Study of Long-Range Force of $L_\mu - L_\tau$ Symmetry @ INO

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Long-Range Force and New Interaction via $Z - Z'$ Mixing

- Minimal extension of the Standard Model (SM) is anomaly free with an extra abelian gauge group U(1)′ if its charge follows $X = a_0(B-L) + a_1(L_e - L_\mu) + a_2(L_e - L_\tau) + a_3(L_\mu - L_\tau)$, a_i is arbitrary constant and L_l is lepton number.
- We study $L_\mu - L_\tau$ symmetry which must be broken since neutrino flavors oscillate.
- If new gauge boson Z' is ultralight ($m_{\mu\tau} \sim 0$), then the force is long ranged (Long-Range Force, LRF). Also, this LRF is lepton number dependent.
- Lagrangian after breaking $\mathbf{SU(3)} \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y} \times \mathbf{U'(1)_{L_\mu - L_\tau}}$ symmetry

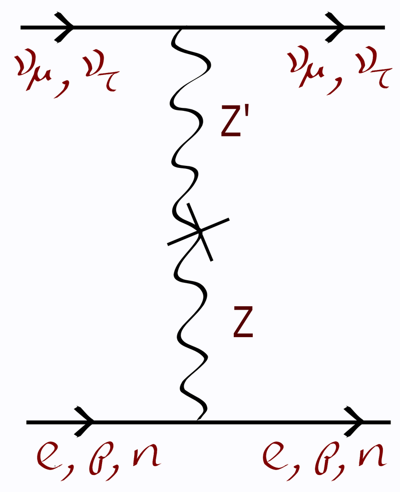
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Z'} + \mathcal{L}_{mix}$$

with

$$\mathcal{L}_{Z'} = -\frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu} + \frac{1}{2}\hat{M}^2_{Z'}\hat{Z}'_\mu \hat{Z}'^\mu - \hat{g}' \hat{j}'^\mu \hat{Z}'_\mu,$$

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

$$\mathcal{L}_{mix} = -\frac{\sin\chi}{2}\hat{Z}'_{\mu\nu}\hat{B}_{\mu\nu} + \delta\hat{M}^2_{Z'}\hat{Z}'_\mu \hat{Z}^\mu$$



New Potentials for Terrestrial Neutrinos due to LRF of $L_\mu - L_\tau$

- Coherent forward elastic interactions of terrestrial neutrinos with electron, proton, and neutron in Sun produce new potentials.
- Contributions from electrons and protons cancel each other, thus only neutrons contribute to the extra potential for terrestrial neutrinos and antineutrinos.
- For $1/m_{\mu\tau} >$ Earth-Sun distance ($R_{\rm SE}$) or $m_{\mu\tau} \ll 1$ AU$^{-1} \approx 1.32 \times 10^{-18}$ eV, effective potential due to neutrons in Sun is $V^{\odot}_{\mu\tau} = \alpha_{\mu\tau}\frac{e}{4\, s_W\, c_W}\frac{N^{\odot}_n}{4\pi R_{\rm SE}}$, where $N^{\odot}_n$ is total number of neutrons in Sun.
- Due to neutrons in Earth, the effective LRF potential is $V^{\oplus}_{\mu\tau} = \alpha_{\mu\tau}\frac{e}{4\, s_W\, c_W}\frac{N^{\oplus}_n}{4\pi R_\oplus}$, where $N^{\oplus}_n$ is total number of neutrons in Earth, and $R_\oplus$ is radius of Earth.
- Assuming proper neutron number density in the Sun, we get $V^{\odot}_{\mu\tau} = 3.6 \times 10^{-14} \times \frac{\alpha_{\mu\tau}}{10^{-50}}$ eV
- We get contribution from neutron in Earth considering PREM profile $V^{\oplus}_{\mu\tau} = 0.79 \times 10^{-14} \times \frac{\alpha_{\mu\tau}}{10^{-50}}$ eV

The total LRF induced potential for the neutrons in Sun and Earth is

$$\boldsymbol{V_{\mu\tau} = V^{\odot}_{\mu\tau} + V^{\oplus}_{\mu\tau} = 4.4 \times 10^{-14} \times \frac{\alpha_{\mu\tau}}{10^{-50}}\ \mathrm{eV}\,.} \quad (1)$$

The parameter $\alpha_{\mu\tau}$ is combination of coupling strength of LRF and $Z - Z'$ mixing parameters

