Core-passing atmospheric neutrinos: a unique probe to discriminate between Lorentz violation and non-standard interactions

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Introduction — The Standard Model (SM) of particle physics is one of the most successful theories of elementary particles and their fundamental interactions, which can explain most of the observed phenomena with a high accuracy [1]. However, there are certain experimental observations that cannot be accounted for in the SM framework, the phenomenon of neutrino oscillations being one of the most established ones. In the last half a century, the measurements of neutrino events from solar [2–9], atmospheric [10–14], reactor [15–22], and accelerator [23–28] neutrino experiments have established that neutrinos have masses, as a result of which the three neutrino flavors can transform into each other.

To accommodate tiny neutrino masses and large mixing angles, we need physics beyond the Standard Model (BSM). Therefore, neutrinos are one of the most promising portals to BSM physics. The study of their properties can reveal the nature of the BSM physics that has so far been elusive to us. With the advancement of modern detection techniques and large detectors, neutrino oscillation physics has entered its precision era. Future long baseline experiments and the measurements of the reactor and atmospheric neutrinos will be probing many new physics models like neutrino decay, the presence of sterile neutrinos, or new interactions of neutrinos [29].

Two of the BSM scenarios widely discussed in the literature are (i) neutrino interactions involving Lorentz violation (LV) [30–46], and (ii) neutrino non-standard interactions (NSI) with ambient matter [47–60]. Note that the origins of these two scenarios are completely different: LV arises from the interactions of neutrinos with the spacetime itself, while NSI effects manifest themselves in the presence of matter. The effects of LV can manifest themselves both in vacuum and matter, whereas the NSI effects only appear in matter. In this Letter, we investigate the imprints of these scenarios simultaneously.

In spite of the intrinsic differences between these two scenarios, both affect the neutrino propagation in the Earth matter in a very similar manner. So much so that, in a fixed-baseline neutrino oscillation experiment, the effective Hamiltonians of these two scenarios can mimic each other to a very high precision. Therefore, if one of these two scenarios is realized in Nature, it would be difficult to identify the actual scenario from observations.

In this Letter, we demonstrate for the first time that the degeneracy between these scenarios would be broken by the observations at an atmospheric neutrino experiment, which can detect neutrinos that have travelled through a wide range of baselines through the Earth. The observation of neutrinos and antineutrinos passing through the core of the Earth would play a critical role in discriminating between these two scenarios. We further find that the sensitivity towards distinguishing between them would be enhanced by the charge identification (CID) capability of a detector like the proposed iron calorimeter (ICAL) at the India-based Neutrino Observatory (INO) [61].

Lorentz Violation (LV) — Lorentz symmetry is a fundamental pillar of the SM, and indeed, of local quantum field theories in general. However, there are a few proposed models in string theory [62–69] and quantum loop gravity [70–74] which give rise to LV. We shall focus on a scenario in which the Lorentz Symmetry is broken spontaneously, giving nonzero vacuum expectation value (vev) to a 4-vector $a^\lambda$. The couplings of $a^\lambda$ with neutrinos are flavor-dependent, and hence the Lagrangian density of the LV interaction may be written as [46, 75, 76]

$$\mathcal{L}_{LV} = -a^\lambda_{\alpha\beta}(\bar{\nu}_\alpha \gamma_\lambda P_L \nu_\beta),$$

(1)

where $a^\lambda_{\alpha\beta}$ combines the information on the vev and couplings of $a^\lambda$. Here $\lambda$ is the spacetime index, and $\alpha, \beta$ are the flavor indices. The hermiticity of interactions...
imposes \( a_{\alpha\beta}^\Lambda = (a_{\alpha\beta}^\Lambda)^* \). Note that the above interaction also breaks the Charge conjugation - Parity - Time reversal (CPT) symmetry, since the elements of \( a^\Lambda \) change sign under CPT transformation [46, 77]. Our scenario may therefore also be termed as a CPT-violating scenario, which guarantees IV automatically [78]. Since there are strong constraints on the observed LV, it is expected that the magnitudes of \( a^\Lambda \) elements are suppressed by the Planck scale \( M_P \) [30, 77, 79–83].

