Flavor-Dependent Long-Range Forces in Long-Baseline Experiments

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This talk is based on arXiv:1509.03517 [hep-ph]

Work done in collaboration with

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Long-Range Forces from Gauged U(1) Symmetries

- **The SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ can be extended with minimal matter content by introducing anomaly free $U(1)_X$ symmetries under which the SM remains invariant & renormalizable**

  P. Langacker, Rev. Mod. Phys. 81 (2009) 1199-1228, [arXiv:0801.1345]

- **Three lepton flavor combinations: $X = L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$ They can be gauged in an anomaly free way with the particle content of the SM**

  R. Foot, Mod.Phys.Lett. A6 (1991) 527-530
  X.-G. He, G. C. Joshi, H. Lew, and R. Volkas, Phys.Rev. D44 (1991) 2118-2132
  R. Foot, X. G. He, H. Lew, and R. R. Volkas, Phys. Rev. D50 (1994) 4571-4580

- **These $U(1)$ gauge symmetries have to be broken in Nature to allow neutrinos to mix among each other giving rise to neutrino oscillation**

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  A. Joshipura, S. Mohanty, Phys.Lett. B584 (2004) 103-108, [hep-ph/0310210]
  Bandyopadhyay, Dighe, Joshipura, Phys. Rev. D 75 (2007) 093005

- **Two possibilities for the extra gauge boson Z': very heavy or very light but in both the cases, it couples to matter very feebly to escape direct detection. If Z' is massless/extremely light, force is long range**
- **This neutral gauge boson can give rise to additional flavor-diagonal neutral current interactions: $\mathcal{L}_X = g_X \bar{\Psi} \gamma^\mu Z'_\mu X \Psi$**

$$\mathcal{L}_{Z'}^{current} = -g_{z'} \left(L_e \, \overline{e} \gamma^\alpha e - L_\mu \, \overline{\mu} \gamma^\alpha \mu + L_e \, \overline{\nu}_{eL} \gamma^\alpha \nu_{eL} - L_\mu \, \overline{\nu}_{\mu L} \gamma^\alpha \nu_{\mu L} \right) Z'_\alpha \quad (1)$$

$$j_{z'}^\alpha = \overline{e} \gamma^\alpha e + \overline{\nu}_{eL} \gamma^\alpha \nu_{eL} - \overline{\mu} \gamma^\alpha \mu - \overline{\nu}_{\mu L} \gamma^\alpha \nu_{\mu L} \quad (2)$$

- **Additional forward scattering NC amplitude:**

$$\Omega \left(\nu_e e^- \to \nu_e e^- \right) \propto +g_{z'}^2 / q^2$$
$$\Omega \left(\nu_\mu e^- \to \nu_\mu e^- \right) \propto -g_{z'}^2 / q^2$$
$$\Omega \left(\nu_\tau e^- \to \nu_\tau e^- \right) = 0$$

- **Important feature: the induced force is flavor-dependent**

Constraints from gravity experiments

- **Long-range forces are $1/r^2$ type, just like gravity, but only between leptons and depend on flavor**
- **Should have signatures in gravity experiments that test the violation of equivalence principle**
- **Lunar ranging and torsion balance experiments provide a constraint on the effective gauge coupling of this new force: $\alpha_{e\mu/e\tau} < 3.4 \times 10^{-49}$ at 2σ**

  Adelberger, Heckel, Nelson, hep-ph/0307284

Flavour dependent effective potential due to $L_e - L_\mu$ global symmetry:

We can write the effective potential in flavor basis as

$$V_{ee} = +\alpha_{e\mu} \int d^3r \; n_e(\vec{r})/r \equiv V_{e\mu} \equiv +\frac{g_{z'}^2}{4\pi} \frac{N_e^{\odot}}{R_{ES}} \equiv \alpha_{e\beta} \frac{N_e^{\odot}}{R_{ES}} \equiv V_{e\mu} \tag{3}$$

$$V_{\mu\mu} = -\alpha_{e\mu} \int d^3r \; n_e(\vec{r})/r \equiv V_{e\mu} \equiv -\frac{g_{z'}^2}{4\pi} \frac{N_e^{\odot}}{R_{ES}} \equiv -\alpha_{e\beta} \frac{N_e^{\odot}}{R_{ES}} \equiv -V_{e\mu} \tag{4}$$

$$V_{\tau\tau} = 0 \tag{5}$$

Potential due to the LRF I

- Potential due to Sun

$$V_{e\beta}^{\odot} = \frac{\alpha_{e\beta} N_e^{\odot}}{R_{ES}} \approx \frac{\alpha_{e\beta} \times 10^{57}}{7.6 \times 10^{26}\, GeV^{-1}} \approx 1.3 \times 10^{-11} eV \left(\frac{\alpha_{e\beta}}{10^{-50}}\right) \tag{6}$$

- Potential due to Earth

$$V_{e\mu}^{E} = \frac{M_E}{M_{\odot}} \frac{R_{ES}}{R_E} V_{e\mu}(r_{ES}) \approx 0.1 V_{e\mu}(r_{ES}) \tag{7}$$

- Potential due to Earth can be neglected.
- Potential due to Sun is almost constant across the earth.

Analytical Expressions for the Effective Oscillation Parameters :

$$H_f = \left(U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + \begin{bmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} V_{e\mu} & 0 & 0 \\ 0 & -V_{e\mu} & 0 \\ 0 & 0 & 0 \end{bmatrix} \right) , \quad (8)$$

Set-up	1^{st} osc. max. (GeV)	$\frac{\Delta m^2_{31}}{2E}$ (eV)	V_{CC} (eV)	$V_{e\mu}$ (eV)	
				$\alpha_{e\mu} = 10^{-52}$	$\alpha_{e\mu} = 10^{-53}$
DUNE	2.56	4.8×10^{-13}	1.0×10^{-13}	1.3×10^{-13}	1.3×10^{-14}
LBNO	4.54	2.7×10^{-13}	1.3×10^{-13}	1.3×10^{-13}	1.3×10^{-14}

Table 1: Comparision between different potential strength faced by neutrino.

