# Physics Opportunities Above the Greisen-Zatsepin-Kuzmin Cutoff: Lorentz Symmetry Violation at the Planck Scale


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**Abstract.** Special relativity has been tested at low energy with great accuracy, but these results cannot be extrapolated to very high-energy phenomena: this new domain of physics may actually provide the key to the, yet unsettled, question of the ether and the absolute rest frame. Introducing a critical distance scale, $a$ , below $10^{-25}$ $cm$ (the wavelength scale of the highest-energy observed cosmic rays) allows to consider models, compatible with standard tests of special relativity, where a small violation of Lorentz symmetry ($a$ can, for instance, be the Planck length) leads to a deformed relativistic kinematics (DRK) producing dramatic effects on the properties of very high-energy cosmic rays. For instance, the Greisen-Zatsepin-Kuzmin (GZK) cutoff does no longer apply and particles which are unstable at low energy (neutron, some hadronic resonances like the $\Delta^{++}$, possibly several nuclei...) become stable at very high energy. In these models, an absolute local rest frame exists (the **vacuum rest frame**, VRF) and special relativity is a low-momentum limit. We discuss the possible effects of Lorentz symmetry violation (LSV) on kinematics and dynamics, as well as the cosmic-ray energy range (well below the energy scale associated to the fundamental length) and experiments (on earth and from space) where they could be detected.


## STATUS OF THE RELATIVITY PRINCIPLE

H. Poincaré was the first author to consistently formulate the relativity principle on the grounds of experiment, stating in 1895 [1]:

*"Experiment has provided numerous facts justifying the following generalization: absolute motion of matter, or, to be more precise, the relative motion of weighable matter and ether, cannot be disclosed. All that can be done is to reveal the motion of weighable matter with respect to weighable matter"*

The deep meaning of this law of Nature was further emphasized by the same author when he wrote in 1901 [2], in connexion with Lorentz contraction:

*"Such a strange property seems to be a real coup de pouce presented by Nature itself, for avoiding the disclosure of absolute motion... I consider quite probable*

*that optical phenomena depend only on the relative motion of the material bodies present, of the sources of light and optical instruments, and this dependence is not accurate... but rigorous. This principle will be confirmed with increasing precision, as measurements become more and more accurate"*

The role of H. Poincaré in building relativity, and the relevance of his thought, have often been emphasized [3,4]. In his June 1905 paper [5], published before Einsteins's article [6] arrived (on June 30) to the editor, he explicitly wrote the relativistic transformation law for the charge density and velocity of motion and applied to gravity the "Lorentz group" (that he introduced), assumed to hold for "forces of whatever origin". From this, he inferred that "gravitational waves" propagate at the speed of light. However, his priority is sometimes denied [7,8] on the grounds that *"Einstein essentially announced the failure of all ether-drift experiments past and future as a foregone conclusion, contrary to Poincaré's empirical bias"* [7], that Poincaré did never *"disavow the ether"* [7] or that *"Poincaré never challenges... the absolute time of newtonian mechanics... the ether is not only the absolute space of mechanics... but a dynamical entity"* [8]. It is implicitly assumed that A. Einstein was right in 1905 when *"reducing ether to the absolute space of mechanics"* [8] and that H. Poincaré was wrong because *"the ether fits quite nicely into Poincaré's view of physical reality: the ether is real..."* [7]. A basic physics issue (whether ether and an absolute rest frame exist or not), perhaps not definitely settled, underlies the debate on priority. Actually, modern particle physics has brought back the concept of a non-empty vacuum where free particles propagate: without such an "ether" where fields can condense, the standard model of electroweak interactions could not be written and quark confinement could not be understood. Modern cosmology is not incompatible with an "absolute local frame" (the **vacuum rest frame**, VRF) close to that suggested by the study of cosmic microwave background radiation. If "ether" and the VRF actually exist, the relativity principle (the impossibility to disclose absolute motion) will become a symmetry, a concept whose paternity was attributed to H. Poincaré by R.P. Feynman [9]:

*"Precisely Poincaré proposed investigating what could be done with the equations without altering their form. It was precisely his idea to pay attention to the symmetry properties of the laws of physics"*

As symmetries in particle physics are in general violated at some scale, Lorentz symmetry may be broken and an absolute local rest frame may be detectable through experiments performed beyond the relevant scale. It may even happen that Lorentz symmetry be just an infrared attractor. Poincaré's special relativity (a symmetry applying to physical processes) could live with this situation, in which case the relativity principle would refer to the impossibility to disclose absolute motion *through low-energy experiments*. But Einstein's approach, such as it was formulated in 1905 (an absolute geometry of space-time that matter cannot escape), could not survive. We discuss here two issues: a) the scale where we may expect Lorentz symmetry to be violated; b) the physical phenomena and experiments potentially able to uncover Lorentz symmetry violation (LSV). Previous papers on the subject are references [10] to [20] and references therein.

# RELATIVITY AS A LOW-ENERGY LIMIT

Low-energy tests of special relativity have confirmed its validity to an extremely good accuracy [21,22], in impressive agreement with Poincaré's 1901 conjecture. But the situation at very high energy remains more uncertain (see [10] to [20]): high-energy physics corresponds to a domain never covered by the experiments that motivated special relativity a century ago. Figures can change by more than 20 orders of magnitude between the highest oberved cosmic-ray energies and the scale explored by the above mentioned tests of Lorentz symmetry. If LSV follows a $E^2$ law ($E$ = energy), similar to the effective gravitational coupling, it can be of order 1 at $E \approx 10^{21}\ eV$ and $\approx 10^{-26}$ at $E \approx 100\ MeV$ (corresponding to the highest momentum scale involved in nuclear magnetic resonance experiments), in which case it will escape all existing low-energy bounds. If LSV is $\approx 1$ at Planck scale ($E \approx 10^{28}\ eV$), and following a similar law, it will be $\approx 10^{-40}$ at $E \approx 100\ MeV$ . Our suggestion is not in contradiction with Einstein's thought after he had developed general relativity. In 1921 , A. Einstein wrote [23]:

*"The interpretation of geometry advocated here cannot be directly applied to submolecular spaces... it might turn out that such an extrapolation is just as incorrect as an extension of the concept of temperature to particles of a solid of molecular dimensions"*.

It is in itself remarkable that special relativity holds at the attained accelerator energies, thus confirming Poincaré's conjecture far beyond expectations. But there is no fundamental reason for this dazzling success to persist above Planck scale. A typical (and natural) example of models violating Lorentz symmetry at very short distance is provided by models where an absolute local rest frame exists and non-locality in space is introduced through a fundamental length scale $a$ [11]. Such models lead in the VRF to a deformed relativistic kinematics of the form [11,12]:

$$E \ = \ (2\pi)^{-1}\ h\ c\ a^{-1}\ e\ (k\ a) \tag{1}$$

A where $h$ is the Planck constant, $c$ the speed of light, $k$ the wave vector and $[e\ (k\ a)]^2$ is a convex function of $(k\ a)^2$ obtained from vacuum dynamics. Expanding equation (1) for $k\ a \ll 1$ , we can write:

$$e\ (k\ a) \ \simeq \ [(k\ a)^2 \ - \ \alpha\ (k\ a)^4 \ + \ (2\pi\ a)^2\ h^{-2}\ m^2\ c^2]^{1/2} \tag{2}$$

$m$ being the mass, $\alpha$ a model-dependent positive constant $\approx 0.1 - 0.01$ for full-strength LSV at momentum scale $p \approx a^{-1}\ h$ , and in terms of momentum $p$ :

$$E \ \simeq \ p\ c \ + \ m^2\ c^3\ (2\ p)^{-1} \ - \ p\ c\ \alpha\ (k\ a)^2/2 \tag{3}$$

