

Testing Lorentz invariance with the ultrahigh energy cosmic ray spectrumXiao-Jun Bi,^{1,2} Zhen Cao,¹ Ye Li,^{1,*} and Qiang Yuan¹¹*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China*²*Center for High Energy Physics, Peking University, Beijing 100871, People's Republic of China*

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The Greisen-Zatsepin-Kuzmin cutoff predicted at the ultrahigh energy cosmic ray spectrum has been observed by the HiRes and Auger experiments. The results put severe constraints on the effect of Lorentz invariance violation (LIV), which has been introduced to explain the absence of the Greisen-Zatsepin-Kuzmin cutoff indicated in the AGASA data. Assuming a homogeneous source distribution with a single power-law spectrum, we calculate the ultrahigh energy cosmic ray spectrum observed on the Earth by taking photopion production, e^+e^- pair production, and the adiabatic energy loss into account. The effect of LIV is also taken into account in the calculation. By fitting the HiRes monocular spectra and the Auger combined spectra, we show that the LIV parameter is constrained to $\xi = -0.8_{-0.5}^{+3.2} \times 10^{-23}$ and $0.0_{-0.4}^{+1.0} \times 10^{-23}$, respectively, which is very consistent with strict Lorentz invariance up to the highest energy.

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I. INTRODUCTION

A number of extensions of the standard model suggest that Lorentz invariance (LI) is only a low-energy approximation and it may be deformed at very high energies, e.g., approaching the Planck scale $\sim 10^{28}$ eV [1–4]. In a simple form shown by Coleman and Glashow, Lorentz invariance violation (LIV) can be expressed as a modified energy-momentum relation $E^2 = m^2 + p^2 + \xi p^2$, under the assumption that LI is violated perturbatively in the context of conventional quantum field theory [5]. It can also be interpreted in terms of different maximal attainable velocities for different particles. Modified energy-momentum relations with LIV terms proportional to the cube of the momentum, or a higher power, are also considered [6]. Although LI has been confirmed at accelerators up to 2 TeV for protons [7], 104.5 GeV for electrons, and 300 GeV for photons [8], it is still possible to see LIV in astrophysical processes with much higher energy, especially in the ultrahigh energy cosmic rays (UHECRs) with energies above 10^{18} eV [9].

Since the gyration radius of UHECRs is larger than the height of our Galaxy in the Galactic magnetic field, UHECRs are generally thought to be of extragalactic origin. Propagating through intergalactic space, the UHECRs will interact with cosmic microwave background (CMB) photons, which results in energy and flux depletion. In particular, the photomeson process will induce a suppression in the spectrum above $(3-6) \times 10^{19}$ eV and lead to the well-known Greisen-Zatsepin-Kuzmin (GZK) cutoff [10,11]. The spectrum of UHECRs can be calculated theoretically by assuming the source distribution and injection energy spectrum. The energy loss processes for UHECRs propagating in the intergalactic space include photopion

production and e^+e^- pair production when interacting with CMB, as well as the adiabatic energy loss due to the expansion of the Universe [12–14]. Because of the short mean-free path of photopion production, the spectrum of UHECRs above 6×10^{19} eV falls sharply and results in the GZK cutoff.

However, measurements of the UHECR spectrum have led to great confusion in the last decade. The result of the Akeno-AGASA experiment clearly shows an extension of the spectrum beyond the GZK cutoff [15]. To account for the AGASA data beyond the GZK cutoff, LIV has been introduced [5]. Even a LIV parameter as small as $\xi \approx 3 \times 10^{-23}$ may lead to the removal of the GZK cutoff [5,9,16]. However, the measurements by HiRes [17] and Yakutsk [18] seem to show the existence of the GZK cutoff.

Recently, the situation tends to be clear. Having accumulated data for years, the HiRes Collaboration confirms their previous result and observes the GZK cutoff with a 5σ standard deviation [19]. The Pierre Auger Collaboration gives results consistent with HiRes and rejects a single power-law spectrum above $\sim 10^{19}$ eV at the 6σ confidence level [20,21]. As confirmation of the GZK cutoff, severe constraints can be placed on the effect of LIV.

