# Probing Lorentz Violation at Ultra-High Energies Using Air Showers

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## Take-Home Message

- Isotropic, nonbirefringent **Lorentz violation (LV)** leads to significant changes in the development of air showers, depending solely on the LV-parameter $\kappa$
- LV effects (e.g., **photon decay** for $\kappa < 0$ and **vacuum-Cherenkov radiation** for $\kappa > 0$) were implemented in the air-shower simulation code CONEX
- The significant reduction of $\langle X_{\max} \rangle$ due to LV in combination with $\sigma(X_{\max})$ has been used to **improve previous bounds on LV**

## Theory Background

### Introduction

- A more **fundamental theory** beyond the Standard Model of Elementary Particle Physics (SM) is needed (to explain, e.g., dark matter, dark energy; to include gravity)
- In many current approaches, **Lorentz violation (LV)** is well possible
- Implement **LV in the photon sector** of the SM through an added term in the QED Lagrangian [1,2]:

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

- For **isotropic, nonbirefringent LV** in the photon sector, the LV coefficient $k_F$ depends only on a **single, dimensionless parameter $\kappa \in (-1, 1]$**
- For $\kappa \neq 0$, the LV term allows processes that are **kinematically forbidden** in the SM
- Exploit the fact that in an air shower initiated by an ultra-high-energy (UHE) cosmic ray, **secondary particles** with very high energies are produced for which these LV processes become relevant and derive bounds on LV using the expected **changes in the air-shower development**

### $\kappa < 0$: Photon Decay (PhD)

- Nonstandard photons **decay almost immediately** into an electron-positron pair if they are above the **threshold energy**

$$E_\gamma^{\text{th}}(\kappa) = 2m_e\sqrt{\frac{1-\kappa}{-2\kappa}} \cong \frac{2m_e}{\sqrt{-2\kappa}}$$

- Exact **decay rate** for the process $\tilde{\gamma} \to e^+ + e^-$ is given by [3]

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

- Changes in the **decay time of neutral pions** are also expected [4], but they have a negligible impact on the air-shower observables used here
- A previous bound on $\kappa$ ($\kappa > -9 \times 10^{-16}$ at 98 % C.L.) has been derived from observations of **TeV $\gamma$-rays** [5]
- A **much stricter bound** ($\kappa > -3 \times 10^{-19}$ at 98 % C.L.) was obtained using **secondary photons** from air showers [6]

### $\kappa > 0$: Vacuum Cherenkov Radiation (VC)

- Charged particles with mass $m$ lose their energy quickly by **radiating photons** if they are above the **threshold energy**

$$E_{\text{VC}}^{\text{th}}(\kappa) = m\sqrt{\frac{1+\kappa}{2\kappa}} \cong \frac{m}{\sqrt{2\kappa}}$$

- **Decay rate** for this process is given by [5]

$$\Gamma_{\text{VC}}(E) = 4\alpha(E - E_{\text{VC}}^{\text{th}})\left(\kappa\left(\frac{E}{E_{\text{VC}}^{\text{th}}} - 1\right) - \frac{1}{3}\left(\frac{E}{E_{\text{VC}}^{\text{th}}} - 1\right)^2\right)$$

- Produced VC 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 [5]
- In an air shower, mostly **electrons and positrons** are affected by VC, as they are the lightest charged particles

## Simulation Study

- We used the **Monte Carlo code CONEX v2r7.50** [7,8] to simulate extensive air showers; with modifications to include the LV effects outlined before; **large simulation samples** have been created for different values of $\kappa$
- Simulations were performed using the most up-to-date **hadronic interaction model SIBYLL 2.3d** [9]; detailed **cross checks** with other models (EPOS LHC, QGSJET-II-04) were done
- **Key observation:** the average depth of the shower maximum $\langle X_{\max} \rangle$ **decreases with increasing** $|\kappa|$, if the energies are above the respective threshold, while the shower-to-shower fluctuations $\sigma(X_{\max})$ **remain largely unaffected**
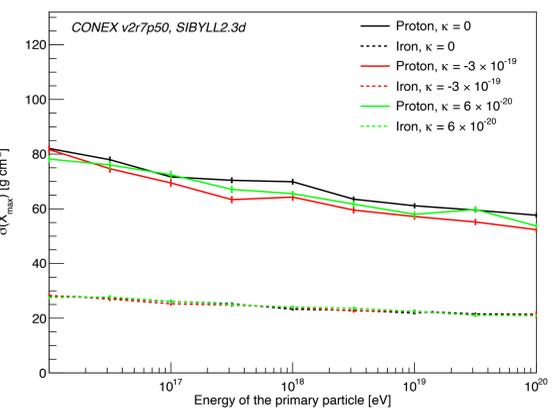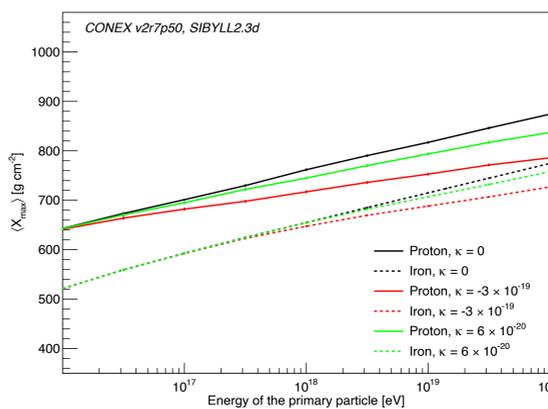


