Can ICAL be sensitive to Leptonic Flavor Dependent LRF of $L_\mu - L_\tau$ symmetry

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Additional U(1) gauge symmetry with ultralight gauge boson

- Minimal extension of SM: introduction of additional $\mathrm{U}^{'}(1)$ symmetry, SM remains invariant and renormalizable. P. Langacker, arxiv:0801.1345
- Anomaly free $U'(1)$ with gauge quantum number E. Ma PLB(1998)

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- If the associated gauge boson Z' is ultralight, then the force has long range.
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- For LRF with $L_e - L_\mu$ and $L_e - L_\tau$ symmetries, electrons in Sun contribute to new potential for neutrino, are studied using atmospheric neutrino experiment ICAL, AK et.al. JHEP 04 (2018) 023
- Here, $L_\mu - L_\tau$ symmetry is studied, neutrons contribute to new potential

Extension with $U(1)'$ having $L_\mu - L_\tau$ symmetry

Lagrangian of $SU(3) \times SU(2)_L \times U(1)_Y \times U(1)'$

K.S. Babu et.al Phys. Rev. D 57, 6788 (1998)

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

Interaction term of Z' is J. Heeck et.al. J.Phys.G 38 (2011) 085005

$$j'^{\mu} = \bar{\mu}\,\gamma^{\mu}\,\mu + \bar{\nu}_{\mu}\,\gamma^{\mu}\,P_L\,\nu_{\mu} - \bar{\tau}\,\gamma^{\mu}\,\tau - \bar{\nu}_{\tau}\,\gamma^{\mu}\,P_L\,\nu_{\tau}\,,$$

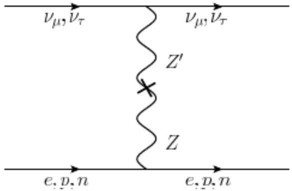
- Since there are no μ and τ in matter, this term does not contribute to new potential for neutrino

But in presence of $\mathcal{L}_{mix}$ term

$$\mathcal{L}_{Z_2} = -\Big(g'\,(j')_{\mu} - (\xi - s_W\,\chi)\frac{e}{s_W\,c_W}\big((j_3)_{\mu} - s_W^2\,(j_{\text{EM}})_{\mu} - e\,c_W\,\chi(j_{\text{EM}})_{\mu}\,\big)\Big)Z_2^{\mu}\,.$$

New potential due to LRF for terrestrial neutrinos

If $1/m_{Z'} > R_{\rm SE}$ or $m_{\mu\tau} \ll 1\ \text{AU}^{-1} = (1.5 \times 10^8\,\text{km})^{-1} \approx 1.32 \times 10^{-18}$ eV, new interactions via Z' due to e, p, n in Sun create potential for terrestrial neutrinos



For a neutral and unpolarized Sun, the potential due to electron and proton get cancelled. The potential is contributed by neutrons in the Sun, which is given by

$$
\begin{aligned}
V^{\odot}_{\mu\tau} &= \pm g'(\xi - s_W\,\chi)\,\frac{e}{4\,s_W\,c_W}\frac{N_n^{\odot}}{4\pi R_{\rm SE}}\,, \\
&= \pm\frac{\alpha_{\mu\tau}}{4\pi}\,\frac{e}{4\,s_W\,c_W}\frac{N_n^{\odot}}{R_{\rm SE}}\,;\ \ \alpha_{\mu\tau} = g'(\xi - s_W\,\chi)
\end{aligned}
$$

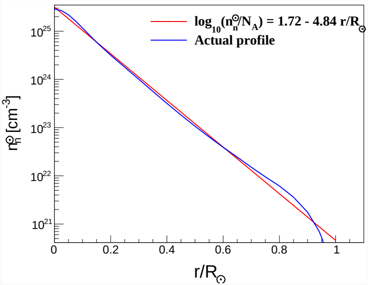
N_n = total number of neutrons in Sun, $R_{\rm SE}$ is Earth-Sun distance

LRF induced potential due to neutrons in Sun

We obtain $N_n = 1.5 \times 10^{56}$ using neutron number density profile in Sun as provided astro-ph/0511337

