Long-range interactions at neutrino oscillation experiments

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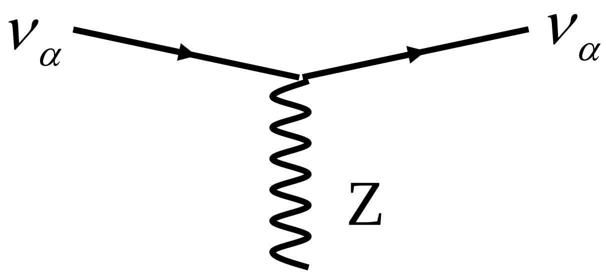
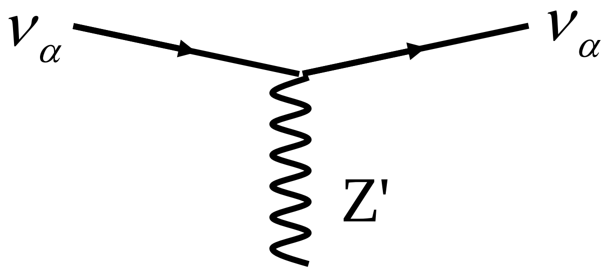
Long-range interactions (LRIs)

- Standard Model neutral-current interactions of neutrinos:
  - Flavour diagonal and universal



- Consider an anomaly-free $U(1)_X$ extension of the Standard Model, for eg. X = B-L, L_e-L_μ, etc. with gauge boson Z' and fine-structure constant α'.
  - Flavour diagonal but not universal

