

Search for Violation of CPT and Lorentz Invariance in B_s^0 Meson Oscillations

V. M. Abazov,³¹ B. Abbott,⁶⁷ B. S. Acharya,²⁵ M. Adams,⁴⁶ T. Adams,⁴⁴ J. P. Agnew,⁴¹ G. D. Alexeev,³¹ G. Alkhazov,³⁵ A. Alton,^{56,a} A. Askew,⁴⁴ S. Atkins,⁵⁴ K. Augsten,⁷ C. Avila,⁵ F. Badaud,¹⁰ L. Bagby,⁴⁵ B. Baldin,⁴⁵ D. V. Bandurin,⁷³ S. Banerjee,²⁵ E. Barberis,⁵⁵ P. Baringer,⁵³ J. F. Bartlett,⁴⁵ U. Bassler,¹⁵ V. Bazterra,⁴⁶ A. Bean,⁵³ M. Begalli,² L. Bellantoni,⁴⁵ S. B. Beri,²³ G. Bernardi,¹⁴ R. Bernhard,¹⁹ I. Bertram,³⁹ M. Besançon,¹⁵ R. Beuselinck,⁴⁰ P. C. Bhat,⁴⁵ S. Bhatia,⁵⁸ V. Bhatnagar,^{38,l} G. Blazey,⁴⁷ S. Blessing,⁴⁴ K. Bloom,⁵⁹ A. Boehnlein,⁴⁵ D. Boline,⁶⁴ E. E. Boos,³³ G. Borissov,³⁹ M. Borysova,^{38,l} A. Brandt,⁷⁰ O. Brandt,²⁰ R. Brock,⁵⁷ A. Bross,⁴⁵ D. Brown,¹⁴ X. B. Bu,⁴⁵ M. Buehler,⁴⁵ V. Buescher,²¹ V. Bunichev,³³ S. Burdin,^{39,b} C. P. Buszello,³⁷ E. Camacho-Pérez,²⁸ B. C. K. Casey,⁴⁵ H. Castilla-Valdez,²⁸ S. Caughron,⁵⁷ S. Chakrabarti,⁶⁴ K. M. Chan,⁵¹ A. Chandra,⁷² E. Chapon,¹⁵ G. Chen,⁵³ S. W. Cho,²⁷ S. Choi,²⁷ B. Choudhary,²⁴ S. Cihangir,⁴⁵ D. Claes,⁵⁹ J. Clutter,⁵³ M. Cooke,^{45,k} W. E. Cooper,⁴⁵ M. Corcoran,⁷² F. Couderc,¹⁵ M.-C. Cousinou,¹² J. Cuth,²¹ D. Cutts,⁶⁹ A. Das,⁷¹ G. Davies,⁴⁰ S. J. de Jong,^{29,30} E. De La Cruz-Burelo,²⁸ F. Déliot,¹⁵ R. Demina,⁶³ D. Denisov,⁴⁵ S. P. Denisov,³⁴ S. Desai,⁴⁵ C. Deterre,^{41,c} K. DeVaughan,⁵⁹ H. T. Diehl,⁴⁵ M. Diesburg,⁴⁵ P. F. Ding,⁴¹ A. Dominguez,⁵⁹ A. Dubey,²⁴ L. V. Dudko,³³ A. Duperrin,¹² S. Dutt,²³ M. Eads,⁴⁷ D. Edmunds,⁵⁷ J. Ellison,⁴³ V. D. Elvira,⁴⁵ Y. Enari,¹⁴ H. Evans,⁴⁹ A. Evdokimov,⁴⁶ V. N. Evdokimov,³⁴ A. Fauré,¹⁵ L. Feng,⁴⁷ T. Ferbel,⁶³ F. Fiedler,²¹ F. Filthaut,^{29,30} W. Fisher,⁵⁷ H. E. Fisk,⁴⁵ M. Fortner,⁴⁷ H. Fox,³⁹ S. Fuess,⁴⁵ P. H. Garbincius,⁴⁵ A. Garcia-Bellido,⁶³ J. A. García-González,²⁸ V. Gavrilov,³² W. Geng,^{12,57} C. E. Gerber,⁴⁶ Y. Gershtein,⁶⁰ G. Ginther,^{45,63} O. Gogota,³⁸ G. Golovanov,³¹ P. D. Grannis,⁶⁴ S. Greder,¹⁶ H. Greenlee,⁴⁵ G. Grenier,¹⁷ Ph. Gris,¹⁰ J.-F. Grivaz,¹³ A. Grohsjean,^{15,c} S. Grünendahl,⁴⁵ M. W. Grünewald,²⁶ T. Guillemain,¹³ G. Gutierrez,⁴⁵ P. Gutierrez,⁶⁷ J. Haley,⁶⁸ L. Han,⁴ K. Harder,⁴¹ A. Harel,⁶³ J. M. Hauptman,⁵² J. Hays,⁴⁰ T. Head,⁴¹ T. Hebbeker,¹⁸ D. Hedin,⁴⁷ H. Hegab,⁶⁸ A. P. Heinson,⁴³ U. Heintz,⁶⁹ C. Hensel,¹ I. Heredia-De La Cruz,^{28,d} K. Herner,⁴⁵ G. Hesketh,^{41,f} M. D. Hildreth,⁵¹ R. Hirosky,⁷³ T. Hoang,⁴⁴ J. D. Hobbs,⁶⁴ B. Hoeneisen,⁹ J. Hogan,⁷² M. Hohlfeld,²¹ J. L. Holzbauer,⁵⁸ I. Howley,⁷⁰ Z. Hubacek,^{7,15} V. Hynek,⁷ I. Iashvili,⁶² Y. Ilchenko,⁷¹ R. Illingworth,⁴⁵ A. S. Ito,⁴⁵ S. Jabeen,^{45,m} M. Jaffré,¹³ A. Jayasinghe,⁶⁷ M. S. Jeong,²⁷ R. Jesik,⁴⁰ P. Jiang,⁴ K. Johns,⁴² E. Johnson,⁵⁷ M. Johnson,⁴⁵ A. Jonckheere,⁴⁵ P. Jonsson,⁴⁰ J. Joshi,⁴³ A. W. Jung,⁴⁵ A. Juste,³⁶ E. Kajfasz,¹² D. Karmanov,³³ I. Katsanos,⁵⁹ M. Kaur,²³ R. Kehoe,⁷¹ S. Kermiche,¹² N. Khalatyan,⁴⁵ A. Khanov,⁶⁸ A. Kharchilava,⁶² Y. N. Kharzheev,³¹ I. Kiselevich,³² J. M. Kohli,²³ A. V. Kozelov,³⁴ J. Kraus,⁵⁸ A. Kumar,⁶² A. Kupco,⁸ T. Kurča,¹⁷ V. A. Kuzmin,³³ S. Lammers,⁴⁹ P. Lebrun,¹⁷ H. S. Lee,²⁷ S. W. Lee,⁵² W. M. Lee,⁴⁵ X. Lei,⁴² J. Lellouch,¹⁴ D. Li,¹⁴ H. Li,⁷³ L. Li,⁴³ Q. Z. Li,⁴⁵ J. K. Lim,²⁷ D. Lincoln,⁴⁵ J. Linnemann,⁵⁷ V. V. Lipaev,³⁴ R. Lipton,⁴⁵ H. Liu,⁷¹ Y. Liu,⁴ A. Lobodenko,³⁵ M. Lokajicek,⁸ R. Lopes de Sa,⁴⁵ R. Luna-Garcia,^{28,g} A. L. Lyon,⁴⁵ A. K. A. Maciel,¹ R. Madar,¹⁹ R. Magaña-Villalba,²⁸ S. Malik,⁵⁹ V. L. Malyshev,³¹ J. Mansour,²⁰ J. Martínez-Ortega,²⁸ R. McCarthy,⁶⁴ C. L. McGivern,¹⁶ M. M. Meijer,^{29,30} A. Melnitchouk,⁴⁵ D. Menezes,⁴⁷ P. G. Mercadante,³ M. Merkin,³³ A. Meyer,¹⁸ J. Meyer,^{20,i} F. Miconi,¹⁶ N. K. Mondal,²⁵ M. Mulhearn,⁷³ E. Nagy,¹² M. Narain,⁶⁹ R. Nayyar,⁴² H. A. Neal,⁵⁶ J. P. Negret,⁵ P. Neustroev,³⁵ H. T. Nguyen,⁷³ T. Nunnemann,²² J. Orduna,⁷² N. Osman,¹² J. Osta,⁵¹ A. Pal,⁷⁰ N. Parashar,⁵⁰ V. Parihar,⁶⁹ S. K. Park,²⁷ R. Partridge,^{69,e} N. Parua,⁴⁹ A. Patwa,^{65,j} B. Penning,⁴⁰ M. Perfilov,³³ Y. Peters,⁴¹ K. Petridis,⁴¹ G. Petrillo,⁶³ P. Pétroff,¹³ M.-A. Pleier,⁶⁵ V. M. Podstavkov,⁴⁵ A. V. Popov,³⁴ M. Prewitt,⁷² D. Price,⁴¹ N. Prokopenko,³⁴ J. Qian,⁵⁶ A. Quadt,²⁰ B. Quinn,⁵⁸ P. N. Ratoff,³⁹ I. Razumov,³⁴ I. Ripp-Baudot,¹⁶ F. Rizatdinova,⁶⁸ M. Rominsky,⁴⁵ A. Ross,³⁹ C. Royon,¹⁵ P. Rubinov,⁴⁵ R. Ruchti,⁵¹ G. Sajot,¹¹ A. Sánchez-Hernández,²⁸ M. P. Sanders,²² A. S. Santos,^{1,h} G. Savage,⁴⁵ M. Savitskiy,³⁸ L. Sawyer,⁵⁴ T. Scanlon,⁴⁰ R. D. Schamberger,⁶⁴ Y. Scheglov,³⁵ H. Schellman,⁴⁸ M. Schott,²¹ C. Schwanenberger,⁴¹ R. Schwienhorst,⁵⁷ J. Sekaric,⁵³ H. Severini,⁶⁷ E. Shabalina,²⁰ V. Shary,¹⁵ S. Shaw,⁴¹ A. A. Shchukin,³⁴ V. Simak,⁷ P. Skubic,⁶⁷ P. Slattery,⁶³ D. Smirnov,⁵¹ G. R. Snow,⁵⁹ J. Snow,⁶⁶ S. Snyder,⁶⁵ S. Söldner-Rembold,⁴¹ L. Sonnenschein,¹⁸ K. Soustruznik,⁶ J. Stark,¹¹ D. A. Stoyanova,³⁴ M. Strauss,⁶⁷ L. Suter,⁴¹ P. Svoisky,⁶⁷ M. Titov,¹⁵ V. V. Tokmenin,³¹ Y.-T. Tsai,⁶³ D. Tsybychev,⁶⁴ B. Tuchming,¹⁵ C. Tully,⁶¹ L. Uvarov,³⁵ S. Uvarov,³⁵ S. Uzunyan,⁴⁷ R. Van Kooten,⁴⁹ W. M. van Leeuwen,²⁹ N. Varelas,⁴⁶ E. W. Varnes,⁴² I. A. Vasilyev,³⁴ A. Y. Verkheev,³¹ L. S. Vertogradov,³¹ M. Verzocchi,⁴⁵ M. Vesterinen,⁴¹ D. Vilanova,¹⁵ P. Vokac,⁷ H. D. Wahl,⁴⁴ M. H. L. S. Wang,⁴⁵ J. Warchol,⁵¹ G. Watts,⁷⁴ M. Wayne,⁵¹ J. Weichert,²¹ L. Welty-Rieger,⁴⁸ M. R. J. Williams,^{49,n} G. W. Wilson,⁵³ M. Wobisch,⁵⁴ D. R. Wood,⁵⁵ T. R. Wyatt,⁴¹ Y. Xie,⁴⁵ R. Yamada,⁴⁵ S. Yang,⁴ T. Yasuda,⁴⁵ Y. A. Yatsunenko,³¹ W. Ye,⁶⁴ Z. Ye,⁴⁵ H. Yin,⁴⁵ K. Yip,⁶⁵ S. W. Youn,⁴⁵ J. M. Yu,⁵⁶ J. Zennamo,⁶² T. G. Zhao,⁴¹ B. Zhou,⁵⁶ J. Zhu,⁵⁶ M. Zielinski,⁶³ D. Zieminska,⁴⁹ and L. Zivkovic¹⁴

