

## Abstract

The nature of CP violation in the lepton sector is one of the biggest open questions in particle physics. Long-baseline accelerator 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 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

BNL HET Lunch Discussion

October 30, 2020

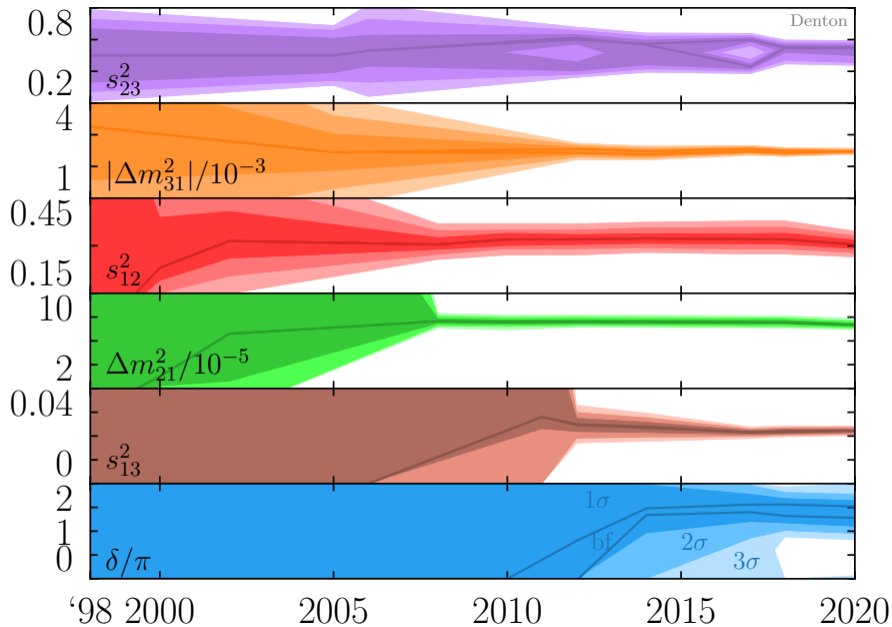
2006.09384

with Rebekah Pestes

2008.01110

with Julia Gehrlein and Rebekah Pestes





# CP Violation in the SM



1. Weak interaction: CP **maximally violated**

J. Cronin, V. Fitch, et al. [PRL 13, 138 \(1964\)](#)

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

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

3. Quark mass matrix: non-zero but **small** CP violation  $|J_{\text{CKM}}|/J_{\text{max}} = 3 \times 10^{-4}$

CKMfitter [1501.05013](#)

4. Lepton mass matrix: ?  $|J_{\text{PMNS}}|/J_{\text{max}} < 0.34$

[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:  $n^2 = 9$  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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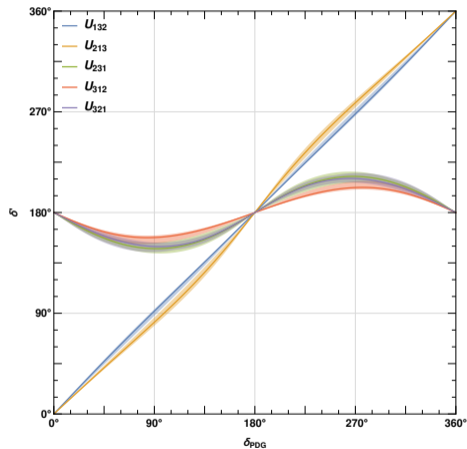
What about other orders?

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

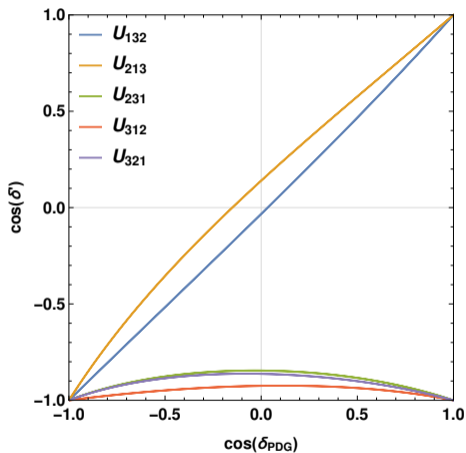
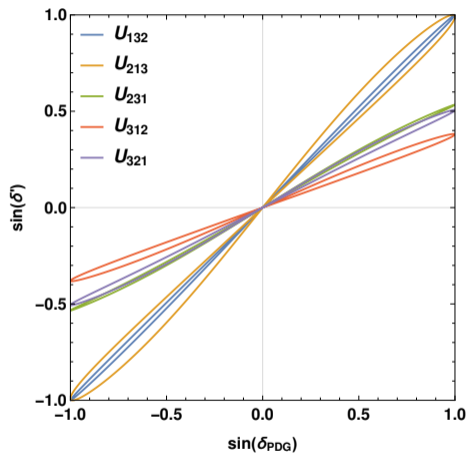
# Complex phase in different parameterizations

