# Exploring Long-Range Force in Neutrino Oscillation at ESSnuSB Experiment

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For the ESSnuSB Collaboration

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# Long-range forces (LRF): An Introduction

- Standard Model neutral-current interactions of neutrinos are ***flavour diagonal and universal*** making no effect in neutrino flavour oscillations; .i.e. $\nu_e, \nu_\mu$, and $\nu_\tau$ are getting affected by same way.

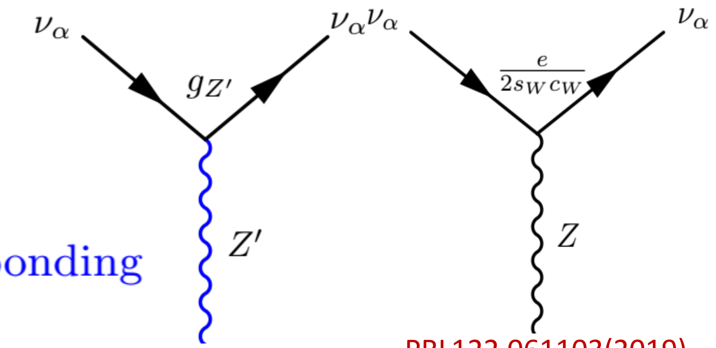
- However, there exist anomaly-free global symmetries $U(1)_X$ in the extension of the Standard Model which can be *flavour diagonal but NOT universal* and hence may affect the neutrino flavour transition providing an opportunity to search for physics beyond SM.

$$\text{Model}: SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

$U(1)' \rightarrow Z'$

Xiao-Gang He, Girish C. Joshi, H. Lew, and R. R. Volkas, Simplest $Z'$ model, Phys. Rev. D 44, 2118 2132 (1991).

X= $L_e - L_\mu$ , $L_e - L_\tau$ and $L_\mu - L_\tau$ are the charges of the corresponding symmetries.




PRL122,061103(2019)

- Range of this new interaction will depend upon $Z'$ mass and if these $Z'$ gauge bosons are massless or extremely light then the forces are long range.

- Nearby and distant matter — primarily electrons and neutrons — in the Earth, Moon, Sun, Milky Way, and the local Universe, may source a large matter potential that modifies neutrino oscillation probabilities.

# Long-range matter potential due to $U(1)'_X$ symmetry

- When such symmetries ($U(1)'_X$) are broken; new neutrino interactions are induced which affects $\nu_e, \nu_\mu$, and $\nu_\tau$ differently

- Such new interactions induce flavour - dependent Yukawa potentials, sourced by electrons and neutrons, that affect the mixing of neutrinos.

Long-range matter potential involving electrons as a source is given by

$$V_{e\mu/\tau} = g'^2_{e\mu/\tau} \frac{N_e}{4\pi d} e^{-m'_{Z'_{e\mu/\tau}} d} .$$

where, $g'_{e\mu/\tau}$ is the new coupling strength i.e., $g'_{e\mu}$ for $U(1)_{L_e - L_\mu}$ and $g'_{e\tau}$ for $U(1)_{L_e - L_\tau}$ gauge symmetries, $N_e$ is the number of electrons inside the object, $m'_{Z_{e\mu/\tau}}$ is the mass of new mediating gauge boson $Z'_{e\mu/\tau}$ and $d$ denotes the distance between the source of potential to the location of neutrino.

- For $L_\mu - L_\tau$, the long-range matter potential experienced by neutrinos are given by

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

where $m'_{\mu\tau}$ is the mass of the mediating $Z'_{\mu\tau}$ boson, $\chi$ is the kinetic mixing parameter between $Z$ and $Z'_{\mu\tau}$, and $\xi$ is the rotation angle between mass and flavour bases of gauge bosons, $\theta_w$ is the Weinberg angle.

# Modification in the propagation Hamiltonian due to LRF

Assuming the three new $U(1)$ gauge symmetries, generated by $L_e - L_\mu$, $L_e - L_\tau$, and $L_\mu - L_\tau$, in the nature that introduce new neutrino-matter interactions we can write the effective Hamiltonian for neutrino propagation in flavour basis as

$$H^{\text{eff}} = \frac{1}{2E}\left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger\right] + V_{CC} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + V_{\alpha\beta}. \quad (2.1)$$

$$V_{CC} \approx 7.6 \cdot Y_e \cdot 10^{-14} \left(\frac{\rho_{avg}}{\text{g cm}^{-3}}\right) \text{eV}$$

**The contribution due to the Long-range interaction is given by the potential**

$$V_{\alpha\beta} = \begin{cases} \text{diag}(V_{e\mu}, -V_{e\mu}, 0), & \text{for } L_e - L_\mu \\ \text{diag}(V_{e\tau}, 0, -V_{e\tau}), & \text{for } L_e - L_\tau \\ \text{diag}(0, V_{\mu\tau}, -V_{\mu\tau}), & \text{for } L_\mu - L_\tau \end{cases}$$

For the new matter interactions to affect the oscillation probability, the new matter potential must be at least comparable to the standard contributions in eq. (2.1), i.e., in vacuum,

$$V_{\alpha\beta} \gtrsim (\Delta m^2_{31}/2E) \text{ [inside the Earth, this is instead } V_{\alpha\beta} \gtrsim \max(\Delta m^2_{31}/2E, V_{CC})].$$

# Questions to be addressed in this project

*1) Can ESSnuSB distinguish between the standard oscillation scenario and LRFs?*

*2) Will the CPV measurement of ESSnuSB be affected by the presence of LRFs? If yes, How and by what factor!*

# ESSnuSB configuration used in the present analysis

- The European Spallation Source neutrino Super-Beam (ESSnuSB) is a proposed accelerator-based long-baseline
- neutrino experiment in Sweden to study the neutrino oscillation by probing the second oscillation maximum.

