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# 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

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We measure the  $\Lambda_b^0$  lifetime in the fully reconstructed decay  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  using  $10.4 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions collected with the D0 detector at  $\sqrt{s} = 1.96 \text{ TeV}$ . The lifetime of the topologically similar decay channel  $B^0 \rightarrow J/\psi K_S^0$  is also measured. We obtain  $\tau(\Lambda_b^0) = 1.303 \pm 0.075 \text{ (stat.)} \pm 0.035 \text{ (syst.) ps}$  and  $\tau(B^0) = 1.508 \pm 0.025 \text{ (stat.)} \pm 0.043 \text{ (syst.) ps}$ . Using these measurements, we determine the lifetime ratio of  $\tau(\Lambda_b^0)/\tau(B^0) = 0.864 \pm 0.052 \text{ (stat.)} \pm 0.033 \text{ (syst.)}$ .

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Lifetime measurements of particles containing  $b$  quarks provide important tests of the significance of strong interactions between the constituent partons in the weak decay of  $b$  hadrons. These interactions produce measurable differences between  $b$  hadron lifetimes that the heavy quark expansion (HQE) [1] predicts with good accuracy through the calculation of lifetime ratios. While the agreement of the ratios between experimental measurements and HQE is excellent for  $B$  mesons [2], there are remaining discrepancies between experimental results and theoretical predictions for  $b$  baryons. Recently, the CDF Collaboration [3] used the exclusive decay  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  to report the single most precise determination of the  $\Lambda_b^0$  lifetime which is more than 2 standard deviations higher than the world average [4] and slightly higher than the  $B^0$  lifetime. The CDF measurement of the lifetime

ratio,  $\tau(\Lambda_b^0)/\tau(B^0)$ , is higher than the HQE calculation including  $\mathcal{O}(1/m_b^4)$  effects,  $0.88 \pm 0.05$  [5, 6]. On the other hand, theoretical predictions are in agreement with measurements by the D0 Collaboration in the  $J/\psi \Lambda^0$  [7] and semileptonic [8] channels, by the CDF Collaboration in the  $\Lambda_c^+ \pi^-$  final state [9], by the DELPHI, OPAL and ALEPH Collaborations in semileptonic decays [10–12], and previous measurements also in semileptonic channels by the CDF Collaboration [13]. More measurements of the  $\Lambda_b^0$  lifetime and of the ratio  $\tau(\Lambda_b^0)/\tau(B^0)$  are required to resolve this discrepancy.

In this article we report a measurement of the  $\Lambda_b^0$  lifetime using the exclusive decay  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ . The  $B^0$  lifetime is also measured in the topologically similar channel  $B^0 \rightarrow J/\psi K_S^0$ . This provides a cross-check of the measurement procedure, and allows the lifetime ratio to be determined directly. The data used in this analysis were collected with the D0 detector during the complete Run II of the Tevatron Collider, from 2002 to 2011, and correspond to an integrated luminosity of  $10.4 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at a center of mass energy  $\sqrt{s} = 1.96 \text{ TeV}$ .

A detailed description of the D0 detector can be found in Refs. [14–17]. Here, we describe briefly the most relevant detector components used in this analysis. The D0 central tracking system is composed of a silicon mi-

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crostrip tracker (SMT) and a central scintillating fiber tracker (CFT) immersed in a 2 T solenoidal field. The SMT and the CFT are optimized for tracking and vertexing for the pseudorapidity region  $|\eta| < 3.0$  and  $|\eta| < 2.0$ , respectively, where  $\eta \equiv -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle with respect to the proton beam direction. Preshower detectors and electromagnetic and hadronic calorimeters surround the tracker. A muon spectrometer is located beyond the calorimeter, and consists of three layers of drift tubes and scintillation trigger counters covering  $|\eta| < 2.0$ . A 1.8 T toroidal iron magnet is located outside the innermost layer of the muon detector.

For all Monte Carlo (MC) simulations in this article, we use PYTHIA [18] to simulate the  $p\bar{p}$  collisions, EVTGEN [19] for modeling the decay of particles containing  $b$  and  $c$  quarks, and GEANT [20] to model the detector response. Multiple  $p\bar{p}$  interactions are modeled by overlaying hits from random bunch crossings onto the MC.

