Probing Lorentz Invariance Violation at the Pierre Auger Observatory

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Lorentz invariance violation: why test it?
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Dispersion relation

\[ E_a^2 = p_a^2 + m_a^2 + \sum_n \frac{\eta_{a,n}}{M_{Pl}^n} p_a^{n+2} \]

CMS Energy

\[ s = E_a^2 - p_a^2 = m_a^2 + \sum_n \frac{\eta_{a,n}}{M_{Pl}^n} p_a^{n+2} \]
\[ \delta_{a,n} := \frac{\eta_{a,n}}{M_{Pl}^n} \]

\[ S_a = m_a^2 + \sum_n \delta_{a,n} E_a^{n+2} \]

Lorentz invariance violation: CMS energy
LIV effects are expected to be stronger for higher energies;

Ultra-high energy cosmic rays (UHECR) could provide a powerful tool for testing LIV.

Ultra-high energy cosmic rays

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The Pierre Auger Observatory is a state of the art experiment for UHECRs;
- Over 500 scientists from 18 countries;
- Largest cosmic ray observatory (3000 km²);
- 1440 water tanks and 27 fluorescence telescopes.

See X. Bertou’s contribution for more information
Objectives
\[
\left( -\frac{1}{E} \frac{dE}{dt} \right) = c \int_{-1}^{1} \frac{d \cos \theta}{2} \int_{\epsilon_{th}}^{\infty} d\epsilon n(\epsilon) \sigma(E, \epsilon, \theta) K(E, \epsilon, \theta)
\]

**Interactions with the Photon Background**

- **Threshold Energy**
- **Inelasticity**

*UHECR propagation: energy losses* Rodrigo Guedes Lang
Photopion production

\[ p + \gamma \rightarrow p + \pi \]

- LIV on the proton and pion sectors;
  - n=0;

Photodisintegration

\[ N_A + \gamma \rightarrow N_{A-1} + p \]

- LIV on the nuclei sector;
  - n=0;
Photopion production: inelasticity $L_1$

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Photopion production: inelasticity LIV

\( \delta_p = 10^{-23} \)
\( \delta_\pi = 0 \)
Photopion production: attenuation length

Photodisintegration: energy threshold $L_1$
Photodisintegration: energy threshold LIV

$\delta p = 10^{-22}$

$N_A + \gamma \rightarrow N_{A-1} + p$

Initial mass dependency

Energy dependency
Photodisintegration: mean free path

$\lambda[Mpc]$ vs $\log_{10}(E/eV)$ for $^{28}\text{Si}$ with $\delta = 10^{-22}$ (green), $\delta = 10^{-23}$ (red), and $\delta = 0$ (black).
• Even though the effects on propagation are very strong, it cannot be directly measured;
• It is necessary to obtain the effects on measurements, such as the spectrum and the composition;
• To do such, the modified energy losses were implemented in a propagation Monte Carlo code: SimProp v2r3;
• Spectra with 5 free parameters were simulated and fitted to both the spectrum and the composition for four cases:
  • $\delta_p = 0$ (LI)
  • $\delta_p = 10^{-23}$
  • $\delta_p = 10^{-23}$
  • $\delta_p \rightarrow \infty$ (maximal LIV)
Energy Distribution at the Sources

\[
\frac{dN}{dE_S} = \begin{cases} 
E_S^{-\Gamma} & \text{for } R_s < R_{\text{Max}} \\
E_S^{-\Gamma} e^{(1-R_s/R_{\text{Max}})} & \text{for } R_s \geq R_{\text{Max}}
\end{cases}
\]

Injected Masses

- pH
- pHe
- pN
- pFe

Source Evolution

\[ q(z) \propto \frac{1}{dz/dt} \]

5 free parameters
Denise Boncioli for the Pierre Auger Collaboration, 35th ICRC (2017)
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• The propagation of UHECR considering LIV has been calculated by changing the kinematics of pion production and photodisintegration (GZK effect);
• The modified energy losses have been implemented on SimProp v2r3;
• A combined fit of both spectrum and composition has been done for several LIV coefficients;
• The fit favours low rigidity cutoffs, suppressing the LIV effects;
• The maximal LIV case is disfavored by 3 $\sigma$. This case, however, is more dependent on the fit conditions;
• Next steps:
  • Photon propagation;
  • Air showers;