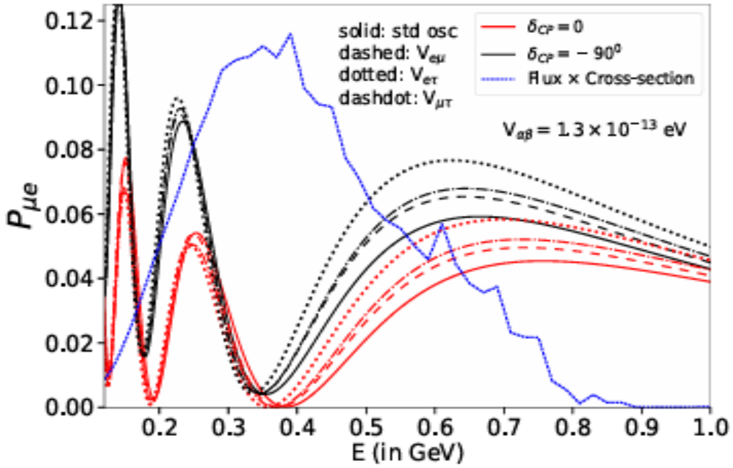
- The main goal of the experiment is to measure the Dirac CP phase with very good precision.

- We consider the configuration given in ESSnuSB CDR (Eur. Phys. J. Spec. Top. (2022) 231:3779–3955) along with

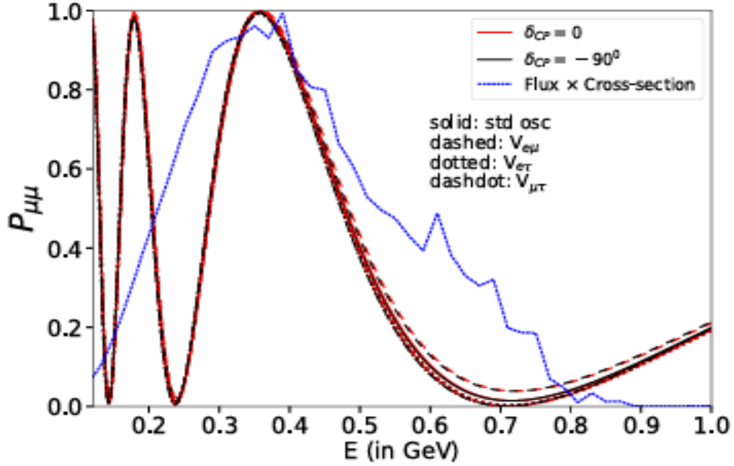
- Baseline L = 360 km
- Water Cherenkov detector of fiducial volume 538 kt
- 5 years of neutrino + 5 years of antineutrino run-time

- All these information are incorporated in GloBES to generate the results

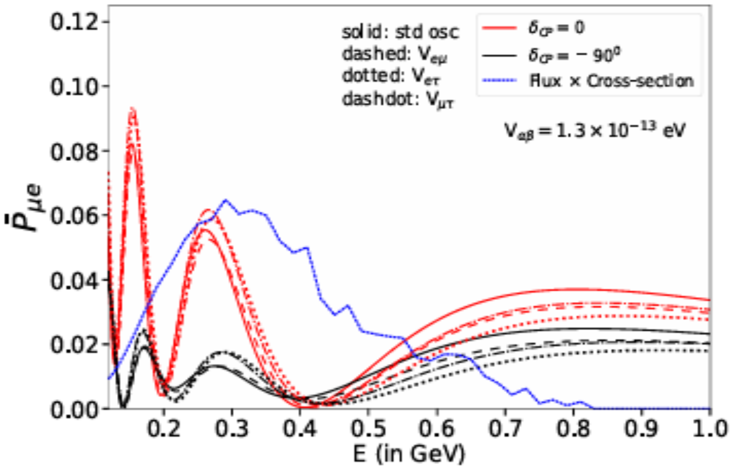
# Probability plots for ESSnuSB in presence of LRF



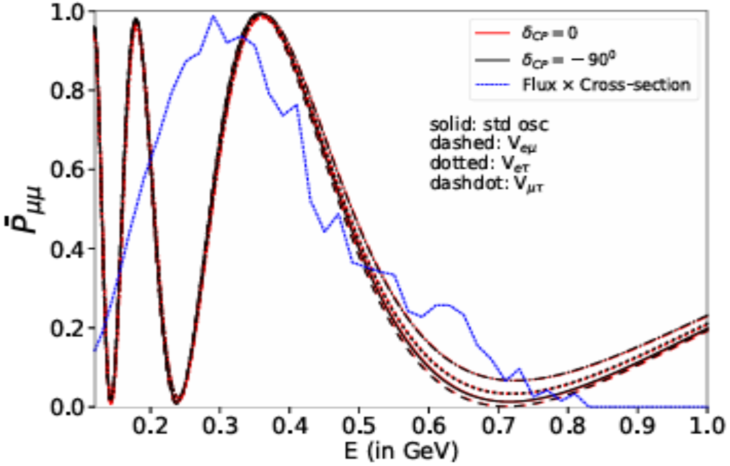

(a)



