Abstract

I will review some broad highlights of the neutrino frontier in the US's Snowmass process. I will then focus on some particular neutrino reviews such as the status of tau neutrinos, neutrino physics at the LHC, and the upcoming ultra-high energy neutrino program. I will wrap up with a recent study on identifying new physics at next generation experiments.

Neutrinos at Snowmass

Peter B. Denton

KCL

January 27, 2023

Brookhaven National Laboratory

Brookhaven NDI
Neutrino Discovery Initiative

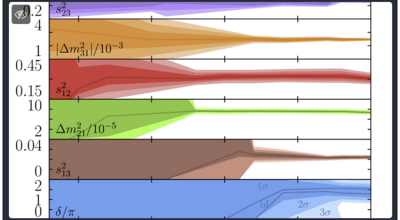
Speaking from Setauket land

Peter Denton
@jazzwhiz

Dec 5, 2022 *

Want to know what the current status of three-flavor oscillations is? Hiro, Mark, Megan, & I put out our summary report from the Snowmass process (along with external input from Sebastian, Joao, Mathieu, & Tom). arxiv.org/abs/2212.00809

I get to showcase this plot I love. It shows the improvement in our knowledge of the 6 oscillation parameters. Like how theta23 was first measured by SK but we still don't know if it's >45deg, <45deg, or how close to 45deg it is: the octant problem. 1/3



1+

Jost Migenda
@JostMigenda@mastodon.social

@jazzwhiz Could I invite you to give an online seminar talk on the NF01 Report (and perhaps Snowmass more broadly) to our group at King's College London?

Dec 19, 2022, 10:03 · Mastodon for iOS · 0 · 1

Peter Denton
@jazzwhiz

Dec 19, 2022

@JostMigenda sure, send me an email

Snowmass

What is it?

- US based
  - Strong international participation at all levels
  - Many projects discussed are international
  - Important to quantify non-US experiments as well
- Organized by the American Physical Society to quantify where we are and where we'd like to be
- Is followed by the Particle Physics Project Prioritization Panel (P5)
  - Just started!
  - Formed by HEPAP which responds to calls from the US funding agencies
- Snowmass process includes:
  - Open meetings on every aspect of particle physics that people are interested in
  - Whitepapers written by anyone on any topic
  - 10 Frontiers each of which has ~ 3 organizers and one report
  - Each frontier has ~ 10 topical groups each of which has ~ 3 organizers and one report

Other organizational efforts

- Astro decadal survey (US, 2020)
- Nuclear physics long range plan (US, starting now)
- European strategy for particle physics (2018)
- African Strategy for Fundamental and Applied Physics (2020)
- Others

Snowmass flow: top down

- HEPAP/DPF
- Snowmass steering group consists of the DPF Chair line and one representative of each of the related units DAP, DPB, DNP, and DGRAV:
  - Joel Butler (Chair, DPF)
  - Sekhar Chivukula (DPF)
  - Priscilla Cushman (DPF)
  - Andre de Gouvea (DPF)
  - Glennys Farrar (DAP)
  - Tao Han (DPF)
  - Young-Kee Kim (DPF)
  - Yury Kolomensky (DNP)
  - Sergei Nagaitsev (DPB)
  - Nicolas Yunes (DGRAV)
- Frontiers:
  - Energy frontier
  - Neutrino frontier
  - Rare processes and precision frontier
  - Cosmic frontier
  - Theory frontier
  - Accelerator frontier
  - Instrumentation frontier
  - Computational frontier
  - Underground facilities
  - Community engagement

Snowmass flow: top down

Neutrino frontier:

1. Patrick Huber
2. Kate Scholberg
3. Elizabeth Worcester

Ten topical groups:

- NF01: Neutrino Oscillations (me!)
- NF02: Understanding Experimental Neutrino Anomalies
- NF03: BSM
- NF04: Neutrinos from natural sources
- NF05: Neutrino properties
- NF06: Neutrino Interaction Cross Sections
- NF07: Applications
- NF08 (TF11): Theory of Neutrino Physics
- NF09: Artificial Neutrino Sources
- NF10: Neutrino Detectors

Snowmass flow: bottom up

1. Letters of interest: helps structure meetings
2. Whitepapers written by anyone inform topical reports
3. Topical reports inform frontier reports
4. Frontier reports inform the Snowmass report
5. The Snowmass report informs the P5 Report
6. The P5 Report is the guide for HEP funding in the US for the next ~decade

All Snowmass reports are now on the arXiv!

P5 report in probably ~ 1 year

My letters of interest

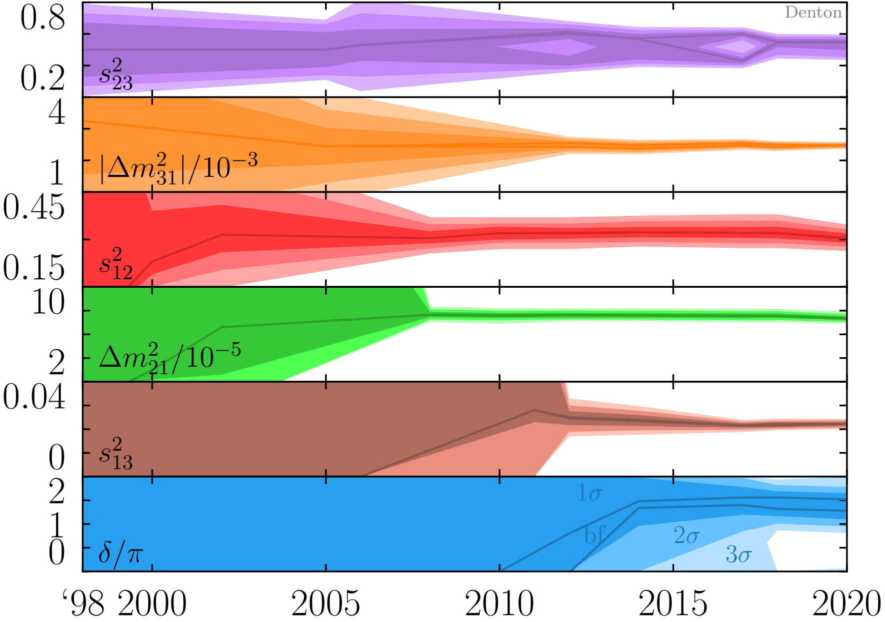
- Neutrino Non-Standard Interactions (ed.)
- Direct Probes of the Matter Effect in Neutrino Oscillations (ed.)
- Ultra-High-Energy Neutrinos (ed.)
- Computing Neutrino Oscillations in Matter Efficiently (ed.)
- Cosmic Neutrino Probes of Fundamental Physics
- Opportunities and signatures of non-minimal HNLs
- Neutrino Opportunities at the ORNL Second Target Station
- CEvNS: Theoretical and experimental impact
- Supernova neutrinos and particle-physics opportunities
- Synergy of astro-particle physics and collider physics
- Studies of the Muon Excess in Cosmic Ray Air Showers
- Forward Physics Facility

My whitepapers

- Snowmass Neutrino Frontier Report
- NF01 Topical Group Report on Three-Flavor Neutrino Oscillations (ed.)
- Snowmass TF11 (aka NF08) Topical Group Report
- Tau neutrinos in the next decade: from GeV to EeV (ed.)
- Beyond the Standard Model effects on Neutrino Flavor
- Neutrino Self-Interactions: A White Paper
- White Paper on Light Sterile Neutrino Searches and Related Phenomenology
- Coherent elastic neutrino-nucleus scattering: Terrestrial and astrophysical applications
- The Forward Physics Facility at the High-Luminosity LHC
- High-energy and ultra-high-energy neutrinos
- Ultra high energy cosmic rays The intersection of the Cosmic and Energy Frontiers
- Cosmology intertwined: A review of the particle physics…
- Low-Energy Physics in Neutrino LArTPCs

