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Bounds on Planck-scale deformations of CPT

Using lifetimes and interference

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Invariance under CPT: strongly believed to be strict due to general theorems and naturalness of their premise

CPT theorem and its various mutations, 1951-57: Schwinger, Lüders, Jost, Pauli, Bell, Zumino

Assumptions:

- Hermiticity of H
- unitary evolution
- locality: fields commute (bosonic) or anticommute (fermionic) at spacelike separations
- finite vacuum expectations of field products
- Lorentz invariance

Imply CPT-invariance

$[CPT, H] = 0$

Some phenomenological consequences of CPT invariance

- particles and antiparticles have the same masses
- particles and antiparticles have the same lifetimes (decay rates)
- CPT-coupled decay channels have the same widths (decay rates, lifetimes)
- ..

Many experimental tests of CPT;

most impressive experimental constraint
$|m_{K^0} - m_{\bar{K}^0}| < 4 \times 10^{-19}$ GeV at 95% cl.,
world data, main contribution by CPLEAR at CERN

CPT as a fundamental symmetry of Nature

Basic theorems and experimental facts, 3

- Theorem by Greenberg, 2002 (Anti-CPT theorem)
  O. Greenberg, Phys.Rev.Lett. 89 (2002)231602-1

  CPT violation necessarily entails violation of Lorentz invariance (interacting theory)
- However, examples are given of non-local Lagrangian breaking CPT and still Lorentz-invariant
  M. Chaichian et al., Phys.Lett. B699 (2011) 177
- Standard-model extension by CPT violating term
  V.A. Kostelecky, many papers starting from 1990's
- Lots of subtleties but clear hint for phenomenology:
  CPT invariance probes Lorentz invariance

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R.M. Wald, PR D21 (1980) 2742
S.W. Hawking, Commun. Math. Phys. 87 (1982) 395

- No fundamental arrow of time in its own right but only with a choice of matter vs. antimatter
- In presence of fundamental quantum-gravity-induced decoherence, CPT operator is no longer well defined: scattering operator cannot map pure in-states into pure out-states, and vice versa, due to destruction of information in presence of micro black holes
- Analog to dissipative processes but here irreversibility is conected to CPT
- Dissipative Kossakowski-Lindbladt dynamics parametrization 1980's and 90's (Ellis, Hagelin, Nanopoulos, Srednicki, Huet, Peskin, Benatti, Floreanini), spin-statistics aspects and ω*-model* (Bernabeu), specific string-inspired space-time background model (Mavromatos, Sarkar, many papers)

Concept of minimal energy- and length scale leads to non-commutative geometry, by analogy to uncertainty relation

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

Motivated in-depth in string theories
Developed to deformed geometry generated by κ-deformed Poincaré algebra (generators of boosts, momenta and rotations) and defined by commutation relations

$$[t, x^j] = ix^j/\kappa; \qquad [t, k^j] = -ik^j/\kappa; \quad \text{etc.}$$

κ naturally expected to be m_{Planck}

J.Kowalski-Glikman, S.Nowak, Class. Quant. Grav. 20 (2003) 4799

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Normal, i.e. undeformed CPT

$$\begin{aligned} CPT: p_0 &\rightarrow p_0 \\ CPT: \vec{p} &\rightarrow \vec{p} \end{aligned}$$

Naively, try to deform CPT$_\kappa$ expanding to linear terms in $1/\kappa$

$$\begin{aligned} CPT_\kappa: p_0 &\rightarrow p_0 - \frac{\vec{p}^2}{\kappa} + \mathcal{O}\big(\frac{1}{\kappa^2}\big) \\ CPT_\kappa: \vec{p} &\rightarrow \vec{p} - \frac{p_0\vec{p}}{\kappa} + \mathcal{O}\big(\frac{1}{\kappa^2}\big) \end{aligned}$$