- ▶ 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  $\delta$ ”  
 $\Rightarrow$  parameterization dependent

DUNE TDR II [2002.03005](#)



# 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

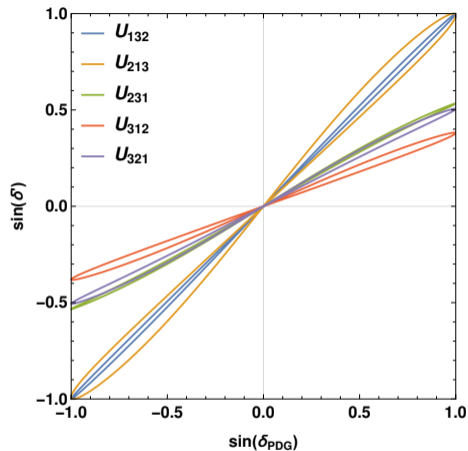
Can easily related  $\delta_{\text{PDG}} \rightarrow \delta'$ :

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

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

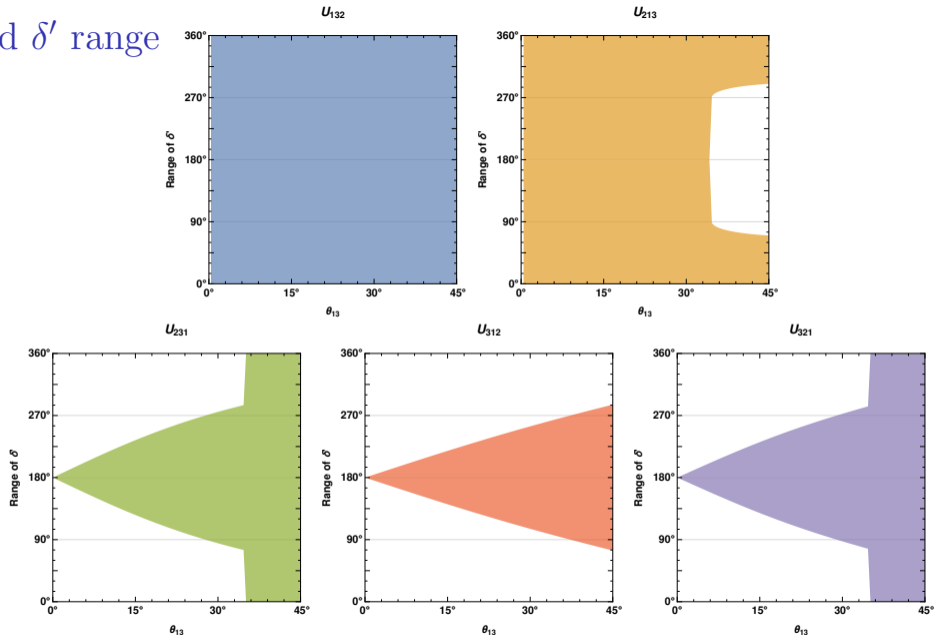
$$d_{312} \approx s_{13} \frac{1 - c_{12}^2 s_{23}^2}{s_{12} c_{12} s_{23} c_{23}} \approx 0.39$$

