Long Baseline Neutrino Oscillation Phenomenology

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Neutrino oscillations

$\mathcal{O}(1)$

2 flavor-like oscillations

20 years ago

↓

Non-zero neutrino mass and mixing

Physics beyond Standard Model

Neutrino oscillations

$\mathcal{O}(1)$

2 flavor-like oscillations

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Non-zero neutrino mass and mixing

Physics beyond Standard Model

Big Questions

- What is the origin of neutrino mass?
- What is the nature of the neutrino?
- Is there a theory of flavor?
- Why are lepton and quark mixings so different?
- Neutrino in cosmology, relation to baryon asymmetry, dark matter, …

Neutrino oscillations

$\mathcal{O}(1)$

2 flavor-like oscillations

20 years ago

$\mathcal{O}(10\%)$

3 flavor oscillations

now

Non-zero neutrino mass and mixing

Physics beyond Standard Model

Specific Questions

- What are the 3 flavor oscillation parameters?
  2 mass square differences, 3 mixing angles
- Is there CP violation in the lepton sector?
  measure phase
- What is the mass ordering?
- Are there additional light neutrino states?

Three-flavor neutrino oscillations

- Three-flavor mixing matrix

$$U = R_{23}\, K\, R_{13}\, K^*\, R_{12}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\Delta m^2_{21} = \Delta m^2_{sol} \qquad \Delta m^2_{32} = \Delta m^2_{atm}$$

$$\theta_{12} = \theta_{sol} \qquad \theta_{13} = \theta_{reactor} \qquad \theta_{23} = \theta_{atm} \qquad \delta$$

NO

IO

NuFIT 4.1 (2019)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.2$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$	$0.563^{+0.019}_{-0.026}$	$0.430 \to 0.612$
	$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$	$0.02261^{+0.00067}_{-0.00064}$	$0.02066 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	285^{+24}_{-26}	$205 \to 354$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$	$-2.509^{+0.032}_{-0.030}$	$-2.603 \to -2.416$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
	$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
	$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
	$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

Ivan Esteban
M.C. Gonzalez-Garcia
Alvaro Hernandez-Cabezudo
Michele Maltoni
Thomas Schwetz

JHEP 01 (2019) 106
[arXiv:1811.05487]
NuFIT 4.1 (2019)
www.nu-fit.org.

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.11–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO)	$2.56^{+0.03}_{-0.04}$	2.49–2.62	2.46–2.65
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO)	2.46 ± 0.03	2.40–2.52	2.37–2.55
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.70
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.66^{+0.16}_{-0.22}$	5.05–5.96	4.41–6.09
$\theta_{23}/^\circ$ (NO)	$48.79^{+0.93}_{-1.25}$	45.26–50.56	41.63–51.32
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.66^{+0.18}_{-0.23}$	5.14–5.97	4.46–6.09
$\theta_{23}/^\circ$ (IO)	$48.79^{+1.04}_{-1.30}$	45.78–50.59	41.88–51.30
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.225^{+0.055}_{-0.078}$	2.081–2.349	2.015–2.417
$\theta_{13}/^\circ$ (NO)	$8.58^{+0.11}_{-0.15}$	8.30–8.82	8.16–8.94
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.250^{+0.056}_{-0.076}$	2.107–2.373	2.039–2.441
$\theta_{13}/^\circ$ (IO)	$8.63^{+0.11}_{-0.15}$	8.35–8.86	8.21–8.99
δ/π (NO)	$1.20^{+0.23}_{-0.14}$	0.93–1.80	0.80–2.00
$\delta/^\circ$ (NO)	216^{+41}_{-25}	168–325	144–360
δ/π (IO)	1.54 ± 0.13	1.27–1.79	1.14–1.90
$\delta/^\circ$ (IO)	277^{+23}_{-24}	229–322	205–342

P.F. de Dalas, D.V. Forero,
S. Gariazzo, P. Martinez-Mirave,
O. Mena, C.A. Ternes,
M. Tortola, J.W.F. Valle
arXiv:2006.11237

Neutrino oscillations

$\mathcal{O}(1)$

2 flavor-like oscillations

20 years ago

$\mathcal{O}(10\%)$

3 flavor oscillations

now

$\mathcal{O}(1\%)$

future

Non-zero neutrino mass and mixing

Physics beyond Standard Model

Specific Questions

- What are the 3 flavor oscillation parameters?
  2 mass square differences, 3 mixing angles
  Is 2-3 mixing maximal? if not, what is the octant, …
- Is there CP violation in the lepton sector?
  measure phase
- What is the mass ordering?
- Are there additional light neutrino states?

