Abstract

I will consider a number of scenarios where different experiments, phenomenological parameters, and theoretical models can be mixed up. Sometimes this leads to additional confusion and sometimes to additional clarity. Hopefully, these examples will guide experimental efforts, phenomenological fits, and model building efforts to develop a robust understand of the standard neutrino sector, and beyond.

Untangling Systematic Uncertainties from BSM Physics

Peter B. Denton

NPN: Cincinnati

June 19, 2025

Brookhaven National Laboratory

How to Mix Stuff Up in Neutrino Oscillations

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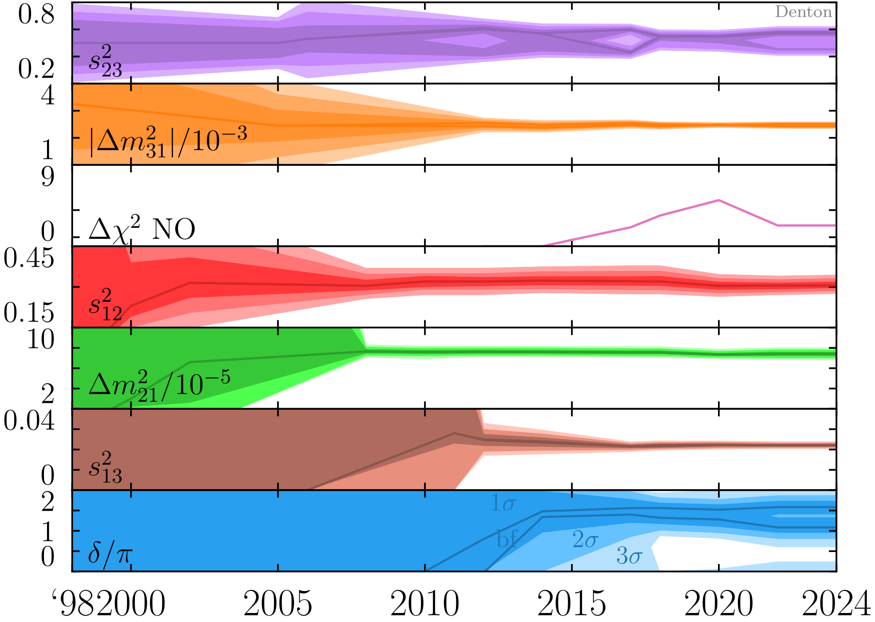
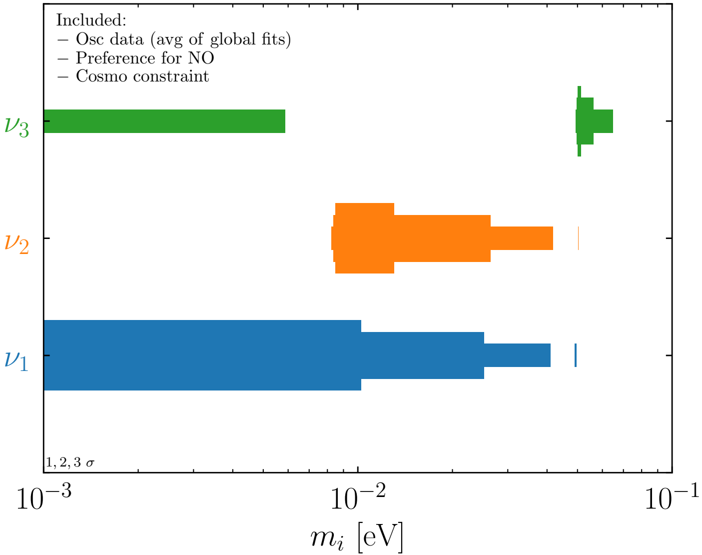


Denton
0.8
0.2
s^2_{23}
4
1
$|\Delta m^2_{31}|/10^{-3}$
9
0
$\Delta\chi^2$ NO
0.45
0.15
s^2_{12}
10
2
$\Delta m^2_{21}/10^{-5}$
0.04
0
s^2_{13}
2
1
0
δ/π
1σ
bf
2σ
3σ
‘98 2000 2005 2010 2015 2020 2024

Absolute masses



CP violation is Hard

How do we know it is right?

PBD 2309.03262

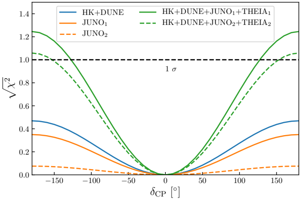
Non-standard CPV probes

1. Some information in solar due to loops in elastic scattering

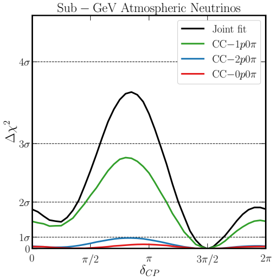
V. Brdar, X-J. Xu 2306.03160
K. Kelly, et al. 2407.03174 requires 3k Borexinos

2. Sub-GeV → sub-100 MeV atmospherics

K. Kelly, et al. 1904.02751
See also e.g. A. Suliga, J. Beacom 2306.11090



Solar (no systematics)



Atmospherics at DUNE

Non-standard CPV probes: disappearance

Possible to get at CPV with CPC processes

Disappearance probability:

$$\begin{aligned} P(\nu_\alpha \to \nu_\alpha) = 1 &- 4|U_{\alpha 1}|^2|U_{\alpha 2}|^2 \sin^2 \Delta_{21} \\ &- 4|U_{\alpha 1}|^2|U_{\alpha 3}|^2 \sin^2 \Delta_{31} \\ &- 4|U_{\alpha 2}|^2|U_{\alpha 3}|^2 \sin^2 \Delta_{32}\,, \end{aligned}$$

