Flavor-Dependent Long-Range ν Interactions in DUNE and T2HK: Synergy Breeds Power

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Based on: Flavor-dependent long-Range neutrino interactions in DUNE and T2HK: alone they constrain, together they discover; arXiv: 2305.05184.

19th Rencontres du Vietnam, Neutrino Workshop at IFIRSE,
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Introduction

Short distances
(heavy mediators)

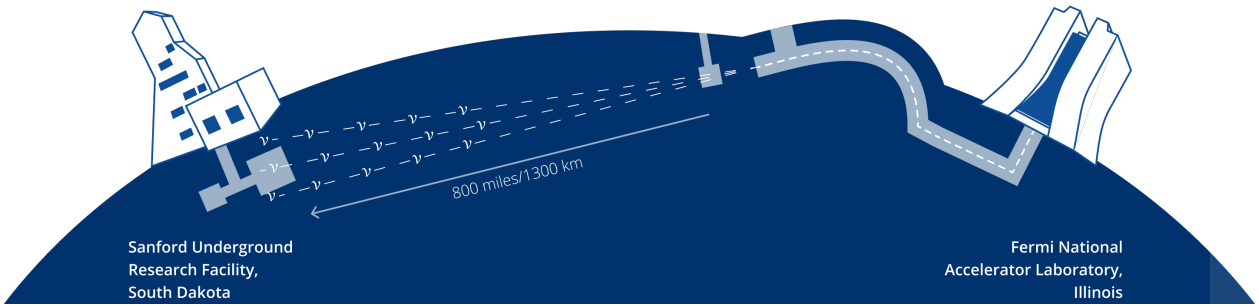
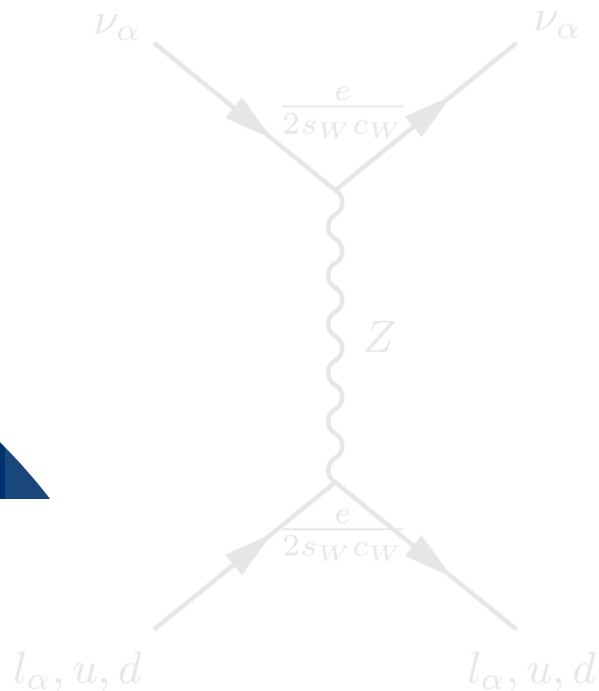


Image Credit: Chicago Sun-Times



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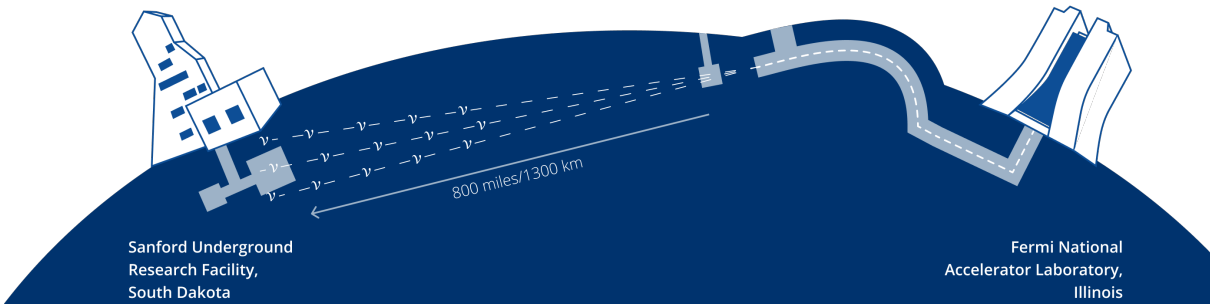
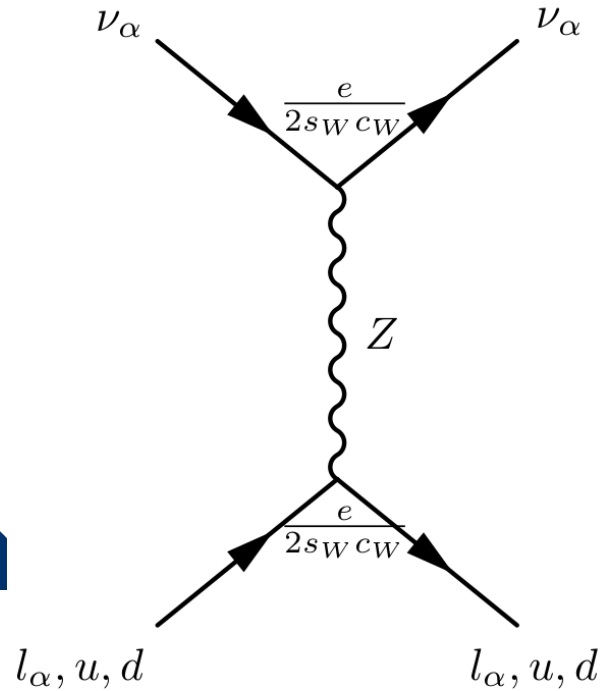
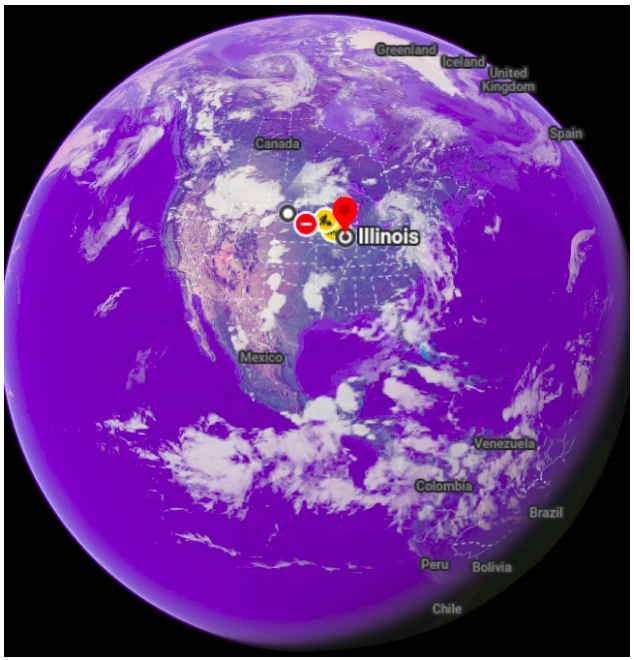


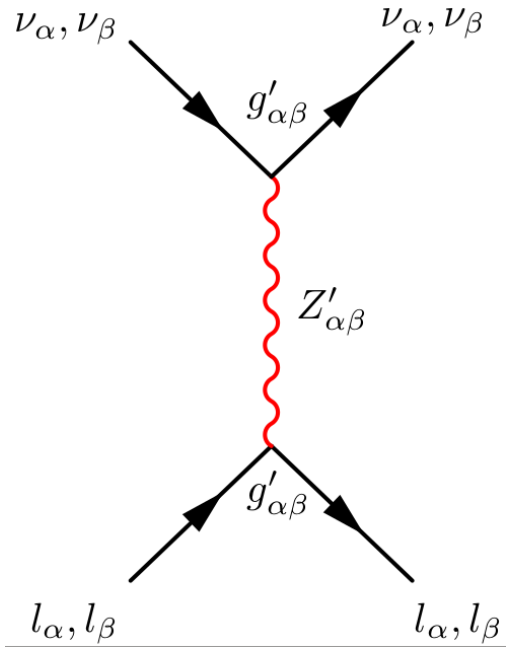


$SU(3)_C \times SU(2)_L \times U(1)_Y$
Standard Model contribution
mediated by Z boson

