PROCEEDINGS OF SCIENCE

Probing Lorentz violation in the ultra-high-energy regime using air showers

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Current efforts towards a more fundamental theory beyond the Standard Model of Particle Physics open up a window for deviations from exact Lorentz symmetry. To test Lorentz symmetry, one can make use of the extreme energies reached by ultra-high-energy cosmic rays (UHECRs), which are far beyond what is accessible by other means. We use the air showers initiated by UHECRs in the Earth's atmosphere to study the effects of Lorentz violation (LV), focusing on isotropic, non-birefringent LV in the photon sector. New processes, which are forbidden in case exact Lorentz symmetry holds, can significantly change the shower development. One such process is vacuum Cherenkov radiation, a very efficient energy-loss process for charged particles such as electrons and positrons. We primarily focus on the average depth of the shower maximum $\langle X_{\max} \rangle$ and its shower-to-shower fluctuations $\sigma(X_{\max})$, which we study using air-shower simulations. Comparing our results to measurements, we obtain a new upper bound on the key LV parameter κ, which improves the previous bound by a factor of 2. This is the first bound based on vacuum Cherenkov radiation from fundamental particles in air showers. This result also complements previous bounds on $\kappa < 0$. Also here, our approach - then involving photon decay instead of vacuum Cherenkov radiation - led to the world's best bound on κ. In addition to summarizing these results, we explore related changes in the muonic shower component, which may lead to further improvements.

The 38th International Cosmic Ray Conference (ICRC2023)
26 July – 3 August, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

*Speaker

PoS(ICRC2023)217

1. Introduction

Current theories aiming to establish a more fundamental understanding of particle physics beyond the Standard Model (SM) can allow for deviations from exact Lorentz symmetry (see, e.g., [1, 2]). To test for possible effects of Lorentz violation (LV), the extremely high energies of cosmic rays and gamma rays have been used, obtaining some of the best limits on LV (see, e.g., [3–6]).

In this work, we focus on the effects of isotropic, nonbirefringent LV in the photon sector on air showers, which is implemented through the framework of modified Maxwell theory (Sec. 2). Specifically, we study the impact of this type of LV on extensive air showers initiated by ultra-high-energy (UHE) cosmic rays with energies above 10^{18} eV in the Earth's atmosphere (Sec. 3).

2. Theory and previous bounds

To give rise to Lorentz violation (LV) in the photon sector in a comparatively simple extension of standard quantum electrodynamics (QED), a single term can be added to the Lagrange density [2]:

$$\begin{aligned}\mathcal{L} =& \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \overline{\psi}\left[\gamma^{\mu}(i\partial_{\mu} - eA_{\mu}) - m\right]\psi}_{\text{standard QED}} \\ & \underbrace{-\frac{1}{4}(k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}}_{\text{CPT-even LV term}} .\end{aligned} \tag{1}$$

This added term breaks Lorentz invariance but preserves CPT and gauge invariance. Throughout this work, natural units ($\hbar = c = 1$) and the Minkowski metric $g_{\mu\nu}(x) = \eta_{\mu\nu} = [\mathrm{diag}(+1, -1, -1, -1)]_{\mu\nu}$ are used. Although the added tensor-valued background field $(k_F)_{\mu\nu\rho\sigma}$ consists of 20 independent components, it is controlled by a single dimensionless parameter κ in the case of isotropic, nonbirefringent LV in the photon sector, which is discussed here:

$$(k_F)^{\lambda}{}_{\mu\lambda\nu} = \frac{\kappa}{2}\,[\mathrm{diag}(3, 1, 1, 1)]_{\mu\nu} . \tag{2}$$

This leads to changes in the photon phase velocity:

$$v_{\mathrm{ph}} = \frac{\omega}{|\vec{k}|} = \sqrt{\frac{1-\kappa}{1+\kappa}}\,c. \tag{3}$$

It has to be noted that here that c in this context no longer corresponds to the speed of light, but to the maximum velocity of a massive Dirac fermion. In the case of $\kappa < 0$, the photon is faster than c, for $\kappa > 0$, the photon is slower, and $\kappa = 0$ is the SM case.