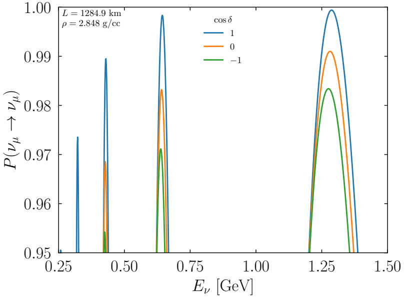
$$\Delta_{ij} = \Delta m^2_{ij} L/4E$$

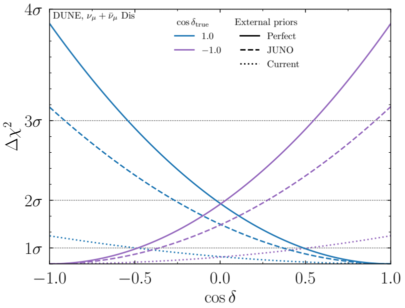
Can measure all three coeffs of each frequency $\Rightarrow$ 2 dofs

δ (and CPV) needs 4 dofs $\Rightarrow$ two dis measurements

ν_e: Daya Bay and KamLAND/JUNO

ν_μ: precision at DUNE/HK



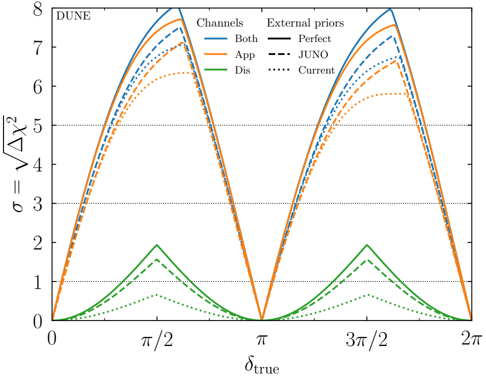


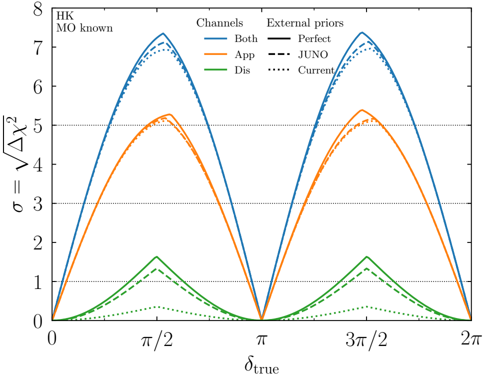
Important cross check

Different and cleaner systematics than appearance

CP violation discovery with disappearance

Need JUNO and DUNE or HK



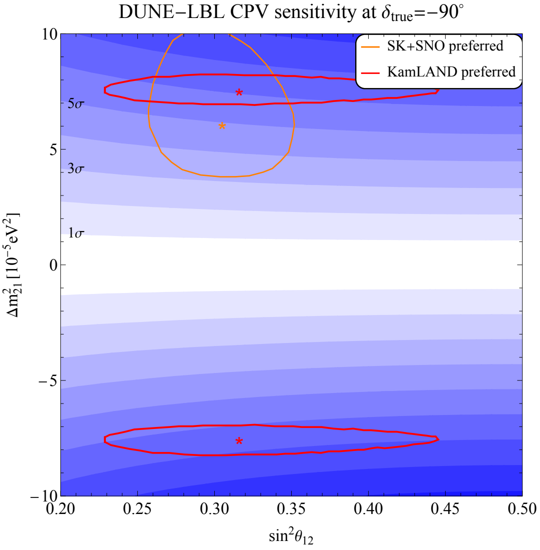


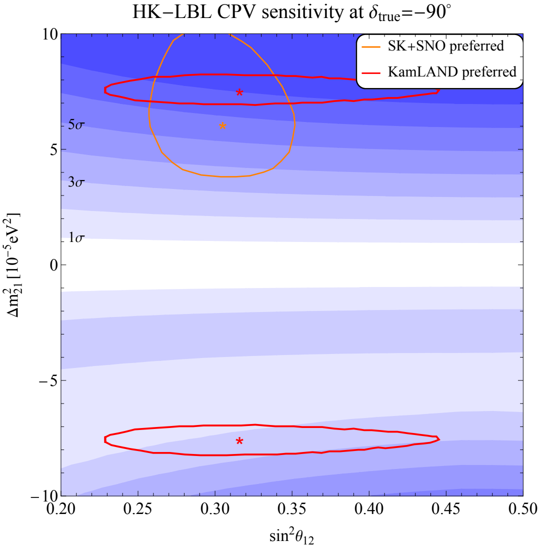
PBD 2309.03262

JUNO plays more roles in CPV searches

PBD, J. Gehrlein 2302.08513

Impact of the true solar parameters on δ





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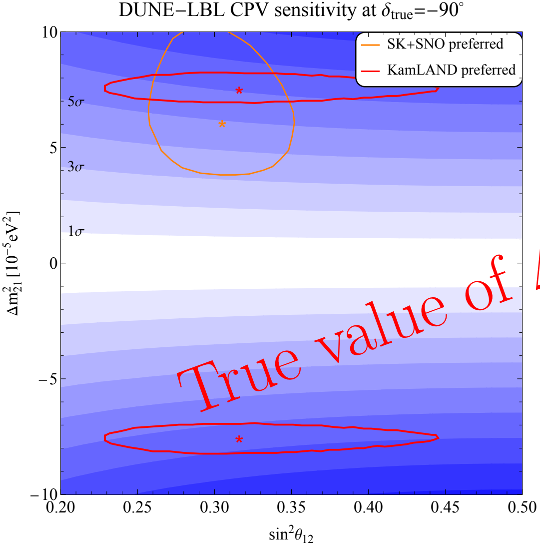
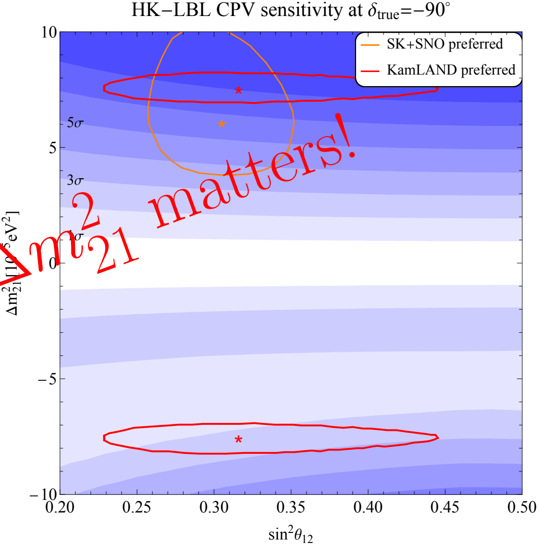


