

## Measurement of the $\Lambda_b^0$ Lifetime in $\Lambda_b^0 \rightarrow J/\psi\Lambda^0$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report a measurement of the  $\Lambda_b^0$  lifetime in the exclusive decay  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV using an integrated luminosity of  $1.0 \text{ fb}^{-1}$  of data collected by the CDF II detector at the Fermilab Tevatron. Using fully reconstructed decays, we measure  $\tau(\Lambda_b^0) = 1.593_{-0.078}^{+0.083}(\text{stat}) \pm 0.033(\text{syst})$  ps. This is the single most precise measurement of  $\tau(\Lambda_b^0)$  and is  $3.2\sigma$  higher than the current world average.

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The weak decay of quarks depends on fundamental parameters of the standard model, including elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix which describe mixing between quark families. Extraction of these parameters from weak decays is complicated since observed quarks are not free but are confined within color-singlet hadrons, as described by quantum chromodynamics (QCD). An essential tool used in this extraction is the heavy quark expansion (HQE) technique [1]. In HQE, the total decay width of a heavy hadron is expressed as an

expansion in inverse powers of the heavy quark mass  $m_q$ . Lifetime ratios of  $b$ -flavored hadrons are predicted to be unity through  $O(1/m_b)$ , and  $O(1/m_b^2)$  corrections are small ( $\leq 2\%$ ) [2]. Detailed analysis of  $O(1/m_b^3)$  corrections to the lifetime ratio [3], summed with the  $O(1/m_b^2)$  corrections, leads to an expected value of  $\frac{\tau(\Lambda_b^0)}{\tau(B^0)} \simeq 0.94$ . This theoretical prediction has been in poor agreement with measurements for more than a decade [4–8]. Recent calculations including next-to-leading-order QCD and  $O(1/m_b^4)$  corrections

lower the predictions to  $0.90 \pm 0.05$  [9] and  $0.86 \pm 0.05$  [10], respectively. The  $\Lambda_b^0$  lifetime world average of  $\tau(\Lambda_b^0) = 1.230 \pm 0.074$  ps, corresponding to a ratio of  $\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.804 \pm 0.049$  [11], is consistent with the lower end of the theory predictions. In this Letter, we report a measurement of  $\tau(\Lambda_b^0)$  consistent with the higher end of the theory predictions.

We measure  $\tau(\Lambda_b^0)$  in the fully reconstructed decay  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ , with  $J/\psi \rightarrow \mu^+ \mu^-$  and  $\Lambda^0 \rightarrow p \pi^-$ . Charge conjugate modes are implied throughout. Our data sample consists of  $1.0 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  collected by the CDF II detector at the Fermilab Tevatron. This is the first measurement of  $\tau(\Lambda_b^0)$  using fully reconstructed decays that is competitive with the best previous measurements, which are based on semileptonic decays. As compared to fully reconstructed decays, measurements using partially reconstructed semileptonic decays have additional uncertainties due to the missing energy of the unobserved neutrino and the modeling of background from other  $b$ -flavored baryons.

As a check of our method, we also measure  $\tau(B^0)$  using a sample of  $B^0 \rightarrow J/\psi K_S^0$  decays, which has larger yield than the  $\Lambda_b^0$  sample. This decay channel is topologically similar to  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ , since both  $K_S^0$  and  $\Lambda^0$  decay with large displacement from the  $b$ -hadron-decay vertex. The analysis procedure for  $\Lambda_b^0$  is developed using  $B^0 \rightarrow J/\psi K_S^0$  only and checked using other  $b$ -meson decays containing a  $J/\psi \rightarrow \mu^+ \mu^-$  in the final state. The  $\Lambda_b^0$  lifetime was not extracted until all procedures were established including the systematic uncertainty estimate.

The components of the CDF II detector relevant to this analysis are described briefly here; a more complete description can be found elsewhere [12]. Charged particles are reconstructed using an open-cell drift chamber called the central outer tracker (COT) [13] and 7 layers of silicon microstrip detectors with radii between 2.4 and 28 cm [14]. These are immersed in a 1.4 T solenoidal magnetic field and cover the range  $|\eta| \leq 1$ , where  $\eta$  is the pseudorapidity defined as  $\eta \equiv -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle [15]. Four layers of planar drift chambers (CMU) [16] detect muons with transverse momentum  $p_T > 1.4 \text{ GeV}/c$  within  $|\eta| < 0.6$ . Additional chambers and scintillators (CMX) [17] cover  $0.6 < |\eta| < 1.0$  for muons with  $p_T > 2.0 \text{ GeV}/c$ .

