Search for Violation of CPT and Lorentz Invariance in $B^0_s$ Meson Oscillations using the DØ Detector

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A search is presented for CPT-violating effects in the mixing of $B^0_s$ mesons using the DØ detector at the Fermilab Tevatron Collider. The CPT-violating asymmetry in the decay $B^0_s \to \mu^\pm D^{\mp}sX$ as a function of sidereal phase is measured. No evidence for CPT-violating effects is observed and limits are placed on CPT- and Lorentz-invariance violating coupling coefficients.

1. Introduction

Lorentz invariance requires that the description of a particle is independent of its direction of motion or boost velocity. The Standard-Model Extension (SME)\(^1\) provides a framework for potential Lorentz and CPT invariance violation (CPTV) suggesting that such violations occur at the Planck scale, but still result in potentially observable effects at currently available collider energies. In neutral meson systems, the hamiltonian is a $2 \times 2$ matrix relating the mass and weak eigenstates. Mixing between particle and antiparticle is driven by nonzero off-diagonal matrix elements due to a box diagram between $B^0_{(d, s)}$ and $\bar{B}^0_{(d, s)}$. T (or CP) violation in mixing can be due to differences between these off-diagonal terms and results in the two probabilities for oscillation between particle and antiparticle not being equal, i.e., $P(B^0 \to \bar{B}^0; t) \neq P(\bar{B}^0 \to B^0; t)$. CPT and Lorentz violation involves differences between diagonal terms of this matrix and differences in the probabilities $P(B^0 \to \bar{B}^0; t) \neq P(\bar{B}^0 \to B^0; t)$ and can be expressed with the parameter\(^2\)

$$\xi = \frac{(M_{11} - M_{22}) - i}{\Delta m - \frac{1}{2} \Delta \Gamma} \approx \frac{\beta \mu \Delta a_\mu}{\Delta m - \frac{1}{2} \Delta \Gamma}, \quad (1)$$

*http://www-d0.fnal.gov
where $\beta^\mu = \gamma(1, \vec{\beta})$ is the 4-velocity of the neutral $B$ meson, $\Delta m$ and $\Delta \Gamma$ are the mass and width difference between the heavy and light mass eigenstates, and $\Delta a_\mu = r q_1 a_\mu ^{q_1} - r q_2 a_\mu ^{q_2}$ with $r$ being coefficients with $q_1$ and $q_2$ as meson valence quarks and $a_\mu$ being the constant 4-vector in the SME Lagrange density. For the $B^0_s$-$\bar{B}^0_s$ system, the fractional difference between the mass eigenvalues is of the order of $10^{-12}$. Due to this, $B^0_s$-$\bar{B}^0_s$ oscillations form an interferometric system that is very sensitive to small couplings between the valence quarks and a possible Lorentz-invariance violating field, making it an ideal place to search for new physics.

2. Dimuon and $B^0_s$ semileptonic decay charge asymmetries

The measurement of the like-sign dimuon asymmetry by the DØ Collaboration shows evidence of anomalously large CP-violating effects. This anomalous asymmetry could also arise from T-invariant CP violation in $B^0_s$-$\bar{B}^0_s$ mixing and this sensitivity to CPT breaking has been used to obtain the first quantitative indirect measure and limit of CPT violation in the $B^0_s$-$\bar{B}^0_s$ system.

CP- and CPT-violating effects can be explored using the semileptonic decay $B^0_s \to \mu^+D^-\pi X$, where $D^- \to \phi \pi^-$ and $\phi \to K^+K^-$ (charge conjugate states are assumed throughout). CP-violating asymmetries are usually between “wrong-sign” decays $B^0_s \to \bar{B}^0_s \to \mu^-D^+\pi X$, and the DØ Collaboration has measured this flavor-specific asymmetry to be $a_\Delta = [-1.12 \pm 0.74\,(\text{stat}) \pm 0.17\,(\text{syst})]\%$, i.e., consistent with zero.

