

## Abstract

The nature of CP violation in the lepton sector is one of the biggest open questions in particle physics. Long-baseline accelerator neutrino experiments have the opportunity to determine if CP is violated in the mass matrix. I will discuss some theoretical issues about how CP is parameterized and, in particular, that using  $\delta$  is misleading. Then I will look at the most recent NOvA and T2K data which show a slight and very interesting tension. While this tension possibly indicates a flipping in the mass ordering, it is better fit by new physics such as non-standard neutrino interactions (NSI) with an additional source of CP violation. The strength of this NSI can be easily estimated analytically and I will present a numerical analysis of the preferred regions which are generally consistent with other constraints.

# CP Violation at Long-Baseline Neutrino Experiments

Peter B. Denton

LAW Physics

April 27, 2022

2006.09384 (JHEP)

with Rebekah Pestes

2008.01110 (PRL)

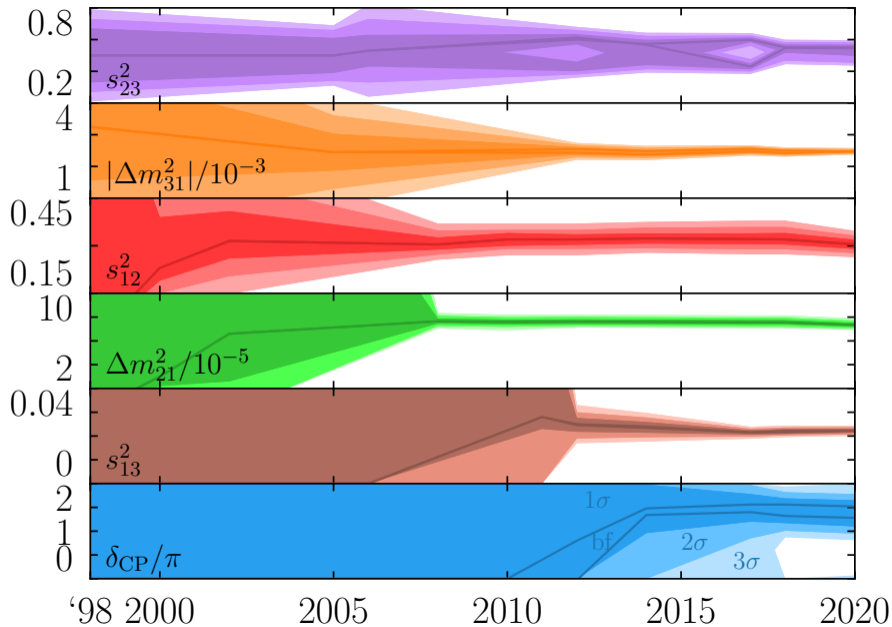
with Julia Gehrlein and Rebekah Pestes



Brookhaven<sup>™</sup>  
National Laboratory



Speaking from [Setauket](#) land



# CP Violation in the SM

1. Strong interaction: no observed EDM  $\Rightarrow$  CP (nearly) **conserved**

$$\frac{\bar{\theta}}{2\pi} < 10^{-11}$$

J. Pendlebury, et al. [1509.04411](#)

2. Quark mass matrix: non-zero but **small** CP violation

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

CKMfitter [1501.05013](#)

3. Lepton mass matrix: ?

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

[PBD](#), J. Gehrlein, R. Pestes [2008.01110](#)

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



# Overview

- ▶ Different parameterizations lead to different conclusions
- ▶ NOvA and T2K slightly disagree
- ▶ New physics can resolve this

# Parameterization of the PMNS matrix

A matrix takes us from mass states to flavor states and back

1.  $3 \times 3 \mathbb{C}$ : 18 dof
2. +Unitary:  $n^2$  constraints: 9 dof
3. +Charged lepton rephasing: 6 dof
4. +Neutrino rephasing: 4 dof

Focused on oscillations not  $0\nu\beta\beta$

# Parameterization of the PMNS matrix

Many possible parameterizations in the literature

1. Product of three rotations and a complex phase on one rotation

- ▶ Possibly including the same axis twice

H. Fritzsch, Z.-z. Xing [hep-ph/0103242](#)

2. Gell-Mann matrices

K. Merfeld, D. Latimer [1412.2728](#)

D. Boriero, D. Schwarz, H. Velten [1704.06139](#)

A. Davydova, K. Zhukovsky [PAN 82, 281 \(2019\)](#)

3. Four complex phases

R. Aleksan, B. Kayser, D. London [hep-ph/9403341](#)

4. Perturbative

L. Wolfenstein [PRL 51 1945 \(1983\)](#)

5. ⋮

## Sequence of rotations

$$U_1 \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad U_2 \equiv \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \quad U_3 \equiv \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Location of  $e^{i\delta}$  on  $\pm s_{ij}$  has no impact\*

Standard parameterization is  $U_{\text{PDG}} \equiv U_{123} = U_1 U_2 U_3$ .

$$U_{\text{PDG}} \equiv U_{123} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$



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What about other orders?

