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# Search for $CPT$ and Lorentz Violation in $B^0$-$\overline{B}^0$ Oscillations with Inclusive Dilepton Events

The *BABAR* Collaboration

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## Abstract

We report preliminary results of a search for $CPT$ and Lorentz violation in $B^0$-$\overline{B}^0$ oscillations using an inclusive dilepton sample collected by the *BABAR* experiment at the PEP-II $B$ Factory. Using a sample of 232 million $B\overline{B}$ pairs, we search for time-dependent variations in the complex $CPT$ parameter $\mathsf{z} = \mathsf{z}_0 + \mathsf{z}_1 \cos(\Omega\hat{t} + \phi)$ where $\Omega$ is the Earth's sidereal frequency and $\hat{t}$ is sidereal time. We measure $\mathrm{Im}\,\mathsf{z}_0 = (-14.1 \pm 7.3(\mathrm{stat.}) \pm 2.4(\mathrm{syst.})) \times 10^{-3}$, $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_0 = (-7.2 \pm 4.1(\mathrm{stat.}) \pm 2.1(\mathrm{syst.})) \times 10^{-3}\ \mathrm{ps}^{-1}$, $\mathrm{Im}\,\mathsf{z}_1 = (-24.0 \pm 10.7(\mathrm{stat.}) \pm 5.9(\mathrm{syst.})) \times 10^{-3}$, and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1 = (-18.8 \pm 5.5(\mathrm{stat.}) \pm 4.0(\mathrm{syst.})) \times 10^{-3}\ \mathrm{ps}^{-1}$, where $\Delta\Gamma$ is the difference between the decay rates of the neutral $B$ mass eigenstates. The statistical correlation between the measurements of $\mathrm{Im}\,\mathsf{z}_0$ and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_0$ is 76%; between $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1$ it is 79%. These results are used to evaluate expressions involving coefficients for Lorentz and $CPT$ violation in the general Lorentz-violating standard-model extension. In a complementary approach, we examine the spectral power of periodic variations in $\mathsf{z}$ over a wide range of frequencies and find no significant signal.

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# 1 INTRODUCTION

It has been shown [1] that "If *CPT* invariance is violated in an interacting quantum field theory, then that theory also violates Lorentz invariance." The general Lorentz-violating standard-model extension (SME) [2] has been used to show that the parameter for *CPT* violation in neutral meson oscillations depends on the 4-velocity of the meson [3]. In studies of $\Upsilon(4S) \to B\overline{B}$ decays at asymmetric-energy $e^+e^-$ colliders, any observed *CPT* asymmetry should vary with sidereal time as the $\Upsilon(4S)$ boost direction rotates together with the Earth [4], completing one revolution with respect to the Universe in one sidereal day ($\approx 0.99727$ solar day). We report a search for such effects using inclusive dilepton events recorded by the *BABAR* detector at the PEP-II collider.

The physical states of the $B^0$-$\overline{B}^0$ system are eigenstates of a complex $2\times 2$ effective Hamiltonian and may be written as

$$\begin{aligned} |B_L\rangle &= p\sqrt{1-\mathsf{z}}|B^0\rangle + q\sqrt{1+\mathsf{z}}|\overline{B}^0\rangle, \\ |B_H\rangle &= p\sqrt{1+\mathsf{z}}|B^0\rangle - q\sqrt{1-\mathsf{z}}|\overline{B}^0\rangle, \end{aligned} \tag{1}$$

where $L$ and $H$ indicate "light" and "heavy." The complex parameter $\mathsf{z}$ vanishes if *CPT* is preserved. $T$ invariance implies $|q/p| = 1$, and *CP* invariance requires $|q/p| = 1$ and $\mathsf{z} = 0$.

The leading-order *CPT*-violating contributions in the SME imply $\mathsf{z}$ depends on the meson 4-velocity $\beta^\mu = \gamma(1, \vec{\beta})$ in the observer frame as [5]

$$\mathsf{z} \approx \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}. \tag{2}$$

Here $\beta^\mu \Delta a_\mu$ is the real part of the difference between the diagonal elements of the effective Hamiltonian, and the magnitude of the decay rate difference $\Delta\Gamma = \Gamma_H - \Gamma_L$ is known to be small compared to the $B^0$-$\overline{B}^0$ oscillation frequency $\Delta m = m_H - m_L$. The sidereal time dependence of $\mathsf{z}$ arises from the rotation of $\vec{\beta}$ relative to the constant vector $\Delta\vec{a}$. The $\Delta a_\mu$ contain flavor-dependent *CPT*- and Lorentz-violating coupling coefficients for the valence quarks in the $B^0$ meson. Analogous, but distinct, $\Delta a_\mu$ apply to oscillations of other neutral mesons. Limits on the $\Delta a_\mu$ specific to $K^0\overline{K}^0$ oscillations [6] and on the $\Delta a_\mu$ specific to $D^0\overline{D}^0$ oscillations [7] have been reported by the KTeV and FOCUS collaborations, respectively. KTeV has also reported constraints on sidereal-time variation of the *CPT* violation parameter $\phi_{+-}$ [8].

We approximate the 4-velocity of each $B$ meson by the $\Upsilon(4S)$ 4-velocity so that $\mathsf{z}$ is common to each $B$ in a pair. We choose the meson 3-velocity to lie along $-\hat{z}$ in the rotating laboratory frame shown in Fig. 1. The non-rotating frame containing the constant vector $\Delta\vec{a}$ has $\hat{Z}$ along the Earth's rotation axis, corresponding to declination 90° in celestial equatorial coordinates. $\hat{X}$ and $\hat{Y}$, each in the equatorial plane, lie at right ascension 0° and 90°, respectively. At sidereal time $\hat{t} = 0$, $\hat{z}$ lies in the $\hat{X}$-$\hat{Z}$ plane and $\hat{y}$ is coincident with $\hat{Y}$. The *CPT* parameter $\mathsf{z}$ may then be expressed as

$$\mathsf{z} \equiv \mathsf{z}(\hat{t}\,) = \frac{\gamma}{\Delta m - i\Delta\Gamma/2}\left[\Delta a_0 - \beta\Delta a_Z \cos\chi - \beta\sin\chi\left(\Delta a_Y \sin\Omega\hat{t} + \Delta a_X \cos\Omega\hat{t}\right)\right], \tag{3}$$

where $\cos\chi = \hat{z}\cdot\hat{Z}$ and $\Omega = 2\pi/24$ rad·sidereal-hour$^{-1}$ is the Earth's sidereal frequency.

