BSM Searches in Neutrino Experiments

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Motivation for BSM Searches in Neutrino Experiments

- Physics beyond the Standard Model (BSM) has manifested itself in one clear way – neutrino masses are non-zero

- Rich experimental program in neutrino physics for the coming decade or two to validate the three-neutrino paradigm and to have extensive search for BSM physics

- The upcoming high-precision neutrino oscillation experiments are expected to determine the neutrino mass ordering, mixing angles, and CP violation at high C.L. and to provide a rigorous test of the three-flavor neutrino oscillation framework at various baselines (L) and energies (E) in the presence of Earth's matter effect

- These facilities are supposed to measure the mixing angles and mass-squared differences with a precision around *few %* and therefore, these next generation neutrino experiments may be sensitive to various BSM scenarios at low-energies

- BSM searches in low-energy neutrino experiments complement the quest for new physics at the ongoing LHC and future collider facilities at high-energies

Few Interesting Issues in Neutrino BSM Physics

- **To what extent does the three-flavor neutrino oscillation framework describe Nature?**
- Can future high-precision neutrino oscillation experiments reveal the presence of new fundamental particles or interactions?
- How do the oscillation parameters get modified in the presence of flavor conserving and flavor violating non-standard interactions (NSIs) of the neutrino inside the Earth matter?
- Can we Improve the constraints on NSIs using upcoming scattering and oscillation data?
- How many neutrino species are there? Do sterile neutrinos exist? How can they affect the measurements of various oscillation parameters in neutrino experiments?
- Possibility of new sources of CP violation due to the new phases with a light sterile neutrino?
- How can we discriminate between various new physics models in neutrino experiments?
- Importance of second oscillation maximum, spectral information, near detector, highly precise tracking and energy measurements, low energy thresholds, excellent timing resolution, charge identification capabilities, hadron energy information (inelasticity)
- **Machine learning techniques in data analysis to develop improved selection criteria**

BSM Physics at Neutrino Experiments

arXiv:1907.08311v3 [hep-ph] 18 Oct 2019

White Paper on New Opportunities at the Next-Generation Neutrino Experiments

(Part 1: BSM Neutrino Physics and Dark Matter)

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White Paper on Landscape of BSM Physics at Neutrino Experiment. It asks the questions like:

- What BSM results look like at present?
- What results on BSM physics expected from the upcoming high-precision neutrino experiments and on what time scale?
- What tasks need to be accomplished to have a rigorous search for BSM physics and how much time do we have in hand for this?

Lots of activity under SNOWMASS 2021
https://snowmass21.org/neutrino/

SNOWMASS-NF02-STERILES

SNOWMASS-NF03-BSM

Contact the conveners & contribute!

Neutrino NSIs

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Neutrino non-standard interactions: A status report

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Updated constraints on non-standard interactions from global analysis of oscillation data

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Abstract: We quantify our present knowledge of the size and flavor structure of non-standard neutrino interactions which affect the matter background in the evolution of solar, atmospheric, reactor and long-baseline accelerator neutrinos as determined by a global analysis of oscillation data — both alone and in combination with the results on coherent neutrino-nucleus scattering from the COHERENT experiment. We consider general neutral current neutrino interactions with quarks whose lepton-flavor structure is independent of the quark type. We study the dependence of the allowed ranges of non-standard interaction coefficients, the status of the LMA-D solution, and the determination of the oscillation parameters on the relative strength of the non-standard couplings to up and down quarks. Generically we find that the conclusions are robust for a broad spectrum of up-to-down strengths, and we identify and quantify the exceptional cases related to couplings whose effect in neutrino propagation in the Earth or in the Sun is severely suppressed. As a result of the study we provide explicit constraints on the effective couplings which parametrize the non-standard Earth matter potential relevant for long-baseline experiments.

Keywords: Beyond Standard Model, Neutrino Physics, Solar and Atmospheric Neutrinos

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JHEP08(2018)180

Neutrino NC-NSIs in Propagation

2σ allowed ranges for the NSI couplings $\varepsilon^u_{\alpha\beta}$, $\varepsilon^d_{\alpha\beta}$ and $\varepsilon^P_{\alpha\beta}$

dimension-6 4-fermion operators

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

$f, f' \in \{e, u, d\}$ and $P \in \{P_L, P_R\}$

	OSC			+COHERENT	
	LMA	LMA ⊕ LMA-D		LMA	LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$	ε^u_{ee}	$[-0.008, +0.618]$	$[-0.008, +0.618]$
			$\varepsilon^u_{\mu\mu}$	$[-0.111, +0.402]$	$[-0.111, +0.402]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$	$\varepsilon^u_{\tau\tau}$	$[-0.110, +0.404]$	$[-0.110, +0.404]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$	$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.049]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$	$\varepsilon^u_{e\tau}$	$[-0.248, +0.116]$	$[-0.248, +0.116]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$	$\varepsilon^u_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$	ε^d_{ee}	$[-0.012, +0.565]$	$[-0.012, +0.565]$
			$\varepsilon^d_{\mu\mu}$	$[-0.103, +0.361]$	$[-0.103, +0.361]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$	$\varepsilon^d_{\tau\tau}$	$[-0.102, +0.361]$	$[-0.102, +0.361]$
$\varepsilon^d_{e\mu}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$	$\varepsilon^d_{e\mu}$	$[-0.058, +0.049]$	$[-0.058, +0.049]$
$\varepsilon^d_{e\tau}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$	$\varepsilon^d_{e\tau}$	$[-0.206, +0.110]$	$[-0.206, +0.110]$
$\varepsilon^d_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$	$\varepsilon^d_{\mu\tau}$	$[-0.011, +0.009]$	$[-0.011, +0.009]$
$\varepsilon^P_{ee} - \varepsilon^P_{\mu\mu}$	$[-0.041, +1.312]$	$\oplus[-3.327, -1.958]$	ε^P_{ee}	$[-0.010, +2.039]$	$[-0.010, +2.039]$
			$\varepsilon^P_{\mu\mu}$	$[-0.364, +1.387]$	$[-0.364, +1.387]$
$\varepsilon^P_{\tau\tau} - \varepsilon^P_{\mu\mu}$	$[-0.015, +0.426]$	$[-0.424, +0.426]$	$\varepsilon^P_{\tau\tau}$	$[-0.350, +1.400]$	$[-0.350, +1.400]$
$\varepsilon^P_{e\mu}$	$[-0.178, +0.147]$	$[-0.178, +0.178]$	$\varepsilon^P_{e\mu}$	$[-0.179, +0.146]$	$[-0.179, +0.146]$
$\varepsilon^P_{e\tau}$	$[-0.954, +0.356]$	$[-0.954, +0.949]$	$\varepsilon^P_{e\tau}$	$[-0.860, +0.350]$	$[-0.860, +0.350]$
$\varepsilon^P_{\mu\tau}$	$[-0.035, +0.027]$	$[-0.035, +0.035]$	$\varepsilon^P_{\mu\tau}$	$[-0.035, +0.028]$	$[-0.035, +0.028]$

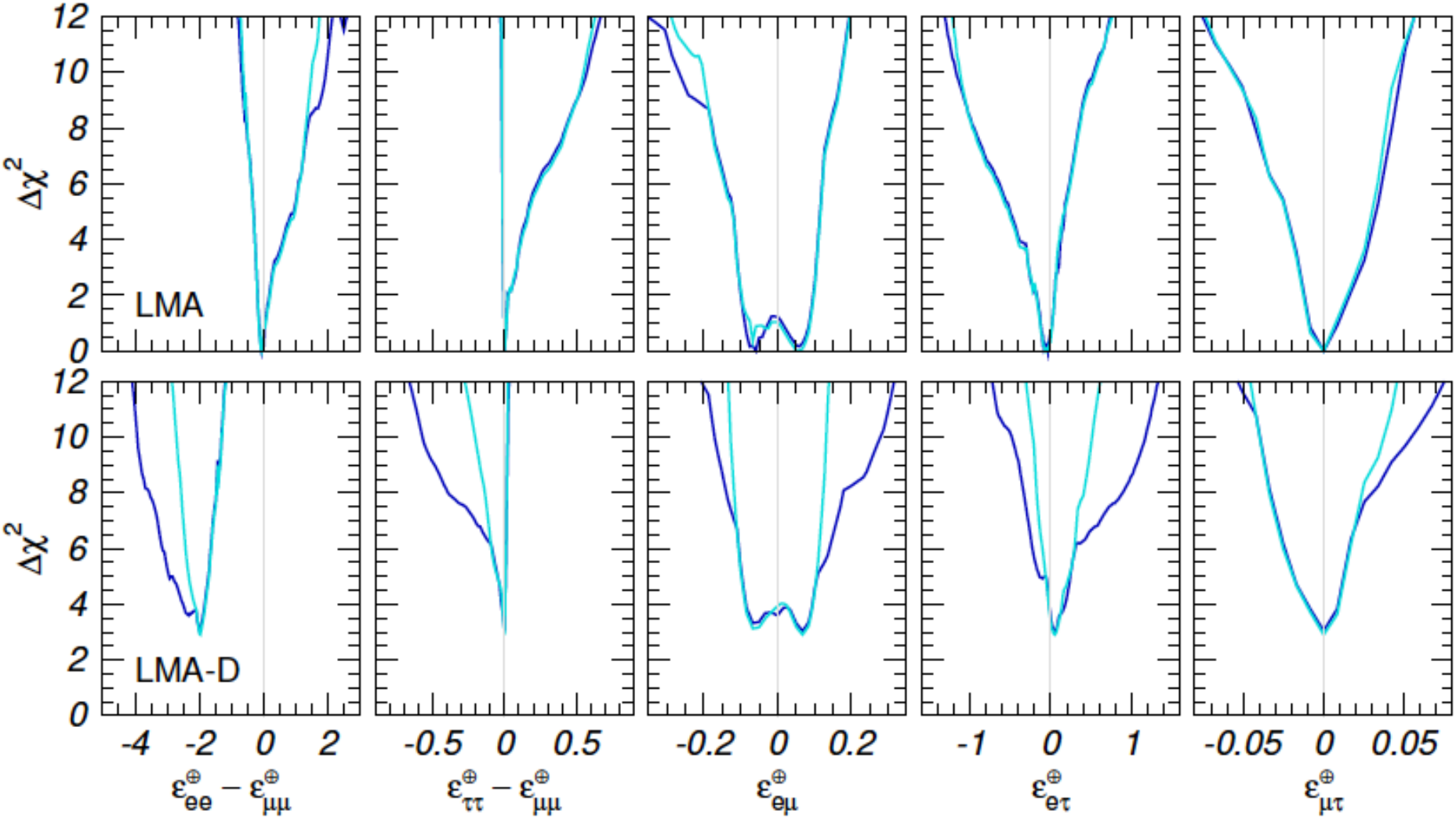
$$H = \frac{1}{2E}\left[U_{\rm PMNS}\begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{\rm PMNS} + a\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

$$a \equiv 2\sqrt{2}G_F N_e E$$

Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, JHEP 08 (2018) 180

Neutrino NC-NSIs in Propagation

Dependence of the $\Delta\chi^2$ function on the effective NSI parameters



Blue lines: All Oscillation data **Cyan lines: All Oscillation data + COHERENT data**

Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, JHEP 08 (2018) 180

Neutrino CC-NSIs at Production and Detection

dimension-6 4-fermion operators

$$\mathcal{L}_{CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)(\bar{f}\gamma_\mu P f')$$

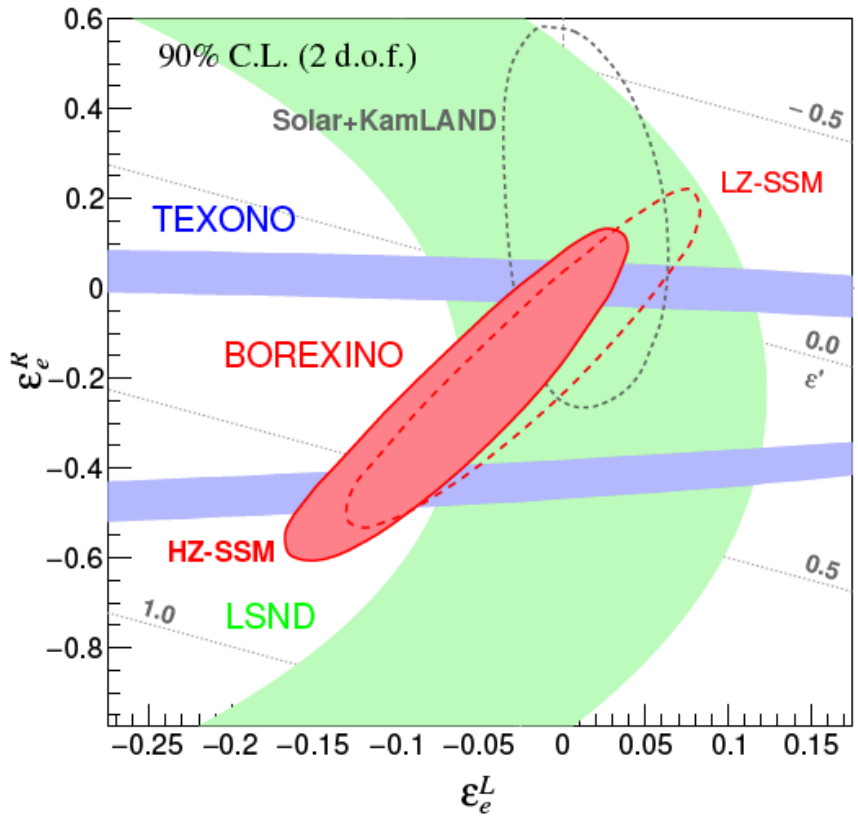
$f, f' \in \{e, u, d\}$ and $P \in \{P_L, P_R\}$

