Hypothetical Lorentz invariance violation and the muon content of extensive air showers

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LV: Dispersion relations and Effective Field Theory

- Motivation: how to produce the theories with the traces of the Planck scale.
- Kinematical approach – **modified dispersion relation**:

$$E^2 = m^2 + p^2\,(1 \pm \eta_0) \pm \frac{p^3}{E_{\mathrm{LIV},1}} \pm \frac{p^4}{E^2_{\mathrm{LIV},2}} \pm \ldots \tag{1}$$

  Kinematical effects:
    - time delays,
    - birefringence,
    - threshold modifications (decays, ...)
- Dynamical approach EFT Lagrangian — dynamical effects:
    - (Non–threshold) Modification of cross–sections,
      Example: Bethe-Heitler process $\gamma N \to N e^+ e^-$
      (the 1st interaction in γ-induced air shower).

The Idea of LIV: Or How to Stop Worrying and Calculate LIV Effects Using LI EFT

The main idea is to use effective field theory to produce non-trivial dispersion relations:

$$E^2 = m^2 + p^2 + \frac{p^3}{M_{\mathrm{LIV},1}} + \frac{p^4}{M^2_{\mathrm{LIV},2}} + \dots$$

Nevertheless, if we have a model that produces generic LIV, we can use the corresponding dispersion relations derived from it! Models such as Horava-Lifshitz gravity and non-commutative theories can naturally achieve this.

The model: the quartic LIV

$$\mathcal{L} = \underbrace{i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{QED}}$$
$$+ \underbrace{i\kappa\bar{\psi}\gamma^{i}D_{i}\psi + \frac{ig}{M^2}D_j\bar{\psi}\gamma^{i}D_iD_j\psi + \frac{\xi}{4M^2}F_{kj}\partial_i^2F^{kj}}_{\text{dim 6 operators that break LI}}, \qquad (2)$$

where $D_{\mu}\psi = (\partial_{\mu} + ieA_{\mu})\,\psi$. The strength of LV is characterized by three parameters: $[\kappa] = [m]^0$, $[g] = [m]^0$, $[\xi] = [m]^0$.

The LV terms modify the dispersion relations for photons and electrons/positrons:

$$E_{\gamma}^2 = k^2 + \frac{\xi k^4}{M^2}, \qquad (3)$$

$$E_e^2 = m^2 + p^2\left(1 + \kappa + \frac{gp^2}{M^2}\right)^2 \approx m^2 + p^2(1 + 2\kappa) + \frac{2gp^4}{M^2}. \qquad (4)$$

The cross-section

The classical result for the Bethe–Heitler process — pair production in the Coulomb field of an atomic nucleus in the air, $\gamma^*\gamma \to e^+e^-$:

$$\sigma_{BH} = \frac{28Z^2\alpha^3}{9m_e^2}\left(\log\frac{183}{Z^{1/3}} - \frac{1}{42}\right) \tag{5}$$

with screening.
The suppression of the cross-section:

$$\frac{\sigma_{\mathrm{BH}}^{\mathrm{LV}}}{\sigma_{BH}} \simeq \frac{12m_e^2M_{\mathrm{LV}}^2}{7E_\gamma^4}\cdot\log\frac{E_\gamma^4}{2m_e^2M_{\mathrm{LV}}^2}. \tag{6}$$

arXiv: 1204.5782.