Neutrino oscillations

$\mathcal{O}(1)$

2 flavor-like oscillations

20 years ago

$\mathcal{O}(10\%)$

3 flavor oscillations

now

$\mathcal{O}(1\%)$

future

Non-zero neutrino mass and mixing

Physics beyond Standard Model

Questions

- What is the correct framework?
- Are 3-flavor oscillations a complete description at accessible energies?
  - are there additional light neutrino states?
  - are there additional interactions?
  - are there other phenomena affecting neutrino oscillations?

Neutrino oscillations

$\mathcal{O}(1)$	$\longrightarrow$	$\mathcal{O}(10\%)$	$\longrightarrow$	$\mathcal{O}(1\%)$
20 years ago		now		future

Tools evolve:

- natural sources $\longrightarrow$ man made sources $\longrightarrow$ better/more sources
- bigger, better, different types of detectors
- better experimental simulation and analysis tools

Neutrino oscillations

$\mathcal{O}(1)$	→	$\mathcal{O}(10\%)$	→	$\mathcal{O}(1\%)$
2 flavor-like oscillations		3 flavor oscillations		3 flavor + more
20 years ago		now		future

Tools evolve:

- natural sources → man made sources → better/more sources
- bigger, better, different types of detectors
- better experimental simulation and analysis tools
- better theoretical analysis framework

Neutrino oscillations

What is the correct framework?

- Three flavors + BSM*
- are there additional light neutrino states? (SKA & Pedro Machado)
- are there additional interactions?
- are there other phenomena affecting neutrino oscillations?
  -decay, decoherence, LIV, CPTV, …
- Is leptonic mixing unitary?

* Sanjib Kumar Agarwalla (SKA)'s talk

Three flavor neutrino oscillations (the new - or ν - standard model)

- Weak interactions (*W* & *Z* exchange) are the *only* neutrino interactions
- There are no additional neutrino states that can mix with the three SM flavors

- Mixing matrix: $U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$

  U is unitary: $UU^\dagger = U^\dagger U = \mathbb{1}$

  - Can be parameterized by 3 mixing angles and 1 phase

  - Oscillation probabilities depend on two mass square differences and 4 mixing parameters

  + matter effects due to *W* exchange only

Three flavor neutrino oscillations (the new - or ν - standard model)

- Weak interactions (*W* & *Z* exchange) are the *only* neutrino interactions
- There are no additional neutrino states that can mix with the three SM flavors

- *not true:* - additional states and/or interactions *needed* to generate neutrino masses and mixing

  - other interactions and new light states possible

- do not know correct scale/model
  - *if all* new physics is at high scale (e.g. GUT models)
    $\longrightarrow$ all deviations are negligibly small
  - observable corrections possible in many models

- ultimately observational question

Non-Standard Neutrino Interactions (NSI)

- any interaction beyond weak (*W*, *Z* exchange)
- pheno approach: parametrize most general interaction i.t.o. known particle content → explore observational consequences
  - long baseline neutrino oscillations
    - matter effects sensitive to any new vector-type interactions propagation effects large
    - source/detector effects smaller, but can include other types of interactions
  - other types of experiments (scattering) are complementary

  → need overall consistency
  - current and future sensitivity: 10% to under 1% of G_F

  → probing relevant, unexplored physics scales
- construct model → explore observational consequences in all relevant experiments (ν , collider, flavor, etc.)

* Sanjib Kumar Agarwalla's talk

ν SM Leptonic Mixing Unitarity

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.243 \to 0.490 & 0.473 \to 0.674 & 0.651 \to 0.772 \\ 0.295 \to 0.525 & 0.493 \to 0.688 & 0.618 \to 0.744 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