And always $CPT_\kappa: q \rightarrow \bar{q}$

Planck-scale deformations of discrete symmetries
Still simple-minded

Effect of CPT_κ to be derived by generalizing κ-Poincaré to Hopf algebras

In simpler terms, sufficient to require preservation of mass-shell relation under $\Theta_\kappa = CPT_\kappa$

$$
\begin{aligned}
m^2 &= p_0^2 - \vec{p}^2 \\
&= \Theta_\kappa(p_0)^2 - \Theta_\kappa(\vec{p})^2
\end{aligned}
$$

and de Sitter metric in momentum space, with radius = κ

CPT thus deforms observables

e.g. Lorentz factors

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Usual Lorentz boost factor γ for a particle

$$\gamma = \frac{E}{m}$$

becomes Θ_κ = CPT$_\kappa$-deformed for antiparticle

$$\begin{aligned} \gamma_\kappa &= \Theta_\kappa \gamma \\ &= \frac{\Theta_\kappa(E)}{m} \\ &= \frac{1}{m}\left(E - \vec{p}^2/\kappa\right) \end{aligned}$$

Approach and results:

M.Arzano, J.Kowalski-Glikman, W.Wislicki, Phys.Lett. B794 (2019) 41

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Unstable particle at rest

$$\psi = \sqrt{\Gamma} e^{-\Gamma t/2 + imt}$$

Mass m and lifetime $\tau = 1/\Gamma$ are $\Theta =$CPT-invariant.

At rest, CPT undeformed, hence $m_p = m_a$ and $\Gamma_p = \Gamma_a$ due to CPT theorem.

In their rest frames, decay probability laws the same for particle and antiparticle

$$\begin{aligned}
\mathcal{P}_p &= \psi \star \psi^{\ddagger} \\
&= \Gamma e^{-\Gamma t} \\
&= \Theta\psi \star (\Theta\psi)^{\ddagger} \\
&= \mathcal{P}_a
\end{aligned}$$

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But they differ after Lorentz transformation

$$
\begin{aligned}
\mathcal{P}_p &= \frac{\Gamma E}{m} e^{-\Gamma t E/m} \\
\mathcal{P}_a &= \Gamma\left(\frac{E}{m} - \frac{\vec{p}^2}{\kappa m}\right) e^{-\Gamma t\left(\frac{E}{m} - \frac{\vec{p}^2}{\kappa m}\right)}
\end{aligned}
$$

Consequences could be examined experimentally by precisely measuring the particle and antiparticle lifetimes..

.. provided lifetime is dilated and deformed enough w.r.t. precision of its measurement

Correction to lifetime at least comparable to experimental accuracy $\vec{p}^2/(\kappa m) \simeq \sigma_\tau/\tau$

Crucial points

Momentum-dependence of CPT violation

- In this scheme, CPT violation is momentum-dependent, thus explicitly depends on the Lorentz frame
- Implementation of interplay between CPT and Lorentz (non)invariance, as suggested by general theorems
- Perhaps the only proposed CPT-violation mechanism where CPT violation entails breakdown of Lorentz invariance, explicitly (and in a simple way)
- Model still under development, we have no Lagrangian yet

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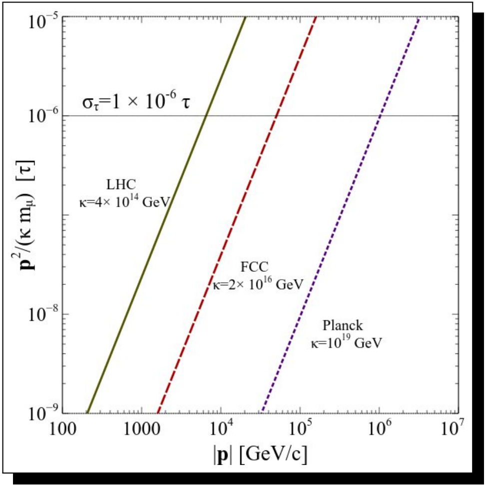
$\tau_{\mu} = (2.1969811 \pm 0.0000022) \times 10^{-6}$ s

LHC: $p = 6.5$ TeV/c
FCC: $p = 50$ TeV/c
☺

Possible experimental setup:
$J/\psi \to \mu^{+}\mu^{-}$

Measure τ_{μ^+} and τ_{μ^-} for same energy muons



In addition to experimental accuracy, need to control possible subtle effects distorting decay law

