CPT- and Lorentz-symmetry breaking: a review

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Outline:

A. Introduction and motivation

B. Types of Lorentz/CPT violation

C. The Standard-Model Extension (SME)

D. Predictions for neutral-meson interferometry

E. Summary

A. Introduction and Motivation

Why test Lorentz/CPT symmetry?

Lorentz/CPT symmetry is cornerstone of:

- present-day physics
- many candidate fundamental theories

↓

⟶ Lorentz/CPT symmetry must be tested

Why look for Lorentz/CPT violation?

Nongravitational physics is well described by Standard Model (SM),

but: - phenomenological (many parameters)
- several distinct interactions
- excludes gravity

Solution: look for more fundamental theory

Candidates: string (M) theory, loop gravity, varying scalars, ...

Problem: Planck-scale measurements
(attainable energies $\ll$ Planck scale)

Idea: experimentally check relations that
- hold exactly in Standard Model
- may be violated at fundamental level
- can be measured with ultrahigh precision

Lorentz/CPT symmetry satisfy these criteria:

Standard Model (SM):

Lorentz/CPT symm. holds exactly

theories beyond SM:

Lorentz/CPT violation possible

prospect of ultrahigh-precision Lorentz/CPT tests

(e.g., KTeV, FOCUS, KLOEII?, ...)

Lorentz/CPT tests are useful tool in search for physics beyond SM

Local, point-particle quantum field theories:

CPT theorem (Pauli, Lüders, Bell, '54):
"Lorentz symmetry implies CPT invariance"

Lorentz transf. { - rotations - boosts

CPT transf. { - charge conjugation C - parity inversion P - time reversal T

Anti-CPT theorem (Greenberg, PRL '02):
"CPT violation implies Lorentz breaking"

Result: CPT violation at low *E* controlled by a unitary effective field theory
→ kaon-system parameter δ_K is typically direction and *E* dependent

Note: need further deviations from conventional physics to get constant δ_K

B. Types of Lorentz/CPT violation

2 different types of Lorentz/CPT violation

(1) modification of transfs. between inertial frames

- primarily kinematical
- CPT properties unclear

Examples:

- Robertson's framework
- its Mansouri-Sexl extension
- modified dispersion relations

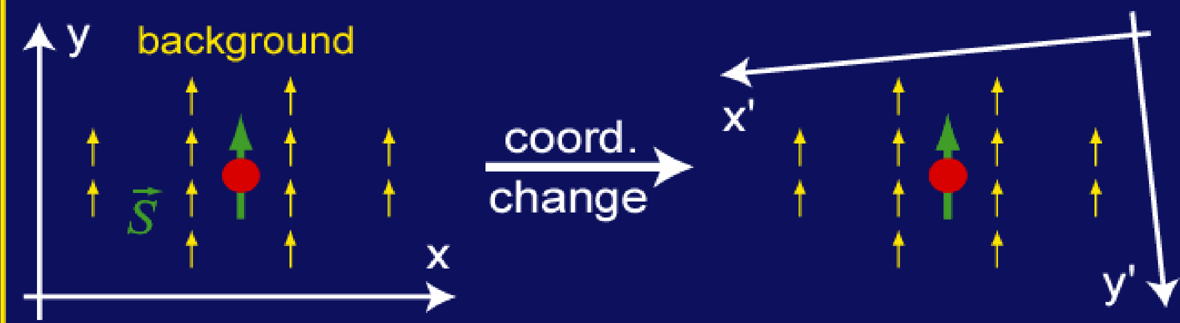
(2) nontrivial vacuum, coordinate Lorentz/CPT sym. maintained

- motivated by candidate underlying theories (see this Sec)
- fully dynamical+microscopic framework exists (see Sec C)
- incorporates some of the kinematical approaches

this talk only considers Lorentz/CPT breakdown through nontrivial vacua

For Lorentz/CPT breaking through nontrivial vacua
observer and particle Lorentz tranformations must be distinguished:

Coordinate independence (covariance under observer LT): maintained



different observers,
same experiment

Lorentz violation (covariance lost under "particle Lorentz transfs."):

actual
experimental
situation

Some mechanisms for Lorentz/CPT violation through nontrivial vacua:

String field theory (Kostelecký *et al.* '90)
nontrivial vacuum through spontaneous LV

Nontrivial spacetime topology (Klinkhamer '00)
nontrivial vacuum through compact conventional dim.

Loop quantum gravity (Alfaro *et al.* '00)
nontrivial vacuum through choice of spin-network state

Varying scalars (Kostelecký, R.L., Perry '02)
nontrivial vacuum through gradient of scalar

⋮

C. The Standard-Model Extension (SME)

Why low-energy effective theory?