Neutrino oscillations: today

See the NF01 report: PBD, M. Friend, M. Messier, H. Tanaka, et al. 2212.00809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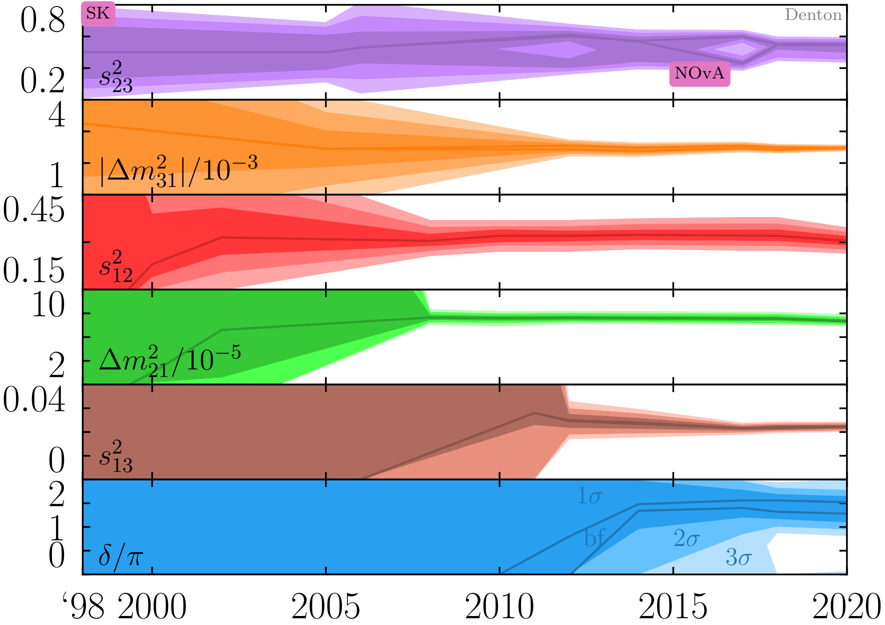
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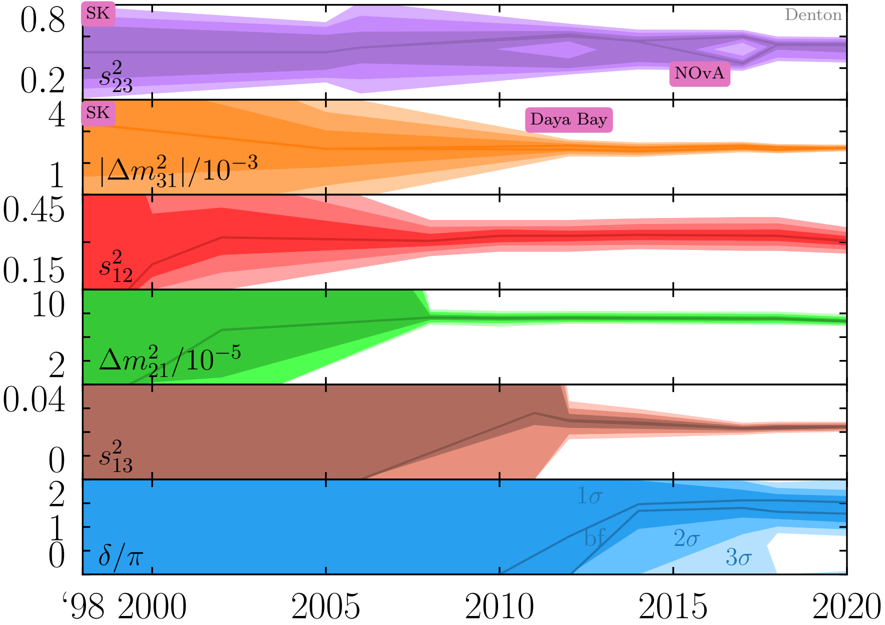

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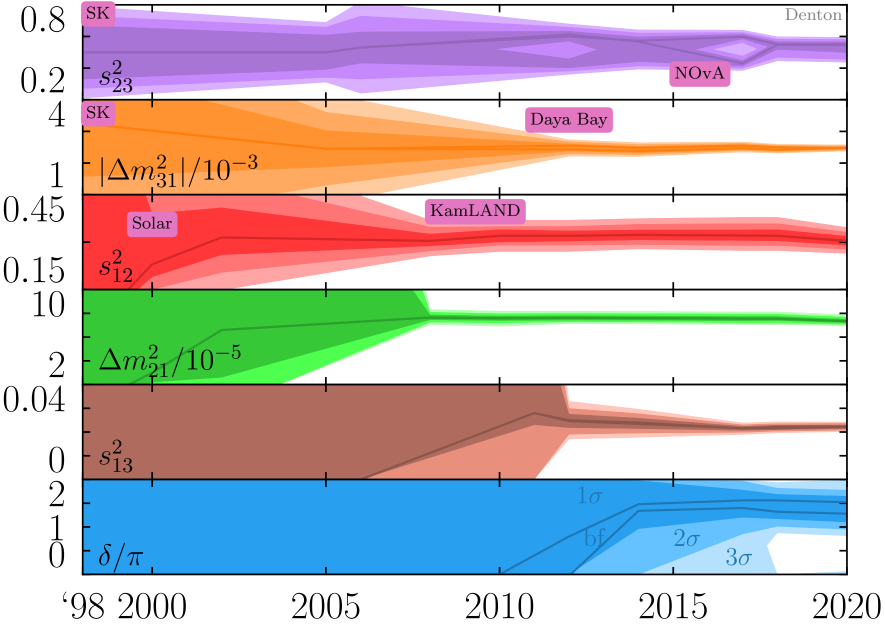
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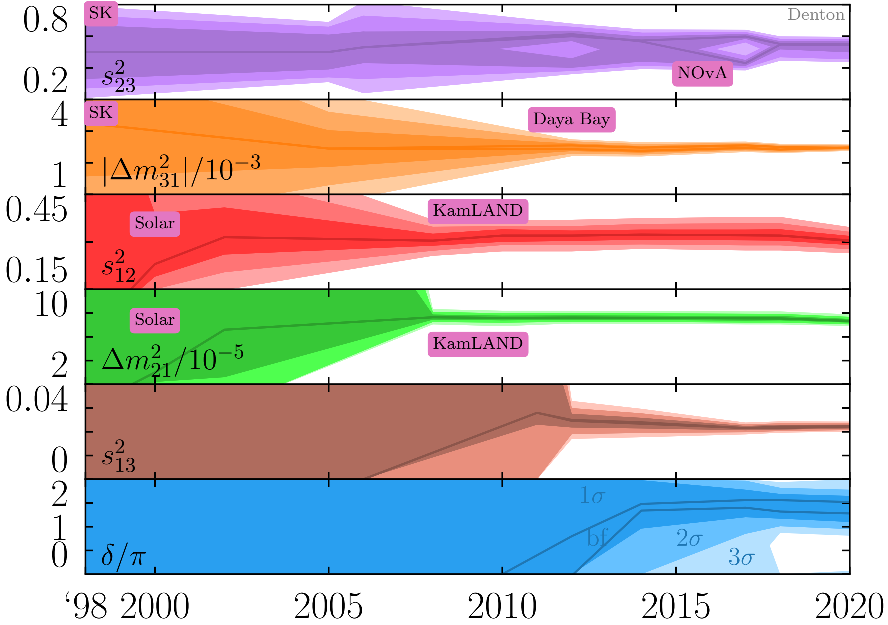
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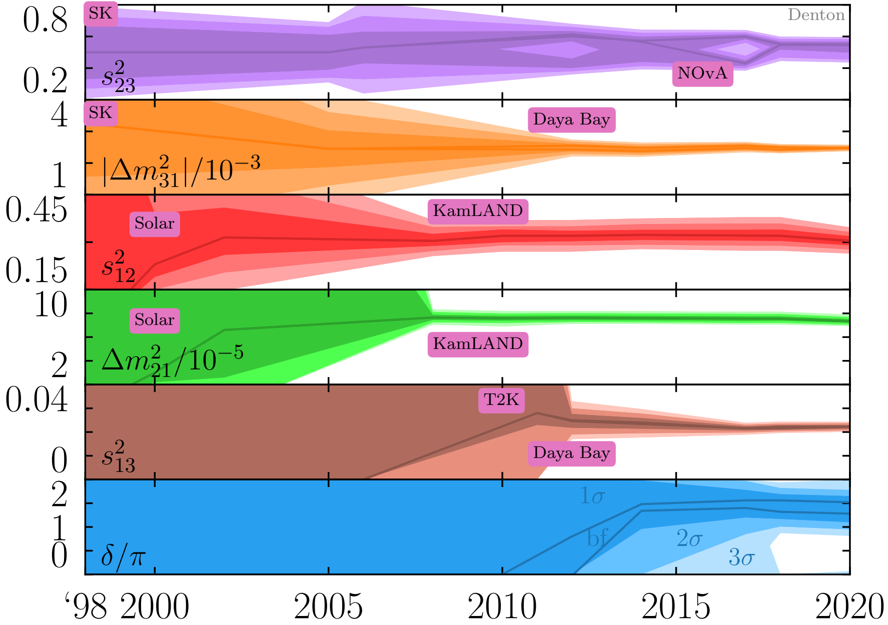
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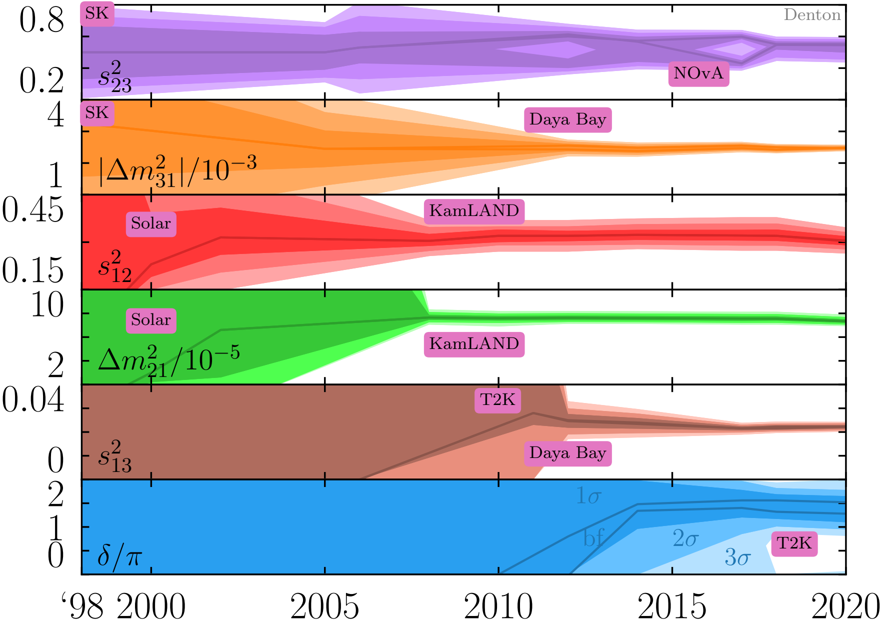

