

Probing Lorentz violation at ultra-high energies using air showers

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Abstract. In air showers initiated by ultra-high-energy cosmic rays in the Earth’s atmosphere, even the secondary particles created in the start-up phase are produced at energies far above those accessible by other means. These high-energy particles can be used to search for New Physics, such as a violation of Lorentz invariance. We focus on isotropic, nonbirefringent Lorentz violation in the photon sector and consider the two cases $\kappa < 0$ and $\kappa > 0$ (i.e., the velocity of photons is larger/smaller than the maximum attainable velocity of standard Dirac fermions). In both cases, processes that are forbidden in the standard, Lorentz-invariant theory ($\kappa = 0$) become allowed, in particular photon decay in the case $\kappa < 0$ and vacuum-Cherenkov radiation for $\kappa > 0$. Implementing these processes into air-shower simulations, we found that the development of an air shower at the highest energies can be significantly impacted, specifically the average atmospheric depth of the shower maximum $\langle X_{\max} \rangle$ and its shower-to-shower fluctuations $\sigma(X_{\max})$. Comparing these simulations to actual measurements, we were able to obtain much stricter bounds on this specific type of LV in the case $\kappa < 0$ than possible with previous methods. We discuss these limits and, in addition, present first results for the case $\kappa > 0$.

1 Introduction

In current theories aiming to establish a more fundamental understanding of particle physics beyond the current Standard Model (SM), Lorentz invariance (LI) can be broken (see, e.g., [1, 2]). In the search for the effects of a violation of Lorentz invariance (LV), ultra-high energy (UHE) cosmic rays were used to produce some of the strongest bounds (see [3] for a yearly-updated compilation). In the analyses presented here, isotropic, nonbirefringent LV in the photon sector is implemented through the framework of modified Maxwell theory (Sec. 2). We study the impact of LV on the development of air showers initiated by UHE cosmic rays (Sec. 3). Through the comparison to current air shower measurements, LI can be probed and improved bounds on LV can be set (Sec. 4).

2 Theory Background

We use a fairly simple extension of standard quantum electrodynamics (QED). A single term is added to the Lagrange density which breaks Lorentz invariance but preserves CPT and gauge invariance [4, 5]¹:

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

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¹Note that natural units ($\hbar = c = 1$) and the Minkowski metric $g_{\mu\nu}(x) = \eta_{\mu\nu} = [\text{diag}(+1, -1, -1, -1)]_{\mu\nu}$ are used here.

For isotropic, nonbirefringent LV in the photon sector, the LV coefficient $(k_F)_{\mu\nu\rho\sigma}$ depends only on a single, dimensionless parameter $\kappa \in (-1, 1]$, which is related to k_F by [6]

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

For $\kappa \neq 0$, the LV term allows processes that are kinematically forbidden in the SM. We exploit the fact that in an air shower initiated by a UHE cosmic ray, secondary particles with very high energies are produced, for which these LV processes become relevant. We can then derive bounds on LV using the expected changes in the air-shower development (see Sec. 3).

In the case of $\kappa < 0$, nonstandard photons decay almost immediately into an electron-positron pair if they are above the threshold energy

$$E_\gamma^{\text{th}}(\kappa) = 2m_e \sqrt{\frac{1-\kappa}{-2\kappa}} \simeq \frac{2m_e}{\sqrt{-2\kappa}}. \quad (3)$$

The exact decay rate for the process $\tilde{\gamma} \rightarrow e^+ + e^-$ is given by [7]

$$\Gamma_{\text{phD}}(E_\gamma) = \frac{\alpha}{3} \frac{-\kappa}{1-\kappa^2} \sqrt{E_\gamma^2 - (E_\gamma^{\text{th}})^2} \left(2 + (E_\gamma^{\text{th}})^2 / E_\gamma^2 \right) \quad (4)$$

Changes in the decay time of neutral pions also occur [8], but they have a negligible impact on the air-shower observables used here. A previous bound of $\kappa > -9 \times 10^{-16}$ (98% C.L.) has been derived from observations of TeV γ -rays [9]. A much stricter bound of $\kappa > -3 \times 10^{-19}$ (98% C.L.) was obtained using secondary photons from air showers [10].

