As next generation neutrino experiments, JUNO, HyperK, and DUNE are beginning to come online, the three-flavor oscillation picture should fall into shape. As it crystalizes, our ability to test this picture will improve considerably. To this end, I will discuss some new physics scenarios where neutrinos interact with regular matter in new ways. I will show how current long-baseline accelerator data from NOvA and T2K may already be hinting at such an interaction and that it can be tested in atmospheric neutrinos at IceCube or solar neutrinos in dark matter experiments LZ, XENONnT, and PandaX-4T. I will highlight key degeneracies and show the role that a future neutrino factory from a muon storage ring could play.

Understanding New Physics in Neutrinos

Peter B. Denton

Wayne State University

October 28, 2026

2008.01110 with J. Gehrlein and R. Pestes

2210.00109 with A. Giarnetti and D. Meloni

2407.02572 with J. Gehrlein

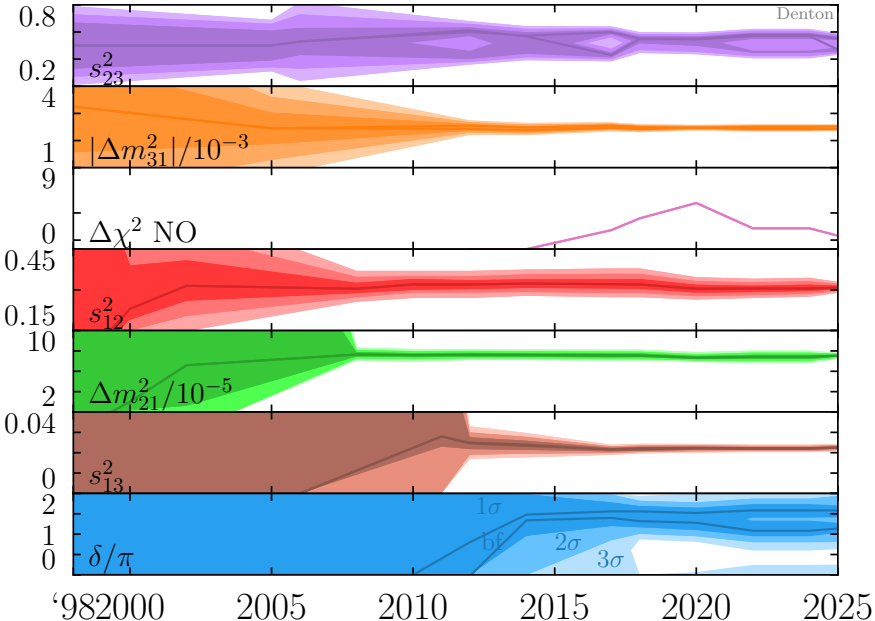
2502.14027 with J. Gehrlein and C-F. Kong

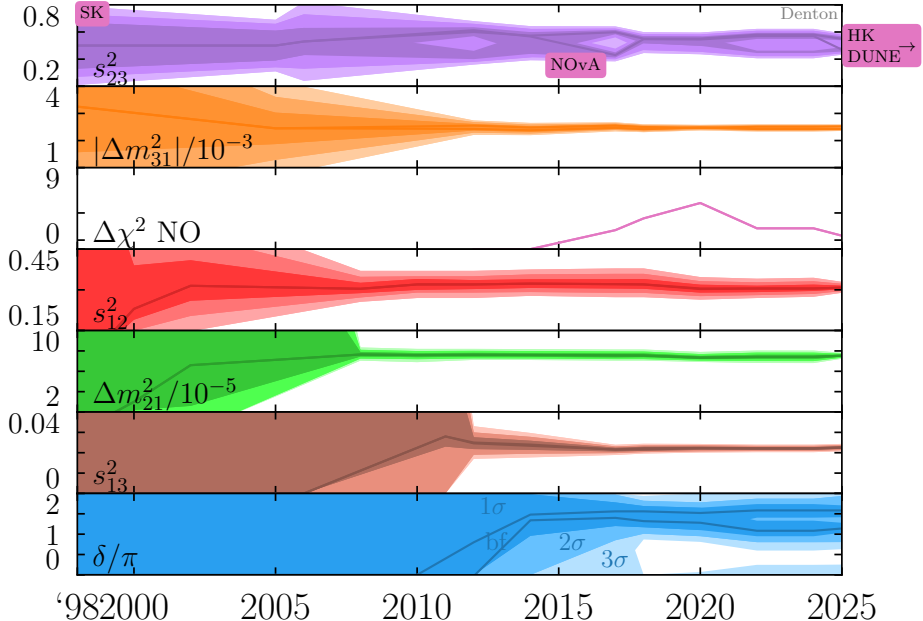
2610.18971 with D. Amaral, D. Cerdeño, A. Cheek, V. Costa, P. Foldenauer