For $\kappa \neq 0$, processes forbidden in the SM become allowed. In the case of $\kappa < 0$, photons become unstable above the energy threshold $E_{\gamma}^{\mathrm{th}}(\kappa)$ and decay into electron-positron pairs, with $m_e \simeq 511$ keV being the rest mass of the electron:

$$E_{\gamma}^{\mathrm{th}}(\kappa) = 2\,m_e\sqrt{\frac{1-\kappa}{-2\kappa}} \simeq \frac{2\,m_e}{\sqrt{-2\kappa}}. \tag{4}$$

The decay length of the photon drops to scales of centimeters and below right above this threshold, which corresponds to a quasi-instantaneous decay of photons into eletron-positron pairs [5, 8]. Additionally, the decay of neutral pions into such nonstandard photons is modified [7], increasing the lifetime of the pion until it becomes stable above the threshold energy:

$$E^{\mathrm{th}}_{\pi^0}(\kappa) = m_{\pi^0}\sqrt{\frac{1-\kappa}{-2\kappa}} \simeq \frac{m_{\pi^0}}{\sqrt{-2\kappa}}. \tag{5}$$

In the case of $\kappa > 0$, vacuum Cherenkov (VCh) radiation becomes possible for charged particles above the threshold energy

$$E^{\mathrm{th}}_{\mathrm{VCh}}(\kappa) = m\sqrt{\frac{1+\kappa}{2\kappa}} \simeq \frac{m}{\sqrt{2\kappa}}. \tag{6}$$

This threshold depends on the mass m of the charged particle, with heavier particles emitting VCh radiation only at higher energies. In earlier works, measurements of UHE cosmic rays have been used to set bounds on LV of $-9 \times 10^{-16} < \kappa < 6 \times 10^{-20}$ [5]. In both cases of $\kappa < 0$ and $\kappa > 0$, the possibility of processes forbidden in the SM changes the expected development of air showers initiated by UHE cosmic rays. In particular, the change in the average atmospheric depth of the shower maximum $\langle X_{\max}\rangle$ is significant. This has been used to set a stricter lower bound of $\kappa > -3 \times 10^{-19}$ [3]. The inclusion of the fluctuations of the shower maximum $\sigma(X_{\max})$ in the analysis led to even tighter bounds on LV of $\kappa > -6 \times 10^{-21}$ [9] and $\kappa < 3 \times 10^{-20}$ [10], improving the previous bounds by a factor of 50 and 2 respectively.

The addition of further appropiate observables such as the muon content at ground level should improve the sensitivity even further. The impact of LV on the analyzed shower observables, as well as the methods used to gain the current best limits are described in the following section.

3. Analysis

The impact of LV on air showers has been studied using a full Monte Carlo (MC) approach. Simulations of air showers were produced using a modified version of the MC code CONEX [11, 12]. The modifications done include both the instant decay of photons above the energy threshold given in Eq. (4) as well as the modification of the neutral-pion decay time for $\kappa < 0$ and the implementation of VCh radiation for charged particles for $\kappa > 0$. Hadronic interactions were simulated using SIBYLL 2.3d [13], cross checks were done using both EPOS LHC [14] and QGSJET-II-04 [15]. For settings not explicitly mentioned here, the defaults of the CONEX code were used.

For both $\kappa < 0$ and $\kappa > 0$, the simulations show a decrease in the average depth of the shower maximum $\langle X_{\max}\rangle$ and no significant changes in its shower-to-shower fluctuations $\sigma(X_{\max})$ for $\kappa \neq 0$, which is illustrated in Fig. 1 and Fig. 2. The changes in the showers only appear once there are particles affected by LV in the shower, with the magnitude of the effect increasing for higher energies.

The differences in $\langle X_{\max}\rangle$ are mostly induced by the impact of LV on the electromagnetic component of the shower. For $\kappa < 0$, this is the nonstandard photon decay. In the case of $\kappa > 0$, the VCh radiation emitted by electrons and positrons leads to the majority of the decline in $\langle X_{\max}\rangle$. Since the shower development is dependent on the energy per nucleon of the primary cosmic ray, the onset of the effects of LV is shifted to higher energies for higher primary particle masses.

