Long range forces at atmospheric neutrino experiment (Non-Universal NC Interactions)

Amina Khatun
(INO GTP Student)

Institute of Physics, Bhubaneswar

PANE-2018, ICTP

- Minimal extension of SM: introduction of additional $U^{'}(1)$ symmetry, SM remains invariant and renormalizable. (Ref. P. Langacker, arxiv:0801.1345)

Extension with Extra U(1)

- Minimal extension of SM: introduction of additional $U'(1)$ symmetry, SM remains invariant and renormalizable. (Ref. P. Langacker, arxiv:0801.1345)

- $X = a_0(B - L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau)$: anomaly free with minimal matter content. (Ref. E. Ma, PLB(1998))

- Minimal extension of SM: introduction of additional $\mathrm{U}'(1)$ symmetry, SM remains invariant and renormalizable. (Ref. P. Langacker, arxiv:0801.1345)

- $X = a_0(B - L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau)$: anomaly free with minimal matter content. (Ref. E. Ma, PLB(1998))

- Lepton combinations: $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$

- Minimal extension of SM: introduction of additional $U'(1)$ symmetry, SM remains invariant and renormalizable. (Ref. P. Langacker, arxiv:0801.1345)
- $X = a_0(B - L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau)$: anomaly free with minimal matter content. (Ref. E. Ma, PLB(1998))
- Lepton combinations: $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$
- To have nonzero mass and non-maximal mixing of flavors, these symmetries have to be broken.

- Minimal extension of SM: introduction of additional $U^{'}(1)$ symmetry, SM remains invariant and renormalizable. (Ref. P. Langacker, arxiv:0801.1345)

- $X = a_0(B - L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau)$: anomaly free with minimal matter content. (Ref. E. Ma, PLB(1998))

- Lepton combinations: $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$

- To have nonzero mass and non-maximal mixing of flavors, these symmetries have to be broken.

- For mass-less/ultralight gauge boson $Z^{'}$, force is long range (LRF).

- Minimal extension of SM: introduction of additional $\mathrm{U}^{'}(1)$ symmetry, SM remains invariant and renormalizable. (Ref. P. Langacker, arxiv:0801.1345)
- $X = a_0(B - L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau):$ anomaly free with minimal matter content. (Ref. E. Ma, PLB(1998))
- Lepton combinations: $L_e - L_\mu$, $L_e - L_\tau$, $L_\mu - L_\tau$
- To have nonzero mass and non-maximal mixing of flavors, these symmetries have to be broken.
- For mass-less/ultralight gauge boson $Z^{'}$, force is long range (LRF).
- Gravity like force ($\propto 1/r^2$), but depend on leptonic flavor content in object.

Long range Non-Universal NC interactions

- For $L_e - L_\mu$, flavor dependent forward elastic NC interactions

$\nu_e e^- \rightarrow \nu_e e^-$

$\nu_\mu e^- \rightarrow \nu_\mu e^-$

Long range Non-Universal NC interactions

- For $L_e - L_\mu$, flavor dependent forward elastic NC interactions

  $\nu_e e^- \to \nu_e e^-$

  $\nu_\mu e^- \to \nu_\mu e^-$

- Effective potentials in neutrino flavor state

  $V_{ee} = \int d^3r \; n(e^-)/r \equiv V_{e\mu}$
  $V_{\mu\mu} = -\int d^3r \; n(e^-)/r \equiv -V_{e\mu}$
  $V_{\tau\tau} = 0$

Long range NC interactions

- For $L_e - L_\tau$, flavor dependent forward elastic NC interactions

$\nu_e e^- \rightarrow \nu_e e^-$

$\nu_\tau e^- \rightarrow \nu_\tau e^-$

Long range NC interactions

- For $L_e - L_\tau$, flavor dependent forward elastic NC interactions

  $\nu_e e^- \to \nu_e e^-$

  $\nu_\tau e^- \to \nu_\tau e^-$

- Effective potentials in neutrino flavor state

$$V_{ee} = \int d^3r \; n(e^-)/r \equiv V_{e\tau}$$
$$V_{\mu\mu} = 0$$
$$V_{\tau\tau} = -\int d^3r \; n(e^-)/r \equiv -V_{e\tau}$$

Effective potential due to Solar electrons

- If $R \gtrsim R_{SE}$, then electrons in the sun produce the flavor dependent potential for neutrinos at the Earth surface.

$$V_{e\mu/e\tau} = \alpha_{e\mu/e\tau} \frac{N_e^{\odot}}{R_{SE}} \sim 1.3 \times 10^{-11} \left(\frac{\alpha_{e\mu/e\tau}}{10^{-50}}\right) \mathrm{eV} \qquad (1)$$

- Neglected the contribution from Earth electrons, 1 order of magnitude smaller. ($N_E \sim 10^{-6} N_e^{\odot}$, $R_E \sim 10^{-5} R_{SE}$.)

