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Combined search for Lorentz invariance violation with ANTARES, IceCube, and KM3NeT

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Lorentz invariance (LI) is a fundamental symmetry in the Standard Model that may be violated in quantum gravity. The "Standard-Model extension" (SME) framework incorporates this hypothetical Lorentz invariance violation (LIV) by introducing a complete set of LI- and CPT-violating operators coupled with corresponding SME coefficients. A non-zero value of one or more of these coefficients would result in a deviation of the predicted neutrino oscillation probability from the case of standard neutrino oscillations, which enables neutrino telescopes to measure or constrain these coefficients.
The four neutrino telescopes ANTARES, IceCube, KM3NeT/ARCA, and KM3NeT/ORCA are sensitive to the atmospheric neutrino flux, which has energies and baselines suitable for constraining LIV coefficients. We report on the progress of a combined analysis using data from all four telescopes, which enables an extended energy range coverage and more statistics compared to previous single-experiment studies. This analysis focuses on isotropic LIV coefficients, of which some are still unconstrained.

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1. Introduction

The behaviour of the most fundamental constituents of our Universe — such as space, time, and matter — are currently best described by two physical theories: *General Relativity* (GR) and the *Standard Model of particle physics* (SM). GR governs gravity and the structure of spacetime, while the SM describes all known elementary particles and their interactions, except gravity. Although both theories are highly successful within their respective domains, their combination leads to problems at energy scales near the Planck scale $M_\mathrm{P} \sim 10^{19}$ GeV [1]. Consequently, both GR and the SM are widely believed to be low-energy effective approximations of a more fundamental, yet unknown theory, often referred to as *quantum gravity* (QG) [2]. Many experimental and theoretical efforts are underway to uncover the nature of this underlying theory.

A promising avenue to search for QG effects is to test the validity of well-established symmetries, such as *Lorentz invariance* (LI). LI ensures that the laws of physics are the same for all observers and independent of the inertial laboratory in which the experiment is performed. Both GR and the SM are Lorentz-invariant, making LI a cornerstone of modern physics. However, several candidate theories of QG allow for *Lorentz invariance violation* (LIV), and some models of the structure of spacetime even incorporate LIV explicitly [3]. Since LI is a fundamental assumption of the current standard theories, and since there are theoretical motivations to suspect it might not hold at all energy scales, it is of utmost importance to test this symmetry as precisely as possible.

2. Isotropic LIV with neutrinos

The *Standard-Model Extension* (SME) is an effective field theory that includes the SM, GR, and all possible Lorentz- and CPT-violating operators that can result from spontaneous Lorentz-symmetry breaking [4]. Each of these operators of a given mass dimension d is contracted with a corresponding coefficient that can be interpreted as an effective coupling constant [5]. In the neutrino sector, nonzero values of these coefficients lead to deviations from standard neutrino oscillations. In this study, we consider the special case of an *isotropic* LIV model for neutrinos, including only Lorentz-violating operators that preserve rotational symmetry [2].

To calculate the effect of isotropic LIV in the evolution of a neutrino system, we start from an effective Hamiltonian derived from the SME, which can be written as [2]:

$$H = UH_0U^\dagger + H_I + H_{LIV}, \tag{1}$$

with U denoting the PMNS mixing matrix,

$$H_0 = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}, \tag{2}$$

accounting for the standard oscillation Hamiltonian that applies to the neutrino mass eigenstates,

$$H_I = \pm\sqrt{2}G_F\begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \tag{3}$$

denoting the Hamiltonian that applies to the neutrino flavour states accounting for matter effects in the regime of coherent scattering, and

$$H_{LIV} = \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{e\tau} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{e\tau} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - E \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{e\tau} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{e\tau} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} + E^2 \mathring{a}^{(5)} - E^3 \mathring{c}^{(6)} + \dots , \tag{4}$$

