

Abstract

Neutrino oscillations in matter provide a unique probe of new physics. Leveraging the advent of neutrino appearance data from NOvA and T2K in recent years, we investigate the presence of CP-violating neutrino non-standard interactions in the oscillation data. We first show how to very simply approximate the expected NSI parameters to resolve differences between two long-baseline appearance experiments analytically. Then, by combining recent NOvA and T2K data, we find a tantalizing hint of CP-violating NSI preferring a new complex phase that is close to maximal: $\phi_{e\mu}$ or $\phi_{e\tau} \approx 3\pi/2$ with $|\epsilon_{e\mu}|$ or $|\epsilon_{e\tau}| \sim 0.2$. We then compare the results from long-baseline data to constraints from IceCube and COHERENT.

CP-Violating Neutrino Non-Standard Interactions in Long-Baseline-Accelerator Data

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PASCOS

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2008.01110 - PRL

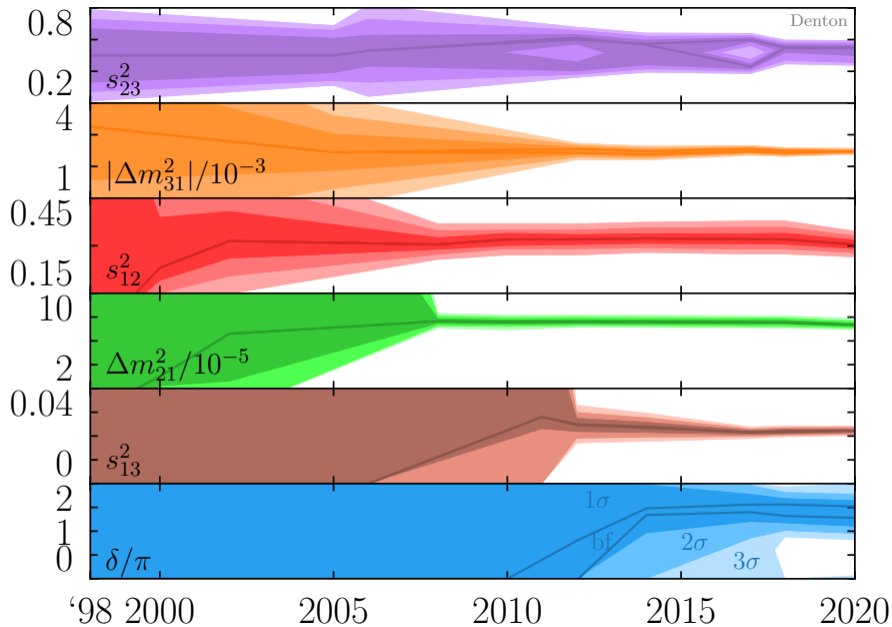
with Julia Gehrlein and Rebekah Pestes



BROOKHAVEN
NATIONAL LABORATORY



Speaking from [Setauket](#) land



CP Violation in the SM



1. Weak interaction: CP **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](#)

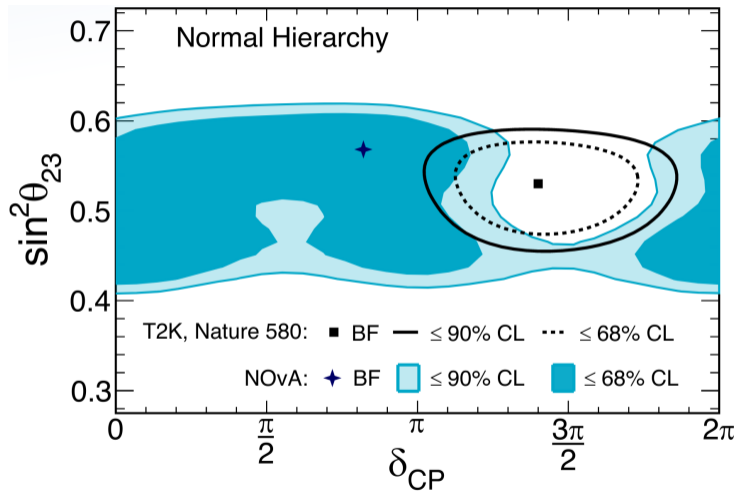
4. Lepton mass matrix: ? $|J_{\text{PMNS}}|/J_{\text{max}} < 0.34$

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

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

CP violation at NOvA and T2K?