3. DØ search for CPT-violating asymmetry

A DØ published analysis explores the asymmetry between the “right-sign” decays $B^0_s \to B^0_s \to \mu^-D^+_s\pi X$ and its charge conjugate using 10.4 fb$^{-1}$ of integrated luminosity collected at the Fermilab Tevatron collider. The CPT-violating parameter is extracted using the asymmetry

$$A = \frac{N_+ - N_-}{N_+ + N_-},$$

where $N_+$ [$N_-]$ is the number of reconstructed $B^0_s \to \mu^+D^+_s\pi X$ events where $\text{sgn}(\cos \theta)Q > 0$ [$\text{sgn}(\cos \theta)Q < 0$], $\theta$ is the polar angle between the $B^0_s$ reconstructed momentum and the proton beam direction, and $Q$ is the charge of the muon. The initial state at production is not flavor tagged, but after experimental selection requirements, the $B^0_s$ system is fully mixed, so the probability of observing a $B^0_s$ or $\bar{B}^0_s$ is essentially equal regardless of
the flavor at production. We assume no CP violation in mixing, so only about half of the observed \( B^0_s \) have the same flavor as they had at birth, and observed \( B^0_s \) mesons that have changed their flavor do not contribute to CPTV, leading to a \( \sim 50\% \) dilution in the measured asymmetry.

In the SME, spontaneous Lorentz symmetry breaking generates constant expectation values for the quark fields that are Lorentz vectors represented by \( \Delta a_{\mu} \), so any observed CPT violation and the asymmetry above should vary in the frame of the detector with a period of one sidereal day as the direction of the Tevatron’s proton beam follows the Earth’s rotation with respect to the distant stars. A search is therefore made for variations of the form

\[
A(t) = A_0 - A_1 \sin(\Omega t + \phi),
\]

where \( A_0 \), \( A_1 \) and \( \phi \) are constants and are extracted by measuring the asymmetry \( A \) in Eq. (2) in bins of the sidereal phase \( \Omega t \), and fitting to the value in each bin with Eq. (3). Measurements of \( A_0 \) and \( A_1 \) are then interpreted as limits on \( \Delta a_{\mu} \) (transverse \( \Delta a_{\perp} = \sqrt{\Delta a_X^2 + \Delta a_Y^2} \), longitudinal \( \Delta a_Z \), and time component \( \Delta a_T \)) from \( B^0_s - \bar{B}^0_s \) oscillations. A nonzero value of \( \Delta a_Z \) and \( \Delta a_T \) would lead to a CPTV asymmetry not varying with sidereal time.

A typical fit to find the sum \( (N_+ + N_-) \) and difference \( (N_+ - N_-) \) yields of \( B^0_s \to \mu^+ D_s^- X \) in a particular sidereal phase bin are shown in Fig. 1. Figure 1(c) then shows a fit testing for a sidereal phase dependence, finding \( A_0 = (-0.40 \pm 0.31)\% \) and \( A_1 = (0.87 \pm 0.45)\% \), both consistent with zero and hence exhibiting no significant evidence of Lorentz or CPT violation. From these results, a 95\% upper limit of \( \Delta a_{\perp} < 1.2 \times 10^{-12} \) GeV and two-sided confidence interval of \( (-0.8 < \Delta a_T - 0.396\Delta a_Z < 3.9) \times 10^{-13} \) GeV are extracted.

4. Discussion

These results represent the first direct search for CPT-violating effects exclusively in the \( B^0_s - \bar{B}^0_s \) oscillation system. For CPTV to explain the difference between the DØ like-sign asymmetry and the SM requires that \( \Delta a_T - 0.396\Delta a_Z \) be of the order of \( 10^{-12} \), implying that CPT violation is unlikely to contribute a significant fraction of the observed dimuon charge asymmetry. These limits constrain a linear combination of the Lorentz-violating coupling constants \( a_{\mu} \) for the \( b \) and \( s \) valence quarks in the \( B^0 \) meson that are different from the linear combinations of valence quarks in the \( B^0 \), \( D^0 \), and \( K^0 \) mesons. As presented at this conference, a subsequent publication from the LHCb Collaboration has improved on the
previous best limits presented here by an order of magnitude primarily due to the much larger boost of the $B^0_s$ mesons at LHCb.

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**References**

2. V.A. Kostelecký and R. Van Kooten, Phys. Rev. D 82, 101702 (2010), and references therein.