In this paper, we investigate how the LIV can be constrained according to the latest HiRes and Auger data. We give details of the method used to calculate the UHECR spectrum with LI in Sec. II. Then LIV is introduced to our calculation of the spectrum of UHECRs in Sec. III. The modified spectrum with different LIV parameters and the constraints on the LIV parameters are also shown in this section. Section IV gives conclusions and discussions.

II. THE SPECTRUM OF ULTRAHIGH ENERGY PROTONS IN THE STANDARD MODEL

We assume the composition of UHECRs is pure proton. When propagating in intergalactic space, the ultrahigh

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energy (UHE) protons will experience energy losses through the adiabatic expansion of the Universe, e^+e^- pair production, and photopion production due to the interaction with CMB photons. Then the energy evolution equation for a proton is

$$-\frac{1}{E} \frac{dE}{dt} = \beta_z^{\text{ad}}(E) + \beta_z^{e^+e^-}(E) + \beta_z^\pi(E), \quad (1)$$

where $\beta_z^{\text{ad}}(E)$, $\beta_z^{e^+e^-}(E)$, and $\beta_z^\pi(E)$ are the proton energy loss rate due to the Universe expansion, pair production, and pion production, respectively.

The energy loss rates of protons at $z = 0$ are [14,22]

$$\begin{aligned} \beta_0^{\text{ad}}(E) &= H_0, \\ \beta_0^{e^+e^-,\pi}(E) &= \frac{1}{2\gamma^2} \int_{\epsilon'_{\text{th}}}^{\infty} \sigma(\epsilon') K(\epsilon') \epsilon' d\epsilon' \int_{\epsilon'/2\gamma}^{\infty} \frac{n(\epsilon)}{\epsilon^2} d\epsilon \\ &= \frac{T}{2\pi^2\gamma^2} \int_{\epsilon'_{\text{th}}}^{\infty} d\epsilon' \sigma(\epsilon') K(\epsilon') \epsilon' \\ &\quad \times \left[-\ln \left[1 - \exp\left(-\frac{\epsilon'}{2\gamma T}\right) \right] \right], \end{aligned} \quad (2)$$

where H_0 is today's Hubble expansion rate, E and ϵ are the energies of the proton and the CMB photon in the laboratory system (LS), respectively, ϵ' is the photon energy in the proton rest system, γ is the Lorentz factor of the proton in the LS, $\sigma(\epsilon')$ is the interaction cross section, $K(\epsilon')$ is the average fraction of energy loss, i.e., the inelasticity in the LS, $n(\epsilon)$ is the differential number density of CMB photons, and $T \approx 2.73$ K is the temperature of CMB. ϵ'_{th} in Eq. (2) is the threshold energy of the photon in the proton

rest system above which the e^+e^- pair or pion production can occur. Thus, $\epsilon'_{\text{th}}^{e^+e^-} = 2m_e(1 + m_e/m_p) = 1.022$ MeV and $\epsilon'_{\text{th}}^\pi = m_\pi(1 + m_\pi/2m_p) = 149$ MeV for $p\gamma \rightarrow pe^+e^-$ and $p\gamma \rightarrow p\pi$, respectively.

Because of the redshifts of CMB photons, the energy loss rate will be larger at redshift z . The energy loss rate $\beta_z(E)$ can be derived as [14]

$$\beta_z^{\text{ad}}(E) = H(z), \quad \beta_z^{e^+e^-,\pi}(E) = (1+z)^3 \beta_0[(1+z)E], \quad (3)$$

where $H(z) = H_0 \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$ is the Hubble parameter. In this work we use the following cosmological parameters: $H_0 = 71$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$, according to the recent observations [23].

