# CPT-Symmetry Studies Involving Quarks

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## Rare Processes and Precision Measurements Frontier

## Topical Group RF1: Weak decays of b and c quarks
## Topical Group RF2: Weak decays of strange and light quarks

## Energy Frontier

## EF08: BSM: Model specific explorations

## EF09: BSM: More general explorations

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Confinement impedes direct experimental access to the Standard Model's quark degrees of freedom. However, the last decades have witnessed the operation of various meson factories as well as the LHC, a facility that can reasonably be viewed as a top factory. This has opened an avenue for precision measurements involving strange, charm, and bottom quarks as well as the top quark, respectively. Interferometric studies at meson factories are known for their extraordinary CPT sensitivity, and have therefore been instrumental in assessing this symmetry for the strange, charm, and bottom flavors. Likewise, the high statistical power of the LHC dataset enables studies of CPT invariance in top-quark physics. Experimental signatures that have featured prominently in these investigations are the 4-momentum, direction, and species dependence of CPT violation predicted within effective field theory. This insight has uncovered more CPT observables beyond the single parameter in the usual quantum-mechanical treatment and has contributed to a surge of interest in such measurements. Current theoretical progress has extended these results and found an additional set of experimental signals paving the way for measurements of previously unexplored types of CPT breakdown. These developments bode well for increased efforts in this research field in the coming decade.

## INTRODUCTION

Nature has gifted us with four neutral-meson systems, $K^0$, $D^0$, $B_d^0$, $B_s^0$, that produce flavor oscillations via mixing with their antiparticles. The interferometric nature of these oscillations offers crucial sensitivity to new physics. The neutral-meson systems have historically played a key role in our understanding of fundamental symmetries, notably including the discovery of CP violation [1]. They are also associated with the earliest precision tests of CPT invariance, a fundamental symmetry of central importance in relativistic quantum field theory.

Traditionally, the propagation and oscillation of a neutral meson has been analyzed in a quantum-mechanical approach based on a $2 \times 2$ effective Hamiltonian $\Lambda$ in meson–antimeson state space. In this formalism, indirect CPT violation is associated with nonzero values of a complex parameter, denoted here by $\xi$, which is proportional to the diagonal-element difference $\Delta\Lambda = (\Lambda_{11} - \Lambda_{22})/2$ and is independent of phase conventions and the size of any CPT violation [2].

Investigations of CPT symmetry using this approach based predominantly on quantum-mechanical reasoning began many decades ago [3], long before the advent of the Standard Model (SM) and the heyday of quantum field theory. These early efforts adopted the natural-seeming assumption that the complex parameter $\xi$ governing CPT violation is both constant and universal across all the neutral-meson systems. However, in the intervening decades the establishment of the SM and its phenomenological success have led to the paradigm that effective quantum field theories (EFTs) provide the backbone for modeling small corrections to the SM. Within this paradigm, CPT violation is constrained by the CPT theorem [4], a result based on the intimate relation between CPT and Lorentz symmetry. This constraint implies that CPT breakdown would be accompanied by Lorentz violation in physically reasonable EFTs [5].

This key insight has been instrumental in the realization that the parameter $\xi$ can depend on the meson flavor and *must* depend on the meson 4-momentum for compatibility with EFT. The phenomenology of CPT violation in the neutral-meson systems is thus substantially more intriguing than the historical approach would lead us to believe. For example, experiments that historically have been viewed as measuring identical observables in fact turn out to have been studying distinct physical effects. Moreover, qualitatively new observables come into play, many of which remain experimentally unmeasured to date in any of the neutral-meson systems.

CPT tests involving the top quark require different theoretical and experimental analyses, as its large mass prevents it from hadronization. For suitable processes, such as single-top and single-antitop production comparisons, the CPT-invariant theory is already based on field-theory concepts, so that in the event of CPT breakdown the presence of Lorentz violation may perhaps not be too surprising.

## EFT FOR CPT VIOLATION

The general EFT framework for CPT and Lorentz breakdown is the Standard-Model Extension (SME) [6, 7]. Its coefficients can be generated in a number of proposals for more fundamental physics, such as string theory [8, 9]. To date, the SME has formed the basis for over 300 tests of these foundational symmetries in a wide range of physical systems across all energy scales including meson interferometry [10]. The SME has been employed to relate CPT-violating coefficients in its field-theory quark Lagrangian to the quantum-mechanical $2 \times 2$ $\Lambda$ Hamiltonian for mesons and to study CPT-breaking observables [2, 11–13, 15–18]. As expected, species, motion, and orientation dependences of observables are predicted, and these results have formed the basis for CPT studies at major meson interferometers including KTeV, FOCUS, BaBar, KLOE, D0, and LHCb [19–24].

