

## Search for Baryon-Number Violating $\Xi_b^0$ Oscillations

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A search for baryon-number violating  $\Xi_b^0$  oscillations is performed with a sample of  $pp$  collision data recorded by the LHCb experiment, corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$ . The baryon number at the moment of production is identified by requiring that the  $\Xi_b^0$  come from the decay of a resonance  $\Xi_b^{*-} \rightarrow \Xi_b^0 \pi^-$  or  $\Xi_b^{\prime-} \rightarrow \Xi_b^0 \pi^-$ , and the baryon number at the moment of decay is identified from the final state using the decays  $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ ,  $\Xi_c^+ \rightarrow p K^- \pi^+$ . No evidence of baryon-number violation is found, and an upper limit at the 95% confidence level is set on the oscillation rate of  $\omega < 0.08 \text{ ps}^{-1}$ , where  $\omega$  is the associated angular frequency.

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Three conditions are necessary for the formation of a matter-dominated universe:  $C$  and  $CP$  violation, baryon-number violation (BNV), and the absence of thermal equilibrium [1]. The existence of  $C$  and  $CP$  violation has been established experimentally for decades [2–4], although the amount of  $CP$  violation present in the standard model (SM) is known to be insufficient to generate the matter-antimatter asymmetry observed in the Universe today [5,6], prompting numerous searches for sources of  $CP$  violation beyond the SM. By contrast, despite baryon-number conservation being an accidental low-temperature symmetry of the SM, BNV has never been observed experimentally, and stringent lower limits have been placed on the mean lifetimes of protons and of bound neutrons [7]. These limits impose constraints on generic models of physics beyond the SM. In particular, in supersymmetric extensions of the SM, a mechanism such as  $R$ -parity conservation is required to naturally suppress baryon-number violation [8–11]. An alternative is that the new physics has nongeneric flavor interactions, such that only certain BNV processes are allowed, and the experimental constraints are respected. One possibility would be for new BNV couplings to be entirely flavor diagonal [12,13], such as a six-fermion operator that couples two fermions from each generation. This would couple two from each of  $\{u, d, e, \nu_e\}$ ,  $\{c, s, \mu, \nu_\mu\}$ , and  $\{t, b, \tau, \nu_\tau\}$ , with duplication allowed within a generation, e.g., a  $usb\overline{u}s\overline{b}$  vertex would be permitted. Such an operator could arise in models with leptoquarks or  $R$ -parity-violating supersymmetric extensions of the SM [13,14]. The six-fermion operator could

allow BNV while being consistent with the experimental limit on the proton lifetime, since the proton initial state contains only first-generation fermions and, therefore, its coupling to the operator would require two flavor-changing neutral processes and would be heavily suppressed [13].

Most experimental processes involving such an operator are difficult to observe, since they include multiple third-generation fermions. For example, the signatures proposed in Ref. [13] require performing asymmetry measurements of same-sign dilepton pairs produced in association with a top-quark jet. However, there is a process that could give rise to a clean, unambiguous experimental signature: baryon-antibaryon oscillations of hadrons that contain a valence quark from each generation. The only such baryon observed to date that decays weakly is the  $\Xi_b^0$  ( $bsu$ ). The interest of searching for  $\Xi_b^0$  oscillations was noted in Refs. [15,16], with an oscillation period potentially as short as  $\mathcal{O}(0.1 \text{ ps})$  suggested. More recently, heavy baryon oscillations have been proposed as a possible mechanism for baryogenesis [14,17].

The signature for a BNV process is that a  $\Xi_b^0$  baryon is produced and decays weakly as an antibaryon to a final state such as  $\Xi_c^- \pi^+$  (or, vice versa, that an antibaryon is produced and decays as a baryon). The strong decays (the inclusion of charge-conjugate processes is implied throughout)  $\Xi_b^{\prime-} \rightarrow \Xi_b^0 \pi^-$  and  $\Xi_b^{*-} \rightarrow \Xi_b^0 \pi^-$  (denoted  $\Xi_b^{\prime*-} \rightarrow \Xi_b^0 \pi^-$ ), where  $\Xi_b^{\prime-}$  and  $\Xi_b^{*-}$  are the narrow resonances  $\Xi_b^{\prime}(5935)^-$  and  $\Xi_b^*(5955)^-$  recently observed by the LHCb Collaboration [18], allow the baryon number at the time of production to be determined from the charge of the pion. Figure 1 shows quark-level diagrams of example non-BNV [Fig. 1(a)] and BNV processes [Fig. 1(b)].