$$U_{123}, U_{132}, U_{213}, U_{231}, U_{312}, U_{321}$$

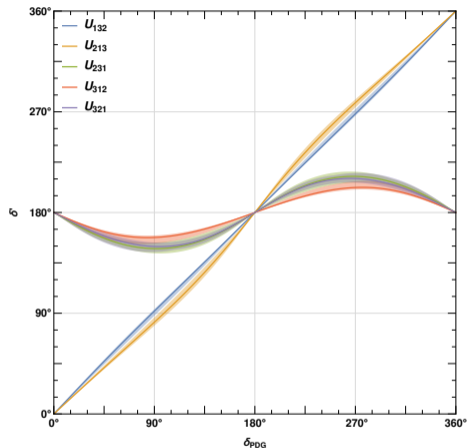
What about repeated rotations?

$$U_{121}, U_{131}, U_{212}, U_{232}, U_{313}, U_{323}$$

# Complex phase in different parameterizations

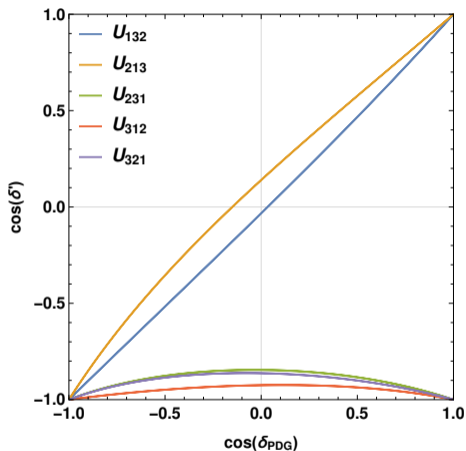
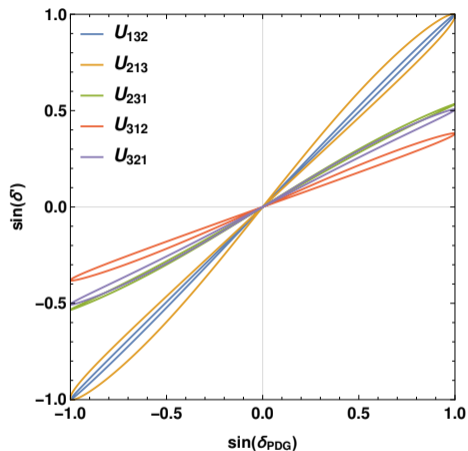
- ▶ Can relate the complex phase in one parameterization to that in another
- ▶  $U_{132}$  and  $U_{213}$  similar to  $U_{123}$
- ▶  $\delta$  constrained to  $\sim [150^\circ, 210^\circ]$  in  $U_{231}, U_{312}, U_{321}$
- ▶ Bands indicate  $3\sigma$  uncertainty on  $\theta_{12}, \theta_{13}, \theta_{23}$
- ▶ “50% of possible values of  $\delta$ ”  
⇒ parameterization dependent

DUNE TDR II [2002.03005](#)



Repeated rotations in backups

# The importance of $\cos \delta$



In these parameterizations  $\cos \delta \lesssim -0.8$

$|U_{e3}|$  is small

Given  $\theta_{12}, \theta_{13}, \theta_{23}$ :

$$|U| = \begin{pmatrix} 0.822 & 0.550 & 0.150 \\ \sqrt{0.138 + 0.068 \cos(\delta_{\text{PDG}})} & \sqrt{0.293 - 0.068 \cos(\delta_{\text{PDG}})} & 0.754 \\ \sqrt{0.186 - 0.068 \cos(\delta_{\text{PDG}})} & \sqrt{0.405 + 0.068 \cos(\delta_{\text{PDG}})} & 0.640 \end{pmatrix}$$

$$|U_{\alpha i}| > 0.23 \quad \text{except} \quad |U_{e3}| = 0.15$$

In  $U_{231}, U_{312}, U_{321}$ :

$$|U_{e3}| = \sqrt{A + B \cos(\delta')}$$

$$A, B > 0$$

Requires a partial cancellation  $\Rightarrow \cos(\delta') \sim -1$

Terms with sums or differences are “complicated”

Terms without are “simple”

## Quick approximation

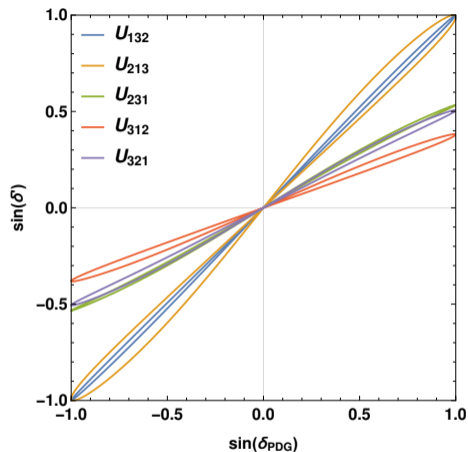
Can easily related  $\delta_{\text{PDG}} \rightarrow \delta'$ :