In order to reconstruct the  $\Lambda_b^0$  and  $B^0$  candidates, we start by searching for  $J/\psi \rightarrow \mu^+\mu^-$  candidates, which are collected by single muon and dimuon triggers. The triggers used do not rely on the displacement of tracks from the interaction point. At least one  $p\bar{p}$  interaction vertex (PV) must be identified in each event. The interaction vertices are found by minimizing a  $\chi^2$  function that depends on all reconstructed tracks in the event and uses the transverse beam position averaged over multiple beam crossings. The resolution of the PV is  $\approx 20 \mu\text{m}$  in the plane perpendicular to the beam (transverse plane). Muon candidates are reconstructed from tracks formed by hits in the central tracking system and with transverse momentum ( $p_T$ ) greater than 1 GeV/ $c$ . At least one muon candidate in the event must have hits in the inner layer, and in at least one outer layer of the muon detector. A second muon candidate, with opposite charge, must either be detected in the innermost layer of the muon system or have a calorimeter energy deposit consistent with that of a minimum-ionizing particle along the direction of hits extrapolated from the central tracking system. Each muon track is required to have at least 2 hits in the SMT and 2 hits in the CFT to ensure a high quality common vertex. The probability associated with the vertex fit must exceed 1%. The dimuon invariant mass is required to be in the range 2.80 – 3.35 GeV/ $c^2$ , consistent with the  $J/\psi$  mass.

Events with  $J/\psi$  candidates are reprocessed with a version of the track reconstruction algorithm that identifies with increased efficiency the low  $p_T$  and high impact parameter tracks resulting from the decay of  $\Lambda^0$  and  $K_S^0$  [21], without introducing any biases in the decay time distribution. We then search for  $\Lambda^0 \rightarrow p\pi^-$  candidates reconstructed from pairs of oppositely charged tracks. The tracks must form a vertex with a probability associated with the vertex fit greater than 1%. The transverse impact parameter significance (the transverse impact parameter with respect to the PV divided by its

uncertainty) for the two tracks forming  $\Lambda^0$  candidates must exceed 2, and 4 for at least one of them. Each  $\Lambda^0$  candidate is required to have a mass in the range 1.105 – 1.127 GeV/ $c^2$ . The track with the higher  $p_T$  is assigned the proton mass. MC simulations indicate that this is always the correct assumption, given the track  $p_T$  detection threshold of 120 MeV/ $c$ . To suppress contamination from decays of more massive baryons such as  $\Sigma^0 \rightarrow \Lambda^0\gamma$  and  $\Xi^0 \rightarrow \Lambda^0\pi^0$ , the  $\Lambda^0$  momentum vector must point within 1 degree back to the  $J/\psi$  vertex. The same selection criteria are applied in the selection of  $K_S^0 \rightarrow \pi^+\pi^-$  candidates, except that the mass window is chosen in the range 0.470 – 0.525 GeV/ $c^2$  and pion mass assignments are used. Track pairs simultaneously reconstructed as both  $\Lambda^0$  and  $K_S^0$ , due to different mass assignments to the same tracks, are discarded from both samples. This requirement rejects 23% (6%) of the  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  ( $B^0 \rightarrow J/\psi K_S^0$ ) signal, as estimated from MC, without introducing biases in the lifetime measurement. The fraction of background rejected by this requirement is 58% (48%) as estimated from data. It is important to remove these backgrounds from the samples to avoid the introduction of biases in the lifetime measurements.

The  $\Lambda_b^0$  candidates are reconstructed by performing a kinematic fit that constrains the dimuon invariant mass to the world-average  $J/\psi$  mass [4], and the  $\Lambda^0$  and two muon tracks to a common vertex, where the  $\Lambda^0$  has been extrapolated from its decay vertex according to the reconstructed  $\Lambda^0$  momentum vector. The invariant mass of the  $\Lambda_b^0$  candidate is required to be within the range 5.15 – 6.05 GeV/ $c^2$ . The PV is recalculated excluding the  $\Lambda_b^0$  final decay products. The final selection requirements are obtained by maximizing  $\mathcal{S} = S/\sqrt{S+B}$ , where  $S$  ( $B$ ) is the number of signal (background) candidates in the data sample: the decay length of the  $\Lambda^0$  (measured from the  $\Lambda_b^0$  vertex) and its significance are required to be greater than 0.3 cm and 3.5, respectively; the  $p_T$  of the  $J/\psi$ ,  $\Lambda^0$  and  $\Lambda^0$  daughter tracks are required to be greater 4.5, 1.8 and 0.3 GeV/ $c$ , respectively; and the isolation of the  $\Lambda_b^0$  [22] is required to be greater than 0.35. After this optimization, if more than one candidate is found in the event, which happens in less than 0.3% of the selected events, the candidate with the best  $\Lambda_b^0$  decay vertex fit probability is chosen. We have verified that this selection is unbiased by varying the selection values chosen by the optimization as described in more detail later. The same selection criteria are applied to  $B^0 \rightarrow J/\psi K_S^0$  decays, except that the  $B^0$  mass window is chosen in the range 4.9 – 5.7 GeV/ $c^2$ .