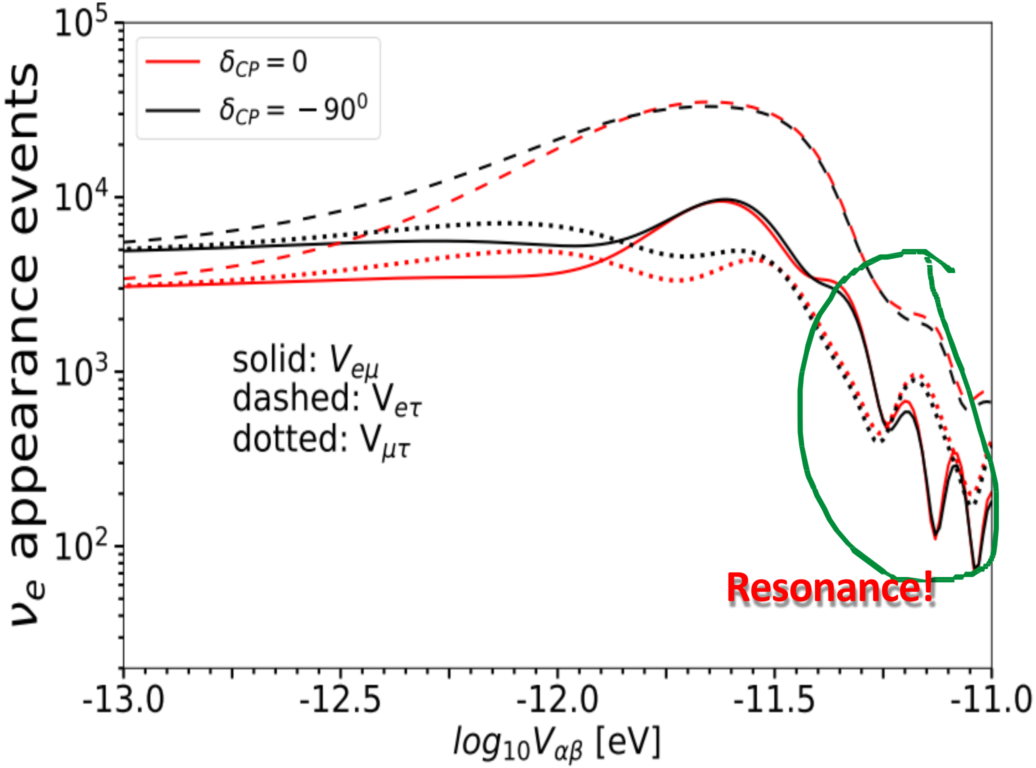

(b)

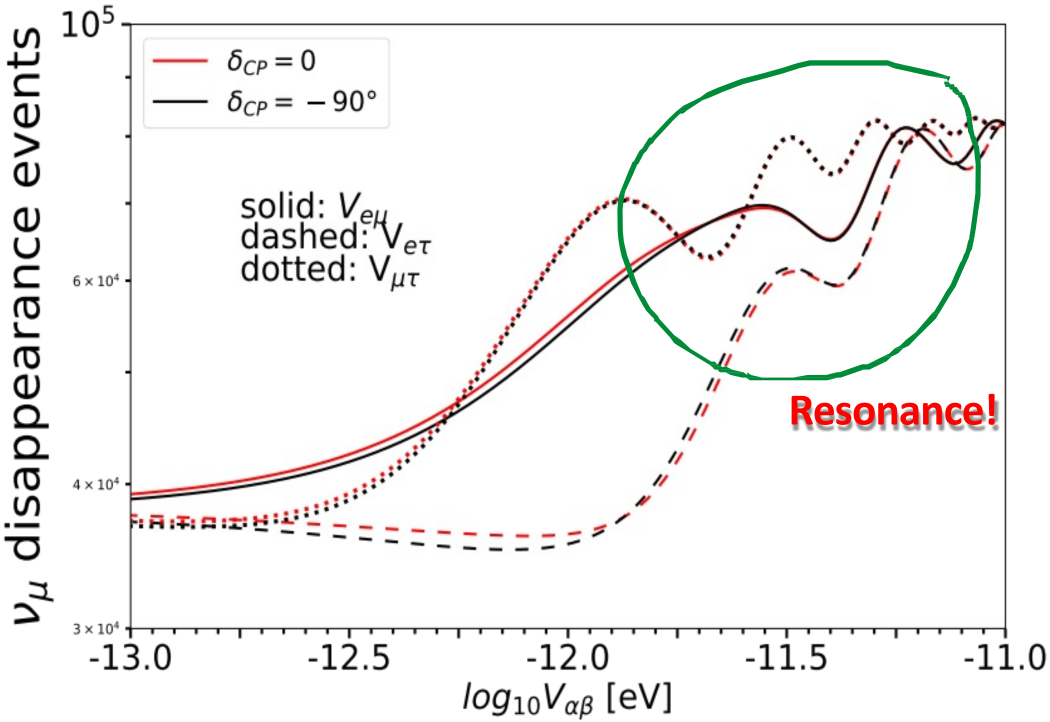



(c)




(d)

