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Feasibility studies on the search of Lorentz invariance violation signatures from relativistic jets with the Cherenkov Telescope Array

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The current paradigm in General Relativity (GR), Quantum Mechanics (QM), and Quantum Field Theory (QFT) is that the physical laws must be invariant under Lorentz transformations. However, some theories aiming at unifying GR and QM (such as Quantum Gravity (QG) and string theory) allow Lorentz Invariance Violation (LIV) at the Planck scale ($\sim 10^{-35}$ m, $\sim 10^{19}$ GeV), potentially leading to several observable consequences. Due to a modified energy-momentum dispersion relation for photons, LIV effects might be identified by searching for time delays in the TeV gamma-ray photons coming from distant and highly variable astrophysical sources, such as relativistic outflows from pulsars, Gamma-ray Bursts (GRBs), and Active Galactic Nuclei (AGN). In particular, blazar jets possess the desired characteristics to search for LIV effects. Using the AGN Evolution Simulator (AGNES) code, the broadband spectrum of a blazar can be modeled by using the time-dependent one-zone Synchrotron-Self-Compton (SSC) scenario during a flaring state, and the presupposed LIV delays can be introduced alongside the intrinsic time lags from the source. In this work, we aim to analyze the capacity of the Cherenkov Telescope Array (CTA) to detect global time delays and to discriminate between the contribution of intrinsic phenomena in the jet and possible LIV effects. The methodology and preliminary results from the simulations performed for the feasibility studies with CTA are presented.

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1. Introduction

Lorentz Invariance Violation (LIV) effects arise in QG theories due to quantum fluctuations that may occur at the Planck scale (Planck length, $L_P \approx 10^{-35}$ m). One searching strategy is to identify LIV signatures from Very High Energy (VHE) remote cosmic sources by looking for energy-dependent time delays on the arrival time of photons at different energies. Gamma-ray Bursts (GRBs), flaring AGNs and fast-spinning pulsars are among the possible candidates. See [1] for a list of LIV limits obtained with various instruments and types of astrophysical sources.

The MAGIC Collaboration performed a temporal and spectral variability study for the gamma-ray flare from Mrk 501 recorded on July 2005, with the time delay of 4 ± 1 min between two sub-energy bands, one below 0.25 TeV and the second above 1.2 TeV [2]. It is the only delay ever reported at TeV energies from a blazar flare up to now, and it could be interpreted as an intrinsic effect due to a progressive acceleration of electrons in the emitting plasma blob.

The upcoming Cherenkov Telescope Array (CTA) represents the next generation of IACTs. Consisting of two arrays located in each hemisphere for full-sky coverage, it will provide gamma-ray observations from around 20 GeV and up to 300 TeV with unprecedented sensitivity, energy, and angular resolution, improving by an order of magnitude in comparison to the current generation of IACTs [3]. As part of its scientific program, CTA will explore problems in fundamental physics, including searching for LIV effects and setting constraints on the analyzed astrophysical sources.

The preliminary results from a feasibility study of the expected CTA potential to detect global time delays from flaring blazars are presented alongside the methodology and analysis tools used for this purpose. As a first approach, we model a typical weak flare from a BL Lac object and simulate CTA observations under realistic conditions.

2. Blazar time-dependent modeling

To describe the emission of a BL Lac object during a flaring episode, we adopt the Synchrotron Self-Compton (SSC) scenario as presented in [4, 5]. This model assumes a single spherical bulk of leptonic plasma moving inside the jet of the blazar as the emitting zone. Considering a homogeneous population of electrons, the time evolution of the flare will be dictated by the transfer equation:

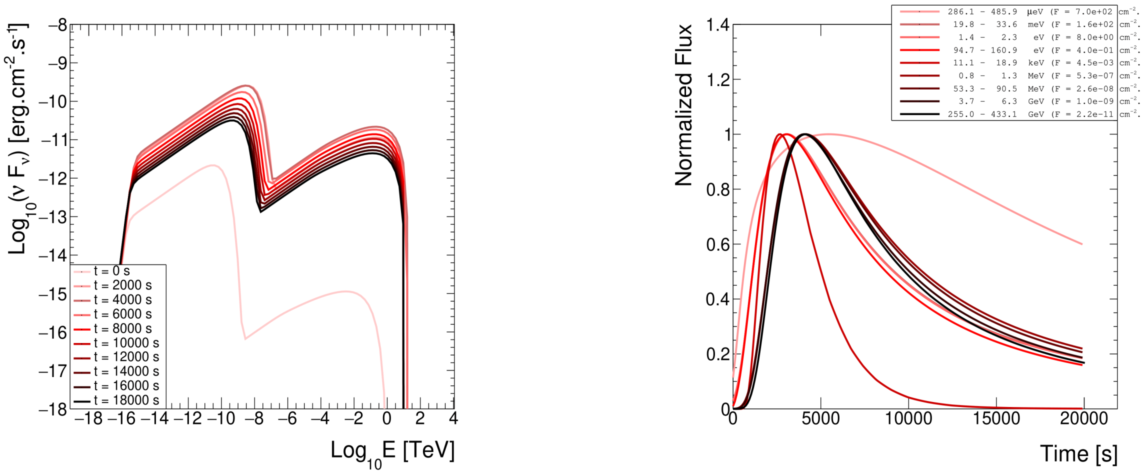
$$\frac{\partial N(t,\gamma)}{\partial t} = \frac{\partial}{\partial \gamma}\{[\gamma^2 C_{\text{cool}}(t) - \gamma C_{\text{acc}}(t)]N(t,\gamma)\} \tag{1}$$

where $N(t,\gamma)$ is the lepton number density, $\gamma = E/m_e c$ is the associated Lorentz factor, $C_{\text{cool}}(t)$ is the term that accounts for the radiative cooling, and $C_{\text{acc}}(t)$ is the acceleration term. Injection, escape, creation and loss of particles are not considered in this scenario.

The particle acceleration is approximated with a time-dependent function of the type:

$$C_{\text{acc}}(t) = A_0 \left(\frac{t_0}{t}\right)^{m_a} \tag{2}$$

where A_0 is the initial acceleration amplitude, m_a is the acceleration evolution index and $t_0 = \frac{\sqrt{3}R_0}{c}$ is the characteristic evolution time, with R_0 being the size of the blob. In this scenario, the accelerated particles will cool down through synchrotron and SSC processes, giving the Spectral



(a) Temporal evolution of the SED. **(b)** Ligh curves in different energy bands,

Figure 1: Weak flare for a BL Lac source computed with AGNES (the contribution of the stationary state is not included).

Energy Distribution (SED) its characteristic two-bump shape. Neglecting adiabatic losses and following the simplifications given in [4, 5], the cooling term can be written as:

$$C_{\mathrm{cool}}(t) = \frac{4\sigma_T}{3m_e c} U_B(t)[1 + \frac{1}{\eta}] \tag{3}$$

where σ_T is the Thomson cross-section, m_e is the electron mass at rest, $U_B(t) = B^2(t)/8\pi$ is the magnetic field energy density and $\eta = U_B(t)/U_{\mathrm{syn}}(t)$, with $U_{\mathrm{syn}}(t)$ being the synchrotron energy density. The decrease over time in the magnetic field strength $B(t)$ is approximated by:

$$B(t) = B_0 \left(\frac{t_0}{t}\right)^{m_b} \tag{4}$$

where B_0 is the initial magnetic field strength and m_b is the magnetic evolution index. Eq. 1 admits an analytical solution with the initial electron spectrum given by a cut-off power-law of the type:

$$N(t_0, \gamma) = N_0 \gamma^{-\alpha} \left[1 - \left(\frac{\gamma}{\gamma_{\mathrm{cut}}(t_0)}\right)^{\alpha+2}\right] \tag{5}$$

where N_0 is the initial particle number density, $\gamma_{\mathrm{cut}}(t_0)$ is the cut-off value of the Lorentz factor and α is the power-law index. The temporal evolution of the flare is computed using the AGNES code [6]. The model parameters used are summarised in Table **??**, and were selected based on the properties of a "weak" flare of Markarian 501 [4, 6]. The evolution of the SED is computed for 5.5 hr (See Figure 1a). Intrinsic time delays could arise depending on the given parameterization. In this case, the system has fast acceleration leading to a quick rise of the observed flux, followed by a dominant cooling effect, inducing the highest energy light curves to decay first. The influence that the different model parameters have on the intrinsic time delays was investigated in [7].

