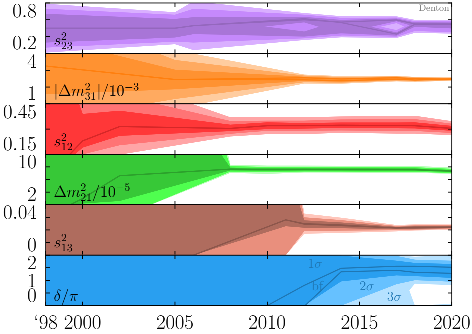
- Four known unknowns in particle physics: all neutrinos
- Mass ordering will be measured (robustness?)
- θ_{23} octant is important for flavor models
- δ could shed light on CP violation
- Hints of new physics pointing towards NSI & steriles
- Unitarity violation is phenomenologically very rich
- Lots of existing tau neutrino 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

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

Models with large NSIs consistent with CLFV:

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U. Dey, N. Nath, S. Sadhukhan 1804.05808 Y. Farzan 1912.09408

Affects oscillations via new matter effect

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

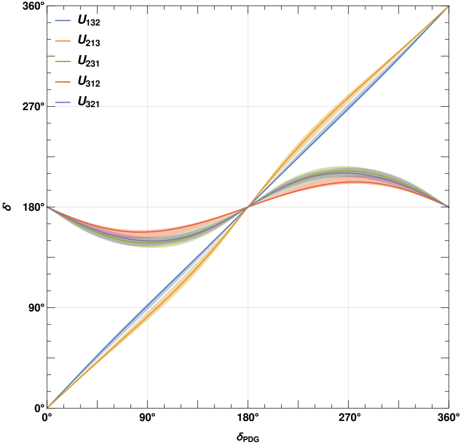
Matter potential $a\propto G_F\rho E$

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 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

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

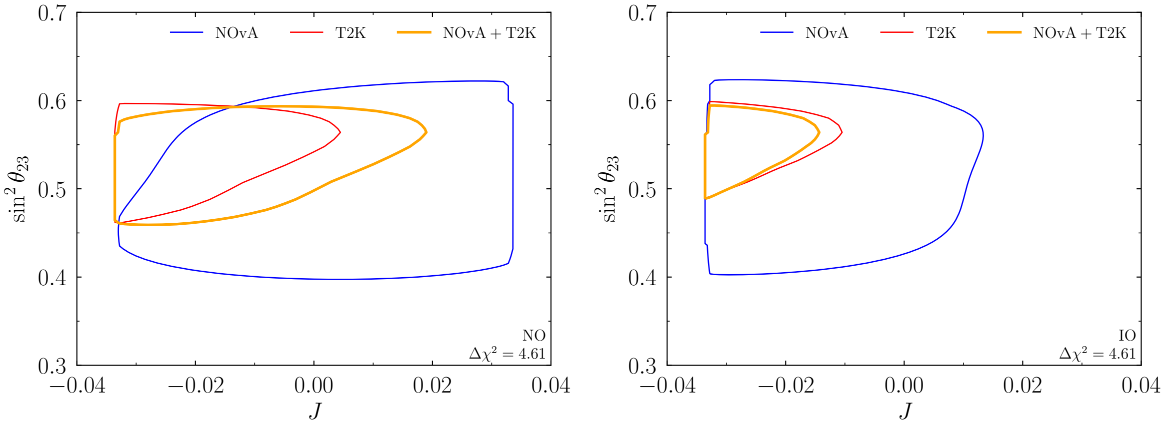
Looks like "large" CPV:

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

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

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

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

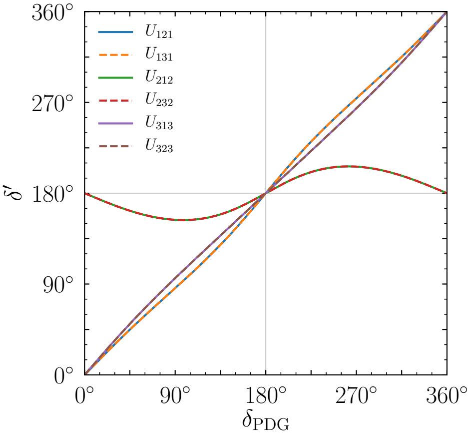
e.g. $P(\nu_\mu \to \nu_\mu)$ depends on $\cos\delta$ a tiny bit