Solving Eq. (1) with the boundary condition $E(z=0) = E_0$, we can get the initial energy distribution of protons which will be observed with energy E_0 at the Earth. We denote this function as $E_g(E_0, z)$, which means the initial energy distribution as a function of redshift z and observational energy E_0 . We employ two assumptions: (1) proton sources are distributed homogeneously in the Universe without the evolution effect; (2) the source spectrum is a power law with index γ_g . Then the observational proton spectrum at the Earth can be written as [14]

$$\begin{aligned} J(E_0) &= \frac{L_0}{4\pi} (\gamma_g - 2) \int_0^{z_{\text{max}}(E_0)} dz \left| \frac{dt}{dz} \right| (1+z)^m E_g^{-\gamma_g} \\ &\quad \times \frac{dE_g(E_0, z)}{dE_0}, \end{aligned} \quad (4)$$

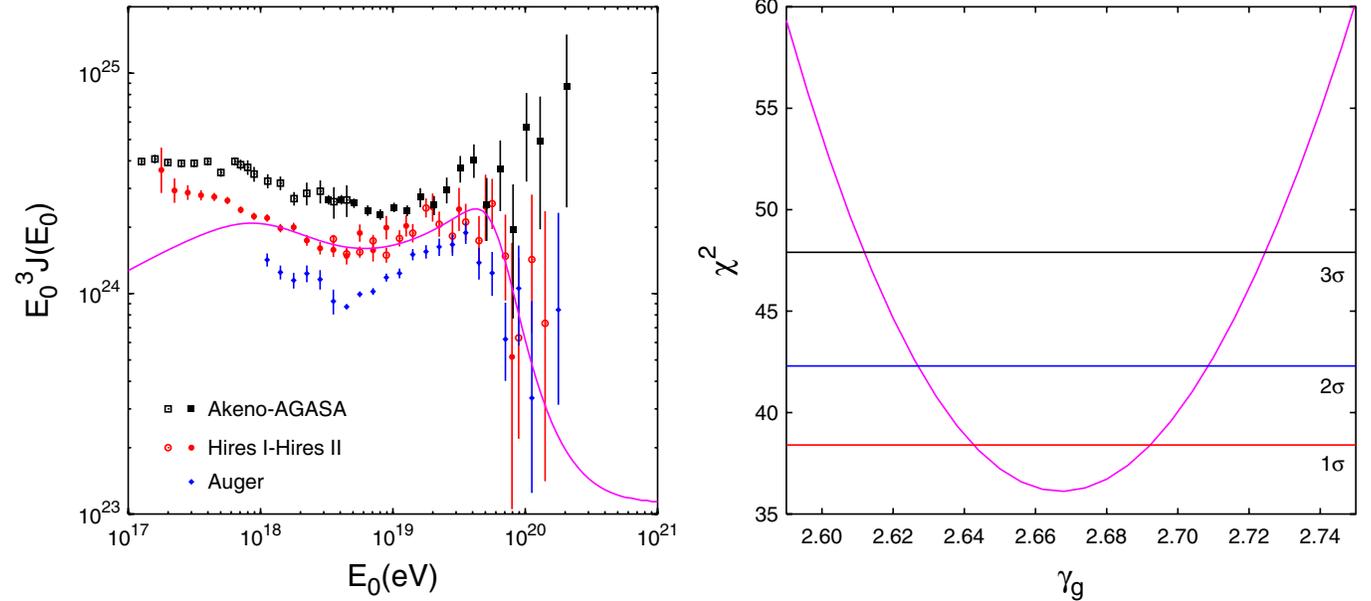


FIG. 1 (color online). Left panel: the expected UHE proton energy spectrum (magenta curve) compared with the observational data from the AGASA [15], HiRes [19], and Auger [20] experiments. The source spectrum of the theoretical curve is adopted as $\gamma_g = 2.67$, and the flux is normalized to the data of HiRes above 10^{18} eV. Right panel: the fitting χ^2 distribution as a function of the parameter γ_g for HiRes data. The three horizontal lines show the uncertainty ranges of γ_g at 1σ , 2σ , and 3σ confidence levels, respectively.

