Landscape of BSM Physics @ Neutrino Experiments

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सत्यमेव जयते
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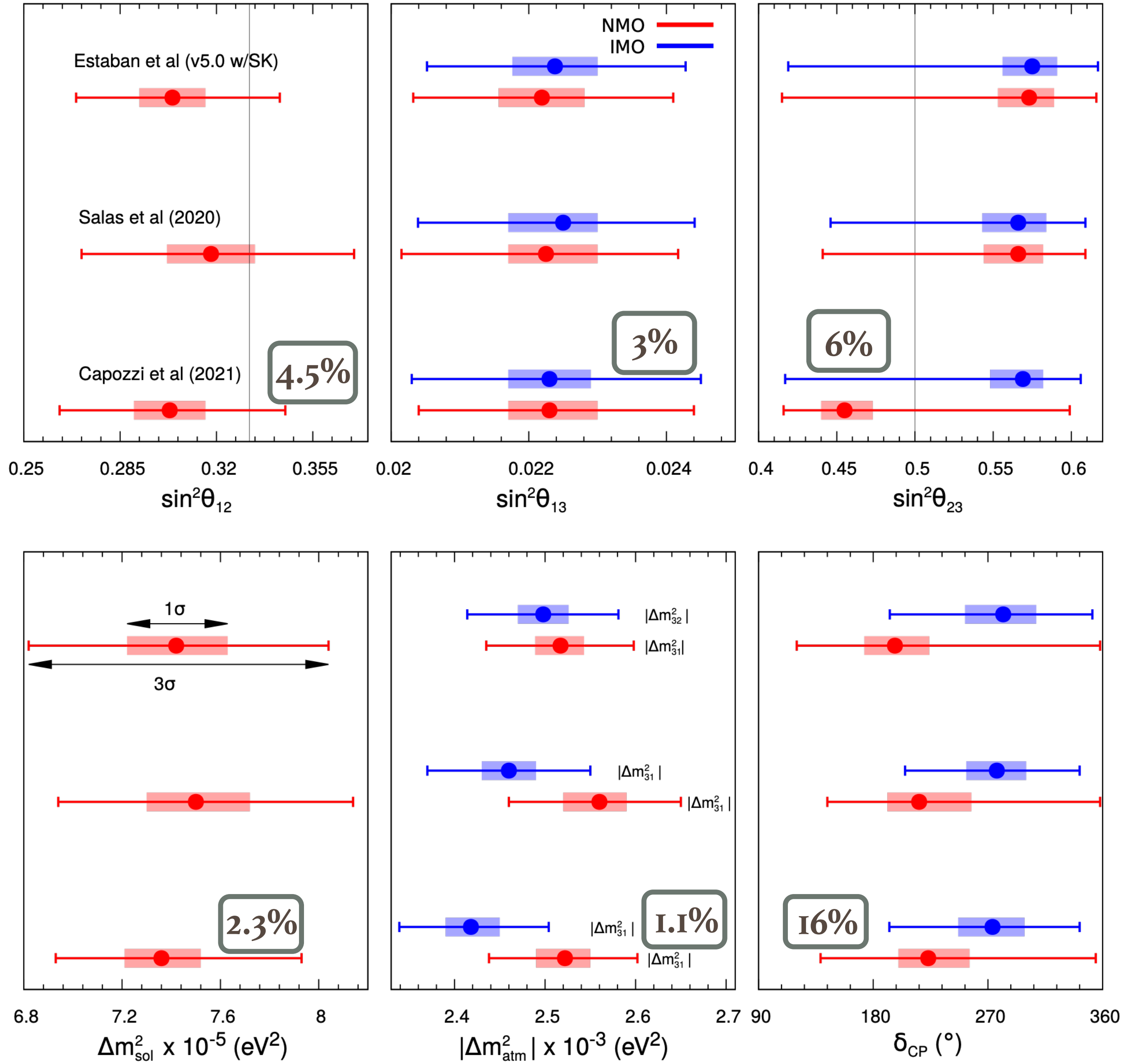
Remarkable Precision on Neutrino Oscillation Parameters

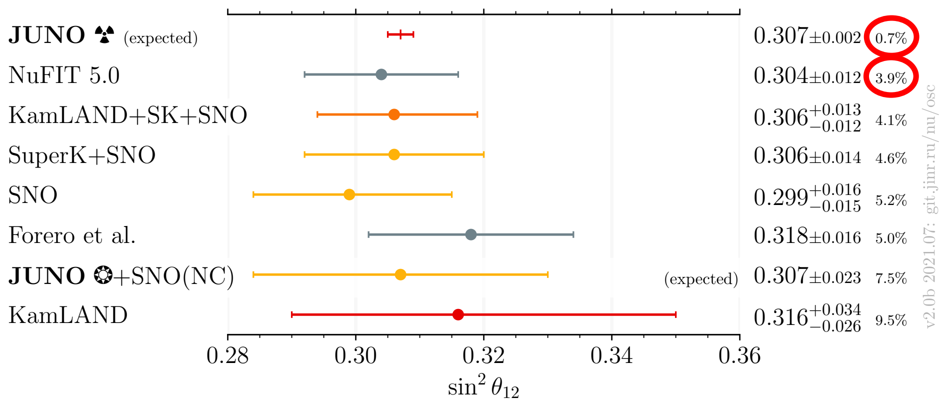
Robust three-flavor neutrino oscillation paradigm

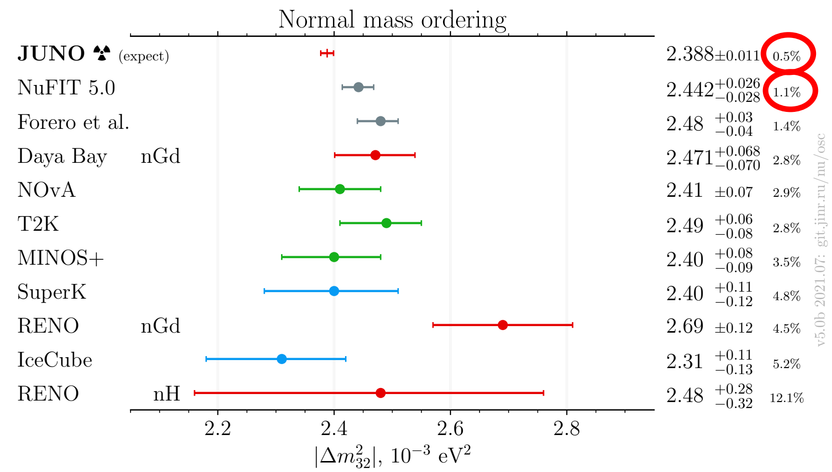


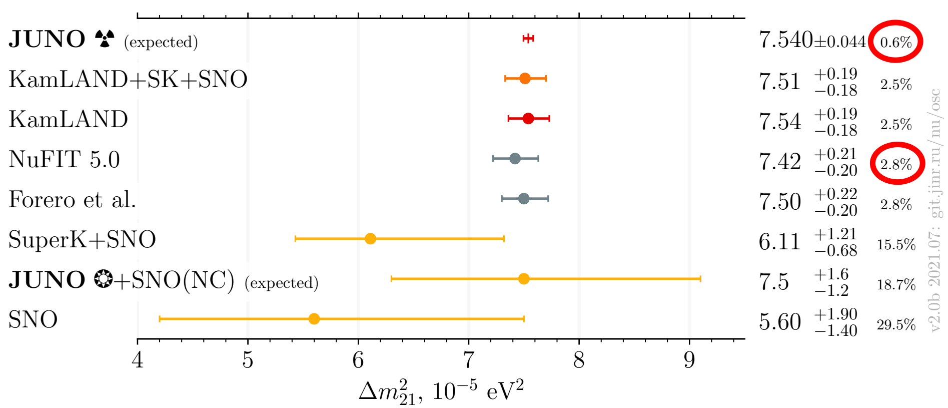
Tremendous boost to search for BSM physics at ν expts

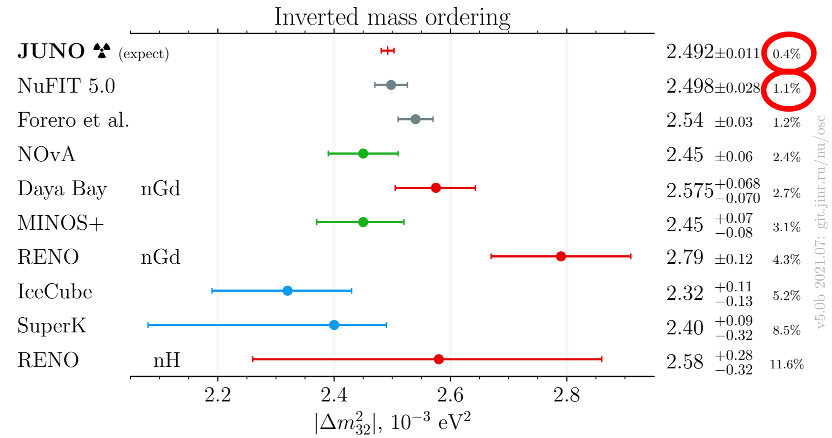
Agarwalla, Kundu, Prakash, Singh, in preparation

Very Bright Future Ahead: Triumph of JUNO









Maxim Gonchar (JUNO Collaboration) EPS-HEP 2021, July 26

JUNO will improve significantly our knowledge on neutrino oscillation parameters. These developments are very crucial to probe sub-leading BSM effects at next generation long-baseline and atmospheric experiments, IceCube-Upgrade, IceCube-Gen2

Non-zero neutrino mass: first experimental proof (gateway) for BSM physics

Several BSM possibilities can be introduced in the framework of Effective Field Theory (EFT)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \cdots$$

d=5 Weinberg Operator: LLHH, Λ: New Physics Scale
S. Weinberg, PRL 43 (1979) 1566

BSM Scenarios naturally arise due to different mechanisms for generating ν masses (e.g. seesaw)

Many models of BSM physics suggest: new fundamental particles and interactions, new sources of CP-invariance violation, lepton number and lepton flavor violations

Probing BSM Scenarios Across 18 orders in E and 25 orders in L

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Probe BSM Physics at High Energies (TeV-PeV)

High-Energy (TeV-PeV) Astrophysical Neutrinos coming from cosmic distances (Mpc-Gpc)

Giant Neutrino Telescopes: IceCube@South Pole, KM3NeT@Mediterranean Sea, future IceCube-Gen2

Novel Approach --
New Physics beyond the reach of modern Colliders

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Probe BSM Physics at Low Energies (MeV-GeV)

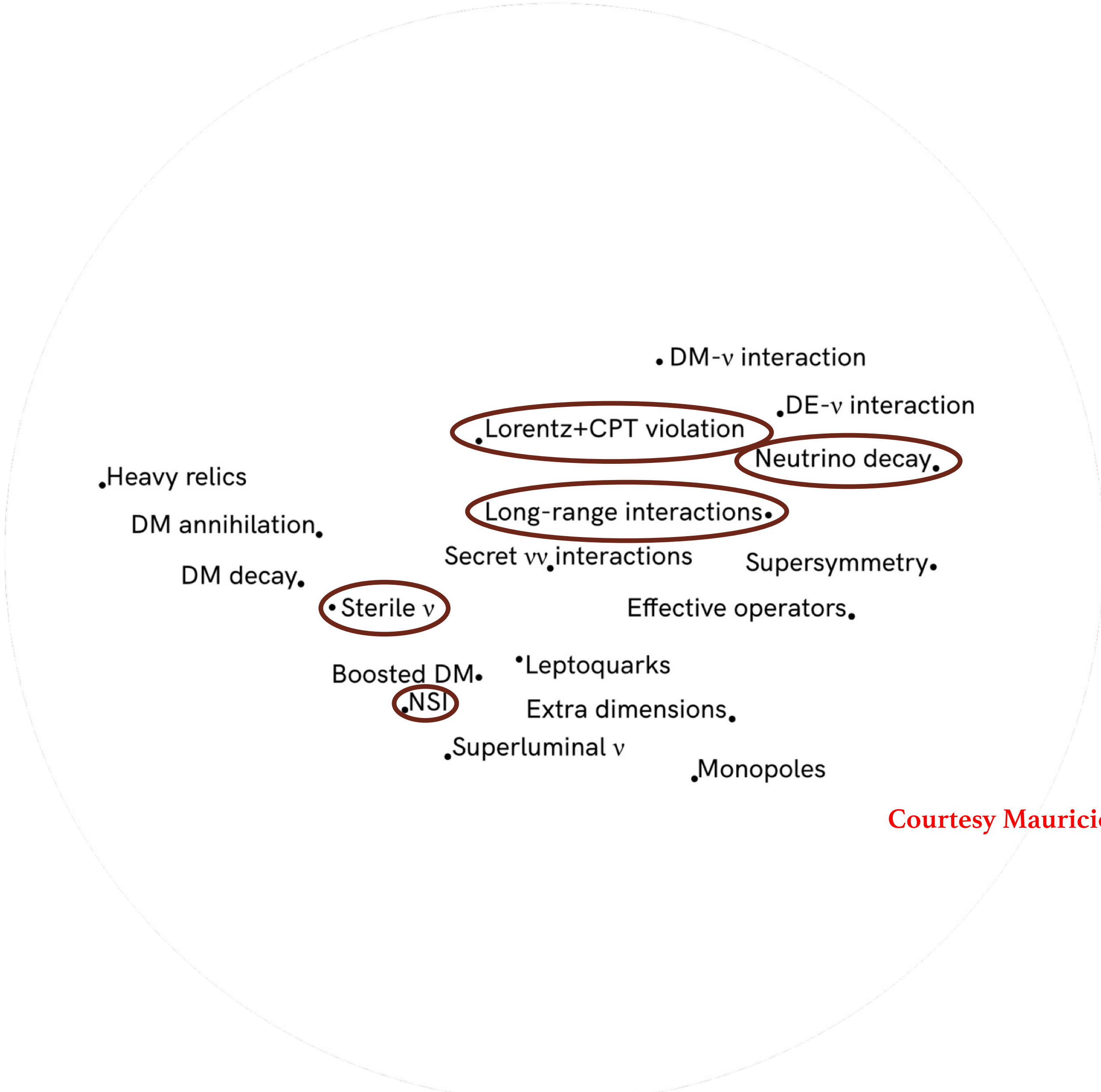
Low-Energy (MeV-GeV) Accelerator & Atmospheric νs travelling terrestrial distances (few m - 1000s of km)