Excitement at Neutrino2020 last summer!



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

Significances are low

What kinds of new physics is there if
NO_vA(DUNE) and T2(H)K continue to disagree?

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?

▶ Unitary violation?

L. Miranda, et al. [1911.09398](#)

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

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

Matter potential $a \propto G_F \rho E$

L. Wolfenstein [PRD 17, 2369 \(1978\)](#)

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

Estimate size of effect: magnitude

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

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

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 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 $\delta_{\text{NO}\nu\text{A}} \neq \delta_{\text{T2K}}$

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

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

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

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

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 ν , $\bar{\nu}$, 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](#)

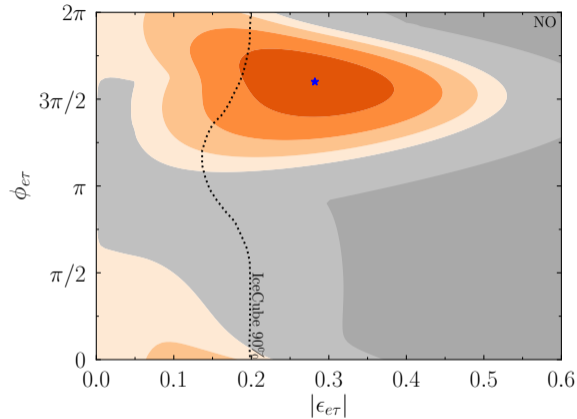
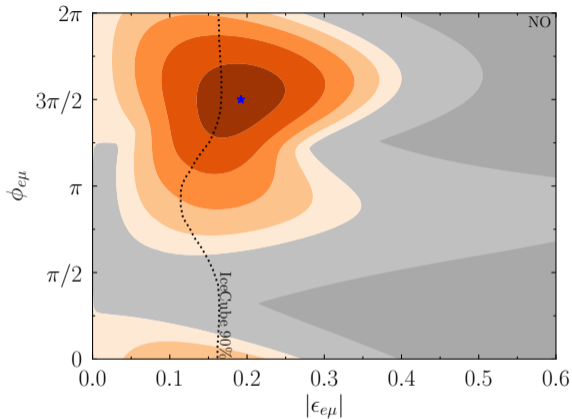
T2K: Δm_{32}^2 and θ_{23} likelihoods

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

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} $	$\phi_{\alpha\beta}/\pi$	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

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

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

Other CP violating NSI constraints

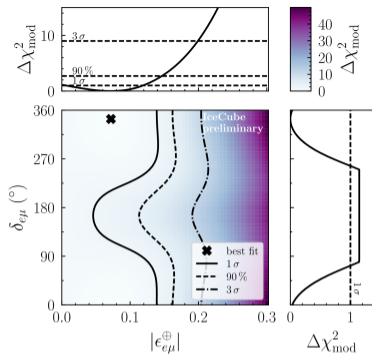
NSI effects grow with energy, density, and distance

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](#)

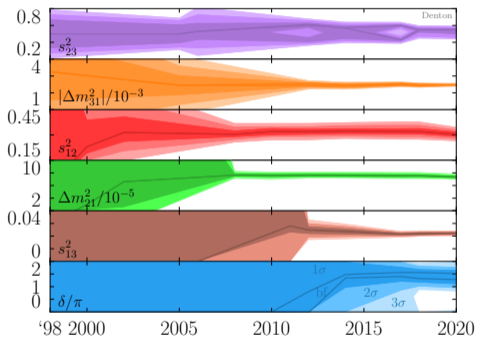
Key Takeaways

- ▶ NO ν A 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](#)

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](#)

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 odd number of these and the probability becomes “small”

Flip an even number and probability remains “large”

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 :

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

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 δ :

