Long-Range Interactions of $L_\mu - L_\tau$ symmetry at INO-ICAL

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Long-range Neutrino Interactions due to $L_\mu - L_\tau$ symmetry

- We focus on new interactions generated by the anomaly-free, gauged, abelian lepton-number symmetry $L_\mu - L_\tau$. This is a renormalizable and minimal extension of the Standard Model (SM).
- Due to neutrino flavor oscillation, this symmetry must be broken, which gives rise to a new gauge boson Z'. This Z' can mix with Z and introduces a four-fermion neutrino matter interaction term via $Z - Z'$ mixing (Phys. Rev. D 57 (1998) 6788):

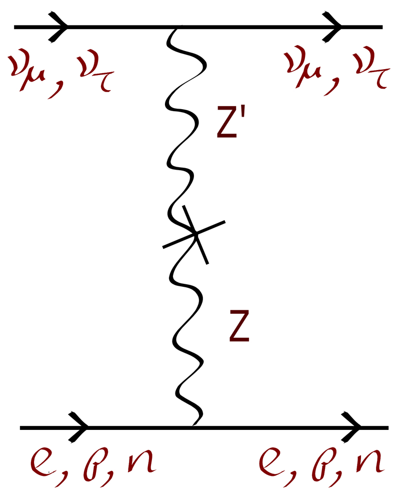
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Z'} + \mathcal{L}_{mix}$$

with

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

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

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



- Under $L_\mu - L_\tau$ symmetry, a neutrino experiences a flavor-dependent Yukawa interaction with a range $\sim 1/m'_{\mu\tau}$. If the mass of the new gauge boson is ultralight ($m'_{\mu\tau} \sim 0$), then the interaction is long ranged, which is denoted as Long-Range Interaction (LRI).

New Flavor-diagonal NC Interactions for Atmospheric Neutrinos

- 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_{SE}) or $m_{\mu\tau} \ll 1$ AU^{-1} $\approx 1.32 \times 10^{-18}$ eV, effective potential due to neutrons in Sun is $V^{\odot}_{\mu\tau} = \alpha_{\mu\tau}\frac{e}{4\, s_W\, c_W}\frac{N_n^{\odot}}{4\pi R_{SE}}$, where $N_n^{\odot}$ is total number of neutrons in Sun.
- Due to neutrons in Earth, the effective LR potential is $V^{\oplus}_{\mu\tau} = \alpha_{\mu\tau}\frac{e}{4\, s_W\, c_W}\frac{N_n^{\oplus}}{4\pi R_{\oplus}}$, where $N_n^{\oplus}$ 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 Earth's neutrons with PREM profile $V^{\oplus}_{\mu\tau} = 0.79 \times 10^{-14} \times \frac{\alpha_{\mu\tau}}{10^{-50}}$ eV.

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

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

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

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

Impact of LRI on the Evolution of Neutrinos

The Effective Hamiltonian in presence matter and LRI 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 LR 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.