Solar contribution

$$V_{\mu\tau}^{\odot} = \frac{\alpha_{\mu\tau}}{4\pi} \frac{e}{4\, s_W\, c_W} \frac{N_n^{\odot}}{R_{\rm SE}}\,, \\ = 3.6 \times 10^{-14} \times \frac{\alpha_{\mu\tau}}{10^{-50}} \;\; \mathrm{eV}$$



Current bound on $\alpha_{\mu\tau}$

- Analysis of MINOS data in 2010, to explain different oscillation patterns of ν_μ and $\bar{\nu}_\mu$, best fit $\alpha_{\mu\tau} \approx 1.5 \times 10^{-50}$, however, later this mismatch was resolved. J. Heeck et.al. J.Phys.G 38 (2011) 085005

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- Gravity experiments should observe the effect of this new force since it violates the equivalence principle
- 95% C.L. limit on the neutron dependent fifth force with range $\sim$ Earth-Sun distance can be used to get the constraint on angle of $Z - Z'$ mixing: $\xi - s_W \chi < 5 \times 10^{-24}$

  J. Heeck et.al. J.Phys.G 38 (2011) 085005, Phys.Rev.Lett.100:041101,2008

Effective Hamiltonian and value of oscillation parameters

Effective hamiltonian of neutrino in presence of LRF with $L_\mu - L_\tau$ symmetry is

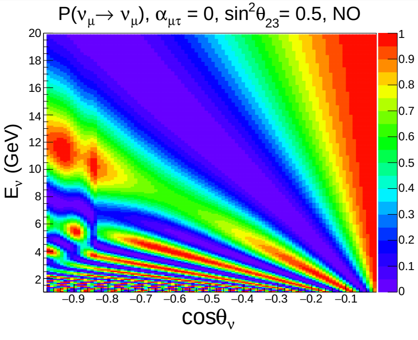
$$H_f = \left(U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + \begin{bmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & V_{\mu\tau} & 0 \\ 0 & 0 & -V_{\mu\tau} \end{bmatrix}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

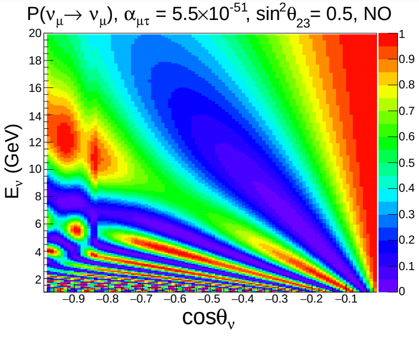
U is PMNS matrix, V_{CC} is the matter induced potential due to W-mediated interactions of ν_e with electrons in matter

$\sin^2\theta_{23}$	Δm^2_{31} [eV^2]	$\sin^2 2\theta_{12}$	Δm^2_{21} [eV^2]	$\sin^2 2\theta_{13}$	δ_{CP}
0.5, 0.4, 0.6	2.5×10^{-3}	0.855	7.39×10^{-5}	0.0876	0

- With $E = 5$ GeV, $\Delta m^2_{31}/2E \approx 2.5 \times 10^{-13}$ eV, which is approximately same as $V_{\mu\tau}$ with $\alpha_{\mu\tau} = 10^{-49}$