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

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

Leverage approximate expressions for NSI in LBL

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

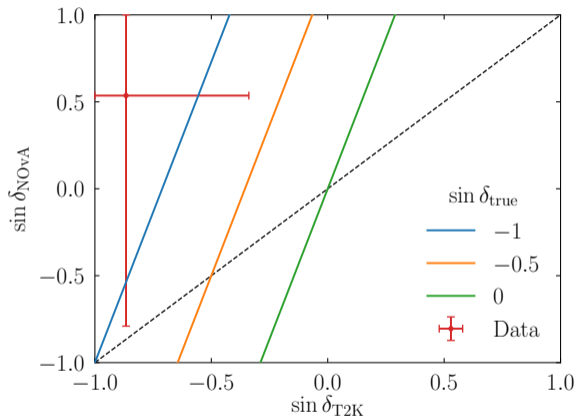
Estimate size of effect: measured phases

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

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

Alleviated by:

- ▶ Statistical fluctuations
- ▶ Relaxing the ansatz that only δ matters



Other experiments

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

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

Daya Bay [1809.02261](#)

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

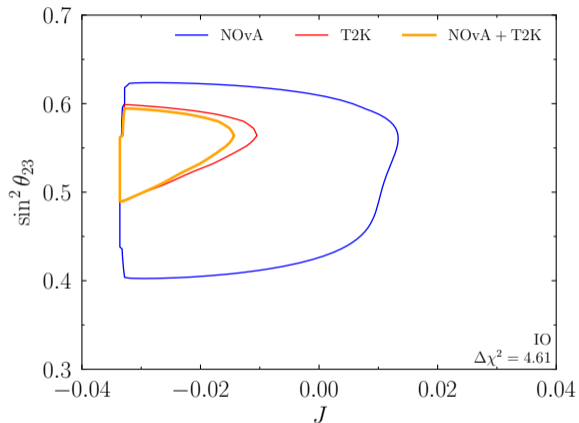
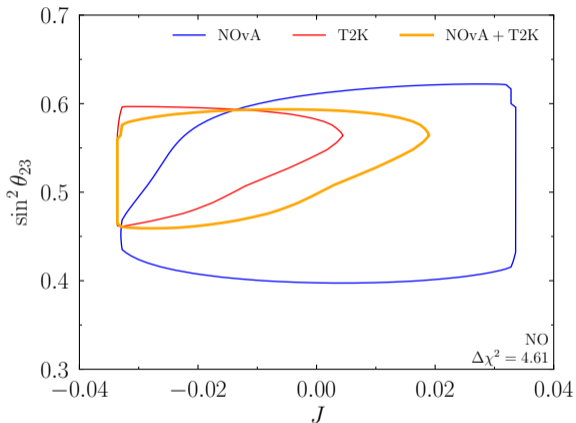
KamLAND [1303.4667](#)

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

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

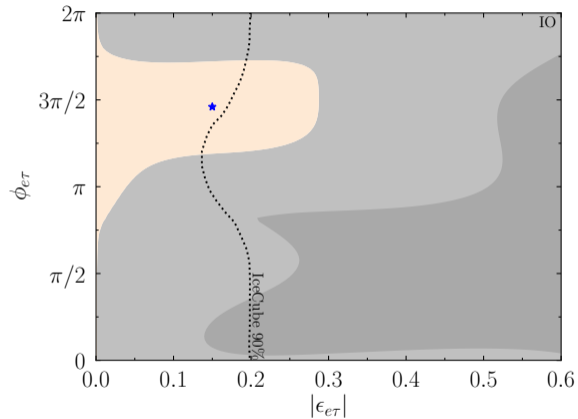
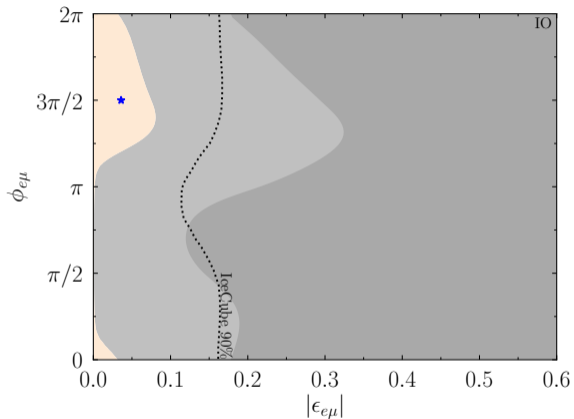
This depends on NSI but LBL parameters don't cancel

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: IO



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