The samples of  $\Lambda_b^0$  and  $B^0$  candidates have two primary background contributions: combinatorial background and partially reconstructed  $b$  hadron decays. The combinatorial background can be divided in two categories: prompt background, which accounts for  $\approx 70\%$  of the total background, primarily due to direct produc-

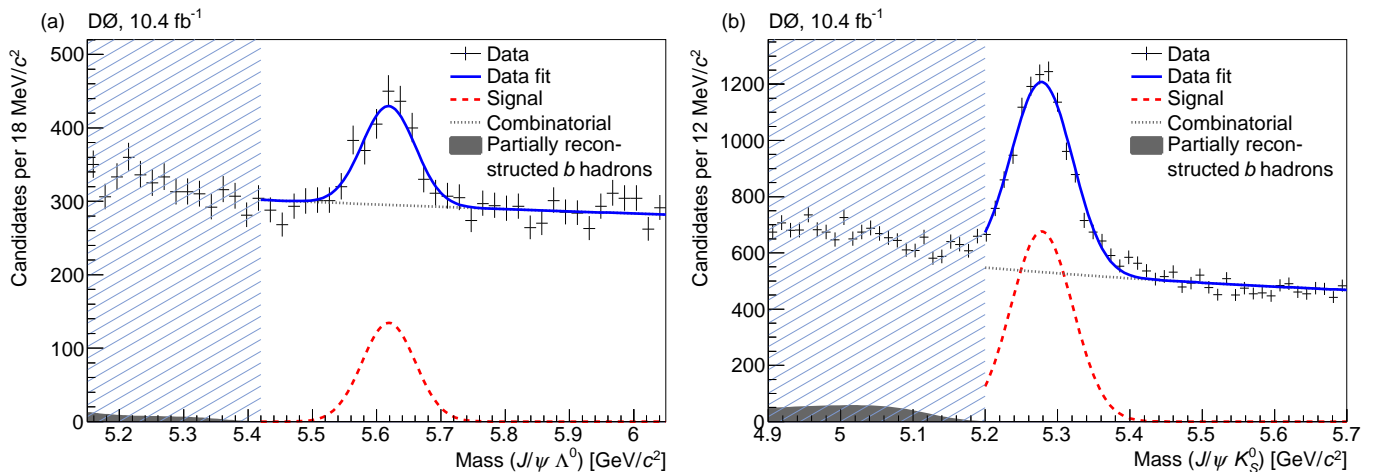


FIG. 1: (color online) Invariant mass distributions for (a)  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  and (b)  $B^0 \rightarrow J/\psi K_S^0$  candidates, with fit results superimposed. Events in mass regions contaminated with partially reconstructed  $b$  hadrons (hatched region) are excluded from the maximum likelihood function used to determine the  $\Lambda_b^0$  and  $B^0$  lifetimes.

tion of  $J/\psi$  mesons; and non-prompt background, mainly produced by random combinations of a  $J/\psi$  meson from a  $b$  hadron and a  $\Lambda^0$  ( $K_S^0$ ) candidate in the event. Contamination from partially reconstructed  $b$  hadrons come from  $b$  baryons ( $B$  mesons) decaying to a  $J/\psi$  meson, a  $\Lambda^0$  baryon ( $K_S^0$  meson), and additional decay products that are not reconstructed.

We define the transverse proper decay length as  $\lambda = cML_{xy}/p_T$ , where  $M$  is the mass of the  $b$  hadron taken from the PDG [4], and  $L_{xy}$  is the vector pointing from the PV to the  $b$  hadron decay vertex projected on the  $b$  hadron transverse momentum ( $\vec{p}_T$ ) direction. Due to the fact that signal and partially reconstructed  $b$  hadron decays have similar  $\lambda$  distributions that are particularly hard to disentangle in the lifetime fit, we remove partially reconstructed  $b$  hadrons by rejecting events with  $\Lambda_b^0$  ( $B^0$ ) invariant mass below 5.42 (5.20)  $\text{GeV}/c^2$  from the  $\Lambda_b^0$  ( $B^0$ ) sample, as shown in Fig. 1. This figure shows the  $\Lambda_b^0$  and  $B^0$  invariant mass distributions with results of unbinned maximum likelihood fits superimposed, excluding events in zones contaminated by partially reconstructed  $b$  hadrons. The signal peak is modeled by a Gaussian function. The combinatorial background is parametrized by an exponentially decaying function, while partially reconstructed  $b$  hadrons are derived from MC. It can be seen from Fig. 1 that partially reconstructed  $b$  hadrons contribute minimally to the signal mass region.