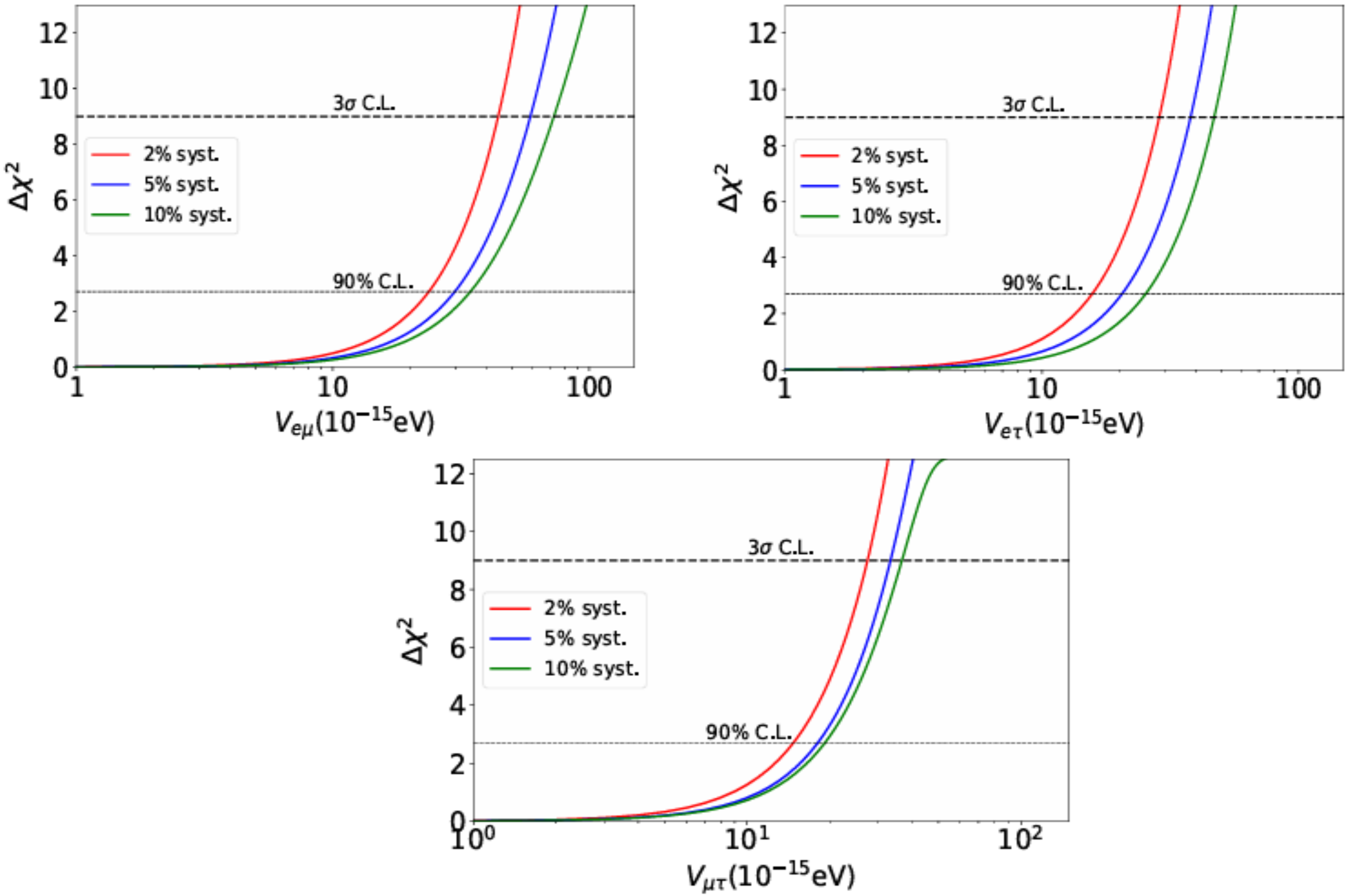



Total number of events as function of LRF (potential) parameters -------→ Initial guess about the limits on LRF by ESSnuSB

We can observe a transition between the SM dominated case and the LRF dominated case.