- For antineutrino, $V_{e\mu/e\tau}$ appears with -ve sign.

First paper on Long-range force in atmospheric neutrino experiment

ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT

Physics Letters B 584 (2004) 103–108

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Constraints on flavour-dependent long-range forces from atmospheric neutrino observations at Super-Kamiokande

Anjan S. Joshipura [a], Subhendra Mohanty [a,b]

[a] *Physical Research Laboratory, Ahmedabad 380009, India*

[b] *International Center for Theoretical Physics, Trieste, Italy*

Received 29 October 2003; received in revised form 20 January 2004; accepted 21 January 2004

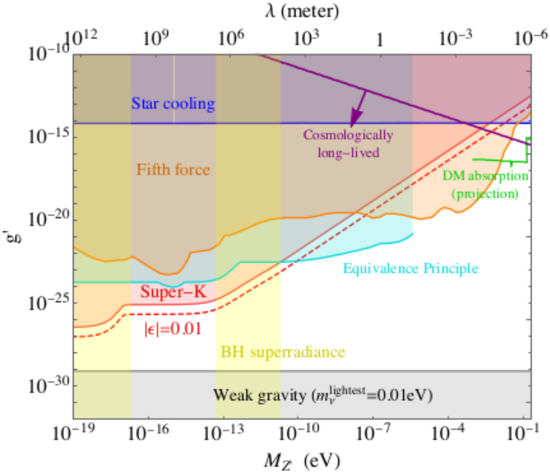
Editor: G.F. Giudice

Abstract

In the minimal standard model it is possible to gauge any one of the following global symmetries in an anomaly free way: (i) $L_e - L_\mu$, (ii) $L_e - L_\tau$ or (iii) $L_\mu - L_\tau$. If the gauge boson corresponding to (i) or (ii) is (nearly) massless then it will show up as a long range composition dependent fifth force between macroscopic objects. Such a force will also influence neutrino oscillations due to its flavour-dependence. We show that the latter effect is quite significant in spite of very strong constraints

- Limits: $\alpha_{e\mu} < 5.5 \times 10^{-52}$ and $\alpha_{e\tau} < 6.4 \times 10^{-52}$ at 90% C.L. using atmospheric neutrino data in super-Kamiokande (Ref. hep-ph/0310210).
- By the global fit of solar neutrino and KamLAND data, limits are put on these parameters as $\alpha_{e\mu} < 3.4 \times 10^{-53}$ and $\alpha_{e\tau} < 2.5 \times 10^{-53}$ at 3σ C.L. with $\theta_{13} = 0^\circ$ (Ref. A. Dighe et.al. PRD 75, 093005 (2007)).
- The cosmological bound on light $Z^{'}$ is presented as $g^{'2}/4\pi \lesssim 10^{-11}$ considering the process $Z^{'} Z^{'} \rightarrow \nu_{\mu,\tau}\, \nu_{\mu,\tau}$ (Ref. arxiv:hep-ph/9611360, arxiv:astro-ph/9610205).
- It should affect the gravity experiments which test equivalence principles
- Can be tested in lunar ranging experiments.
- The present bounds from lunar ranging and torsion balance experiments are $\alpha_X < 3.4 \times 10^{-49}$. (Ref. Adelberger,Heckel,Nelson, hep-ph/0307284)

Depth dependent long-range force



(Mark B Wise et. al., arxiv:1803.00591)

The effective Hamiltonian in presence of $L_e - L_\mu$ symmetry for neutrino is

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

U is PMNS matrix

For $L_e - L_\tau$,

$$\begin{bmatrix} V_{e\tau} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -V_{e\tau} \end{bmatrix}.$$