Impact on oscillations of neutrino and antineutrino with LRI

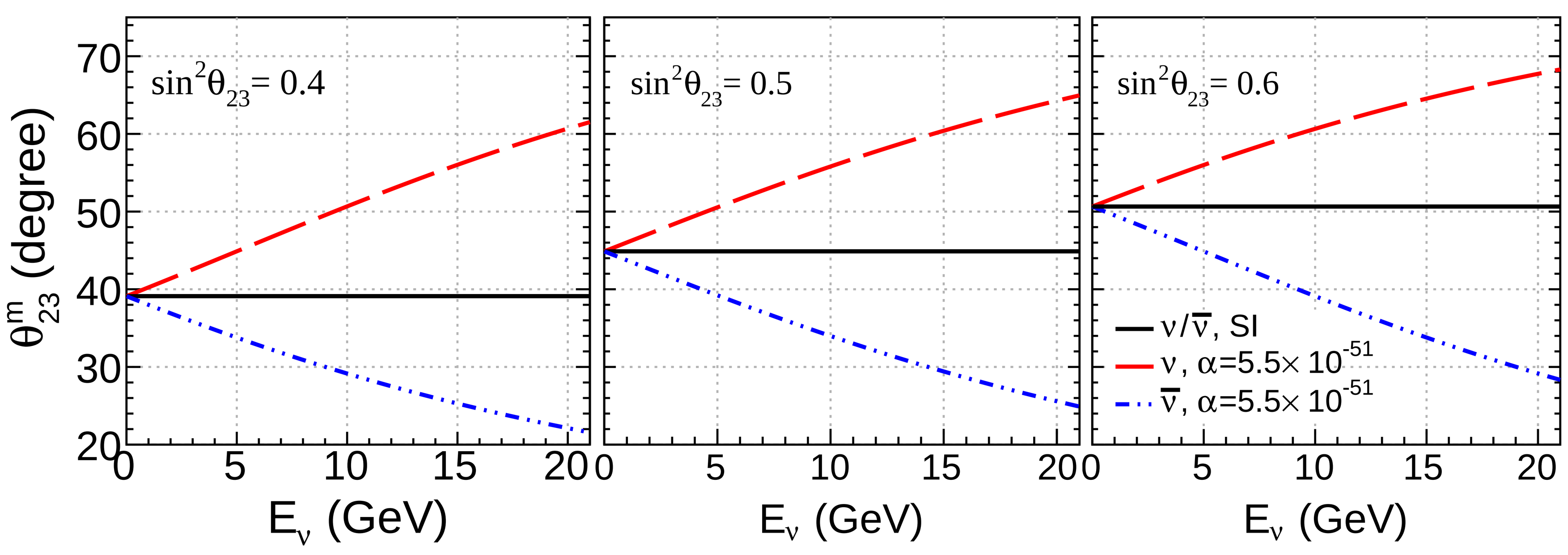


Figure 1: The variation of 2-3 mixing angle with neutrino energy for 5000 km baseline and normal mass ordering.

- In the presence of LRI, θ^m_{23} changes from its vacuum value (θ_{23}) in opposite ways for neutrino and antineutrino.Depending on whether it approaches 45°, the survival probabilities of neutrinos change differently with different θ_{23}.
- With $\sin^2\theta_{23} = 0.5$, $P(\nu_\mu \to \nu_\mu)$ is higher with SI+LRI than with SI for neutrino as well as antineutrino.
- With $\sin^2\theta_{23} \neq 0.5$, when θ^m_{23} approaches 45°, $P(\nu_\mu \to \nu_\mu)$ with SI + LRI is smaller than SI.

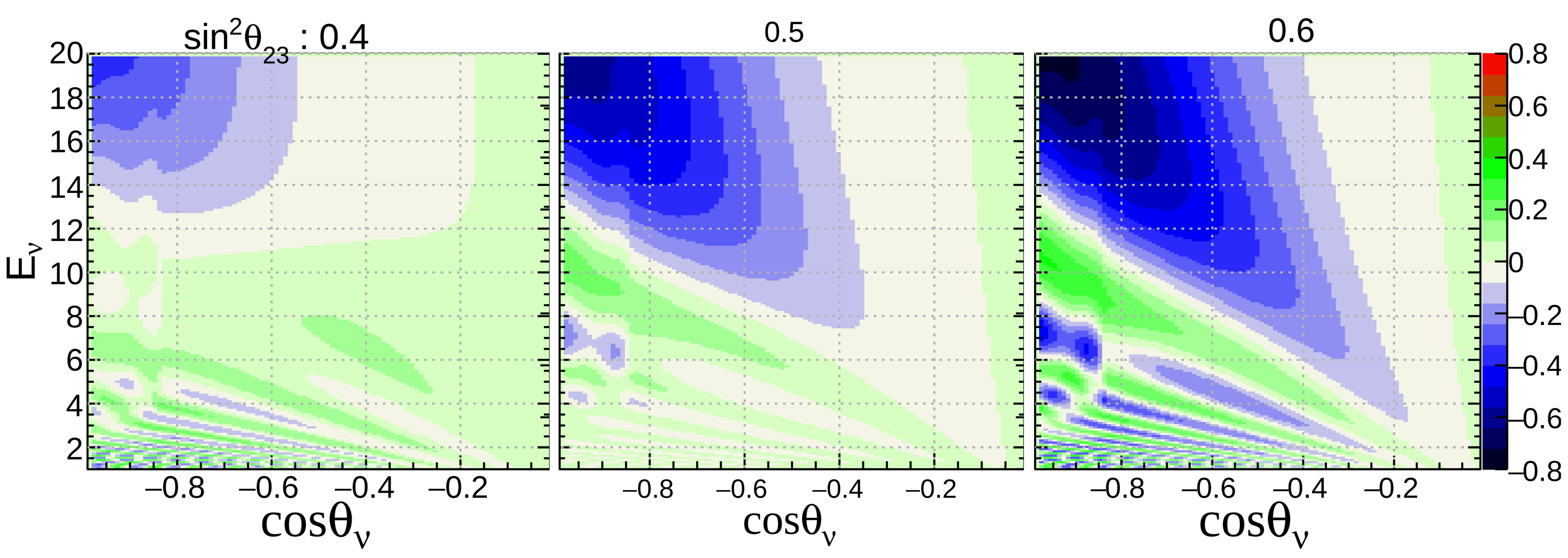


Figure 2: Difference of $P(\nu_\mu \to \nu_\mu) + 0.5 \times P(\nu_e \to \nu_\mu)$ between SI ($\alpha_{\mu\tau} = 0$) and SI + LRI ($\alpha_{\mu\tau} = 5.5 \times 10^{-51}$).