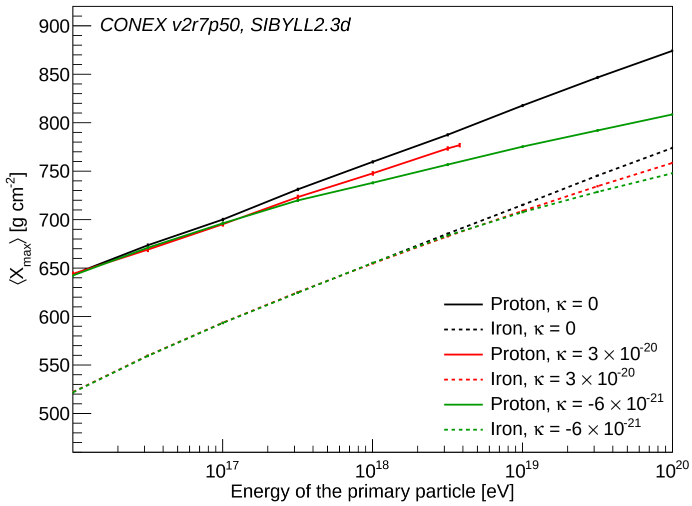

Figure 1: Illustration of the changes of $\langle X_{\max} \rangle$ as a function of the primary energy for primary protons and iron nuclei for the absence of LV ($\kappa = 0$) and for the current best bounds ($-6 \times 10^{-21} < \kappa < 3 \times 10^{-20}$).

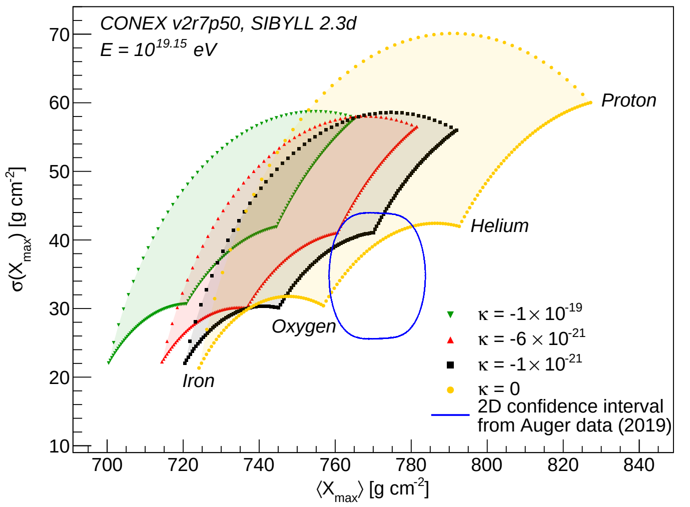

Figure 2: $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$ values allowed by simulations with and without LV ($\kappa < 0$), as well as the two-dimensional confidence interval derived from $\langle X_{\max} \rangle$ measurements from the Pierre Auger Observatory [17]. The corners of the simulated umbrella shaped plots correspond to pure cosmic-ray compositions.

Additionally, primary particles above the VCh energy threshold given by Eq. (6) cannot reach Earth at all due to the expected rapid energy loss. This restricts the allowed primaries to particles of higher masses at higher energies for $\kappa > 0$.

The actual cosmic-ray particle composition is uncertain, especially at the highest energies. To account for this, samples of air showers induced by cosmic rays of different particles representative of their mass ranges were simulated. In the case of $\kappa < 0$, protons (mass number $A = 1$), helium ($A = 4$), oxygen ($A = 16$) and iron ($A = 56$) were chosen. By combining these simulations in different fractions, any possible primary particle composition can be approximated.