accounting for the Lorentz-invariance-violating contributions. The coefficients in each mass dimension d are structured in a hermitian 3×3 matrix, which includes three real-valued diagonal and three complex-valued off-diagonal coefficients. For brevity, the above expression does not write the matrices of dimensions $d > 4$ out. Instead, they are denoted as $\mathring{a}^{(d)}$ or $\mathring{c}^{(d)}$. The circle over the coefficients is used to indicate isotropic LIV coefficients. The $\mathring{a}$ coefficients are CPT-odd, whereas the $\mathring{c}$ coefficients are CPT-even. As shown in table 1, the mass dimension d of the LIV-operator determines the unit of the coefficient and the oscillation effect introduced by a non-zero value of the coefficient. The dependence of the oscillation phase on the baseline L and the neutrino energy E differ from the phase relation of standard oscillations, which is L/E. This allows us to constrain LIV effects with neutrino telescopes, where such modifications in oscillations would alter the observed energy- and zenith-dependent distribution of atmospheric neutrinos.

Table 1: LIV coefficients: for comparison, the oscillation effect of H_0 is L/E.

Coefficient	Unit	CPT	Oscillation effect
$\mathring{a}^{(3)}$	GeV	odd	$\propto L$
$\mathring{c}^{(4)}$	–	even	$\propto LE$
$\mathring{a}^{(5)}$	GeV^{-1}	odd	$\propto LE^2$
$\mathring{c}^{(6)}$	GeV^{-2}	even	$\propto LE^3$
$\mathring{a}^{(7)}$	GeV^{-3}	odd	$\propto LE^4$
$\mathring{c}^{(8)}$	GeV^{-4}	even	$\propto LE^5$

3. Atmospheric neutrino event samples of ANTARES, IceCube, and KM3NeT

The analyses described in this work use atmospheric neutrino data from the ANTARES, IceCube, and KM3NeT neutrino telescopes. These instruments detect Cherenkov light from the secondary particles produced in neutrino interactions, enabling the reconstruction of the neutrino energy and direction. Together, these detectors are able to detect atmospheric neutrinos in the energy range from a few GeV to about 10 TeV. At higher energies, neutrinos from astronomical sources begin to dominate over the atmospheric flux component. The baseline is determined by the zenith angle, with up-going events traversing up to the Earth's diameter. This broad energy–baseline phase space makes atmospheric neutrinos well suited to probe oscillations and possible Lorentz invariance violation (LIV).

The KM3NeT Collaboration is building two deep-sea neutrino detectors in the Mediterranean Sea: ORCA, near Toulon (France) at a depth of 2500 m, and ARCA, near Sicily (Italy) at 3500 m depth. ORCA is optimized for oscillation studies with atmospheric neutrinos in the GeV–TeV range, while ARCA is designed for neutrino astronomy in the TeV–PeV range. This analysis uses data from the ORCA6 configuration, a sub-detector of the planned 115-line ORCA, consisting of six detection units. It was operational from January 2020 to November 2021 and recorded 5828 neutrino candidates, with the event selection described in [6]. For ARCA, we use data collected with the 21-line configuration (ARCA21), a sub-detector of the planned full detector that will contain 230 detection units. ARCA21 was operational from September 2022 to September 2023. The preliminary atmospheric ν_μ sample was specifically optimized for this analysis, with Monte Carlo simulations predicting 826 neutrino events and a contamination level below 1%.

ANTARES, also located in the Mediterranean, operated from 2007 to 2022 with 12 detection lines and was sensitive to neutrinos in the energy range from about 20 GeV to PeV. The preliminary high-energy atmospheric neutrino dataset was specifically optimized for this analysis and comprises 5398 ν_μ events, with a contamination level below 1% as estimated from Monte Carlo simulations. The optimization procedure is detailed in our previous work [7].