Current experimental limits on LV parameters

e^-/γ	Test of QG	Sub(-) or super(+) luminal	Limits			Source	Ref.
			$\lvert\xi_0\rvert(\lvert\eta_0\rvert)$	$E_{\rm LIV}^{(1)}$ (eV)	$E_{\rm LIV}^{(2)}$ (eV)		
e^-	Synch.	both	2×10^{-20}	10^{33}	2×10^{25}	CRAB	[1340,1341,1361]
e^-	VC	(+)	10^{-20}	10^{31}	10^{23}	CRAB	[1338,1344,1362]
γ	PD	(+)	7.1×10^{-19}	1.7×10^{33}	1.4×10^{24}	LH. J2032+4102	[1163]
γ	PD	(+)	1.3×10^{-17}	2.2×10^{31}	8×10^{22}	MultiSrc	[1356]
γ	PD	(+)	1.8×10^{-17}	1.4×10^{31}	5.8×10^{22}	eHWCJ1825–134	[1356]
γ	PD	(+)	2.2×10^{-17}	9.9×10^{30}	4.7×10^{22}	eHWCJ1907+063	[1356]
γ	3γ	(+)	–	–	2.5×10^{25}	LH. J2032+4102	[1163]
γ	3γ	(+)	–	–	1.2×10^{24}	eHWC J1825–134	[1356]
γ	3γ	(+)	–	–	1.0×10^{24}	eHWC J1907+063	[1356]
γ	3γ	(+)	–	–	4.1×10^{23}	CRAB	[1355]
γ	AS	(-)	–	–	1.7×10^{22}	diffuse (Tibet)	[1164]
γ	AS	(-)	–	–	6.8×10^{21}	LH. J1908+0621	[1164]
γ	AS	(-)	–	–	1.4×10^{21}	CRAB	[1355]
γ	AS	(-)	–	–	9.7×10^{20}	CRAB	[1355]
γ	AS	(-)	–	–	2.1×10^{20}	CRAB	[1361]
γ	PP	(-)	–	1.2×10^{29}	2.4×10^{21}	MultiSrc (6)	[1363]
γ	PP	(-)	2×10^{-16}	2.6×10^{28}	7.8×10^{20}	Mrk 501	[1348,1364]
γ	PP	(-)	–	1.9×10^{28}	3.1×10^{20}	MultiSrc (32)	[1359]

Figure: Strong and recent astrophysical bounds to LIV in the QED sector using synchrotron radiation (Synch.), vacuum Cherenkov radiation (VC), photon decay (PD), photon splitting (3γ), air shower suppression (AS), and pair production (PP) on the EBL. From A. Addazi et al. (2022)

Current experimental limits on LV parameters for dim 6 operators

- Constraints on LV in electrons: $M_{\text{LV}} > 2 \times 10^{16}$ GeV.
- Photon time of flight from distant sources: $M_{\text{LV},\gamma} > 6.4 \times 10^{10}$ GeV (AGN), $M_{\text{LV}} > 1.3 \times 10^{11}$ GeV (GRB).

See data tables for Lorentz and CPT violation arXiv: 0801.0287.

Current experimental limits on LV parameters for dim 6 operators

- Photon splitting $\gamma \to 3\gamma$: $M_{\mathrm{LV}} > 4.9 \times 10^{15}$ GeV (for superluminal case). arXiv: 2106.06393
- Modification of pair production on background photons. Subluminal LV in photons shifts the threshold of pair production upward. This leads to higher predictions for the VHE photon flux from extragalactic sources than in the LI case: $M_{\mathrm{LV}} \gtrsim 2.4 \times 10^{13}$ GeV. (subluminal) arXiv:1810.13215
- Suppression of shower formation of primary photon of energies 100 TeV - 1 PeV, $M_{LV} = 1.7 \cdot 10^{13}$ GeV. (subluminal) arXiv: 2106.06393

Muon puzzle. How Can LIV Effects Help Solve It?

