Measurements of CPT Violation at LHCb

J. van Tilburg
Nikhef, Science Park 105
1098 XG Amsterdam, Netherlands

On behalf of the LHCb Collaboration

Recent measurements of CPT violation and Lorentz symmetry breaking in $B^0 - \bar{B}^0$ mixing and $B^0_s - \bar{B}^0_s$ mixing, obtained from data taken by the LHCb experiment, are highlighted. The results are expressed in terms of the Standard-Model Extension (SME) coefficients, which incorporate both CPT and Lorentz violation. Due to the large boost of the $B$ mesons at LHCb, the SME coefficients can be determined with high precision. The bounds on these coefficients are improved significantly compared to previous measurements.

1. Introduction

The LHCb detector\cite{1,2} is a single-arm forward spectrometer designed for the study of heavy flavor hadrons. Many results have been published by the LHCb collaboration, in particular on CP violation in decays of $b$ and $c$ hadrons. In contrast, until recently LHCb had made no measurements on CPT violation in these decays. In these proceedings, a new result\cite{3} from the LHCb collaboration on CPT violation in $B^0 - \bar{B}^0$ mixing and $B^0_s - \bar{B}^0_s$ mixing is highlighted.

Violation of CPT symmetry implies a breaking of Lorentz invariance in a local, interacting quantum field theory.\cite{4} This means that any CPT-violating parameter must also violate Lorentz invariance. The Standard-Model Extension (SME) is an effective field theory, where CPT- and Lorentz-violating terms are added to the Standard-Model lagrangian.\cite{5,6} This framework provides the experimental opportunity to measure the coupling coefficients in these terms. The LHCb result\cite{3} presented here is given in terms of these SME coefficients.

In the past, there have been many experimental searches for CPT violation in neutral-meson systems.\cite{7,8} The majority of these searches have been done without any assumption on the breaking of Lorentz invariance, referred to as the classical approach. In the last 15 years, more searches have been performed within the SME framework, placing tight constraints
on its coefficients.  

2. Formalism of CPT violation in neutral-meson systems

The particle-antiparticle mixing between neutral-meson states creates an interferometric system that enhances the sensitivity to CPT violation enormously. Conservation of CPT symmetry implies equal mass and lifetime of particles and antiparticles. The CPT-violating observable in the mixing process is given by

\[ z = \frac{\delta m - i\delta \Gamma / 2}{\Delta m + i\Delta \Gamma / 2}, \] (1)

where \( \delta m \) and \( \delta \Gamma \) are the (CPT-violating) mass and decay width differences between the particle and antiparticle states. The high sensitivity to \( z \) comes through the small values in the denominator of the eigenvalue differences, \( \Delta m \) and \( \Delta \Gamma \), of the two-state system. In the SME framework, the \( z \) observable becomes\(^{10,11}\)

\[ z = \frac{\beta^\mu \Delta a_\mu}{\Delta m + i\Delta \Gamma / 2}, \] (2)

where \( \beta^\mu = (\gamma, \gamma \vec{\beta}) \) is the four velocity of the neutral meson and \( \Delta a_\mu \) is a real four-vector vacuum expectation value that describes the coupling with the mesons. The complex parameter \( z \) can be determined directly from the decay rates as function of the decay time of the neutral meson\(^{3,8}\).

There are four systems of neutral mesons. In all of them, the mixing formalism is identical, however, their phenomenology is very different owing to the different values of \( \Delta m \) and \( \Delta \Gamma \), and number of decay modes. In the \( K^0 - \bar{K}^0 \) system, there have been many searches for CPT violation by dedicated kaon experiments (KLOE, KTeV, CPLEAR, and NA48) following the classical approach. An experimental overview is given in Ref. 7. Strong constraints on the SME coefficients have been made using data from KLOE, KTeV and E773.\(^9\) It will be difficult for LHCb to compete with these dedicated kaon experiments due to the lower statistics and worse kaon lifetime acceptance. The situation is already different in the \( D^0 - \bar{D}^0 \) system. Only a single measurement exists, by the FOCUS collaboration,\(^{12}\) using a sample of 35k \( D^0 \to K^-\pi^+ \) decays. LHCb would be able to improve this measurement significantly owing to the 50M \( D^0 \to K^-\pi^+ \) decays, collected during Run 1.\(^8\) In the following, I will focus on the two remaining neutral-meson systems: the \( B^0 \) and \( B^0_s \) systems.
3. Measurements at LHCb