Accelerator: DUNE@USA, T2HK@Japan
Atmospheric: India-based Neutrino Observatory (INO)

Expected to measure oscillation parameters with a precision around a few % -- sensitive to sub-leading BSM physics at low energies

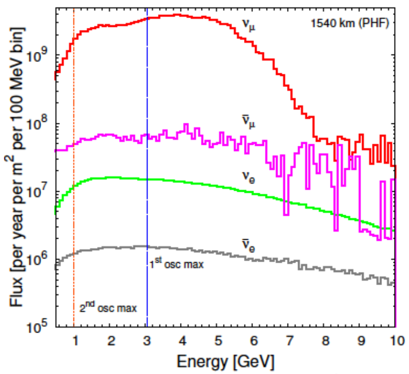
Complement BSM search @ High-Energy Colliders

Landscape of BSM Scenarios affecting Neutrino Experiments

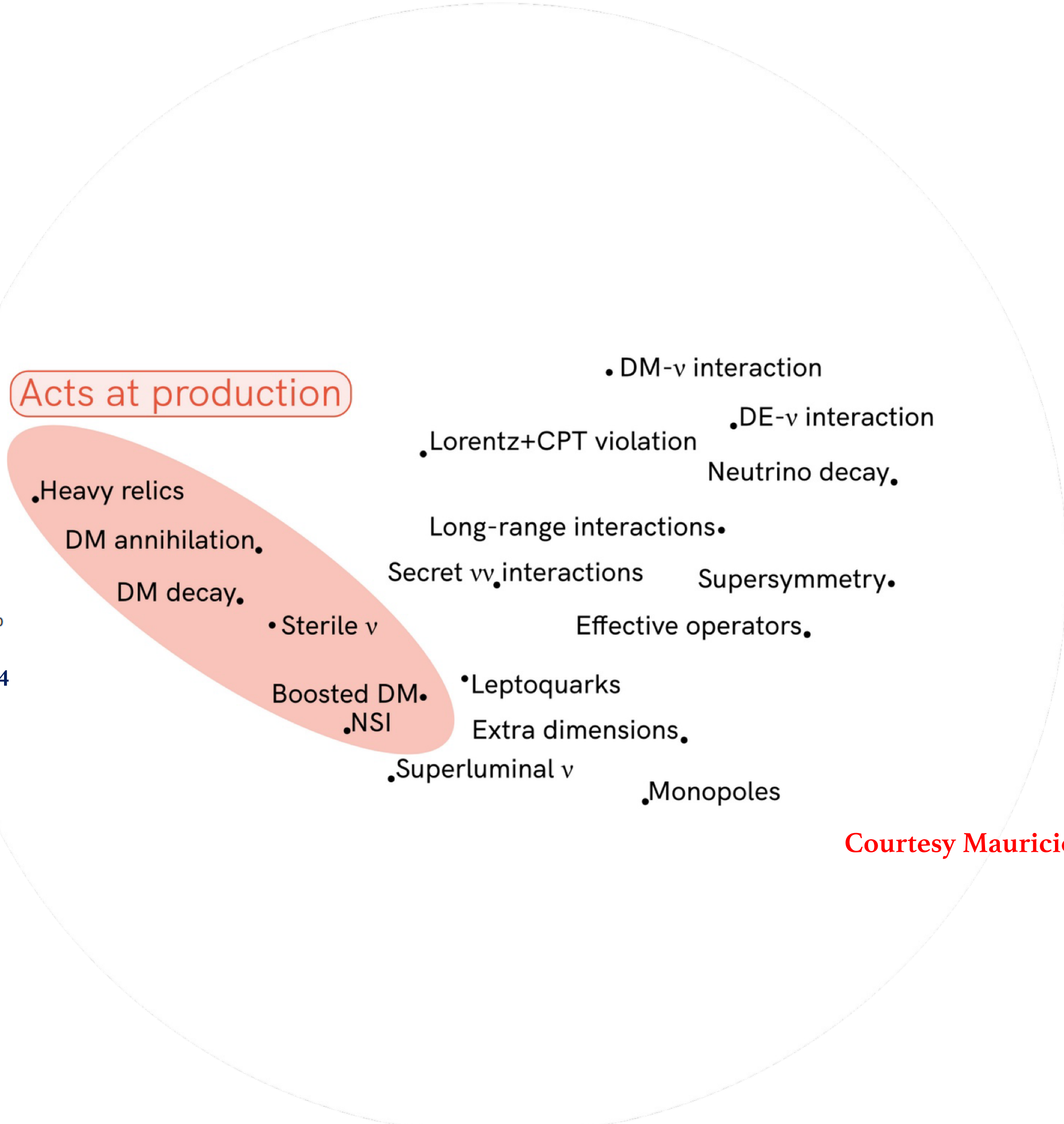


Courtesy Mauricio Bustamante

Alters neutrino flux



Agarwalla et al., JHEP 05 (2012) 154

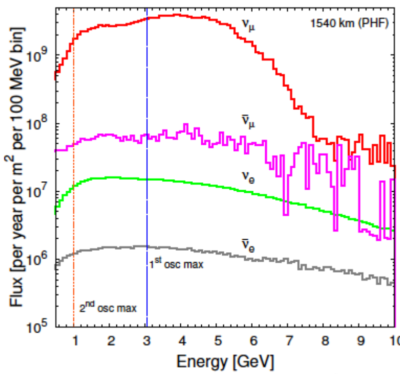


Courtesy Mauricio Bustamante

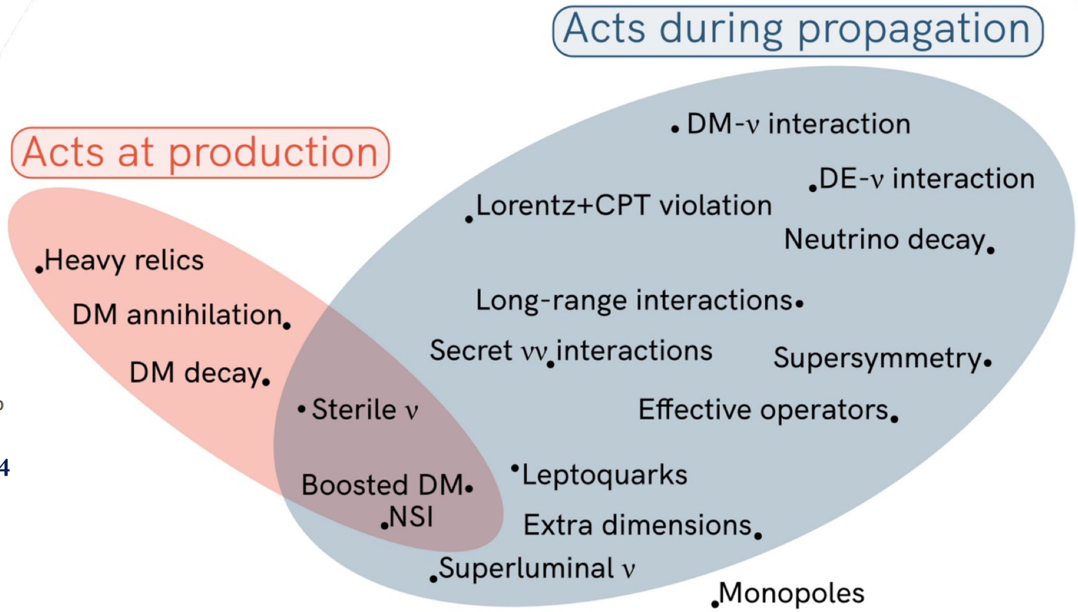
Landscape of BSM Scenarios affecting Neutrino Experiments

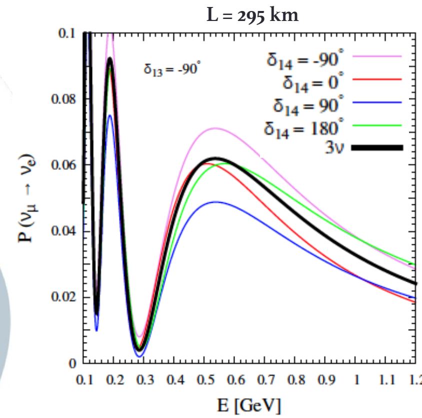
Alters neutrino flux, oscillation, mixing

Alters neutrino flux



Agarwalla et al., JHEP 05 (2012) 154





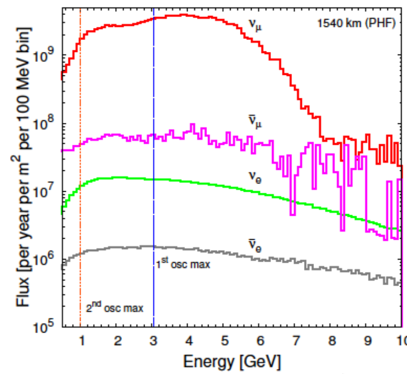
Agarwalla et al., JHEP 02 (2016) 111

Courtesy Mauricio Bustamante

Landscape of BSM Scenarios affecting Neutrino Experiments

Alters neutrino flux, oscillation, mixing

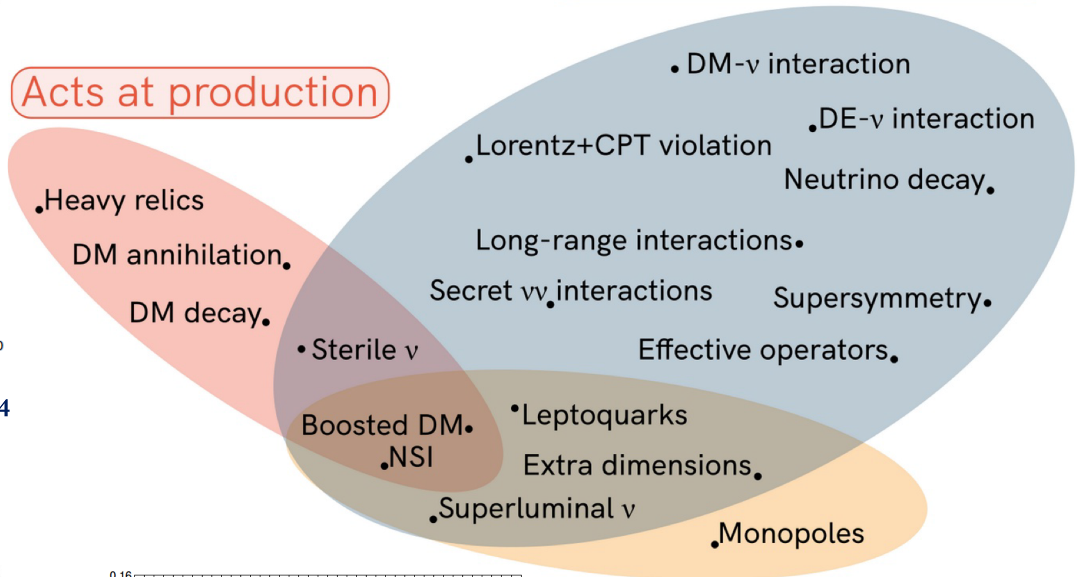
Alters neutrino flux

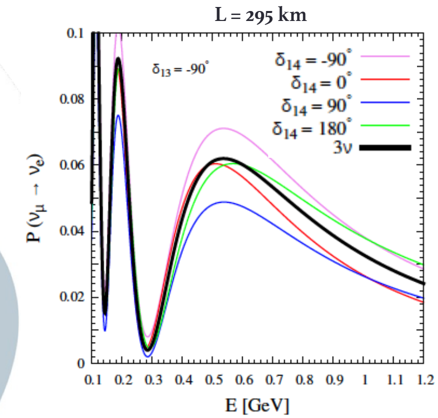


Agarwalla et al., JHEP 05 (2012) 154

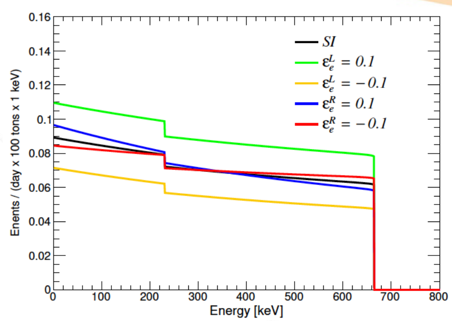
Acts at production

Acts during propagation





Agarwalla et al., JHEP 02 (2016) 111



Agarwalla et al., JHEP 02 (2020) 038

Acts at detection

Courtesy Mauricio Bustamante

Alters neutrino detection cross sections

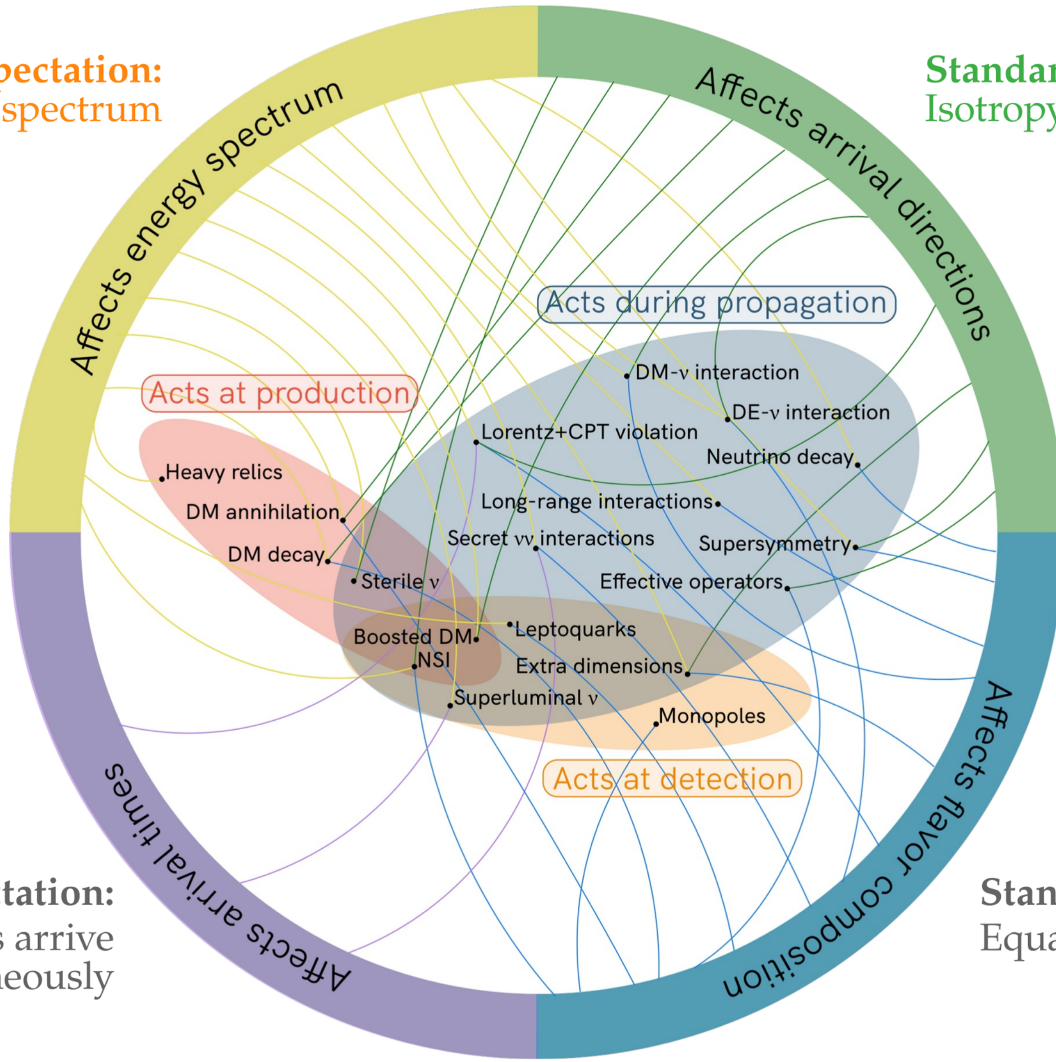
Novel Connections between Observables and BSM Scenarios in IceCube

