Abstract

First I will present a scenario wherein sterile neutrinos experience a new interaction with matter. This model requires a relatively strong new interaction which is typically ruled out; I will present a model that evades other constraints. This can explain the sterile hints and some of the sterile constraints. I will then examine if this can address sterile hints and constraints. 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.

3+1+NSI and CP Violation

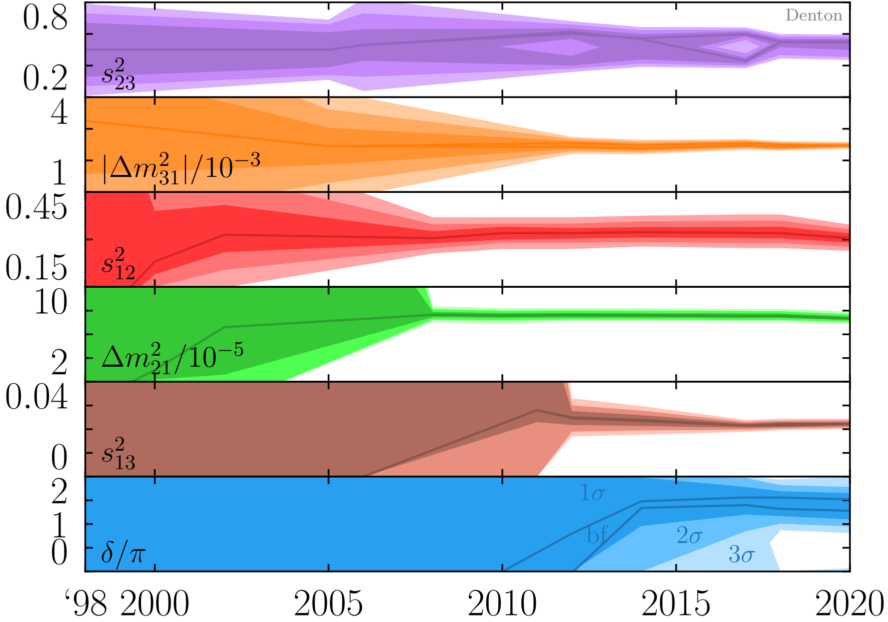
Peter B. Denton

KIAS Seminar

November 11/12, 2020


1811.01310
with Yasaman Farzan and Ian Shoemaker
2008.01110
with Julia Gehrlein and Rebekah Pestes


BROOKHAVEN NATIONAL LABORATORY
Brookhaven NDI



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

Overview

- Sterile neutrinos
- Add in sterile neutrino non-standard interactions

- NOvA and T2K slightly disagree
- New physics (with CP violation) can resolve this

Sterile neutrino motivation

- Probably required for neutrino mass generation
- $m_4 \gtrsim 1$ keV $\Rightarrow$ DM (also 7 keV sterile from X-ray line)

S. Dodelson, L. Widrow hep-ph/9303287

E. Bulbul, et al. 1402.2301

- Experimental evidence for $m_4 \sim 1$ eV
  - LSND + MiniBooNE: 6.1σ

LSND hep-ex/0104049

MiniBooNE 1805.12028

  - Reactor Antineutrino Anomaly: 3σ

G. Mention, et al. 1101.2755

A. Hayes, et al. 1707.07728

  - Gallium anomaly: $3\sigma \to 2.3\sigma$

C. Giunti, M. Laveder 1006.3244

J. Kostensalo, J. Suhonen, C. Giunti, P. Srivastava 1906.10980

  - NEOS & DANSS: $\sim 3\sigma \to 1.7\sigma$ & $2.8\sigma \to 1.8\sigma$

NEOS Neutrino, '18 $\to$ RENO, NEOS 2011.00896

DANSS Neutrino, '18 $\to$ 1911.10140

1 eV steriles: constraints

Experimental constraints from:

- IceCube 1605.01990
- MINOS/MINOS+ 1710.06488

  See also W. Louis 1803.11488
- Super-K 1410.2008
- KARMEN hep-ex/0203021
- CDHS PLB 134, 281 (1984)
- Daya Bay, MINOS, Bugey-3 1607.01177
- OPERA 1303.3953
- ICARUS 1209.0122
- NOvA 1706.04592
- PROSPECT 1806.02784

⋮

Some sterile observations

- $\nu_\mu \to \nu_e$ appearance requires both ν_e disappearance and ν_μ disappearance
- All evidence measurements are energy dependent only
  - Small or no matter potential
- Constraints leverage distance (or angle)
  - Large matter potential

New matter effect?

