

Presentation of the Lorentz-Violating Standard-Model Extension

Ralf Lehnert

Indiana University Center for Spacetime Symmetries



Probing space-time properties (LIV/NC) at HEP experiments,
May 29, 2023

Review

Relativity:



//

//

|
 φ

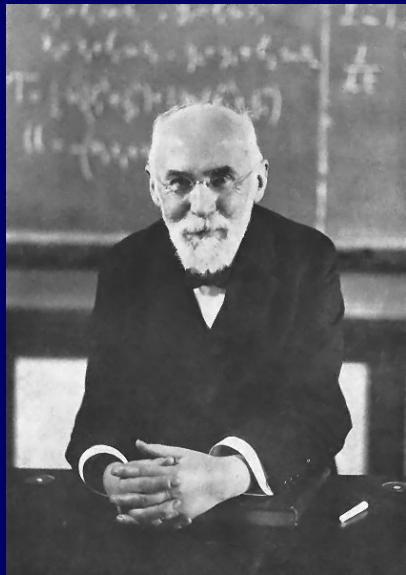


$\vec{v} = \text{const}$



Implemented via Lorentz transformation:

Example:
Lorentz Boost



$$\vec{x}' = \frac{\vec{x} - \vec{v}t}{\sqrt{1 - v^2/c^2}}$$

$$t' = \frac{t - \vec{v} \cdot \vec{x}/c^2}{\sqrt{1 - v^2/c^2}}$$

invariance in physics: symmetry

invariance under Lorentz transformations

→ Lorentz symmetry: - 3 boosts (in x, y, z)
- 3 rotations (around x, y, z)

Note: boosts and rotations are closely intertwined
→ rotation-symmetry tests \subset Lorentz tests
→ Lorentz tests in nonrel. systems possible

CPT symmetry

discrete transformations:

- charge conjugation **C** (particle \leftrightarrow antiparticle)
- parity inversion **P** ($\vec{x} \rightarrow -\vec{x}$)
- time reversal **T** ($t \rightarrow -t$)



==



Roughly: **matter** and **antimatter** systems behave **identically**

CPT theorem:

C Charge Conjugation
P Parity Inversion
T Time Reversal

real-valued Lorentz
transformations

complex-valued Lorentz
transformations

• CPT

Relativity + QM + mild assumptions → CPT symmetry
(Bell, Pauli, Lüders, Jost '50s)

Continued Tests Lorentz and CPT Symmetry:

philosophical necessity

physics is an experimental science

→ solid **experimental confirmation** of
foundations of physics is **crucial**



Outline:

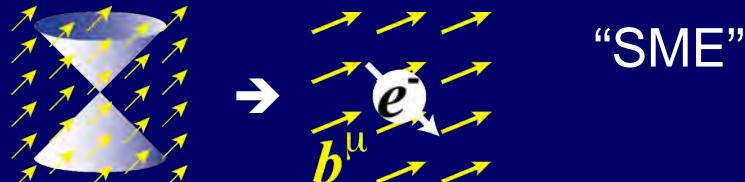
Motivation 1: Scientific Method



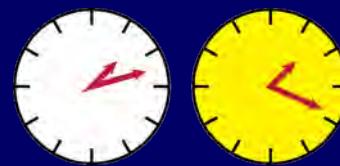
(B) Motivation 2:
Mechanisms
for Lorentz/CPT
violation



(A) Test Framework:
identification, interpretation,
and comparison of such tests



(C) Experimental Tests:
accelerators, neutrinos, AMO physics,
particle decays, astrophysics, ...



(A) Framework for Lorentz and CPT Tests

The framework for Lorentz and CPT tests is based on the principle of relativity and the symmetry of spacetime.

The framework is used to test whether the laws of physics are the same in all inertial frames of reference.