(D0 Collaboration)

- ¹LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
²Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
³Universidade Federal do ABC, Santo André, Brazil
⁴University of Science and Technology of China, Hefei, People's Republic of China
⁵Universidad de los Andes, Bogotá, Colombia
⁶Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
⁷Czech Technical University in Prague, Prague, Czech Republic
⁸Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
⁹Universidad San Francisco de Quito, Quito, Ecuador
¹⁰LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
¹¹LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
¹²CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
¹³LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
¹⁴LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
¹⁵CEA, Irfu, SPP, Saclay, France
¹⁶IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
¹⁷IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
¹⁸III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
¹⁹Physikalisches Institut, Universität Freiburg, Freiburg, Germany
²⁰II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
²¹Institut für Physik, Universität Mainz, Mainz, Germany
²²Ludwig-Maximilians-Universität München, München, Germany
²³Panjab University, Chandigarh, India
²⁴Delhi University, Delhi, India
²⁵Tata Institute of Fundamental Research, Mumbai, India
²⁶University College Dublin, Dublin, Ireland
²⁷Korea Detector Laboratory, Korea University, Seoul, Korea
²⁸CINVESTAV, Mexico City, Mexico
²⁹Nikhef, Science Park, Amsterdam, The Netherlands
³⁰Radboud University Nijmegen, Nijmegen, The Netherlands
³¹Joint Institute for Nuclear Research, Dubna, Russia
³²Institute for Theoretical and Experimental Physics, Moscow, Russia
³³Moscow State University, Moscow, Russia
³⁴Institute for High Energy Physics, Protvino, Russia
³⁵Petersburg Nuclear Physics Institute, St. Petersburg, Russia
³⁶Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain
³⁷Uppsala University, Uppsala, Sweden
³⁸Taras Shevchenko National University of Kyiv, Kiev, Ukraine
³⁹Lancaster University, Lancaster LA1 4YB, United Kingdom
⁴⁰Imperial College London, London SW7 2AZ, United Kingdom
⁴¹The University of Manchester, Manchester M13 9PL, United Kingdom
⁴²University of Arizona, Tucson, Arizona 85721, USA
⁴³University of California Riverside, Riverside, California 92521, USA
⁴⁴Florida State University, Tallahassee, Florida 32306, USA
⁴⁵Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
⁴⁶University of Illinois at Chicago, Chicago, Illinois 60607, USA
⁴⁷Northern Illinois University, DeKalb, Illinois 60115, USA
⁴⁸Northwestern University, Evanston, Illinois 60208, USA
⁴⁹Indiana University, Bloomington, Indiana 47405, USA
⁵⁰Purdue University Calumet, Hammond, Indiana 46323, USA
⁵¹University of Notre Dame, Notre Dame, Indiana 46556, USA
⁵²Iowa State University, Ames, Iowa 50011, USA
⁵³University of Kansas, Lawrence, Kansas 66045, USA
⁵⁴Louisiana Tech University, Ruston, Louisiana 71272, USA
⁵⁵Northeastern University, Boston, Massachusetts 02115, USA
⁵⁶University of Michigan, Ann Arbor, Michigan 48109, USA
⁵⁷Michigan State University, East Lansing, Michigan 48824, USA
⁵⁸University of Mississippi, University, Mississippi 38677, USA
⁵⁹University of Nebraska, Lincoln, Nebraska 68588, USA
⁶⁰Rutgers University, Piscataway, New Jersey 08855, USA

⁶¹Princeton University, Princeton, New Jersey 08544, USA⁶²State University of New York, Buffalo, New York 14260, USA⁶³University of Rochester, Rochester, New York 14627, USA⁶⁴State University of New York, Stony Brook, New York 11794, USA⁶⁵Brookhaven National Laboratory, Upton, New York 11973, USA⁶⁶Langston University, Langston, Oklahoma 73050, USA⁶⁷University of Oklahoma, Norman, Oklahoma 73019, USA⁶⁸Oklahoma State University, Stillwater, Oklahoma 74078, USA⁶⁹Brown University, Providence, Rhode Island 02912, USA⁷⁰University of Texas, Arlington, Texas 76019, USA⁷¹Southern Methodist University, Dallas, Texas 75275, USA⁷²Rice University, Houston, Texas 77005, USA⁷³University of Virginia, Charlottesville, Virginia 22904, USA⁷⁴University of Washington, Seattle, Washington 98195, USA

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We present the first search for CPT -violating effects in the mixing of B_s^0 mesons using the full Run II data set with an integrated luminosity of 10.4 fb^{-1} of proton-antiproton collisions collected using the D0 detector at the Fermilab Tevatron Collider. We measure the CPT -violating asymmetry in the decay $B_s^0 \rightarrow \mu^\pm D_s^\pm$ as a function of celestial direction and sidereal phase. We find no evidence for CPT -violating effects and place limits on the direction and magnitude of flavor-dependent CPT - and Lorentz-invariance violating coupling coefficients. We find 95% confidence intervals of $\Delta a_\perp < 1.2 \times 10^{-12} \text{ GeV}$ and $(-0.8 < \Delta a_T - 0.396 \Delta a_Z < 3.9) \times 10^{-13} \text{ GeV}$.

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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 can occur at the Planck scale but still result in potentially observable effects at currently available collider energies. The process of neutral meson oscillations is described by a 2×2 effective Hamiltonian with mass eigenvalues of the propagating particles having very small differences between them that drive the oscillation probability. For the $B_s^0 - \bar{B}_s^0$ system, the fractional difference between the eigenvalues is of the order of 10^{-12} . Because of this, $B_s^0 - \bar{B}_s^0$ 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].