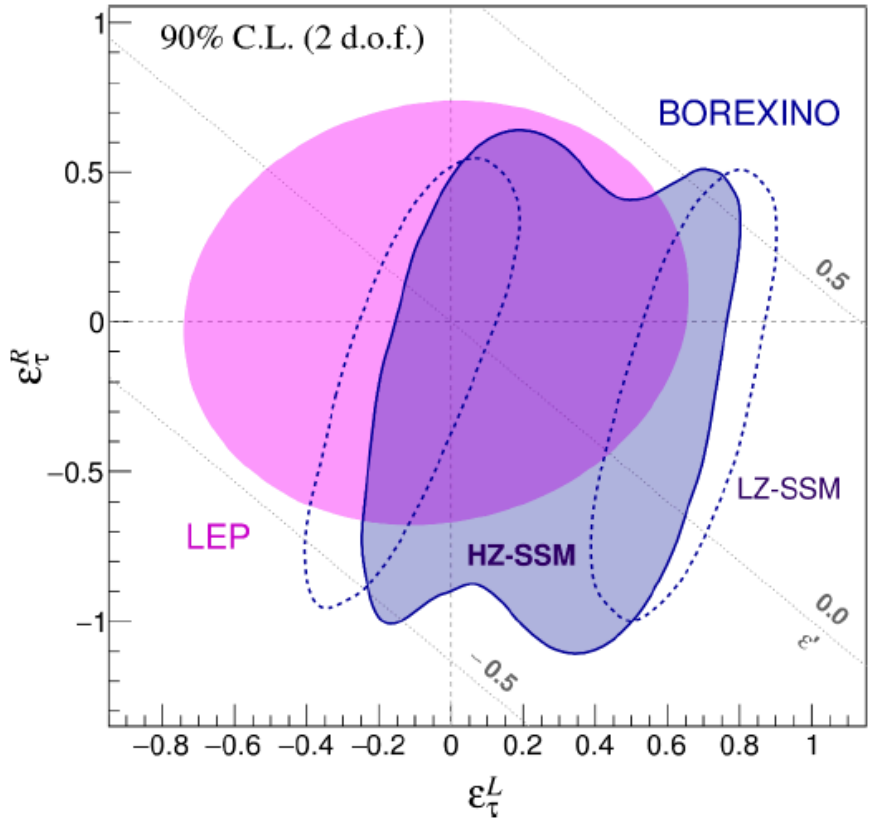
	90% C.L. range	origin	Ref.
		semileptonic NSI	
ϵ^{udP}_{ee}	$[-0.015, 0.015]$	Daya Bay	[13]
$\epsilon^{udL}_{e\mu}$	$[-0.026, 0.026]$	NOMAD	[33]
$\epsilon^{udR}_{e\mu}$	$[-0.037, 0.037]$	NOMAD	[33]
$\epsilon^{udL}_{\tau e}$	$[-0.087, 0.087]$	NOMAD	[33]
$\epsilon^{udR}_{\tau e}$	$[-0.12, 0.12]$	NOMAD	[33]
$\epsilon^{udL}_{\tau\mu}$	$[-0.013, 0.013]$	NOMAD	[33]
$\epsilon^{udR}_{\tau\mu}$	$[-0.018, 0.018]$	NOMAD	[33]
		purely leptonic NSI	
$\epsilon^{\mu eL}_{\alpha e}$, $\epsilon^{\mu eR}_{\alpha e}$	$[-0.025, 0.025]$	KARMEN	[33]
$\epsilon^{\mu eL}_{\alpha\beta}$, $\epsilon^{\mu eR}_{\alpha\beta}$	$[-0.030, 0.030]$	kinematic G_F	[33]

Farzan, Tortola, Front.in Phys. 6 (2018) 10

Ref. [13]: Agarwalla, Bagchi, Forero, Tortola, JHEP 07 (2015) 060
Ref. [33]: Biggio, Blennow, Fernandez-Martinez, JHEP 08 (2009) 090

New Constraints on Flavor-Diagonal NSIs from Borexino Phase-II





	HZ-SSM	LZ-SSM
ε_e^R	[−0.15, +0.11]	[−0.20, +0.03]
ε_e^L	[−0.035, +0.032]	[−0.013, +0.052]
ε_τ^R	[−0.83, +0.36]	[−0.42, +0.43]
ε_τ^L	[−0.11, +0.67]	[−0.19, +0.79]

one parameter at-a-time limit at 90% C.L. (1 d.o.f.)

$$g_{\alpha R} \rightarrow \tilde{g}_{\alpha R} = g_{\alpha R} + \varepsilon_\alpha^R$$
$$g_{\alpha L} \rightarrow \tilde{g}_{\alpha L} = g_{\alpha L} + \varepsilon_\alpha^L$$

$$\frac{d\tilde{\sigma}_{\nu_\alpha}(E_{\nu_\alpha}, T)}{dT} = \frac{2G_F^2 m_e}{\pi}\left[\tilde{g}_{\alpha L}^2 + \tilde{g}_{\alpha R}^2\left(1 - \frac{T}{E_{\nu_\alpha}}\right)^2 - \tilde{g}_{\alpha L}\tilde{g}_{\alpha R}\frac{m_e T}{E_{\nu_\alpha}^2}\right]$$

Nice complementarity between Borexino and Texono

S. K. Agarwalla et al., JHEP 02 (2020) 038

Ultimate Bounds on Ultra-light Neutrino NSIs

PHYSICAL REVIEW LETTERS **122**, 061103 (2019)

Editors' Suggestion | Featured in Physics

Universe's Worth of Electrons to Probe Long-Range Interactions of High-Energy Astrophysical Neutrinos

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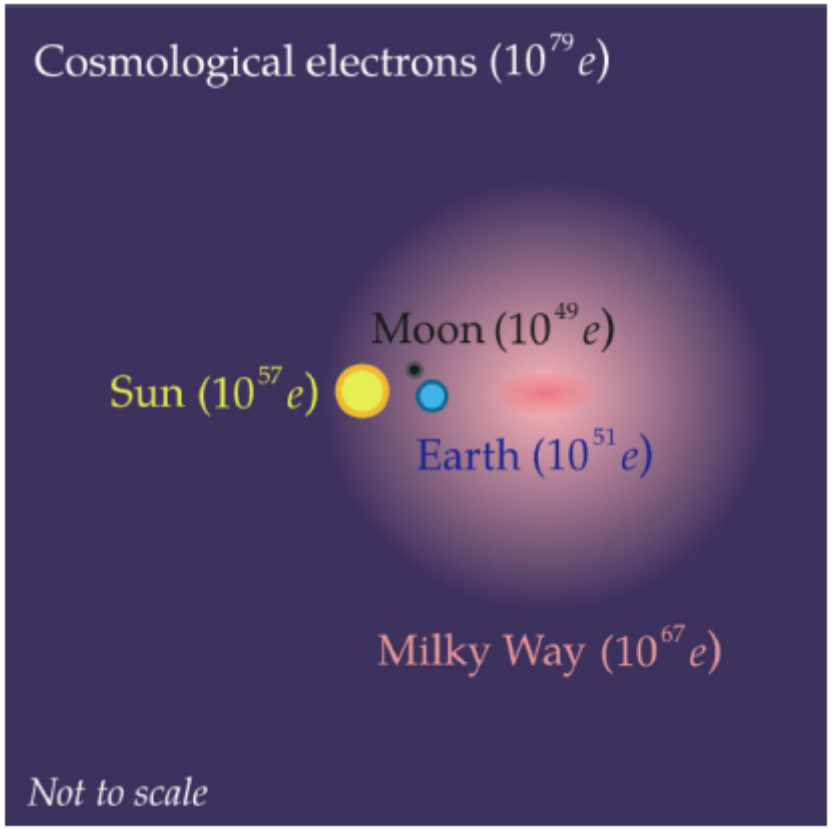
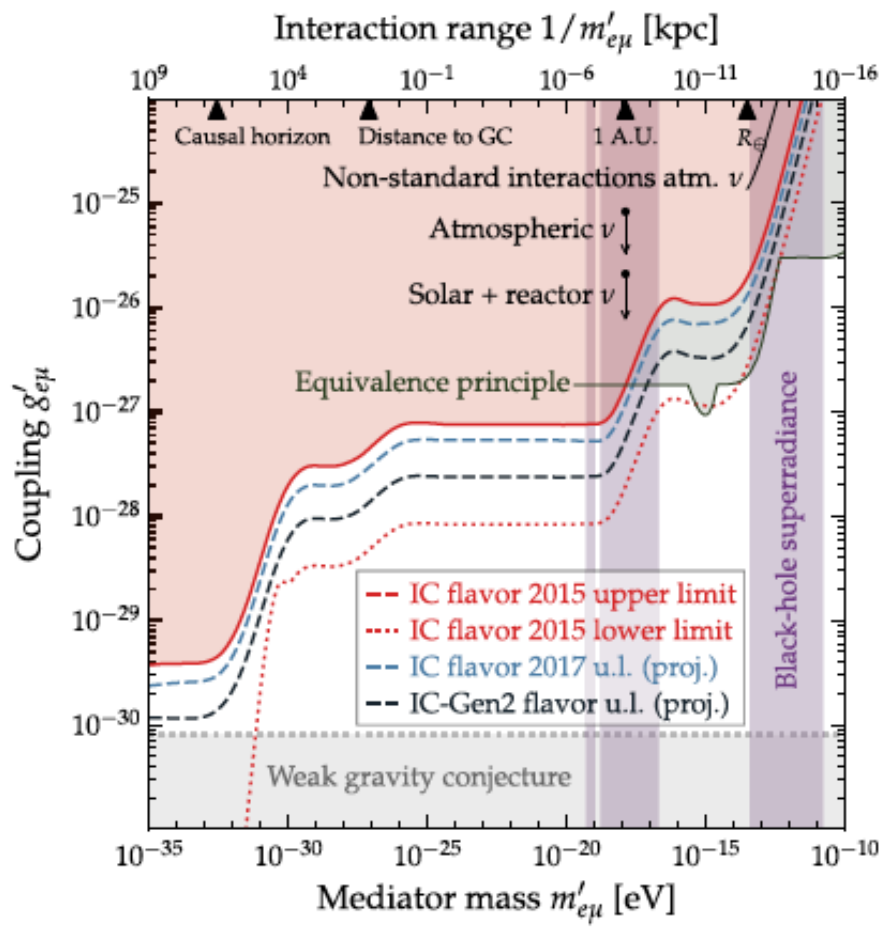
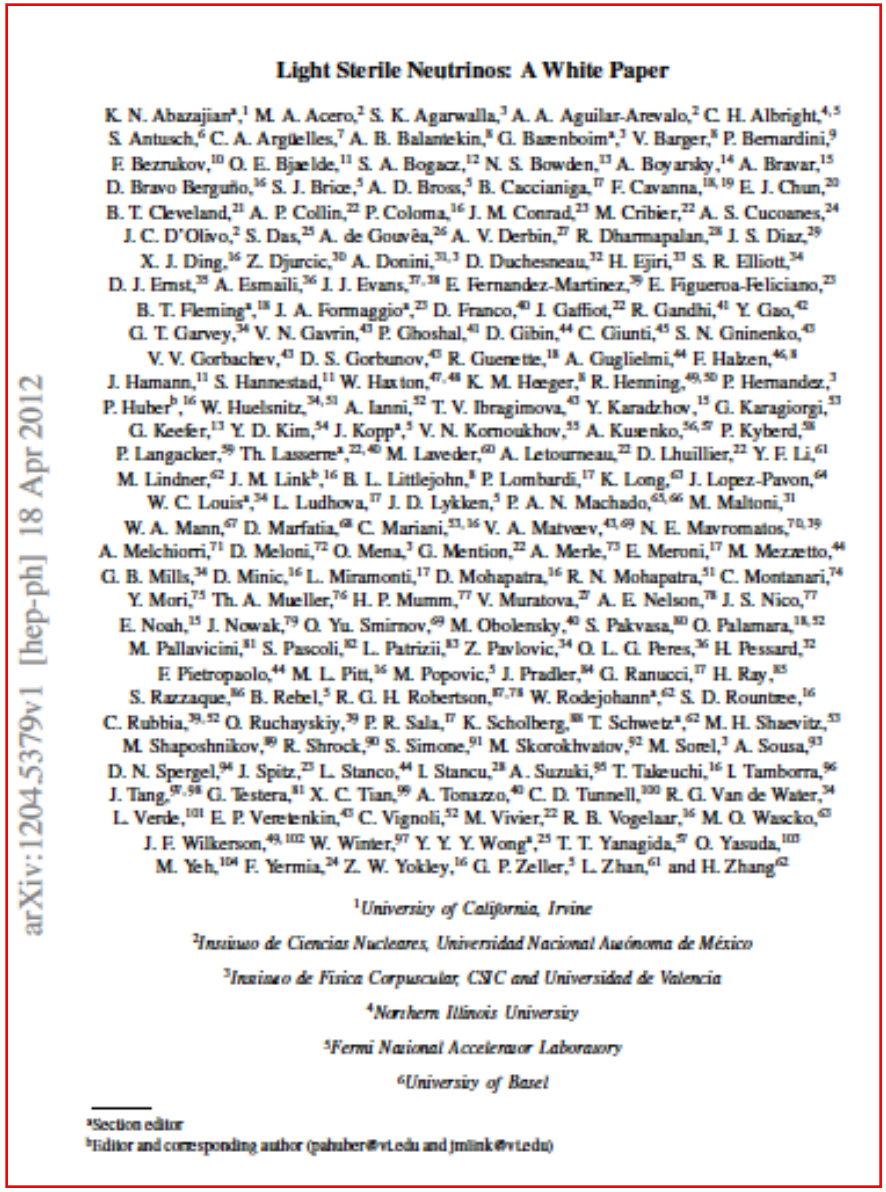
- **Oscillations sensitive to long-ranged flavored interactions between ν & e**
- **$L_e - L_\mu$ or $L_e - L_\tau$ abelian symmetries**
- **Use flavor composition of TeV-PeV astrophysical neutrinos at IceCube**



Huge Electron repositories in the local and distant Universe



Light Sterile Neutrinos: Huge Interest in the Community



Light Sterile Neutrinos: A White Paper

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arXiv:1204.5379v1 [hep-ph] 18 Apr 2012

According to INSPIRE: 799 Citations

Sterile neutrinos: singlets of SU(2) × U(1) gauge group, provide economical extension of the SM

Extensive study of sterile neutrinos at various energy scales

GUT: see-saw models of neutrino mass, leptogenesis

TeV: production at LHC and impact on EWPOs

keV: (warm) dark matter candidates

eV: SBL and LBL oscillation experiments

sub-eV: θ_{13} - reactors and solar neutrinos

Several Anomalies at Short-Baseline Experiments

Long-standing saga of eV-scale anomalies!

