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Constraining Lorentz Invariance Violation using the muon content of extensive air showers measured at the Pierre Auger Observatory

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Lorentz Invariance (LI) implies that the space-time structure is the same for all observers. On the other hand, various quantum gravity theories suggest that it may be violated when approaching the Planck scale. At extreme energies, like those available in the collision of Ultra-High Energy Cosmic Rays (UHECRs) with atmosphere nuclei, one should also expect a change in the interactions due to Lorentz Invariance Violation (LIV). In this work, the effects of LIV on the development of Extensive Air Showers (EAS) have been considered. After having introduced LIV as a perturbation term in the single-particle dispersion relation, a library of simulated showers with different energies, primary particles and LIV strengths has been produced. Possible LIV has been studied using the muon content of air showers measured at the Pierre Auger Observatory. Limits on LIV parameters have been derived from a comparison between the Monte Carlo expectations and muon fluctuation measurements from the Pierre Auger Observatory.

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1. Introduction

Violations of Lorentz symmetry could change the energy threshold of photo-hadronic interactions; in particular, depending on the composition of the UHECRs at the highest energies, the attenuation length of photo-meson production or photo-disintegration may become extremely large and suppress particle interaction during propagation in the extragalactic space [1–4]. As a consequence, the existing evidence of the suppression of the flux at the highest energies [5] can be used to put a limit on LIV. In particular, LIV can be tested by searching the best description of the UHECR observables, under LIV assumptions, as already done in [6–11]. However, the scenario is complicated by the fact that the best description of the UHECR spectrum and composition is found corresponding to values of maximum energy at the source smaller than or comparable to the typical threshold energy for photo-meson or photo-disintegration reactions [12]. For this reason, the sensitivity of the deviations from LI in UHECR propagation is smaller than previously expected, and alternative approaches need to be investigated. One possibility to constrain LIV models is that, depending on the strength of the violation, the high energy available in the collision of cosmic rays with the atmosphere can lead to modifications of the shower development with respect to the standard LI case.

2. The Pierre Auger Observatory

The Pierre Auger Observatory [13], located on a vast plain in Argentina, just northeast of the town of Malargüe, in the Province of Mendoza, 1440 m above the sea level, is the largest observatory to detect UHECRs ever built and it has been in operation since 2004. It covers an area of 3000 km^2 with a Surface Detector array (SD) overlooked by a Fluorescence Detector (FD). The SD consists of 1660 water-Cherenkov detectors arranged in a triangular grid operating with a nearly 100% duty cycle. Each SD station detects at ground level the secondary particles of the EAS produced by the primary UHECR interacting in the atmosphere. The FD consists of a set of telescopes that measure the UV fluorescence light from nitrogen molecules excited by the EAS particles along their path in the atmosphere. FD operations are limited to clear moonless nights, resulting in a duty cycle of about 15%. This hybrid detection technique combines the calorimetric measurement of the shower energy through fluorescent light with the high-statistics data of the surface array. The combination of the information from both techniques results in a quasi-calorimetric determination of the energy scale, a geometric direction reconstruction and an estimator of the primary particle mass.

3. Lorentz Invariance Violation framework

A well established phenomenological approach to introduce LIV effects [14, 15] consists of adding effective terms in the dispersion relation of particles as:

$$E^2 - p^2 = m^2 + f(\vec{p}, M_{\mathrm{Pl}}; \eta) \tag{1}$$

where m is the particle mass at rest, E its energy, and f represents the violated contribution due to the quantum gravity effects. In this approach the violation depends on the momentum of the particle $\vec{p}$ and on the Planck mass M_{Pl} through the LIV parameter η, a dimensionless constant coefficient to