Introduction- looking for New Interactions

Long distances
(light mediators)

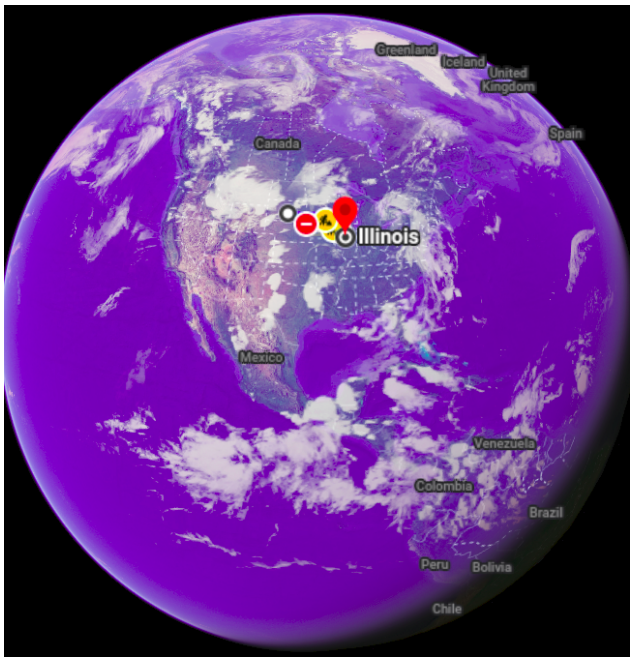




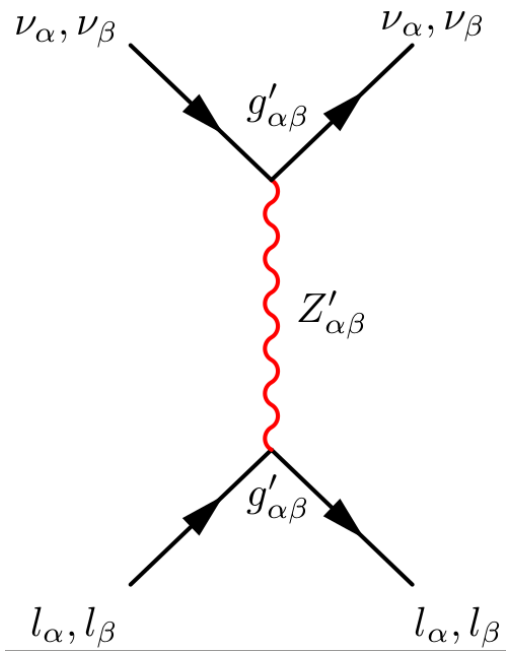
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{L_e - L_\beta}$$

Introduction- looking for New Interactions

Long distances
(light mediators)



$$V_{e\beta} = -g'^2_{e\beta}\frac{N_e}{4\pi d}e^{-m'_{e\beta}d}$$

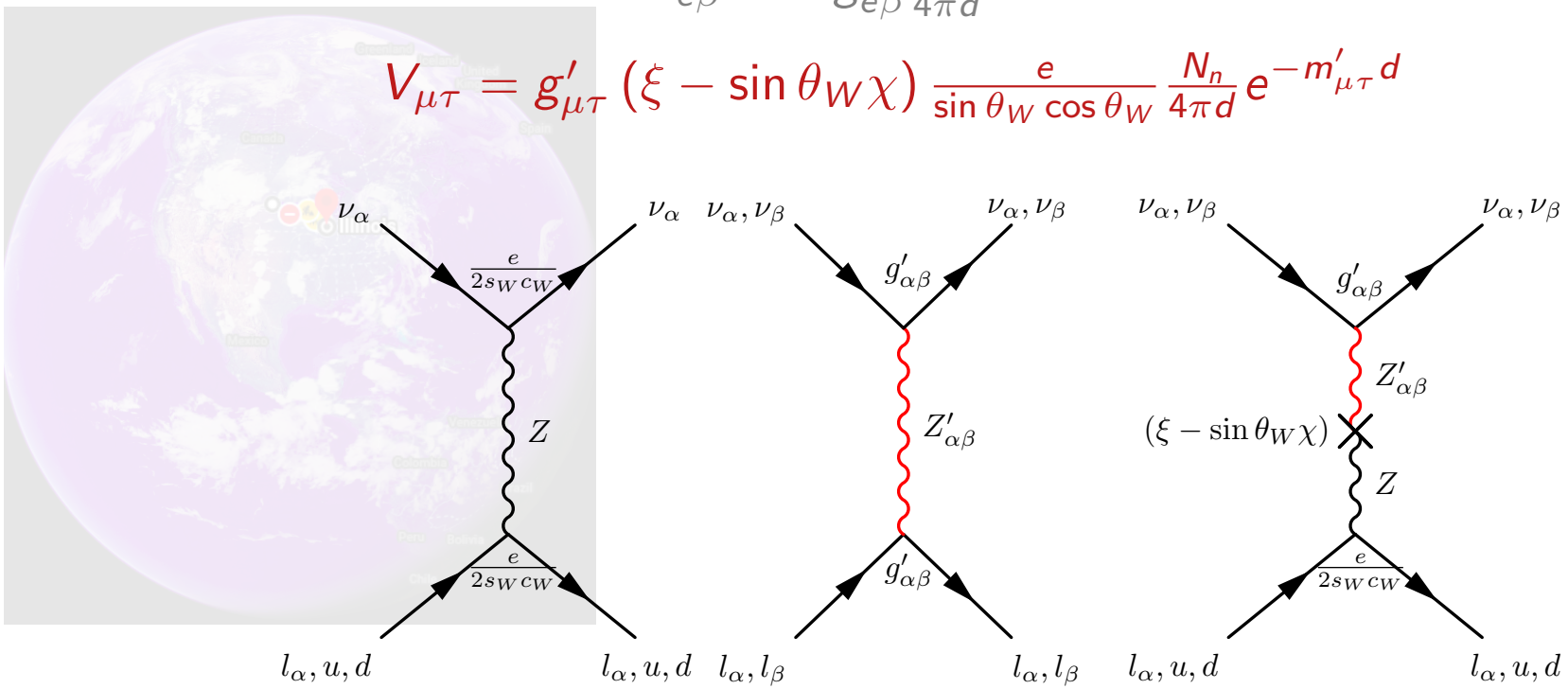


$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{L_e - L_\beta}$$

Long distances
(light mediators)

$$V_{e\beta} = -g'^2_{e\beta}\frac{N_e}{4\pi d}e^{-m'_{e\beta}d}$$

$$V_{\mu\tau} = g'_{\mu\tau}\left(\xi - \sin\theta_W\chi\right)\frac{e}{\sin\theta_W\cos\theta_W}\frac{N_n}{4\pi d}e^{-m'_{\mu\tau}d}$$

