Photon decay in UHE air showers: a stringent bound on Lorentz violation

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Take-Home Message

- With isotropic, nonbirefringent Lorentz violation (LV) in the photon sector the decay of UHE photons is possible, leading to significant changes of the shower development.
- Observations of the average depth of the shower maximum $\langle X_{\mathrm{max}}\rangle$ have been used to place a stringent bound on LV.
- The inclusion of observations of the shower-to-shower fluctuations $\sigma(X_{\mathrm{max}})$ can be used to place a stricter bound of $\kappa > -6 \times 10^{-21}$ (98 % CL) improving the previous bound by a factor 50. This is the most stringent bound on this type of LV.

Background and previous bounds

- A more fundamental theory beyond the Standard model of Elementary Particle Physics (SM) is needed (to explain e.g. dark matter and dark energy, include gravity).
- In many approaches, deviation from exact Lorentz symmetry is possible.
- Lorentz violation (LV) in the photon sector can be achieved by adding a single term which breaks Lorentz invariance but preserves CPT and gauge invariance to the Lagrange density [1]:

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

- For isotropic, nonbirefringent LV in the photon sector k_F is controlled by a single parameter κ:

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

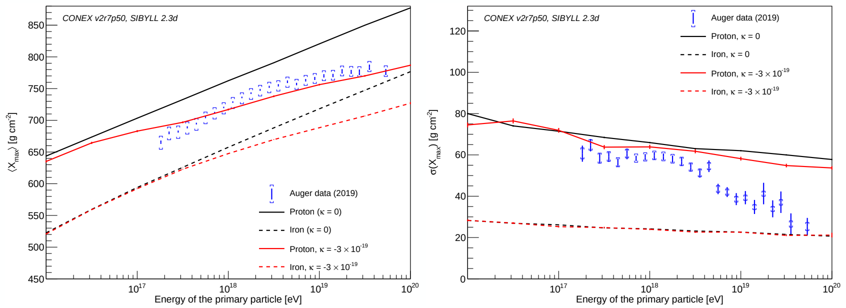
- In the case of $\kappa \neq 0$, processes which are forbidden in the SM become possible.
- Here, we focus on negative values of κ:
  - Photons decay into electron-positron pairs very efficiently above the energy threshold

$$E^{\mathrm{th}}_{\gamma}(\kappa) = 2\,m_e\sqrt{\frac{1-\kappa}{-2\kappa}} \simeq \frac{2\,m_e}{\sqrt{-2\kappa}},$$

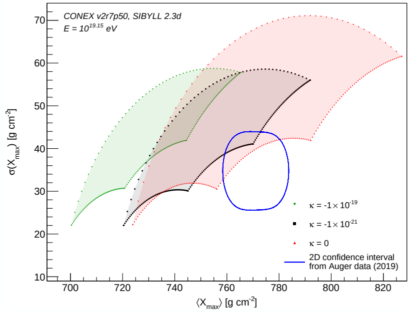
- If photons with energies above this threshold occur in air showers induced by UHE cosmic rays, a decrease of the depth of the shower maximum $\langle X_{\mathrm{max}}\rangle$ can be observed.
- In addition, changes in the decay time of pions are expected.
- Previous bounds were set using observations of gamma rays [2] ($\kappa > -9 \times 10^{-16}$ (98 % CL)) and comparisons of the depth of the shower maximum $\langle X_{\mathrm{max}}\rangle$ [3] ($\kappa > -3 \times 10^{-19}$ (98 % CL)).

Analysis

- The impact of LV on the development of air showers is analyzed using simulations done with a modified version of the MC code CONEX [4, 5].
  - We implemented photon decay as well as a modification of the decay time of the neutral pion.
- The average depth of the shower maximum $\langle X_{\mathrm{max}}\rangle$ decreases with larger values of κ, while the shower-to-shower fluctuations $\sigma(X_{\mathrm{max}})$ remain largely unaffected.

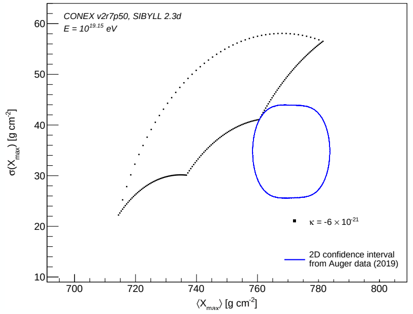


- We extend the approach from the previous bound using only $\langle X_{\mathrm{max}}\rangle$-observations by also including $\sigma(X_{\mathrm{max}})$.
- The exact composition of cosmic ray particles is unknown.
  - Especially at high energies, there are significant differences between the values of $\sigma(X_{\mathrm{max}})$ for the most conservative pure proton composition and measurements of $\sigma(X_{\mathrm{max}})$.
  - Possible compositions are simulated by combinations of protons, helium nuclei (A = 4), oxygen nuclei (A = 16) and iron nuclei (A = 56).
  - Use combination of $\langle X_{\mathrm{max}}\rangle$ and $\sigma(X_{\mathrm{max}})$ to constrain possible compositions.
  - For a specific value of κ all possible compositions lead to a umbrella-shaped region.
- To establish possible $\langle X_{\mathrm{max}}\rangle/\sigma(X_{\mathrm{max}})$-combinations use Auger measurements [6] to set a 2-D confidence interval at 98 %, assuming gaussian distributions for statistical uncertainties and uniform distributions for systematic uncertainties.
- If no overlap between simulated combinations of $\langle X_{\mathrm{max}}\rangle/\sigma(X_{\mathrm{max}})$ and data taken from the Auger observatory [6] is found, the corresponding value of κ can be excluded.
- This process is repeated until κ_{crit} is found, for which every $\kappa \leq \kappa_{crit}$ can be excluded while any $\kappa > \kappa_{crit}$ cannot.



Results

- The new bound gained through this method is $\kappa > -6 \times 10^{-21}$ (98 % CL), which improves the previous bound by a factor of 50.
- The compositions used to set this new bound consist of almost only Helium nuclei.
  - Since UHE cosmic rays are unlikely to be only Helium nuclei, further restrictions on compositions are expected to further improve this limit.
- Improvements of this bound are also expected with a reduction of statistical uncertainties.
- The three hadronic interaction models EPOS LHC [7], QGSJET-II-04 [8] as well as SIBYLL 2.3d [9] were used, although only SIBYLL 2.3d is shown here, since it produces the most conservative results.



- The important value for determining the bound obtained in this paper is the Auger data in the energy range from $10^{19.1}$ eV to $10^{19.2}$ eV with a mean energy of $10^{19.15}$ eV, primarily due to the combination of the low $\sigma(X_{\mathrm{max}})$ value at this energy paired with the comparatively small statistical uncertainty of $\sigma(X_{\mathrm{max}})$.
  - Excluding this energy from the analysis would result in a slightly weaker bound of $\kappa > -8 \times 10^{-21}$ (98 % CL) from three different energy ranges, making the result quite stable against the choice of the energy bin.
- A minor portion of the improvement is due to the increase in statistics between Auger measurements used for previous bounds [10] and those used here [6].

Acknowledgments

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

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