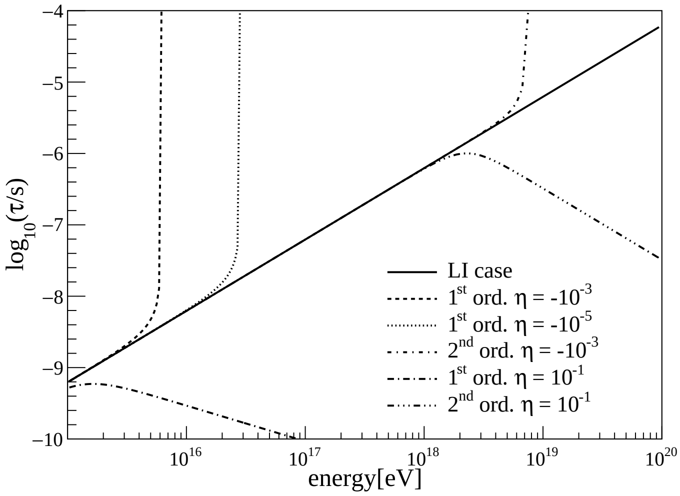


Figure 1: Neutral pion mean lifetime as a function of energy for the Lorentz invariant case and for different strengths of LIV.

be constrained. At $p \ll M_{\mathrm{Pl}}$, the factor f can be expanded and, considering only the leading order of the expansion, Eq. 1 becomes:

$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\mathrm{Pl}}^n} \tag{2}$$

Interpreting the right-hand side of the Eq. 2 as an energy dependent mass, $m_{\mathrm{LIV}}^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\mathrm{Pl}}^n}$, the Lorentz factor for a LI violating particle at energy E can be defined as:

$$\gamma_{\mathrm{LIV}} = E/m_{\mathrm{LIV}} \tag{3}$$

Depending on the value assumed by $\eta^{(n)}$, the LIV effects can be easly analyzed considering the lifetime of the considered particle $\tau = \gamma_{\mathrm{LIV}}\tau_0$ that will change accordingly. For negative/positive values of $\eta^{(n)}$ the lifetime of the particle should increase/decrease with respect to the LI case producing modifications in the EAS development which depends both on the energy and the strength of the violation. To understand the expectations, the π^0 decay can be taken into account. The π^0 lifetime as a function of the energy for the standard case and for different values of the LIV parameters is shown in Fig. 1. The energy at which the lifetime evolution deviates from the standard LI case depends both on the order and the strength of the violation. To have a qualitative idea of what one should expect, let us consider the simple model [17] where a primary hadron interacting in the atmosphere produces 2/3 of charged pions $\pi^\pm$ and 1/3 of $\pi^0 s$. In the standard case, charged pions decay producing muons and neutrinos while the neutral ones suddenly decay in two photons producing an electromagnetic sub-shower. Otherwise, in the presence of LIV and for negative values of $\eta^{(n)}$, the π^0 lifetime grows and the probability to interact before decaying increases. The re-interacting π^0s will behave as the source of a hadronic sub-showers like those initiated by the primary cosmic ray particle. As the energy decreases in the further shower generations, π^0s will start again to produce a standard electromagnetic sub-shower. The consequence is a modification of the shower development in the atmosphere. The amount of energy deposited in the atmosphere will be reduced (i.e. invisible energy going to neutrinos will grow) leading to an underestimation of the primary energy if the event is treated as a standard physics one. Moreover, the position of the shower maximum ($X_{\rm max}$) [18] will be slightly modified with respect to the standard LI case. In addition, as the muon content correlates with the energy of the hadronic component of the shower, we can expect that the number of muons produced in the EAS will increase and the physical fluctuations will decrease, as almost all the energy is kept into the hadronic component after the first stages of the shower developement, with little room for stochastic leakage to the electromagnetic component [19]. In this work only the effects due to negative values of the η parameter are considered. Our purpose is to find only the lower limit of the bound for LIV at first order.