Comparison between V_{CC} and $V_{e\tau}$

L (km) ($\cos\theta_\nu$)	E (GeV)	$\frac{\Delta m^2_{31}}{2E}$ (eV)	V_{CC} (eV)	$V_{e\mu/e\tau}$ (eV) ($\alpha_{e\mu/e\tau} = 10^{-52}$)
5000 (-0.39)	5	2.5×10^{-13}	1.5×10^{-13}	1.3×10^{-13}
8000 (-0.63)	15	0.84×10^{-13}	1.6×10^{-13}	1.3×10^{-13}

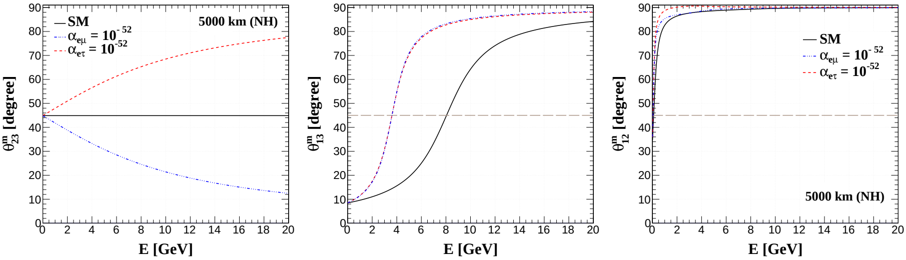
(JHEP 04(2018)023, **AK**, T. Thakore, S.K. Agarwalla)

$$V_{CC} = 7.6 \times 0.5 \times \frac{\rho}{10^{14}\mathrm{g/cm^3}}\mathrm{eV}\,, \quad (3)$$

$$V_{e\tau} = 1.3 \times 10^{-11} \times \left(\frac{\alpha_{e\tau}}{10^{-50}}\right)\mathrm{eV}\,. \quad (4)$$

The mixing angles in matter

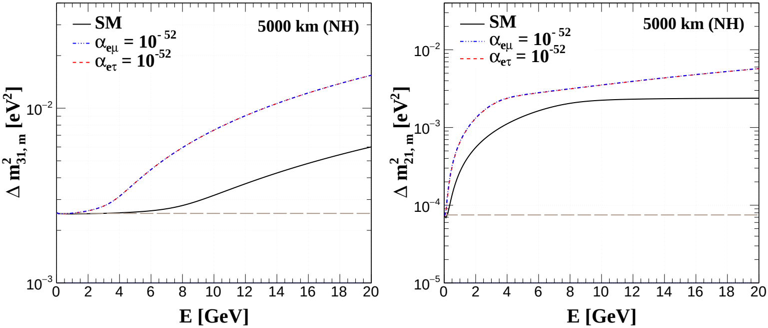
- We put $\delta_{\rm CP} = 0^\circ$ and $\theta_{23} = 45^\circ$
- Diagonalize the effective Hamiltonian (H_f) by $\tilde{U} \equiv R_{23}(\theta_{23}^m)\, R_{13}(\theta_{13}^m)\, R_{12}(\theta_{12}^m)$.
- $\tilde{U}^T\, H_f\, \tilde{U} \simeq {\rm Diag}(m_{1,m}^2/2E, m_{2,m}^2/2E, m_{3,m}^2/2E)$
- The oscillation parameters in matter "run" with neutrino energy and baseline.



(SS Chatterjee, SK Agarwalla, A Dasgupta, JHEP12(2015)167

(JHEP 04(2018)023, **AK**, T. Thakore, S.K. Agarwalla)

- θ^m_{23} (SM) remains constant.
- θ^m_{23} with $\alpha_{e\mu}$ and $\alpha_{e\tau}$ changes in opposite direction.
- For both SM and SM + LRF, independent on baseline.
- θ_{13} resonance with SM+LRF happens at lower energy and lower baseline than SM case.
- For SM, as well as SM+LRF, θ^m_{12} very quickly shoots to its value 90°.