A sample of  $J/\psi \rightarrow \mu^+ \mu^-$  candidates, collected using a dimuon trigger, is selected to begin the reconstruction of  $\Lambda_b^0$  and  $B^0$  candidates. At level 1 of a three-level trigger system, the eXtremely Fast Tracker (XFT) [18] uses COT information to fit tracks. Those tracks with  $p_T > 1.5(2.0) \text{ GeV}/c$  are extrapolated to the CMU (CMX) chambers and compared with the positions of muon-chamber tracks. The event passes level 1 if two or more XFT tracks are matched to muon-chamber tracks. Opposite-charge and opening-angle requirements are imposed at level 2. At level 3, full tracking information is used

to reconstruct  $J/\psi \rightarrow \mu^+ \mu^-$  candidates. Events with a candidate in the mass range 2.7 to 4.0  $\text{GeV}/c^2$  are accepted at level 3 and recorded for further analysis.

Tracks corresponding to two triggered muon candidates are constrained to originate from a common vertex to make a  $J/\psi \rightarrow \mu^+ \mu^-$  candidate. To ensure a high-quality vertex for the lifetime measurement, each muon track is required to have at least 3 axial hits in the silicon system. The reconstructed  $\mu^+ \mu^-$  invariant mass is required to be in the range  $3.014 < M_{\mu^+ \mu^-} < 3.174 \text{ GeV}/c^2$ . This corresponds to approximately  $\pm 4\sigma$ , where  $\sigma$  is the rms of the reconstructed signal and is dominated by experimental resolution [19].

We construct  $K_S^0 \rightarrow \pi^+ \pi^-$  and  $\Lambda^0 \rightarrow p \pi^-$  candidates from pairs of oppositely charged tracks fit to a common vertex. Since many  $K_S^0$  and  $\Lambda^0$  decays occur outside some layers of the silicon system due to their long lifetime, their tracks are not required to have silicon hits. We suppress  $K_S^0$  and  $\Lambda^0$  cross contamination by rejecting  $K_S^0$  ( $\Lambda^0$ ) candidates with proton-pion (dipion) invariant mass in the range [1.1085, 1.1235] ([0.48175, 0.51115])  $\text{GeV}/c^2$ .

The  $B^0$  and  $\Lambda_b^0$  candidates are reconstructed by associating  $J/\psi$  candidates with  $K_S^0$  or  $\Lambda^0$  candidates in each event. We choose further selection requirements that optimize  $S/\sqrt{S+B}$ , where  $S$  and  $B$  are the numbers of signal and background events, respectively. In the optimization procedure,  $S$  is estimated using a Monte Carlo simulation, while  $B$  is estimated using the  $b$ -hadron invariant mass sidebands, which are chosen to exclude the data used in the lifetime fits to avoid any potential bias.

The selection requirements resulting from the optimization are described below. We require  $0.473 < M_{\pi\pi} < 0.523 \text{ GeV}/c^2$  and  $p_T > 1.5 \text{ GeV}/c$  for  $K_S^0$  candidates. For  $\Lambda^0$  candidates, we require  $1.107 < M_{p\pi} < 1.125 \text{ GeV}/c^2$  and  $p_T > 2.6 \text{ GeV}/c$ . We require  $L_{xy}^{V^0}/\sigma_{L_{xy}^{V^0}} > 6$  for  $K_S^0$  and  $L_{xy}^{V^0}/\sigma_{L_{xy}^{V^0}} > 4$  for  $\Lambda^0$ , where  $L_{xy}^{V^0}$  is defined as the distance from the  $J/\psi$  vertex to the  $V^0$  ( $\equiv K_S^0, \Lambda^0$ ) vertex projected onto the  $V^0$  transverse momentum vector and  $\sigma_{L_{xy}^{V^0}}$  is its estimated uncertainty. Both  $B^0$  and  $\Lambda_b^0$  candidates are required to have  $p_T > 4.0 \text{ GeV}/c$ . Finally, the  $\chi^2$  of a  $b$ -hadron kinematic fit is required to be less than 26 for 5 degrees of freedom. This fit finds the best  $b$ -hadron decay vertex and momentum subject to the constraints that the muon tracks originate from a common vertex, the  $K_S^0$  or  $\Lambda^0$  daughter tracks originate from a common vertex with combined momentum pointing back in three dimensions to the dimuon vertex, and the invariant mass of the two muons is equal to the world average  $J/\psi$  mass [11]. The invariant mass distributions of the  $B^0$  and  $\Lambda_b^0$  candidates passing these requirements are shown in Fig. 1. The yields are  $N(B^0 \rightarrow J/\psi K_S^0) = 3376 \pm 88(\text{stat})$  and  $N(\Lambda_b^0 \rightarrow J/\psi \Lambda^0) = 538 \pm 38(\text{stat})$ .



