PROCEEDINGS OF SCIENCE

Lorentz Invariance Violation with KM3NeT/ORCA115

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Lorentz invariance (LI) underlies both the Standard Model of particle physics and General Relativity, and it represents our understanding of the nature of spacetime. It is therefore of fundamental interest to test its validity in every accessible regime as this would allow us to probe the microscopic structure of space-time and to constrain quantum gravity models. Lorentz Invariance Violation (LIV) would modify the observed energy and zenith angle distributions of atmospheric neutrinos that can be detected by neutrino telescopes such as KM3NeT. KM3NeT/ORCA115 is a next-generation neutrino telescope under construction in the Mediterranean sea, and is optimised for atmospheric neutrino oscillations studies. In this contribution, the sensitivity of ORCA115 to the presence of LIV is presented.

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1. Introduction

Lorentz invariance underlies both the Standard Model (SM) of particle physics and General Relativity (GR), and it represents our understanding of the nature of spacetime. This symmetry guarantees that physical phenomena are observed to be the same by all inertial observers. Violations of this symmetry at or below the Planck scale, $m_P \sim 10^{19}$ GeV, have been predicted in a variety of quantum gravity (QG) models attempting to unify quantum field theory (QFT) and GR [1]. Indeed, many QG models involve some form of discretisation of spacetime, which is hard to reconcile with e.g. Lorentz boost invariance. It is actually possible to define a QG model which has LI sub-Planckian structure, however, this does not guarantee the preservation of LI at intermediate scales.

It is therefore of fundamental interest to test the validity of LI in every accessible regime as this would allow us to probe the microscopic structure of space-time and to constrain QG models.

The comprehensive effective field theory incorporating the SM and GR and characterizing general Lorentz and CPT violation is the Standard Model Extension (SME) [1]. In the SME, each Lorentz-violating term is formed by contracting a Lorentz-violating operator of a given mass dimension d with a controlling coefficient that can be experimentally constrained.

Specifically, in the neutrino sector, deviations from standard neutrino oscillations can be expected in case of LIV. Such contributions would modify the observed energy and zenith angle distributions of atmospheric neutrinos that can be detected by neutrino telescopes.

2. Isotropic LIV with neutrinos

As discussed in Ref. [1], the general effective Hamiltonian describing neutrino propagation and mixing in the presence of LIV operators of renormalizable dimension contains four types of coefficients, leading to many novel effects that can be revealed in suitable experiments. The phenomenological approach to LIV assumes two separate cases: in one case, the rotational symmetry is preserved, and this is referred to as *isotropic* LIV. Other cases assume a breaking of the rotational symmetry, referred as to *sidereal* LIV. The analysis here presented focuses on isotropic LIV: the Lorentz symmetry is broken in the time coordinate.

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 [1]:

$$H = H_0 + H_I + H_{LIV} \tag{1}$$

with

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

being the standard oscillation Hamiltonian that applies to the neutrino mass states,

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

being the Hamiltonian that applies to the neutrino flavour states which accounts for matter effects in the regime of coherent scattering, and

$$H_{LIV} = \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{e\tau} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{e\tau} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - E \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{e\tau} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{e\tau} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} + E^2 \mathring{a}^{(5)} - E^3 \mathring{c}^{(6)} + E^4 \mathring{a}^{(7)} - E^5 \mathring{c}^{(8)} + \ldots \tag{4}$$

being the isotropic Lorentz-violating Hamiltonian: the $\mathring{a}$ coefficients are CPT-odd, whereas the $\mathring{c}$ coefficients are CPT-even. From the Hamiltonian formulation, every dimension coefficient has a different impact in neutrino oscillations, which is summarised in Tab. 1. Specifically, the oscillation effect of H_0 is $\propto L/E$, which means that, fixing longer baselines L and higher neutrino energies E allow to probe higher dimension coefficients.