In the case of $\kappa > 0$, vacuum Cherenkov radiation (VCh) can occur, leading to charged particles with mass m losing their energy quickly by radiating photons if they are above the threshold energy

$$E_{\text{VCh}}^{\text{th}}(\kappa) = m \sqrt{\frac{1+\kappa}{2\kappa}} \simeq \frac{m}{\sqrt{2\kappa}}, \quad (5)$$

The decay rate for this process is given by [9]

$$\Gamma_{\text{VCh}}(E) = \alpha E \left(\left(\frac{4}{3}\kappa + \frac{1}{6}\kappa^2 \right) + \left(-\frac{3}{2} - \frac{1}{3}\kappa - \frac{23}{24}\kappa^2 \right) \frac{m^2}{E^2} \right) \quad (6)$$

VCh photons can inherit a significant fraction of the radiating particle's energy. A previous bound ($\kappa < 6 \times 10^{-20}$ at 98 % C.L.) has been derived from observations of UHE cosmic rays with energies above 100 EeV [9, 11, 12]. In an air shower, mostly electrons and positrons are affected by VCh, as they are the lightest charged particles.

3 Simulation Studies

We used the Monte Carlo code CONEX v2r7.50 [13, 14] to simulate extensive air showers. The code was modified to include the LV effects outlined in the preceding section. Large simulation samples have been created for different values of κ to analyze the potential impact of LV on the development of air showers. The full MC approach used here is outlined in greater detail in [10, 15]. Simulations were performed using the most up-to-date hadronic interaction model SIBYLL 2.3d [16]. In addition, detailed cross checks with other models (EPOS LHC [17], QGSJET-II-04 [18]) were done. We found that SIBYLL 2.3d gave the most conservative results, hence we focus on this model. An example of the impact of LV on the shower observables $\langle X_{\text{max}} \rangle$ and $\sigma(X_{\text{max}})$ can be seen in Fig. 1. The average depth of the shower maximum $\langle X_{\text{max}} \rangle$ decreases with increasing $|\kappa|$, if the energies are above the respective threshold, while the shower-to-shower fluctuations $\sigma(X_{\text{max}})$ remain largely unaffected. The previous analysis for $\kappa < 0$ [10] only used $\langle X_{\text{max}} \rangle$. This approach was extended to include also information from $\sigma(X_{\text{max}})$ as well as the primary composition, taking into account any allowed combination of protons, helium nuclei, oxygen nuclei and iron nuclei [15]. We apply a similar approach for the first time to the case $\kappa > 0$. [19]. In the following section, we briefly summarize the main results.

4 Results

We focus first on the analysis for $\kappa < 0$ [15]. For a given κ and primary energy, plotting $\langle X_{\text{max}} \rangle$ against $\sigma(X_{\text{max}})$ for all combinations of the four primary particle types used in this study leads to the ‘‘umbrella plots’’ shown in Fig. 2(a).

We then compare our simulations to measurements of $\langle X_{\text{max}} \rangle$ and $\sigma(X_{\text{max}})$ from the Pierre Auger Observatory [20], taking into account both statistical and systematic uncertainties in the form of two-dimensional confidence intervals. It is checked if there are primary particle compositions that are allowed by both simulations and