IceCube is a cubic-kilometer neutrino detector located at the geographic South Pole, using Antarctic ice as the Cherenkov emission medium. For this analysis, we use the event selection described in [8], which was originally optimized for sterile neutrino searches. The dataset was recorded between May 2011 and June 2022 and corresponds to 10.7 years of high-energy atmospheric neutrino data. It contains 368,071 up-going charged-current ν_μ events with reconstructed energies between 500 GeV and 100 TeV and a contamination level of 0.1%. This event sample was already used to perform an isotropic LIV analysis in 2023 [9], which is used in the combined analysis presented in this contribution.

4. Analysis strategy

The analysis is divided into two energy regimes to target different Lorentz-invariance-violating effects with the most suitable detectors. The low-energy analysis uses the ORCA6 dataset, focusing on neutrino events in the energy range from GeV-TeV. In contrast, the high-energy analysis specializes in the energy range from TeV-PeV by combining ANTARES, ARCA21, and IceCube. All event samples are dominated by muon neutrinos. The analysis focuses on modifications to the ν_μ survival probability induced by isotropic LIV coefficients.

At low energies, the dominant effect arises from diagonal LIV coefficients of the form $a^{(d)}_{\mu\mu} - a^{(d)}_{\tau\tau}$ or $c^{(d)}_{\mu\mu} - c^{(d)}_{\tau\tau}$, which we refer to as $\mu\mu{-}\tau\tau$ coefficients. A non-zero value suppresses flavor transitions between ν_μ and ν_τ, leading to a reduced oscillation amplitude. Since standard $\nu_\mu \to \nu_\tau$ oscillations occur primarily below 100 GeV, ORCA has the best sensitivity to this coefficient combination since its detector layout was specifically optimized to this energy range. The oscillation effects introduced by the $\mu\mu{-}\tau\tau$ coefficients are illustrated in the top panel of Fig. 1, which shows the relative difference between standard and LIV-induced oscillation probabilities for a non-zero $\mu\mu - \tau\tau$ coefficient. Red regions indicate an excess of muon neutrinos under LIV, corresponding to suppressed oscillations.

Off-diagonal LIV coefficients, such as $a^{(d)}_{\mu\tau}$ or $c^{(d)}_{\mu\tau}$, induce additional oscillations between ν_μ and ν_τ. For $d > 3$, the smaller the coefficient, the higher the energy of the first oscillation maximum, which motivates the use of high-energy detectors for constraining these parameters. The bottom panel of Fig. 1 shows the corresponding oscillogram for a non-zero $\mu\tau$ coefficient. Blue regions indicate a deficit of muon neutrinos under LIV, as additional oscillations are introduced.