Table 1: LIV coefficients: for a 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. LIV analysis with ORCA115

The analysis presented here follows the same procedure of Ref. [2]. Specifically, the analysis is based on detailed Monte Carlo (MC) simulations, accounting for neutrino interactions, secondary particles production and Cherenkov light emission and propagation. The atmospheric neutrino flux is computed from the Honda model [3] for the Gran Sasso site without mountain over the detector, assuming minimum solar activity. Atmospheric muons are generated with MUPAGE [2].

Event reconstruction is performed via a maximum likelihood fit to shower and track hypotheses. Background events arising from noise and atmospheric muons are rejected with two independent Random Decision Forests (RDF) trained on MC simulations. A third RDF was used to separate neutrino candidates into three topology classes defined by the output score of the RDF, trained to identify track-like events. Events with a track score larger than 0.7 are labelled as track-like, track scores less than 0.3 are labelled as shower-like, and other values are labelled as an intermediate topology. Moreover, as in Ref. [4], only upgoing events are considered in order to get rid of the atmospheric muon contamination.

Instead of using parametrised response functions as in Ref. [4], the analysis reported here is based on the aforementioned MC simulations to directly model the detector response. The two approaches have been compared and found consistent.

The MC-based modelling of the detector response is implemented in the KM3NeT framework

Swim [5]. The detector response is represented by a 4-dimensional matrix, as a function of true and reconstructed neutrino energy E, E', and zenith angle θ, θ', for each interaction channel ν_x, $R^{[\nu_x \to i]}(E, \theta, E', \theta')$. Each entry of this matrix summarises in a single dimensionless coefficient the efficiency of detection, classification and probability of reconstruction for a given true bin (E, θ). Therefore, R incorporates all the effects related both to the detector and to the event selection, which, in this analysis, uses atmospheric neutrino events with reconstructed energy up to 20 GeV. The values of the standard neutrino parameters used in this analysis is taken from the NuFit v5.2 global fit result with Super-Kamiokande (SK) data [6] and are summarised in Tab. 2 for normal ordering (NO). Oscillation probabilities are evaluated with the software package OscProb [7], and to account for Earth's matter effects the PREM model [8] with 44 layers is used.

	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}	$\Delta m^2_{21}\,(\mathrm{eV}^2)$	$\Delta m^2_{31}\,(\mathrm{eV}^2)$
NO	0.303	0.451	0.02225	232°	7.41×10^{-5}	2.507×10^{-3}

Table 2: Benchmark oscillation parameters for NO, taken from the NuFit v5.2 result [6].

The above information can be used to define the distinguishability $\Delta\chi^2$, as a quick estimator of sensitivity of measurements, with the goal of illustrating the impact of LIV in the event distributions, as

$$\Delta\chi^2 = \frac{(N_{\mathrm{LIV}} - N_{\mathrm{Std}})|N_{\mathrm{LIV}} - N_{\mathrm{Std}}|}{N_{\mathrm{LIV}}}, \tag{5}$$

where N_{LIV} and N_{Std} are the number of events, as a function of reconstructed energy and zenith angle, in the LIV and standard hypothesis respectively. Fig. 1 shows the distinguishability distribution for LIV assuming dimension 3 coefficient.