If not at rest, the exponential law with constant Γ is not exact (L. Khalfin, J. Exp. Theor. Phys. 33 (1957) 1371)

$$\begin{aligned} \psi(t) &= \int dm\, e^{-it\sqrt{m^2+\vec{p}^2}}\, f_{\text{Breit-Wigner}}(m;\Gamma) \\ \mathcal{P}(t) &\sim e^{-\Gamma(\vec{p})t} \end{aligned}$$

However, $\vec{p}$-dependent deviations of $\Gamma(\vec{p})$ from $\gamma\Gamma = m\Gamma/\sqrt{m^2+\vec{p}^2}$ shown to be extremely small (F. Giacosa, A. Phys. Pol. B47 (2016) 2145) if Γ/m negligible; for $\mu^\pm$, $\Gamma/m = 3\times10^{-18}$ and estimated correction to decay rate $< 10^{-37}\Gamma$

More hopes: interference phenomena

Known to be precise tool in measuring subtle effects

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Consider neutral-meson interference (K^0, B^0, etc.)

$$K_{L,S} \longleftarrow \phi^0(1020) \longrightarrow K_{S,L}$$

$$B_{H,L} \longleftarrow \Upsilon(10580) \longrightarrow B_{L,H}$$

Decay-time Δt spectrum in meson rest frames and the same decay channels

$$I(\Delta t) \sim e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2\, e^{-\bar{\Gamma} \Delta t} \cos(\Delta m \Delta t), \qquad \Delta m = m_{\text{heavier}} - m_{\text{lighter}}$$

CPT meson-to-antimeson does not affect Δt spectrum

Following results are preliminary

$$\begin{aligned} I(\Delta t) &\sim (\gamma - \vec{p}^2/(m\kappa))(e^{-\gamma\Gamma_L \Delta t} + e^{-\gamma\Gamma_S \Delta t}) \\ &+ \gamma \Delta t\, \vec{p}^2/(m\kappa)(\Gamma_L e^{-\gamma\Gamma_L \Delta t} + \Gamma_S e^{-\gamma\Gamma_S \Delta t}) \\ &- 2\gamma\, e^{-\gamma\bar{\Gamma}\Delta t}\, [(1 + \bar{\Gamma}\Delta t\, \vec{p}^2/(m\kappa)) \cos(\gamma \Delta\, m \Delta t) + \Delta m \Delta t\, \vec{p}^2/(m\kappa) \sin(\gamma \Delta m \Delta t)] \end{aligned}$$

$\kappa \to \infty$ is no deformation

Experimental limitation:
Lorentz-amplified oscillation frequency cannot exceed inverse time resolution of experiment

$$\frac{1}{\gamma \Delta m} > \sigma_t$$

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LHCb gets 0.045 ps in wide momentum range

Corresponds to:

<u>For K</u>

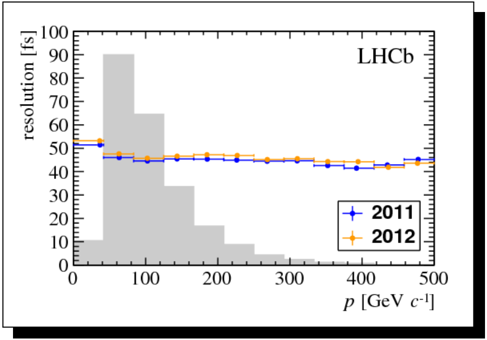
$\gamma = 4.3$

$E = 2.2$ GeV

<u>For B</u>

$\gamma = 44$

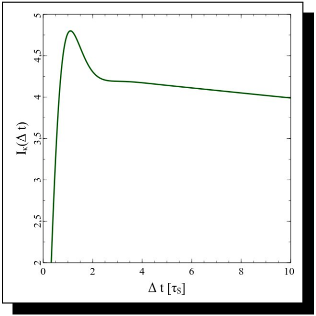
$E = 232$ GeV



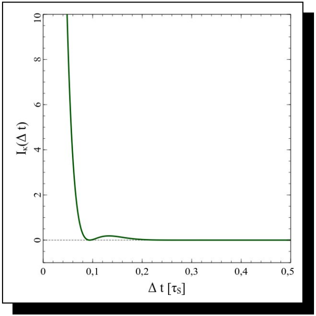
Meson interference

Monte Carlo estimates of p-values for $\kappa < \infty$ hypotheses, 1

$\phi(1020) \to K_L K_S$



$\Upsilon(10580) \to B_H B_L$



Lorentz-boosted spectra

Likelihoods for randomly chosen samples from κ-deformed and non-deformed spectra $\mathcal{L}(\kappa) = \sum_{i=1}^{N} I(\Delta t, \kappa)$