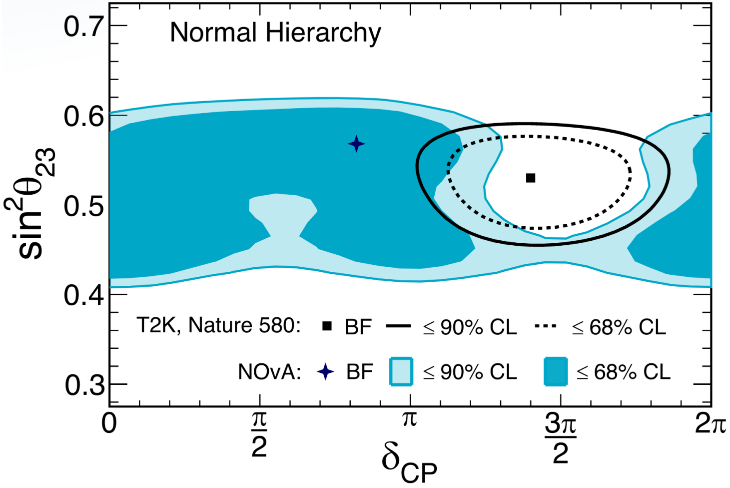


True value of Δm^2_{21} matters!

How to handle problems in CP violation measurement

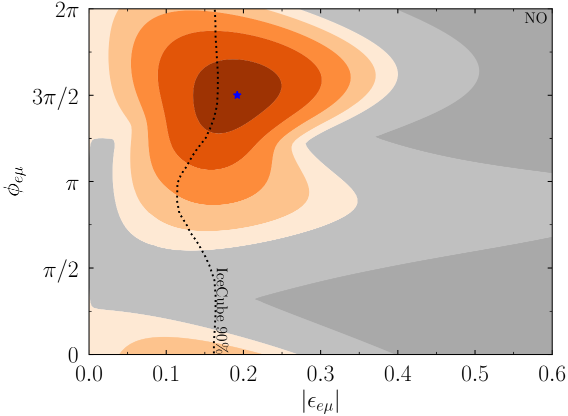
PBD, J. Gehrlein, R. Pestes 2008.01110

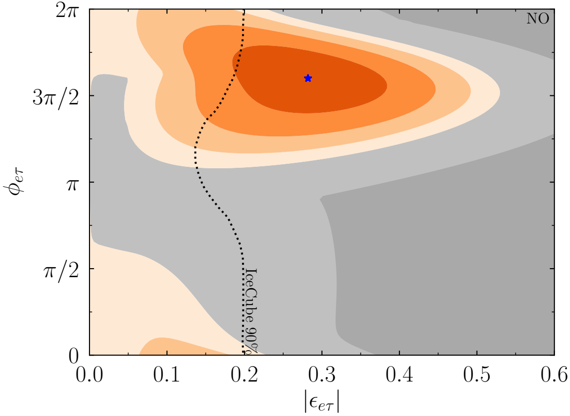
An example of disagreement in CP violation measurements



A. Himmel for NOvA 10.5281/zenodo.3959581

NSI parameters





New physics or systematics?

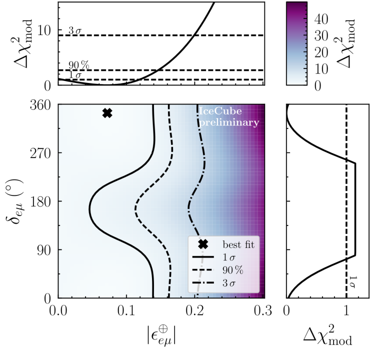
Look elsewhere!

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



T. Ehrhardt, IceCube PPNT (2019)

- 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

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

Estimate size of effect: magnitude

Skip the fit; compute the result!

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

$a \propto \rho E$
$w_\beta = s_{23},\, c_{23}$ 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

Correctly identifying new physics scenarios using DUNE

PBD, A. Giarnetti, D. Meloni 2210.00109

Benchmarks

Three scenarios taken as best fits to NOvA+T2K

1. CPV flavor changing vector NSI, either MO
2. Flavor changing scalar NSI, either MO
3. Sterile neutrino at 1 eV

Absolute mass scale?

If one benchmark is true,
and another scenario is considered,
can DUNE tell?

Vector NSI identification

DUNE sensitivity

Test scenario

True scenario	$\Delta\chi^2$	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 differentiation

- In general, DUNE can often correctly identify what the new physics is, if it is at the NOvA+T2K level
- Varying all off-diagonal parameters does not significantly weaken results
- Presumably goodness of fit can provide information on whether an anomaly is new physics or systematics

Four oscillation channels, DUNE+HK, LBL+Atm

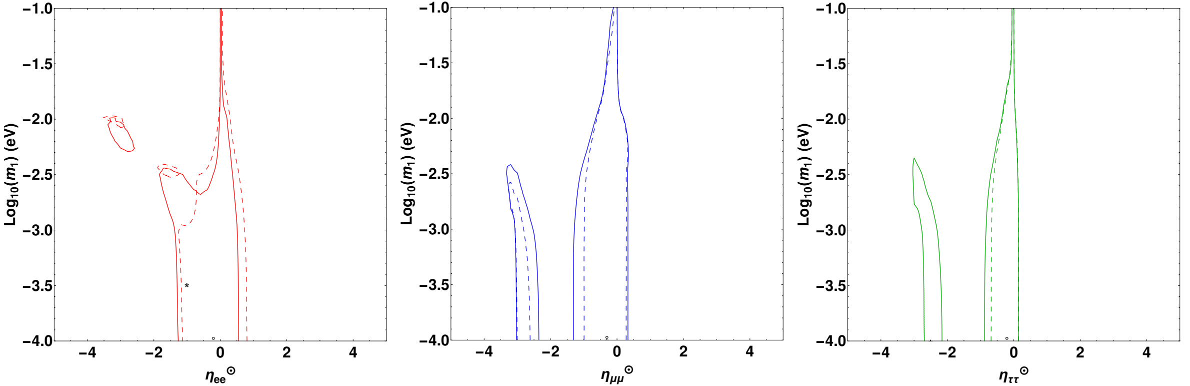
- HyperK-LBL will also help, as will atmospherics, ...
- See also A. de Gouvêa, K. Kelly 1511.05562, ...