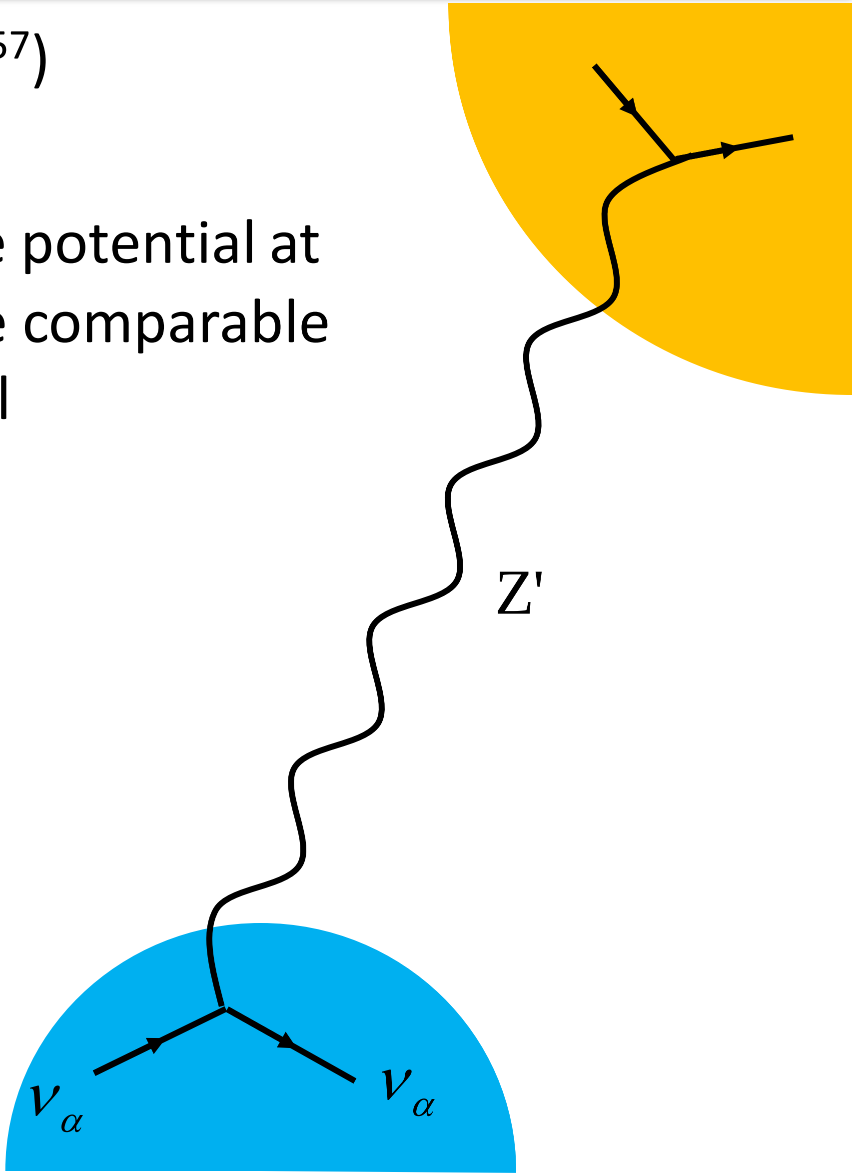


- The range of this interaction will depend on the Z' mass.

Long-range interactions (LRIs)

- Baryons and electrons in sun: $\mathcal{O}(10^{57})$
- Earth-sun distance: 1.5×10^{11} m
- If α' is $\mathcal{O}(10^{-52})$, then the long-range potential at earth with the sun as source will be comparable to the Wolfenstein matter potential