Values of κ with no cosmic-ray composition matching the experimental observations can

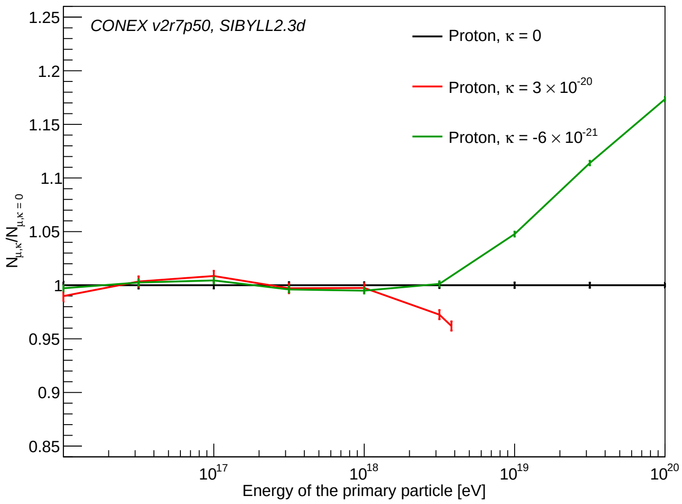

Figure 3: The change in the muon number at the ground level as a function of the primary energy for primary protons in relation to its value in the absence of LV ($\kappa = 0$) for the current best bounds ($-6 \times 10^{-21} < \kappa < 3 \times 10^{-20}$). The shower inclination is fixed at 45°.

thus be excluded. Through comparison of this set of $\langle X_{\text{max}} \rangle / \sigma(X_{\text{max}})$ values to observations taken by the Pierre Auger Observatory [16, 17] the strictest bounds on κ to date have been set at $-6 \times 10^{-21} < \kappa < 3 \times 10^{-20}$ [9, 10].

It is worth noting that the compositions producing those bounds are pure, thus a restriction of the purity of the cosmic-ray composition would lead to a further improvement of those bounds.

Another possible indicator of the purity of the cosmic-ray composition is the number of muons measured at ground level N_μ and its correlation to X_{max} [18]. The value of N_μ also changes for $\kappa \neq 0$, increasing for $\kappa < 0$ and decreasing for $\kappa > 0$ (see Fig. 3). This is different to $\langle X_{\text{max}} \rangle$, which is decreasing in both cases of $\kappa < 0$ and $\kappa > 0$, and can thus potentially be used to differentiate between the two cases. N_μ is sensitive to the shower inclination, differing from X_{max} which is mostly independent of it. The simulations were done for a fixed zenith angle of 45°. From the output of the simulations, the muon number was extracted for a slant depth of 1240 $\frac{\text{g}}{\text{cm}^2}$.

In the case of $\kappa < 0$, the increase of N_μ can be explained by the modification of the decay time of the neutral pion. Since neutral pions above the energy threshold given by Eq. (5) do not decay into photons quasi-intantaneously, they may instead produce more pions through hadronic interactions, leading to an increase of the number of muons on ground level of up to 20 %.

For $\kappa > 0$, the decrease of N_μ is due to the pions of the highest energies rapidly losing their energy through VCh radiation (and hence not undergoing further hadronic interaction), thus producing up to 4 % less muons.

The correlation between X_{max} and N_μ can be quantified through the Pearson correlation coefficient

$$r_{X_{\text{max}}, N_\mu} = \frac{\text{cov}(X_{\text{max}}, N_\mu)}{\sigma_{X_{\text{max}}} \sigma_{N_\mu}}. \tag{7}$$

The changes in both X_{max} and N_μ due to LV are expected to produce a difference in the correlation between both observables. For mixed cosmic-ray compositions, this effect is larger, since a shift in the observables induced by LV is observed at lower energies for lighter primary