A new multi-dimensional approach → four key observables of astrophysical neutrinos

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Arguelles, Bustamante, Kheirandish, Palomares-Ruiz, Salvado, Vincent, *PoS* ICRC2019 (2020) 849



For applications, see: Song, Li, Arguelles, Bustamante, Vincent, arXiv: 2012.12893 [hep-ph]

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

energy spectrum, arrival directions, flavor composition, and arrival times to explore BSM Physics

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

Mauricio Bustamante[1,*] and Sanjib Kumar Agarwalla[2,3,4,†]

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[2] *Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India*
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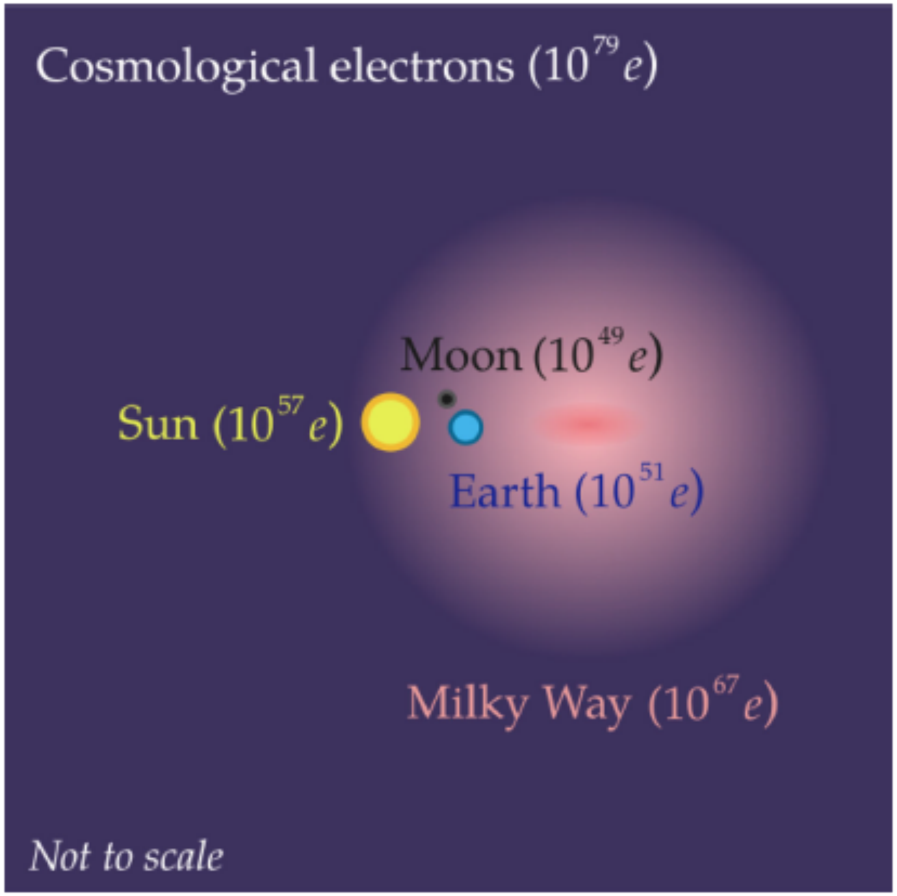
Astrophysical searches for new long-range interactions complement collider searches for new short-range interactions. Conveniently, neutrino flavor oscillations are keenly sensitive to the existence of long-ranged flavored interactions between neutrinos and electrons, motivated by lepton-number symmetries of the standard model. For the first time, we probe them using TeV-PeV astrophysical neutrinos and accounting for all large electron repositories in the local and distant Universe. The high energies and colossal number of electrons grant us unprecedented sensitivity to the new interaction, even if it is extraordinarily feeble. Based on IceCube results for the flavor composition of astrophysical neutrinos, we set the ultimate bounds on long-range neutrino flavored interactions.

DOI: 10.1103/PhysRevLett.122.061103

Ultimate Bounds on Long-Range Interactions



Under the L_e-L_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —

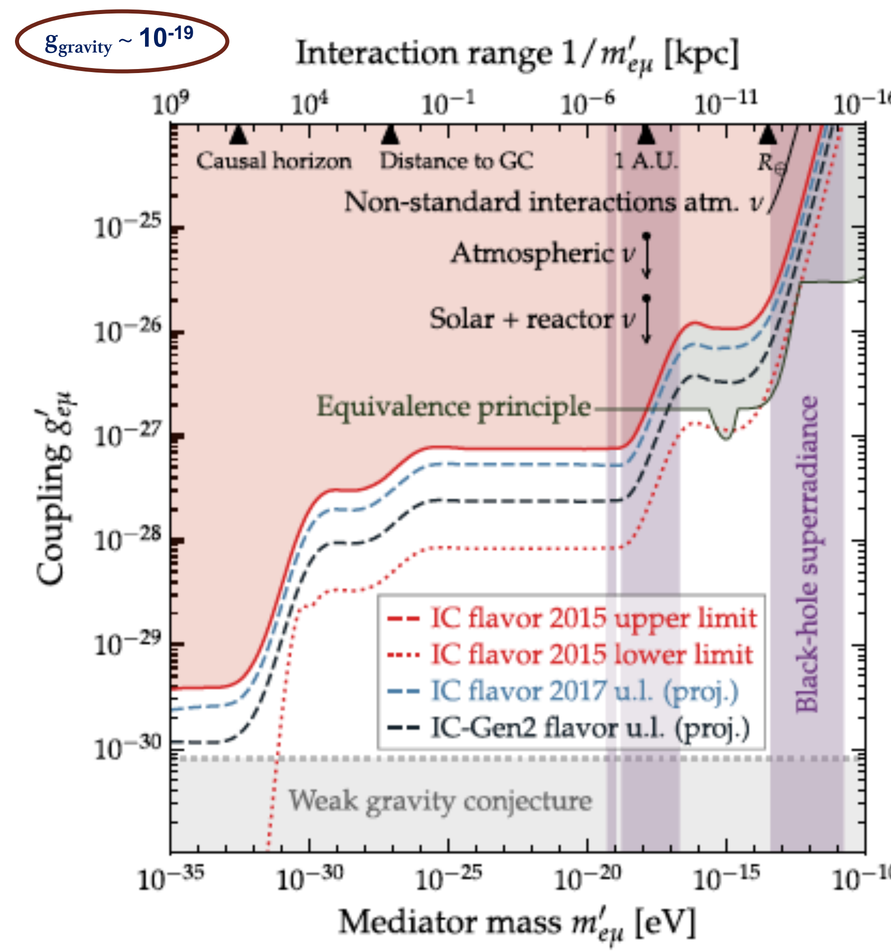
Z′ coupling

Z′ mass

$$V \sim \frac{g'^{2}_{e\beta}}{r} e^{-m'_{e\beta} r}$$

Distance to neutrino

A neutrino "feels" all the electrons within the interaction range $\sim (1/m')$

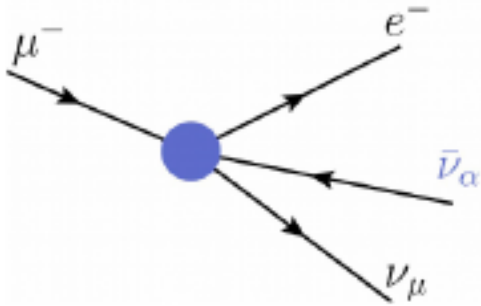
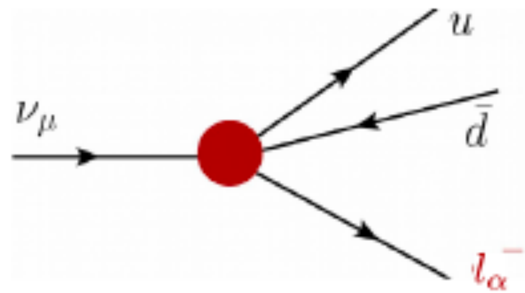
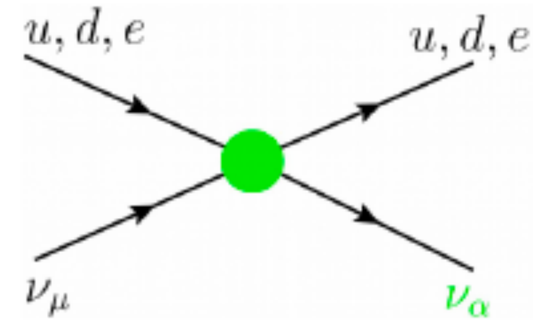


Huge Electron repositories in the local and distant Universe

Oscillations sensitive to long-ranged flavored interactions between neutrino and electron. Use flavor composition of TeV-PeV astrophysical neutrinos at IceCube

Bustamante, Agarwalla PRL 122, 061103 (2019)

Neutrino Non-Standard Interactions (NSIs)

NSI affecting production	NSI affecting detection	NSI affecting propagation
		
$\varepsilon^{e\mu,P}_{\mu\alpha}\,(\bar{e}\gamma^{\rho}P\mu)\,(\bar{\nu}_{\mu}\gamma_{\rho}P_{L}\nu_{\alpha})$	$\varepsilon^{ud,P}_{\mu\alpha}\,(\bar{d}\gamma^{\rho}Pu)\,(\bar{\nu}_{\mu}\gamma_{\rho}P_{L}l_{\alpha})$	$\varepsilon^{f,P}_{\mu\alpha}\,(\bar{f}\gamma^{\rho}Pf)\,(\bar{\nu}_{\mu}\gamma_{\rho}P_{L}\nu_{\alpha})$
CC	CC	NC

NC-NSIs may explain tension between T2K and NOvA

See talk by S. Chatterjee

See also, Denton, Pestes PRL 126 (2021) 5, 051801

SciPost Phys. Proc. 2, 001 (2019)

Neutrino non-standard interactions: A status report

P. S. Bhupal Dev[1,2*], K. S. Babu[2,3], Peter B. Denton[4], Pedro A. N. Machado[2], Carlos A. Argüelles[5], Joshua L. Barrow[6,7], Sabya Sachi Chatterjee[8], Mu-Chun Chen[9], André de Gouvêa[10], Bhaskar Dutta[11], Dorival Gonçalves[12], Tao Han[12], Matheus Hostert[8], Sudip Jana[1,2], Kevin J. Kelly[2], Shirley Weishi Li[13], Ivan Martinez-Soler[2,10,14], Poonam Mehta[15], Irina Mocioiu[16], Yuber F. Perez-Gonzalez[2,10,14], Jordi Salvado[17], Ian M. Shoemaker[18], Michele Tammaro[19], Anil Thapa[1,2], Jessica Turner[2] ans Xun-Jie Xu[20]

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Neutrino Non-Standard Interactions,
FERMILAB-CONF-19-299-T
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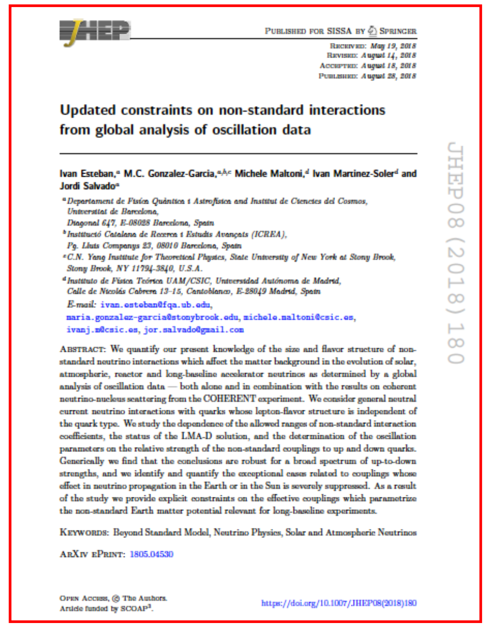

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Updated constraints on non-standard interactions from global analysis of oscillation data

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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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https://doi.org/10.1007/JHEP08(2018)180