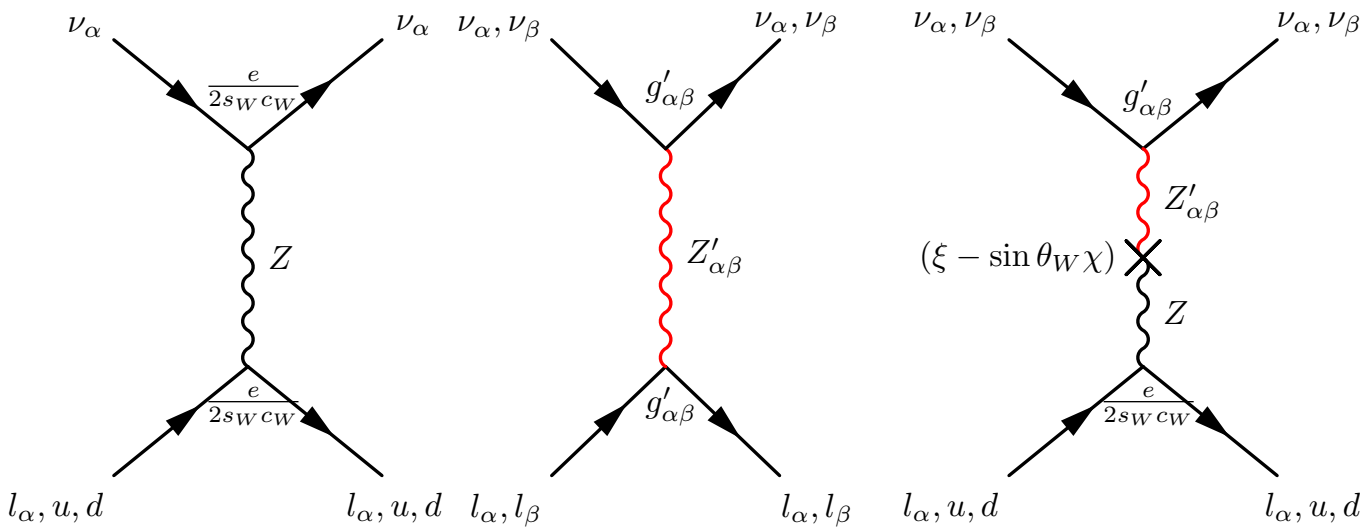


$$\mathrm{SU(3)}_C \times \mathrm{SU(2)}_L \times \mathrm{U(1)}_Y \times \mathrm{U(1)}_{L_\alpha - L_\beta}$$

Long distances: light mediators

Under $L_e - L_\mu$ and $L_e - L_\tau$, new interactions are sourced by electrons only.

Under $L_\mu - L_\tau$, new interactions are sourced by neutrons only.



$$\mathrm{SU(3)}_C \times \mathrm{SU(2)}_L \times \mathrm{U(1)}_Y \times \mathrm{U(1)}_{L_\alpha - L_\beta}$$

Introduction and Motivation

- Consequential effect of light mediators $\Longleftrightarrow$ long-range interactions in the 3-ν oscillation phenomenon.

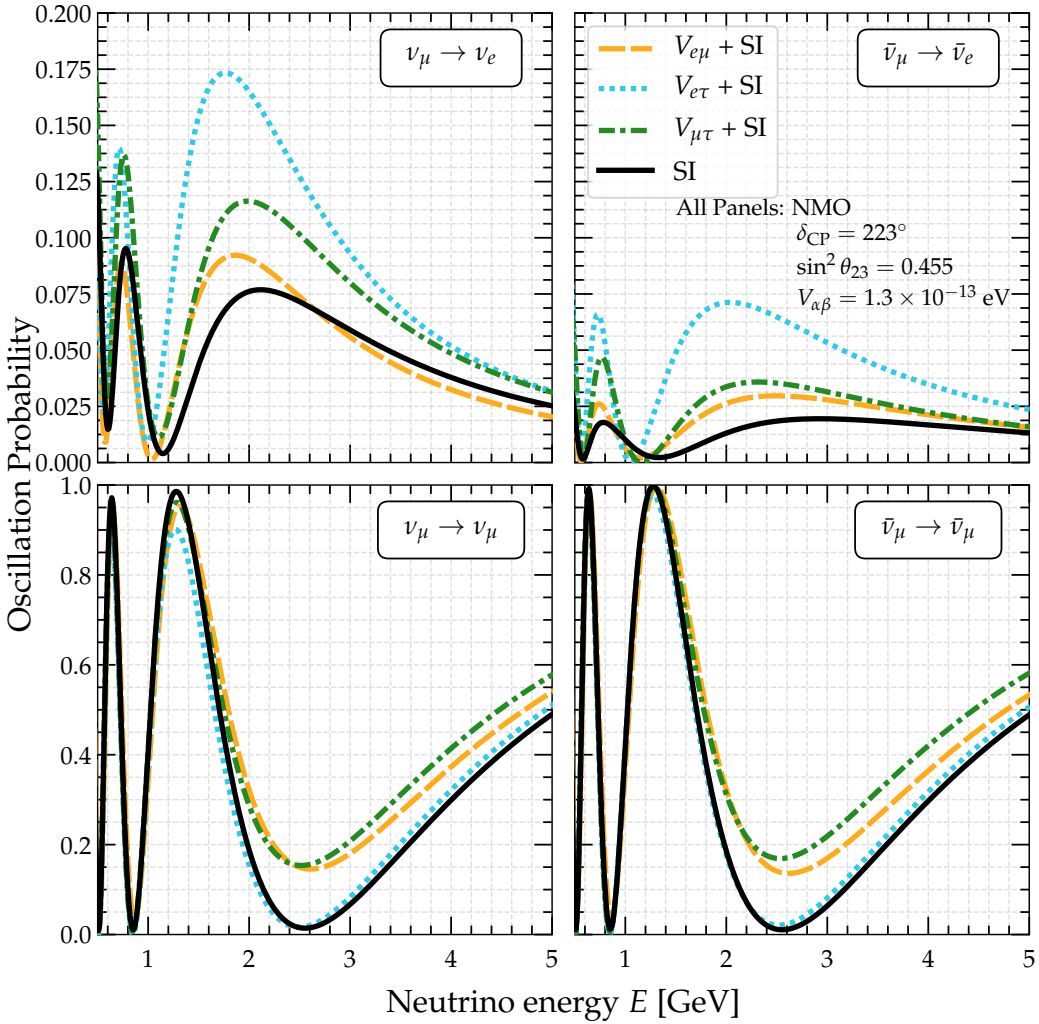
Order of $\frac{\Delta m^2_{31}}{2E} \sim \sqrt{2} G_F n_e \sim V_{\alpha\beta}$

- Consequential effect of light mediators $\Longleftrightarrow$ long-range interactions in the 3-ν oscillation phenomenon.

Order of $\mathbf{V_{\alpha\beta} \gtrsim 10^{-13}\ eV}$

- Sensitivity reach of next-generation long-baseline exp.: DUNE and T2HK
- Focussing on complementarity in DUNE + T2HK
  - Projected constraints?
  - Discovery potential?

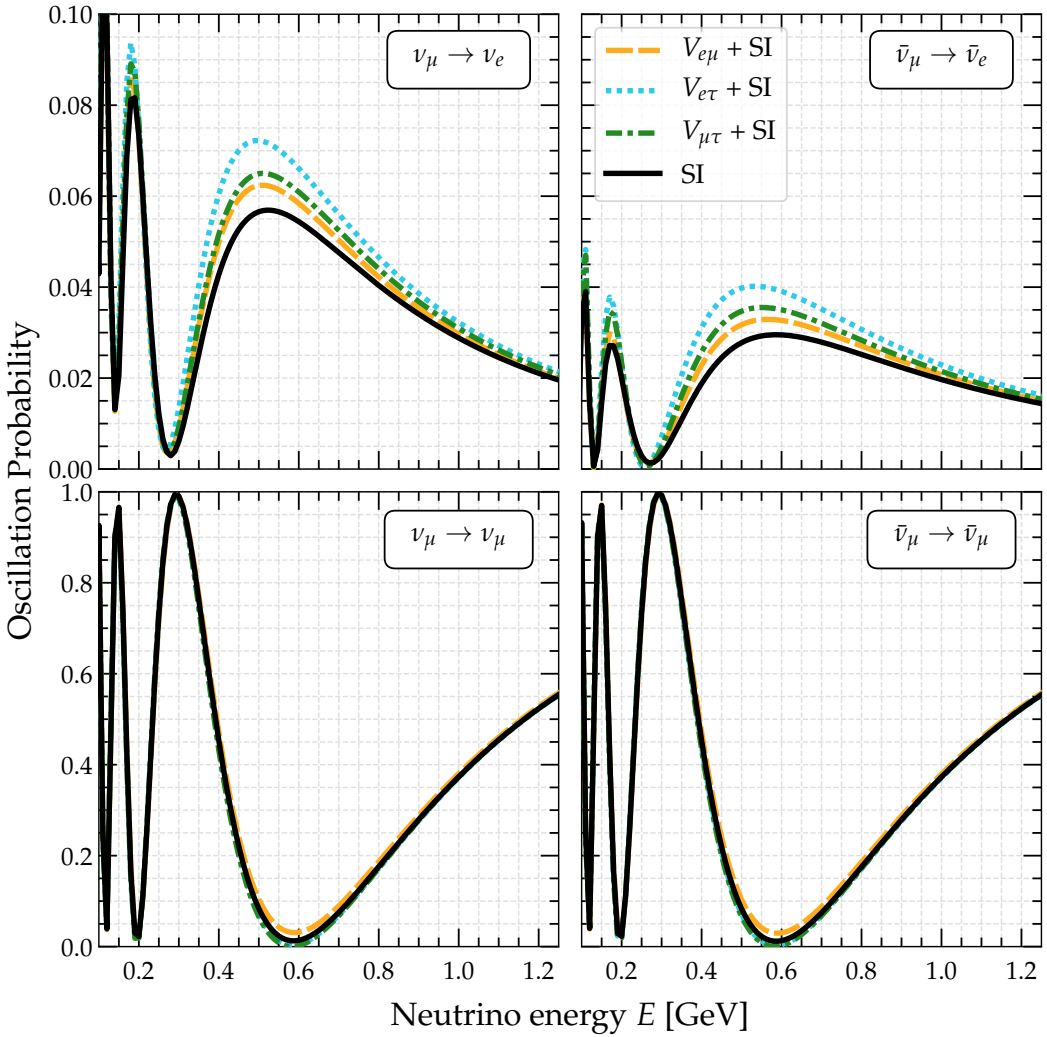
Oscillation Probability in presence of Long-Range Interactions