The "deformation" $\Delta\ E \ = \ -\ p\ c\ \alpha\ (k\ a)^2/2$ in the right-hand side of (3) implies a Lorentz symmetry violation in the ratio $E\ p^{-1}$ varying like $\Gamma\ (k) \ \simeq \ \Gamma_0\ k^2$ where $\Gamma_0 \ = \ -\ \alpha\ a^2/2$ . If $c$ and $\alpha$ are universal parameters for all particles, LSV does not lead to the spontaneous decays predicted in [24]: the existence of very high-energy cosmic rays cannot be regarded as an evidence against LSV. With the deformed relativistic kinematics (DRK) defined by (1)-(3), Lorentz symmetry remains valid in the limit $k \rightarrow 0$, contrary to the standard $TH\epsilon\mu$ model [25]. The above nonlocality may actually be an approximation to an underlying dynamics involving superluminal particles [10,12–14,17], just as electromagnetism looks nonlocal in the potential approximation to lattice dynamics in solid-state physics: it would then correspond to the limit $c\ c_i^{-1} \rightarrow 0$ where $c_i$ is the superluminal critical speed.

As recently pointed out [16], equation (1) is a fundamental property of old scenarios (f.i. [26]) breaking local Lorentz invariance (LLI). An ansatz based on an isotropic, continuous modification of the Bravais lattice dynamics is [11]:

$$e\ (k\ a) \ = \ [4\ sin^2\ (ka/2)\ +\ (2\pi\ a)^2\ h^{-2}\ m^2\ c^2]^{1/2} \tag{4}$$

and simple extensions of the ansatz by Rédei [26] lead [16] to expressions like:

$$\begin{aligned} e\ (k\ a) \ = \ & [10\ +\ 30\ (k\ a)^{-2}\ cos\ (k\ a)\ - \\ & 30\ (k\ a)^{-3}\ sin\ (k\ a)\ +\ (2\pi\ a)^2\ h^{-2}\ m^2\ c^2]^{1/2} \end{aligned} \tag{5}$$

In any case, we expect observable kinematical effects when the term $\alpha(ka)^3/2$ becomes as large as the term $2\ \pi^2\ h^{-2}\ k^{-1}\ a\ m^2\ c^2$ . This happens at:

$$E \ \simeq (2\pi)^{-1}\ h\ c\ k \ \approx \ E_{trans} \ \approx \ \alpha^{-1/4}\ (h\ c\ a^{-1}/2\pi)^{1/2}\ (m\ c^2)^{1/2} \tag{6}$$

Thus, contrary to conventional estimates of LLI breaking predictions [27] where the modification of relativistic kinematics is ignored, observable effects will be produced at wavelength scales well above the fundamental length. For a nucleon, taking $a \approx 10^{-33}\ cm$ and $\alpha \approx 0.1$, this corresponds to $E \approx 10^{19}\ eV$ , below the highest energies at which cosmic rays have been observed. With full-strength LSV, for a proton at $E \approx 10^{20}\ eV$ and with the above value of $a$ , we get:

$$\alpha\ (k\ a)^2/2 \ \approx \ 10^{-18} \ \gg \ 2\ \pi^2\ h^{-2}\ k^{-2}\ m^2\ c^2 \ \approx \ 10^{-22} \tag{7}$$

and, although $\alpha(ka)^3/2$ is very small as compared to the value of $e\ (k\ a)$ , the term $2\ \pi^2\ h^{-2}\ k^{-1}\ a\ m^2\ c^2$ represents an even smaller fraction. Although relativity reflects to a very good approximation the reality of physics at large distance scales and can be considered as its low-energy limit, no existing experimental result proves that it applies with the same accuracy to high-energy cosmic rays.

Are $c$ and $\alpha$ universal? This may be the case for all "elementary" particles, i.e. quarks, leptons, gauge bosons..., but the situation is less obvious for hadrons, nuclei and heavier objects. From a naive soliton model [11], we inferred that: a) $c$ is expected to be universal up to very small corrections ($\sim 10^{-40}$) escaping all existing bounds; b) a possible approximate rule can be to take $\alpha$ universal for leptons, gauge bosons and light hadrons (pions, nucleons...) and assume a $\alpha \propto m^{-2}$ law for nuclei and heavier objects, the nucleon mass setting the scale.