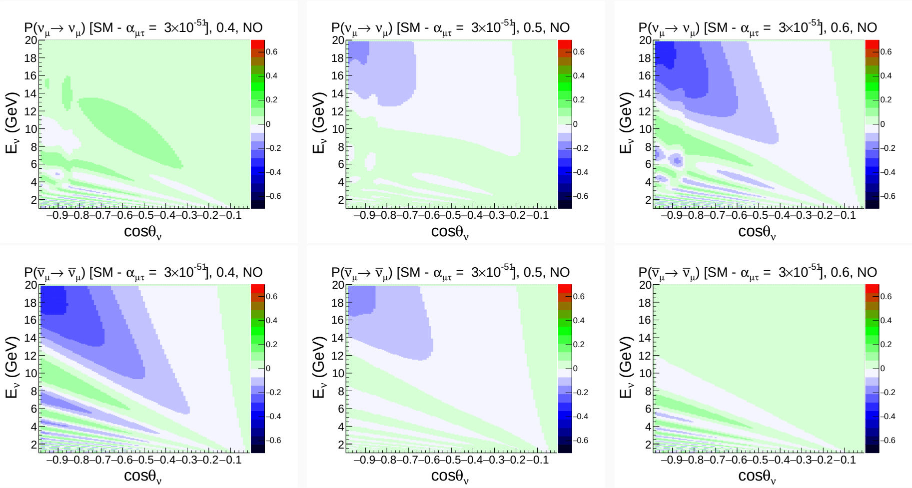
Oscillograms of $P(\nu_\mu \to \nu_\mu)$ with $\sin^2\theta_{23} = 0.5$





- The survival probabilities of ν_μ increases with nonzero value of $\alpha_{\mu\tau}$
- Same change is seen for $\bar{\nu}_\mu$ with maximal mixing
- For nonmaximal θ_{23}, the survival probabilities changes in opposite way for ν_μ and $\bar{\nu}_\mu$

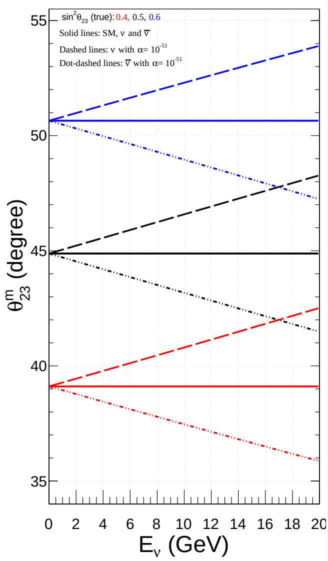
Difference of survival probabilities



✓opposite behaviour of neutrino and antineutrino survival probabilities dilute the sensitivity towards $\alpha_{\mu\tau}$ if charge of muons can not be distinguished

Running of θ_{23}^m with different vacuum θ_{23}

Used the analytical expression for this running from S.K. Agarwalla et.al. arXiv:2103:13431

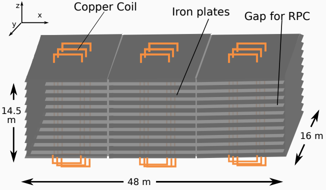


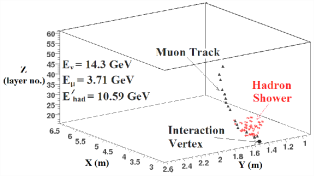
$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23}^m \left[\cos^2\theta_{13}^m \sin^2 \frac{\Delta m_{31,m}^2 L}{4E} + \frac{1}{4}\tan^2\theta_{23}^m \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta m_{32,m}^2 L}{4E} + \sin^2\theta_{13}^m \sin^2 \frac{\Delta m_{21,m}^2 L}{4E} \right].$$

- For $\theta_{23} = 45^\circ$, $\sin^2 2\theta_{23}^m \downarrow$, $P_{\mu\mu} \uparrow$ for ν & $\bar{\nu}$.
- For $\theta_{23} < 45^\circ$, $\sin^2 2\theta_{23}^m \uparrow$, $P_{\mu\mu} \downarrow$, for ν until $\theta_{23}^m \to 45^\circ$, but for $\bar{\nu}$, $P_{\mu\mu} \uparrow$
- For $\theta_{23} > 45^\circ$, $\sin^2 2\theta_{23}^m \uparrow$, $P_{\mu\mu} \downarrow$, for $\bar{\nu}$ until $\theta_{23}^m \to 45^\circ$, but $P_{\mu\mu} \uparrow$ for ν

Introduction to ICAL@INO

Main goal is to solve neutrino mass hierarchy and precisely measure the atmospheric neutrino parameters.