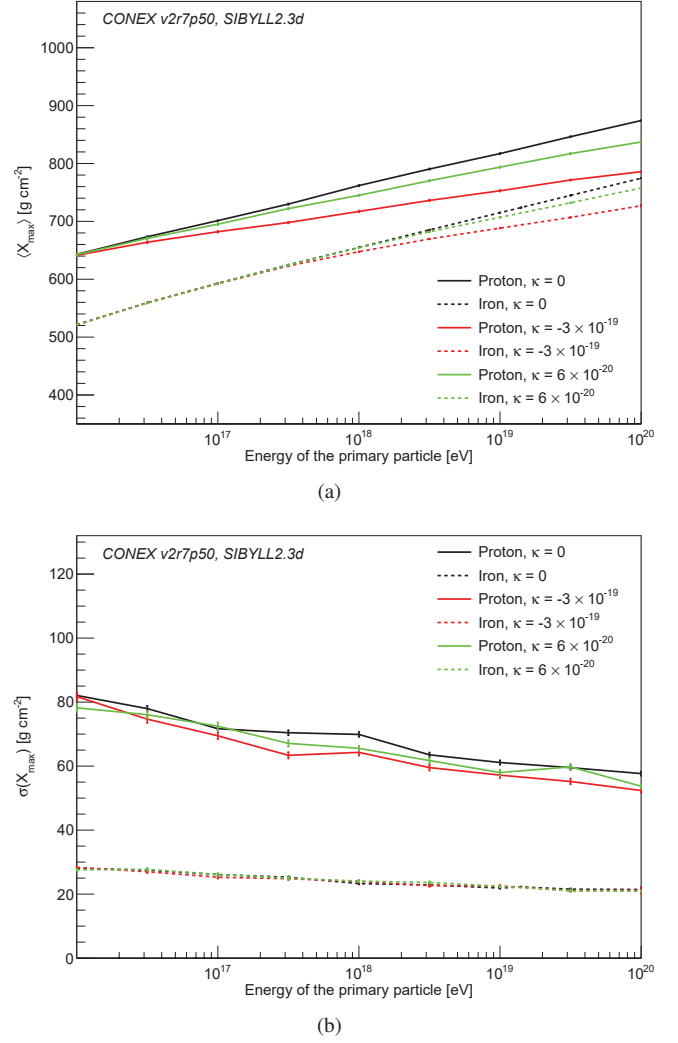


Figure 1. $\langle X_{\text{max}} \rangle$ and $\sigma(X_{\text{max}})$ as a function of the primary energy for primary protons and iron nuclei for the absence of LV ($\kappa = 0$) and for different values of κ . All lines were obtained from CONEX simulations using the hadronic interaction model SIBYLL 2.3d.

data. If there are no such compositions for a given κ , then this value of κ can be excluded. Using this approach, the bound on $\kappa < 0$ was improved to $\kappa > -6 \times 10^{-21}$ at 98 % C.L. [15].

For $\kappa > 0$, lighter primaries at high energies lose their energy due to VCh even before reaching Earth, restraining possible compositions to higher masses, as visualized in the umbrella plots in Fig. 2(b): with increasing κ , the umbrellas shrink, since primary particles of increasing mass do not reach Earth anymore. Apart from this major effect, also a shift of the umbrellas can be seen, similar to the shift observed in Fig. 2(a). This is expected, as VCh radiation affecting electrons and positrons—which are the most abundant charged secondary particles in an air shower—is expected to lead to shorter showers in a similar way as photon decay affecting secondary photons leads to shorter showers for the case $\kappa < 0$. We also performed a preliminary comparison to data, taking into account the most common isotopes in primary cosmic rays and following