DUNE [5 ν + 5 $\bar{\nu}$]

- 480 kton MW year of exposure
  (arXiv: 2103.04797)
- Presence of $V_{e\tau}$ enhances first osc. maximum peak the most in appearance
- Presence of $V_{\mu\tau}$ and $V_{e\mu}$ affects first osc. minimum dip the most in disappearance
- Wide-band beam helps in analyzing different L/E ratios

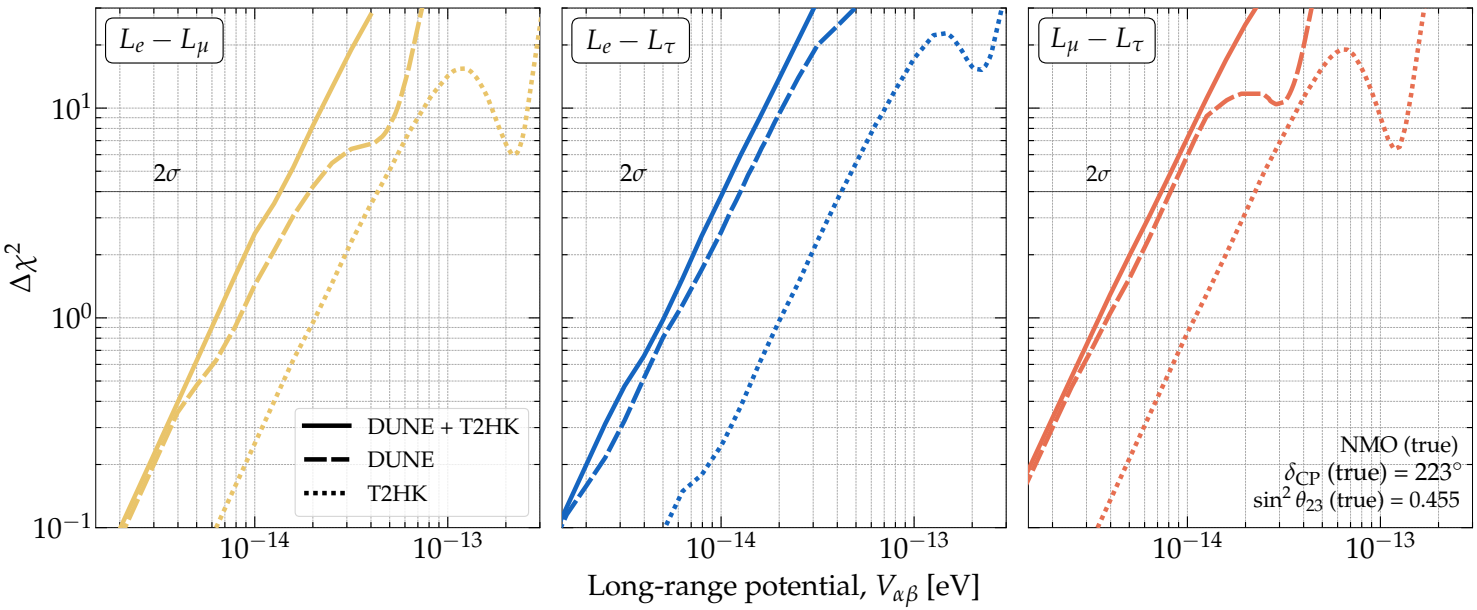
Oscillation Probability in presence of Long-Range Interactions



T2HK [2.5 ν + 7.5 $\bar{\nu}$]

- 2431 kton MW year of exposure (PTEP 2018 (2018) 6)
- Presence of $V_{e\tau}$ enhances first osc. maximum peak the most in appearance
- Presence of $V_{\mu\tau}$ and $V_{e\mu}$ affects first osc. minimum dip the most in disappearance

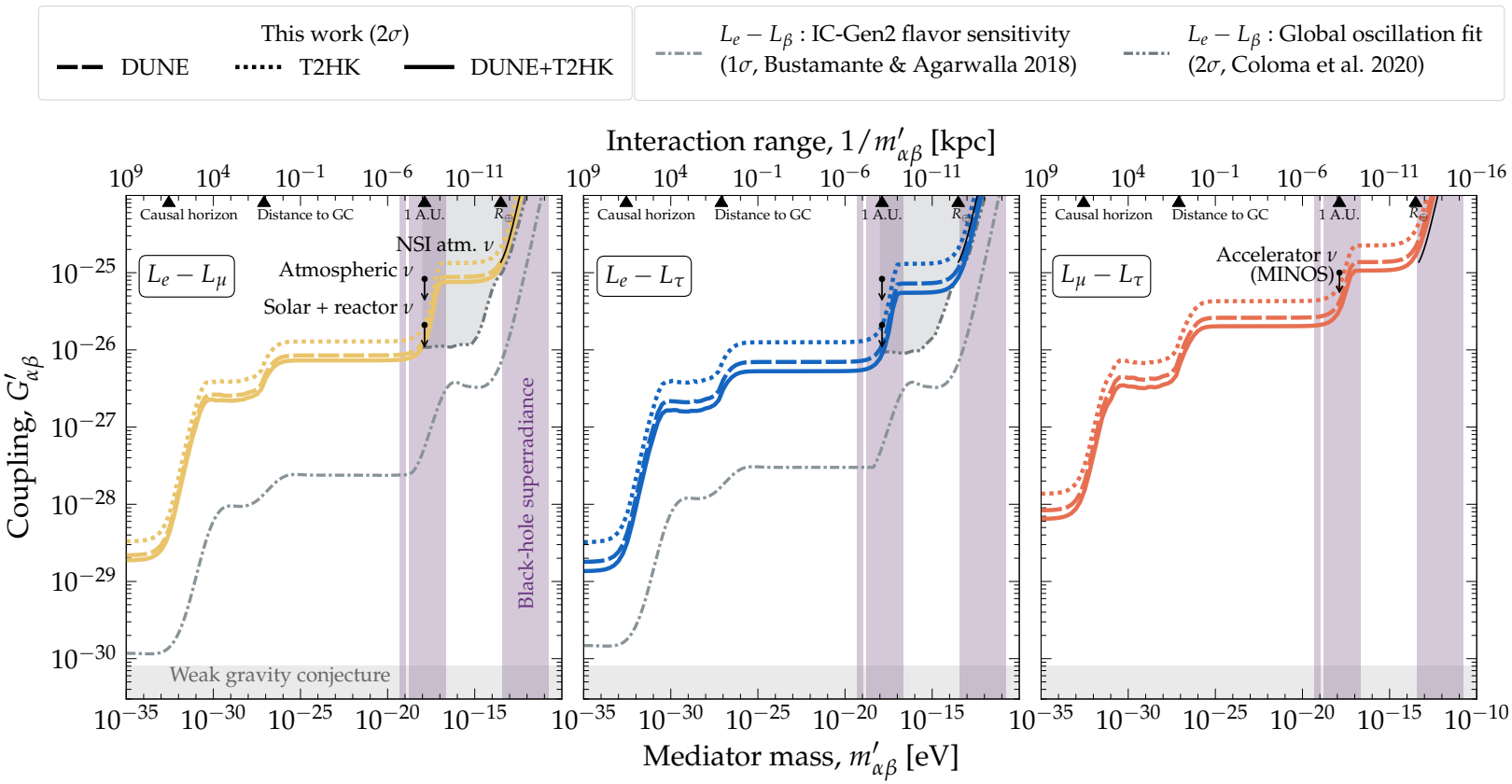
RESULT: Constraining Long-Range Interactions