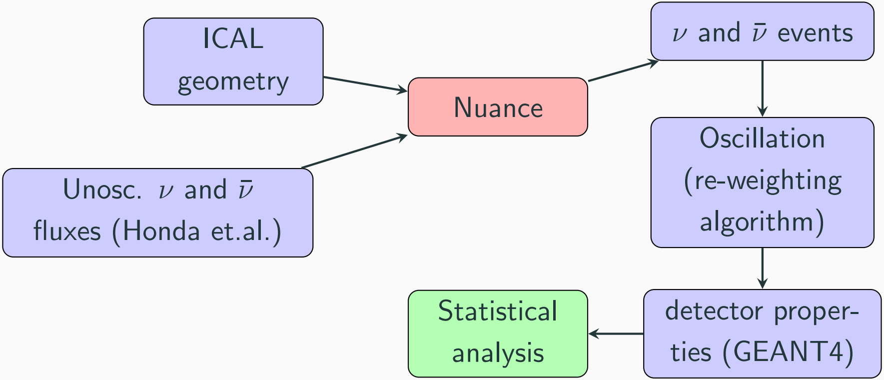




Devi et al. JINST8 (2013) P11003

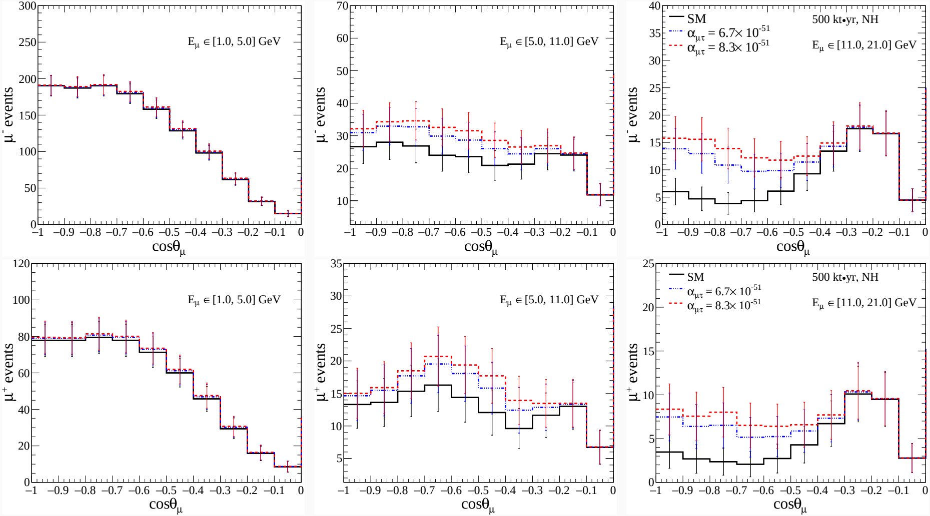
- 50 kiloton magnetized (1.5 T) iron, and around 30000 Resistive Plate Chambers.
- Charge identification efficiency to distinguish μ^- and μ^+ $\sim 98\%$.
- Very good energy ($\sim 10\%$) and angular resolution ($< 2^\circ$) for multi-GeV muons . A. Chatterjee et al. JINST 9 (2014) P07001