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. JINST 9 (2014) P07001
- **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%. JINST 8 (2013) P11003

Event Distributions at ICAL after 10 Years of Running

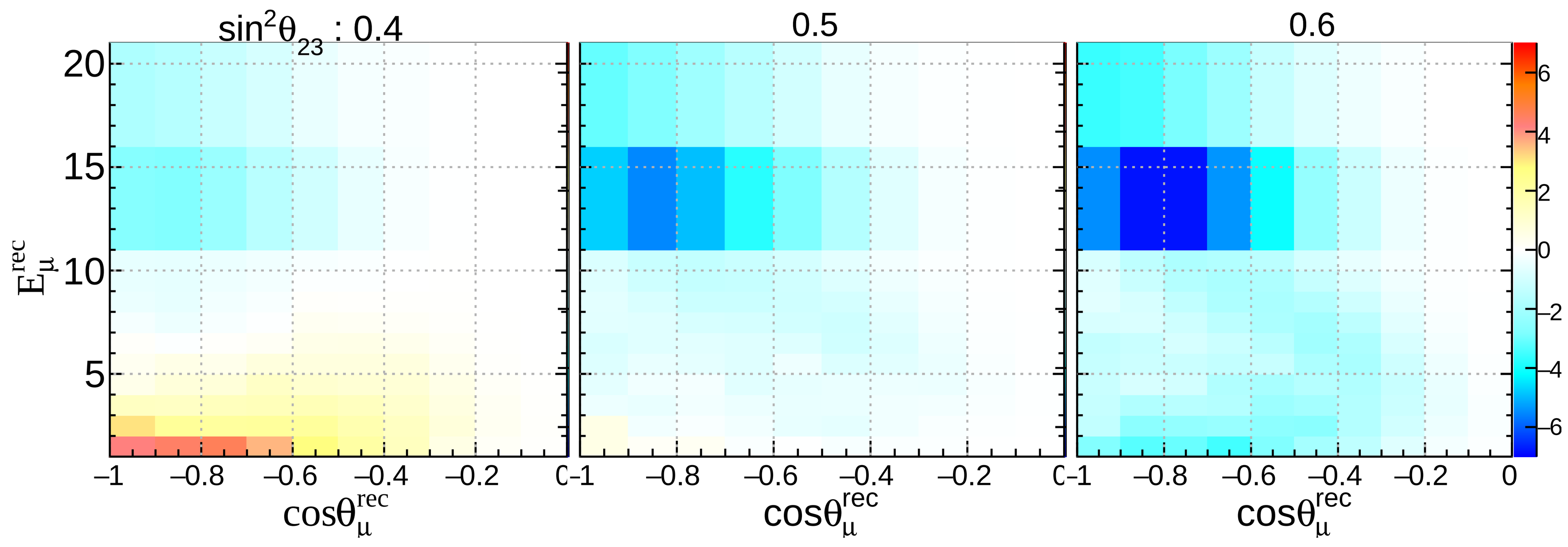


Figure 3: Difference in reconstructed μ^- events between SI ($\alpha_{\mu\tau} = 0$) and SI + LRI ($\alpha_{\mu\tau} = 5.5 \times 10^{-51}$).