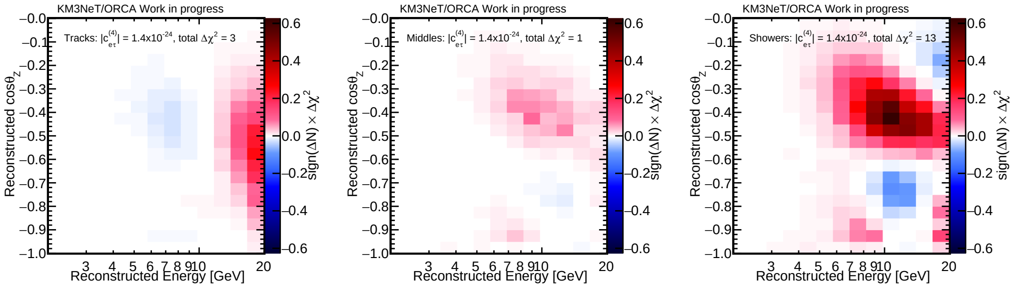

Figure 1: $\Delta\chi^2$ distribution of the three topologies considered in the analysis (tracks, intermediates and showers) assuming three years of data taking. The colour scale denotes the S_σ value for each bin, whereas the total S_σ is reported on top of the plots. The LIV parameters are $\left|\mathring{c}^{(4)}_{e\tau}\right| = 1.4 \times 10^{-24}$.

The same figure can be produced by fitting all the parameters of the analysis in order to see the impact of systematics. This is shown in Fig. 2.

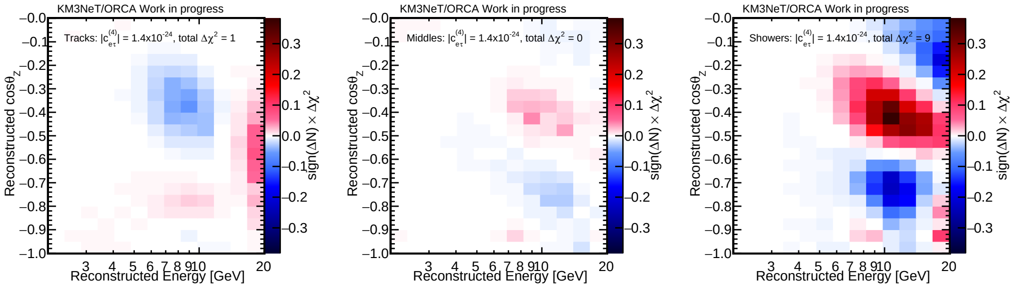

Figure 2: Same as Fig. 1 but by fitting all the analysis parameters.

The sensitivity evaluation is based on the minimisation of a negative log-likelihood function describing the agreement between a model prediction and observed data. This is done with the Asimov approach [2] assuming the negative log-likelihood follows a chi-squared distribution. Specifically, the negative log-likelihood function is defined as:

$$\begin{aligned}\chi^2 = &- 2\log L = \chi^2_{\text{stat}} + \chi^2_{\text{syst}} = \\ &2\sum_{i=1}^{N_{E'}}\sum_{j=1}^{N_{\cos\theta'}}\sum_{t=1}^{3}\left[N^{\text{model}}_{ijt}(\eta) - N^{\text{data}}_{ijt} + N^{\text{data}}_{ijt}\log\left(\frac{N^{\text{data}}_{\text{ijt}}}{N^{\text{model}}_{ijt}(\eta)}\right)\right] \\ &+\sum_{k=1}^{N_{\text{Syst}}}\left(\frac{\eta'_k - \langle\eta'_k|\eta'_k\rangle}{\sigma_{\eta'_k}}\right)^2,\end{aligned} \tag{6}$$

where N^{model}_{ijt} and N^{data}_{ijt} represent the number of expected and measured events in bin (i, j) respectively and the sum over t runs over the three event topologies: tracks, intermediates and showers. η represents the model parameters, which comprise both the oscillation parameters listed in Tab. 2, and nuisance parameters η', which are related to systematic uncertainties. The second sum runs over the nuisance parameters and $\langle\eta'_k|\eta'_k\rangle$ is the assumed prior of the parameter k and $\sigma_{\eta'_k}$ its uncertainty. The set of free parameters considered in this analysis, together with the assumed gaussian priors with mean μ and standard deviation σ, is summarised in Tab. 3. More details can be found in Ref. [2].

4. Results

Fig. 3 shows the sensitivity of KM3NeT/ORCA115 to isotropic LIV coefficients up to dimension 4 which is represented by the area of excluded region of the parameters space. ORCA115 sensitivity is compared with current upper limits from 12 years of SK atmospheric neutrino data [9], two years of IceCube atmospheric neutrino data [10] and DUNE sensitivity assuming 7 years of data taking [11].