In order to extract the lifetimes, we perform separate unbinned maximum likelihood fits for  $\Lambda_b^0$  and  $B^0$  candidates. The likelihood function ( $\mathcal{L}$ ) depends on the probability of reconstructing each candidate event  $j$  in the sample with the mass  $m_j$ , the proper decay length  $\lambda_j$

and proper decay length uncertainty  $\sigma_j^\lambda$ :

$$\mathcal{L} = \prod_j [f_s \mathcal{F}_s(m_j, \lambda_j, \sigma_j^\lambda) + (1-f_s) \mathcal{F}_b(m_j, \lambda_j, \sigma_j^\lambda)], \quad (1)$$

where  $f_s$  is the fraction of signal events, and  $\mathcal{F}_s$  ( $\mathcal{F}_b$ ) is the product of the probability distribution functions that model each of the three observables being considered for signal (background) events. The background is further divided into prompt and non-prompt components. For the signal, the mass distribution is modeled by a Gaussian function; the  $\lambda$  distribution is parametrized by an exponential decay,  $e^{-\lambda_j/c\tau}/c\tau$ , convoluted with a Gaussian function  $\mathcal{R} = e^{-\lambda_j^2/2(s\sigma_j^\lambda)^2}/\sqrt{2\pi}s\sigma_j^\lambda$  that models the detector resolution; the  $\sigma^\lambda$  distribution is obtained from MC simulation and parametrized by a superposition of Gaussian functions. Here  $\tau$  is the lifetime of the  $b$  hadron, and the event-by-event uncertainty  $\sigma_j^\lambda$  is scaled by a global factor  $s$  to take into account a possible underestimation of the uncertainty. The mass distribution of the prompt component of the background is parametrized by a constant function, since we observe that the total amount of background is reduced uniformly over the entire mass range when the requirement  $\lambda > 100 \mu\text{m}$  is applied. The non-prompt component of the background is modeled by an exponential function, as observed using the data satisfying this requirement. The prompt component of the  $\lambda$  distribution is parametrized by the resolution function, and the non-prompt component by the superposition of two exponential decays for  $\lambda < 0$  and two exponential decays for  $\lambda > 0$ , as observed from events in the high-mass sideband of the  $b$  hadron peak (above 5.80 and 5.45  $\text{GeV}/c^2$  for  $\Lambda_b^0$  and  $B^0$ , respectively). Finally, the background  $\sigma^\lambda$  distribution is modeled by two exponential functions convoluted with a Gaussian function as determined empirically from the high-mass sideband

region. All the events, except for those corresponding to the invariant mass region contaminated by partially reconstructed  $b$  hadrons, are used in each likelihood fit to determine a total of 19 parameters: lifetime, mean and width of the signal mass, signal fraction, prompt background fraction, one non-prompt background mass parameter, 7 non-prompt background  $\lambda$  parameters, 5 background  $\sigma^\lambda$  parameters, and one resolution scale factor.

The maximum likelihood fits to the data yield  $c\tau(\Lambda_b^0) = 390.7 \pm 22.4 \mu\text{m}$  and  $c\tau(B^0) = 452.2 \pm 7.6 \mu\text{m}$ . Figure 2 shows the  $\lambda$  distributions for the  $\Lambda_b^0$  and the  $B^0$  candidates. Fit results are superimposed. The numbers of signal events, derived from  $f_s$ , are  $755 \pm 49$  ( $\Lambda_b^0$ ) and  $5671 \pm 126$  ( $B^0$ ). The ratios of the event yields in this and in the previous measurement [7] do not scale with the integrated luminosity because the most recent D0 data was collected at higher instantaneous luminosities, which required tighter, and less efficient, trigger requirements and also resulted in a reduction of the reconstruction efficiency caused by the presence of multiple interactions in a single bunch crossing.