The framework is also used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

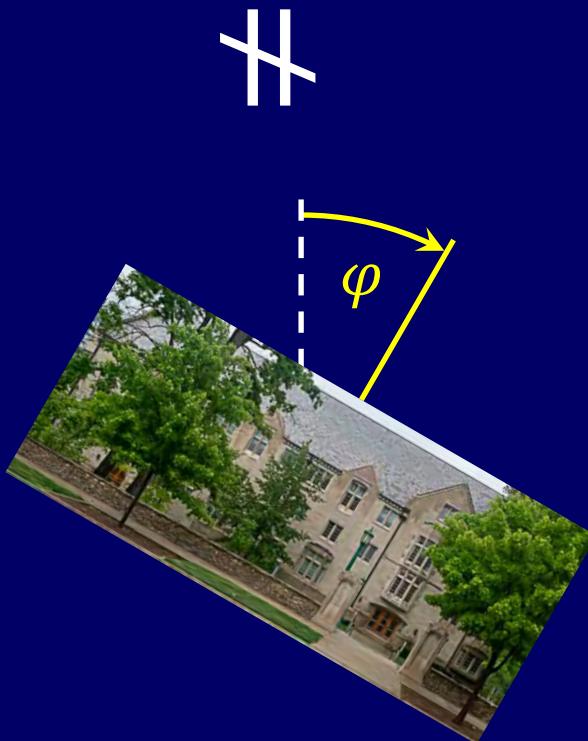
The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

The framework is used to test whether the laws of physics are the same in all frames of reference, including non-inertial frames.

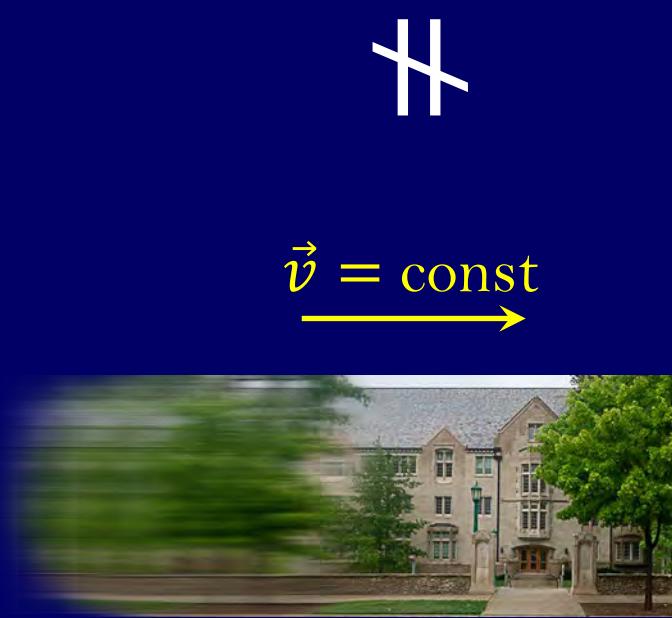
Lorentz/CPT violation



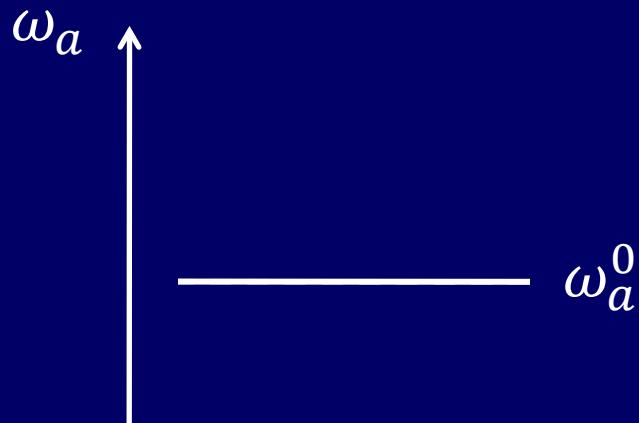
\neq



\neq



Sample expected effect due to rotation of Earth



Expect: $\omega_a^{\varphi(t)} = \sum_{n=0}^{\infty} R_n^c \cos n\omega_{\oplus} t + R_n^s \sin n\omega_{\oplus} t$

R_n^c, R_n^s parameters to be measured

$\omega_{\oplus} \simeq 2\pi/23\text{h } 56\text{ min}$ Earth's sidereal frequency

