Lorentz invariance violation and muon anomaly in 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**:

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

  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).

How to construct LIV in QFT with all benefits of classical QFT?

The simplest guiding-scheme of a building of the lagrangian:

1. Quadratic in the same field;
2. One more derivative than the usual kinetic term;
3. Gauge invariant;
4. Lorentz invariant, except for the appearance of n^α;
5. Not reducible to lower dimension operators by the equations of motion;
6. Not reducible to a total derivative.

The model: the quartic LV

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

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:

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

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

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:

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

arXiv: 1204.5782.

Current experimental limits on LV parameters

e^-/γ	Test of QG	Sub(-) or super(+) luminal	Limits			Source	Ref.
			$\lvert\xi_0\rvert(\lvert\eta_0\rvert)$	$E^{(1)}_{\rm LIV}$ (eV)	$E^{(2)}_{\rm LIV}$ (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).

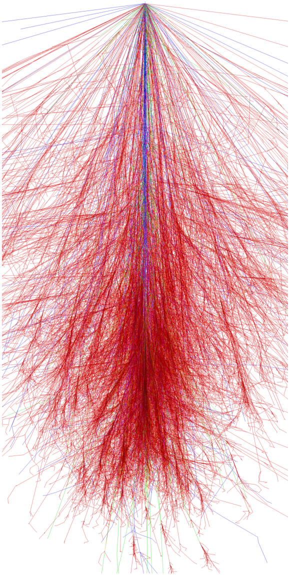
Current experimental limits on LV parameters for dim 6 operators

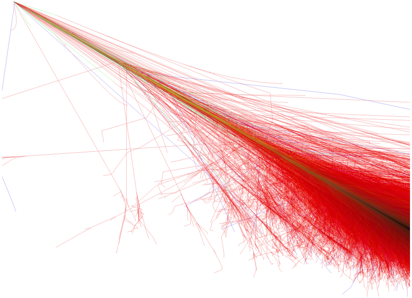
- Photon decay to e^+e^- pair: $M_{\rm LV} > 2.8 \times 10^{12}$ GeV (for superluminal case).
- Modification of pair production on background photons. Subluminal LV in photons shifts the threshold of pair production upward. This leads to higher predictions for the VHE photon flux from extragalactic sources than in the LI case: $M_{\rm LV} \gtrsim 3 \times 10^{11}$ GeV.
- Non-obervation of a photon component in UHECR. In LI case VHE photons get absorbed throught pair produciton on CMB, whereas LV at a scale below $M_{\rm LV}$ would suppress this process and UHE photons would reach the Earth. This constraint relies on the assumption that the dominant component of UHECR are protons that give rise to UHE photons through a cascade starting with a pion production on CMB (GZK process). $M_{\rm LV} \gtrsim 1.2 \times 10^{22}$ GeV.

The idea

1. The energy of the primal 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^{17} eV, more sensitive, than for energies 10^{15} eV. In case of LV $\sigma_{\mathrm{LV}} < \sigma_{\mathrm{LI}}$, therefore, $\lambda_{\mathrm{LV}} > \lambda_{\mathrm{LI}}$, 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, $[N_e/N_{\mu}]^{\mathrm{LV}} < [N_e/N_{\mu}]^{\mathrm{LI}}$.

Air showers: iron and proton initiated showers





The observable value

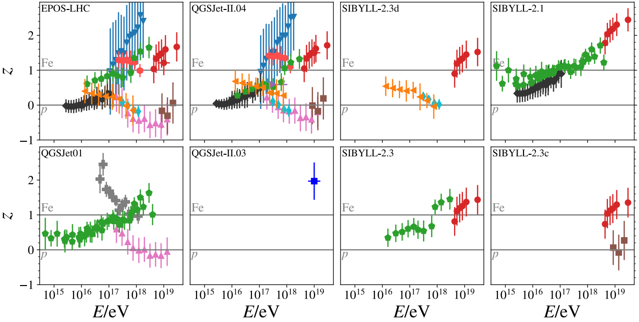
$$z = \frac{\ln \langle N_\mu \rangle - \ln \langle N_{\mu,p} \rangle}{\ln \langle N_{\mu,Fe} \rangle - \ln \langle N_{\mu,p} \rangle}, \tag{7}$$

where $z = 0$ is for proton-induced air shower and $z = 1$ is for iron-induced air shower.

