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

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What problem are we solving?

Many experiments have observed an unexplained excess of muons in extensive air showers (EASs). This phenomenon is known as the *'muon puzzle'*—an open question in science.

The muon excess is often parametrized by the variable

the mean value of the measured muon density

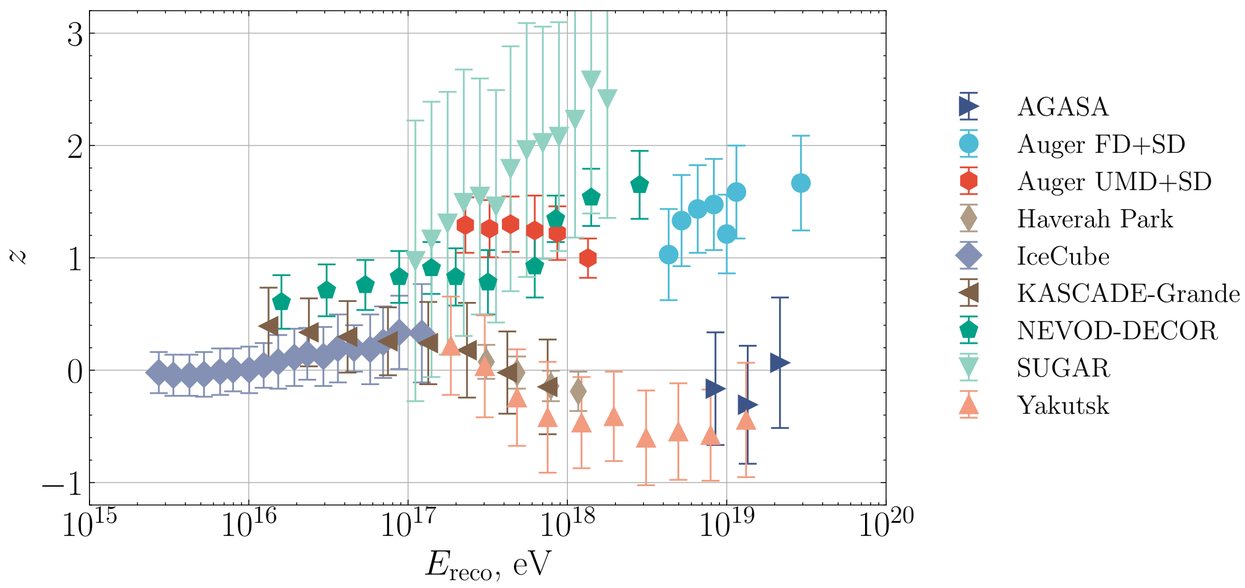
the mean value of the predicted muon density by Monte-Carlo simulations for proton-ray nucleus

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

the mean value of the predicted muon density by Monte-Carlo simulations for iron-ray nucleus

Experimental data:

all dots should be kept in the region between z=0 and z=1!!!



How to solve the muon puzzle? — Of course, let's modify the SM!

Let's modify, especially, the QED sector:

$$\mathcal{L} = \mathcal{L}_{\rm QED} + \mathcal{L}_\gamma,$$

where the following term modify the dispersion relation:

$$\mathcal{L}_\gamma = \frac{s_2}{4M_{\rm LIV}^2} F_{kj}\partial_i^2 F^{kj},$$

the mass scale parameter for LI breaking

and we get

$$E_\gamma^2 = k_\gamma^2 - \frac{k_\gamma^4}{M_{\rm LIV}^2}.$$

How does this theory affect EAS behavior?

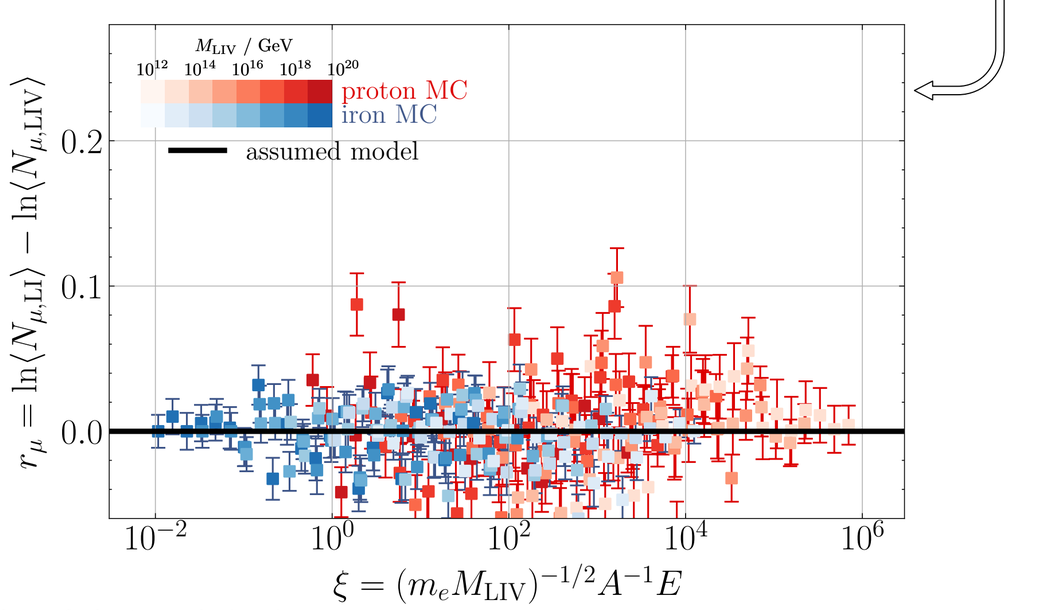
Such a theory significantly changes the cross section in the photon-induced pair production reaction on a nucleus:

$$\frac{\sigma_{\rm BH}^{\rm LIV}}{\sigma_{\rm BH}^{\rm LI}} \simeq \frac{12m_e^2M_{\rm LIV}^2}{7E_\gamma^4} \times \log\frac{E_\gamma^4}{2m_e^2M_{\rm LIV}^2}$$