Combine solar and reactor to best probe scalar NSI

Absolute mass scale?

PBD, A. Giarnetti, D. Meloni 2409.15411
See also K. Babu, G. Chauhan, B. Dev 1912.13488

Combine solar and KamLAND/JUNO



Dashed: +JUNO

Combining data sets is essential

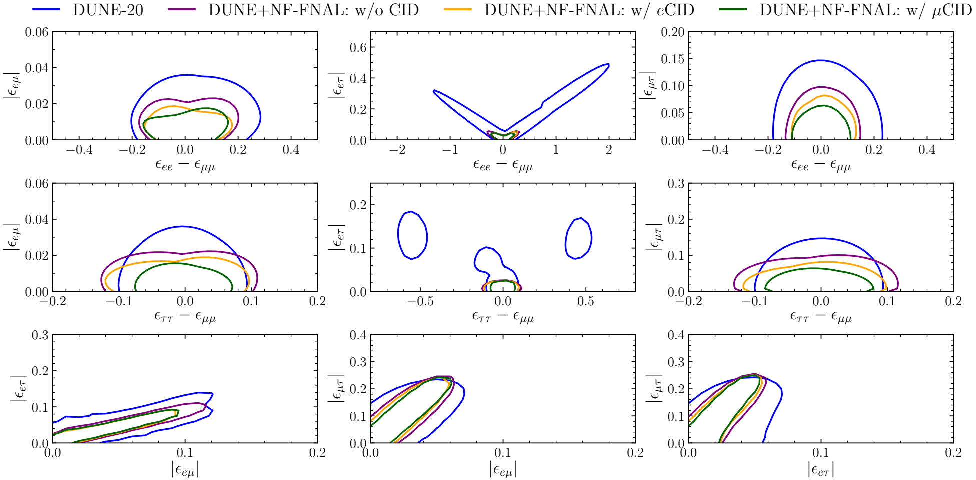
Absolute mass scale accessible in oscillation experiments with new physics

Go beyond JUNO, DUNE, and HyperK to get at BSM

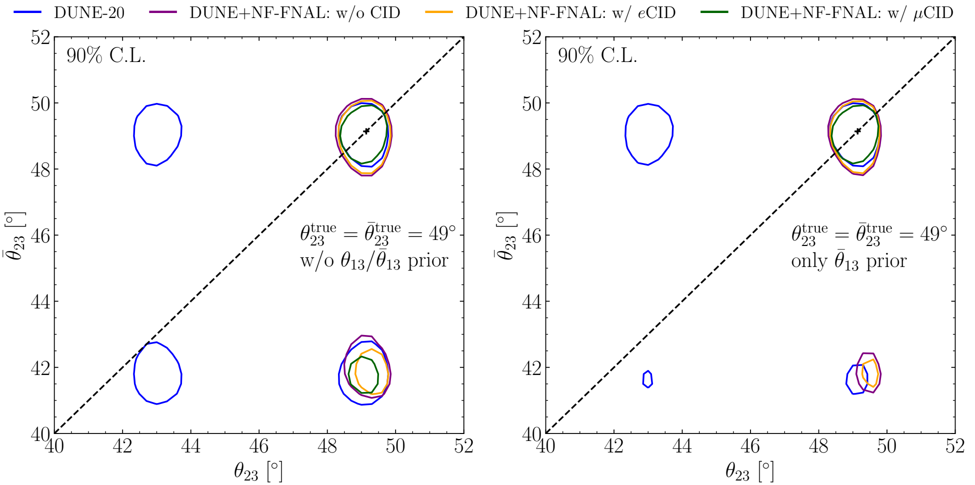
Neutrino Factory to DUNE far detectors

PBD, J. Gehrlein, C.-F. Kong 2502.14027
↑ built on PBD, J. Gehrlein 2407.02572

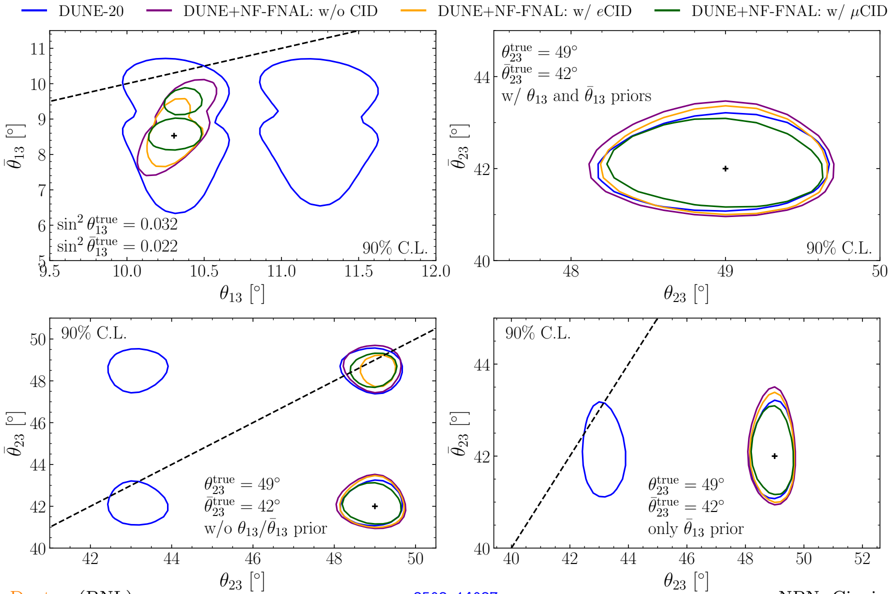
Neutrino Factory breaks vNSI degeneracies