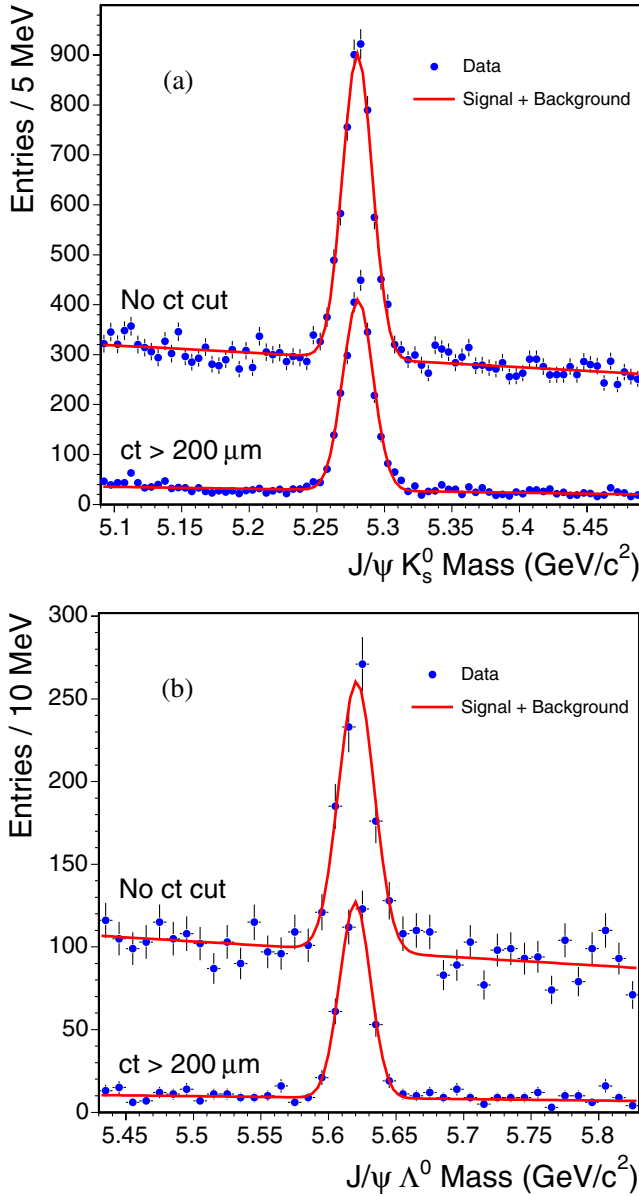


FIG. 1 (color online). Invariant mass distribution of (a)  $B^0 \rightarrow J/\psi K_S^0$  and (b)  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  candidates. The distributions with  $ct > 200 \mu\text{m}$ , where  $t$  is the proper decay time, illustrate that the majority of backgrounds originate from the primary interaction vertex. The distributions are fit to the sum of a Gaussian signal and linear background.