Log-likelihood ratio ($N = 10^6$) is asymptotically χ_1^2

$$\Lambda = -2 \log \frac{\mathcal{L}(\kappa)}{\mathcal{L}(\kappa = \infty)}$$

Probability that $\kappa \geq \kappa_0$ is larger than 99.9 % for

- $\kappa_0 = 2 \times 10^5$ GeV, $\phi \to K_L K_S$
- $\kappa_0 = 1.2 \times 10^8$ GeV, $\Upsilon \to B_H B_L$

Limitations weaker than from τ_μ ☹

Final remarks

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- How big is quantum-gravitational deformation? $\kappa \sim m_{\text{Planck}}$?
- A way exists to estimate quantum-gravitational deformation κ by using CPT invariance as a tool
- CPT-violating corrections to energy-momenta $\sim p^2/(m\kappa)$, hence high energy desirable
- This kind of CPT violation has Lorentz violaton built in
- What kind of high-precision observables? [1]
  - Precisely known lifetimes, e.g. τ_μ
  - Precisely measured masses, e.g. m_μ or m_π
- From τ_μ, $\kappa \sim 10^{14}$ GeV at LHC energy, good perspective to have 10^{16} GeV at future $\sqrt{s} = 100$ GeV collider (FCC at CERN)
- Neutral-meson interferometry not that promising

[1] Precisely known at low energy, well-controlled Lorentz boost required when going ultra-relativistic

Backup

Action of C, P and T

How do C, P and T act?

Space, time and charges:

$$C : q \longrightarrow -q \qquad P : q \longrightarrow q \qquad T : q \longrightarrow q$$
$$C : \vec{x} \longrightarrow \vec{x} \qquad P : \vec{x} \longrightarrow -\vec{x} \qquad T : \vec{x} \longrightarrow \vec{x}$$
$$C : t \longrightarrow t \qquad P : t \longrightarrow t \qquad T : t \longrightarrow -t$$

Energy and momenta:

$$C : \vec{p} \longrightarrow \vec{p} \qquad P : \vec{p} \longrightarrow -\vec{p} \qquad T : \vec{p} \longrightarrow -\vec{p}$$
$$C : E \longrightarrow E \qquad P : E \longrightarrow E \qquad T : E \longrightarrow E$$
$$T : i \longrightarrow -i$$

Action of κ-deformed C, P and T

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How do deformed C, P and T act?

- 0^{th} order undeformed
- 1^{st} in $1/\kappa$ to keep de Sitter metric and conserve Casimir

Antipodal operations on energy-momentum

$$\begin{aligned} S(p)_0 &\simeq -p_0 + \vec{p}^2/\kappa \\ S(p)_i &\simeq -p_i + p_0 p_i/\kappa \end{aligned}$$

$$\begin{aligned} C_\kappa(p_0) &= -S(p)_0 & P_\kappa(p_0) &= -S(p)_0 & T_\kappa(p_0) &= -S(p)_0 \\ C_\kappa(p_i) &= -S(p)_i & P_\kappa(p_i) &= S(p)_i & T_\kappa(p_i) &= S(p)_i \end{aligned}$$

Accurate measurements of lifetimes and masses

Very good but at low energy ..

- Both muon lifetime and mass are precisely measured at low energy
- For masses, hard to find method for comparable precision at TeV energy
- For lifetime, $\sigma_\tau = 0.045$ ps, at LHC energy $\sigma_\tau/(\tau\gamma) = 0.3 \times 10^{-13}$ for $\gamma = 6 \times 10^4$

κ-deformed momenta as coordinates of de Sitter space

$$-p_0^2 + \sum_i p_i^2 = \kappa^2$$

$S(p)_i$ defined as Hopf antipode

$$\begin{aligned} S(p)_i &= \ominus p_i \\ &= -p_i \frac{\kappa}{p_0 + p_4} \end{aligned}$$