To study the possible LIV effects on future observations with CTA, a time delay was injected into the flare description. The time delay term will shift the light curves depending on their energy:

$$F_{E_{LC}}(t) \rightarrow F_{E_{LC}}(t + \tau_n E^n_{LC}) \tag{6}$$

Model Parameter	δ	B_0	R_0	N_0	γ_{cut}	α	z
	70	100 mG	5×10^{15} cm	300 cm^{-3}	4×10^4	2.4	0.034
Evolution Parameter	A_0	m_a	m_b				
	5.5×10^{-5} s^{-1}	5.6	1.0				

Table 1: Model parameters used to describe a weak flaring state of a BL Lac source.

where E_{LC} is the mean value of the energy band considered for the computed light curve, and n is the correction order, here we consider a linear correction with $\tau_1 = 400$ s/TeV, which corresponds to a strong subluminal LIV effect. The LIV term will affect the highest energy light curves with a larger time delay, which means the LIV effect is opposite to the intrinsic time delays for the modeled flare.

3. CTA simulations

To simulate CTA observations we made use of the `CTA-AGN-VAR`[1] pipeline [8], a python package based on `Gammapy`. This tool allowed us to produce realistic predictions of AGN flares by taking into account observational constraints, assuming follow-up of the source, and dynamic selection of the Prod5 v0.1 Instrument Response Functions (IRFs) [9] for the CTA Alpha array configuration (CTA-North: 4 LSTs and 9 MSTs; CTA-South: 14 MSTs and 37 SSTs).

The spectral evolution models during a typical flare with and without an injected LIV delay were used as input to the pipeline. Our simulations considered 5.5 hr of effective observation time with the CTA-North Alpha array, in the energy range between 30 GeV and 10 TeV. The gamma-ray emission from the source was fitted with the spectral model of a power-law with an exponential cut-off:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma} e^{-\frac{E}{E_{\rm cut}}} e^{-\tau_{\gamma\gamma}(E)} \tag{7}$$

where ϕ_0 is the flux normalization, Γ is the spectral index, E_0 is the reference energy, and $E_{\rm cut}$ is the cut-off energy. The Extragalactic Background Light (EBL) attenuation effect was also considered in the fit, the values for the optical depth $\tau_{\gamma\gamma}$ were taken from [10]. Light curves in different energy bands were reconstructed from the simulations using 5 min time bins. The low-energy band was defined between 30 GeV and 300 GeV, while the high-energy band was considered between 300 GeV and 10 TeV (See Fig. 2). The results for the "intrinsic + LIV" delay model appear as blue points, while the model considering purely intrinsic time delays is shown in black.

4. Preliminary Results

The asymmetric Gaussian function was used to fit the reconstructed light curves:

$$F_{lc}(t) = B_{lc} + A_{lc} \begin{cases} e^{-\frac{t-\mu}{2\sigma_1}} & \text{if } t < \mu \\ e^{-\frac{t-\mu}{2\sigma_2}} & \text{if } t > \mu \end{cases} \tag{8}$$