Note that for antineutrinos, \( a^\Lambda_{\alpha\beta} \rightarrow -(a^\Lambda_{\alpha\beta})^* \).

We work in the isotropic Sun-centered celestial-equatorial (SCCE) coordinates [36] as an observer-inertial frame, and ignore the frame dependence due to the boost associated with the Earth’s motion. Restricting ourselves to the case where only the timelike component of \( a^\Lambda \) is nonzero, the total effective Hamiltonian of ultra-relativistic left-handed neutrinos passing through Earth matter can be written in the 3ν flavor basis as

\[
\mathcal{H}_{LV} = \frac{1}{2E} \mathbf{U} \mathbf{M}^2 \mathbf{U}^\dagger + \sqrt{2} G_F N_e \mathbf{I} + \mathbf{A} ,
\]

where \( \mathbf{U} \) is the neutrino mixing matrix, also called as the Pontecorvo - Maki - Nakagawa - Sakata (PMNS) matrix, while \( \mathbf{M}^2 \) is the diagonal matrix with elements \( (0, \Delta m_{21}^2, \Delta m_{31}^2) \). The first term represents the Hamiltonian in vacuum in the absence of any LV interaction. The second term incorporates the effective matter potential experienced by neutrinos as they propagate through matter with electron density \( N_e \), due to their charged-current interactions with ambient electrons. Here \( G_F \) is the Fermi constant and \( \mathbf{I} \) is the diagonal matrix with elements \( (1, 0, 0) \). In terms of the density \( \rho \) of the medium through which the neutrinos propagate, one may write

\[
\sqrt{2} G_F N_e \approx 7.6 \times 10^{-23} \cdot Y_e \cdot \rho \ (g/cm^3) \ \text{GeV} ,
\]

where \( Y_e \) is the electron-number fraction in the medium. The last term arises from eq. (1), with \( \mathbf{A} \) being the LV matrix in the neutrino flavor space with its elements \( a_{\alpha\beta}^0 \). (Henceforth, we shall omit the superscript ‘0’ for the sake of brevity.) For antineutrino, \( \mathbf{U} \rightarrow \mathbf{U}^\dagger \), while both the second and third terms change sign. Note, while the third term is intrinsically CPT-violating, the second term gives rise to matter-induced CPT violation [84, 85].

For the atmospheric neutrino experiments that are sensitive to multi-GeV neutrinos, more than 98% of charged-current muon events are generated in the \( \nu_\mu \) disappearance channel. The relevant survival probability \( P(\nu_\mu \rightarrow \nu_\mu) \) depends, at the leading order, on \( a_{\mu\tau} \) [86]. Current experimental constraints give \( |a_{\mu\tau}| \lesssim 10^{-23} \ \text{GeV} \) [42, 45]. In Fig. 1 we show the effect of a representative value of \( a_{\mu\tau} = 10^{-23} \ \text{GeV} \) on the survival probability of upward-going multi-GeV \( \nu_\mu \) and \( \bar{\nu}_\mu \), in the plane of zenith angle and energy \( (\cos \theta, E) \). It can be clearly seen that the oscillation valley (the region with the smallest survival probability), which would be an almost triangular strip in the absence of any BSM physics [57, 87], bends due to the LV term, the bending being in opposite directions for \( \nu_\mu \) and \( \bar{\nu}_\mu \) [88]. The strong matter effects at \( \cos \theta < -0.85 \), especially at low energies, arise from the \( \sqrt{2} G_F N_e \mathbf{I} \) term.