- ▶  $\delta' \approx \delta_{\text{PDG}}$  in  $U_{132}$  and  $U_{213}$
- ▶  $\sin(\delta') \approx d_{ijk} \sin(\delta_{\text{PDG}})$

$$d_{231} \approx s_{13} \frac{1 - s_{12}^2 c_{23}^2}{s_{12} c_{12} s_{23} c_{23}} \approx 0.57$$

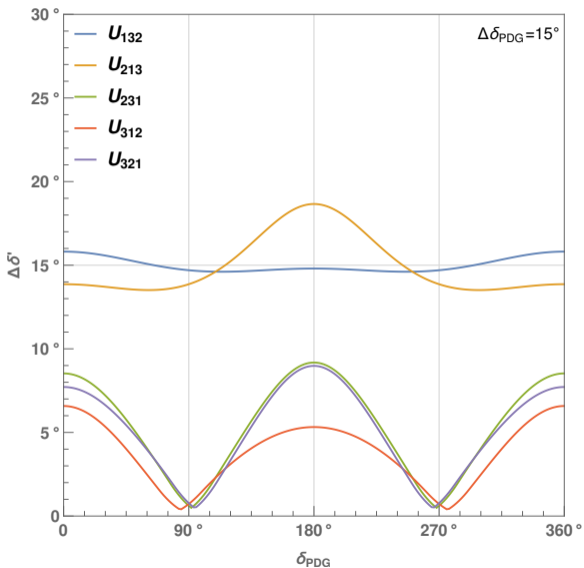
$$d_{312} \approx s_{13} \frac{1 - c_{12}^2 s_{23}^2}{s_{12} c_{12} s_{23} c_{23}} \approx 0.39$$

$$d_{321} \approx s_{13} \frac{1 - s_{12}^2 s_{23}^2}{s_{12} c_{12} s_{23} c_{23}} \approx 0.54$$



$\theta_{23} > 45^\circ$  plotted

## Precision on $\delta$



“For instance, the CKM angle  $\gamma$ , which is a very close analog of  $\delta$  in the neutrino sector, is determined to  $70.4^{+4.3}_{-4.4}$  and thus, a precision target for  $\delta$  of roughly  $5^\circ$  would follow.”

“A  $3\sigma$  distinction between models translates into a target precision for  $\delta$  of  $5^\circ$ .”

A. de Gouvea, et al. Snowmass 2013  
Neutrino Working Group [1310.4340](#)

Precision on  $\delta$  is parameterization dependent

## CP violation in oscillations

In vacuum at first maximum:

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

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

C. Jarlskog [PRL 55, 1039 \(1985\)](#)

- ▶ Extracting  $\delta$  from data requires every other oscillation parameter
- ▶  $J$  requires only  $\Delta m_{21}^2$  (up to matter effects)

Matter effects are easily accounted for

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

[PBD](#), S. Parke [1902.07185](#)

[PBD](#), H. Minakata, S. Parke [1604.08167](#)

## Jarlskog parameter space

- ▶ 50%  $\delta$  space is parameterization dependent
- ▶  $\Delta\delta$  is parameterization dependent
- ▶  $\delta_{\text{PDG}} = \pi/2, 3\pi/2 \neq$  maximal CP violation

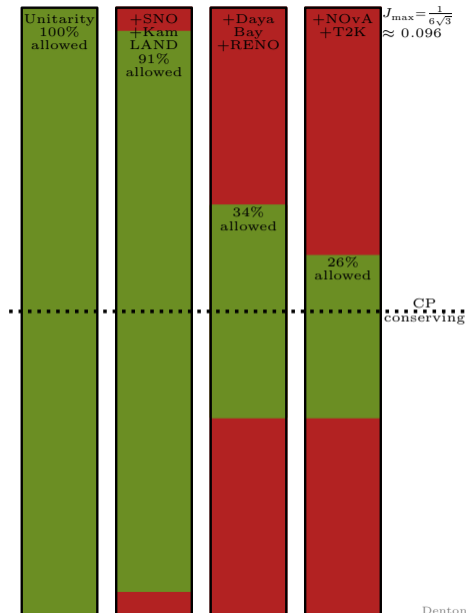


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- ▶  $\delta_{\text{PDG}} = \pi/2, 3\pi/2 \neq$  maximal CP violation

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)  $\sigma$
3.  $\theta_{23} = 45^\circ$  allowed at  $\sim 1\sigma$



# Optimal Parameterization

Want to be able to write

$$P \approx \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

1. Solar/long-baseline reactor:  $U_{e2}$
2. Medium-baseline reactor:  $U_{e3}$
3. Atmospheric/long-baseline accelerator disappearance:  $U_{\mu 3}$

Want these “simple” not the sum/difference of trig functions

	$U_{123}$	$U_{132}$	$U_{213}$	$U_{231}$	$U_{312}$	$U_{321}$
$ U_{e2} $	✓	✓	✗	✗	✓	✗
$ U_{e3} $	✓	✓	✓	✗	✗	✗
$ U_{\mu 3} $	✓	✗	✓	✓	✗	✗

Other priorities (theoretical, computational, ...) may prefer different parameterizations

# Optimal Parameterization

Location of the phase?