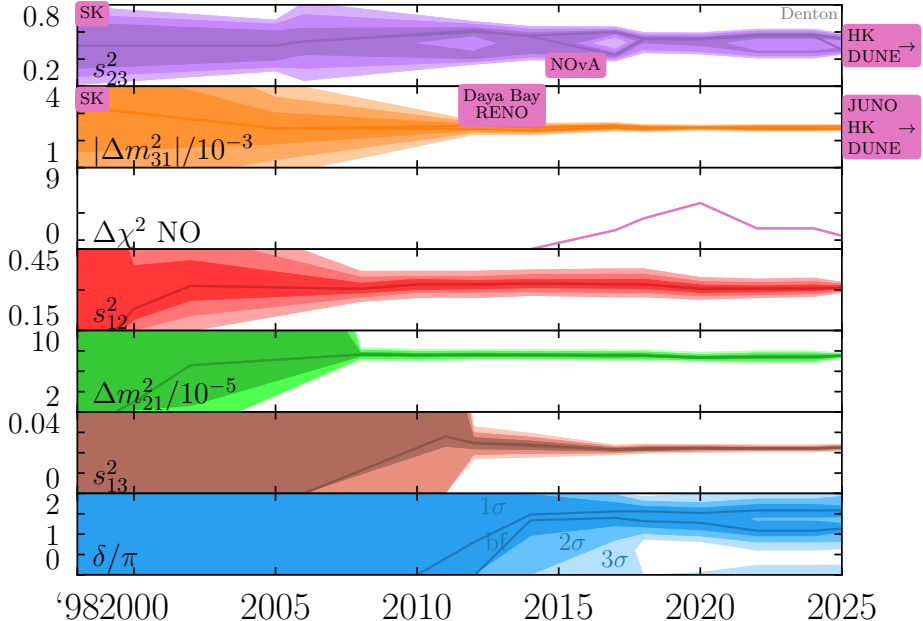


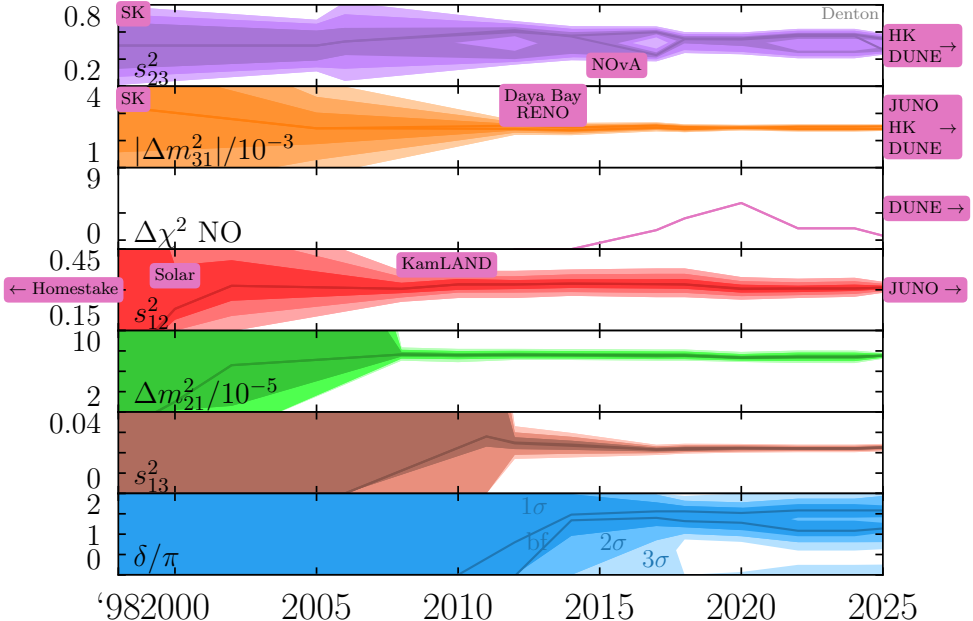
Brookhaven™
National Laboratory

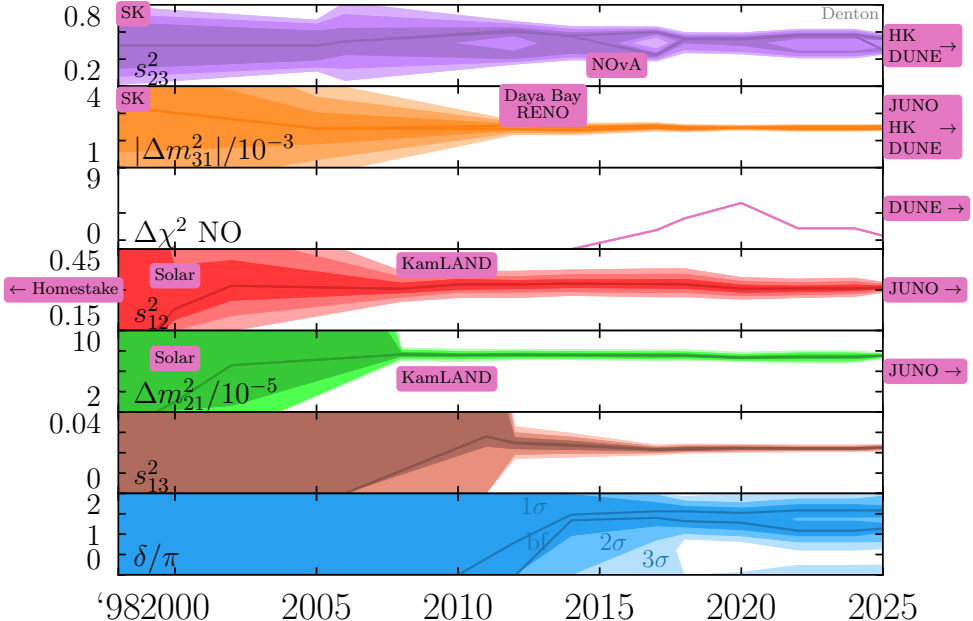

The BSM
Physicists

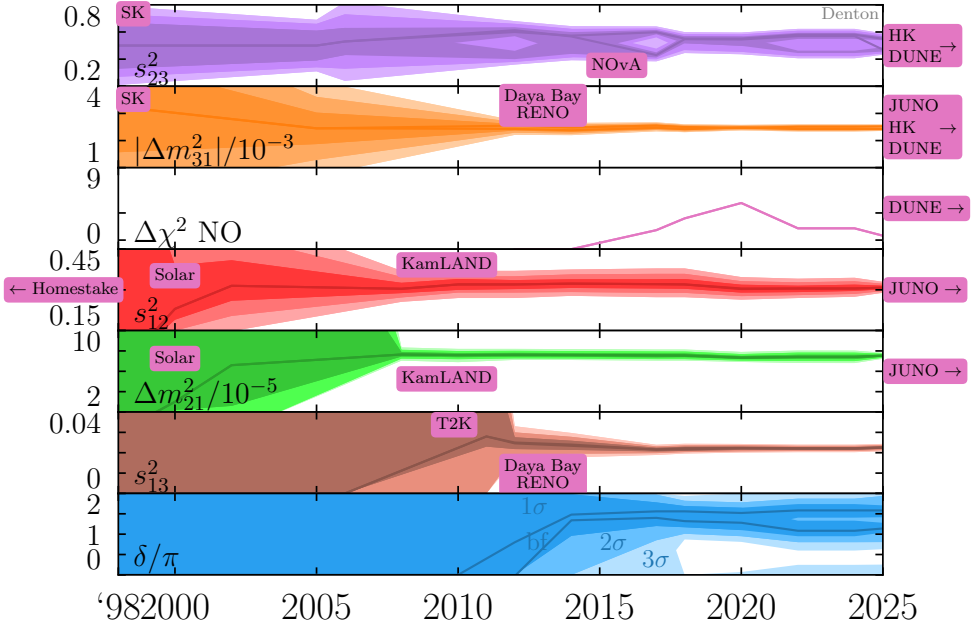

Denton
0.8
0.2
s^2_{23}
4
1
$|\Delta m^2_{31}|/10^{-3}$
9
0
$\Delta\chi^2$ NO
0.45
0.15
s^2_{12}
10
2
$\Delta m^2_{21}/10^{-5}$
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020
2025

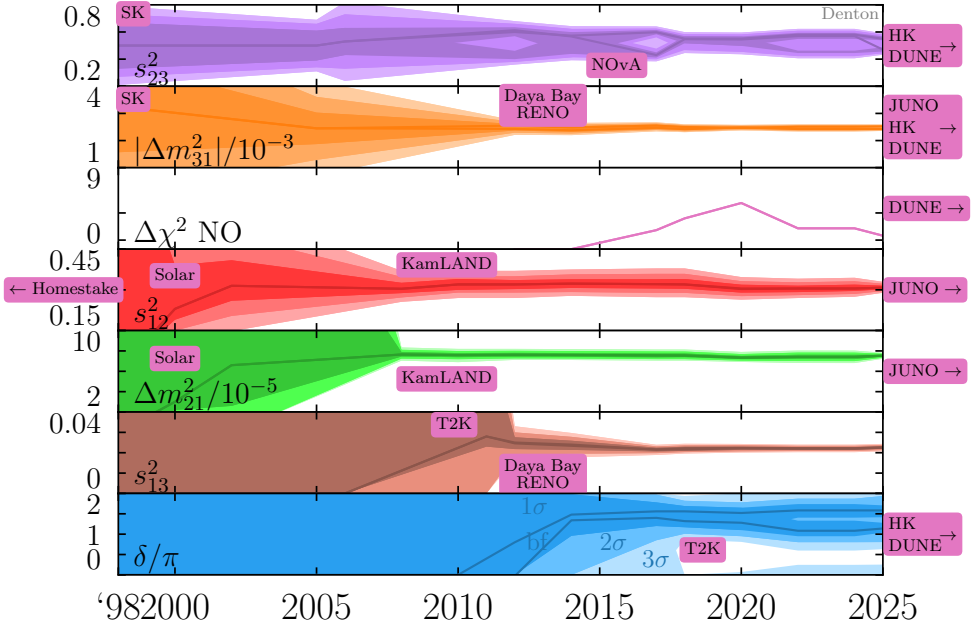

SK
Denton
HK
DUNE
NOvA
s^2_{23}
$|\Delta m^2_{31}|/10^{-3}$
$\Delta\chi^2$ NO
s^2_{12}
$\Delta m^2_{21}/10^{-5}$
s^2_{13}
δ/π
1σ
bf
2σ
3σ
0.8
0.2
4
1
9
0
0.45
0.15
10
2
0.04
0
2
1
0
'98
2000
2005
2010
2015
2020
2025


SK
Denton
s^2_{23}
NOvA
HK
DUNE
SK
Daya Bay
RENO
$|\Delta m^2_{31}|/10^{-3}$
JUNO
HK
DUNE
$\Delta\chi^2$ NO
s^2_{12}
$\Delta m^2_{21}/10^{-5}$
s^2_{13}
δ/π
1σ
bf
2σ
3σ
0.8
0.2
4
1
9
0
0.45
0.15
10
2
0.04
0
2
1
0
'98
2000
2005
2010
2015
2020
2025


0.8
0.2
SK
s^2_{23}
Denton
NOvA
HK
DUNE →
4
1
SK
$|\Delta m^2_{31}|/10^{-3}$
Daya Bay
RENO
JUNO
HK →
DUNE
9
0
$\Delta\chi^2$ NO
DUNE →
0.45
0.15
← Homestake
Solar
s^2_{12}
KamLAND
JUNO →
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
2025


0.8
0.2
SK
s^2_{23}
Denton
NOvA
HK
DUNE →
4
1
SK
$|\Delta m^2_{31}|/10^{-3}$
Daya Bay
RENO
JUNO
HK →
DUNE
9
0
$\Delta\chi^2$ NO
DUNE →
0.45
0.15
← Homestake
Solar
s^2_{12}
KamLAND
JUNO →
10
2
Solar
$\Delta m^2_{21}/10^{-5}$
KamLAND
JUNO →
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
'98
2000
2005
2010
2015
2020
2025

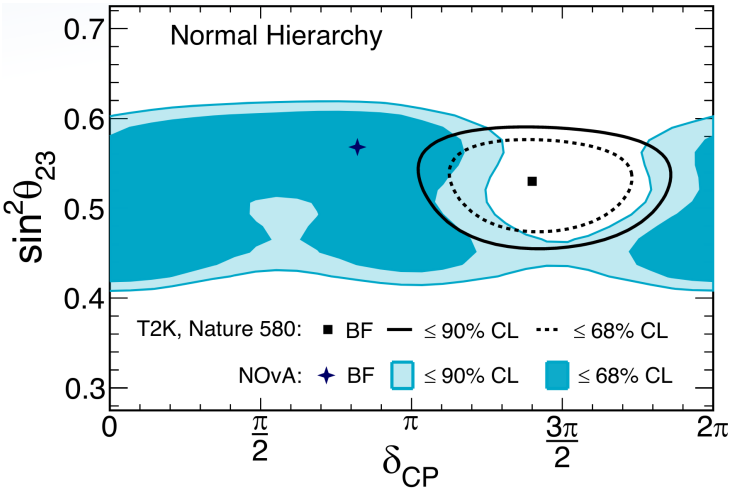

Denton
SK
s^2_{23}
NOvA
HK
DUNE →
SK
$|\Delta m^2_{31}|/10^{-3}$
Daya Bay
RENO
JUNO
HK →
DUNE
$\Delta\chi^2$ NO
DUNE →
← Homestake
Solar
s^2_{12}
KamLAND
JUNO →
Solar
$\Delta m^2_{21}/10^{-5}$
KamLAND
JUNO →
T2K
s^2_{13}
Daya Bay
RENO
δ/π
1σ
bf
2σ
3σ
0.8
0.2
4
1
9
0
0.45
0.15
10
2
0.04
0
2
1
0
'98
2000
2005
2010
2015
2020
2025


Denton
SK
NOvA
HK
DUNE
s^2_{23}
0.8
0.2
SK
Daya Bay
RENO
JUNO
HK
DUNE
$|\Delta m^2_{31}|/10^{-3}$
4
1
DUNE
$\Delta\chi^2$ NO
9
0
Solar
KamLAND
← Homestake
JUNO
s^2_{12}
0.45
0.15
Solar
KamLAND
JUNO
$\Delta m^2_{21}/10^{-5}$
10
2
T2K
Daya Bay
RENO
s^2_{13}
0.04
0
1σ
bf
2σ
3σ
T2K
HK
DUNE
δ/π
2
1
0
'98
2000
2005
2010
2015
2020
2025

Outline

1. Tension in NOvA and T2K data
2. DUNE's power to discover and identify
3. Degeneracies in new physics searches at DUNE: multiple parameters
4. Addressing with solar ν's at DM direct detection or a neutrino factory

CP Violation Searches at NOvA and T2K?



A. Himmel for NOvA 10.5281/zenodo.3959581

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? U. Rahaman 2103.04576
- Unitary violation? D. Forero, et al. 2103.01998

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? U. Rahaman 2103.04576
- Unitary violation? D. Forero, et al. 2103.01998
- NSI with complex CP violating phases
  1. Different matter effects ⇒ 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"

PBD, J. Gehrlein, R. Pestes 2008.01110
See also S. Chatterjee, A. Palazzo 2008.04161

Vector NSI

NSI at the Lagrangian Level

EFT Lagrangian:

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

L. Wolfenstein, PRD 17 (1978)

with $\Lambda \sim \frac{1}{\sqrt{2\sqrt{2}\epsilon G_F}}$.

NSI at the Lagrangian Level

EFT Lagrangian:

$$\mathscr{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha,\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

L. Wolfenstein, PRD 17 (1978)

with $\Lambda \sim \frac{1}{\sqrt{2\sqrt{2}\epsilon G_F}}$.