$$\Delta\chi^2 = \min_{\sin^2\theta_{23}\,,\,\delta_{\rm CP}\,,\,\pm\Delta m^2_{31}} \left\{\chi^2({\rm SI})({\rm test}) - \chi^2({\rm SI}+{\rm LRI})({\rm true})\right\},$$

- Complementarity between DUNE + T2HK facilitates degeneracy-free constraints.
- Limits on $V_{\mu\tau}$ are strongest.
- Degeneracy in DUNE: Uncertainty in $\delta_{\rm CP}$ and θ_{23}
- Degeneracy in T2HK: Uncertainty in θ_{23} and sign of Δm^2_{31}

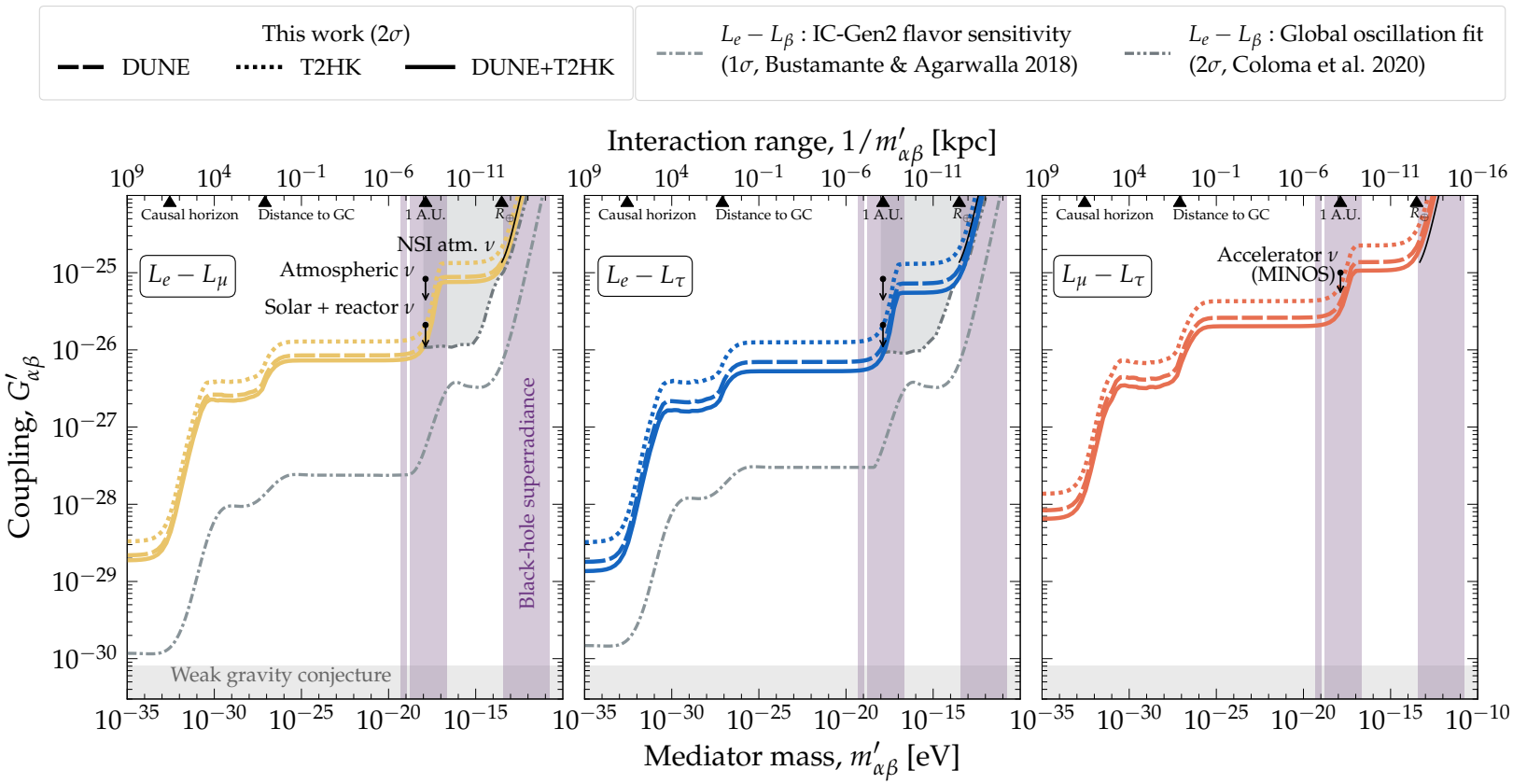
RESULT: Upper Limits on Coupling vs Mass plane (2σ)



where

$$G'_{\alpha\beta} = \begin{cases} g'_{e\mu} & , \quad \text{for } \alpha,\beta = e,\mu \\ g'_{e\tau} & , \quad \text{for } \alpha,\beta = e,\tau \\ \sqrt{g'_{\mu\tau}(\xi - \sin\theta_W \chi)} & , \quad \text{for } \alpha,\beta = \mu,\tau \end{cases} .$$

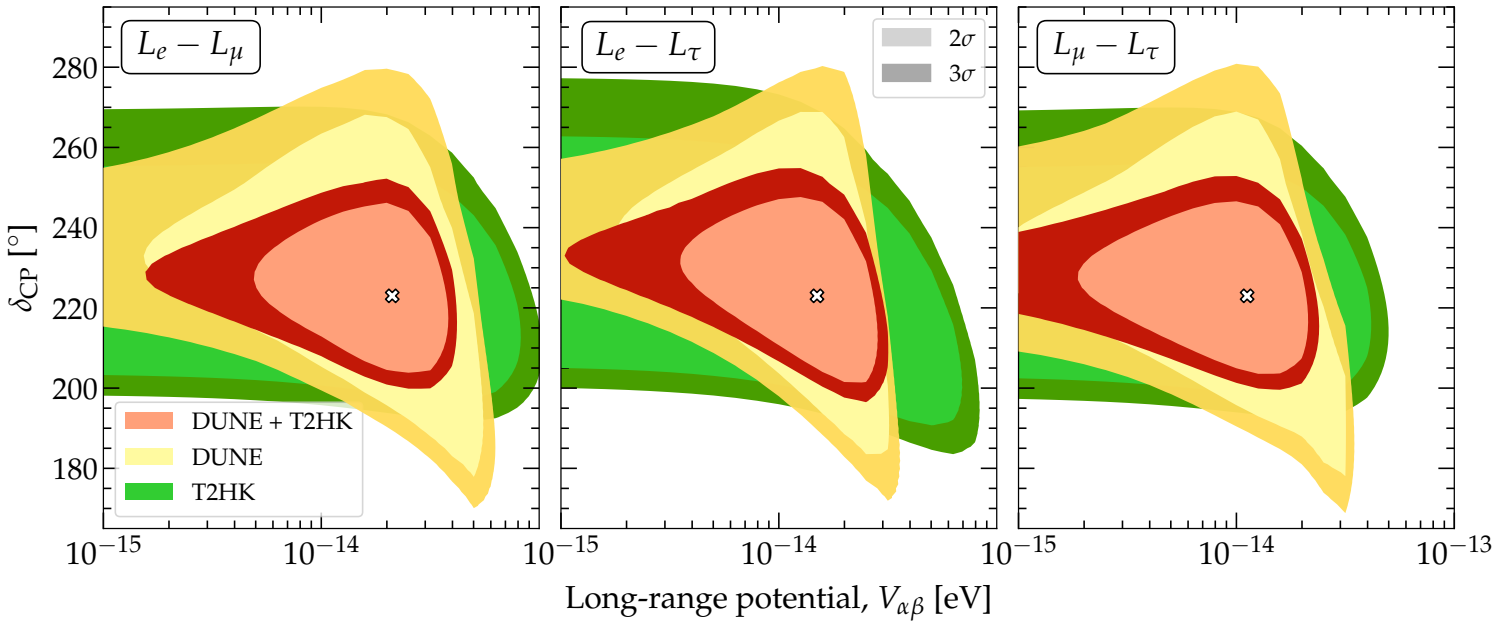
RESULT: Upper Limits on Coupling vs Mass plane (2σ)