Conventional:

$$U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta)U_{12}(\theta_{12})$$

Sometimes useful when dealing with matter effect:

$$U_{23}(\theta_{23}, \delta)U_{13}(\theta_{13})U_{12}(\theta_{12})$$

$\delta$  is the same (up to  $\pm$ ) in each case

# Optimal Parameterization

Location of the phase?

Conventional:

$$U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta)U_{12}(\theta_{12}) \quad \checkmark$$

Sometimes useful when dealing with matter effect:

$$U_{23}(\theta_{23}, \delta)U_{13}(\theta_{13})U_{12}(\theta_{12})$$

$\delta$  is the same (up to  $\pm$ ) in each case

## Quark mixing

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

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

Looks like “large” CPV:

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

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

Switch to  $V_{212}$  parameterization,  $\Rightarrow \delta' = 1^\circ$  and  $\sin \delta' = 0.02$ .

## One caveat in support of $\delta$

If the goal is **CP violation** the Jarlskog should be used

however

If the goal is **measuring the parameters** one must use  $\delta$

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

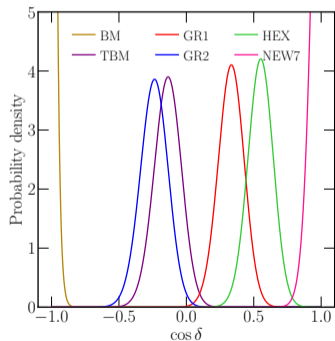
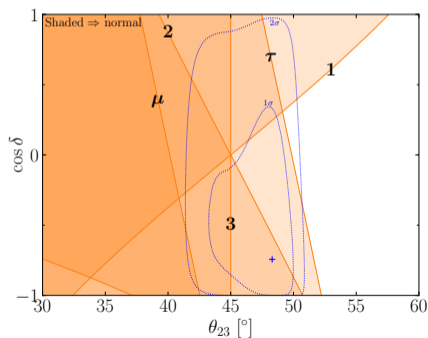
e.g.  $P(\nu_\mu \rightarrow \nu_\mu)$  depends on  $\cos \delta$  a tiny bit

- ▶ T2K/HK are mostly sensitivity to  $\sin \delta$ ; they should focus on  $J$
- ▶ NOvA/DUNE has modest  $\cos \delta$  sensitivity; both  $J$  and  $\delta$  should be reported

# The importance of $\cos \delta$

- ▶ If only  $\sin \delta$  is measured  $\Rightarrow$  sign degeneracy:  $\cos \delta = \pm \sqrt{1 - \sin^2 \delta}$
- ▶ Most models predict  $\cos \delta$

J. Gehrlein, et al [2203.06219](#)



PBD [2003.04319](#)

[2006.09384](#)

L. Everett, et al [1912.10139](#)

LAW Physics: April 27, 2022 19/42

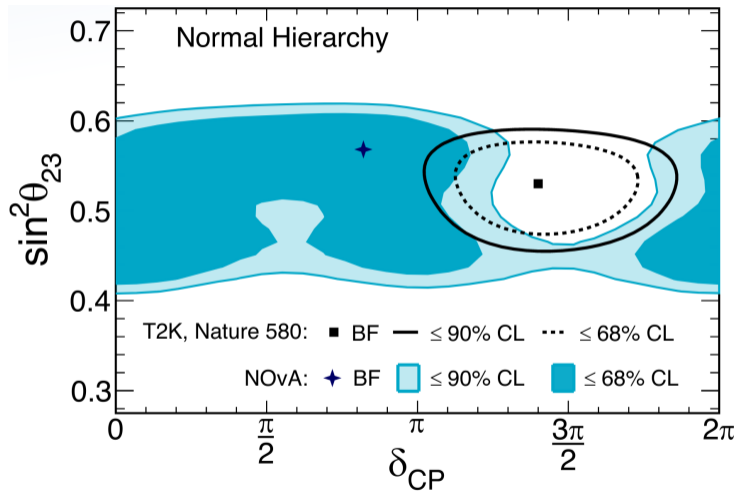
# Parameterization summary

- ▶ Phase in different parameterizations can behave quite differently than  $\delta_{\text{PDG}}$
- ▶ Maximal CP violation is ruled out
- ▶ CP violation should be presented in terms of the Jarlskog coefficient
- ▶ PDG parameterization is great



# CP violation at NOvA and T2K?

Excitement at Neutrino2020 last summer!



A. Himmel for NOvA [10.5281/zenodo.3959581](https://zenodo.org/record/3959581)

# Mass ordering?

Measuring the mass ordering is important in of itself

Phenomenological implications:

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

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The NOvA+T2K issue is *slightly* resolved by swapping the mass ordering

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 provide some information

K. Kelly, et al. [2007.08526](#)

I. Esteban, et al. [2007.14792](#)

PBD, J. Gehrlein, R. Pestes [2008.01110](#)

# Is the mass ordering robust?

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

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

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

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](#)

This is known as the **LMA-Dark** solution

A. de Gouvêa, A. Friedland, H. Murayama [hep-ph/0002064](#)



# Is the mass ordering robust?

Need **scattering** to break



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

PBD, et al [1701.04828](#)

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

PBD, Y. Farzan, I. Shoemaker [1804.03660](#)

Dresden-II for any mediator mass

PBD, J. Gehrlein [2204.09060](#)

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

Currently significances are low

What kinds of new physics is there if  
NO<sub>v</sub>A(DUNE) and T2(H)K continue to disagree?