The measurement of the like-sign dimuon asymmetry by the D0 Collaboration [3] shows evidence of anomalously large CP -violating effects. This is currently one of the few significant deviations from the standard model of particle physics. One of the interpretations of this effect could be a CPT -invariant CP violation (CPV) in neutral B -meson mixing. The propagating “light” (L) and “heavy” (H) mass eigenvalues of the $B_s^0 - \bar{B}_s^0$ system can be written as [4]

$$|B_{sL}\rangle \propto p\sqrt{1-\xi_s}|B_s^0\rangle + q\sqrt{1+\xi_s}|\bar{B}_s^0\rangle, \quad (1)$$

$$|B_{sH}\rangle \propto p\sqrt{1+\xi_s}|B_s^0\rangle - q\sqrt{1-\xi_s}|\bar{B}_s^0\rangle. \quad (2)$$

If the complex parameter ξ_s is zero, CPT is conserved and CPV is due to $|q/p| \neq 1$, so that the oscillation probability $P(B_s^0 \rightarrow \bar{B}_s^0)$ is different from $P(\bar{B}_s^0 \rightarrow B_s^0)$. An alternative interpretation is that the asymmetry could arise from T -invariant CPV in a $B_s^0 - \bar{B}_s^0$ mixing [5] where $|q/p|=1$, but ξ_s is nonzero, so the probability of nonoscillation or oscillation back to the original state $P(B_s^0 \rightarrow B_s^0)$ is different from $P(\bar{B}_s^0 \rightarrow \bar{B}_s^0)$. By integrating these two probabilities in time, the asymmetry \mathcal{A}_{CPT} between the B_s^0 and \bar{B}_s^0 meson decays can be investigated. It can be shown that the CPTV contributions to the 2×2 effective Hamiltonian governing $B_s^0 - \bar{B}_s^0$ oscillations depend on the difference between the diagonal mass and decay rate terms [4]:

$$\xi_s = \frac{(M_{11} - M_{22}) - \frac{i}{2}(\Gamma_{11} - \Gamma_{22})}{-\Delta m_s + i\Delta\Gamma_s/2} \approx \frac{-\beta^\mu \Delta a_\mu}{\Delta m_s - i\Delta\Gamma_s/2}, \quad (3)$$

where Δa_μ is a four vector direction and magnitude in space-time characterizing Lorentz-invariance violation which in the SME is given by $\Delta a_\mu = r_s a_\mu^s - r_b a_\mu^b$, where a_μ^q are Lorentz-violating coupling constants for the two valence quarks in the B_s^0 meson, and where the factors r_q allow for quark-binding or other normalization effects. The four velocity of the B_s^0 meson is given by $\beta^\mu = \gamma(1, \vec{\beta})$, $\beta^\mu \Delta a_\mu$ is the difference between the diagonal elements of the effective Hamiltonian, and the mass and decay rate differences of the mass eigenstates are $\Delta m_s = m_H - m_L$ and $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ [6]. The small fractional values of

Δm_s and $\Delta \Gamma_s$ make the B_s^0 system sensitive to CPTV effects. In the underlying theory, spontaneous Lorentz symmetry breaking generates constant background expectation values for the quark fields that are Lorentz vectors represented by Δa_μ or tensors instead of scalars [4].

Any observed CPT violation should vary in the frame of the detector denoted with indices (t, x, y, z) . The period will be one sidereal day (≈ 0.99727 solar days) as the direction of the proton beam follows Earth's rotation with respect to the distant stars [4]. In the SME the variation would depend on CPT- and Lorentz-invariance violation coupling coefficients Δa_μ with indices (T, X, Y, Z) . We choose (T, X, Y, Z) as coordinates in the standard Sun-centered frame, with the rotation axis of Earth taken as the Z axis and X (Y) at right ascension 0° (90°) [7] (see the Supplemental Material [8] for a diagram of the coordinate system). If CPTV in $B_s^0 - \bar{B}_s^0$ oscillations is allowed, then $\mathcal{A}_{CPT} = (\Delta m_s / \Gamma_s) \text{Im}(\xi_s)$ if ξ_s is small. By translating from the Sun-centered frame to the detector frame we have [4]

$$\mathcal{A}_{CPT} = \frac{-\Delta \Gamma_s \gamma^{D0}}{\Gamma_s \Delta m_s} \left[\Delta a_T - C_\alpha S_\chi \beta_z^{D0} \Delta a_Z + \sqrt{C_\alpha^2 C_\chi^2 + S_\alpha^2} \sin(\Omega \hat{t} + \delta + \kappa) \beta_z^{D0} \Delta a_\perp \right], \quad (4)$$

where $C_x = \cos(x)$, $S_x = \sin(x)$, \hat{t} is the elapsed time with respect to the vernal equinox of the year 2000, $\Omega = 2\pi$ rad/sidereal day, $\beta_z^{D0} = \beta^{D0} \cos \theta$ is the velocity $\vec{\beta}$ of the B_s^0 meson in the detector frame projected onto the z axis (proton beam direction) of the D0 detector, θ is the polar angle between the B_s^0 momentum and the proton beam direction, $\gamma^{D0} = 1/\sqrt{1 - (\beta^{D0})^2}$, χ is the colatitude of the D0 detector, α is the orientation of the z axis of the detector in Earth's coordinate system, where the proton beam has a bearing of 219.53° , $\Delta a_\perp = \sqrt{\Delta a_X^2 + \Delta a_Y^2}$ is the transverse and Δa_Z the longitudinal components of Δa_μ , $\delta = \tan^{-1}(\Delta a_Y / \Delta a_X)$, $\kappa = \tan^{-1}(-S_\alpha / C_\alpha C_\chi)$, and Δa_T is the time component of the Δa_μ four-vector. A variation with sidereal time could arise from the rotation of β_z^{D0} with respect to $\Delta \vec{a}$. In this Letter we place limits on Δa_\perp and $\Delta a_T - C_\alpha S_\chi \beta_z^{D0} \Delta a_Z$.

Past experiments and analyses have placed constraints on the flavor-dependent Δa_μ in other neutral meson oscillating systems: $K^0 - \bar{K}^0$ [9], $D^0 - \bar{D}^0$ [10], and $B^0 - \bar{B}^0$ [11], as well as indirect limits for $B_s^0 - \bar{B}_s^0$ [5].