# ESSnuSB bounds on $V_{\alpha\beta}$



# ESSnuSB bounds on $V_{\alpha\beta}$

**Our Work**

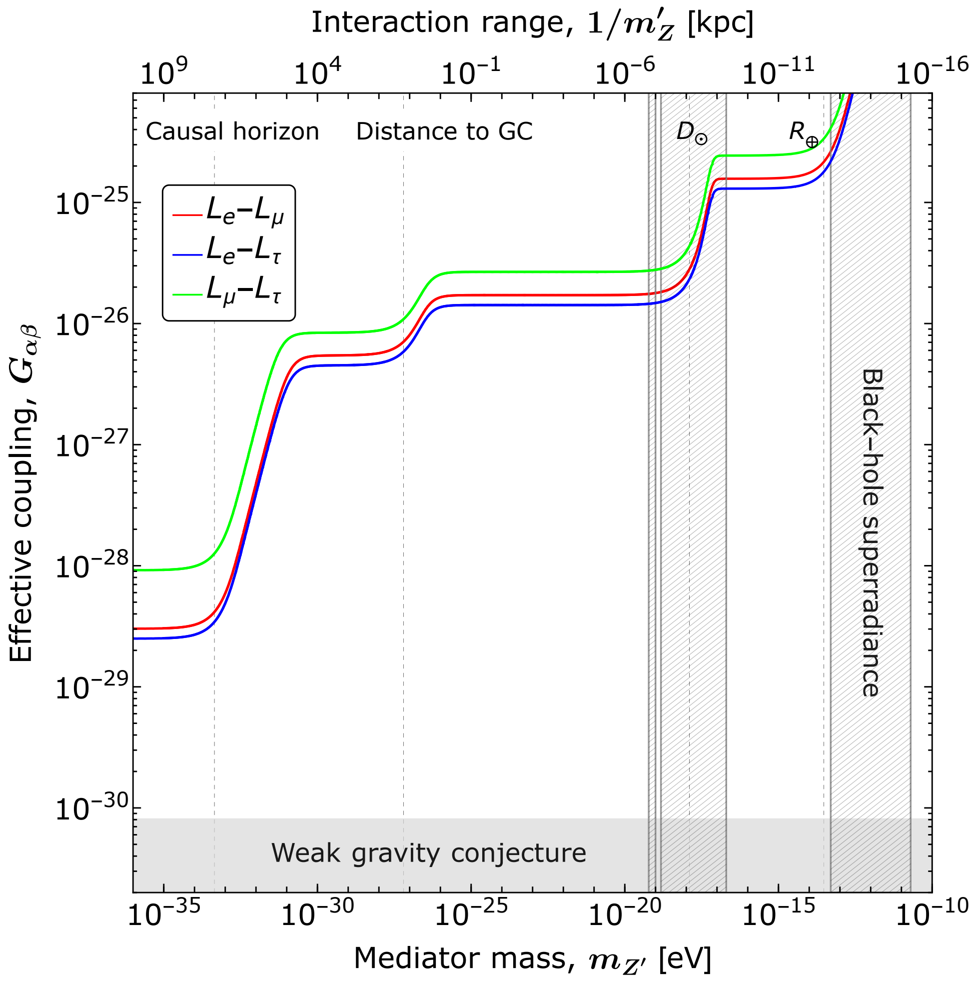
| LRF Potential (in eV) | $3\sigma$ C.L. | | | 90% C.L. | | |
|---|---|---|---|---|---|---|
| | 2% syst. | 5% syst. | 10% syst. | 2% syst. | 5% syst. | 10% syst. |
| $V_{e\mu}(\times 10^{-14})$ | 4.41 | 5.89 | 7.28 | 2.37 | 2.99 | 3.44 |
| $V_{e\tau}(\times 10^{-14})$ | 2.86 | 3.79 | 4.68 | 1.57 | 2.05 | 2.54 |
| $V_{\mu\tau}(\times 10^{-14})$ | 2.75 | 3.34 | 3.67 | 1.48 | 1.81 | 1.92 |

**Other Experimental Constraints (90% C.L.)**

| LRF Potential $[eV]$ | SK [17] | INO [22] | DUNE [23] | T2HK [23] | 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 |

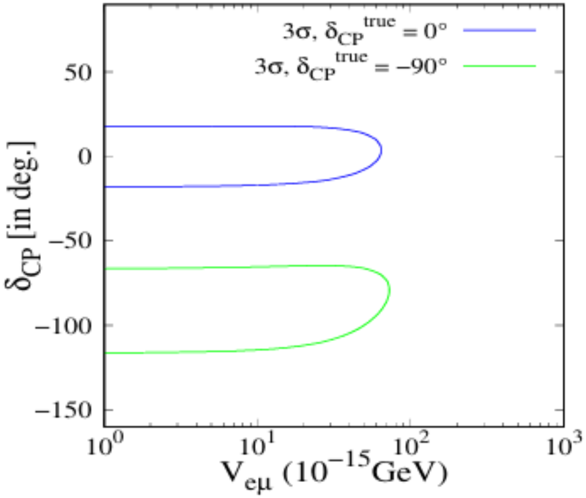
2402.19178 (arxiv.org)

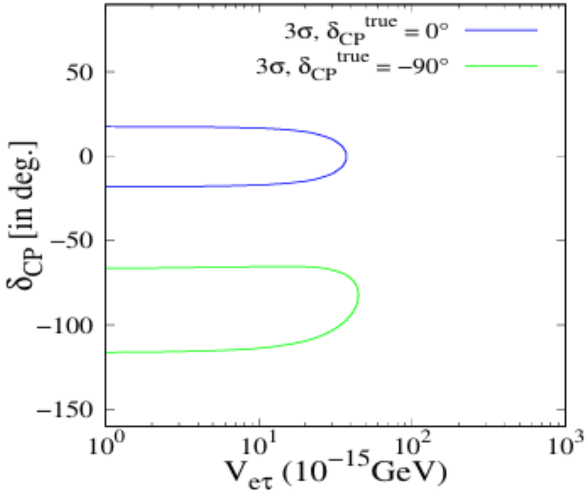
# Bounds on coupling and mediator mass



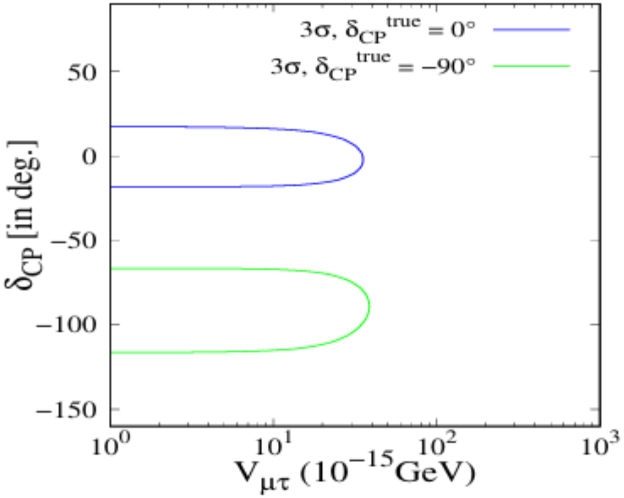

Given the ESSnuSB bound, one can obtain exclusion plots on the plane containing the mass of the mediator and the strength of the new interactions. This will depend on the matter densities that the interactions can reach!

