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

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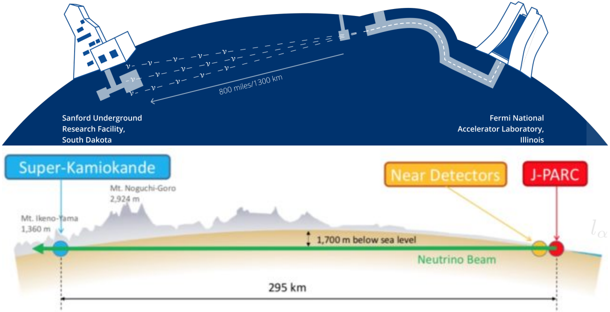
NuFact 2024

Short distances
(heavy mediators)



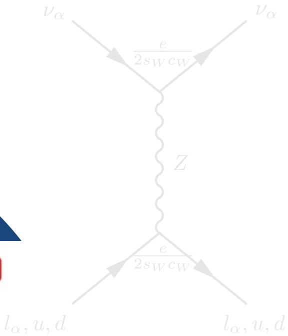
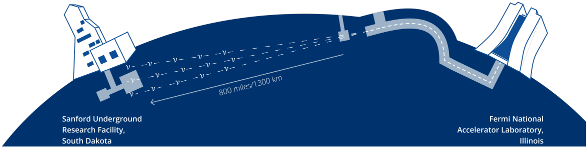
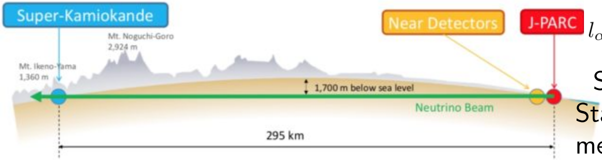


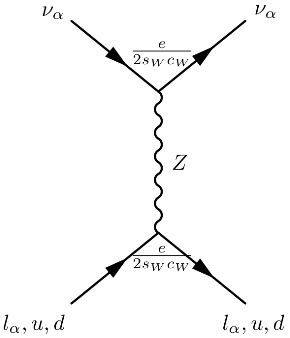
Image Credit: Chicago Sun-Times

Short distances

(heavy mediators)



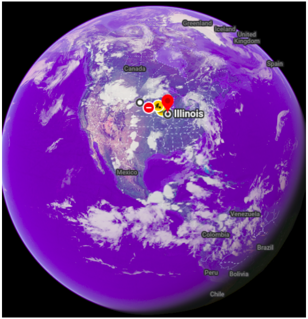


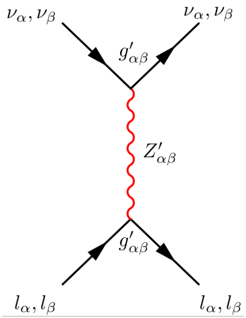


$SU(3)_C \times SU(2)_L \times U(1)_Y$

Standard Model contribution mediated by Z boson

Long distances
(light mediators)

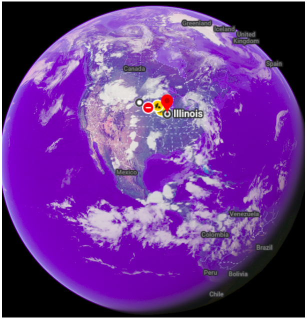




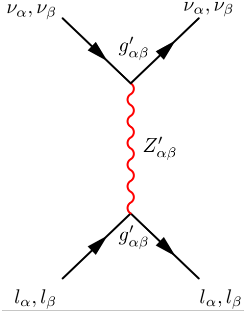
$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{L_e - L_\beta}$

New interaction induces flavor-dependent Yukawa potentials

Long distances
(light mediators)



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



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

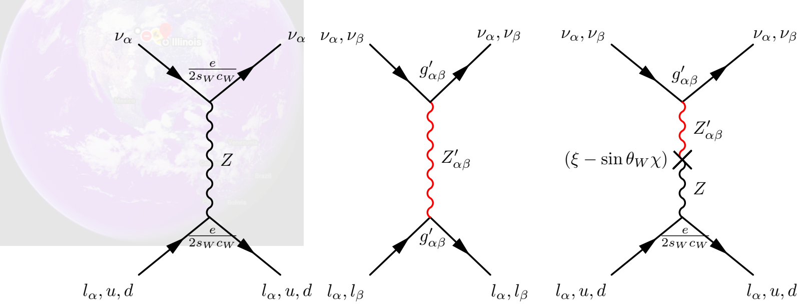
hep-ph/0310210, hep-ph/0610263

Long distances

(light mediators)