For baryon states propagating in free space, the formalism for oscillations is similar to that of neutral mesons [7,19,20], which has been studied extensively in the context of  $K^0$ ,  $D^0$ ,  $B^0$ , and  $B_s^0$  mixing [21]. However, a difference arises in the presence of a magnetic field  $\vec{B}$  due to the nonzero magnetic moment  $\mu$  possessed by the baryons,

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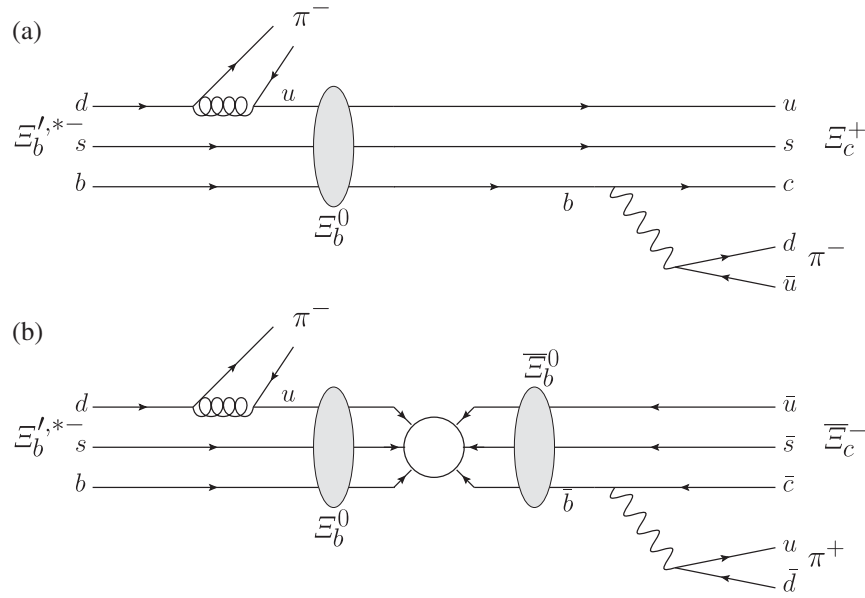


FIG. 1. (a) A non-BNV quark diagram for a  $\Xi_b'^{*,*} \rightarrow \Xi_b^0 \pi^-$  strong decay followed by a  $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$  weak decay. (b) The corresponding BNV diagram with a  $\Xi_b^0$  to  $\bar{\Xi}_b^0$  oscillation followed by a decay to the final state  $\bar{\Xi}_c^- \pi^+$ .

resulting in a splitting of the baryon and antibaryon energy levels of  $\Delta E = 2\vec{\mu} \cdot \vec{B}$ . This splitting leads to a damping of the oscillations over time. For the case of neutron oscillations, even a modest ambient magnetic field would greatly suppress the oscillation probability on the time scale of the neutron lifetime [22]. The criterion for the effect of the magnetic field to be negligible is  $|\Delta E|t/2 \ll 1$ , where  $t$  is the time of propagation of the baryon. Taking the  $\Xi_b^0$  magnetic moment to be comparable to the nuclear magneton [7], the energy splitting associated with the magnetic field in the interaction region of the LHCb detector, which is  $\lesssim 10$  mT, may be computed. For a typical time of propagation equal to the known  $\Xi_b^0$  lifetime [23] of  $1.477 \pm 0.032$  ps,  $|\Delta E|t/2 \lesssim 10^{-4}$ . This effect can, therefore, be neglected and, in the limit of small mixing, the ratio of the rate of oscillated decays  $P_{X \rightarrow \bar{X}}(t)$  to the rate of nonoscillated decays  $P_{X \rightarrow X}(t)$  varies over time as

$$R(t) \equiv \frac{P_{X \rightarrow \bar{X}}(t)}{P_{X \rightarrow X}(t)} = \tan^2(t/\tau_{\text{mix}}) \simeq \frac{t^2}{\tau_{\text{mix}}^2} \equiv (\omega t)^2, \quad (1)$$

where  $2\pi\tau_{\text{mix}}$  is the oscillation period, and  $\omega = 1/\tau_{\text{mix}}$  gives the corresponding angular frequency and is zero in the absence of oscillations. This angular frequency is related to the mass difference  $\Delta M$  and the width difference  $\Delta\Gamma$  between the eigenstates of the Hamiltonian by  $\omega^2 = (\Delta M/2)^2 + (\Delta\Gamma/4)^2$ , and in the limit that BNV in the decay itself is negligible,  $\omega = \Delta M/2$ .