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Four known unknown in particle physics: all neutrinos

Atmospheric mass ordering

θ_{23} octant

Complex phase

Absolute mass scale

Four known unknown in particle physics: all neutrinos

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θ_{23} octant

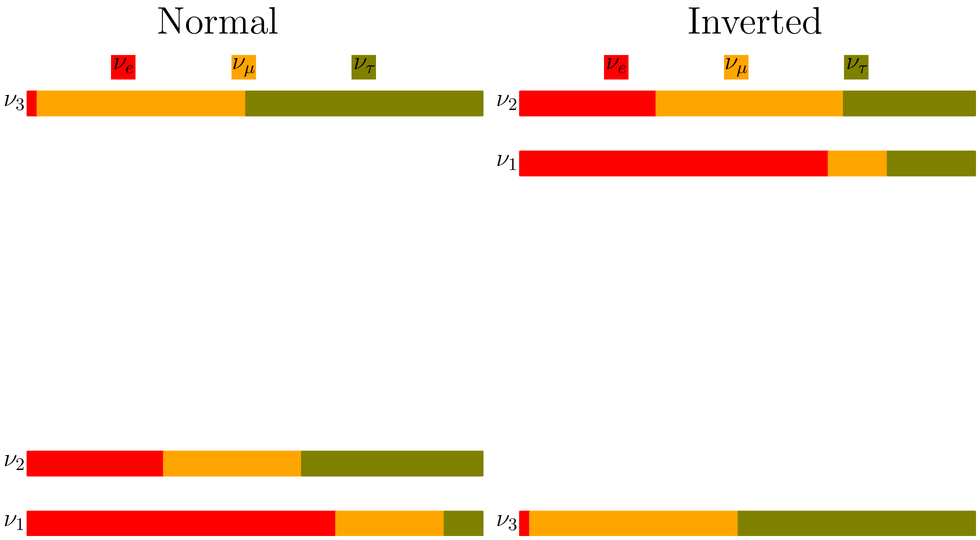
Complex phase

Absolute mass scale

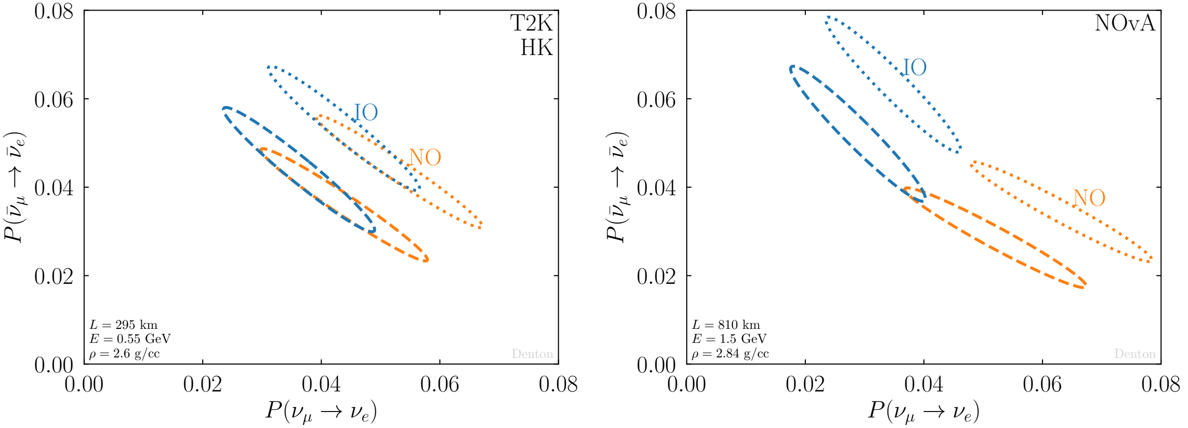
Cosmology, scattering, $0\nu\beta\beta$, ...

Atmospheric mass ordering

Mass ordering: what is it?



Mass ordering: what is it really?



Mass ordering current status: oscillations

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 $\Rightarrow$ slight preference NO
6. $= 2.5 - 2.7\sigma$

K. Kelly, et al. 2007.08526

PBD, J. Gehrlein, R. Pestes 2008.01110

I. Esteban, et al. 2007.14792

F. Capozzi, et al. 2107.00532

P. de Salas, et al. 2006.11237

Mass ordering current status: all

Cosmology: $m_1 + m_2 + m_3 < 90$ meV at 95% CL

E. Valentino, S. Gariazzo, O. Mena 2106.15267

$\rightarrow$ 20 meV precision with DESI, EUCLID, ...

From oscillations:

$$\text{Normal}: \quad m_1 + m_2 + m_3 > 60 \text{ meV} \qquad \text{Inverted}: \quad m_1 + m_2 + m_3 > 100 \text{ meV}$$

See also KATRIN 2105.08533

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See also KATRIN 2105.08533

PRIORS?

Some claim "decisive" Bayesian evidence for normal

R. Jimenez, et al. 2203.14247

More general prior assumptions $\Rightarrow$ no significant information from cosmology

S. Gariazzo, et al. 1801.04946

S. Gariazzo, et al. 2205.02195

Mass ordering: three ways to determine

A measurement of the matter effect is **always** required!

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1. Matter effect in Δm^2_{31} appearance
   - DUNE will do this well $> 5\sigma$
   - NOvA, HK will do this a little bit $\sim 3\sigma$
   - Also atmospherics with SK/HK/IceCube/KM3NeT
     - Atmospheric sensitivity is at best $\sim 3\sigma$ except in the NO upper octant $> 5\sigma$

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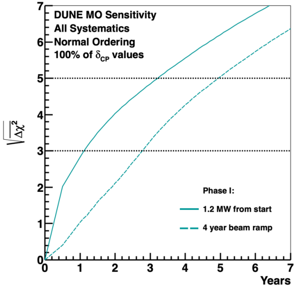
   - JUNO will do this okay $\sim 3\sigma$
   - Requires input from solar experiments like SNO, SK, and Borexino
3. Comparison of Δm^2_{31} at ν_μ disappearance and ν_e disappearance
   - Combine JUNO with KM3NeT/IceCube/HK/DUNE

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

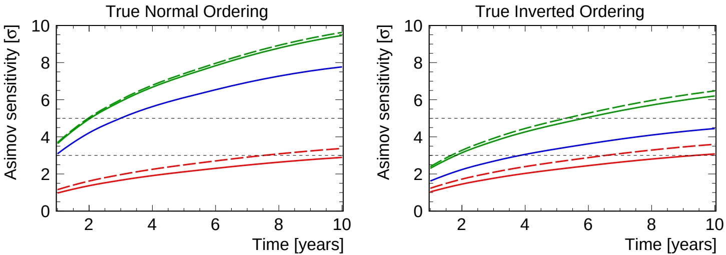
Differ by $\pm \sim 1.5\%$ in each mass ordering