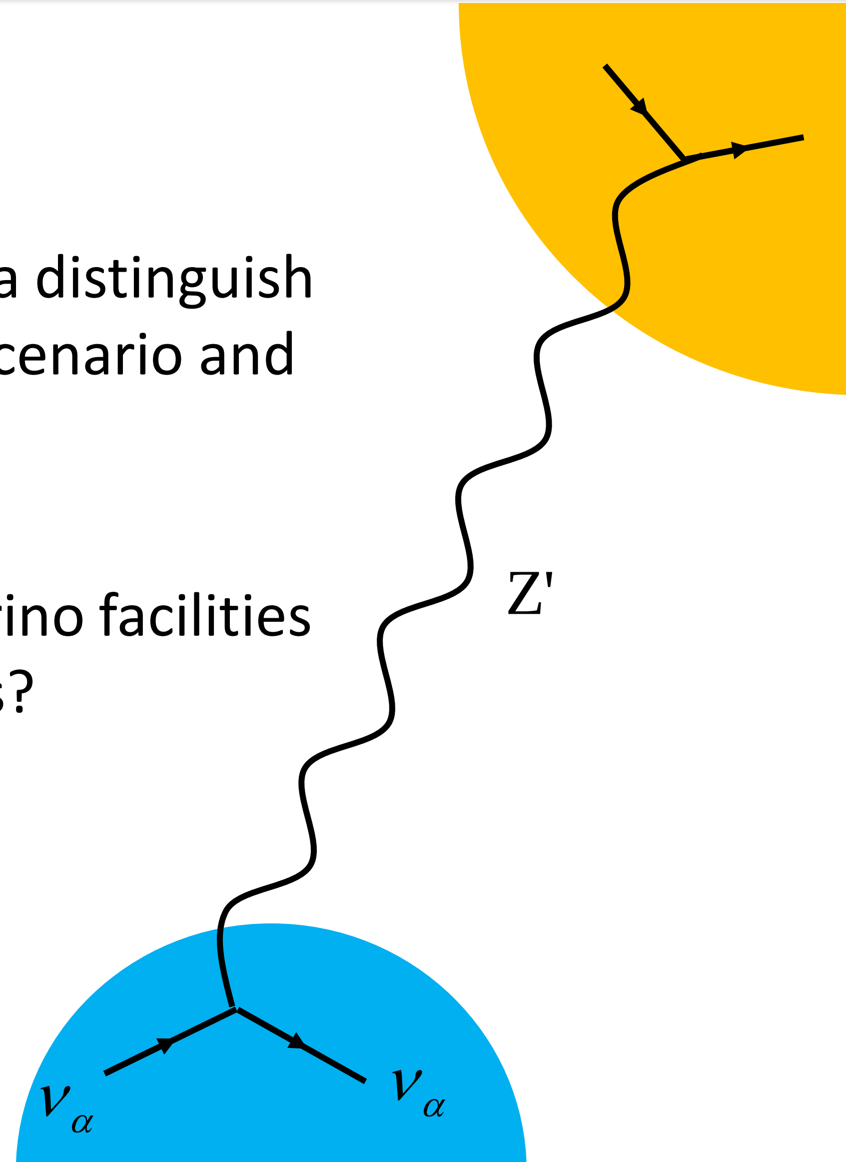
Joshipura, Mohanty 2004
Gonzalez-Garcia, do Holanda, Masso, Zukanovich Funchal 2007
Bandyopadhyay, Dighe, Joshipura 2007
Davoudiasl, Lee, Marciano 2011
Samanta 2011
Agarwalla, Chatterjee, Dasgupta 2015
Agarwalla, Khatun, Thakore 2018
Wise, Zhang 2018



