Impact of Lorentz violation in the photon sector on extensive air showers

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Why Lorentz violation?

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- The **Standard Model of Elementary Particle Physics (SM)** has been extremely successful…
  - Predictions have been tested to very high precision
  - Discovery of the Higgs boson at the LHC in 2012
- ...but we know it's **not complete**
  - Dark matter and dark energy?
  - Gravity?
  - Observed matter/antimatter asymmetry in the Universe?
- We want a **fundamental theory** that combines all forces
- In current approaches (e.g. string theory), **Lorentz violation (LV)** may well be possible
  - Small LV effects may be accessible already at lower energies

Standard Model Extension (SME)

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- SME is an **extension of the SM** that allows for minuscule violations of Lorentz symmetry [Colladay & Kostelecký 1997] [Colladay & Kostelecký 1998]
  - **General framework** to systematically study LV in any sector of the SM
  - SME provides a handle for experimentalists to perform **generic searches for LV**
- Now focus on **LV in the photon sector**:

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \overline{\psi}\left[\gamma^{\mu}(i\partial_{\mu} - eA_{\mu}) - m\right]\psi - \frac{1}{4}(k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

- First two terms in the Lagrangian correspond to **conventional QED**
- **Last term** introduces a dimension-four operator that breaks Lorentz symmetry while preserving CPT and gauge invariance [Chadha & Nielsen 1983] [Kostelecký & Mewes 2002]
  - Degree of LV is controlled by the **dimensionless coefficient $(k_F)_{\mu\nu\rho\sigma}$**

The coefficient $(k_F)_{\mu\nu\rho\sigma}$

- $(k_F)_{\mu\nu\rho\sigma}$ has **19 independent components**
  - 10 components produce **birefrigence** in the photon sector: can be constrained to high precision using cosmological observations
  - 8 components lead to **direction-dependent modifications** of the photon-propagation properties: not discussed here
  - Remaining component leads to **isotropic modifications** of the photon-propagation properties

[Carroll, Field, & Jackiw 1990]
[Carroll & Field 1997]
[Kostelecký & Mewes 2001]

- **Isotropic, nonbirefringent LV** in the photon sector is therefore controlled by a **single dimensionless parameter κ**, which enters the coefficient $(k_F)_{\mu\nu\rho\sigma}$ in the following way:

$$(k_F)^{\lambda}_{\mu\lambda\nu} = \frac{\kappa}{2}\begin{pmatrix} 3 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Isotropic, nonbirefringent LV

- κ endows the vacuum with an effective index of refraction, leading to a **modification of the photon dispersion relation**

$$\omega(q) = \frac{1}{n_{\text{eff}}} q = \sqrt{\frac{1-\kappa}{1+\kappa}} q$$

- This modification allows for processes which are **kinematically forbidden** in the conventional Lorentz-invariant theory
  - $\kappa > 0$: **vacuum Cherenkov radiation** possible above a threshold $E_{\text{thr}}(\kappa)$

$$f \to f + \tilde{\gamma}$$

    efficient energy loss mechanism for charged particles, current constraints ($\kappa < 6 \times 10^{-20}$ at 98 % C.L.) derived from **observations of UHECRs** [Klinkhamer & Risse 2008] [Klinkhamer & Schreck 2008]
  - $\kappa < 0$: **photon becomes unstable** above a threshold $\omega_{\text{thr}}(\kappa)$

$$\tilde{\gamma} \to e^+ + e^-$$

    decay length is very small, current constraints ($\kappa > -9 \times 10^{-16}$ at 98 % C.L.) derived from **gamma-ray astronomy** [Klinkhamer & Schreck 2008]

LV and extensive air showers

- Constraint on $\kappa < 0$ has been derived from the observation of photons with **energies around 10^{13}-10^{14} eV**
  - **Tighter constraints** require higher-energy photons: prospect of observing such photons in **primary** cosmic rays?
- **Alternative approach:** exploit extensive air showers initiated by (hadronic) primaries in the Earth's atmosphere [Díaz, Klinkhamer & Risse 2016]
  - **General idea**: it is expected that a shower initiated by a UHE (> 10^{18} eV) primary contains at least a couple of very-high-energy photons as **secondary** particles (mainly expected in the startup phase)
  - A modification of these very-high-energy photons due to LV would lead to a **different shower development** as compared to conventional physics
  - First question: what could be the **magnitude of this difference**? $\longrightarrow$ Use a **modified Heitler model** to describe electromagnetic cascades under the assumption of LV