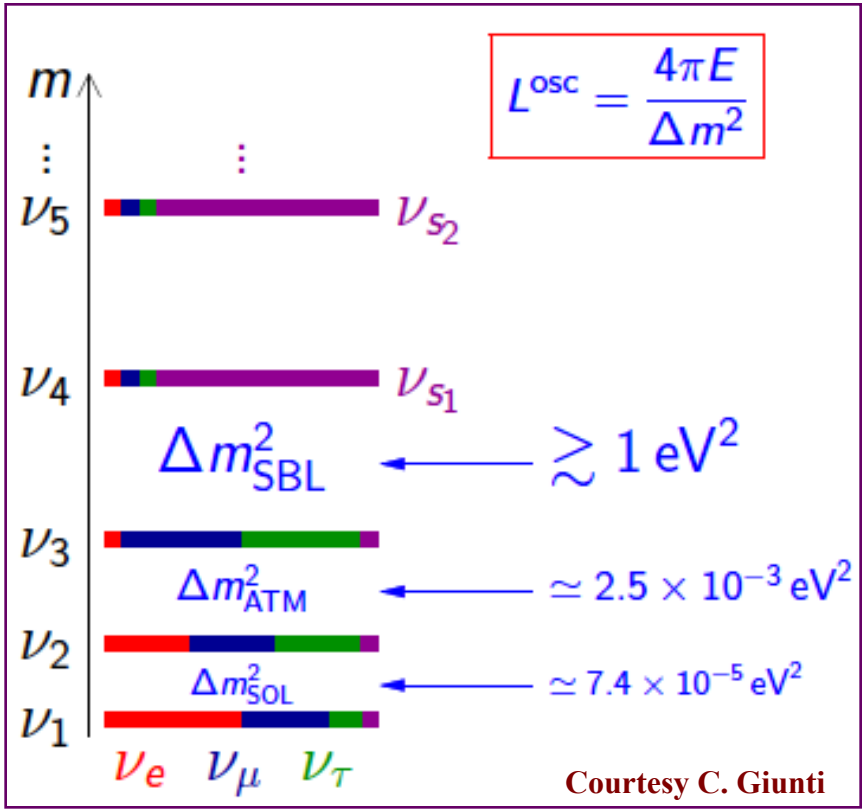
- **LSND: 3.8σ** **[PRD 64 (2001) 22, 112007]**
- **MiniBooNE (combined ν and anti- ν): 4.7σ** **[PRL 121 (2018) 22, 221801]**
- **Reactor Antineutrino Anomaly: 3σ** **[PRD 83 (2011) 073006, PRC 84 (2011) 024617]**
- **Gallium Neutrino Anomaly: 3σ** **[PRC 83 (2011) 065504, PLB 795 (2019) 542]**
- **NEOS: 3σ** **[PRL 118, 121802 (2017)]**
- **DANSS: 2.8σ** **[PLB 787 (2018) 56]**
- **Neutrino-4: 2.8σ** **[JETP Lett. 109 (2019) 4, 213]**

For more on sterile neutrinos, attend the talk by Pedro A.N. Machado

SBL data point towards a light eV-Scale Sterile Neutrino

SBL results hint towards high $\Delta m^2 \approx 0.1 - 10\ eV^2$ oscillation

Require additional neutrinos with masses at eV-scale



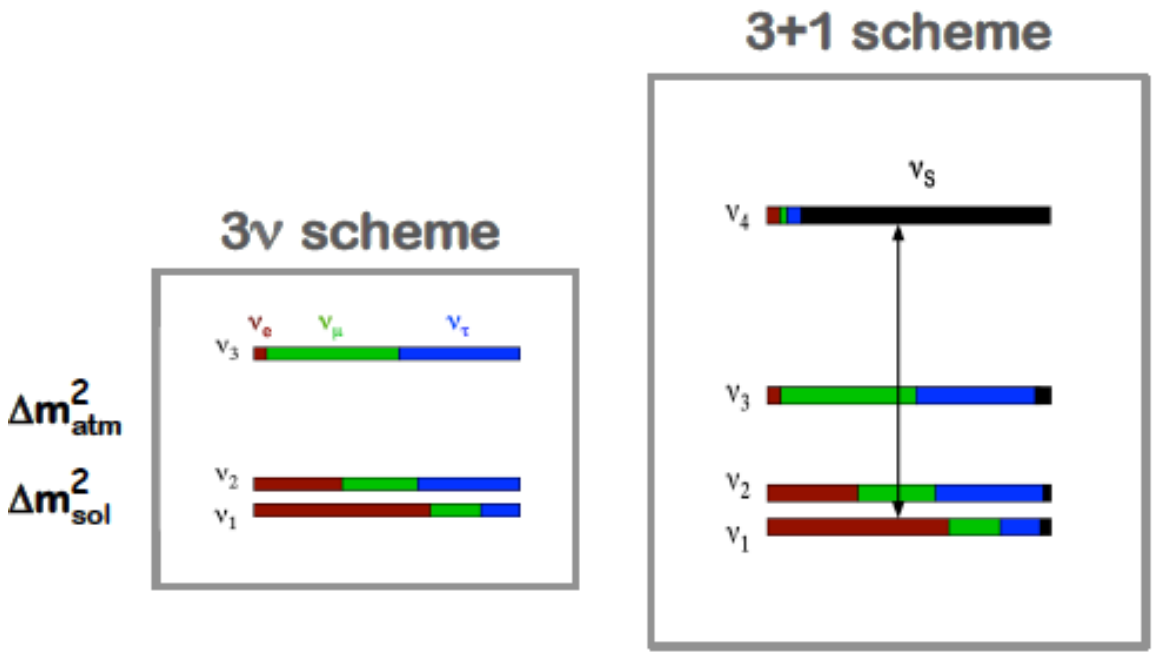
- ν_s : Sterile states (no weak interactions)
- Can feel gravity
- Can affect oscillations through mixing
- Well postulated in see-saw models
- In all these models, sterile neutrinos couple to active neutrinos via Yukawa couplings

Introduce ν_R in the SM: Dirac mass $m_D \overline{\nu_R} \nu_L$ + Majorana mass $m_M \overline{\nu_R^c} \nu_R$

6 massive Majorana neutrinos : $(\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}) + (\nu_{eR}, \nu_{\mu R}, \nu_{\tau R})$

Light left-handed anti-ν_R = Light left-handed sterile neutrino : $\nu_R^c \rightarrow \nu_{sL}$

One Light eV-Scale Sterile Neutrino



$\Delta m^2_{41} \sim 1\ \text{eV}^2$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

Add one sterile ν with three active ones at the eV-scale

Small perturbation of 3ν mixing

$|U_{e4}|^2 << 1,\ |U_{\mu 4}|^2 << 1,\ |U_{\tau 4}|^2 << 1,\ |U_{s4}|^2 \approx 1$

3+1 Short-Baseline Oscillation

Appearance ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- Amplitude of ν_e disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- Amplitude of ν_μ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \simeq 4|U_{\mu 4}|^2$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

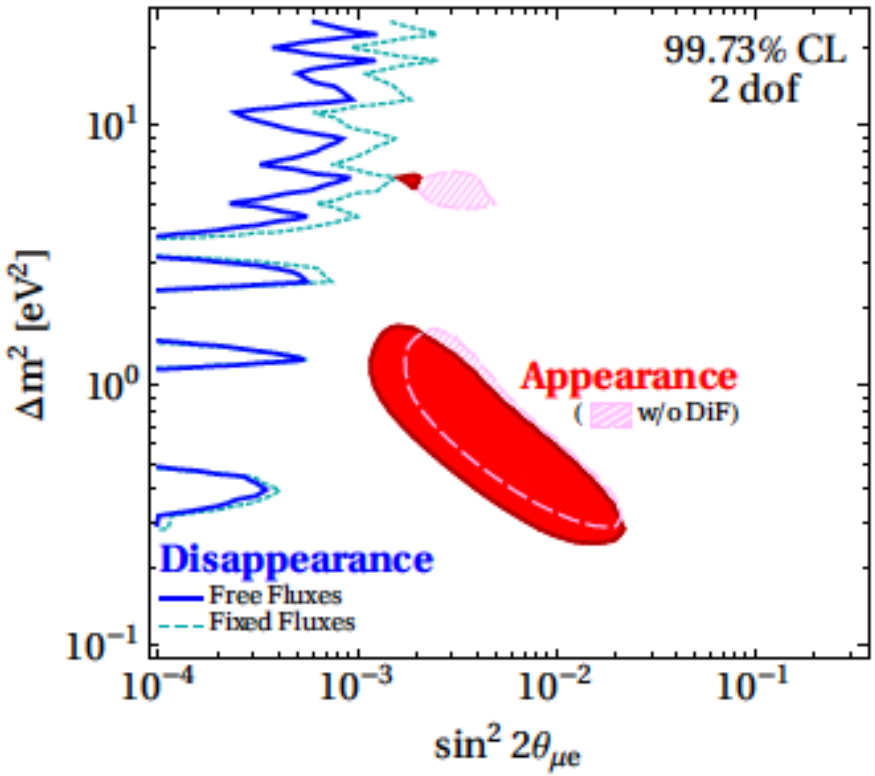
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

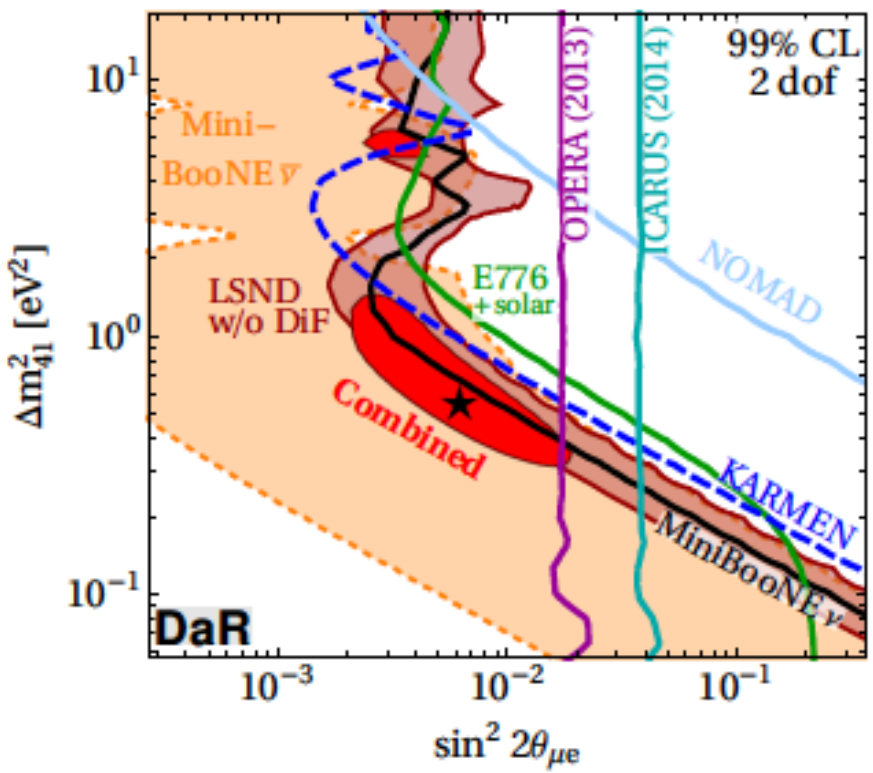
$\Downarrow$

Appearance-Disappearance Tension

See reviews by C. Giunti

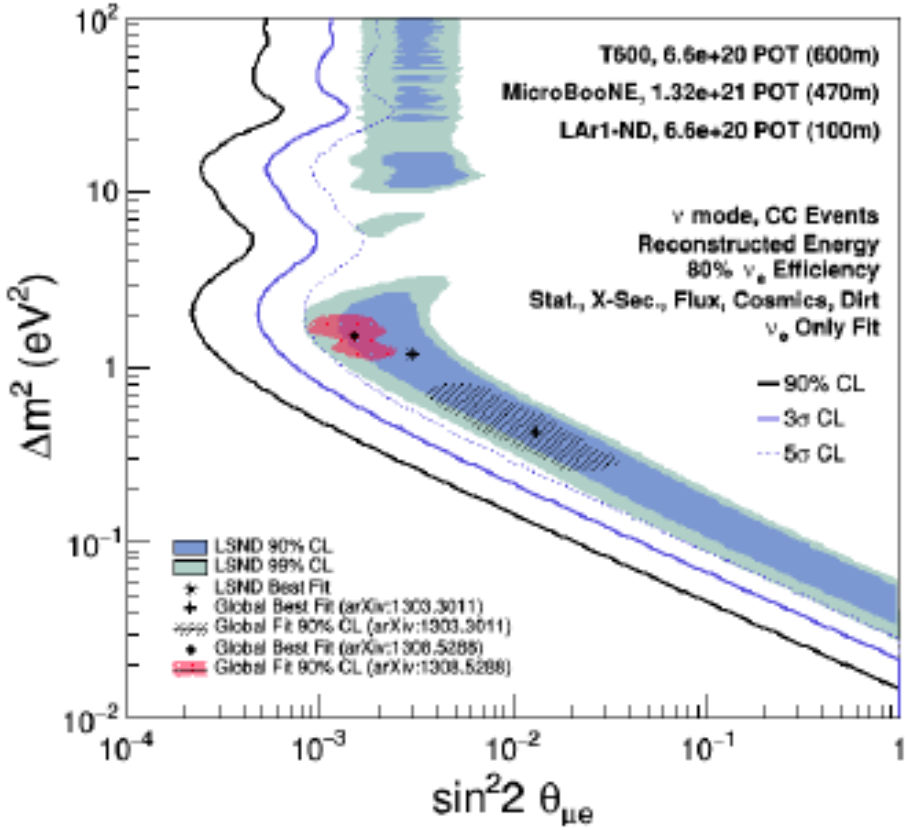
Significant tension between appearance and disappearance results