We use the latitude (37.4° N) and longitude (122.2° W) of the *BABAR* detector, together with the Lorentz boost of the $\Upsilon(4S)$ ($\beta\gamma = 0.55$ directed 37.8° east of south), to determine $\cos\chi = 0.63$

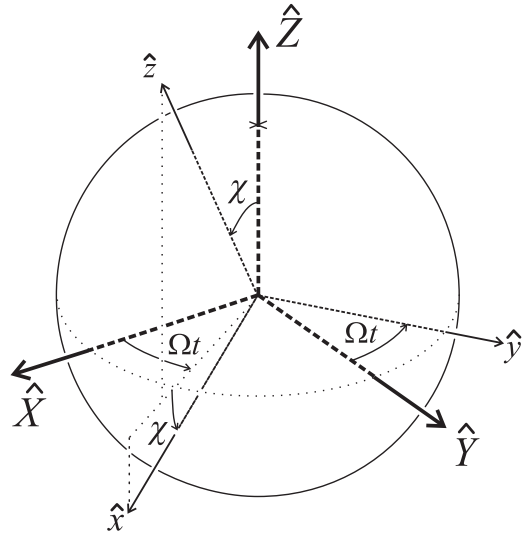


Figure 1: Basis $(\hat{x}, \hat{y}, \hat{z})$ for the rotating laboratory frame, and basis $(\hat{X}, \hat{Y}, \hat{Z})$ for the fixed non-rotating frame. The laboratory frame precesses around the Earth's rotation axis $\hat{Z}$ at the sidereal frequency $\varOmega$. The angle between $\hat{Z}$ and the direction $\hat{z}$ opposite to the $\varUpsilon(4S)$ boost direction at PEP-II is $\chi = 51°$.

and $\hat{t} = (\hat{t}_G + 7.3)$ sidereal-hours, where $\hat{t}_G$ is Greenwich Mean Sidereal Time (GMST) for each event; hence

$$\mathsf{z}(\hat{t}\,) = \frac{\left[1.14\Delta a_0 - 0.35\Delta a_Z - 0.43\left(\Delta a_Y \sin \varOmega\hat{t} + \Delta a_X \cos \varOmega\hat{t}\right)\right]}{\Delta m - i\Delta\Gamma/2}. \tag{4}$$

We convert the "timestamp" that records when the event occurred to the Julian date (J) and calculate GMST as specified by the U.S. Naval Observatory [9]:

$$\hat{t}_G = \mathrm{mod}(18.697374558 + 24.06570982441908\,\mathrm{D},\ 24), \tag{5}$$

where $\mathrm{D} = \mathrm{J} - 2451545.0$ is the number of Julian days since $12^{\mathrm{h}}$: 00 Universal Time on January 1, 2000.

The clock used to set the event timestamp has a rate governed by the PEP-II 59.5 MHz master oscillator and is resynchronized with U.S. time standards via Network Time Protocol at intervals of less than four months. During such intervals the event timestamps are conservatively estimated to accumulate absolute errors of less than 30 seconds per month. The sidereal phase of each timestamp is therefore determined to better than 0.2%.

Since sidereal time gains 12 hours every six months relative to solar time, possible day/night variations in detector response tend to cancel over sidereal time for long data-taking periods. The data used in this analysis were accumulated over a period of more than four years.

Inclusive dilepton events, where both $B$ mesons decay semileptonically ($b \to X\ell\nu$, with $\ell = e$ or $\mu$), comprise 4% of all $\varUpsilon(4S) \to B\overline{B}$ decays and provide a very large data sample for studies of *CPT* violation in mixing. In *direct* semileptonic neutral $B$ decays, the flavor $B^0(\overline{B}^0)$ is tagged by the charge of the daughter lepton $\ell^+(\ell^-)$.

At the $\Upsilon(4S)$ resonance, neutral $B$ mesons are produced in a coherent P-wave state. The $B$ mesons remain in orthogonal flavor states until one decays, after which the flavor of the other $B$ meson continues to evolve in time. Neglecting second order terms in $\mathsf{z}$, the decay rates for the three semileptonic decay configurations ($\ell^+\ell^+$, $\ell^-\ell^-$, $\ell^+\ell^-$) are given by

$$\begin{aligned}
N^{++} &\propto e^{-\Gamma|\Delta t|}|p/q|^2\left\{\cosh(\Delta\Gamma\Delta t/2)-\cos(\Delta m\Delta t)\right\},\\
N^{--} &\propto e^{-\Gamma|\Delta t|}|q/p|^2\left\{\cosh(\Delta\Gamma\Delta t/2)-\cos(\Delta m\Delta t)\right\},\\
N^{+-} &\propto e^{-\Gamma|\Delta t|}\left\{\cosh(\Delta\Gamma\Delta t/2)-2\,\mathrm{Re}\,\mathsf{z}\sinh(\Delta\Gamma\Delta t/2)+\cos(\Delta m\Delta t)+2\,\mathrm{Im}\,\mathsf{z}\sin(\Delta m\Delta t)\right\},
\end{aligned}\tag{6}$$

where $\Gamma$ is the average neutral $B$ decay rate, and $\Delta t$ is the difference between the proper decay times of the two $B$ mesons. The sign of $\Delta t$ has a physical meaning only for opposite-sign dileptons and is given by $\Delta t = t^+ - t^-$, where $t^+(t^-)$ corresponds to $\ell^+(\ell^-)$, respectively.