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

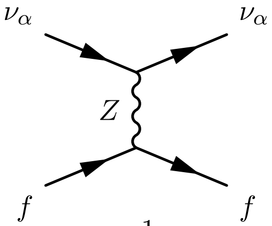
Affects oscillations via new matter effect

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

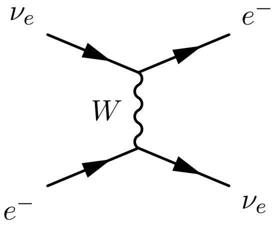
Matter potential $a \propto G_F \rho E$

B. Dev, K. Babu, PBD, P. Machado, et al. 1907.00991

Matter effects in feynman diagrams

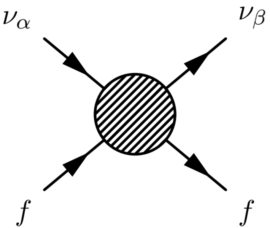


$$V_{\rm NC} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$



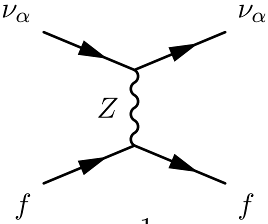
$$V_{\rm CC} = \pm\sqrt{2}G_F n_e$$

L. Wolfenstein PRD 17 (1978)

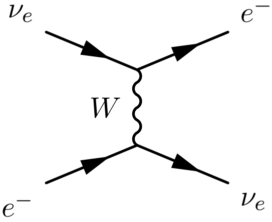


$$V_{\rm NSI} = \pm\epsilon_{\alpha\beta}^{f,X}\sqrt{2}G_F n_f$$

Matter effects in feynman diagrams

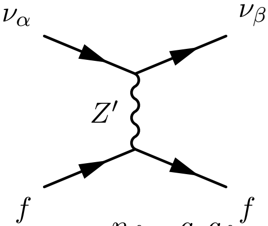


$$V_{\mathrm{NC}} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$



$$V_{\mathrm{CC}} = \pm\sqrt{2}G_F n_e$$

L. Wolfenstein PRD 17 (1978)



$$V_{\mathrm{NSI}} = \frac{n_f}{2}\frac{g_\nu g_f}{q^2 + m_{Z'}^2}$$

The sterile NSI model

Main components:

- $m_s \sim 1$ eV
- $m_{Z'} \sim 10$ eV

New $U_X(1)$ where fermions carry charge

$$B + a_e L_e + a_\mu L_\mu + a_\tau L_\tau$$

Need $\sum_\alpha a_\alpha = -3$ for chiral anomaly cancellation

This leads to negligible NSI among active neutrinos.

Sterile is charged under $U_X(1)$ with $a_s = g_s/g_B$.

Active-sterile mixing breaks gauge invariance.

The sterile NSI model

Add $U_X(1)$ charged Higgs doublet H'

- vev $\langle H' \rangle$
- Same charge as ν_s
- Mixing $U_{\alpha 4} = y_\alpha \langle H' \rangle / m_{\nu_s}$
- Contributes to the Z' mass $\langle H' \rangle < 10$ keV $\left(\frac{m_{Z'}}{10\text{ eV}}\right)\left(\frac{10^{-3}}{g_s}\right)$

Heavy H' with small vev?
New singlet scalar S with same $U_X(1)$ charge

$$\mathcal{L} \supset -m_S^2|S|^2 + \lambda_S|S|^4 + \mu S^\dagger H' \cdot H$$

$$\langle H' \rangle = -\langle S \rangle \frac{\mu \langle H \rangle}{2m_{H'}^2}$$

The S vev comes from m_S and $\langle S \rangle$ gives the Z' its mass.