Simplified model Lagrangian:

$$\mathscr{L}_{\rm NSI} = g_\nu Z'_\mu \bar{\nu}\gamma^\mu \nu + g_f Z'_\mu \bar{f}\gamma^\mu f$$

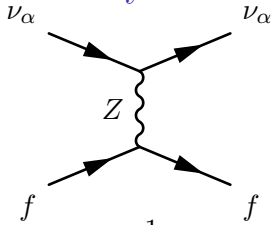
which gives a potential

$$V_{\rm NSI} \propto \frac{g_\nu g_f}{q^2 + m^2_{Z'}}$$

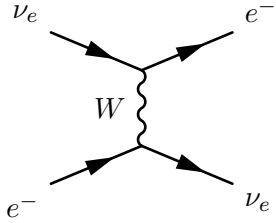
Models with large NSIs consistent with CLFV:

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

Matter Effects in Feynman Diagrams

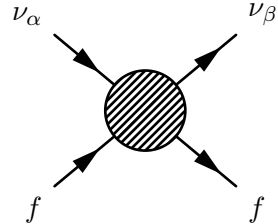


$$V_{\rm NC} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$



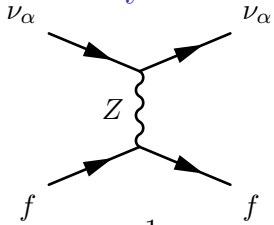
$$V_{\rm CC} = \pm\sqrt{2}G_F n_e$$

L. Wolfenstein, PRD 17 (1978)

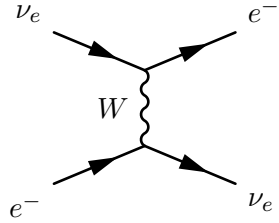


$$V_{\rm NSI} = \pm\epsilon^{f,X}_{\alpha\beta}\sqrt{2}G_F n_f$$

Matter Effects in Feynman Diagrams

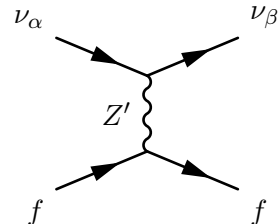


$$V_{\rm NC} = \mp\frac{1}{2}\sqrt{2}G_F n_n$$



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

L. Wolfenstein, PRD 17 (1978)



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

NSI at the Hamiltonian Level

$$H^{\text{vac}} = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger$$

$$H^{\text{mat,SM}} = \frac{a}{2E} \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix} \qquad \text{(NC subtracted out)}$$

$$H^{\text{mat,NSI}} = \frac{a}{2E} \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

$$\epsilon_{\alpha\beta} = \sum_{f \in \{e,u,d\}} \epsilon^{f,V}_{\alpha\beta} \frac{N_f}{N_e}$$

$$H = H^{\text{vac}} + H^{\text{mat,SM}} + H^{\text{mat,NSI}}$$

Estimate Size of NSI LBL Effect: Magnitude

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

$a \propto \rho E$
$w_\beta = s_{23}, c_{23}$ for $\beta = \mu, \tau$
Assumed upper octant $\theta_{23} > 45°$

Consistency checks:

- $\sin\delta_{\text{NOvA}} = \sin\delta_{\text{T2K}} \Rightarrow |\epsilon| = 0$
- $\sin\delta_{\text{NOvA}} \neq \sin\delta_{\text{T2K}}$ and $a_{\text{NOvA}} = a_{\text{T2K}} \Rightarrow |\epsilon| \to \infty$
- 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

Fit 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

Must include wrong sign leptons

Disappearance:
NOvA:

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

K. Kelly, et al. 2007.08526

T2K: Δm^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

Completing the Fit

Appearance measurements depend on all six parameters
Can NOT use input from global fits

T2K affects θ_{13}

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

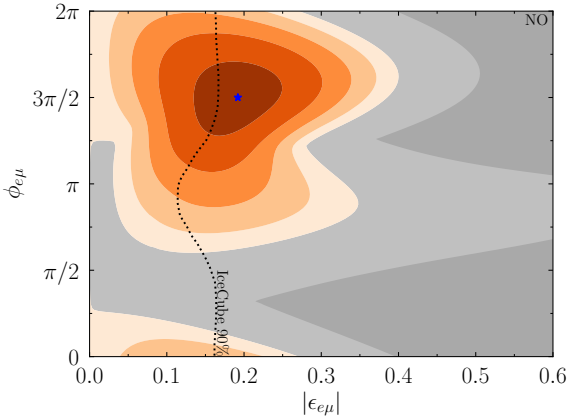
  KamLAND 1303.4667

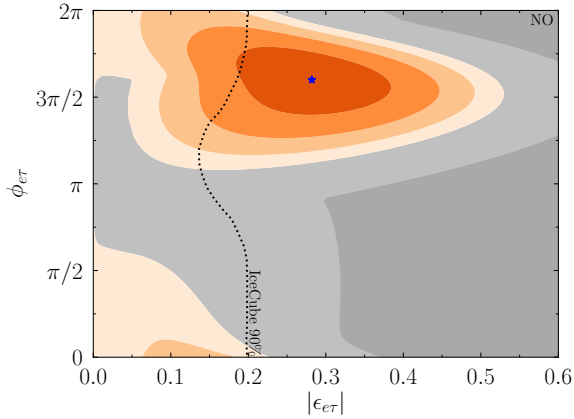
Solar ν's tell us $\Delta m^2_{21} > 0$

or $\theta_{12} < 45°$ depending on $|\nu_i\rangle$ definition,
See PBD 2003.04319

Solar ν's depend on NSI but NSI relevant for LBL doesn't swap sgn Δm^2_{21}

NSI Parameters





Orange is preferred over SM at integer values of $\Delta\chi^2$, dark gray is disfavored at 4.61

PBD, J. Gehrlein, R. Pestes 2008.01110
T. Ehrhardt, IceCube PPNT (2019)
$\epsilon_{\mu\tau}$, IO in backups

BSM Differentiation at DUNE

If there is new physics at NOvA & T2K levels,
can its nature be identified?

BSM Differentiation at DUNE

If there is new physics at NOvA & T2K levels,
can its nature be identified?

Consider scenarios which "address" current LBL data

- Vector NSI which works well for $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$
- Scalar NSI: $\mathcal{L}^{eff}_{\text{scalar NSI}} = \frac{y_f y_{\alpha\beta}}{m^2_\phi}(\bar{\nu}_\alpha \nu_\beta)$
- 3+1 at $\Delta m^2_{41} = 1$ eV^2 and $\theta_{14} = \theta_{24} = 8^\circ$

BSM Differentiation at DUNE

If there is new physics at NOvA & T2K levels,
can its nature be identified?

Consider scenarios which "address" current LBL data

- Vector NSI which works well for $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$
- Scalar NSI: $\mathcal{L}^{eff}_{\text{scalar NSI}} = \frac{y_f y_{\alpha\beta}}{m^2_\phi}(\bar{\nu}_\alpha \nu_\beta)$
- 3+1 at $\Delta m^2_{41} = 1$ eV^2 and $\theta_{14} = \theta_{24} = 8°$

Test if DUNE can tell the difference
DUNE's high energy, broad band $\Rightarrow$ unparalleled new physics identification

Assume best fit points from NOvA+T2K data
DUNE: 40 kt, 1.2 MW, 6.5+6.5 years

BSM Differentiation at DUNE

		Scalar NSI			Vector NSI			
$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
$\varepsilon_{e\mu}$ NO	200	140	140	170	/	180	160	80
$\varepsilon_{e\tau}$ NO	60	48	50	45	50	/	50	40
$\varepsilon_{\mu\tau}$ NO	200	180	170	180	160	180	/	80
$\varepsilon_{e\mu}$ IO	170	80	75	90	/	10	13	3
$\varepsilon_{e\tau}$ IO	70	50	50	45	45	/	60	20
$\varepsilon_{\mu\tau}$ IO	500	400	400	400	300	350	/	160

PBD, A. Giarnetti, D. Meloni 2210.00109

BSM Differentiation at DUNE

			Scalar NSI			Vector NSI			
	$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
→	$\varepsilon_{e\mu}$ NO	200	140	140	170	/	180	160	80
→	$\varepsilon_{e\tau}$ NO	60	48	50	45	50	/	50	40
	$\varepsilon_{\mu\tau}$ NO	200	180	170	180	160	180	/	80
	$\varepsilon_{e\mu}$ IO	170	80	75	90	/	10	13	3
	$\varepsilon_{e\tau}$ IO	70	50	50	45	45	/	60	20
	$\varepsilon_{\mu\tau}$ IO	500	400	400	400	300	350	/	160

PBD, A. Giarnetti, D. Meloni 2210.00109

BSM Differentiation at DUNE

		Scalar NSI			Vector NSI			
$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
$\varepsilon_{e\mu}$ NO	200	140	140	170	/	180	160	80
$\varepsilon_{e\tau}$ NO	60	48	50	45	50	/	50	40
$\varepsilon_{\mu\tau}$ NO	200	180	170	180	160	180	/	80
$\varepsilon_{e\mu}$ IO	170	80	75	90	/	10	13	3
$\varepsilon_{e\tau}$ IO	70	50	50	45	45	/	60	20
$\varepsilon_{\mu\tau}$ IO	500	400	400	400	300	350	/	160

New physics is easily discovered

PBD, A. Giarnetti, D. Meloni 2210.00109

BSM Differentiation at DUNE

		Scalar NSI			Vector NSI			
$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$	3+1
$\varepsilon_{e\mu}$ NO	200	140	140	170	/	180	160	80
$\varepsilon_{e\tau}$ NO	60	48	50	45	50	/	50	40
$\varepsilon_{\mu\tau}$ NO	200	180	170	180	160	180	/	80
$\varepsilon_{e\mu}$ IO	170	80	75	90	/	10	13	3
$\varepsilon_{e\tau}$ IO	70	50	50	45	45	/	60	20
$\varepsilon_{\mu\tau}$ IO	500	400	400	400	300	350	/	160

New physics is easily discovered

Other new physics scenarios are easily rejected

PBD, A. Giarnetti, D. Meloni 2210.00109

More New Physics

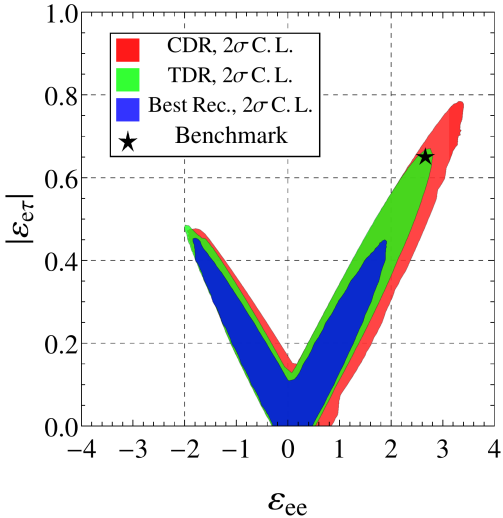
- So far, assumed one ($\mathbb{R}$ or $\mathbb{C}$) new physics parameter at a time
- Multiple NSI parameters, especially complex CPV, lead to degeneracies

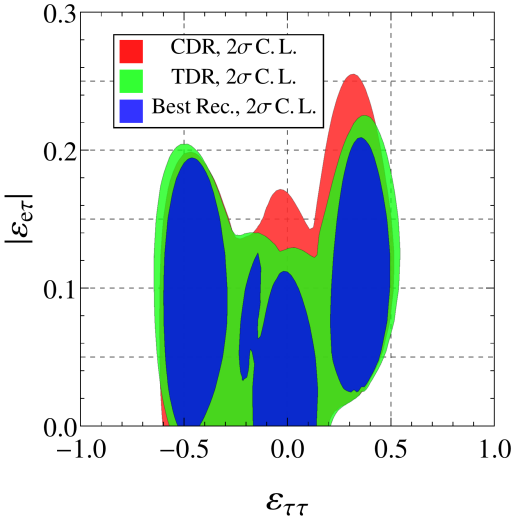
J. Liao, D. Marfatia, K. Whisnant 1601.00927
P. Coloma, T. Schwetz 1604.05772
S. Chatterjee, B. Dev, P. Machado 2106.04597
PBD, J. Gehrlein, C-F. Kong 2502.14027