# Effects of different parameters

Sign of  $\delta$  is such that:

1.  $\delta = 3\pi/2$
2. Electron neutrino appearance at first maximum

results in a “large” probability.

Flip an odd number of these and the probability becomes “small”

Flip an even number and probability remains “large”

# New physics

If this is new physics what could lead to this kind of effect?

- ▶ Steriles? S. Chatterjee, A. Palazzo [2005.10338](#)
- ▶ Decay?
- ▶ Decoherence?
- ▶ Dark matter interaction?
- ▶ LIV/CPT? U. Rahaman [2103.04576](#)
- ▶ Unitary violation? D. Forero, et al. [2103.01998](#)
- ▶ NSI with complex CP violating phases
  1. Different matter effects  $\Rightarrow$  different NSI effect
  2. New phases partially degenerate with standard phase
  3. T2K is closer to vacuum so they measure the vacuum parameters
  4. NOvA measures “vacuum” + “NSI”

See also S. Chatterjee, A. Palazzo [2008.04161](#)



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

Models with large NSIs consistent with CLFV:

Y. Farzan, I. Shoemaker [1512.09147](#)   Y. Farzan, J. Heeck [1607.07616](#)   D. Forero and W. Huang [1608.04719](#)  
 K. Babu, A. Friedland, P. Machado, I. Mocioiu [1705.01822](#)   [PBD](#), Y. Farzan, I. Shoemaker [1804.03660](#)  
 U. Dey, N. Nath, S. Sadhukhan [1804.05808](#)   Y. Farzan [1912.09408](#)

Affects oscillations via new matter effect

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

Matter potential  $a \propto G_F \rho E$

B. Dev, K. Babu, [PBD](#), P. Machado, et al. [1907.00991](#)

# NSI parameters

Many parameters:

- ▶ Neutrino flavor: 3 diagonal +  $3 \times 2$  flavor changing 9
- ▶ Matter fermion:  $u, d, e$ : 3 27
- ▶ V vs. A (or L vs. R): 2 54

If SPVAT then 135

Generally leads to  $\nu\nu$  interactions in SNe and early universe:  $\times 2 \rightarrow 270$

- ▶ For oscillations  $u, d, e$  doesn't matter (much)
- ▶ Focus on V for propagation effects
- ▶ Since we want CP violation, focus on flavor changing

6 parameters:  $|\epsilon_{e\mu}|e^{i\phi_{e\mu}}$   $|\epsilon_{e\tau}|e^{i\phi_{e\tau}}$   $|\epsilon_{\mu\tau}|e^{i\phi_{\mu\tau}}$

Take one of these three at a time

## Relate NSI to vacuum parameters

There is a mapping between vacuum parameters with and without NSI that depends on  $\rho$ ,  $E$ :

$$UM^2U^\dagger + A + N = \tilde{U}\tilde{M}^2\tilde{U}^\dagger + A$$

Vacuum    SM    NSI    apparent    SM  
matter    matter    matter    vacuum    matter

Works for off-axis experiments

# Estimate size of effect

Ansatz:

- ▶ The data is well described by NSI
- ▶ NSI mainly modifies  $\delta$ :

$$P(\epsilon, \delta_{\text{true}}) \approx P(\epsilon = 0, \delta_{\text{meas}})$$

$$\bar{P}(\epsilon, \delta_{\text{true}}) \approx \bar{P}(\epsilon = 0, \delta_{\text{meas}})$$

Leverage approximate expressions for NSI in LBL

T. Kikuchi, H. Minakata, S. Uchinami [0809.3312](#)

## Estimate size of effect: magnitude

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

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

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

Consistency checks:

- ▶  $\sin\delta_{\text{NOvA}} = \sin\delta_{\text{T2K}} \Rightarrow |\epsilon| = 0$
- ▶  $\sin\delta_{\text{NOvA}} \neq \sin\delta_{\text{T2K}}$  and  $a_{\text{NOvA}} = a_{\text{T2K}} \Rightarrow |\epsilon| \rightarrow \infty$
- ▶ Octant:
  1. LBL is governed by  $\nu_3$
  2. Upper octant  $\Rightarrow \nu_3$  is more  $\nu_\mu$
  3. More  $\nu_\mu \Rightarrow$  need less new physics coupling to  $\nu_\mu$  to produce a given effect

## Estimate size of effect: NSI phase

Under the ansatz, if  $\delta_{\text{NO}\nu\text{A}} \neq \delta_{\text{T2K}}$

$$\sin(\delta_{\text{true}} + \phi_{e\beta}) \approx 0$$

Since  $a_{\text{NO}\nu\text{A}} > a_{\text{T2K}}$  and the data suggests  $\sin \delta_{\text{T2K}} \lesssim \sin \delta_{\text{NO}\nu\text{A}}$ :

$$\cos(\delta_{\text{true}} + \phi_{e\beta}) \approx -1$$

$$\delta_{\text{true}} \approx \delta_{\text{T2K}} \quad \Rightarrow \quad \phi_{e\beta} \approx \frac{3}{2}\pi$$