- Potential in atmospheric sector is basically $\frac{\Delta m^2}{2E} \approx 10^{-13}$. So, even if $\alpha = 10^{-52}$, it can affect neutrino oscillation significantly.

- Neutrino oscillation experiments are only experiments which can probe such tiny coupling strength.

In a CP-conserving scenario ($\delta_{\rm CP} = 0^\circ$), the effective Hamiltonian in the flavor basis given in Eq. (8) takes the form

$$H_f = R_{23}\left(\theta_{23}\right) R_{13}\left(\theta_{13}\right) R_{12}\left(\theta_{12}\right) H_0 R_{12}^T\left(\theta_{12}\right) R_{13}^T\left(\theta_{13}\right) R_{23}^T\left(\theta_{23}\right) + V\,, \qquad (9)$$

where $H_0 = {\rm Diag}\left(0, \Delta_{21}, \Delta_{31}\right)$ with $\Delta_{21} \equiv \Delta m^2_{21}/2E$ and $\Delta_{31} \equiv \Delta m^2_{31}/2E$. In the above equation, $V = {\rm Diag}\left(V_{CC} + V_{e\mu}, -V_{e\mu}, 0\right)$ for $L_e - L_\mu$ symmetry. We can rewrite H_f in Eq. (9) as

$$H_f = \Delta_{31} \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{pmatrix}, \qquad (10)$$

where

$$a_{11} = A + W + \sin^2\theta_{13} + \alpha\cos^2\theta_{13}\sin^2\theta_{12}\,, \qquad (11)$$

$$a_{12} = \frac{1}{\sqrt{2}}\left[\cos\theta_{13}(\alpha\cos\theta_{12}\sin\theta_{12} + \sin\theta_{13} - \alpha\sin^2\theta_{12}\sin\theta_{13})\right]\,, \qquad (12)$$

$$a_{13} = \frac{1}{\sqrt{2}}\left[\cos\theta_{13}(-\alpha\cos\theta_{12}\sin\theta_{12} + \sin\theta_{13} - \alpha\sin^2\theta_{12}\sin\theta_{13})\right]\,, \qquad (13)$$

$$a_{22} = \frac{1}{2}\left[\alpha\cos^2\theta_{12} + \cos^2\theta_{13} - 2\alpha\cos\theta_{12}\sin\theta_{12}\sin\theta_{13} + \alpha\sin^2\theta_{12}\sin^2\theta_{13} - 2W\right] , \tag{14}$$

$$a_{23} = \frac{1}{2}\left[\cos^2\theta_{13} - \alpha\cos^2\theta_{12} + \alpha\sin^2\theta_{12}\sin^2\theta_{13}\right] , \tag{15}$$

$$a_{33} = \frac{1}{2}\left[\cos^2\theta_{13} + \alpha\cos^2\theta_{12} + \alpha\sin\theta_{13}(\sin 2\theta_{12} + \sin^2\theta_{12}\sin\theta_{13})\right] . \tag{16}$$

In the above equations, we introduce the terms A, W, and α which are defined as

$$A \equiv \frac{V_{CC}}{\Delta_{31}} = \frac{2EV_{CC}}{\Delta m^2_{31}} , \; W \equiv \frac{V_{e\mu}}{\Delta_{31}} = \frac{2EV_{e\mu}}{\Delta m^2_{31}} , \; \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} , \tag{17}$$

and we assume that the vacuum value of θ_{23} is 45°. Note that we have kept the terms of all orders in $\sin\theta_{13}$ and α.

We can almost diagonalize H_f with the help of a unitary matrix

$$\tilde{U} \equiv R_{23}\left(\theta^m_{23}\right) R_{13}\left(\theta^m_{13}\right) R_{12}\left(\theta^m_{12}\right) , \tag{18}$$

such that

$$\tilde{U}^T H_f \tilde{U} \simeq \text{Diag}\left(m^2_{1,m}/2E,\, m^2_{2,m}/2E,\, m^2_{3,m}/2E\right) , \tag{19}$$

where off-diagonal terms are quite small and can be safely neglected. The lower right 2×2 block in Eq. (10) gives us the angle θ_{23}^m which has the form

$$\tan 2\theta_{23}^m = \frac{\cos^2\theta_{13} - \alpha\cos^2\theta_{12} + \alpha\sin^2\theta_{12}\sin^2\theta_{13}}{W + \alpha\sin 2\theta_{12}\sin\theta_{13}}\,. \tag{20}$$

The mixing angles θ_{13}^m and θ_{12}^m can be obtained by subsequent diagonalizations of the (1,3) and (1,2) blocks respectively and we get the following expressions

$$\tan 2\theta_{13}^m = \frac{\sin 2\theta_{13}(1-\alpha\sin^2\theta_{12})\left(\cos\theta_{23}^m + \sin\theta_{23}^m\right) - \alpha\sin 2\theta_{12}\cos\theta_{13}\left(\cos\theta_{23}^m - \sin\theta_{23}^m\right)}{\sqrt{2}\left(\lambda_3 - A - W - \sin^2\theta_{13} - \alpha\sin^2\theta_{12}\cos^2\theta_{13}\right)} \tag{21}$$

and

$$\tan 2\theta_{12}^m = \frac{\cos\theta_{13}^m\left[\sin 2\theta_{13}(1-\alpha\sin^2\theta_{12})\left(\cos\theta_{23}^m - \sin\theta_{23}^m\right) + \alpha\sin 2\theta_{12}\cos\theta_{13}(\cos\theta_{23}^m + \sin\theta_{23}^m)\right]}{\sqrt{2}\left(\lambda_2 - \lambda_1\right)} \tag{22}$$