- 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

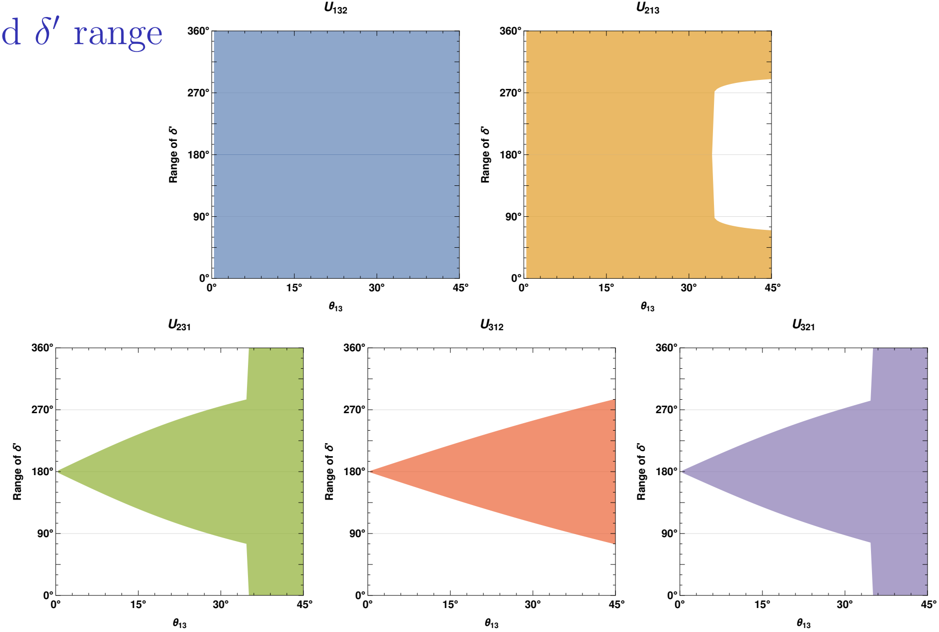
Repeated rotations



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

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

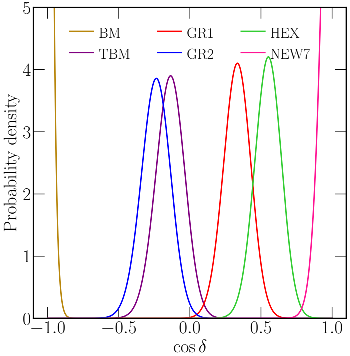
Allowed δ' range



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

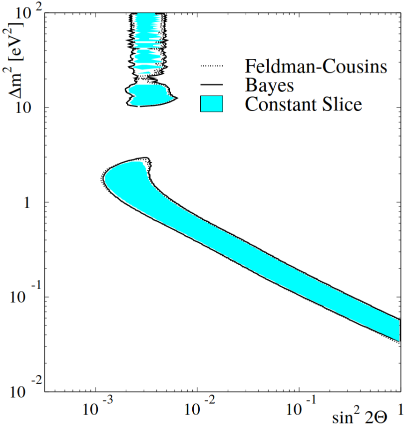


L. Everett, et al. 1912.10139

Accelerator: LSND

- LSND ran from 1993-1998
- $E_{\bar\nu_\mu} \in [20, 53]$ MeV
- $L = 30$ m
- Looked for $\bar\nu_\mu \to \bar\nu_e$ appearance
- Excess of: $87.9 \pm 22.4 \pm 6.0 \Rightarrow 3.8\sigma$ (1 dof)
- Interesting region:
  - $\Delta m^2_{41} \sim 1$ eV^2
  - $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu4}|^2 \sim 0.002$