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

Mass ordering: future sensitivities



Matter effect ⇒ DUNE 2203.06100



Joint
KM3NeT
JUNO

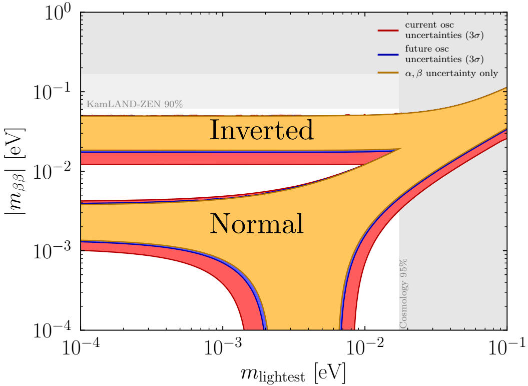
JUNO, KM3NeT 2108.06293

Note: if lower octant, KM3NeT is less sensitive

JUNO, IceCube 1911.06745

Mass ordering: broad implications

- Affects cosmology
- Affects $0\nu\beta\beta$
- Affects end point measurements
- Affects CνB



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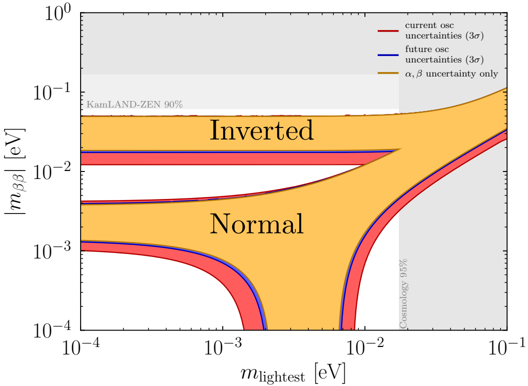
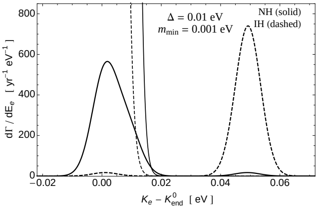
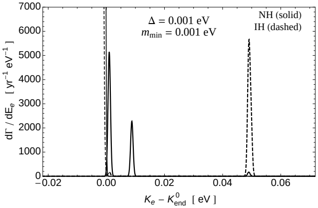


A. Long, C. Lunardini, E. Sabancilar 1405.7654





2212.00809

Mass ordering: new physics degeneracies

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

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

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

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

P. Bakhti, Y. Farzan 1403.0744

P. Coloma, T. Schwetz 1604.05772

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...

CHARM and NuTeV for $M_{Z'} \gtrsim 10$ GeV

PBD, et al. 1701.04828

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

PBD, Y. Farzan, I. Shoemaker 1804.03660

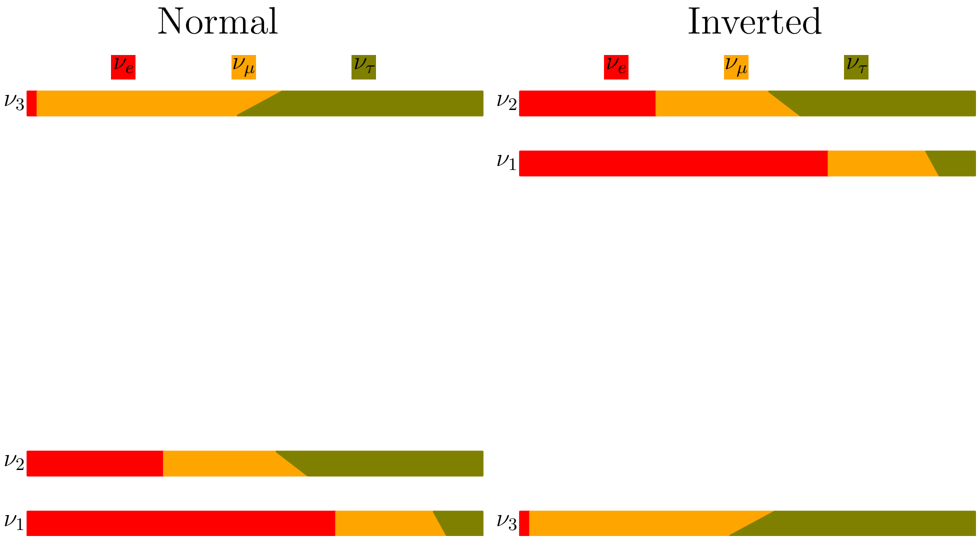
Dresden-II for any mediator mass

PBD, J. Gehrlein 2204.09060

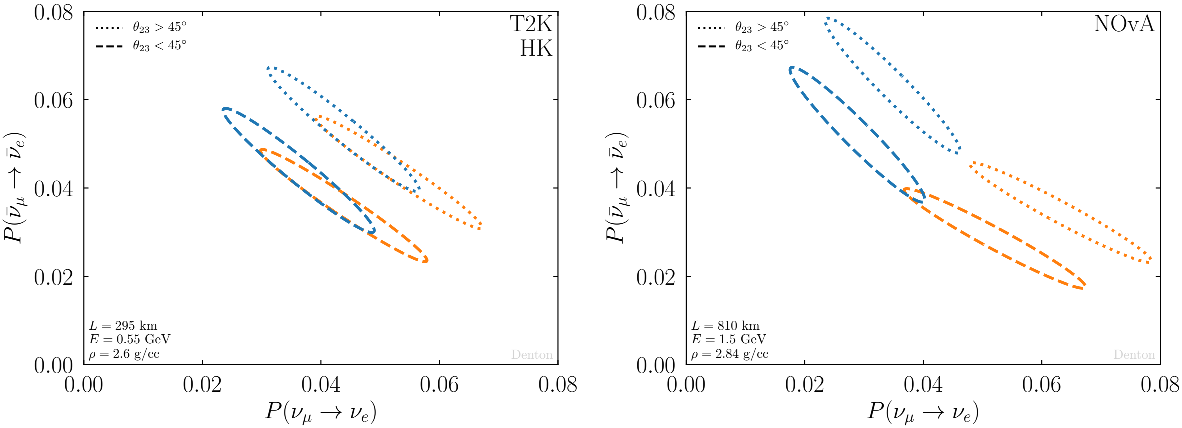
Can still evade with $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 2$ or certain u / d combinations

θ_{23} octant

θ_{23} octant: what is it?

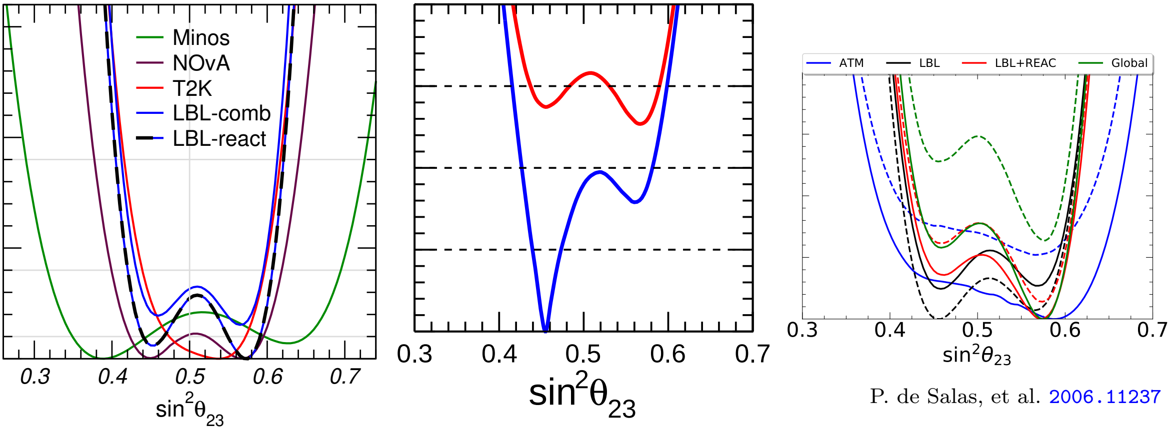


θ_{23} octant: what is it really?