The opposite-sign dilepton *CPT* asymmetry $A_{CPT}$, between events with $\Delta t > 0$ and $\Delta t < 0$, compares the oscillation probabilities $P(B^0 \to B^0)$ and $P(\overline{B}^0 \to \overline{B}^0)$ and is sensitive to *CPT* violation through the parameter $\mathsf{z}$:

$$\begin{aligned}
A_{CPT}(|\Delta t|) &= \frac{P(B^0\to B^0)-P(\overline{B}^0\to\overline{B}^0)}{P(B^0\to B^0)+P(\overline{B}^0\to\overline{B}^0)} = \frac{N^{+-}(\Delta t>0)-N^{+-}(\Delta t<0)}{N^{+-}(\Delta t>0)+N^{+-}(\Delta t<0)}\\
&\simeq 2\frac{-\mathrm{Re}\,\mathsf{z}\sinh(\Delta\Gamma\Delta t/2)+\mathrm{Im}\,\mathsf{z}\sin(\Delta m\Delta t)}{\cosh(\Delta\Gamma\Delta t/2)+\cos(\Delta m\Delta t)}.
\end{aligned}\tag{7}$$

The experimental bound on $|\Delta\Gamma|$ [10] is sufficiently small for the approximation $\mathrm{Re}\,\mathsf{z}\sinh(\Delta\Gamma\Delta \mathrm{t}/2) \simeq \Delta\Gamma \times \mathrm{Re}\,\mathsf{z} \times (\Delta \mathrm{t}/2)$ to be valid over the range $-15 < \Delta t < 15\,\mathrm{ps}$ used in this analysis, and we measure the product $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}$ instead of $\mathrm{Re}\,\mathsf{z}$ alone.

We present measurements of $\mathrm{Im}\,\mathsf{z}$ and $\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}$ using a simultaneous two-dimensional likelihood fit to the observed $\Delta t$ and sidereal time ($\hat{t}$) distributions of opposite-sign and same-sign dilepton events. Inclusion of the same-sign events allows a better determination of the fraction of non-signal events (called "*obc*" in Sect. 3) in which the lepton from one $B$ meson is not a *direct* daughter. We search for variations in $\mathsf{z}$ of the form

$$\mathsf{z} = \mathsf{z}_0 + \mathsf{z}_1 \cos\left(\Omega\hat{t} + \phi\right) \tag{8}$$

with a period of one sidereal day, and extract values for the *CPT*- and Lorentz-violating coupling coefficients $\Delta a_\mu$ in the SME from the measured quantities $\mathrm{Im}\,\mathsf{z}_0$, $\mathrm{Im}\,\mathsf{z}_1$, $\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_0$, and $\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_1$. This extends our previous sidereal-time-independent analysis that measured $\mathrm{Im}\,\mathsf{z}_0$, $\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_0$, and $|q/p|$ with the same events [11]. In the decay rates, we use $|\Delta\Gamma| = 6\times10^{-3}\,\mathrm{ps}^{-1}$ in the $\cosh(\Delta\Gamma\Delta t/2)$ term and $|q/p| = 1$, consistent with the values reported in Ref. [10] and Ref. [11], respectively. In a complementary approach, we use the periodogram method [12], developed for studies of variable stars, to detect directly any periodic variations in $\mathsf{z}$ over a wide range of frequencies and to measure their spectral power $\mathrm{P}(\nu)$.

## 2 THE *BABAR* DETECTOR AND DATASET

This analysis is based on about 232 million $\Upsilon(4S) \to B\overline{B}$ decays collected during 1999–2004 with the *BABAR* detector at the PEP-II asymmetric-energy $e^+e^-$ storage ring. An additional 16 $\mathrm{fb}^{-1}$ of "off-resonance" data recorded 40 MeV below the $\Upsilon(4S)$ is used to model continuum background.

The *BABAR* detector is described in detail elsewhere [13]. This analysis uses the tracking system composed of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH), the

Cherenkov radiation detector (DIRC) for charged $\pi$–$K$ discrimination, the CsI(Tl) calorimeter (EMC) for electron identification, and the 18-layer flux return (IFR) located outside the 1.5-T solenoid coil and instrumented with resistive-plate chambers for muon identification and hadron rejection. A detailed Monte Carlo program based on GEANT4 [14] is used to simulate the response and performance of the *BABAR* detector.

# 3 ANALYSIS METHOD AND LIKELIHOOD FIT

The event selection is similar to that described in Ref. [15]. Non-$B\overline{B}$ background, mainly due to $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) continuum events, is suppressed by applying requirements on the shape and the topology of the event.

Lepton candidate tracks must have at least 12 hits in the DCH, at least one $z$-coordinate measurement in the SVT, and momentum between 0.8 and 2.3 GeV/$c$ in the $\Upsilon(4S)$ rest frame. Electrons are selected by requirements on the ratio of the energy deposited in the EMC to the momentum measured in the DCH. Muons are identified through the energy released in the EMC, as well as the strip multiplicity, track continuity, and penetration depth in the IFR. Lepton candidates are rejected if their signal in the DIRC is consistent with that of a kaon or a proton. The electron and muon selection efficiencies are about 85% and 55%, with pion misidentification probabilities around 0.2% and 3%, respectively.

Electrons from photon conversions are identified and rejected with a negligible loss of efficiency for signal events. Leptons from $J/\psi$ and $\psi(2S)$ decays are identified by pairing them with other oppositely-charged candidates of the same lepton species, selected with looser criteria. The event is rejected if the invariant mass of any such lepton pair satisfies $3.037 < m_{\ell^+\ell^-} < 3.137\,\mathrm{GeV}/c^2$ or $3.646 < m_{\ell^+\ell^-} < 3.726\,\mathrm{GeV}/c^2$. Remaining events with at least two leptons are retained, and the two highest momentum leptons in the $\Upsilon(4S)$ rest frame are used as the dilepton candidates.

Separation between *direct* leptons (" $b \to \ell$ ") and background *cascade* leptons from the " $b \to c \to \ell$ " decay chain is achieved with a neural network that combines five discriminating variables: the momenta of the two lepton candidates, the angle between the momentum directions of the two leptons, and the total visible energy and missing momentum in the event, all computed in the $\Upsilon(4S)$ rest frame. Of the original sample of 232 million $B\overline{B}$ pairs, 1.4 million pass the selection.

In the inclusive approach used here, the $z$ coordinate of the $B$ decay point is approximated by the $z$ coordinate of the lepton candidate's point of closest approach in the transverse plane to our best estimate of the $(x, y)$ decay point of the $\Upsilon(4S)$. In the transverse plane, both the intersection point of the lepton tracks and the beam-spot position provide information about the $\Upsilon(4S)$ decay point. We combine this information in a $\chi^2$-fit that optimizes our estimate of the $\Upsilon(4S)$ decay point in the transverse plane using the transverse distances to the two lepton tracks and the transverse distance to the beam-spot position. The proper time difference $\Delta t$ between the two $B$ meson decays is taken as $\Delta t = \Delta z/\langle\beta\gamma\rangle c$, where $\Delta z$ is the difference between the $z$ coordinates of the $B$ decay points, with the same sign convention as for $\Delta t$, and $\langle\beta\gamma\rangle = 0.55$ is the nominal Lorentz boost. For same-sign dileptons, the sign of $\Delta t$ is chosen randomly.