Sterile NSI model: oscillations

$$V_s = 3(2\sqrt{2})G_F n_n \epsilon_{ss}$$

$$\epsilon_{ss} = \frac{g_s g_B}{m_{Z'}^2}\frac{1}{6\sqrt{2}G_F}$$

$$H_\nu^{\mathrm{mat}} = \begin{pmatrix} V_{\mathrm{CC}} + V_{\mathrm{NC}} & & & \\ & V_{\mathrm{NC}} & & \\ & & V_{\mathrm{NC}} & \\ & & & V_{\mathrm{s}} \end{pmatrix}$$

Sterile NSI model bounds

$Z-Z'$ mixing constrained to $\delta \lesssim 0.01$

H. Davoudiasl, H. Lee, W. Marciano 1203.2947

We have $\delta < 7\times10^{-8}\left(\frac{m_{Z'}}{10\text{ eV}}\right)\left(\frac{10^{-3}}{g_s}\right)$

Consistent with fifth force and stellar cooling constraints.

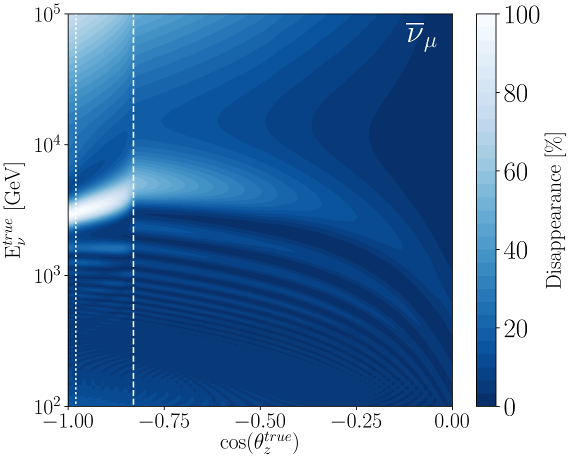
M. Bordag, U. Mohideen, V. Mostepanenko quant-ph/0106045

E. Hardy, R. Lasenby 1611.05852

Negligible contribution to $N_{\rm eff}$.

IceCube is sensitive to steriles

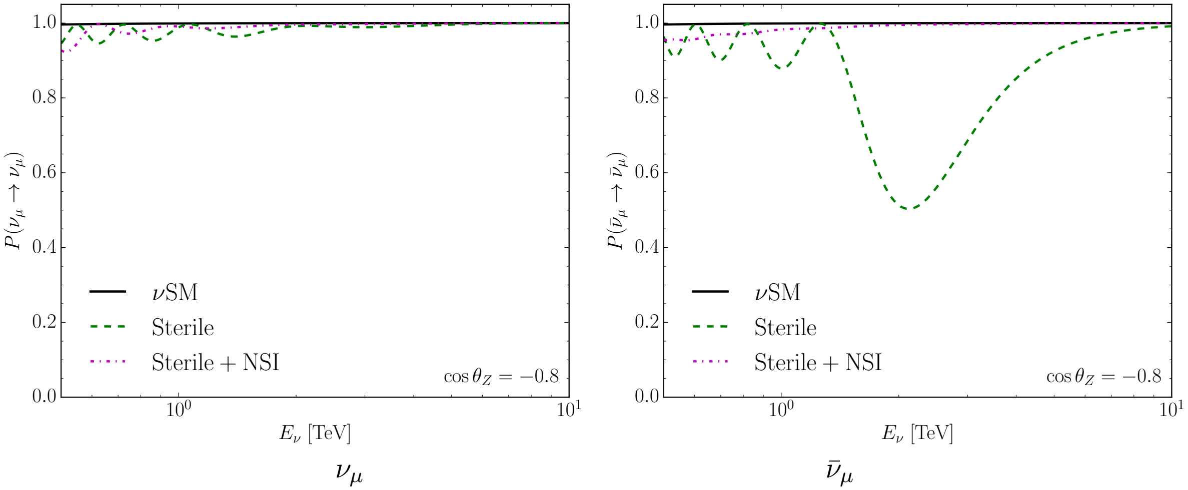
- Parametric resonance
- Core passing events
- Only for $\bar{\nu}_\mu$ disappearance
- $\Delta m^2_{41} \sim 1$ eV^2 $\rightarrow E_{\bar{\nu}_\mu} \sim 1$ TeV