with

$$\frac{dE_g(E_0, z)}{dE_0} = (1+z) \times \exp \left[\frac{1}{H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \times \left(\frac{db_0(E')}{dE'} \right)_{E'=(1+z')E_g(E_0, z')} \right], \quad (5)$$

where $b_0(E) \equiv -dE/dt = E\beta_0(E)$, $|dt/dz| = 1/[(1+z)H(z)]$, and z_{\max} is the redshift of protons with maximum energy E_{\max} that reach us with energy E_0 . In this work we adopt $E_{\max} \approx 10^{22}$ eV. Larger E_{\max} do not affect the results. L_0 is the total luminosity of UHE protons and is determined by matching the calculated spectrum to the observational data. The $(1+z)^m$ indicates the evolution of primary UHECR sources. However, this term is still unclear at present. Among the possible sources of UHECRs, the galaxies and some types of active galactic nuclei show $m \approx 2.6$ redshift evolution in radio, optical, and x-ray bands [24], while for BL Lacertae objects there is a strong “negative” evolution [25]. It can be proven that for several reasonable evolution regimes, including the no-evolution case, the UHECR spectra can be reproduced well with different primary spectra [14]. Therefore, we adopt the no-evolution case for the source luminosity ($m = 0$) in this work.

Equation (4) can be simply understood: the protons within the initial energy interval $(E_g, E_g + dE_g)$ at redshift z contribute to the detected energy interval $(E_0, E_0 + dE_0)$; the sum of all redshifts gives the total flux.

In Fig. 1 we show the theoretical spectrum of the UHE protons with the source index $\gamma_g = 2.67$, which corresponds to the best fitting results of HiRes monocular data [19]. Data from AGASA [15] and Auger [20] are also shown in Fig. 1. The theoretical flux has been normalized to the data of HiRes above 10^{18} eV. The cosmic rays below 10^{18} eV are usually thought to be of Galactic origin [26], and we ignore them in this work. The right panel of Fig. 1 shows the fitting χ^2 distribution as a function of the source spectrum index γ_g using the HiRes data. The best fitting γ_g is 2.67, with a $\chi^2/\text{d.o.f.} = 36.1/31$. The statistical 1 σ range of γ_g is $2.58 < \gamma_g < 2.73$.

III. THE SPECTRUM OF UHE PROTONS WITH LIV

In this section we discuss how the LIV can modify the UHE proton spectrum. We adopt the framework of LIV developed by Coleman and Glashow, that a small first order perturbation is added to the free-particle Lagrangian [5]. The modification of the Lagrangian is then translated into the change of the dispersion relation of free particles,

$$E^2 = m^2 + p^2 + \xi p^2, \quad (6)$$

where ξp^2 is the perturbation term. $|\xi|$ is a very small

parameter ($\sim 10^{-23}$) and may be different for various particle species.

Since the dispersion relation is changed by LIV, the kinematics of the reaction $p\gamma \rightarrow NX$, with N the nuclei and X the mesons, will also be changed, and finally, the UHE proton spectrum is modified. For a detailed treatment of the effect of LIV on the kinematics of $p\gamma$ collision, we will closely follow the work of Alfaro and Palma [27]. In this work we only consider the process $p\gamma \rightarrow N\pi$, for simplicity.

The LIV effect generally modifies the kinematical inelasticity K , which is defined as the ratio between the energy of the pion, E_π , and the primary proton energy E_p , $K = E_\pi/E_p$. The equation of inelasticity under the modified kinematics is given as [27]

$$(1 - K_\theta)\sqrt{s} = F + \beta \cos\theta \sqrt{F^2 - s_N(K_\theta)}, \quad (7)$$

with

$$F = \frac{s + s_N(K_\theta) - s_\pi(K_\theta)}{2\sqrt{s}}, \quad (8)$$

where K_θ is the inelasticity as a function of the angle θ between the proton momentum in the center of mass system (CMS) and the direction of the CMS relative to the LS, $s = E_{\text{tot}}^2 - p_{\text{tot}}^2 = (E + \epsilon)^2 - (\vec{p} - \vec{k})^2$ is the square of the total rest energy in the CMS, and s_π and s_N are the CMS energies of the pion and recoil nuclei, defined as

$$s_a = E_a^2 - p_a^2 = m_a^2 + \xi_a p_a^2. \quad (9)$$

Note that for $\xi < 0$, s_a can be negative and the particle will have a spacelike four-momentum. We require $s_a > 0$ in this work to guarantee that the particle is timelike [27]. According to the definition of inelasticity, we have

$$s_N = m_N^2 + \xi_N [(1 - K_\theta)E_p]^2, \quad (10)$$

$$s_\pi = m_\pi^2 + \xi_\pi (K_\theta E_p)^2,$$

in which we replace the perturbation term ξp^2 in Eq. (6) with ξE^2 , for simplicity.