Details of data simulation at ICAL

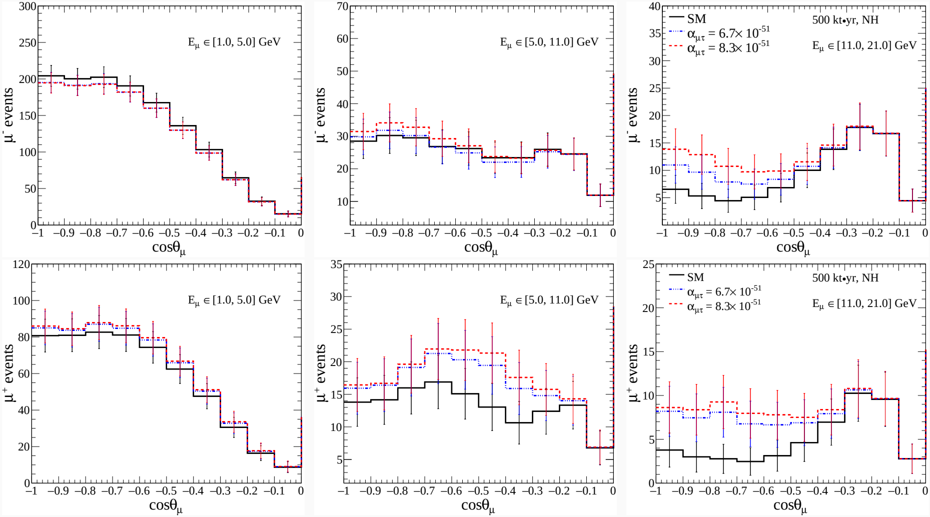


✓The statistical fluctuation is reduced by generating the events for very high exposure (1000 years), and then scale down to a 10 year exposure.

Events with $\sin^2\theta_{23} = 0.5$



Events with $\sin^2 \theta_{23} = 0.4$



Details of Statistical Analysis

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

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

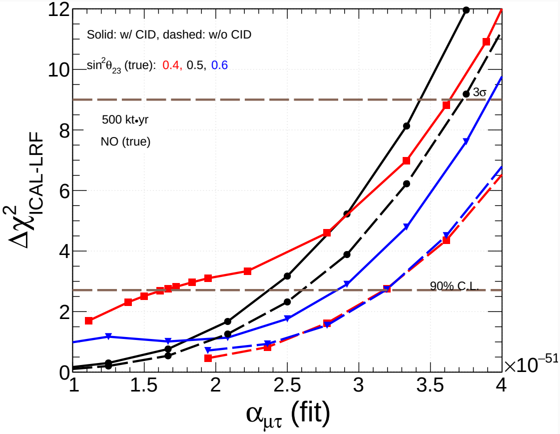
✓The uncertainties are included by pull method

- flux normalization (20%)
- flux shape (5%) in energy
- θ_z dependence of flux (5%)
- crosssection (10%)
- overall systematics (5%)

Observable	Range	Bin width	Total Bins
E_μ (GeV)	$[1, 11]$ $[11, 21]$	1 5	12
$\cos\theta_\mu$	$[-1.0, 0.0]$ $[0.0, 1.0]$	0.1 0.2	15
$E'_{\rm had}$ (GeV)	$[0, 2]$ $[2, 4]$ $[4, 25]$	1 2 21	4

Constraint with different true θ_{23}, marginalized

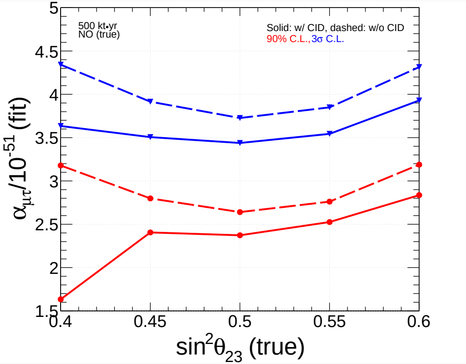
$$\Delta\chi^2_{\mathrm{ICAL-LRF}} = \chi^2(\alpha_{\mu\tau}(\mathrm{fit})) - \chi^2(\alpha_{\mu\tau} = 0)$$



(b) Marginalized over Δm^2_{32}, θ_{23} and MO

Constraint with different true θ_{23}, marginalized

✓Marginalized over Δm^2_{32}, θ_{23} and MO



✓For θ_{23} in lower octant, the marginalization effect is small, particularly at small $\alpha_{\mu\tau}$. This is due to nature of running of θ^m_{23} for neutrino for $\theta_{23} < 45°$, which can not be mimicked by other θ_{23} and Δm^2_{32} since $\chi^2_- > \chi^2 + -$

Effect on MH Measurement due to $\alpha_{\mu\tau}$ in fit

$$\Delta\chi^2_{\rm MH}(\rm SM) = \chi^2(\rm false\,MO, \alpha_{\mu\tau} = 0) - \chi^2(\rm true\,MO,\ \alpha_{\mu\tau} = 0)$$