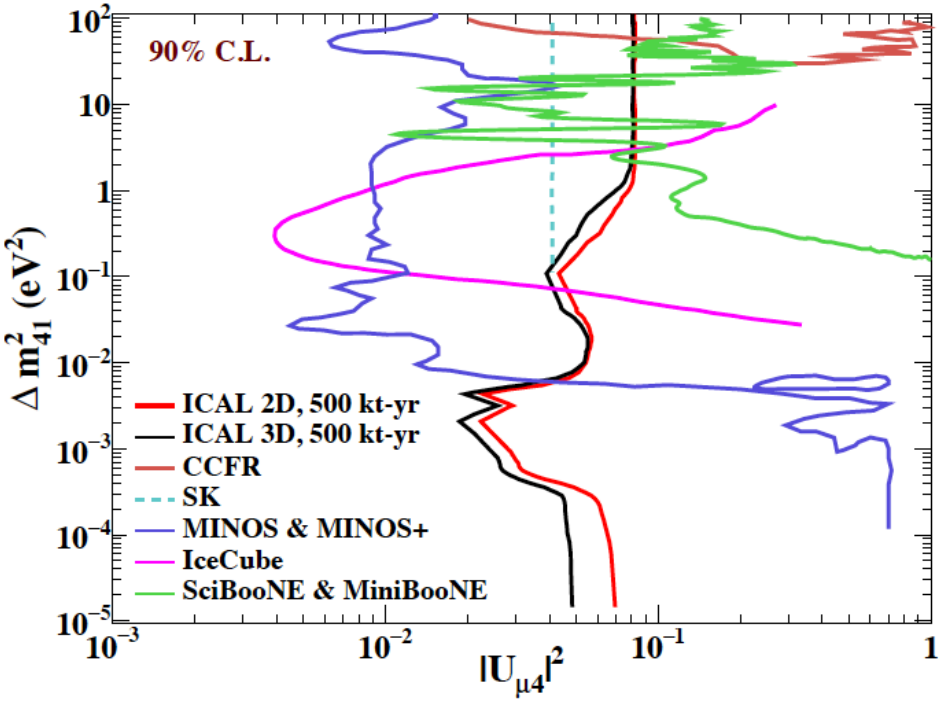


Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, JHEP 08 (2018) 010

Future Facilities to Search for Sterile Neutrino

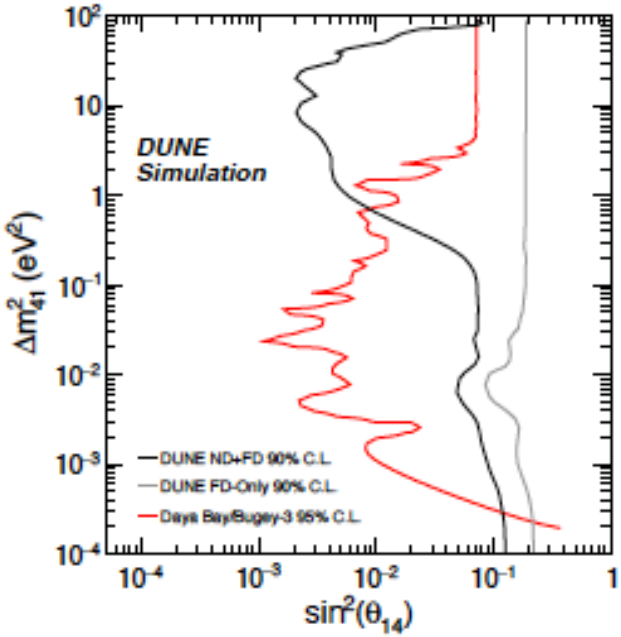


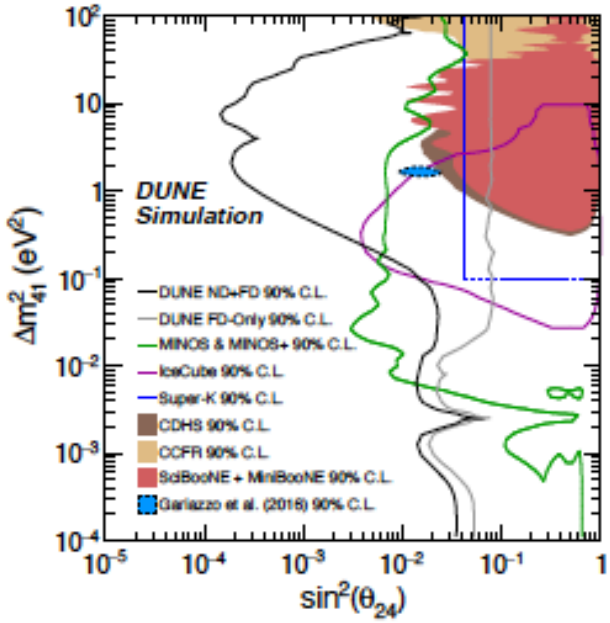
Fermilab SBN Program: 1503.01520

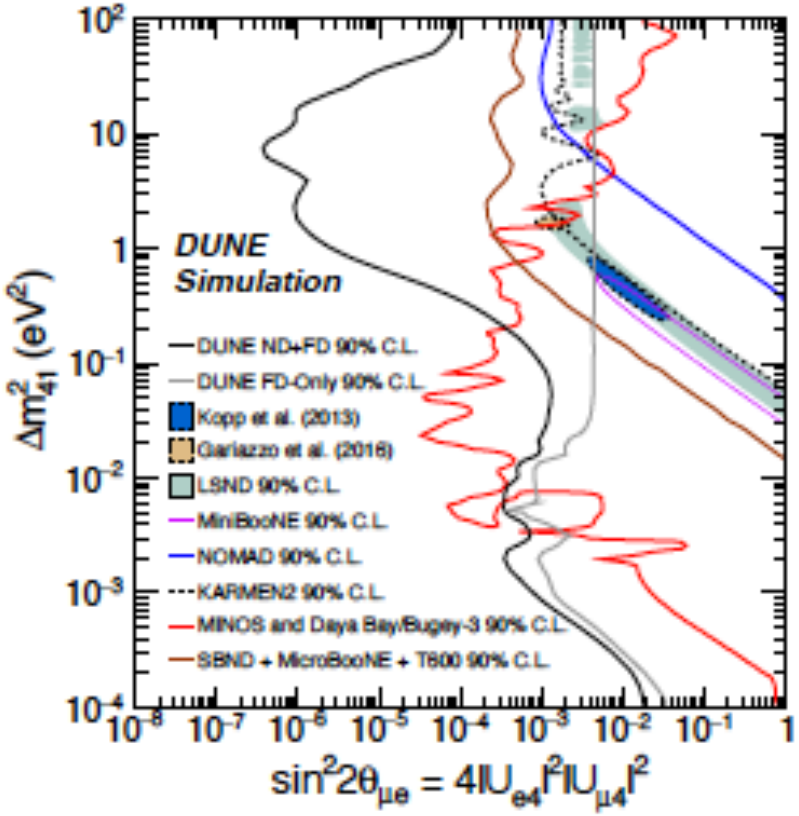


ICAL detector at INO: 1804.09613

Search for Sterile Neutrino @ DUNE







DUNE Physics Volume II, arXiv:2002.03005v2 [hep-ex]

A New Interference term in the 3+1 Scheme

- $\Delta_{14} >> 1$: **fast oscillations are averaged out**

- **But interference of Δ_{14} & Δ_{13} survives and is observable**

$$P^{4\nu}_{\mu e} \simeq P^{\rm ATM} + P^{\rm INT}_{\rm I} + P^{\rm INT}_{\rm II}$$

$$s_{13} \sim s_{14} \sim s_{24} \sim 0.15 \sim \varepsilon$$

$$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$$

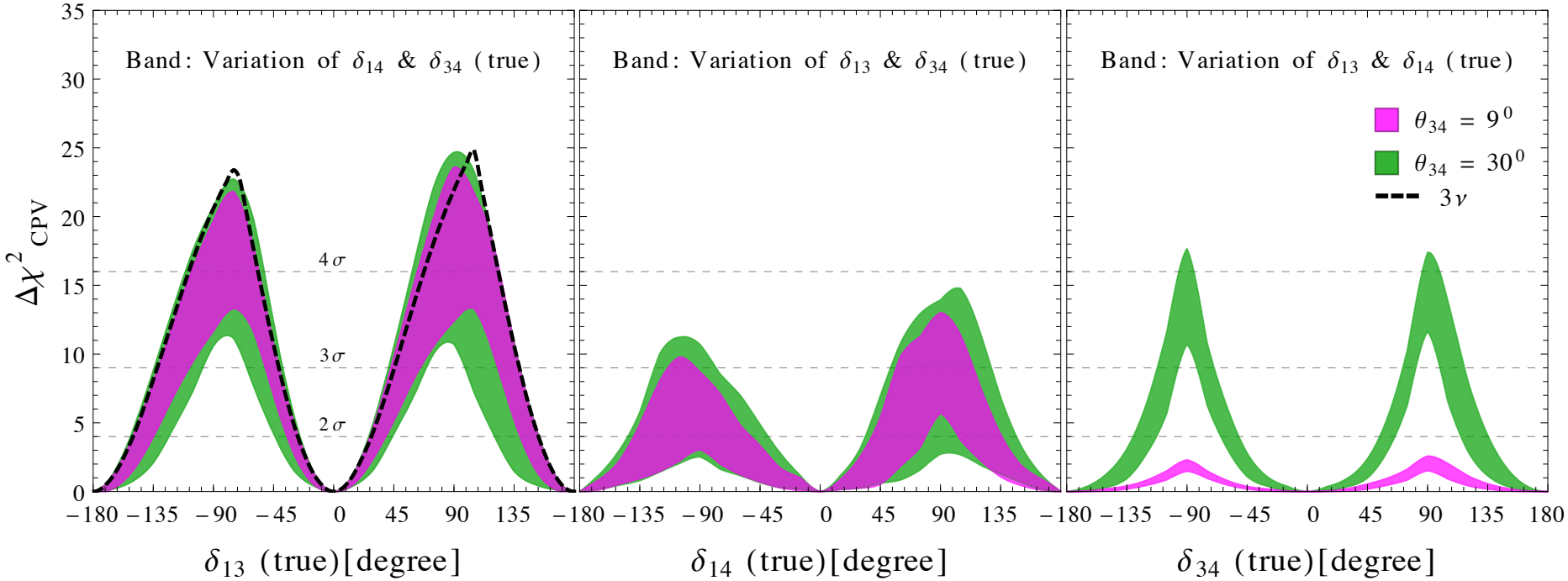
$$\begin{cases} P^{\rm ATM} \simeq 4 s_{23}^2 s_{13}^2 \sin^2\Delta & \sim \varepsilon^2 \\ P^{\rm INT}_{\rm I} \simeq 8 s_{13} s_{23} c_{23} s_{12} c_{12} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) & \sim \varepsilon^3 \\ P^{\rm INT}_{\rm II} \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) & \sim \varepsilon^3 \end{cases}$$

Sensitivity to the new CP-phase δ_{14}

Klop and Palazzo, arXiv:1412.7524v3 [hep-ph]

In vacuum, it is independent of θ_{34} and δ_{34}

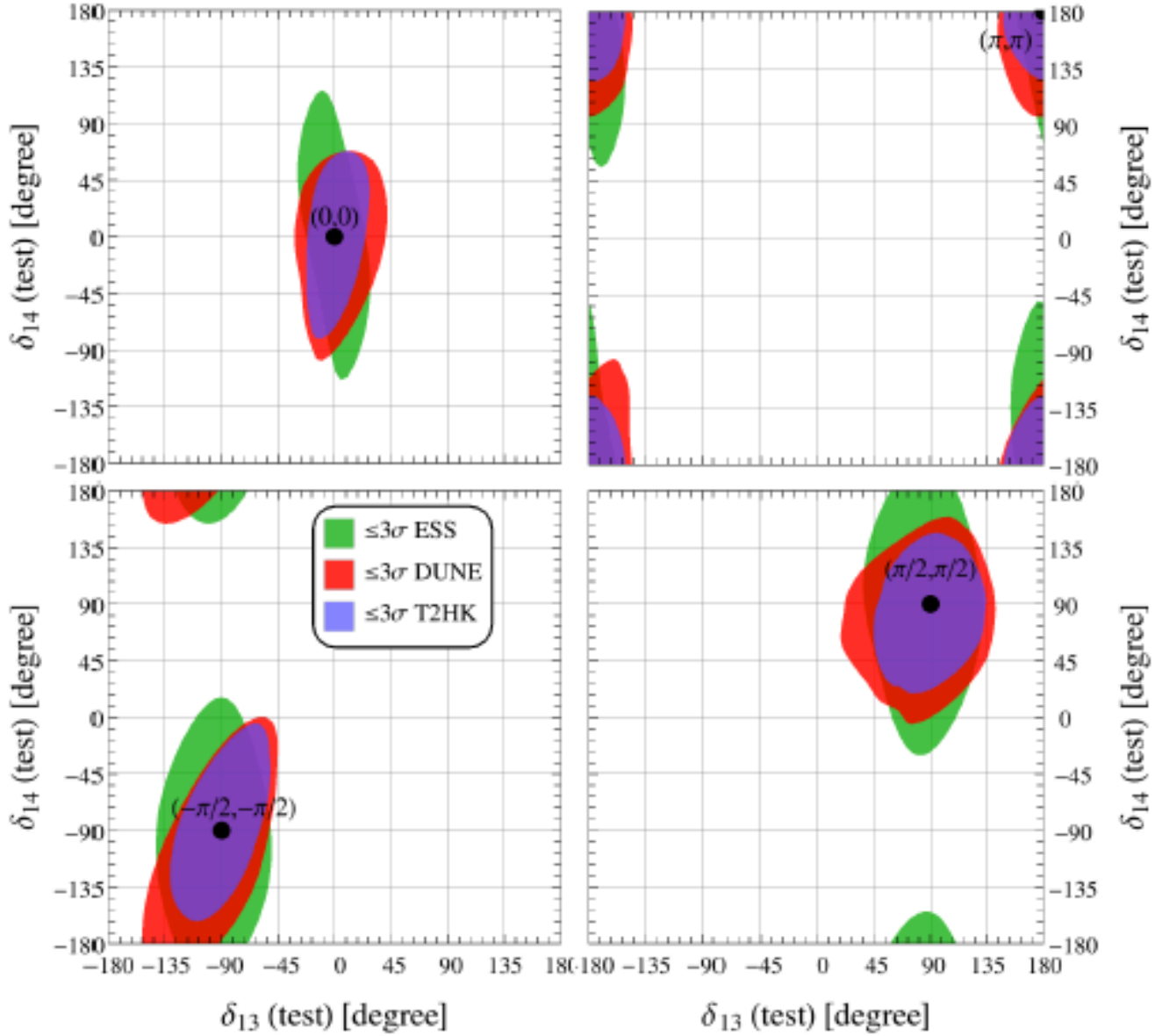
CP violation Searches at DUNE in 3+1 Scheme



Agarwalla, Chatterjee, Palazzo, JHEP 09 (2016) 016

- Sensitivity to CPV induced by δ_{13} reduced in 3+1 scheme
- Potential sensitivity also to the new CP-phases δ_{14} e δ_{34}
- Clear hierarchy in the sensitivity: $\delta_{13}>\delta_{14}>\delta_{34}$ for $\theta_{14}=\theta_{24}=\theta_{34}=9^0$

