The gravitational Standard-Model Extension (SME) is the general field-theory based framework for the analysis of CPT and Lorentz violation. In this work we summarize the implications of Lorentz and CPT violation for antimatter gravity in the context of the SME. Implications of various attempts to place indirect limits on anomalous antimatter gravity are considered in the context of SME-based models.

Keywords: Antimatter and Lorentz violation and Gravity

PACS numbers: 11.30.Cp and 04.80.Cc and 11.30.Er

1. Introduction

Antimatter physics is an area in which many predictions of our current best theories, the Standard Model of particle physics and General Relativity remain unverified. Thus experiments with antimatter provide the opportunity to place these theories on a stronger experimental foundation. One aspect of both of our existing theories that can be tested with antimatter is Lorentz symmetry, along with the associated CPT symmetry. Beyond improving the foundation of our existing theories, the search for Lorentz and CPT violation offers the potential to detect Planck-scale physics. Standard lore holds that our current theories are the low-energy limit of a more fundamental theory. Lorentz violation has been shown to arise in some candidates for the underlying theory including string theory scenarios and others, thus providing a means of searching for Planck-scale physics with current technology.

A comprehensive field-theoretic framework for investigating Lorentz and CPT symmetry as an expansion about known physics is provided by the SME. The SME is not a specific model, but a comprehensive test framework containing known physics and having the power to predict the outcome of relevant experiments that is ideally suited for a broad search. These predictions are then compared with experimental results. Since no compelling evidence for Lorentz or CPT violation has been found to date, a broad and systematic search may offer a more efficient way of seeking such violations than the consideration of many specific models. With this philosophy, a few models that illustrate aspects of the general framework are use-
ful; however, aggressive model building is avoided until new physics is found. This proceedings contribution reviews SME-based work in the context of gravitational experiments as well as an SME-based model that illustrates several possibilities in antimatter gravity.

2. Basics

The action for the QED-extension limit of the gravitationally coupled SME

\[ S = S_\psi + S_{\text{gravity}} + S_A, \]  

provides the basic theory relevant for the discussion to follow. From left to right the partial actions are the gravitationally coupled fermion sector, the pure-gravity sector, and the photon sector. Each term consists of known physics along with all Lorentz-violating terms that can be constructed from the associated fields. Since they are not directly relevant for the discussion to follow, the explicit forms of \( S_{\text{gravity}} \) and \( S_A \) are omitted here, though in general they are of considerable interest and have been the subject of a large number of tests. Here we specialize to the popular minimal-SME limit, involving operators of mass dimension 3 and 4 where the fermion-sector action takes the form:

\[ S_\psi = \int d^4x \left( \frac{1}{2} i e \tau^a \bar{\psi} \Gamma^a D_\mu \psi - e \psi M \psi \right), \]

with

\[ \Gamma^a \equiv \gamma^a - c_{\mu\nu} e^{\nu a} e^\mu_b \gamma^b - d_{\mu\nu} e^{\nu a} e^\mu_b \gamma^b - e_{\mu} e^{\nu a} - i f_{\mu} e^{\nu a} \gamma_5 - \frac{1}{2} g \lambda_{\mu\nu} e^{\nu a} e^\mu_e \sigma^{bc}, \]

\[ M \equiv m + a_{\mu} e^{\mu a} \gamma^a + b_{\mu} e^{\mu a} \gamma_5 \gamma^a + \frac{1}{2} H_{\mu\nu} e^{\mu a} e^{\nu b} \sigma^{ab}. \]

Here \( a_{\mu}, b_{\mu}, c_{\mu\nu}, d_{\mu\nu}, e_{\mu}, f_{\mu}, g_{\lambda_{\mu\nu}}, H_{\mu\nu} \) are coefficient fields for Lorentz violation and gravitational couplings occur via the vierbein \( e^{\mu a} \) and the covariant derivative. The Minkowski-spacetime fermion-sector limit can be recovered via \( e^{\mu a} \to \delta^{\mu}_a \).