$$V_{\alpha\beta} = V^{\oplus}_{\alpha\beta} + V^{\leftmoon}_{\alpha\beta} + V^{\odot}_{\alpha\beta} + V^{\rm MW}_{\alpha\beta} + V^{\rm cos}_{\alpha\beta}$$

DUNE + T2HK may place strongest constraints on long-range interactions, especially for mediators lighter than 10^{-18} eV.

RESULT: Allowed Region in $V_{\alpha\beta} - \delta_{\rm CP}$ plane in presence of LRI



True Values:
$V_{e\mu} = 2.12 \times 10^{-14}$ eV
$V_{e\tau} = 1.6 \times 10^{-14}$ eV
$V_{\mu\tau} = 1.12 \times 10^{-14}$ eV
$\delta_{\rm CP} = 223^\circ$

$$\Delta\chi^2 = \min_{\sin^2\theta_{23}\ \pm\Delta m^2_{31}} \left\{ \chi^2(\mathrm{SI}+\mathrm{LRI})(\mathrm{test}) - \chi^2(\mathrm{SI}+\mathrm{LRI})(\mathrm{true}) \right\},$$

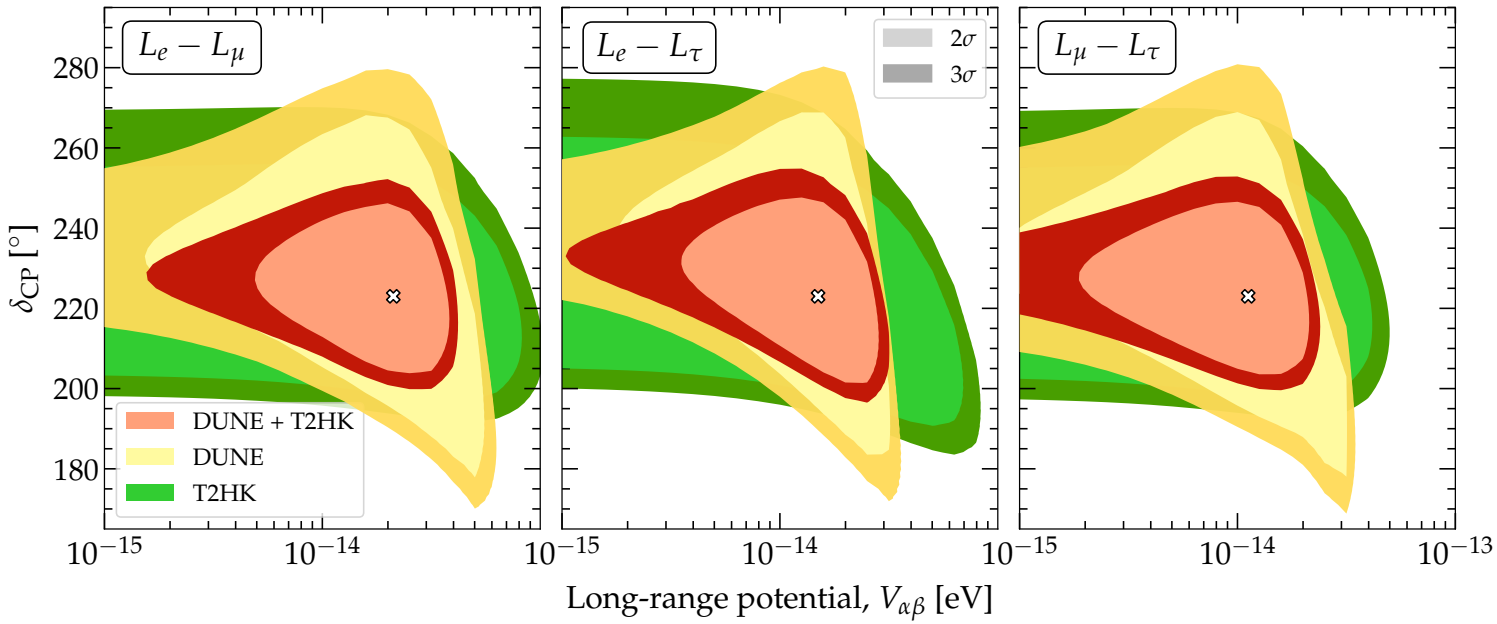
T2HK:

- short baseline $\Rightarrow$ less matter-contaminated CP $\Rightarrow$ high precision measurements of $\delta_{\rm CP}$
- short baseline $\Rightarrow$ less matter effect $\Rightarrow$ less sensitivity to mass ordering

DUNE:

- longer baseline $\Rightarrow$ more fake CP $\Rightarrow$ less precision in $\delta_{\rm CP}$
- longer baseline $\Rightarrow$ more matter effect $\Rightarrow$ high sensitivity to mass ordering

RESULT: Allowed Region in $V_{\alpha\beta} - \delta_{CP}$ plane in presence of LRI



T2HK:

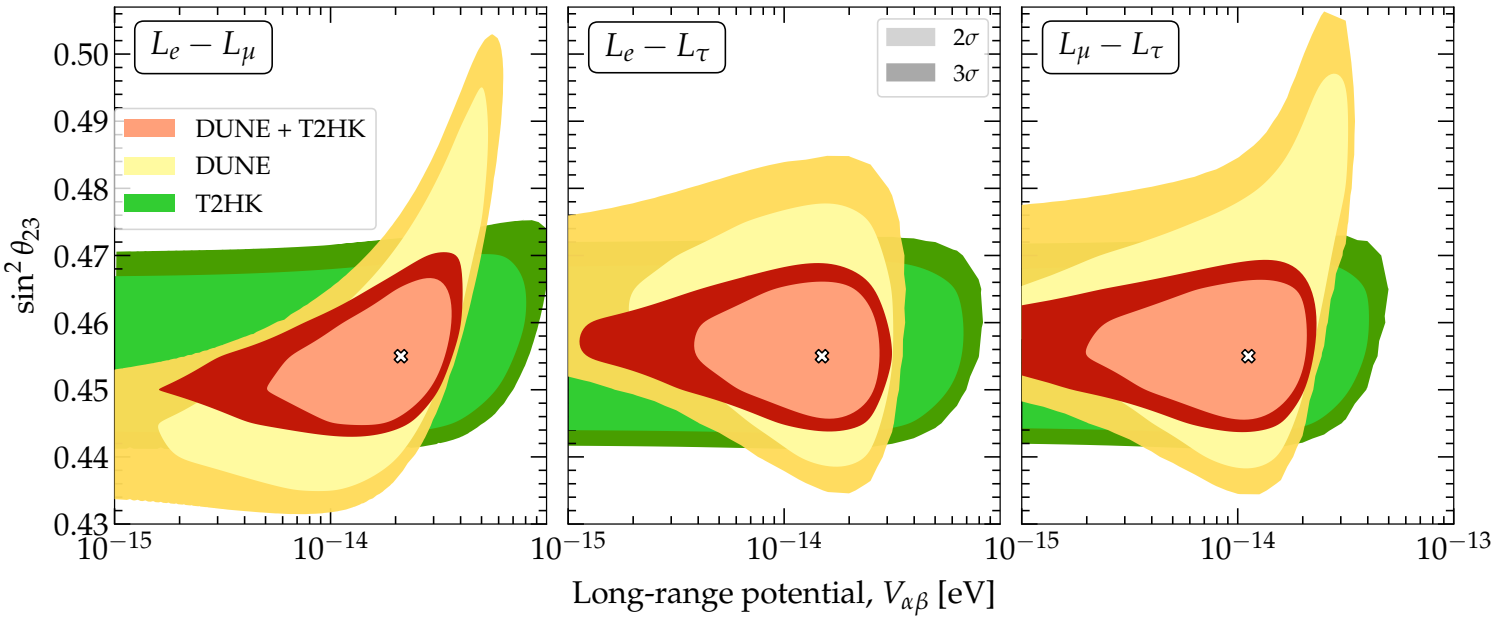
- Short baseline; less matter-contaminated fake CP; high precision measurements of δ_{CP}
- Short baseline; less matter effect; less sensitivity to mass ordering