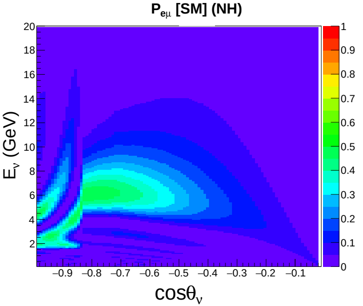


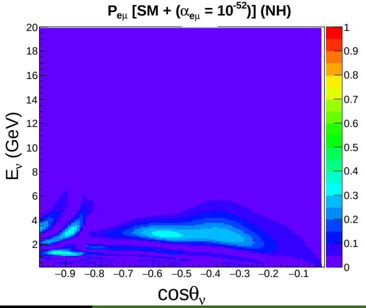
(JHEP 04(2018)023, **AK**, T. Thakore, S.K. Agarwalla)

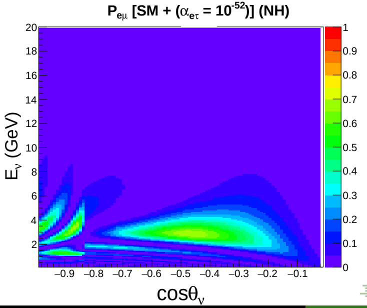
Oscillograms $P_{e\mu}$

With $\theta_{12}^{m} = 90^\circ$

$$P_{e\mu} = \sin^2\theta_{23}^{m}\,\sin^2 2\theta_{13}^{m}\,\sin^2\frac{\Delta m^2_{32,m}\,L}{4E}\,. \qquad (5)$$



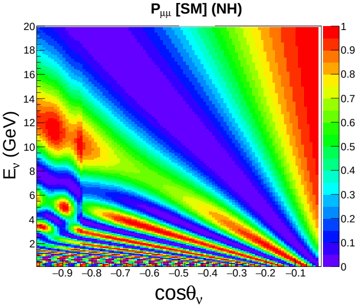


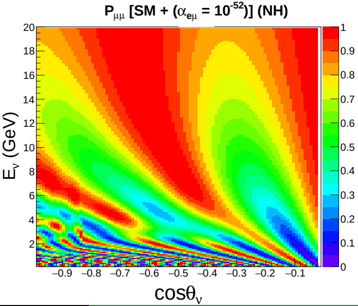


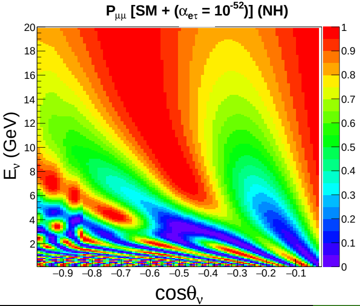
With $\theta_{12}^m = 90^\circ$

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23}^m \Big[\cos^2 \theta_{13}^m \sin^2 \frac{\Delta m^2_{31,m} L}{4E} + \frac{1}{4} \tan^2 \theta_{23}^m \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta m^2_{32,m} L}{4E} + \sin^2 \theta_{13}^m \sin^2 \frac{\Delta m^2_{21,m} L}{4E} \Big]. \quad (6)$$

main .







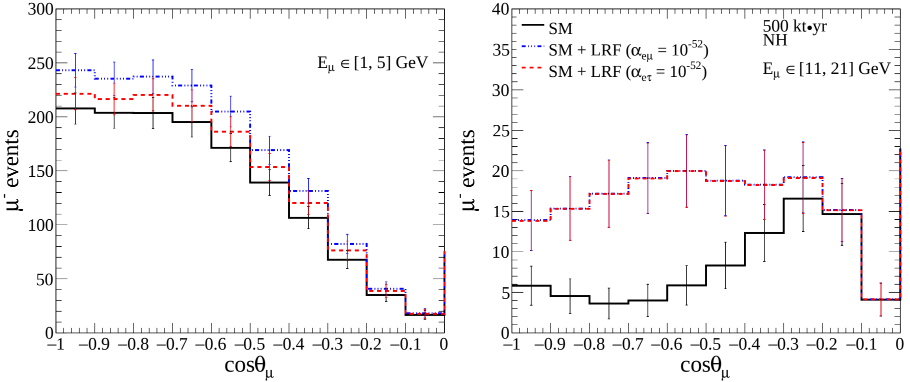
Magnetized Iron CALorimeter (ICAL)

Features of the ICAL detector

- Very good energy resolution in the range 1 GeV to 20 GeV.
- Precise reconstruction of direction of muon ($< 1^\circ$).
- Distinguish the charge of muon with good efficiency.
- Neutrinos traveled through huge Earth matter which have imprints of matter effect.

Talk by V. Datar, S. Umasankar, S. Choubey, and more than one posters

Event distributions



(JHEP 04(2018)023, **AK**, T. Thakore, S.K. Agarwalla)

Hadron energy is in the range 0 to 25 GeV.