IC 2005.12942

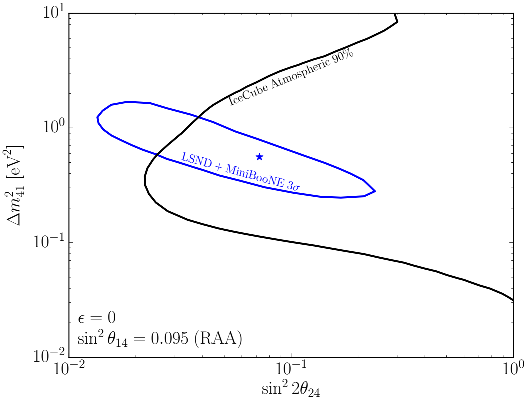
IceCube oscillation probabilities

Resonant MSW conversion of $\Delta m^2_{41} \simeq 1$ eV^2 through the core

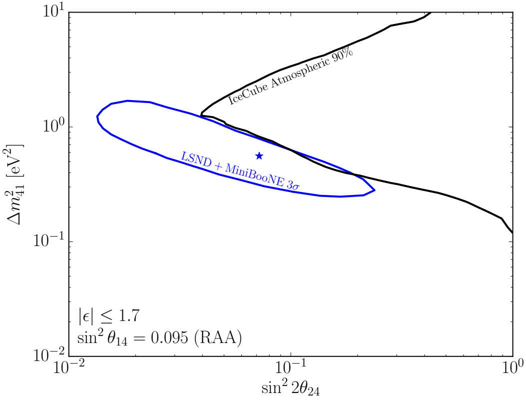


PBD, Y. Farzan, I. Shoemaker 1811.01310

Removing IceCube sterile constraints with NSI



Sterile



Sterile + Interaction

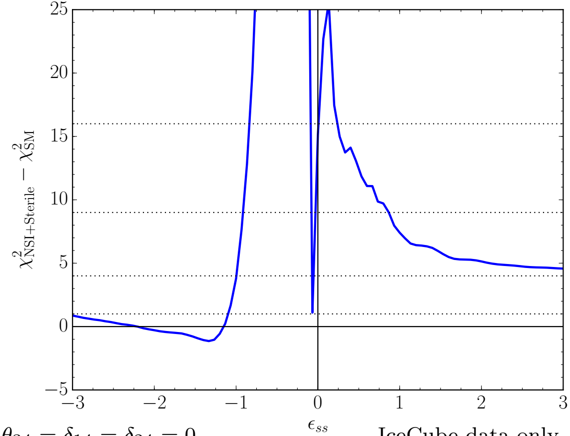
M. Dentler, et al. 1803.10661

$\theta_{34} = \delta_{14} = \delta_{24} = 0$

See also J. Liao, D. Marfatia 1602.08766

Removing IceCube sterile constraints with NSI

Sterile parameters fixed to global best fit



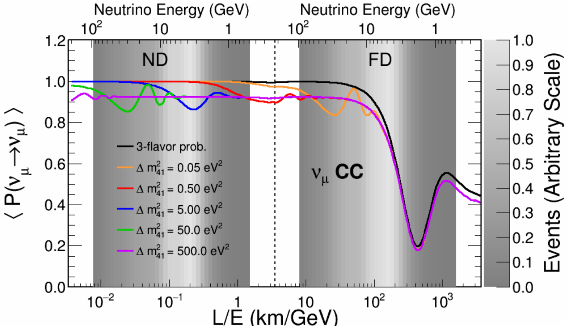
$\theta_{34} = \delta_{14} = \delta_{24} = 0$ IceCube data only

- $\epsilon_{ss} \sim -1.5$ with best fit sterile is slightly preferred over 3ν with IC data alone
- Also has a 6.1σ improvement in terms of LSND/MiniBooNE
- $\epsilon_{ss} = -\frac{1}{12} \Rightarrow$ sterile has the same NC interaction as active neutrinos

