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

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We report results of a search for *CPT* and Lorentz violation in B^0-$\overline{B}^0$ oscillations using inclusive dilepton events from 232 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays recorded by the *BABAR* detector at the PEP-II B Factory at SLAC. We find 2.8σ significance, compatible with no signal, for variations in the complex *CPT* violation parameter z at the Earth's sidereal frequency and extract values for the quantities Δa_μ in the general Lorentz-violating standard-model extension. The spectral powers for variations in z over the frequency range $0.26\,\mathrm{year}^{-1}$ to $2.1\,\mathrm{day}^{-1}$ are also compatible with no signal.

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It was shown recently [1] that an interacting quantum field theory need not be local for *CPT* violation to imply violation of Lorentz invariance. In the general Lorentz-violating standard-model extension (SME) [2], the parameter for *CPT* violation in neutral meson oscillations depends on the 4-velocity of the meson [3].

We report a search for this effect using $\Upsilon(4S) \to B\overline{B}$ decays recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider. Any observed *CPT* violation should vary with a period of one sidereal day ($\simeq 0.99727$ solar days) as the $\Upsilon(4S)$ boost direction follows the Earth's rotation with respect to the distant stars [4].

The physical states of the B^0-$\overline{B}^0$ system are

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

where L (H) labels the "light" ("heavy") eigenstate of the effective Hamiltonian. The complex parameter z vanishes if *CPT* is conserved; T invariance implies $|q/p| = 1$.

In the SME, *CPT*- and Lorentz-violating coupling coefficients $a_\mu^{q_i}$ for the two valence quarks in the B^0 meson are contained in quantities $\Delta a_\mu = r_{q_1} a_\mu^{q_1} - r_{q_2} a_\mu^{q_2}$, where the r_{q_i} are due to quark-binding and normalization effects. The *CPT* parameter z depends on the meson 4-velocity $\beta^\mu = \gamma(1, \vec{\beta})$ in each experiment's observer frame as [3]

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

where $\beta^\mu \Delta a_\mu$ is real and varies with sidereal time due to the rotation of $\vec{\beta}$ relative to the constant vector $\Delta\vec{a}$. The magnitude of the decay rate difference $\Delta\Gamma \equiv \Gamma_H - \Gamma_L$ is known to be small compared to the B^0-$\overline{B}^0$ oscillation frequency $\Delta m \equiv m_H - m_L$; hence Eq. 2 constrains

$$\Delta m \mathrm{Re}\,\mathsf{z} \simeq 2\Delta m(\Delta m/\Delta\Gamma)\mathrm{Im}\,\mathsf{z} \simeq \beta^\mu \Delta a_\mu. \tag{3}$$

Limits on analogous flavor-dependent Δa_μ specific to $K^0\overline{K}^0$ oscillations [5] and to $D^0\overline{D}^0$ oscillations [6] have been reported by the KTeV and FOCUS collaborations, respectively. KTeV has also reported a limit on sidereal variation of the phase ϕ_{+-} of the *CP*-violating amplitude ratio $\eta_{+-} = \mathcal{A}(K_L \to \pi^+\pi^-)/\mathcal{A}(K_S \to \pi^+\pi^-)$ [7].

We adopt the basis $(\hat{x}, \hat{y}, \hat{z})$ for the rotating laboratory frame and the basis $(\hat{X}, \hat{Y}, \hat{Z})$ for the Sun-centered nonrotating frame containing $\Delta\vec{a}$ [8]. $\hat{Z}$ is parallel to the Earth's rotation axis, $\hat{X}(\hat{Y})$ is at right ascension $0^\circ(90^\circ)$, and $\hat{y}$ is at declination 0°. We take β^μ for each B meson to be the $\Upsilon(4S)$ 4-velocity, and choose $\hat{z}$ to lie along $-\vec{\beta}$. The event sidereal time $\hat{t}$ is given by the right ascension of $\hat{z}$ as it precesses around $\hat{Z}$ at the sidereal frequency $\varOmega = 2\pi$ rad/sidereal-day. We find $\hat{t} = 14.0$ sidereal-hours at the Unix epoch (00:00:00 UTC, 1 Jan. 1970) from the latitude (37.4° N) and longitude (122.2° W) of *BABAR* and the $\Upsilon(4S)$ boost ($\langle\beta\gamma\rangle \simeq 0.55$ toward 37.8° east of south), which also yield $\cos\chi = \hat{z}\cdot\hat{Z} = 0.628$ in Eq. 4:

$$\begin{aligned} \beta^\mu \Delta a_\mu &= \gamma\left[\Delta a_0 - \beta\Delta a_Z \cos\chi \right. \\ &\quad \left. -\beta\sin\chi\left(\Delta a_Y \sin\varOmega\hat{t} + \Delta a_X \cos\varOmega\hat{t}\right)\right]. \end{aligned} \tag{4}$$

Neutral B mesons from $\Upsilon(4S)$ decay evolve in orthogonal flavor states until one decays, after which the flavor of the other continues to oscillate. We use *direct* semileptonic decays ($b \to X\ell\nu$, where $\ell = e$ or μ) to tag the flavor of each $B^0(\overline{B}^0)$ by the charge of the lepton $\ell^+(\ell^-)$. The decay rate for opposite-sign dilepton ($\ell^+\ell^-$) events is

$$\begin{aligned} N^{+-} \propto e^{-|\Delta t|/\tau_{B^0}} &\left\{(1+|\mathsf{z}|^2)\cosh(\Delta\Gamma\Delta t/2)\right. \\ &+ (1-|\mathsf{z}|^2)\cos(\Delta m\Delta t) \\ &\left. -2\,\mathrm{Re}\,\mathsf{z}\sinh(\Delta\Gamma\Delta t/2) + 2\,\mathrm{Im}\,\mathsf{z}\sin(\Delta m\Delta t)\right\}. \end{aligned} \tag{5}$$

We define $1/\tau_{B^0}$ to be the average neutral B decay rate, and $\Delta t \equiv t^+ - t^-$, where $t^+(t^-)$ is the proper time for one of a pair of B mesons to decay to $\ell^+(\ell^-)$. We make the approximation $\sinh(\Delta\Gamma\Delta t/2) \simeq \Delta\Gamma\Delta t/2$, which is valid for the range $|\Delta t| < 15\,\mathrm{ps}$ used in this analysis. We use $|\Delta\Gamma| = 6 \times 10^{-3}\,\mathrm{ps}^{-1}$ in the $\cosh(\Delta\Gamma\Delta t/2)$ term, consistent with the value reported in Ref. [9].

The asymmetry between the decay rates at $\Delta t > 0$ and $\Delta t < 0$ compares the probabilities $P(B^0 \to B^0)$ and $P(\overline{B}^0 \to \overline{B}^0)$. Omitting second-order terms in z gives

$$A_{CPT}(\Delta t) \simeq \frac{-\mathrm{Re}\,\mathsf{z}\,\Delta\Gamma\Delta t + 2\,\mathrm{Im}\,\mathsf{z}\sin(\Delta m\Delta t)}{\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m\Delta t)}. \tag{6}$$

The *BABAR* detector is described elsewhere [12]. We use about 232 million $\Upsilon(4S) \to B\overline{B}$ decays and 16 fb^{-1} of off-resonance data, from 40 MeV below the $\Upsilon(4S)$ resonance, collected during 1999–2004 to search for variations in z with sidereal time of the form

$$\mathsf{z} = \mathsf{z}_0 + \mathsf{z}_1 \cos(\varOmega\hat{t} + \phi). \tag{7}$$

For long data-taking periods, any day/night variations in detector response tend to cancel over sidereal time.

We have previously measured [10] time-integrated values of $\mathrm{Im}\,\mathsf{z}$ and $\mathrm{Re}\,\mathsf{z}\,\Delta\Gamma$ from the Δt distribution of the same events. Here, we measure $\mathrm{Im}\,\mathsf{z}_0$, $\mathrm{Re}\,\mathsf{z}_0\,\Delta\Gamma$, $\mathrm{Im}\,\mathsf{z}_1$, and $\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma$ by extending the likelihood fit to include the event sidereal time $\hat{t}$, and extract values for the SME quantities Δa_μ. In a complementary approach, we also measure the spectral power of periodic variations in z over a wide frequency band using the periodogram method [11] developed to study variable stars.