DUNE:

- longer baseline; more fake CP; less precision in δ_{CP}
- longer baseline; more matter effect; high sensitivity to mass ordering

DUNE + T2HK complement each other and remove inherent degeneracies in standalone experiments.

RESULT: Allowed Region in $V_{\alpha\beta} - \theta_{23}$ plane in presence of LRI



True Values:
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$V_{e\tau} = 1.6 \times 10^{-14}$ eV
$V_{\mu\tau} = 1.12 \times 10^{-14}$ eV
$\sin^2\theta_{23} = 0.455$

$$\Delta\chi^2 = \min_{\delta_{CP}\ \pm\Delta m^2_{31}} \left\{\chi^2(\text{SI} + \text{LRI})(\text{test}) - \chi^2(\text{SI} + \text{LRI})(\text{true})\right\},$$

T2HK:

- huge detector $\Rightarrow$ large statistics $\Rightarrow$ better precision in $\sin^2\theta_{23}$
- short baseline $\Rightarrow$ less matter effect $\Rightarrow$ less sensitivity to mass ordering

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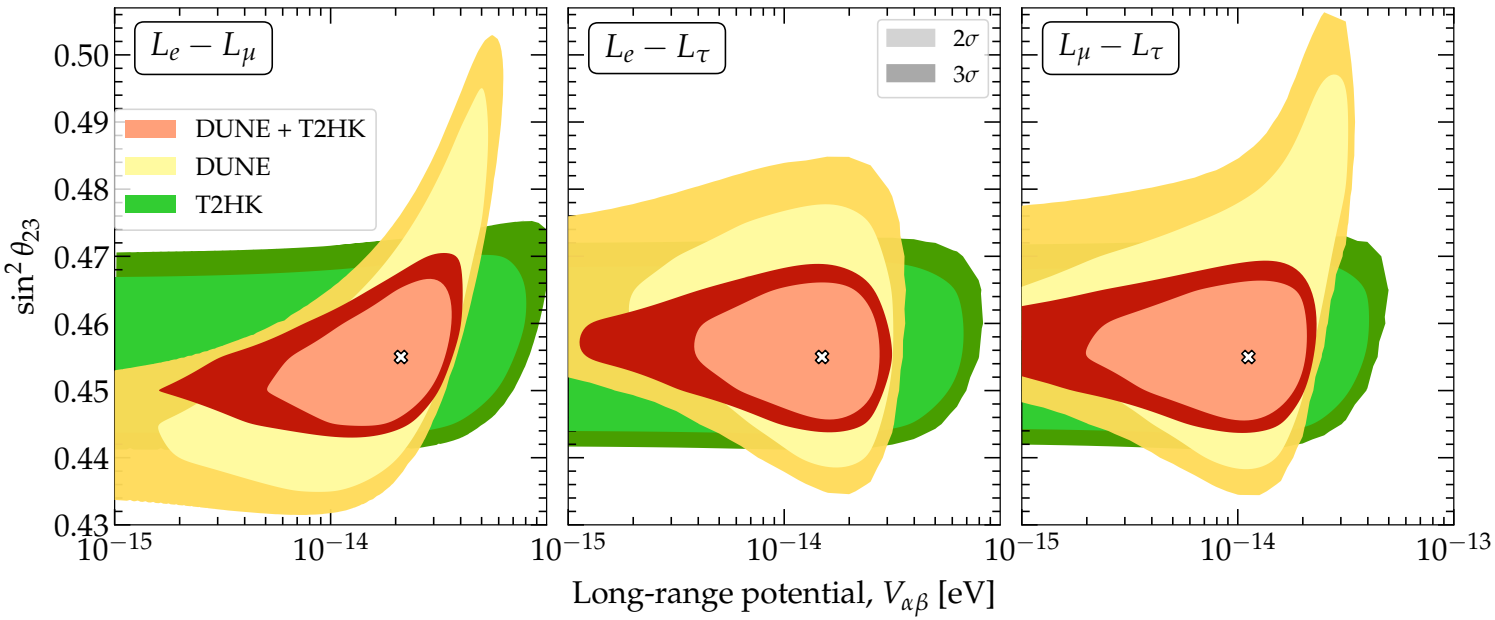


T2HK

- huge detector; large statistics; better precision in $\sin^2\theta_{23}$
- Short baseline; less matter effect; less sensitivity to mass ordering

DUNE + T2HK complement each other and remove inherent degeneracies in standalone experiments.

DUNE:

- longer baseline; more matter effect; high sensitivity to mass ordering

Key Takeaways

- High event rates and well characterized neutrino beams in the next-generation long-baseline experiments: DUNE and T2HK, make studies beyond the standard neutrino interactions promising.

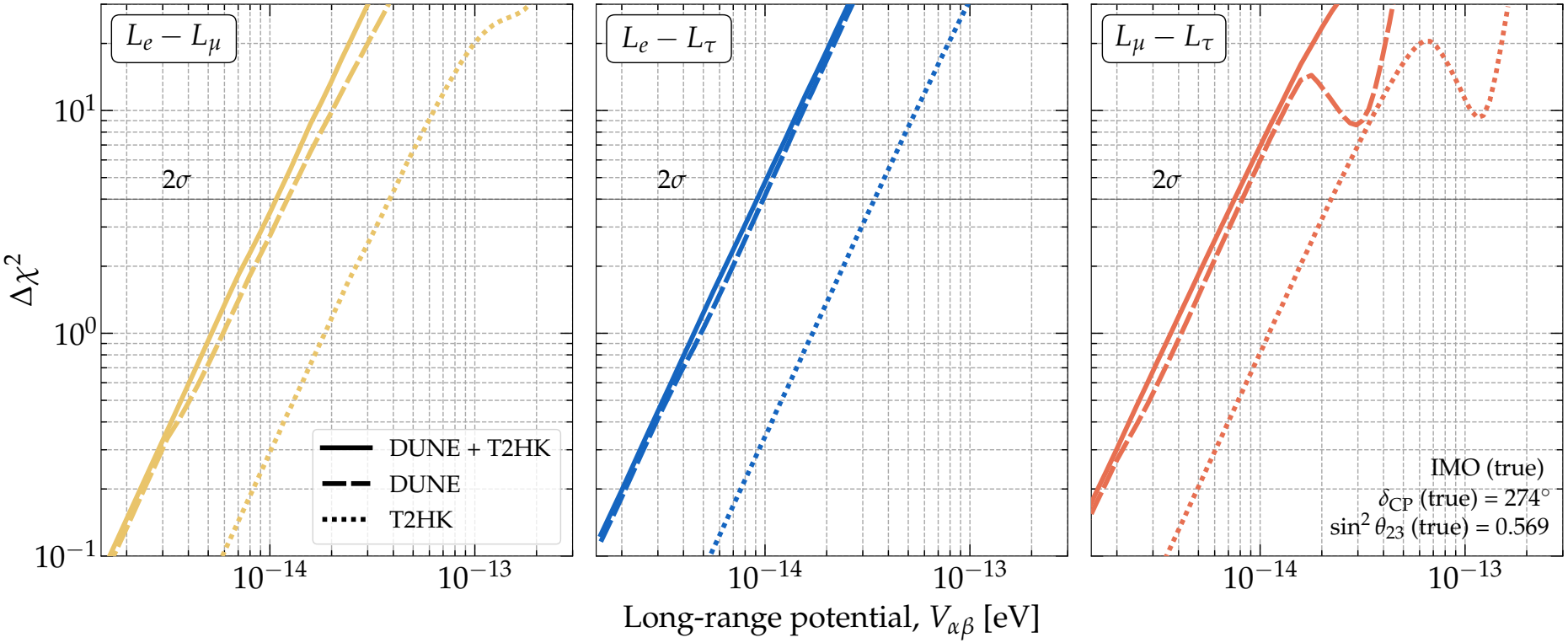
- Together DUNE + T2HK may place strongest constraints on long-range interactions, especially for mediators lighter than 10^{-18} eV.