The content of the coefficient fields can be understood in two ways: explicit Lorentz violation and spontaneous Lorentz violation. Explicit Lorentz violation involves the specification of the content of the coefficient fields as an external choice, whereas spontaneous Lorentz violation involves dynamical coefficient fields that receive vacuum expectation values via the spontaneous breaking of Lorentz symmetry. Spontaneous Lorentz violation is analogous to the spontaneous breaking of \( SU(2) \times U(1) \) symmetry in the Standard Model; however, unlike electroweak-symmetry breaking, the vacuum values that arise are vector or tensor objects known as coefficients for Lorentz violation that can be thought of as establishing preferred directions in spacetime. In nongravitational experiments analyzed in Minkowski spacetime seeking effects associated with the vacuum values, the distinction between explicit and spontaneous Lorentz-symmetry breaking is not relevant, and spacetime-independent coefficients for Lorentz violation are typically assumed. This
assumption could be regarded as a leading term in an expansion of a more general function. Energy and momentum conservation is also preserved in this limit.

It has been shown that explicit Lorentz violation is typically incompatible with the Riemann geometry of existing gravity theories. This suggests that consideration of Lorentz violation in a gravitational context should either be done in the context of a more general geometry or one should specialize to the case of spontaneous breaking. Here we consider the latter case. As in Minkowski-spacetime work, we consider spacetime-independent vacuum values, but geometric consistency requires consideration of certain contributions to the fluctuations about the vacuum values as well.

3. Gravitational Tests

In a gravitational context, Lorentz-violating effects can stem from the pure-gravity sector or gravitational couplings in other sectors. The framework for post-newtonian experimental searches in the pure-gravity sector is developed in Ref. 10, and numerous searches have been performed and proposed. Reference 12 provides an analysis of gravitational couplings in the fermion sector including a detailed analysis of the experimental and observational implications of spin-independent coefficient fields $a_\mu$, $c_{\mu
u}$, and $e_{\mu}$. The vacuum values associated with these coefficient fields are denoted $(\tau_{\text{eff}})_\mu$, for the countershaded (observable only under special circumstances) combination $\tau_\mu - m^2 \tau_{\mu}$, and $\tau_{\mu
u}$ for the vacuum value associated with $c_{\mu
u}$. These vacuum values correspond to the coefficients for Lorentz violation discussed in Minkowski spacetime. The experimental implications of these fermion-sector coefficients, including those relevant for antimatter, are reviewed here. Additional work on spin couplings has also been done.

Sensitivity to coefficients $(\tau_{\text{eff}})_\mu$ and $\tau_{\mu
u}$ can be achieved via a wide variety of gravitational experiments, including gravimeter experiments, tests of the universality of free fall, redshift tests, spin-precession tests, experiments with devices traditionally used for short-range gravity tests, and solar-system tests. In laboratory tests, the key point is that the above coefficients generate tiny corrections to the gravitational force both along and perpendicular to the usual free-fall trajectory near the surface of the Earth. The coefficients also alter the effective inertial mass of a test body in a direction-dependent way resulting in a nontrivial relation between force and acceleration. These effects are time dependent varying at the annual and sidereal frequencies, and may also be particle-species dependent. These properties lead naturally to a 4-category classification of laboratory tests that use Earth as a source. Measurements of the coefficients for Lorentz violation can be made by monitoring the gravitational acceleration or force over time, which constitute free-fall gravimeter tests or force-comparison gravimeter tests respectively. Similarly the relative acceleration of, or relative force on, a pair of test bodies may be monitored resulting in free-fall or force-comparison Weak Equivalence Principle (WEP) tests respectively.
While the above tests with ordinary, neutral matter yield numerous sensitivities to Lorentz violation, versions of the tests highlighted above performed with antimatter, charged particles, and second- and third-generation particles can yield sensitivities to Lorentz and CPT violation that are otherwise impossible or difficult to achieve. Reference 12 considers gravitational experiments with antihydrogen, charged-particle interferometry, ballistic tests with charged particles, and signals in muonium free fall. Positronium may also offer an interesting possibility. Here we consider antimatter tests further. A recent direct measurement of the fall of antihydrogen by the ALPHA collaboration has generated an initial direct limit on differences in the free-fall rate of matter and antimatter. Improved measurements are in preparation or have been suggested, including tests using a Moiré accelerometer, trapped antihydrogen, gravitational quantum states, and tests in space. Such experiments could obtain special sensitivities to the SME coefficients \((a_{\text{w}})_{\mu}\) and \((c_{\text{w}})_{\mu\nu}\) since the sign of \((a_{\text{w}})_{\mu}\) reverses under CPT, while the sign of \((c_{\text{w}})_{\mu\nu}\) does not. Hence antimatter experiments could place cleaner constraints on certain combinations of SME coefficients than can be obtained with matter and could in principle observe novel behaviors stemming from Lorentz violation in the SME.

