# Investigating the Effects of Long-Range Force in the P2SO and T2HKK Experiments

**Priya Mishra** [1] Rudra Majhi [2] Sambit Kumar Pusty [1] Monojit Ghosh [3] Rukmani Mohanta [1]

[1]School of Physics, University of Hyderabad, Hyderabad, India, [2]Nabarangpur College, Odisha, India

[3]Center of Excellence for Advanced Materials and Sensing Devices, Ruđer Bošković Institute, Zagreb, Croatia

## Abstract

This work investigates the sensitivity of future long-baseline neutrino experiments, P2SO and T2HKK, to long-range forces (LRF) [1]. It aims to evaluate their ability to constrain LRF parameters, the impact of LRF on standard oscillation parameters, and their potential to limit the mass of the new gauge boson and coupling constant. The study finds that P2SO provides the best bounds on LRF parameters and that LRF affects the measurement of standard oscillation parameters, except for the precision of $\Delta m^2_{31}$, which remains unchanged.

## Introduction

When neutrinos travel through Earth-matter, encounter a potential due to e, p, n present in it ($H_{matter} = \text{diag}(\sqrt{2}G_F N_e, 0, 0)$). We assume that if Long Range Force exist in nature, the electrons present inside the Sun, generate a potential on the Earth. In this context, we take three cases of U(1) symmetries for the extension of standard model and generation of light gauge boson ($Z'$).

$$\mathrm{U(1)}_{\mathrm{L_e - L_\mu}}, \quad \mathrm{U(1)}_{\mathrm{L_e - L_\tau}}, \quad \mathrm{U(1)}_{\mathrm{L_\mu - L_\tau}}. \tag{1}$$

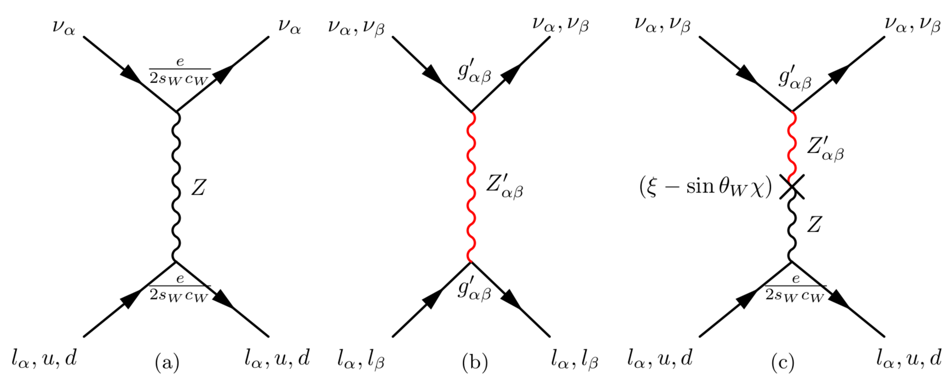


Figure 1. Neutrino interaction with matter. (Image courtesy: Ref. [2])

The long range potential is defined as below, for $L_e - L_\mu$ and $L_e - L_\tau$:

$$V_{ej} = g'^{\,2}_{ej} \frac{N_e}{4\pi r} e^{-r M_{Z_{ej}}} \tag{2}$$

For $L_\mu - L_\tau$:

$$V_{\mu\tau} = g'_{\mu\tau}(\xi - \sin\theta_w \chi) \frac{e}{4 \sin\theta_w \cos\theta_w} \frac{N_n}{4\pi r} e^{-r M_{Z_{\mu\tau}}} \tag{3}$$

The total Hamiltonian is now modified as:

$$H_{\nu/\bar{\nu}} = H_{vacuum} \pm H_{\text{matter}} \pm H_{LRF}, \tag{4}$$

$$H_{LRF} = \begin{cases} \text{diag}(V_{e\mu}, -V_{e\mu}, 0) & \text{for } U(1)_{L_e - L_\mu}, \\ \text{diag}(V_{e\tau}, 0, -V_{e\tau}) & for\ U(1)_{L_e - L_\tau}, \\ \text{diag}(0, V_{\mu\tau}, -V_{\mu\tau}) & for\ U(1)_{L_\mu - L_\tau}, \end{cases} \tag{5}$$

## Experimental Details

We used General Long Baseline Neutrino Experiments (GLoBES) package to simulate the results in P2SO (Protvino to Super-ORCA) and T2HKK (an alternative idea of Tokai to Hyper kamioka experiment) experiments. Values of oscillation parameters are taken from NuFit v5.2.