Prediction of observable effects

Example: CPT $\Rightarrow$ particle mass = antiparticle mass

~~CPT~~ $\not\Rightarrow$ particle mass $\neq$ antiparticle mass

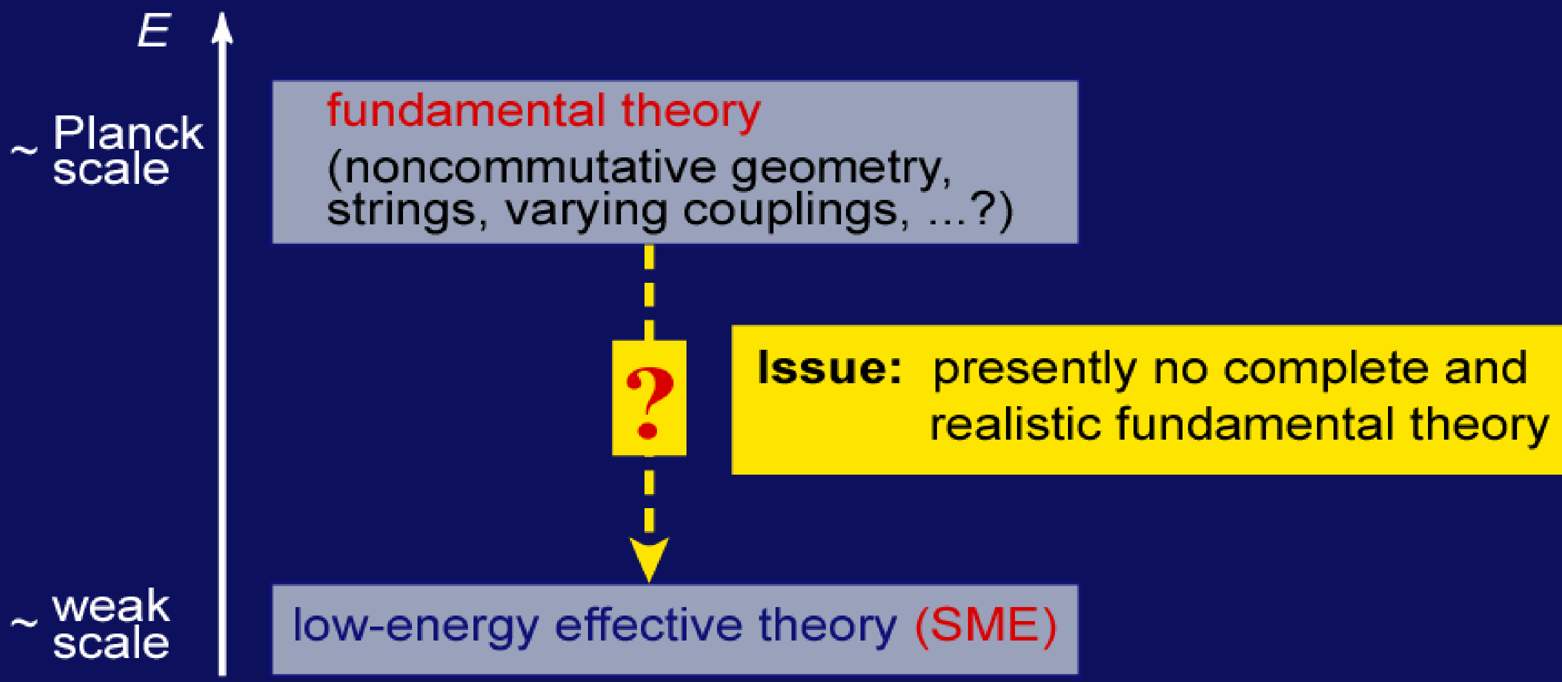
Relation between CPT-/Lorentz-breaking coefficients in different physical systems

Example: CPT-/Lorentz-breaking coefficients of quarks determine conventional, phenomenological CPT-violating parameters of kaon system

Insight into underlying theory

Example: stability / causality constrain underlying physics

How to obtain low-energy effective theory?



Idea: - examine manifestations of Lorentz/CPT violating vacuum
- construct all possible modifications to SM

Advantage: - independent of underlying theory
- describes all low-energy effects of Lorentz violation

Construction of the SME

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

where $\delta\mathcal{L}$ contains all operators of the form

(tensorial background) covariantly contracted w/ (SM fields)

particle LV — coordinate invariance

Sample terms:

$$b^{\mu}\,\bar{\psi}\,\gamma^5\gamma_{\mu}\psi\,,\ \ (\,b^{\mu}\,\bar{\psi}\,\gamma^5\gamma_{\mu}\psi\,)^2,\ \ c^{\mu\nu}\,\bar{\psi}\,i\gamma_{\mu}D_{\nu}\psi\,,\ \ (k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma},\ \ldots$$

Remarks:

- at low E ($\ll M_{\text{Pl}}$), the background is taken as constant and the renormalizable sector of the SME dominates
- other features (gauge and transl. invariance, ...) can be imposed

} **minimal SME**

- can be extended to General Relativity

(Colladay, Kostelecký '97; '98; Kostelecký '03)

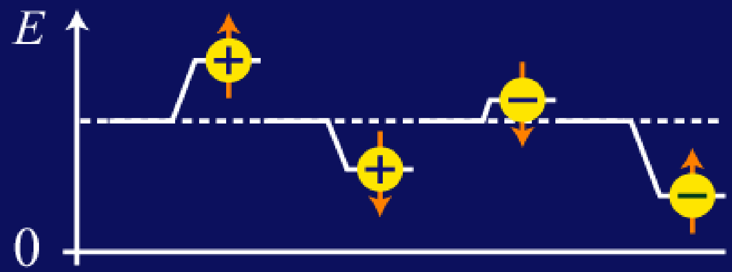
Sample consequences of the SME

(i) modified, Lorentz-violating dispersion relations

Example:
general fermion dispersion relation (DR)

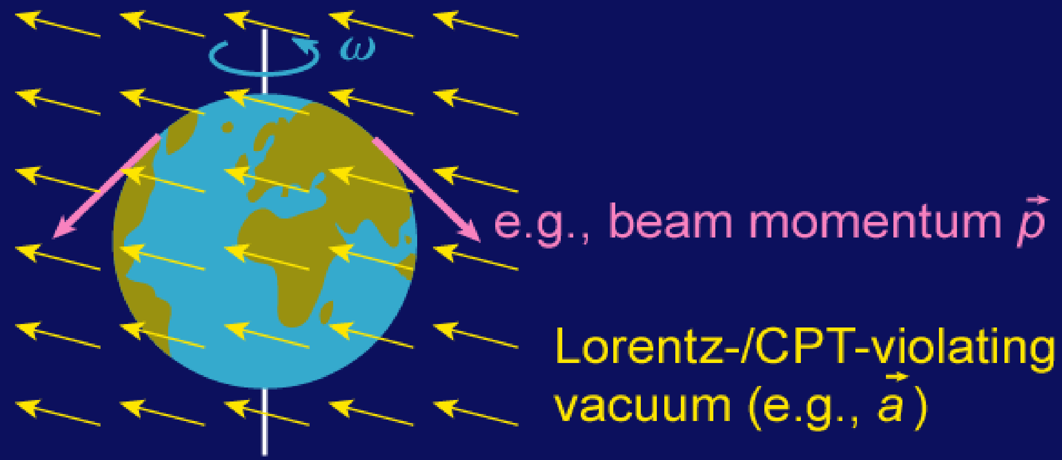
$$(p^2 - m^2)^2 + \text{CPT-/Lorentz-breaking corrections} = 0$$

in general,
4-fold degeneracy of
$E(\vec{p} = \text{const.})$ is lifted

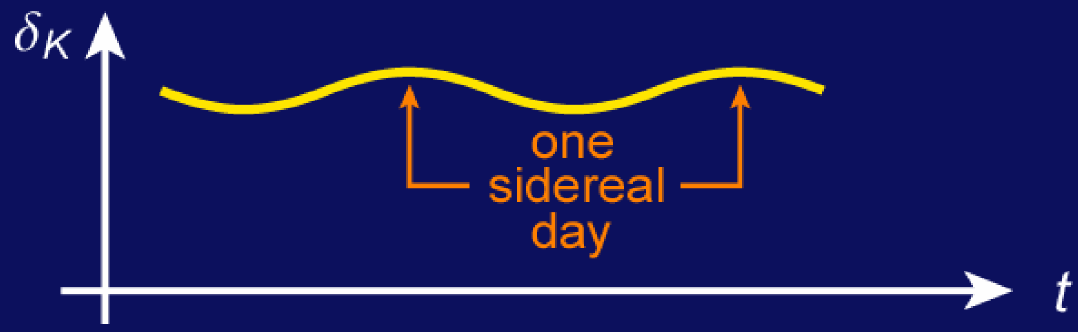


Remark: can lead to CPT-violating $\Delta\Lambda = \Lambda_{11} - \Lambda_{22}$
in the kaon effective Hamiltonian $\Lambda = M - i\Gamma$ (see Sec D)

(ii) sidereal variations of observables



observables ~ $\vec{a} \cdot \vec{p}$ (e.g., δ_K, see Sec D) become time dependent:



Some analyses performed within the minimal SME

Studies of neutral-meson systems (see Sec D)

Kostelecký *et al.* '95; '96; '98; '00
KTeV Collaboration, Hsiung *et al.* '99
FOCUS Collaboration, Link *et al.* '03
OPAL Collaboration, Ackerstaff *et al.* '97
DELPHI Collaboration, Feindt *et al.* '97
BELLE Collaboration
BaBar Collaboration