NSI: $\Delta\chi^2 = 15.1 \to -1.1$

MINOS/MINOS+ ND and FD

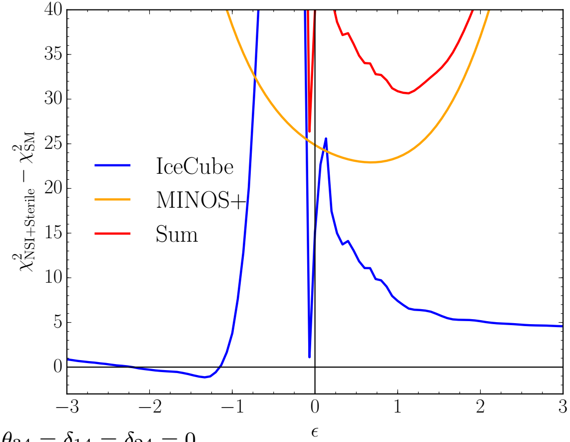
- Expect large dip in FD for atmospheric oscillations
- With steriles, use FD to normalize
- Look for oscillation signature in ND



MINOS+ 1710.06488

IceCube and MINOS+ sterile constraints with NSI

Sterile parameters fixed to global best fit



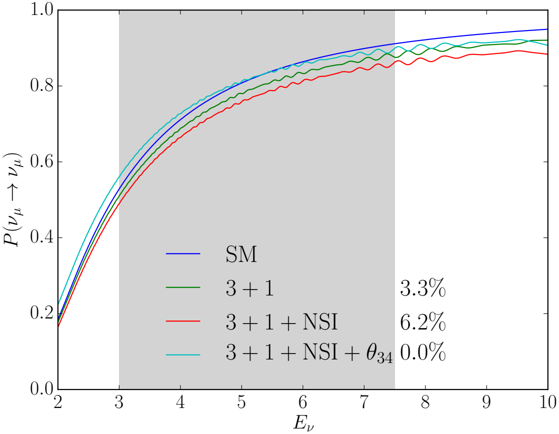
$\theta_{34} = \delta_{14} = \delta_{24} = 0$

- NSI can somewhat help MINOS+
- MINOS+ prefers $\epsilon_{ss} > 0$, IC prefers $\epsilon_{ss} < 0$
- Best fit is now $\epsilon_{ss} \sim -\frac{1}{12}$

NSI: $\Delta\chi^2 = 40 \to 26$

MINOS+ FD

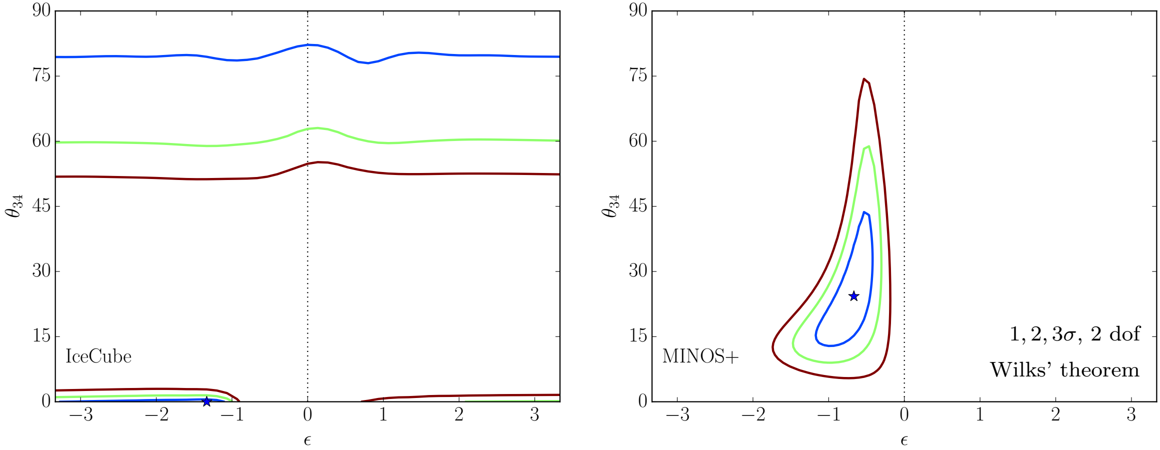
- NSI: $\Delta\chi^2 = 24.9 \to 22.9$
- θ_{34}: $\Delta\chi^2 \to 10.9$