Following Ref. [27] we assume $|\xi_\pi| \gg |\xi_N| \approx 0$, and denote ξ_π as ξ ; then Eq. (7) can be further simplified. Equation (7) is solved numerically to get K_θ , and the average with respect to θ gives the total inelasticity $K = \frac{1}{\pi} \int_0^\pi K_\theta d\theta$. We can see from the above equations that the inelasticity K is a function of E_p and $s = (E + \epsilon)^2 - (\vec{p} - \vec{k})^2 = s_p + 2\sqrt{s_p}\epsilon'$, where s_p is the energy of the proton in its CMS and ϵ' is the photon energy in this system. For LI with $\xi = 0$, K is independent of E_p and is only a function of ϵ' .

In Fig. 2 we show the inelasticity as a function of the proton energy E_p in the LS and the CMB photon energy ϵ' in the proton rest system, for the standard model as well as

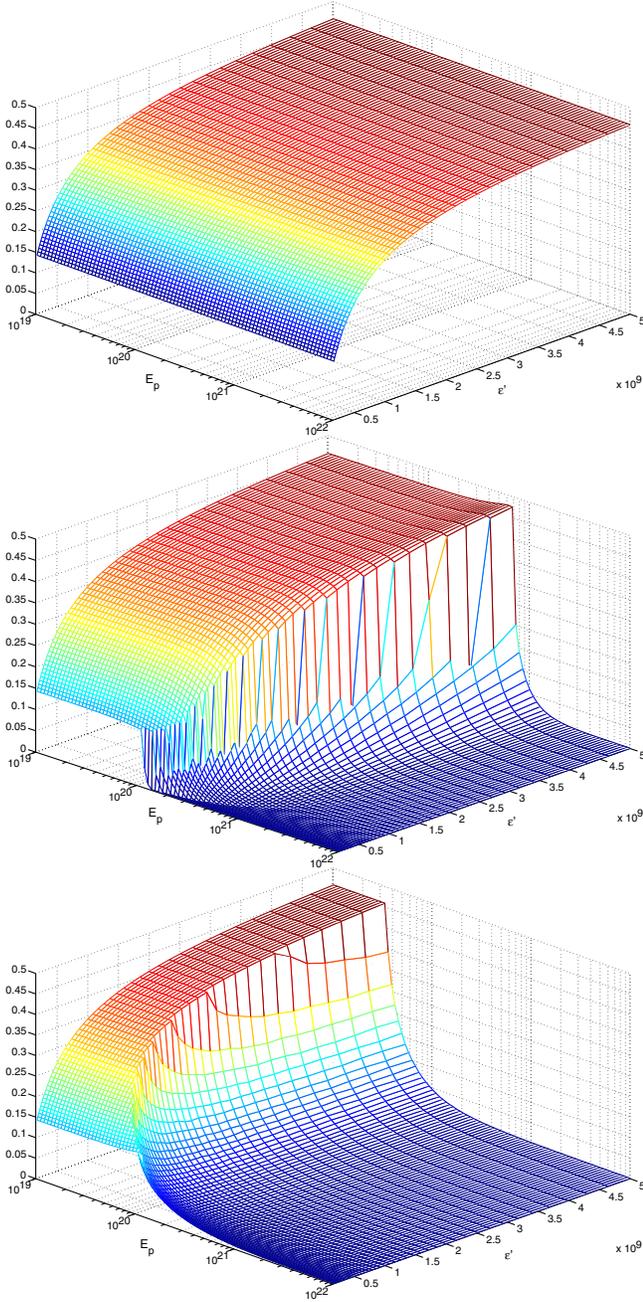


FIG. 2 (color online). The inelasticity as a function of the proton energy E_p in the LS and the CMB photon energy ϵ' in the proton rest system, for the standard model (upper panel), LIV modified models with $\xi = 1 \times 10^{-23}$ (middle panel), and $\xi = -1 \times 10^{-23}$ (lower panel), respectively.