JHEP08(2018)180

NSIs in radiative neutrino mass models, See talk by S. Jana

Neutrino NC-NSIs in Propagation

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 $P \in \{P_L, P_R\}$

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

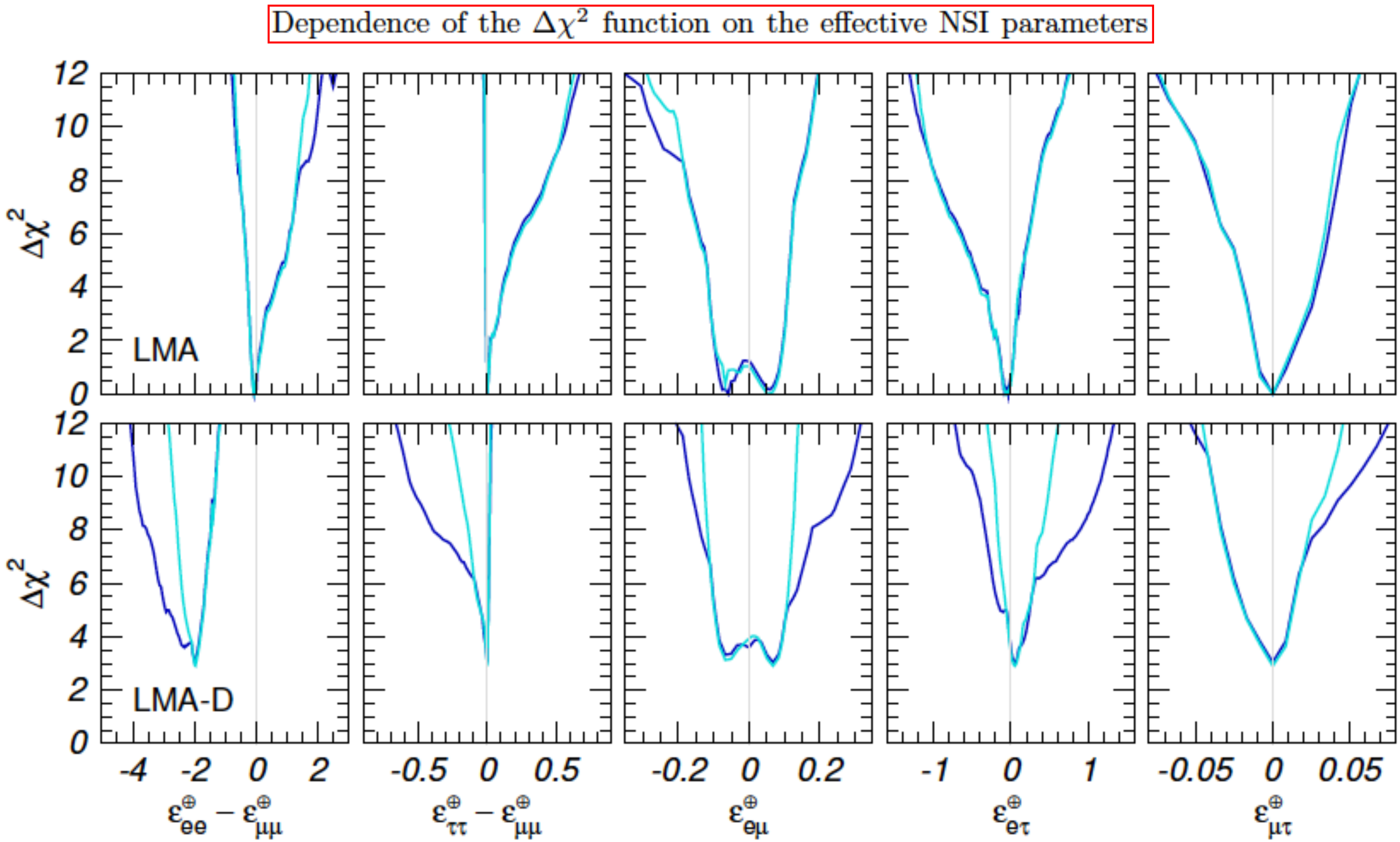
OSC			+COHERENT		
	LMA	LMA $\oplus$ LMA-D		LMA	LMA $\oplus$ LMA-D
			ε^u_{ee}	$[-0.008, +0.618]$	$[-0.008, +0.618]$
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$	$\varepsilon^u_{\mu\mu}$	$[-0.111, +0.402]$	$[-0.111, +0.402]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$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

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

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

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

Neutrino NC-NSIs in Propagation



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

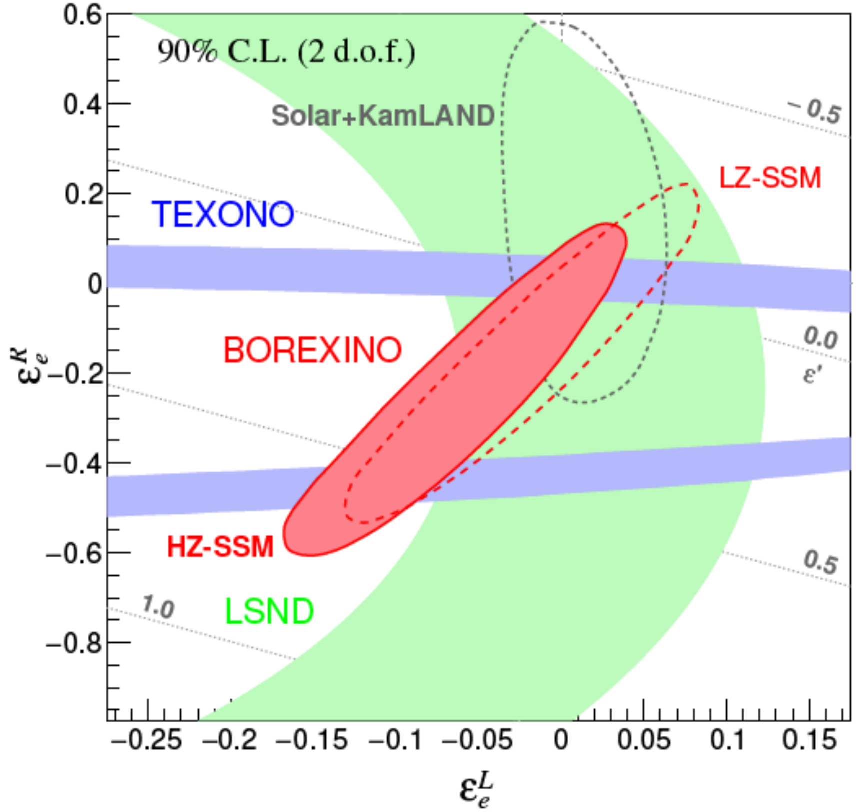
$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)(\bar{f}\gamma_\mu P f')$$

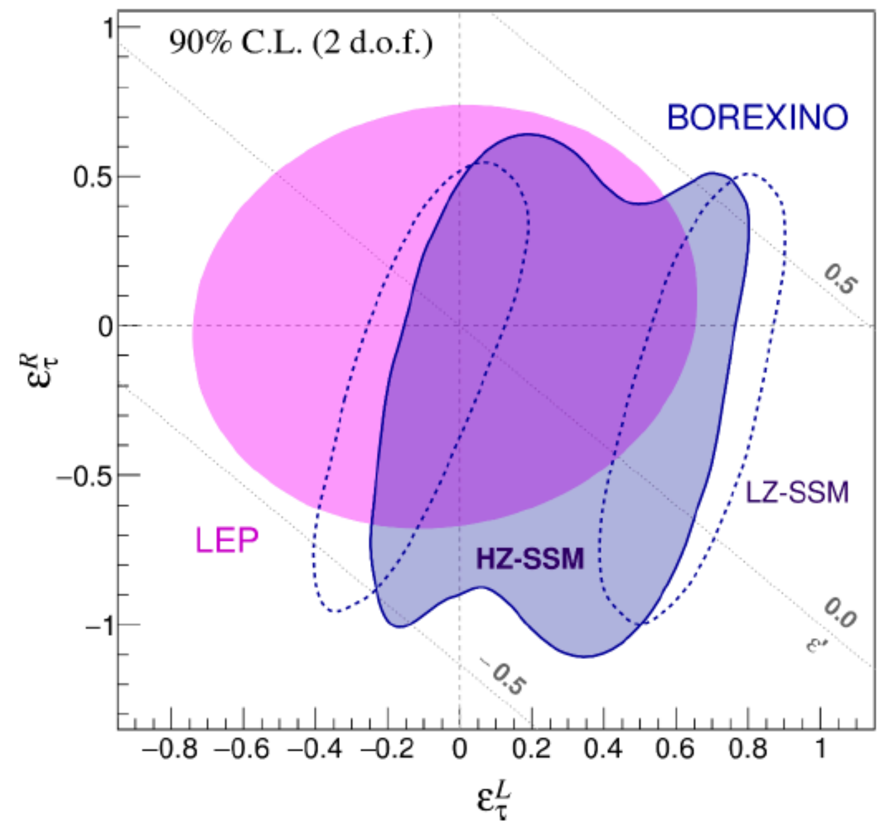
$f, f' \in \{e,u,d\}$ and $P \in \{P_L, P_R\}$

	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





	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.)

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

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

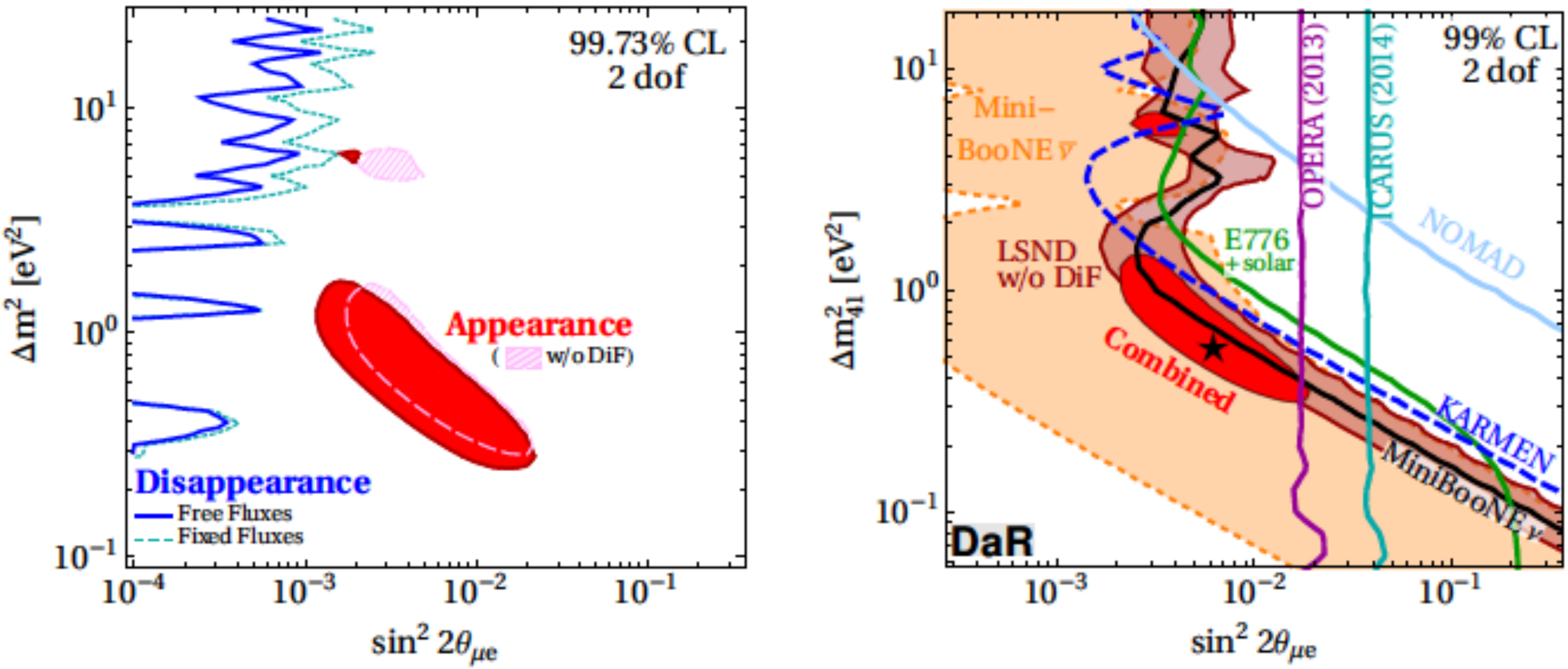
Nice complementarity between Borexino and Texono

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

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]**

See talks by S. H. Seo, A. Minotti, M. Danilov, A Serebrov, R. Samoilov, A. Fomin



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

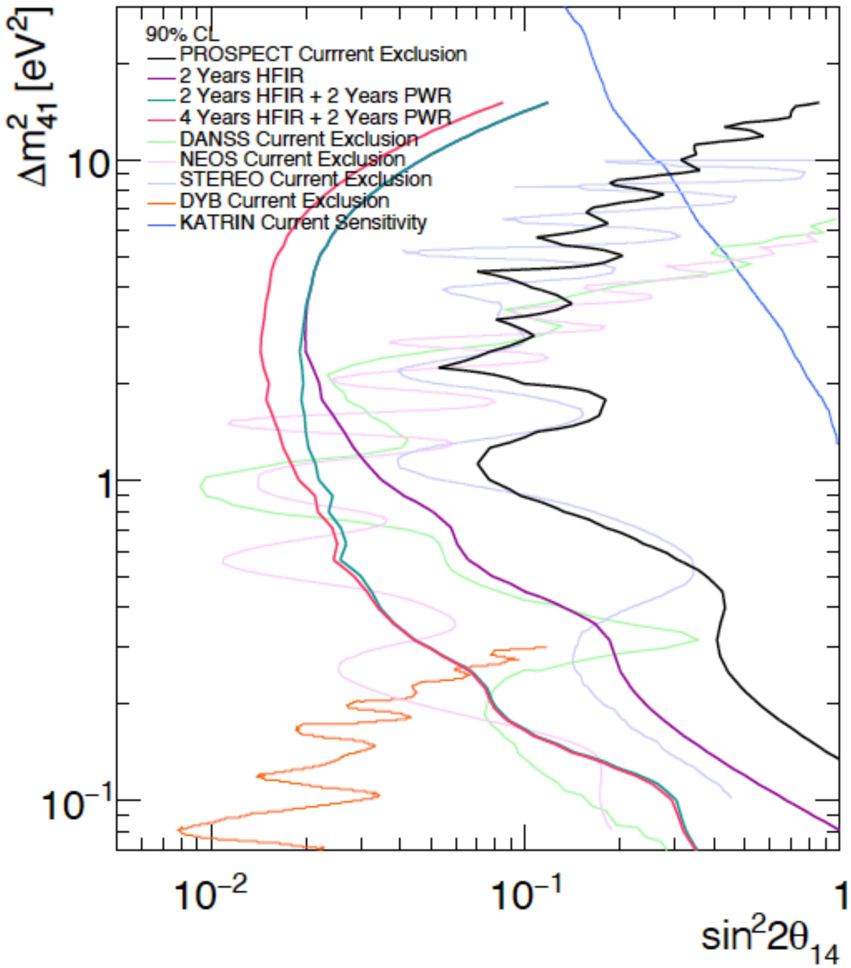
Very Short-Baseline Reactor Experiments

	DANSS	NEOS	NEUTRINO-4	PROSPECT	SoLid	STEREO
Power [MW]	3100	2815	100	85	50-80	58
Core size [cm]	$\varnothing = 320$	$\varnothing = 310$	42×42	$\varnothing = 51$	$\varnothing = 50$	$\varnothing = 40$
	$h = 370$	$h = 380$	$h = 35$	$h = 44$	$h = 90$	$h = 80$
Overburden [mwe]	50	20	3.5	< 1	10	15
Distance [m]	10.7-12.7	24	6-12	7-9	6-9	9-11
	movable		movable			
IBD events/day	5000	2000	200	750	~450	400
PSD	No	Yes	No	Yes	Yes	Yes
Readout	3D	1D	2D	3D	3D	2D
S/B	33	23	0.54	1.36	~3	0.9
σ_E/E [%] at 1 MeV	34	5	16	4.5	14	8