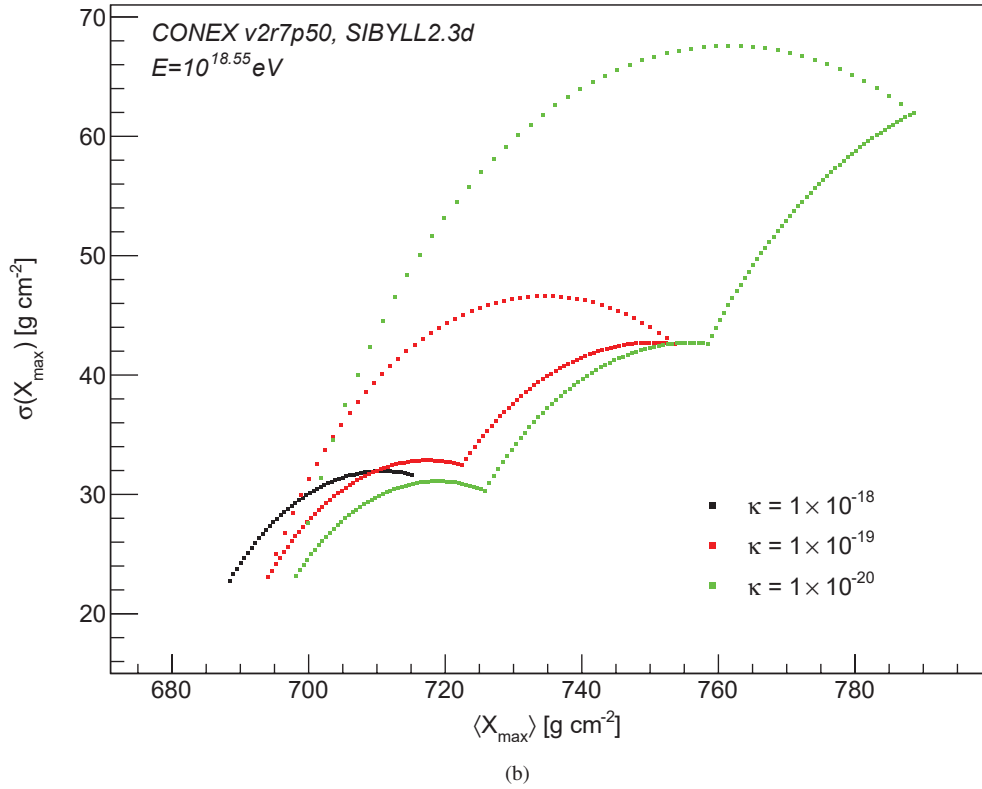
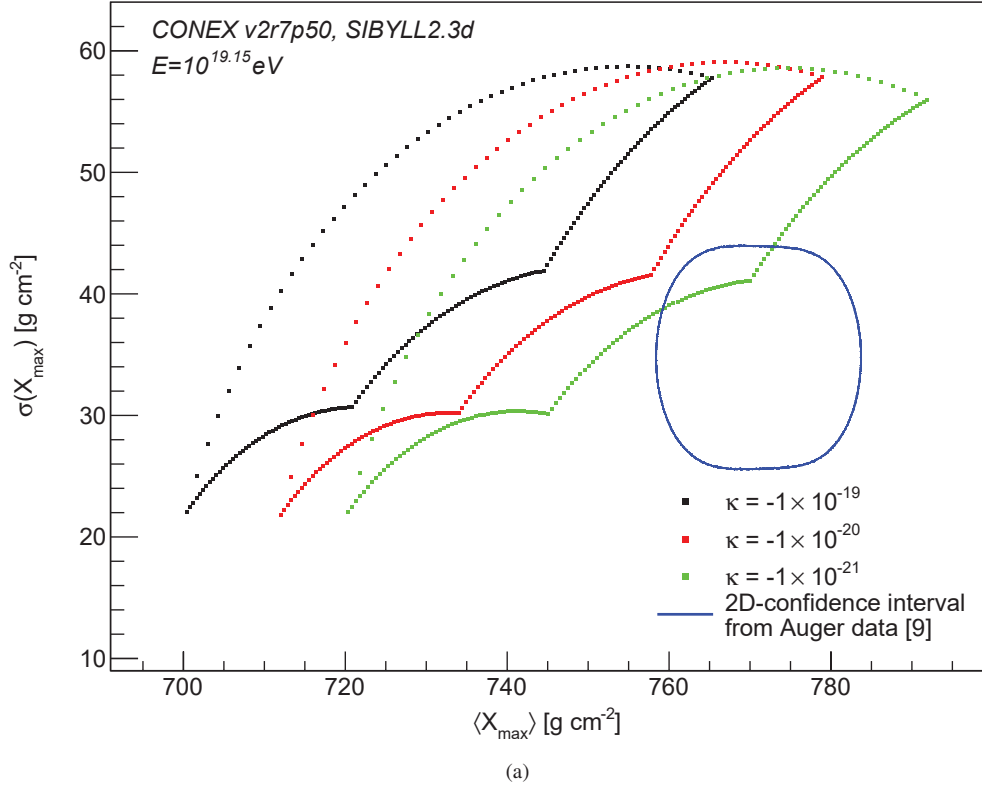


Figure 2. Comparison of combinations of $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$ derived by simulations using CONEX and the hadronic interaction model SIBYLL 2.3d. For a given κ , the corresponding “umbrella” covers all values allowed by arbitrary combinations of these primaries. In (a), the case $\kappa < 0$ is shown, for different values of $\kappa < 0$ and a primary energy of $10^{19.15}$ eV. In addition, the two-dimensional confidence interval given by measurements from the Pierre Auger Observatory [20] is included. In (b), the case $\kappa > 0$ is shown, for different values of $\kappa > 0$ and a primary energy of $10^{18.55}$ eV. Note that in this case, combinations with particles above the VCh radiation threshold are excluded.

the same logic as for $\kappa < 0$. This comparison yields a preliminary bound of $\kappa < 3 \times 10^{-20}$ at 98 % C.L. confirming and slightly improving the previous bound from [9]. This bound is the first bound on $\kappa > 0$ using air showers and electrons/positrons. Future extensions of this work will also include the number of muons on ground (N_μ) as well as the correlation between X_{\max} and N_μ and the resulting composition constraints.

Acknowledgements

The many fruitful discussions with F.R. Klinkhamer are greatly appreciated. We thank T. Pierog for his help in modifying the CONEX source code. This work was supported by the German Research Foundation (DFG Project No. 408049454).

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