✓For antineutrino, the sign of $V_{\mu\tau}$ is reversed

Impact of LRF on the Evolution of Neutrinos

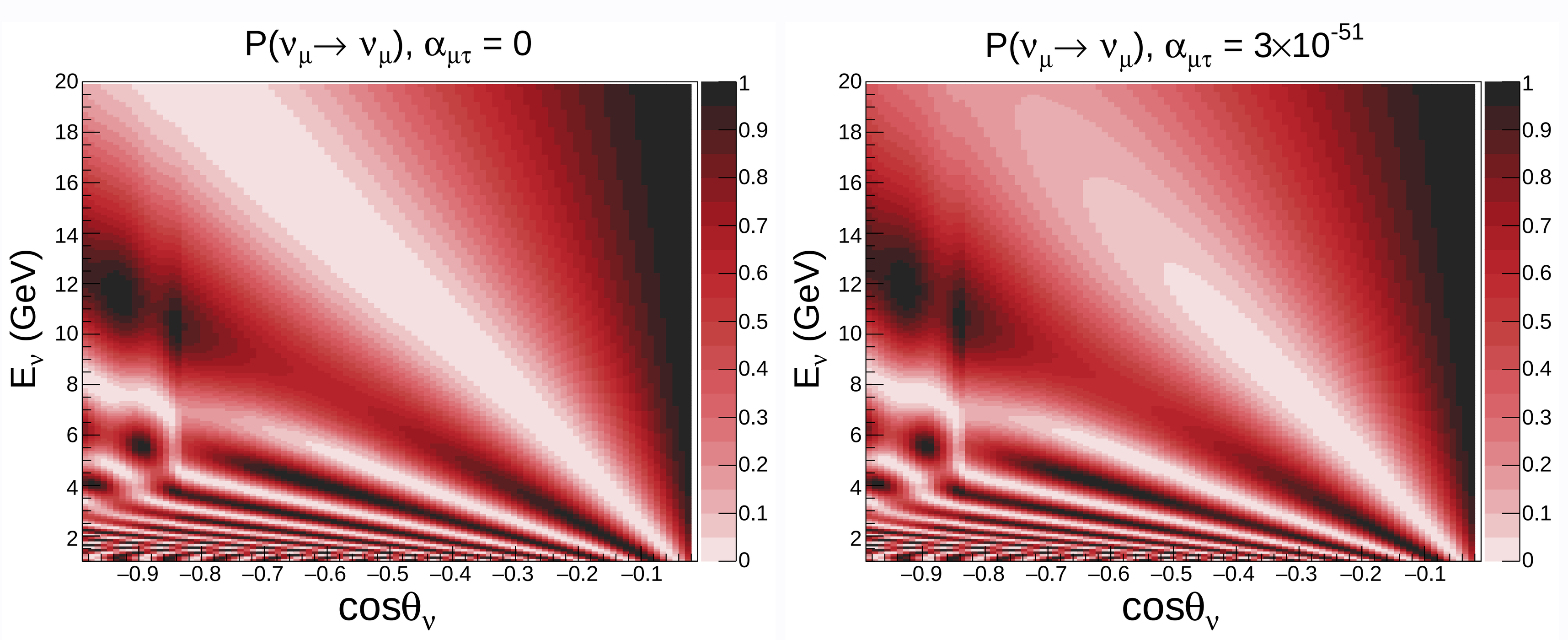
The Effective Hamiltonian in presence matter and LRF of $L_\mu - L_\tau$ symmetry is

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

U : PMNS matrix, V_{CC} : Matter induced potential

$\alpha_{\mu\tau} \sim 5 \times 10^{-50}$ corresponds to the LRF potential (2.2×10^{-13} eV) which is similar to the value of $\Delta m^2_{31}/2E_\nu$ (2.5×10^{-13} eV) with $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2 and $E_\nu = 5$ GeV, thus is expected to affect neutrino and antineutrino oscillations.