1. The energy of the primary particle is $\sim 10^{19}$ eV.
2. There were born charged and neutral pions during the first interaction: $p \to \pi^{\pm}\pi^{0}$.
3. Decay modes: $\pi^{+} \to \mu^{+}\nu_{\mu}$, $\pi^{-} \to \mu^{-}\bar{\nu}_{\mu}$, $\pi^{0} \to 2\gamma$.
4. These created photons have the energies $\sim 10^{17}$ eV (that is bigger by 2 order than the energies of air showers initiated by photons 10^{15} eV. In case of LV $\sigma_{\rm LV} < \sigma_{\rm LI}$, therefore, $\lambda_{\rm LV} > \lambda_{\rm LI}$, from which the shower decreases in the plane XY. The main thing is — fewer N_e electrons born.
5. The number of N_{μ} muons is the same if photonuclear reactions are not modified.
6. Therefore, $[N_e/N_{\mu}]^{\rm LV} < [N_e/N_{\mu}]^{\rm LI}$.

Muon puzzle

We introduce so called z–scale, which is defined as

$$z \equiv \frac{\ln \left\langle N_\mu^{\mathrm{obs}} \right\rangle - \ln \left\langle N_{\mu,p}^{\mathrm{MC}} \right\rangle}{\ln \left\langle N_{\mu,Fe}^{\mathrm{MC}} \right\rangle - \ln \left\langle N_{\mu,p}^{\mathrm{MC}} \right\rangle}, \tag{7}$$

where $\left\langle N_\mu^{\mathrm{obs}} \right\rangle$ is the mean value of the measured muon density, $\left\langle N_{\mu,p}^{\mathrm{MC}} \right\rangle$ and $\left\langle N_{\mu,Fe}^{\mathrm{MC}} \right\rangle$ are the predicted values for the average muon density for proton and iron cosmic–ray nuclei, respectively.

Does it work? Some tests...

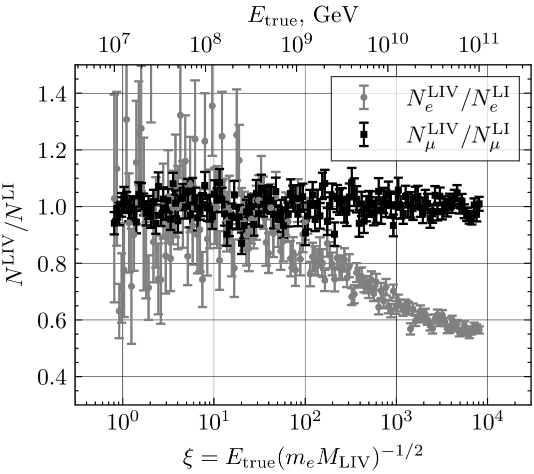


Figure: Proton-induced CR, fixed LIV mass scale $M_{\rm LIV} = 3 \times 10^{17}$ GeV

Does it work? Some tests...

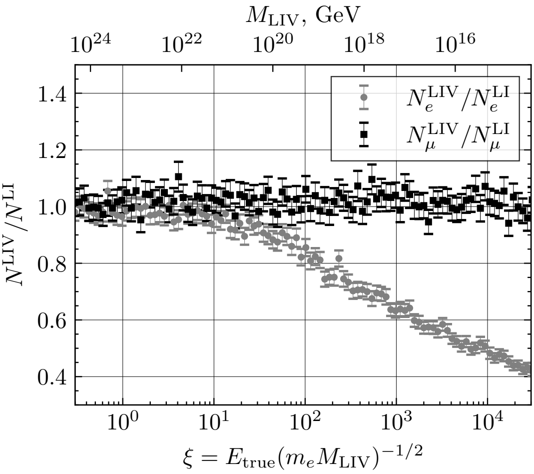


Figure: Proton-induced CR, fixed primary proton energy $E_{\rm true} = 10^{10}$ GeV.