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

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

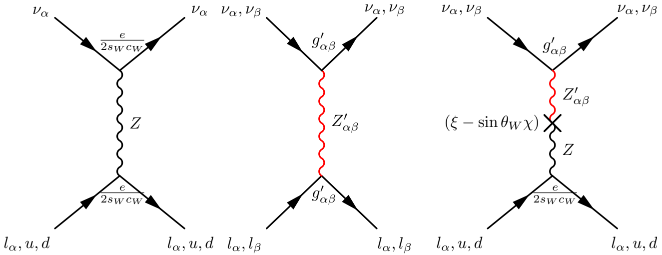


$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{L_\alpha - L_\beta}$ where $\alpha, \beta = e, \mu, \tau \quad \alpha \neq \beta$

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.



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

hep-ph/9710441

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

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

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

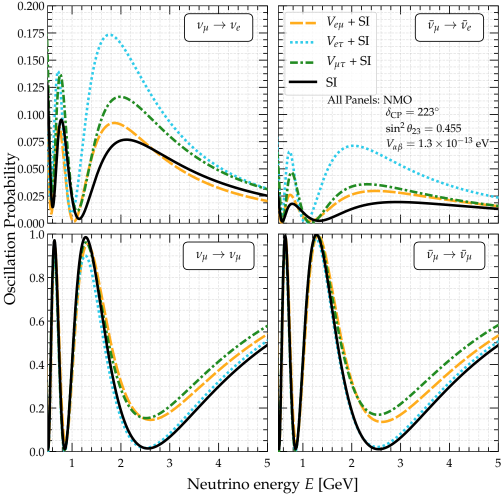
Order of $\frac{\Delta m^2_{31}}{2E} \sim \sqrt{2} G_F n_e \sim V_{\alpha\beta}$

E_ν (first osc. max. in DUNE) $= 2.5$ GeV
(second osc. max. in DUNE) $= 0.8$ GeV
(first osc. max. in T2HK) $= 0.6$ GeV

- 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?



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 LRI shifts the peak to lower E
- 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

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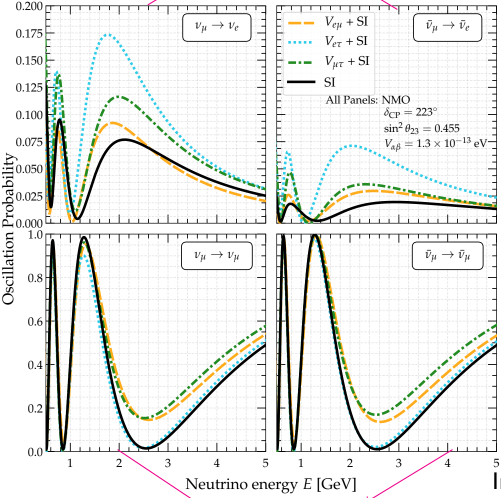
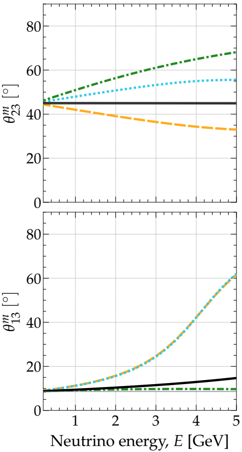
Oscillation Probability in presence of Long-Range Interactions

$P_{\mu e} \propto \sin^2\theta_{23}^m \sin^2\theta_{13}^m$



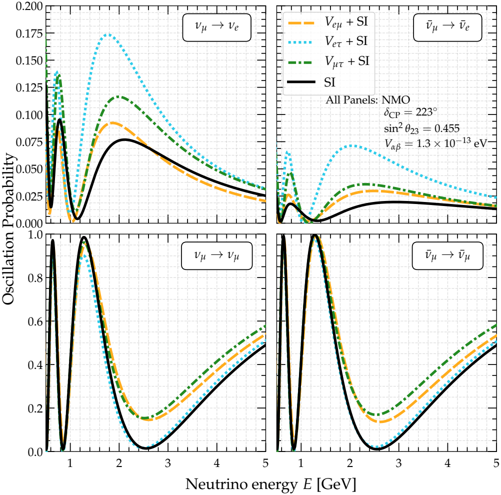
$P_{\mu\mu} \propto \sin^2 2\theta_{23}^m$

