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

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On behalf of the DØ Collaboration*

A search is presented for CPT-violating effects in the mixing of B_s^0 mesons using the D0 detector at the Fermilab Tevatron Collider. The CPT-violating asymmetry in the decay $B_s^0 \to \mu^\pm D_s^\mp X$ as a function of sidereal phase is measured. No evidence for CPT-violating effects is observed and limits are placed on CPT- and Lorentz-invariance violating coupling coefficients.

1. Introduction

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

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

*http://www-d0.fnal.gov

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where $\beta^\mu = \gamma(1, \vec{\beta})$ is the 4-velocity of the neutral B meson, Δm and $\Delta\Gamma$ are the mass and width difference between the heavy and light mass eigenstates, and $\Delta a_\mu = r_{q_1} a_\mu^{q_1} - r_{q_2} a_\mu^{q_2}$ with r being coefficients with q_1 and q_2 as meson valence quarks and a_μ being the constant 4-vector in the SME Lagrange density.[3] For the B_s^0-$\bar{B}_s^0$ system, the fractional difference between the mass eigenvalues is of the order of 10^{-12}. Due to 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.[4]

2. Dimuon and B_s^0 semileptonic decay charge asymmetries

The measurement of the like-sign dimuon asymmetry by the DØ Collaboration[5] shows evidence of anomalously large CP-violating effects. This anomalous asymmetry could also arise from T-invariant CP violation in B_s^0-$\bar{B}_s^0$ mixing and this sensitivity to CPT breaking has been used to obtain the first quantitative *indirect* measure and limit of CPT violation in the B_s^0-$\bar{B}_s^0$ system.[6]

CP- and CPT-violating effects can be explored using the semileptonic decay $B_s^0 \to \mu^+ D_s^- X$, where $D_s^- \to \phi\pi^-$ and $\phi \to K^+K^-$ (charge conjugate states are assumed throughout). CP-violating asymmetries are usually between "wrong-sign" decays $B_s^0 \to \bar{B}_s^0 \to \mu^+ D_s^-$, and the DØ Collaboration has measured[7] this flavor-specific asymmetry to be $a_{\rm sl}^s = [-1.12 \pm 0.74\,({\rm stat}) \pm 0.17\,({\rm syst})]\%$, i.e., consistent with zero.

3. DØ search for CPT-violating asymmetry

A DØ published analysis[8] explores the asymmetry between the "right-sign" decays $B_s^0 \to B_s^0 \to \mu^- D_s^+$ and its charge conjugate using 10.4 fb^{-1} of integrated luminosity collected at the Fermilab Tevatron collider. The CPT-violating parameter is extracted using the asymmetry

$$A = \frac{N_+ - N_-}{N_+ + N_-}, \tag{2}$$

where N_+ $[N_-]$ is the number of reconstructed $B_s^0 \to \mu^\pm D_s^\mp X$ events where ${\rm sgn}(\cos\theta)Q > 0$ $[{\rm sgn}(\cos\theta)Q < 0]$, θ is the polar angle between the B_s^0 reconstructed momentum and the proton beam direction, and Q is the charge of the muon. The initial state at production is not flavor tagged, but after experimental selection requirements, the B_s^0 system is fully mixed, so 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 mixing,[9] so only about half of the observed B_s^0 have the same flavor as they had at birth, and observed B_s^0 mesons that have changed their flavor do not contribute to CPTV, leading to a $\sim 50\%$ dilution in the measured asymmetry.

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

$$A(\hat{t}) = A_0 - A_1 \sin(\Omega\hat{t} + \phi), \tag{3}$$

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

A typical fit to find the sum $(N_+ + N_-)$ and difference $(N_+ - N_-)$ yields of $B_s^0 \to \mu^+ D_s^- X$ in a particular sidereal phase bin are shown in Fig. 1. Figure 1(c) then shows a fit testing for a sidereal phase dependence, finding $A_0 = (-0.40 \pm 0.31)\%$ and $A_1 = (0.87 \pm 0.45)\%$, both consistent with zero and hence exhibiting no significant evidence of Lorentz or CPT violation. From these results, a 95% upper limit of $\Delta a_\perp < 1.2 \times 10^{-12}$ GeV and two-sided confidence interval of $(-0.8 < \Delta a_T - 0.396\Delta a_Z < 3.9) \times 10^{-13}$ GeV are extracted.[8]

4. Discussion

These results represent the first direct search for CPT-violating effects exclusively in the B_s^0-$\bar{B}_s^0$ oscillation system. For CPTV to explain the difference between the DØ like-sign asymmetry[5] and the SM requires that $\Delta a_T - 0.396\Delta a_Z$ be of the order of 10^{-12}, implying that CPT violation is unlikely to contribute a significant fraction of the observed dimuon charge asymmetry.[6] 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, D^0, and K^0 mesons.[10] As presented at this conference, a subsequent publication[11] from the LHCb Collaboration has improved on the

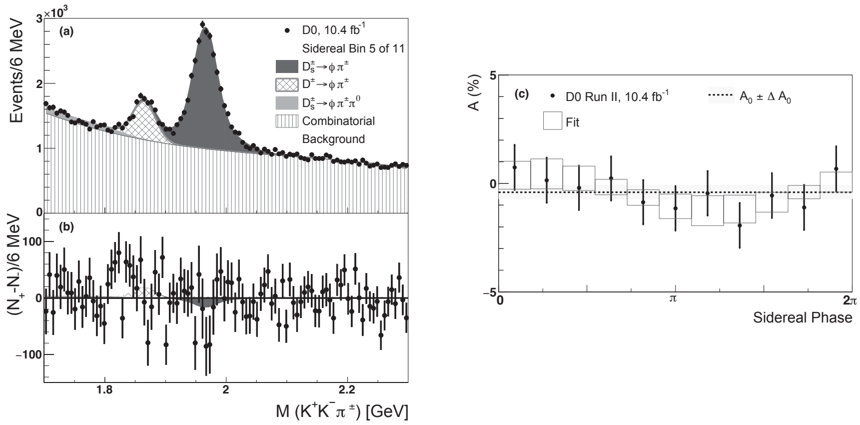

Fig. 1. (a) Reconstructed total signal and fit for yield $(N_+ + N_-)$ in one sidereal bin, (b) distribution of $(N_+ - N_-)$ and fit for the same sidereal bin, and (c) measured asymmetries $A(i)$ as a function of sidereal phase plus fit to test for variation with sidereal phase.

previous best limits presented here by an order of magnitude primarily due to the much larger boost of the B_s^0 mesons at LHCb.

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