## RELEVANCE OF COSMIC-RAY EXPERIMENTS

If Lorentz symmetry is broken at Planck scale or at some other fundamental scale, and assuming that the earth moves slowly with respect to the VRF, the effects of LSV may be observable well below this energy and produce detectable phenomena at the highest observed cosmic-ray energies. This is due to DRK [11,12,15,18]: at energies above $E_{trans}$ , the deformation $\Delta\ E$ dominates over the mass term $m^2\ c^3\ (2\ p)^{-1}$ in (3) and modifies all kinematical balances. Because of the negative value of $\Delta\ E$ , it costs more and more energy, as energy increases above $E_{trans}$, to split the incoming logitudinal momentum. The parton model (in any version), as well as standard formulae for Lorentz contraction and time dilation, are also expected to fail above this energy [12,15] which corresponds to $E\ \approx\ 10^{20}\ eV$ for $m =$ proton mass and $\alpha\ a^2\ \approx\ 10^{-72}\ cm^2$ (f.i. $\alpha\ \approx\ 10^{-6}$ and $a =$ Planck length), and to $E\ \approx\ 10^{18}\ eV$ for $m =$ pion mass and $\alpha\ a^2\ \approx\ 10^{-67}\ cm^2$ (f.i. $\alpha\ \approx\ 0.1$ and $a =$ Planck length). In particular, the following effects are predicted:

a) For $\alpha\ a^2\ >\ 10^{-72}\ cm^2$ , and assuming a universal value of $\alpha$ , the Greisen-Zatespin-Kuzmin (GZK) cutoff [28,29] is suppressed [11,15,16,18] for the particles under consideration and ultra-high energy cosmic rays (e.g. protons) produced anywhere in the presently observable Universe can reach the earth without losing their energy in collisions with the cosmic microwave background radiation.

b) With the same hypothesis, unstable particles with at least two stable particles in the final states of all their decay channels become stable at very high energy [11,16]. Above $E_{trans}$, the lifetimes of all unstable particles (e.g. the $\pi^0$ in cascades) become much longer than predicted by relativistic kinematics [11,16,18].

c) In astrophysical processes at very high energy, similar mechanisms can inhibit radiation under external forces, GZK-like cutoffs, decays, photodisintegration of nuclei, momentum loss through collisions, production of lower-energy secondaries... potentially contributing to solve all basic problems raised by the highest-energy cosmic rays. Therefore, calculations of astrophysical processes at very high energy cannot ignore the possibility that Lorentz symmetry be violated [18].

d) With the same hypothesis, the allowed final-state phase space of two-body collisions is modified and can lead to a sharp fall of cross-sections for incoming cosmic ray energies above $E_{lim}\ \approx\ (2\ \pi)^{-2/3}\ (E_T\ a^{-2}\ \alpha^{-1}\ h^2\ c^2)^{1/3}$, where $E_T$ is the energy of the target [19]. As a consequence, and with the previous figures for the parameters of LSV, above some energy $E_{lim}$ between $10^{22}$ and $10^{24}$ $eV$ a cosmic ray will not deposit most of its energy in the atmosphere and can possibly fake an exotic event with much less energy.

e) Effects a) to d) are obtained using only DRK. If dynamical anomalies are added (failure, at very small distance scales, of the parton model and of the standard Lorentz formulae for length and time [12,15]...), we can expect much stronger effects in the cascade development profiles of cosmic-ray events.

f) Cosmic superluminal particles would produce atypical events with very small total momentum, isotropic or involving several jets [10,12,14,17].

In what follows, we discuss in more detail the implications of these effects.