↑
Generality

Established Physics:
Standard Model coupled
to General Relativity



Maxwell
Equations

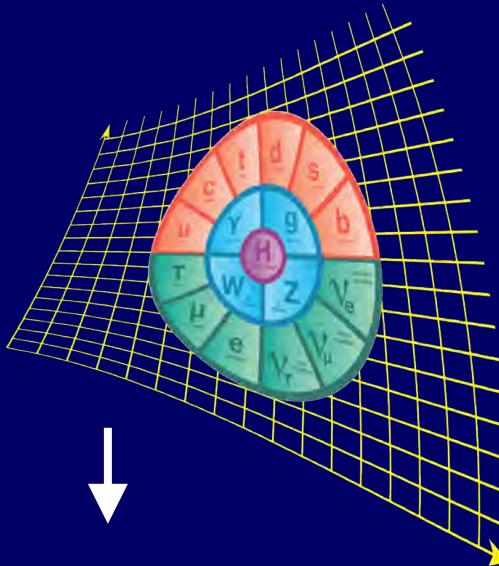
$$\vec{F} = m\vec{a}$$

$$i\hbar \frac{\partial}{\partial t} \Psi = \left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V \right) \Psi$$

$$PV = nRT$$

...

indiv. phys. systems (e.g., H atom, SHO, ...)

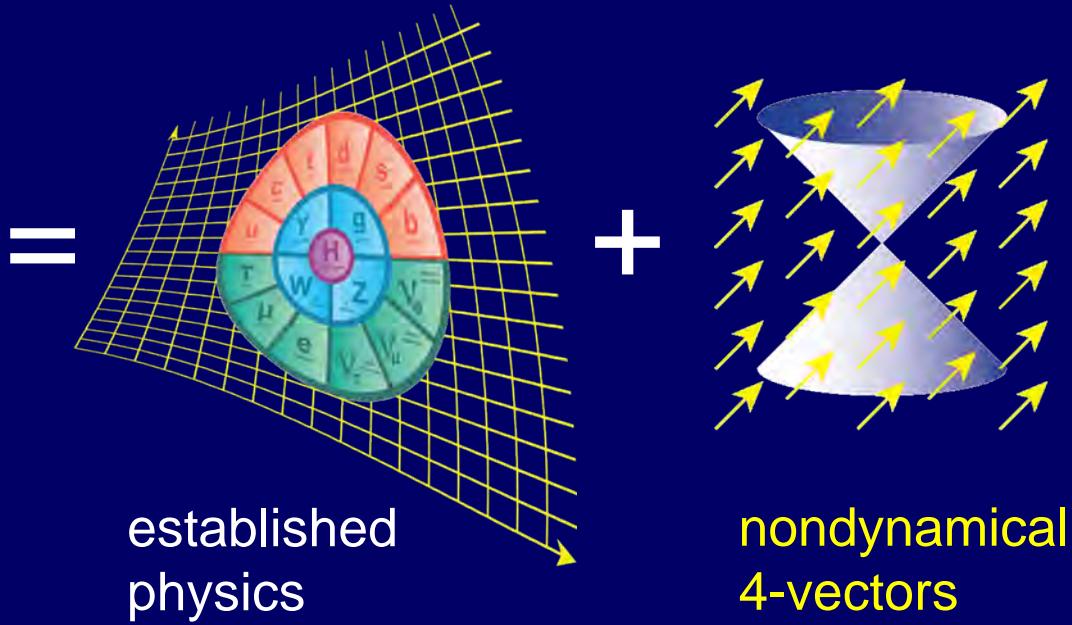


Goal: parametrize
Lorentz & CPT
violation at this
level

Fourier coeffs. for
each phys. system

Idea 1: tensor-valued couplings

Test Framework
for Lorentz/CPT
Symmetry *m*



Example:

$$\begin{aligned} & -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \dots + A_\nu k_\mu \tilde{F}^{\mu\nu} - \frac{1}{4} k_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu} \\ & + A_\nu k_\mu \partial^\alpha \partial^\beta \partial_\alpha \partial_\beta \tilde{F}^{\mu\nu} \\ & + \lambda_{\mu\nu} F^{12} F^{\mu\nu} + \dots \end{aligned}$$

idea 2: effective field theory:

high-energy states
not excitable

low-energy
excitable states

$$+ \quad \square \quad + \quad \square \quad + \quad \square \quad + \quad \square \quad + \dots$$