Reconstruction of CP Phases in LBL Experiments in 3+1 Scheme



Agarwalla, Chatterjee, Palazzo, JHEP 12 (2019) 174

First Study on θ_{23} Octant with Light Sterile Neutrino

PRL 118, 031804 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

Octant of θ_{23} in Danger with a Light Sterile Neutrino

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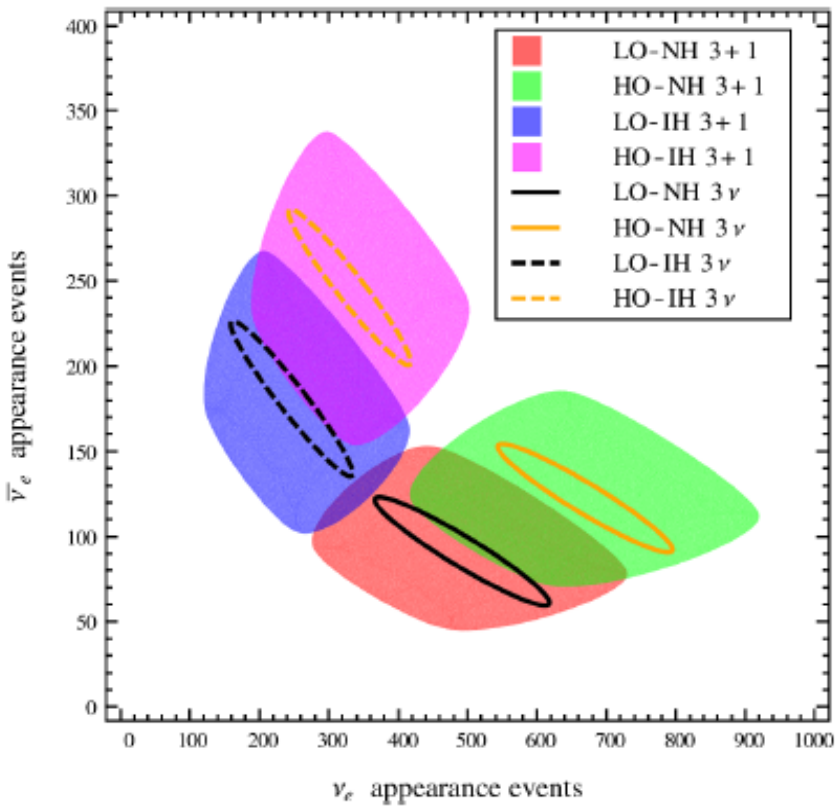
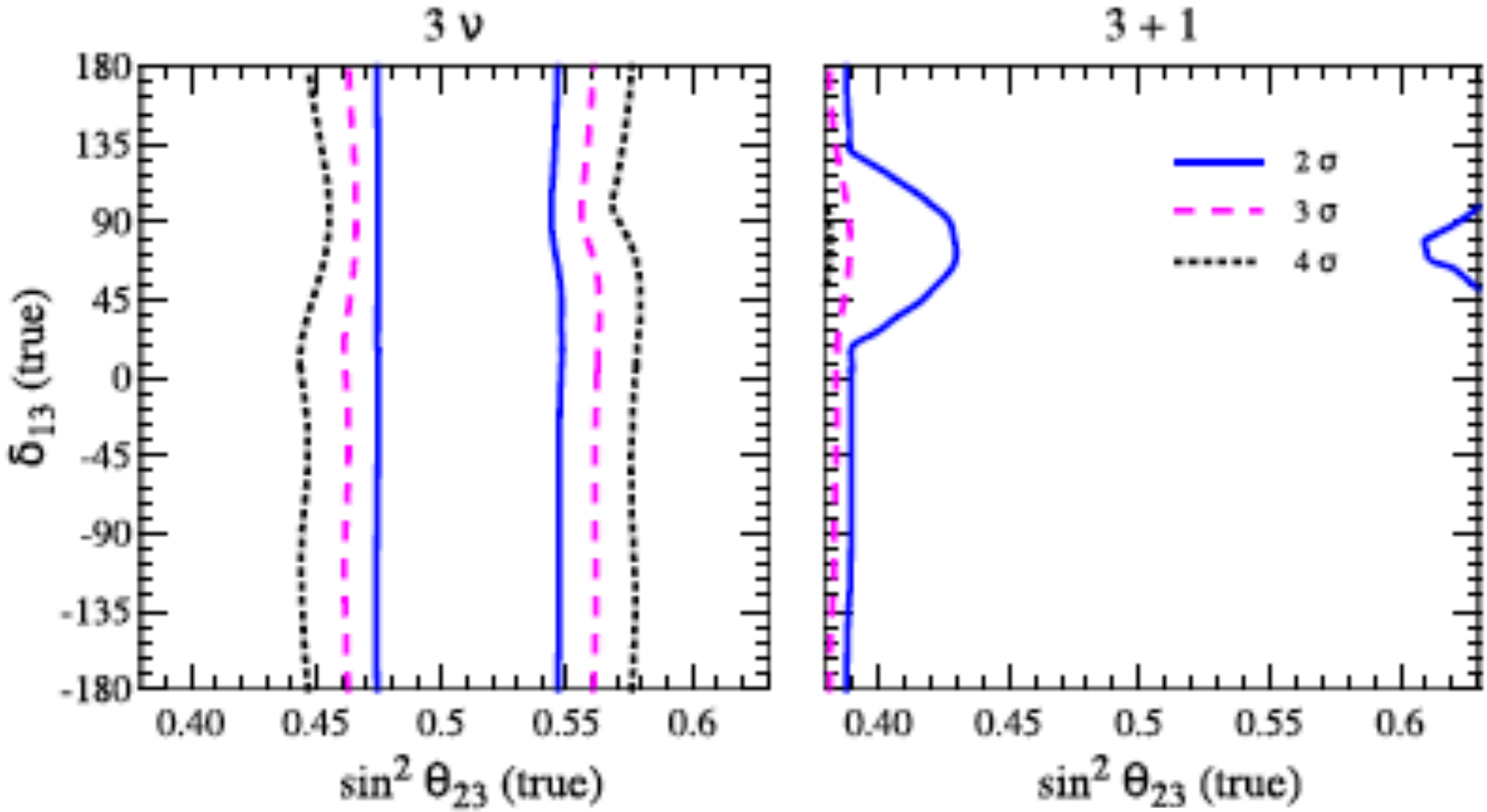


$$\sin^2\theta_{23} = 0.42 \;\; (0.58)$$
LO (HO)

- Three-flavor ellipses due to variation in δ_{13} in [-π to π]
- Four-flavor blobs due to variation in δ_{13} and δ_{14} in [-π to π]
- DUNE Exposure 248 kt.MW.yr

No Knowledge on Octant with a light Sterile ν



$$P_{II}^{INT} \simeq 4\, s_{13}\, s_{23}\, s_{14}\, s_{24} \sin\Delta \sin\left(\Delta + \delta_{13} - \delta_{14}\right)$$

extra degree of freedom

In 3+1, the sensitivity to the octant of θ_{23} gets completely lost.

CPT and Lorentz Symmetry Violation

- **Unified theories, such as string theory, allow for violation of Lorentz symmetry by inducing new spacetime structure at the quantum gravity scale**

- **The direct observation of Lorentz Invariance Violation (LIV) at low-energy would provide access to the Planck-scale (M_p) physics**

☞ **Introduce LIV or CPT violation in the framework**

If one extends the SM to include LIV/CPT-violating terms using the SME framework:

$$H = H_{std} + \frac{p_\lambda}{E}\begin{pmatrix} a^\lambda_{ee} & a^\lambda_{e\mu} & a^\lambda_{e\tau} \\ a^{\lambda *}_{e\mu} & a^\lambda_{\mu\mu} & a^\lambda_{\mu\tau} \\ a^{\lambda *}_{e\tau} & a^{\lambda *}_{\mu\tau} & a^\lambda_{\tau\tau} \end{pmatrix} + \frac{p_\lambda p_\sigma}{E}\begin{pmatrix} c^{\lambda\sigma}_{ee} & c^{\lambda\sigma}_{e\mu} & c^{\lambda\sigma}_{e\tau} \\ c^{\lambda\sigma *}_{e\mu} & c^{\lambda\sigma}_{\mu\mu} & c^{\lambda\sigma}_{\mu\tau} \\ c^{\lambda\sigma *}_{e\tau} & c^{\lambda\sigma *}_{\mu\tau} & c^{\lambda\sigma}_{\tau\tau} \end{pmatrix}$$

here $p_\lambda = (E, \vec{p})$

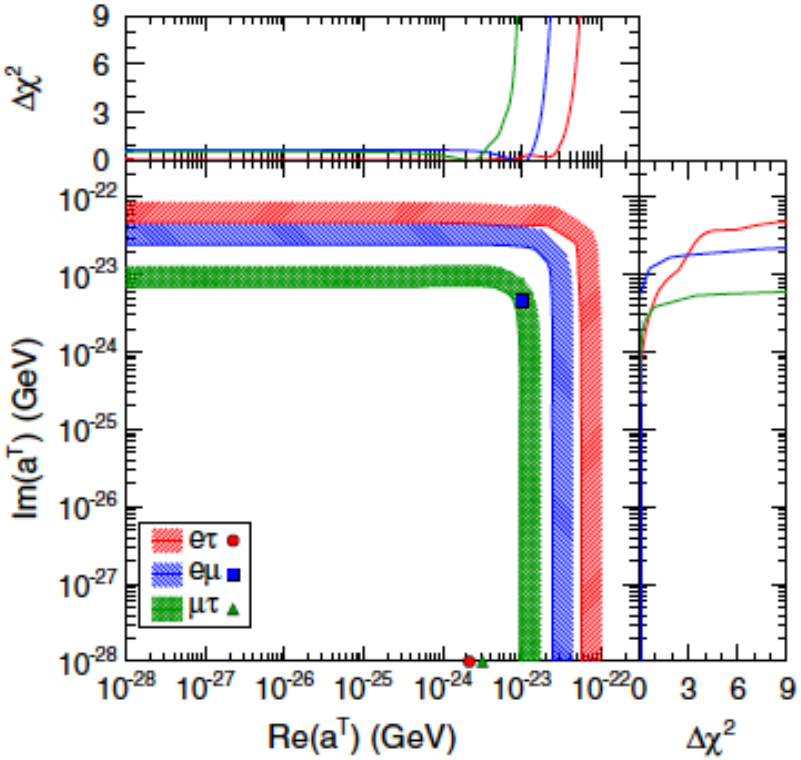
We assume that "a" and "c" only have a time component: $H = H_{std} + \tilde{a}^{\mathsf{T}} + E\tilde{c}^{\mathsf{TT}}$

Kostelecky, Mewes, PRD 69 (2004) 016005

For a comprehensive list of the constraints on all the relevant LIV/CPT-violating parameters, see Kostelecky, Russel, RMP 83 (2011) 11, arXiv:0801.0287v13 [hep-ph]

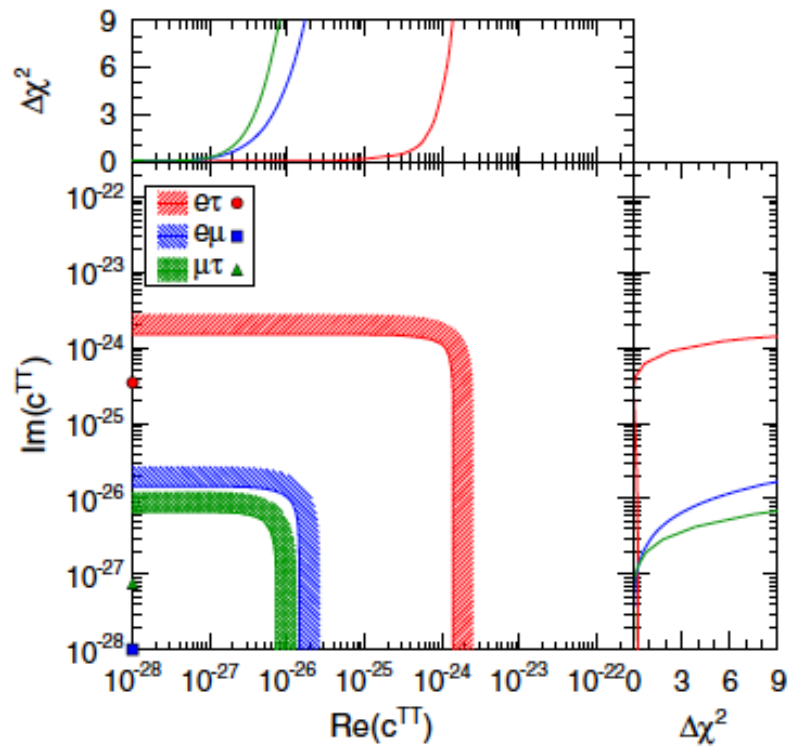
Current Bounds on LIV using Super-K Atmospheric Neutrino Data

PRD 91 (2015) 052003



$$H_{\rm LV} = \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - \frac{4E}{3} \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$

LV Parameter		Limit at 95% C.L.	Best Fit	No LV $\Delta\chi^2$	Previous Limit
$e\mu$	Re (a^T)	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV [58]
	Im (a^T)	1.8×10^{-23} GeV	4.6×10^{-24} GeV		
	Re (c^{TT})	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20} [58]
	Im (c^{TT})	8.0×10^{-27}	1.0×10^{-28}		
$e\tau$	Re (a^T)	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV [59]
	Im (a^T)	2.8×10^{-23} GeV	1.0×10^{-28} GeV		
	Re (c^{TT})	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17} [59]
	Im (c^{TT})	1.0×10^{-24}	3.5×10^{-25}		
$\mu\tau$	Re (a^T)	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	–
	Im (a^T)	5.1×10^{-24} GeV	1.0×10^{-28} GeV		
	Re (c^{TT})	4.4×10^{-27}	1.0×10^{-28}	0.1	–
	Im (c^{TT})	4.2×10^{-27}	7.5×10^{-28}		



Current Bounds on LIV using IceCube Atmospheric Neutrino Data

nature physics

ARTICLES

https://doi.org/10.1038/s41567-018-0172-2

Neutrino interferometry for high-precision tests of Lorentz symmetry with IceCube

The IceCube Collaboration*

Lorentz symmetry is a fundamental spacetime symmetry underlying both the standard model of particle physics and general relativity. This symmetry guarantees that physical phenomena are observed to be the same by all inertial observers. However, unified theories, such as string theory, allow for violation of this symmetry by inducing new spacetime structure at the quantum gravity scale. Thus, the discovery of Lorentz symmetry violation could be the first hint of these theories in nature. Here we report the results of the most precise test of spacetime symmetry in the neutrino sector to date. We use high-energy atmospheric neutrinos observed at the IceCube Neutrino Observatory to search for anomalous neutrino oscillations as signals of Lorentz violation. We find no evidence for such phenomena. This allows us to constrain the size of the dimension-four operator in the standard-model extension for Lorentz violation to the 10^{-28} level and to set limits on higher-dimensional operators in this framework. These are among the most stringent limits on Lorentz violation set by any physical experiment.

Very small violations of Lorentz symmetry, or Lorentz violation (LV), are allowed in many ultrahigh-energy theories, including string theory[1], non-commutative field theory[2] and supersymmetry[3]. The discovery of LV could be the first indication of such new physics. Worldwide efforts are therefore underway to search for evidence of LV. The standard-model extension (SME) is an effective-field-theory framework to systematically study LV[4]. The SME includes all possible types of LV that respect other symmetries of the standard model such as energy–momentum conservation and coordinate independence. Thus, the SME can provide a framework to compare results of LV searches from many different fields such as photons[5–8], nucleons[8–11], charged leptons[12–14] and gravity[15]. Recently, neutrino experiments have performed searches for LV[16–18]. So far, all searches have obtained null results. The full list of existing limits from all sectors and a brief overview of the field are available elsewhere[19,20]. Our focus here is to present the most precise test of LV in the neutrino sector.