A large control sample of $e^+e^- \to \mu^+\mu^-(\gamma)$ events, with true $\Delta z = 0$, was used to check for any sidereal-time-dependent bias in the $\Delta z$ measurement that could mimic a signal for Lorentz violation. The measured amplitude for such a bias at the sidereal frequency is $(0.015 \pm 0.025)\,\mu$m, consistent with no variation around the mean value $\langle\Delta z\rangle = (0.030 \pm 0.018)\,\mu$m. The corresponding amplitude for a sidereal-time-dependent bias in $\Delta t$ for $B\overline{B}$ events is $(9 \pm 15) \times 10^{-5}$ ps. Similar amplitudes are found for possible day/night variations in the $\Delta z$ and $\Delta t$ measurements.

We model the contributions to our sample from $B\overline{B}$ decays using five categories of events, $i$, each represented by a probability density function (PDF) in $\Delta t$ and sidereal time $\hat{t}$, denoted by $\mathcal{P}_i^{n,c}$. Their shapes are determined using the $B^0\overline{B}^0$ ($n$) and $B^+B^-$ ($c$) Monte Carlo simulation separately, with the approach described in Ref. [16].

The five categories of dilepton $B\overline{B}$ decays, with contributions estimated from Monte Carlo simulation, are the following. Pure signal events with two direct leptons ($sig$), comprising 81% of the selected $B\overline{B}$ events, give information about the *CPT* parameter $\mathsf{z}$. "Opposite $B$ cascade" (*obc*) events, where the direct lepton and the cascade lepton come from different $B$ decays, contribute about 9%. "Same $B$ cascade" (*sbc*) events, in which the direct lepton and the cascade lepton stem from the same $B$ decay, contribute around 4%. About 3% of the dilepton events originate from the decay chain " $b \to \tau^- \to \ell^-$ " ($1d1\tau$), which tags the $B$ flavor correctly. The remaining $B\overline{B}$ events (*other*) consist mainly of one direct lepton and one lepton from the decay of a charmonium resonance from the other $B$ decay.

The signal event PDFs, $\mathcal{P}_{sig}^{n,c}$, are the convolution of an oscillatory term containing the sidereal-time dependent *CPT* parameter (Eq. 6) for neutral $B$ decays (or an exponential function for charged $B$ decays) with a resolution function that is the sum of three Gaussians (core, tail, and outlier) with means fixed to zero [17]. The widths of the narrower core and tail Gaussians are free parameters in the fit to data; the width of the outlier Gaussian is fixed to 8 ps. The fractions of all three Gaussians are determined by the fit: the tail and outlier fractions are free parameters, and the sum of the three fractions is constrained to unity.

The *obc* event PDFs, $\mathcal{P}_{obc}^{n,c}$, are modeled by the convolution of $(\Delta t, \hat{t}\,)$-dependent terms, similar in form to those for signal, with a resolution function that takes into account the effect of the charmed meson lifetimes. Since both short-lived $D^0$ and $D_s^+$, and long-lived $D^+$ mesons are involved in cascade decays, the resolution function for the long-lived and short-lived components is the convolution of a double-sided exponential with the sum of three Gaussians. To allow for possible outliers not present in the Monte Carlo simulation, the fraction of the outlier Gaussian is a free parameter in the fit to data. The parameterization of the *sbc* event PDFs, $\mathcal{P}_{sbc}^{n,c}$, account for the lifetimes of charmed mesons in a similar way.

The PDFs for $1d1\tau$ events, $\mathcal{P}_{1d1\tau}^{n,c}$, are similar to those for the signal events. The resolution function takes into account the $\tau$ lifetime and is chosen to be the convolution of two double-sided exponentials with two Gaussians. The PDFs for the remaining $B\overline{B}$ events, $\mathcal{P}_{other}^{n,c}$, are the convolution of an exponential function with an effective lifetime and two Gaussians.

The fractions ($f_{sbc}^{n,c}$, $f_{1d1\tau}^{n,c}$ and $f_{other}^{n,c}$) of *sbc*, $1d1\tau$ and *other* events are determined directly from the $B^0\overline{B}^0$ and $B^+B^-$ Monte Carlo simulations. The fraction $f_{+-}$ of $B^+B^-$ events and the fraction $f_{obc}^n$ of $B^0\overline{B}^0$ *obc* events are free parameters in the fit to data. The ratio $f_{obc}^c/f_{obc}^n$ is constrained to the estimate obtained from Monte Carlo samples.

Non-$B\overline{B}$ events are estimated, using off-resonance data, to comprise $f_{cont} = (3.1 \pm 0.1)\%$ of the dilepton candidates. The PDF for this component is modeled using off-resonance dilepton candidates selected with looser criteria and on-resonance events that fail the continuum-rejection criteria.

The *CPT* violation parameter $\mathsf{z}$ is extracted from a binned maximum likelihood fit to the events that pass the dilepton selection. The likelihood $\mathcal{L}$ contains the $(\Delta t, \hat{t}\,)$-dependent PDFs described previously and combines 24 sidereal-time bins.