# Effect of LRF on $\delta_{CP}$




**CPV measurements** by ESSnuSB seems to be **NOT affected significantly** by long-range interaction potential $V_{\alpha\beta}$



# CPV Sensitivity of ESSnuSB in Presence of LRF

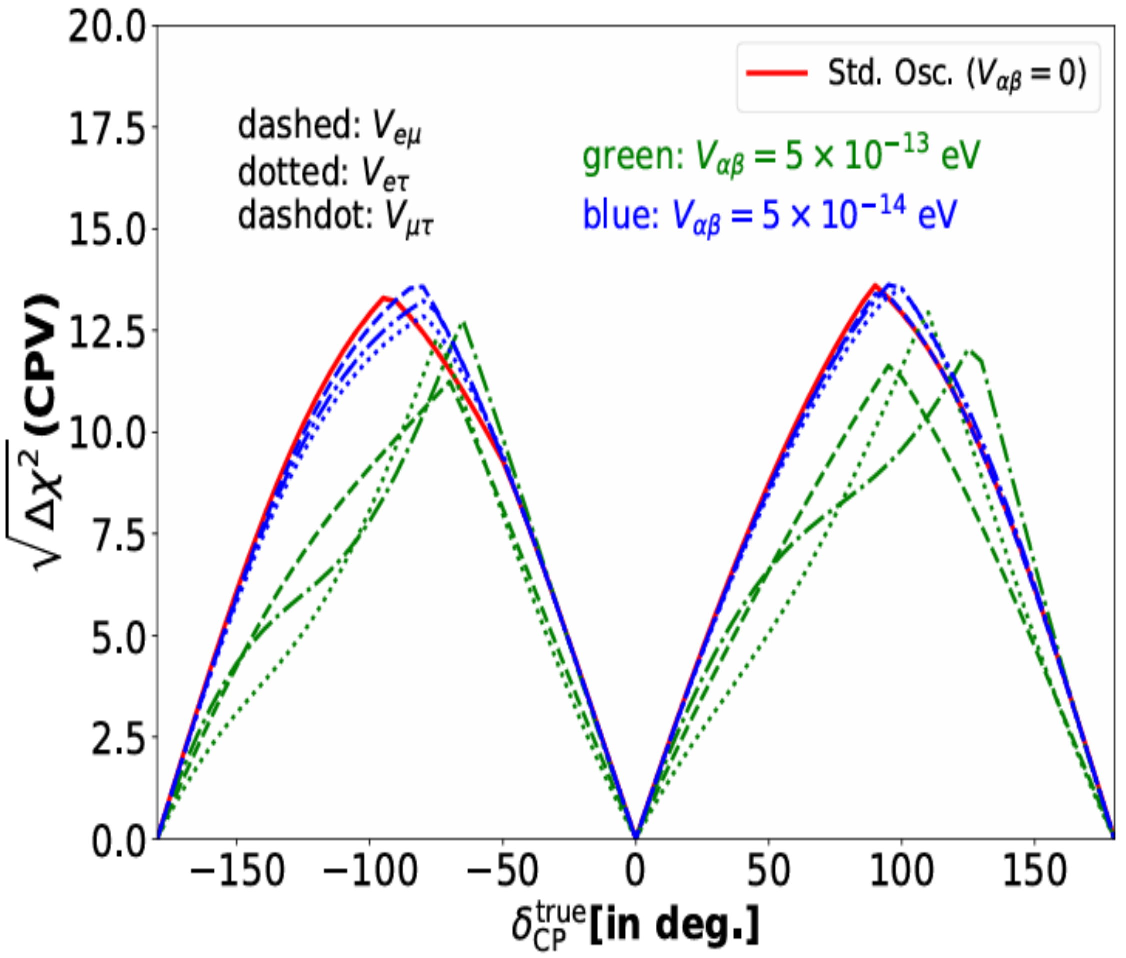
CP violation discovery refers to the capability of an experiment to distinguish a particular value of $\delta_{CP}$ other than $0^0$ and $180^0$.

**i.e. significance to exclude $sin(\delta_{CP}) = 0$.**

$$\Delta\chi^2 = \chi^2(LRF, CPV) - \chi^2(LRF, \delta_{CP} = 0^\circ, 180^\circ)$$

**Conclusion:**

CPV measurement of ESSnuSB is ROBUST!



