Remnant low-energy effects of Planck-scale Lorentz breaking in candidate fundamental theories typically include modified one-particle dispersion relations. Theoretical constraints on such modifications are discussed leading to the exclusion of a variety of previously considered Lorentz-violating parameters. In particular, the fundamental principle of coordinate independence, the role of an effective dynamical framework, and the conditions of positivity and causality are investigated.

1. Introduction
An important open issue in current fundamental-physics research is a quantum theory underlying the Standard Model and General Relativity. The characteristic scale of such a theory is likely to be associated with the Planck mass $M_{Pl} \simeq 10^{19}$ GeV. Presently attainable energies are minuscule compared to this scale, so that experimental signals are expected to be heavily suppressed. For observational progress in this subject, it is therefore necessary to identify generic effects of potential fundamental theories that are accessible to high-precision tests with present-day technology.

Relativity violations associated with the breaking Lorentz symmetry provide a promising candidate signal for Planck-scale physics [1]. At low energies, the effects of Lorentz violation are described by an effective field theory called the Standard-Model Extension (SME) [2, 3]. The classical action of the SME contains, for example, all leading-order contributions to the Lagrangian formed by contracting Standard-Model and gravitational fields with Lorentz-breaking coefficients such that coordinate independence is maintained. A theoretically attractive mechanism for Lorentz violation is spontaneous symmetry breaking in string field theory [4]. More recently,
also other candidate sources have been considered including theories of quantum gravity [5], noncommutative field theories [6], varying couplings [7], random dynamics [8], multiverses [9], and brane-world scenarios [10]. The flat-spacetime limit of the SME has provided the basis for numerous analyses of Lorentz breaking involving mesons [11, 12], baryons [13, 14], electrons [15, 16], photons [17, 18], muons [19], and neutrinos [2, 20, 21].

One-particle dispersion relations extracted from the SME generally exhibit Lorentz-violating modifications [17, 2, 3]. In principle, this offers the possibility of Lorentz tests with purely kinematical methods. For instance, primary ultrahigh-energy cosmic rays (UHECR) with momenta eight orders of magnitude below the Planck scale have been observed. At such energies, Lorentz-breaking effects might be more pronounced relative to those in low-energy tests leading to potentially observable shifts in particle-reaction thresholds. This idea has recently received a lot of attention in the literature [5, 20, 22, 23]. However, in many of these investigations the dispersion-relation modifications are constructed with a certain degree of arbitrariness and without reference to the underlying dynamics and other physical principles.

In this talk, we investigate how some of this arbitrariness can be avoided. Our analysis is primarily based on the fundamental principle of coordinate independence and on the requirement of compatibility with an effective dynamical framework. We argue that these two conditions form cornerstones of physics regardless of the details of the Planck-scale theory. General dynamical considerations also increase the scope of threshold investigations and may even be necessary in certain situations. In addition, we briefly discuss positivity and causality, properties that further contribute to the viability of kinematical studies. Throughout we assume translational invariance and the associated energy-momentum conservation.

Section 2 comments on the necessity of coordinate independence and its consequences for dispersion relations. In Sec. 3, we discusses dispersion relations from the viewpoint of compatibility with the SME. Section 4 addresses issues regarding positivity and causality. Further useful results are contained in Sec. 5. A brief summary can be found in Sec. 6.

2. Coordinate independence

On the one hand, coordinate independence is a fundamental physics principle, its role in the context of Lorentz breaking is well established [2, 23], and it permits a rough classification of different types of Lorentz violation. On
the other hand, there still exists a certain amount of confusion about this principle in the published literature. For instance, dispersion-relation corrections considered by some authors can only be reconciled with coordinate invariance by introducing unsatisfactory features. Occasionally Lorentz violation is even identified with the loss of coordinate independence. We therefore begin with a few remarks about this requirement.

Coordinate systems, which label spacetime points in a largely arbitrary way, are descriptive tools rather than objects with physical reality. Physics must therefore remain independent of the choice of coordinates. This fundamental requirement permits different observers, each describing the same physical system within a different reference frame, to relate their observations. This principle is therefore also called observer invariance. Mathematically, coordinate independence can be implemented by working on a spacetime manifold and representing physical quantities by geometric objects like tensors or spinors. Note, however, that this principle does not fix the type of the underlying manifold. A Lorentzian and a Galilean manifold, for example, would be equally consistent with coordinate independence. The manifold type can only be determined by observation. The point is that coordinate independence is much more general than Lorentz symmetry. It is only on Lorentzian manifolds where Lorentz transformations acquire the significant role of implementing changes between local Minkowski frames.

