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Studying effects of Lorentz violation in the photon sector using extensive air shower simulations

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Introduction

- Standard model of particle physics is not complete, e.g. gravity
- Current approaches for more comprehensive theories (e.g. Quantum Gravity) allow for deviations from exact Lorentz symmetry
- Ultra-high-energy cosmic rays and photons are advantageous to determine bounds on Lorentz violation, because of their high energy
- Lorentz violation affects shower development and the reduction of $\langle X_{max} \rangle$ is significant compared to the resolution of current air shower experiments.

Liberati and Maccione, Ann.Rev.Nucl.Part.Sci. 59:245-267, 2009

LV in SME framework

- QED Lagrangian extended by a single Lorentz violating, but CPT and gauge invariance preserving term
- Tensor with 20 independent components
- One parameter κ controls isotropic nonbirefringent LV
- Photon propagation is determined by field equations
- SM for $\kappa = 0$,
  here: focus on negative κ

$$\mathcal{L}(x) = \mathcal{L}_{\text{QED}} - \frac{1}{4}(k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

$$(k_F)_{\mu\nu\rho\sigma} = \frac{1}{2}(\eta_{\mu\rho}\tilde{\kappa}_{\nu\sigma} - \eta_{\mu\sigma}\tilde{\kappa}_{\nu\rho} + \eta_{\nu\sigma}\tilde{\kappa}_{\mu\rho} - \eta_{\nu\rho}\tilde{\kappa}_{\mu\sigma})$$

$$\tilde{\kappa}_{\mu\nu} = \frac{\kappa}{2}[\text{diag}(3,1,1,1)]_{\mu\nu}$$

$$\kappa \in (-1, 1]$$

$$v_{\text{ph}} = \frac{\omega}{|\vec{k}|} = \sqrt{\frac{1-\kappa}{1+\kappa}}c$$

Klinkhamer and Schreck, Nucl.Phys.B 848:90-107,2011

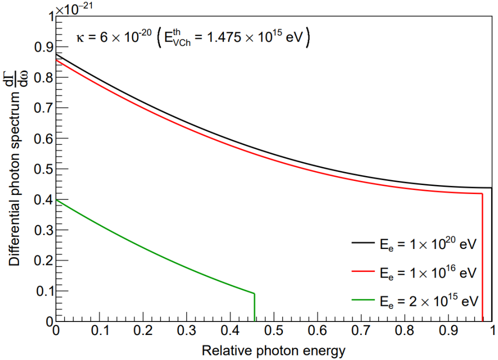
Consequences of positive κ

- "Slow" photons: $v_{\mathrm{ph}} = \sqrt{\frac{1-\kappa}{1+\kappa}}c > c$
- new process introduced

Vacuum Cherenkov radiation

- Charged particles above $E_{\mathrm{VCh}}^{\mathrm{thresh}}$ emit VCh radiation

$$E_{\mathrm{VCh}}^{\mathrm{thresh}} = m\sqrt{\frac{1+\kappa}{2\kappa}} \approx \frac{m}{\sqrt{2\kappa}}$$



Dünkel, Niechciol, Risse. Physical Review D 107:083004, 2023

Consequences of negative κ

- "Fast" photons: $v_{\text{ph}} = \sqrt{\frac{1-\kappa}{1+\kappa}}c > c$
- 2 new processes are introduced

Photons

- $\tilde{\gamma} \to e^- + e^+$
- Photon decay above E_γ^{thresh}

$$E_\gamma^{\text{thresh}} = 2m_e\sqrt{\frac{1-\kappa}{-2\kappa}} \approx \frac{2m_e}{\sqrt{-2\kappa}}$$

Neutral pions

- $\pi^0 \to \tilde{\gamma} + \tilde{\gamma}$
- Stable above $E_{\pi^0}^{\text{cut}}$

$$E_{\pi^0}^{\text{cut}} = 2m_{\pi^0}\sqrt{\frac{1-\kappa}{-2\kappa}} \approx 132\ E_\gamma^{\text{thresh}}$$

Limits on LV

$\kappa > -9 \times 10^{-16}$ (98% C.L.)