- Previous analysis for $\kappa < 0$ [6] only used $\langle X_{\max} \rangle$; this approach was **extended** to include also information from $\sigma(X_{\max})$ as well as the primary **composition** (taking into account any allowed combination of protons, helium nuclei, oxygen nuclei and iron nuclei) [10]
- We apply a similar approach **for the first time** to the case $\kappa > 0$

## Results

- For a given $\kappa$ and primary energy, plotting $\sigma(X_{\max})$ against $\langle X_{\max} \rangle$ for all combinations of the four primary particle types leads to the **"umbrella plots"** shown on the right
- We compare our simulations to **measurements of $\langle X_{\max} \rangle$ and $\sigma(X_{\max})$ from the Pierre Auger Observatory** [11], taking into account both statistical and systematic uncertainties in the form of 2D confidence intervals
- Check for primary particle compositions **allowed by both simulations and data**: if there are no allowed compositions for a given $\kappa$, then this $\kappa$ can be **excluded**
- Using this approach, the bound on $\kappa < 0$ was **improved to $\kappa > -6 \times 10^{-21}$** at 98 % C.L. [10]
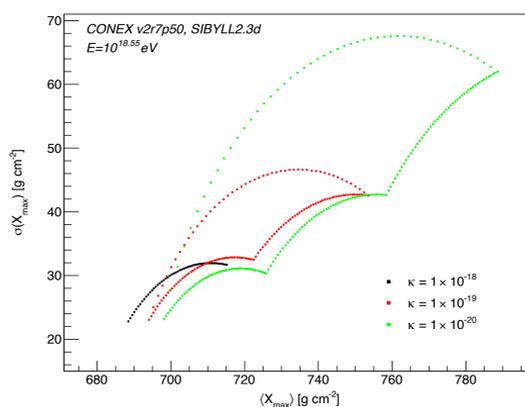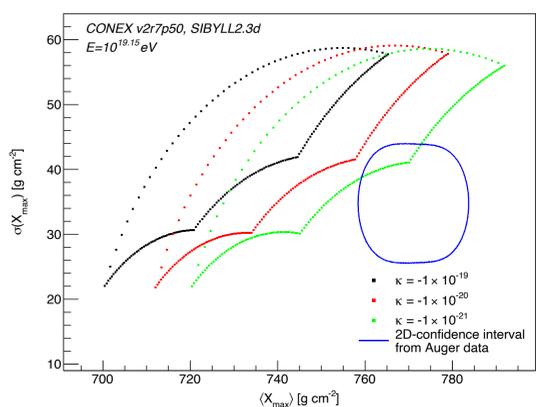




- For $\kappa > 0$, lighter primaries at high energies lose their energy due to VC even **before reaching Earth**, restraining possible compositions to **higher masses**, as visualized in the umbrella plots on the left
- **Comparison to data**, taking into account the most common isotopes in cosmic rays, yields a **preliminary bound $\kappa < 3 \times 10^{-20}$ at 98 % C.L.**, confirming and slightly improving the previous bound from [5]
- 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 ($N_\mu$) as well as the **correlation** between $X_{\max}$ and $N_\mu$ and the resulting composition constraints

## References

[1] S. Chadha & H.B. Nielsen, Nucl. Phys. B 217 (1983) 125
[2] V. Kostelecký & M. Mewes, Phys. Rev. D 66 (2002) 056005
[3] J.S. Díaz, F.R. Klinkhamer & M. Risse, Phys. Rev. D 94 (2016) 085025
[4] F.R. Klinkhamer, Mod. Phys. Lett. A 33 (2018) 1850104
[5] F.R. Klinkhamer & M. Schreck, Phys. Rev. D 78 (2008) 085026
[6] F.R. Klinkhamer, M. Niechciol & M. Risse, Phys. Rev. D 96 (2017) 116011
[7] T. Bergmann et al., Astropart. Phys. 26 (2007) 420
[8] T. Pierog et al., Nucl. Phys. Proc. Suppl. 151 (2006) 159
[9] F. Riehn et al., Phys. Rev. D 102 (2020) 063002
[10] F. Duenkel, M. Niechciol & M. Risse, Phys. Rev. D 105 (2021) 015010
[11] A. Yushkov (Pierre Auger Coll.), PoS (ICRC 2019) (2019) 482