NuFIT 4.1 (2019) 3σ ranges
assuming unitarity

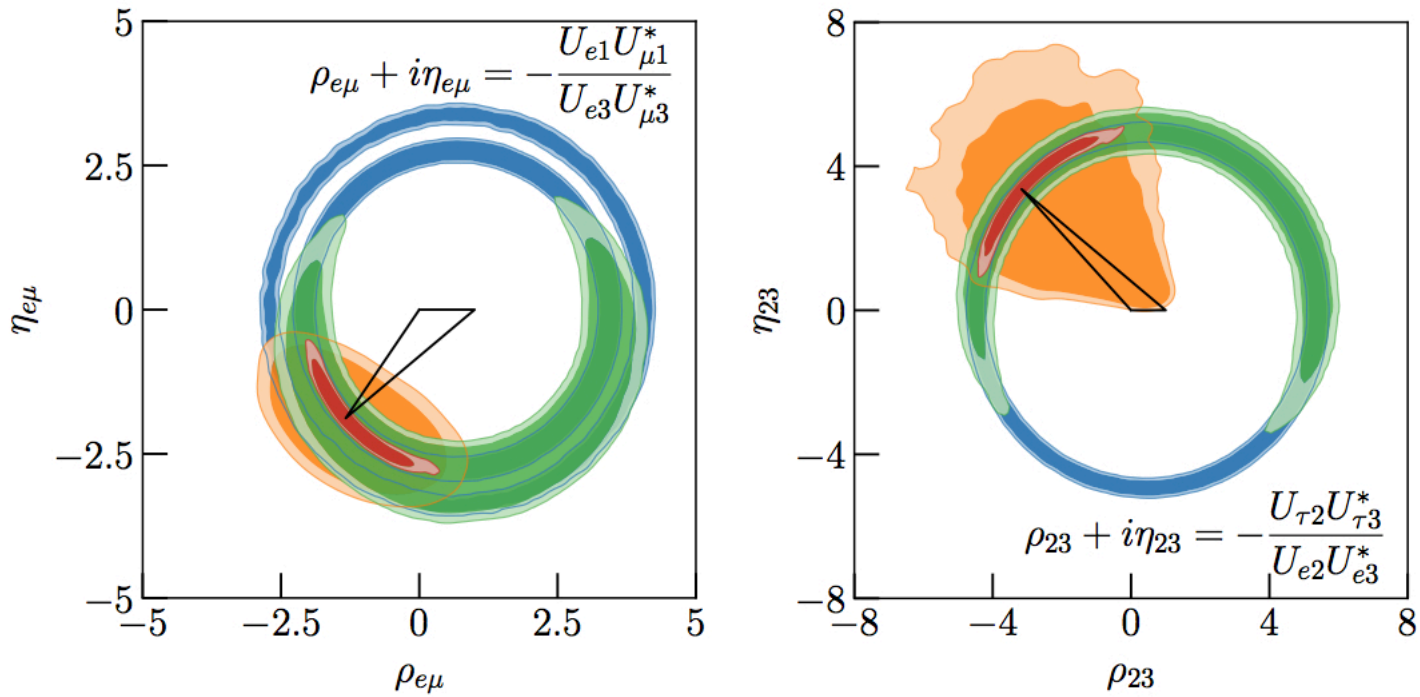
standard parametrization, but it is just one of many

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j=1}^{3} \mathrm{Re}(U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j}) \sin^2 \frac{\Delta m^2_{ij} L}{4E}$$
$$+ 4 \sum_{i>j=1}^{3} \mathrm{Im}(U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j}) \sin \frac{\Delta m^2_{ij} L}{4E} \cos \frac{\Delta m^2_{ij} L}{4E}$$

Invariant measure of CP violation

$$|J| = |\mathrm{Im}(U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j})| = c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} |\sin \delta|$$