## THE GZK CUTOFF DOES NO LONGER APPLY

For $\alpha\ a^2\ >\ 10^{-72}\ cm^2$, with a universal value of $\alpha$ , a $E\ \approx\ 10^{20}\ eV$ proton interacting with a cosmic microwave background photon would be sensitive to DRK effects [11]. After having absorbed a $10^{-3}\ eV$ photon moving in the opposite direction, the proton gets an extra $10^{-3}\ eV$ energy, whereas its momentum is lowered by $10^{-3}\ eV/c$ . In the conventional scenario with exact Lorentz invariance, this is enough to allow the excited proton to decay into a proton or a neutron plus a pion, losing an important part of its energy. The small increase in the $E/p$ ratio is enough to generate, in the final state, the increase of the nucleon mass term $m^2\ (2\ p)^{-1}$ (as momentum gets lower) as well as the pion mass term and the transverse energy of both particles. However, it can be checked [11] that in our scenario with LSV such a reaction is strictly forbidden, as the $\approx 2.10^{-23}$ increase of the $E/p$ ratio cannot provide the energy required, due to the deformation term $\Delta\ E$ , by the splitting of the incoming momentum. Elastic $p\ +\ \gamma$ scattering is permitted, but allows the proton to release only a small amount of its energy. Similar or more stringent bounds exist for channels involving lepton production. Obvious phase space limitations will also lower the collision rate, as compared to standard calculations using exact Lorentz invariance which predict photoproduction of real pions at such cosmic proton energies. The effect is strong enough to invalidate the GZK cutoff and explain the existence of the highest-energy cosmic-ray events. It will become more important at higher energies, as we get closer to the $a^{-1}$ wavelength scale. If $\alpha$ is not universal, the particle with the highest value of $\alpha$ can always reach the earth, and other particles can below some energy above the GZK cutoff. Assuming exact universality of $c$ , the situation for nuclei will crucially depend on the precise values of $\alpha$ for each nucleus and on the energy range. Models where $c$ is not exactly universal are not ruled out, as the results from [24] do not apply [13] , and deserve cosideration [18]. Our result is limited by the history of the Universe, as cosmic rays coming from distances closer and closer to horizon size will be older and older and, at early times, will have been confronted to rather different scenarios. But it is clear that DRK allows much older ultra-high energy cosmic rays, generated at much more remote sources, to reach the earth nowadays.

A previous attempt to explain the experimental absence of the predicted GZK cutoff by Lorentz symmetry violation at high energy [30] proposed an ansatz replacing relativistic kinematics by the relation:

$$E\ \ =\ \ m\ \ h\ (p^2\ E^{-2}) \tag{8}$$

where the positive function $h$ tends to $(1\ -\ p^2\ E^{-2})^{-1/2}$ in the relativistic limit. These authors considered an expansion in powers of $\gamma^4$ , where $\gamma\ =\ (1\ -\ v^2c^{-2})^{-1/2}$ , $v$ is the speed of the particle and the coefficient of the linear term in $\gamma^4$ had to be arbitrarily tuned to $\approx 10^{-44}$ in order to produce an effect of order 1 for a $10^{20}\ eV$ proton (leading to a potentially divergent expansion at higher energies). No such problems are encountered in our approach, where the required orders of magnitude come out naturally in terms of small perturbations.

## LIFETIMES AT VERY HIGH ENERGY

In standard relativity, we can compute the lifetime of any unstable particle in its rest frame and, with the help of a Lorentz transformation, obtain the Lorentz-dilated lifetime for a particle moving at finite speed. The same procedure had been followed in previous estimates of the predictions of LLI breaking [27] for the decay of high-energy particles. This is no longer possible with the kinematics defined by (1), which explicitly incorporates LSV. Instead, two results are obtained [11,16]:

i) Assuming universal values of $c$ and $\alpha$ , unstable particles with at least two massive particles in the final state of all their decay channels become stable at very high energy, as a consequence of the effect of LSV through (1). A typical order of magnitude for the energy $E^{st}$ at which such a phenomenon occurs is:

$$E^{st} \approx c^{3/2}\ h^{1/2}\ (a\ m_2)^{-1/2}\ (m^2 - m_1^2 - m_2^2)^{1/2} \tag{9}$$