$\delta_{14} = \delta_{24} = 0$, sterile parameters fixed to global best fit

More parameters

θ_{34} works ... one experiment at a time



$\delta_{14} = \delta_{24} = 0$

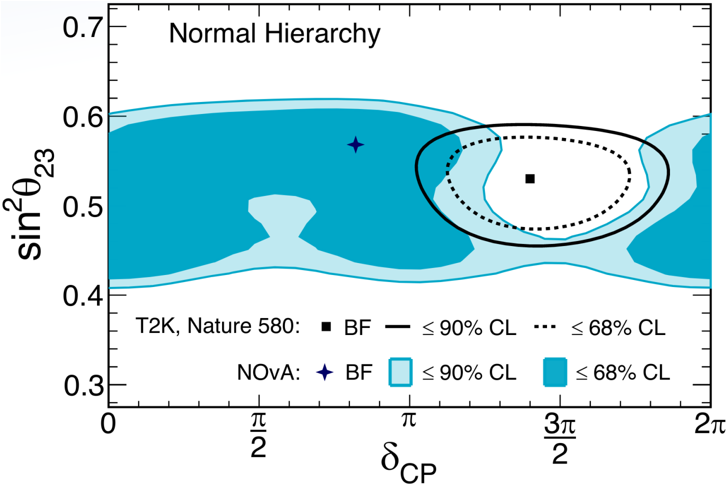
Including CP phases unlikely to help

3+1+NSI wrap up

- High significance evidence for light sterile
- NSI modifies constraining experiments, not evidence experiments
- Can fully relax IceCube, can mostly relax MINOS+
- Can't relax both

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 $C\nu B$

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. NO
3. 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 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:

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

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: 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 $\theta_{23} > 45°$

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 $\delta_{\text{NOvA}} \neq \delta_{\text{T2K}}$

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

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

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

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

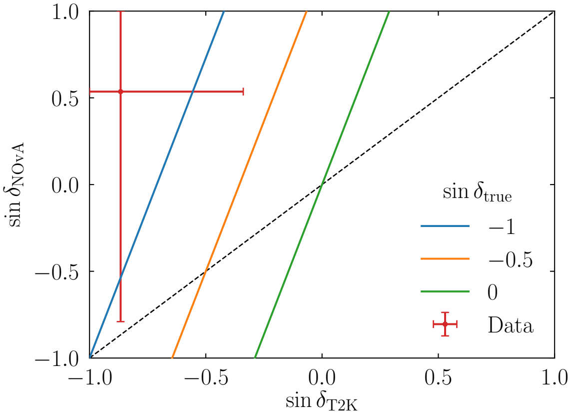
Estimate size of effect: measured phases