We determine  $\tau(B^0)$  and  $\tau(\Lambda_b^0)$  from the distribution of proper decay time  $t$  given by  $ct \equiv L_{xy}^b / (\beta\gamma)_T^b = L_{xy}^b c M_b / p_T^b$ , where  $L_{xy}^b$  is the distance traveled by each  $b$ -hadron candidate along the direction of its transverse momentum  $p_T^b$  and  $(\beta\gamma)_T^b \equiv p_T^b / (cM_b)$  is the transverse boost, where  $M_b$  is the world average mass of the  $b$  hadron [11]. Since the  $J/\psi$  vertex occurs at the same point as the  $b$  hadron decay and is well determined, it is used as the  $b$ -hadron decay vertex. The  $b$  hadron is assumed to originate from the average beamline determined on a run-by-

run basis using inclusive jet data. The primary vertex for a given event is the  $x$ - $y$  position of this beam line at the average  $z$  coordinate of the muon tracks at their closest approach to the beam line.

The lifetimes are extracted using the maximum likelihood method. The likelihood function  $\mathcal{L}$  is multivariate, and is constructed from the products of single variable probability density functions describing the distributions of the invariant mass  $m_i$ ,  $ct_i$ , and their respective estimated resolutions  $\sigma_i^m$  and  $\sigma_i^{ct}$ . It is given by

$$\mathcal{L} = \prod_{i=1}^N [(1 - f_B) \mathcal{P}_S^{ct}(ct_i | \sigma_i^{ct}) \mathcal{P}_S^{\sigma^{ct}}(\sigma_i^{ct}) \mathcal{P}_S^m(m_i | \sigma_i^m) + f_B \mathcal{P}_B^{ct}(ct_i | \sigma_i^{ct}) \mathcal{P}_B^{\sigma^{ct}}(\sigma_i^{ct}) \mathcal{P}_B^m(m_i | \sigma_i^m)],$$

where  $N$  is the number of events in the  $b$ -hadron mass window,  $f_B$  is the background fraction, and  $\mathcal{P}^{ct}$ ,  $\mathcal{P}^{\sigma^{ct}}$ , and  $\mathcal{P}^m$  are probability density functions for  $ct$ ,  $\sigma^{ct}$ , and mass, respectively. The mass resolution probability distributions  $\mathcal{P}^{\sigma^m}(\sigma_i^m)$  do not appear in  $\mathcal{L}$  because they are equal for signal and background, within the available statistics. Since this is not true for the  $ct$  resolution distributions,  $\mathcal{P}^{\sigma^{ct}}$  must be included in  $\mathcal{L}$  [20].

The mass distribution is modeled as the sum of a Gaussian signal and linear background, where the Gaussian width  $\sigma_i^m$  is scaled by a parameter to account for misestimation of the mass resolutions. The  $ct$  distribution is modeled by the sum of five components, all convoluted with a Gaussian resolution function with a scale factor parameter for the  $\sigma_i^{ct}$ : a positive exponential ( $e^{-ct_i/c\tau}/c\tau$ ) for the signal, a  $\delta$ -function representing the zero-lifetime component, one negative and two positive exponentials accounting for mismeasured decay vertices and background from other heavy-flavor decays. The relative contribution of each of the background components is determined by the fit. The  $\sigma^{ct}$  distribution is modeled by a Gaussian convoluted with an exponential for both signal and background.

We fit over the mass range [5.170, 5.390] and [5.521, 5.721]  $\text{GeV}/c^2$  for  $B^0$  and  $\Lambda_b^0$ , respectively. These ranges provide a sufficient sideband to constrain the background shape while avoiding regions where the mass distribution has complex structure. For both  $B^0$  and  $\Lambda_b^0$ , we require  $\sigma_i^m < 20 \text{ MeV}/c^2$  and fit over the range  $[-2000, 4000] \mu\text{m}$  in  $ct$  and  $[0, 100] \mu\text{m}$  in  $\sigma^{ct}$ . We maximize the likelihood to determine the best values of all fit model parameters, including the signal lifetimes  $c\tau(B^0) = 456.8_{-8.9}^{+9.0} \mu\text{m}$  and  $c\tau(\Lambda_b^0) = 477.6_{-23.4}^{+25.0} \mu\text{m}$ . Fit projections are shown in Fig. 2.

Systematic uncertainties come from four main sources: fitting procedure and model, primary vertex determination, alignment of detector elements, and  $K_S^0$  or  $\Lambda^0$  pointing requirement in the  $B^0$  or  $\Lambda_b^0$  kinematic fit. The fitting bias is determined using a simple Monte Carlo simulation in which events are distributed according to the fit model.