where: a) $m$ is the mass of the decaying particle; b) we select the two heaviest particles of the final product of each decay channel, and $m_2$ is the mass of the lightest particle in this list; c) $m_1$ is the mass of the heaviest particle produced together with that of mass $m_2$ . With $a \approx 10^{-33}\ cm$ and $\alpha \approx 0.1$ for all particles, **the neutron would become stable** above $E \approx 10^{20}\ eV$ . **Some hadronic resonances** (e.g. the $\Delta^{++}$ , whose decay product contains a proton and a positron) **would become stable** above $E \approx 10^{21}\ eV$ . Similar considerations may apply to some supersymmetric particles. Most of these objects will decay before they can be accelerated to such energies, but they may result of a collision at very high energy or of the decay of a superluminal particle [10], The study of very high-energy cosmic rays can thus reveal as stable particles objects which would be unstable if produced at accelerators. If one of the light neutrinos ($\nu_e$ , $\nu_\mu$) has a mass in the $\approx 10\ eV$ range, **the muon would become stable** at energies above $\approx 10^{22}\ eV$ . Weak neutrino mixing may restore muon decay, but with very long lifetime. **Similar considerations apply to the $\tau$ lepton**, which would become stable above $E \approx 10^{22}\ eV$ if the mass of the $\nu_\tau$ is $\approx 100\ eV$ but, again, a decay with very long lifetime can be restored by neutrino oscillations. For nuclei, the situation will depend on the details of DRK (basically, the value of $\alpha$ for each nucleus) and deserves further investigation using more precise theoretical models.

ii) With the same hypothesis as i), all unstable particles live longer than naively expected with exact Lorentz invariance and, at high enough energy, the effect becomes much stronger than previously estimated [27] ignoring the effects of DRK. At energies well below the stability region, partial decay rates are already modified by large factors leading to observable effects. Irrespectively of whether $m_2$ vanishes or not, the phenomenon occurs above $E \approx c^{3/2}\ h^{1/2}\ (m^2 - m_1^2)^{1/4}\ a^{-1/2}$ ($\approx 10^{18}\ eV$ for $\pi^+ \rightarrow \mu^+ + \nu_\mu$ , if $a \approx 10^{-33}\ cm$ and $\alpha \approx 0.1$). The effect has a sudden, sharp rise, since a fourth power of the energy is involved in the calculation. In the LSV scenario, partial branching ratios become energy-dependent.

## FINAL-STATE PHASE SPACE

No special constraint seems to arise from (2) if, in the VRF, two particles with equal, opposite momenta of modulus $p$ with $\alpha\ (k\ a)^2\ \ll\ 1$ collide to produce a multiparticle final state. But, as a consequence of LSV, the situation becomes fundamentally different at very high energy if one of the incoming particles is close to rest with respect to the VRF where formulae (1) - (3) apply. Assume a very high-energy particle (particle 1) with momentum $\vec{\mathbf{p}}$ , impinging on a particle at rest (particle 2). We take both particles to have mass $m$ , and $p\ \gg\ mc$ . In relativistic kinematics, we would have elastic final states where particle 1 has, with respect to the direction of $\vec{\mathbf{p}}$ , longitudinal momentum $p_{1,L}\ \gg\ mc$ and particle 2 has longitudinal momentum $p_{2,L}\ \gg\ mc$ with $p_{1,L}\ +\ p_{2,L}\ =\ p$ . A total transverse energy $E_\perp\ \simeq\ mc^2$ would be left for the outgoing particles. But the balance is drastically modified by DRK if $\alpha\ (k\ a)^2\ p$ becomes of the same order as $m\ c$ or larger. As the energy increases, stronger and stronger limitations of the available final-state phase space appear: the final-state configuration $p_{1,L}\ =\ p\ -\ p_{2,L}\ =\ (1\ -\ \lambda)\ p$ becomes kinematically forbidden for $\alpha\ (k\ a)^2\ p\ >\ 2\ m\ c\ \lambda^{-1}(1\ -\ \lambda)^{-1}/3$ . Above $p\ \approx (m\ c\ a^{-2}\ h^2)^{1/3}$ , "hard" interactions become severely limited by kinematical constraints. Similarly, with the same initial state, a multiperipheral final state configuration with $N$ particles ($N\ >\ 2$) of mass $m$ and longitudinal momenta $g^{i-1}\ p'_L$ ($i\ =\ 1, ..., N$ , $g\ >\ 1$), where $p'_L\ =\ p\ (g\ -\ 1)\ (g^N\ -\ 1)^{-1}$ , $g^N\ \gg\ 1$ and $p'_L\ \gg\ m\ c$ , would have in standard relativity an allowed total transverse energy $E_\perp\ (N\ ,\ g)\ \simeq\ m\ c^2\ [1\ -\ m\ c\ (2\ p'_L)^{-1}\ (1\ -\ g^{-1})^{-1}]$ which is positive definite. Again, using the new kinematics and the approximation (3), we find that such a longitudinal final state configuration is forbidden for values of the incoming momentum such that $\alpha\ (k\ a)^2\ p\ c\ >\ 2\ (3\ g)^{-1}\ (1\ +\ g\ +\ g^2)\ E_\perp\ (N\ ,\ g)$ . *Elastic, multiparticle and total cross sections will sharply fall at very high energy.*