This Letter presents a search for CPT and Lorentz violation using the decay $B_s^0 \rightarrow \mu^+ D_s^- X$, where $D_s^- \rightarrow \phi \pi^-$ and $\phi \rightarrow K^+ K^-$ (charge conjugate states are assumed in this article). CP-violating asymmetries are usually between “wrong-sign” decays $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow \mu^+ D_s^-$, but we want to study the asymmetry between the “right-sign” decays $B_s^0 \rightarrow B_s^0 \rightarrow \mu^- D_s^+$ and their charge conjugate.

We extract the CPT-violating parameter using the asymmetry

$$A = \frac{N_+ - N_-}{N_+ + N_-}, \quad (5)$$

where N_+ [N_-] is the number of reconstructed $B_s^0 \rightarrow \mu^\pm D_s^\mp X$ events where $\text{sgn}(\cos \theta) Q > 0$ [$\text{sgn}(\cos \theta) Q < 0$], which results from the $\beta_z^{D0} = \beta^{D0} \cos \theta$ terms in Eq. (4) and Q is the charge of the muon. The direction of the $\mu^+ D_s^-$ system differs from that of the parent B_s^0 due to the missing neutrino. However, the migration between N_+ and N_- terms near $\theta = \pi/2$ causes a negligible correction to the measured asymmetry. The initial state at production is not flavor tagged in our study, but after experimental selection requirements, the B_s^0 system is fully mixed, so that the probability of observing a B_s^0 or \bar{B}_s^0 is essentially equal regardless of the flavor at production. We assume no CP violation in the mixing [12], so only about half of the observed B_s^0 's have the same flavor as they had at birth. We assume no CP violation, so those observed B_s^0 mesons which have changed their flavor do not contribute to CPTV, leading to a 50% dilution in the measured asymmetry. In the presence of CPT violation, the asymmetry is expected to have a period of one sidereal day, so a search is made for variations of the form

$$A(\hat{t}) = A_0 - A_1 \sin(\Omega \hat{t} + \phi), \quad (6)$$

where A_0 , A_1 , and $\phi = \delta + \kappa$ are constants and are extracted by measuring the asymmetry A in Eq. (5) in bins of the sidereal phase $\Omega \hat{t}$, and a fitting to the value in each bin with Eq. (6). Measurements of A_0 and A_1 are then interpreted as limits on Δa_μ from $B_s^0 - \bar{B}_s^0$ oscillations. A nonzero value of Δa_z and Δa_T would lead to a CPTV asymmetry that does not vary with sidereal time.

The data selection and the signal extraction are identical to those used in Ref. [13]. The main details of the data selection using the D0 detector [14] are described here.

The data are collected with a suite of single and dimuon triggers. The selection and the reconstruction of $\mu^+ D_s^- X$ decays require tracks with at least two hits in both the central fiber tracker and the silicon microstrip tracker. The muon track segment outside the calorimeter has to be matched to a particle found in the central tracking system which has momentum $p > 3$ GeV and transverse momentum $2 < p_T < 25$ GeV. The $D_s^- \rightarrow \phi \pi^-$, $\phi \rightarrow K^+ K^-$ decay is reconstructed by assuming the two ϕ decay particles are kaons, requiring $p_T > 0.7$ GeV, opposite charges, and $M(K^+ K^-) < 1.07$ GeV. The charge of the third particle, assumed to be the charged pion, must have charge opposite to that of the muon and $0.5 < p_T < 25$ GeV. The three tracks are combined to create a common D_s^- decay vertex using the algorithm described in Ref. [15]. The reconstructed $\mu^\pm D_s^\mp$ candidate is required to pass

several kinematic selection criteria and satisfy likelihood ratio criteria that are identical to those described in Ref. [13].

The effective $K^+K^-\pi^\pm$ mass distribution is fitted using bins of 6 MeV over a range of $1.7 < M(K^+K^-\pi^\pm) < 2.3$ GeV, and the number of signal and background events is extracted by a χ^2 fit of an empirical model to the data. The D_s^\pm meson mass distribution is well modeled by two Gaussian functions constrained to have the same mean, but with different widths and normalizations. There is a negligible peaking background under the D_s^\pm peak. A second peak in the $M(K^+K^-\pi^\pm)$ distribution corresponding to the Cabibbo-suppressed $D^\pm \rightarrow \phi\pi^\pm$ decay is also modeled by two Gaussian functions with widths set to those of the D_s^\pm meson model scaled by the ratio of the fitted D^\pm and D_s^\pm masses. The combinatoric background is modeled by a fifth-order polynomial function. Partially reconstructed decays such as $D_s^\pm \rightarrow \phi\pi^\pm\pi^0$, where the π^0 is not reconstructed, are modeled with a threshold function that extends to the D_s^\pm mass after the π^0 mass has been subtracted, given by $T(m) = \tan^{-1}[p_1(mc^2 - p_2)] + p_3$, where p_i are the fit parameters.

The raw asymmetry [Eq. (5)] is extracted by fitting the $M(K^+K^-\pi^\pm)$ distribution of the $\mu^\pm D_s^\mp$ candidates using a χ^2 minimization. The fit is performed simultaneously, using the same models, on the sum and the difference of the $M(K^+K^-\pi^\pm)$ distribution of N_+ candidates and N_- candidates. The functions used to model the two distributions are

$$W_{\text{sum}} = W_{D_s} + W_D + W_{\text{cb}} + W_{\text{pt}}, \quad (7)$$

$$W_{\text{diff}} = AW_{D_s} + A_D W_D + A_{\text{cb}} W_{\text{cb}} + A_{\text{pt}} W_{\text{pt}}, \quad (8)$$

where W_{D_s} , W_D , W_{cb} , and W_{pt} describe the distribution of the D_s^\pm and D^\pm mass peaks, the combinatorial background, and the partially reconstructed events, respectively, and the A factors are the corresponding asymmetries which are extracted from the fit. The number of signal events in the sample is $N(D_s^\pm) = 205865 \pm 626$.