The event selection is the same as in Ref. [10]. Briefly, we suppress non-$B\overline{B}$ background by event-shape and event-topology requirements, and select events having at least two well-identified lepton candidates with momenta $0.8-2.3$ GeV/c in the $\Upsilon(4S)$ rest frame that are not part of reconstructed $J/\psi, \psi(2S) \to e^+e^-, \mu^+\mu^-$ decays or photon conversions. Lepton candidates must have at least one z-coordinate measurement in the silicon vertex tracker to allow Δt to be well-measured. We reject events in which either of the two highest-momentum lepton candidates (the *dilepton*) is classified as a *cascade* lepton from a $b \to (c, \tau) \to \ell$ transition by a neural-network algorithm that uses as input variables the momenta and opening angle of the two leptons together with the event's visible energy and missing momentum. The selected dilepton sample comprises 1.18 million opposite-sign events and 0.22 million same-sign events.

We estimate the $\Upsilon(4S)$ decay point in the transverse plane with a χ^2-fit using the transverse distances to the two lepton tracks and the beam-spot. To measure Δt, we assume each lepton originates from a direct B meson decay at the point on the lepton track with the least transverse distance to the $\Upsilon(4S)$. The component Δz, along the Lorentz boost, of the distance between these two points yields $\Delta t = \Delta z/\langle\beta\gamma\rangle c$. For opposite-sign events $\Delta z = z^+ - z^-$; for same-sign events we use $|\Delta z|$.

We model the Δt-distribution of the dilepton sample with the probability density functions (PDFs) used in Ref. [10] to represent contributions from $B^0\overline{B}^0$ and B^+B^- decays and non-$B\overline{B}$ events. The latter are estimated, using off-resonance data, to be 3.1% of the sample. The fit to data determines that 59% of the $B\overline{B}$ events are B^+B^- decays. With minor $B\overline{B}$ background contributions fixed to values from Monte Carlo (MC) simulation, the fit to data also determines the fractions of $B^0\overline{B}^0$ and B^+B^- decays that are *signal* events ($\simeq 80\%$) with two direct leptons, and the fractions ($\simeq 10\%$) that are events with one direct lepton and a $b \to c \to \ell$ cascade decay of the other B meson. Same-sign dilepton events are retained primarily to improve the determination of these fractions.

Each PDF is a convolution of a decay rate in Δt with a resolution function that is a sum of Gaussians or, for events with a cascade lepton, its convolution with one or two double-sided exponentials accounting for the lifetimes of intermediate τ or $D_{(s)}$ meson states, respectively. We use a sum of three Gaussians for signal events. The fit to data determines their fractions and also their widths except that of the widest, which is fixed to 8 ps. For leptons from different B mesons, our $B^0\overline{B}^0$ decay rate contains z to first-order (cf. Eq. 5) for opposite-sign events and is $\propto e^{-|\Delta t|/\tau_{B^0}}\{\cosh(\Delta\Gamma\Delta t/2) - \cos(\Delta m\Delta t)\}$ for same-sign events; for B^+B^- decays, it is $\propto e^{-|\Delta t|/\tau_{B^\pm}}$. For leptons from the same B meson, the decay rates are exponentials with effective lifetimes determined from MC simulation. Dilution factors are included to account for wrong flavor tags in cascade decays.

Each event's timestamp yields the time elapsed since the Unix epoch. We use this time, folded over one sidereal day and shifted in phase by 14.0 sidereal-hours, for $\hat{t}$.

We extract z from a two-dimensional maximum likelihood fit to the opposite-sign and same-sign data events binned separately in Δt and $\hat{t}$. The likelihood function in Δt for each of the 24 sidereal-time slices contains a common sum of the PDFs, and z varies with $\hat{t}$ as in Eq. 7. The likelihood fit corresponds to A_{CPT} in Eq. 6. We obtain the values for z and ϕ reported in Table I (upper left). The statistical correlation between $\mathrm{Im}\,\mathsf{z}_0$ and $\mathrm{Re}\,\mathsf{z}_0\,\Delta\Gamma$ is 76%; between $\mathrm{Im}\,\mathsf{z}_1$ and $\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma$ it is 79%.