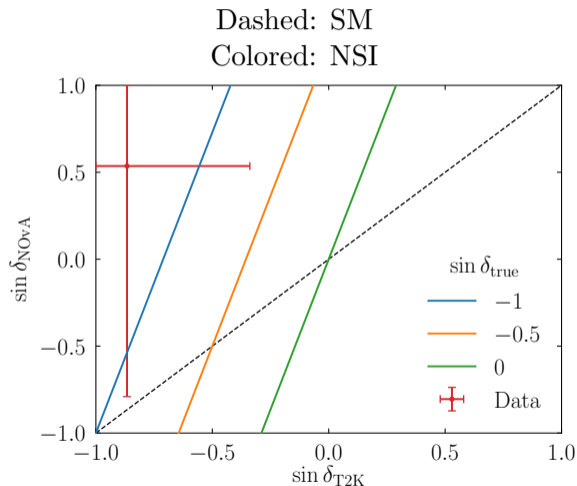
## Estimate size of effect: measured phases

$$\sin \delta_{\text{true}} \approx \frac{\sin \delta_{\text{NOvA}} a_{\text{T2K}} - \sin \delta_{\text{T2K}} a_{\text{NOvA}}}{a_{\text{T2K}} - a_{\text{NOvA}}}$$

Since  $\sin \delta_{\text{T2K}} \sim -1$  this suggests  
 $\sin \delta_{\text{true}} < -1$

Alleviated by:

- ▶ Statistical fluctuations
- ▶ Relaxing the ansatz that only  $\delta$  matters



How good are these approximations?  
How significant?



## Approximate the experiments

### Appearance:

$$n(\nu_e) = xP(\nu_\mu \rightarrow \nu_e) + yP(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) + z$$

Fit to all points on bivalent plots for  $\nu$ ,  $\bar{\nu}$ , NOvA, T2K

Wrong sign leptons are non-zero at high significance

### Disappearance:

NOvA:

$$|\Delta m_{32}^2| = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2 \quad \text{and} \quad 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) = 0.99 \pm 0.02$$

K. Kelly, et al. [2007.08526](#)

T2K:  $\Delta m_{32}^2$  and  $\theta_{23}$  likelihoods

Assume that  $P_{\mu\mu} \approx \bar{P}_{\mu\mu}$  and that most info comes from disappearance

NOvA:  $E \sim 1.9 \text{ GeV}$ ,  $\rho = 2.84 \text{ g/cc}$ ,  $L = 810 \text{ km}$

T2K:  $E \sim 0.6 \text{ GeV}$ ,  $\rho = 2.60 \text{ g/cc}$ ,  $L = 295 \text{ km}$

## Completing the fit

Appearance measurements depend on all six parameters  
Can NOT use input from global fits

T2K affects  $\theta_{13}$

Use other vacuum experiments to constrain other parameters independent of NSI:

- ▶ Daya Bay: Constrains  $\theta_{13}$  and  $\Delta m_{32}^2$  for each atmospheric mass ordering

Daya Bay [1809.02261](#)

- ▶ KamLAND: Constrains  $\theta_{12}$  and  $|\Delta m_{21}^2|$

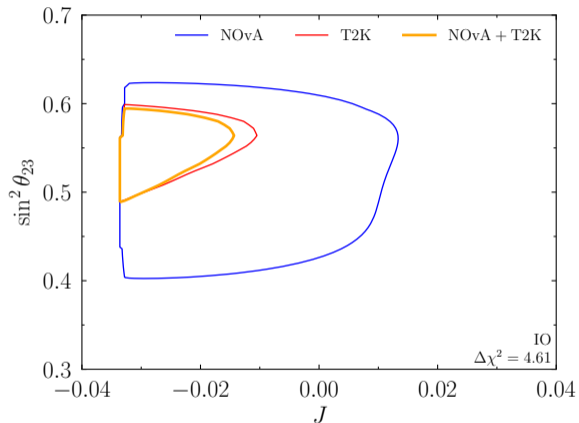
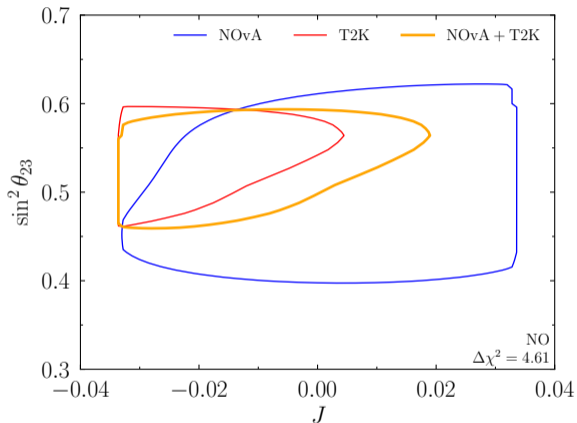
KamLAND [1303.4667](#)