The likelihood for each sidereal-time bin is given by

$$\begin{aligned}\mathcal{L}(\Delta t) &= f_{cont}\mathcal{P}_{cont} + (1 - f_{cont})\{f_{+-}\mathcal{P}_{B^+B^-} + (1 - f_{+-})\mathcal{P}_{B^0\overline{B}^0}\}, \text{ where} \\ \mathcal{P}_{B^0\overline{B}^0} &= (1 - f_{sig}^n)\mathcal{P}_{casc}^n + f_{sig}^n\mathcal{P}_{sig}^n,\end{aligned}$$

$$
\begin{aligned}
\mathcal{P}_{B^+B^-} &= (1-f^c_{sig})\mathcal{P}^c_{casc} + f^c_{sig}\mathcal{P}^c_{sig}, \\
\mathcal{P}^{n,c}_{casc} &= f^{n,c}_{other}\mathcal{P}^{n,c}_{other} + f^{n,c}_{1d1\tau}\mathcal{P}^{n,c}_{1d1\tau} + f^{n,c}_{sbc}\mathcal{P}^{n,c}_{sbc} + f^{n,c}_{obc}\mathcal{P}^{n,c}_{obc}.
\end{aligned} \tag{9}
$$

Here we omit small charge asymmetries ($\sim 10^{-3}$) induced by charge-dependent lepton reconstruction and identification efficiencies. While affecting the same-sign decay rates, these asymmetries cancel at first order for opposite-sign dilepton events. Our previous sidereal-time-independent analysis [11] found these asymmetries to be a source of systematic uncertainty only for $|q/p|$.

The likelihood fit gives $\mathrm{Im}\,\mathsf{z}_0 = (-14.1 \pm 7.3) \times 10^{-3}$, $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_0 = (-7.2 \pm 4.1) \times 10^{-3}\,\mathrm{ps}^{-1}$, $\mathrm{Im}\,\mathsf{z}_1 = (-24.0 \pm 10.7) \times 10^{-3}$, and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1 = (-18.8 \pm 5.5) \times 10^{-3}\,\mathrm{ps}^{-1}$. The statistical correlation between the measurements of $\mathrm{Im}\,\mathsf{z}_0$ and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_0$ is 76%; between the measurements of $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1$ it is 79%. The fitted fractions of $B^+B^-$ and *obc* events are $f_{+-} = (59.1 \pm 0.3)\%$ and $f^n_{obc} = (10.7 \pm 0.1)\%$, respectively.

Figure 2 shows the asymmetry $A_{CPT}$, defined in Eq. 7, as a function of sidereal time. The curve is a projection of the two-dimensional asymmetry onto the sidereal-time axis. To exhibit better the measured asymmetry, the projection is performed by integrating over $|\Delta t| > 3\,\mathrm{ps}$ thereby omitting highly-populated bins near $|\Delta t| = 0$ where any asymmetry is predicted to be small and is diluted by $\Delta t$ resolution effects.

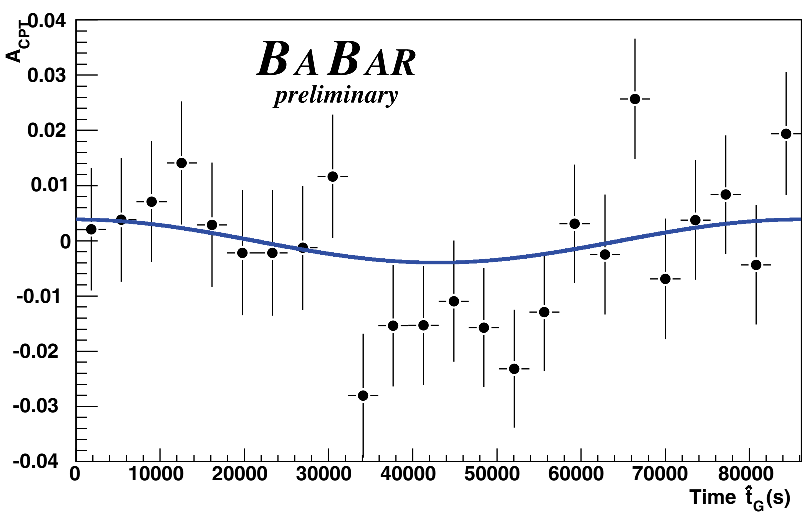


Figure 2: The asymmetry $A_{CPT}$, integrated over $|\Delta t| > 3\,\mathrm{ps}$, as a function of Greenwich Mean Sidereal Time in seconds folded over a period of 24 sidereal hours. The curve is a projection from the two-dimensional likelihood fit onto the sidereal time axis.

## 4 SYSTEMATIC STUDIES

There are several sources of systematic uncertainty in these measurements. To determine their magnitude, we vary each source of systematic effect by its known or estimated uncertainty, and take the resulting deviation in each of the measured parameters as its error.

The widths of the core and tail Gaussians of the resolution function for the *obc* and *sbc* categories as well as the pseudo-lifetime for the $1d1\tau$ and *other* categories are varied separately by 10%. This variation is motivated by comparing the fitted parameters of the signal resolution function obtained from $B\overline{B}$ Monte Carlo samples and from data. The fractions of the short-lived and long-lived charmed meson components for *obc* and *sbc* are varied by 10%. Modeling of the PDFs is the main source of systematic uncertainty in $\mathrm{Im}\,\mathsf{z}_0$.

We have also varied the parameters $\Delta m$, $\tau_{B^0}$ and $\tau_{B^\pm}$ independently within their known uncertainties [18]. For $\Delta\Gamma$, we have allowed for $3\sigma$ deviations from the value reported in Ref. [10] by varying $|\Delta\Gamma|$ over the range $0-0.1\,\mathrm{ps}^{-1}$. The lifetimes $\tau_{B^0}$ and $\tau_{B^\pm}$ are the dominant sources of systematic uncertainty in $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_1$. The dominant systematic uncertainty in $\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_0$ is imperfect knowledge of the absolute $z$ scale of the detector and residual uncertainties in the SVT local alignment. A possible sidereal-time-dependent bias in the $\Delta t$ measurement with amplitude $24\times10^{-5}$ ps, derived from the amplitude $(9\pm15)\times10^{-5}$ ps found with $e^+e^-\to\mu^+\mu^-(\gamma)$ events, contributes a negligible systematic uncertainty.