To quantify the effect of LIV on the shower development, we have performed a library of simulated showers by using CONEX software [20, 21] in both LI and LIV cases. For the violated scenario, the software has been modified by changing the lifetimes of all the unstable particles according to Eq. 3. In particular, in the velocity definition $\beta = \frac{|\mathbf{P}|}{m\gamma}$, the Lorentz factor γ has been replaced with the LIV expression $\gamma_{\rm LIV} = E/m_{\rm LIV}$. The values of $\eta^{(n)}$ considered[1] for this study are $-10^{-1}, -10^{-2}, -10^{-3}, -10^{-4}, -10^{-5}, -10^{-6}, -10^{-7}, -10^{-8}$ and order of the violation $n = 1, 2$. For each value of η, 5000 primary cosmic ray particles have been produced in the energy range between 10^{16} eV and 10^{21} eV, using EPOS LHC [22] and QGSJETII-04 [23] hadronic interaction models and for different primary particle types i.e. proton, helium, nitrogen, silicon and iron.

4. Lorentz Invariance Violation effects on air shower development: Muon content distribution

As a result of the modified air shower simulation in the presence of LIV at first order, we have considered the mean longitudinal profile dE/dx. For larger values of $|\eta|$ (only negative LIV parameters are taken into account) the effects due to the violation increase. In fact, we have found a shift of $X_{\rm max}$, and a reduction in the height of the maximum energy deposit in the atmosphere.

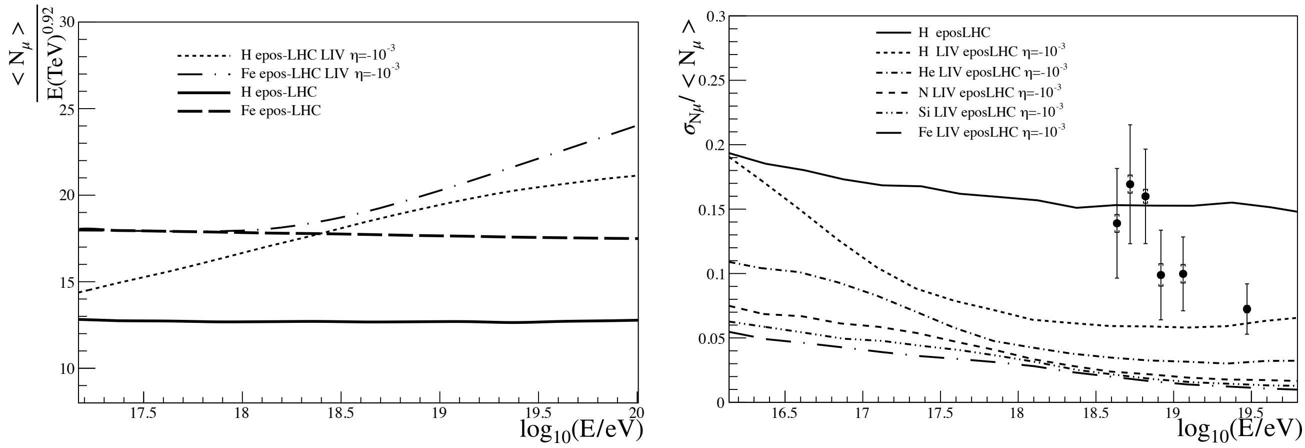
First of all, the displacement in the position of the maximum of the longitudinal profile leads to different values of $X_{\rm max}$. The change in the energy threshold of particle decays (mainly neutral pions), consuming the electromagnetic part of the shower faster, generates the effect to move the shower maximum to higher altitudes. This is due to the fact that a proton from the point of view of the shower development is behaving like a heavier nucleus. In fact, in the presence of LIV, the measured mass composition corresponds to a greater fraction of protons at the highest energies. This result has been already used in order to constrain LIV models in a previous work [24] and it is not considered in this contribution.

On the other hand, the reduction in the normalization of the longitudinal profile is linked to a change in the number of muons at the ground. In particular, the calorimetric energy deposited in the atmosphere in the presence of LIV is lower than the standard one. The modification of the energy-momentum relation allows hadronic interactions of neutral pions that contribute to the growth of the hadronic cascade producing an increase in the number of muons, as shown in Fig. 2(a),

[1]Positive values of LIV parameter have been also considered but no effect on the shower development has been found because in these cases, the lifetime of neutral pions, already negligible in the LI case, decreases above the critical energy and the pions decay faster than in the standard one.

where the average number of muons at ground as a function of the primary energy in LI and LIV cases are shown. For proton-induced air showers, the number of muons is considerably increased, in any of the LIV cases considered here, while for iron primaries the effect is in general milder.