where

$$\lambda_3 = \frac{1}{2}\left[\cos^2\theta_{13} + \alpha\cos^2\theta_{12} + \alpha\sin^2\theta_{12}\sin^2\theta_{13} - W + \frac{W + \alpha\sin 2\theta_{12}\sin\theta_{13}}{\cos 2\theta_{23}^m}\right], \tag{23}$$

$$\lambda_2 = \frac{1}{2}\left[\cos^2\theta_{13} + \alpha\cos^2\theta_{12} + \alpha\sin^2\theta_{12}\sin^2\theta_{13} - W - \frac{W + \alpha\sin 2\theta_{12}\sin\theta_{13}}{\cos 2\theta_{23}^m}\right], \quad (24)$$

and

$$\lambda_1 = \frac{1}{2}\left[\left(\lambda_3 + A + W + \sin^2\theta_{13} + \alpha\cos^2\theta_{13}\sin^2\theta_{12}\right) - \frac{\left(\lambda_3 - A - W - \sin^2\theta_{13} - \alpha\cos^2\theta_{13}\sin^2\theta_{12}\right)}{\cos 2\theta_{13}^m}\right]. \quad (25)$$

The eigenvalues $m_{i,m}^2/2E\,(i = 1, 2, 3)$ are given by the expressions

$$m_{3,m}^2/2E = \frac{\Delta_{31}}{2}\left[\left(\lambda_3 + A + W + \sin^2\theta_{13} + \alpha\cos^2\theta_{13}\sin^2\theta_{12}\right) + \frac{\left(\lambda_3 - A - W - \sin^2\theta_{13} - \alpha\cos^2\theta_{13}\sin^2\theta_{12}\right)}{\cos 2\theta_{13}^m}\right], \quad (26)$$

$$m_{2,m}^2/2E = \frac{\Delta_{31}}{2}\left[\lambda_1 + \lambda_2 - \frac{(\lambda_1 - \lambda_2)}{\cos 2\theta_{12}^m}\right], \quad (27)$$

and

$$m_{1,m}^2/2E = \frac{\Delta_{31}}{2}\left[\lambda_1 + \lambda_2 + \frac{(\lambda_1 - \lambda_2)}{\cos 2\theta_{12}^m}\right]. \quad (28)$$

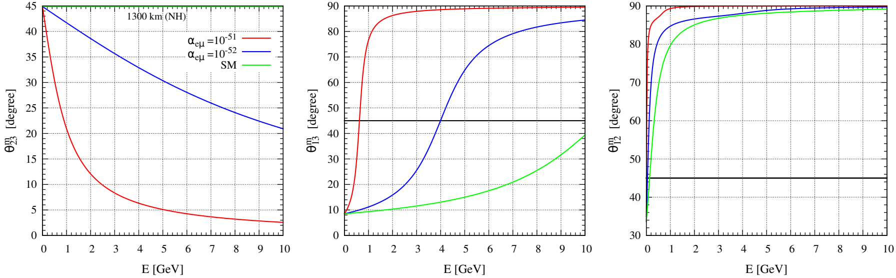


Figure 1: The variations in the effective mixing angles with the neutrino energy E in the presence of the Earth matter potential (V_{CC}) and long-range potential ($V_{e\mu}$). The left, middle, and right panels show the 'running' of θ_{23}^m, θ_{13}^m, and θ_{12}^m respectively.

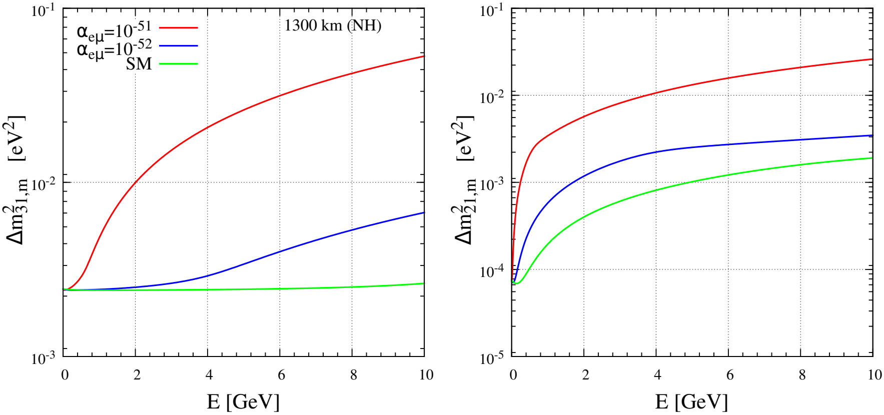


Figure 2: The variations in the effective mass-squared differences with the neutrino energy E in the presence of V_{CC} and $V_{e\mu}$. Left panel shows the 'running' of $\Delta m^2_{31,m}(\equiv m^2_{3,m} - m^2_{1,m})$ while right panel is for $\Delta m^2_{21,m}(\equiv m^2_{2,m} - m^2_{1,m})$.