Table 1: Summary of systematic uncertainties for $\mathrm{Im}\,\mathsf{z}_0$, $\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_0$, $\mathrm{Im}\,\mathsf{z}_1$, and $\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_1$.

| **Systematic Effects** | $\sigma(\mathrm{Im}\,\mathsf{z}_0)$ $(\times10^{-3})$ | $\sigma(\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_0)$ $(\times10^{-3}\,\mathrm{ps}^{-1})$ | $\sigma(\mathrm{Im}\,\mathsf{z}_1)$ $(\times10^{-3})$ | $\sigma(\Delta\Gamma\times\mathrm{Re}\,\mathsf{z}_1)$ $(\times10^{-3}\,\mathrm{ps}^{-1})$ |
|---|---|---|---|---|
| PDF modeling | $\pm2.0$ | $\pm1.0$ | $\pm2.5$ | $\pm1.2$ |
| Bkgd component fractions | $\pm0.1$ | $\pm0.1$ | $\pm0.2$ | $\pm0.2$ |
| $\Delta\Gamma$, $\Delta m$, $\tau_{B^0}$, $\tau_{B^\pm}$ | $\pm1.3$ | $\pm1.0$ | $\pm4.9$ | $\pm3.6$ |
| SVT alignment | $\pm0.6$ | $\pm1.5$ | $\pm2.0$ | $\pm1.1$ |
| Total | $\pm2.4$ | $\pm2.1$ | $\pm5.9$ | $\pm4.0$ |

For each parameter, the total systematic uncertainty is the sum in quadrature of the estimated systematic uncertainties from each source, as summarized in Table 1.

## 5 *CPT* VIOLATION PARAMETER FREQUENCY ANALYSIS

To perform a more general search for periodic variations in the *CPT* violation parameter $\mathsf{z}$ over a wide frequency range, we adopt the periodogram method [12] used in astronomy to study the periodicity of variable stars such as Cepheids. For each test frequency $\nu$, the method determines the spectral power $\mathrm{P}(\nu)$, defined by

$$\mathrm{P}(\nu)\equiv\frac{1}{N\sigma_w^2}\Big|\sum_{j=1}^{N}w_je^{2i\pi\nu T_j}\Big|^2, \tag{10}$$

from $N$ data points measured at times $T_j$ and having weights $w_j$ with variance $\sigma_w^2$. In our case $T_j$ is the Universal Time of event $j$. In the absence of an oscillatory signal, the probability that the largest $\mathrm{P}(\nu)$ exceeds a value $S$ is given by

$$\Pr\{\mathrm{P}_{\max}(\nu)>S;M\}=1-\left(1-e^{-S}\right)^M, \tag{11}$$

where $M$ is the number of independent frequencies tested.

Our search uses 20994 test frequencies from $0.26\,\mathrm{year}^{-1}$ to $2.1\,\mathrm{day}^{-1}$ in units of (solar time)$^{-1}$, with steps of $10^{-4}\,\mathrm{day}^{-1}$. To guard against underestimating the spectral power of a signal, we have

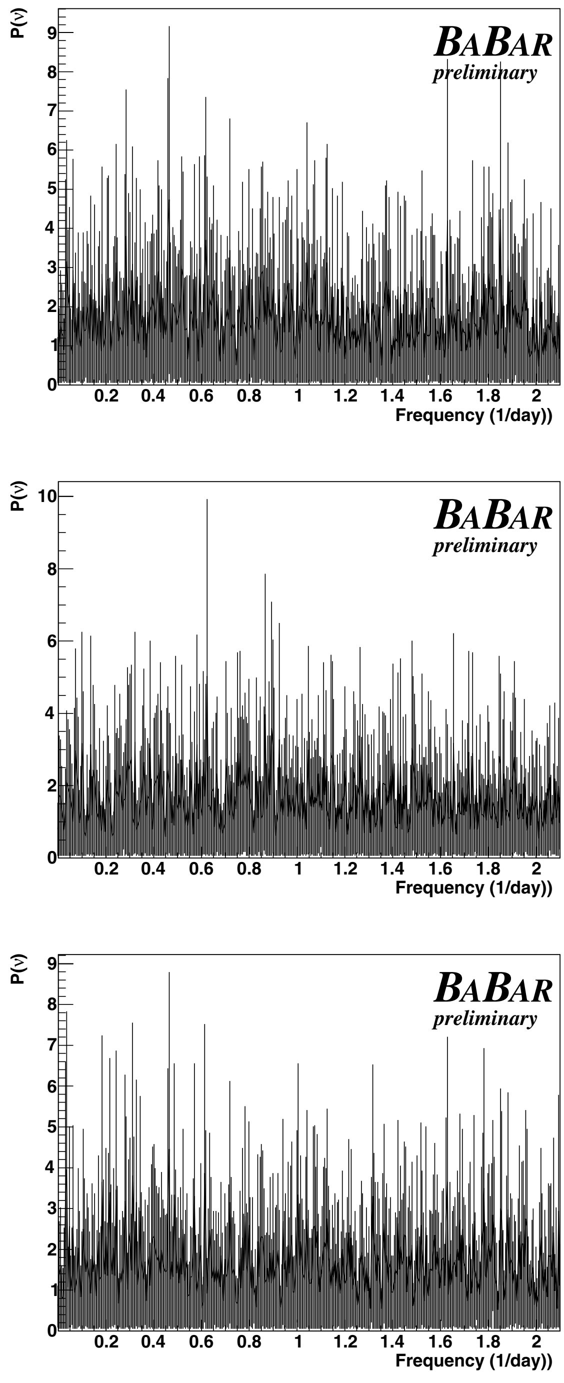


Figure 3: Periodograms for opposite-sign dileptons showing spectral power $\mathrm{P}(\nu)$ for weights $w_j \propto \Delta t_j$ (top), $w_j \propto \sin(\Delta m \Delta t_j)$ (center), and $w_j \propto \Delta m \Delta t_j - \sin(\Delta m \Delta t_j)$ (bottom) providing sensitivity to $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1$, to $\mathrm{Im}\,\mathsf{z}_1$, and to $\mathrm{Im}\,\mathsf{z}_1$ subject to the SME constraint $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z} = 2\Delta m\,\mathrm{Im}\,\mathsf{z}$, respectively.