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

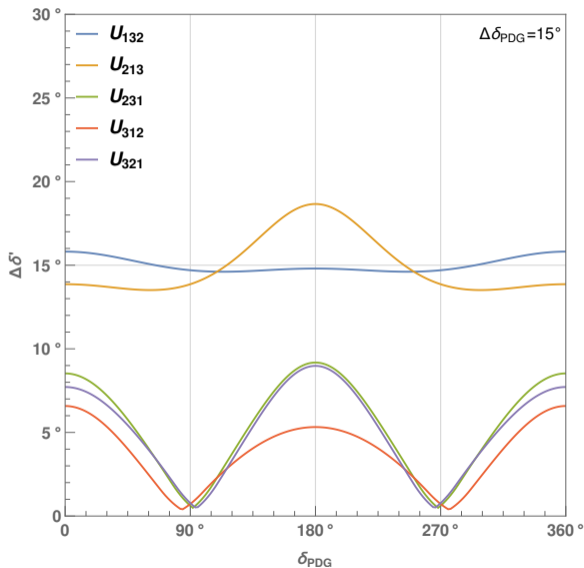


$\theta_{23} > 45^\circ$  here

# Allowed $\delta'$ range



# Precision on $\delta$



Precision on complex phase 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

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

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



## Jarlskog parameter space

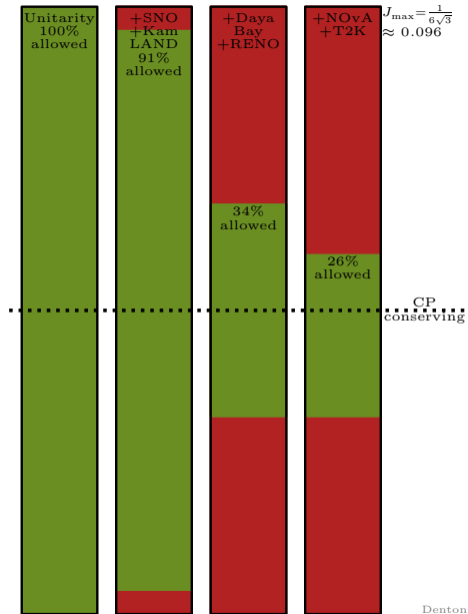
- ▶ 50%  $\delta$  space is parameterization dependent
- ▶  $\Delta\delta$  is parameterization dependent
- ▶  $\delta_{\text{PDG}} = \pi/2, 3\pi/2 \neq$  maximal CP violation

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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  $\sigma$
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:

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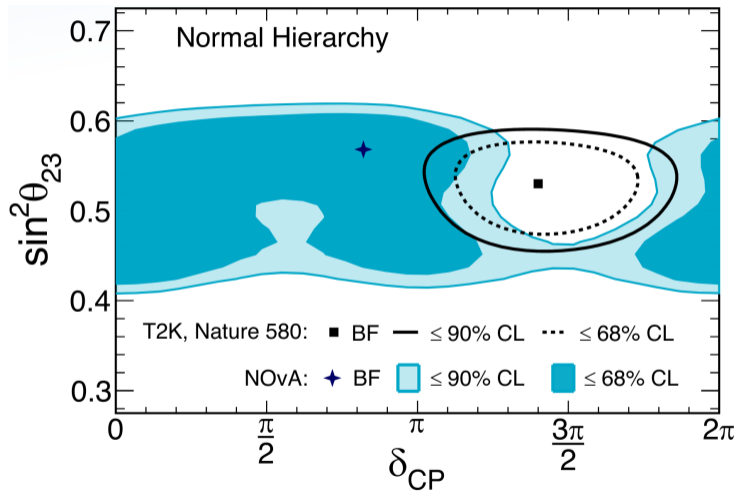
$\delta$  is the same (up to  $\pm$ ) in each case

# 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!



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

## Significances are low

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



# Mass ordering?

Measuring the mass ordering is important in of itself

Phenomenological implications:

- ▶ Affects cosmology
- ▶ Affects end point measurements
- ▶ Affects  $0\nu\beta\beta$
- ▶ 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. MBL reactors provide some information

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

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

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

# 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 even number and probability remains “large”

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

# New physics

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

- ▶ Steriles?
- ▶ Decay?
- ▶ Decoherence?
- ▶ Dark matter interaction?
- ▶ LIV/CPT?
- ▶ 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”

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

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

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

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  $\rho$ ,  $E$ :

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

Vacuum    SM   NSI    apparent    SM  
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

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

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

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

Consistency checks:

- ▶  $\sin\delta_{NOvA} = \sin\delta_{T2K} \Rightarrow |\epsilon| = 0$
- ▶  $\sin\delta_{NOvA} \neq \sin\delta_{T2K}$  and  $a_{NOvA} = a_{T2K} \Rightarrow |\epsilon| \rightarrow \infty$
- ▶ 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  $\sin \delta_{\text{T2K}} \lesssim \sin \delta_{\text{NO}\nu\text{A}}$ :

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

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

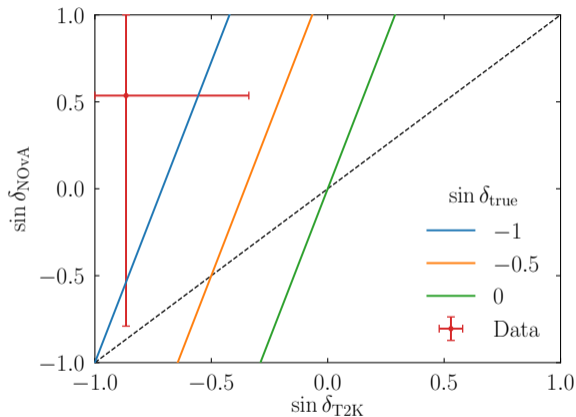
## Estimate size of effect: measured phases

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

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

## Other experiments

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  $|\Delta m_{21}^2|$

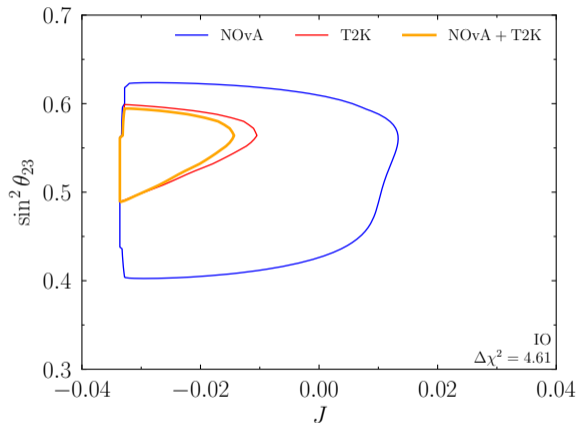
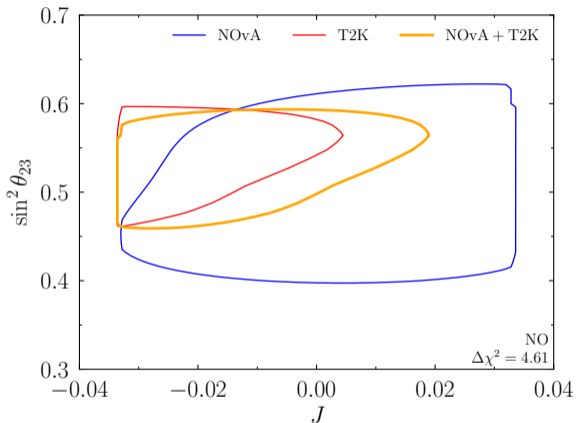
KamLAND [1303.4667](#)

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

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

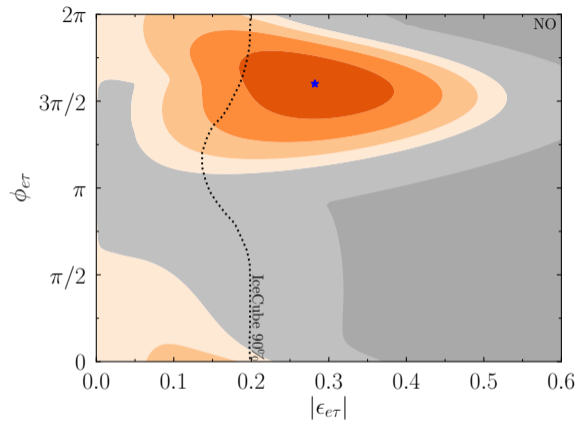
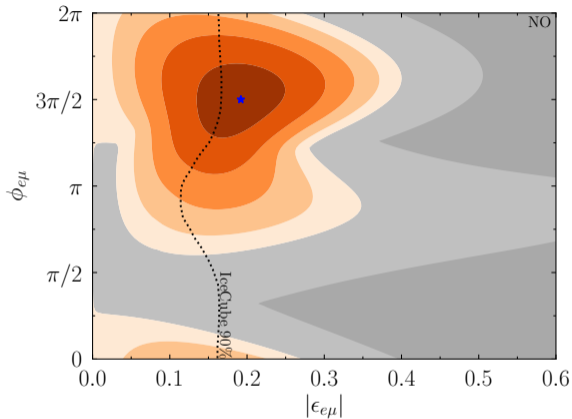
This depends on NSI but LBL parameters don't cancel