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

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

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

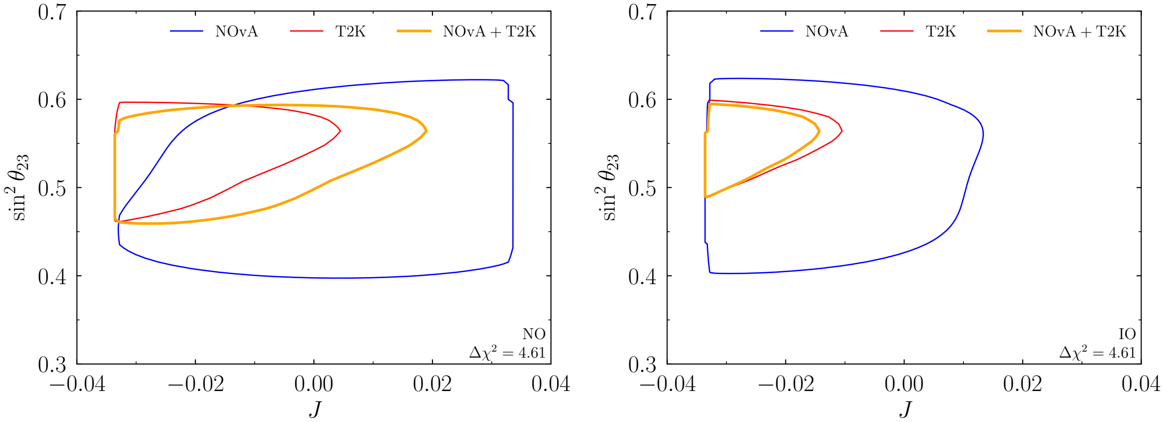
KamLAND 1303.4667

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



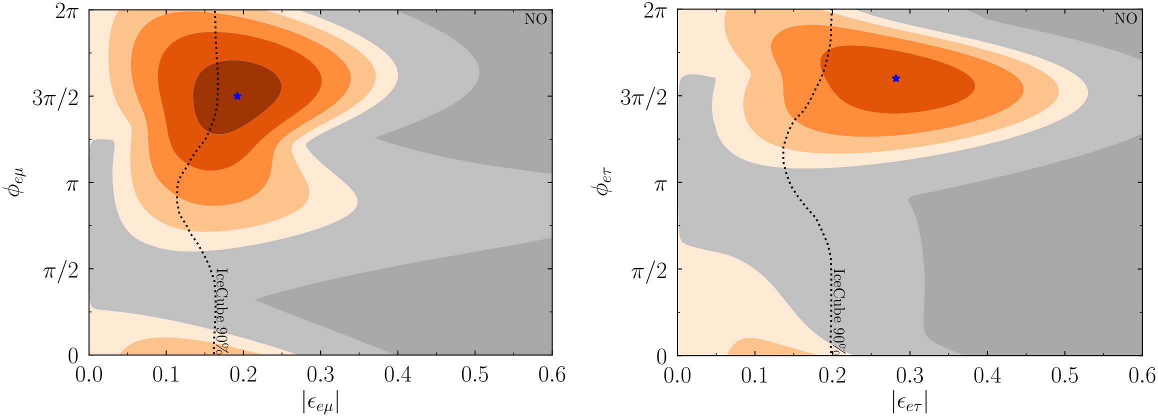
Can see that the combination doesn't like the NO while it does like the IO

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

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

C. Jarlskog PRL 55, 1039 (1985)

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

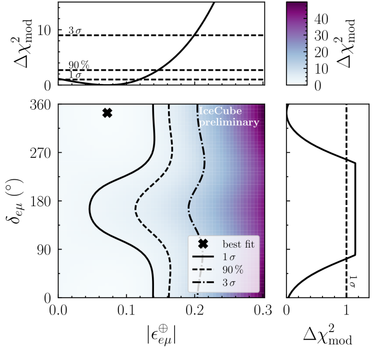
Best probes:

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

- IceCube
  - Slightly disfavoring LBL best fit point
  - Prefers non-zero $|\epsilon_{e\mu}|$ at $\sim 1\sigma$

- 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

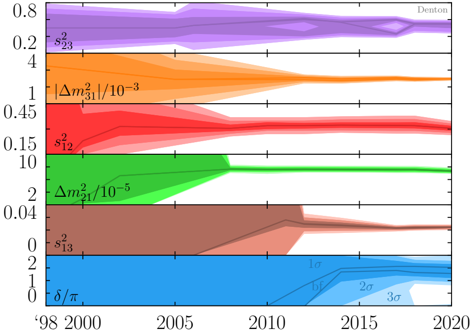
Summary

- IceCube and MINOS+ disfavor 3+1 explanations of LSND/MiniBooNE/RAA
- NSI addresses IceCube and mostly MINOS+
- Can't do both at once
- 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

Questions?

Backups

References



SK hep-ex/9807003

M. Gonzalez-Garcia, et al. hep-ph/0009350

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T. Schwetz, M. Tortola, J. Valle 0808.2016

M. Gonzalez-Garcia, M. Maltoni, J. Salvado 1001.4524

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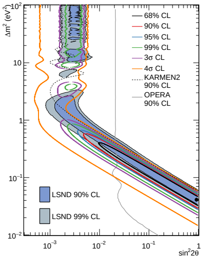
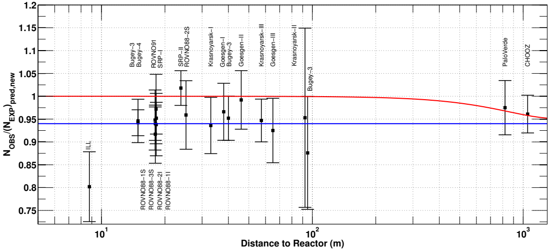
D. Forero, M. Tortola, J. Valle 1405.7540