For the oscillograms click here. For event of μ^+ is here.

Numerical details

$$\chi^2_- = \min_{\xi_l} \sum_{i=1}^{N_{E'_{\rm had}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos\theta_\mu}} \left[2(N_{ijk}^{\rm theory} - N_{ijk}^{\rm data}) - 2N_{ijk}^{\rm data} \ln\left(\frac{N_{ijk}^{\rm theory}}{N_{ijk}^{\rm data}}\right)\right] + \sum_{l=1}^{5} \xi_l^2 \,, \tag{7}$$

$$\chi^2_{ICAL} = \chi^2_- + \chi^2_+ \tag{8}$$

The uncertainties on the flux normalization (20%), flux shape (5%), zenith angle dependence of flux (5%), cross-section (10%), and overall systematics (5%) taken care by the pull method.

Observable	Range	Bin width	Bin No	Total Bins
E_μ (GeV)	$[1, 11]$	1	10	12
	$[11, 21]$	5	2	
$\cos\theta_\mu$	$[-1.0, 0.0]$	0.1	10	15
	$[0.0, 1.0]$	0.2	5	
$E'_{\rm had}$ (GeV)	$[0, 2]$	1	2	4
	$[2, 4]$	2	1	
	$[4, 25]$	21	1	

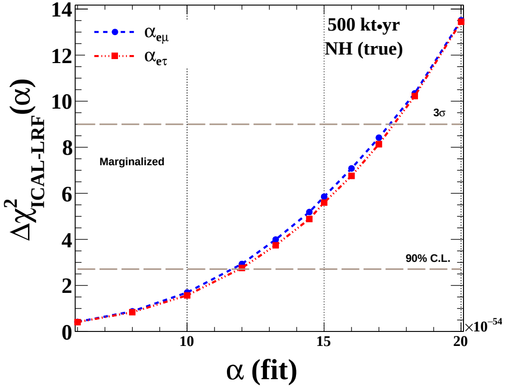
Table: The binning scheme adopted for the reconstructed observable E_μ, $\cos\theta_\mu$, and $E'_{\rm had}$ for each muon polarity. The last column shows the total number of bins taken for each observable.

Talk by A. Dighe

Oscillation parameters

Parameter	Best fit value	Marginalizing range
$\sin^2\theta_{23}$	0.5	$0.385 \rightarrow 0.635$
$\sin^2 2\theta_{13}$	0.0847	
$\frac{\Delta m^2_{eff}}{10^{-3} eV^2}$	2.471	$2.353 \rightarrow 2.59$
$\sin^2 2\theta_{12}$	0.849	
Δm^2_{21}	7.5×10^{-5} eV^2	
$\delta_{\rm CP}$	0°	

Table: Values of oscillation parameters



Existing bounds

1. $\alpha_{e\mu} < 5.5 \times 10^{-52}$ and $\alpha_{e\tau} < 6.4 \times 10^{-52}$ at 90% C.L from SK
2. $\alpha_{e\tau} < 2.5 \times 10^{-53}$ at 3σ C.L. from Solar and KamLAND data.
3. $\alpha_{e\mu/e\tau} < 1.65 \times 10^{-53}$ at 3σ C.L. from 1Mton·yr ICAL
4. $\alpha_{e\mu} < 1.9 \times 10^{-53}$ at 90% from 35 kt DUNE.

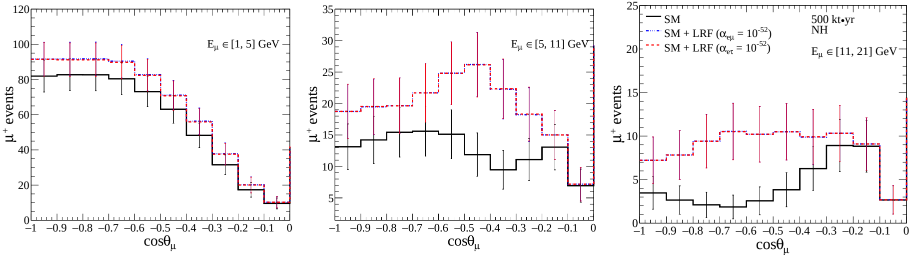
Expected limit $\alpha_{e\mu/e\tau} < 1.2 \times 10^{-53} (1.75 \times 10^{-53})$ at 90%(3σ) C.L.

