Lorentz Invariance Violation on UHECR propagation

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Abstract. In the present work possible consequences of the Lorentz symmetry breaking are presented. Those consequences are encoded through the modification of dispersion relations which are applied to the processes of pair and pion photo production generated at UHECR scale. The produced physics from such modifications contains scenarios where the expected photo production thresholds under Lorentz symmetry are shifted; the other scenarios predict that the cosmic ray flux will be recover at higher energies due to the suppression of the production processes. This phenomenon is repeated for different components of the diffuse photon background and generates opacity bands in distinct parts of the energy spectrum; we expose scenarios that have not been considered previously by other authors. Moreover, in contrast with previous studies, in this work the scenarios generated by the Lorentz symmetry breaking are measured by a generic parameter, unique for each process, independent of the correction origin (E^2 or p^2) in the dispersion relations, as well as the nature of the particle involved and possible corrections to the relations of conservation energy-momentum laws. Additionally, the Pierre Auger result for the pion photo production is used to estimate the energy scale parameter of the Lorentz symmetry breaking.

1. Introduction

Many Quantum Gravity theories suggest the breaking of Lorentz Invariance (LI) with the strength of the effects increasing with energy [1]. If LI is broken in form of non-standard dispersion relations for various particles, absorption and energy loss processes for cosmic radiation interactions can be modified. Conversely, experimental confirmation that such processes occur at the expected thresholds would allow to put strong constraints on such LI breaking effects.

In the next section we expose the general background that has been used in the forward analysis. In section 3, we introduce the method. In section 4, we present the effects of the LI violation (LIV) for the pair and pion photo production by n-order modification. In section 5, we present the special case $n = 1$ and also a generic example, then we explore an experimental restrictions for the LIV pion photo production. Finally in section 6, conclusions are presented.

2. Diffuse γ-background

Since the early universe, several phenomena had contributed for the generation of a diffuse gamma background, which fills the space in an almost homogeneous way. One of the most known components of this background, and probably the most important in cosmology, is the Cosmic Microwave Radiation (CMB). Other relevant radiations are the Far Infrared Background (FIRB) and Radio Background (RB). The mean energies for those photons are $\omega_{CMB} \approx 6 \times 10^{-4} eV$, $\omega_{FIRB} \approx 10^{-2} eV$ and $\omega_{RB} \approx 4 \times 10^{-9} eV$.

The diffuse background has a certain probability of interacting with cosmic rays. One can use Special Relativity (SR) to compute the minimum energy needed by the colliding particles to reproduce the pair and pion photo production ($\gamma_{HE}\gamma_b \to e^+e^-$; $p\gamma_{CMB} \to \Delta \to p\pi^0$, $p\gamma_{CMB} \to \Delta \to n\pi^+$) and they are: $\omega_{th} = m_e^2/\omega_b$ and $E_{p_ith} \approx [m_\pi(2m_p + m_\pi)]/4E_\gamma$. Then, for the diffuse γ-background components stated before, the thresholds predictions by this SR approximations are $\omega_{th_{FIRB}} \sim 3 \times 10^{13}$ eV, $\omega_{th_{CMB}} \sim 5 \times 10^{14}$ eV, $\omega_{th_{Rb}} \sim 6 \times 10^{19}$ eV and $E_{th_{FIRB}} \sim 7 \times 10^{18}$ eV, $E_{th_{CMB}} \sim 1 \times 10^{20}$ eV $E_{th_{RB}} \sim 2 \times 10^{25}$ eV. The CMB pion photo production is very important for UHECR study since it predicts a cosmic ray flux suppression at $\sim 10^{20} eV$ (GZK cutoff). The Pierre Auger Observatory has already measured that there is a cosmic ray flux suppression at 4×10^{19} eV [2]. Auger has also set upper limits to the UHC-γs flux: 0.4 %, 0.5 %, 1%, 2.6 % and 8.9% above 1,2,3,4 and 10 EeV [3]. In an Invariant Lorentz regime, these processes are examples of low energy processes in the mass center which are boosted at the laboratory system with extremely high Lorentz factors.

3. Lorentz Invariance Violation (LIV)

LI is the invariance under the Lorentz group transformations. The symmetry under boost says that if a particle (or any system) has energy and momentum $P^\mu = (E, \vec{p})$ in a system C, then the energy and momentum $P'^\mu = (E', \vec{p'})$ for the same particle in the system C' will be given by Lorentz transformations, where $S := P_\mu P^\mu = E^2 - p^2 = m^2$ is a Lorentz invariant and define the well-known dispersion relation.

A common way to break the Lorentz symmetry is adding no LI terms in the Lagrangian in order to modify the dispersion relation. Since it can be done by modifying both the energy or the momenta, without loss of generality we can expand the new dispersion relation as

$$E^2 - p^2 - m^2 = A^2 \left(\epsilon(0) + \epsilon'(0) \left(\frac{A}{M} \right) + \epsilon''(0) \left(\frac{A}{M} \right)^2 + \ldots \right), \tag{1}$$

where ϵ parametrizes the LIV in such way that it returns the LI regime at low energies and it is proposed as a function of (A/M), where A can take the form of E or p and M parametrizes the LIV energy scale. As a conclusion, a new general class of dispersion relation can be proposed

$$E^2 - p^2 = m^2 + \alpha_n A^{n+2}, \tag{2}$$

where $\alpha_n := \epsilon^{(n)}/M^n \simeq 1/M^n$. Equation (2) is a general form for many cases, that one can find on literature, that break LI by a dispersion relation modification (see for instance [1],[4],[5]).