Long-range interactions (LRIs)

- Can future neutrino oscillation data distinguish between the standard oscillation scenario and LRIs?

- Will measurements at future neutrino facilities be affected by the presence of LRIs?



Formalism

- Most general anomaly-free combination:

$$\eta(B-L)+\beta(L_e-L_\mu)+\gamma(L_\mu-L_\tau)+\delta(L_\tau-L_e)$$
$$\equiv p_0 B + p_1 L_e + p_2 L_\mu + p_3 L_\tau$$

- Potential at earth because of matter in the sun:

$$V^{\odot} = \frac{\alpha'}{R_{ES}}(p_0 N_n^{\odot} + p_0 N_p^{\odot} + p_1 N_e^{\odot})$$
$$= \frac{\alpha' N_n^{\odot}}{R_{ES}}(p_0 + p_0 Y_p^{\odot} + p_1 Y_e^{\odot}) \; ,$$

- Similarly, for earth. Then,

$$V_{LR} = V^{\odot} + V^{\oplus}$$

Formalism

- Neutrino propagation Hamiltonian:

$$\begin{bmatrix} V_{SM} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} p_1 V_{LR} & 0 & 0 \\ 0 & p_2 V_{LR} & 0 \\ 0 & 0 & p_3 V_{LR} \end{bmatrix}$$

$$\frac{\Delta m^2_{31}}{2E} \left\{ \begin{bmatrix} \hat{A} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} p & 0 & 0 \\ 0 & \xi/2 & 0 \\ 0 & 0 & -\xi/2 \end{bmatrix} \right\}$$

with $\hat{A} = 2EV_{SM}/\Delta m^2_{31}$, $p = 2E(p_1 - \frac{p_2+p_3}{2})V_{LR}/\Delta m^2_{31}$
and $\xi = 2E(p_2 - p_3)V_{LR}/\Delta m^2_{31}$.

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α'

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- Effect of LRIs at NOvA > Effect of LRIs at T2K

$$\sin^2 2\tilde{\theta}_{23} = \frac{\sin^2 2\theta_{23}}{(\xi - \cos 2\theta_{23})^2 + \sin^2 2\theta_{23}}$$

- If LRIs are sizeable, the effective value of θ_{23} measured by NOvA should deviate from maximal mixing

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- NOvA sees slight deviation, but is still compatible with T2K, consistent with maximal mixing

Gauge group	Best-fit α' (90% bound) $\times 10^{-52}$
$L_e - L_\mu$	0.631 (1.26)
$L_e - L_\tau$	0.794 (1.41)
$B - L_e - 2L_\tau$	2.0 (3.55)

Translating NSI bounds into LRI bounds

- Note similarity with non-standard interactions (NSIs) in matter:

$$\sqrt{2}G_F n_e \left\{ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{bmatrix} \right\}$$

$$\varepsilon_{ee} = \frac{p_1 V_{LR}}{\sqrt{2}G_F n_e}\ , \ \varepsilon_{\mu\mu} = \frac{p_2 V_{LR}}{\sqrt{2}G_F n_e}\ , \ \varepsilon_{\tau\tau} = \frac{p_3 V_{LR}}{\sqrt{2}G_F n_e}$$

$$\text{and } \varepsilon_{\alpha\beta} = 0 \text{ for } \alpha \neq \beta\ .$$

Farzan, Tortola 2018	ε_{ee}	$\varepsilon_{\mu\mu}$	$\varepsilon_{\tau\tau}$
90% bounds from various sources	$\mathcal{O}(1)$	$\mathcal{O}(0.1)$	$\mathcal{O}(1)$

$\alpha' < 0.11 \times 10^{-52}$ L_e-L_μ ← Wise, Zhang 2018

$\alpha' < 0.75 \times 10^{-52}$ L_e-L_τ

$\alpha' < 3.85 \times 10^{-52}$ B-L_e-$2L_\tau$

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Caveats: The correspondence between bounds on NSIs and LRIs is not exact.