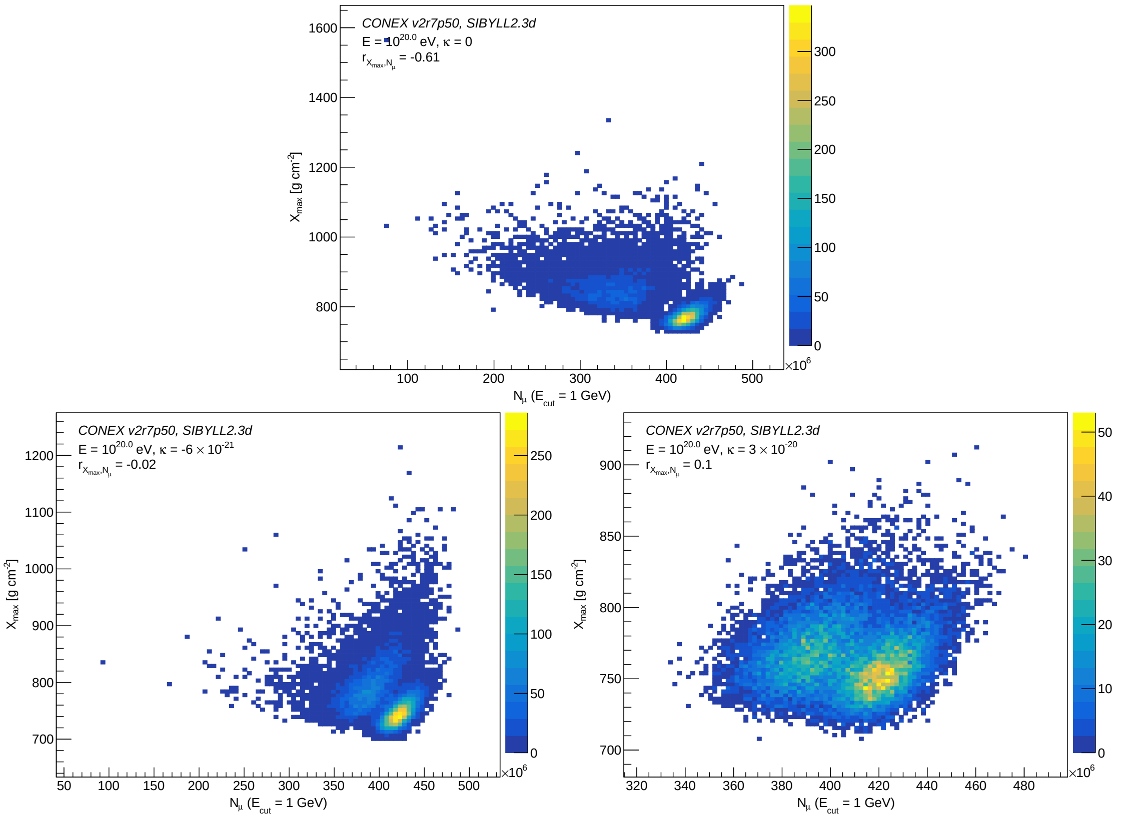

Figure 4: Visual example of the changes in the distribution of $\langle X_{\max} \rangle$ and the number of muons observed at ground level N_μ and their correlation for $\kappa = 0$ (top), $\kappa = -6 \times 10^{-21}$ (bottom left) and $\kappa = 3 \times 10^{-20}$ (bottom right) and an energy of 10^{20} eV. Shown is the extreme case of a cosmic ray spectrum consisting of 50 % protons and 50 % iron nuclei for $\kappa = 0$ and $\kappa = -6 \times 10^{-21}$. For $\kappa = 3 \times 10^{-20}$ most light particles are excluded by VCh radiation, thus aluminium is used instead of protons as the lightest possible primary particle.

particles. This leads to the lighter cosmic-ray component being stronger affected than the heavier component. This effect is larger, the more mixed a cosmic-ray composition is. An example of the change for the maximally-mixed composition consisting of 50 % contribution of the lightest allowed primary particle and 50 % iron can be seen in Fig.4. In the cases of $\kappa < 0$ and $\kappa = 0$, the lightest allowed primary particle is the proton, for $\kappa > 0$ the lighter primary particles are excluded due to VCh radiation, as they would lose energy before reaching Earth. Thus the lightest possible primary particle changes with the energy, with only higher mass particles allowed at higher energies.