These two main effects, caused by the LIV framework, affect the fluctuations of the number of muons. In fact, the ratio of the fluctuations to the average number of muons (hereinafter referred to as relative fluctuations), dominated mostly by the first interaction [19], considerably decreases in the presence of LIV, as shown in Fig. 2(b), where the relative fluctuations of the number of muons as a function of the primary energy are reported.



(a) (b)

Figure 2: (a) Average number of muons at ground vs primary energy in LI and LIV cases; (b) Data (black points with error bars) compared to LI and LIV models for the relative fluctuation of the number of muons vs primary energy. The LIV case corresponds to $\eta = -10^{-3}$. The statistical uncertainty is indicated by the error bars. The total systematic uncertainty is indicated by the square brackets.

Limits on LIV parameter η can be derived comparing the observed strong decrease of the relative fluctuations with the muon fluctuation measurement [25] from the Pierre Auger Observatory.

5. Results and Discussion

Considering the dependence of the decrease of the relative fluctuations on the different LIV strengths, a new bound for the LIV parameter $\eta^{(1)}$ has been obtained. To find this, the most conservative LIV model with respect to data, depending on the particular mixture of primary particles, should be considered. In particular, the effects of different composition scenarios on both fluctuations and average number of muons have been taken into account. It can be noticed, referring to Fig. 3 in [25], that the mixture of the two components, p and Fe, gives the maximum value of relative fluctuations. Therefore, the most conservative LIV model corresponds to the ratio of the fluctuations to the average number of muons for a mixture of proton and iron.

We have defined the average number of muons $\langle N_\mu \rangle_{\mathrm{mix}}$ and the fluctuations $\mathrm{RMSD}_{\mathrm{mix}}(N_\mu)$ for a mixture of p and Fe using the following expressions:

$$\begin{aligned} \langle N_\mu \rangle_{\text{mix}}(\alpha;\eta) &= (1-\alpha)\langle N_\mu \rangle_p + \alpha \langle N_\mu \rangle_{Fe} \\ \text{RMSD}^2_{\text{mix}}(N_\mu)(\alpha;\eta) &= (1-\alpha)\text{RMSD}^2(N_\mu)_p + \alpha \text{RMSD}^2(N_\mu)_{Fe} + \alpha(1-\alpha)(\langle N_\mu \rangle_p - \langle N_\mu \rangle_{Fe})^2 \end{aligned} \tag{4}$$

where α, which depends on the energy, is the relative abundance of iron nuclei and the subscripts p and Fe label the averages and RMSD of pure proton and iron primaries respectively that are retrieved from the air shower simulations[2]. These values have been used to parametrize $\langle N_\mu \rangle$ and the RMSD between $\log(E/\text{eV}) = 10^{16.5}$ and $\log(E/\text{eV}) = 10^{20}$, for $-10^{-3} < \eta < -10^{-15}$ and for different masses. For each value of η, the parameterizations can be used to calculate the expected relative fluctuations for a certain mixture of proton and iron nuclei (hereinafter referred to as mixed relative fluctuations) as:

$$\frac{\sigma_\mu}{\langle N_\mu \rangle}(\alpha;\eta) = \frac{\sqrt{\text{RMSD}^2_{\text{mix}}(N_\mu)(\alpha;\eta)}}{\langle N_\mu \rangle_{\text{mix}}(\alpha;\eta)} \tag{5}$$