Since this analysis is limited to events up to 20 GeV, and as discussed in Sec. 2, the best sensitivity to higher dimension coefficients is reached with high energy neutrinos, currently the ORCA115 results do not extend to dimensions > 4. An update of this work, with events > 20 GeV is foreseen, which will include also higher dimension coefficients.

Current results show that with three years of data taking ORCA115 will allow to probe regions of the parameter space not yet probed by current analyses.

Parameter	**Gaussian Prior** ($\mu \pm \sigma$)
$\nu_e/\bar{\nu}_e$	0 ± 0.07
$\nu_\mu/\bar{\nu}_\mu$	0 ± 0.05
ν_e/ν_μ	0 ± 0.02
NC Scale	No prior
Energy Scale	1 ± 0.05
Energy Slope	No prior
Zenith Angle Slope	0 ± 0.02
Track Normalisation	No Prior
Intermediate Normalisation	No Prior
Shower Normalisation	No Prior
Δm^2_{31}	No prior
θ_{13}	$\theta_{13} \pm 0.13°$
θ_{23}	No prior

Table 3: List of fitted values and relative gaussian priors considered in this analysis. θ_{13} refers to the values listed in Tab. 2

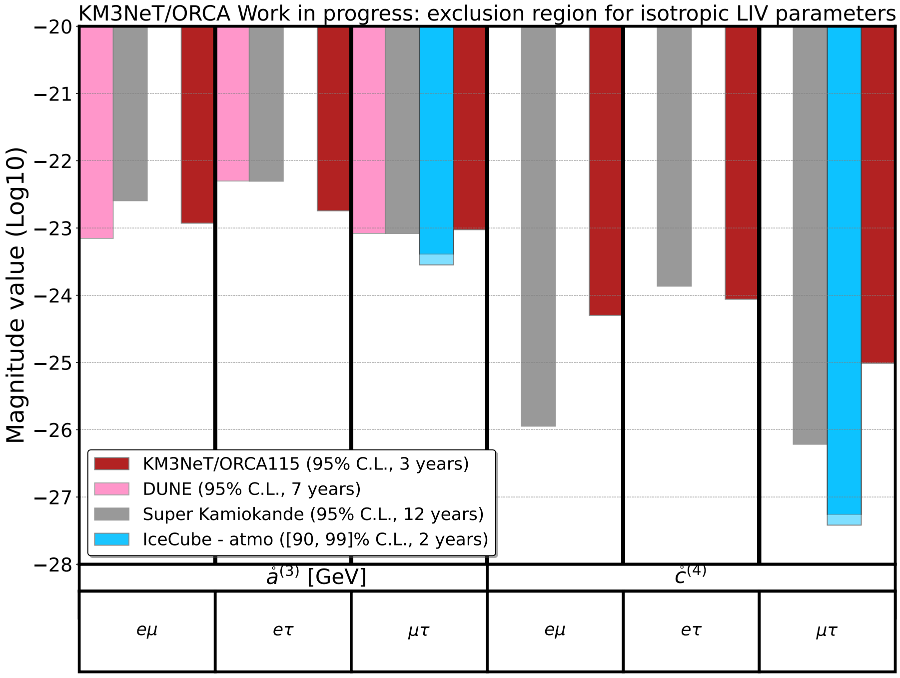

Figure 3: Two-dimensional sensitivity of KM3NeT/ORCA115 at the 95% C.L. for the real and imaginary parts of the isotropic coefficients of dimension 3 $a_{e\mu}$, $a_{\mu\tau}$, $a_{e\tau}$, for three years of data taking. Sensitivity results are compared with DUNE sensitivity [11] and current upper limits from 12 years of SK [9], two years of IC-atmospheric neutrino analysis [10].

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