Conventional Heitler model

- **Heitler model** describes particle multiplication in an electromagnetic shower as a **binary tree** [Heitler 1949]
  - Each photon produces two charged leptons via **pair production**; each charged lepton produces a charged lepton and a photon via **bremsstrahlung**
  - **Simplifying assumption**: each interaction occurs after exactly one splitting length $d = \ln(2)\, X_0$, with the radiation length X_0 (in air 37 g/cm^2)
  - The energy of the primary particle is **shared equally** between all secondary particles
  - The cascade continues until the energy per particle reaches the **critical energy E_c** (in air 80 MeV)
  - **Maximum number of particles** for a shower initiated by a photon of energy ω_0 is reached at the depth

$$X_{\max} = X_0 \ln\left(\frac{\omega_0}{E_c}\right)$$

Modified Heitler model: photon decay

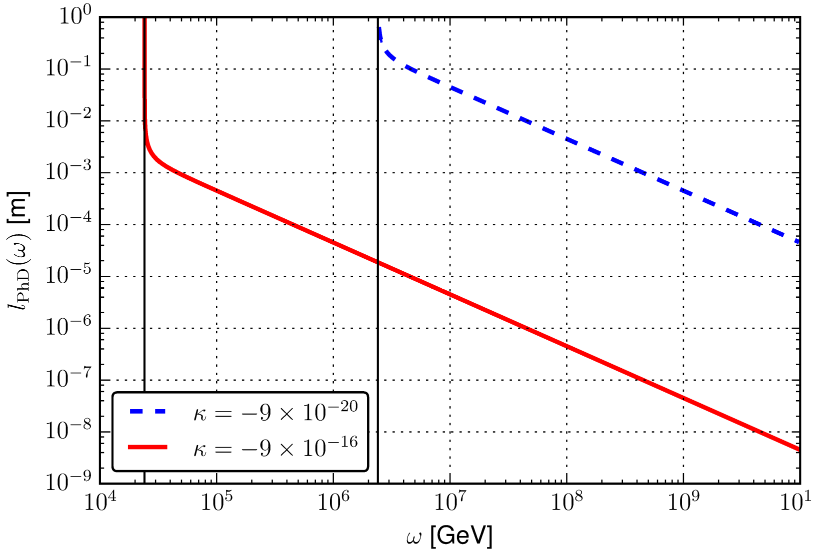
- LV **only affects photons** in the electromagnetic cascade
  - Decay of photons above the **threshold**

$$\omega_{\mathrm{thr}} = 2\, m_e \sqrt{\frac{1-\kappa}{-2\,\kappa}}$$

For κ = -9 × 10^{-16} (-9 × 10^{-20}): ω_{thr} = 2.4 × 10^{13} eV (2.4 × 10^{15} eV)

  - **Decay rate** for the process $\tilde{\gamma} \to e^+ + e^-$ is given by

$$\Gamma_{PhD}(\omega) = \frac{\alpha}{3} \frac{-\kappa}{1-\kappa^2} \sqrt{\omega^2 - \omega_{\mathrm{thr}}^2} \left(2 + \omega_{\mathrm{thr}}^2/\omega^2\right)$$ [Díaz & Klinkhamer 2015]