To determine the most conservative LIV model the result of the mixed relative fluctuations for different mixtures of proton-iron composition are considered as a function of the energy. In particular, it has been found that the maximum with respect to α is above all the mixed relative fluctuations for a scan of the relative abundance α between 0 and 1. This effect has been observed for all the violation strengths. Therefore, only if all the curves are below the data points, the maximum with respect to $\alpha(E)$ of the Eq. 5 in each energy bin corresponds to the most conservative LIV model. For any LIV parameter value, the most conservative LIV relative fluctuations as a function of the energy can be found without repeating any shower simulation. In Fig. 3, the coloured thin curves represent the maxima with respect to α for the relative fluctuations obtained from the parameterizations considering the η parameter in the range $[-10^{-3}, -10^{-15}]$. Considering only the curves that are below the data, the χ^2 can be calculated as a function of η using each resulting mixed fluctuation and all the experimental data points. In this way, a continuous confidence level to exclude the LIV model has been found. This continuous result allows to determine the strictest lower η parameter bound. As a consequence, the new bound for $\eta^{(1)}$ is $[-5.95 \cdot 10^{-6}, 10^{-1}]$ at 90.5% of CL.

In conclusion, we have found a new lower bound of the η parameter range of values using the maximum relative fluctuation for a mixed initial proton-iron composition for LIV at first order. A similar approach using the minimum of the relative fluctuation with respect to α could lead to the definition of a negative upper bound of the LIV parameter.

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[2] $\langle N_\mu \rangle_p$, $\langle N_\mu \rangle_{Fe}$, RMSD^2_{p} and $\text{RMSD}^2_{\text{Fe}}$ depend on energy and on LIV parameter η

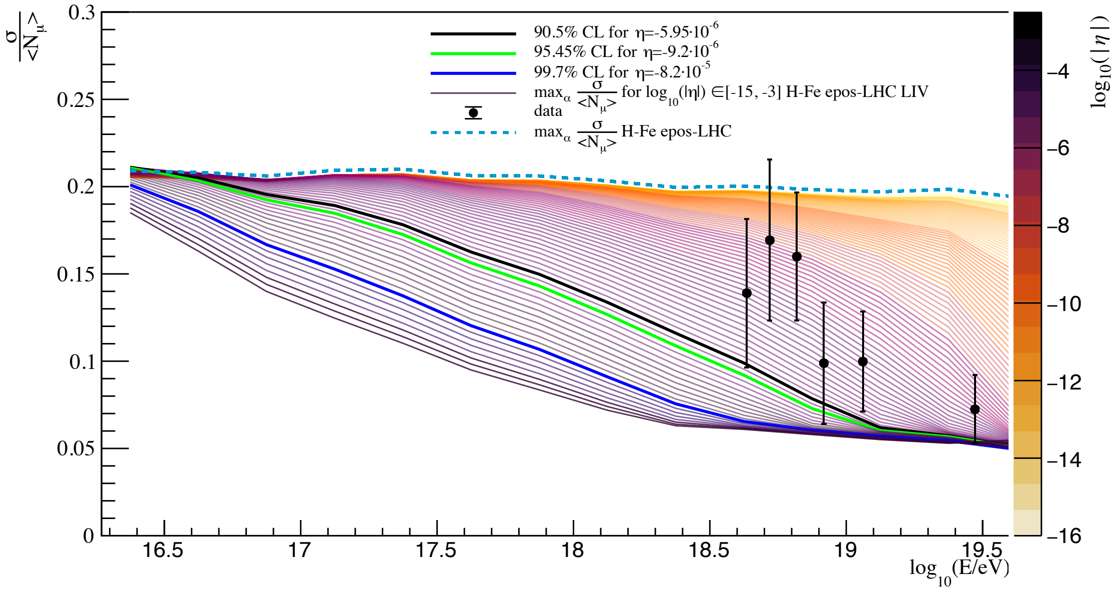

Figure 3: Maximum with respect to α of the mixed relative fluctuations obtained using the parameterizations in the standard case (dashed curve) and in the presence of LIV considering η in the range $[-10^{-3}, -10^{-15}]$ (coloured curves) as a function of the primary energy. Each color corresponds to a different violation strength (right axis). The black points with error bars (statistical uncertainties) represent the measured relative fluctuations in the number of muons.

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PIERRE AUGER OBSERVATORY

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