the models modified by LIV. Two kinds of LIV scenarios with $\xi = 1 \times 10^{-23}$ and $\xi = -1 \times 10^{-23}$ are investigated. We show that the modification of the LIV is the reduction of the inelasticity at high energies. This effect is understood as the LIV leading to a reduction of the allowed phase space for the interaction [27,28]. It is interesting to note that no matter if ξ is positive or negative, the effect is similar—the inelasticity is reduced. Therefore, if the LIV

exists, we can expect that the spectrum of UHE protons will be less suppressed by the γp interaction.

The modified spectra of UHE protons for several values of LIV parameters are shown in Fig. 3, together with the unmodified spectrum from the standard model. We see that the GZK suppression effect becomes less significant for LIV cases. For very high energies or for large magnitudes of LIV parameters, the source spectra tend not to be distorted; i.e., the photopion production process $\gamma p \rightarrow N\pi$ does not play an important role anymore.

We employ a minimum χ^2 fitting method to derive the implication of the HiRes and Auger data on the LIV parameter. A scan in the (ξ, γ_g) plane is taken to calculate the UHECR spectra and the corresponding χ^2 . Minimizing the χ^2 distribution, we give a combined fit to get the source spectrum index γ_g and the LIV parameter ξ simultaneously. The confidence regions for 1σ , 2σ , and 3σ confidence levels in the ξ - γ_g plane are shown in Fig. 4 for the HiRes monocular spectra and the Auger combined spectrum, respectively. The best fitting results and 1σ uncertainties of the parameters are $\gamma_g = 2.67^{+0.01}_{-0.02}$, $\xi = -0.8^{+3.2}_{-0.5} \times 10^{-23}$ for HiRes and $\gamma_g = 2.57^{+0.02}_{-0.02}$, $\xi = 0.0^{+1.0}_{-0.4} \times 10^{-23}$ for Auger, respectively. It is shown that the standard model with $\xi = 0$ is very consistent with the present data. Compared to previous work, here we employ a more strictly statistical analysis and include the negative part of ξ .

Considering an evolution factor $(1+z)^{2.6}$, we find that the best fitting results are $\gamma_g = 2.55^{+0.02}_{-0.01}$, $\xi = -0.1^{+1.2}_{-1.2} \times 10^{-23}$ for HiRes data, and $\gamma_g = 2.37^{+0.01}_{-0.02}$, $\xi = 0.0^{+0.5}_{-0.5} \times 10^{-23}$ for Auger surface data, respectively. It is shown that the source spectrum differs a bit from the case with no source evolution. As for the LIV parameter, the results are very consistent within the statistical errors, and the conclusion is almost unchanged.

IV. CONCLUSION AND DISCUSSION

The recent observations of the UHECR spectrum by HiRes [19] and Auger [20] show the existence of GZK suppression. In this work we use these observational data to test the LIV model and set constraints on the LIV parameter. The composition of UHECRs is assumed to be pure proton. We then solve the propagation equation of UHE protons in an expanding universe after incorporating the LIV effect in the energy loss rate of protons. A minimum χ^2 fit to the observational data above 10^{18} eV is adopted to derive the source spectrum of UHE protons and the LIV parameter. We find that the current data can limit the LIV parameter for pions to the level $\sim 3 \times 10^{-23}$. The standard model with the GZK cutoff is very consistent with the observational data.

Only the LIV on the photopion production process is considered in this work. The pair production occurs at lower energy and the LIV effect might be less significant.