For all the numerical results in this Letter, we use the benchmark oscillation parameters as \( \sin^2 2\theta_{12} = 0.855, \sin^2 2\theta_{13} = 0.0875, \sin^2 2\theta_{23} = 0.5, \Delta m_{21}^2 = +2.46 \times 10^{-3} \ \text{eV}^2 \) (normal mass ordering), \( \Delta m_{32}^2 = 7.4 \times 10^{-5} \ \text{eV}^2 \), and \( \delta_{CP} = 0 \) [89–91]. We use the Preliminary Reference Earth Model (PREM) [92] for the Earth density profile.

**Non-Standard Interactions (NSI)** — In this scenario, neutrinos undergo additional coherent forward scattering with the matter fermions due to a new interaction that occurs at an energy scale \( \Lambda \), higher than the scale of electroweak interactions \( m_W \), or \( m_Z \). Such NSI may be written in the EFT language in terms of effective four-fermion operators with mass-dimension six [93]. In this Letter, we focus on the neutral-current NSI, for which the Lagrangian density is written as

\[
\mathcal{L}_{NSI} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^C (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f}_\gamma P_C f) ,
\]

where \( f \) are the matter fermions (up-quark \( u \), down-quark \( d \), electron \( e \), and \( C \in \{ L, R \} \) with \( P_C \) the corresponding chiral projections operators. The hermiticity of the interaction imposes \( \varepsilon_{\alpha\beta}^C = (\varepsilon_{\alpha\beta}^C)^* \). The strength of interaction is expected to be supressed by \( (m_W/\Lambda)^2 \), which is reflected in the smallness of \( \varepsilon_{\alpha\beta} \). For Earth
matter, we assume \( N_p \approx N_n = N_e \), which leads to \( N_a \approx N_d \approx 3N_e \). Therefore, the effective NSI parameter
\[
\varepsilon_{\alpha\beta} = \varepsilon^0_{\alpha\beta} + 3\varepsilon_{\alpha\beta}^u + 3\varepsilon_{\alpha\beta}^d,
\]
where \( \varepsilon^0_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}^L + \varepsilon_{\alpha\beta}^R \). The effective Hamiltonian for neutrinos propagating through Earth matter can be expressed, in the 3ν flavor basis, as
\[
\mathcal{H}_{\text{NSI}} = \frac{1}{2E} \sum_{\alpha\beta} U M^2 U^\dagger + \sqrt{2} G_F N_e \varepsilon^0 \mathcal{E},
\]
where \( \mathcal{E} \) is a matrix with elements \( \varepsilon_{\alpha\beta} \). For antineutrino, the signs of the second and third term are reversed.

The element \( \varepsilon_{\mu\tau} \) is expected to affect the muon survival probabilities at the leading order [86]. With the above convention, the current experimental constraints give \( |\varepsilon_{\mu\tau}| \lesssim 0.03 \) [51, 53, 54, 57, 59, 60]. In Fig. 2, we show the effect of non-zero \( \varepsilon_{\mu\tau} \) at a representative value \( \varepsilon_{\mu\tau} = +0.05 \). One may observe that the bending of the oscillation valley is almost identical to that due to LV, as long as \( \cos \theta_\mu \gtrsim -0.85 \). However, for upward-going neutrinos that have passed through the core of the Earth, i.e. for \( \cos \theta_\nu \lesssim -0.85 \), the figures 1 and 2 show major differences. These similarities and differences are the cause of the degeneracy between the LV and NSI scenarios, and the key to our ability of resolving it.