- Obtained by detection of $\sim 30\,\mathrm{TeV}$ photons
- $E_\gamma^{\text{measured}} \leq E_\gamma^{\text{thresh}} \rightarrow$ otherwise photons would have decayed (decay length of centimeters)

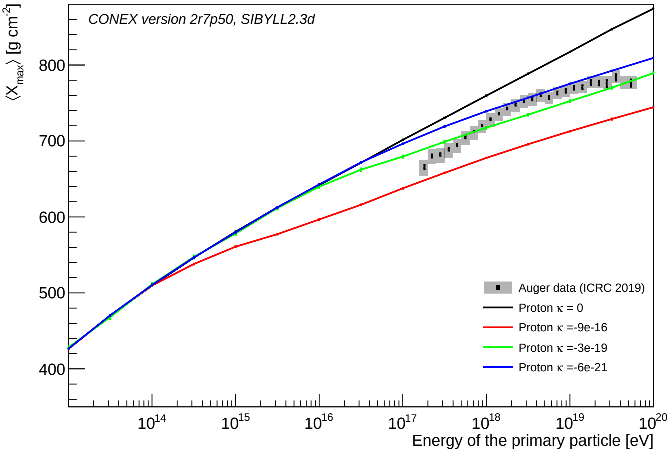
Klinkhamer and Schreck, Phys.Rev.D 78:085026, 2008

Effects of LV on longitudinal shower development

CONEX

- MC simulations at high energies
- Fast numerical cascade equations for low energies
- 1 dimensional

Bergmann et al.,Astropart.Phys. 26:420-432, 2007
Pierog et al, Nucl.Phys.Proc.Suppl. 151:159-162, 2006



$$\text{with } \kappa = -9 \times 10^{-16}$$

$$E_{\gamma}^{\text{thresh}} \approx 2.4 \times 10^{13}\,\mathrm{eV}$$

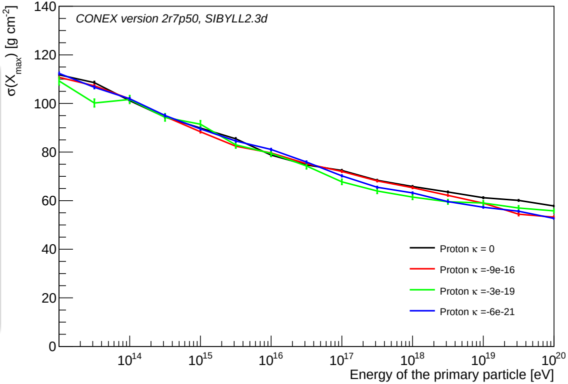
$$E_{\pi^0}^{\text{cut}} \approx 3.2 \times 10^{15}\,\mathrm{eV}$$

Yushkov for the Pierre Auger Collaboration. PoS ICRC2019:482, 2020

Other observables

$\sigma(X_{max})$

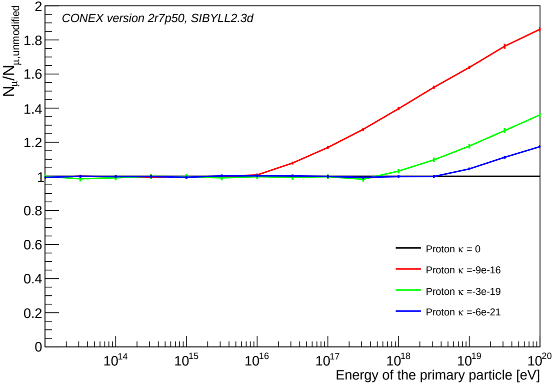
- Nearly independent of the modification
- Fluctuations of X_{max} mainly due to the first interaction
- If the air shower is induced by a proton, the first interaction is unaffected by the modification



Other observables

Number of muons at ground level

- Increase in muons
- Stable π^0 now interact hadronically, instead of feeding the em shower
- Onset shifts to higher energies for $\kappa \to 0$
- Only partial contribution to explain muon deficiency in simulations



Limits on LV through air shower simulations

$\kappa > -3 \times 10^{-19}$ (98% C.L.)

