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New measurement of b-hadron lifetimes at CDF

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A measurement of b-hadron lifetimes in the fully reconstructed decay modes $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^0_s$, and $\Lambda^0_b \to J/\psi \Lambda^0$ is reported using data corresponding to an integrated luminosity of 4.3 fb^{-1}, collected by the CDF II detector at the Fermilab Tevatron. The measured values are $\tau(B^+) = 1.639 \pm 0.009\,(\mathrm{stat}) \pm 0.009\,(\mathrm{syst})$ ps, $\tau(B^0) = 1.507 \pm 0.010\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})$ ps and $\tau(\Lambda^0_b) = 1.537 \pm 0.045\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})$ ps. The lifetime ratios are $\tau(B^+)/\tau(B^0) = 1.088 \pm 0.009\,(\mathrm{stat}) \pm 0.004\,(\mathrm{syst})$ and $\tau(\Lambda^0_b)/\tau(B^0) = 1.020 \pm 0.030\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})$. These are the most precise measurements of these lifetimes and ratios.

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The lifetime of a ground-state hadron containing a b quark and lighter quarks is largely determined by the charged weak decay of the b quark. Interactions involving the lighter quarks, referred to as non-spectator interactions, alter b-hadron lifetimes at approximately the 10% level. The ratios of b-hadron lifetimes are predicted by the Heavy Quark Expansion (HQE) [1]. This framework of theoretical calculation is used to predict low energy QCD effects in many flavor observables, some of which are critical to high profile new physics searches. For example, the standard model expectations of the width difference in the B_s^0 system and the semileptonic asymmetry are calculated using the HQE. The measurement of lifetime ratios provides a relatively simple and accurate way to test the HQE framework since no new physics effects are expected to be visible in lifetimes.

A measurement of the lifetimes of the B^+, B^0 and Λ_b^0 hadrons and of the lifetime ratios τ_{B^+}/τ_{B^0}, and $\tau_{\Lambda_b}/\tau_{B^0}$ is presented [2]. The measurement is performed using exclusive decays to states containing a J/ψ . The work reported here is based on an integrated luminosity of 4.3 fb^{-1}.

Systematic errors are controlled to the level necessitated by the B^0 and B^+ modes, and then we apply the same methods across the board to Λ_b^0. The vertex formed by the two tracks from the J/ψ decay ($J/\psi \to \mu^+\mu^-$) is used as an estimate of the transverse decay length so that systematic errors common to the estimate of decay length cancel to some extent in the ratio of lifetimes.

The components of the CDF II detector relevant to this analysis are described briefly here. Charged particles are reconstructed using an open-cell drift chamber called the central outer tracker (COT) [3] and six layers of silicon microstrip detectors with radii between 2.4 cm and 23 cm [4]. These are immersed in a 1.4 T solenoidal magnetic field and cover the range $|\eta| \leq 1$, where η is the pseudorapidity. Four layers of planar drift chambers (CMU) [5] detect muons with $p_T > 1.4$ GeV/c within $|\eta| < 0.6$ (p_T refers to the momentum transverse to the beam direction). Additional chambers and scintillators (CMX) [6] cover $0.6 < |\eta| < 1.0$ for muons with $p_T > 2.0$ GeV/c.