The existing experimental analyses for neutral mesons have searched for effects arising from SME contributions of the form $\mathcal{L}_{\rm SME} \supset -a_q^\mu \bar{q}\gamma_\mu q$, where $q = u, d, s, c, b$ denotes a quark field, and $\gamma_\mu$ are the usual Dirac gamma matrices. The Lorentz- and CPT-violating SME coefficient $a_q^\mu$ is a flavor-dependent 4-vector. This Lagrangian correction to the SM quark sector dominates low-order observable effects and permits the direct calculation of the individual $\xi_P$ parameters pertaining to the mesons $P = K^0, D^0, B_d^0, B_s^0$ [12]:

$$\xi_P \propto (a_{q2}^\mu - a_{q1}^\mu)\beta_\mu \, , \tag{1}$$

where $a_{q1}^\mu, a_{q2}^\mu$ are 4-vector coefficients in the SME for two valence quarks $q1, q2$ of the meson $P$ in question. The meson's 4-velocity $\beta_\mu$ is measured relative to a standard fixed inertial frame [7] and exhibits the motion and orientation dependence of CPT violation. We note that neutral-meson interferometry is one of the few physical systems permitting CPT tests for strange, charm, and bottom quarks, and such studies represent the only presently feasible method for measuring their $a^\mu$-type CPT violation.

In the SM, the top-quark processes considered here are already amenable to the usual perturbative treatment. A generalized analysis within the SME merely adds further perturbative effects to this treatment, which can be viewed as Lorentz and CPT-violating insertions into the conventional Feynman diagrams for the process under consideration.

## MESON MEASUREMENTS

Interferometric CPT tests in neutral-meson systems vary widely by production and detection mechanism and by meson momentum, so there is a correspondingly wide array of theoretical methods for extracting asymmetries that isolate CPT breakdown and measure $\xi_P$ [12–18]. Future meson-interferometry studies harbor the potential for complementary searches for this type of CPT violation and could therefore yield improved limits on various combinations of $a_q^\mu$ coefficients. For example, the high-luminosity correlated-meson Belle II data [25] promise competitive constraints on these CPT-violating SME observables for the $b$ and $d$ quarks.

A recent development [26] of EFT techniques using effective scalar field theory to describe meson oscillations has permitted the calculation of contributions to $\xi_P$ from subdominant operators. For example, the correction term $\mathcal{L}_{\rm CPT} \supset -\frac{1}{2} i k_P^{\mu\rho\sigma} \phi_P^\dagger \partial_\mu \partial_\rho \partial_\sigma \phi_P + \text{h.c.}$, where $\phi_P$ is the effective scalar field governing the meson $P$ and $k_P^{\mu\alpha\beta}$ is the corresponding Lorentz- and CPT-violating coefficient, gives rise to

$$\delta_P \propto \beta_\mu \beta_\rho \beta_\sigma \, k_P^{\mu\rho\sigma} \, . \tag{2}$$

Each of the $k_P^{\mu\rho\sigma}$ contains 16 independent components, resulting in a total of 64 novel CPT observables across the four meson systems $P = K^0, D^0, B_d^0, B_s^0$. Sixteen of these components exhibit phenomenological signatures related to those of the $a_q^\mu$ and could be constrained by reanalysis of existing data. However, the other 48 components are currently unconstrained by any experimental analysis, revealing that tests of CPT symmetry with neutral mesons still have much territory to explore. A theoretical analysis expanding the study of $k_P$ including its relation to the quark-level $\mathcal{L}_{\rm SME} \supset -a_q^{\mu\rho\sigma} \bar{q} \gamma_\mu \partial_\rho \partial_\sigma q$ operator is presently underway [27]. All these developments provide substantial motivation for further studies and can be expected to spawn intensified research activities aiming to probe CPT invariance via neutral-meson interferometry over the coming decade.

## TOP-QUARK CPT AND LORENTZ TESTS

High-statistics studies of top-quark physics are part of the Energy Frontier. Highest-energy colliders, such as the LHC at CERN and its predecessor, the Tevatron at Fermilab, are therefore uniquely positioned for CPT and Lorentz tests involving the top quark [28]. For example, an analysis of D0 data has searched for SME effects in events that produce $t\bar{t}$ pairs that decay into a final state including two light quarks $(\bar{q}, q')$, two $b$ quarks $(b, \bar{b})$, and a lepton–neutrino pair $(l, \nu_l)$ via the mode $t\bar{t} \to W^+ b W^- \bar{b} \to l \nu_l b \bar{q} q' \bar{b}$, where $l = e, \mu$ [29]. This groundbreaking measurement represents the first experimental investigation of Lorentz symmetry in the top-quark sector. It has led to a subsequent theoretical proposal that includes the first phenomenological study of CPT symmetry in top physics at the LHC [30]. More specifically, it was found that a cross-section asymmetry in single-(anti)top production through the four basic processes of $q\bar{q}$ annihilation via $W$ in the $s$ channel, $bq$ and $b\bar{q}$ weak interactions in the $t$ channel, and $b$–gluon production of $tW$ provides access to the SME's unexplored CPT-violating $b_t^\mu$ coefficient for the top quark. With current efforts aimed at such challenging measurements [31, 32] and ample grounds for further theoretical explorations of SME's top sector, this field offers the unique potential for pioneering spacetime-symmetry studies in top-quark physics.

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