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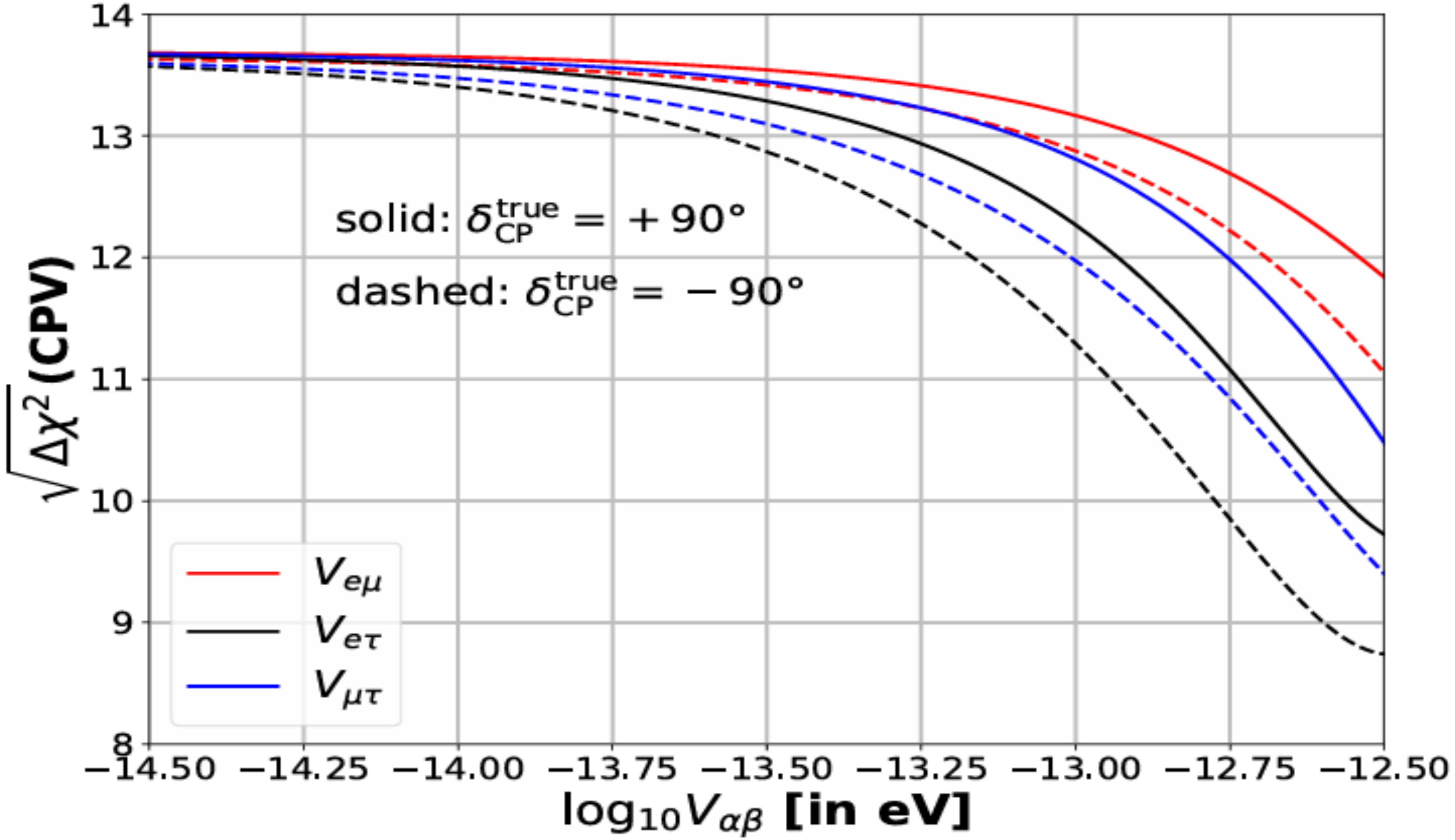
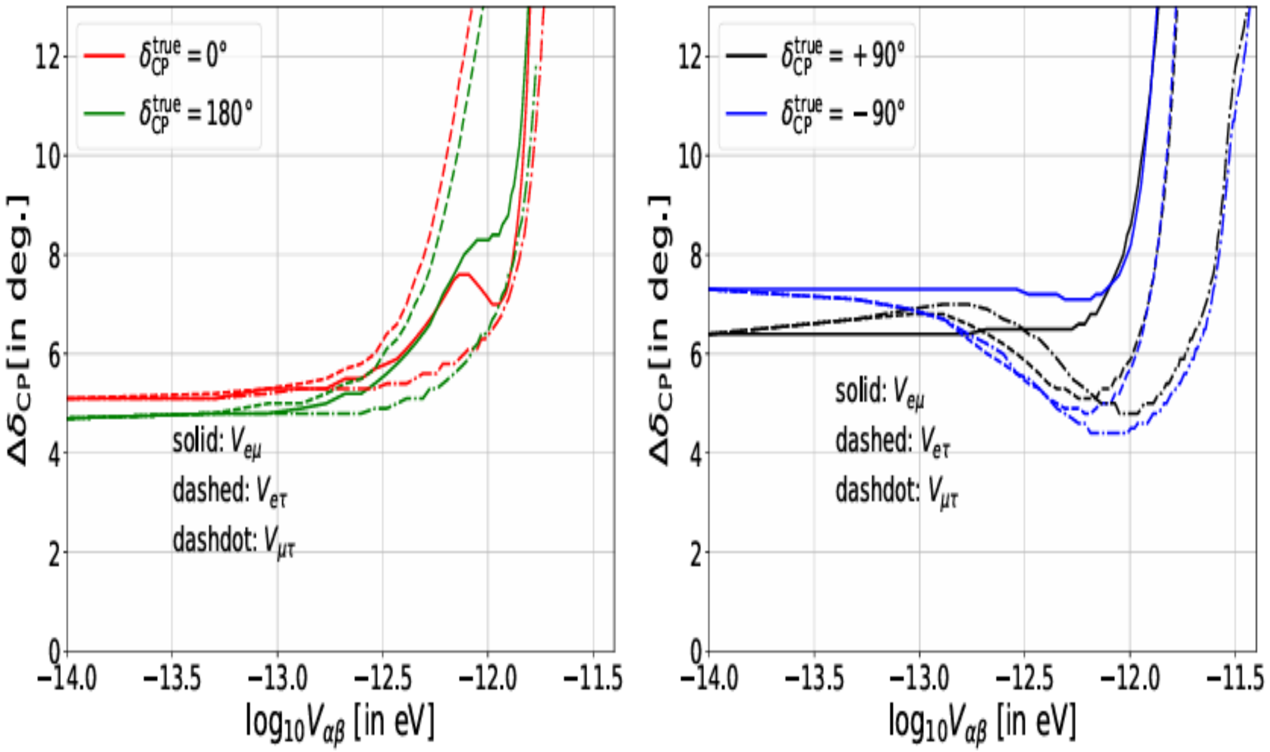