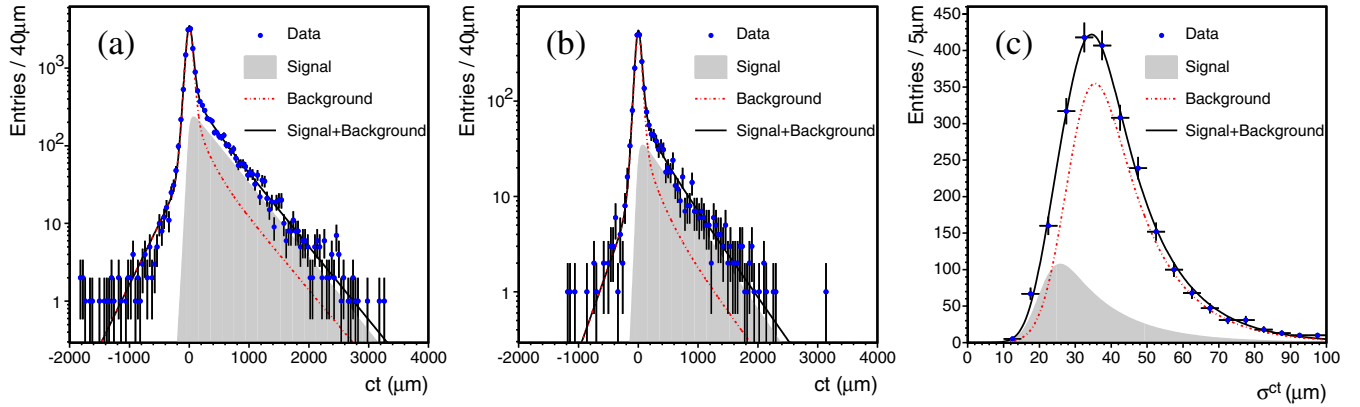


FIG. 2 (color online). (a)  $ct$  fit projection for  $B^0 \rightarrow J/\psi K_S^0$  candidates; and (b)  $ct$  and (c)  $\sigma^{ct}$  fit projections for  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  candidates.

The bias was found to be less than  $0.4 \mu\text{m}$  and  $0.5 \mu\text{m}$  for  $B^0$  and  $\Lambda_b^0$ , respectively. The systematic uncertainties due to  $ct$  resolution and mass resolution are estimated by including additional Gaussian components to their respective parts of the model in separate fits to the data and observing the deviations from the nominal result. We estimate the contribution from our mass background model by fitting with a uniform rather than linear background shape. The systematic uncertainty due to the  $ct$  background model is estimated by fitting with two or four background exponentials convoluted with the resolution function and fitting with two, three, or four background exponentials without convolution. We study a possible mass dependence in the  $ct$  background shape by separately fitting for  $B^0$  ( $\Lambda_b^0$ ) lifetime in the following low and high mass regions:  $[5.170, 5.3225]$  ( $[5.521, 5.651]$ ) and  $[5.2375, 5.390]$  ( $[5.591, 5.721]$ )  $\text{GeV}/c^2$ . The observed shifts are consistent with the statistical differences of the two samples for both modes. We use the average shift of  $1.9$  and  $4.1 \mu\text{m}$  for  $B^0$  and  $\Lambda_b^0$ , respectively, as an estimate of the systematic uncertainty due to a mass-dependent  $ct$  background. We estimate the systematic uncertainty due to our  $\sigma^{ct}$  and  $\sigma^m$  distribution models by the observed shift between simple Monte Carlo events generated with the data distributions but fit with our model compared with simple Monte Carlo events both generated and fit with our model. Using the same simple Monte Carlo technique, we estimate the systematic uncertainty due to a correlation between the  $ct$  and  $\sigma^{ct}$  for the background by generating simple Monte Carlo events with the correlation observed in the data and fitting with our baseline model where this correlation is absent.