This Letter presents a search for baryon-number violating  $\Xi_b^0$  oscillations performed with a sample of  $pp$  collision data recorded by the LHCb experiment, corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$  collected at center-of-mass

energies  $\sqrt{s} = 7$  and  $8$  TeV. This is the first such search for oscillations in heavy baryons. The LHCb detector [24,25] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$  designed for the study of particles containing  $b$  or  $c$  quarks. The detector elements that are particularly relevant to this analysis are a silicon-strip vertex detector surrounding the  $pp$  interaction region that allows  $c$  and  $b$  hadrons to be identified from their characteristically long flight distance, a tracking system that provides a measurement of momentum  $p$  of charged particles, and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons. Samples of simulated events are used to study the detector response and its effect on the measurement. In the simulation,  $pp$  collisions are generated using PYTHIA [26] with a specific LHCb configuration [27]. Decays of hadronic particles are described by EVTGEN [28], in which final-state radiation is generated using PHOTOS [29]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [30] as described in Ref. [31].

Two classes of  $\Xi_b'^{*,*}$  candidates are defined. Baryon-number conserving decays, in which a strong decay  $\Xi_b'^{*,*} \rightarrow \Xi_b^0 \pi^-$  is followed by weak decays  $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$  and  $\Xi_c^+ \rightarrow pK^- \pi^+$ , are referred to as opposite-sign (OS) candidates, since the  $\pi^-$  emitted in the strong decay and the  $p$  have charges of opposite sign. Conversely, in same-sign (SS) candidates, the first decay  $\Xi_b'^{*,*} \rightarrow \Xi_b^0 \pi^-$  is followed by weak decays to a final state of different baryon number,  $\bar{\Xi}_b^0 \rightarrow \bar{\Xi}_c^- \pi^+$  and  $\bar{\Xi}_c^- \rightarrow \bar{p}K^+ \pi^-$ .

The reconstruction and selection procedures are the same as those described in Ref. [18], except for one additional requirement on the track quality of the pion produced in the

$\Xi_b^{\prime,*-}$  decay. This requirement rejects a source of peaking background that can arise when a genuine  $\Xi_b^{\prime,*-} \rightarrow \Xi_b^0 \pi^-$  decay occurs but the  $\pi^-$  track is misreconstructed such that its charge is incorrect, and the candidate migrates from the OS to the SS class [32]. In studies of simulated events, the fitted SS yield of this contribution is found to be smaller than that of correctly reconstructed OS signal by a factor of  $(1.3 \pm 0.3) \times 10^{-3}$ , where the uncertainty is statistical. Applying the additional track quality requirement reduces the SS contribution in simulation by an order of magnitude, such that it becomes smaller than the OS yield by a factor of  $(1.6 \pm 2.0) \times 10^{-4}$ , corresponding to an expected SS peaking background yield of less than 0.1, which is negligible. The track quality requirement also reduces the OS signal yield in the data by approximately 10% and the combinatorial background by approximately 20% compared to Ref. [18]. Figure 2 shows the spectra of the mass difference  $\delta m$  for the selected OS and SS candidates, defining  $\delta m \equiv m(\Xi_b^0 \pi) - m(\Xi_b^0) - m_\pi$ , where  $m_\pi$  is the known  $\pi^\pm$  mass [7], and  $m(\Xi_b^0 \pi)$  and  $m(\Xi_b^0)$  are the reconstructed invariant masses of the  $\Xi_b^0 \pi$  and  $\Xi_b^0$  candidates. The figure also shows an unbinned extended maximum likelihood fit to the OS candidates, performed following the same procedure as described below and in Ref. [18], as a blue curve.