| Exp | P2SO | T2HKK |
|---|---|---|
| Baseline | 2595 km | 1100 km |
| Beam power | $4 \times 10^{20}$ POT | $27 \times 10^{21}$ POT |
| Energy Peak | 0.2-10 GeV | 0-3GeV |
| Run-Time ($\nu : \bar{\nu}$) | 3 years: 3 years | 2.5 years: 7.5 years |

Table 1. Experimental characteristics

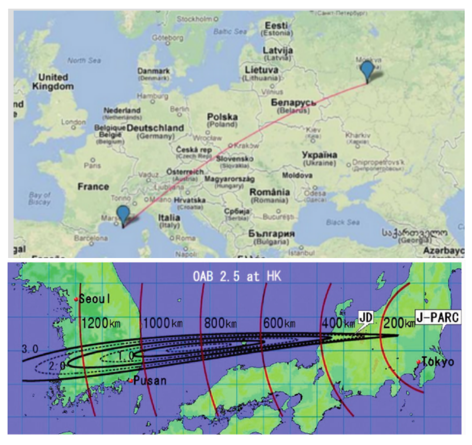

Figure 2. Upper panel: P2SO exp., Lower panel: T2HKK exp.

## Bounds Obtained

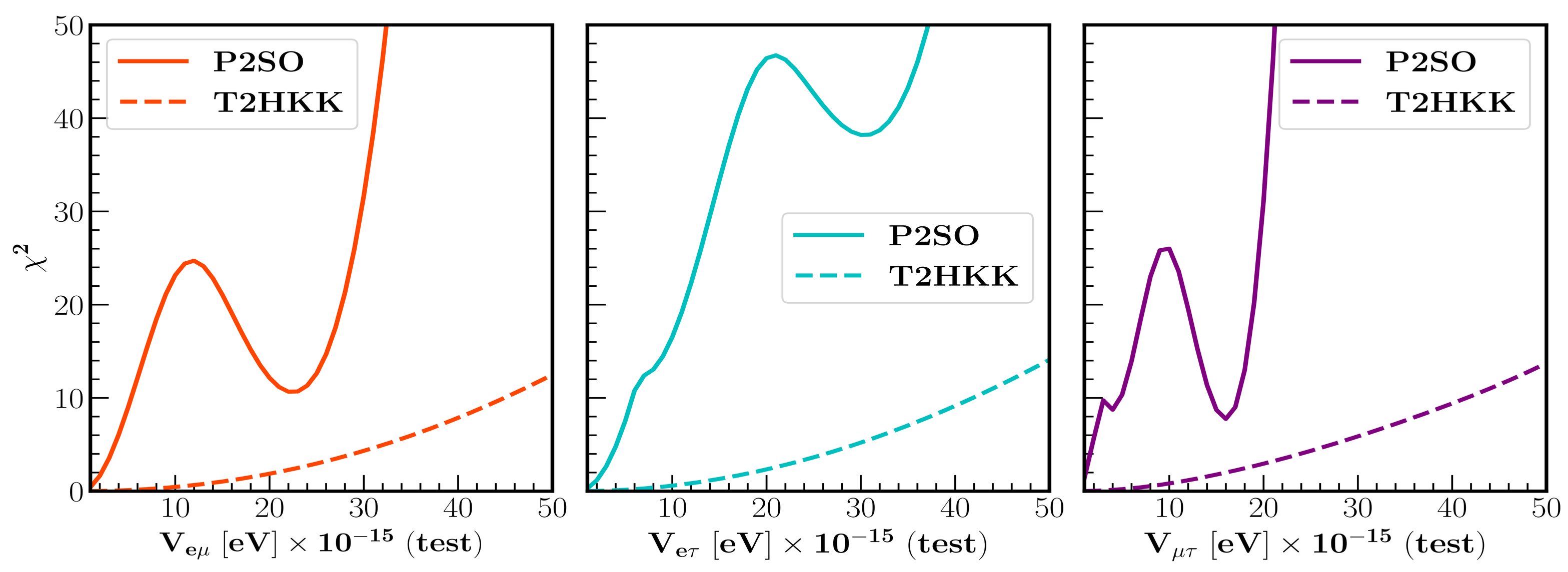


Figure 3. Bounds obtaioned for the value of long range potential.

| LRF Potential $[eV]$ | SK [3] | DUNE [2] | T2HK [2] | P2SO (This work) | T2HKK (This work) |
|---|---|---|---|---|---|
| $V_{e\mu}(\times 10^{-14})$ | 71.5 | 1.46 | 3.45 | 0.23 | 2.40 |
| $V_{e\tau}(\times 10^{-14})$ | 83.2 | 1.03 | 3.43 | 0.23 | 2.15 |
| $V_{\mu\tau}(\times 10^{-14})$ | - | 0.67 | 1.84 | 0.13 | 1.5 |

Table 2. Sensitivity limits at 90% C.L. on LRF parameters from several experiments.