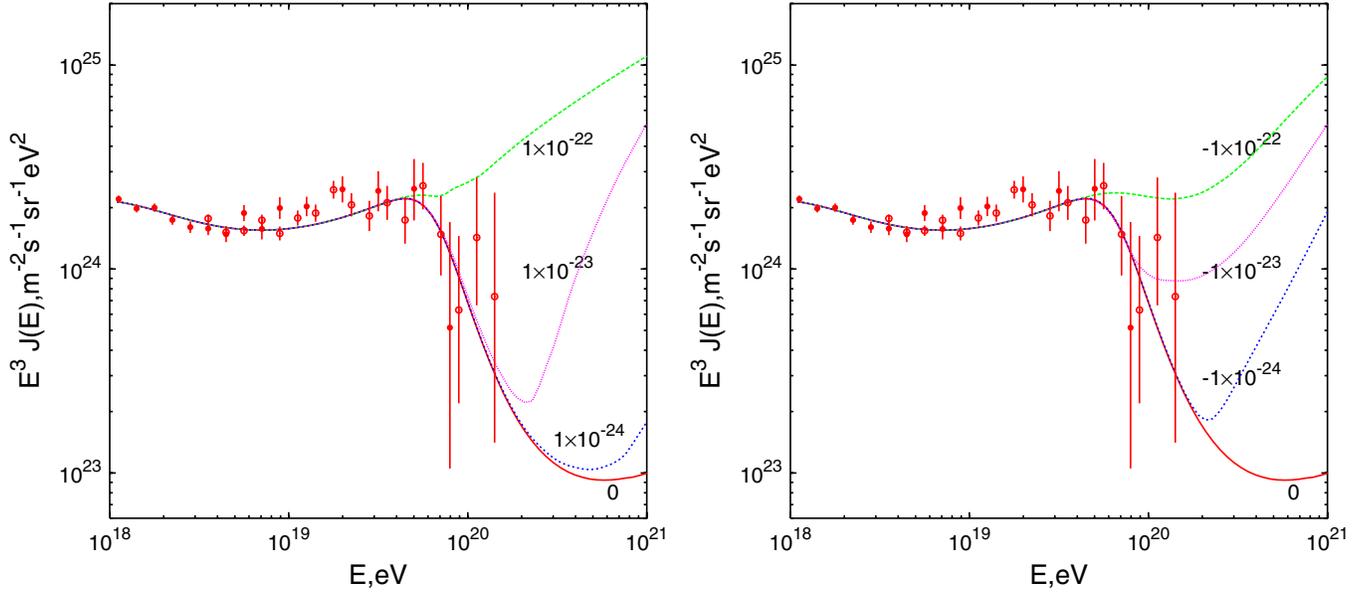


FIG. 3 (color online). The UHE proton spectra modified by LIV compared with the one predicted by the standard model. Left panel: $\xi > 0$; right panel: $\xi < 0$. The observational data are from HiRes [19].

To incorporate the LIV effect into the e^+e^- production process, the analysis will be more complicated. In addition, we need to restrict the treatment to the case $\xi_\pi \gg \xi_N \approx 0$. This has been shown to be due to the weakness of the presentation of the theory. We are unable to determine whether the perturbation term comes from the initial proton or the final state proton, which have different energy in the LS [27].

In this work the composition of UHECRs is assumed to be pure proton. However, the composition of UHECRs is poorly known from the experimental point of view. The observations of HiRes show that the UHECRs are proton dominant [29], while the results from the Auger experi-

ment indicate a mediate mass composition [30]. The determination of the UHECR composition depends on the interaction model and has a relatively large uncertainty at present. If the UHECRs are heavy nuclei dominant, the main process during the propagation in the CMB photon field is photo-disintegration, which will lead to the change of the composition and energy of primary cosmic rays and, accordingly, form a GZK-like spectrum [31–33].

We can make a rough estimate of the LIV effect in such a case, by assuming the primary composition of UHECRs to be iron and considering the process $^{56}\text{Fe} + \gamma(\text{CMB}) \rightarrow ^{55}\text{Mn} + p$. The analysis is greatly simplified by assuming $\xi_{\text{Mn}} \approx \xi_p \approx 0$, while the physics is not changed as only

