Implications of Long-Range Forces in P2SO and T2HKK Experiments

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Outline

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2. Introduction to Long-Range Force (LRF)
3. Simulation Details
4. Impacts of LRF on long-baseline experiment
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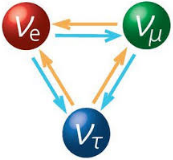
Introduction

- Neutrinos are the most elusive particle postulated by Pauli in 1930.
- Several dedicated experiments have observed the phenomenon of neutrino flavor transitions during their propagation.



  - Neutrino Oscillation confirms the neutrino mass and mixing.
  - Also resolve the Solar and Atmospheric neutrino Anomalies.
  - Neutrino mass states (ν_1, ν_2, ν_3) are related to flavour states by Unitary mixing matrix.

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle \quad \alpha = e, \mu, \tau, \quad i = 1, 2, 3$$

Flavour States Mass States

- The Mixing Matrix is Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

$$U_{\rm PMNS} = R(\theta_{23})O(\theta_{13},\delta_{13})R(\theta_{12}),$$

where $$O(\theta_{13},\delta_{13}) = \begin{pmatrix} \cos\theta_{13} & \sin\theta_{13}e^{-i\delta_{13}} \\ -\sin\theta_{13}e^{i\delta_{13}} & \cos\theta_{13} \end{pmatrix},$$

$$R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

NuFIT 6.0 (2024)

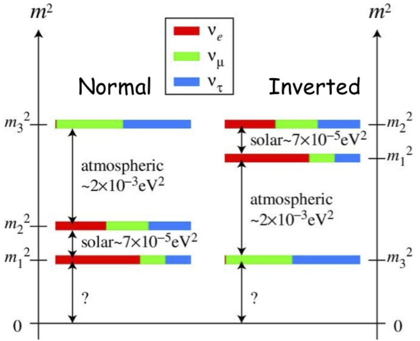
IC19 without SK atmospheric data

	Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
$\delta_{\rm CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$

- Precise measurement of neutrino oscillation parameters.

* J arXiv:2410.05380 & NuFIT 6.0 (2024), www.nu-fit.org.

Mass Hierarchy.



- $\Delta m^2_{31} > 0$ (Normal Hierarchy)
  $m_3 >> m_2 > m_1$
- $\Delta m^2_{31} < 0$ (Inverted Hierarchy)
  $m_2 > m_1 >> m_3$

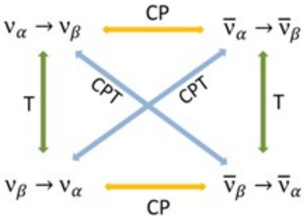
* R. N. Mohapatra et al., arXiv:hep-ph/0510213

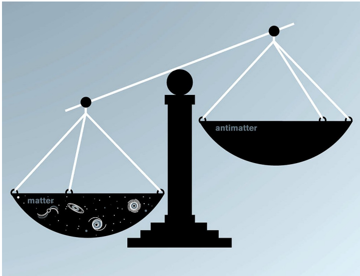
- Absolute scale of neutrino mass is unknown to us.
- Nature of Neutrinos: Dirac or Majorana type?

CP Violation

C[Particle] = Antiparticle

Parity changes the helicity of a state.





Is $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$?

- *CP non-invariance comes from δ_{CP} phase in the Leptonic mixing matrix U.*

- CP violation can explain the matter-anti matter asymmetry in universe.

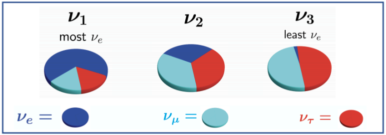
*A. S. Joshipura et al. JHEP 08 (2001), 029

Octant of θ_{23}

- Atmospheric mixing angle (θ_{23}) deviates from maximum-mixing value 45°

$\theta_{23} < 45^\circ$ Lower Octant (LO)

$\theta_{23} > 45^\circ$ Higher Octant (HO)



Is there more ν_μ or ν_τ in ν_2?

- Are there more than 3 neutrino mass eigenstates? (Do sterile neutrinos exit?)
- Do neutrinos break the CPT and Lorentz invariance?
- Are there Non-Standard Interaction (NSI) effects?

- The unknowns in neutrino sector can be studied through Long Baseline neutrino oscillation experiment.
- Earth matter effect in Long Baseline experiment will help to study the unknowns.
- It can give new signals of beyond standard model.

* M. Freund, Phys. Rev. D 64 (2001) 053003, arXiv:hep-ph/0103300.