## Key Results

**CPV, Hierarchy and Octant sensitivities:**

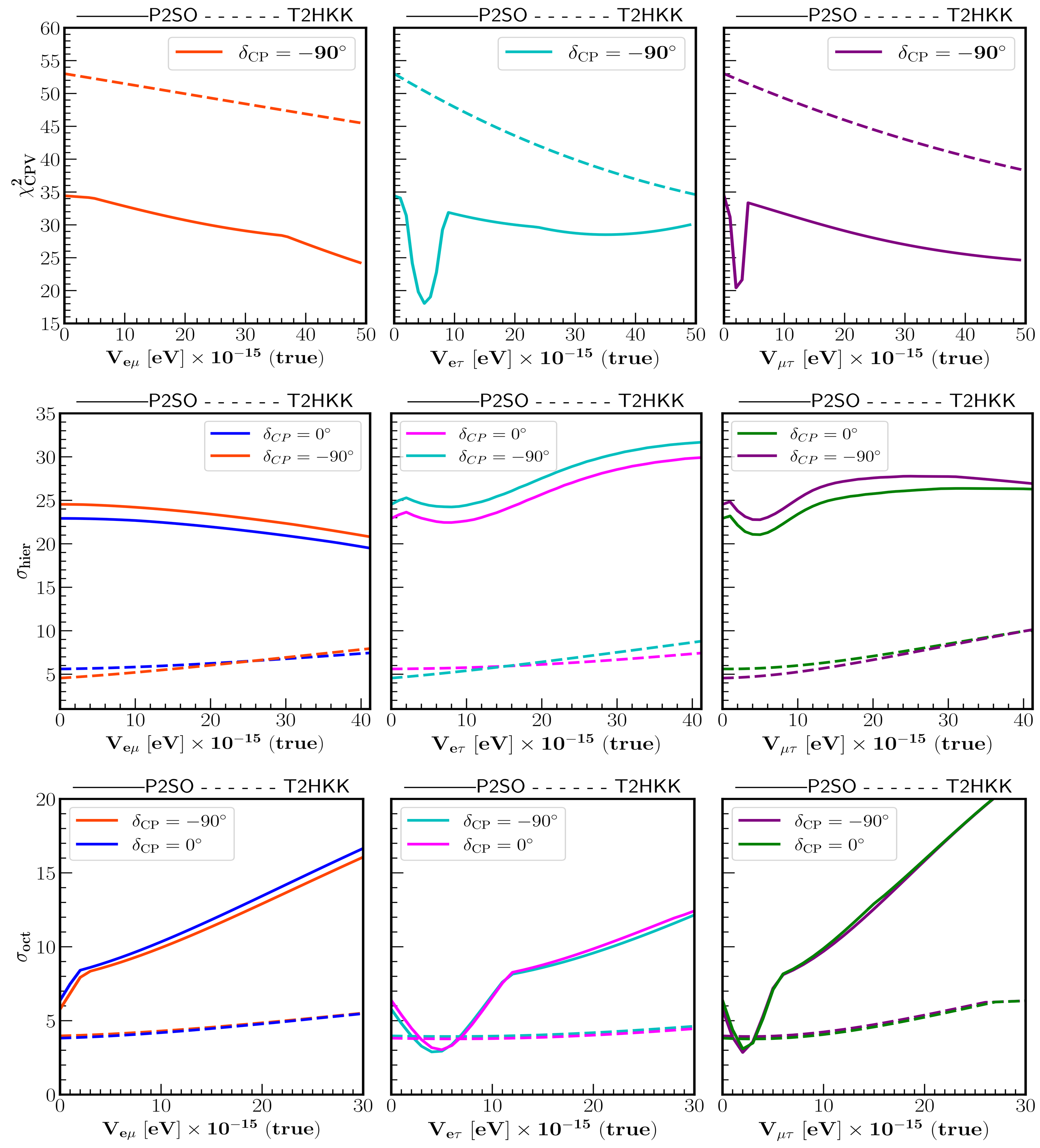


Figure 4. Upper panels: CPV sensitivity, middle panels: hierarchy sesnsitivity and lower panels: octant sensitivity for all three cases of LRF.