Neutrino Factory breaks CPTV degeneracies



Neutrino Factory breaks CPTV degeneracies: benchmarks



BSM at a Neutrino Factory

- Different baseline: BNL→SURF in backups
- vNSI degeneracies in LBL known for sometime
- HyperK helps, but does not solve

A. de Gouvêa, K. Kelly 1511.05562
P. Coloma 1511.06357
S. Chatterjee, B. Dev, P. Machado 2106.04597

- Neutrino factory leads to improvement in constraints at 5-10x level, much better than naive estimate
- CPTV degeneracies at DUNE can be largely lifted by NF
- Possible to determine standard oscillation questions at 5σ even in presence of new physics
- A NF may be essential to understand if a possible DUNE+HK tension is systematics or new physics

Atmospherics may help in many cases here

Other thoughts on disentangling BSM

- Mass ordering seems to be easy to determine: DUNE, IceCube/KM3NeT, JUNO, combine ν_e and ν_μ disappearance
  - New physics typically weakens sensitivities
  - Can completely destroy mass ordering sensitivity
  - Requires combining data from oscillations in Earth/Sun, CEvNS in reactors/accelerators, early Universe

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- Astrophysical neutrinos not understood, but can still probe BSM
  - IceCube: flavor ratio can only vary a small amount with energy
  - More variation $\Rightarrow$ new physics, e.g. neutrino decay

PBD, I. Tamborra 1805.05950
PBD, A. Abdullahi 2005.07200
For UHE ν's, see e.g. L. Leal, D. Naredo-Tuero, R. Funchal 2504.10576

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For UHE ν's, see e.g. L. Leal, D. Naredo-Tuero, R. Funchal 2504.10576

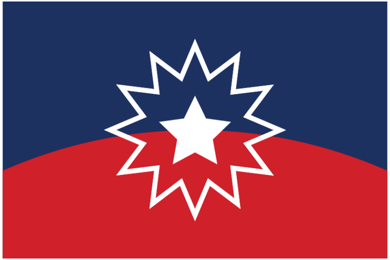
- See also UV, NSI via NC, etc.
  - Atmospheric tau appearance is robust w/o PID even under assumption of UV

PBD 2109.14576

Neutrino oscillation summary

- A complicated dance among the oscillation parameters even in standard picture
- New physics scenarios leads to many degeneracies in standard or new parameters
- Measure many channels, wide range of energies and baselines, combine the right data sets
- If its new physics and not systematics, need a broad range of probes

Happy Juneteenth!



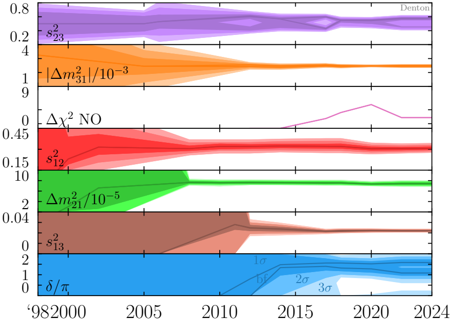
Celebrates the final enforcement of the end of slavery 160 years ago

en.wikipedia.org/wiki/Juneteenth

Thanks for listening!

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

Many interesting new physics scenarios in oscillations

1. Sterile neutrinos
2. Non-standard neutrino interactions (NSI)
   with any Lorentz structure: SPVAT
3. Non-standard neutrino self interactions
4. Neutrino decay
   with visible or invisible final states
5. Unitarity violation
6. Many others: neutrino – dark matter interactions, environmental decoherence, and Lorentz invariance or CPT violation

Many interesting new physics scenarios in oscillations

1. Sterile neutrinos

   PBD, Y. Farzan, I. Shoemaker 1811.01310
   PBD 2111.05793
   H. Davoudiasl, PBD 2301.09651

2. Non-standard neutrino interactions (NSI)

   with any Lorentz structure: SPVAT

   PBD, Y. Farzan, I. Shoemaker 1804.03660
   P. Coloma, PBD, et al. 1701.04828
   PBD, J. Gehrlein, R. Pestes 2008.01110
   PBD, J. Gehrlein 2008.06062, 2204.09060
   PBD, A. Giarnetti, D. Meloni 2210.00109, 2409.15411

3. Non-standard neutrino self interactions

   Barenboim, PBD, Oldengott 1903.02036

4. Neutrino decay
   with visible or invisible final states

   PBD, I. Tamborra 1805.05950
   PBD, A. Abdullahi 2005.07200

5. Unitarity violation

   PBD 2109.14576
   PBD, J. Gehrlein 2109.14575

6. Many others: neutrino – dark matter interactions, environmental decoherence, and Lorentz invariance or CPT violation

   See e.g. PBD, J. Gehrlein, C.-F. Kong 2502.14027

Shape-shifting sterile neutrinos

How to evade constraints?

Suppose:

1. Sterile neutrinos talk to dark matter

DM is ultralight boson

2. Dark matter talks to baryons

Then:

1. Sterile neutrinos aren't abundantly produced in the early universe
2. Mixing angle in the Sun is suppressed
3. Reactor constraints still exist

H. Davoudiasl, PBD 2301.09651
PBD 2301.11106

NSI review

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

Models with large NSIs consistent with CLFV:

Y. Farzan, I. Shoemaker 1512.09147 Y. Farzan, J. Heeck 1607.07616 D. Forero and W. Huang 1608.04719
K. Babu, A. Friedland, P. Machado, I. Mocioiu 1705.01822 PBD, Y. Farzan, I. Shoemaker 1804.03660
U. Dey, N. Nath, S. Sadhukhan 1804.05808 Y. Farzan 1912.09408 N. Bernal, Y. Farzan 2211.15686
S. Abbaslu, Y. Farzan 2407.13834