The LV-NSI degeneracy — The comparison between eqs. (2) and (5) shows that, if
\[
\Delta = \sqrt{2} G_F N_e \mathcal{E},
\]
the effective Hamiltonians of the LV and NSI scenarios are identical [46, 94, 95]. In such a case, the effects of the LV scenario will be completely mimicked by NSI with appropriate parameter values, and vice versa. This degeneracy would make it impossible to identify whether a signal of BSM physics is due to one scenario or the other. The LV-NSI degeneracy occurs quite naturally, and is in fact inescapable, at any current or planned fixed-baseline experiment. This is because the longest fixed-baseline experiment planned so far is the Deep Underground Neutrino Experiment (DUNE) [96, 97], with a baseline of \( \sim 1300 \) km. At such baselines, the survival probabilities can be approximated to a great accuracy by assuming the matter density along the path of the neutrinos to be uniform, with the value equal to the line-averaged matter density along path [98, 99]. Therefore, eq. (6) is always satisfied to a high accuracy. Indeed, with the line-averaged density of \( \rho_{\text{avg}}^{\text{DUNE}} \approx 2.85 \text{ g/cm}^3 \) at DUNE [97, 100], the signals of \( a_{\mu\tau} = 10^{-23} \text{ GeV} \) are completely mimicked by \( \varepsilon_{\mu\tau} = 0.092 \), with the maximum difference in \( \nu_\mu \) survival probabilities predicted with the above two scenarios being \( |\Delta P| < 0.0012 \), where
\[
\Delta P = P(\text{SM} + \text{LV}) - P(\text{SM} + \text{NSI}).
\]

Resolving the degeneracy using atmospheric neutrinos — The atmospheric neutrino experiments detect neutrinos coming from all directions. The range of distances travelled by these neutrinos through the Earth is from zero, all the way up to \( \sim 12750 \) km. Not only is the line-averaged density different for all the neutrinos, but the line-averaged density approximation itself is not valid for the neutrinos that have passed through the core. Therefore, the condition in eq. (6) is not satisfied for all neutrinos, and hence the almost-exact degeneracy between LV and NSI scenarios ceases to exist.

To illustrate this point, we first consider the Earth as a uniform solid sphere of average mass density \( \rho_{\text{avg}}^{\text{Earth}} \approx 5.5 \text{ g/cm}^3 \), which would give the corresponding value \( \varepsilon_{\mu\tau} = 0.0475 \) for \( a_{\mu\tau} = 10^{-23} \text{ GeV} \), using Eq. (6). In Fig. 3, we show the difference \( \Delta P \) between the probabilities predicted by these two scenarios. It is observed that for neutrinos that travel only through the mantle, i.e. for \( \cos \theta_\nu \gtrsim -0.85 \), we get \( |\Delta P| \lesssim 0.1 \). On the other hand, this difference grows for neutrinos passing through the core, reaching values as high as \( |\Delta P| \approx 0.34 \).

A concrete case study — Now, it is clear that the atmospheric neutrino measurements can distinguish between the LV and NSI scenarios in principle, we use the proposed 50 kt ICAL detector at INO as a specific example to quantify the extent to which this discrimination is possible. ICAL would be sensitive to multi-GeV atmospheric neutrinos, via detecting muons with the energy resolution of 10–15% in the energy range of 1 to 25 GeV, and an excellent zenith angle resolution of \( < 1^\circ \) for all but the almost-horizontal muons. In addition, the magnetic field of 1.5 Tesla gives ICAL the unique capability of muon charge identification (CID), which in turn, enables it to observe neutrino and antineutrino events separately. We simulate the events at the ICAL detector by using the NUANCE neutrino event generator [101] with the atmospheric neutrino flux [102] as a source to estimate the number of unoscillated events generated via the charge-current interactions. We incorporate the probabilities using the reweighting algorithm [103, 104], and the detector properties using the ICAL migration matrices [105, 106].
We use the reconstructed values of muon energy and $\mu_4$ obtained for a given value of $a_{\mu\tau}$ using fine bins in $\cos \theta$ ($\varepsilon_{\mu\tau}$ results without (with) CID). Some of the best-fit values of $\varepsilon_{\mu\tau}$, obtained for a given value of $a_{\mu\tau}$, are shown with numbers.