powers of fields/derivatives

$$-\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \dots$$

$$+ A_\nu k_\mu \tilde{F}^{\mu\nu} - \frac{1}{4} k_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu}$$

$$+ A_\nu k_\mu \partial^\alpha \partial^\beta \partial_\alpha \partial_\beta \tilde{F}^{\mu\nu}$$

$$+ \lambda_{\mu\nu} F^{12} F^{\mu\nu} + \dots$$

higher
order

→ can truncate expansion

→ finite # of Lorentz/CPT-violating correction suffice for exp. studies

$$\mathcal{L}_{\text{SME}}^{(3,4)}$$

$$\begin{aligned}
&= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{GR}} + \frac{1}{2} i(c_L)_{\mu\nu AB} \bar{L}_A \gamma^\mu \overleftrightarrow{D}^\nu L_B + \frac{1}{2} i(c_R)_{\mu\nu AB} \bar{R}_A \gamma^\mu \overleftrightarrow{D}^\nu R_B \\
&\quad - (a_L)_{\mu AB} \bar{L}_A \gamma^\mu L_B - (a_R)_{\mu AB} \bar{R}_A \gamma^\mu R_B + \frac{1}{2} i(c_Q)_{\mu\nu AB} \bar{Q}_A \gamma^\mu \overleftrightarrow{D}^\nu Q_B \\
&\quad + \frac{1}{2} i(c_U)_{\mu\nu AB} \bar{U}_A \gamma^\mu \overleftrightarrow{D}^\nu U_B + \frac{1}{2} i(c_D)_{\mu\nu AB} \bar{D}_A \gamma^\mu \overleftrightarrow{D}^\nu D_B - (a_U)_{\mu AB} \bar{U}_A \gamma^\mu U_B \\
&\quad - (a_D)_{\mu AB} \bar{D}_A \gamma^\mu D_B \\
&\quad - \frac{1}{2} [(H_L)_{\mu\nu AB} \bar{L}_A \phi \sigma^{\mu\nu} R_B + (H_U)_{\mu\nu AB} \bar{Q}_A \phi^c \sigma^{\mu\nu} U_B + (H_D)_{\mu\nu AB} \bar{Q}_A \phi \sigma^{\mu\nu} D_B] \\
&\quad + \text{h. c.} + \frac{1}{2} (k_{\phi\phi})^{\mu\nu} (D_\mu \phi)^\dagger D_\nu \phi + \text{h. c.} - \frac{1}{2} (k_{\phi B})^{\mu\nu} \phi^\dagger \phi B_{\mu\nu} - \frac{1}{2} (k_{\phi W})^{\mu\nu} \phi^\dagger W_{\mu\nu} \phi \\
&\quad + i(k_\phi)^\mu \phi^\dagger D_\mu \phi + \text{h. c.} - \frac{1}{2} (k_G)_{\kappa\lambda\mu\nu} \text{Tr}(G^{\kappa\lambda} G^{\mu\nu}) - \frac{1}{2} (k_W)_{\kappa\lambda\mu\nu} \text{Tr}(W^{\kappa\lambda} W^{\mu\nu}) \\
&\quad - \frac{1}{4} (k_B)_{\kappa\lambda\mu\nu} B^{\kappa\lambda} B^{\mu\nu} + (k_3)_\kappa \epsilon^{\kappa\lambda\mu\nu} \text{Tr}\left(G_\lambda G_{\mu\nu} + \frac{2}{3} i g_3 G_\lambda G_\mu G_\nu\right) \\
&\quad + (k_2)_\kappa \epsilon^{\kappa\lambda\mu\nu} \text{Tr}\left(W_\lambda W_{\mu\nu} + \frac{2}{3} i g W_\lambda W_\mu W_\nu\right) + (k_1)_\kappa \epsilon^{\kappa\lambda\mu\nu} B_\lambda B_{\mu\nu} + (k_0)_\kappa B^\kappa
\end{aligned}$$

sample theoretical investigations of the SME

- construction of SME (Colladay, Kostelecký, Mewes, Li '97-'13)
- radiative corrections (Pérez-Victoria '99; Altschul '06-'19)
- causality and stability (Kostelecký, R.L. '01)
- supersymmetry (Berger, Kostelecký '02)
- "Anti-CPT Theorem" (Greenberg '02)
- renormalizability (Altschul, Colladay, Kostelecký, ...'02-'09)
- dispersion relations and kinematical analyses (R.L. '03)
- asymptotic Hilbert space(Cambiaso, R.L., Potting '04; '06)
- symmetry studies (Cohen, Glashow '06; Hariton, R.L. '07)
- modified Dirac theory (R.L. '04; Schreck '19)
- . . .