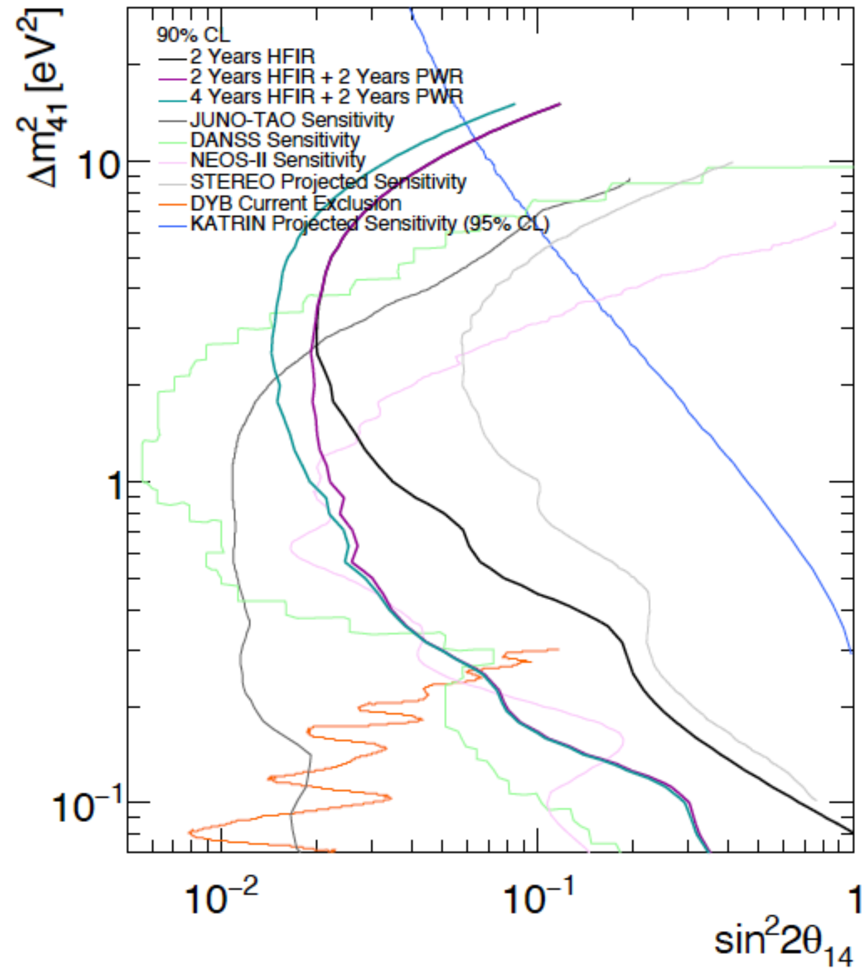
DANSS: Kalinin Nuclear Power Plant (KNPP), Moscow, Russia
Neutrino-4: SM-3 Research Reactor at Dmitrovgrad, Russia
SoLid: SCK-CEN BR2 Research Reactor in Belgium

NEOS: Hanbit Nuclear Power Complex in Yeong-gwang, Korea
PROSPECT: High Flux Isotope Reactor (HFIR) at ORNL, USA
STEREO: High Flux Reactor of the Institute Laue-Langevin, France

Present and Future Sensitivity from Very SBL Reactor Experiments



Present Sensitivity

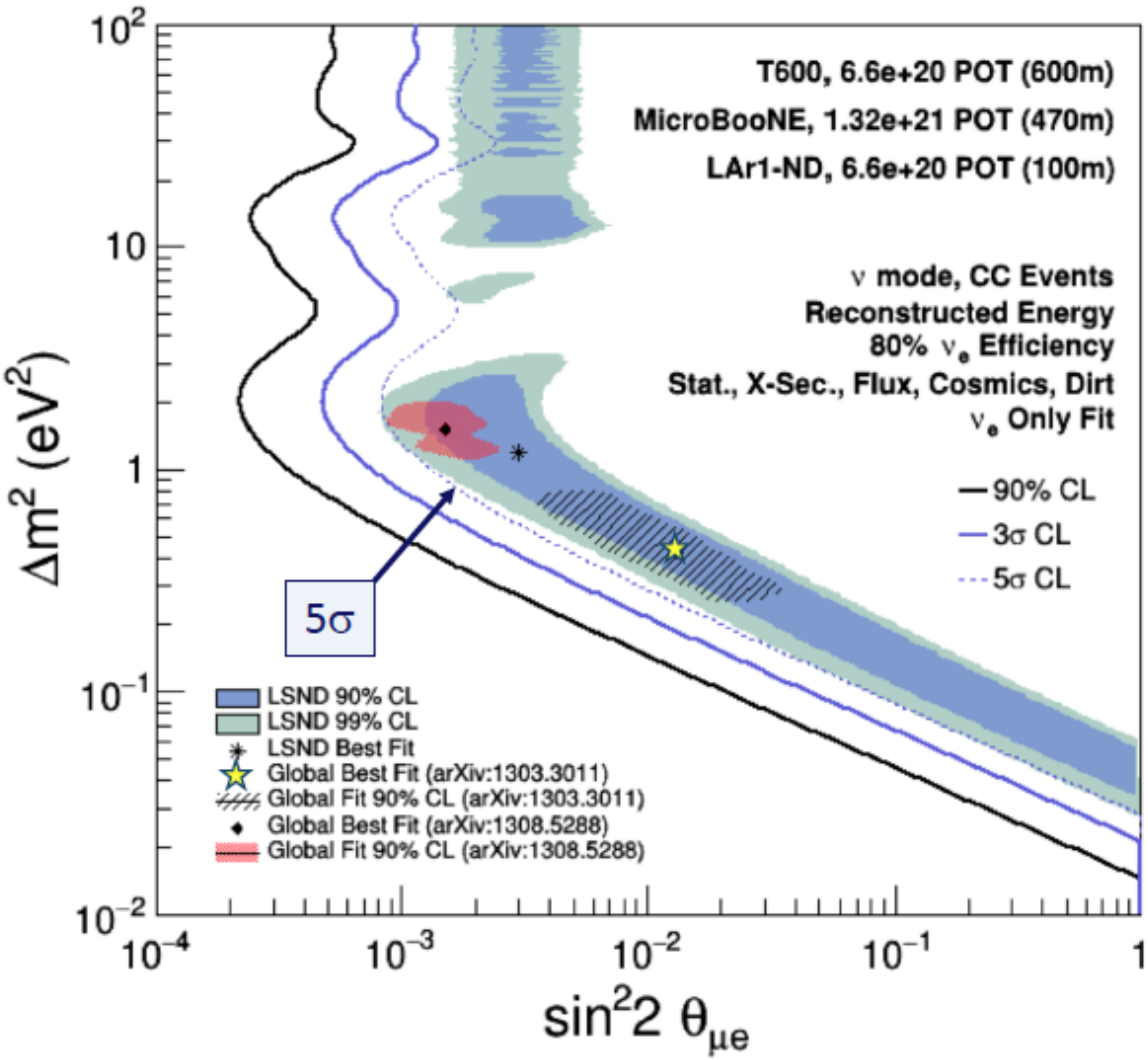


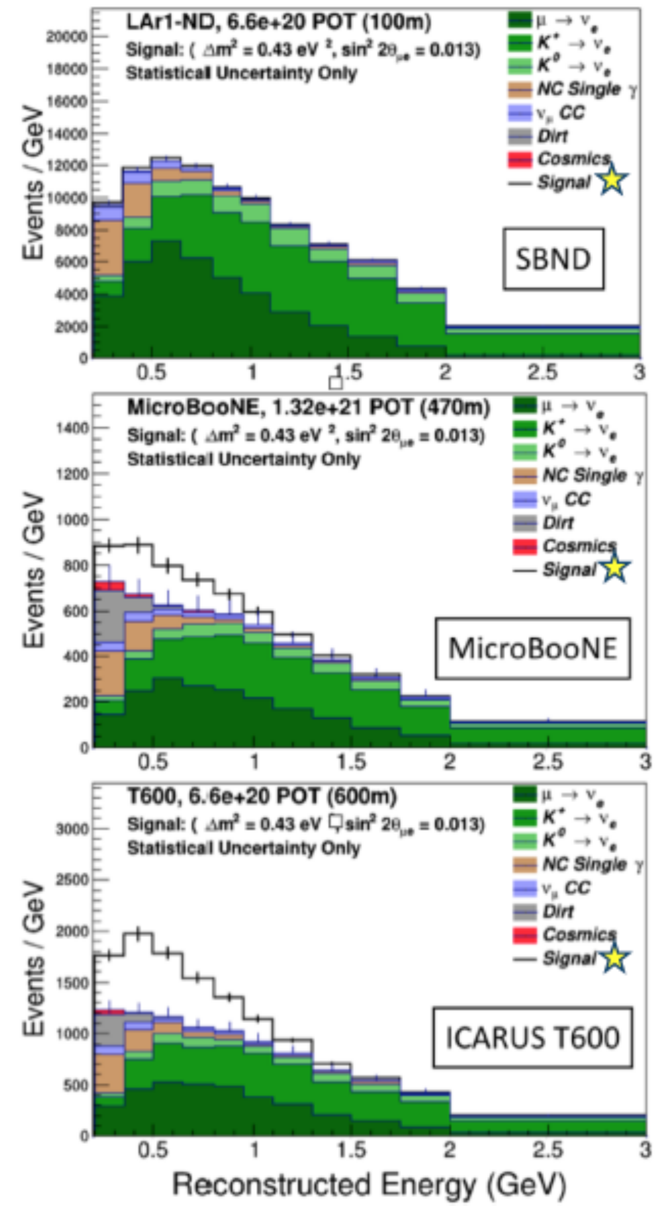
Future Sensitivity

PWR = Pressurized Water Reactor
HFIR: High Flux Isotope Reactor

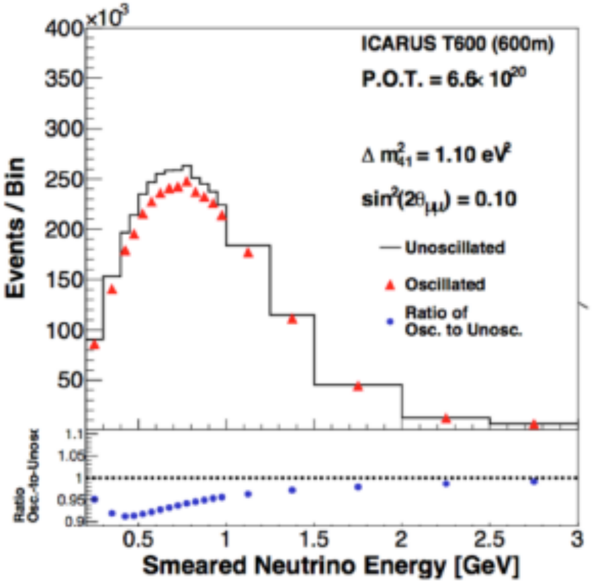
Courtesy Bryce Littlejohn

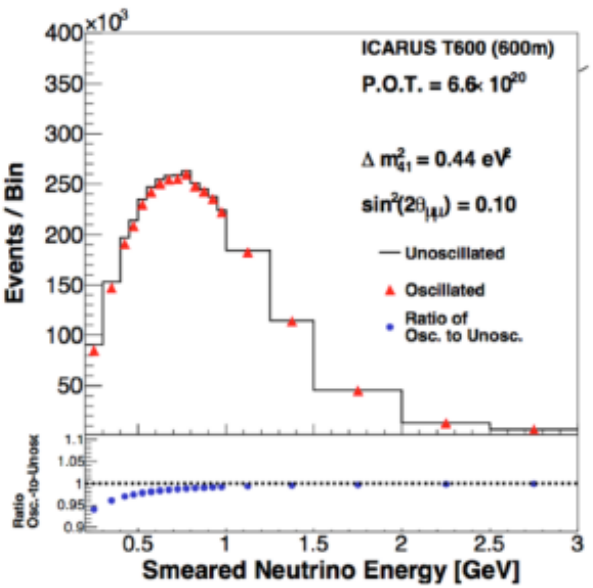
Fermilab: Short-Baseline Neutrino Appearance Oscillation Sensitivity