- Two-flavour vs three-flavour analyses
- Number of non-zero diagonal NSIs

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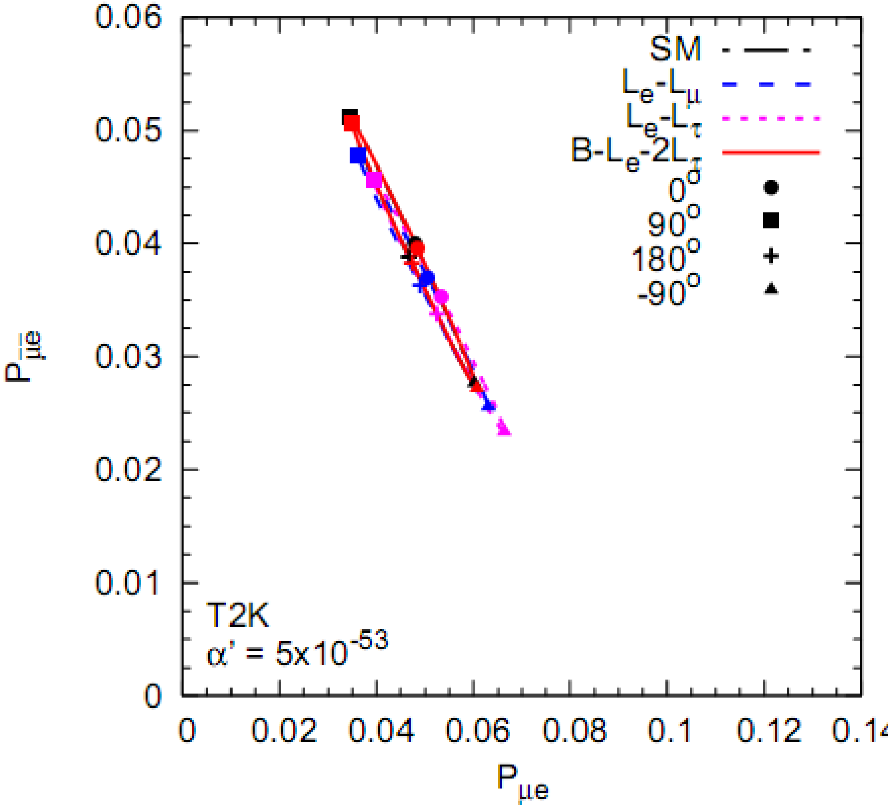