We investigate possible sources of systematic uncertainties on the measured lifetimes related to the models used to describe the mass,  $\lambda$ , and  $\sigma^\lambda$  distributions. For the mass we consider a double Gaussian to model the signal peak instead of the nominal single Gaussian, an exponential function for the prompt background in place of a constant function, and a second order polynomial for the non-prompt background. The alternative mass models are combined in a single maximum likelihood fit to take into account correlations between the effects of the different models, and the difference with respect to the result of the nominal fit is quoted as the systematic uncertainty on the mass model. For  $\lambda$  we study the following variations: the introduction of a second Gaussian function along with a second scale factor to model the resolution, the exponential functions in the non-prompt background replaced by exponentials convoluted with the resolution function, one non-prompt negative exponential instead of two, and one long positive exponential together with a double-Gaussian resolution as a substitute for two non-prompt exponentials and one Gaussian resolution. All  $\lambda$  model changes are combined in a fit, and the difference between the results of this fit and the nominal fit is quoted as the systematic uncertainty due to  $\lambda$  parametrization. For  $\sigma^\lambda$  we use two different approaches: we use the distribution extracted from data by background subtraction, parameterized similarly to the nominal background  $\sigma^\lambda$  model, instead of the MC model, and we use  $\sigma^\lambda$  distributions from MC samples generated with different  $\Lambda_b^0$  ( $B^0$ ) lifetimes. The largest variation in the lifetime (with respect to the nominal measurement) between these two alternative approaches is quoted as the systematic uncertainty due to  $\sigma^\lambda$  parametrization. Residual effects due to contamination from partially re-

TABLE I: Summary of systematic uncertainties on the measurements of  $c\tau(\Lambda_b^0)$  and  $c\tau(B^0)$ , and on their ratio. Individual uncertainties are combined in quadrature to obtain the total uncertainties.

Source	$\Lambda_b^0$ ( $\mu\text{m}$ )	$B^0$ ( $\mu\text{m}$ )	Ratio
Mass model	2.2	6.4	0.008
Proper decay length model	7.8	3.7	0.024
Proper decay length uncertainty	2.5	8.9	0.020
Partially reconstructed $b$ hadrons	2.7	1.3	0.008
$B_s^0 \rightarrow J/\psi K_S^0$	–	0.4	0.001
Alignment	5.4	5.4	0.002
Total	10.4	12.9	0.033

constructed  $b$  hadrons in the samples are investigated by changing the requirement on the invariant mass of the  $\Lambda_b^0$  and  $B^0$  candidates which are included in the likelihood fits: the threshold is moved to lower (higher) invariant masses by 40 (20)  $\text{MeV}/c^2$ , where 40  $\text{MeV}/c^2$  is the resolution on the invariant mass of the reconstructed signal. The largest variation in the lifetime is quoted as the systematic uncertainty due to possible contamination from partially reconstructed  $b$  hadrons. In the lifetime fit the contamination from the fully reconstructed decay  $B_s^0 \rightarrow J/\psi K_S^0$  is assumed to have little impact on the final result. To test this assumption the  $B_s^0 \rightarrow J/\psi K_S^0$  contribution is included in the non-prompt component. The lifetime shift is found to be negligible. The systematic uncertainty due to the alignment of the SMT detector was estimated in a previous study [7] by reconstructing the  $B^0$  sample with the positions of the SMT sensors shifted outwards radially by the alignment uncertainty and then fitting for the lifetime. The systematic uncertainties are summarized in Table I.

We perform several cross-checks of the lifetime measurements. We extract the signal yield in bins of  $\lambda$  by fitting the mass distribution in each of these regions. From these measurements, lifetimes are obtained by the  $\chi^2$  minimization of the signal yield expected in each  $\lambda$  bin according to the first term in Eq. 1. While this method is statistically inferior with respect to the maximum likelihood fit, it is also less dependent on the modeling of the different background components. The results of this study are  $c\tau_{\Lambda_b^0} = 391.4 \pm 35.8$  (stat.)  $\mu\text{m}$  and  $c\tau_{B^0} = 458.3 \pm 8.9$  (stat.)  $\mu\text{m}$ . The sample is also split into different data taking periods,  $\eta$  regions, and numbers of hits in the SMT detector. All results obtained with these variations are consistent with our measurement. In order to check that the optimization procedure does not give a potential bias to the selection, we verify that our results remain stable when all requirements in variables used in the optimization process are removed one at a time, when looser and tighter requirements are applied to kinematic variables, and when multiple candidates that pass all selection requirements per event are allowed. The results also remain stable after removing