4. LIV processes

In general, LI is expected to be broken at very high energy and it can be done by modifying the dispersion relation. Additionally, in most cases a special frame is needed (CMB-frame), since there is no more Lorentz symmetry, however, it is possible to modify the boost action in order to save the invariance under inertial frames [6]. These corrections have consequences to the energy-momentum conservation laws. In order to include such modifications on the analysis, we propose that the energy-momentum laws are corrected by a lineal LIV coefficients that could be functional dependent on $\{E, p\}$. Then, we use the inelasticity, K, in two particles collision where $E_{1_{final}} := K(E_{1_{initial}} + \omega_b + \Xi_E)$ and $E_{2_{final}} := (1 - K)(E_{1_{initial}} + \omega_b + \Xi)$, where Ξ_E is a LIV term and ω_b the energy photon from the diffuse background. We use the system where the collision is head on; since the UHECR has higher energy than the photon background, the final momentums are collinear. Additionally, we introduce the ultra relativistic regime approximation $m \ll \{E, p\} \ll M$ and $\omega_b \ll \{E_{proton}, \omega\}$. We also demand only first order LIV coefficients.
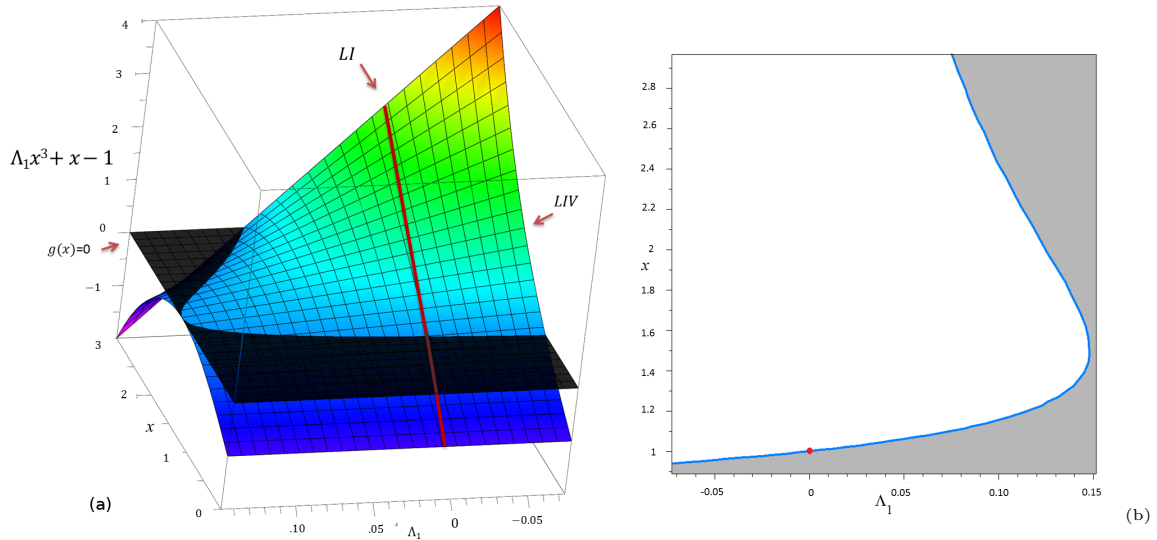
Figure 1. LIV scenarios. On the left the behavior of $g(x) = \Lambda_1 x^3 - x + 1$ for several Λ. At right, the black plane that points the zeros of $g(x)$ for a given range of Λ's.

Henceforth, for general modifications of n-order in the dispersion relation (2), the energy threshold equation has the form

$$\Lambda_n x^{n+2} - x + 1 = 0 \tag{3}$$

where $x = E_{th}^{VIL}/E_{th}^{IL}$ and $\Lambda_n := B(E_{th}^{IL})$; λ_n, is the energy independent LIV parameter and both B and λ_n are different for each process. As we expected, if $\lambda_n = 0$, LI regime is recover. In both cases, equation (3) is independent from particle nature, the functional form of A in equation (2) and Ξ, the last one means that the results do not depend on lineal corrections of the energy-momentum laws. For the pair production case we denote $\Lambda_n = \Omega_n(\alpha_{\gamma_{UHE}}, \alpha_\gamma, \alpha_{e^\pm}) := \omega_0^{n+1}/(4\omega_b)\beta_n$ and $\Lambda_n = \Upsilon_n(\alpha_p, \alpha_\gamma, \alpha_\pi)$ for pion photo production.