The data are divided into seven bins of decay time (illustrated in Fig. 3) that have approximately equal OS signal yields and cover the range  $0 < t < 8$  ps, corresponding to approximately 5.4 times the mean  $\Xi_b^0$  lifetime. The OS resonance yields in the  $i$ th bin are determined from a fit to the  $\delta m$  distribution of the OS data in that bin, with the resonance masses and the  $\Xi_b^{\prime,*-}$  width fixed to values obtained in a fit to the whole OS data sample. In each bin of decay time, the shape and normalization of the SS

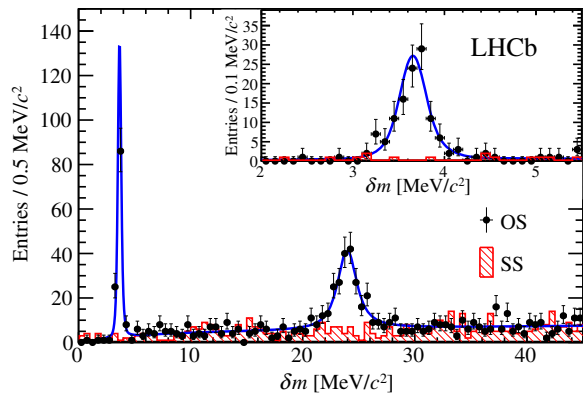


FIG. 2. Spectra of the mass difference  $\delta m \equiv m(\Xi_b^0 \pi) - m(\Xi_b^0) - m_\pi$  in the data after the full selection, for the OS sample (black points with error bars) and SS decays (red, hatched histogram). The blue curve is a fit to the OS data. The  $\Xi_b^{\prime-}$  and  $\Xi_b^{*-}$  peaks are at  $\delta m \approx 3.7$  and  $24$   $\text{MeV}/c^2$ , and the  $\delta m$  resolution at these points is approximately  $0.2$  and  $0.5$   $\text{MeV}/c^2$ , respectively; the  $\Xi_b^{*-}$  also has a non-negligible natural width of  $\Gamma \approx 1.7$   $\text{MeV}$  [23]. Inset: Detail of the region  $2.0 < \delta m < 5.5$   $\text{MeV}/c^2$ .

combinatorial background are obtained from a fit to the  $\delta m$  sideband regions of the SS data in that bin (the sidebands being  $0-2$ ,  $6-15$ , and  $32-45$   $\text{MeV}/c^2$ ). For a given value of the angular frequency  $\omega$  of the oscillations, the expected ratio of SS to OS decays in the bin may be computed. In combination with the OS yield and the shape and normalization of the SS background obtained as described above, this fully determines the probability density function for the SS data in bin  $i$ , and the corresponding likelihood  $L_i(\omega)$  is evaluated. The overall likelihood is obtained by combining all bins as  $L(\omega) = \prod_i L_i(\omega)$ .

A test statistic  $\Delta$  is defined based on the likelihood ratio approach as  $\Delta \equiv 2 \ln L(\hat{\omega}) - 2 \ln L(0)$ , where  $\hat{\omega}$  is the best-fit value of  $\omega$  and is estimated from a likelihood scan. Only the physical domain  $\omega \geq 0$  is considered, and, consequently,  $\hat{\omega}$  is expected to be zero approximately half of the time under the null hypothesis. The best-fit value for the data is found to be  $\hat{\omega} = 0$ , and the test statistic is, therefore,  $\Delta = 0$ .

Since no evidence of BNV oscillations is found, an upper limit at the 95% confidence level is placed on  $\omega$  following the  $CL_s$  method [33,34]. Ensembles of parametrized simulations referred to as pseudoexperiments are generated for a range of different oscillation angular frequencies  $\omega$ . The pseudoexperiments include variation of efficiency with decay time, decay time and mass resolution, combinatorial background, and misclassification of OS candidates as SS via the misreconstruction described earlier. To incorporate the associated systematic uncertainties, the input parameters used to define the distributions (the masses and yields of the resonances, the natural width of the  $\Xi_b^{\prime,*-}$ , the background yield and shape parameters, and the signal misclassification rate) are varied randomly within their uncertainties for each pseudoexperiment. Each pseudoexperiment is analyzed in the same way as the data, and its

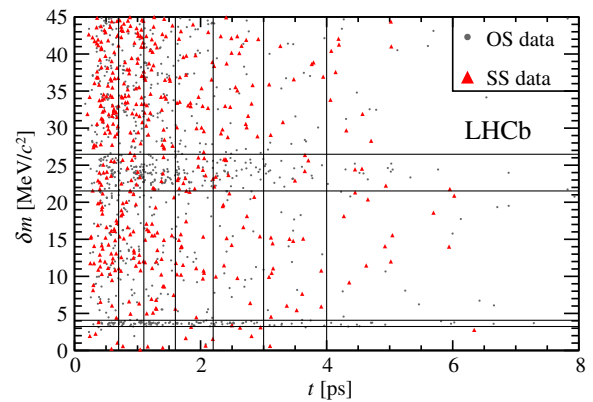


FIG. 3. Distribution of  $\delta m$  vs decay time. The OS data are shown as grey points and the SS data as larger red triangles. The vertical lines indicate the decay time bins. The horizontal lines are intended to guide the eye and indicate the  $\Xi_b^{\prime-}$  and  $\Xi_b^{*-}$  regions. Because of selection requirements, few candidates are present at short decay times.