- Dominant degeneracies: $\epsilon_{e\tau}$ and either ϵ_{ee} or $\epsilon_{\tau\tau}$

WLOG set $\epsilon_{\mu\mu} = 0$

Partial Degeneracies in New Physics Scenarios





$\phi_{e\tau}$ marginalized over

S. Chatterjee, B. Dev, P. Machado 2106.04597

Break These Degeneracies

Go beyond DUNE with:
solar neutrinos at DM direct detection now,
and neutrino factory later

Solar Neutrinos

- Fusion is a source of ν_e
- We have detected pp, ^{7}Be, pep, CNO, and ^{8}B sources

Hopefully hep with HK & DUNE

- Propagate out of Sun as nearly eigenstates of Hamiltonian in dense environment

L. Wolfenstein, PRD 17 (1978)
S. Mikheyev, A. Smirnov 1985

- Decohere to the Earth
- Pass through sharply varying Earth density profile
- Interact via
  - CC: ν_e
  - eES (CC+NC): mostly ν_e, some $\nu_\mu + \nu_\tau$
  - NC/CEvNS: equal cross sections for each flavor

Solar Neutrinos Standard Picture

pp:

- low energy <MeV
- matter effect is small
- oscillation averaged:

$$P_{ee}^{\odot,LE} \approx 1 - \frac{1}{2}\sin^2 2\theta_{12} \approx 0.57$$

^{8}B:

- high energy >MeV
- matter effect dominates
- MSW effect:

$$P_{ee}^{\odot,HE} \approx s_{12}^2 \approx 0.31$$

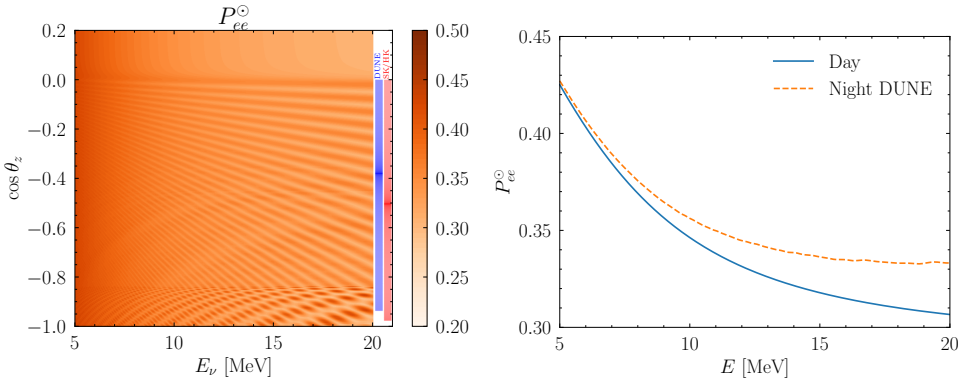
- Neutrinos leave the Sun as ν_2

See e.g. PBD 2501.08374

Nighttime Solar Neutrinos Standard Picture

Nighttime neutrinos:

- Leads to very fast oscillations through Earth
- On average a slight enhancement in the ν_e rate over daytime
- SuperK has $\sim 2\sigma$ evidence for it, HK & DUNE aim to measure it well



PBD, S. Parke 2511.04735
NuFast-Earth

New Interactions in Solar Neutrinos

- Modifies the evolution in the Sun
- Modifies the evolution in the Earth
- Modifies the cross section

New Interactions in Solar Neutrinos

- Modifies the evolution in the Sun
- Modifies the evolution in the Earth
- Modifies the cross section

For a NC detection:

- Changing flavors during propagation alone does nothing
- Changing cross sections in a flavor dependent fashion changes rate
- Changing flavors during propagation changes flavor dependent cross sections

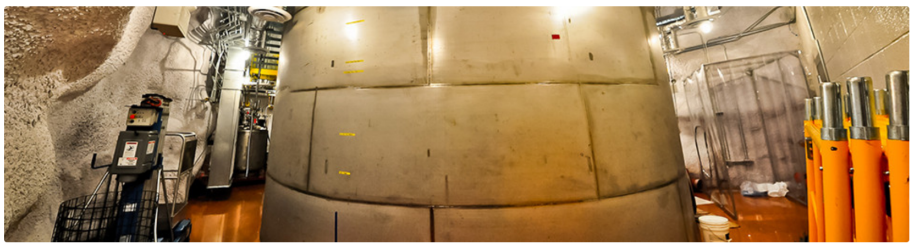
DM Direct Detection Program is Now in the Neutrino Program

The LZ Dark Matter Experiment

The status and science of the LZ dark matter experiment.

DETECTOR LABORATORY COLLABORATION PUBLICATIONS TALKS NEWS PHOTOS LINKS

REQUEST AN LZ SPEAKER



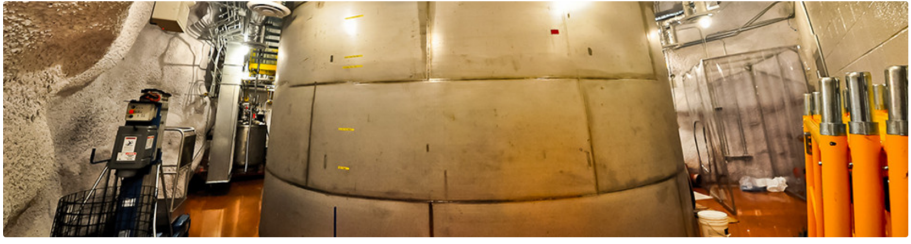
DM Direct Detection Program is Now in the Neutrino Program

The LZ Dark Matter Experiment Neutrino

The status and science of the LZ dark matter experiment.

DETECTOR LABORATORY COLLABORATION PUBLICATIONS TALKS NEWS PHOTOS LINKS

REQUEST AN LZ SPEAKER



DM Direct Detection Program is Now in the Neutrino Program

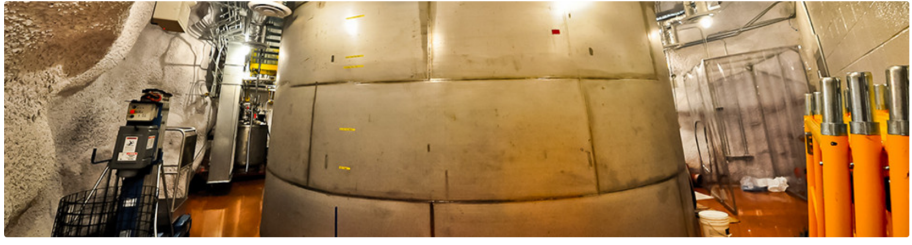
The LZ Dark Matter Experiment

Neutrino

The status and science of the LZ dark matter experiment.

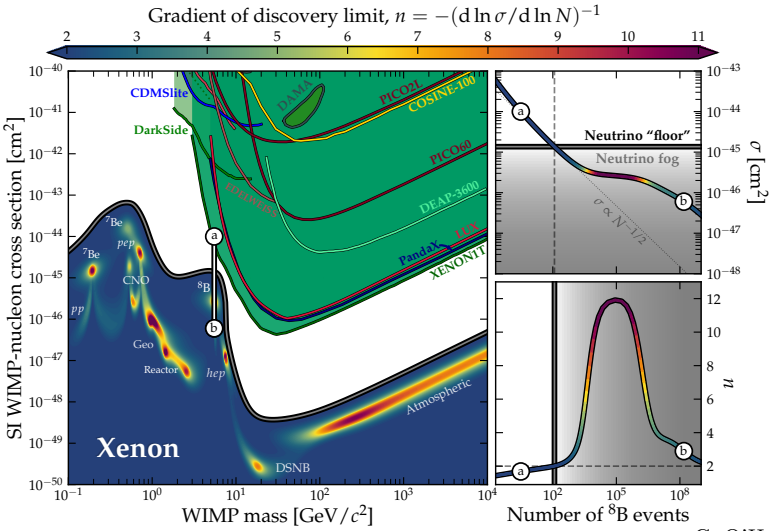
DETECTOR LABORATORY COLLABORATION PUBLICATIONS TALKS NEWS PHOTOS LINKS

REQUEST AN LZ SPEAKER



and XENONnT and PandaX-4T

Entering the Neutrino Fog



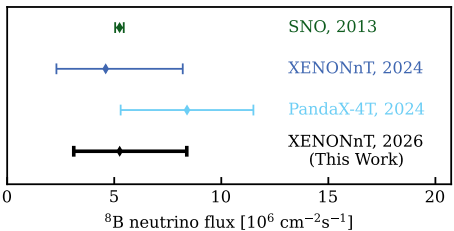
C. O'Hare 2109.03116

See also J. Monroe, P. Fisher 0706.3019, ...

DM-DD of Solar Neutrinos

^{8}B with CEvNS NR

2.6σ	PandaX-4T 2407.10892
4.5σ	LZ 2512.08065
3.3σ	XENONnT 2604.06002



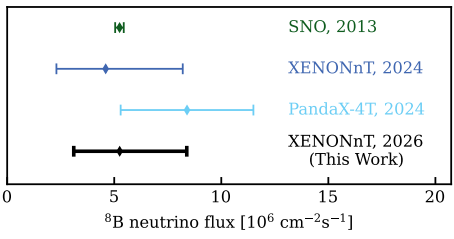
DM-DD of Solar Neutrinos

^{8}B with CEvNS NR

2.6σ PandaX-4T 2407.10892

4.5σ LZ 2512.08065

3.3σ XENONnT 2604.06002

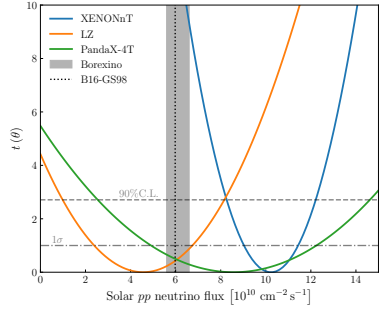


pp with EvES ER

2.2σ PandaX-4T 2607.02405

5.0σ XENONnT 2608.29450
1.9σ higher than BOREXINO

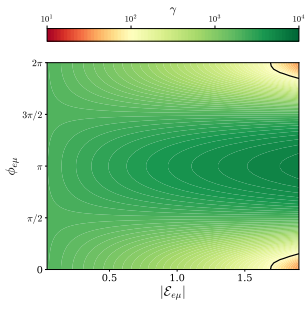
2.1σ LZ PBD, et al. 2610.18971



New Physics in Solar Neutrinos: Consistency Check

Adiabatic approximation?