The above discussion reveals one possibility to speculate how Lorentz symmetry might be lost: local inertial frames have a structure different from the usual Minkowskian one, so that Lorentz transformations no longer generate changes between inertial coordinates, i.e., observer Lorentz covariance is replaced by observer covariance under some other symmetry transformation. Note that coordinate independence is maintained. This point of view is taken in the so called “doubly special relativities” [24]. The associated modified dispersion relations still exhibit the conventional energy degeneracy for a given 3-momentum, which is intuitively reasonable because the number of spacetime symmetries remains unchanged relative to the conventional case. We mention that the interpretation and viability of this approach is currently still controversial [25]. We therefore leave such Lorentz-symmetry deformations unaddressed in the present work.

A less speculative approach to Lorentz-symmetry breakdown maintains the conventional Lorentzian manifold structure and considers the vacuum to be nontrivial instead. Such vacua are associated with nondynamical tensorial backgrounds, which can lead, e.g., to direction-dependent propagation properties. This situation has some parallels with the behavior of particles
inside certain crystals. Although coordinate independence is maintained (e.g., invariance under rotations of the coordinate system), rotations of the propagation direction are generally no longer a symmetry in such situations. One then says that particle Lorentz symmetry is broken \[2\]. Note, however, that the presence of the conventional manifold structure implies that locally one can still work with the metric \(\eta^{\mu\nu} = \text{diag}(1, -1, -1, -1)\), particle 4-momenta still transform in the usual way under coordinate changes, and the conventional tensors and spinors still represent physical quantities. In what follows, we consider this latter type of Lorentz violation.

The usual form of Lorentz-violating dispersion relations considered in the literature is

\[
\lambda_0^2 - \vec{\lambda}^2 = m^2 + \delta f(\lambda_0, \vec{\lambda}).
\]

(1)

Here, \(m\) is the mass and \(\lambda^\mu = (\lambda_0, \vec{\lambda})\) is the plane-wave 4-vector (before the QFT reinterpretation of the negative energies). The function \(\delta f(\lambda_0, \vec{\lambda})\) parametrizes the Lorentz breaking. Arbitrary choices of \(\delta f(\lambda_0, \vec{\lambda})\) include situations with nonconserved and possibly complex-valued momenta unsuitable for kinematical analyses.\(^b\) We exclude such situation here and proceed under the assumption that the dynamics of the free particle is described by a linear partial differential equation with constant coefficients, as usual. In the absence of nonlocalities, this yields a polynomial ansatz:

\[
\delta f(\lambda_0, \vec{\lambda}) = \sum_{n \geq 1} T_{\alpha\beta\cdots}^{(n)} \lambda_\alpha \lambda_\beta \cdots.
\]

(2)

Here, \(T_{\alpha\beta\cdots}^{(n)}\) is a constant tensor of rank \(n\) parametrizing particle Lorentz violation. All the tensor indices \(\alpha, \beta, \ldots\) are distinct and each one is contracted with a momentum factor, so that all terms in the sum are observer Lorentz invariant.

We mention two immediate consequences of the general ansatz (2). First, Eq. (1) becomes a polynomial in \(\lambda_0\), so that one expects multiple roots for a given \(\vec{\lambda}\). Thus, the conventional energy degeneracy between particle,\(^a\)} dispersion relations in the minimal SME are typically fourth-order polynomials in \(\lambda_0\), so that (1) together with ansatz (2) is inconvenient. However, SME dispersion relations can be generated if \(\delta f\) is allowed to contain unsuppressed terms.\(^b\) For instance, a discrete background, such as in condensed-matter systems, lacks translation invariance resulting in the violation of momentum conservation. Another example is given by finite-temperature dispersion relations, which typically contain imaginary terms.
antiparticle, and possible spin-type states is typically lifted. This is intuitively reasonable because degeneracies normally arise through symmetries, and here the number of symmetries is reduced. Moreover, rotational invariance is in general lost in any frame. As opposed to all previous threshold analyses, generality therefore requires the consideration degeneracy-lifting anisotropic dispersion relations. Second, inspection of ansatz (2) shows that under the usual assumption of rotational symmetry the correction $\delta f(\lambda_0, \vec{\lambda})$ cannot contain odd powers of $|\vec{\lambda}|$.