SNO tells us  $\Delta m_{21}^2 > 0$

or  $\theta_{12} < 45^\circ$  depending on definition, see [PBD 2003.04319](#)

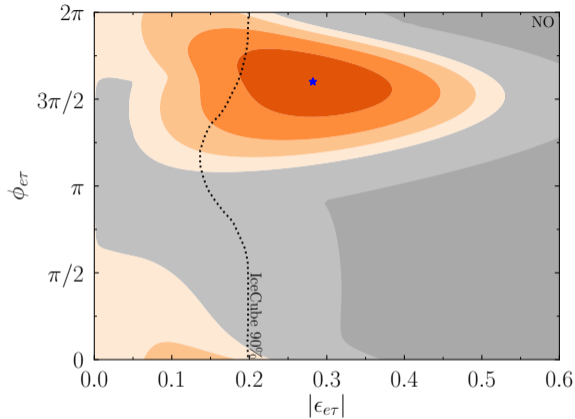
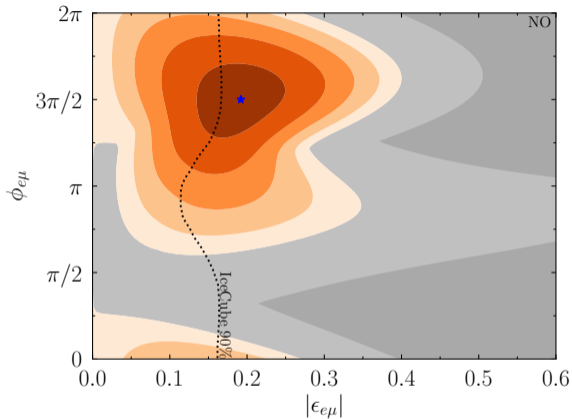
This depends on NSI but LBL parameters don't cancel

# Standard oscillation parameters



Can see that the combination doesn't like the NO while it does like the IO  
IO preferred over NO at  $\Delta\chi^2 = 2.3$

# 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

# NSI parameters

Analytic estimations:

$$|\epsilon_{e\mu}| \approx 0.22$$

$$|\epsilon_{e\tau}| \approx 0.24$$

$$\phi_{e\beta}/\pi \approx 1.5$$

$$\delta/\pi \approx 1.5$$

Numerical fit:

MO	NSI	$ \epsilon_{\alpha\beta} $	$\phi_{\alpha\beta}/\pi$	$\delta/\pi$	$\Delta\chi^2$
NO	$\epsilon_{e\mu}$	0.19	1.50	1.46	4.44
	$\epsilon_{e\tau}$	0.28	1.60	1.46	3.65
	$\epsilon_{\mu\tau}$	0.35	0.60	1.83	0.90
IO	$\epsilon_{e\mu}$	0.04	1.50	1.52	0.23
	$\epsilon_{e\tau}$	0.15	1.46	1.59	0.69
	$\epsilon_{\mu\tau}$	0.17	0.14	1.51	1.03

$$\Delta\chi^2 = \chi_{\text{SM}}^2 - \chi_{\text{NSI}}^2$$

For the SM:  $\chi_{\text{NO}}^2 - \chi_{\text{IO}}^2 = 2.3$

## Other CP violating NSI constraints

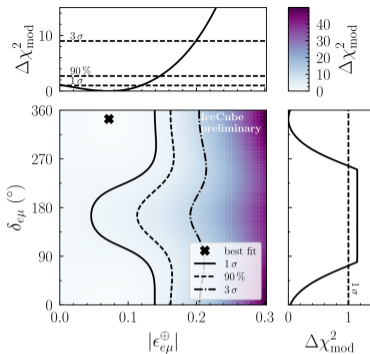
NSI effects grow with energy, density, and distance

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  $\sim 1\sigma$

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

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



T. Ehrhardt, IceCube [PPNT \(2019\)](#)

Super-K [1109.1889](#)

COHERENT [1708.01294](#)

[PBD](#), Y. Farzan, I. Shoemaker [1804.03660](#)

[PBD](#), J. Gehrlein [2008.06062](#)

# Summary

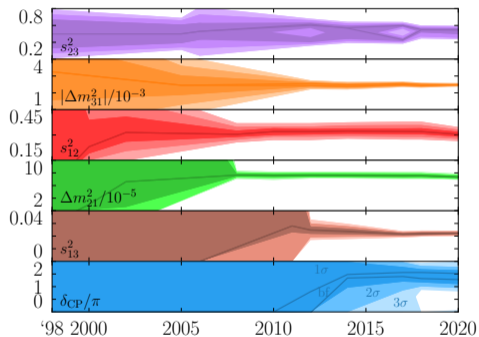
- ▶ Care is required in choice of parameterizations
- ▶ Jarlskog invariant is best for CP violation
- ▶ NOvA and T2K tension can be mitigated by NO  $\rightarrow$  IO
- ▶ Tension can be fully resolved by NSI
- ▶ Easy to approximate magnitude and phase of NSI
- ▶ NSI introduces more CP violation
- ▶ Consistent with, and soon tested by, other experiments

