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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DPF

July 14, 2021

2008.01110 - PRL

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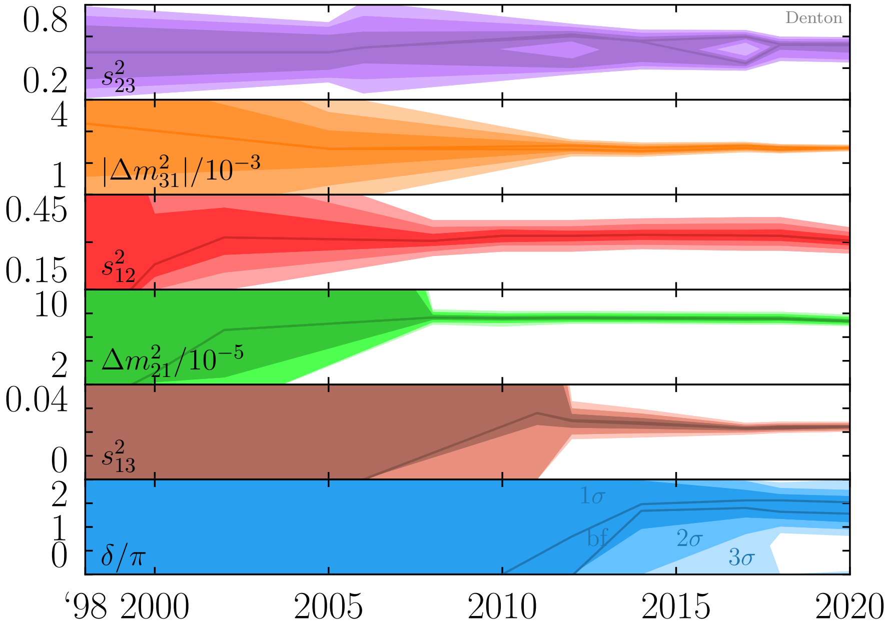
Brookhaven NDI
Neutrino Discovery Initiative

Speaking from Setauket land



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 **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

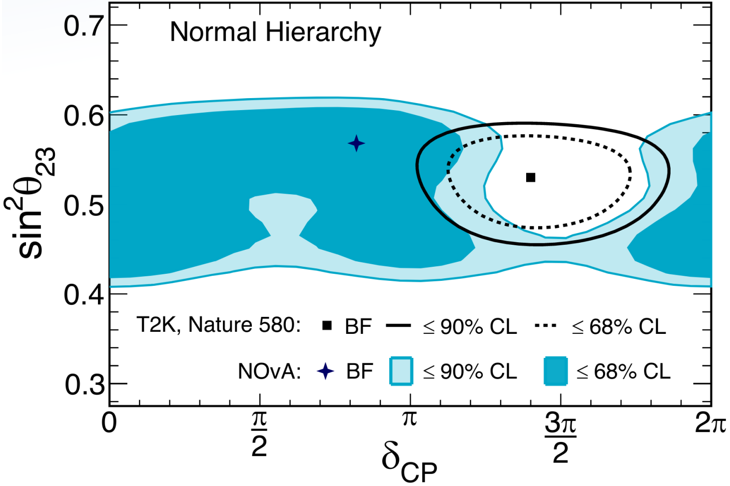
4. Lepton mass matrix: **?** $|J_{\rm PMNS}|/J_{\max} < 0.34$

   PBD, J. Gehrlein, R. Pestes 2008.01110

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

CP violation at NOvA and T2K?

Excitement at Neutrino2020 last summer!



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?

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

See also S. Chatterjee, A. Palazzo 2008.04161

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

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

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

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

$w_\beta = s_{23}, c_{23}$ 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 $\sin\delta_{\rm T2K} \lesssim \sin\delta_{\rm NOvA}$:

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

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

How good are these approximations?
How significant?