- $\langle N_\mu \rangle$ — the measured value of muons' number,
- $\langle N_{\mu,Fe} \rangle$, $\langle N_{\mu,p} \rangle$ are MC–values for proton (iron) simulations.

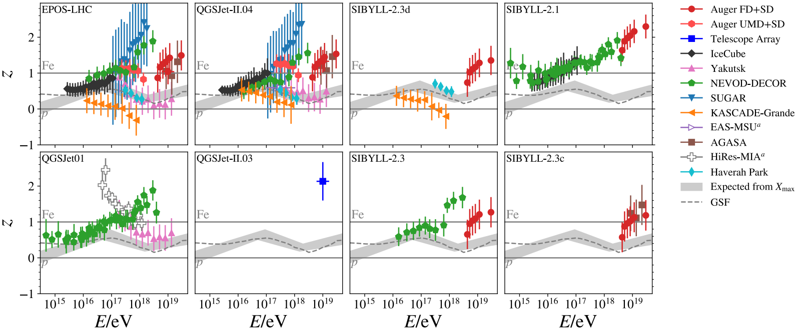
The muon puzzle

Muon excess in data with regard to p/Fe predictions appears at energies $> 10^{17}$ eV in Auger, Telescope Array, SUGAR and NEVOD–DECOR measurements.



J. C. Arteaga — Update on the combined analysis of μ data

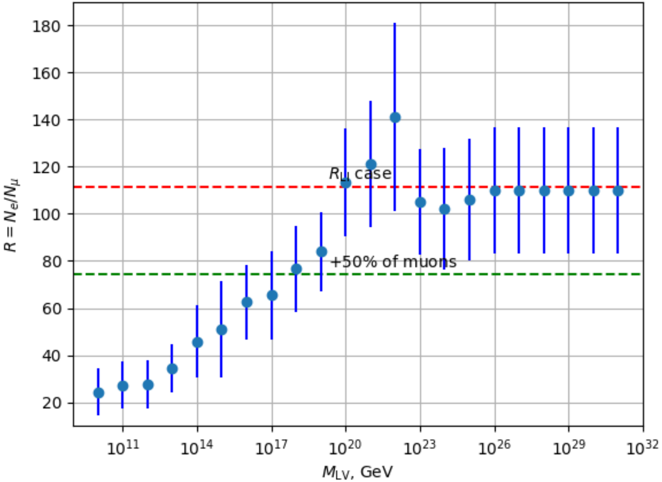
The muon puzzle



J. C. Arteaga — Update on the combined analysis of μ data

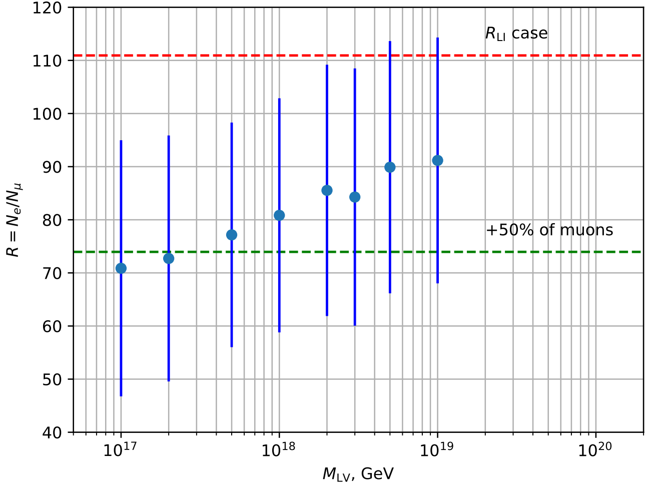
The result: preliminary scanning for M_{LV}

The parameters of the primal particle: proton with $E_0 = 10^{19}$ eV, spherical coordinates $\theta = \varphi = 0$, averaged by 40 showers of MC.



The result

The parameters of the primal particle: proton with $E_0 = 10^{19}$ eV, spherical coordinates $\theta = \varphi = 0$, averaged by 300 showers of MC.



The result and the comparison

Our constraint:

$$\boxed{M_{\rm LV} \gtrsim 2 \times 10^{17} \ \text{GeV}.} \tag{8}$$

The strongest astrophysical constraint:

$$M_{\rm LV} \gtrsim 3 \times 10^{12} \ \text{GeV}, \tag{9}$$

if we do not take into account the constraint from non-observation of a photon component in UHECR ($\gtrsim 10^{19}$ eV):
$M_{\rm LV} \gtrsim 1.2 \times 10^{22}$ GeV.

Thank you!