Lower octant more "normal" than upper octant

θ_{23} octant: current status



I. Esteban, et al. 2007.14792

F. Capozzi, et al. 2107.00532

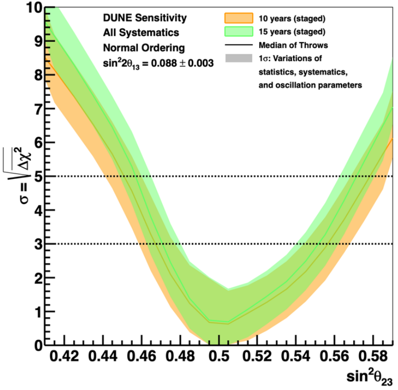
P. de Salas, et al. 2006.11237

Prefers **upper** at $< 1\sigma$

Prefers **lower** at $\sim 1.5\sigma$

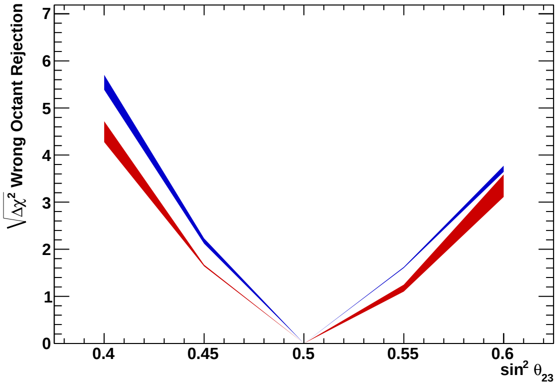
Prefers **upper** at $> 2\sigma$

θ_{23} octant: future sensitivities



$\sim 3-5\sigma$

DUNE 2002.03005



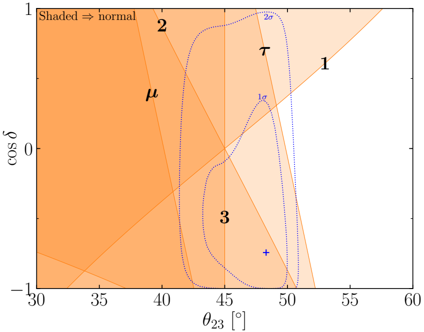
Beam+Atm$\Rightarrow\sim 3-6\sigma$

HK 1805.04163

θ_{23}: broader implications

Normalcy

Is the heaviest neutrino mostly ν_τ?
Is the lightest neutrino least ν_τ?



Quarks easily satisfy normalcy PBD 2003.04319

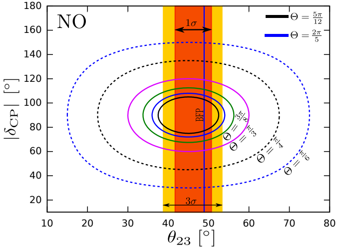
μ-τ interchange/reflection symmetry

$$\nu_\mu \leftrightarrow \nu_\tau$$

$$M_\nu^* = X M_\nu X^T \qquad X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$M_\nu \equiv U D_\nu U^\dagger$$

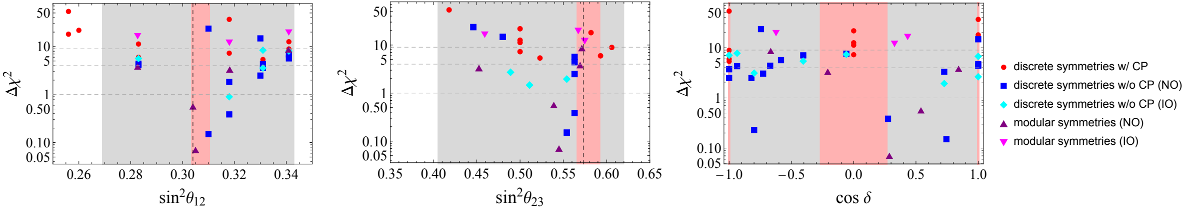
Predicts: $\theta_{23} = 45°$, often $\theta_{13} = 0$



P. Chen, et al. 1512.01551

Parameter interplay

Models predict specific correlations among the parameters



J. Gehrlein, et al. 2203.06219 (Snowmass)

Complex phase

δ and CP violation

$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta$$

C. Jarlskog PRL 55, 1039 (1985)

δ and CP violation

$$J_{CP} = s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta$$

C. Jarlskog PRL 55, 1039 (1985)

1. Strong interaction: no observed EDM $\Rightarrow$ CP (nearly) **conserved**

$$\frac{\bar\theta}{2\pi} < 10^{-11}$$

J. Pendlebury, et al. 1509.04411

2. Quark mass matrix: non-zero but **small** CP violation

$$\frac{|J_{\rm CKM}|}{J_{\rm max}} = 3\times 10^{-4}$$

CKMfitter 1501.05013

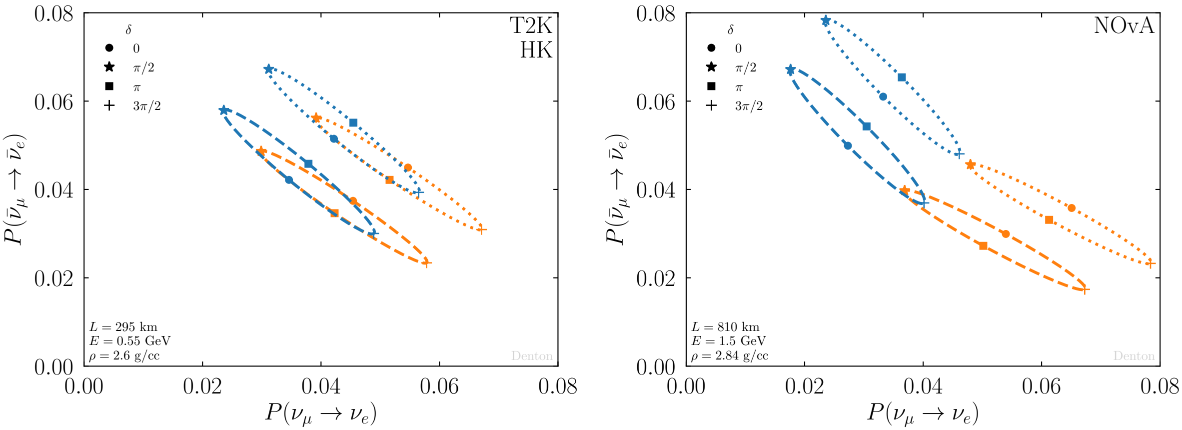
3. Lepton mass matrix: **?**

$$\frac{|J_{\rm PMNS}|}{J_{\rm max}} < 0.34$$

PBD, J. Gehrlein, R. Pestes 2008.01110

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

δ: what is it really?



δ: what is it not?

$$\delta \not\Rightarrow \text{Baryogenesis}$$

The amount of leptogenesis is a function of:

1. δ
2. the heavy mass scale
3. α, β (Majorana phases)
4. CP phases in the RH neutrinos
5. …

C. Hagedorn, et al. 1711.02866

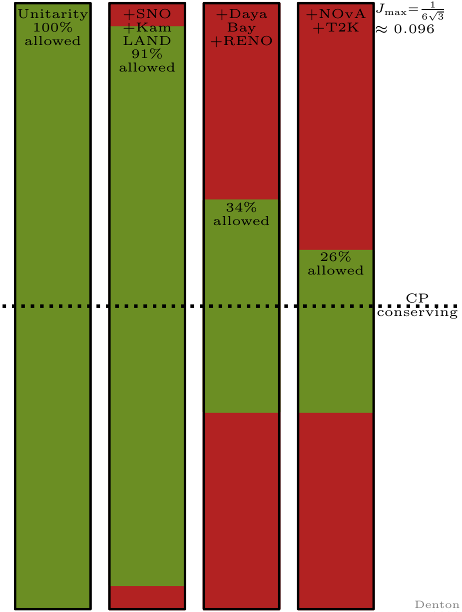
K. Moffat, et al. 1809.08251

$$\text{Measuring } \delta = 0, \pi \quad \not\Rightarrow \quad \text{no leptogenesis}$$
$$\text{Measuring } \delta \neq 0, \pi \quad \not\Rightarrow \quad \text{leptogenesis}$$

δ, J: current status

Maximal CP violation is already ruled out:

1. $\theta_{12} \neq 45^\circ$ at $\sim 15\sigma$
2. $\theta_{13} \neq \tan^{-1}\frac{1}{\sqrt{2}} \approx 35^\circ$ at many (100) σ
3. $\theta_{23} = 45^\circ$ allowed at $\sim 1\sigma$
4. $|\sin\delta| = 1$ allowed



Neutrinos: more new physics?