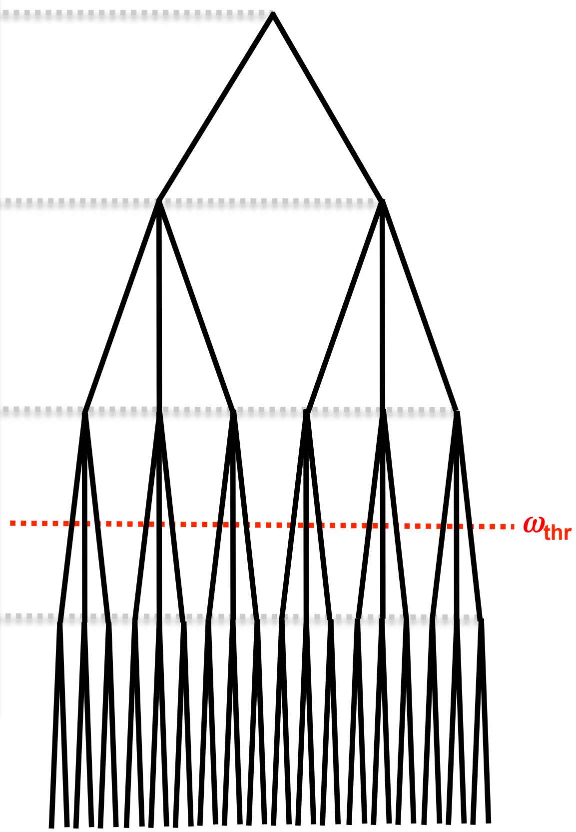
Modified Heitler model: cascade

- **Modified cascade** initiated by a photon above threshold

$n = X / X_0$	N	E / ω_0
0	2	$1/2$
1	2×3	$1/2 \times 1/3$
2	2×9	$1/2 \times 1/9$
3	2×9×2	$1/2 \times 1/9 \times 1/2$

$$N = 2 \times 3^{n-1}$$

$$E = \frac{\omega_0}{2 \times 3^{n-1}}$$



- **Instant decay** of the initial photon into two leptons
- Each lepton produces an additional photon (above threshold) via Bremsstrahlung

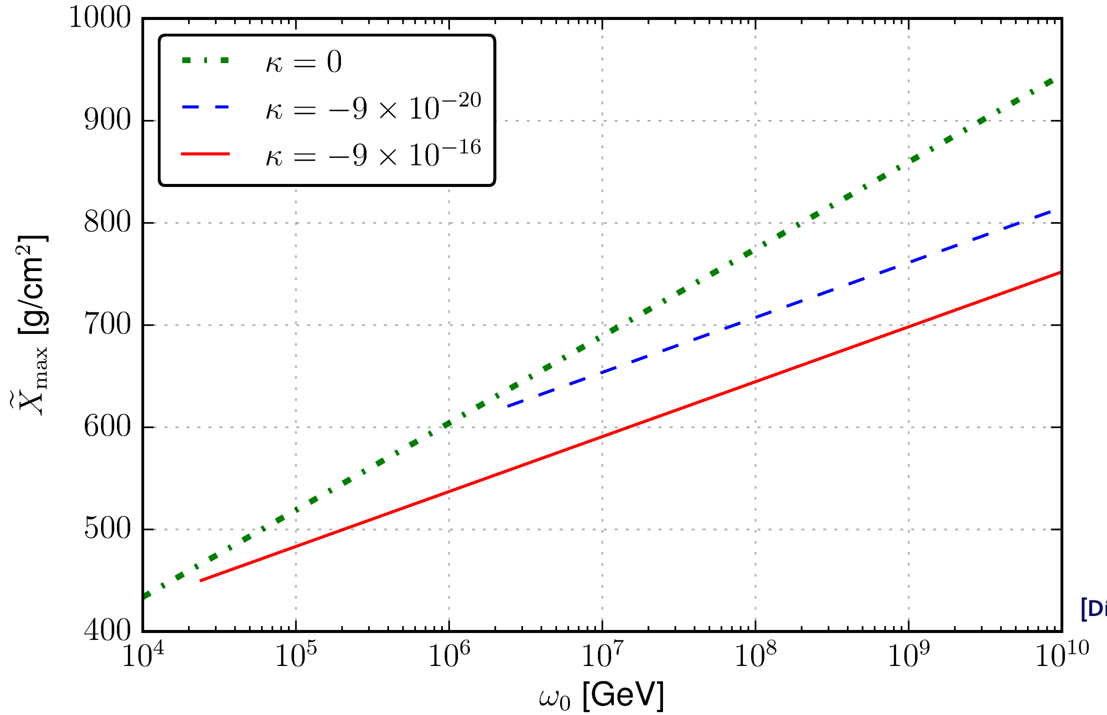
$$e^{\pm} \rightarrow e^{\pm} + \tilde{\gamma} \Rightarrow e^{\pm} + e^{-} + e^{+}$$

- **Simplifying assumption**: At each interaction step, three leptons are produced which share the initial energy equally
- If the energy per particle falls **below the threshold**, the cascade continues according to the conventional Heitler model

Modified Heitler model: X_{max}

- Due to the **different shower development**, the X_{max} of the electromagnetic cascade changes:

$$\tilde{X}_{\max} = X_0 \underbrace{\frac{\ln(2)}{\ln(3)}}_{\eta} \ln\left(\frac{\omega_0/2}{\omega_{\rm thr}}\right) + X_0 \ln\left(\frac{\omega_{\rm thr}}{E_c}\right), \qquad \text{for } \omega_0 > \omega_{thr} > E_c$$