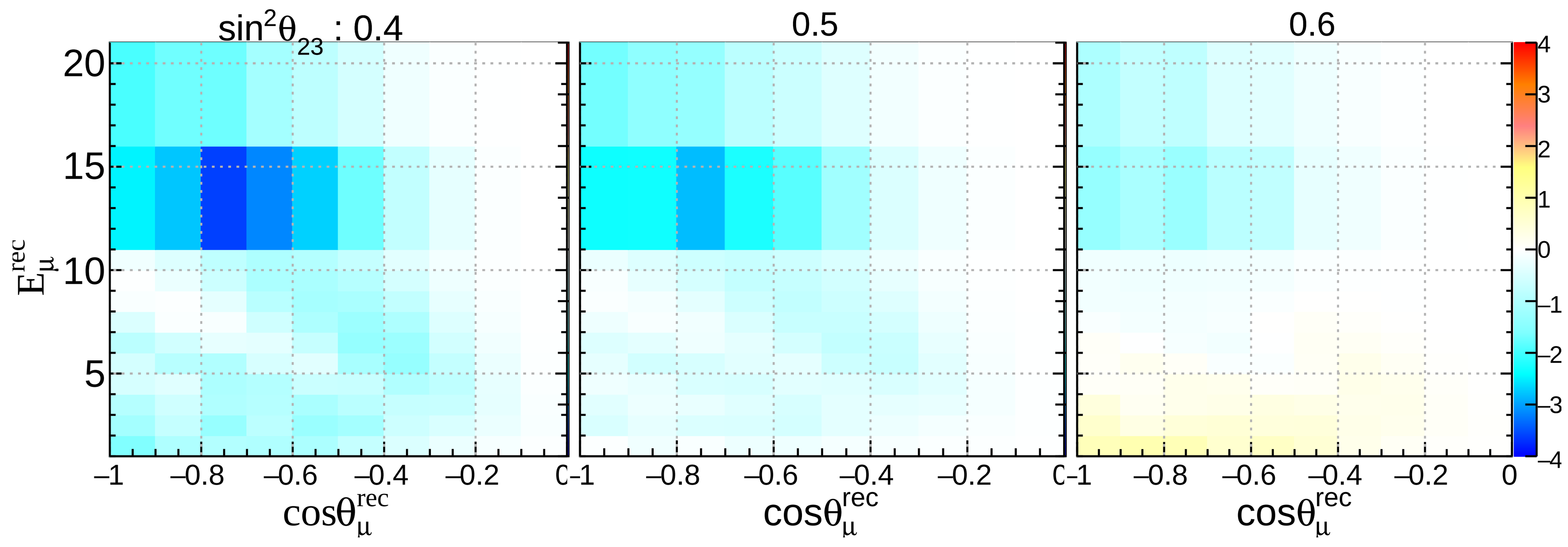
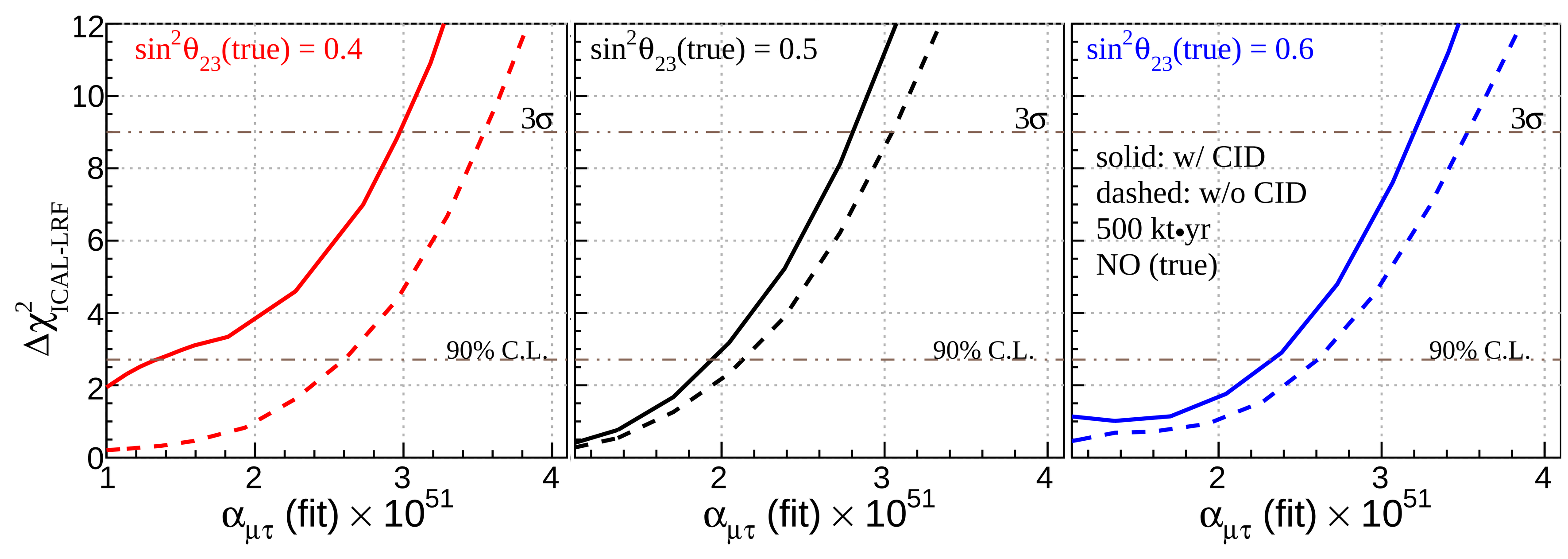


Figure 4: Difference in reconstructed μ^+ events between SI ($\alpha_{\mu\tau} = 0$) and SI + LRI ($\alpha_{\mu\tau} = 5.5 \times 10^{-51}$).