The fact that neutrinos have mass has been established by a series of experiments[21–26]. The field has incorporated these results into the neutrino standard model (νSM)—the standard model with three massive neutrinos. Although the νSM parameters are not yet fully determined[27], the model is rigorous enough to be brought to bear on the question of LV. In the Methods, we briefly review the history of neutrino oscillation physics and tests of LV with neutrinos.

To date, neutrino masses have proved to be too small to be measured kinematically, but the mass differences are known via neutrino oscillations. This phenomenon arises from the fact that production and detection of neutrinos involves the flavour states, while the propagation is given by the Hamiltonian eigenstates. Thus, a neutrino with flavour $|\nu_\alpha\rangle$ can be written as a superposition of Hamiltonian eigenstates $|\nu_i\rangle$; that is, $|\nu_\alpha\rangle = \sum_{i=1}^{3} V_{\alpha i}(E)|\nu_i\rangle$, where V is the unitary matrix that diagonalizes the Hamiltonian and, in general, is a function of neutrino energy E. When the neutrino travels in vacuum without new physics, the Hamiltonian depends only on the neutrino masses, and the Hamiltonian eigenstates coincide with the mass eigenstates. That is, $H=\frac{1}{2E}U^\dagger \mathrm{diag}(m_1^2, m_2^2, m_3^2)U=\frac{m^2}{2E}$, where m_i are the neutrino masses and U is the Pontecorvo–Maki–Nakagawa–Sakata matrix that diagonalizes the mass matrix m (ref. [27]).

A consequence of the flavour misalignment is that a neutrino beam that is produced purely of one flavour will evolve to produce other flavours. Experiments measure the number of neutrinos of different flavours, observed as a function of the reconstructed energy of the neutrino, E, and the distance the beam has travelled, L. The microscopic neutrino masses are directly tied to the macroscopic neutrino oscillation length. In this sense, neutrino oscillations are similar to photon interference experiments in their ability to probe very small scales in nature.

Lorentz-violating neutrino oscillations

Here, we use neutrino oscillations as a natural interferometer with a size equal to the diameter of Earth. We look for anomalous flavour-changing effects caused by LV that would modify the observed energy and zenith angle distributions of atmospheric muon neutrinos observed in the IceCube Neutrino Observatory[28] (see Fig. 1). Beyond flavour change due to small neutrino masses, any hypothetical LV fields could contribute to muon neutrino flavour conversion. We therefore look for distortion of the expected muon neutrino distribution. As this analysis does not distinguish between a muon neutrino (ν_μ) and its antineutrino ($\bar{\nu}_\mu$), when the word 'neutrino' is used, we are referring to both.

Past searches for LV have mainly focused on the directional effect in the Sun-centred celestial-equatorial frame[19] by looking only at the time dependence of physics observables as direction-dependent physics appears as a function of Earth's rotation. However, in our case, we assume no time dependence, and instead look at the energy distribution distortions caused by direction- and time-independent isotropic LV. Isotropic LV may be a factor ~10^3 larger than direction-dependent LV in the Sun-centred celestial-equatorial frame if we assume that the new physics is isotropic in the cosmic microwave background frame[20]. It would be most optimal to simultaneously look for both effects, but our limited statistics do not allow for this.

*A full list of authors and affiliations appears in the online version of this paper.

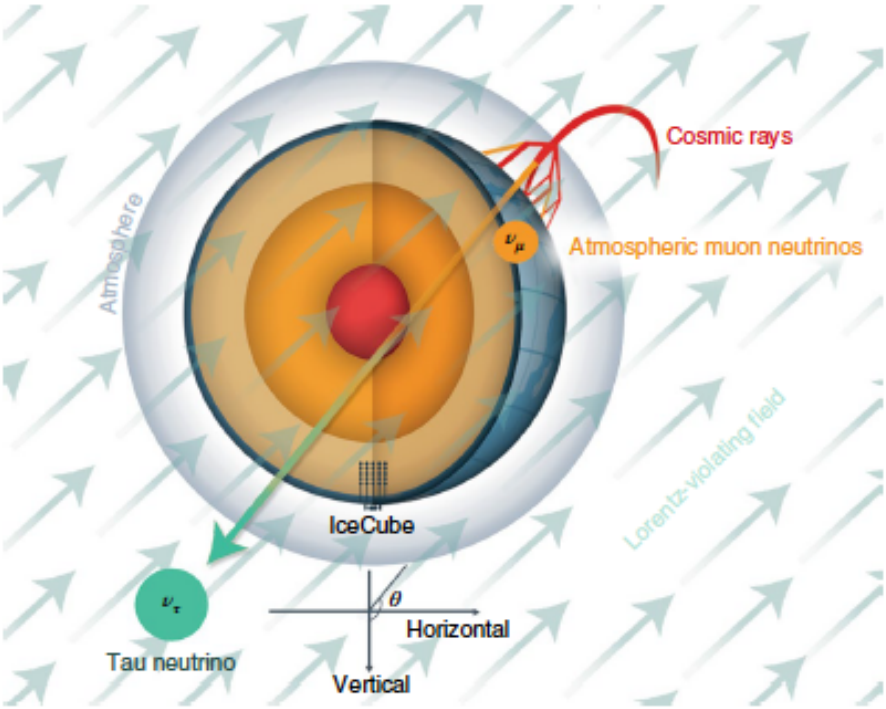
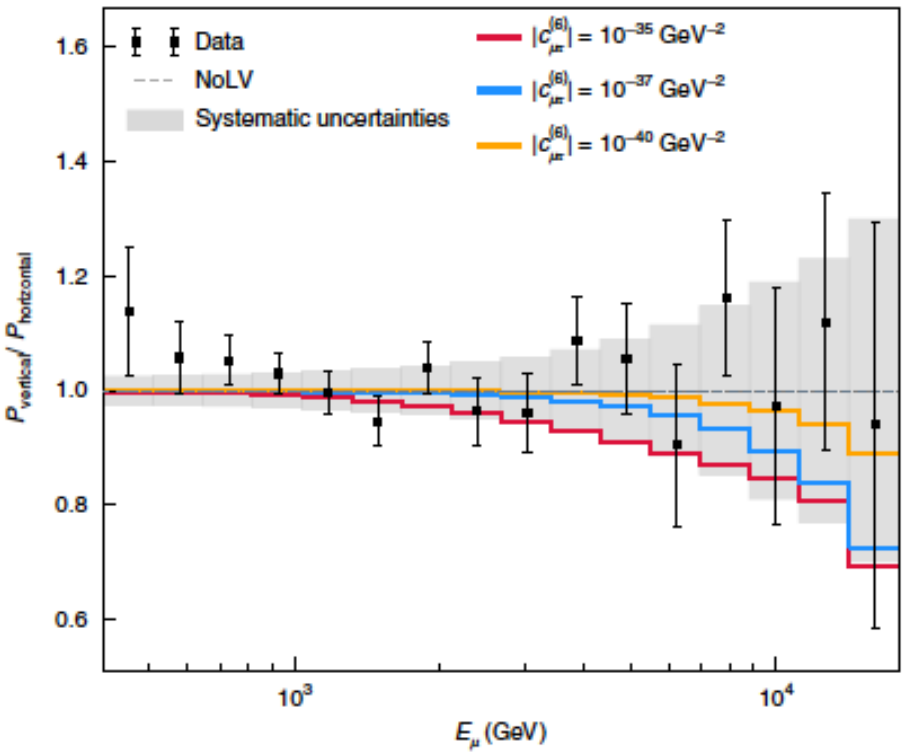
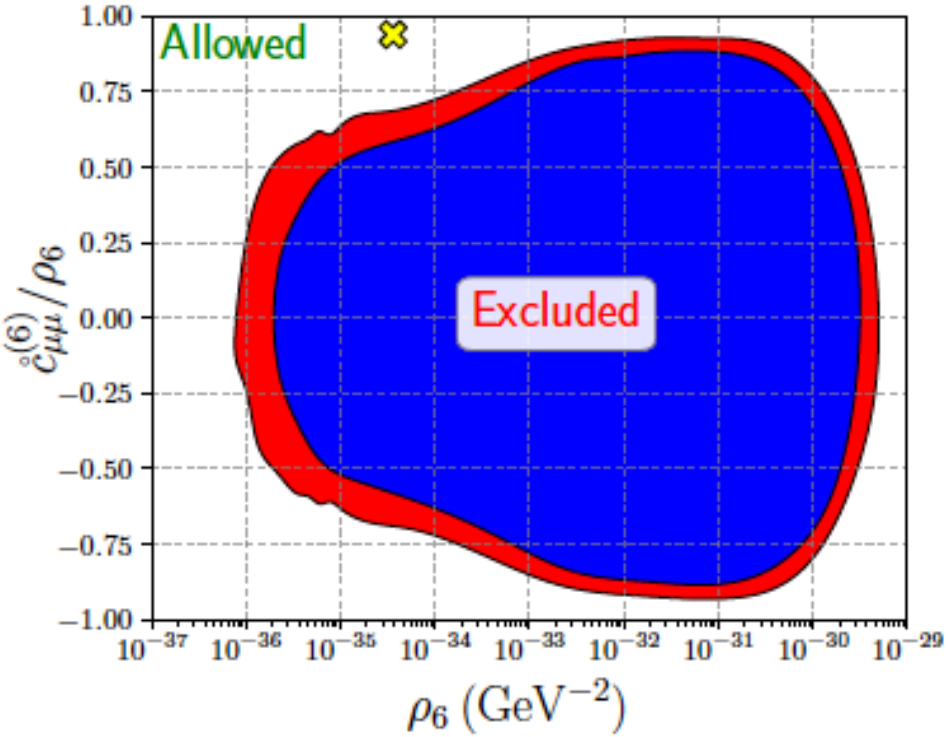


Fig. 1 | Test of LV with atmospheric neutrinos. Muon neutrinos are produced in the upper atmosphere by the collisions of cosmic rays with air molecules. These atmospheric muon neutrinos pass through the entire Earth and are then detected by IceCube in Antarctica. The LV, indicated by arrows, permeates space and could induce an anomalous neutrino oscillation to tau neutrinos. Therefore, a potential signal of LV is the anomalous disappearance of muon neutrinos. Note, here we test only the isotropic component.

2 years of IceCube data ~ 35,000 atmospheric muon neutrino events with E < 20 TeV and -1<cosθ<0.2

Current Bounds on LIV using IceCube Atmospheric Neutrino Data





Effective Hamiltonian derived from the Standard Model Extension

$$H \approx \frac{m^2}{2E} + \mathring{a}^{(3)} - E\mathring{c}^{(4)} + E^2\mathring{a}^{(5)} - E^3\mathring{c}^{(6)} \cdots$$

$$\mathring{c}^{(6)} = \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

$$P(\nu_\mu \to \nu_\tau) \sim \left(1 - \frac{[\mathring{a}^{(d)}_{\mu\mu} - \mathring{c}^{(d)}_{\mu\mu}]^2}{\rho_d^2}\right) \sin^2(L\rho_d \cdot E^{d-3}) = \frac{\left|\mathring{a}^{(d)}_{\mu\tau} - \mathring{c}^{(d)}_{\mu\tau}\right|^2}{\rho_d^2} \sin^2(L\rho_d \cdot E^{d-3}).$$

$$\rho_6 \equiv \sqrt{(\mathring{c}^{(6)}_{\mu\mu})^2 + \mathrm{Re}(\mathring{c}^{(6)}_{\mu\tau})^2 + \mathrm{Im}(\mathring{c}^{(6)}_{\mu\tau})^2}$$

× marks the best-fit point: compatible with the absence of LIV

Wilk's theorem with 3 d.o.f. used

Red (Blue): 90% (99%) C.L. exclusion regions

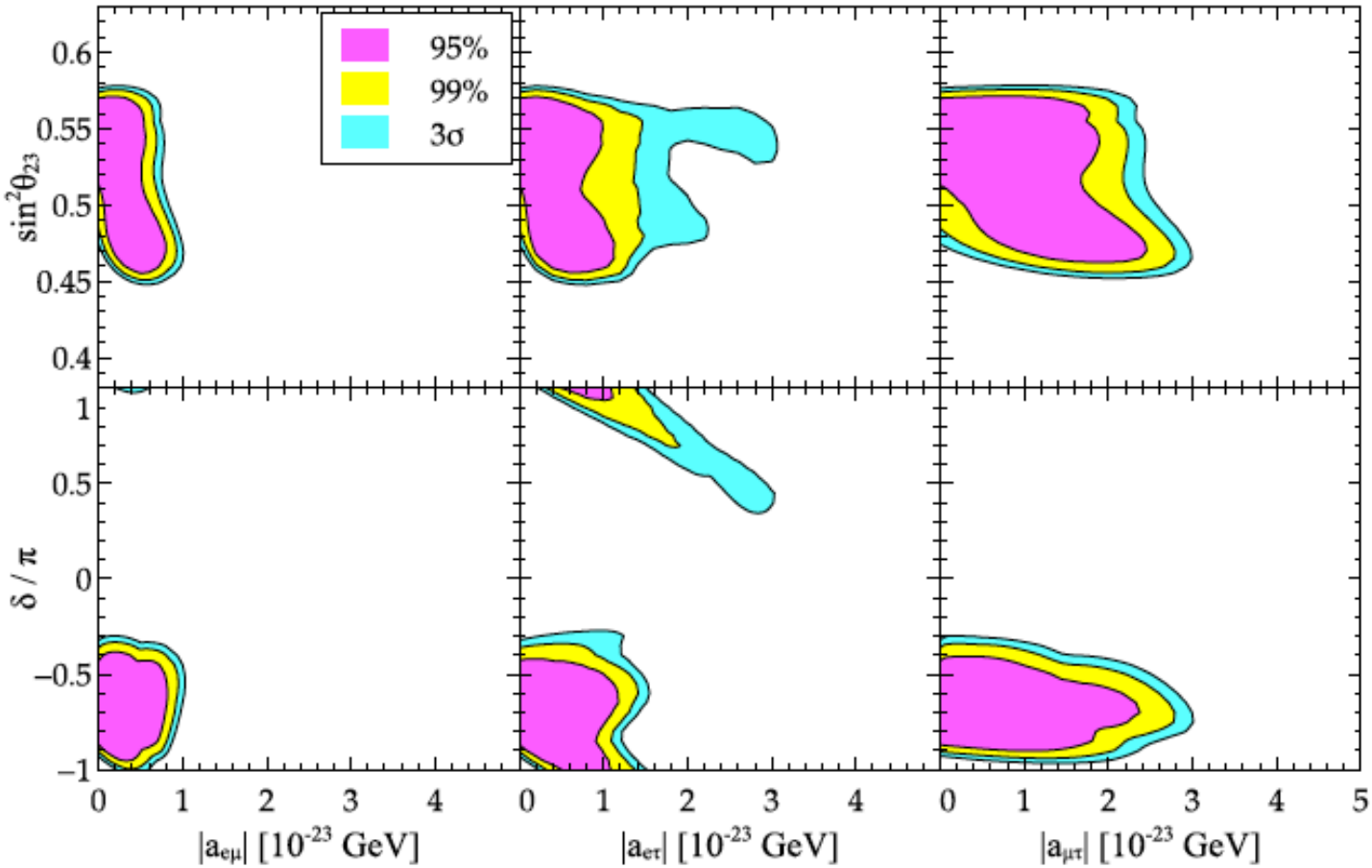
Current Bounds on LIV using IceCube Atmospheric Neutrino Data

dim.	method	type	sector	limits	ref.
3	CMB polarization	astrophysical	photon	$\sim 10^{-43}$ GeV	[5]
	He-Xe comagnetometer	tabletop	neutron	$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron	$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon	$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$ $< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-38}$	[6]
	Laser interferometer	LIGO	photon	$\sim 10^{-22}$	[7]
	Sapphire cavity oscillator	tabletop	photon	$\sim 10^{-18}$	[8]
	Ne-Rb-K comagnetometer	tabletop	neutron	$\sim 10^{-29}$	[11]
	trapped Ca^{+} ion	tabletop	electron	$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$ $< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-34}$ GeV^{-1}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$ $< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon	$\sim 10^{-31}$ GeV^{-2}	[6]
	ultra-high-energy cosmic ray	astrophysical	proton	$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{\delta}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{\delta}^{(6)}_{\mu\tau})\rvert$ $< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon	$\sim 10^{-28}$ GeV^{-3}	[6]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$ $< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity	$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$ $< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

Very strong limits on LIV induced by dimension-six operators!