ν SM Leptonic Mixing Unitarity



Current: Joint Fit
Future: Joint Fit
Disappearance
Appearance

$$\sum_i U_{\alpha i} U^*_{\beta i} = 0 \qquad \alpha \neq \beta$$

$$\sum_\alpha U_{\alpha i} U^*_{\alpha j} = 0 \qquad i \neq j$$

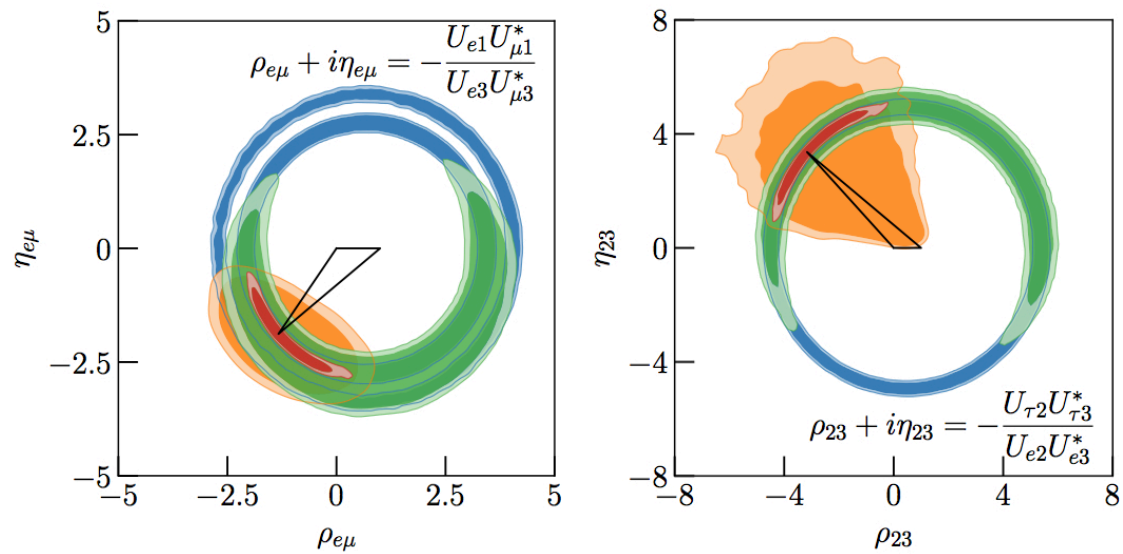
Sebastian A.R. Ellis, Kevin J. Kelly, Shirley Weishi Li, arXiv:2004.13719

Beyond ν SM Leptonic Mixing Unitarity

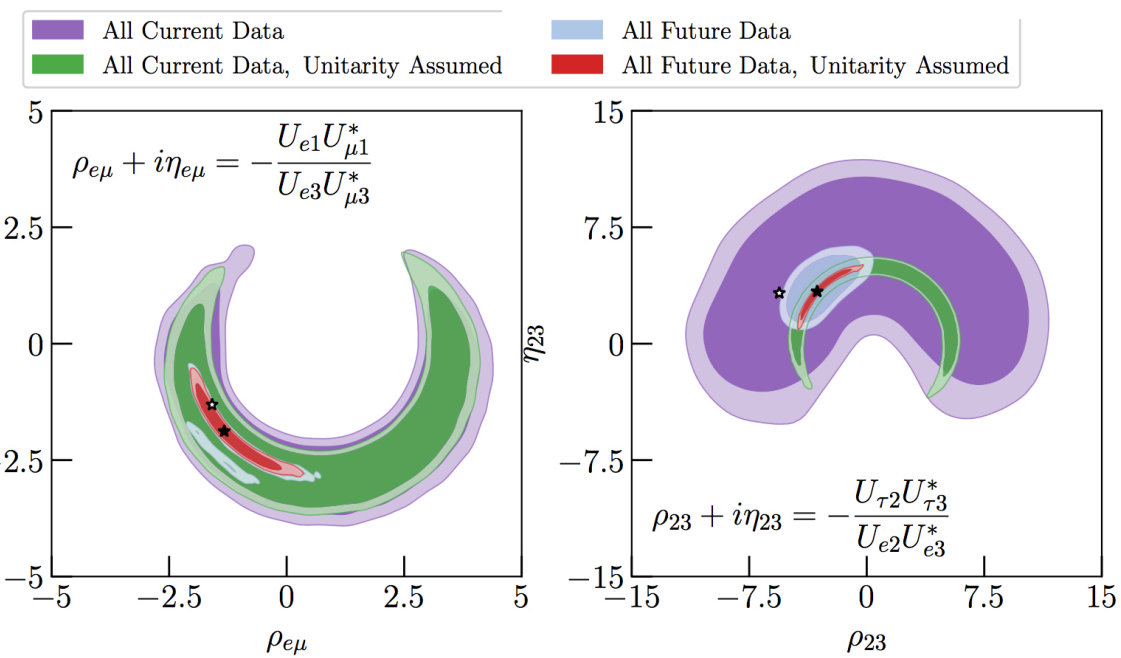
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