For "soft" strong interactions, the approach were the two-body total cross section is the less sensitive to final-state phase space is, in principle, that based on dual resonance models and considering the imaginary part of the elastic amplitude as being dominated by the shadow of the production of pairs of very heavy resonances of masses $M_1$ and $M_2$ of order $\approx (p\ m\ c^3/2)^{1/2}$ in the direct channel [31,32]). Even in this scenario, we find important limitations to the allowed values of $M_1$ and $M_2$ , and to the two-resonance phase space, when $\alpha\ (k\ a)^2\ p$ becomes $\approx m\ c$ or larger. Above $E\ \approx (2\pi)^{-2/3}\ (m\ \alpha^{-1}\ a^{-2}\ h^2\ c^4)^{1/3}$ , nonlocal effects play a crucial role and invalidate considerations based on Lorentz invariance and local field theory used to derive the Froissart bound [33], which seems not to be violated but ceases to be significant given the expected behaviour of total cross sections which, at very high-energy, seem to fall far below this bound. An updated study of noncausal dispersion relations [34,35], incorporating DRK and nonlocal dynamics, can possibly lead to new bounds. If the target is not at rest in the VRF, but its energy is small as compared to that of the incoming particle, its rest energy must be replaced by the actual target energy $E_T$ in the above discussions. The absence of GZK cutoff is a particular application of this analysis, which has a much general validity.

## EXPERIMENTAL IMPLICATIONS

With DRK, a small violation of the universality of $c$ would not necessarily produce the Cherenkov effect in vacuum considered by Coleman and Glashow [24] for high-energy cosmic rays. If $c$ and $\alpha$ are both universal and $\alpha$ is positive, all stable particles remain stable when accelerated to ultra-high energies and can reach any energy without spontaneously decaying or radiating in vacuum (the case $\alpha < 0$ , not considered here, would lead to spontaneous decays and "Cherenkov" phenomena for particles at very high energy). If $c$ is universal but $\alpha$ (positive) is not, there will in any case be at least one stable particle at ultra-high energy (that with the highest positive value of $\alpha$). If none of the two constants is universal, any scenario is *a priori* possible. The mechanisms we just described compete with those considered in [24] and tend to compensate their effect: therefore, the bounds obtained by these authors do not apply to our ansatz where small violations of the universality of $c$ can be compensated by the deformation term [13,18]. On the other hand, the discussion of velocity oscillations of neutrinos presented in [36] for the low-energy region is compatible with our theory. However, the universality of $c$ seems natural in unified field theories (whereas that of the mass is naturally violated) and preserves the Poincaré relativity principle in the low-momentum limit. As previously stressed, deviations from the universality of $c$ due to nucleon or nucleus structure are expected to be very small according to naive soliton models.