Effect on MH Measurement due to $\alpha_{\mu\tau}$ in fit

$$\Delta\chi^2_{\mathrm{MH}}(\mathrm{SM}) = \chi^2(\mathrm{false\,MO}, \alpha_{\mu\tau} = 0) - \chi^2(\mathrm{true\,MO},\ \alpha_{\mu\tau} = 0)$$

$$\Delta\chi^2_{\mathrm{MH}}(\mathrm{LRF}) = \chi^2(\mathrm{false\,MO},\ \alpha_{\mu\tau}\,\mathrm{marginalized}) - \chi^2(\mathrm{true\,MO}, \alpha_{\mu\tau} = 0)$$

✓ $\alpha_{\mu\tau}$ varied in theory in the range of $[0 - 10^{-50}]$.

Effect on MH Measurement due to $\alpha_{\mu\tau}$ in fit

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$$\Delta\chi^2_{\rm MH}({\rm LRF}) = \chi^2({\rm false\,MO},\ \alpha_{\mu\tau}\,{\rm marginalized}) - \chi^2({\rm true\,MO}, \alpha_{\mu\tau} = 0)$$

✓ $\alpha_{\mu\tau}$ varied in theory in the range of $[0 - 10^{-50}]$.

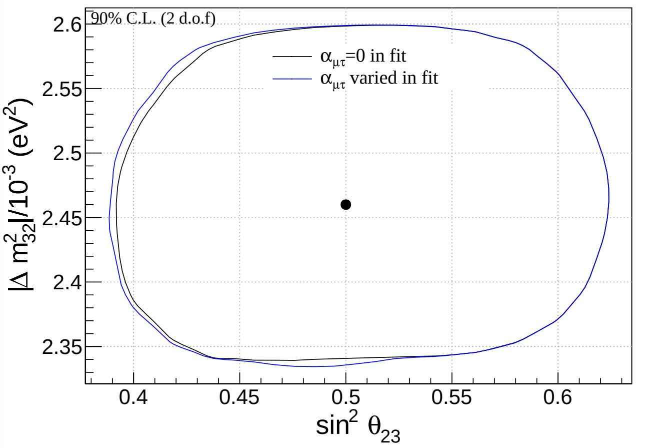
$\Delta\chi^2_{\rm MH}$ (SM)	$\Delta\chi^2_{\rm MH}$ (LRF)
7.56	7.56

- We do not see the change sensitivity of the ICAL for the MO measurement
- This may be due to the negligible impact of $\alpha_{\mu\tau}$ in matter effect part of ν_μ oscillation

***For the dedicated study of MO measurement at ICAL, please see JHEP 10 (2014) 189 which shows ICAL will be able to determine MO with 3σ C.L. in 10 years with optimized binning scheme.

Precision measurements

Data: SM ($\alpha = 0$)



Summary

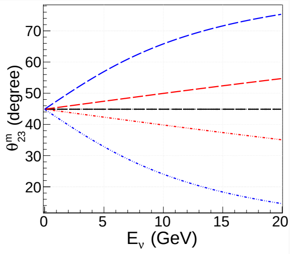
- Phenomenology of additional abelian $U(1)'$ gauge group with ultralight mediator in the context of neutrino oscillation experiments is interesting
- In presence of $Z - Z'$ mixing, and $L_\mu - L_\tau$ symmetry associated with $U(1)'$ gauge group, neutrons in Sun produce new potential for terrestrial neutrinos if $m_{Z'} \leq 1.32 \times 10^{-18}$
- Survival probabilities of ν_μ and $\bar{\nu}_\mu$ modifies in similar way with maximal θ_{23}. However, with nonmaximal θ_{23}, survival probabilities of ν_μ and $\bar{\nu}_\mu$ change in opposite way at smaller energy or smaller $\alpha_{\mu\tau}$
- The constraint on $\alpha_{\mu\tau}$ depends on true value of θ_{23}.
- Using 10 years running of ICAL, the expected constraint is around $\alpha_{\mu\tau} \leq 2.4 \times 10^{-51}$ at 90% C.L. with $\sin^2\theta_{23} = 0.5$.
- The precision measurement and mass ordering measurement at ICAL remains unaffected with $\alpha_{\mu\tau}$ marginalized in fit.