Oscillogram of neutrino and antineutrino with LRF



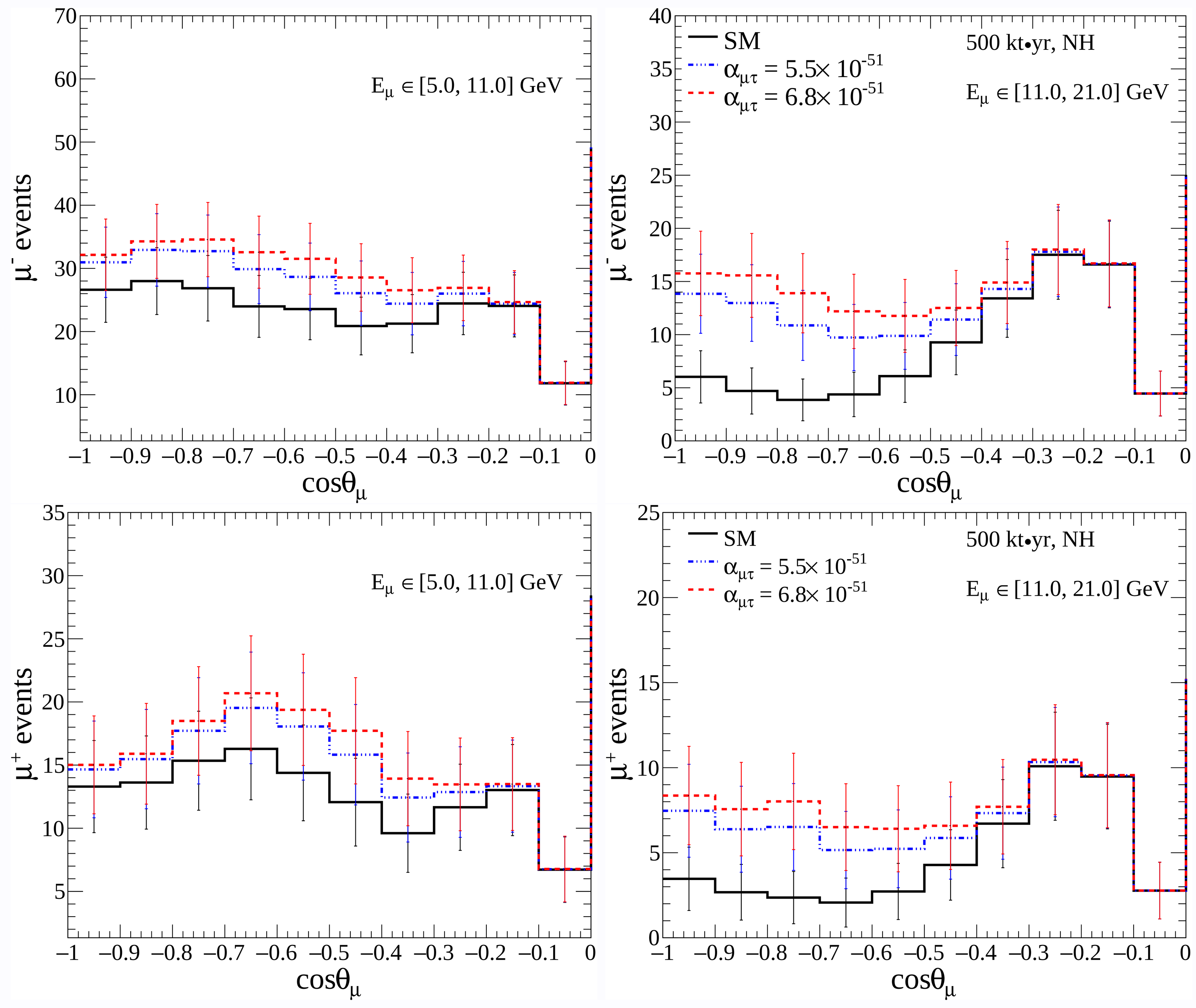
In presence of $\alpha_{\mu\tau}$ as small as 3×10^{-51}, $\nu_\mu \to \nu_\mu$ transition is enhanced significantly in multi-GeV energy range and for few hundreds to 10,000 km baselines.

✓A similar modification is seen for antineutrino also

Important Features of Proposed ICAL Detector at INO

- **Optimized for multi-GeV energy and wide ranges of baselines**
- **Good energy and direction resolutions for muons:** in multi-GeV energy range, energy resolution for muons $\sim 10\%$ to 15%, direction resolution is $< 1°$
- **Excellent charge identification capability (CID):** distinguish μ^- from μ^+, thus ν_μ from $\bar{\nu}_\mu$ CC interactions with $\sim 99\%$ efficiency arXiv:1405.7243
- **Reconstruction of hadron energy** (E'_{had}): energy carried by hadrons at final state of neutrino and antineutrino interactions can be reconstructed at ICAL with a resolution of around 40% arXiv:1304.5115