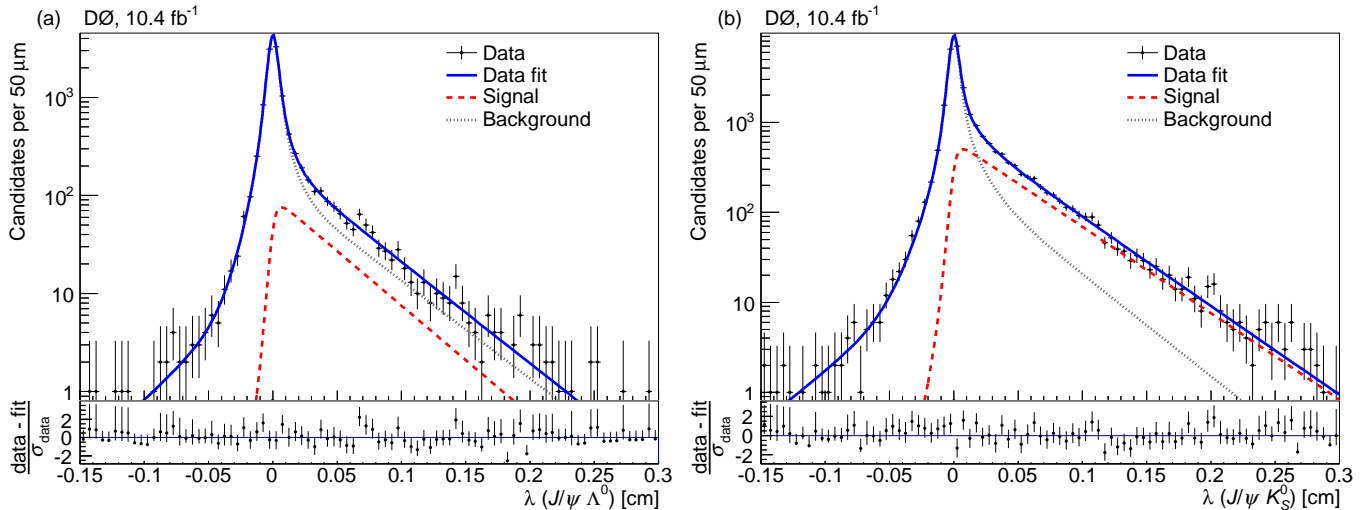


FIG. 2: (color online) Proper decay length distributions for (a)  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  and (b)  $B^0 \rightarrow J/\psi K_S^0$  candidates, with fit results superimposed. Residuals normalized by the corresponding uncertainty in each bin are given in the bottom panel.

the high-end tail (above  $100 \mu\text{m}$ ) of the  $\sigma^\lambda$  distribution, mainly populated by background events. We also cross check the fitting procedure and selection criteria by measuring the  $\Lambda_b^0$  and  $B^0$  lifetimes in MC events. The lifetimes obtained are consistent with the input values.

In summary, using the full data sample collected by the D0 experiment, we measure the lifetime of the  $\Lambda_b^0$  baryon in the  $J/\psi \Lambda^0$  final state to be

$$\tau(\Lambda_b^0) = 1.303 \pm 0.075 \text{ (stat.)} \pm 0.035 \text{ (syst.) ps,} \quad (2)$$

consistent with the world-average,  $1.425 \pm 0.032$  ps [4]. The method to measure the  $\Lambda_b^0$  lifetime is also used for  $B^0 \rightarrow J/\psi K_S^0$  decays, for which we obtain

$$\tau(B^0) = 1.508 \pm 0.025 \text{ (stat.)} \pm 0.043 \text{ (syst.) ps,} \quad (3)$$

in good agreement with the world average,  $1.519 \pm 0.007$  ps [4].

Using these measurements we calculate the ratio of lifetimes,

$$\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.864 \pm 0.052 \text{ (stat.)} \pm 0.033 \text{ (syst.)}, \quad (4)$$

where the systematic uncertainty is determined from the differences between the lifetime ratio obtained for each systematic variation and the ratio of the nominal measurements, and combining these differences in quadrature, as shown in Table I. Our result,  $0.86 \pm 0.06$ , is in good agreement with the HQE prediction of  $0.88 \pm 0.05$  [5] and compatible with the current world-average,  $1.00 \pm 0.06$  [4], but differs with the latest measurement of the CDF Collaboration,  $1.02 \pm 0.03$  [3], at the 2.2 standard deviations level. Our measurements supersede the previous D0 results of  $\tau(\Lambda_b^0)$ ,  $\tau(B^0)$  and  $\tau(\Lambda_b^0)/\tau(B^0)$  [7].

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