4. Isotropic Parachute Model

Beyond providing a framework for the analysis of antimatter gravity experiments, the general field-theoretic approach of the SME illuminates some aspects of attempts to place indirect limits on the possibility of unconventional antimatter gravity. Consideration of toy-model limits of the SME such as the isotropic ‘parachute’ model (IPM) can help facilitate the discussion. The IPM is constructed by restricting the classical nonrelativistic Lagrange density of the SME in the Sun-centered frame \(S\), to the limit in which the only nonzero coefficients are \((a_{\text{w}})_{\mu}\) and \((c_{\text{w}})_{\mu\nu}\) since the sign of \((a_{\text{w}})_{\mu}\) reverses under CPT, while the sign of \((c_{\text{w}})_{\mu\nu}\) does not. Hence antimatter experiments could place cleaner constrains on certain combinations of SME coefficients than can be obtained with matter and could in principle observe novel behaviors stemming from Lorentz violation in the SME.

The effective Lagrangian in this limit can be written in the suggestive form

\[
L_{\text{IPM}} = \frac{1}{2} m_T^T v^2 + \frac{G_N m_T^T m_S^S}{r},
\]  

where \(v\) is the velocity, \(r\) is distance from the source, \(m_T^T\) is the effective inertial mass of \(T\), and \(m_T^T\) and \(m_S^S\) are the effective gravitational masses of \(T\) and \(S\), respectively. The effective masses are defined in terms of the coefficients for Lorentz violation and the conventional Lorentz invariant body masses \(m_B\) as follows:

\[
m_B^T = m_B + \sum_w \frac{5}{3}(N_w + N_{\bar{w}})m_w(a_{\text{w}})_{TT}
\]

\[
m_B^S = m_B + \sum_w \left((N_w + N_{\bar{w}})m_w(c_{\text{w}})_{TT} + 2\alpha(N_w - N_{\bar{w}})(a_{\text{w}})_{TT}\right).
\]  

Here \(B\) is \(T\) or \(S\), \(N_w\) and \(N_{\bar{w}}\) are the number of particles and antiparticles of type \(w\), respectively, and \(m_w\) is the mass of a particle of type \(w\).
The defining conditions of the IPM for electrons, protons, and neutrons, is

\[ \alpha(\sigma_{\text{eff}}^w)_T = \frac{1}{3} m^w_{\gamma}(\tau^w)_{TT}, \]  

where \( w \) ranges over \( e, p, n \). The conditions result in equal gravitational and inertial masses for a matter body \( B, m^B_i = m^B_g \), which implies that no Lorentz-violating effects appear in gravitational tests to third post-newtonian order using ordinary matter. In contrast, for an antimatter test body \( T, m^T_i \neq m^T_g \) within the IPM, which implies observable signals may arise in comparisons of the gravitational responses of matter and antimatter or of different types of antimatter. The following paragraphs consider the implications of some typical arguments against anomalous antimatter gravity for the IPM as well as some new indirect limits.

As a first classic argument, we consider the question of whether energy remains conserved when matter and antimatter have different gravitational responses.35 This argument is likely moot in the present SME-based discussion since conservation of energy and momentum play a starring role in developing the model.12 Still, consideration of the classic thought experiment in which a particle and an antiparticle are lowered in a gravitational field, converted to a photon pair, raised to the original location, and reconverted to the original particle-antiparticle pair is interesting. Here one normally assumes, for example, that the particle-antiparticle pair gain a particular amount of energy from the gravitational field as they fall, and this energy is converted to a pair of photons with no additional change in gravitational field energy. The photons are assumed to couple differently to gravity than the particle-antiparticle pair, and hence they lose a different amount of energy on the way back to the original height than that gained by the particle-antiparticle pair on the way down, resulting in a violation of conservation of energy. To explore these issues in the IPM, we first note that in the analysis of Ref. 12, the photons are conventional, partly via an available coordinate choice. Then we note that the CPT-odd coefficient \( (\sigma_{\text{eff}}^w)_T \) shifts the effective gravitational coupling of the particles and the antiparticles relative to the photons by equal and opposite amounts. This implies no net difference for the particle-antiparticle combination and the photons occurs as a result of \( (\sigma_{\text{eff}}^w)_T \). The role of the \( \sigma_{\mu\nu} \) coefficient appears to challenge the assumption of no change in the gravitational field energy as the particle-antiparticle pair converts to photons. If the two systems have different gravitational couplings such that they exchange different amounts of energy with the gravitational field during their trips, the field energy will also change as the coupling changes during the reaction. Hence differing gravitational couplings are not in conflict with energy conservation when field energy is considered.