oversampled the frequency range by a factor of about 2.2. The number of independent frequencies is about 9500. Twenty-seven test frequencies lie between the Earth's sidereal and solar rotation frequencies. Each weight $w_j$ depends on the decay time difference $\Delta t_j$ reconstructed for event $j$ occuring at time $T_j$. Periodic variations in $\mathsf{z}$ affect the decay rate $N^{+-}$ through the terms $\mathrm{Im}\,\mathsf{z}\sin(\Delta m \Delta t)$ and $\mathrm{Re}\,\mathsf{z}\sinh(\Delta\Gamma\Delta t/2) \simeq \Delta\Gamma \times \mathrm{Re}\,\mathsf{z}\,(\Delta \mathrm{t}/2)$ in Eq. 6. Sensitivity to variations in $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}$ and $\mathrm{Im}\,\mathsf{z}$ is attained by employing weights $w_j \propto \Delta t_j$ and $w_j \propto \sin(\Delta m \Delta t_j)$, respectively. In the context of the SME, the imaginary part of Eq. 2 implies $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z} = 2\Delta m\,\mathrm{Im}\,\mathsf{z}$, and hence in Eq. 6 we have $\mathrm{Im}\,\mathsf{z}\,\sin(\Delta m \Delta t) - \mathrm{Re}\,\mathsf{z}\,\sinh(\Delta\Gamma\Delta t/2) \;\simeq\; \mathrm{Im}\,\mathsf{z}\,[\sin(\Delta m\Delta t) - \Delta m \Delta t\,]$. Accordingly, we also search for periodic variations in $\mathrm{Im}\,\mathsf{z}$ using weights $w_j \propto \Delta m \Delta t_j - \sin(\Delta m \Delta t_j)$.

Figure 3 shows the spectral powers $\mathrm{P}(\nu)$ measured in the opposite-sign dilepton data sample using the weights $\Delta t_j$, $\sin(\Delta m \Delta t_j)$, and $\Delta m \Delta t_j - \sin(\Delta m \Delta t_j)$. The largest spectral power obtained for each of these weights corresponds to statistical fluctuation probabilities of 62%, 36%, and 76%, respectively, consistent with no periodic variation in the *CPT* violation parameter over the frequency range $0.26\,\mathrm{year}^{-1}$ to $2.1\,\mathrm{day}^{-1}$. At the Earth's sidereal frequency ($\approx 1.0027\,\mathrm{day}^{-1}$), $\mathrm{P}(\nu) = 3.73$, 0.71, and 6.24 for the three weight types. At the Earth's solar-day frequency, the corresponding $\mathrm{P}(\nu) = 1.50$, 0.97, and 1.47.

To check the validity of these results, we performed several tests of the periodogram method using events from data and from Monte Carlo simulation. Test periodograms showed large spectral powers at expected frequencies for (i) a generic dilepton Monte Carlo sample assigned event times $T_j$ with a $0.5\,\mathrm{sidereal\text{-}day}^{-1}$ frequency modulation, and (ii) unweighted dilepton data events, which give sensitivity to variations in the overall event rate — generally higher during night and weekend shifts, corresponding to frequencies of $1\,\mathrm{day}^{-1}$ and $1\,\mathrm{week}^{-1}$. Test periodograms for same-sign dilepton data events, which are not sensitive to *CPT* violation, showed no significant spectral power. The largest $\mathrm{P}(\nu)$ value, obtained with $\Delta t_j$ weights, corresponds to a statistical fluctuation probability of 7%. Test periodograms for opposite-sign dilepton data events, with the sign of $\Delta t$ randomized to remove any measurable *CPT* violation, also showed no significant spectral power. We used these periodograms to check whether the distribution of $\mathrm{P}(\nu)$ values has a probability density $\propto \exp\{-k \cdot \mathrm{P}(\nu)\}$ with $k = 1$, consistent with Eq. 11. A fit to the $\mathrm{P}(\nu)$ values yields $k = 1.006 \pm 0.001$ with $\chi^2 = 68.2$ for 53 degrees of freedom.

# 6 RESULTS

Figure 4 shows confidence level contours for the parameters $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1$ including both statistical and systematic errors. A significance of $2.2\sigma$ is found for periodic variations in the *CPT* violation parameter $\mathsf{z}$ at the sidereal frequency, characteristic of Lorentz violation.

In the framework of the SME, the quantities $\mathrm{Im}\,\mathsf{z}_0$, $\mathrm{Im}\,\mathsf{z}_1$, $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_0$, and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1$ are related by Eq. 4 to the $\Delta a_\mu$ containing *CPT*- and Lorentz-violating coupling coefficients. With $|\Delta\Gamma| \ll \Delta m$, and using the SME constraint $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z} = 2\Delta m\,\mathrm{Im}\,\mathsf{z}$ implied by Eq. 2, we obtain

$$\begin{aligned} 1.14\Delta a_0 - 0.35\Delta a_Z &\approx (\Delta m/\Delta\Gamma)\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_0 = 2\Delta m(\Delta m/\Delta\Gamma)\mathrm{Im}\,\mathsf{z}_0, \\ 0.43^2\left[(\Delta a_X)^2 + (\Delta a_Y)^2\right] &\approx \left[(\Delta m/\Delta\Gamma)\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1\right]^2 = 4\left[\Delta m(\Delta m/\Delta\Gamma)\mathrm{Im}\,\mathsf{z}_1\right]^2. \end{aligned} \tag{12}$$

Taking into account error correlations between $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_0$ and $\mathrm{Im}\,\mathsf{z}_0$, and between $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1$ and $\mathrm{Im}\,\mathsf{z}_1$, we find

$$\Delta a_0 - 0.30\Delta a_Z \approx -(5.2 \pm 4.0)(\Delta m/\Delta\Gamma) \times 10^{-15}\,\mathrm{GeV},$$