The part of the overall distribution contributed by iron primaries remains mostly unchanged by LV. The change in the part contributed by protons however is distinctly visible. The simultaneous decrease of $X_{\max}$ and increase in N_μ for $\kappa < 0$ shifts the proton $X_{\max}/N_\mu$ distribution towards the iron $X_{\max}/N_\mu$ distribution, leading to a significantly larger overlap. The shape of the distribution also changes, reducing the correlation between both observables significantly. For $\kappa > 0$, both $X_{\max}$ and N_μ decrease, initially leading to a higher separation between the proton and iron distributions. However, since lighter primary particle become excluded by VCh radiation at higher energies, only heavier primary particles can occur at those energies. This corresponds to an increase in N_μ and a

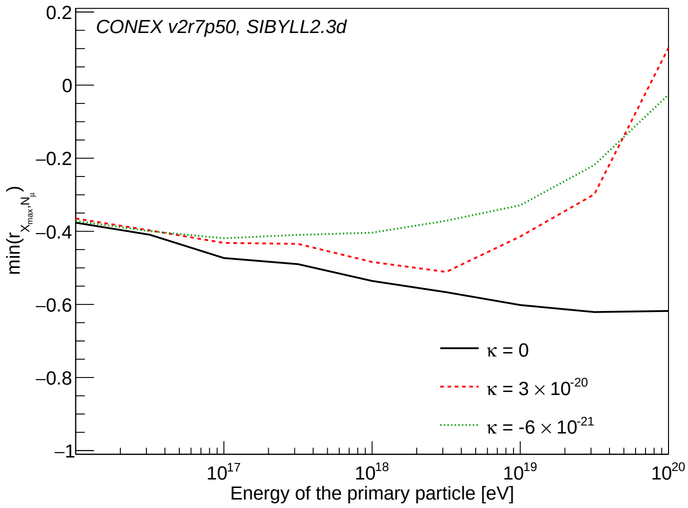

Figure 5: The lowest possible correlation $\texttt{min}(r_{X_{\max},N_\mu})$ in relation to the primary particle energy for $\kappa = 0$, $\kappa = -6 \times 10^{-21}$ and $\kappa = 3 \times 10^{-20}$. The lowest possible correlation is achieved by a mixture of 50 % of the lightest allowed primary particles and 50 % iron nuclei.

decrease in $X_{\max}$, getting closer to the iron $X_{\max}/N_\mu$ distribution and thus reducing the correlation between $X_{\max}$ and N_μ, as can be seen in the bottom right plot of Fig. 4.

Thus both $\kappa < 0$ and $\kappa > 0$ lead to a less negative minimal correlation between $X_{\max}$ and N_μ. The minimal values of the correlation are displayed in Fig. 5. In future works, we plan on studying the correlation between $X_{\max}$ and N_μ at the highest energies in greater detail, in particular whether this effect can be used to further improve the bounds on LV.

4. Conclusion and Outlook

Utilizing the expected changes of both $\langle X_{\max}\rangle$ and $\sigma(X_{\max})$ of air showers initiated by UHE cosmic rays in the presence of LV, strict bounds on the value of the LV parameter κ have been set at $-6 \times 10^{-21} < \kappa < 3 \times 10^{-20}$. These bounds are based on pure cosmic-ray compositions, and can thus be improved by further restricting possible cosmic-ray compositions. The correlation between N_μ and $\langle X_{\max}\rangle$ is also sensitive to the purity of the cosmic-ray composition.

We also investigated the changes in N_μ due to LV and showed that N_μ significantly increases in the case of $\kappa < 0$ and decreases in the case of $\kappa > 0$ for pure primary-particle compositions at the highest energies. Additionally, the minimal correlation between N_μ and $\langle X_{\max}\rangle$ significantly increases at the highest energies for both $\kappa < 0$ and $\kappa > 0$. In future works, further studies of the muon number will be done expanding on the preliminary studies presented here, possibly gaining additional restrictions on the cosmic-ray purity and resulting in improved tests of LV.

Acknowledgments

The many fruitful discussions with Frans R. Klinkhamer are greatly appreciated. We thank T. Pierog for his help in modifying the CONEX source code. This work was funded by the German Research Foundation (DFG project 408049454).

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