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 δ 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

Fermilab

October 22, 2020

2006.09384

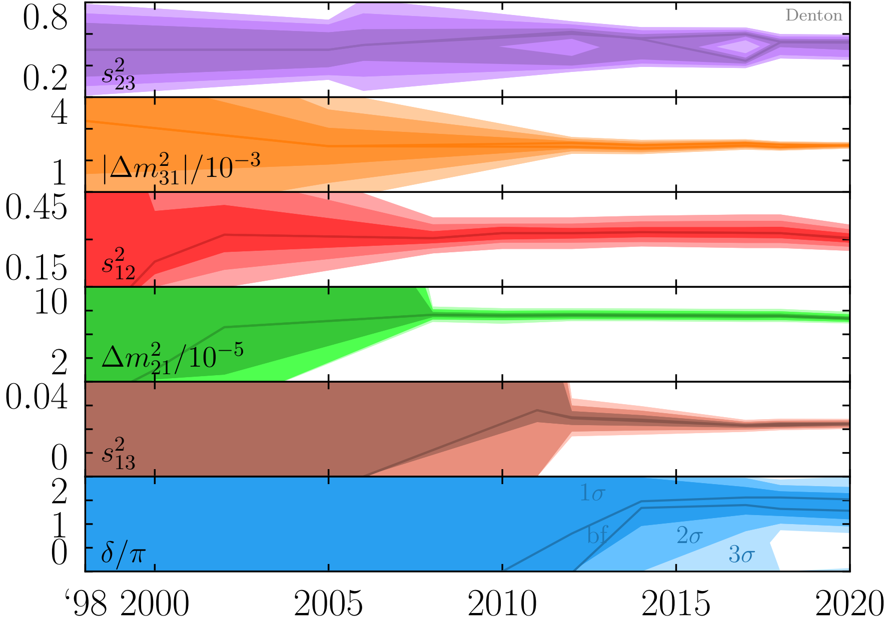
with Rebekah Pestes

2008.01110

with Julia Gehrlein and Rebekah Pestes

BROOKHAVEN NATIONAL LABORATORY

Brookhaven NDI Neutrino Discovery Initiative


Denton
0.8
0.2
s^2_{23}
4
1
$|\Delta m^2_{31}|/10^{-3}$
0.45
0.15
s^2_{12}
10
2
$\Delta m^2_{21}/10^{-5}$
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
‘98 2000
2005
2010
2015
2020

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

   CKMfitter 1501.05013

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

   PBD, J. Gehrlein, R. Pestes 2008.01110

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

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. 3×3 $\mathbb{C}$: 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. $\vdots$

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

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

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

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

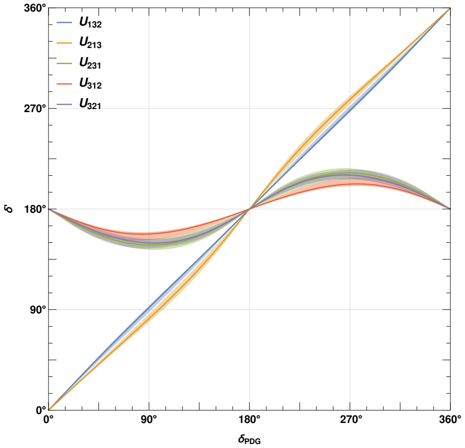
What about other orders?

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

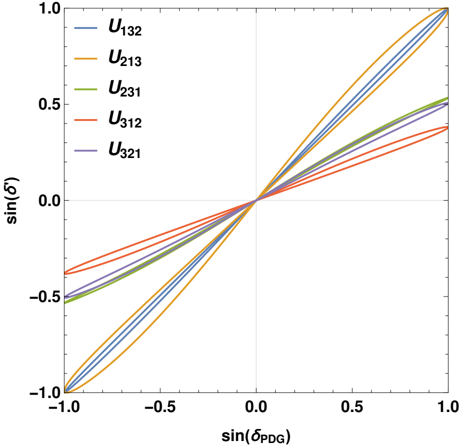
Complex phase in different parameterizations