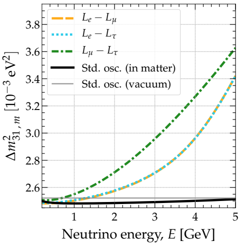


- θ_{23}^m (↓) $L_e - L_\mu$
- θ_{23}^m (↑) $L_e - L_\tau$
- θ_{23}^m (↑) $L_\mu - L_\tau$
- θ_{13}^m (↑) $L_e - L_\mu$
- θ_{13}^m (↑) $L_e - L_\tau$
- θ_{13}^m (↓) $L_\mu - L_\tau$

Interplay between running of θ_{23}^m and θ_{13}^m decides the nature of peak and dip

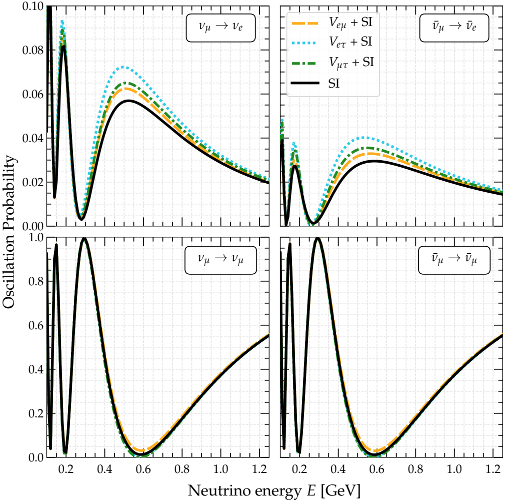
Oscillation Probability in presence of Long-Range Interactions





- In presesnce of LRI, at low E , $\Delta m^2_{31,m}$ $(\downarrow)$
- Shifts the first osc. max. peak to low E

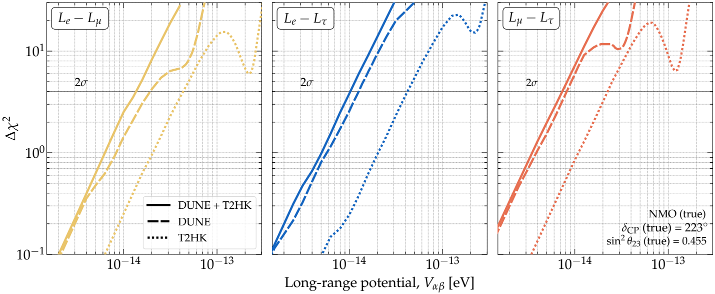
Oscillation Probability in presence of Long-Range Interactions



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 (NMO true)



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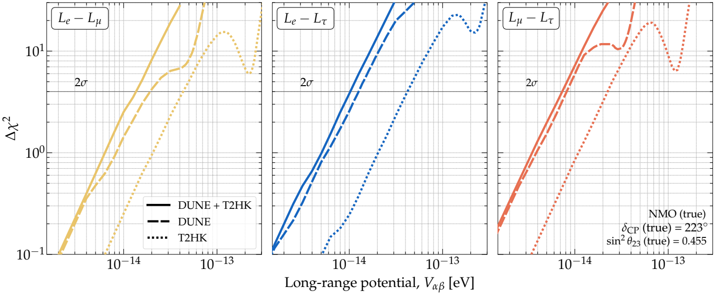
$$\Delta\chi^2 = \min_{\sin^2\theta_{23},\, \delta_{CP},\, \pm\Delta m^2_{31}} \left\{\chi^2(\mathrm{SI}+\mathrm{LRI}) - \chi^2(\mathrm{SI})\right\},$$

	Standard mixing parameters (NMO)					
	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	$\frac{\Delta m^2_{31}}{10^{-3}\,\mathrm{eV}^2}$	$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2}$	δ_{CP} (°)
Benchmark	0.303	0.455	0.0223	2.522	7.36	223
Status in fits	Fixed	Minimized	Fixed	Minimized	Fixed	Minimized
Range	–	[0.4, 0.6]	–	[2.438, 2.602]	–	[139, 355]

RESULT: Constraining Long-Range Interactions (NMO true)



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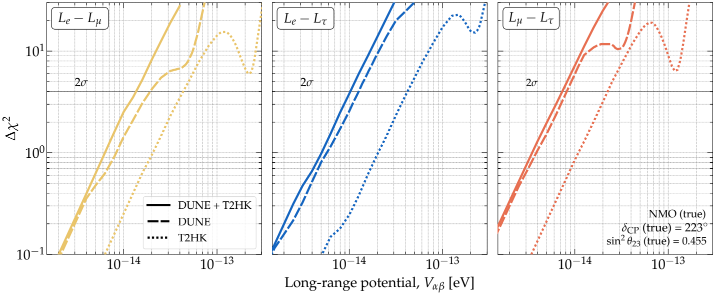
$$\Delta\chi^2 = \min_{\sin^2\theta_{23}\,,\,\delta_{\rm CP}\,,\,\pm\Delta m^2_{31}} \left\{\chi^2({\rm SI}+{\rm LRI}) - \chi^2({\rm SI})\right\},$$