[1]https://gitlab.cta-observatory.org/guillaume.grolleron/ctaagnvar

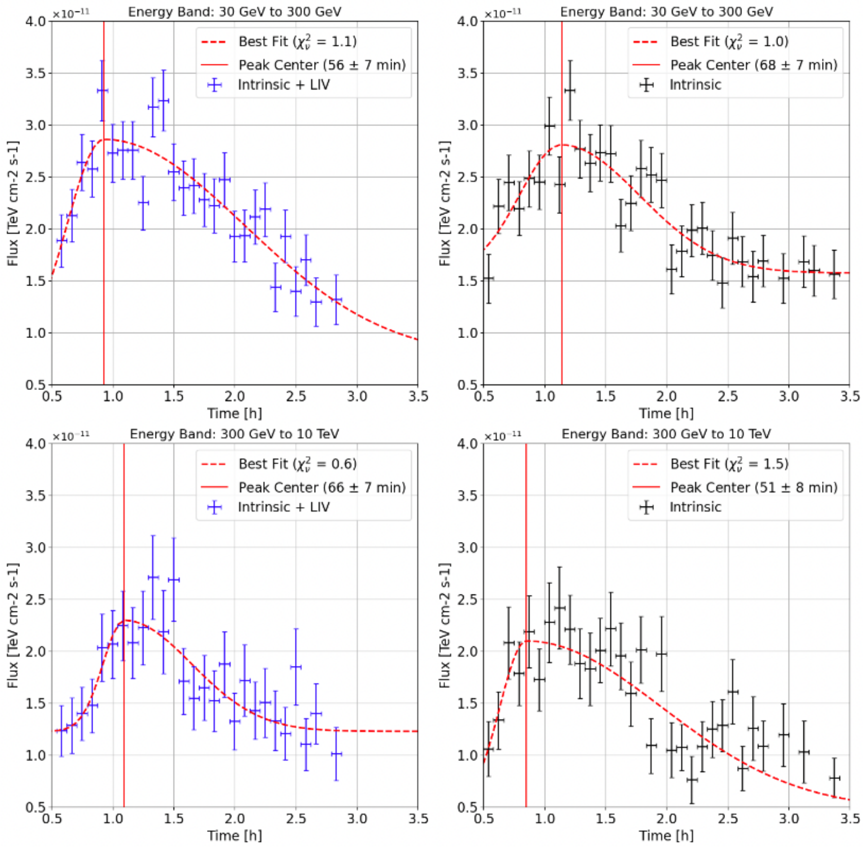


Figure 2: Reconstructed light curves in low (upper panel: 30 GeV to 300 GeV) and high (lower panel: 300 GeV to 10 TeV) energy bands. The best-fit curve and peak center are shown in red. Left: Intrinsic + LIV delay model (blue points). Right: Intrinsic model (black points).

where μ determines the peak location, σ_1 and σ_2 the assymetric spread of the curve, A_{lc} is a normalization constant, and B_{lc} the baseline. The global time delay can be estimated by computing the difference between locations of the peaks in different energy bands: $\Delta t_E = t_{HE} - t_{LE}$. This simple method is straightforward to obtain a first approximation.

The results from the purely intrinsic scenario are consistent with the injected model, showing a decreasing time delay at the high energy band ($\Delta t_E \sim -17 \pm 11$ min). In our simulations, the CTA Alpha array configuration for the North site appears to be just sensitive enough to register the intrinsic time delays from a weak flare episode of a BL Lac source. For the model with an injected LIV delay, the effect is mixed with the intrinsic time delay. The injected LIV delay is high enough to counteract the intrinsic effect, leaving a time difference between energy bands of $\Delta t_E \sim 10 \pm 10$ min. However, the significance of this modification of the total delay by the LIV effect is rather poor at this stage.

5. Conclusion and outlook

The outcome from our first round of simulations and analysis suggests that CTA-North Alpha configuration should be able to detect intrinsic delays even in weak and therefore frequent blazar flares, but detecting the LIV effects with such kind of flares seems challenging. As no significant change in the delay was found when LIV effects were tested, further analysis with a refined methodology and other LIV signature tests appear necessary. Several options will be explored in the near future, such as: testing exceptional blazar flares (up to 2 orders of magnitude higher SED) with the `CTA-AGN-VAR` pipeline, checking the southern (CTA-South) and the CTA Omega configurations, testing different values for the LIV injected delays (subluminal and superluminal) with cooling/acceleration-driven regimes, and carrying out various tests on data analysis to further highlight the effect of LIV.

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References

[1] J. Bolmont et al., *First Combined Study on Lorentz Invariance Violation from Observations of Energy-dependent Time Delays from Multiple-type Gamma-Ray Sources. I. Motivation, Method Description, and Validation through Simulations of H.E.S.S., MAGIC, and VERITAS Data Sets*, *ApJ* **930** (2022) 75.

[2] J. Albert et al., *Variable VHE gamma-ray emission from Markarian 501*, *ApJ* **669** (2007) 862.

[3] B. S. Acharya et al. *Science with the Cherenkov Telescope Array*, Edited by CTA Consortium, Published by World Scientific Publishing Co. Pte. Ltd., ISBN #9789813270091 (2019).

[4] K. Katarzyński et al., *The multifrequency emission of Mrk 501*, *A&A*, **367** (2001) 809.

[5] K. Katarzyński et al., *The multifrequency variability of Mrk 421*, *A&A* **410** (2003) 101.

[6] C. Levy et al., in Proc. of *37th International Cosmic Ray Conference*, 907 (ICRC 2021).

[7] C. Perennes et al., *Modeling spectral lags in active galactic nucleus flares in the context of Lorentz invariance violation searches*, *A&A* **633** (2020) A143.

[8] G. Grolleron et al., *Variability studies of active galactic nuclei from the long-term monitoring program with the Cherenkov Telescope Array*, in Proc. of *38th International Cosmic Ray Conference*, 766, (ICRC 2023).

[9] CTA Observatory & CTA Consortium (2021). CTAO Instrument Response Functions - prod5 version v0.1, Zenodo: https://doi.org/10.5281/zenodo.5499840

[10] A. Domínguez et al., *Extragalactic background light inferred from AEGIS galaxy-SED-type fractions*, *MNRAS* **410** (2011) 2556.