Neutral-meson systems which provide natural interferometers mixing particle and antiparticle states provide another classic indirect argument against anomalous antimatter gravity.36 These systems have already been used to place tight constraints on certain differences among the \( (\sigma_{\text{eff}}^w)_{\mu\nu} \) coefficients for \( w \) ranging over quark flavors via flat spacetime considerations.37,38 These limits imply no dominant constrains for baryons, which involve three valence quarks, or for leptons in
the context of the IPM. Moreover, the tests involve valence $s$, $c$, or $b$ quarks, which are largely irrelevant for protons and neutrons. The essential point is that the flavor dependence of Lorentz and CPT violation in the SME implies that the IPM evades constraints from meson systems.

A final popular argument against anomalous antimatter gravity considered following the construction of the IPM in Ref. 12, is based on the binding energy content of baryons, atoms, and bulk matter. A version of the argument relevant for the discussion of antihydrogen could begin by noting that the quarks in hydrogen contain less than about 10% of the mass, with much of the remainder contained in the gluon and sea binding. It might then be concluded that the gravitational response of the two cannot differ by more than about 10% based on their comparable binding forces. Such arguments typically assume implicitly that the gravitational response of a body is determined by its mass and hence by binding energy. In the IPM, the coefficient $(\sigma_{\text{eff}})^T$, leads to a correction to the gravitational force that is independent of mass, but can vary with flavor. Hence the modifications to the gravitational responses are determined primarily by the flavor content of the valence particles. A scenario in which the anomalous gravitational effect is associated purely with the positron could even be considered, as would occur in the IPM when $(\sigma_{\text{eff}})^T$ is the only nonzero coefficient. An investigation of radiative effects involving $(\sigma_{\text{eff}})^T$, $(\tau^w)_{TT}$, and other SME coefficients for Lorentz violation could result in more definitive statements along the above lines, perhaps with the IPM condition imposed after renormalization; however, the key points illustrated with the IPM are: the anomalous gravitational response of a body can be independent of mass, can vary with flavor, and can differ between particles and antiparticles.

An argument against anomalous antimatter gravity not previously considered in the context of the IPM is based on treating the cyclotron frequency of a trapped particle/antiparticle as a clock, which could receive an anomalous redshift in certain models with differing gravitational responses for matter and antimatter. The basic idea is to assume equivalent frequencies for the clock and anticklock far from the source of the gravitational potential, constrain the difference in the frequencies in the lab, and extract a constraint based on the difference in the gravitational potential. Contributions from the CPT even $c_{\mu\nu}$ coefficient in the IPM have no effect since they are the same for a particle and the corresponding antiparticle. Though the $\sigma_{\nu\mu}$ coefficient takes the opposite value for particles and antiparticles, it does not typically enter the redshift as can be seen in the example of the Bohr levels of hydrogen as well as in other systems that have been considered in this context. Hence the IPM is not likely impacted by this argument.

Though the IPM is a field-theoretic toy model generating an anomalous gravitational response for antimatter that appears to evade many of the typical indirect limits, the model can be limited by a rather different type of investigation with matter. Certain experiments with sensitivity to higher powers of velocity, including the recent redshift analysis of matter systems, considerations of bound kinetic energy and double-boost suppression terms, if analyzed, in some flat-spacetime
Gravity Effects on Antimatter in the Standard-Model Extension
tests have or could constrain the IPM below the sensitivity goals of many upcoming
antimatter gravity experiments. The best constraints at present are based on bound
kinetic energy and limit the anomalous gravitational response of antimatter in the
IPM to parts in \(10^{-8}\). However it is important to note that these constraints are
quite different from many of the usual arguments against anomalous antimatter
gravity such as those noted above. They involve different types of physical argu-
ments and different experimental systems highlighting the freedom that may exist
in constructing models that are insensitive to the usual constraints. Note also that
these constraints are of immediate relevance only to the IPM, a special toy-model
limit of the SME. The possibility of constructing models similar to the IPM based
on the recently analyzed higher-order terms in the SME remains.

5. Summary
The SME provides a general field-theoretic framework for seeking Lorentz and CPT
violation, a search that probes Planck-scale physics with existing technology. The
comparison of matter and antimatter provides a means of conducting such tests,
and a special limit of the SME provides a field-theoretic toy model for investigating
indirect limits on antimatter gravity.