Introduction to LRF

- Standard Model (SM) can be extended by adding extra $U(1)$ symmetry to it.
- $U(1)$ symmetry with combination of Lepton symmetry $L_e - L_\mu$, $L_e - L_\tau$ and $L_\mu - L_\tau$ can be added to SM without any anomaly.
  (* R. Foot, Mod. Phys. Lett. A 6 (1991) 527.
  X.G. He et. al., Phys. Rev. D 43 (1991) 22.)
- To have nonzero mass and non-maximal mixing of flavors, these symmetries have to be broken.
- New Vector Boson (Z') introduced for these symmetries can mediated interaction between neutrino and matter.

Introduction to LRF

- For ultralight mass of gauge boson Z' the force between matter particles and neutrinos can be extended over long distances :Long Range Force (LRF).
- LRF depends on the leptonic content and the mass of an object.
- Interactions induced by LRF parameter alter the matter potential in neutrino propagation.

* A.S. Joshipura, Phys. Lett. B 584 (2004) 103 [hep-ph/0310210] [INSPIRE].

- The effective potential for neutrinos on Earth

$$V_{ej} = g_{ej}^2 \frac{N_e}{4\pi r} e^{-M_{Z_{ej}} r}, \text{where } j = \mu, \tau \tag{1}$$

$$V_{\mu\tau} = g_{\mu\tau}\zeta - \sin\theta_w \chi \frac{e}{4\sin\theta_w \cos\theta_w} \frac{N_n}{4\pi r} e^{-M_{Z_{ej}} r} \tag{2}$$

$g_{\alpha\beta}$ are the gauge couplings, $M_{Z\alpha\beta}$ are gauge boson mass. $N_n \approx \frac{N_e}{4}$, N_e is the number of electron inside the Sun.

- The effective Hamiltonian for neutrino in presence of matter potential and LRF potential.

$$H_{\nu/\bar{\nu}} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger\right] \pm H_{\rm matter} \pm H_{LRF}\,, \quad (3)$$

with

$$H_{LRF} = \begin{cases} {\rm diag}(V_{e\mu}, -V_{e\mu},\ 0) & {\rm for} \quad U(1)_{L_e-L_\mu}\,, \\ {\rm diag}(V_{e\tau},\ 0, -V_{e\tau}) & {\rm for} \quad U(1)_{L_e-L_\tau}\,, \\ {\rm diag}(0, V_{\mu\tau}, -V_{\mu\tau}) & {\rm for} \quad U(1)_{L_\mu-L_\tau}\,, \end{cases} \quad (4)$$

where + sign is for neutrino and − sign is for antineutrino flavor states

Globes

- General Long Baseline Experiment Simulator (GLoBES).
- C-library based software package for simulation of experiments.

* P. Huber et al., Comput. Phys. Commun. 167, 195 (2005)
* P. Huber et al., Comput. Phys. Commun. 177, 432 (2007)

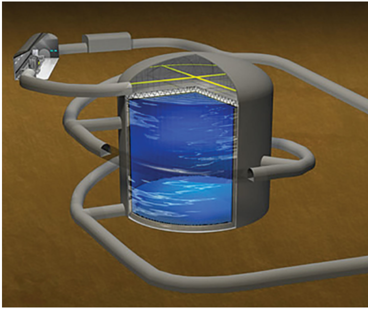
Protvino to Super-ORCA (P2SO)

- Neutrinos will be produced at U-70 synchrotron located at Protvino, Russia.
- Neutrinos will be detected at Super-ORCA detector at distance of 2595 km away.
- 10 times more densed detector than ORCA.
- Higher energy resolution capability.
- Beam power : 450 KW (4×10^{20} POT)
- Run time : 6 years (3 yrs + 3 yrs)

* J. Hofestdt, et al., PoS ICRC2019 (2020) 911, [arXiv:1907.12983]
* A. V. Akindinov et al., Eur. Phys. J. C 79 (2019), no. 9 758, [arXiv:1902.06083].

Simulation Details

- T2HKK is an alternative choice to T2HK, where the proposed FD is placed in Korea, which is 1100 km away from the JPARC facility with an off-axis angle of 1.5°.
- The other detector (187 kt) will be placed at 295 km with an off-axis angle of 2.5°.
- Neutrino beam power 1.3 MW and a total exposure 27×10^{21} POT.
- Time Period: 10 Years (2.5 Years in ν mode and 7.5 Years in $\overline{\nu}$ mode)



* PTEP 2018 (2018) 063C01 [arXiv:1611.06118] [IN SPIRE].