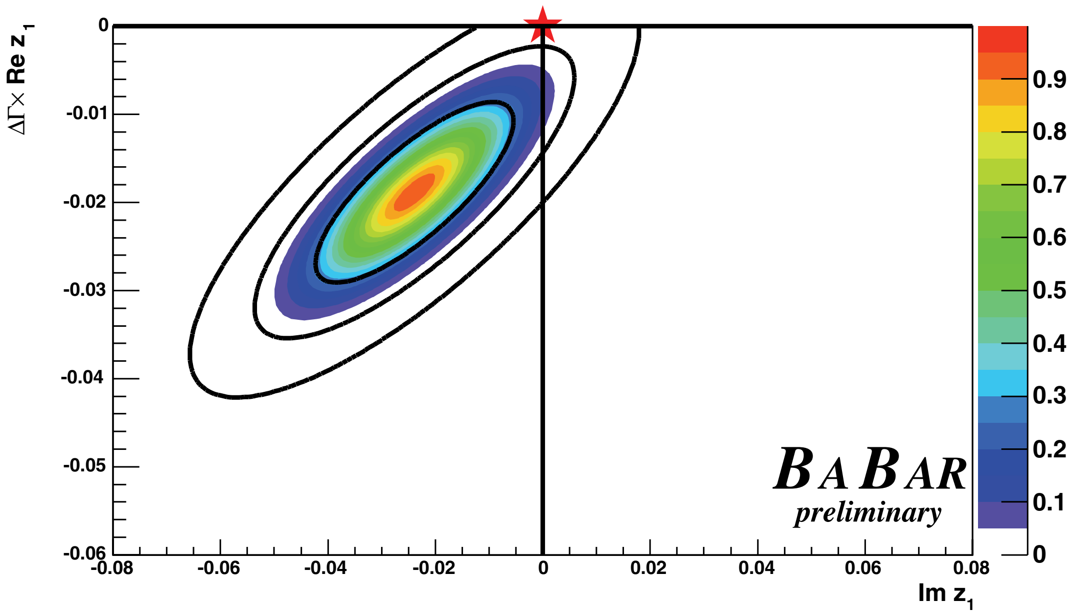


Figure 4: Confidence level contours for the parameters $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1$ including both statistical and systematic errors. The correlation between the measurements of $\mathrm{Im}\,\mathsf{z}_1$ and $\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1$ is 79%. The line contours indicate $1\sigma$, $2\sigma$, and $3\sigma$ significance. The star at $\mathrm{Im}\,\mathsf{z}_1 = \Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1 = 0$ indicates the condition for no sidereal-time dependence in $\mathsf{z}$.

$$\sqrt{(\Delta a_X)^2 + (\Delta a_Y)^2} \quad \approx \quad (37 \pm 16)|\Delta m/\Delta\Gamma| \times 10^{-15}\,\mathrm{GeV}.$$

Here we use $\Delta m = (0.507 \pm 0.004)\,\mathrm{ps}^{-1} = (3.34 \pm 0.03) \times 10^{-13}\,\mathrm{GeV}$ [19], and note that lattice QCD calculations give $\Delta m/\Delta\Gamma \sim -200$ in the standard model [20].

# 7 CONCLUSIONS

We have used data containing 232 million $B\overline{B}$ pairs to perform a simultaneous likelihood fit of same-sign and opposite-sign dilepton events that includes both the decay time difference $\Delta t$ and the sidereal time $\hat{t}$ of each event. We have measured the *CPT* violation parameter of form $\mathsf{z} = \mathsf{z}_0 + \mathsf{z}_1 \cos{(\Omega\hat{t} + \phi)}$ and find

$$\begin{aligned}
\mathrm{Im}\,\mathsf{z}_0 &= (-14.1 \pm 7.3(\mathrm{stat.}) \pm 2.4(\mathrm{syst.})) \times 10^{-3}, \\
\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_0 &= (-7.2 \pm 4.1(\mathrm{stat.}) \pm 2.1(\mathrm{syst.})) \times 10^{-3}\,\mathrm{ps}^{-1}, \\
\mathrm{Im}\,\mathsf{z}_1 &= (-24.0 \pm 10.7(\mathrm{stat.}) \pm 5.9(\mathrm{syst.})) \times 10^{-3}, \\
\Delta\Gamma \times \mathrm{Re}\,\mathsf{z}_1 &= (-18.8 \pm 5.5(\mathrm{stat.}) \pm 4.0(\mathrm{syst.})) \times 10^{-3}\,\mathrm{ps}^{-1}.
\end{aligned}$$

A significance of $2.2\sigma$, compatible with no sidereal-time dependence, is found for periodic variations in $\mathsf{z}$ at the sidereal frequency that are characteristic of Lorentz violation. The complementary periodogram method provides no strong evidence for Lorentz and *CPT* violation, or for any periodicity in $\mathsf{z}$ over the frequency range 0.26 year$^{-1}$ to 2.1 day$^{-1}$. The results of the likelihood fit are used to constrain the quantities $\Delta a_\mu$ containing *CPT*- and Lorentz-violating coupling coefficients for neutral $B$ oscillations in the general Lorentz-violating standard-model extension.

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# References

[1] O. W. Greenberg, Phys. Rev. Lett. **89**, 231602 (2002).

[2] D. Colladay and V. A. Kostelecký, Phys. Rev. D **55**, 6760 (1997); Phys. Rev. D **58**, 116002 (1998); V. A. Kostelecký, Phys. Rev. D **69**, 105009 (2004).

[3] V. Alan Kostelecký, Phys. Rev. Lett. **80**, 1818 (1998).

[4] V. Alan Kostelecký, Phys. Rev. D **64**, 076001 (2001).

[5] Ref. [3] uses the "$w\xi$" formalism. In our notation $\mathsf{z} = -\xi$ and $|q/p| = w$.

[6] KTeV Collaboration, H. Nguyen, in V. A. Kostelecký, ed., *CPT and Lorentz Symmetry II*, World Scientific, Singapore, 2002.

[7] FOCUS Collaboration, J. M. Link *et al.*, Phys. Lett. B **556**, 7 (2003).

[8] KTeV Collaboration, Y. B. Hsiung, Nucl. Phys. B (Proc. Suppl.) **86**, 312 (2000).

[9] http://aa.usno.navy.mil/faq/docs/GAST.html gives equations for GMST adapted from Appendix A of USNO Circular No. 163 (1981).

[10] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **70**, 012007 (2004).

[11] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **96**, 251802 (2006).

[12] N. R. Lomb, Astrophys. Space Sci., **39**, 447 (1976); J. D. Scargle, Astrophys. J, **263**, 835 (1982).

[13] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods **A479**, 1 (2002).

[14] S. Agostinelli *et al.*, Nucl. Instrum. Methods **A506**, 250 (2003).

[15] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **88**, 231801 (2002).

[16] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **88**, 221803 (2002).

[17] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **66**, 032003 (2002).

[18] Heavy Flavor Averaging Group, K. Anikeev *et al.*, hep-ex/0505100.

[19] 2006 Review of Particle Physics, W.-M. Yao *et al.*, Journal of Physics G **33**, 1 (2006).

[20] O. Schneider,"$B^0$-$\overline{B}^0$ Mixing" in W.-M. Yao *et al.*, Journal of Physics G **33**, 1 (2006).