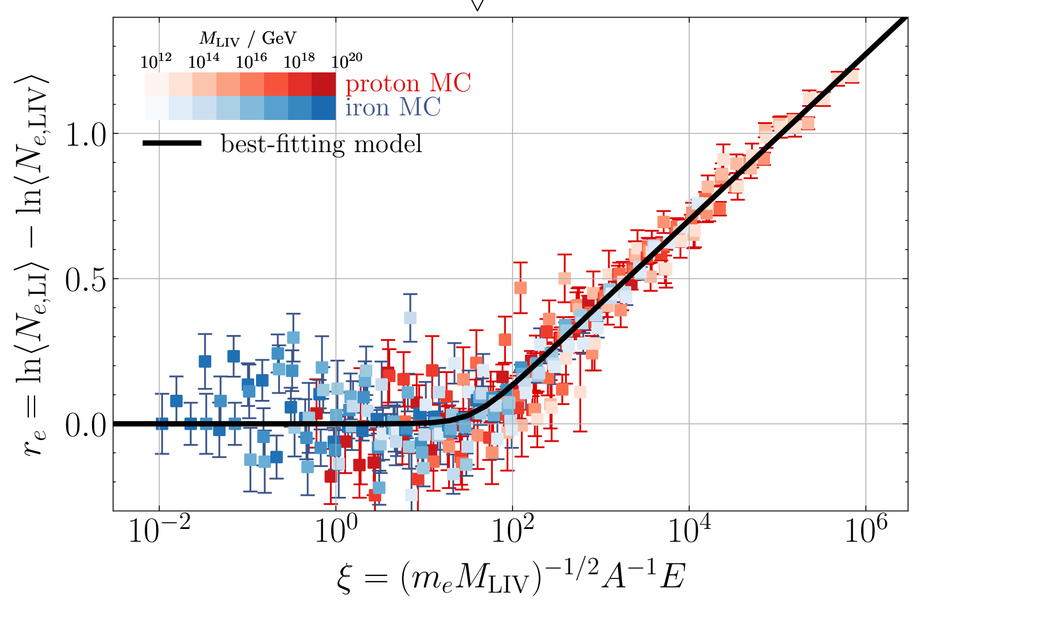
Key idea: The number of produced electrons decreases, which leads to incorrect reconstruction of the primary particle's energy, consequently resulting in an underestimation of the muon density.

Simulations:

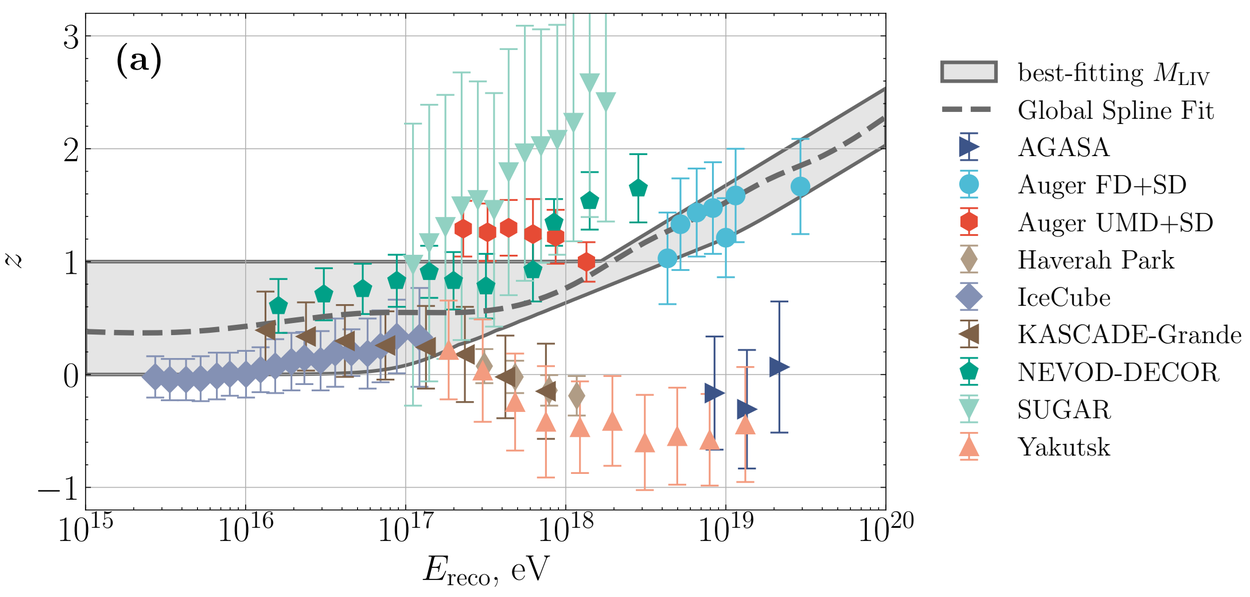
the number of muons truly remains unchanged



the number of electrons indeed decreases with increasing energy



Results:



We have shown that a subluminal LIV in the photon sector on the mass scale of $M_{\rm LIV} \sim 10^{16}$ GeV could be an explanation for the muon puzzle!

Where to read about this:

1. arXiv: 2412.08349 — this work (and see PRD publication),
2. PoS ICRC2023 (2023) 466 — review by the WHISP group on the muon puzzle,
3. arXiv: 0802.1561 — on the test of Lorentz invariance violation (my personal recommendation).

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