Result: Effect at Probability Level

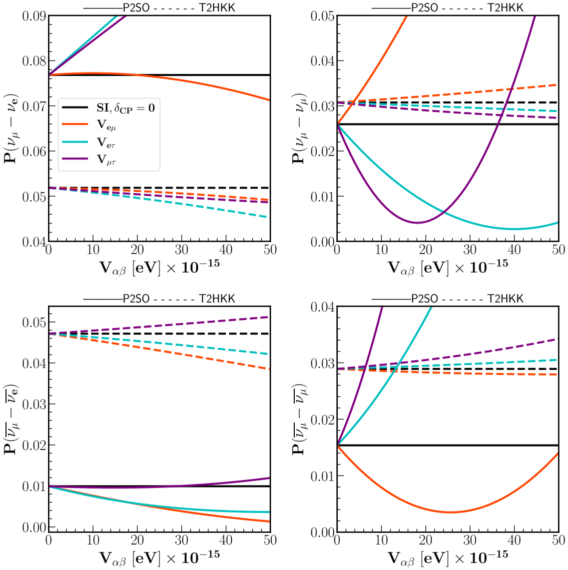


Figure: Appearance and disappearance probabilities.

Sensitivity Limits on LRF Parameters

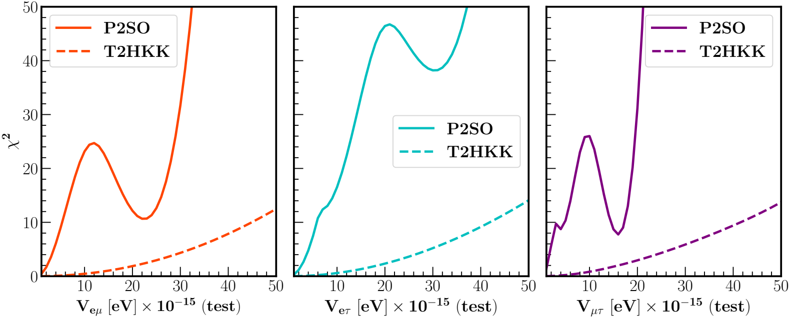


Figure: Sensitivity limits on LRF parameters for $\delta_{CP}(\text{true}) = 232^\circ$.

LRF Potential [eV]	SK	INO	DUNE	T2HK	P2SO (This work)	T2HKK (This work)
$V_{e\mu}(\times 10^{-14})$	71.5	1.56	1.46	3.45	0.23	2.40
$V_{e\tau}(\times 10^{-14})$	83.2	1.56	1.03	3.43	0.23	2.15
$V_{\mu\tau}(\times 10^{-14})$	-	-	0.67	1.84	0.13	1.5

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

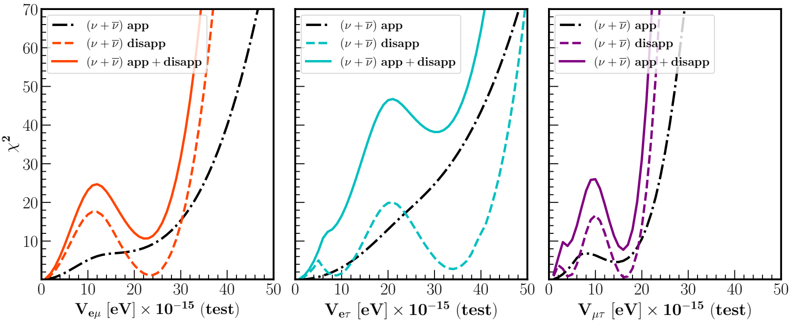


Figure: Sensitivity limits on LRF parameters for $\delta_{CP}(\text{true}) = 232^\circ$.

- The dip is mainly due to the contribution of disappearance neutrino events.
- We have verified the dip is due to the octant degeneracy in the disappearance channel.

Effects on CPV Sensitivity

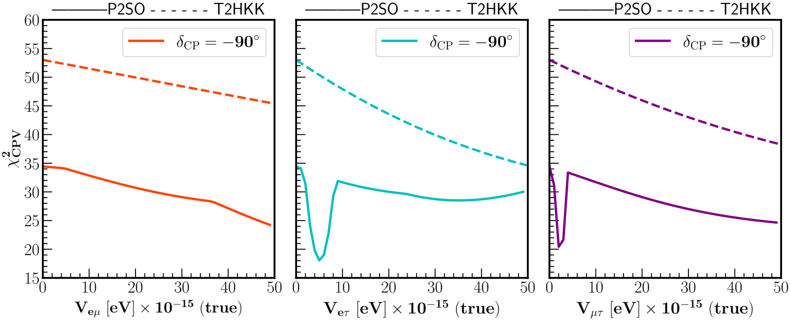


Figure: CPV sensitivities as a function of $V_{\alpha\beta}$ for the true value of $\delta_{CP} = -90°$ for P2SO and T2HKK experiments.