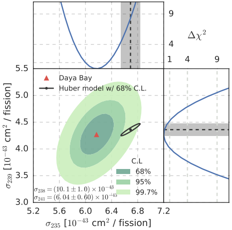
P. de Salas, et al. 1708.01186

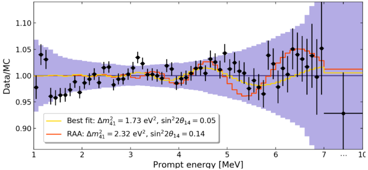
F. Capozzi et al. 2003.08511

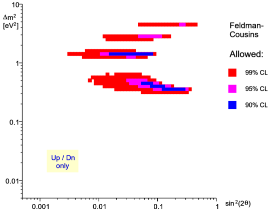
1 eV Steriles: Evidence





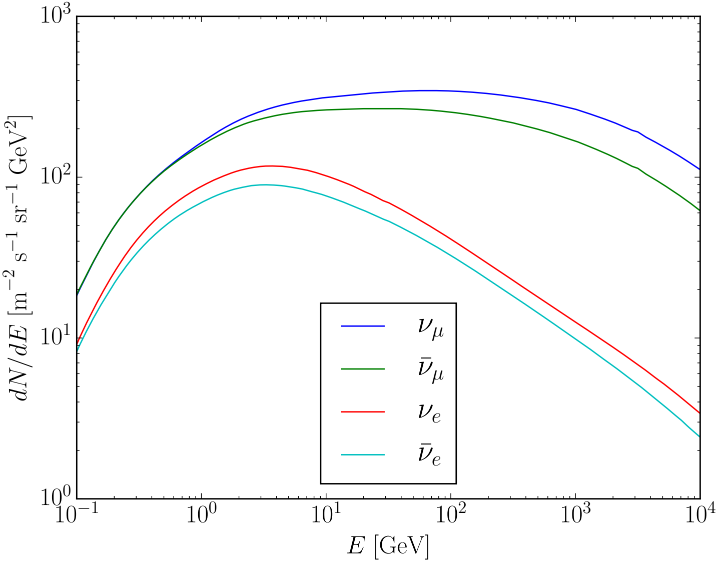




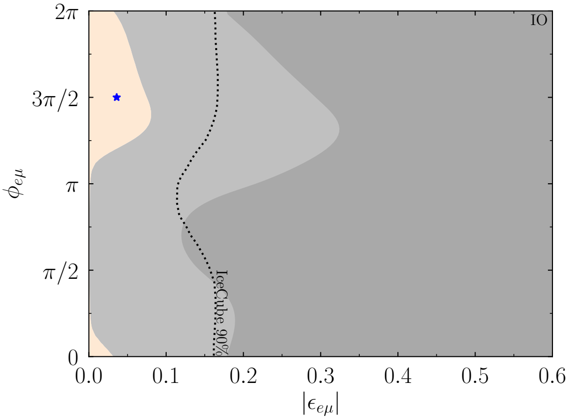


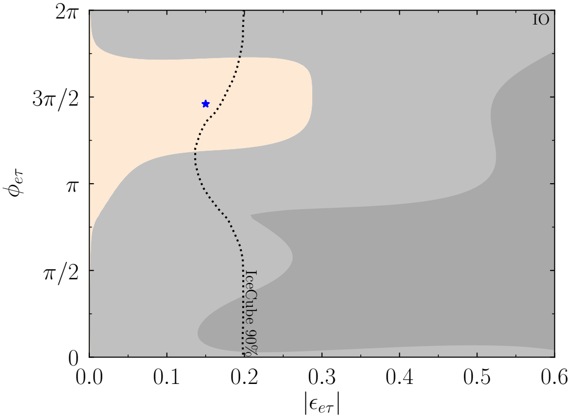
Daya Bay 1704.01082

Atmospheric flux



NSI parameters: IO





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