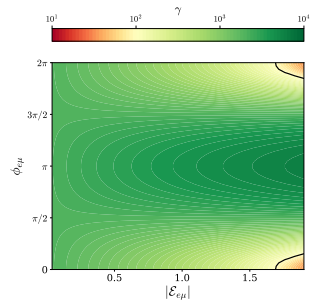
$$P_{\text{jump}} = \exp(-\frac{\pi}{2}\gamma)$$



New Physics in Solar Neutrinos: Consistency Check

Adiabatic approximation?

$$P_{\text{jump}} = \exp(-\frac{\pi}{2}\gamma)$$

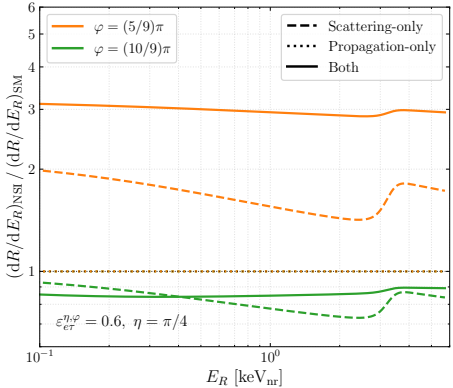


In SM: $\gamma \gg 1$,

this is also true for all NSI parameters of interest

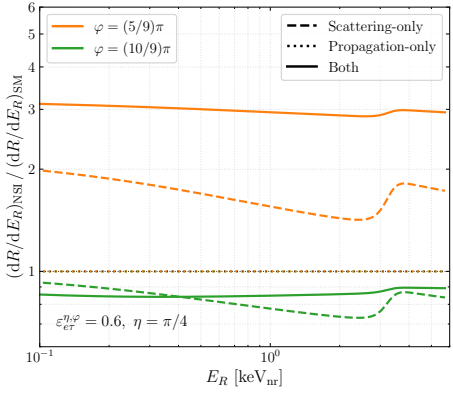
New Physics in Solar Neutrinos: Consistency Check

Relative role of propagation vs. scattering?



New Physics in Solar Neutrinos: Consistency Check

Relative role of propagation vs. scattering?



Propagation alone does nothing,
but scattering and propagation have comparable size effects

Our Analysis

- Fit to the existing NR and ER data
- Projected sensitivities for future detectors
- Included backgrounds with uncertainties
- Log-likelihood fit validated to experimental results
- Marginalized over oscillation and NSI parameters

- For oscillation studies, NSI to u, d, e makes little difference;
  when comparing to DM-DD it makes a big difference

  It does matter somewhat for combining regular CC solar neutrinos with LBL and atm

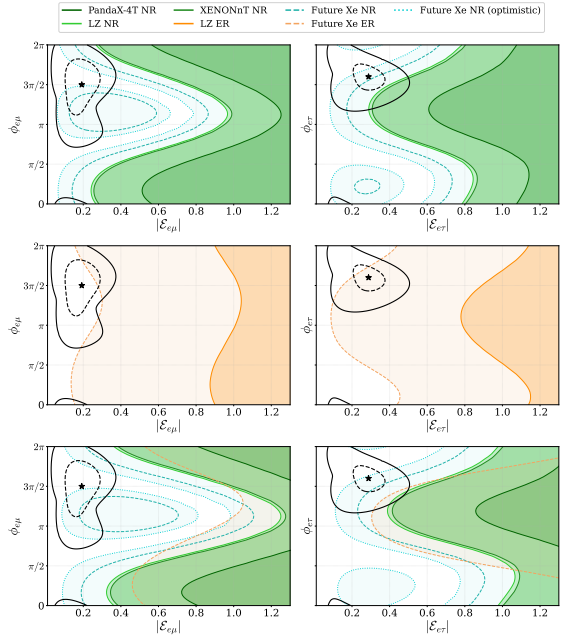
DM-DD vs. NOvA and T2K

$$\epsilon^p = \epsilon^n,\ \epsilon^e = 0$$

$$\epsilon^p = \epsilon^n = 0$$

$$\epsilon_p = \epsilon_e = \epsilon_n/\sqrt{2}$$

Did not consider XENONnT's ER due to their slight excess



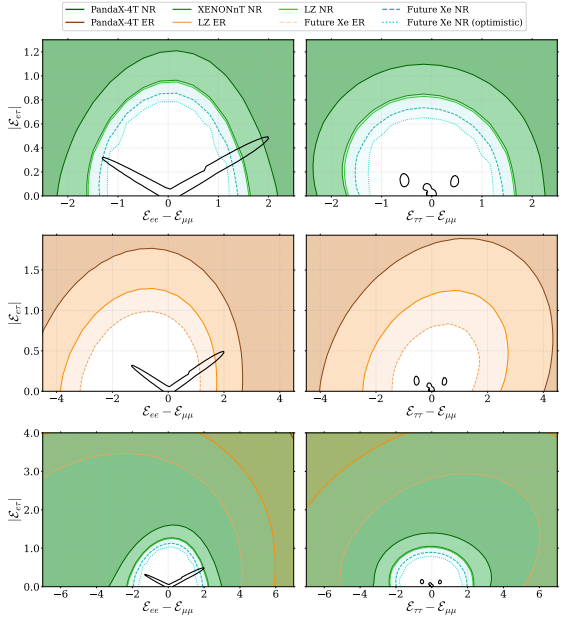
DM-DD vs. Future DUNE

$$\epsilon^p = \epsilon^n,\ \epsilon^e = 0$$

$$\epsilon^p = \epsilon^n = 0$$

$$\epsilon_p = \epsilon_e = \epsilon_n/\sqrt{2}$$

Did not consider XENONnT's ER due to their slight excess



Dark Matter-Direct Detection data is relevant **today** for NOvA, T2K, and DUNE new physics searches

Dark Matter-Direct Detection data is relevant **today** for NOvA, T2K, and DUNE new physics searches

How to go clearly beyond?

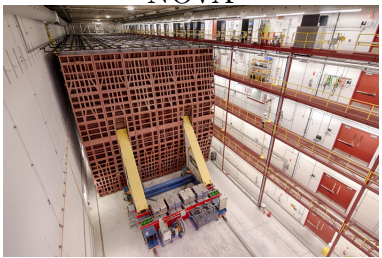
Dark Matter-Direct Detection data is relevant **today** for NOvA, T2K, and DUNE new physics searches

How to go clearly beyond?
Neutrino factory?

Experimental Oscillation Landscape Today

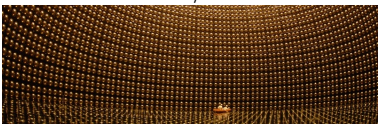
Three-flavor oscillation focused:

NOvA



LBL-acc: $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, and $\bar{\nu}_\mu \to \bar{\nu}_e$

T2K/SK

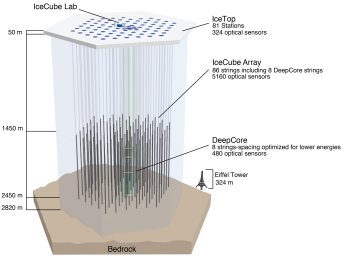


LBL-acc: $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, and $\bar{\nu}_\mu \to \bar{\nu}_e$

Atm: $+\ \nu_e \to \nu_\mu$, $\nu_e \to \nu_e$, $\bar{\nu}_e \to \bar{\nu}_e$, $\bar{\nu}_e \to \bar{\nu}_\mu$, $\nu_\mu \to \nu_\tau$, $\bar{\nu}_\mu \to \bar{\nu}_\tau$, $\nu_e \to \nu_\tau$, $\bar{\nu}_e \to \bar{\nu}_\tau$

Solar: $\nu_e \to \nu_e$

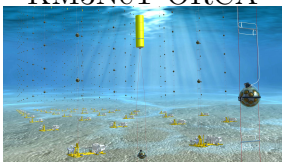
IceCube



Atm: $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_e \to \nu_\mu$, $\nu_e \to \nu_e$, $\bar{\nu}_e \to \bar{\nu}_e$, $\bar{\nu}_e \to \bar{\nu}_\mu$, $\nu_\mu \to \nu_\tau$, $\bar{\nu}_\mu \to \bar{\nu}_\tau$, $\nu_e \to \nu_\tau$, $\bar{\nu}_e \to \bar{\nu}_\tau$

Experimental Landscape Tomorrow

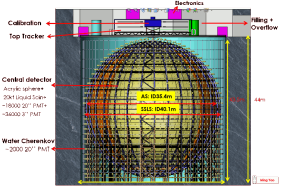
KM3NeT-ORCA



Atmospherics
Partially constructed

Has preliminary results

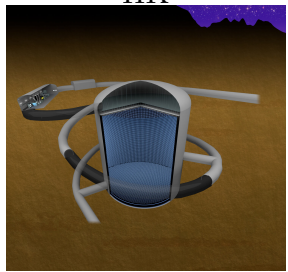
JUNO



LBL-reactor

Data taking just began

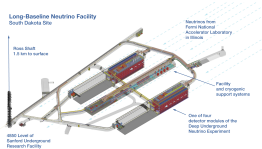
HK



LBL-accelerator,
atmospherics, solar
Under construction

Data taking in ∼several years

DUNE



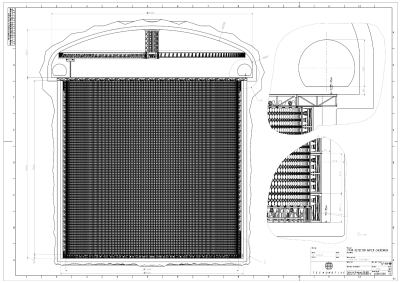
LBL-accelerator,
atmospherics, solar
Under construction

Data taking in ∼5 years

Plus IceCube upgrade

Possible Experimental Landscape of the Future

ESSnuSB

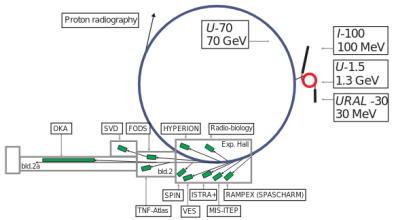


LBL-accelerator
Requires upgrades to ESS
Targets the second maximum

Also discussing a nuSTORM option

2303.17356

P2O

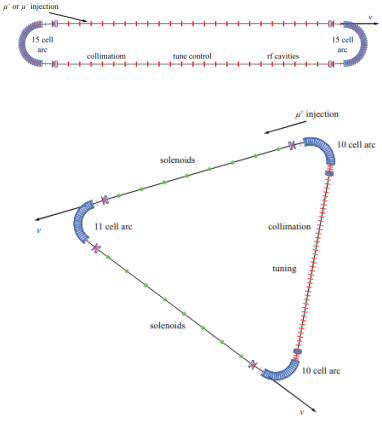


LBL-accelerator
Targets the second maximum

Tagged neutrinos?