(B) More Motivations for Lorentz/CPT Tests



Continued

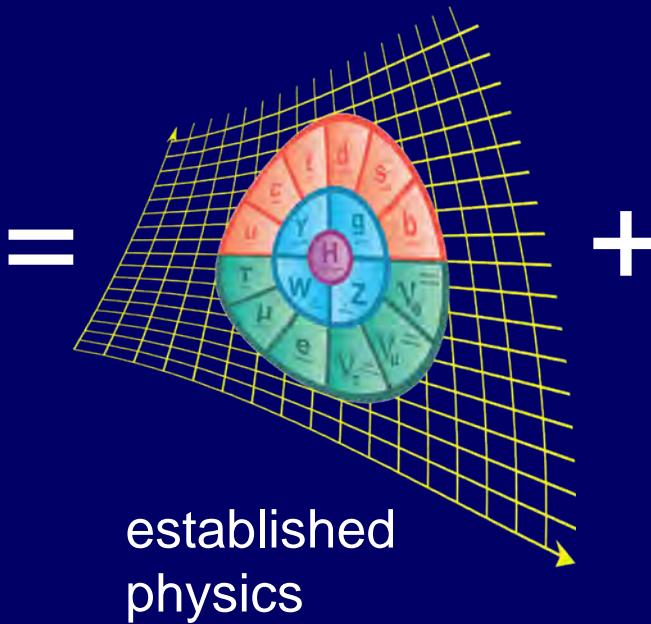
↑
Generality



???

Test Framework
for Lorentz/CPT
Symmetry m

Possible underlying sources for
SME coefficients $(c_R)_{\mu\nu AB}, (a_L)_{\mu AB}, \dots$?



nondynamical
4-vectors

$$\begin{aligned}
 &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{GR}} + \frac{1}{2} i(c_L)_{\mu\nu AB} \bar{L}_A \gamma^\mu \vec{D}^\nu L_B + \frac{1}{2} i(c_R)_{\mu\nu AB} \bar{R}_A \gamma^\mu \vec{D}^\nu R_B - (a_L)_{\mu AB} \bar{L}_A \gamma^\mu L_B - (a_R)_{\mu AB} \bar{R}_A \gamma^\mu R_B + \frac{1}{2} i(c_Q)_{\mu\nu AB} \bar{Q}_A \gamma^\mu \vec{D}^\nu Q_B \\
 &+ \frac{1}{2} i(c_U)_{\mu\nu AB} \bar{U}_A \gamma^\mu \vec{D}^\nu U_B + \frac{1}{2} i(c_D)_{\mu\nu AB} \bar{D}_A \gamma^\mu \vec{D}^\nu D_B - (a_U)_{\mu AB} \bar{U}_A \gamma^\mu U_B - (a_D)_{\mu AB} \bar{D}_A \gamma^\mu D_B \\
 &- \frac{1}{2} [(H_L)_{\mu\nu AB} \bar{L}_A \phi \sigma^{\mu\nu} R_B + (H_U)_{\mu\nu AB} \bar{Q}_A \phi^c \sigma^{\mu\nu} U_B + (H_D)_{\mu\nu AB} \bar{D}_A \phi \sigma^{\mu\nu} D_B] + \text{h.c.} + \frac{1}{2} (k_{\phi\phi})^{\mu\nu} (D_\mu \phi)^\dagger D_\nu \phi + \text{h.c.} - \frac{1}{2} (k_{\phi B})^{\mu\nu} \phi^\dagger \phi B_{\mu\nu} \\
 &- \frac{1}{2} (k_{\phi W})^{\mu\nu} \phi^\dagger W_{\mu\nu} \phi + i(k_\phi)^\mu \phi^\dagger D_\mu \phi + \text{h.c.} - \frac{1}{2} (k_G)_{\kappa\lambda\mu\nu} \text{Tr}(G^{\kappa\lambda} G^{\mu\nu}) - \frac{1}{2} (k_W)_{\kappa\lambda\mu\nu} \text{Tr}(W^{\kappa\lambda} W^{\mu\nu}) - \frac{1}{4} (k_B)_{\kappa\lambda\mu\nu} B^{\kappa\lambda} B^{\mu\nu} \\
 &+ (k_3)_\kappa \epsilon^{\kappa\lambda\mu\nu} \text{Tr}\left(G_\lambda G_{\mu\nu} + \frac{2}{3} i g_3 G_\lambda G_\mu G_\nu\right) + (k_2)_\kappa \epsilon^{\kappa\lambda\mu\nu} \text{Tr}\left(W_\lambda W_{\mu\nu} + \frac{2}{3} i g W_\lambda W_\mu W_\nu\right) + (k_1)_\kappa \epsilon^{\kappa\lambda\mu\nu} B_\lambda B_{\mu\nu} + (k_0)_\kappa B^\kappa
 \end{aligned}$$