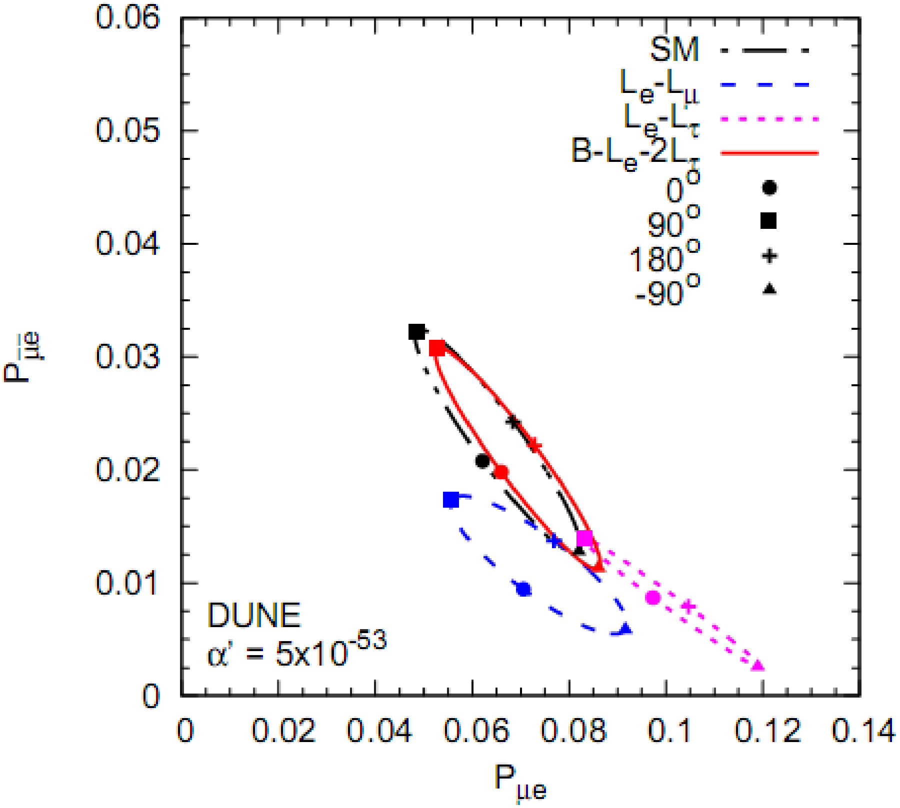
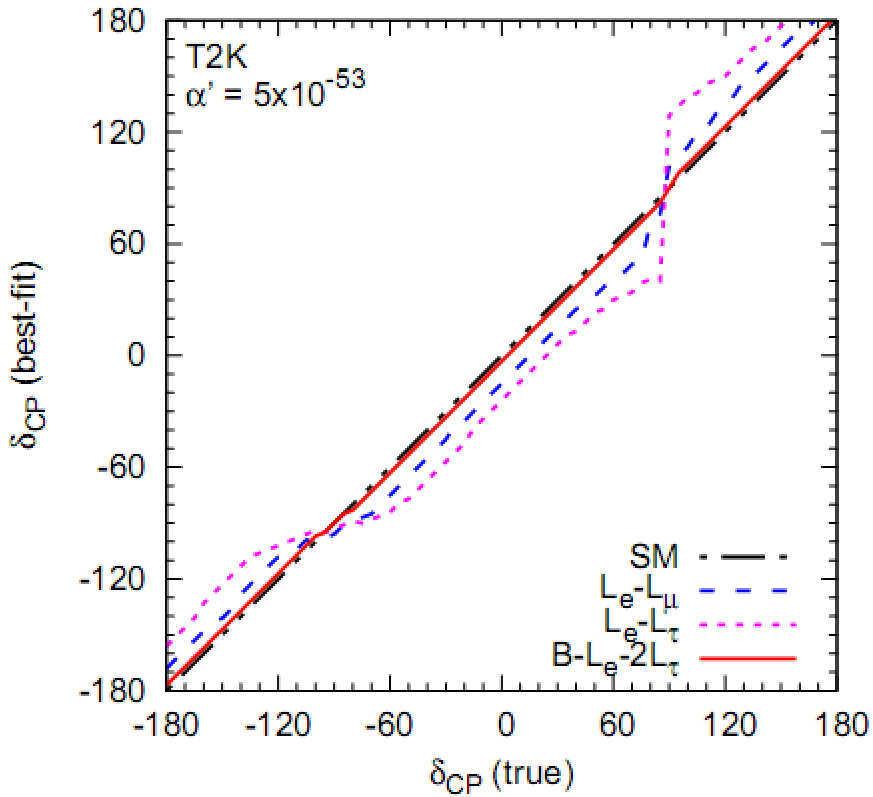
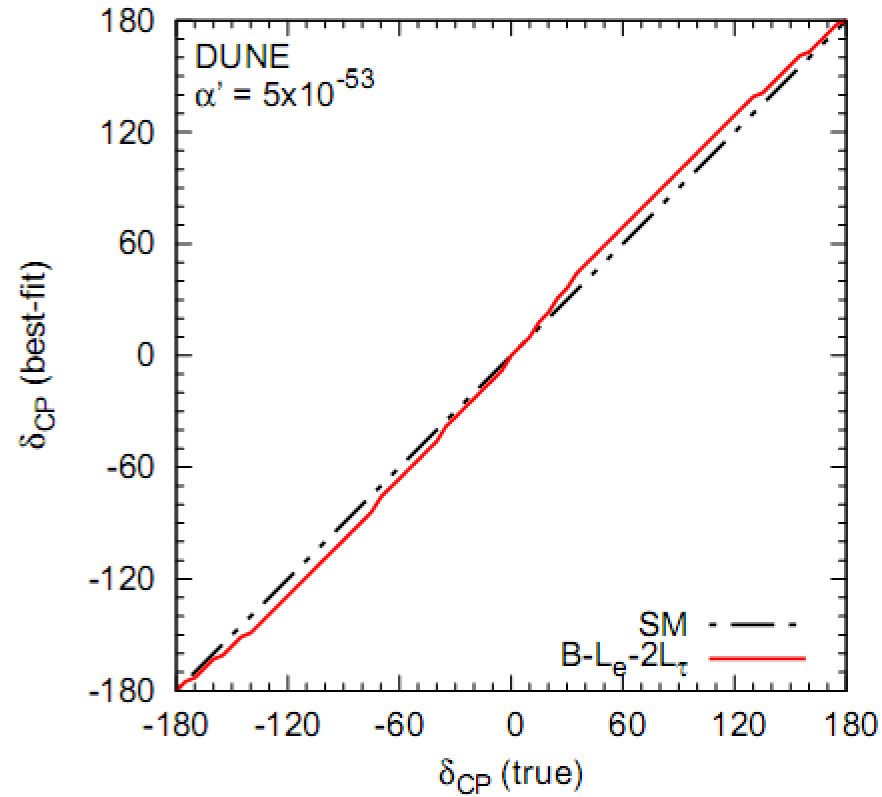
Effect of LRIs on CP measurement at DUNE