The simplified probability expressions for the two channels of interest are

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}^m \, \sin^2 2\theta_{13}^m \, \sin^2 \frac{\Delta m_{32,m}^2 L}{4E}\,, \tag{29}$$

and

$$\begin{aligned} P(\nu_\mu \to \nu_\mu) \quad = \quad & 1 - \sin^2 2\theta_{23}^m \sin^2\theta_{13}^m \sin^2 \frac{\Delta m_{21,m}^2 L}{4E} \\ & - \sin^2 2\theta_{23}^m \cos^2\theta_{13}^m \sin^2 \frac{\Delta m_{31,m}^2 L}{4E} \\ & - \sin^4\theta_{23}^m \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta m_{32,m}^2 L}{4E}\,. \end{aligned} \tag{30}$$

For $\alpha_{e\mu} = 10^{-52}$ (10^{-51}), the resonance occurs around 4 GeV (0.6 GeV) for 1300 km baseline. We can obtain an analytical expression for the resonance energy demanding $\theta_{13}^m = 45^\circ$ in Eq. (21). In one mass scale dominance approximation where Δm_{21}^2 can be neglected *i.e.*assuming $\alpha = 0$, the condition for the resonance energy (E_{res}) takes the form:

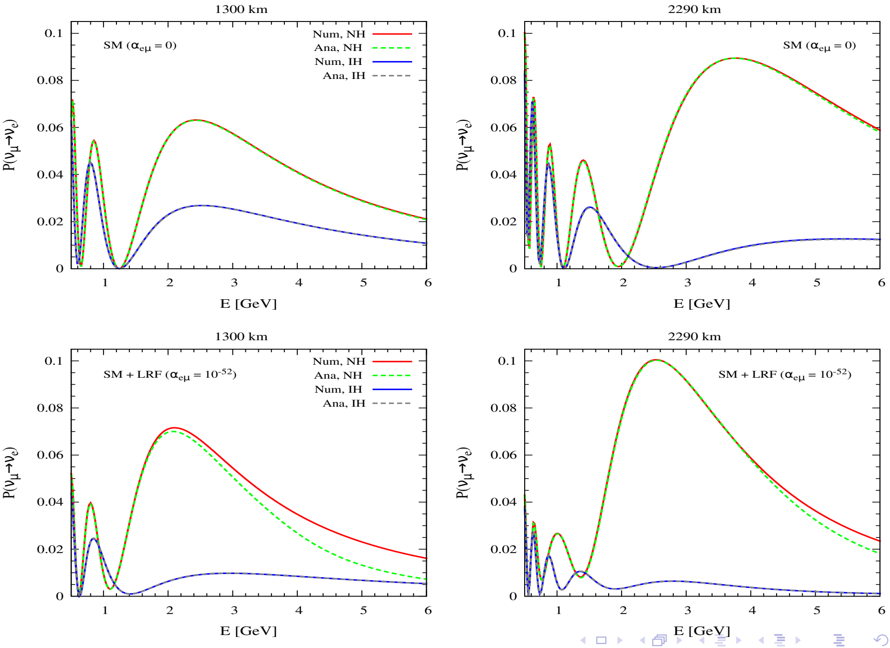
$$\lambda_3 = A + W + \sin^2\theta_{13}\,. \tag{31}$$

Now, putting $\alpha = 0$ in Eqs. (23) and (20), we get a simplified expression for λ_3 which has the following form

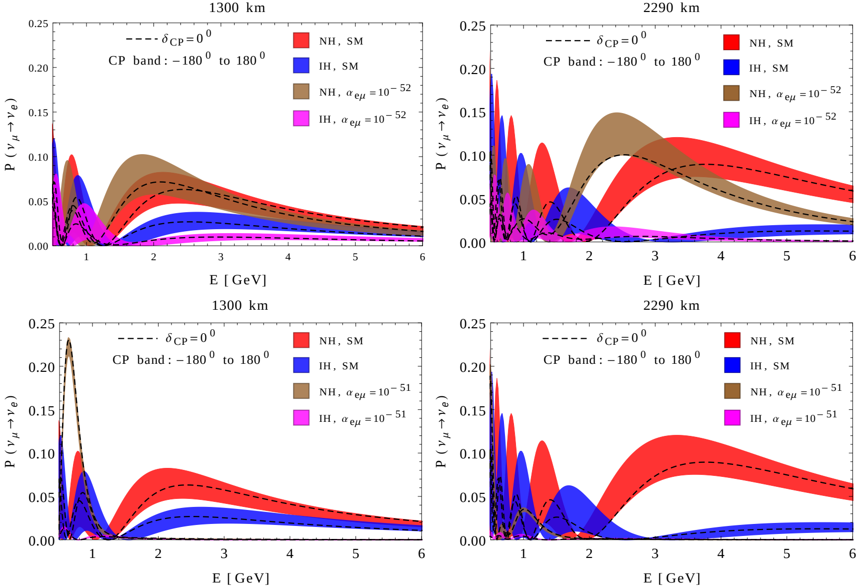
$$\lambda_3 = \frac{1}{2}\left[\cos^2\theta_{13} - W + \sqrt{W^2 + (\cos^2\theta_{13})^2}\right] \simeq \frac{1}{2}\left[2\cos^2\theta_{13} - W\right] , \qquad (32)$$

$$E_{res} = \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2V_{cc} + 3V_{e\mu}} . \qquad (33)$$

In the absence of long-range potential $V_{e\mu}$, Eq.(33) gives us the standard expression for the resonance energy in the SM framework.



1300 km
SM ($\alpha_{e\mu} = 0$)
Num, NH
Ana, NH
Num, IH
Ana, IH
$P(\nu_\mu \to \nu_e)$
E [GeV]
2290 km
SM ($\alpha_{e\mu} = 0$)
$P(\nu_\mu \to \nu_e)$
E [GeV]
1300 km
SM + LRF ($\alpha_{e\mu} = 10^{-52}$)
Num, NH
Ana, NH
Num, IH
Ana, IH
$P(\nu_\mu \to \nu_e)$
E [GeV]
2290 km
SM + LRF ($\alpha_{e\mu} = 10^{-52}$)
$P(\nu_\mu \to \nu_e)$
E [GeV]



Numerical plots of Oscillation Amplitude :

Previous Bound from different Experiments :