- The kinks appear due to the degeneracy associated with the parameter θ_{23}.

Effects on Octant Sensitivity

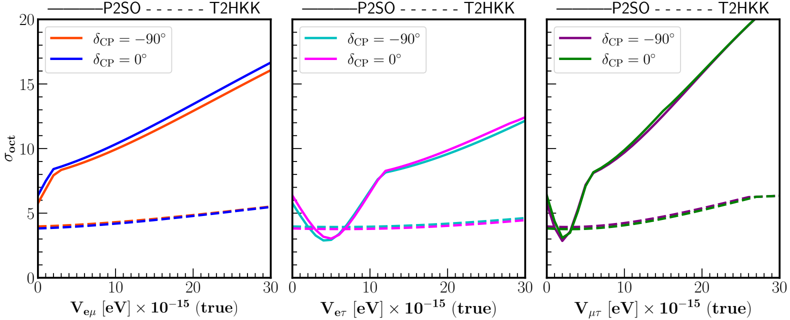


Figure: Octant sensitivity as a function of $V_{\alpha\beta}$ for P2SO and T2HKK experiments. We have considered the parameter θ_{23} to be in LO.

- The kinks appear due to the parameter θ_{23}.

Effects on Mass Hierarchy Sensitivity

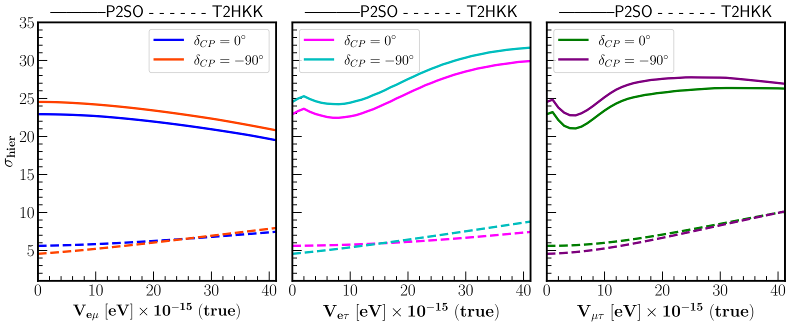


Figure: MH sensitivity as a function of $V_{\alpha\beta}$ for two different true values of δ_{CP} for P2SO and T2HKK experiments.

We have verified that these kinks are due to the large backgrounds of the P2SO experiment.

Sensitivity limits on $M_{Z_{\alpha\beta}}$ and $g_{\alpha\beta}$

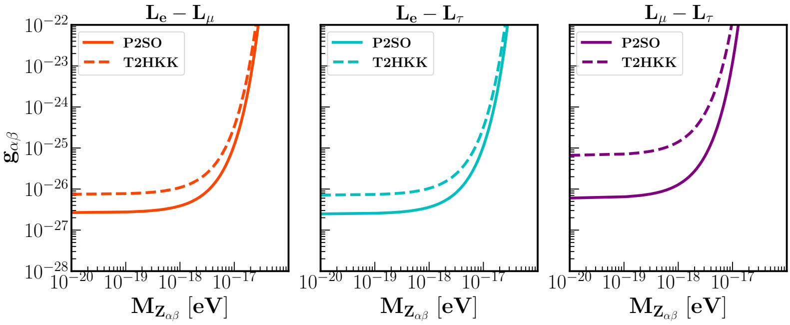


Figure: Allowed range for gauge coupling vs mass of gauge boson for LRF potential in all three cases at 2σ C.L. for P2SO and T2HKK experiments.

Experiment	$L_e - L_\mu$	$L_e - L_\tau$	$L_\mu - L_\tau$
P2SO (This work)	2.66×10^{-27}	2.48×10^{-27}	6.03×10^{-27}
T2HKK (This work)	7.47×10^{-27}	7.12×10^{-27}	6.637×10^{-26}
T2HK	1.30×10^{-26}	1.24×10^{-26}	4.31×10^{-26}
DUNE	8.55×10^{-27}	7.03×10^{-27}	2.59×10^{-26}

Table: Projected upper bound on $g_{\alpha\beta}$ from various experiments.

- The new lightweight mediator can gives rise to a long range potential which can affect the neutrino oscillation.
- LRF can be probed in neutrino oscillation experiment.
- P2SO can give the strongest bound on the LRF parameters .
- LRF parameters can affect the CPV Sensitivity, Octant Sensitivity and Mass Hierarchy Sensitivity for both P2SO and T2HKK experiment.
- Obtained bounds on the mass of the new gauge boson and its coupling strength associated with the LRF. Bounds obtained for P2SO are better than T2HKK experiment.

Thank You...