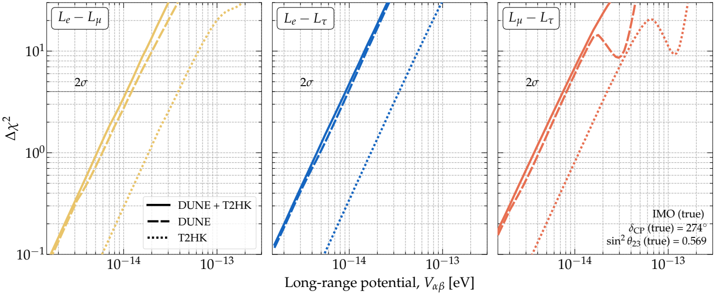
- Degeneracy in DUNE: Uncertainty in $\delta_{\rm CP}$ and θ_{23}
- Degeneracy in T2HK: Uncertainty in θ_{23} and sign of Δm^2_{31}
- Complementarity between DUNE + T2HK facilitates degeneracy-free constraints.

RESULT: Constraining Long-Range Interactions (NMO true)



- Limits on $V_{\mu\tau}$ are strongest, followed by $V_{e\tau}$ and $V_{e\mu}$.
- $L_\mu - L_\tau$: dominant contribution from disappearance channel.
- $L_e - L_\tau$: dominant contribution from appearance channel.
- $L_e - L_\mu$: both appearance and disappearance channel.

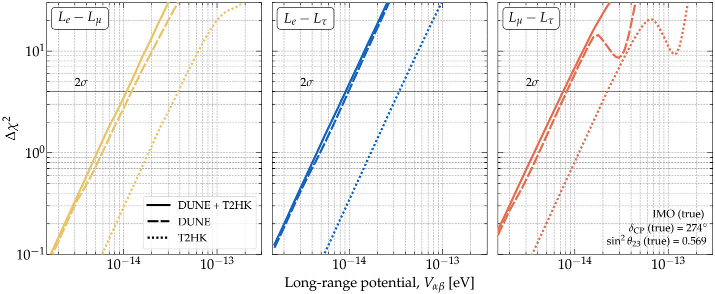
RESULT: Constraining Long-Range Interactions (IMO true)



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

	Standard mixing parameters (IMO)					
	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	$\frac{\Delta m^2_{31}}{10^{-3}\,\mathrm{eV}^2}$	$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2}$	$\delta_{\rm CP}$ (°)
Benchmark	0.303	0.569	0.0223	2.418	7.36	274
Status in fits	Fixed	Minimized	Fixed	Minimized	Fixed	Minimized
Range	–	[0.4, 0.6]	–	[2.341, 2.501]	–	[193, 342]

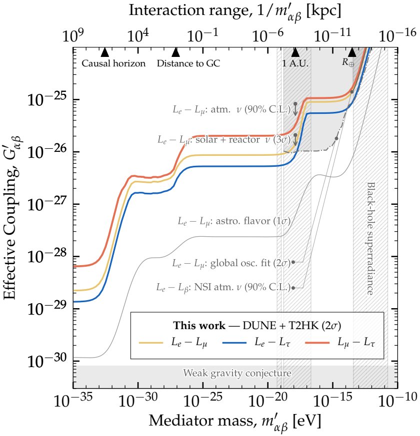
RESULT: Constraining Long-Range Interactions (IMO true)



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

- Limits on $V_{\mu\tau}$ are strongest, irrespective of mass ordering.
- Affect of inherent parameter degeneracies is relatively less in IMO that NMO.
- $\sin^2\theta_{23}$ in HO, less $\sin^2\theta_{23} - \delta_{CP}$ degeneracy.