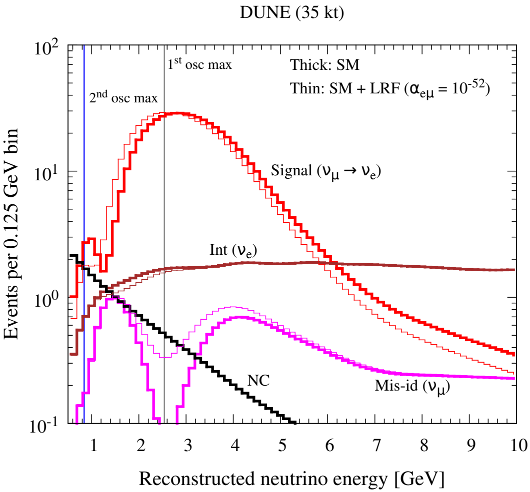
1. The **Super-K data** of oscillation of multi-GeV atmospheric neutrinos put an upper bound on coupling $\alpha_{e\tau} < 6.4 \times 10^{-52}$ and $\alpha_{e\mu} < 5.5 \times 10^{-52}$ at 90% CL. [Joshipura and Mohanty, Physics Letters B 584 (2004) 103–108].
2. **Solar neutrino and KamLAND data** gives the 3σ limits $\alpha_{e\mu} < 3.4 \times 10^{-53}$ and $\alpha_{e\tau} < 2.5 \times 10^{-53}$. [Bandyopadhyay, Dighe and Joshipura, Physical Review D 75, 093005 (2007)].

We address the following interesting issues in this work:

- Can we constrain/discover these long-range FDNC interactions in upcoming long-baseline neutrino experiments?

- If this LRF exists in Nature, can it become fatal in our attempts to resolve the remaining unknowns in neutrino oscillation?

Event Spectrum



Channel	DUNE 35 Kt		LBNO 70 Kt	
	Signal	Background	Signal	Background
	CC	Int+Mis-id+NC=Total	CC	Int+Mis-id+NC=Total
$\nu_\mu \to \nu_e$(NH)[SM]	590	125+29+24=178	1228	115+31+29=175
$\nu_\mu \to \nu_e$(NH)[SM + LRF]	588	123+34+24=181	786	112+53+29=194
$\nu_\mu \to \nu_e$(IH)[SM]	268	129+29+24=182	220	126+31+29=186
$\nu_\mu \to \nu_e$(IH)[SM + LRF]	108	130+33+24=187	49	128+50+29=207
$\bar{\nu}_\mu \to \bar{\nu}_e$(NH)[SM]	116	43+10+7=60	117	33+11+13=57
$\bar{\nu}_\mu \to \bar{\nu}_e$(NH)[SM + LRF]	44	44+12+7=63	22	34+19+13=66
$\bar{\nu}_\mu \to \bar{\nu}_e$(IH)[SM]	210	42+10+7=59	484	30+11+13=54
$\bar{\nu}_\mu \to \bar{\nu}_e$(IH)[SM + LRF]	220	41+12+7=60	343	29+19+13=61

Table 2: Comparison of the total signal and background event rates in the $\nu_e/\bar{\nu}_e$ appearance channel. Here 'Int' means intrinsic beam contamination, 'Mis-id' means misidentified muon events and 'NC' stands for neutral current.

- 15% $\sqrt{E/GeV}$ energy resolution, 5% signal and 5% background normalization error has been considered for both the experiments. Also we have used 100% detection efficiency for $\mu^\pm$ and 80% for $e^\pm$. Both the experiments uses LArTPC as their detector.

LRF at event level I

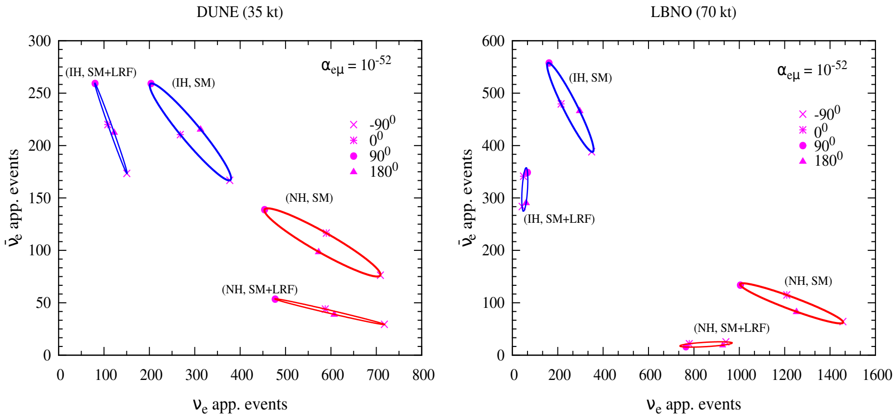


Figure 3: Maximal mixing has been assumed here.

LRF at event level II

Important points to note from these plots are :

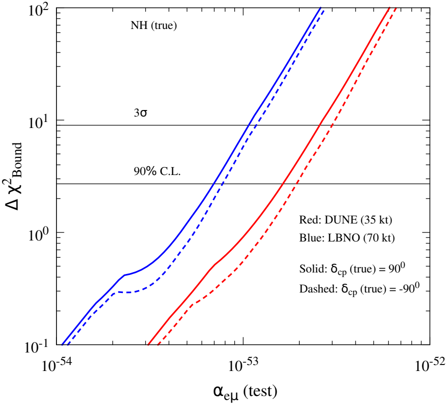
- With the impact of LRF, we see that the area of ellipses under antineutrino events diminishes for NH and the area under neutrino events diminishes for IH.

- The reason is that for NH and $\alpha_{e\mu} = 10^{-52}$, the antineutrino probability goes down leading to low event numbers. Similarly opposite phenomena happens for IH and neutrino.

- The most important feature from these bi-events plots is that IH true has significant effect on CP-violation discovery in presence of LRF. The reason is that the difference in event numbers between CP conserving and CP violating scenario becomes very low compare to NH case.