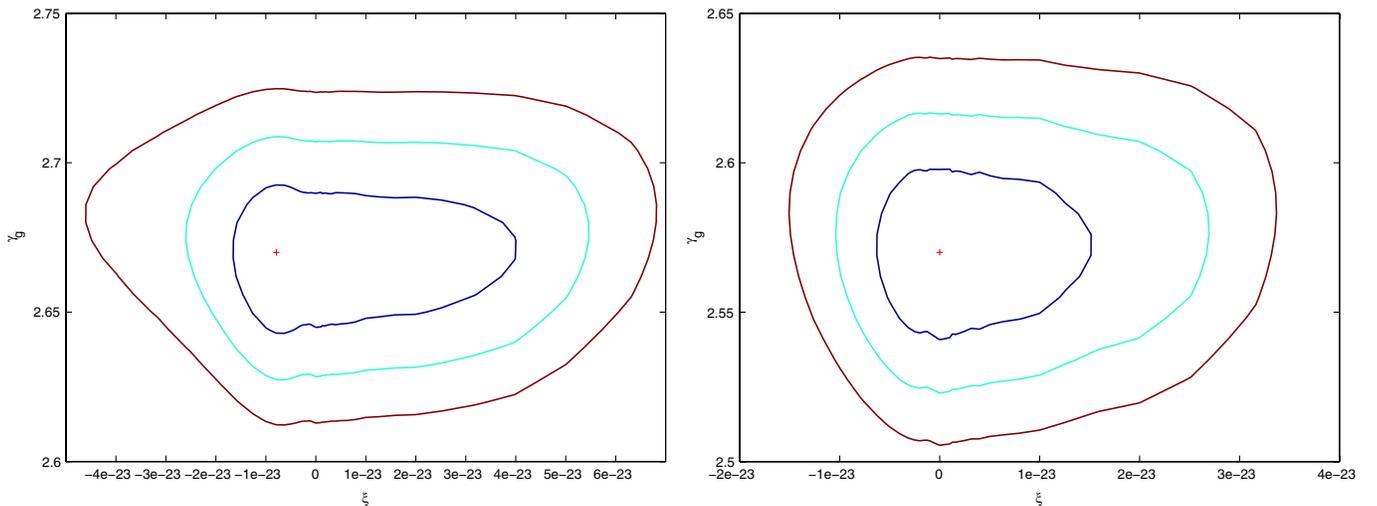


FIG. 4 (color online). The 1σ , 2σ , and 3σ confidence regions (from inside to outside) on the ξ - γ_g parameter plane using HiRes (left panel [19]) and Auger (right panel [20]) data above 10^{18} eV. The red cross shows the best fitting values.

the difference of the ξ 's in the initial and final states is relevant for the kinematics [5]. On the one hand, the interaction of photo-disintegration is possible only if $m_{\text{Fe}}^2 + 4\epsilon E_{\text{Fe}} + \xi_{\text{Fe}} E_{\text{Fe}}^2 \geq (m_{\text{Mn}} + m_p)^2$, resulting in $\xi_{\text{Fe}} \geq -4\epsilon^2 / [(m_{\text{Mn}} + m_p)^2 - m_{\text{Fe}}^2] \approx -2 \times 10^{-25} [\epsilon / \epsilon_0]^2$ for CMB energy $\epsilon_0 = 2.35 \times 10^{-4}$ eV. On the other hand, the spontaneous fragmentation $^{56}\text{Fe} \rightarrow ^{56}\text{Mn} + p$ should be forbidden for iron with energy lower than $\sim 3 \times 10^{20}$ eV since cosmic rays with such energies have been detected. This condition requires $m_{\text{Fe}}^2 + \xi_{\text{Fe}} E_{\text{Fe}}^2 < (m_{\text{Mn}} + m_p)^2$, which gives $\xi_{\text{Fe}} < 1.2 \times 10^{-23}$ for $E_{\text{Fe}} = 3 \times 10^{20}$ eV. Therefore, we get $-2 \times 10^{-25} \leq \xi_{\text{Fe}} \leq 1.2 \times 10^{-23}$. It should be noted that the above estimates are quite rough. It will be more complicated to use the

UHECR spectrum to study the LIV effects for heavy nuclei because there will be a chain of nuclei species taking effect in the interactions. Further detailed analysis is needed to probe the LIV if the UHECRs are proved to be heavy nuclei in future experiments.

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