Table I shows the sources of systematic uncertainties in the asymmetry parameters. Separate contributions are added in quadrature in the totals. We vary separately τ_{B^0}, $\tau_{B^\pm}$, and Δm by 1σ from their known values [13], and vary $|\Delta\Gamma|$ over the range $0-0.1\,\mathrm{ps}^{-1}$ to allow 3σ deviations from the value reported in Ref. [9]. Fixed parameters in the PDF resolution functions for non-signal events are varied separately by 10%, motivated by a comparison of resolution parameters fitted to signal events in data and MC simulation. The fractions of the $D_{(s)}$ meson components in background cascade decays are also varied by 10%. The effects of possible internal misalignments of the silicon vertex tracker (SVT) and uncertainty in the absolute z-scale are evaluated in $B^0\overline{B}^0$ MC samples. The clock that sets the event timestamps is governed by the PEP-II master oscillator, which is stable to within 0.001% of its set frequency. Resynchronization of the clock with U.S. time standards at intervals of less than four months limits relative sidereal phase errors to less than 0.2%. Another small uncertainty in sidereal phase arises in calculating the $\Upsilon(4S)$ boost's right ascension. We use $e^+e^- \to \mu^+\mu^-(\gamma)$ data events, with true $\Delta z = 0$, to check for sidereal variations in measured Δz that could mimic a Lorentz-violation signal. The measured amplitude $(0.022 \pm 0.025)\,\mu$m and mean $(0.030 \pm 0.018)\,\mu$m are sources of negligible uncertainties. At the solar-day frequency, the amplitude is $(0.028 \pm 0.025)\,\mu$m.

In Fig. 1 we plot the sidereal-time dependence of the measured asymmetry A_{CPT}^{meas} for the opposite-sign dilepton events with $|\Delta t| > 3\,\mathrm{ps}$, thereby omitting highly-populated bins where any asymmetry is predicted to be small. Figure 2 shows confidence level contours for $\mathrm{Im}\,\mathsf{z}_1$ and $\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma$. The significance for sidereal variations in z, characteristic of *CPT* and Lorentz violation, is 2.8σ.

The results of the fit described above are compatible with the SME constraint $\mathrm{Re}\,\mathsf{z}\,\Delta\Gamma \simeq 2\Delta m\,\mathrm{Im}\,\mathsf{z}$ (Eq. 3) for $\Delta m = 0.507\,\mathrm{ps}^{-1}$ [13]. We repeat the likelihood fit subject to this constraint. The asymmetry in Eq. 6 becomes

$$A_{CPT}(\Delta t) \simeq \frac{2\,\mathrm{Im}\,\mathsf{z}\,\{-\Delta m\Delta t + \sin(\Delta m\Delta t)\}}{\cosh(\Delta\Gamma\Delta t/2) + \cos(\Delta m\Delta t)}. \tag{8}$$

We obtain the results reported in Table I (right). The statistical correlation between $\mathrm{Im}\,\mathsf{z}_1$ and ϕ is 48%. The significance for sidereal variations in z is again 2.8σ. We

TABLE I: Asymmetry parameter values, with statistical errors, for A_{CPT} in Eq. 6 (upper left) and with SME constraint in Eq. 8 (upper right). Equation 7 implies $\mathsf{z}_1 \to -\mathsf{z}_1$ for $\phi \to \phi + \pi$. Systematic uncertainties are shown in lower part of Table.