OPERA, ICARUS disfavor $\sin^2 2\theta_{\mu e} \gtrsim 0.02$



LSND hep-ex/0104049

Accelerator: MiniBooNE

- Built to test LSND, higher energy, longer baseline, similar L/E, both $\nu, \bar{\nu}$
- $E_{\nu_\mu} \sim 500$ MeV
- $L = 541$ m
- Excesses:
  - ν_e: $381.2 \pm 85.2 \Rightarrow 4.5\sigma$ (1 dof)
  - $\bar{\nu}_e$: $79.3 \pm 28.6 \Rightarrow 2.8\sigma$ (1 dof)
  - Combined: 4.7σ (1 dof)
  - Excesses consistent with LSND under sterile hypothesis
  - Combined with LSND: $\Rightarrow 6.0\sigma$ (1 dof)

MiniBooNE 1805.12028

MicroBooNE disappearance

MicroBooNE is focused on ν_e appearance
Can do ν_μ and ν_e disappearance too!

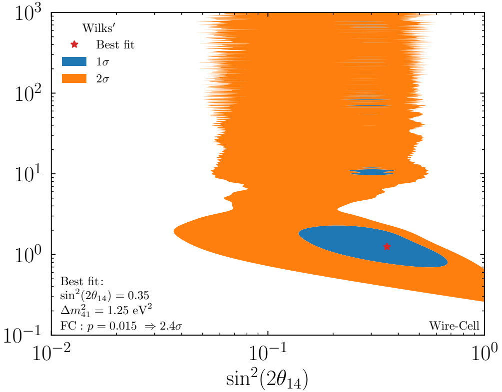
See also D. Cianci, et al. `1702.01758`

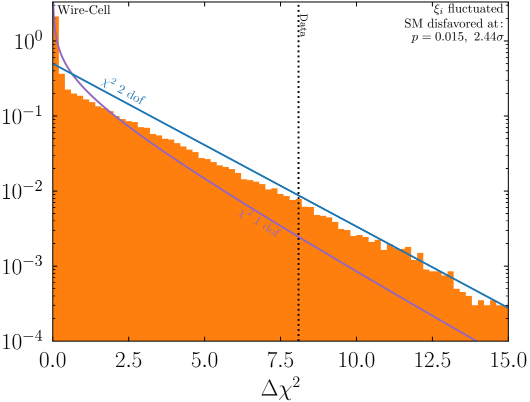
MiniBooNE backgrounds too big, plus anomaly

Analysis procedure

1. Take systematics as fully uncorrelated bin to bin
2. Unfold predicted spectrum to spectrum in true energy
    - Use a derivative regulator
3. Apply oscillation probability
4. Reapply energy smearing
5. Compare to data with LLR-Poisson with pull terms
6. Apply Feldman-Cousins
    - Fluctuate systematics
    - Literature suggests this is conservative
    - Verified that it is conservative in this case
7. Get contours via Wilks'
    - FC contours are very similar

Results and Monte Carlo significance





Other MicroBooNE analysis channels

Analysis	$\sin^2(2\theta_{14})$	Δm^2_{41} (eV^2)	$N\sigma$ (FC)
Wire-Cell	$0.35^{+0.19}_{-0.16}$	$1.25^{+0.74}_{-0.39}$	2.4
Deep-Learning	$0.88^{+0.12}_{-0.41}$	$3.91^{+0.40}_{-0.40}$	1.8
Pandora-Np	$0.81^{+0.19}_{-0.47}$	[1.28,2.44] $6.73^{+1.75}_{-0.90}$ $\vdots$	2.4
Pandora-0p	$1_{-0.29}$	$2.21^{+0.82}_{-0.60}$ $\vdots$	1.8

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 constraints

Unitary violation: the study of how $U_{3\times3}$ is not unitary independent of m_4, m_5, ...
Constraints vary considerably in the literature:

$$1-|U_{e1}|^2-|U_{e2}|^2-|U_{e3}|^2<\begin{cases}0.05\\0.001\end{cases}\quad\text{at }2\sigma$$

S. Parke, M. Ross-Lonergan 1508.05095

Z. Hu, et al. 2008.09730

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All analyses *assume* unitarity
Throw out LSND, MiniBooNE, RAA, gallium, etc.

S. Parke, M. Ross-Lonergan `1508.05095`
Z. Hu, et al. `2008.09730`

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: 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