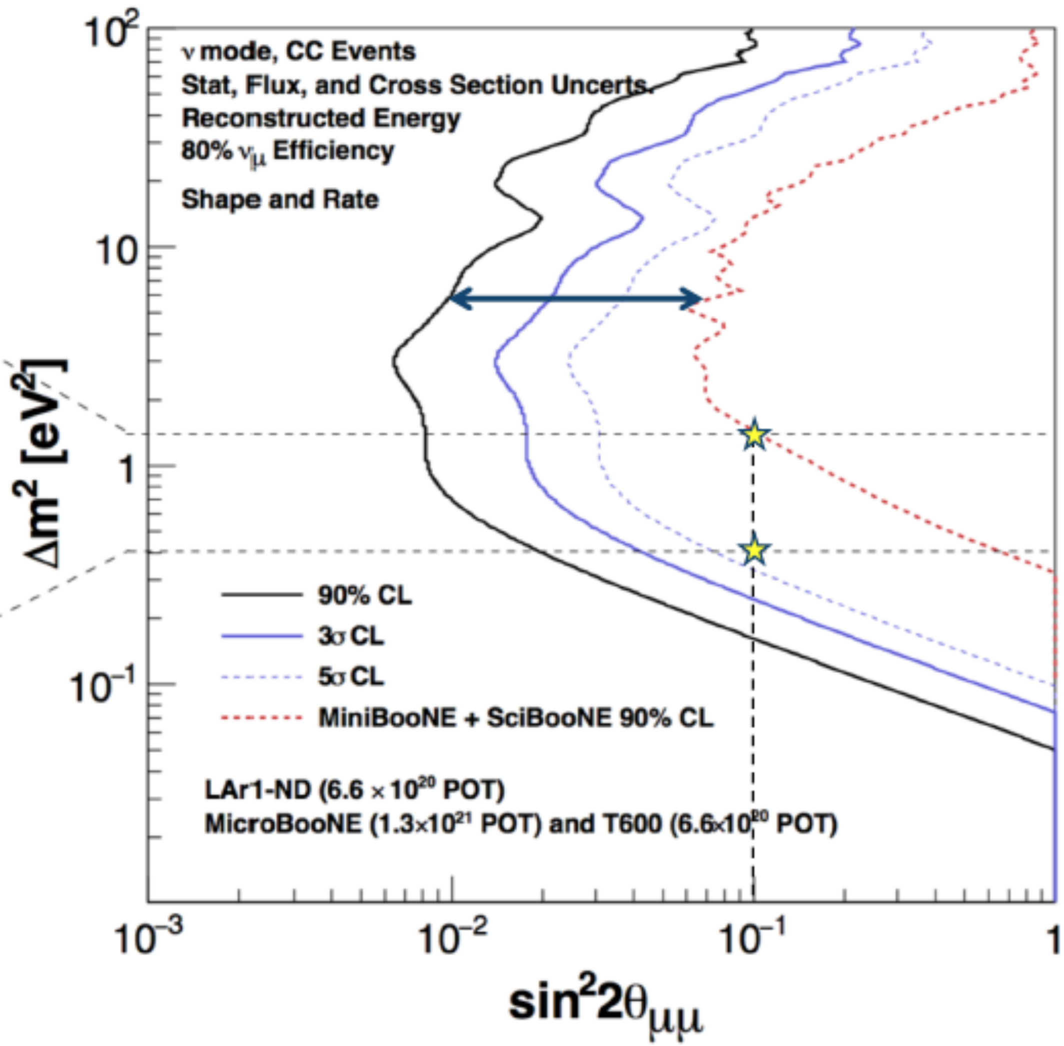




Fermilab: Short-Baseline ν Disappearance Oscillation Sensitivity







Very little background. Near detector key to controlling flux and cross-section uncertainties.

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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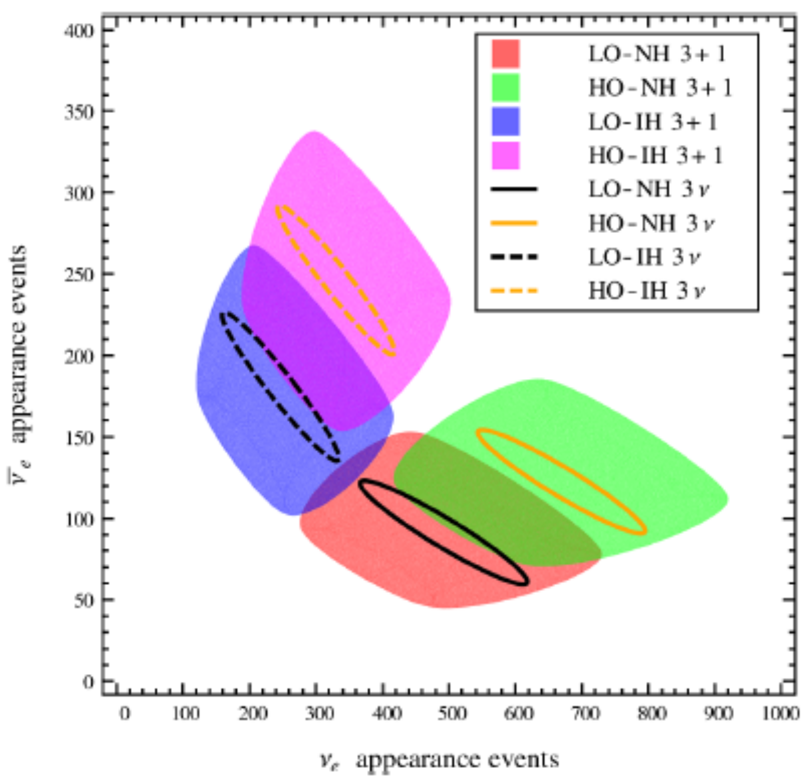


$\sin^2\theta_{23}$ = 0.42 (LO) and 0.58 (HO)

- 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]
- Due to new CP phases, sensitivity towards octant lost in DUNE

- **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:

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

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

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

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 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	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$ $< 1.5 \times 10^{-36}$ 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.

Nature Phys 14, 961–966 (2018)

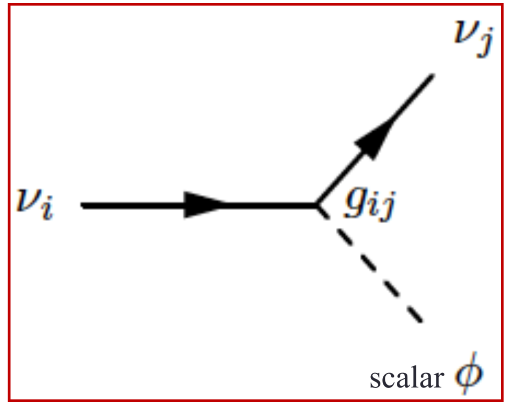
Very strong limits on LIV induced by dimension-six operators!

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]

Concluding Remarks

High-energy astrophysical neutrinos detected by big neutrino telescopes may reveal the presence of new fundamental particles and interactions, probing energy and distance scales far exceeding those accessible in the laboratory

Various BSM scenarios may affect the outcome of next generation high-precision neutrino oscillation experiments as the precision on the neutrino oscillation parameters and CP violation measurements continues to improve in the near future

BSM physics may become the dominant physics topics of next generation neutrino experiments!

So stay tuned!

I apologize for missing your important work, time is too short to cover everything

Thank you!

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**

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[9–11], 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 ($\overline{\nu}_\mu$), 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.

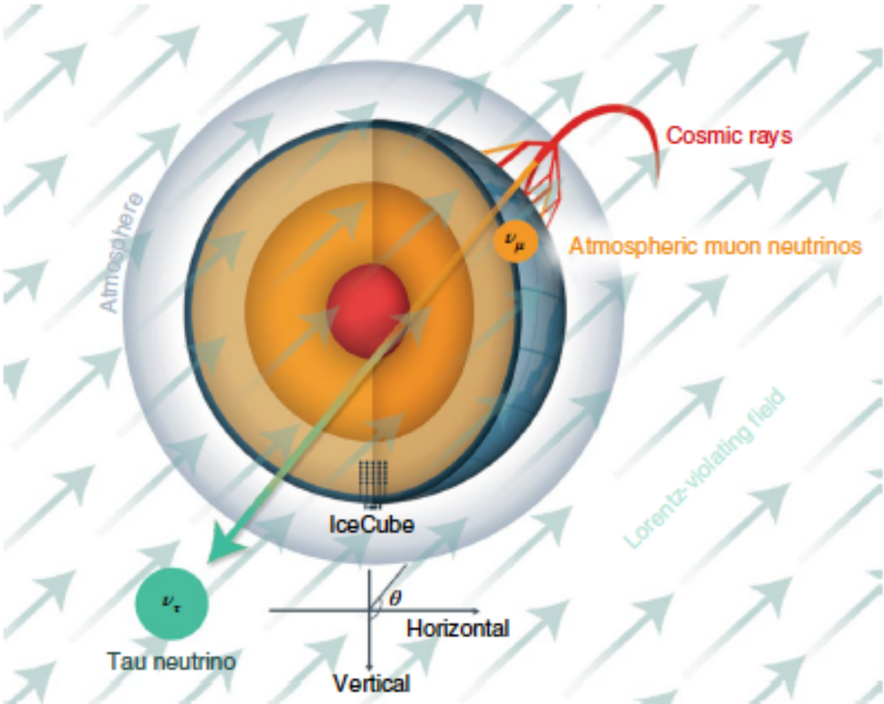
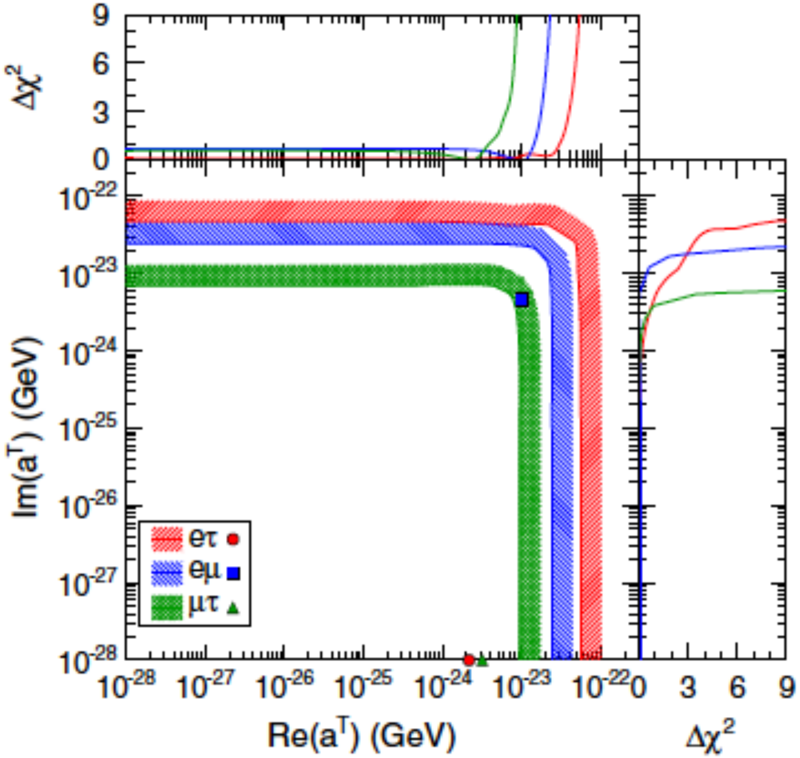


Fig. 1 | Test of LV with atmospheric neutrinos. Muon neutrinos are produced in the upper atmosphere by the collisions of cosmic rays with air molecules. These atmospheric muon neutrinos pass through the entire Earth and are then detected by IceCube in Antarctica. The LV, indicated by arrows, permeates 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

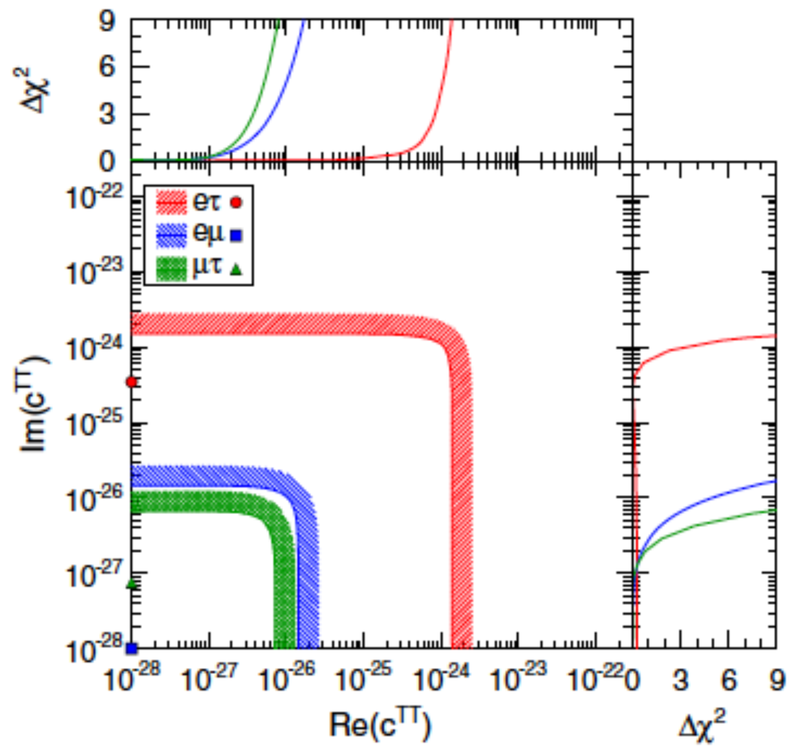
Current Bounds on LIV using Super-K Atmospheric Neutrino Data