Tests involving photons and radiative effects

Carroll, Field, Jackiw '90
Colladay, Kostelecký '98
Jackiw, Kostelecký '99
Kostelecký, Mewes '01; '02
Kostelecký, R.L., Perry '02
Müller *et al.* '03
Lipa *et al.* '03

Hydrogen and Antihydrogen spectroscopy

Bluhm, Kostelecký, Russell '99
Phillips *et al.* '01

Penning-Trap experiments

Bluhm, Kostelecký, Russell '97; '98
Gabrielse *et al.* '99
Mittelman *et al.* '99
Dehmelt *et al.* '99

Studies of muons

Bluhm, Kostelecký, Lane '99
Hughes *et al.* '00

Clock-comparison tests

Kostelecký, Lane '99
Hunter *et al.* '99
Stoner '99
Bear et al. '00

Studies of baryogenesis

Bertolami *et al.* '97

Studies of neutrinos

Coleman, Glashow '99
Barger, Pakvasa, Weiler, Whisnant '00
Kostelecký, Mewes '03; '04

Kinematical studies of cosmic rays

Coleman, Glashow '99
Bertolami, Carvalho '00
R.L. '03
Jankiewicz, Buniy, Kephart, Weiler '04

Tests on the ISS

Kostelecký *et al.* '02; '03
ACES
PARCS
RACE
SUMO
(OPTIS?)

Tests of Lorentz/CPT violation in gravity

Bailey, Kostelecký '06

D. Predictions for neutral-meson interferometry

from $\mathcal{L}_{SME}$, extract CPT-violating Hamiltonian contribution δH_{SME} for valence quarks of meson $P^0 = K^0$, D^0, B^0_d , B^0_s under consideration

usual quantum perturbation theory in meson rest frame:

$$\delta\Lambda_{jk} = \langle j | \delta H_{SME} | k \rangle \,, \qquad j, k = P^0, \overline{P}^0$$

symmetry considerations, Hermiticity of δH_{SME} , and boosting yield:

$$\Delta\Lambda \equiv \Lambda_{P^0 P^0} - \Lambda_{\overline{P}^0 \overline{P}^0} = \beta^\mu (a_\mu^{quark\,1} - a_\mu^{quark\,2})$$

β^μ … 4-velocity of meson in observer frame

a^μ … Lorentz-/CPT-violating SME parameter for valence quark

→ phenomenological δ_K can be calculated within SME:

$$\delta_K \simeq i \sin \hat{\phi}\, e^{i\hat{\phi}} \gamma(\Delta a_0 - \vec{\beta} \cdot \Delta \vec{a})$$

$\hat{\phi}$ … usual superweak angle

$\gamma^{-1} = \sqrt{1-\beta^2}$ … boost factor from kaon speed β

Notice: - kaon direction is essential exp. parameter, as expected
→ 4π averaging may remove any CPT-violating signals

- larger kaon speeds tend to enhance CPT-violating effects
→ this gives possibilities to increase CPT reach

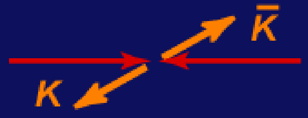
Remark: meson interferometry is the only known class of tests probing a^{μ} -type SME coefficients back to directionality arising from $\delta_K \sim \beta_\mu \, \Delta a^\mu$

rotating lab (motion of Earth) & 4π momentum distribution in this lab

spacetime-fixed quantity to be probed; extends throughout Universe

(1) need ***time binning*** (orientation of lab w.r.t. Δa^μ)

(2) need ***direction binning*** (orientation of β_μ w.r.t. lab)



⟶ 4 independent bounds $(\Delta a^0, \Delta a^X, \Delta a^Y, \Delta a^Z)$ for each meson

Note: standard analysis provides one bound (combination of these)

experimental status:

KTeV: $(\Delta a^\perp, \Delta \tilde{a})$ for K system less than $10^{-20} \ldots 10^{-21}$ GeV

FOCUS: $(\Delta a^0, \Delta a^X, \Delta a^Y, \Delta a^Z)$ for D system less than 10^{-15} GeV

E. Summary

observational tests of Lorentz/CPT symmetry are essential

- this symmetry is key ingredient in established physics
- promising tool in search for Planck-scale effects
- CPT violation comes with Lorentz breakdown → isotropy loss

test model for Lorentz/CPT violation is the SME

- extends our established basic physics laws to include leading-order Lorentz/CPT violation
- most general effective-field-theory test model
- has been basis for numerous Lorentz/CPT tests

neutral-meson interferometry allows precision CPT tests

- bounds coefficients inaccessible by other experiments
- SME predicts direction- and momentum-dependent δ_K
- this leads to sidereal variations of CPT observables