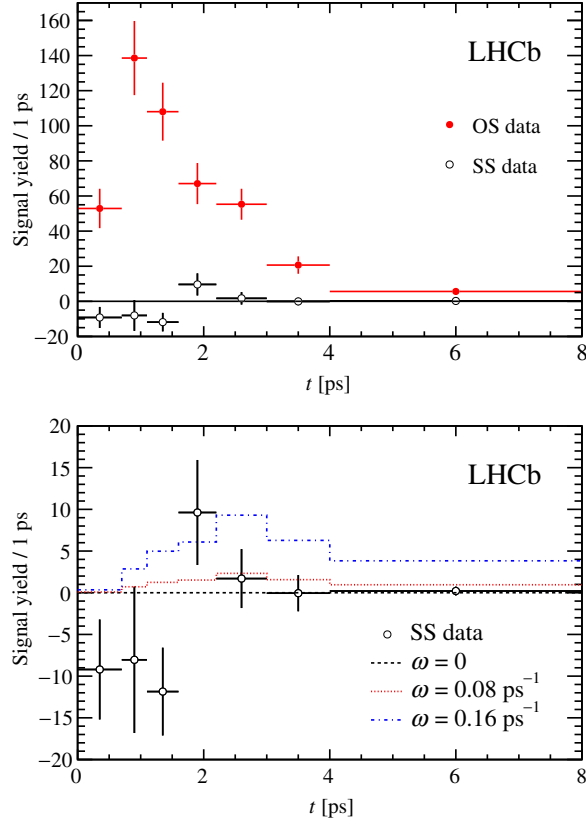


FIG. 4. For illustration, plots of the decay time distribution of signal candidates. In these plots, the two resonance regions are combined, and background is subtracted with a simplified statistical procedure that, unlike the likelihood described in the text, allows negative SS yields. (Upper) The OS and SS data. (Lower) Detail of the SS data, along with the expected SS yields under various hypotheses for the angular frequency  $\omega$  of the oscillations.

test statistic  $\Delta$  computed. Coverage tests with pseudoexperiments indicate that the procedure overcovers for small values of  $\omega$ , with 100% coverage at  $\omega = 0$ , and that the coverage converges asymptotically to 95% as the true value of  $\omega$  increases.

An upper limit of  $\omega < 0.08 \text{ ps}^{-1}$  at the 95% confidence level is obtained, which corresponds to  $\tau_{\text{mix}} > 13 \text{ ps}$ . This result can also be expressed in terms of the time-integrated mixing rate  $\chi$  defined as the fraction of particles produced as  $\Xi_b^0$  that decay as  $\Xi_b^0$  or vice versa. Under the assumption of quadratic time dependence for  $R(t)$ ,  $\chi = 2\omega^2\tau^2 < 2.7\%$  at the 95% confidence level, where  $\tau$  is the known  $\Xi_b^0$  lifetime [23]. For the purposes of illustration, the evolution of the expected SS yield with decay time for  $\omega = 0.08 \text{ ps}^{-1}$  and  $\omega = 0.16 \text{ ps}^{-1}$  is shown in Fig. 4 and compared to the SS yield in the data as obtained with a simplified statistical procedure.

In summary, a search is performed for baryon-antibaryon oscillations in the  $\Xi_b^0$  system. This is the first such search in the heavy-flavor sector and is of particular interest since  $\Xi_b^0$

baryons may couple directly to flavor-diagonal six-fermion operators that violate baryon number [13]. No evidence of baryon-number violating oscillations is found. In the limit of a small oscillation rate, the ratio of same-sign to opposite-sign decays is expected to increase quadratically with decay time. A limit on the oscillation angular frequency  $\omega < 0.08 \text{ ps}^{-1}$  at the 95% confidence level is obtained, equivalent to  $\tau_{\text{mix}} > 13 \text{ ps}$ . This rules out oscillations with a period comparable to the  $\Xi_b^0$  lifetime, as proposed in Ref. [15].

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