# CPV Precision of ESSnuSB in Presence of LRF

The effect of LRF potential on $\delta_{CP}$ precision is **not significantly** large even for moderately higher values of $V_{\alpha\beta}$

CPV precision deteriorates for very large potential.



# SUMMARY

- We have investigated the effects of Long-range interactions at ESSnuSB experiment

- The bounds obtained in this work are better than SK and T2HKK

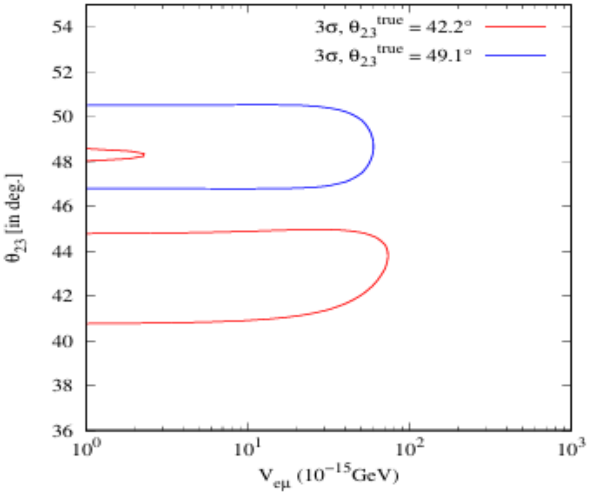
- CP violation sensitivity and CP precision measurement of ESSnuSB remain ROBUST in the presence of new long-range interaction potential.

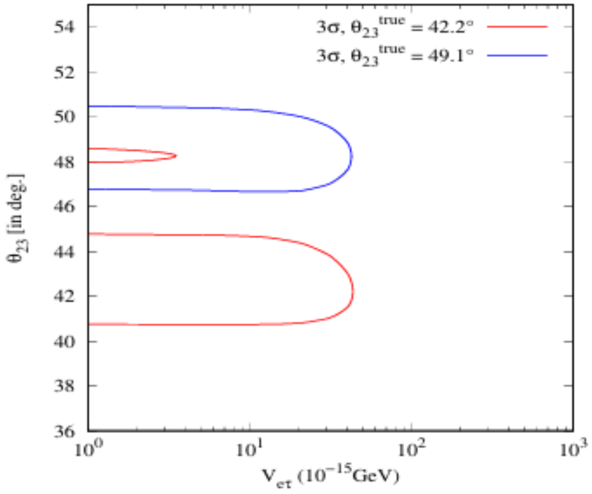
- Currently, we are computing the analytical expressions for better understanding the results and manuscript is in preparation stage.

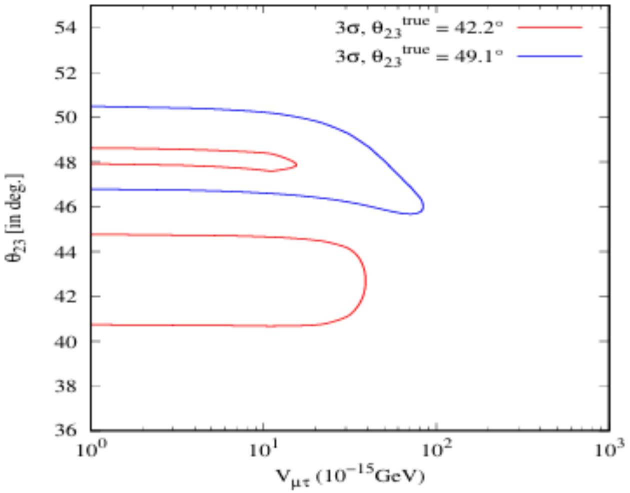
# BACK UP

# Octant of $\theta_{23}$ with $V_{\alpha\beta}$

Degeneracy seems to be broken for lower octant! At least for $L_e - L_\mu$ and $\boldsymbol{L_e - L_\tau}$ **symmetry**



# Probability plots for ESSnuSB in presence of LRF