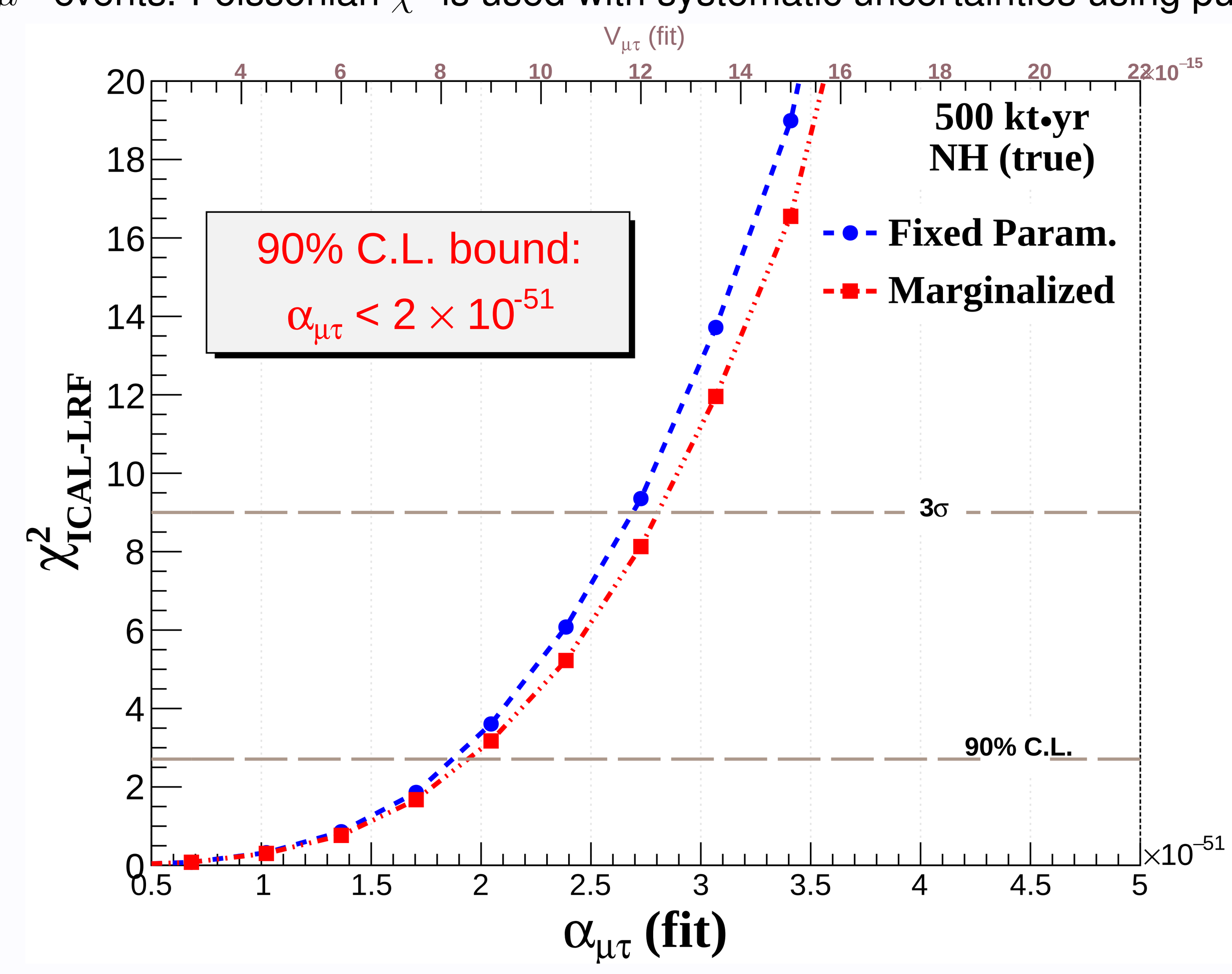
Event Distributions at ICAL after 10 Years of Running



In presence of non-zero $\alpha_{\mu\tau}$, μ^- and μ^+ events are obtained to be higher in number than that with $\alpha_{\mu\tau} = 0$ (SM).