Following previous conventions [16] we shift the origin of the time coordinate to correspond to the vernal equinox of the year 2000. The value of A_1 is extracted by dividing the data into n data sets, each containing a fraction f_i of the data based on the sidereal phase $\Omega\hat{t} + \phi$. In the fit, the parameters that describe the mass distributions W_{sum} and W_{diff} are the same for all sidereal bins, except for A and A_D , which may vary with the sidereal phase.

The number of sidereal bins used to extract the asymmetry is determined by finding the smallest uncertainty on A_1 . By using a MC input of asymmetries that ranges from 0% to 2%, we find that the optimum number of bins is 11. One of the 11 distributions produced in the fit to the data is shown in Fig. 1.

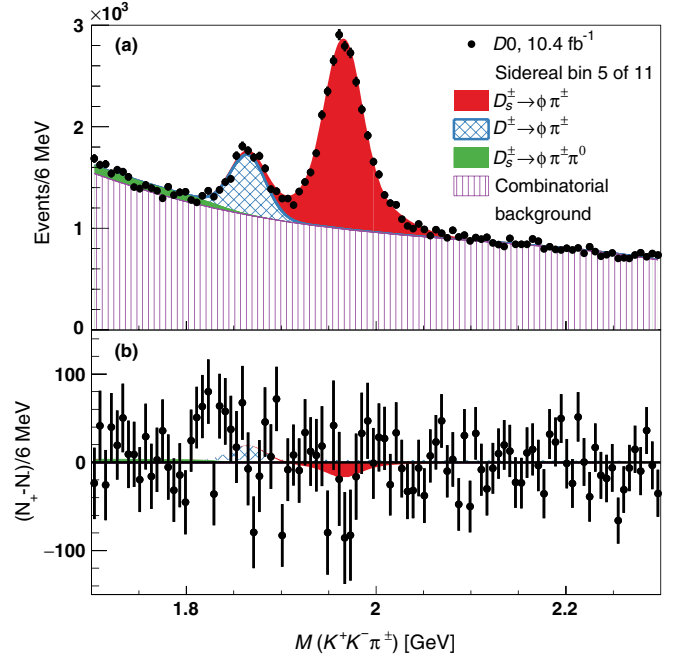


FIG. 1 (color online). (a) The $K^+K^-\pi^\mp$ invariant mass distribution for one of the 11 sidereal bins of the data (bin 5) of the $\mu^\pm\phi\pi^\mp$ sample. The lower mass peak is due to the decay $D^\mp \rightarrow \phi\pi^\mp$ and the second peak is due to the D_s^\mp meson decay. (b) The fit to the $(N_+ - N_-)$ distribution for one of the 11 sidereal bins of the data (bin 5).

Systematic uncertainties of the fitting method on the extracted values of A in sidereal bin i , $A(i)$ are evaluated by varying the fitting procedure and are assigned to be half of the maximal variation in the asymmetry. The mass range of the fit is shifted from $1.700 < M(K^+K^-\pi^\pm) < 2.300$ GeV to $1.724 < M(K^+K^-\pi^\pm) < 2.270$ GeV in steps of 6 MeV resulting in an absolute uncertainty on the measured asymmetries of 0.035%. The width of the mass bins is changed between 1 and 12 MeV, resulting in an absolute uncertainty of 0.071%. The functions modeling the signal are modified to fit the D^\pm and D_s^\pm mass peaks by single Gaussian functions, the background is fitted by varying between a fourth- and seventh-order polynomial function, and the parameter p_1 in the threshold function is allowed to vary. As a test, the fraction of data in each sidereal bin, f_i , is fixed to exactly 1/11. These variations of the signal modeling yield an absolute uncertainty on the asymmetry of 0.085%. The uncertainty for each of these sources is added in quadrature to give the total systematic uncertainty of the fitting procedure of 0.12%. This uncertainty on the measured values of $A(i)$ is found to be independent of the sidereal bin, and it is added in quadrature to the statistical uncertainty to extract the CPT -violating parameters by fitting to Eq. (6) (see Table I). The measured values of the asymmetries, $A(i)$, are plotted in Fig. 2 and are tabulated in the Supplemental Material [8].

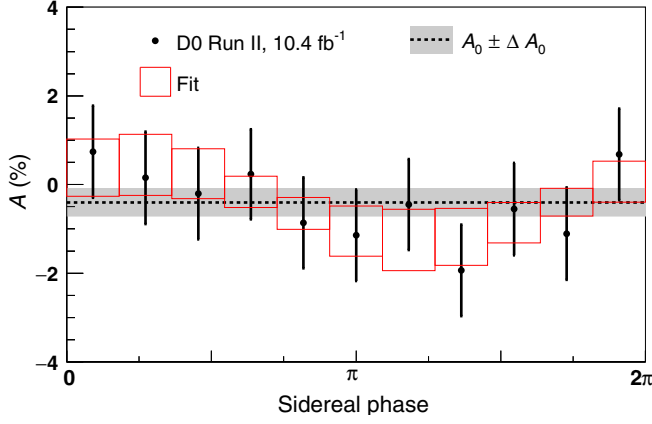


FIG. 2 (color online). The measured asymmetries, $A(i)$, versus the sidereal phase. The uncertainty on each value of $A(i)$ is the sum in quadrature of the statistical and systematic uncertainties. The red boxes show the fit and its uncertainties to the data points [Eq. (6)]. The dashed line shows the extracted value of A_0 and the grey box shows ΔA_0 .

The limits on Δa_μ are extracted using

$$A_1 \sin(\Omega\hat{t} + \phi) = \frac{F_{B_s^0}^{\text{non-osc}} \Delta\Gamma_s \langle \gamma^{D^0} \beta_z^{D^0} \rangle}{\Gamma_s \Delta m_s} \times \sqrt{C_\alpha^2 C_\chi^2 + S_\alpha^2} \sin(\Omega\hat{t} + \delta + \kappa) \Delta a_\perp, \quad (9)$$

$$A_0 = -\frac{F_{B_s^0}^{\text{non-osc}} \Delta\Gamma_s \langle \gamma^{D^0} \rangle}{\Gamma_s \Delta m_s} [\Delta a_T - C_\alpha S_\chi \langle \beta_z^{D^0} \rangle \Delta a_Z], \quad (10)$$

where the angle brackets denote average values. The $F_{B_s^0}^{\text{non-osc}}$ factor is the fraction of $D_s^\pm \rightarrow \phi\pi^\pm$ decays for which an observed B_s^0 has the same flavor as at birth [13]. Combining the fraction of B_s^0 decays in the sample and the 50% dilution factor described earlier gives $F_{B_s^0}^{\text{non-osc}} = 0.465$. Limits are extracted from the probability distribution which is given by $\exp(-\chi^2/2)$, where χ^2 is the χ square as a function of A_1 , A_0 , and δ using Eq. (6). Since we are setting limits, the probability distribution will be characterized by two quantities, the most probable value of A_1 and the 95% upper limit (UL) which is extracted by integrating the normalized probability distribution at the value of δ that gives the most conservative limit.