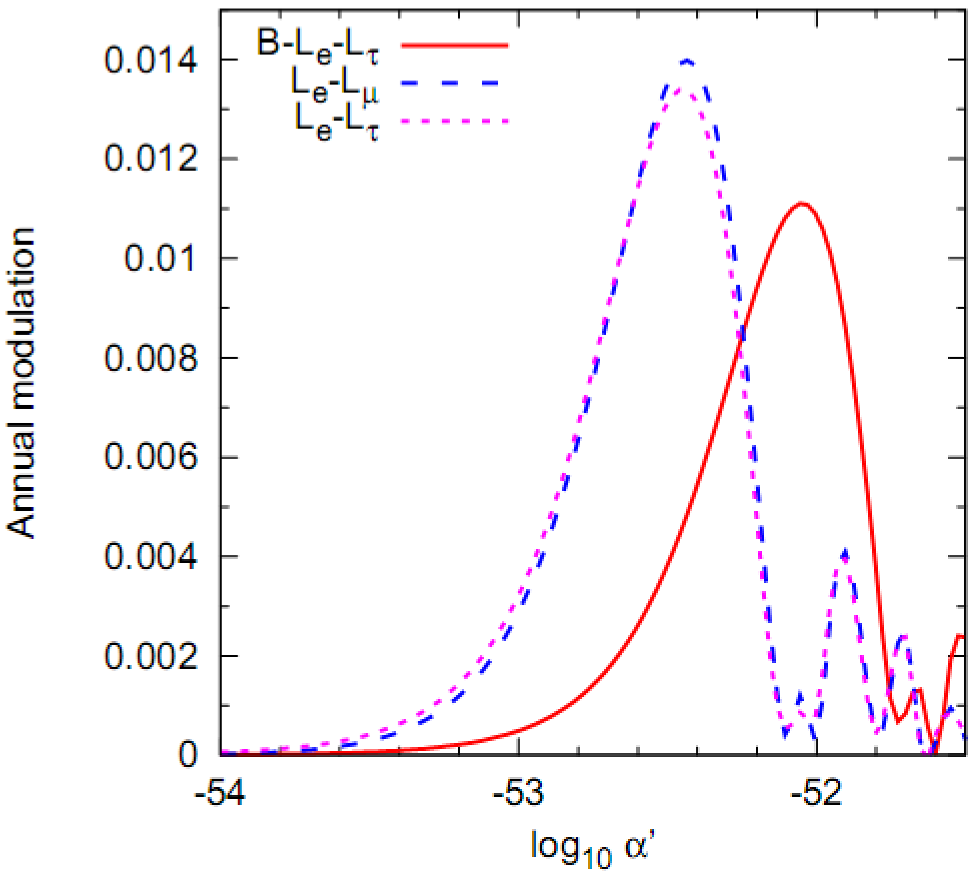
CP precision in presence of LRIs





Annual modulation

Distinguishing LRIs from terrestrial new physics effects

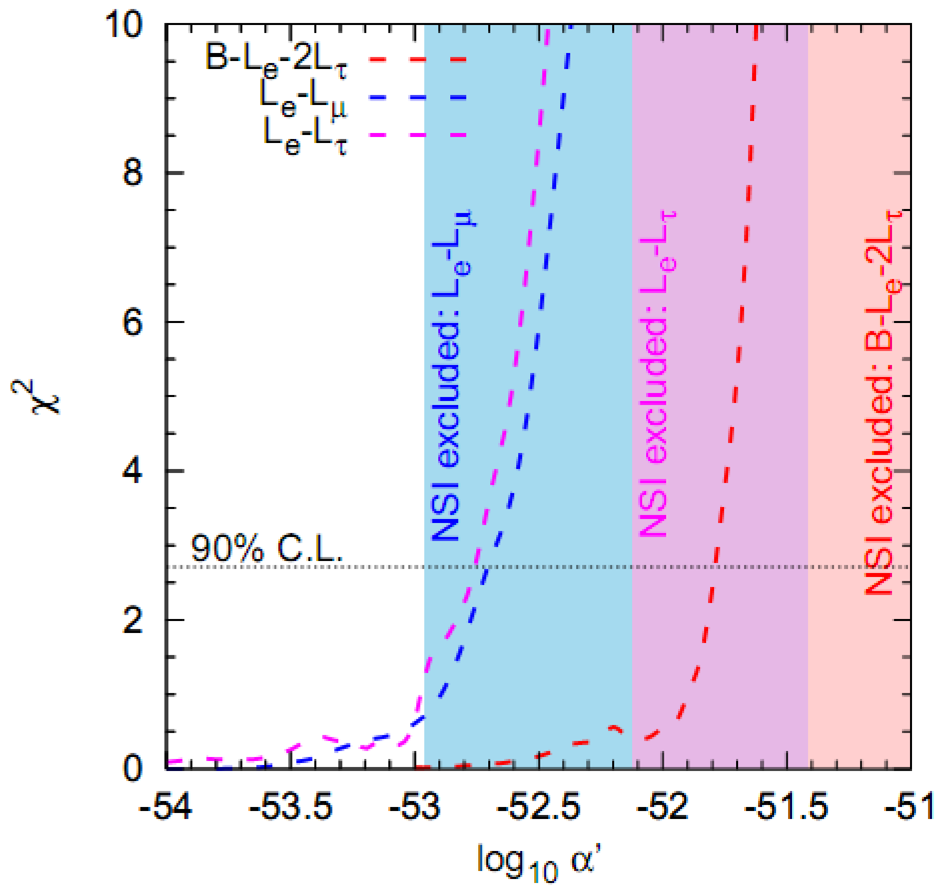


Annual modulation of atmospheric ν_μ events at DeepCore

Summary

- Long-range interactions can arise out of U(1) extensions of the Standard Model with very light Z'
- For the models under consideration, current / future experiments can constrain α' to be less than $\mathcal{O}(10^{-52})$ / $\mathcal{O}(10^{-53})$
- Connecting NSI bounds to LRI bounds is straightforward but not necessarily accurate
- B-L_e-2L_τ model: Hard to distinguish from SM, hence weak bounds. But CP measurement is not compromised much.
- LRIs can be distinguished from other (earth-sourced) NSI models using annual modulation of high energy events

THANK YOU



DUNE, 40 kilotons
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