RESULT: UPPER LIMITS ON COUPLING VS MASS PLANE USING DUNE + T2HK (2σ)



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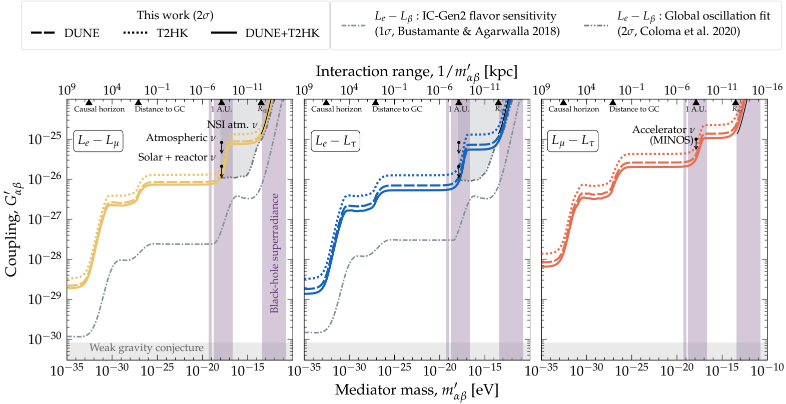
$$G'_{\alpha\beta} = \begin{cases} g'_{e\mu} & , \quad \text{for } \alpha, \beta = e, \mu \\ g'_{e\tau} & , \quad \text{for } \alpha, \beta = e, \tau \\ \sqrt{g'_{\mu\tau}(\xi - \sin\theta_W \chi)} & , \quad \text{for } \alpha, \beta = \mu, \tau \end{cases}$$

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

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



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$$V_{\alpha\beta} = V_{\alpha\beta}^{\oplus} + V_{\alpha\beta}^{☾} + V_{\alpha\beta}^{\odot} + V_{\alpha\beta}^{\mathrm{MW}} + V_{\alpha\beta}^{\mathrm{cos}}$$

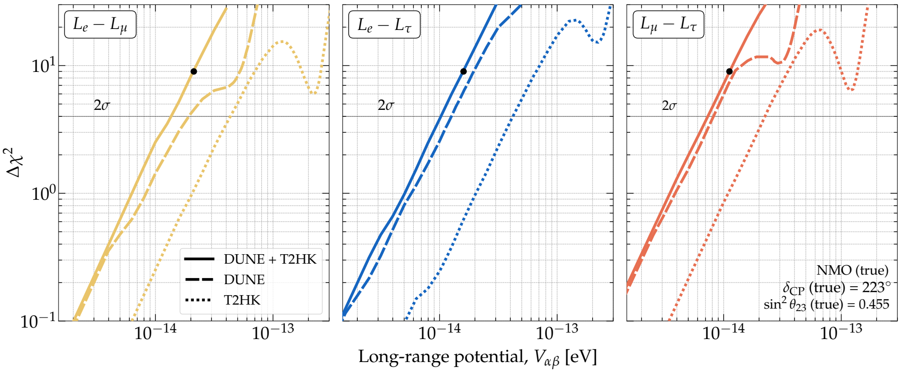
DUNE + T2HK may place strong constraints on long-range interactions, especially for mediators lighter than 10^{-18} eV.

RESULT: Discovery Potential

If Long-Range Interactions exist in Nature.

Ability of DUNE, T2HK, and DUNE + T2HK in constraining them ?

RESULT: Discovery Potential



Illustratively, we generate data with (3σ upper bounds using DUNE + T2HK)

$$V_{e\mu} = 2.12 \times 10^{-14}\ \text{eV};\ V_{e\tau} = 1.6 \times 10^{-14}\ \text{eV};\ V_{\mu\tau} = 1.12 \times 10^{-14}\ \text{eV}$$

RESULT: DISCOVERY POTENTIAL AT 3σ

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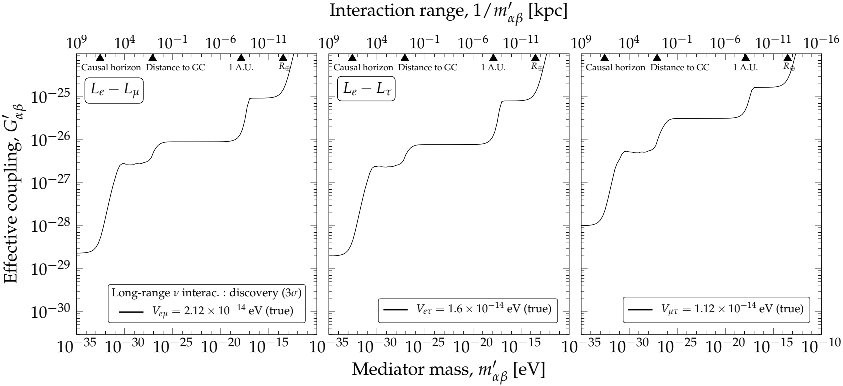
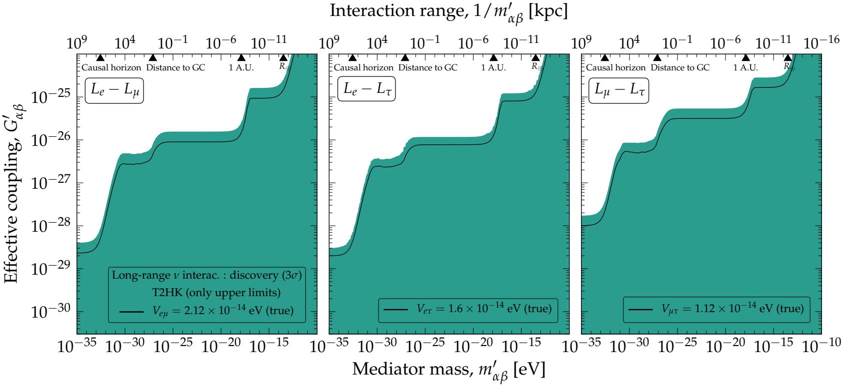