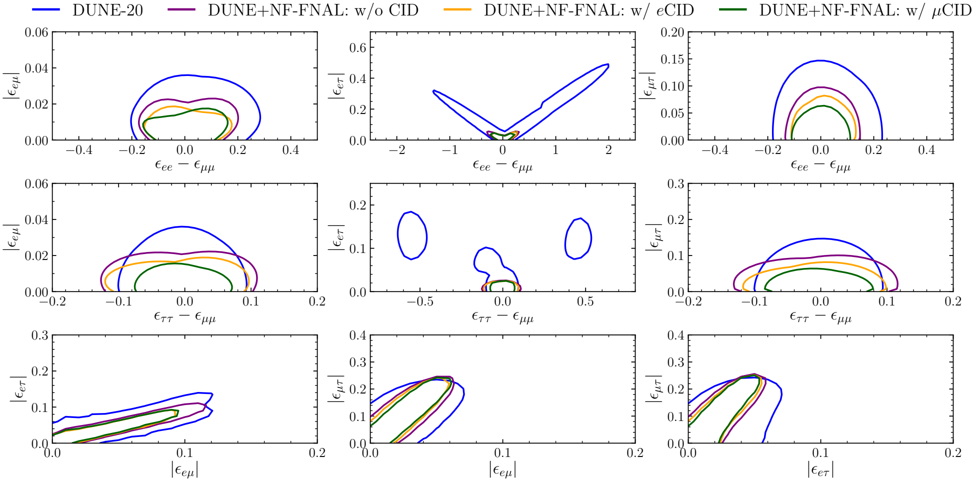
Affects oscillations via new matter effect