The reconstruction of b-hadron candidates begins by collecting $J/\psi \to \mu^+\mu^-$ candidates using a dimuon trigger. The extremely fast tracker (XFT) [7] uses COT hit information to measure the transverse momentum of charged tracks that are then extrapolated to the CMU (CMX) chambers. Tracks corresponding to two triggered muon candidates are constrained to originate from a common vertex to make a $J/\psi \to \mu^+\mu^-$ candidate. The reconstructed $\mu^+\mu^-$ invariant mass is required to be in the range $3.014 < M_{\mu^+\mu^-} < 3.174$ GeV/c^2. The b hadron is assumed to originate from the average beamspot determined as a function of time using inclusive jet data. The primary vertex for a given event is the $x-y$ position of this beamspot at the average z coordinate of the muon tracks at their closest approach to the beamline. The typical beamline size is $\approx 30\ \mu m$ in $x-y$. The projection of the transverse decay distance on to the b p_T direction, L_{xy}, and its uncertainty, σ_{xy}, are also obtained and are used to estimate the proper decay length, $ct = \frac{ML_{xy}}{p_T}$, where M and p_T are the mass and transverse momentum of the b hadron. We reconstruct the b-hadrons by performing a kinematic fit of all b-hadron final state tracks to the appropriate topology: two spatially separated vertices in the case of $\Lambda_b^0 \to J/\psi\Lambda^0$ and $B^0 \to J/\psi K_s^0$, one vertex in all other cases. A mass constraint is applied to the J/ψ fit, and the reconstructed momenta of the K_s^0 and Λ^0 are required to point back to the J/ψ vertex. We exclude candidates with $\sigma^{ct} > 100\ \mu m$ to ensure well measured vertices. Additional selection requirements implying consistency with the fit assumptions (common vertex or vertices, mass and pointing constraints) are then applied. Further selection requirements on the transverse momenta of the b-hadrons and daughter particles, invariant mass of the K_s^0, K^{*0}, and Λ^0, the vertex probability of the b-hadrons, and the L_{xy} significance of the

K_s^0 and Λ^0 were obtained via an optimization procedure, which maximizes the quantity $S/\sqrt{S+B}$ over all of the selection requirements. We observe the following yield of signal events: 45000 $\pm$ 230 (B^+), 16860 $\pm$ 140 (B^0 K^{0*} mode), 12070 $\pm$ 120 (B^0 K_s^0 mode), and 1710 $\pm$ 50(Λ_b^0).

The lifetimes are extracted using an unbinned maximum likelihood method. The likelihood function $\mathscr{L}$ is multivariate, and is based on the probability of observing a candidate decay with reconstructed mass, m_i, decay length, ct_i, decay length uncertainty, σ_i^{ct}, and mass uncertainty, σ_i^m (i refers to the candidate index). It is factorized in the following form:

$$\mathscr{L} = \prod_i [f_s \cdot P_m^s(m_i|\sigma_i^m) \cdot T_t^s(ct_i|\sigma_i^{ct}) \cdot S_{\sigma^{ct}}^s(\sigma_i^{ct}) + (1-f_s) \cdot P_m^b(m_i) \cdot T_t^b(ct_i|\sigma_i^{ct}) \cdot S_{\sigma^{ct}}^b(\sigma_i^{ct})], \quad (1)$$

where P_m, T_{ct}, and $S_{\sigma^{ct}}$, and are the normalized probability density functions (PDF) for each observable, the superscripts s or b refer to the PDF for signal or background candidates, respectively, and f_s is the fraction of signal events. The PDF $S_{\sigma^{ct}}$ is substantially different for signal and background events and therefore needs to be taken into account. All the fit parameters are determined from the data itself. The signal ct distribution is modeled by an exponential ($e^{-ct_i/c\tau}/c\tau$) convolved with a detailed detector ct-resolution model, $\mathscr{R}$. The background ct distribution has four components: a $\delta-$function convolved with $\mathscr{R}$, representing the zero lifetime component of background, and one negative and two positive exponentials that account for mismeasured decay vertices and background from other heavy-flavor decays. The relative contribution of each background component is determined by the data. The same resolution model, $\mathscr{R}$, is used for signal and background events. $\mathscr{R}$ is modeled as a sum of three Gaussians centered at t=0; the number of components is motivated by a study of resolution in an inclusive sample of J/ψ events. The width of the Gaussians is given by the candidate measured uncertainty, σ_i^{ct}, multiplied by a scale factor. Small differences arise in $\mathscr{R}$ between decay channels due to the effect of additional tracks on the B vertex χ^2 distribution, on which selection requirements are made. Therefore the relative fraction of each Gaussian and the scale factors are obtained separately for each channel from a fit to data in the mass sidebands. This yields an accurate determination of $\mathscr{R}$ as between 80-90% of the background events are expected to originate from the primary vertex, depending on decay channel and background model. The mass distribution is modeled as the sum of two Gaussians centered on the b-hadron mass and a linear background. For each event, each Gaussian has a width determined by σ_i^m multiplied by a scale factor. The signal σ^{ct} distribution PDF is given by $A\sum_{m=1}^n f_m \cdot (\sigma^{ct})_m^a e^{-\sigma^{ct}/b_m}$, where f_m, a_m and b_m are determined by the fit to data, $\sum_{m=1}^n f_m = 1$, A is the normalization, and n=2. The same functional form is used to describe the background σ^{ct} distribution except that n=3 for the B meson decay channels due to the larger background yields. Using the mass, ct and σ^{ct} PDFs described above, with the resolution parameters determined from the mass-sideband only fit, the likelihood is calculated. Various projections of the likelihood function are compared with the data in Fig. 1. The systematic error is limited by detector alignment (that cancel in ratios). For lifetime ratios, the total uncertainty has larger contributions from systematic uncertainties due to resolution and mass models.