After an exposure of 1000 kt·yr, about 8800 $\mu^-$ and 4000 $\mu^+$ reconstructed events are expected at ICAL. We use the reconstructed values of muon energy and zenith angle ($E_{\mu}^{\text{rec}}$ and $\cos \theta_{\mu}^{\text{rec}}$), along with hadron energy ($E_{\text{had}}^{\text{rec}}$) as observables [107]. The analysis is carried out using fine bins in $\cos \theta_{\mu}^{\text{rec}}$ for core-passing neutrinos [108]. The data is simulated using nonzero $a_{\mu\tau}^{\text{true}}$, while the fit is attempted using nonzero $a_{\mu\tau}^{\text{test}}$. Using the frequentist approach, the median sensitivity of the detector to distinguish between LV and NSI scenarios, defined as

$$\Delta \chi^2 = \chi^2(a_{\mu\tau}^{\text{test}} = 0, \varepsilon_{\mu\tau}^{\text{test}}) - \chi^2(a_{\mu\tau}^{\text{true}}, \varepsilon_{\mu\tau}^{\text{true}} = 0),$$

is calculated with the Poissonian $\chi^2$ [109]. We restrict the values of $a_{\mu\tau}$ and $\varepsilon_{\mu\tau}$ to be real. The systematic uncertainties are included with the prescription in Refs. [107, 110, 111]. The oscillation parameters values given earlier in this Letter are taken to be fixed, since by the time 1000 kt·yr data is available, the oscillation parameters would have been measured quite precisely.

In Fig. 4, we show the best-fit values of $\varepsilon_{\mu\tau}^{\text{test}}$ obtained for a range of $a_{\mu\tau}^{\text{true}}$ values, and the $\Delta \chi^2$ at which the hypothesis of NSI can be rejected. The figure clearly brings out the advantage that CID provides, enabling the discrimination at the level of $\Delta \chi^2 \approx 4$ for $|a_{\mu\tau}| \gtrsim 0.5 \times 10^{-23}$ GeV.

Figure 5 shows the extent to which any value of $\varepsilon_{\mu\tau}$ would be ruled out, when the actual scenario is LV. The contours in the figure have quite a rich physics content. (i) The line joining P1 and P2 contains information on the extent to which SM would be disfavored, when $a_{\mu\tau}$ has the given value. Beyond P1 and P2, the SM would be disfavored at more than 95% C.L. (ii) The line joining P3 and P4 informs about the extent to which the NSI parameter $a_{\mu\tau}$ would be constrained, if there are no BSM effects in reality. The region between P3 and P4 would be allowed at 95% C.L. (iii) The common major axis of the contours correspond to the best-fit values of $\varepsilon_{\mu\tau}$ that mimic the corresponding values of $a_{\mu\tau}$. (iv) The points outside the black contour convey the values of $\varepsilon_{\mu\tau}$ that would be excluded at 95% C.L. in the presence of the corresponding $a_{\mu\tau}$. (v) The point P5 lies both on the dashed line and blue contour, and corresponds to $a_{\mu\tau} = 0.475 \times 10^{-23}$ GeV. For values of $a_{\mu\tau}$ greater than this, any value of $\varepsilon_{\mu\tau}$, and hence the NSI scenario itself, would be disfavored with 95% C.L.

Concluding remarks — Neutrinos are the most promising portals to new physics beyond the SM. However, it is not enough to identify the presence of BSM physics; it is essential to identify its source and nature. In this Letter, we have pointed out for the first time that a fixed-baseline neutrino oscillation experiment cannot distinguish between the two popular BSM scenarios of LV and NSI. We have argued that the key to resolving this degeneracy is the observation of neutrinos passing through the core of the Earth, and hence atmospheric neutrino experiments are critical for this purpose. Using the concrete example of the ICAL experiment that can identify the muon charge, we have demonstrated the extent to which these two BSM scenarios can be distinguished. The huge amount of high-precision atmospheric neutrino data expected from the currently running experiments like Super-K, IceCube, DeepCore, ORCA, and upcoming ones like Hyper-K, DUNE, P-ONE will certainly improve the prospects of this discrimination.
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