Constraint on LRF parameter I

- **We want to test, upto what upper limit of coupling strength of LRF, our experiment can afford the effect of LRF at certain C.L. if we assume that there is no LRF in nature.**



Constraint on LRF parameter II

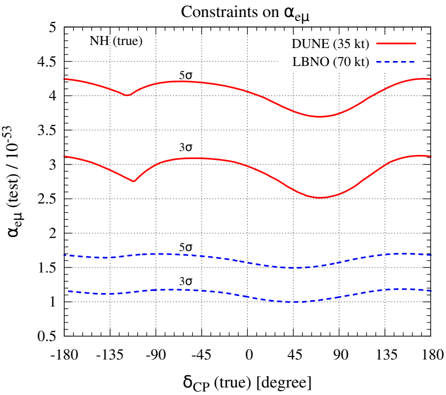


Figure 4: Here we have shown the constraints on $\alpha_{e\mu}$ for all possible values of δ_{CP}(true) at 3σ and 5σ confidence level. NH is considered as true hierarchy.

Constraint on LRF parameter III

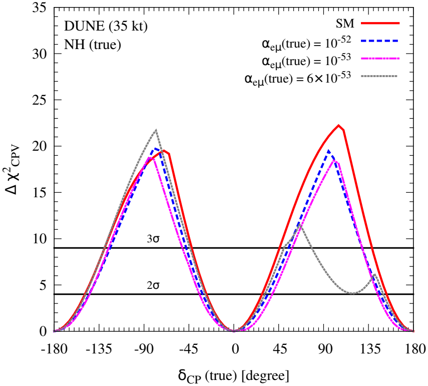
- We have considered LRF with $\mathrm{L_e} - \mathrm{L}_\mu$ global symmetry in theoretical model and no LRF in data. We have also marginalized over θ_{23}, δ_{CP} and MH in the theory.

- We have shown the upper bound of $\alpha_{e\mu}$ in all plots for different setups DUNE and LBNO. The bounds are not very sensitive to the choice of unknown δ_{CP} and Mass-Hierarchy for both the set-ups.

- Here we have shown that if there is no signal of LRF, DUNE (LBNO) can place stringent constraint on effetive gauge coupling $\alpha_{e\mu} < 1.9 \times 10^{-53} (7.8 \times 10^{-54})$ at 90% C.L. which is 30 (70) times improvement than the existing bound of Super-K experiment.

How Robust are CP-violation Searches in Presence of LRF ? I

"Discovery reach of Leptonic CP Violation" means identifying the $\delta_{\rm CP}$(true) from all possible values of CP phases except two CP conserving phase 0 or 180^0.



How Robust are CP-violation Searches in Presence of LRF ? II

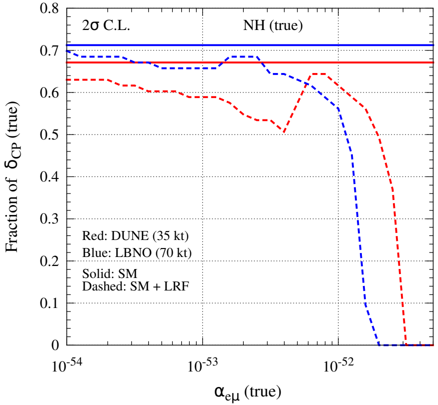


Figure 5: Here we have shown the CP coverage as a function of true $\alpha_{e\mu}$ in 2σ confidence level. θ_{23}(true) is maximal and δ_{CP}(true) have been varied from -180^0 to 180^0.

How Robust are CP-violation Searches in Presence of LRF ? III

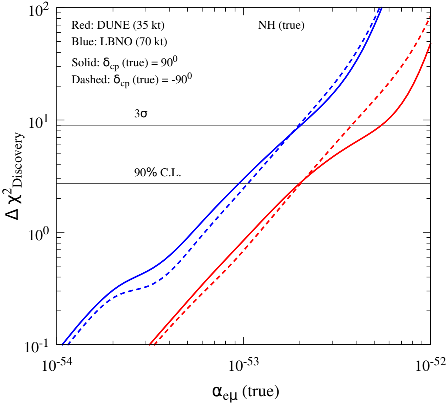
True Hierarchy		DUNE 35 kt		LBNO 70 kt	
		SM	SM+LRF	SM	SM+LRF
2σ C.L.	NH (true)	67.12%	61.64%	71.23%	56.16%
	IH (true)	68.49%	58.90%	72.60%	43.83%
3σ C.L.	NH (true)	47.94%	41.09%	54.79%	30.13%
	IH (true)	53.42%	36.98%	60.27%	12.32%

Table 3: Coverage on $\delta_{\rm CP}$(true) for CP-violation in case of SM and $\alpha_{e\mu} = 10^{-52}$.

- LRF has significant effect on CPV for IH true. For IH true basically antineutrino dominates over neutrino. But the antineutrino statistics is less and the bi-events ellipses get shrunk in presence of LRF. So discovery reach of CPV goes down.
- We observe that if $\alpha_{e\mu} \geq 2 \times 10^{-52}$, CP-violation discovery reach of these future facilities vanishes completely.

Discovery of LRF parameter I

The next important question always comes into our thought that " how lucky we are to observe a positive signal for LRF and hence $\alpha_{e\mu}$ in these highly sophisticated experiments."