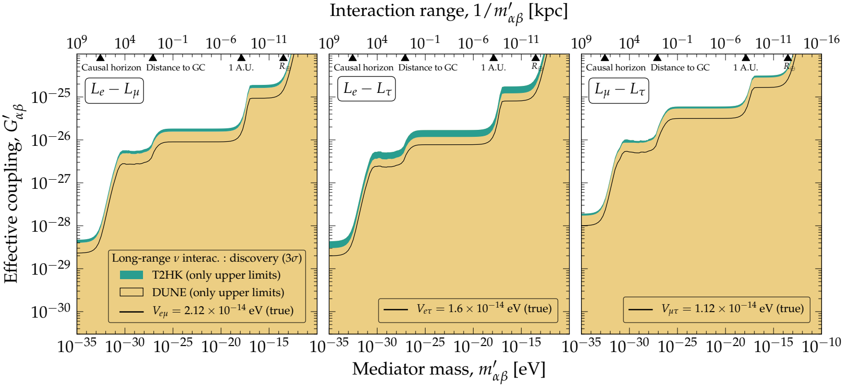
$$\Delta\chi^2 = \min_{\delta_{\rm CP},\, \sin^2\theta_{23},\, \pm\Delta m^2_{31}} \left\{ \chi^2(\text{SI}+\text{LRI}) - \chi^2(\text{SI}+\text{fixed value of LRI}) \right\},$$



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

- Alone DUNE and T2HK can **only** place upper limits on $g'_{\alpha\beta}$.

RESULT: Discovery Potential at 3σ



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

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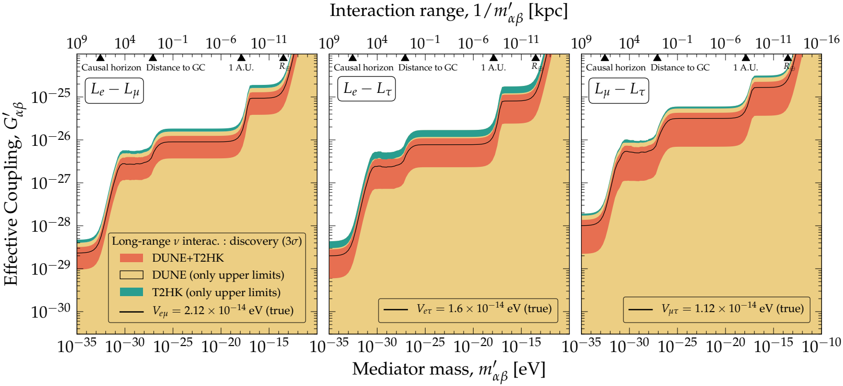

$$\Delta\chi^2 = \min_{\delta_{\rm CP},\, \sin^2\theta_{23},\, \pm\Delta m^2_{31}} \left\{ \chi^2(\text{SI} + \text{LRI}) - \chi^2(\text{SI} + \text{fixed value of LRI}) \right\},$$

- Alone DUNE and T2HK can **only** place upper limits on $g'_{\alpha\beta}$.
- **DUNE + T2HK may discover subdominant long-range interactions.**