We measure $\tau_{B^+} = 1.639 \pm 0.009 \pm 0.009$ ps, $\tau_{B^0} = 1.507 \pm 0.010 \pm 0.008$ ps where the two B^0 measurements have been combined, and the first uncertainty is statistical, and the second systematic. These results are consistent and improve upon the leading measurements from Belle [8] which

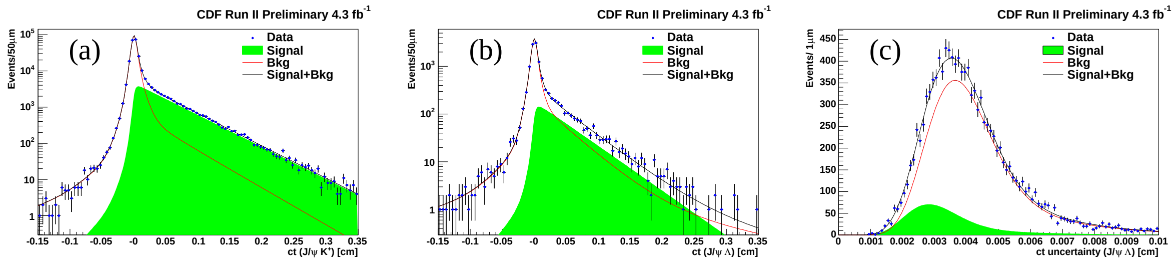

Figure 1: (a) *ct* fit projection for $B^+ \to J/\psi K^+$ candidates, (b) and (c) *ct* fit projection and σ^{ct} fit projection for $\Lambda_b^0 \to J/\psi \Lambda^0$ candidates.

are $\tau_{B^+} = 1.635 \pm 0.011 \pm 0.11$ ps and $\tau_{B^0} = 1.534 \pm 0.008 \pm 0.010$ ps. The similarities between the decay channels allow for the accurate determination of the ratio $\tau_{B^+}/\tau_{B^0} = 1.088 \pm 0.009$ (stat) $\pm$ 0.004 (syst) which favors a slightly higher value than the current average of 1.071±0.009 [9]. These results are consistent with the current HQE predictions [9, 10], giving further confidence in this theoretical framework, and also provide an accurate test for future Lattice QCD calculations. For the Λ_b^0 we measure $\tau_{\Lambda_b^0} = 1.537 \pm 0.045 \pm 0.014$ ps and $\tau_{\Lambda_b^0}/\tau_{B^0} = 1.020 \pm 0.030 \pm 0.008$. This measurement is the most precise measurement of τ_{Λ_b} and is consistent with the previous measurement in this decay channel of $\tau_{\Lambda_b^0} = 1.593^{+0.083}_{-0.078} \pm 0.033$ ps but is more than 2σ above the world average of $1.389^{+0.049}_{-0.048}$ ps. The ratio is also higher than the predicted value of 0.88 ± 0.05 [10] but in agreement with 1.063 ± 0.027 [11]. Note that the complete NLO-QCD calculations have not been included in any of the theoretical results. Nevertheless, improvements both from the experimental and theoretical sides will be necessary before τ_{Λ_b} is well understood. For that reason we aim to have a new meausrement of τ_{Λ_b} with the whole runII statistics. These measurements are complemented by the world-leading $\tau_{B_s^0}$ measurement from the angular analysis of $B_s^0 \to J/\psi\phi$ decays [12].

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