1902.06083

Neutrino Factory



Muon storage ring

Clean sources of ν_μ and ν_e

Plus astro/cosmo/mass experiments...

DUNE and HK will measure remaining oscillation parameters at good level

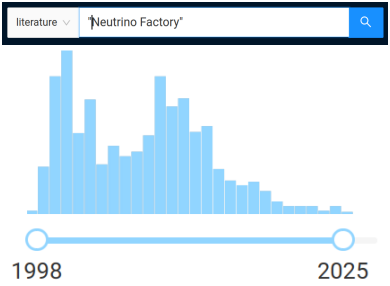
Should we have another oscillation experiment after that?

What does it look like?

What level of precision will it reach?

What new physics searches will it enable?

Neutrino Factory History



- Many designs considered for each stage
- A lot of oscillation theory work done
- Detectors assumed to be very simple, e.g. iron
- R&D on accelerators broadly useful for muon program

2014 P5 Report



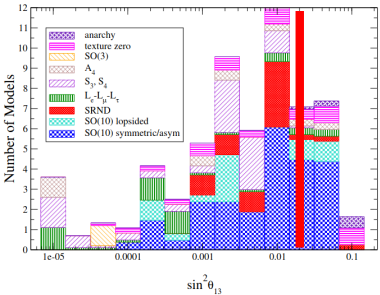
"*The large value of* $\sin^2 2(2\theta_{13})$ *enables the next generation of oscillation experiments to use conventional neutrino beams, pushing the time frame when neutrino factories might be needed further into the future.*"

"*The construction of PIP-II and the beamline for LBNF will bring major advances in accelerator technology in the areas of SCRF and targetry and lay the foundation for a possible future neutrino factory.*"

usparticlephysics.org/2014-p5-report

What Happened?

- $P_{\mu e}(\delta = 3\pi/2) - P_{\mu e}(\delta = \pi/2) \propto \sin 2\theta_{13}$
- Theorists had largely predicted a small value



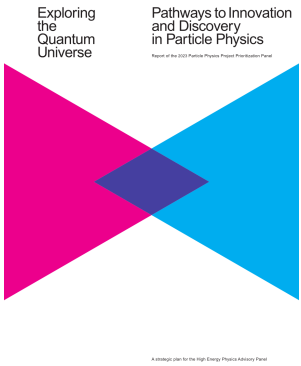
Review: C. Albright, M-C. Chen hep-ph/0608137

- Daya Bay and RENO determined θ_{13} to be $\sim 8.5°$ in 2012

Daya Bay 1203.1669
RENO 1204.0626

- Funding, etc.

2023 P5 Report



"*Such a [10 TeV muon collider] demonstrator might produce intense muon and neutrino beams*"

"*The upgraded facility would also generate bright, well-characterized neutrino beams bringing natural synergies with studies of neutrinos beyond DUNE.*"

"*20-Year Vision: . . . could entail the deployment of a low-energy muon storage ring, as exemplified by the Neutrinos from Stored Muons (nuSTORM) experiment*"

⋮

usparticlephysics.org/2023-p5-report

A Neutrino Factory Today

My perspectives:

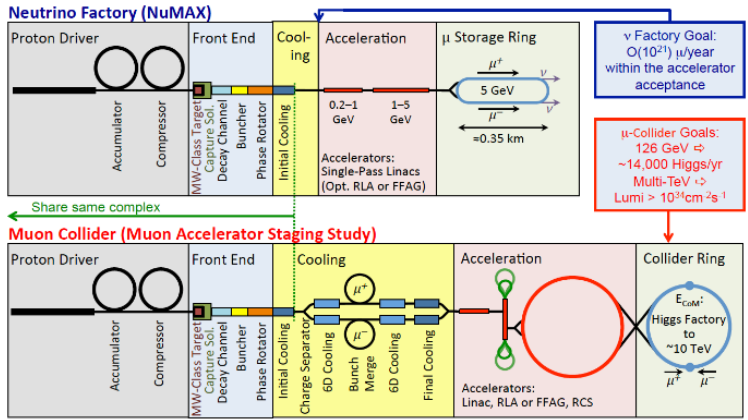
- Likely in the US connected to the development of a high energy muon collider
- Accelerator likely based at FNAL, could be BNL?
- Likely leverage DUNE LArTPC far detectors under construction now

The importance of a new study:

- Interest fell off immediately after $\theta_{13} > 0$ was first determined
- It has now been well measured
- $\Delta|\Delta m^2_{31}|$ has improved by a factor of ~ 2 in the last 10-15 years

  Provides a clear indication of the correct E_μ
- The US landscape is much more clear (DUNE, interest in muon collider)
- The global neutrino oscillation landscape has progressed considerably (HK, JUNO, IceCube, KM3NeT)

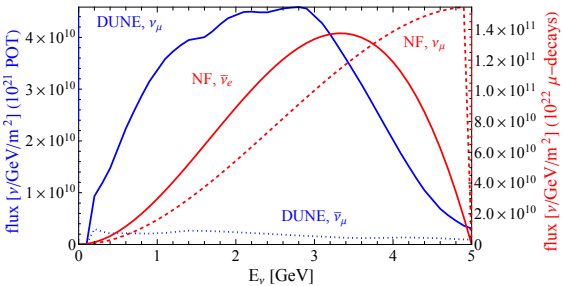
Possible Neutrino Factory Design



A. Bogacz, et al 2203.08094

The Big Advantage

A neutrino factory provides well-characterized beams of ν_μ and ν_e



Charge Identification

CID allows for separation of ν_μ from $\bar{\nu}_e$

$$N_{\nu_{\text{f,obs}}} = \frac{\epsilon_f}{2}\left[(1+\epsilon_{CID})N_{\nu_f} + (1-\epsilon_{CID})N_{\bar{\nu}_f}\right]$$
$$N_{\bar{\nu}_{\text{f,obs}}} = \frac{\epsilon_f}{2}\left[(1+\epsilon_{CID})N_{\bar{\nu}_f} + (1-\epsilon_{CID})N_{\nu_f}\right]$$

Older studies typically assume perfect CID

See e.g. A. Rujula, B. Gavela, P. Hernandez hep-ph/9811390
E. Fernandez-Martinez, T. Li, O. Mena, S. Pascoli 0911.3776

Realistic:

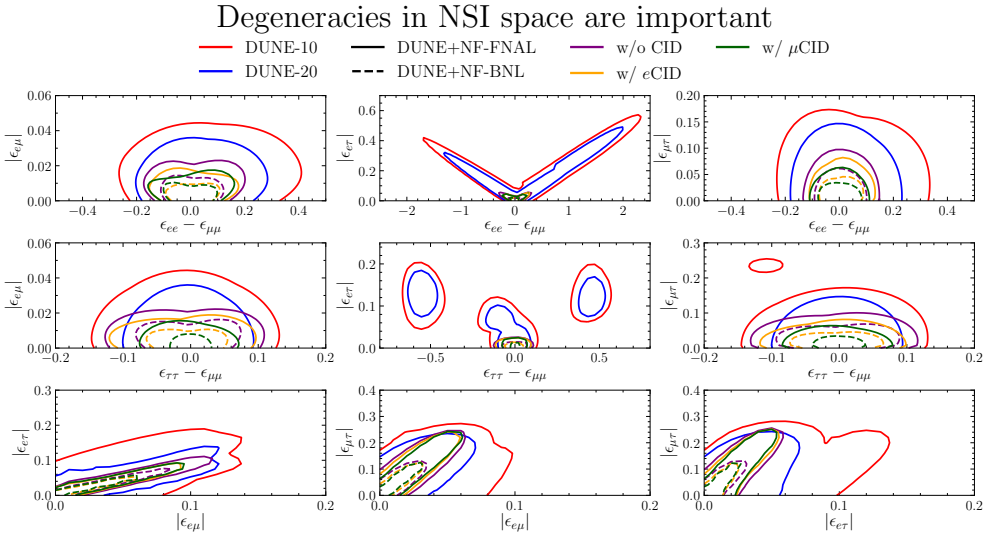
- DUNE may be able to achieve $\epsilon_{CID,\nu_\mu} = 72\%$ from muon capture on Ar

  C. Ternes, et al 1905.03589

- Some ν_e CID can be achieved in a LArTPC and some can happen statistically

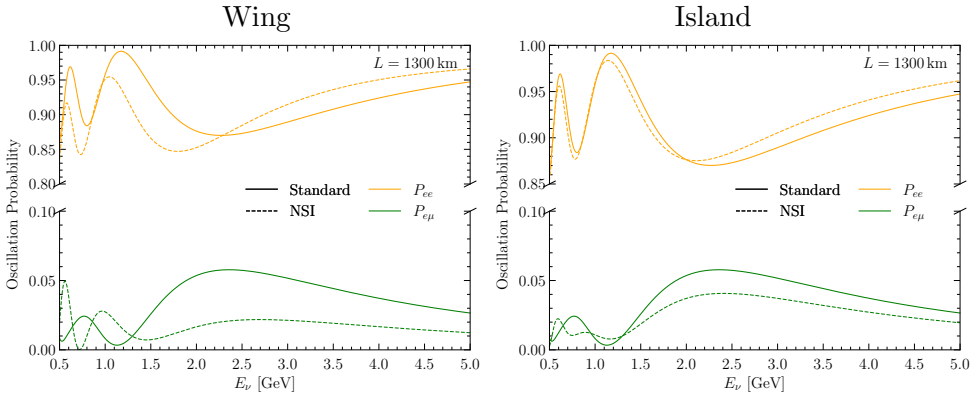
  A. Rubbia 0908.1286
  P. Huber, T. Schwetz 0805.2019

Vector NSI Degeneracies



Marginalized over δ and the relevant $\phi_{\alpha\beta}$

Vector NSI Degeneracies



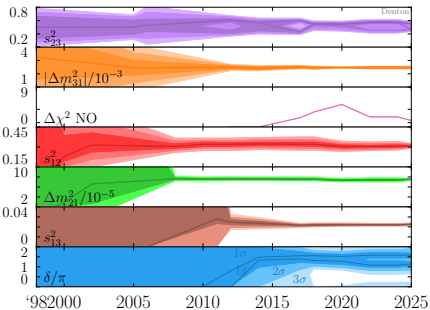
Comparison between the degenerate points
and the standard cases in the new channels

Conclusions

- LBL data from NOvA and T2K hint at new physics: CPV NSI
- DUNE can discover and even confirm this solution
- DUNE loses sensitivity with multiple NSI parameters
- DM solar ν data from LZ, XENONnT, and PandaX-4T probe both
- Future large Xe experiments will push this forward
- Neutrino factory provides the most robust tests due to access to $\nu_e \to \nu_\mu$

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

I. Esteban et al. 2007.14792

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:

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

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: 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