Sensitivity of ICAL to Constrain $\alpha_{\mu\tau}$ with 10 Years data

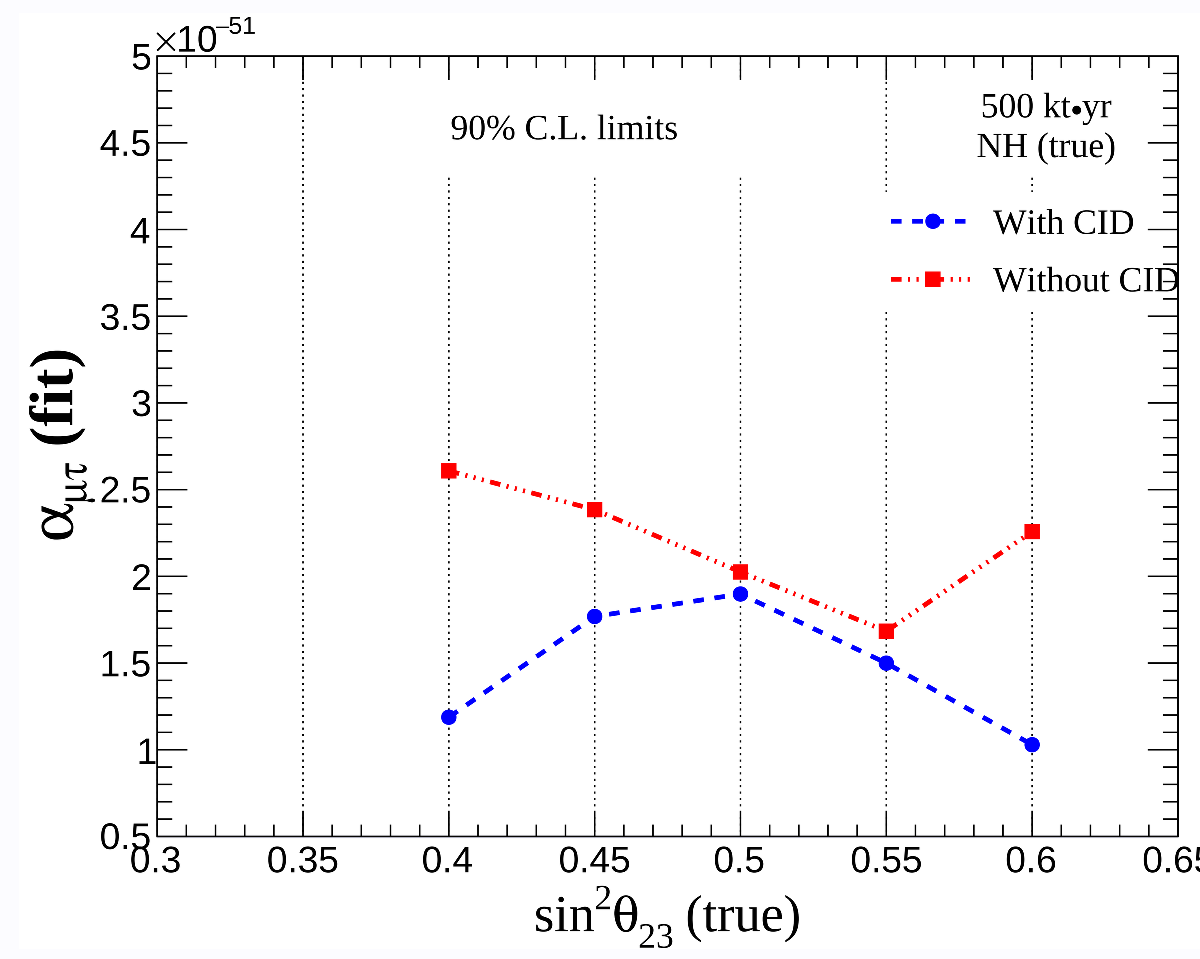
✓Binning scheme: 12 E_μ bins in 1–21 GeV, 15 $\cos\theta$ bins in -1 –1, and 4 $E'_{\rm had}$ bins in 0–25 GeV, for both μ^- and μ^+ events. Poissonian χ^2 is used with systematic uncertainties using pull method.



✓Results are marginalized over systematics as well as the oscillation parameters over current 3σ allowed ranges of θ_{23}, Δm^2_{31}, and choices of neutrino mass hierarchy (NH and IH).

- MINOS anomaly (it has disappeared later) was resolved with $\alpha_{\mu\tau} = 1.5 \times 10^{-50}$ (arXiv:1007:2655)
- From gravitational fifth force searches, based on lunar ranging and torsion balance experiments, the constraint is $\alpha_{\mu\tau} < 5 \times 10^{-24}$ ([arXiv:0712.0607 [gr-qc]], arXiv:1007:2655)

Impact of CID on 90% C.L. Limit on $\alpha_{\mu\tau}$ for Different θ_{23} (true)



✓Result is marginalized over choices of neutrino mass hierarchy in fit, whereas other oscillation parameters are kept fixed at benchmark values that lies within the current allowed ranges.

Summary and Concluding Remarks

- ICAL will provide constraint $\alpha_{\mu\tau} < 2 \times 10^{-51}$ at 90% C.L. with 500 kt·yr exposure.
- The charge identification capability of ICAL helps to improve the limit on $\alpha_{\mu\tau}$.

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