To extract limits, we measure the average values of $\langle \gamma^{D^0} \rangle = \langle E_{B_s^0} \rangle / m_{B_s^0}$, $\langle \beta_z^{D^0} \rangle = \langle p_z \rangle / \langle E_{B_s^0} \rangle$, and $\langle \gamma^{D^0} \beta_z^{D^0} \rangle = \langle p_z \rangle / m_{B_s^0}$, where $\langle p_z \rangle$ is the average momentum in the z direction and $\langle E_{B_s^0} \rangle$ is the average energy of the B_s^0 meson. The average momentum of the μD_s^\pm candidates is measured using sideband subtraction. The signal region is $1.92 < M(K^+K^-\pi^-) < 2.00$ GeV and the sideband regions are $1.75 < M(K^+K^-\pi^-) < 1.79$ GeV and

TABLE I. Parameters and uncertainties in the extraction of the CPT -violating parameters. The uncertainties on A_0 , A_1 , and ϕ are fit uncertainties and are dominated by the statistical uncertainty of the raw asymmetries. All of the other uncertainties are systematic.

Parameter	Value	Ref.
A_0	$(-0.40 \pm 0.31)\%$	Eq. (6)
A_1	$(0.87 \pm 0.45)\%$	Eq. (6)
ϕ	-2.28 ± 0.51	Eq. (6)
$m_{B_s^0}$	(5.36677 ± 0.00024) GeV	[17]
Δm_s	$(17.761 \pm 0.022) \times 10^{12} \text{ } \hbar s^{-1}$	[17]
$\Delta\Gamma_s/\Gamma_s$	(0.138 ± 0.012)	[17]
$F_{B_s^0}^{\text{non-osc}} = F_{B_s^0}^{\text{osc}}$	(0.465 ± 0.017)	[13]
$\langle p_z \rangle$	(17.8 ± 1.6) GeV	
$\langle p \rangle$	(25.3 ± 2.3) GeV	
Proton beam dir ⁿ	219.53°	
Colatitude χ	48.17°	

$2.13 < M(K^+K^-\pi^-) < 2.17$ GeV, and the average is $\langle p \rangle = 21.41 \pm 0.03$ GeV. This momentum needs to be corrected for the missing neutrino in the decay using a k -factor correction. These k factors are taken from Ref. [18] and applied to give a momentum of $\langle p \rangle = 25.3$ GeV. The systematic uncertainty on $\langle p \rangle$ of 1.6 GeV is obtained from the difference between the momentum extracted using sideband subtraction and using a weighted average of the number of signal events in momentum bins, which is then added in quadrature to the uncertainty due to the k factors. The effect of possible reconstruction variations in the x and y directions is found to be less than 1%. If we vary the number of sidereal bins the most probable value of A_1 varies by 8%. These variations are added in quadrature as the relative systematic uncertainty on the value of A_1 .

The final results are obtained by scaling the probability distributions obtained for A_0 , A_1 with the multiplicative factors given in Table I. The systematic uncertainties on the multiplicative factors, the number of sidereal bins, and the reconstruction effects are included by convoluting the probability distribution with a Gaussian function with the width given by the sum in quadrature of the systematic uncertainties. We obtain a 95% UL of $\Delta a_\perp < 1.2 \times 10^{-12}$ GeV. The most probable values of δ and Δa_\perp are $\delta = 4.901$ and $\Delta a_\perp = 5.7 \times 10^{-13}$ GeV.

The limit on $\Delta a_T - C_\alpha S_\chi \beta_z^{D^0} \Delta a_Z$ is obtained from a fit to the asymmetries using Eq. (6). This results in a value of $A_0 = (-0.40 \pm 0.31)\%$. In this case, the systematic uncertainties on the measured values of $A(i)$ are assumed to be 100% correlated between sidereal bins to obtain the most conservative limits and are added to the statistical uncertainty obtained from the fit. Using Eq. (10), we obtain $\Delta a_T - C_\alpha S_\chi \beta_z^{D^0} \Delta a_Z = \Delta a_T - 0.396 \Delta a_Z = (1.5 \pm 1.2) \times 10^{-13}$ GeV, resulting in a two sided 95% confidence interval $(-0.8 < \Delta a_T - 0.396 \Delta a_Z < 3.9) \times 10^{-13}$ GeV.

We did a cross-check using the periodogram methodology [19] which sees no anomalous behavior for the frequency 1/sidereal day [8].

For CPTV to explain the difference between the like-sign dimuon asymmetry [3] and the SM requires that $(\Delta a_T - 0.396\Delta a_Z)$ be of the order of 10^{-12} GeV [5]. These limits imply that *CPT* violation is unlikely to contribute a significant fraction of the observed dimuon charge asymmetry, and that other explanations need to be sought.

In conclusion, we have carried out the first search for *CPT*-violating effects exclusively in the $B_s^0 - \bar{B}_s^0$ oscillation system via semileptonic decays of the B_s^0 mesons. We find no significant evidence for *CPT*-violating effects and place limits on the size of the Lorentz-violating effects, Δa_μ . These limits constrain a linear combination of the Lorentz-violating coupling constants a_μ^q for the *b* and *s* valence quarks in the B_s^0 meson that are different from the linear combinations of valence quarks in the B^0 [11] or K^0 [9] mesons, and therefore they further constrain the possible separate values of the three coefficients a_μ^b , a_μ^s , and a_μ^d . We find 95% confidence intervals for the flavor-dependent coefficients $\Delta a_\perp < 1.2 \times 10^{-12}$ GeV and $(-0.8 < \Delta a_T - 0.396\Delta a_Z < 3.9) \times 10^{-13}$ GeV.