Experiments

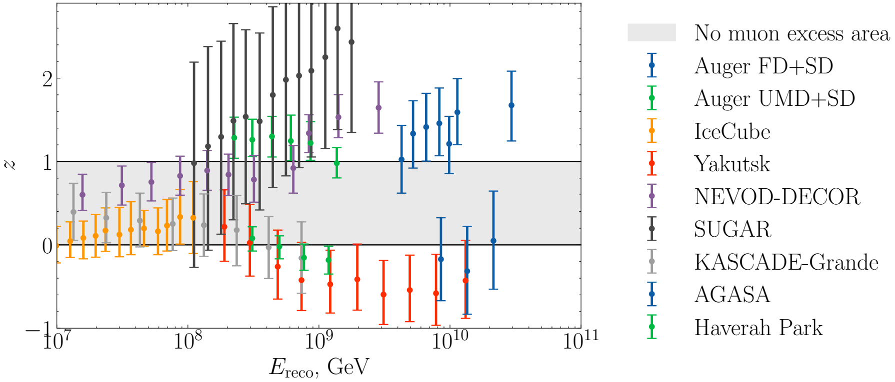
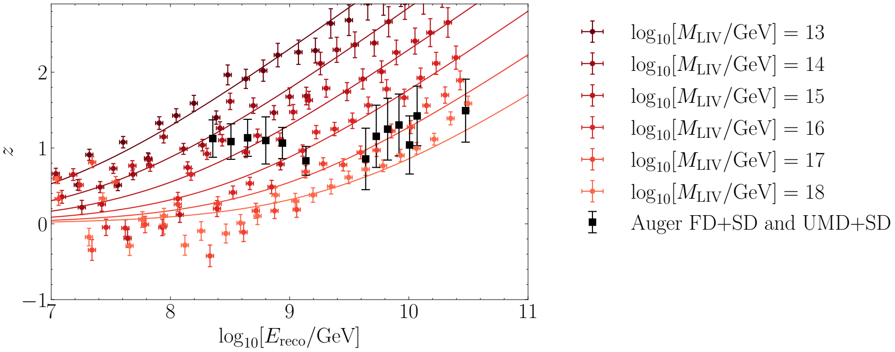


Figure: The derived z-scale from the muon density observations in EPOS-LHC hadronic interaction model.

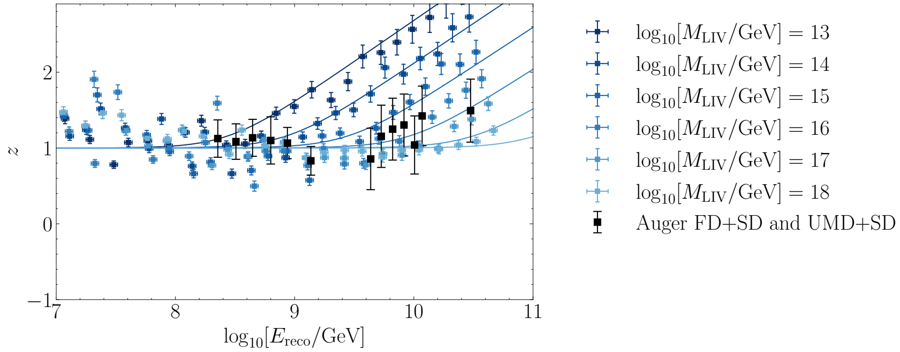
From the WHISP release.

Proton CR and Auger



Auger's reconstructed *z*-scale excludes $M_{\text{LIV}} \leq 10^{15}$ GeV at 99% C. L. for pure proton-CRs.

Iron CR and Auger



Auger's reconstructed z-scale excludes $M_{\rm LIV} \leq 10^{14}$ GeV at 99% C.L. for pure iron-CRs.

Conclusions

We have shown that a subluminal LIV in the photon sector on the mass scale of

$$M_{\text{LIV}} \sim 10^{(16\ldots17)} \ \text{GeV} \tag{8}$$

could be an explanation for muon puzzle.
We set conservative 99% C.L. constraint,

$$M_{\text{LIV}} \gtrsim 10^{14} \ \text{GeV}. \tag{9}$$

The current strongest astrophysical constraint:

$$M_{\text{LIV}} \gtrsim 1.3 \times 10^{13} \ \text{GeV}. \tag{10}$$

Thank you!

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