# 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:

$$|\epsilon_{e\mu}| \approx 0.22 \quad |\epsilon_{e\tau}| \approx 0.24 \quad \phi_{e\beta} \approx \frac{3}{2}\pi \quad \delta_{\text{true}} = \frac{3}{2}\pi$$

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

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

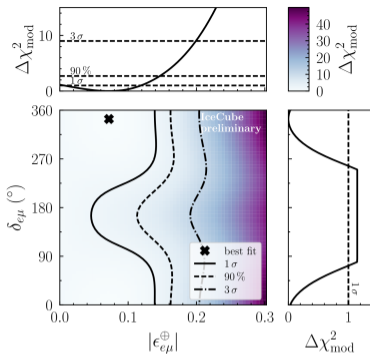
For the SM  $\chi_{\text{NO}}^2 - \chi_{\text{IO}}^2 = 2.3$

## 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
  - ▶ Slightly disfavoring LBL best fit point
  - ▶ 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](#)

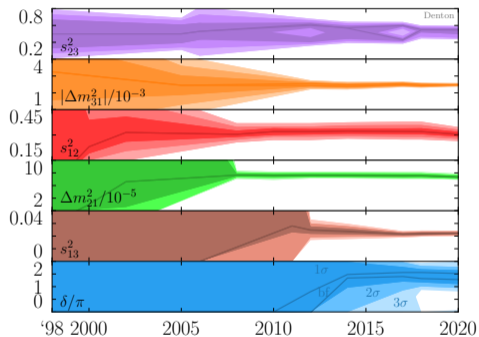
# Summary

- ▶ Care is required in choice of parameterizations
- ▶ Jarlskog is best
- ▶ 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

Thanks!

# Backups

# References



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M. Maltoni, et al. [hep-ph/0207227](#)

SK [hep-ex/0501064](#)

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T. Schwetz, M. Tortola, J. Valle [0808.2016](#)

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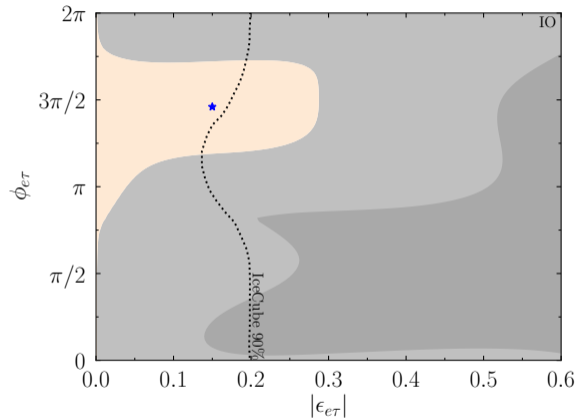
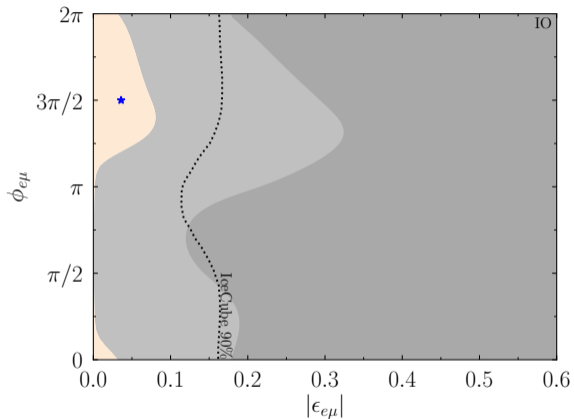
D. Forero, M. Tortola, J. Valle [1205.4018](#)

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

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

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

# NSI parameters: IO



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