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^aVisitor from Augustana College, Sioux Falls, SD, USA.

^bVisitor from The University of Liverpool, Liverpool, United Kingdom.

^cVisitor from DESY, Hamburg, Germany.

^dVisitor from CONACyT, Mexico City, Mexico.

^eVisitor from SLAC, Menlo Park, CA, USA.

^fVisitor from University College London, London, United Kingdom.

^gVisitor from Centro de Investigacion en Computacion—IPN, Mexico City, Mexico.

^hVisitor from Universidade Estadual Paulista, São Paulo, Brazil.

ⁱVisitor from Karlsruher Institut für Technologie (KIT)—Steinbuch Centre for Computing (SCC), D-76128 Karlsruhe, Germany.

^jVisitor from Office of Science, U.S. Department of Energy, Washington, DC 20585, USA.

^kVisitor from American Association for the Advancement of Science, Washington, DC 20005, USA.

^lVisitor from Kiev Institute for Nuclear Research, Kiev, Ukraine.

^mVisitor from University of Maryland, College Park, MD 20742, USA.

ⁿVisitor from European Organization for Nuclear Research (CERN), Geneva, Switzerland.

- [1] V. A. Kostelecký and S. Samuel, Spontaneous breaking of Lorentz symmetry in string theory, *Phys. Rev. D* **39**, 683 (1989); V. A. Kostelecký and R. Potting, *CPT* and strings, *Nucl. Phys.* **B359**, 545 (1991).
- [2] V. A. Kostelecký and R. Potting, *CPT*, strings, and meson factories, *Phys. Rev. D* **51**, 3923 (1995).
- [3] V. M. Abazov *et al.* (D0 Collaboration), Study of *CP*-violating charge asymmetries of single muons and like-sign dimuons in $p\bar{p}$ collisions, *Phys. Rev. D* **89**, 012002 (2014).
- [4] V. A. Kostelecký, *CPT*, *T*, and Lorentz violation in neutral-meson oscillations, *Phys. Rev. D* **64**, 076001 (2001); V. A. Kostelecký, Sensitivity of *CPT* Tests with Neutral Mesons, *Phys. Rev. Lett.* **80**, 1818 (1998); V. A. Kostelecký and R. Van Kooten, Bounding *CPT* violation in the neutral *B* system, *Phys. Rev. D* **54**, 5585 (1996).
- [5] V. A. Kostelecký and R. Van Kooten, *CPT* violation and *B*-meson oscillations, *Phys. Rev. D* **82**, 101702(R) (2010).
- [6] This is the convention of the definition of $\Delta\Gamma_s$ so that it is positive in the standard model.
- [7] V. A. Kostelecký and C. D. Lane, Constraints on Lorentz violation from clock comparison experiments, *Phys. Rev. D* **60**, 116010 (1999); V. A. Kostelecký and N. Russell, Data tables for Lorentz and *CPT* violation, *Rev. Mod. Phys.* **83**, 11 (2011).
- [8] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.115.161601> for additional plots supporting the analysis, including diagrams of the coordinate system, the measured values of *A*, and a brief description of the periodogram analysis.
- [9] D. Babusci *et al.* (KLOE Collaboration), Test of *CPT* and Lorentz symmetry in entangled neutral kaons with the KLOE experiment, *Phys. Lett. B* **730**, 89 (2014).
- [10] J. M. Link *et al.* (FOCUS Collaboration), Charm system tests of *CPT* and Lorentz invariance with FOCUS, *Phys. Lett. B* **556**, 7 (2003).
- [11] B. Aubert *et al.* (BABAR Collaboration), Search for *CPT* and Lorentz Violation in $B^0 - \bar{B}^0$ Oscillations with Dilepton

- Events, *Phys. Rev. Lett.* **100**, 131802 (2008); K. Abe *et al.* (Belle Collaboration), Measurement of $B_d^0 - \bar{B}_d^0$ Mixing Rate from the Time Evolution of Dilepton Events at the Y_{4S} , *Phys. Rev. Lett.* **86**, 3228 (2001); K. Ackerstaff *et al.* (OPAL Collaboration), A study of B meson oscillations using hadronic Z^0 decays containing leptons, *Z. Phys. C* **76**, 401 (1997).
- [12] Y. Amhis *et al.*, Averages of b -hadron, c -hadron, and τ -lepton properties as of summer 2014, [arXiv:1412.7515](https://arxiv.org/abs/1412.7515); see also the online update at <http://www.slac.stanford.edu/xorg/hfag>.
- [13] V.M. Abazov *et al.* (D0 Collaboration), Measurement of the Semileptonic Charge Asymmetry using $B_s^0 \rightarrow \mu^+ D_s^- X$ Decays, *Phys. Rev. Lett.* **110**, 011801 (2013).
- [14] V.M. Abazov *et al.* (D0 Collaboration), The upgraded D0 detector, *Nucl. Instrum. Methods Phys. Res., Sect. A* **565**, 463 (2006).
- [15] J. Abdallah *et al.* (DELPHI Collaboration), b -tagging in DELPHI at LEP, *Eur. Phys. J. C* **32**, 185 (2004).
- [16] V. A. Kostelecký and N. Russell, Data tables for Lorentz and CPT violation, *Rev. Mod. Phys.* **83**, 11 (2011).
- [17] K. A. Olive *et al.* (Particle Data Group), Review of particle physics, *Chin. Phys. C* **38**, 090001 (2014).
- [18] V.M. Abazov *et al.* (D0 Collaboration), Measurement of the B_s^0 Lifetime in the Flavor-Specific Decay Channel $B_s^0 \rightarrow \mu^+ D_s^- \nu X$, *Phys. Rev. Lett.* **114**, 062001 (2015).
- [19] J.D. Scargle, Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data, *Astrophys. J.* **263**, 835 (1982); N.R. Lomb, Least-squares frequency analysis of unequally spaced data, *Astrophys. Space Sci.* **39**, 447 (1976).