(1) Noncommutative field theory

idea (QM of spacetime points):

$$[\hat{x}^\mu, \hat{x}^\nu] = i\theta^{\mu\nu}$$

departures from conventional physics governed by $\theta^{\mu\nu}$

→ expect effective description $\mathcal{L}(\text{fields}, \theta) = \mathcal{L}_{\text{SM}} + \frac{\partial \mathcal{L}}{\partial \theta^{\mu\nu}} \theta^{\mu\nu} + \dots$

Seiberg-Witten: $\hat{x}^\mu \rightarrow$ usual Minkowski coordinates x^μ

→ SME terms emerge: $\mathcal{L}_{\text{photon}} \supset \frac{1}{8} q \theta^{\alpha\beta} F_{\alpha\beta} F^{\mu\nu} F_{\mu\nu}$

see, e.g., Carroll *et al.* '01

(more on this next by Marija Dimitrijevic Cirić & Nikola Konjik)

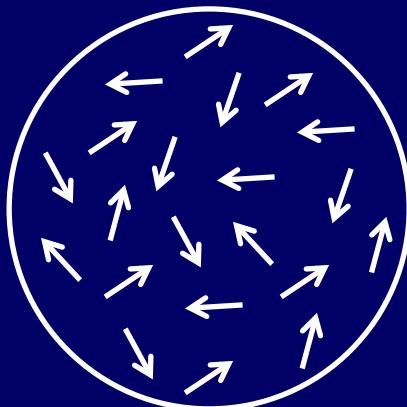
(2) Spontaneous Lorentz violation (e.g., string field theory)

basic idea:

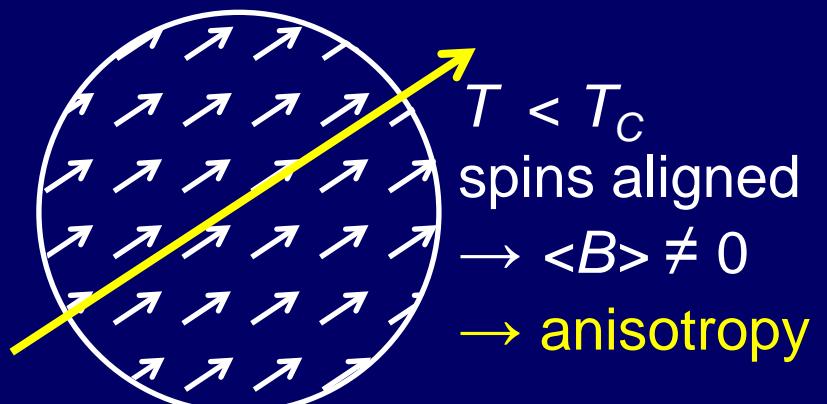
Lorentz-invariant dynamics but Lorentz-violating ground state
(Kostelecký, Perry, Potting, Samuel 90's)

rotational-symmetry example: magnetic phase transition

Hamiltonian $H = -\xi \sum_{jk} \vec{s}_j \cdot \vec{s}_k$ has no preferred direction