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

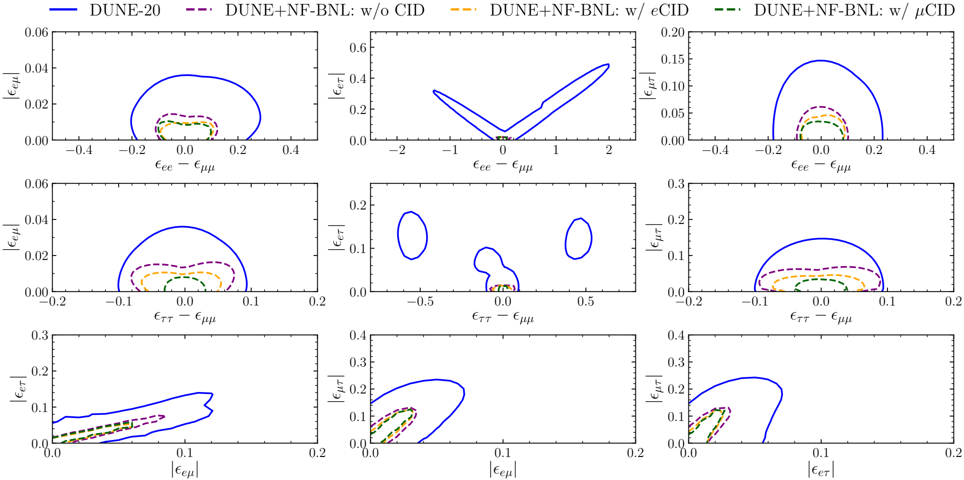
Matter potential $a \propto G_F\rho E$

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

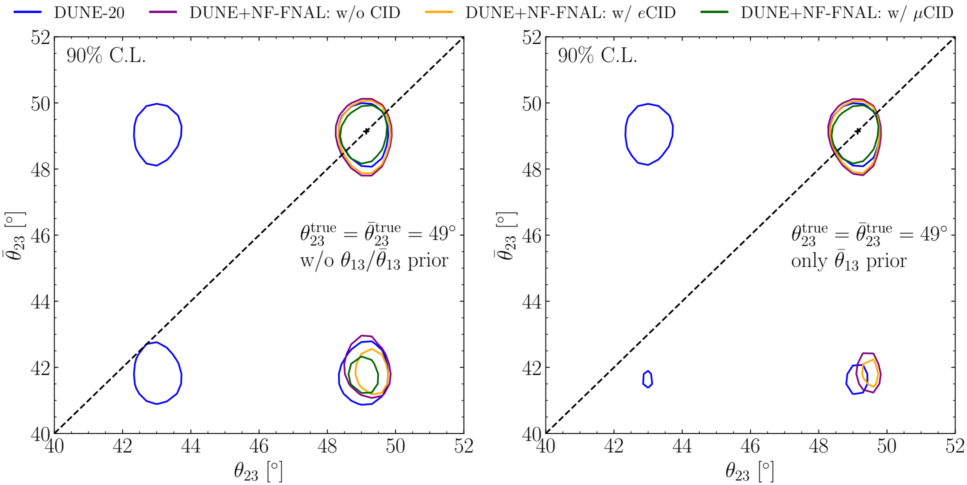
NF vNSI at FNAL



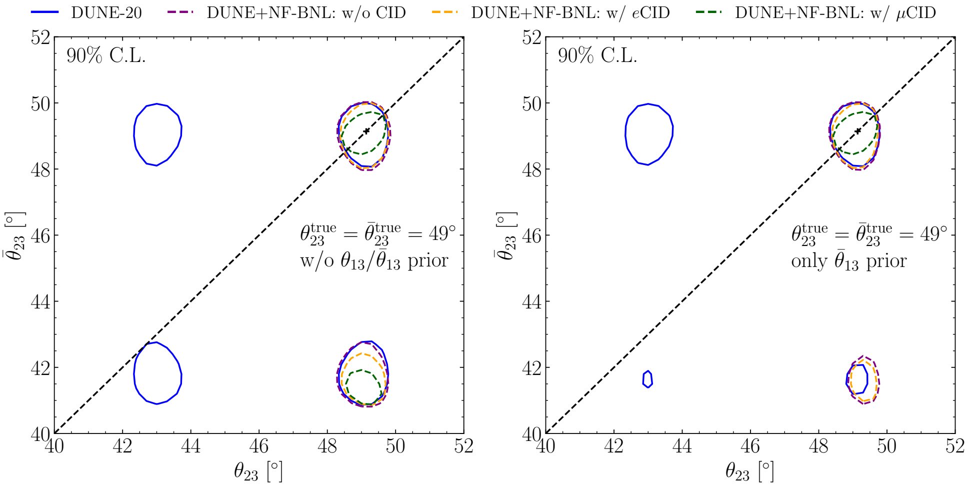
NF vNSI at BNL



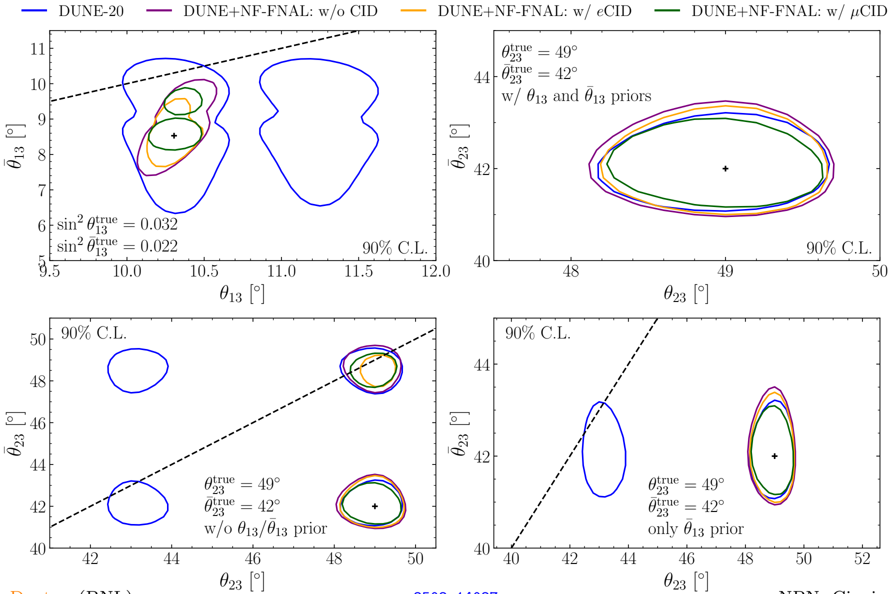
NF CPTV at FNAL



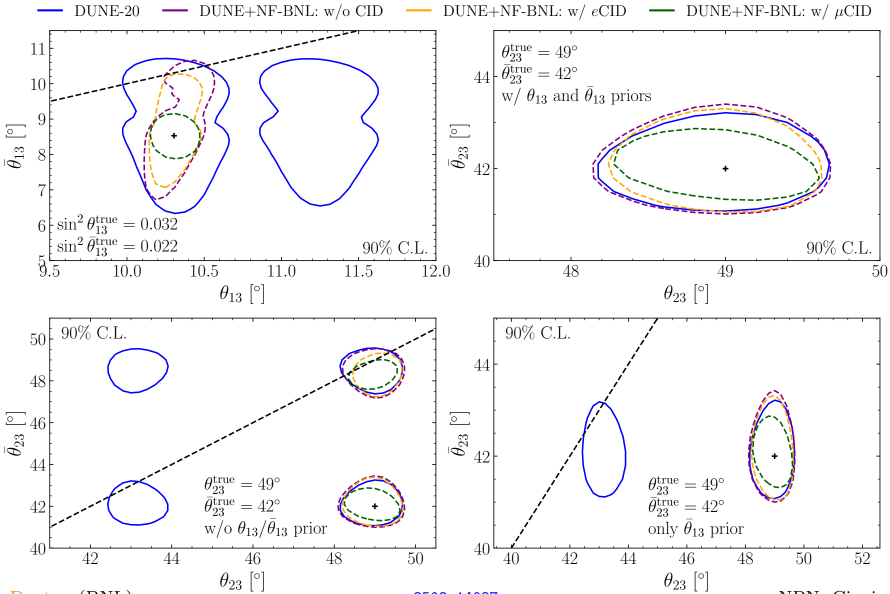
NF CPTV at BNL



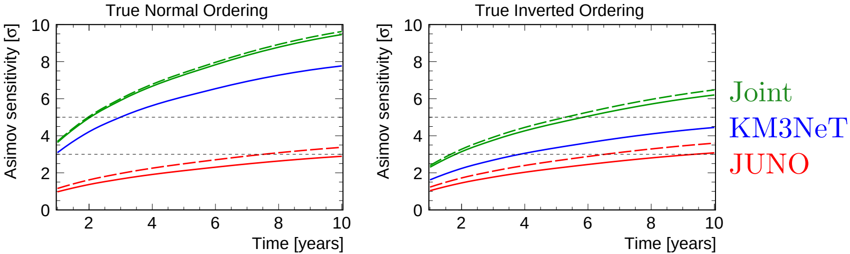
NF CPTV benchmark at FNAL



NF CPTV benchmark at BNL

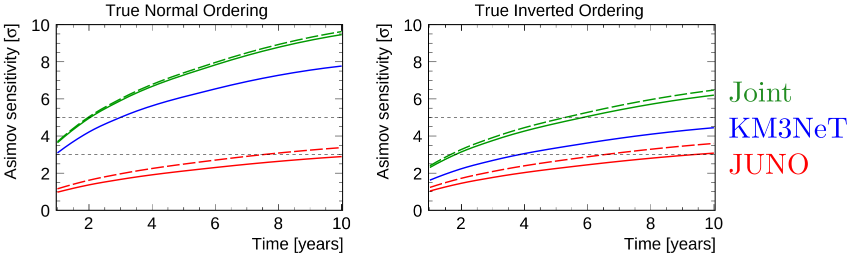


Mass ordering: future sensitivities



JUNO, KM3NeT 2108.06293
JUNO, IceCube 1911.06745
Note: if lower octant, KM3NeT is less sensitive