[Díaz, Klinkhamer & Risse 2016]

- Note: also the **elongation rate** changes due to the factor η

Comparison to conventional physics

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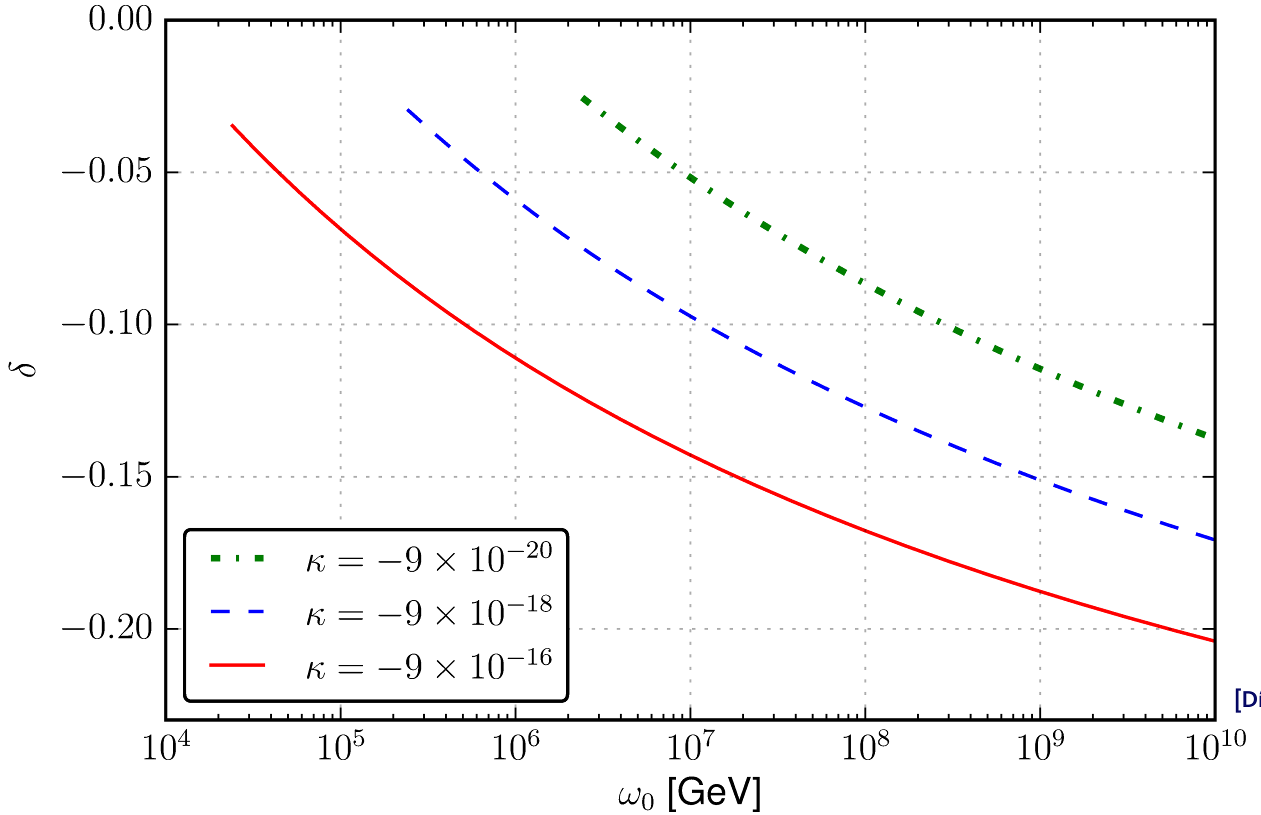
- Express the modified X_{max} **in terms of the conventional X_{max}**:

$$\tilde{X}_{\mathrm{max}} = (1+\delta)\, X_{\mathrm{max}}$$

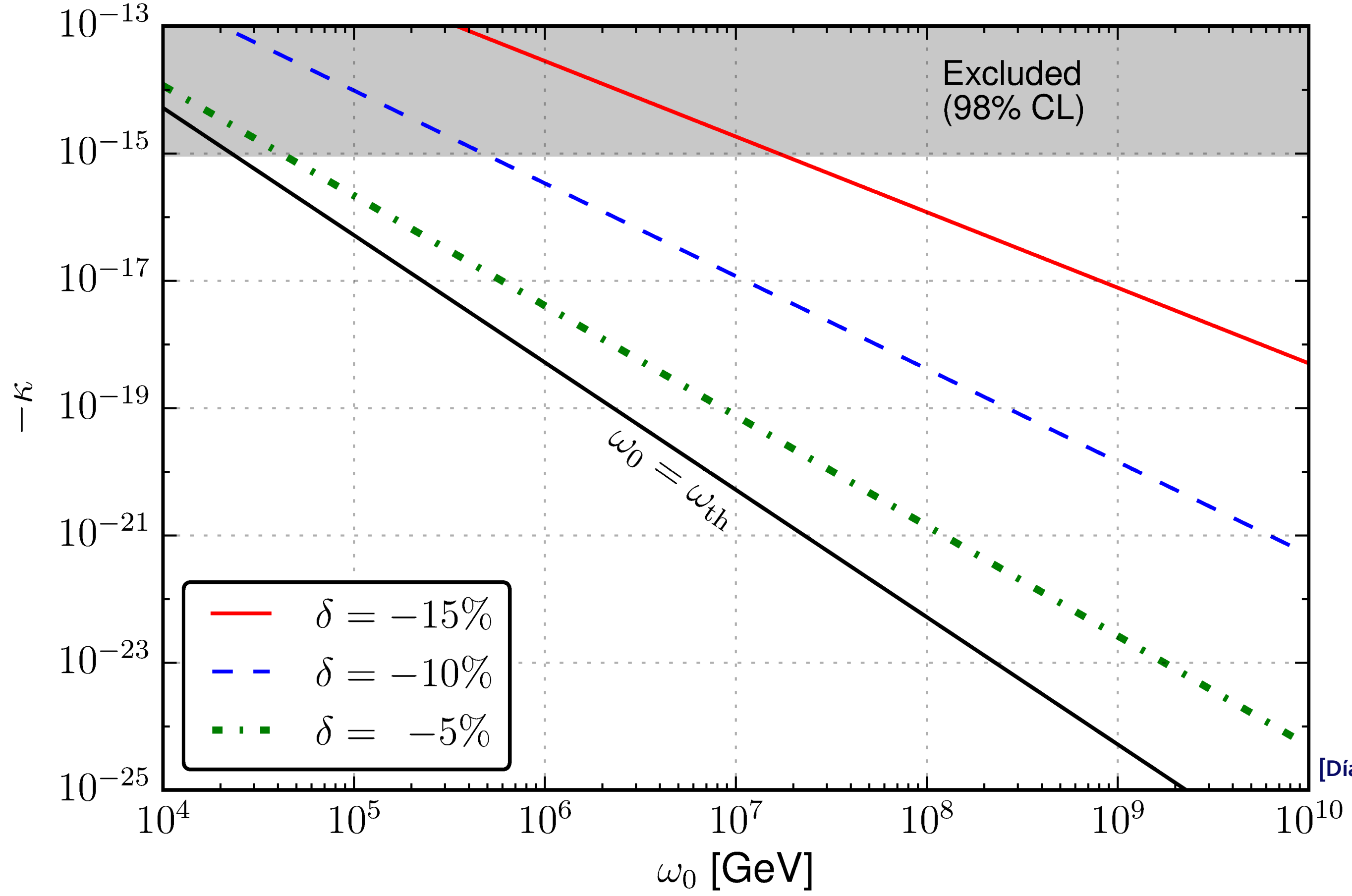
$$\delta = \frac{(\eta - 1)\,\ln(\omega_0/\omega_{\mathrm{thr}}) - \eta\,\ln(2)}{\ln(\omega_0/E_c)}$$



[Díaz, Klinkhamer & Risse 2016]

Constraining κ with X_{max} measurements

- Assuming a relative deviation δ in X_{max} at an energy ω_0 w.r.t. conventional physics is measured: **what can be said about κ?**



[Díaz, Klinkhamer & Risse 2016]

Summary

- Air shower measurements can provide a handle on **Lorentz violation (LV)** in the photon sector
  - LV leads to a **modification of the atmospheric depth of the shower maximum X_{max}** w.r.t. conventional physics
- Analytical calculations of the impact of LV on electromagnetic cascades have been performed using a **modified Heitler model**
- Potential to improve existing limits on the isotropic, nonbirefringent LV parameter κ by **several orders of magnitude** (e.g. up to -10^{-21} assuming a 10 % difference in X_{max} at 10^{19} eV)

- **Outlook:**
  - Implement LV in **air shower simulations** to get a more realistic description of the shower development
  - Extend the study to **hadron-induced air showers**