46 times better than SK bound for $\alpha_{e\mu}$ and 53 times better for $\alpha_{e\tau}$

(JHEP 04(2018)023, **AK**, T. Thakore, S.K. Agarwalla)

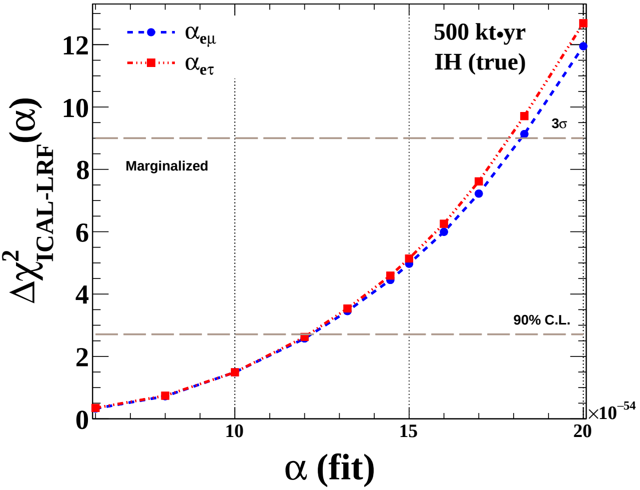
- Very very tiny coupling can be probed in neutrino experiment.
- In presence of long-range force of type $L_e - L_\mu$ and $L_e - L_\tau$, the survival probability of ν_μ increases.
- ICAL can play a very important role in constraining such long-range forces.
- It would be nice if the constraints on such kind of long-range forces can be updated with currently available atmospheric neutrino data.

Thank you!



$E_\mu \in [1, 5]$ GeV
$E_\mu \in [5, 11]$ GeV
SM
SM + LRF ($\alpha_{e\mu} = 10^{-52}$)
SM + LRF ($\alpha_{e\tau} = 10^{-52}$)
500 kt•yr
NH
$E_\mu \in [11, 21]$ GeV
μ^+ events
$\cos\theta_\mu$

back



$\alpha_{e\mu}$
$\alpha_{e\tau}$
500 kt•yr
IH (true)
Marginalized
3σ
90% C.L.
$\Delta\chi^2_{\text{ICAL-LRF}}(\alpha)$
α (fit)
$\times10^{-54}$
0
2
4
6
8
10
12
10
15
20

$$b_{11} = \frac{1}{\sqrt{2}}[\, A + \; W \; + \sin^2\theta_{13} \; + \; \alpha\cos^2\theta_{13}\sin^2_{12}] \,, \tag{9}$$

$$b_{12} = \frac{1}{\sqrt{2}}[\cos\theta_{13}(\alpha\cos\theta_{12}\sin\theta_{12} + \sin\theta_{13} - \alpha\sin^2\theta_{12}\sin\theta_{13})] \,, \tag{10}$$

$$b_{13} = \frac{1}{\sqrt{2}}[\cos\theta_{13}(-\alpha\cos\theta_{12}\sin\theta_{12} + \sin\theta_{13} - \alpha\sin^2\theta_{12}\sin\theta_{13})] \,, \tag{11}$$

$$b_{22} = \frac{1}{2}[\cos^2\theta_{13} \; + \; \alpha\cos^2\theta_{12} \; - \; \alpha\sin 2\theta_{12}\sin\theta_{13} \; + \; \alpha\sin^2\theta_{12}\sin^2\theta_{13}] \,, \tag{12}$$

$$b_{23} = \frac{1}{2}[\cos^2\theta_{13} \; - \; \alpha\cos^2\theta_{12} \; + \; \alpha\sin^2\theta_{12}\sin^2\theta_{13}] \,, \tag{13}$$

$$b_{33} = \frac{1}{2}[\cos^2\theta_{13} + \alpha\cos^2\theta_{12} + \alpha\sin 2\theta_{12}\sin\theta_{13} + \sin^2\theta_{12}\sin^2\theta_{13} - 2W] \,. \tag{14}$$

The terms, A, W, and α are as follows

$$A \equiv \frac{V_{CC}}{\Delta_{31}} = \frac{2EV_{CC}}{\Delta m^2_{31}},\; W \equiv \frac{V_{e\tau}}{\Delta_{31}} = \frac{2EV_{e\tau}}{\Delta m^2_{31}},\; \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \,. \tag{15}$$