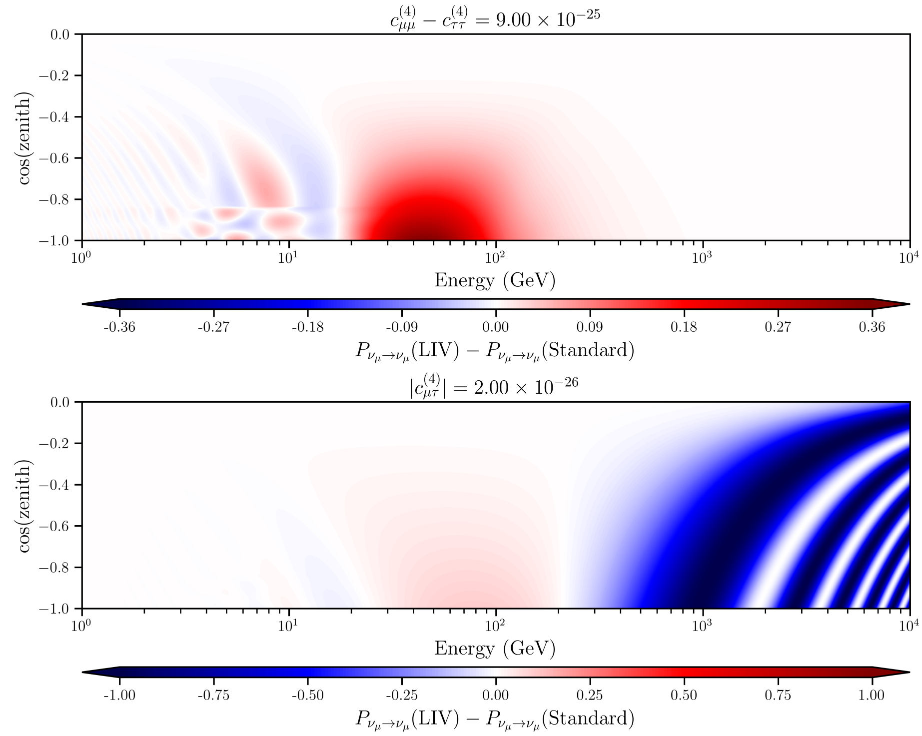

Figure 1: Modification of muon neutrino survival probability due to isotropic Lorentz-invariance-violating (LIV) effects. The color scale shows the difference $P^{\mathrm{LIV}}_{\nu_\mu \to \nu_\mu} - P^{\mathrm{Standard}}_{\nu_\mu \to \nu_\mu}$ as a function of neutrino energy and zenith angle. Top: Diagonal coefficient difference $c^{(4)}_{\mu\mu} - c^{(4)}_{\tau\tau} = 9.00 \times 10^{-25}$. Bottom: Off-diagonal coefficient $|c^{(4)}_{\mu\tau}| = 2.00 \times 10^{-26}$.

An exception occurs for mass dimension $d = 3$, where the oscillation phase is proportional to the baseline L, without energy dependence. In this case, off-diagonal coefficients can also be probed at low energies. For this reason, ORCA6 is used to test not only $\mu\mu - \tau\tau$, but also $\mu\tau$, eμ and eτ coefficients at $d = 3$. This is made possible by ORCA's dedicated shower event class, which includes interactions from ν_e and ν_τ [6].

The ORCA6 analysis uses the Hamiltonian defined in eq. (1), neglecting incoherent scattering effects, which are only significant at energies above $O(\mathrm{TeV})$. Oscillation probabilities are computed using the `OscProb` package [10]. In contrast, the high-energy analysis must account for incoherent scattering processes during neutrino propagation. For this reason, it uses `nuSQuIDS` [11] to evolve the atmospheric and astrophysical neutrino fluxes to the detector level.

The systematics treatment for ORCA6 follows the approach described in [6]. The most significant systematic uncertainty is the value of the mixing angle θ_{23}. Since $\mu\mu - \tau\tau$ coefficients suppress standard $\nu_\mu \to \nu_\tau$ oscillations, a deviation of θ_{23} from 45° (maximal mixing) can mimic the LIV signal. This is followed by the uncertainty on Δm^2_{31}, which shifts the oscillation pattern in energy.

For the high-energy analysis, the conventional and prompt atmospheric neutrino fluxes are modeled using `Daemonflux` [12], with dominant uncertainties arising from the cosmic ray nucleon flux and the hadronic interaction model governing particle yields in atmospheric showers. The latter are constrained by cross-section data from beam experiments. The astrophysical neutrino flux is modeled using a broken power law. All of these flux-related systematics are treated as shared between IceCube, ARCA21, and ANTARES, as they originate from common physical processes.

Detector-specific uncertainties are treated independently for each detector. For IceCube, key uncertainties include the optical properties of the ice, the effects of boreholes and bubbles, and DOM efficiencies. These are modeled using Monte Carlo simulations with varied input parameters, from which reconstructed distributions are histogrammed and interpolated using splines [9]. For ARCA21 and ANTARES, simulations with varied water absorption and scattering lengths, as well as PMT efficiencies, have been prepared. The detector systematics for ARCA21 are not yet included in the presented sensitivities, and their implementation is currently under development. For ANTARES, both flux and detector systematics follow a preliminary treatment described in [7], which will be revised to ensure consistency with the approach used for ARCA21 and IceCube.

Once all flux and detector systematics are finalized, the likelihoods of the individual detectors will be combined in a joint fit to extract constraints on the LIV coefficients.