PRD 91 (2015) 052003

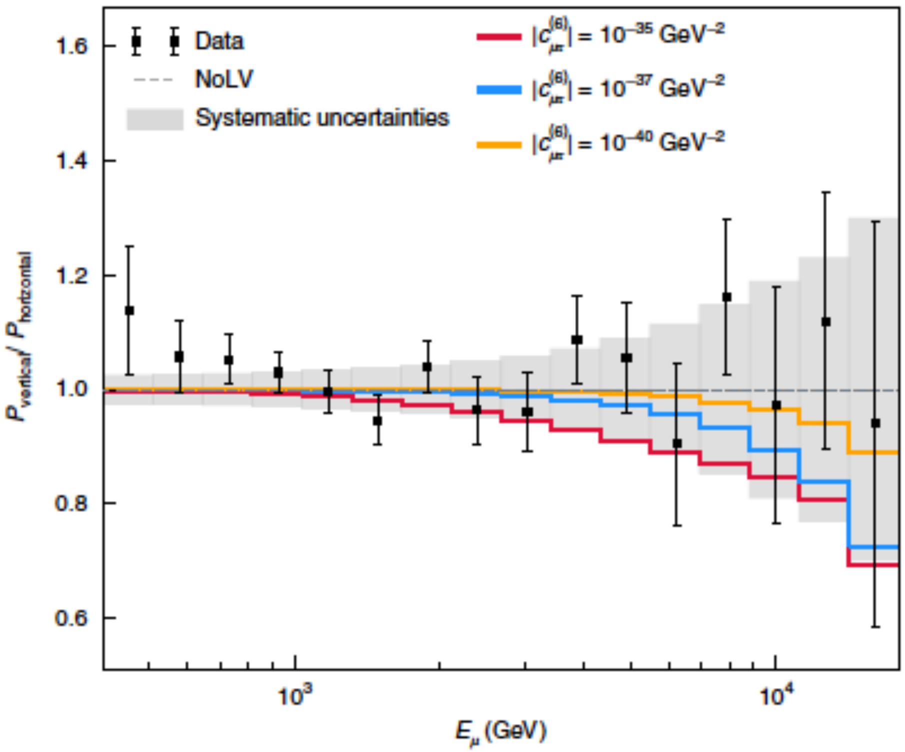


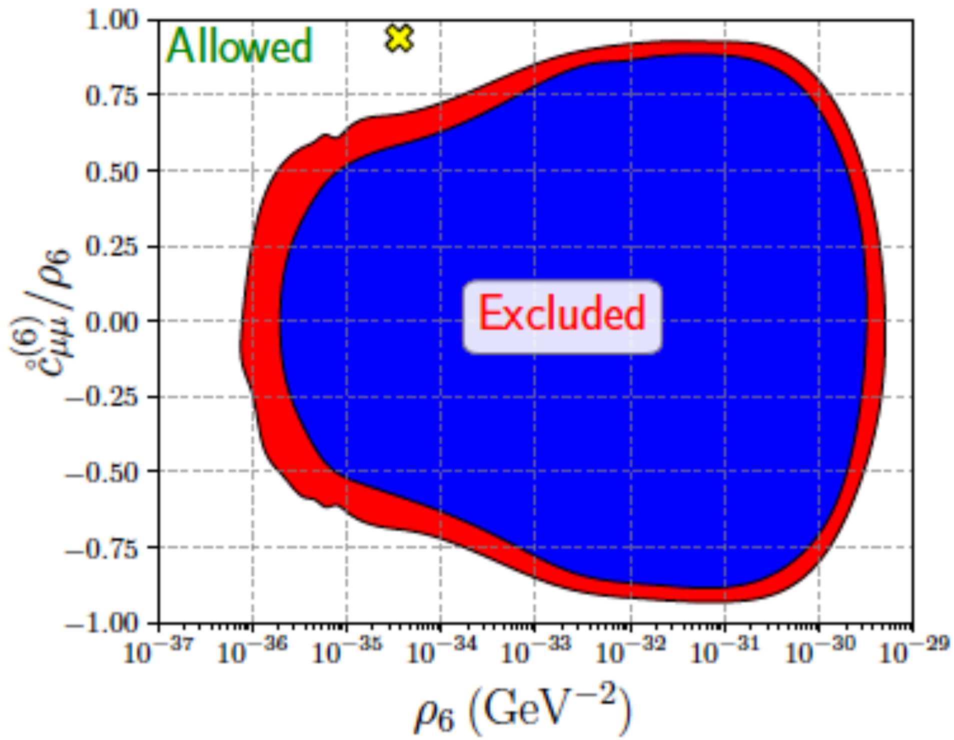
$$H_{\mathrm{LV}} = \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - \frac{4E}{3} \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^*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

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



Current Bounds on LIV using IceCube Atmospheric Neutrino Data





Effective Hamiltonian derived
from the Standard Model Extension

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

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

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

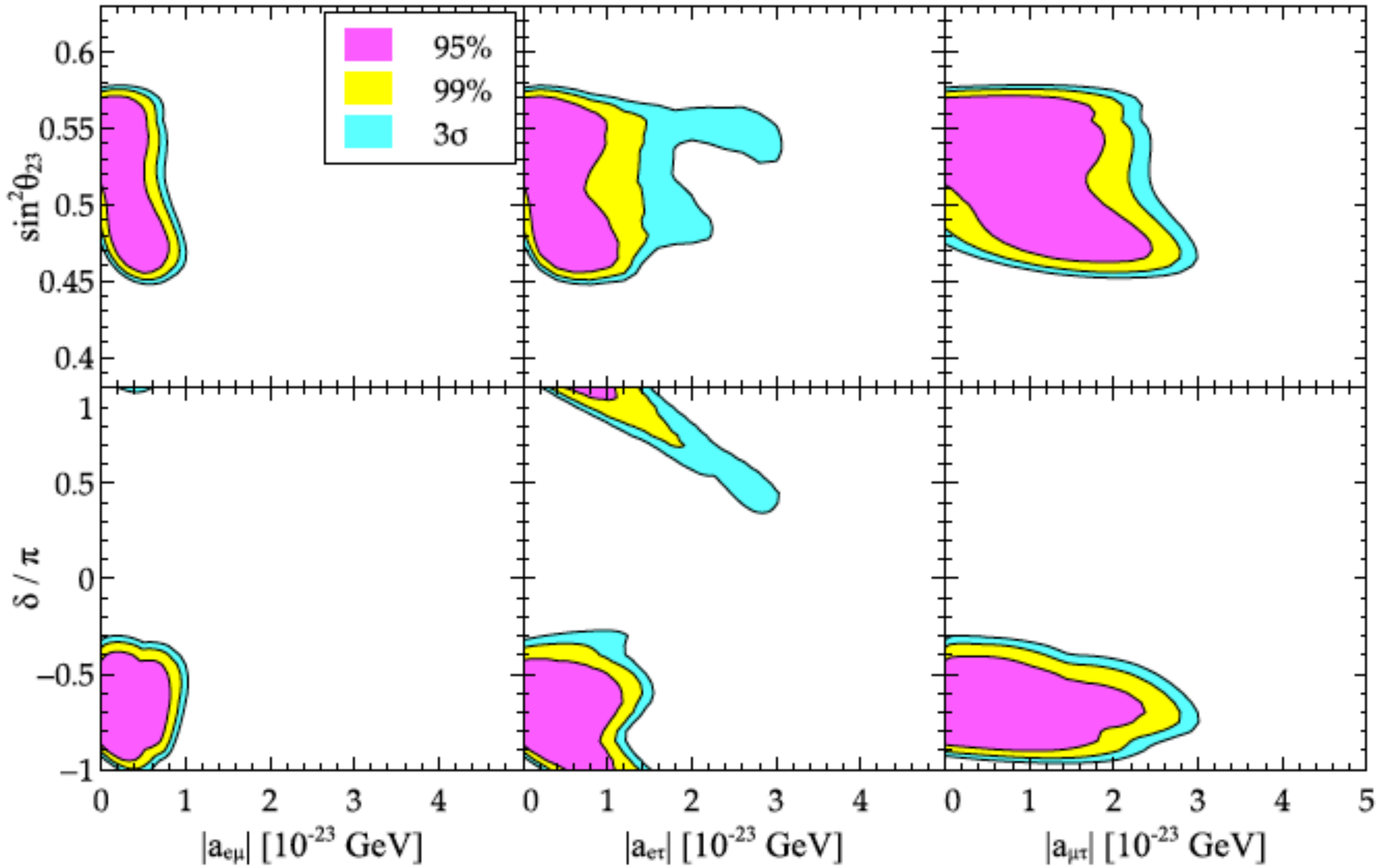
$$\rho_6 \equiv \sqrt{(\mathring{c}^{(6)}_{\mu\mu})^2 + \mathrm{Re}(\mathring{c}^{(6)}_{\mu\tau})^2 + \mathrm{Im}(\mathring{c}^{(6)}_{\mu\tau})^2}$$

× 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

Exploring Intrinsic LIV @ DUNE

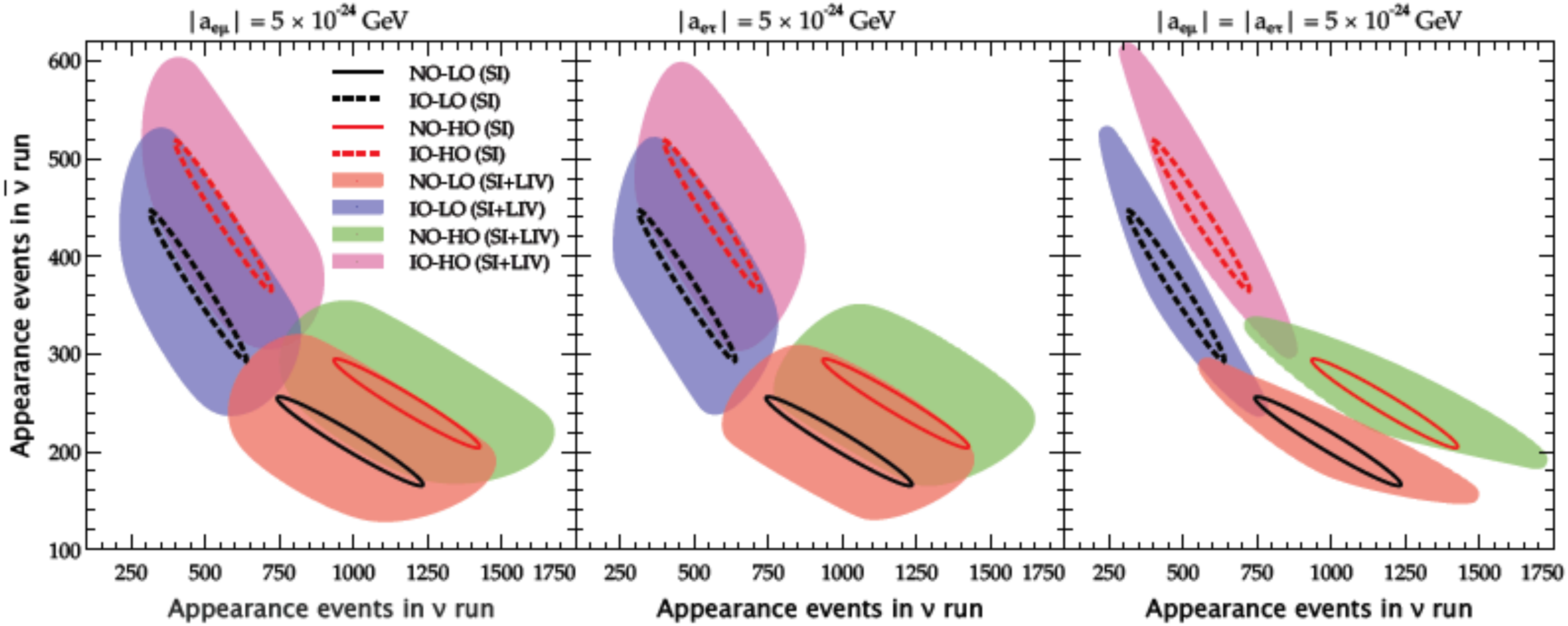


Parameter	Existing Bounds	This work
$\lvert a_{e\mu}\rvert$ [GeV]	2.5×10^{-23} [11]	7.0×10^{-24}
$\lvert a_{e\tau}\rvert$ [GeV]	5.0×10^{-23} [11]	1.0×10^{-23}
$\lvert a_{\mu\tau}\rvert$ [GeV]	8.3×10^{-24} [11]	1.7×10^{-23}

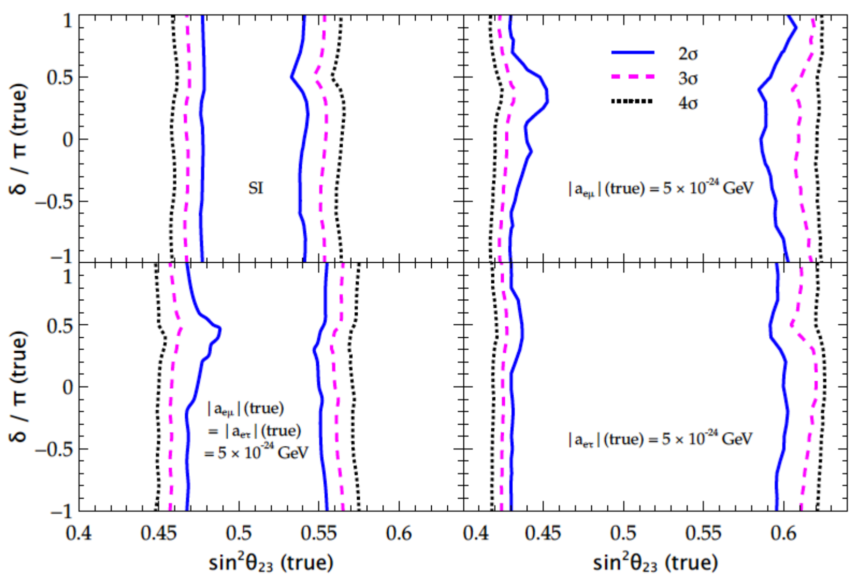
Berenboim, Masud, Ternes, Tortola, PLB 788 (2019) 308

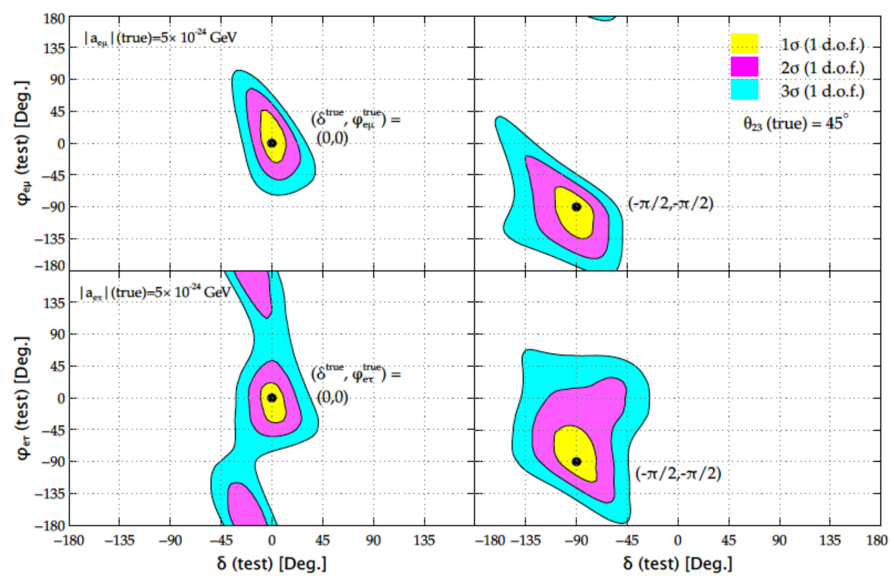
Ref. [11]: Super-K (1410.4267)

Can LIV affect the Sensitivity of DUNE?