Mass ordering: future sensitivities



JUNO, KM3NeT 2108.06293
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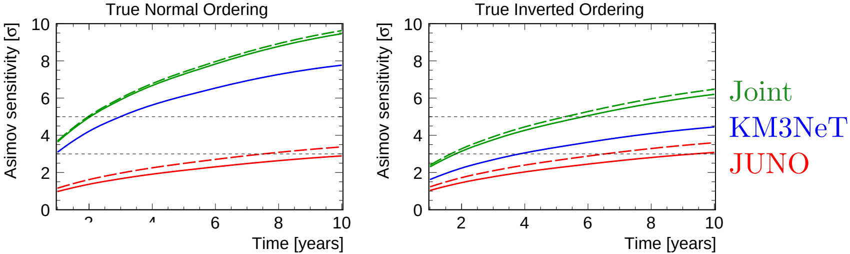
Note: if lower octant, KM3NeT is less sensitive

$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$
$$\Delta m^2_{\mu\mu} = s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + \mathcal{O}(s_{13}\Delta m^2_{21})$$

Differ by $\pm \sim 1.1\%$ in each mass ordering

H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283

Mass ordering: future sensitivities



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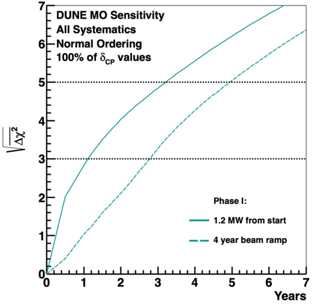


Matter effect ⇒ DUNE 2203.06100

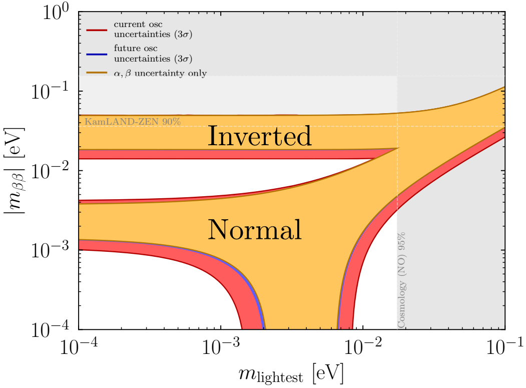
$$\Delta m^2_{ee} = c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32}$$
$$\Delta m^2_{\mu\mu} = s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + \mathcal{O}(s_{13}\Delta m^2_{21})$$

Differ by $\pm\sim 1.1\%$ in each mass ordering

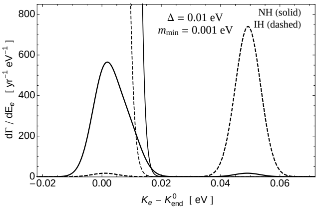
H. Nunokawa, S. Parke, R. Funchal hep-ph/0503283

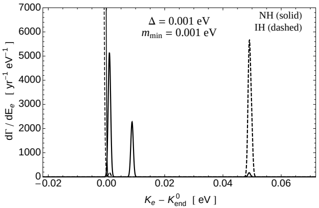
Mass ordering: broad implications

- Affects cosmology
- Affects galactic SN signal
- Affects $0\nu\beta\beta$
- Affects flavor models
- Affects end point measurements
- Affects $C\nu B$



PBD, J. Gehrlein 2308.09737





A. Long, C. Lunardini, E. Sabancilar 1405.7654

Mass ordering: new physics degeneracies

In the presence of new physics such as NSI we have:

$$[\mathrm{NO}] + [\epsilon = 0] \quad \equiv \quad [\mathrm{IO}] + [\epsilon_{ee} = -2]$$

$$[\mathrm{IO}] + [\epsilon = 0] \quad \equiv \quad [\mathrm{NO}] + [\epsilon_{ee} = -2]$$

Equivalences hold even if all oscillation probabilities are *perfectly* measured

P. Bakhti, Y. Farzan 1403.0744
P. Coloma, T. Schwetz 1604.05772
P. Coloma, PBD, et al. 1701.04828
PBD, S. Parke 2106.12436
PBD, J. Gehrlein 2204.09060

This is known as the **LMA-Dark** solution

Is the mass ordering robust?

Need **scattering** to break

Can probe same NC $\epsilon = -2$ process in scattering, but...

1. COHERENT for $M_{Z'} \gtrsim 50$ MeV and cosmology for $M_{Z'} \lesssim 5$ MeV

   PBD, Y. Farzan, I. Shoemaker 1804.03660

2. Dresden-II for ϵ_{ee} for any mediator mass

   PBD, J. Gehrlein 2204.09060

3. Can still evade with specific flavor structures

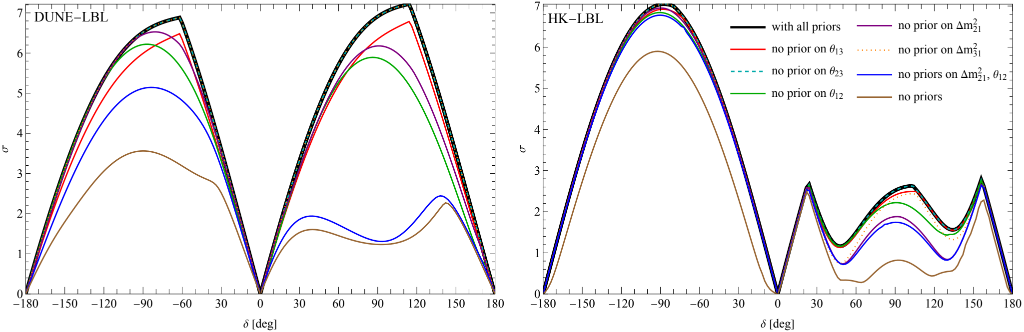
   $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$ or certain u / d combinations

4. CCM & COHERENT can close all loopholes

δ: future sensitivities

DUNE and HK will make great measurements via appearance $\nu_\mu \to \nu_e$

$\nu+\bar{\nu}$ helps systematics but isn't strictly necessary



Need to know solar parameters to measure δ!

Current solar knowledge: okay
Future (JUNO): excellent
PBD, J. Gehrlein 2302.08513