Lots of interesting new physics scenarios

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. Neutrino – dark matter interactions
7. Decoherence
8. Lorentz invariance or CPT violation

Lots of interesting new physics scenarios

1. Sterile neutrinos
   PBD, Y. Farzan, I. Shoemaker 1811.01310
   PBD 2111.05793
2. Non-standard neutrino interactions (NSI)
   with any Lorentz structure: SPVAT
   PBD, J. Gehrlein, R. Pestes 2008.01110
   P. Coloma, PBD, M. Gonzalez-Garcia, M. Maltoni, T. Schwetz 1701.04828
   PBD, J. Gehrlein 2008.06062, 2204.09060
   PBD, A. Giarnetti, D. Meloni 2210.00109
3. Non-standard neutrino SELF interactions G. Barenboim, PBD, I. 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. Neutrino – dark matter interactions
   H. Davoudiasl, PBD 2301.09651
   C. Boehm, P. Fayet, R. Schaeffer astro-ph/0012504
7. Decoherence
   T. Stuttard, M. Jensen 2007.00068
   A. Gouvêa, V. Romeri, C. Ternes 2104.05806
8. Lorentz invariance or CPT violation
   S. Ge, H. Murayama 1904.02518

Can these be differentiated?

Work done with Alessio Giarnetti and Davide Meloni 2210.00109

Three benchmark scenarios

1. Vector NSI with complex off-diagonal elements:
   - Define:

$$\epsilon_{\alpha\beta} = \frac{g_{\nu,\alpha\beta}}{2\sqrt{2} m_{Z'} G_F} \sum_{q\in\{u,d\}} \frac{N_q}{N_e} g_q$$

   - $|\epsilon_{e\mu}|e^{i\phi_{e\mu}}$, $|\epsilon_{e\tau}|e^{i\phi_{e\tau}}$, and $|\epsilon_{\mu\tau}|e^{i\phi_{\mu\tau}}$

PBD, A. Giarnetti, D. Meloni 2210.00109

Three benchmark scenarios

1. Vector NSI with complex off-diagonal elements:
   - Define:
   $$\epsilon_{\alpha\beta}=\frac{g_{\nu,\alpha\beta}}{2\sqrt{2}m_{Z'}G_F}\sum_{q\in\{u,d\}}\frac{N_q}{N_e}g_q$$
   - $|\epsilon_{e\mu}|e^{i\phi_{e\mu}}$, $|\epsilon_{e\tau}|e^{i\phi_{e\tau}}$, and $|\epsilon_{\mu\tau}|e^{i\phi_{\mu\tau}}$
2. Scalar NSI with complex off-diagonal elements:
   - Define:
   $$\eta_{\alpha\beta}=\frac{y_{\alpha\beta}}{m_\phi^2\sqrt{\Delta m_{31}^2}}\sum_{q\in\{u,d\}}N_q y_q$$
   - $|\eta_{e\mu}(3)|e^{i\phi_{e\mu}}$, $|\eta_{e\tau}(3)|e^{i\phi_{e\tau}}$, and $|\eta_{\mu\tau(3)}|e^{i\phi_{\mu\tau}}$
   - η is dimensionless, but a reference density ($\rho=3$ g/cc) must be specified
   - In general $\eta_{e\mu}\neq\eta_{\mu e}^*$; we choose to keep the matrix Hermitian
   - Depends on the absolute mass scale!

PBD, A. Giarnetti, D. Meloni 2210.00109

Three benchmark scenarios

1. Vector NSI with complex off-diagonal elements:
   - Define:
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   - $|\eta_{e\mu}(3)|e^{i\phi_{e\mu}}$, $|\eta_{e\tau}(3)|e^{i\phi_{e\tau}}$, and $|\eta_{\mu\tau(3)}|e^{i\phi_{\mu\tau}}$
   - η is dimensionless, but a reference density ($\rho = 3$ g/cc) must be specified
   - In general $\eta_{e\mu} \neq \eta_{\mu e}^*$; we choose to keep the matrix Hermitian
   - Depends on the absolute mass scale!
3. Sterile neutrino with $m_4 \sim 1$ eV
   - Value of m_4 doesn't matter much for LBL accelerator so long as $\Delta m_{41}^2 \gg \Delta m_{31}^2$

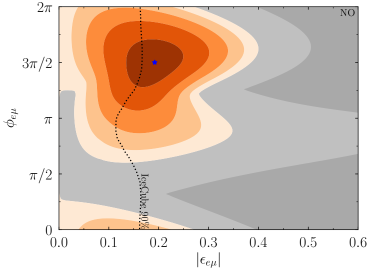
PBD, A. Giarnetti, D. Meloni 2210.00109

Benchmark parameters

Set benchmarks to current long-baseline data: NOvA & T2K

Vector NSI

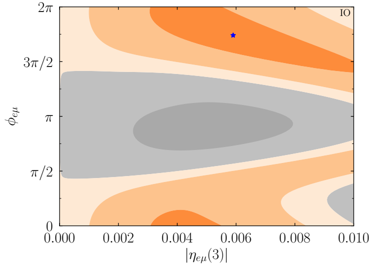
3×2



PBD, J. Gehrlein, R. Pestes 2008.01110

Scalar NSI

3×2



PBD, A. Giarnetti, D. Meloni 2210.00109

Sterile neutrino

2

MO	NO	IO
Δm^2_{41}	1	1
θ_{14}	8°	8°
θ_{24}	8°	8°
δ_{13}/π	1.9	0
δ_{12}/π	0.7	0.5

S. Chatterjee, A. Palazzo 2005.10338

Future sensitivities

Focus on DUNE:

- Broadband
- Matter effect
- Multiple flavor channels
- Good PID

DUNE: good for both seeing regular oscillations and beyond

Encourage similar investigations with other or multiple experiments!

See backups for single BSM scenario sensitivities

Differentiation

True vector NSI:

$\Delta\chi^2$	SM
$\varepsilon_{e\mu}$ NO	200
$\varepsilon_{e\tau}$ NO	60
$\varepsilon_{\mu\tau}$ NO	200
$\varepsilon_{e\mu}$ IO	170
$\varepsilon_{e\tau}$ IO	70
$\varepsilon_{\mu\tau}$ IO	500

Differentiation

True vector NSI:

$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$
$\varepsilon_{e\mu}$ NO	200	140	140	170
$\varepsilon_{e\tau}$ NO	60	48	50	45
$\varepsilon_{\mu\tau}$ NO	200	180	170	180
$\varepsilon_{e\mu}$ IO	170	80	75	90
$\varepsilon_{e\tau}$ IO	70	50	50	45
$\varepsilon_{\mu\tau}$ IO	500	400	400	400

Differentiation

True vector NSI:

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

Differentiation

True 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

Differentiation

True scalar NSI:

$\Delta\chi^2$	SM
$\eta_{e\mu}$ NO	0.14
$\eta_{e\tau}$ NO	0.08
$\eta_{\mu\tau}$ NO	0.60
$\eta_{e\mu}$ IO	100
$\eta_{e\tau}$ IO	60
$\eta_{\mu\tau}$ IO	30

Differentiation

True scalar NSI:

$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$
$\eta_{e\mu}$ NO	0.14	/	0.005	0.088
$\eta_{e\tau}$ NO	0.08	0.003	/	0.041
$\eta_{\mu\tau}$ NO	0.60	0.48	0.48	/
$\eta_{e\mu}$ IO	100	/	4.7	6.3
$\eta_{e\tau}$ IO	60	1.0	/	1.5
$\eta_{\mu\tau}$ IO	30	4.6	4.8	/

Differentiation

True scalar NSI:

$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$
$\eta_{e\mu}$ NO	0.14	/	0.005	0.088	0.071	0.033	0.055
$\eta_{e\tau}$ NO	0.08	0.003	/	0.041	0	0	0
$\eta_{\mu\tau}$ NO	0.60	0.48	0.48	/	0	0	0
$\eta_{e\mu}$ IO	100	/	4.7	6.3	80	70	90
$\eta_{e\tau}$ IO	60	1.0	/	1.5	44	38	50
$\eta_{\mu\tau}$ IO	30	4.6	4.8	/	23	20	29

Differentiation

True scalar 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
$\eta_{e\mu}$ NO	0.14	/	0.005	0.088	0.071	0.033	0.055	0.02
$\eta_{e\tau}$ NO	0.08	0.003	/	0.041	0	0	0	0.01
$\eta_{\mu\tau}$ NO	0.60	0.48	0.48	/	0	0	0	0.02
$\eta_{e\mu}$ IO	100	/	4.7	6.3	80	70	90	21
$\eta_{e\tau}$ IO	60	1.0	/	1.5	44	38	50	11
$\eta_{\mu\tau}$ IO	30	4.6	4.8	/	23	20	29	12

Differentiation

True sterile neutrino:

$\Delta\chi^2$	SM
3+1 NO	20
3+1 IO	20

Differentiation

True sterile neutrino:

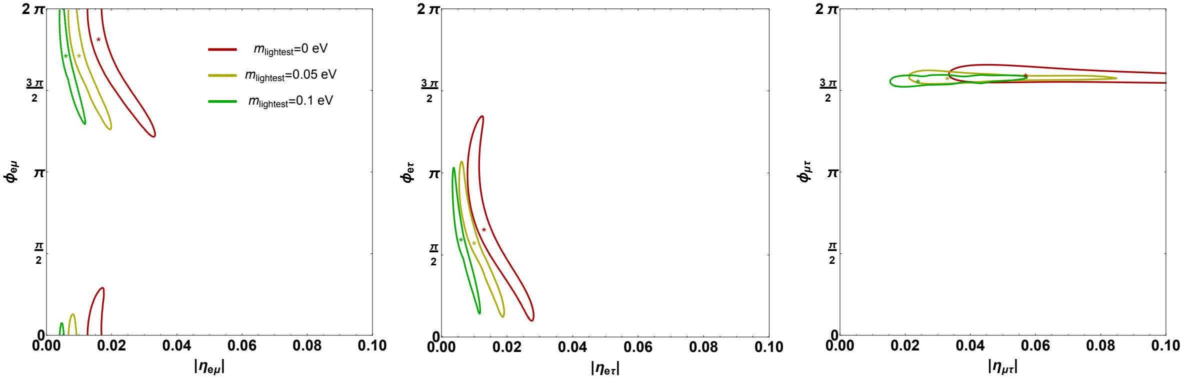
$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$
3+1 NO	20	8.2	7.9	6.7
3+1 IO	20	13	0	18

Differentiation

True sterile neutrino:

$\Delta\chi^2$	SM	$\eta_{e\mu}$	$\eta_{e\tau}$	$\eta_{\mu\tau}$	$\varepsilon_{e\mu}$	$\varepsilon_{e\tau}$	$\varepsilon_{\mu\tau}$
3+1 NO	20	8.2	7.9	6.7	5.2	6.6	10
3+1 IO	20	13	0	18	7.4	6.2	9.5

Scalar NSI: mass scale



Absolute neutrino mass scale plays a role!

Neutrino oscillation summary

- Four known unknowns in particle physics: all neutrinos
- Mass ordering will be measured

Robustness?

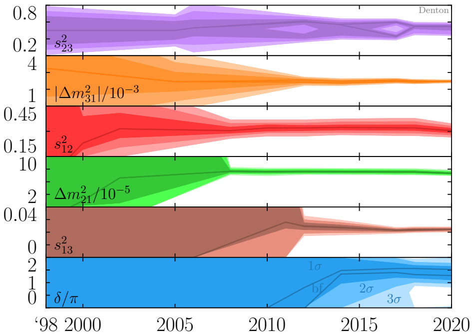
- θ_{23} octant is important for flavor models
- δ could shed light on CP violation
- DUNE can probe *and* differentiate new physics scenarios

Precision is coming to neutrinos!

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

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

Affects oscillations via new matter effect

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

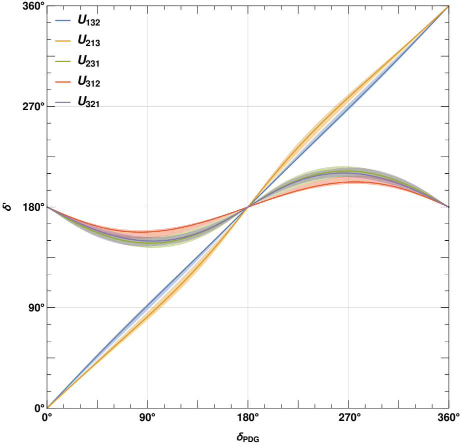
Matter potential $a \propto G_F\rho E$

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

Complex phase in different parameterizations

- Can relate the complex phase in one parameterization to that in another
- U_{132} and U_{213} similar to U_{123}
- δ constrained to $\sim [150°, 210°]$ in U_{231}, U_{312}, U_{321}
- Bands indicate 3σ uncertainty on θ_{12}, θ_{13}, θ_{23}
- "50% of possible values of δ"
  $\Rightarrow$ parameterization dependent

DUNE TDR II 2002.03005



Quark mixing

From the PDG, V_{CKM} in the V_{123} parameterization is

$$\theta_{12} = 13.09^\circ \quad \theta_{13} = 0.2068^\circ \quad \theta_{23} = 2.323^\circ \quad \delta_{\mathrm{PDG}} = 68.53^\circ$$

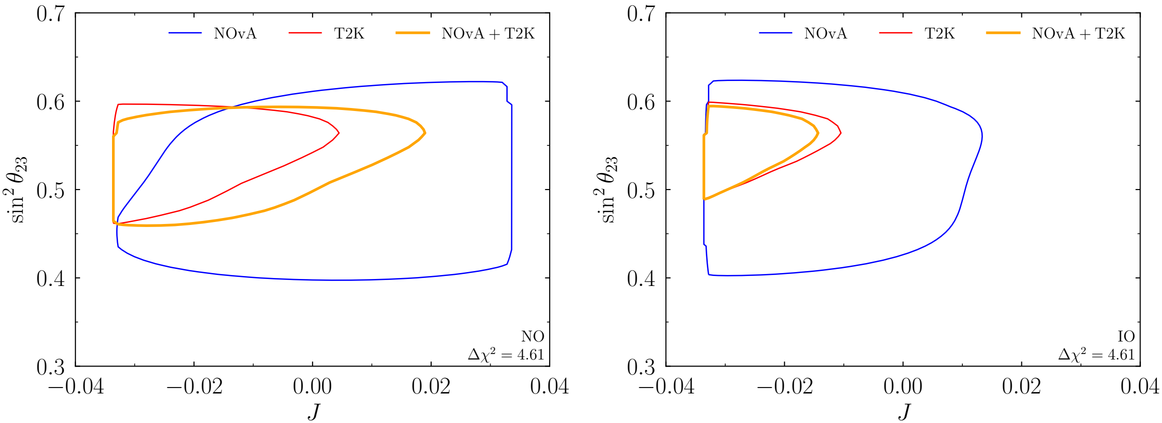
Looks like "large" CPV:

$$\sin\delta_{\mathrm{PDG}} = 0.93 \sim 1$$

yet $J_{\mathrm{CKM}}/J_{\max} = 3 \times 10^{-4}$.

Switch to V_{212} parameterization, $\Rightarrow \delta' = 1^\circ$ and $\sin\delta' = 0.02$.

Standard oscillation parameters



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

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

CP violation in oscillations

In vacuum at first maximum:

$$P_{\mu e} - \bar{P}_{\mu e} \approx 8\pi J \frac{\Delta m^2_{21}}{\Delta m^2_{32}}$$

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

C. Jarlskog PRL 55, 1039 (1985)

- Extracting δ from data requires every other oscillation parameter
- J requires only Δm^2_{21} (up to matter effects)

Matter effects are easily accounted for

$$\hat{J} \simeq \frac{J}{\sqrt{(c_{212} - c^2_{13}a/\Delta m^2_{21})^2 + s^2_{212}}\sqrt{(c_{213} - a/\Delta m^2_{ee})^2 + s^2_{213}}}$$

PBD, S. Parke 1902.07185

PBD, H. Minakata, S. Parke 1604.08167

When δ and when J?

If the goal is **CP violation** the Jarlskog invariant should be used

however

If the goal is **measuring the parameters** one must use δ

Given θ_{12}, θ_{13}, θ_{23}, and J, I can't determine the sign of $\cos\delta$ which is physical

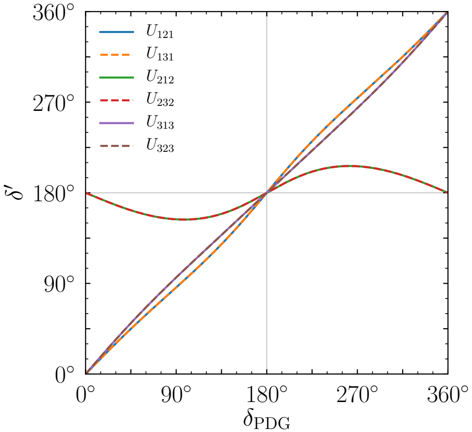
e.g. $P(\nu_\mu \to \nu_\mu)$ depends on $\cos\delta$ a tiny bit

- T2K/HK are mostly sensitivity to $\sin\delta$; they should focus on J

  T2K does this now!