	Without SME constraint					With SME constraint		
A_{CPT} parameter	$\mathrm{Im}\,\mathsf{z}_0$ ($\times 10^{-3}$)	$\mathrm{Re}\,\mathsf{z}_0\,\Delta\Gamma$ ($\times 10^{-3}\,\mathrm{ps}^{-1}$)	$\mathrm{Im}\,\mathsf{z}_1$ ($\times 10^{-3}$)	$\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma$ ($\times 10^{-3}\,\mathrm{ps}^{-1}$)	ϕ (rad)	$\mathrm{Im}\,\mathsf{z}_0$ ($\times 10^{-3}$)	$\mathrm{Im}\,\mathsf{z}_1$ ($\times 10^{-3}$)	ϕ (rad)
Value from fit	-14.2 ± 7.3	-7.3 ± 4.1	-24 ± 11	-18.5 ± 5.6	2.63 ± 0.31	-5.2 ± 3.6	-17.0 ± 5.8	2.56 ± 0.36
Systematic effects								
τ_{B^0}, $\tau_{B^\pm}$, Δm, $\Delta\Gamma$	± 0.7	± 0.4	± 0.6	± 0.5	± 0.05	± 0.4	± 0.7	± 0.01
SVT alignment, z scale	± 0.6	± 1.5	± 2.0	± 1.1	± 0.20	± 1.7	± 1.4	± 0.15
PDF resolution models	± 2.0	± 1.0	± 2.5	± 1.2	± 0.02	± 0.8	± 1.0	± 0.01
Background fractions	± 0.1	± 0.1	± 0.2	± 0.2	± 0.01	± 0.2	± 0.3	± 0.01
Sidereal phase	± 0.0	± 0.0	± 0.0	± 0.0	± 0.03	± 0.0	± 0.0	± 0.03
Total syst. error	± 2.2	± 1.8	± 3.3	± 1.7	± 0.21	± 1.9	± 1.9	± 0.15

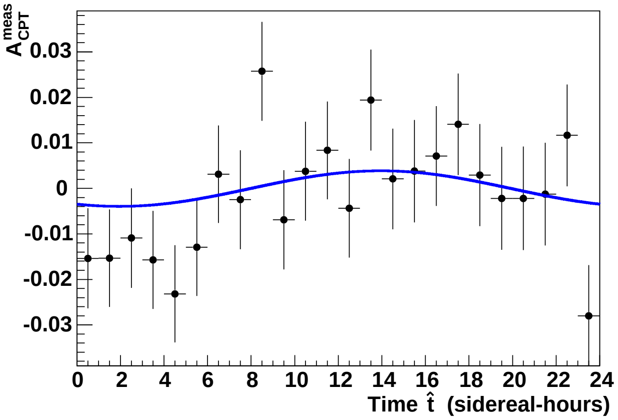

FIG. 1: Asymmetry A_{CPT}^{meas} for opposite-sign dilepton events with $|\Delta t| > 3\,\mathrm{ps}$ versus sidereal time. The sample includes event types, e.g. B^+B^- decays, for which $A_{CPT} = 0$. The curve is a projection, for $|\Delta t| > 3\,\mathrm{ps}$, using results of the two-dimensional likelihood fit for $|\Delta t| < 15\,\mathrm{ps}$.

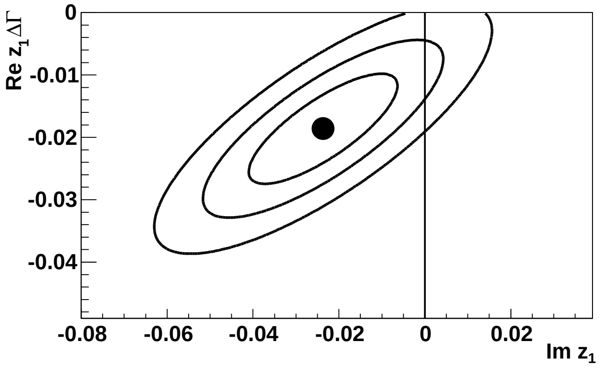

FIG. 2: Contours indicating 1σ, 2σ, and 3σ significance, around the central values of $\mathrm{Im}\,\mathsf{z}_1$ and $\mathrm{Re}\,\mathsf{z}_1\,\Delta\Gamma$ (solid circle).

obtain consistent results for $\mathrm{Im}\,\mathsf{z}_0$, $\mathrm{Im}\,\mathsf{z}_1$, and ϕ when second-order terms (Eq. 5) of form $|\mathsf{z}|^2 = \rho^2\cos^2(\Omega\hat{t}+\phi)$, motivated by finding $|\mathrm{Im}\,\mathsf{z}_1| > |\mathrm{Im}\,\mathsf{z}_0|$, are included in the likelihood fit to data with ρ^2 as a free parameter.