$T > T_c$
spins random
 $\rightarrow \langle B \rangle = 0$
 \rightarrow isotropy



$T < T_c$
spins aligned
 $\rightarrow \langle B \rangle \neq 0$
 \rightarrow anisotropy

(3) Cosmol. varying scalars (e.g., fine-structure parameter)

intuitive argument:



- small scalar
- large scalar

gradient of the scalar selects pref. direction

mathematical argument:

$$\xi = \xi(x) \dots \text{varying coupling}$$
$$\phi, \Phi \quad \dots \text{dynamical fields}$$

$$\mathcal{L} \supset \xi \partial^\mu \phi \partial_\mu \Phi$$



Integration by parts:

$$\mathcal{L}' \supset -(\partial^\mu \xi) \phi \partial_\mu \Phi$$



slow variation of ξ :
 $K^\mu \equiv (\partial^\mu \xi) \simeq \text{const.}$

$$\mathcal{L}' \supset -K^\mu \phi \partial_\mu \Phi$$

Kostelecký, R.L., Perry '03; Arkani-Hamed *et al.* '03

Other mechanisms for Lorentz violation

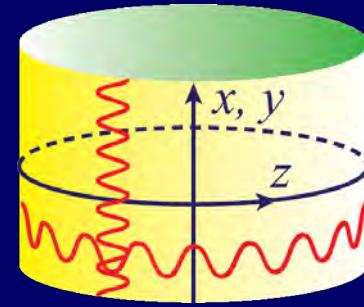
Topology (1 spatial dim. is compact: large radius R)

Vacuum fluctuations along this dim.

have periodic boundary conditions

→ preferred direction in vacuum

→ calculation: $k^\mu A^\nu \tilde{F}_{\mu\nu} \in \mathcal{L}_{\text{SME}}$



Klinkhamer '00

...

(C) Phenomenology and Tests

Phenomenology and Tests

Data Tables for Lorentz and CPT Violation

V. Alan Kostelecký^a and Neil Russell^b

^a*Physics Department, Indiana University, Bloomington, IN 47405*

^b*Physics Department, Northern Michigan University, Marquette, MI 49855*

January 2023 update of *Reviews of Modern Physics* **83**, 11 (2011) [arXiv:0801.0287]

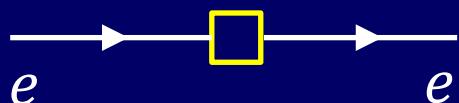
This work tabulates measured and derived values of coefficients for Lorentz and CPT violation in the Standard-Model Extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, neutrino, and gravity sectors. Tables presenting definitions and properties are also compiled.

146 pages; 363 references

Some phenomenological effects:

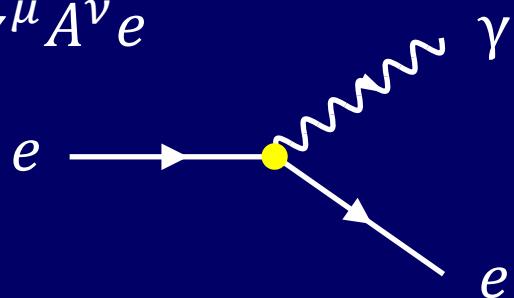
see talks by AW Jung, N Sherrill, E Passemar, M Van Veghel, NP Chanon

$$-b_\mu \bar{e} \gamma_5 \gamma^\mu e$$



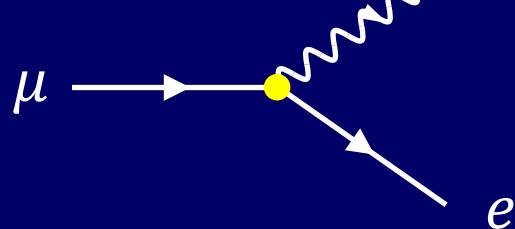
- ext. line: modified dispersion relations
→ modified phase space & kinematics
- int. line: modified propagator
→ modified cross sections