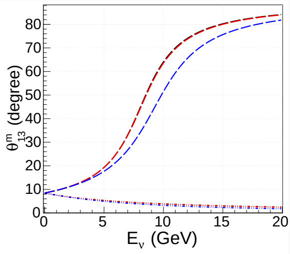
Thank you for attention!

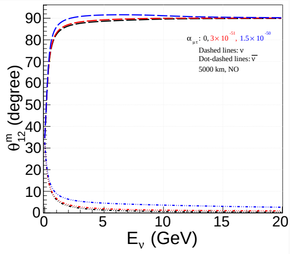
More

Running of Oscillation parameters with $\alpha_{\mu\tau}$

Used the analytical expression for this running from S.K. Agarwalla et.al. arXiv:2103:13431



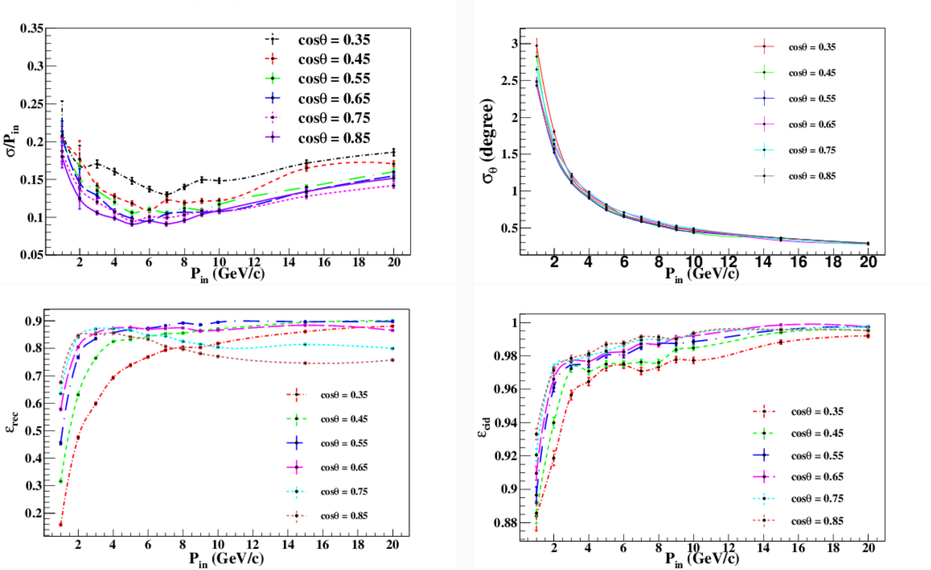




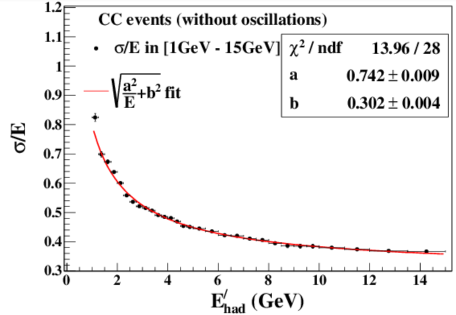
Observations

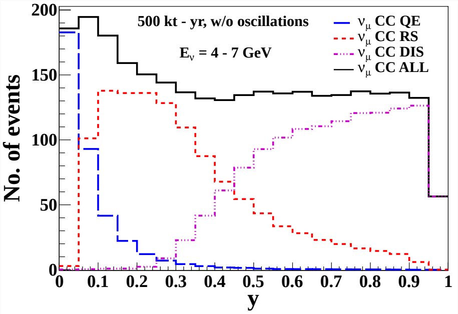
- The major modifications occur in θ^m_{23} running that causes the vacuum dominated oscillation
- The change in θ_{13} and θ_{12} is less, thus matter dominated term remains almost unchanged.

Chatterjee et al. JINST9 (2014) P07001



Hadron energy response at ICAL





Devi et al., JINST8 (2013) P11003

JHEP10(2014)189 Devi,T. Thakore, S.K. Agarwalla, A. Dighe