With ($\delta_{\rm CP} = 0^\circ$) and putting $\theta_{23} = 45^\circ$,

$$H_f = R_{23}(\theta_{23})\, R_{13}(\theta_{13})\, R_{12}(\theta_{12})\, H_0\, R_{12}^T(\theta_{12})\, R_{13}^T(\theta_{13})\, R_{23}^T(\theta_{23}) + V\,.$$

$$H_0 = \mathrm{Diag}(0, \Delta_{21}, \Delta_{31}) \text{ with } \Delta_{ij} = \frac{\Delta m_{ij}^2}{2E}\,. \tag{16}$$

$$V = \begin{bmatrix} V_{CC} + V_{e\tau} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -V_{e\tau} \end{bmatrix} \tag{17}$$

$$H_f = \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{12} & b_{22} & b_{23} \\ b_{13} & b_{23} & b_{33} \end{pmatrix}\,. \tag{18}$$

$$\tilde{U} \equiv R_{23}(\theta_{23}^m)\, R_{13}(\theta_{13}^m)\, R_{12}(\theta_{12}^m)\,. \tag{19}$$

$$\tilde{U}^T\, H_f\, \tilde{U} \simeq \mathrm{Diag}(m_{1,m}^2/2E,\, m_{2,m}^2/2E,\, m_{3,m}^2/2E) \tag{20}$$

$$\tan 2\theta_{23}^m = \frac{\cos^2\theta_{13} \;-\; \alpha\cos^2\theta_{12} \;+\; \alpha\sin^2\theta_{12}\sin^2\theta_{13}}{-W \;+\; \alpha\sin 2\theta_{12}\sin\theta_{13}}\,. \tag{21}$$

$$\tan 2\theta_{13}^m = \frac{\sin 2\theta_{13}(1 \;-\; \alpha\sin^2\theta_{12})(\cos\theta_{23}^m \;+\; \sin\theta_{23}^m) \;+\; \alpha\sin 2\theta_{12}\cos\theta_{13}(\cos\theta_{23}^m \;-\; \sin\theta_{23}^m)}{\sqrt{2}(\lambda_3 \;-\; A \;-\; W \;-\; \sin^2\theta_{13} \;-\; \alpha\sin^2\theta_{12}\sin^2\theta_{13})} \tag{22}$$

$$m_{1,m}^2 = \frac{\Delta m_{31}^2}{2}[\lambda_1 \;+\; \lambda_2 \;+\; \frac{\lambda_1 \;-\; \lambda_2}{\cos 2\theta_{12}^m}]\,, \tag{23}$$

$$m_{2,m}^2 = \frac{\Delta m_{31}^2}{2}[\lambda_1 \;+\; \lambda_2 \;-\; \frac{\lambda_1 \;-\; \lambda_2}{\cos 2\theta_{12}^m}]\,, \tag{24}$$

$$m_{3,m}^2 = \frac{\Delta m_{31}^2}{2}\,[\lambda_3 + A + W + \sin^2\theta_{13} + \alpha\sin^2\theta_{12}\cos^2\theta_{13} + \frac{\lambda_3 \;-\; A \;-\; W \;-\; \sin^2\theta_{13} \;+\; \alpha\sin^2\theta_{12}\cos^2\theta_{13}}{\cos 2\theta_{13}^m}]\,. \tag{25}$$

$$\lambda_2 = \frac{1}{2}[\cos^2\theta_{13} \;+\; \alpha\cos^2\theta_{12} \;+\; \alpha\sin^2\theta_{12}\sin^2\theta_{13} \;-\; W - \frac{-W \;+\; \alpha\sin 2\theta_{12}\sin\theta_{13}}{\cos 2\theta_{23}^m}] \tag{26}$$

$$\lambda_1 = \frac{1}{2}[\lambda_3 \;+\; A \;+ W \;+ \sin^2\theta_{13} \;+\; \alpha\sin^2\theta_{12}\cos^2\theta_{13} \;-\; \frac{\lambda_3 \;-\; A \;-\; W \;-\; \sin^2\theta_{13} \;+\; \alpha\sin^2\theta_{12}\cos^2\theta_{13}}{\cos 2\theta_{13}^m}] \tag{27}$$