We estimate the systematic uncertainty due to our primary vertex determination by comparing different choices of the  $z$  coordinate used to evaluate the run-averaged beam line. We estimate uncertainties due to any residual misalignments of the silicon detector using Monte Carlo samples generated with radial displacements of individual sensors (internal alignment) and relative translation and

rotation of the silicon detector with respect to the COT (global alignment). We also study the resolution and bias on the  $V^0$  pointing to the  $J/\psi$  vertex in data. If these were strongly  $ct$  dependent, the kinematic fit quality requirement could bias the  $b$ -hadron lifetime. We observe no lifetime bias and assign uncertainties of  $0.6 \mu\text{m}$  for  $B^0$  and  $5.4 \mu\text{m}$  for  $\Lambda_b^0$  based on the statistical precision of our study.

The systematic uncertainties are summarized in Table I. We obtain total systematic uncertainties of  $4.9 \mu\text{m}$  for  $B^0$  and  $9.9 \mu\text{m}$  for  $\Lambda_b^0$  by adding the individual uncertainties in quadrature.

A number of cross checks on the analysis procedure are performed. We measure  $B^+$  and  $B^0$  lifetimes that are statistically consistent with the world average values in

TABLE I. Systematic uncertainties (in  $\mu\text{m}$ ) for the measurement of  $c\tau(B^0)$  and  $c\tau(\Lambda_b^0)$ . The total uncertainties are the individual uncertainties added in quadrature.

Source	$c\tau(B^0)$	$c\tau(\Lambda_b^0)$
Fitter Bias	0.4	0.5
Fit Model:		
$ct$ Resolution	3.1	5.5
Mass Signal	0.7	2.3
Mass Background	0.1	0.1
$ct$ Background	0.5	0.7
$\sigma^{ct}$ Distribution Modeling	0.1	0.2
$\sigma^m$ Distribution Modeling	0.6	0.2
Mass- $ct$ Background Correlation	1.9	4.1
$ct$ - $\sigma^{ct}$ Background Correlation	0.3	1.3
Primary Vertex Determination	0.2	0.3
Alignment:		
Silicon Detector (Internal)	2.0	2.0
Silicon Detector/COT (Global)	2.2	3.2
$V^0$ Pointing	0.6	5.4
Total	4.9	9.9

the following decay modes:  $B^0 \rightarrow \psi^{(\prime)} K_S^0$ ,  $B^0 \rightarrow \psi^{(\prime)} K^{*0} (K^{*0} \rightarrow K^+ \pi^-)$ ,  $B^+ \rightarrow \psi^{(\prime)} K^+$ , and  $B^+ \rightarrow \psi K^{*+} (K^{*+} \rightarrow K_S^0 \pi^+)$ , with  $\psi^{(\prime)} \rightarrow \mu^+ \mu^-$  and  $\psi' \rightarrow \psi \pi^+ \pi^-$ . We search for unexpected lifetime dependence on the  $V^0$  and  $b$ -hadron kinematics, data-taking period, number of tracks in the event, and use of silicon hits on  $V^0$  daughter and muon tracks; no dependence is observed. Finally, we determine the lifetime using two alternative techniques which give results consistent with our baseline fit: a  $ct$ -only binned fit applied to sideband-subtracted data and a fit to the mass distribution in  $ct$  bins which is insensitive to the  $ct$  background shape.

In summary, we measure

$$\tau(\Lambda_b^0) = 1.593_{-0.078}^{+0.083}(\text{stat}) \pm 0.033(\text{syst}) \text{ ps.}$$

As a cross check, we also measure  $\tau(B^0) = 1.524 \pm 0.030(\text{stat}) \pm 0.016(\text{syst}) \text{ ps}$  which is consistent with the world average  $\tau(B^0) = 1.530 \pm 0.009 \text{ ps}$ . Our measurement of  $\tau(\Lambda_b^0)$  is consistent with the D0 result in the same channel [6] at the  $1.7\sigma$  level and is the first measurement using a fully reconstructed mode that reaches a precision comparable with the previous best measurements based on semileptonic decays of the  $\Lambda_b^0$ . It is also comparable in precision to the current world average, but is  $3.2\sigma$  higher [11]. Forming a ratio with the world average  $B^0$  lifetime, we determine

$$\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 1.041 \pm 0.057(\text{stat} + \text{syst}).$$

This ratio is consistent with the higher end of the theory predictions [3,9,10].

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