5. Results

Figure 2 summarizes the status of the two analyses. The ORCA6 analysis has been unblinded on data. No significant LIV effect was found, resulting in the exclusion regions shown in the left plot in fig. 2. For this analysis, all limits are shown at the 95% confidence level. The analysis constrains all mass dimension $d = 3$ coefficients, including off-diagonal terms ($e\mu$, $e\tau$, and $\mu\tau$), as well as the diagonal combination $\mu\mu - \tau\tau$. For higher mass dimensions, ORCA6 provides upper limits on the diagonal $\mu\mu - \tau\tau$ coefficients up to $d = 8$. The plot displays the absolute values of these combinations, $|\mathring{a}^{(d)}_{\mu\mu} - \mathring{a}^{(d)}_{\tau\tau}|$ and $|\mathring{c}^{(d)}_{\mu\mu} - \mathring{c}^{(d)}_{\tau\tau}|$, justified by the near-symmetry of the likelihood around zero. For the complex-valued off-diagonal coefficients, such as $\mathring{a}^{(d)}_{\mu\tau}$ and $\mathring{c}^{(d)}_{\mu\tau}$, the plot shows the upper limits on their absolute values.

We note that Super-Kamiokande has previously provided constraints on off-diagonal coefficients for $d = 3$ and $d = 4$ using 12 years of data [13]. In addition, IceCube has reported upper limits at the 99% confidence level from an earlier analysis using two years of data [14], constraining the complex-valued $\mu\tau$ coefficients from mass dimensions $d = 3$ to $d = 8$. However, to our knowledge, this work presents the first constraints on isotropic diagonal LIV coefficients obtained without assumptions on the flavor composition of astronomical sources [15]. As can be seen, although ORCA6 comprises only six detection units out of the planned 115 and collected data for less than two years, it already delivers competitive upper limits for mass dimension $d = 3$. This highlights the potential of the full KM3NeT/ORCA detector to probe Lorentz-invariance-violating effects in the low-energy regime.

For the high-energy analysis, we present sensitivity curves for the $\mu\tau$ coefficients of mass dimensions $d = 4$, 5, and 6, evaluated independently with IceCube, ARCA21, and ANTARES, with the latter two sensitivities being work-in-progress. These are shown as hatched grey, blue, and violet bars, respectively, in the right plot in fig. 2. The earlier IceCube analysis, based on 10.7 years of data and a cubic-kilometer detection volume, achieves the strongest sensitivity [9]. In comparison,