- Combining DUNE + T2HK removes inherent parameter degeneracies from standalone experiments, which may tighten the upper limits of long-range neutrino interactions

- Given that LRI exists in Nature, strong complementarity in DUNE + T2HK is the only solution to stringently constraint the measurement in oscillation parameters.

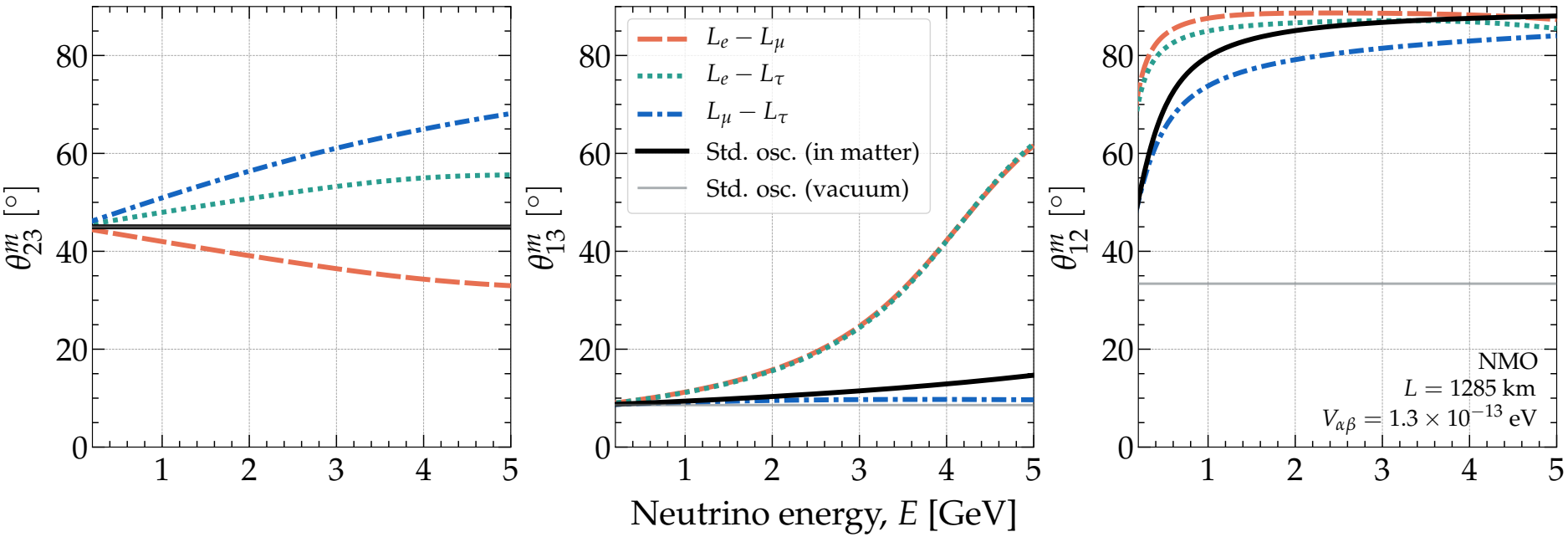
THANK YOU!

Backup 1



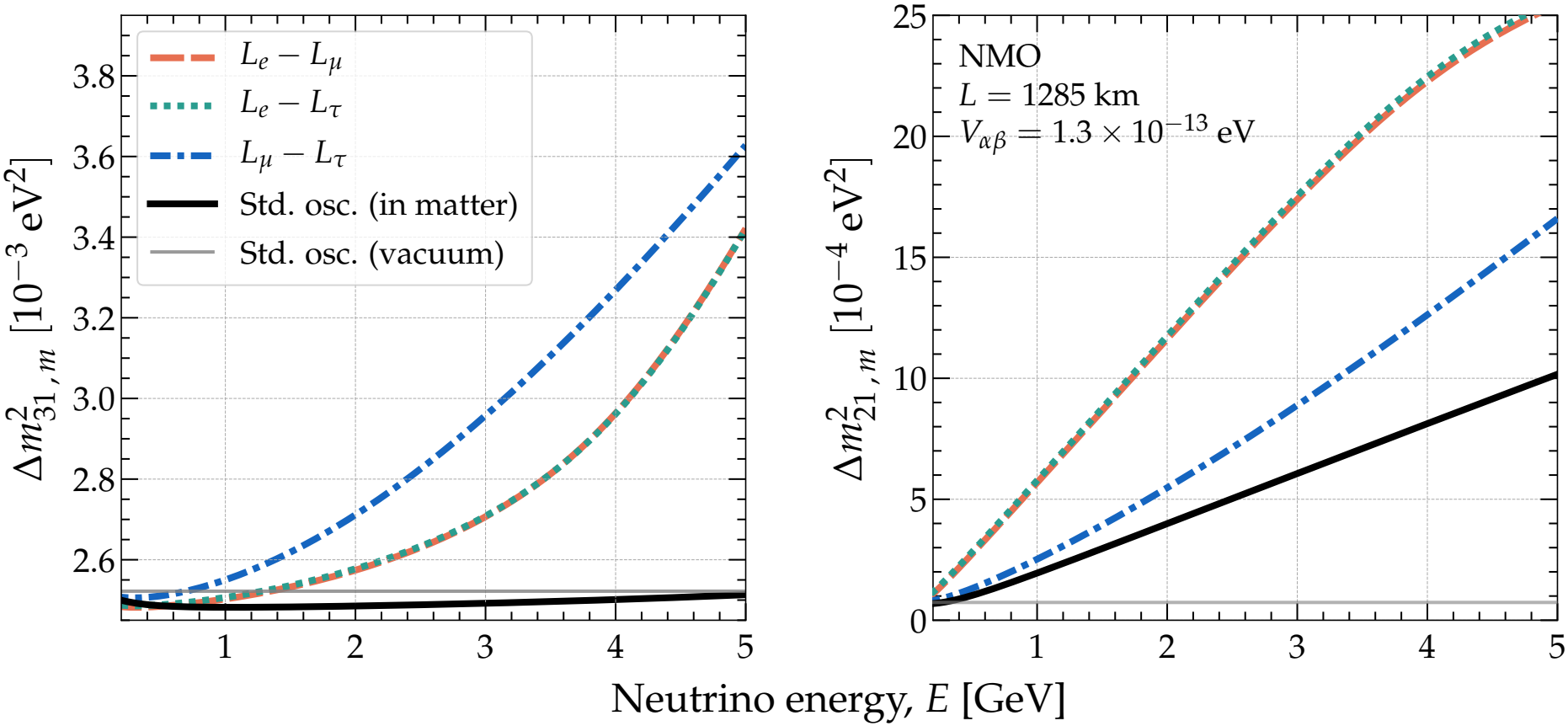
Projected constraints on the long-range matter potentials $V_{e\mu}$, $V_{e\tau}$, and $V_{\mu\tau}$, using DUNE, T2HK, and their combination, assuming inverted mass ordering.

Backup 2



Variation of the effective neutrino mixing angles with neutrino energy, for the three lepton-number symmetries, $L_\alpha - L_\beta$.

Backup 3



Variation of the effective neutrino mass splittings with neutrino energy, for the three lepton-number symmetries, $L_\alpha - L_\beta$.