Exploring Intrinsic LIV @ DUNE

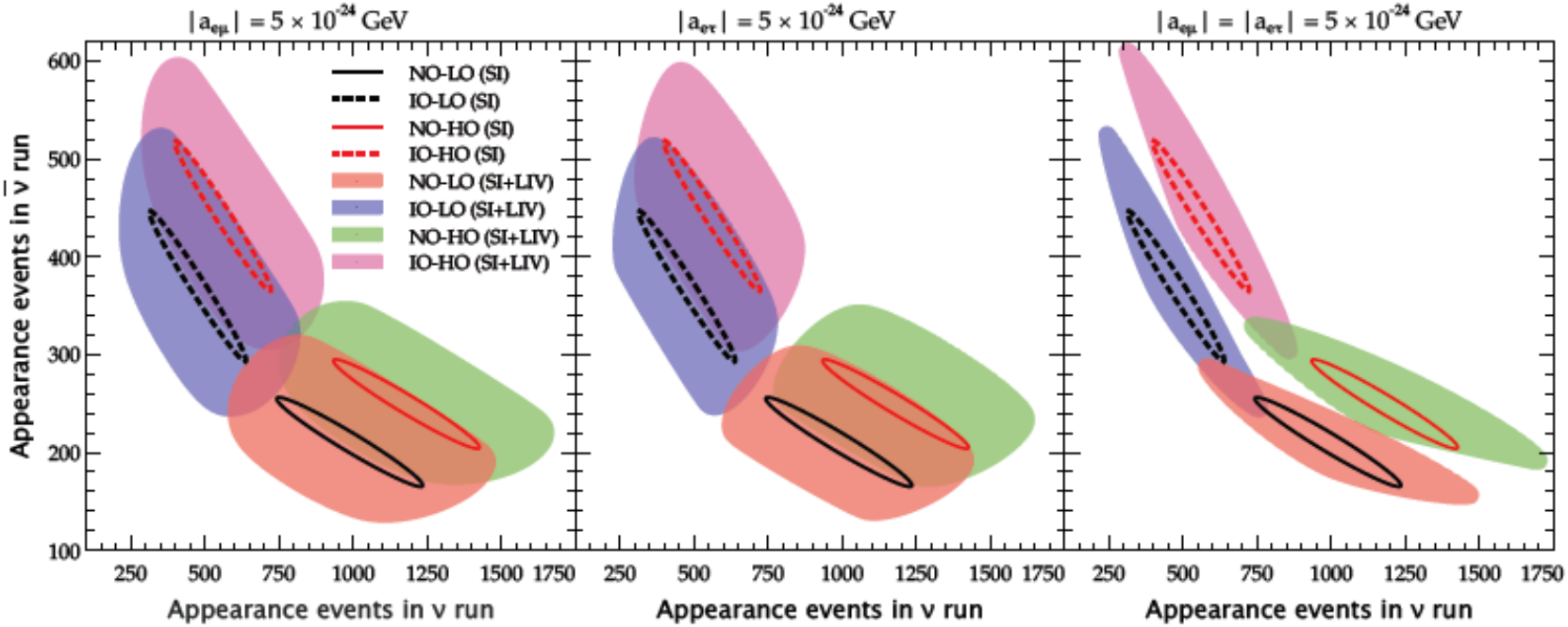


Parameter	Existing Bounds	This work
$\lvert a_{e\mu}\rvert$ [GeV]	2.5×10^{-23} [11]	7.0×10^{-24}
$\lvert a_{e\tau}\rvert$ [GeV]	5.0×10^{-23} [11]	1.0×10^{-23}
$\lvert a_{\mu\tau}\rvert$ [GeV]	8.3×10^{-24} [11]	1.7×10^{-23}

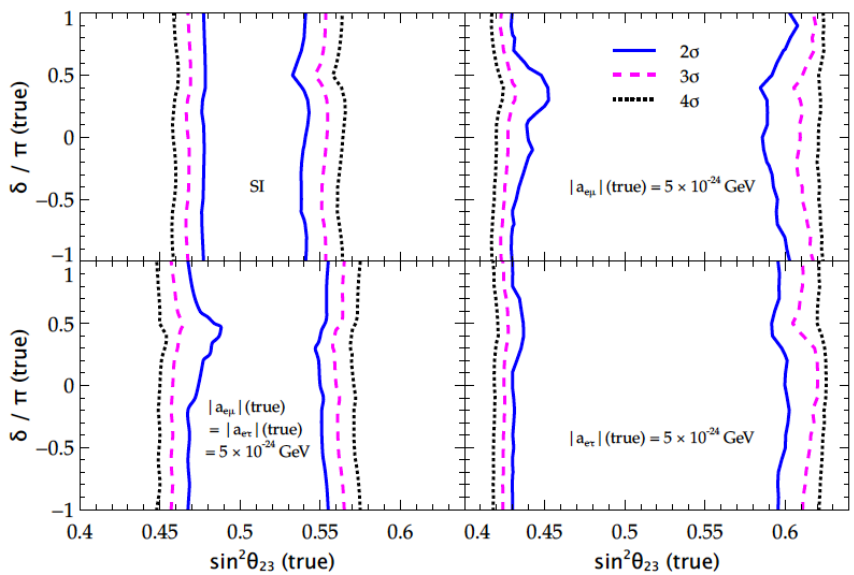
Berenboim, Masud, Ternes, Tortola, PLB 788 (2019) 308

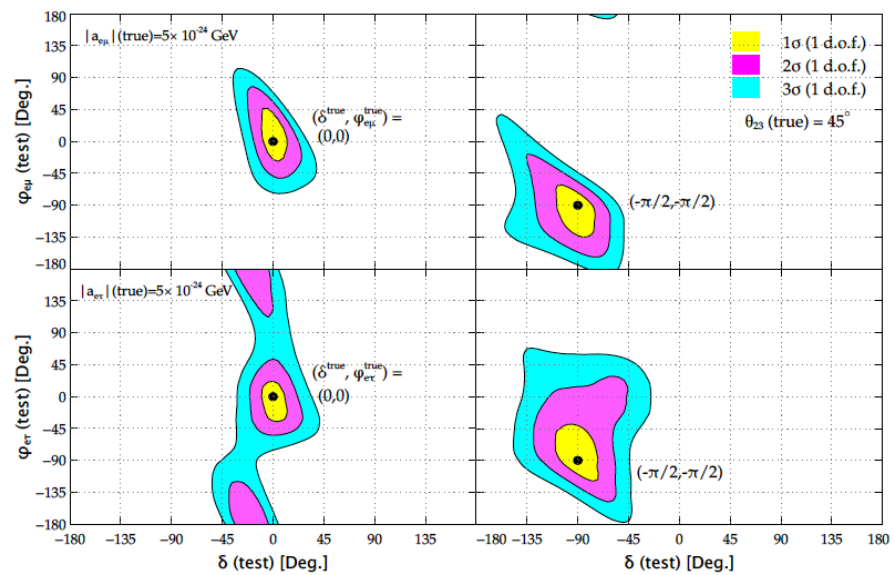
Ref. [11]: Super-K (1410.4267)

Can LIV affect the Sensitivity of DUNE?



Agarwalla, Masud, 1912.13306 [hep-ph]



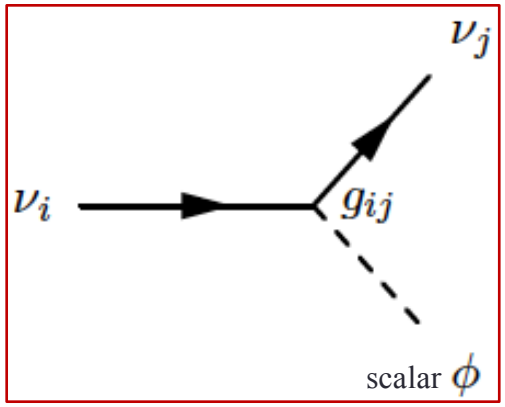


Neutrino Decays (Visible and Invisible)

- **Various new physics models predict neutrino decay**

$$\mathcal{L} \supset g_{ij}\bar{\nu}_j\nu_i\phi + h_{ij}\bar{\nu}_j i\gamma_5\nu_i\phi + \text{h.c.}$$

Chikashige, Mohapatra, Peccei, PLB 98 (1981) 265
Gelmini, Roncadelli, PLB 99 (1981) 411; Gelmini, Valle, PLB 142 (1984) 181



- **Invisible decay:** either the decay products are sterile neutrinos, or have sufficiently low energy avoiding detection
- **Visible decay:** involves regeneration of lower energy neutrinos and provides additional detection signatures

- Invisible decay: $\nu_3 \rightarrow$ sterile neutrino + Majoron ($m_\phi \lesssim m_\nu$)

$$P^{2G}_{\mu\mu} = \left[\cos^2\theta_{23} + \sin^2\theta_{23}\exp(-m_3L/\tau_3E)\right]^2 - \sin^2 2\theta_{23}\exp(-m_3L/\tau_3E)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

☞ **Existing bounds:**

- Super-Kamiokande + K2K + MINOS:
  $\tau_3/m_3 > 2.9 \times 10^{-10}$ s/eV at 90% C.L.
  Gonzalez-Garcia, Maltoni, PLB 663 (2008) 405
- T2K + MINOS:
  $\tau_3/m_3 > 2.8 \times 10^{-12}$ s/eV at 90% C.L.
  Gomes, Gomes, Peres, PLB 740 (2015) 345

Neutrino Decays (Visible and Invisible)

☞ Expected bounds:

- T2K + NOvA:
  $\tau_3/m_3 > 1.5 \times 10^{-12}$ s/eV at 3σ C.L.
  Choubey, Dutta, Pramanik, JHEP 08 (2018) 141
- ICAL@INO (500 kt·yr exposure):
  $\tau_3/m_3 > 1.51 \times 10^{-10}$ s/eV at 90% C.L.
  Choubey, Goswami, Gupta, Lakshmi, Thakore PRD 97 (2018) 3, 033005
- DUNE (40 kt, 5 yr ν + 5 yr anti- ν):
  $\tau_3/m_3 > 4.5 \times 10^{-11}$ s/eV at 90% C.L. for NO
  Choubey, Goswami, Pramanik, JHEP 02 (2018) 055
- KM3NeT-ORCA (after 10 years of run):
  $\tau_3/m_3 > 2.5 \times 10^{-10}$ s/eV at 90% C.L.
  de Salas, Pastor, Ternes, Thakore, Tortola PLB 789 (2019) 472
- JUNO:
  $\tau_3/m_3 > 7.5 \times 10^{-11}$ s/eV at 95% C.L.
  Abrahao, Minakata, Nunokawa, Quiroga JHEP 11 (2015) 001

☞ Limits from CMB:

Hannestad, Raffelt, PRD 72 (2005) 103514; Escudero, Fairbairn, PRD 100 (2019) 10, 103531

☞ Limits from Solar Neutrinos:

Berryman, de Gouvea, Hernandez, PRD 92 (2015) 7, 073003

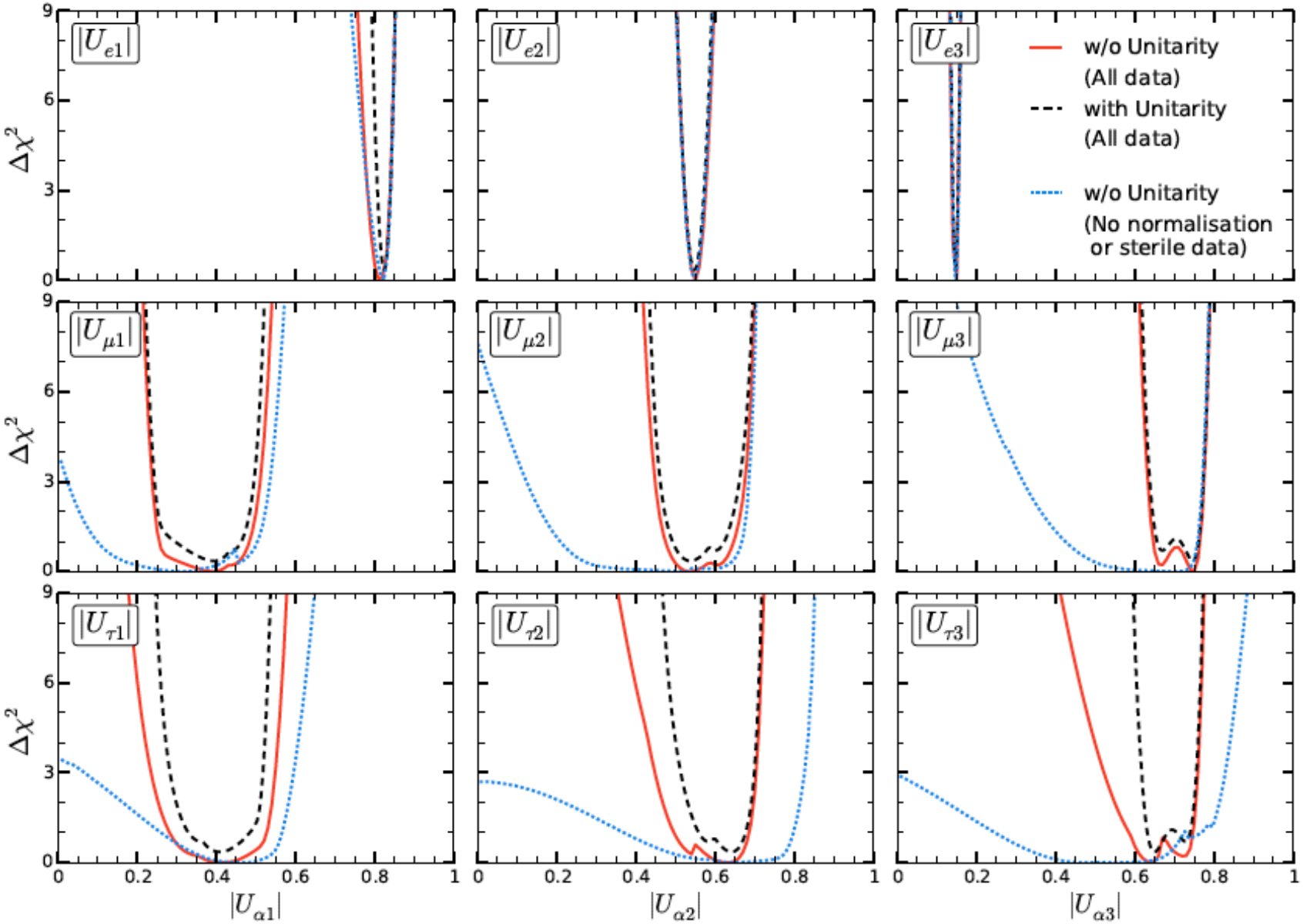
☞ Invisible ν decay ($\tau/m = 10^2$ s/eV) resolves IceCube's track & cascade (> 3σ) tension:

Denton, Tamborra, PRL 121, 121802 (2018)

☞ Visible decay:

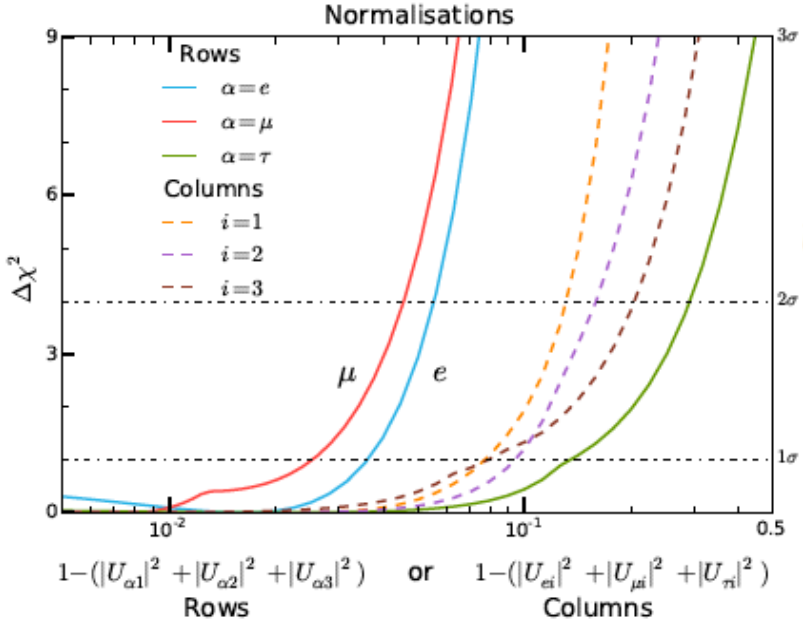
MINOS + T2K: Gago, Gomes, Gomes, Jones-Perez, Peres, JHEP 11 (2017) 022
DUNE: Coloma, Peres, e-Print: 1705.03599 [hep-ph]

Unitarity Constraints



Parke, Ross-Lonergan, PRD 93 (2016) 11, 113009

Unitarity Constraints



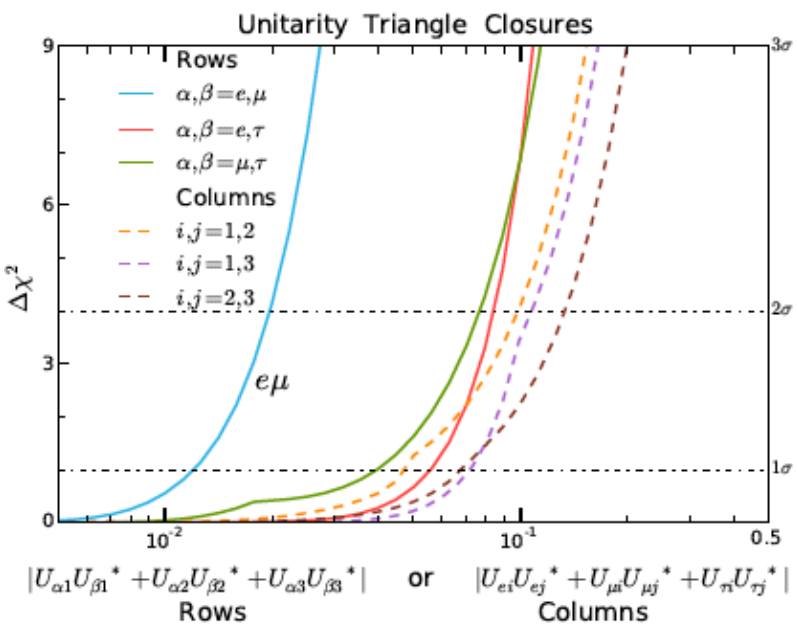
$$U^{\text{Extended}}_{\text{PMNS}} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}}^{U^{3x3}_{\text{PMNS}}} & \cdots & U_{en} \\ \begin{matrix} U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \\ \vdots & \vdots & \vdots \end{matrix} & \cdots & \begin{matrix} U_{\mu n} \\ U_{\tau n} \\ \vdots \end{matrix} \\ \begin{matrix} U_{s_n1} & U_{s_n2} & U_{s_n3} \end{matrix} & \cdots & U_{s_n n} \end{pmatrix}$$

$$\boxed{\sum_{i=1}^{3} |U_{\alpha i}|^2 \leq 1}$$

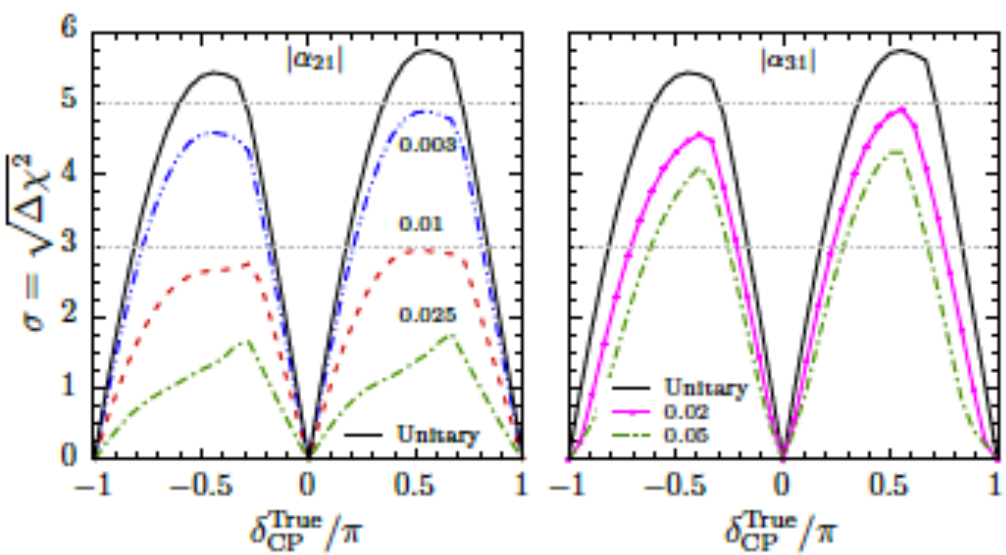
$$\boxed{\sum_{\alpha\in\{e,\mu,\tau\}} |U_{\alpha i}|^2 \leq 1}$$

Triangles no longer close

Parke, Ross-Lonergan, PRD 93 (2016) 11, 113009

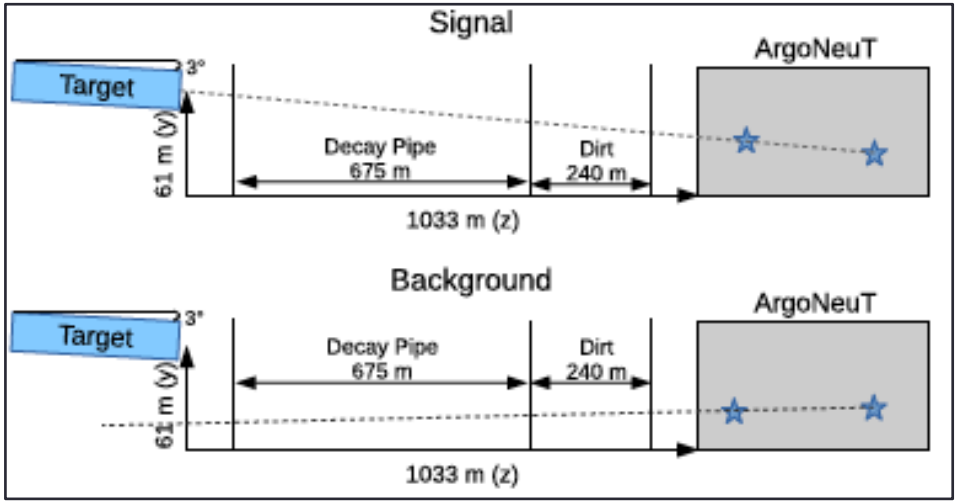


CP violation in DUNE with non-unitary mixing

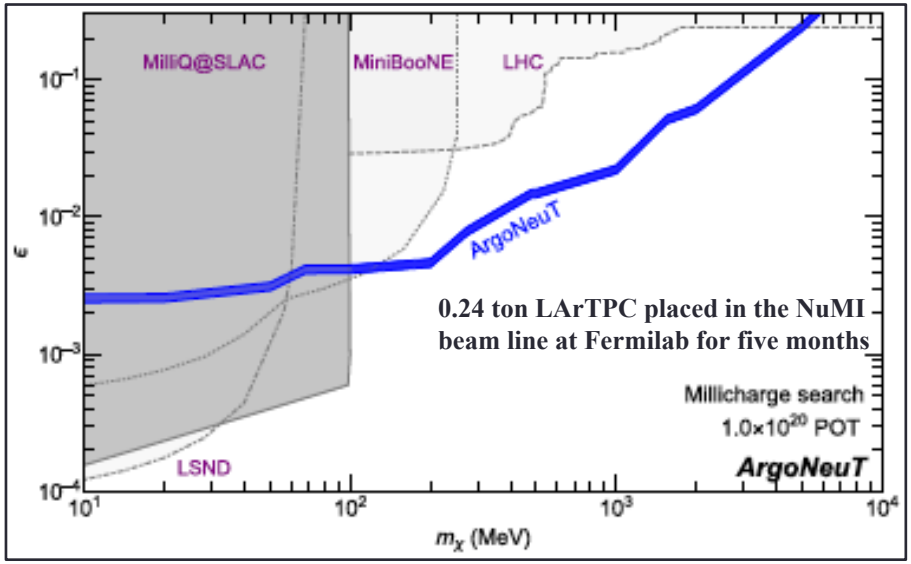


Escrihuela, Forero, Miranda, Tortola, Valle, NJP 19 (2017) 9, 093005

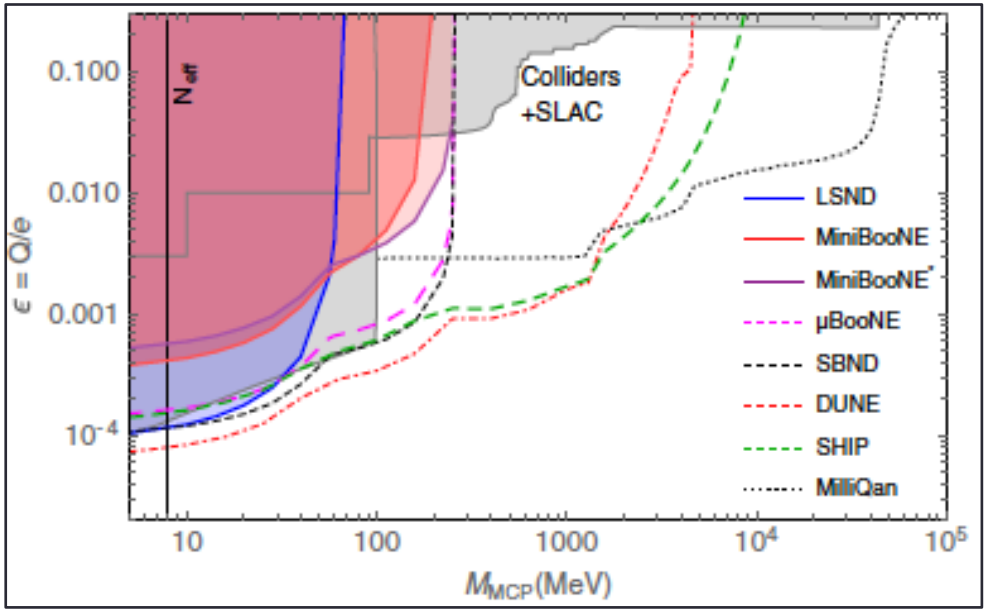
Search for Millicharged Particles (MCPs)



Harnik, Liu, Palamara, JHEP 07 (2019) 170



ArgoNeuT Collaboration, PRL 124, 131801 (2020)



Magill, Plestid, Pospelov, Tsai, PRL 122, 071801 (2019)

MCPs (electric charge $Q_\chi = \epsilon e$ where $\epsilon \ll 1$) mostly violate the quantization of charge seen in the SM and could make up part of the DM in the Universe

MCPs mainly produced at any intense fixed-target produced beam via the decays of neutral meson and detected via elastic scattering with electrons

ArgoNeut search for an event signature with two soft hits (MeV-scale energy depositions) aligned with the upstream target and sensitive to MCPs with charges between $10^{-3}e$ and $10^{-1}e$ with masses in the range from 0.1 to 3 GeV

Concluding Remarks

BSM physics in the next generation neutrino experiments may become the dominant physics topics in the near future as the precision on the neutrino oscillation parameters and CP violation measurements continues to improve!

So stay safe and stay tuned!

Many thanks to the organizers for organizing such an impressive online Neutrino 2020

The show must go on……

I apologize if I have missed your important work, time is too short to cover everything

Thank you!