5. The $n = 1$ case

Each value of Λ_1 produces a different scenario, which describe, the behavior of the photo production processes. Figure (1a) displays in color the function $g(x) = \Lambda_1 x^3 - x + 1$ for $\Lambda_1 \neq 0$, these are all the possible LIV scenarios for $n = 1$. The red line is the expected physics on LI regime ($\Lambda_1 = 0$). The black plane is the intersection plane with $g(x) = 0$, and is also exposed in Figure (1b). The red line cut the black plane at $x = 1$, so $E_{th}^{VIL} = E_{th}^{IL}$. For the LIV scenarios one can distinguish two families by the sign of Λ_1. If $\Lambda_1 < 0$, each $g(x)$ scenario produces a threshold by the only intersection with the plane $g(x) = 0$, like the LI case. If $\Lambda_1 > 0$, $\Lambda_1 < 4/27$ by reality condition, $g(x)$ intersects two times the plane $g(x) = 0$. These solutions represent: the first (at lower energy) the energy threshold for the processes and the second (at higher energy) the value at which the processes will be forbidden again, this phenomena produces *opacity bands*. That means, that in these bands UHECR protons and photons are free of the photo production processes produced by the interactions with the DB. In this sense they can propagate freely in the universe. Additionally, since we demand real values of Λ_1, $\Lambda_1 < 4/27$ so $x \in [1, 1.5)$ and then, there is an upper limit for all the lower energy thresholds of the opacity bands.

In Figure (2) the case $\beta_1 = 1.8 \times 10^{-48} eV^{-1}$ for pair production is exposed. Since $(4/27)(4\omega_b/\omega_0^2) > \beta > 0$ the energy threshold equations has two solutions, so LIV produces *opacity bands*. Each one points out the energy region allowed for the interaction of the UHE-γs
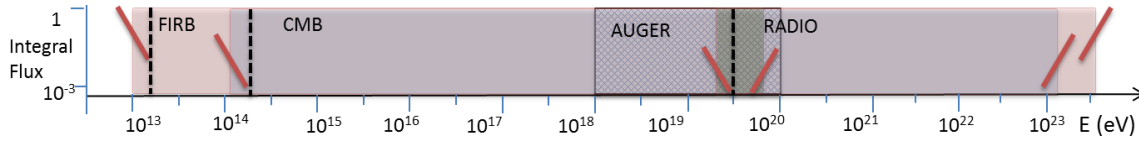
Figure 2. The figure shows the case for $\beta_1 = 1.8 \times 10^{-48} eV^{-1}$ in order to expose the opacity bands for each diffuse gamma background component. The bands are distributed over a wide energy range. The measure of one of these thresholds is enough to predict the location of the others.

with the different components of the DB. The doted lines are the upper limit that can reach the lowers walls of the bands. Outside each band, since the production process is forbidden for each background component, *the universe is transparent to the γs propagation*. The red lines are the slope of the expected flux of the incoming photons in the opacity band. Since pair production is an absorption process, the lines are expected to be pronounced. Dotted region indicates the energy range where Auger has set upper limits for the photon flux.

An extreme scenario would take place if $\beta_1 = 1.1 \times 10^{-32} \ eV^{-1}$, the RB threshold for photo pair production disappear since the solutions to the RB threshold equation has complex solutions. For the cases where $\Omega_1 = 4(\omega_b/\omega_0^2)\beta_1 \leq 0$ the opacity region grows indefinitely.

If Auger reported energy flux suppression, at 4×10^{19} eV, is taken as the $E_{p_{ith_{CMB}}}$, we can use the $n = 1$ results to compute the LIV parameter for CMB, which has the value $\Upsilon_{1_{CMB}} = -8.4$. Once Υ_1 is known, the energy thresholds for the other components for pion photo production are expected to be found at $E_{p_{ith_{FIRB}}} \approx 7 \times 10^{18} eV$ and $E_{p_{ith_{RB}}} \approx 5 \times 10^{19} eV$. In the very particular case where $\alpha_p = \alpha_\gamma = \alpha_\pi$, this means $|\alpha| \simeq 10^{-50} eV^{-1}$ and a LIV scale $M \geq 10^{50} eV$.

6. Conclusions

LIV models have generated observable astrophysical consequences which are measurable with the current state of the CR study. In this work it was found that under ultra relativistic regime, first order LIV terms and $\omega_b \ll E_{UHECR}$, the modifications given in equation (2), produce independent results from the particle nature, the functional form of A (E, p), and lineal corrections on the energy-momentum laws for the threshold analysis. We also found that the physics from LIV modifications contains scenarios where the expected photo productions thresholds can change drastically. These scenarios are measured by a generic parameter. In the scenarios where $E_{th}^{VIL} > E_{th}^{IL}$, it is predicted that the CR flux will be recovered at higher energies due to the presence of a second threshold which suppresses the production process. Then, opacity bands are generated. Hence, bands have direct consequences on the CR propagation through the universe. In second scenarios, the energy threshold is just moved to low energies. It was found that for both processes there is a limit value that each lower wall of the opacity bands could take. This limit exists for each one of the diffuse background components. For photo pion production Pierre Auger results imply a constrain value for the LIV energy scale, at $M \geq 50 \ eV$.

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