3. Dynamical features

Although kinematics imposes tight constraints on particle reactions, it provides only an incomplete description of the process: an expected high-energy reaction can be suppressed not only by modified dispersion relations but also by new additional symmetries, for example. Similarly, the presence of a high-energy reaction kinematically forbidden in conventional physics could perhaps be explained by additional channels due to the loss of low-energy symmetries or novel undetected particles. Moreover, dynamics is involved both in acceleration mechanisms for UHECRs and in the atmospheric shower development. Thus, the study of threshold bounds on Lorentz violation typically requires assumptions outside kinematics such as dynamical quantum-field aspects.

Kinematics investigations are limited to only a few potential Lorentz-violating signatures from candidate fundamental physics. Thus, dynamical features also increase the scope of Lorentz tests. From the above perspectives, it is desirable to explicitly implement dynamics of sufficient generality into the search for Lorentz breaking.

The SME is the general effective-field-theory framework for the dynamical description of Lorentz violation. It is useful to review the idea behind its construction [2] to fully appreciate the generality of the SME. Lorentz-violating terms $\delta \mathcal{L}$ are added to the usual Standard-Model Lagrangian $\mathcal{L}_{\text{SM}}$:

$$\mathcal{L}_{\text{SME}} = \mathcal{L}_{\text{SM}} + \delta \mathcal{L},$$

where, $\mathcal{L}_{\text{SME}}$ denotes the SME Lagrangian. The modification $\delta \mathcal{L}$ is formed by contracting Standard-Model fields with Lorentz-violating tensorial parameters yielding observer Lorentz scalars. Thus, the complete set of poss-

$^6$Odd powers could enter in the degeneracy-lifting form $\pm |\vec{\lambda}|^{2n+1}$ with $n \in \mathbb{N}$ or through (theoretically unmotivated) nonlocal equations of motion involving $\sqrt{-\Delta}$, where $\Delta$ is the Laplacian.
sible contributions to $\delta \mathcal{L}$ gives the most general effective dynamical framework for Lorentz breaking at the level of Lorentz-coordinate-independent effective QFT. We mention that potential Planck-scale features, such as a certain discreteness of spacetime or a possible non-pointlike nature of elementary particles, are unlikely to invalidate the above effective-field-theory approach at present energies. Moreover, Lorentz-symmetric aspects of candidate fundamental theories, such as new symmetries, novel particles, or large extra dimensions, are also unlikely to require a low-energy description beyond effective field theory and can therefore be incorporated into the SME, if necessary.

The SME permits the identification and direct comparison of virtually all Lorentz and CPT tests that are presently feasible. In addition, classical kinematics test models of relativity (such as Robertson’s framework, its Mansouri-Sexl extension, or the $c^2$ model) are contained in the SME as limiting cases. Concerning threshold analyses, the quadratic, translationally invariant sector of the SME determines possible one-particle dispersion relations constraining the ansatz (2). As a further advantage, the SME permits the calculation of reaction rates, which are a determining factor for observational relevance. An explicit example is provided by so called vacuum Čerenkov radiation [20]. The above discussion strongly suggests that particle-reaction investigations are best performed within the framework of the SME.

4. Positivity and causality

In Special Relativity, the presence of an upper speed limit for material bodies left invariant by the Lorentz transformations is associated with a notion of causality. This leads to the common misconception that Lorentz violation necessarily results in superluminal propagation, and thus causality violations. However, conventional situations, in which Lorentz symmetry is broken but causality is maintained, can readily be identified. The anisotropic propagation of electromagnetic waves inside certain crystals, for example, is causal despite Lorentz violation. Moreover, in such a situation the total conserved energy is clearly positive definite for all observers. It follows that the requirements of positivity and causality are a priori independent and distinct from the principle of Lorentz symmetry. Note also that positivity and causality lead, for example, to the spin-statistics theorem, which is a cornerstone of relativistic QFT.