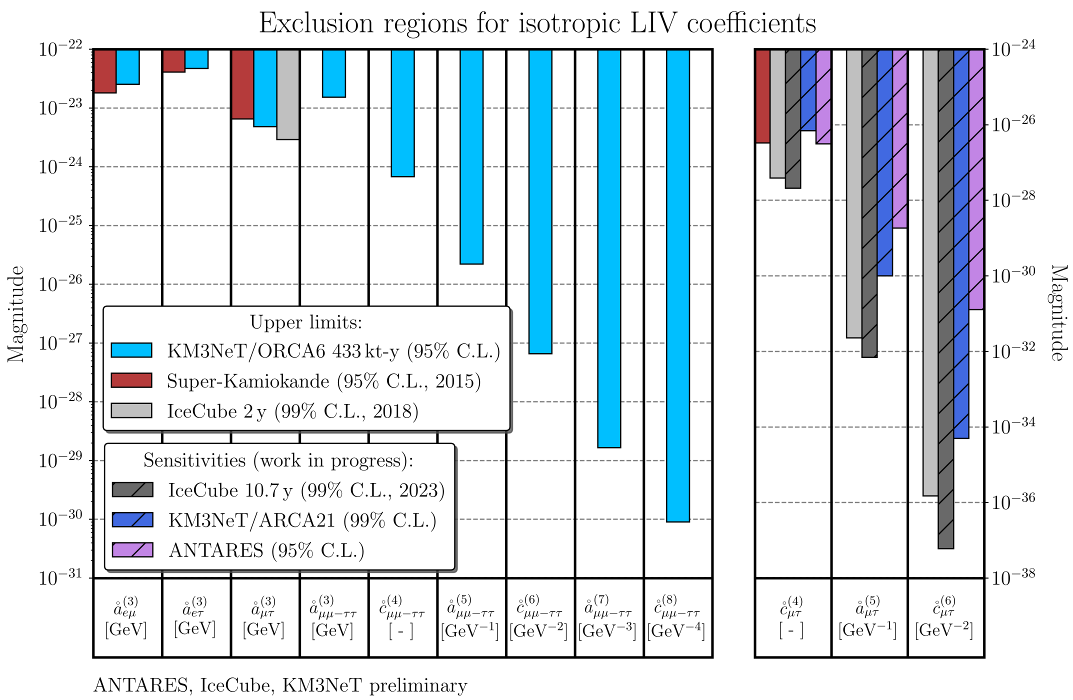

Figure 2: Exclusion regions on isotropic Lorentz-invariance-violating (LIV) coefficients from KM3NeT/ORCA6, IceCube, KM3NeT/ARCA21, and ANTARES. The left panel shows upper limits from the low-energy analysis using KM3NeT/ORCA6. The right panel shows the current status of the high-energy analysis and includes sensitivities from IceCube (10.7 yr) as well as work-in-progress sensitivities from KM3NeT/ARCA21 and ANTARES. Solid bars indicate upper limits at the confidence level specified in the legend, while hatched bars represent sensitivities. Previous upper limits from Super-Kamiokande [13] and from an earlier 2-year IceCube analysis [14] are also shown. The IceCube 10.7 yr sensitivities are taken from [9], and the ANTARES sensitivities are taken from our previous work presented in [7].

ARCA21 and ANTARES provide less stringent sensitivities, as expected given ARCA21's one-year exposure and smaller size, and ANTARES' more limited detection volume.

Nonetheless, this joint effort marks the first step toward future combined analyses of ARCA and IceCube data. As ARCA continues to grow toward its full configuration, its contribution to constraining high-energy LIV coefficients is expected to increase significantly.

6. Conclusion and outlook

We reported on the progress of the first joint search for isotropic Lorentz invariance violation using data from the four neutrino telescopes ANTARES, IceCube, and KM3NeT/ORCA, and KM3NeT/ARCA. The search is organized into two analyses: a low-energy analysis using KM3NeT/ORCA6, and a high-energy analysis based on data from ANTARES, ARCA21, and IceCube.

For the low-energy analysis, we presented finalized upper limits at 95% confidence level from ORCA6, constraining all mass dimension $d = 3$ coefficients, including off-diagonal terms, as well as diagonal $\mu\mu - \tau\tau$ coefficients up to $d = 8$. Despite limited exposure and instrumentation, ORCA6 delivers competitive constraints on $d = 3$ coefficients when compared to the Super-Kamiokande limits [13] and the IceCube limits [14], and represents the first experimental constraints on isotropic diagonal LIV coefficients without assumptions on the flavor composition at astronomical sources [15].

For the high-energy analysis, we optimized an event selection for ARCA21 and evaluated its sensitivity to $\mu\tau$ coefficients. Combined with existing results from ANTARES [7] and IceCube [9], we now have a preliminary full set of individual detector sensitivities across relevant mass dimensions. In addition, we developed a consistent plan for the treatment of systematic uncertainties in the combined high-energy analysis, with flux-related systematics treated as shared among detectors and detector-specific uncertainties handled independently.

This effort represents the first coordinated analysis involving data from the four neutrino telescopes ANTARES, IceCube, KM3NeT/ARCA, and KM3NeT/ORCA, highlighting the growing collaboration within the neutrino telescope community. As detector deployments progress and analyses mature, future joint studies are expected to advance our understanding of neutrino properties and fundamental physics.

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