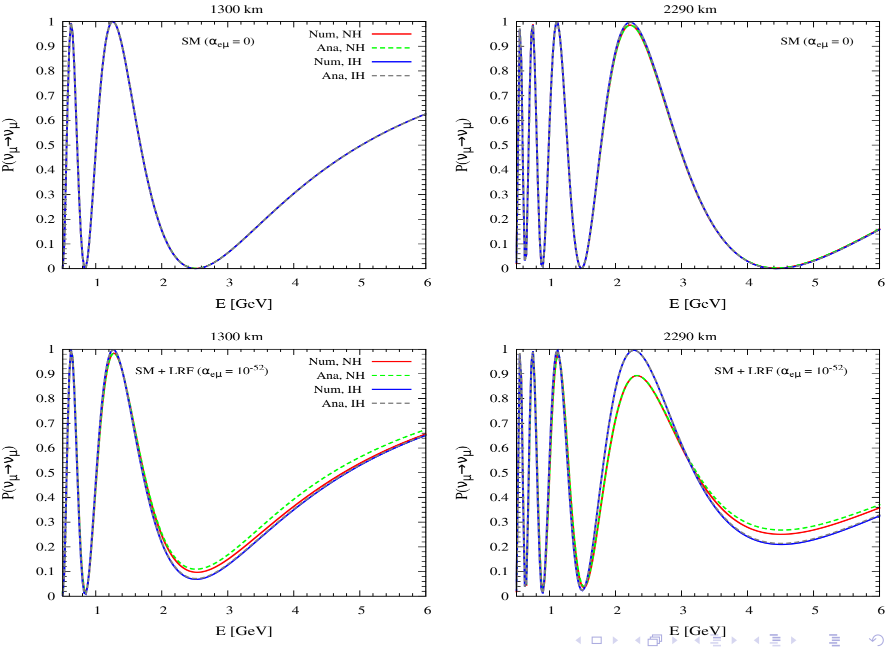
Discovery of LRF parameter II

- Important Points:
- We have considered LRF with $L_e - L_\mu$ global symmetry in observed value and no LRF in theoretical model.
- We have marginalized over θ_{23}, δ_{CP} and MH. NH has been taken as true hierarchy in this plot.
- From our whole simulation we have seen that DUNE (LBNO) can give the lower limit of discovery value approximately as 7×10^{-53} (2×10^{-53}) at 3σ C.L irrespective of MH and unknown δ_{CP}.

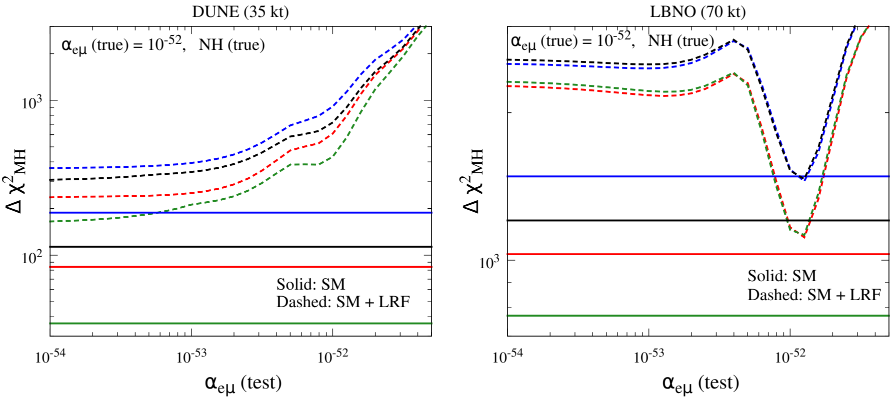
Summary & Conclusion

- I have tried to explain the model in first half of my talk.
- The most important part is the analytical understanding of this new physics in which we have put lots of efforts to calculate the mixing angles, mixing mass and also the resonance energy which are really important to explain the numerical simulations.
- Even though the mass of the mediator of LRF is $\lesssim 10^{-18}$ eV, We can probe it through Neutrino oscillation.
- Even if it presents in nature, it does not have effect on the discovery of mass-hierarchy sensitivity and but it does affect discovery reach of leptonic CP violation significantly.
- Here we have shown that if there is no signal of LRF, DUNE (LBNO) can place stringent constraint on effetive gauge coupling $\alpha_{e\mu} < 1.9 \times 10^{-53}$ (7.8×10^{-54}) at 90% C.L. which is 30 (70) times improvement than the existing bound of Super-K experiment.
- If it exists in nature, it can help to understand the underline theoretical mechanism for the generation of neutrino oscillation parameters.

Thank You.


1300 km
SM ($\alpha_{e\mu} = 0$)
Num, NH
Ana, NH
Num, IH
Ana, IH
$P(\nu_\mu \to \nu_\mu)$
E [GeV]
2290 km
SM ($\alpha_{e\mu} = 0$)
1300 km
SM + LRF ($\alpha_{e\mu} = 10^{-52}$)
2290 km
SM + LRF ($\alpha_{e\mu} = 10^{-52}$)

Impact of LRF on Mass-hierarchy sensitivity



- We have considered NH be the true hierarchy and IH be the test hierarchy. We can exclude the IH to be the possible hierarchy at greater than 5σ level.

The new Lagrangian after breaking the $SU(3) \times SU(2) \times U(1)_Y \times U(1)_{L_e - L_\mu}$ will look like

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{\hat{Z}'} + \mathcal{L}_{mix} \tag{34}$$

where we have followed notations used in [**Phys.Rev.D.57(Jun, 1998) 6788-6792**].

$$\begin{aligned}
\mathcal{L}_{SM} &= -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{W}^a_{\mu\nu}\hat{W}^{a\mu\nu} + \frac{1}{2}\hat{M}_Z^2\hat{Z}_\mu\hat{Z}^\mu - \frac{\hat{e}}{\hat{c}_W} j_Y^\mu \hat{B}_\mu - \frac{\hat{e}}{s_{\hat{W}}} j_W^{a\mu}\hat{W}^a_\mu \\
\mathcal{L}_{\hat{Z}'} &= -\frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu} + \frac{1}{2}\hat{M}_{Z'}^2\hat{Z}'_\mu\hat{Z}'^\mu - g_{\hat{z}'} j^\mu_{\hat{Z}'}\hat{Z}'_\mu \\
\mathcal{L}_{mix} &= -\frac{\sin\chi}{2}\hat{Z}'^{\mu\nu}\hat{B}_{\mu\nu} + \delta\hat{M}^2\hat{Z}'_\mu\hat{Z}^\mu
\end{aligned} \tag{35}$$