- ~~(3 angles + 1 phase)~~ $\longrightarrow$ 13 parameters = 9 $|U_{\alpha i}|$ and 4 phases
  - more possible sources of CP violation
  - $|\mathrm{Im}(U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j})|$ need not be the same
  - 3×3 submatrix of an $N \times N$ unitary matrix $\longrightarrow$ constraints
  - Nontrivial to extract U from some experimental results
    - sometimes analysis uses unitarity to separate different contributions to signal
    - solution: fit for $U_{\alpha i}$ rather than for angles
  - multiple pheno parametrizations $\longrightarrow$ comparisons need care

Beyond ν SM Leptonic Mixing Unitarity



Current: Joint Fit
Future: Joint Fit
Disappearance
Appearance



Sebastian A.R. Ellis,
Kevin J. Kelly,
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arXiv:2004.13719

Beyond ν SM Leptonic Mixing Unitarity

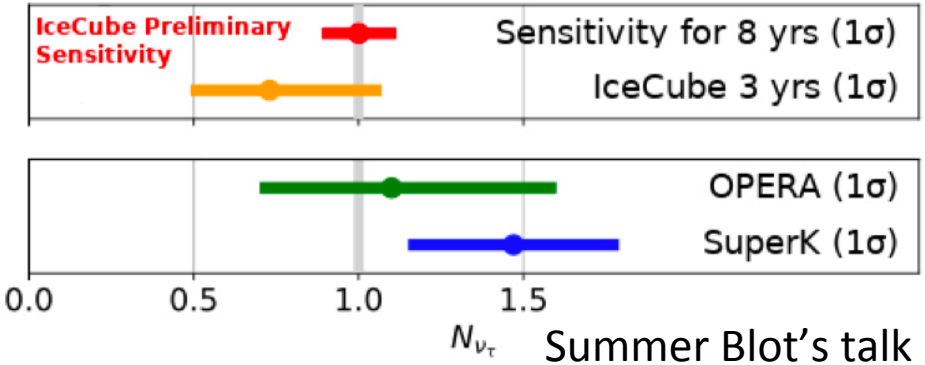
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

- Global fits + other constraints provide information
- True test of unitarity when 3rd row/column measured directly with higher precision: ν_τ appearance

  -May be possible at DUNE: arXiv:1904.07265

  -IceCube/DeepCore: better than 10% measurement of ν_τ appearance possible: *Phys.Rev.D* 81 (2010) 113008 *Phys.Rev.D* 99 (2019) 3, 032007

  -can also probe ν_τ interactions and other interesting physics



Summer Blot's talk

Neutrino oscillations

Testing the framework

- many possible extensions, sometimes manifest in same way in observations
- need new/different observables in many experiments
- need consistency of measurements from different types of experiments

Neutrino oscillations

Testing the framework vs. precision measurements of ν SM

- need consistency of measurements from different types of experiments

Consider the case of mass ordering:

- long baseline beam measurements
  - Mass ordering from matter effects
  - Off-axis: NOvA & T2K
    - $\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$
    - different distances: different weight of matter effect
    - $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$
  - WBB: DUNE
    - add energy spectrum info: lots of information
    - larger distance/ matter effects

Neutrino oscillations

Testing the framework vs. precision measurements of ν SM

- need consistency of measurements from different types of experiments

Consider the case of mass ordering:

- long baseline beam measurements
  - Mass ordering from matter effects $\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$
- ultimate long baseline experiment: atmospheric neutrinos
  - DUNE: use muon charge tag for ν vs. $\bar{\nu}$
    arXiv:1905.03589
  - IceCube/DeepCore: high statistics $\overset{(-)}{\nu}_\mu \longrightarrow \overset{(-)}{\nu}_\mu$
    Phys.Rev.D 78 (2008) 093003, arXiv:1902.07771
- reactor
  - $\bar{\nu}_e \to \bar{\nu}_e$
  - no CP violation, no matter effect- complementary
  - JUNO – interference between Δm^2_{sol} and Δm^2_{atm}

Outlook

- ν Standard Model?
- Need to first measure all properties: guaranteed useful information
- Expect surprises (lots of past examples)
- Anticipate surprises and prepare:
  - Explore different frameworks/scenarios beyond minimal
  - Test framework
    - Sometimes precision parameter measurement in minimal scenario can lead to framework test
    - Often more efficient to seek different ways to over-constrain system in order to get framework test
  - "Model-independent" parametrizations are valuable:
    - very general, easier to constrain from global analysis
  - Models and examples are valuable:
    - can identify special features missed in general analysis (these can either enhance or relax constraints/sensitivity)