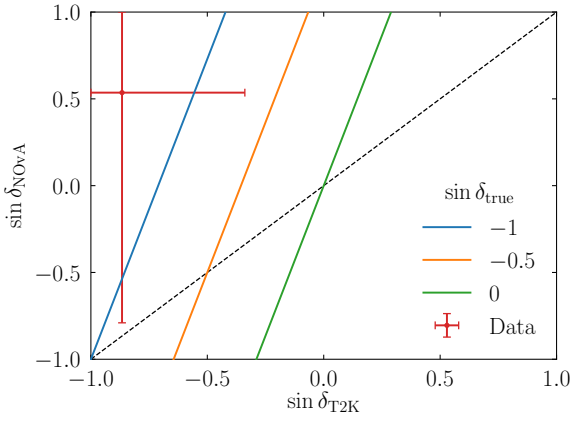
$$\sin\delta_{\text{true}} \approx \frac{\sin\delta_{\text{NOvA}} a_{\text{T2K}} - \sin\delta_{\text{T2K}} a_{\text{NOvA}}}{a_{\text{T2K}} - a_{\text{NOvA}}}$$

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

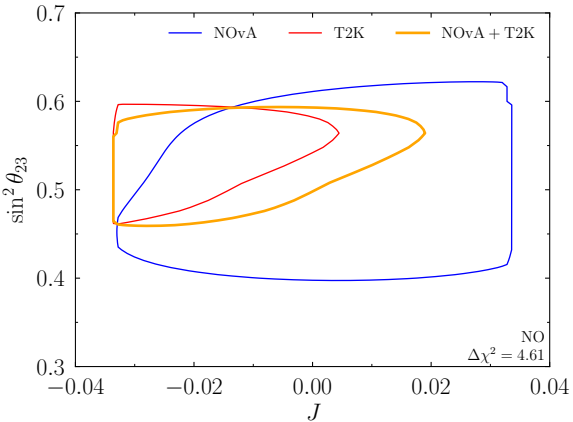
Alleviated by:

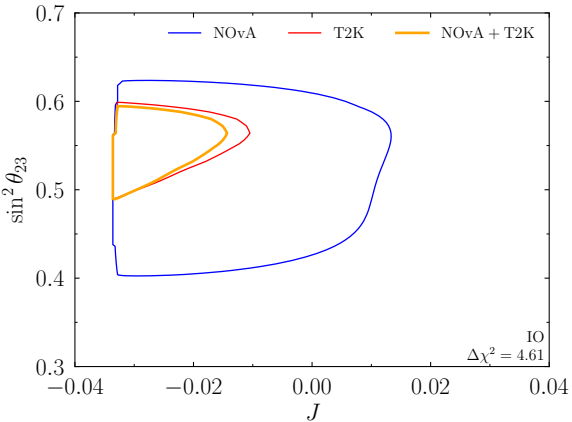
- Statistical fluctuations
- Relaxing the ansatz that only δ matters

Dashed: SM
Colored: NSI



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

Analytic estimations:

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

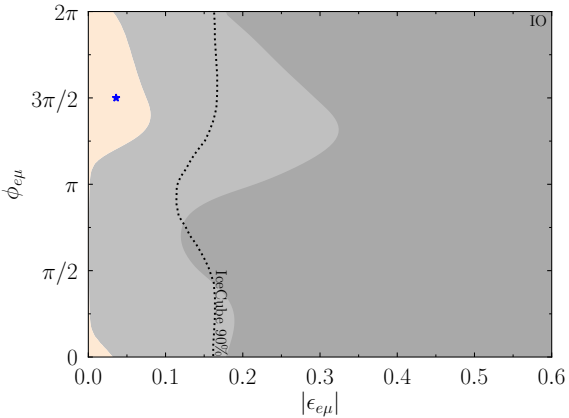
Numerical fit:

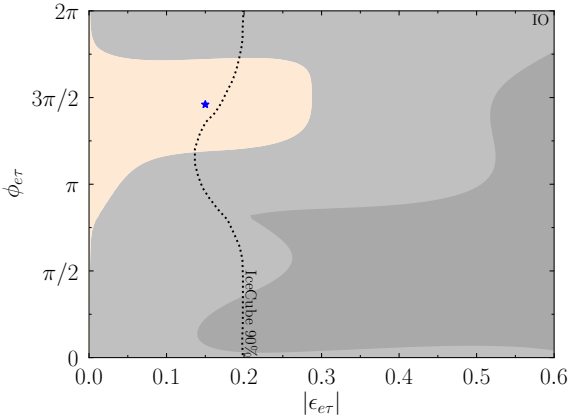
MO	NSI	$\lvert\epsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	δ/π	$\Delta\chi^2$
NO	$\epsilon_{e\mu}$	0.19	1.50	1.46	4.44
	$\epsilon_{e\tau}$	0.28	1.60	1.46	3.65
	$\epsilon_{\mu\tau}$	0.35	0.60	1.83	0.90
IO	$\epsilon_{e\mu}$	0.04	1.50	1.52	0.23
	$\epsilon_{e\tau}$	0.15	1.46	1.59	0.69
	$\epsilon_{\mu\tau}$	0.17	0.14	1.51	1.03

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

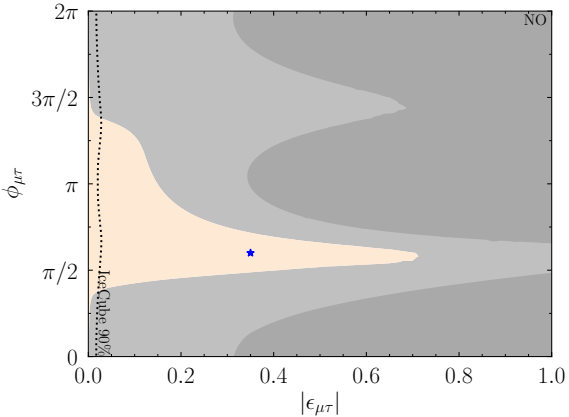
For the SM: $\chi^2_{\rm NO} - \chi^2_{\rm IO} = 2.3$

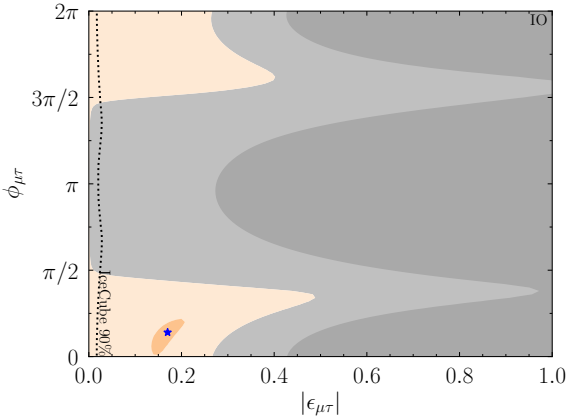
NSI parameters: IO





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





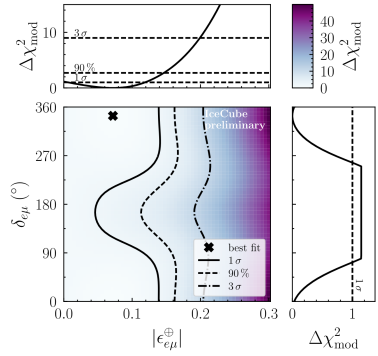
Other CP Violating NSI Constraints

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

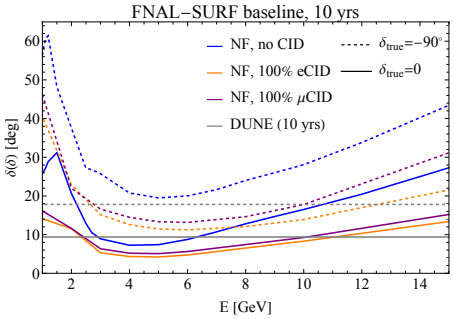
PBD, J. Gehrlein 2008.06062

Neutrino Factory Configurations

FNAL-SURF:

$L = 1284.9$ km

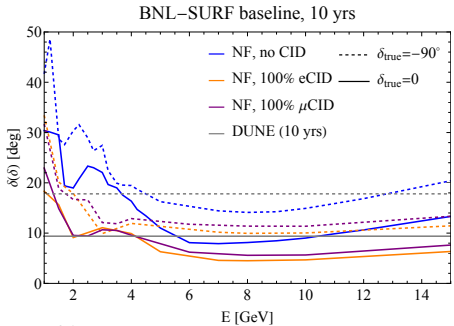
$E_\mu = 5$ GeV



BNL-SURF:

$L = 2542.3$ km

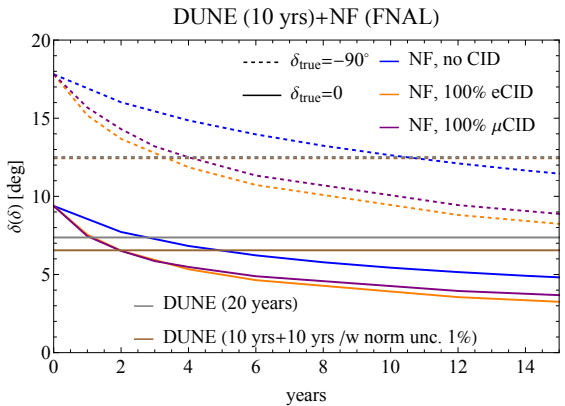
$E_\mu = 8$ GeV

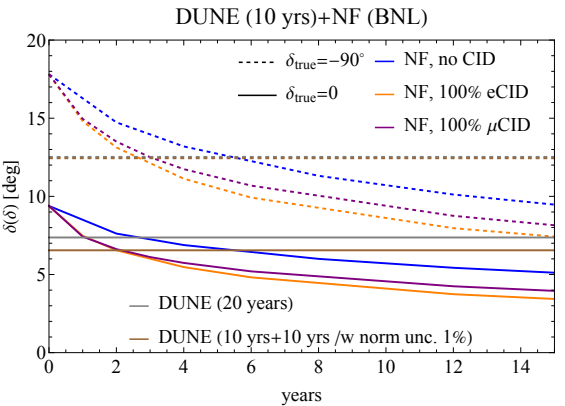


5 years of μ^+ and 5 years of μ^- and 10^{21} μ decays per year

Interim Deisgn Report NF 1112.2853

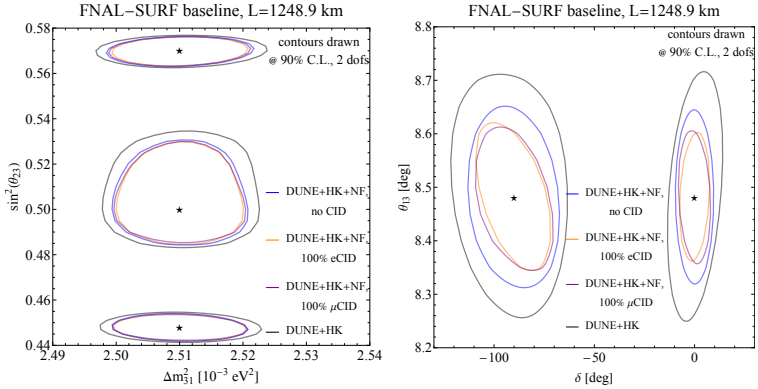
CPV Phase δ



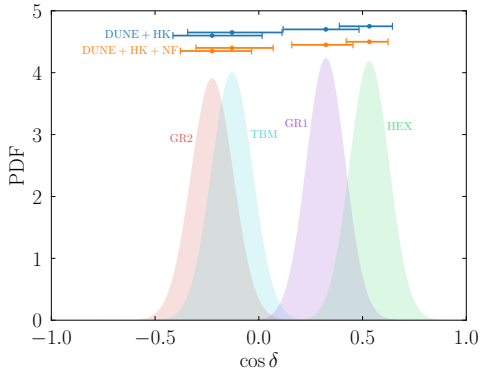


More Precision

Need improvement in all oscillation parameters



Neutrino Factory and Oscillations



Enhanced sensitivity to $\delta \Rightarrow$ flavor model discrimination

New Physics at a Neutrino Factory Near Detector

- Precision in Cross Section Measurements
- Standard Candles
- Precision in $\sin^2\theta_W$ Measurement
- Light Sterile Neutrinos
- Lepton Number Violation
- NSI and New Physics at the Multi-TeV scale
- Light Dark Sectors, Dark Matter
- Decay in flight of new particles