- Obtained by comparison of $\langle X_{\mathrm{max}} \rangle$ with modified CONEX code and measurements from the Pierre Auger Observatory

Klinkhamer, Niechciol, and Risse Phys.Rev.D 96:116011, 2017

$\kappa > -6 \times 10^{-21}$ (98% C.L.)

- Mixed composition
- Combined comparison of $\langle X_{\mathrm{max}} \rangle$ and $\sigma(X_{\mathrm{max}})$ with shower observations allows a much stricter bound

Duenkel, Niechciol, and Risse. Phys.Rev.D 104:015010, 2021

CORSIKA

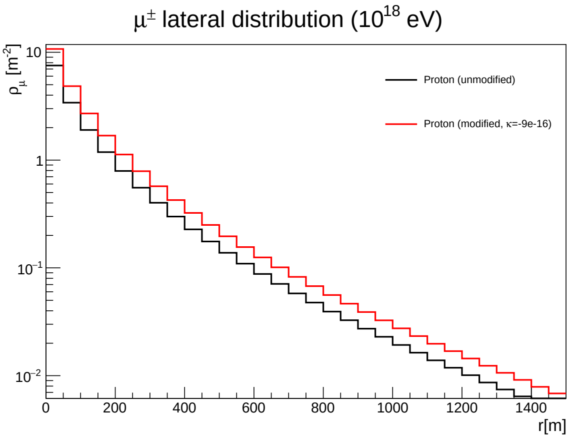
- Motivation: improve limits by including new observables in analysis
- 3 dimensional MC simulation program
- Access to lateral distribution
- New available observables such as muon density at ground level
- CORSIKA option: CONEX within CORSIKA

Heck et al. FZKA 6019, 1998

Lateral distribution of muons at ground level

Muon density ρ_μ

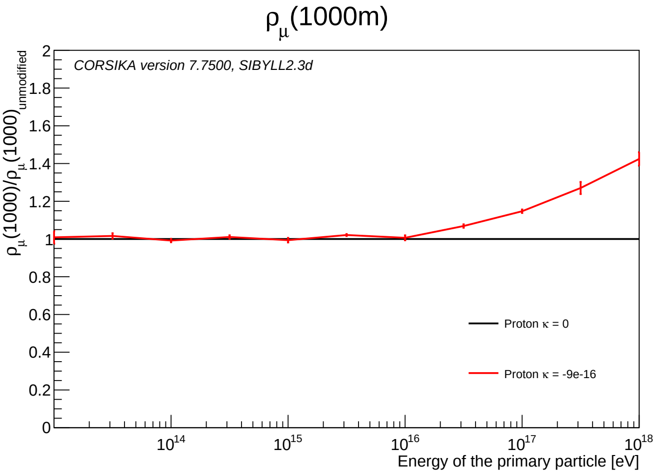
- Simualtions done with zenith angle $\theta = 0°$
- Increase in the number of muons at ground level, for this example $\sim 40\%$
- Shape of distribution unchanged



Change in $\rho_\mu(1000\mathrm{m})$

ρ_μ at 1000 m

- $\rho_\mu(1000\mathrm{m})$ increases with energy
- Correlation with S(1000) can be used for comparison to air shower measurements



Conclusion and Outlook

Current results

- Implemented LV in CONEX within CORSIKA
- Agreement with standalone CONEX
- New available observables such as $\rho(1000\mathrm{m})$

Next steps

- Implement LV in CORSIKA
- Investigate impact of LV on observables connected to the lateral particle distribution