References
1. O.W. Greenberg, Phys. Rev. Lett. 89, 231602 (2002).
2. For a recent review, see, J.D. Tasson Rep. Prog. Phys. 77, 062901 (2014).
3. V.A. Kostelecký and S. Samuel, Phys. Rev. D 39, 683 (1989); V.A. Kostelecký and R.
Potting, Nucl. Phys. B 359, 545 (1991).
4. K. Hashimoto, Int. J. Mod. Phys. Conf. Ser. 30, 1460274 (2014), these proceedings.
5. D. Colladay and V.A. Kostelecký, Phys. Rev. D 55, 6760 (1997); Phys. Rev. D 58,
116002 (1998).
6. V.A. Kostelecký, Phys. Rev. D 69, 105009 (2004).
7. V.A. Kostelecký and M. Mewes, Phys. Rev. D 80, 015020 (2009); Phys. Rev. D 85,
096005 (2012); Phys. Rev. D 88, 096006 (2013).
8. Data Tables for Lorentz and CPT Violation, 2013 edition, V.A. Kostelecký and N.
Russell, arXiv:0801.0287v6.
9. V.A. Kostelecký, Phys. Lett. B 701, 137 (2011).
10. Q.G. Bailey and V.A. Kostelecký, Phys. Rev. D 74, 045001 (2006).
11. K.-Y. Chung et al., Phys. Rev. D 80, 016002 (2009); D. Bennett, V. Skavysh, and
J. Long, in V.A. Kostelecký, ed., CPT and Lorentz Symmetry V, World Scientific,
Singapore, 2010; J.B.R. Battat, J.F. Chandler, and C.W. Stubbs, Phys. Rev. Lett. 99,
241103 (2007); A. Hees et al., arXiv:1301.1058 Q.G. Bailey, R.D. Everett, and J.M.
Overduin, Phys. Rev. D 88, 102001 (2013); J.M. Weisberg in V.A. Kostelecký, ed., CPT
and Lorentz Symmetry VI, World Scientific, Singapore, 2014, Preprint arXiv:1310.7309;
L. Shao and N. Wex, Class. Quantum Grav. 30, 165020 (2013); L. Shao, Phys. Rev.
Lett. 112, 111103 (2014).
12. V.A. Kostelecký and J.D. Tasson, Phys. Rev. D 83, 016013 (2011).
13. V.A. Kostelecký and J.D. Tasson, Phys. Rev. Lett. 102, 010402 (2009).
14. Y. Bonder Phys. Rev. D 88, 105011 (2013); D.W. Atkinson, M. Becker, J.D. Tasson,
arXiv:1308.6743 D.W. Atkinson, in preparation.
15. H. Baumann and A.L. Eichenberger, Int. J. Mod. Phys. Conf. Ser. 30, 1460270 (2014), these proceedings.
16. M. Hohensee, H. Müller, and R.B. Wiringa, Phys. Rev. Lett. 111, 151102 (2013).
17. A.M. Nobili, Int. J. Mod. Phys. Conf. Ser. 30, 1460254 (2014), these proceedings; S. Dickerson, this workshop.
18. H. Müller et al., Phys. Rev. Lett. 100, 031101 (2008); M. Hohensee et al., Phys. Rev. Lett. 106 151102 (2011); Phys. Rev. Lett. 111, 050401 (2013).
19. J.D. Tasson Phys. Rev. D 86, 124021 (2012).
20. H. Panjwani, L. Carbone, and C.C. Speake, in V.A. Kostelecký, ed., CPT and Lorentz Symmetry V, World Scientific, Singapore, 2010.
21. T.H. Bertschinger, N.A. Flowers, J.D. Tasson, arXiv:1308.6572.
22. C. Amole et al., Nat. Commun. 4, 1785 (2013); J. Fajans, this workshop.
23. AEGIS Collaboration, A. Kellerbauer et al., Nucl. Instr. Meth. B 266, 351 (2008) D. Krasnický et al., Int. J. Mod. Phys. Conf. Ser. 30, 1460262 (2014), these proceedings.
24. P. Perez and Y. Sacquin, Class. Quantum Grav. 29, 184008 (2012); D.P. van der Werf, Int. J. Mod. Phys. Conf. Ser. 30, 1460263 (2014), these proceedings; L. Hilico et al., Int. J. Mod. Phys. Conf. Ser. 30, 1460269 (2014), these proceedings.
25. AGE Collaboration, A.D. Cronin et al., Letter of Intent: Antimatter Gravity Experiment (AGE) at Fermilab, February 2009; D. Kaplan, arXiv:1007.4956.