In presence of non-zero $\alpha_{\mu\tau}$, μ^- and μ^+ events are obtained to be higher in number than that with $\alpha_{\mu\tau} = 0$ (SI), except for μ^- events with θ_{23} in low octant and for μ^+ with in θ_{23} in high octant at around reconstructed muon energy $\sim$ 2 GeV.

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

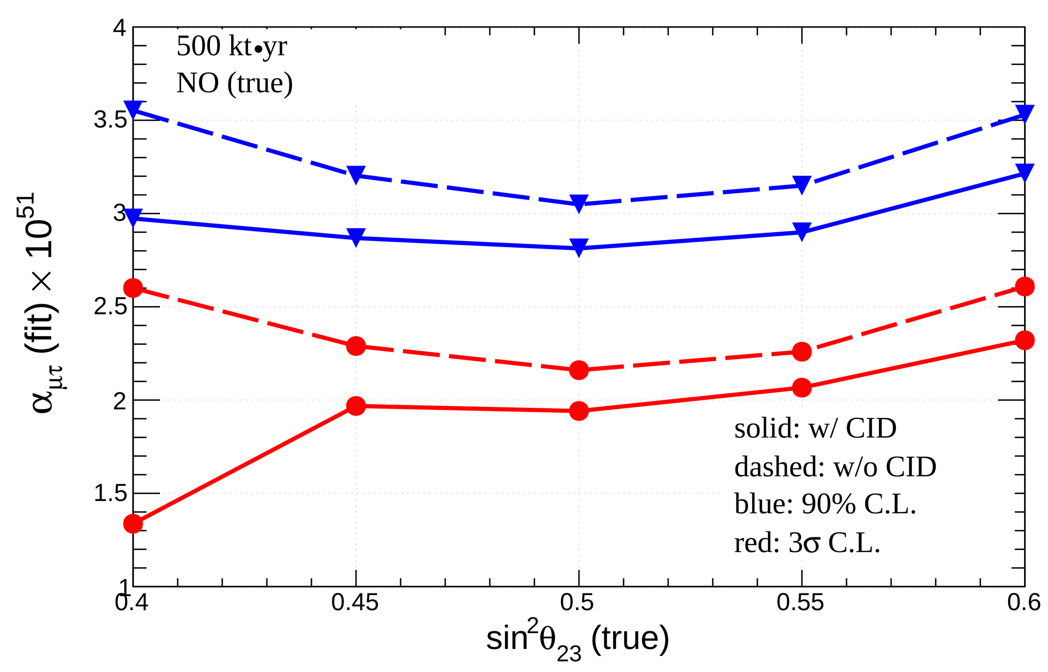
✓Binning scheme: 12 E_μ bins in [1, 21] GeV, 15 $\cos\theta$ bins in [-1, 1], and 4 E'_{had} bins in [0, 25] GeV, for both μ^- and μ^+ events. Poissonian χ^2 is used with systematic uncertainties using pull method.



✓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 (normal and inverted ordering).

- MINOS anomaly (it has disappeared later) was resolved with $\alpha_{\mu\tau} = 1.5 \times 10^{-50}$ J.Phys. G38 (2011)
- From gravitational fifth force searches, based on lunar ranging and torsion balance experiments, the constraint is $\alpha_{\mu\tau} < 5 \times 10^{-24}$. Phys. Rev. Lett. 100 (2008)

Summary and Concluding Remarks



- ICAL will provide constraint $\alpha_{\mu\tau} < 2.82 \times 10^{-51}$ at 3σ C.L. with 500 kt·yr exposure and θ_{23} (true)= 45° .
- The charge identification capability of ICAL helps to improve the limit on $\alpha_{\mu\tau}$.

ICAL will play an important role in breaking the degeneracy between the octant of θ_{23} and neutrino polarities due to LRI of $L_\mu - L_\tau$ symmetry using separate data of μ^- and μ^+.

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