Approximate the experiments

Appearance:

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

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

Wrong sign leptons are non-zero at high significance

Disappearance:
NOvA:

$$|\Delta m^2_{32}| = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{and} \quad 4|U_{\mu3}|^2(1 - |U_{\mu3}|^2) = 0.99 \pm 0.02$$

K. Kelly, et al. 2007.08526

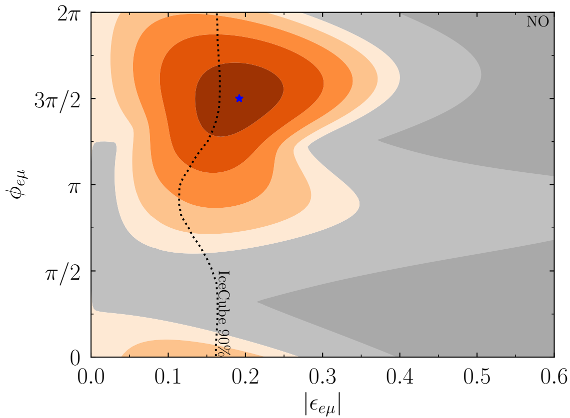
T2K: Δm^2_{32} and θ_{23} likelihoods

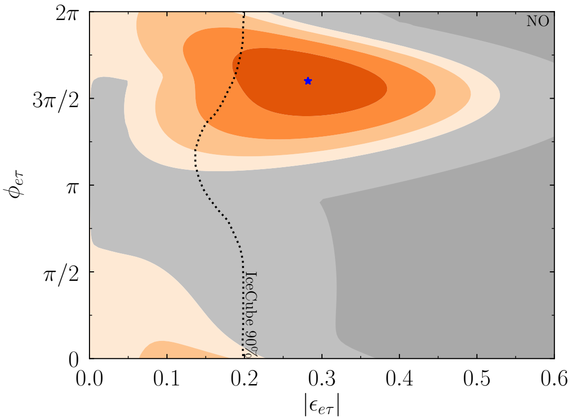
Assume that $P_{\mu\mu} \approx \bar{P}_{\mu\mu}$ and that most info comes from disappearance

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

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:

$|\epsilon_{e\mu}| \approx 0.22$ $\quad |\epsilon_{e\tau}| \approx 0.24$ $\quad \phi_{e\beta}/\pi \approx 1.5$ $\quad \delta/\pi \approx 1.5$

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

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

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

Other CP violating NSI constraints

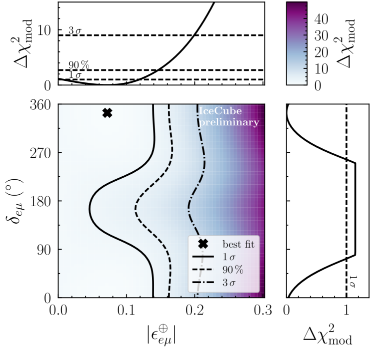
NSI effects grow with energy, density, and distance

Best probes:

- $\epsilon_{\mu\tau}$: atmospheric
- $\epsilon_{e\mu}$, $\epsilon_{e\tau}$: LBL appearance, atmospheric

- IceCube
  - Constraint is at LBL best fit with 3 yrs

    10 yrs of data in the bank
  - Prefers non-zero $|\epsilon_{e\mu}|$ at $\sim 1\sigma$



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

PBD, Y. Farzan, I. Shoemaker 1804.03660

PBD, J. Gehrlein 2008.06062

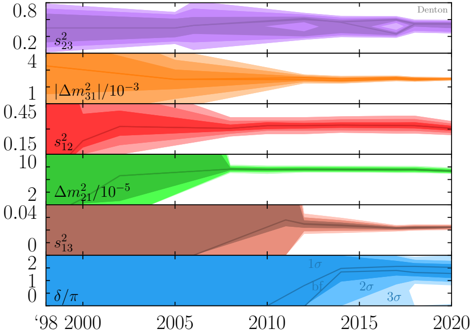
Key Takeaways

- 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
- 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 CνB

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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: $\times 2 \to 270$

- 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:

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

Works for off-axis experiments

Estimate size of effect

Ansatz:

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

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

Leverage approximate expressions for NSI in LBL

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

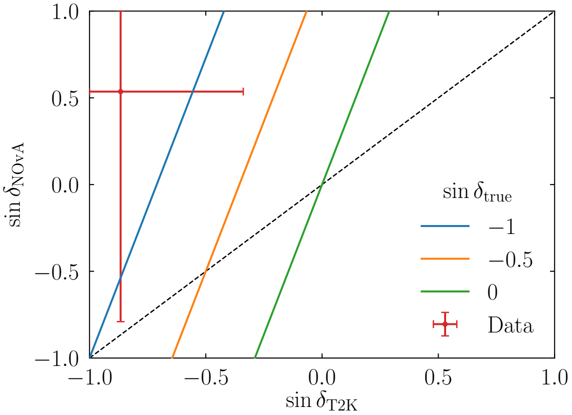
Estimate size of effect: measured phases

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

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



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 $|\Delta m^2_{21}|$

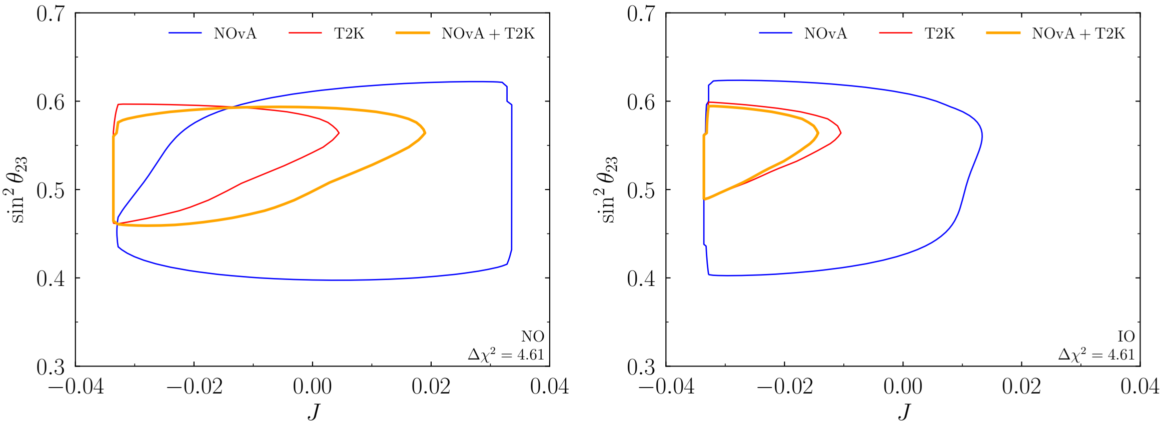
  KamLAND 1303.4667

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

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

This depends on NSI but LBL parameters don't cancel

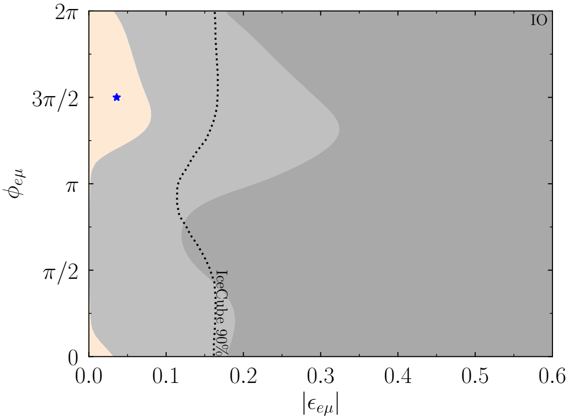
Standard oscillation parameters

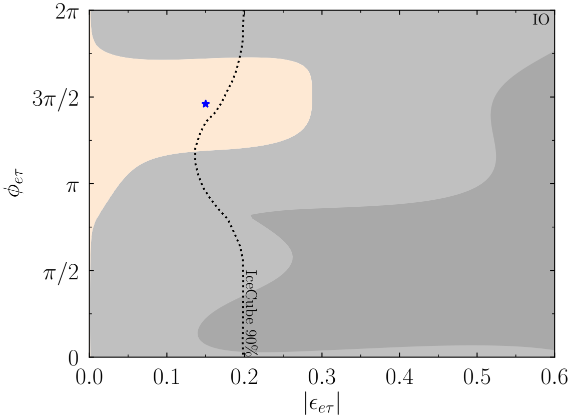


Can see that the combination doesn't like the NO while it does like the IO

IO preferred over NO at $\Delta\chi^2 = 2.3$

NSI parameters: IO





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