In both the $B_0$ system and $B_0^s$ system, $\Delta\Gamma$ is negligibly small compared to $\Delta m$. The Standard Model predicts that $\Delta\Gamma$ is about a factor 200 smaller than $\Delta m$, which is already confirmed in the $B_0^s$ system. Since $\Delta a_\mu$ is real, it follows from Eq. (2) that $\Im(z)$ is a factor 400 smaller than $\Re(z)$. Therefore, to constrain the SME coefficients, $B$ decays to CP eigenstates are used, which are more sensitive to $\Re(z)$ in comparison to using $B$ decays to flavor-specific final states.

The golden $B$ decay modes to CP eigenstates, $B_0^0 \to J/\psi K^0_S$ and $B_0^s \to J/\psi K^+ K^-$, have been used due to their relatively large branching fraction. These modes have been studied already at LHCb to measure $\sin(2\beta)$ and $\phi_\alpha$. For the present analysis, the fit models have been extended to allow for possible CPT violation. The results are shown in Table 1. No significant sidereal variation and no violation of CPT symmetry are observed. In the $B_0^0$ system, there is a large improvement of three orders of magnitude with respect to the previous best result from BaBar. In the $B_0^s$ system, there is an order of magnitude improvement with respect to the previous best result from D0. The improvements are primarily attributed to the large boost of the $B$ mesons at LHCb (i.e., $\langle\beta\gamma\rangle \approx 20$ versus $\langle\beta\gamma\rangle = 4.7$ at D0).

| $B^0$ system | $B_0^s$ system |
|-------------|----------------|
| $\Delta a_1 = (-0.10 \pm 0.82 \pm 0.54) \times 10^{-15}$ GeV | $\Delta a_1 = (-0.89 \pm 1.41 \pm 0.36) \times 10^{-14}$ GeV |
| $\Delta a_\perp = (-0.20 \pm 0.22 \pm 0.04) \times 10^{-13}$ GeV | $\Delta a_\perp = (-0.48 \pm 0.39 \pm 0.08) \times 10^{-12}$ GeV |
| $\Delta a_X = (+1.97 \pm 1.30 \pm 0.29) \times 10^{-15}$ GeV | $\Delta a_X = (+1.01 \pm 2.08 \pm 0.71) \times 10^{-14}$ GeV |
| $\Delta a_Y = (+0.44 \pm 1.26 \pm 0.29) \times 10^{-15}$ GeV | $\Delta a_Y = (-3.83 \pm 2.09 \pm 0.71) \times 10^{-14}$ GeV |
| $\Re(z) = -0.022 \pm 0.033 \pm 0.003$ | $\Im(z) = 0.004 \pm 0.011 \pm 0.002$ |

4. Summary and outlook

In summary, interferometry with neutral mesons provides a sensitive method to test violations of CPT symmetry and Lorentz invariance. The LHCb experiment is well suited to improve the SME bounds, in particular due to the high boost of the particles produced at the LHC. There are plans to measure $z$ and $\Delta a_\mu$ in the $D^0$ system, which aim to improve the current bounds by a factor 40. As highlighted in these proceedings, greatly improved limits on CPT violation and Lorentz symmetry breaking in $B$
mixing have been published by LHCb. These results are based on an integrated luminosity of 3 fb$^{-1}$ obtained in Run 1 of the LHC. At the end of Run 2 in 2019, an expected 4-6 fb$^{-1}$ will be added. Due to the larger cross sections at the new center-of-mass energy of 13 TeV, the heavy flavor yields are almost a factor two higher in Run 2. Furthermore, the $B$ meson boost will also be about 30% higher. Together this means that the uncertainties will reduce by a factor two. A further improvement can be expected from the upgraded LHCb detector that will start data taking after 2019: with a projected 50 fb$^{-1}$ the uncertainties will drop by more than a factor of six.

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