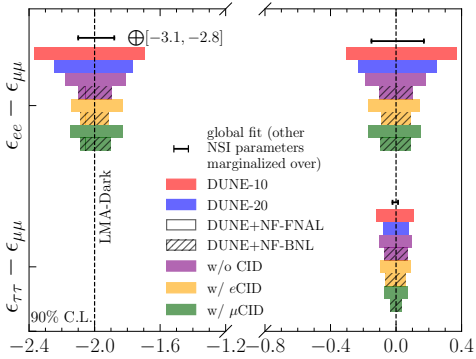
A. Bogacz, et al 2203.08094

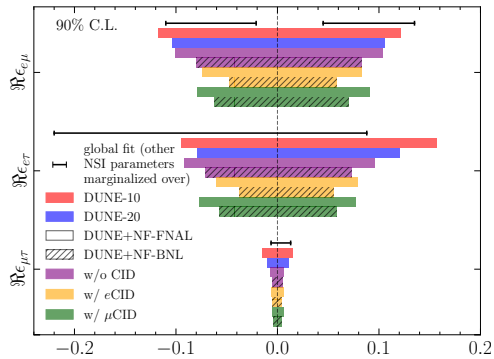
New Oscillation Physics at a Neutrino Factory

Many new physics cases that affect oscillations,
which to focus on?

- Steriles: interesting Δm^2 regions are not easy to probe in a neutrino factory
- Neutrino decay: stronger constraints from solar, astro, cosmo
- Scalar NSI: stronger constraints from solar
- **Vector NSI**: matter effect, controlled beams, multiple channels: yes!
- **CPT violation**: can over constrain the oscillation picture: yes!

Vector NSI Sensitivities



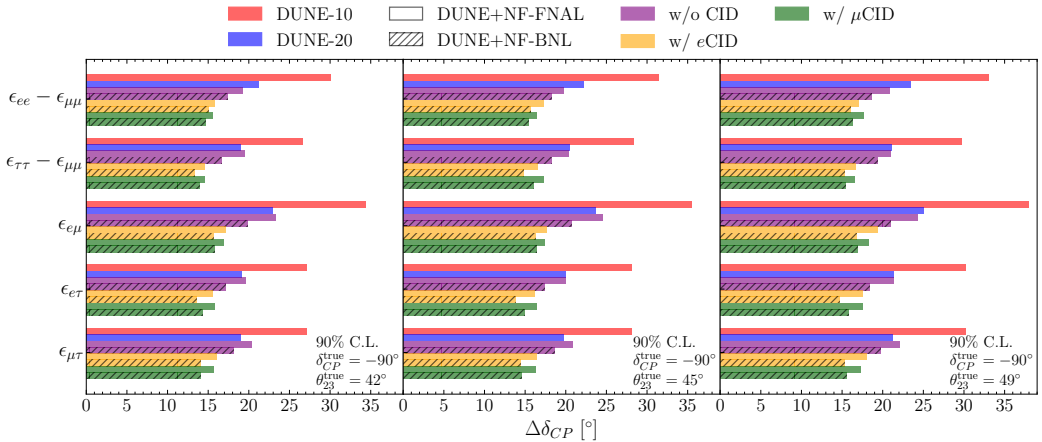


Global fit from: P. Coloma, et al 2305.07698

To rule out LMA-Dark, see:
P. Coloma, PBD, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz 1701.04828
PBD, Y. Farzan, I. Shoemaker 1804.03660
PBD, S. Parke 2106.12436
PBD, J. Gehrlein 2204.09060

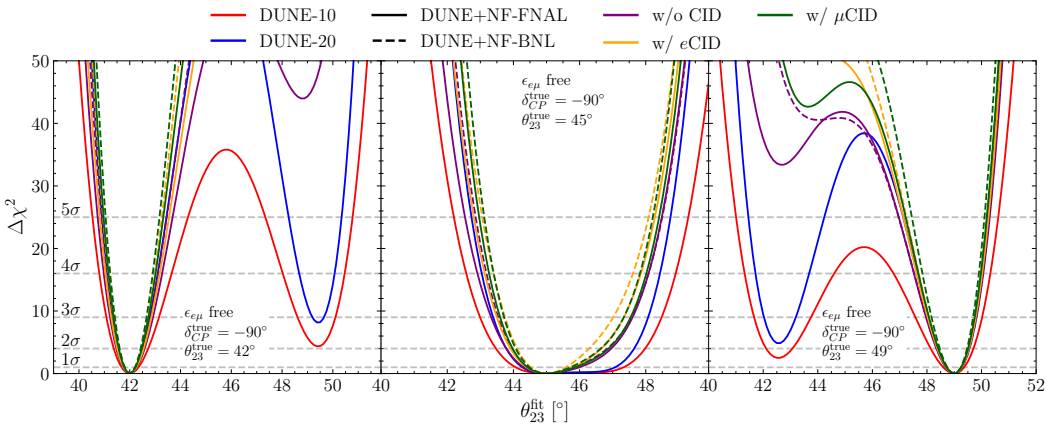
⋮

Impact of Vector NSI on Regular Oscillation Parameters



When considering new physics, DUNE alone has poor sensitivity to δ
DUNE+NF has excellent sensitivity

Impact of Vector NSI on Regular Oscillation Parameters



Marginalized over $|\epsilon_{e\mu}|$ and $\phi_{e\mu}$

Neutrino factory is required to identify the octant

Same for other NSI parameters

Impact of Vector NSI on Regular Oscillation Parameters

A neutrino factory significantly increases the robustness of the oscillation picture under new physics

If there are tensions in DUNE/HK, a neutrino factory will likely be able to identify them

CPT Violation

- CPT violation appears in many UV complete theories

V. Kostelecky, S. Samuel PRD 1989
V. Kostelecky, S. Samuel PRL 1989
V. Kostelecky, S. Samuel PRD 1989
S. Carroll, et al hep-th/0105082
O. Greenberg hep-ph/0201258

- Neutrinos may be the first place CPT violation appears

G. Barenboim, J. Lykken hep-ph/0210411
A. de Gouvea hep-ph/0204077
S. Ge, H. Murayama 1904.02518

- The low energy implementation in neutrinos is usually parameterized as:

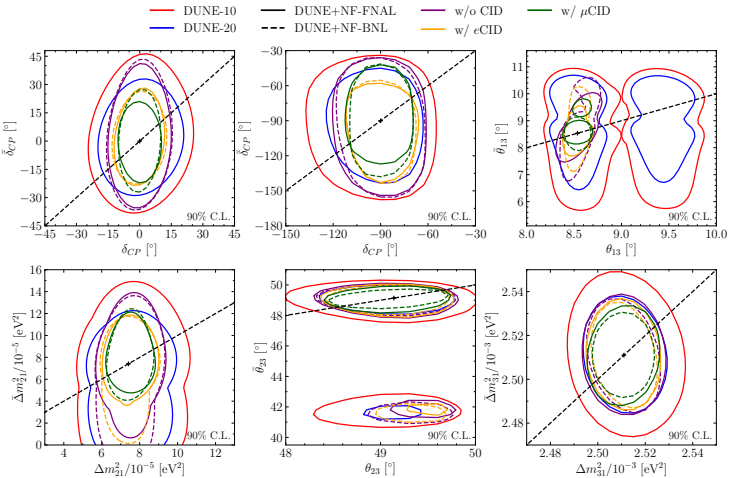
$$\theta_{ij} \to (\theta_{ij}, \bar{\theta}_{ij}), \quad \delta \to (\delta, \bar{\delta}), \quad \Delta m^2_{ij} \to (\Delta m^2_{ij}, \Delta \bar{m}^2_{ij})$$

- Two curious anomalies in θ_{13} and Δm^2_{21}

$$\sin^2 \theta_{13} = 0.032, \quad \sin^2 \bar{\theta}_{13} = 0.022$$

$$\Delta m^2_{21} = 5.4 \times 10^{-5}\ \text{eV}^2, \quad \Delta \bar{m}^2_{21} = 7.5 \times 10^{-5}\ \text{eV}^2$$

CPT Violation Sensitivities

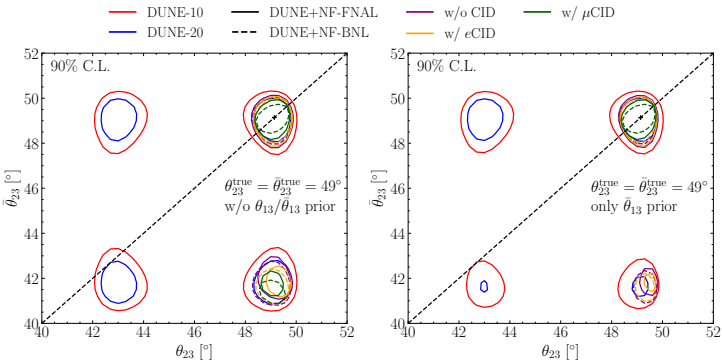


More degeneracies appear: θ_{13}, θ_{23}

Neutrino factory lifts the θ_{13} degeneracy

CPT Violation Sensitivities θ_{23} Degeneracies

With information from Daya Bay and μCID at NF,
all degenerate regions are lifted



$$P_{\mu e} \sim 4 \sin^2\theta_{23} \sin^2\theta_{13} \cos^2\theta_{13} \sin^2\Delta_{31}$$

CPT Violation Discovery Potential