For ultra-high energy cosmic rays in the $E \approx 10^{20}\ eV$ region, we expect the most dramatic physical effects to be governed by the values of $\alpha$ for the particles considered. If Lorentz symmetry is broken and an absolute rest frame exists, high-energy particles are indeed different physical objects from low-energy particles, and high-energy tests of Lorentz symmetry are required. To reach direct comparison with a $\approx 3.10^{20}\ eV$ cosmic ray event, a $p - p$ collider with energy $\approx 400\ TeV$ per beam would be required. Very-forward experiments at LHC and VLHC would be crucial steps in a systematic check of the validity of Lorentz symmetry, comparing their data with those of cosmic-ray events above $\approx 10^{16}\ eV$. Evidence for Lorentz symmetry violation would no doubt be the most important physics outcome of particle physics experiments in the decades to come.

The possibility of taking the value of $a^{-1}$ close to the wave vector of the highest-energy cosmic rays, i.e. $\approx 10^{26}\ cm^{-1}$ , was considered in [16] in connexion with a possible search for DRK effects through particle lifetimes. With $\alpha \approx 0.1$ and formulae (1)-(3), this would not be incompatible with low-energy bounds on LSV. But the value of $E_{lim}$ would become too low leading to obvious incompatibilities with data in the very high-energy region (the fall of final-state phase space). New bounds on LSV thus emerge from high-energy data using the parametrization (1)-(3). Requiring that: a) cosmic rays with energies below $\approx 3.10^{20}\ eV$ deposit most of their energy in the atmosphere; b) the GZK cutoff is suppressed at energies above $\approx 10^{20}\ eV$ , leads in the DRK scenario to the constraint: $10^{-72}\ cm^2 < \alpha\ a^2 < 10^{-61}\ cm^2$ , equivalent to $10^{-20} < \alpha < 10^{-9}$ for $a \approx 10^{-26}\ cm$ . Remarkably enough, assuming full-strength LSV forces $a$ to be in the range $10^{-36}\ cm\ <\ a\ <\ 10^{-30}\ cm$ . Data on high-energy cosmic rays contain information relevant to the search for DRK signatures and should be carefully analyzed. The energy dependence of the $\pi^0$ lifetime above $E\ \approx\ 10^{18}\ eV$ can be a basic ingredient in generating the specific cascade development profile (e.g. electromagnetic showers versus hadronic showers and muons). Beyond DRK, strong signatures can be produced by other LSV effects: failure of the parton model for protons and nuclei (including its dual "soft" version [31,32]), substantially changing the multiplicities and event shape; strong deviations from the relativistic formulae for Lorentz contraction and time dilation leading to basic modifications of the dynamics... Because of its stability at very high energy, the neutron becomes a serious candidate to be a possible primary of the highest-energy cosmic-ray events.

Cosmic rays seem to indeed be able to test the predictions of (1) and set upper bounds on the fundamental length $a$ , as well as constraints on $\alpha$ . Experiments like AUGER, OWL, AIRWATCH FROM SPACE and AMANDA present great potentialities. The study of early cascade development (perhaps with balloons installed in coincidence with the above experiments) will be crucial for the proposed investigation. Very high-energy data may even provide a way to measure neutrino masses and mixing, as well as other parameters related to phenomena beyond the standard model. If Lorentz symmetry were not violated, there would be no fundamental difference between the collision of a very high-energy cosmic ray and the "Lorentz equivalent" event at a collider. But, if Lorentz symmetry is violated, the study of the parameters governing LSV will provide us with a unique microscope directly focused on Planck-scale physics. Indeed, the $E\ \approx\ 10^{20}\ eV$ scale is closer, in order of magnitude, to the Planck scale than to the electroweak scale.

The possibility that above $E_{lim}$ cosmic rays do not deposit all their energy in the atmosphere suggests to operate underground detectors in coincidence with air shower detectors, if ever feasible at the required scales. At $E\ \approx\ E_{lim}$ , the cosmic particle can still deposit enough energy in the atmosphere to produce a detectable air shower for satellite-based and balloon experiments.

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