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

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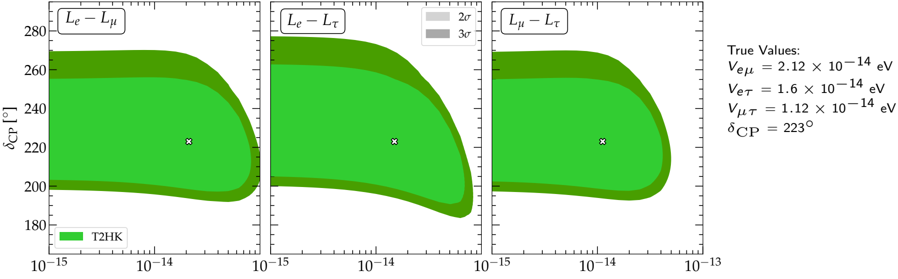
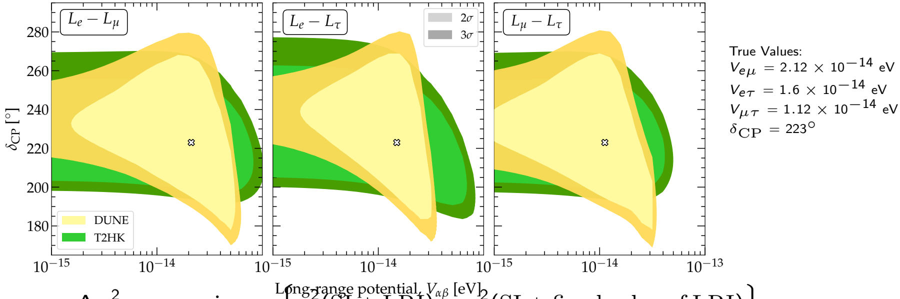


$$\Delta\chi^2 = \min_{\sin^2\theta_{23}\ \pm\Delta m^2_{31}} \left\{\chi^2(\mathrm{SI}+\mathrm{LRI}) - \chi^2(\mathrm{SI}+\text{fixed value of LRI})\right\},$$

T2HK:

- short baseline ⇒ less matter-contaminated CP ⇒ high precision measurements of δ_{CP}
- short baseline ⇒ less matter effect ⇒ less sensitivity to mass ordering

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

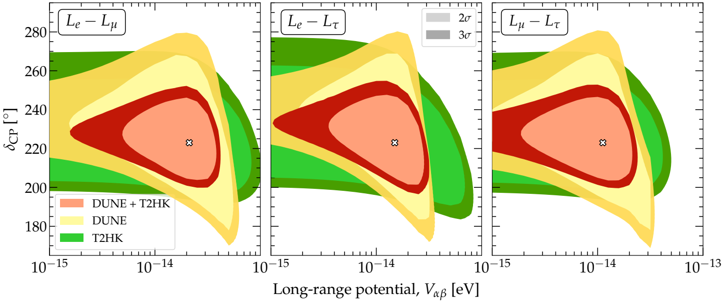


$$\Delta\chi^2 = \min_{\sin^2\theta_{23}\ \pm\Delta m^2_{31}} \left\{ \chi^2(\text{SI} + \text{LRI}) - \chi^2(\text{SI} + \text{fixed value of LRI}) \right\},$$

DUNE:

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

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



T2HK:

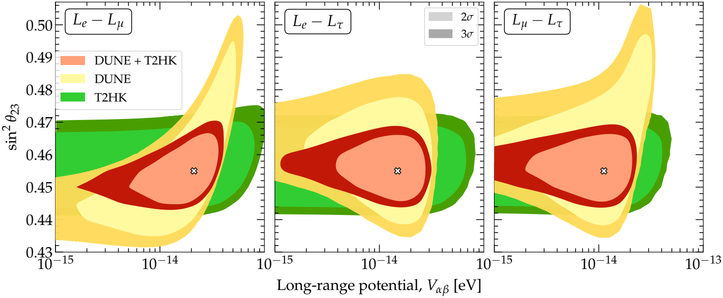
- Short baseline; less matter-contaminated fake CP; high precision measurements of δ_{CP}
- Short baseline; less matter effect; less sensitivity to mass ordering

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:
$V_{e\mu} = 2.12 \times 10^{-14}$ eV
$V_{e\tau} = 1.6 \times 10^{-14}$ eV
$V_{\mu\tau} = 1.12 \times 10^{-14}$ eV
$\sin^2\theta_{23} = 0.455$

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

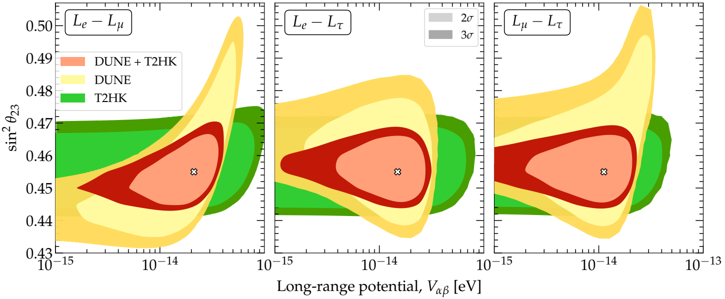
T2HK:

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

DUNE:

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

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



T2HK

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

DUNE:

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

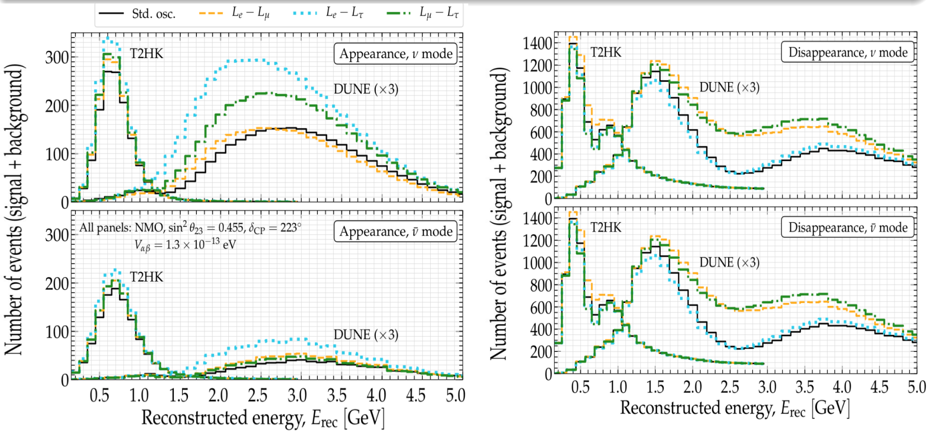
DUNE + T2HK complement each other and remove inherent degeneracies in standalone experiments.

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
- DUNE and T2HK by themselves may be unable to discover subdominant long-range interactions, but their combination may!

THANK YOU!

Backup - Event Distribution in presence of Long-Range Interactions



- Huge detector in T2HK ⇒ event rates in T2HK higher than DUNE
- Shapes of the event spectra reflect nature of curves at Osc. Prob.

Neutrino Interactions with matter

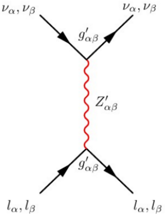
Model: U(1) extension of SM

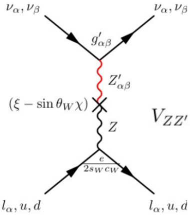
$$\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{L_\alpha - L_\beta}}$$

$$\mathcal{L}^{4f}_{Z'} = g'^2_{\alpha\beta} J'^{\sigma} J'_{\sigma} \qquad \mathcal{L}^{4f}_{ZZ'} = -g'_{\alpha\beta}(\xi - \sin\theta_W \chi)\frac{e}{\sin\theta_W \cos\theta_W} J'_{\rho} J^{\rho}_{3}$$

$$J'^{\sigma} = \bar{l}_\alpha \gamma^\sigma l_\alpha - \bar{l}_\beta \gamma^\sigma l_\beta + \bar{\nu}_\alpha \gamma^\sigma P_L \nu_\alpha - \bar{\nu}_\beta \gamma^\sigma P_L \nu_\beta$$

$$J^{\rho}_{3} = -\frac{1}{2}\bar{e}\gamma^\rho P_L e + \frac{1}{2}\bar{u}\gamma^\rho P_L u - \frac{1}{2}\bar{d}\gamma^\rho P_L d$$

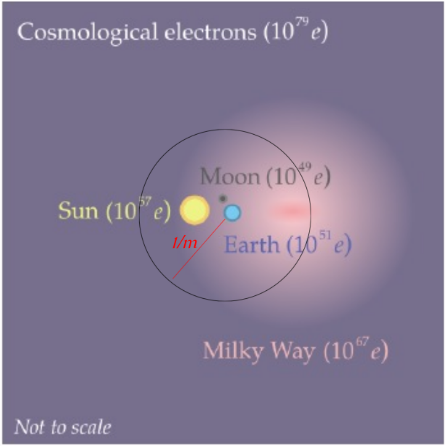




$$V_{Z'} = -g'^2_{\alpha\beta} \frac{N_e}{4\pi d} e^{-m'_{\alpha\beta} d}$$

$$V_{ZZ'} = g'^2_{\alpha\beta} (\xi - s_W \chi) \frac{e}{s_W c_W} \frac{N_n}{4\pi d} e^{-m'_{\alpha\beta} d}$$

Interactions with ultralight mediator (long-range interactions)


Cosmological electrons (10^{79} e)
Moon (10^{49} e)
Sun (10^{57} e)
1/m
Earth (10^{51} e)
Milky Way (10^{67} e)
Not to scale