$$c_{\mu\nu} \bar{e} \gamma^\mu A^\nu e$$



- modified interaction vertices
→ modified cross sections

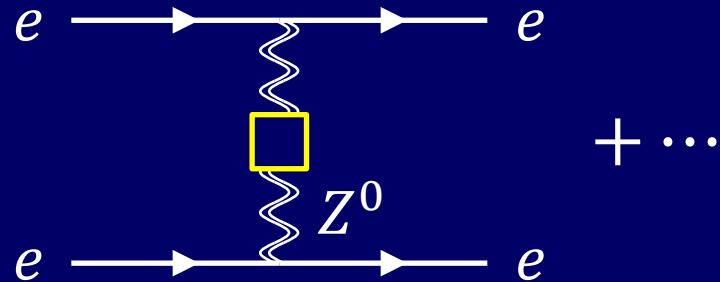
$$-\frac{1}{2} (m_F^{(5)})_{\mu e}^{\alpha\beta} F_{\alpha\beta} \bar{\mu} e$$



- new interaction vertices
→ new processes

Experiments at accelerators: Møller scattering

$$-\frac{1}{4}J_{\kappa\lambda\mu\nu}Z^{\kappa\lambda}Z^{\mu\nu} + \dots$$



SME prediction: sidereal variations of cross section

Data from E158 experiment (at SLAC):

$$J_{\kappa\lambda\mu\nu} < 10^{-7}$$

H. Fu, R.L., PLB **762**, 33 (2016)

Remark: excellent future opportunities with MØLLER at JLab

Some other accelerator-based Lorentz/CPT tests

Measurements of SME quark coefficients using LHC data, see:

Quark-sector Lorentz violation in Z-boson production,

Lunghi, Sherrill, Szczepaniak, Vieira, JHEP **04**, 228 (2021)

1st measurement of SME quark coefficients in mixing of B_s^0 Mesons, see:

Search for violation of CPT/Lorentz invariance in B_s^0 meson oscillations,

D0 Collaboration (Van Kooten), PRL **115**, 161601 (2015)

1st measurement of SME top quark coefficients in $t\bar{t}$ production, see:

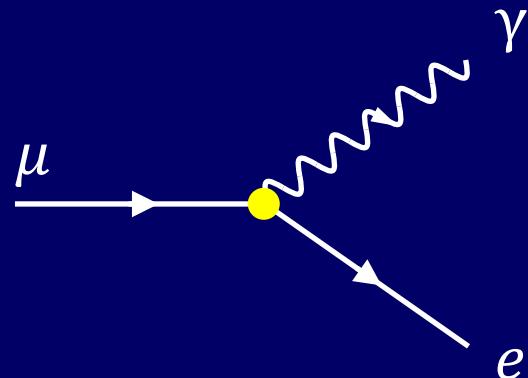
Search for violation of Lorentz inv. in t quark pair production and decay,

D0 Collaboration (Berger, Evans, Kostelecký), PRL **108**, 261603 (2012)

...

Rare Process: $\mu \rightarrow e + \gamma$

$$-\frac{1}{2} (m_F^{(5)})_{\mu e}^{\alpha\beta} F_{\alpha\beta} \bar{\mu} e + \dots$$



Data from MEG (at PSI) and BaBar (at SLAC):

$$\rightarrow (m_F^{(5)})_{\mu e}^{\alpha\beta}, \dots < 10^{-13} \text{ GeV}^{-1}$$

(Kostelecký, Passemar, Sherrill, *PRD* 106, 076016 (2022))

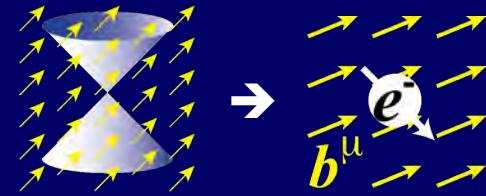
Summary

presently no credible exp. evidence for Relativity violations, but:

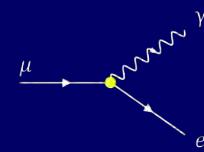
- (1) various theoretical approaches to quantum gravity can cause such violations



- (2) at low E , such violations are described by SME test framework (eff. field theory + background fields)



- (3) high-precision tests (accelerators, but also with other methods, ...) possible



many open issues → ample ground for future studies