where $\hat{c}_W = \cos\theta_W$, $\hat{s}_W = \sin\theta_W$ and θ_W is the Wienberg angle, the currents above are defined as

$$j_Y^\mu = -\sum_{l=e,\mu,\tau}\left[\overline{L}_l\gamma^\mu L_l + 2\bar{l}_R\gamma^\mu l_R\right] + \frac{1}{3}\sum_{quarks}\left[\overline{Q}_L\gamma^\mu Q_L + 4\overline{u}_R\gamma^\mu u_R - 2\overline{d}_R\gamma^\mu d_R\right]$$
$$j_W^{a\mu} = \sum_{l=e,\mu,\tau}\overline{L}_l\gamma^\mu\frac{\sigma^a}{2}L_l + \sum_{quarks}\overline{Q}_L\gamma^\mu\frac{\sigma^a}{2}Q_L,$$
$$j_{\hat{Z}'}^\mu = \overline{e}\gamma^\mu e + \overline{\nu}_e\gamma^\mu P_L\nu_e - \overline{\mu}\gamma^\mu\mu - \overline{\nu}_\mu\gamma^\mu P_L\nu_\mu \qquad (36)$$

where, $P_L = (1-\gamma_5)/2$ and Q_L and L_l are the left-handed $SU(2)$ doublets for quark and leptons . Here the electromagnetic current is defined as $j_{EM}^\mu = j_W^3 + \frac{1}{2}j_Y$ and the weak neutral current is $j_{NC} = 2j_W^3 - 2\hat{s}_W^2 j_{EM}$. From the above Lagrangian we can see that the term $\frac{1}{2}\hat{M}_{Z'}^2\hat{Z'}_\mu\hat{Z'}^\mu$ breaks the $U(1)_{L_e-L_\mu}$ symmetry which in turn is generated from a vev of Higgs sector not shown here explicitely. The mixing of the $\hat{Z}-\hat{Z}'$ is shown in the $\mathcal{L}_{mix}$, where $\sin\chi$ can arise directly or radiatively [**Phys.Lett. B166 (1986) 196**]

The relation between the gauge-eigenstates $\hat{A}, \hat{Z}, \hat{Z}'$ with the mass eiganstates A, Z, Z' is given as [**arXiv: 1107.5238**]

$$\begin{pmatrix} \hat{A} \\ \hat{Z} \\ \hat{Z}' \end{pmatrix} = \begin{pmatrix} 1 & -c_W \sin\xi \tan\chi & -c_W \cos\xi \tan\chi \\ 0 & \cos\xi + s_W \sin\xi \tan\chi & s_W \cos\xi \tan\chi - \sin\xi \\ 0 & \frac{\sin\xi}{\cos\chi} & \frac{\cos\xi}{\cos\chi} \end{pmatrix} \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} \tag{37}$$

Now A, Z and Z' are the new physically observable particles. Here we are interested in Z' particle.

Now to calculate the potential created by this new gauged symmetry, we have to know the dynamiticity of the new particle (Z')

$$\mathcal{L}_{Z'}^{Full} = -\frac{1}{4} Z'_{\alpha\beta} Z'^{\alpha\beta} + \frac{1}{2} M_2 Z'_\alpha Z'^\alpha + \mathcal{L}_{Z'} \tag{38}$$

where,

$$\mathcal{L}_{Z'} = -\left[g_{z'} j_{z'}^\alpha - (\xi - s_W \chi) \frac{e}{s_W c_W} \left(j_W^{\alpha 3} - s_W^2 j_{EM}^\alpha \right) - e c_W \chi j_{EM}^\alpha \right] Z'_\alpha \tag{39}$$

From Euler-Lagrangian equation,

$$\begin{aligned} &\partial_\nu \frac{\partial}{\partial\left(\partial_\nu Z'_\mu\right)} \left(-\frac{1}{4} Z'^{\alpha\beta} Z'_{\alpha\beta} \right) \\ &- \frac{\partial}{\partial Z'_\mu} \left(\frac{1}{2} M_2 Z'_\alpha Z'^\alpha - g_{z'} j'^\alpha Z'_\alpha + \frac{e\left(\xi - s_W \chi\right)}{s_W c_W} j_W^{\alpha 3} Z'_\alpha \right) = 0 \end{aligned} \tag{40}$$

The solution is

$$V(r) = Z'^0(r) = g_{z'} N_e^\odot \frac{1}{4\pi r} \tag{41}$$

Few attempts for Fifth force experiments :

- T. Lee and C.-N. Yang, Conservation of Heavy Particles and Generalized Gauge Transformations, Phys.Rev. 98 (1955) 1501.
- J. G. Williams, S. G. Turyshev, and D. H. Boggs, Progress in lunar laser ranging tests of relativistic gravity, Phys. Rev. Lett. 93 (2004) 261101, [gr-qc/0411113].
- J. Williams, X. Newhall, and J. Dickey, Relativity parameters determined from lunar laser ranging, Phys.Rev. D53 (1996) 6730–6739.
- E. G. Adelberger, B. R. Heckel, and A. E. Nelson, Tests of the gravitational inverse square law, Ann. Rev. Nucl. Part. Sci. 53 (2003) 77–121, [hep-ph/0307284].
- A. Dolgov, Long range forces in the universe, Phys.Rept. 320 (1999) 1–15.
- L. B. Okun, On muonic charge and muonic photons, Yad. Fiz. 10 (1969) 358–362.
- L. Okun, Leptons and photons, Phys. Lett. B382 (1996) 389–392, [hep-ph/9512436].

For a range of Earth-Sun distance, these experiments gave a 2σ bounds $\alpha < 3.4 \times 10^{-49}$.