Since polynomial Lorentz-violating dispersion relations can violate pos-
itivity and causality [3], it is natural to ask whether such violations become acceptable in the presence of Lorentz breaking. Concerning positivity, we are unaware of any internally consistent interacting quantum field theories involving negative-energy particles as asymptotic states. On the contrary, the usual assumptions in perturbation theory, for example, seem to exclude negative energies. Similar arguments apply to superluminal propagation: it is unlikely that such a causality breakdown can be accommodated within the framework of relativistic quantum field theory. Generally, a hermitian Hamiltonian for massive fermions fails to exist in the majority of frames [3]. In addition, the usual covariant perturbative expansion relies on time ordering, an operation no longer coordinate invariant when microcausality is violated [27]. We conclude that positivity and causality remain desirable features in threshold analyses despite Lorentz breaking.

Reaction-threshold kinematics can be affected if positivity and causality are imposed. Let $M$ and $m$ be the respective scales of the underlying theory and present-day low-energy physics. Then, the scale $p_{p,e}$ for the occurrence of positivity or causality problems can be as low as [3]

$$p_{p,e} \sim O\left(\sqrt{mM}\right).$$

(4)

For example, if $M$ is taken to be the Planck scale and $m$ is the proton mass, then $p_{p,e} \sim 3 \times 10^{18}$ eV. UHECRs with a spectrum extending beyond $10^{20}$ eV have been observed. These events are often employed to bound Lorentz breaking or to suggest evidence for Lorentz violation. It follows that imposing positivity and causality could require modifications in threshold analyses.

5. Further results

Consider photon decay $\gamma \rightarrow e^+ + e^-$ into an electron-positron pair, where both the photon ($m = 0$) and the fermion obey dispersion relations with the correction $\delta f(\lambda_0, \bar{\lambda}) = \pm |\bar{\lambda}|^3/M$. Here, $M$ is the fundamental scale. Note that by allowing two simultaneous signs for the correction term, we enforce coordinate independence. This correction gives

$$\lambda_{\pm(\alpha)}^0(\bar{\lambda}) = \pm \sqrt{(-1)^\alpha \frac{|\bar{\lambda}|^3}{M} + \bar{\lambda}^2 + m^2},$$

(5)

where the subscript $\pm$ corresponds to the sign of the square root, and thus, after reinterpretation, to particle and antiparticle. The index $\alpha = 1, 2$ labels the two possible particle (antiparticle) energies, which perhaps correspond...
to different spin-type states. Depending on the $\alpha$ value for each particle in the reaction, there are six kinematically distinct decays that have to be considered. Note, however, that angular-momentum conservation associated with the rotational invariance of the model may preclude some of the six reactions. In general, we conclude that the effects of assumed symmetries, such as rotational invariance, must be incorporated into threshold analyses. This typically requires the use of dynamics as argued before.

Another coordinate-independent dispersion-relation correction is given by $\delta f(\lambda_0, \vec{\lambda}) = \lambda_0 \vec{\lambda}^2 / M$, so that

$$\lambda_0^0(\vec{\lambda}) = \frac{\vec{\lambda}^2}{2M} \pm \sqrt{\frac{\vec{\lambda}^4}{4M^2} + \vec{\lambda}^2 + m^2}. \tag{6}$$

Note that the particle-antiparticle degeneracy is lifted. Consider again photon decay $\gamma \rightarrow e^+ + e^-$, now with dispersion relation (6) for both the photon ($m = 0$) and the fermion. Two kinematically distinct processes must be investigated because Eq. (6) implies two possible incoming photon states $\gamma_+$ and $\gamma_-$. One can show [23] that the reaction $\gamma_- \rightarrow e^+ + e^-$ is kinematically forbidden, while the decay $\gamma_+ \rightarrow e^+ + e^-$ is allowed above a certain threshold. This analysis has been performed previously in the literature employing the approximation $\lambda_0 \approx |\vec{\lambda}|$ in the correction term $\lambda_0 \vec{\lambda}^2 / M$. However, this approximation introduces an additional degeneracy relative to Eq. (6) leading to the false conclusion that the correction $\lambda_0 \vec{\lambda}^2 / M$ precludes photon decay. Thus, many approximations, such as those leading to additional degeneracies, are typically invalid in threshold analyses.

6. Summary

This talk has discussed some issues that arise in the context of Lorentz tests with modified dispersion relations. More specifically, we have investigated the role of a dynamical framework and the conditions of coordinate independence, positivity, and causality in the subject. We have found that these fundamental requirements impose tight constraints on possible dispersion-relation corrections. Correct threshold investigations within the full SME are automatically compatible with these requirements.

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