26. P. Hamilton et al., arXiv:1308.1079.
27. G. Dufour et al., Int. J. Mod. Phys. Conf. Ser. 30, 1460265 (2014), these proceedings; A. Voronin et al., Int. J. Mod. Phys. Conf. Ser. 30, 1460266 (2014), these proceedings.
28. F.M. Huber, E.W. Messerschmid, and G.A. Smith, Class. Quantum Grav. 18, 2457 (2001).
29. K. Blaum, M.G. Raizen, and W. Quint, Int. J. Mod. Phys. Conf. Ser. 30, 1460264 (2014), these proceedings.
30. B. Neyenhuis, D. Christensen, and D.S. Durfee, Phys. Rev. Lett. 99, 200401 (2007).
31. F.S. Witteborn and W.M. Fairbank, Phys. Rev. Lett. 19, 1049 (1967).
32. K. Kirch, arXiv:physics/0702143 these proceedings.
33. P. Crivelli, D.A. Cooke, and S. Friedreich, Int. J. Mod. Phys. Conf. Ser. 30, 1460267 (2014), these proceedings; D.B. Cassidy and S.D. Hogan, Int. J. Mod. Phys. Conf. Ser. 30, 1460259 (2014), these proceedings.
34. M.M. Nieto and T. Goldman, Phys. Rep. 205, 221 (1991); M. Jankowiak, this workshop; S. Karshenboim, this workshop.
35. P. Crivelli, D.A. Cooke, and S. Friedreich, Int. J. Mod. Phys. Conf. Ser. 30, 1460257 (2014), these proceedings; D.B. Cassidy and S.D. Hogan, Int. J. Mod. Phys. Conf. Ser. 30, 1460259 (2014), these proceedings.
36. K. Blaum, M.G. Raizen, and W. Quint, Int. J. Mod. Phys. Conf. Ser. 30, 1460264 (2014), these proceedings.
37. KTeV Collaboration, H. Nguyen, in V.A. Kostelecký, ed., CPT and Lorentz Symmetry II, World Scientific, Singapore, 2002 [hep-ex/0112046]; A. Di Domenico, KLOE Collaboration, J. Phys. Conf. Ser. 171, 012008 (2009); FOCUS Collaboration, J.M. Link et al., Phys. Lett. B 556, 7 (2003); BaBar Collaboration, B. Aubert et al., Phys. Rev. Lett. 100, 131802 (2008); hep-ex/0607103
38. V.A. Kostelecký, Phys. Rev. Lett. 80, 1818 (1998); Phys. Rev. D 61, 016002 (2000); Phys. Rev. D 64, 076001 (2001); V.A. Kostelecký and R. Van Kooten, Phys. Rev. D 82, 101702 (2010).
39. L.I. Schiff, Phys. Rev. Lett. 1, 254 (1958), Proc. Natl. Acad. Sci. 45, 69 (1959).
40. R. Jackiw and V.A. Kostelecký, Phys. Rev. Lett. 82, 3572 (1999); M. Pérez-Victoria, JHEP 0104, 032 (2001); V.A. Kostelecký, C.D. Lane, and A.G.M. Pickering, Phys. Rev. D 65, 056006 (2002); V.A. Kostelecký and A.G.M. Pickering, Phys. Rev. Lett. 91, 031801 (2003); B. Altschul, Phys. Rev. D 69, 125009 (2004); Phys. Rev. D 70, 101701 (2004); B. Altschul and V.A. Kostelecký, Phys. Lett. B 628, 106 (2005); H. Belich et
al., Eur. Phys. J. C 42, 127 (2005); T. Mariz et al., JHEP 0510, 019 (2005); G. de Berredo-Peixoto and I.L. Shapiro, Phys. Lett. B 642, 153 (2006); P. Arias et al., Phys. Rev. D 76, 025019 (2007); D. Colladay and P. McDonald, Phys. Rev. D 75, 105002 (2007); Phys. Rev. D 77, 085006 (2008); Phys. Rev. D 79, 125019 (2009); M. Gomes et al., Phys. Rev. D 78, 025029 (2009); D. Anselmi, Ann. Phys. 324, 874 (2009); Ann. Phys. 324, 1058 (2009).

41. R.J. Hughes and M.H. Holzscheiter, Phys. Rev. Lett. 66, 854 (1991); M.H. Holzscheiter, Int. J. Mod. Phys. Conf. Ser. 30, 1460260 (2014), these proceedings.