**g-Mz parameter space:**

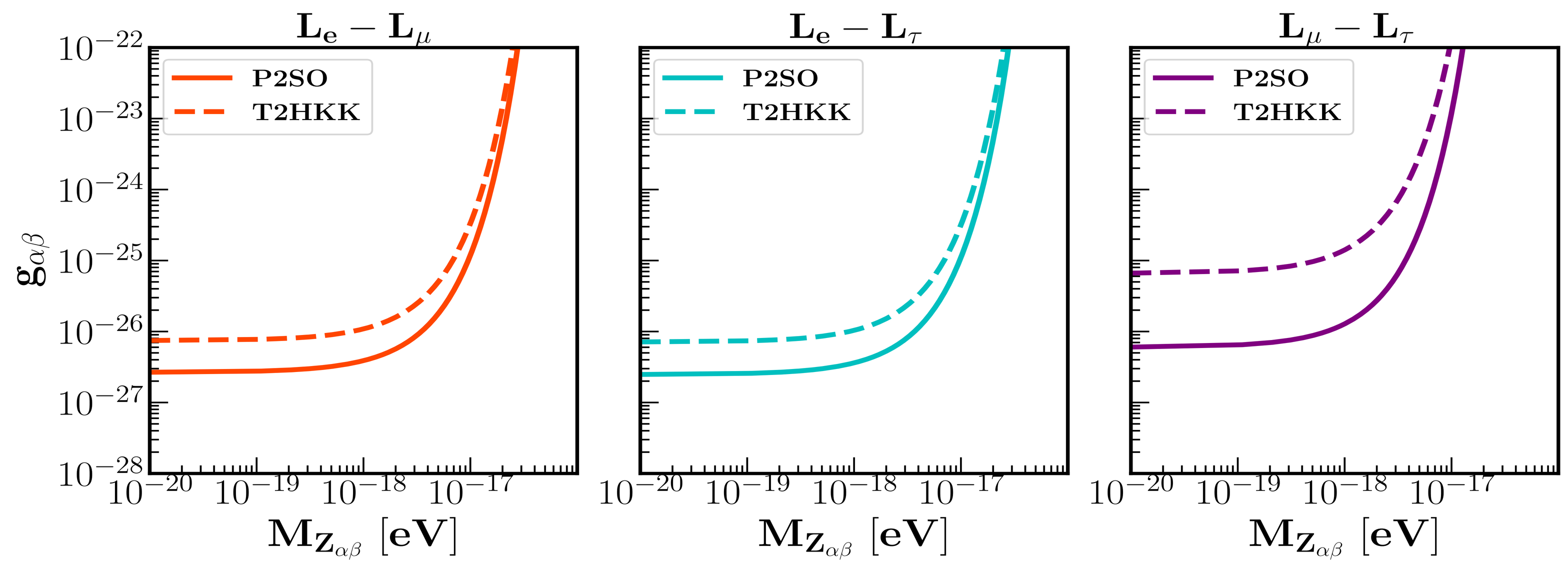


Figure 5. The allowed range for gauge coupling vs mass of gauge boson.

| Experiment &Model | $g_{e\mu}$ | $g_{e\tau}$ | $g_{\mu\tau}$ |
|---|---|---|---|
| P2SO (This work) | $2.66 \times 10^{-27}$ | $2.48 \times 10^{-27}$ | $6.03 \times 10^{-27}$ |
| T2HKK (This work) | $7.47 \times 10^{-27}$ | $7.12 \times 10^{-27}$ | $6.637 \times 10^{-26}$ |
| T2HK [2] | $1.30 \times 10^{-26}$ | $1.24 \times 10^{-26}$ | $4.31 \times 10^{-26}$ |
| DUNE [2] | $8.55 \times 10^{-27}$ | $7.03 \times 10^{-27}$ | $2.59 \times 10^{-26}$ |

Table 3. Projected upper bound on $g_{\alpha\beta}$ from various long-baseline experiments.

## Conclusions

The bounds obtained for LRF potential are more constrained for P2SO experiment compared to T2HKK. In presence for LRF potential: The octant senstivity get increased for P2SO but decreases for T2HKK. The CPV sensitivity get decreased for both P2SO and T2HKK. The bounds on the gauge coupling obtained for P2SO are better than T2HKK and among the three symmetries, the most stringent bound comes for $L_e - L_\tau$.

## Acknowledgement

I would like to thank Prime Minister's Research Fellowship for financial support.

## References

[1] P. Mishra, R. Majhi, S. K. Pusty, M. Ghosh, and R. Mohanta, "Study of Long Range Force in P2SO and T2HKK," 2 2024.

[2] M. Singh, M. Bustamante, and S. K. Agarwalla, "Flavor-dependent long-range neutrino interactions in DUNE & T2HK: alone they constrain, together they discover," *JHEP*, vol. 08, p. 101, 2023.

[3] A. S. Joshipura and S. Mohanty, "Constraints on flavor dependent long range forces from atmospheric neutrino observations at super-Kamiokande," *Phys. Lett. B*, vol. 584, pp. 103–108, 2004.