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](#)

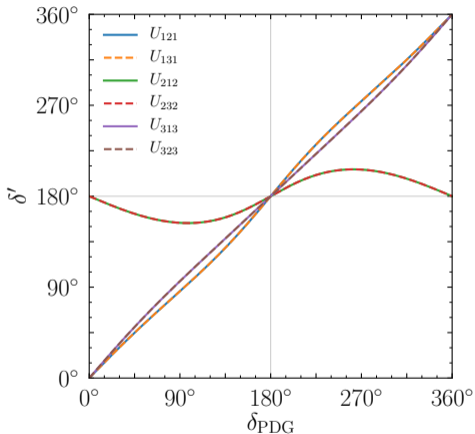
D. Forero, M. Tortola, J. Valle [1205.4018](#)

D. Forero, M. Tortola, J. Valle [1405.7540](#)

P. de Salas, et al. [1708.01186](#)

F. Capozzi et al. [2003.08511](#)

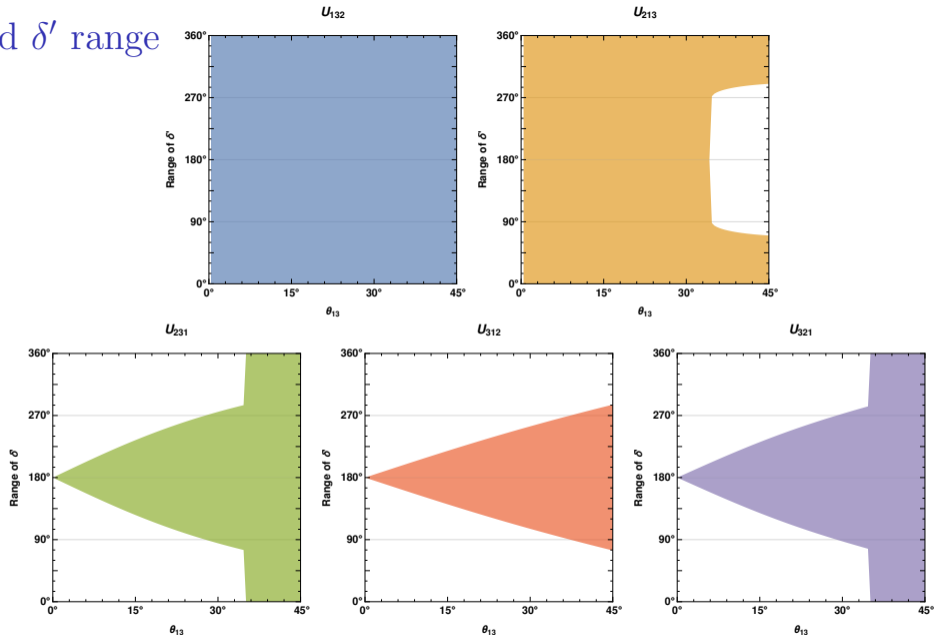
# Repeated rotations



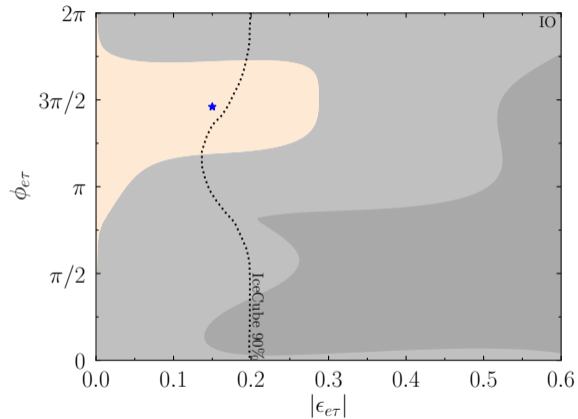
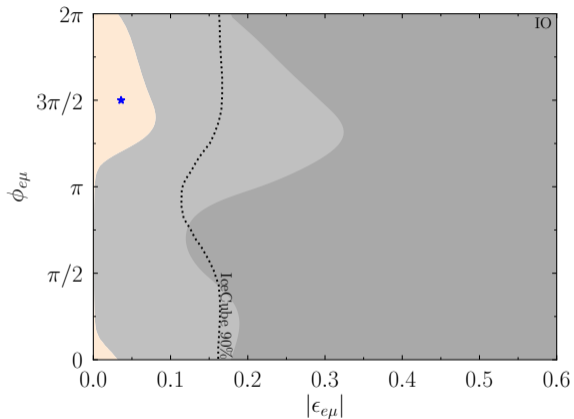
	$U_{121}$	$U_{131}$	$U_{212}$	$U_{232}$	$U_{313}$	$U_{323}$
$ U_{e2} $	✓	✓	✓	✓	✗	✗
$ U_{e3} $	✓	✓	✗	✗	✓	✓
$ U_{\mu 3} $	✗	✗	✓	✓	✓	✓

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

# Allowed $\delta'$ range



# NSI parameters: IO



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