We use Eqs. 3, 4, and 7 to extract the SME quantities

$$\begin{aligned}\Delta a_0 - 0.30\Delta a_Z &\simeq (-3.0 \pm 2.4)(\Delta m/\Delta\Gamma) \times 10^{-15}\,\mathrm{GeV},\\ \Delta a_X &\simeq (-22 \pm 7)(\Delta m/\Delta\Gamma) \times 10^{-15}\,\mathrm{GeV},\\ \Delta a_Y &\simeq (-14^{+10}_{-13})(\Delta m/\Delta\Gamma) \times 10^{-15}\,\mathrm{GeV}.\end{aligned}$$

We now use the periodogram method [11] to compare the spectral power for variations in z at the sidereal frequency with those in a wide band of surrounding frequencies. The spectral power at a test frequency ν is

$$P(\nu) \equiv \frac{1}{N\sigma_w^2}\Big|\sum_{j=1}^{N} w_j e^{2i\pi\nu T_j}\Big|^2, \tag{9}$$

where the data, comprising N measurements w_j made at times T_j, have variance σ_w^2. Here, T_j is the time elapsed since the Unix epoch for opposite-sign dilepton event j, and the weights $w_j = \Delta m\Delta t_j - \sin(\Delta m\Delta t_j)$ are suited to the study of periodic variations in z according to Eq. 8.

In the absence of an oscillatory signal, the probability that $P(\nu)$ exceeds a value S at a given frequency is $\exp(-S)$; if M independent frequencies are tested, the largest $P(\nu)$ value exceeds S with probability

$$\Pr\left\{P_{\max}(\nu) > S; M\right\} = 1 - \left(1 - e^{-S}\right)^M. \tag{10}$$

We use 20994 test frequencies from $0.26\,\mathrm{year}^{-1}$ to $2.1\,\mathrm{solar\text{-}day}^{-1}$, spaced by $10^{-4}\,\mathrm{solar\text{-}day}^{-1}$. This oversamples the frequency range by a factor of about 2.2 and avoids underestimating the spectral power of a signal. The number of independent frequencies is about 9500.

Figure 3 shows the periodogram we obtain. The largest spectral power is $P_{\max}(\nu) = 8.78$, for the test frequency $\nu = 0.46312\,\mathrm{solar\text{-}day}^{-1}$. With no signal, the probability of finding a larger spectral power in our periodogram is 76%. Interpolation to the sidereal frequency

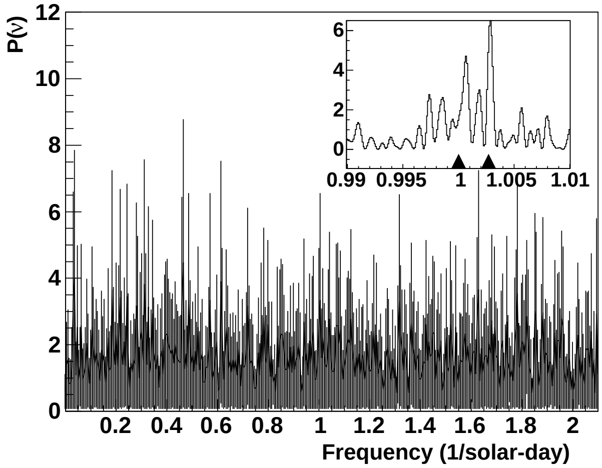

FIG. 3: Periodogram for opposite-sign dilepton events. The solar-day and sidereal-day frequencies are indicated by the left and right triangles, respectively, in the inset.

($\simeq 1.00274\,\text{solar-day}^{-1}$) yields $P(\nu) = 5.28$, a value that is exceeded at 78 test frequencies. At the solar-day frequency, where any effects due to day/night variations in detector response should appear, $P(\nu) = 1.47$.

In conclusion, we report results of a search for sidereal variations in the *CPT* violation parameter z that are complementary to our previous time-integrated measurements [10] using the same events. Neither the likelihood fits nor the periodogram method detect asymmetries large enough to provide evidence for *CPT* and Lorentz violation. We have constrained the quantities Δa_μ of the Lorentz-violating standard-model extension that parameterize *CPT* violation in B^0-$\overline{B}^0$ oscillations.

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