- NOvA/DUNE has modest $\cos\delta$ sensitivity; both J and δ should be reported

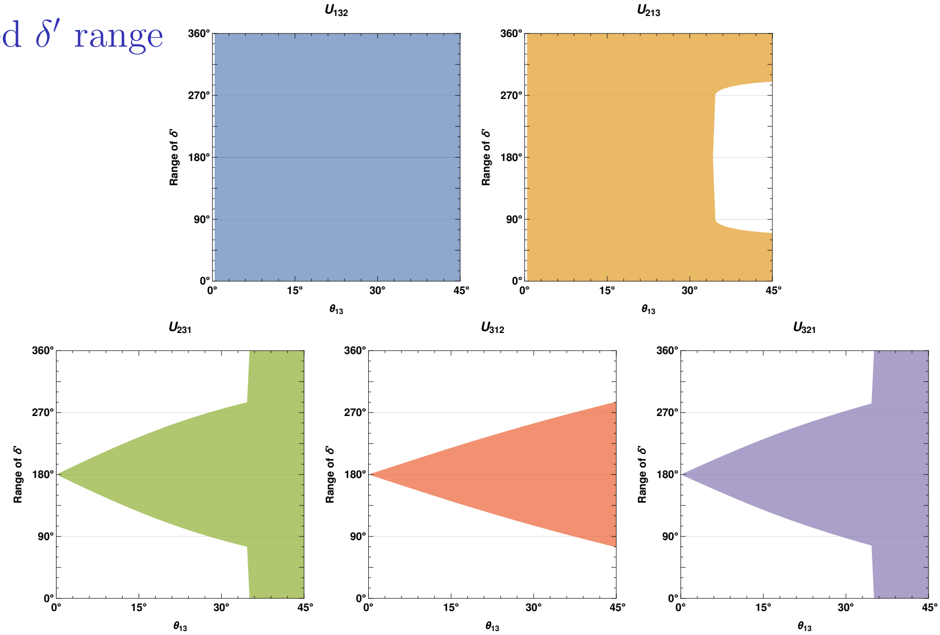
Repeated rotations



	U_{121}	U_{131}	U_{212}	U_{232}	U_{313}	U_{323}
$\lvert U_{e2}\rvert$	✓	✓	✓	✓	✗	✗
$\lvert U_{e3}\rvert$	✓	✓	✗	✗	✓	✓
$\lvert U_{\mu3}\rvert$	✗	✗	✓	✓	✓	✓

Note that $e^{i\delta}$ must be on first or third rotation

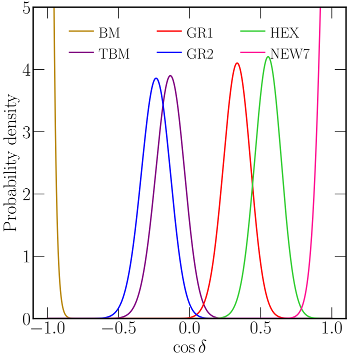
Allowed δ' range



The importance of $\cos\delta$

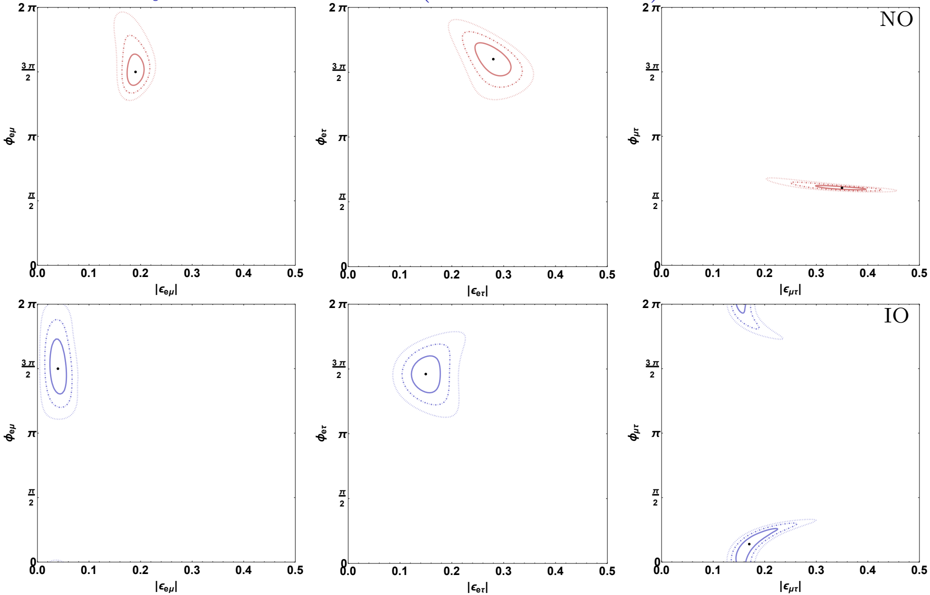
- If only $\sin\delta$ is measured $\Rightarrow$ sign degeneracy: $\cos\delta = \pm\sqrt{1-\sin^2\delta}$
- Most flavor models predict $\cos\delta$

J. Gehrlein, et al. 2203.06219

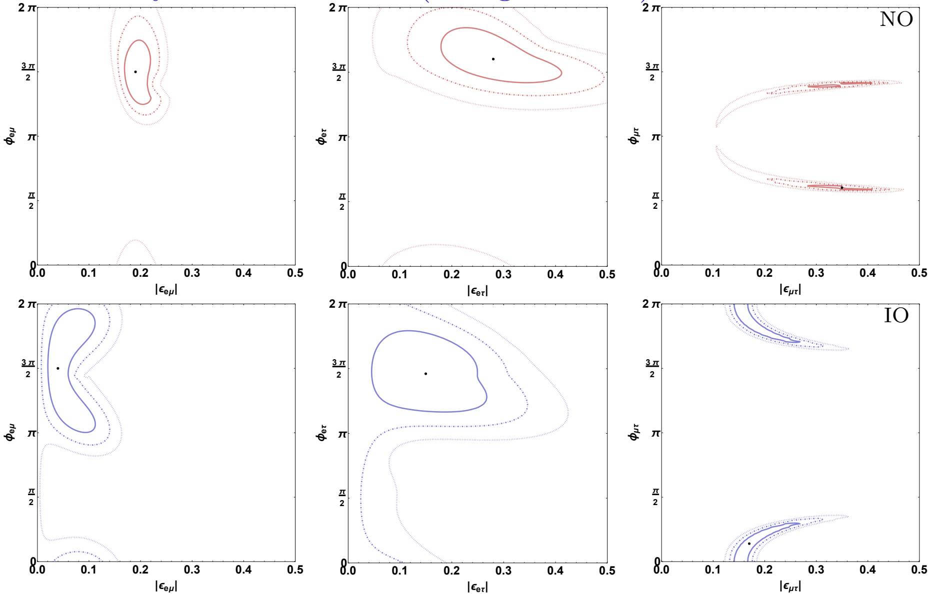


L. Everett, et al. 1912.10139

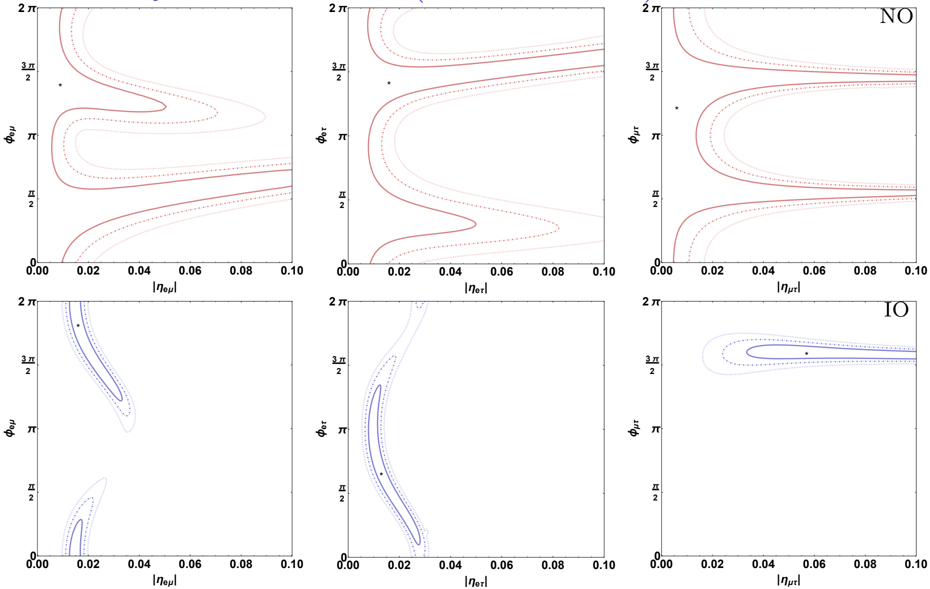
DUNE sensitivity to vector NSI (one at a time)



DUNE sensitivity to vector NSI (marginalized)



DUNE sensitivity to scalar NSI (one at a time)



DUNE sensitivity to steriles