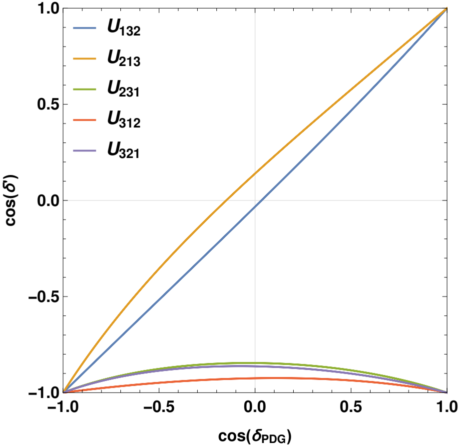
- Can relate the complex phase in one parameterization to that in another
- U_{132} and U_{213} similar to U_{123}
- δ constrained to $\sim [150°, 210°]$ in U_{231}, U_{312}, U_{321}
- Bands indicate 3σ uncertainty on θ_{12}, θ_{13}, θ_{23}
- "50% of possible values of δ"
  $\Rightarrow$ parameterization dependent

DUNE TDR II 2002.03005



The importance of $\cos\delta$





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

$|U_{e3}|$ is small

Given θ_{12}, θ_{13}, θ_{23}:

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

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

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

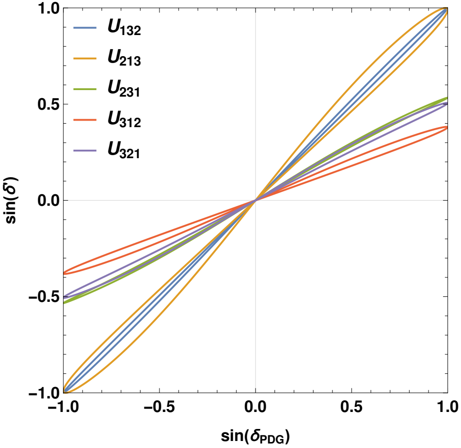
Can easily related $\delta_{\rm PDG} \to \delta'$:

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

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

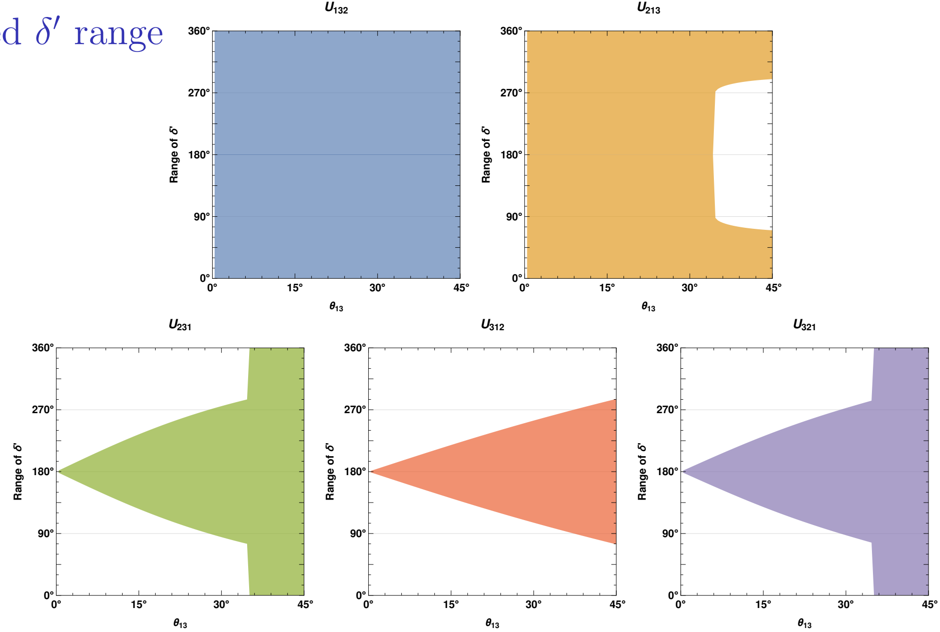
$$d_{312} \approx s_{13} \frac{1 - c_{12}^2 s_{23}^2}{s_{12} c_{12} s_{23} c_{23}} \approx 0.39$$

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

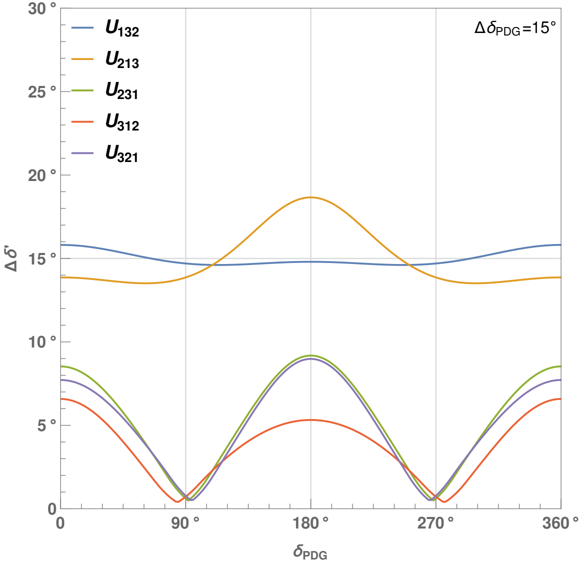


$\theta_{23} > 45^\circ$ here

Allowed δ' range



Precision on δ



Precision on complex phase is parameterization dependent

CP violation in oscillations

In vacuum at first maximum:

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

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

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

PBD, S. Parke 1902.07185

PBD, H. Minakata, S. Parke 1604.08167

Jarlskog parameter space

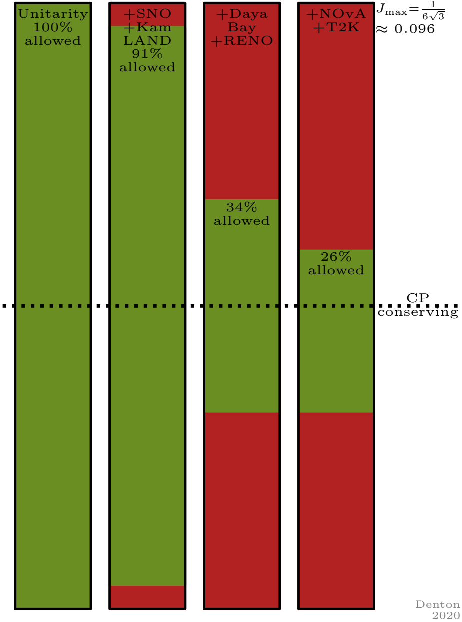
- 50% δ space is parameterization dependent
- $\Delta\delta$ is parameterization dependent
- $\delta_{\rm PDG}=\pi/2,\ 3\pi/2 \not\equiv$ maximal CP violation

Jarlskog parameter space

- 50% δ space is parameterization dependent
- $\Delta\delta$ is parameterization dependent
- $\delta_{\rm PDG} = \pi/2,\ 3\pi/2 \not\equiv$ 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 σ
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}
$\lvert U_{e2}\rvert$	✓	✓	✗	✗	✓	✗
$\lvert U_{e3}\rvert$	✓	✓	✓	✗	✗	✗
$\lvert U_{\mu 3}\rvert$	✓	✗	✓	✓	✗	✗

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:

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

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

Optimal Parameterization

Location of the phase?

Conventional:

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

Sometimes useful when dealing with matter effect:

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

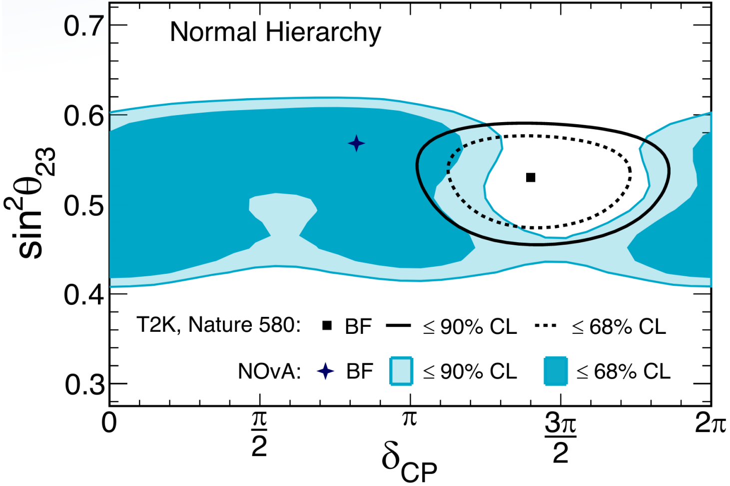
δ is the same (up to $\pm$) in each case

Parameterization summary

- Phase in different parameterizations can behave quite differently than δ_{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

Significances are low

What kinds of new physics is there if
NOvA(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 CνB

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 CνB

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 δ 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"

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

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

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 + 3×2 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 ρ, E:

$$\underbrace{U^\dagger M^2 U}_{\text{Vacuum}} + \underbrace{A}_{\text{SM matter}} + \underbrace{N}_{\text{NSI matter}} = \underbrace{\widetilde{U}^\dagger \widetilde{M}^2 \widetilde{U}}_{\text{apparent vacuum}} + \underbrace{A}_{\text{SM matter}}$$

Estimate size of effect

Ansatz:

- The data is well described by NSI
- NSI mainly modifies δ:

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

Leverage approximate expressions for NSI in LBL

T. Kikuchi, H. Minakata, S. Uchinami 0809.3312

Estimate size of effect: magnitude

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

$w_\beta = s_{23},\, c_{23}$ 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

Estimate size of effect: NSI phase

Under the ansatz, if $\delta_{\rm NOvA} \neq \delta_{\rm T2K}$

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

Since $a_{\rm NOvA} > a_{\rm T2K}$ and the data suggests $\sin\delta_{\rm T2K} \lesssim \sin\delta_{\rm NOvA}$:

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

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

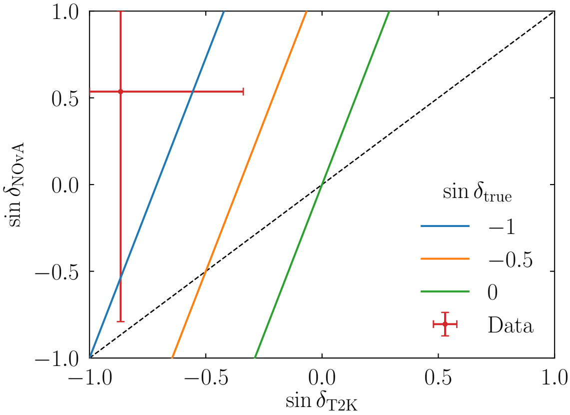
Estimate size of effect: measured phases

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

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

Alleviated by:

- Statistical fluctuations
- Relaxing the ansatz that only δ matters



How good are these approximations?
How significant?

Approximate the experiments

Appearance:

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

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

Wrong sign leptons are non-zero at high significance

Disappearance:

NOvA:

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

K. Kelly, et al. 2007.08526

T2K: Δm^2_{32} and θ_{23} likelihoods

Assume that $P_{\mu\mu} \approx \bar{P}_{\mu\mu}$

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

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

Other experiments

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

- Daya Bay: Constrains θ_{13} and Δm^2_{32} for each atmospheric mass ordering

Daya Bay 1809.02261

- KamLAND: Constrains θ_{12} and $|\Delta m^2_{21}|$

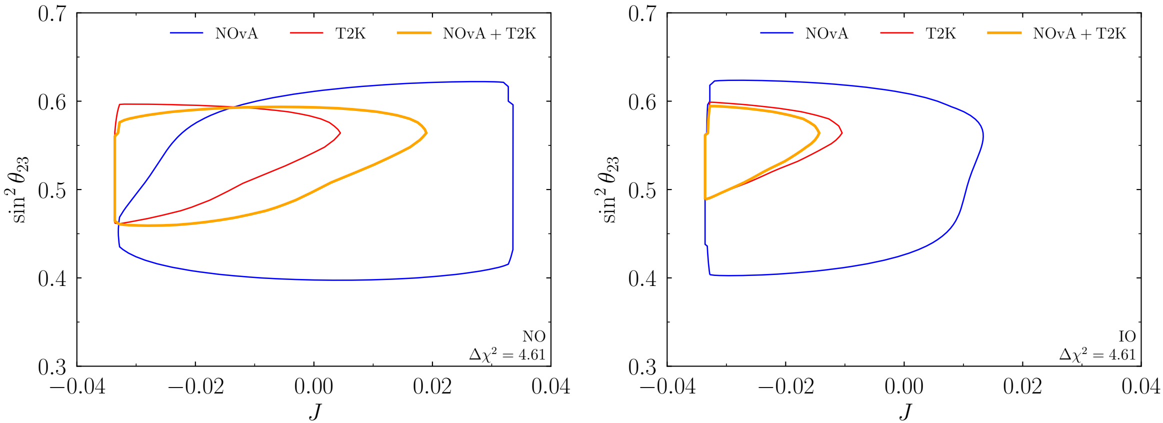
KamLAND 1303.4667

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

or $\theta_{12} < 45^\circ$ depending on definition, see PBD 2003.04319

This depends on NSI but LBL parameters don't cancel

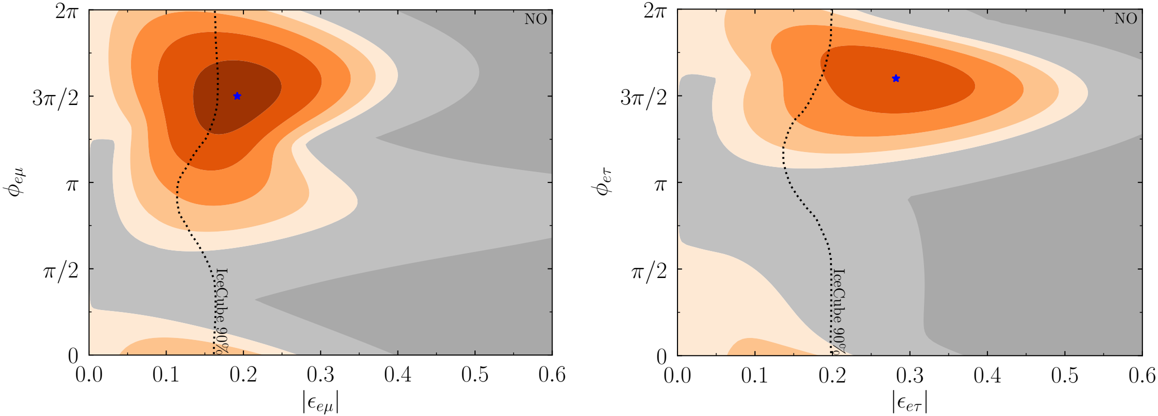
Standard oscillation parameters



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:

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

Numerical fit:

MO	NSI	$\lvert\epsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	δ/π	$\Delta\chi^2$
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

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

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

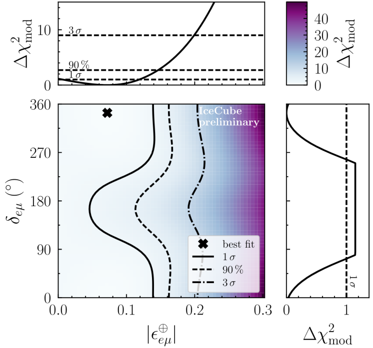
Other CP violating NSI constraints

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 $\sim 1\sigma$



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

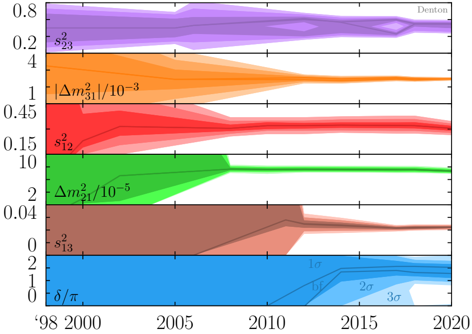
Summary

- Care is required in choice of parameterizations
- Jarlskog is best
- NOvA and T2K tension can be mitigated by NO $\to$ IO
- Tension can be fully resolved by NSI
- Easy to approximate magnitude and phase of NSI
- NSI introduces more CP violation

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

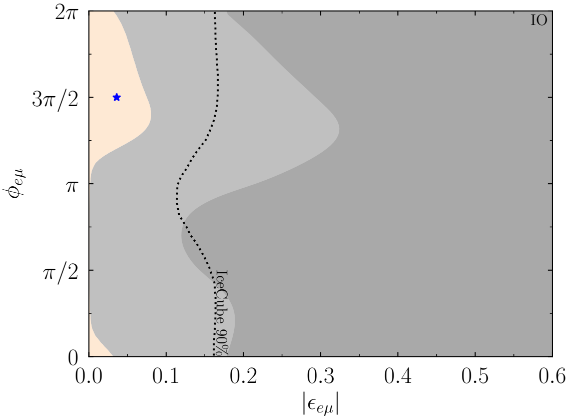
D. Forero, M. Tortola, J. Valle 1205.4018

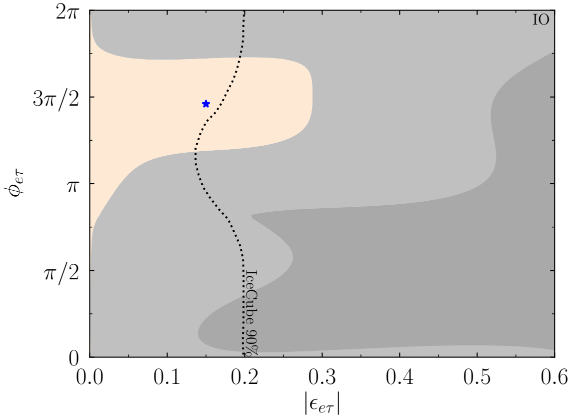
D. Forero, M. Tortola, J. Valle 1405.7540

P. de Salas, et al. 1708.01186

F. Capozzi et al. 2003.08511

NSI parameters: IO





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