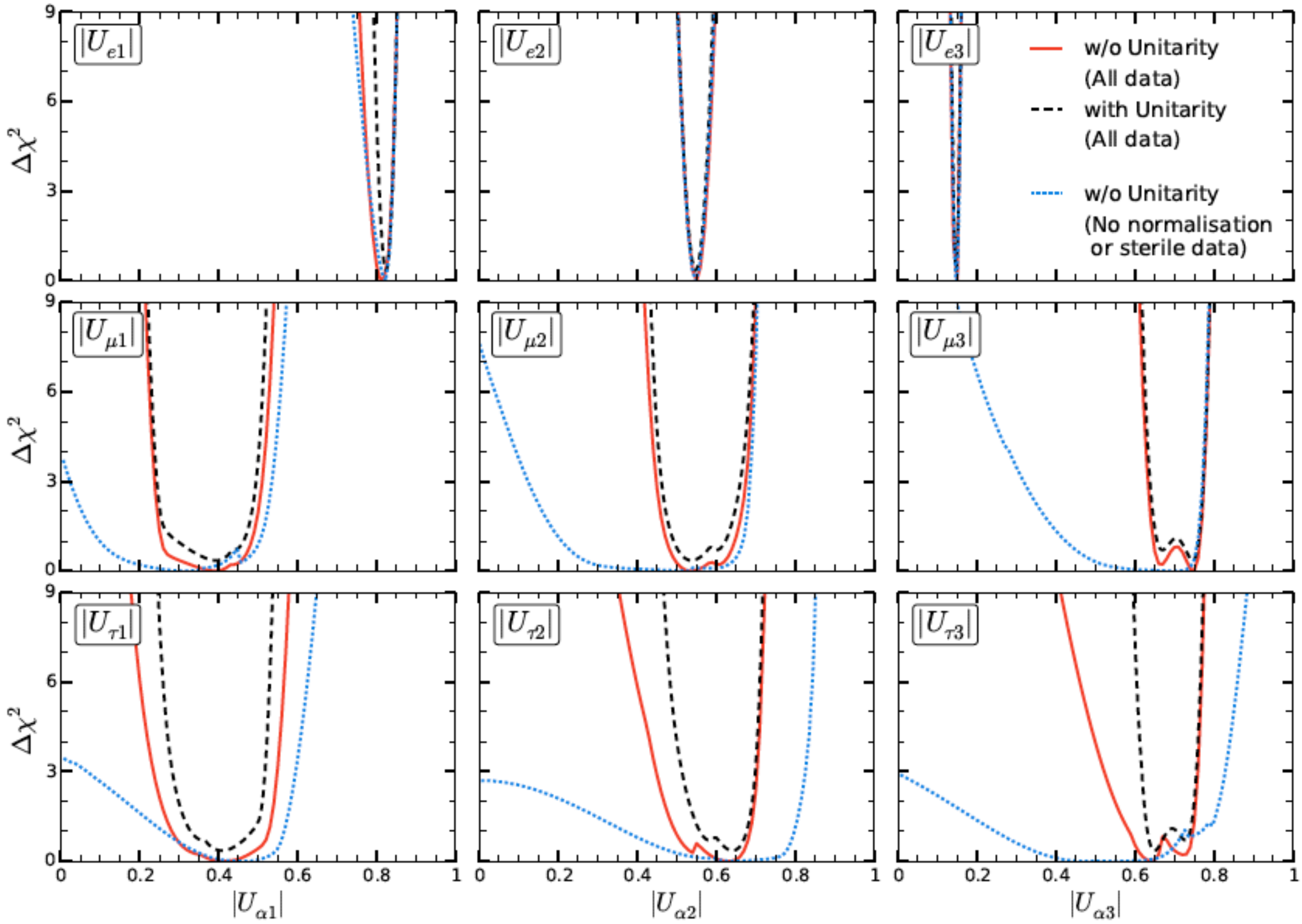


Agarwalla, Masud, 1912.13306 [hep-ph]



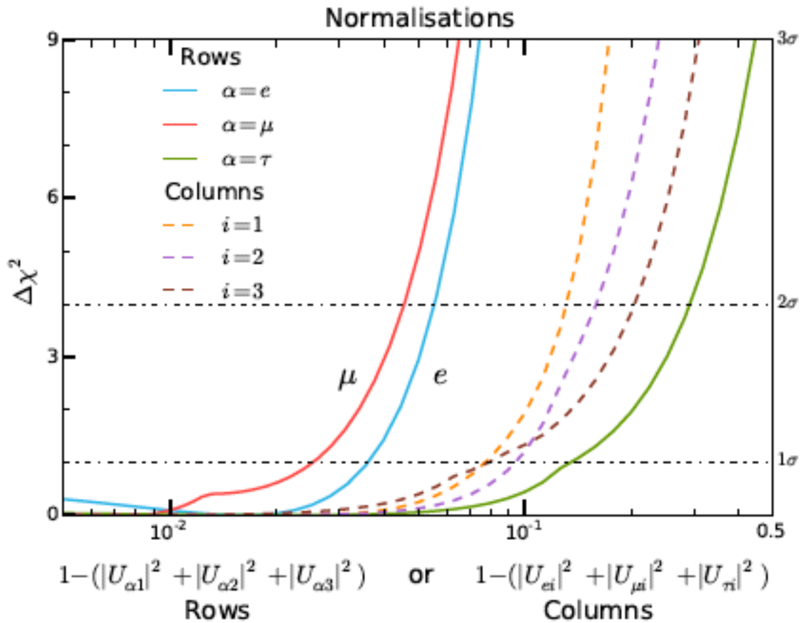


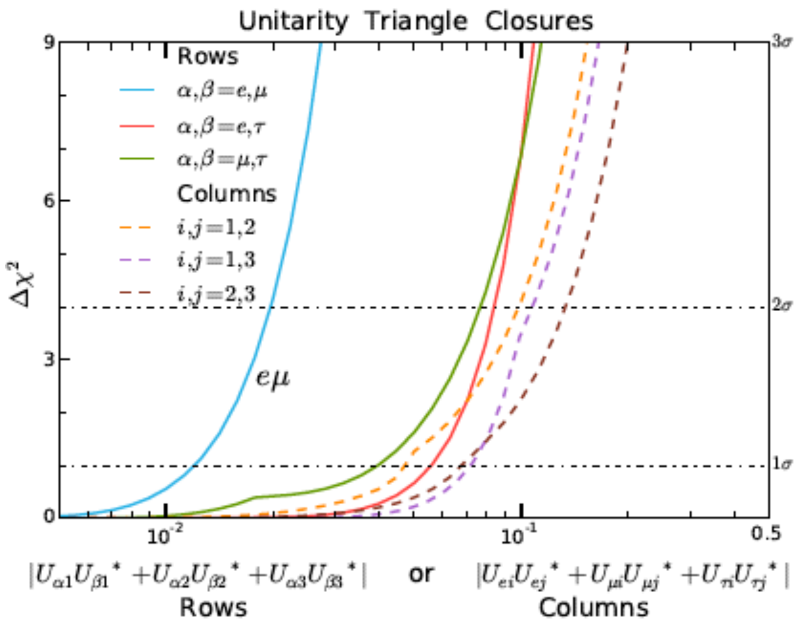
Unitarity Constraints



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

Unitarity Constraints





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

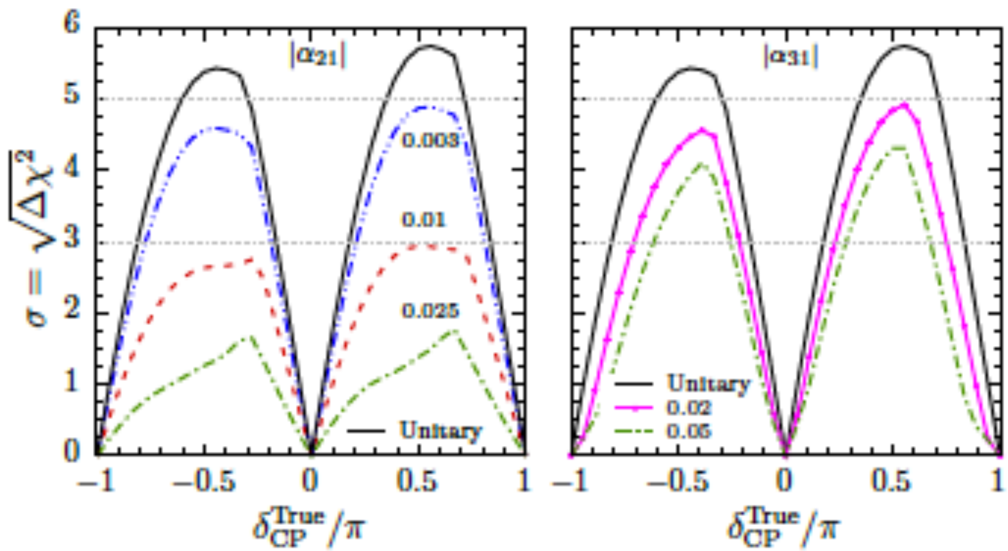
$$\boxed{\sum_{i=1}^{3} |U_{\alpha i}|^2 \le 1}$$

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

Triangles no longer close

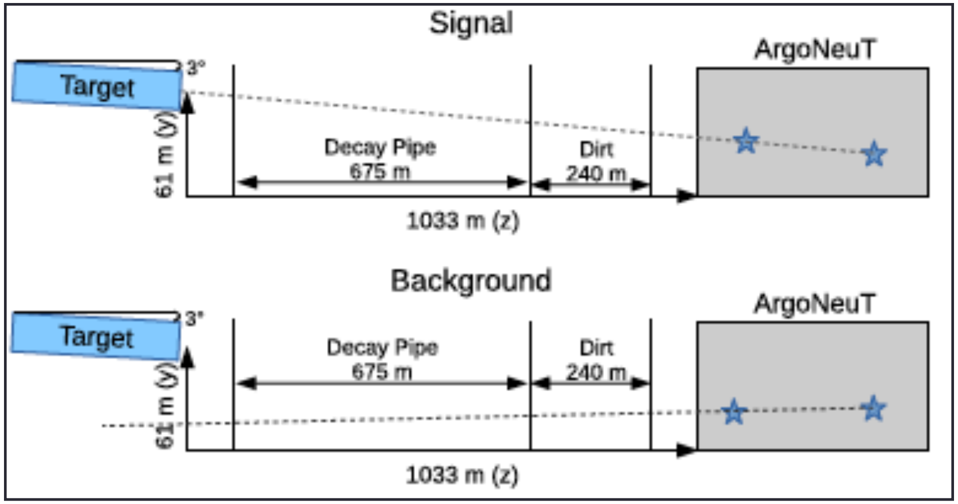
Parke, Ross-Lonergan, PRD 93 (2016) 11, 113009

CP violation in DUNE with non-unitary mixing

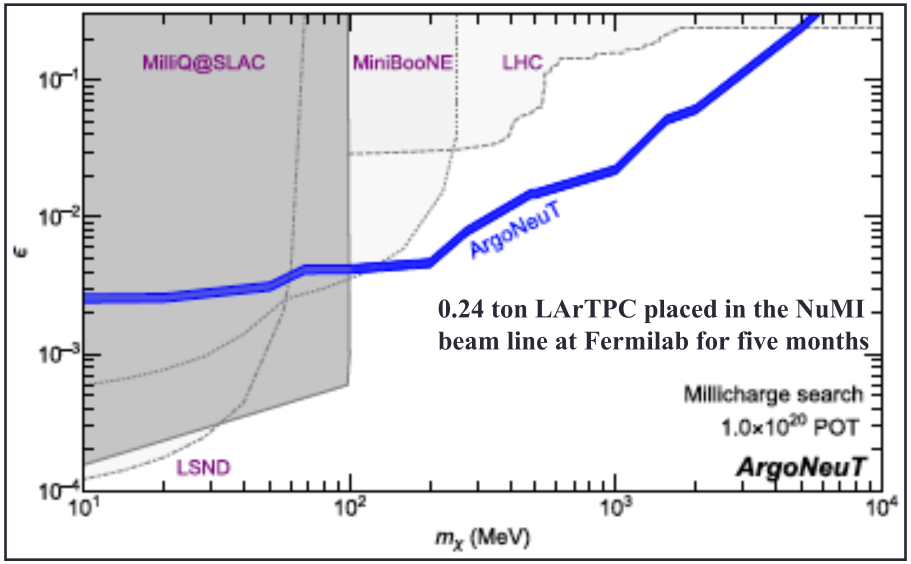


Escrihuela, Forero, Miranda, Tortola, Valle, NJP 19 (2017) 9, 093005

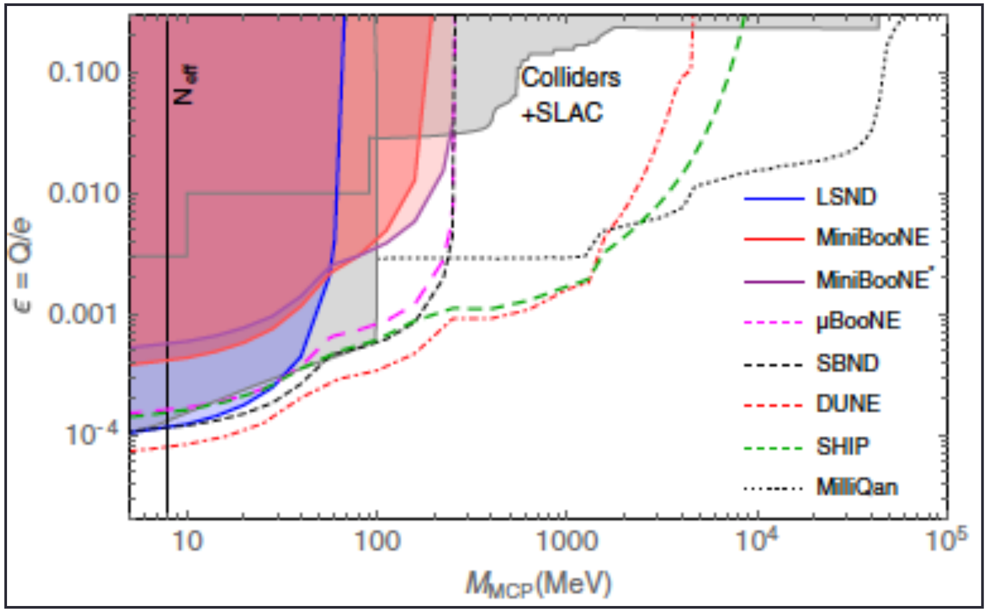
Search for Millicharged Particles (MCPs)



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