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B lifetimes and X,Y,Z states at the Tevatron

Juan Pablo FERNÁNDEZ[∗†]
CIEMAT
E-mail: fernand@fnal.gov

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 $\tau(B^+) = 1.639 \pm 0.009\ (\text{stat}) \pm 0.009\ (\text{syst})$ ps, $\tau(B^0) = 1.507 \pm 0.010\ (\text{stat}) \pm 0.008\ (\text{syst})$ ps and $\tau(\Lambda^0_b) = 1.537 \pm 0.045\ (\text{stat}) \pm 0.014\ (\text{syst})$ ps. The lifetime ratios are $\tau(B^+)/\tau(B^0) = 1.088 \pm 0.009\ (\text{stat}) \pm 0.004\ (\text{syst})$ and $\tau(\Lambda^0_b)/\tau(B^0) = 1.020 \pm 0.030\ (\text{stat}) \pm 0.008\ (\text{syst})$. These are the most precise measurements of these quantities from a single experiment. Observation is also reported for a structure near the $J/\psi\phi$ threshold, in B^+ to $J/\psi\phi K^+$ decays with an integrated luminosity of 6.0 fb^{-1} and a statistical significance of 5 standard deviations. There are 19 +/- 6 events observed for this structure at a mass of $4143.4^{+2.9}_{-3.0} \pm 0.6$ MeV/c^2 and a width of $15.3^{+10.4}_{-6.1} \pm 2.5$ MeV/c^2.

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∗Speaker.
†On behalf of the CDF Collaboration.

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1. B lifetimes:

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 spectator processes, 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, HQE predicts the decay width of B_s mesons to final states common to B_s^0 and $\overline{B_s^0}$, Γ_{12}^s, which enters the decay width difference in the B_s^0 system and several CP violation effects. The measurement of lifetime ratios provides a simple and accurate way to test the HQE framework as non-standard model effects are expected to be highly suppressed 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 channels with $J/\psi \rightarrow \mu^+\mu^-$. The work reported here is based on an integrated luminosity of 4.3 fb^{-1}.

In all decay modes, the decay position of the b hadron is estimated using only J/ψ decay products so that differences in decay time resolution between channels are reduced and certain systematic uncertainties cancel in ratios of lifetimes.

The components of the CDF II detector relevant to this analysis are described in [2].

The reconstruction of b-hadron candidates begins by collecting $J/\psi \rightarrow \mu^+\mu^-$ candidates using a dimuon trigger. 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 time, $ct = \frac{ML_{xy}}{p_T}$, and its uncertainty σ^{ct}, 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 $\Lambda_b^0 \rightarrow J/\psi\Lambda^0$ and $B^0 \rightarrow J/\psi K_s^0$, 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 time, ct_i, decay time uncertainty, σ_i^{ct}, and mass uncertainty, σ_i^m (i

refers to the candidate index). It is factorized in the following form:

$$\mathscr{L} = \prod_i [f_s \cdot P^s_m(m_i|\sigma^m_i) \cdot T^s_t(ct_i|\sigma^{ct}_i) \cdot S^s_{\sigma^{ct}}(\sigma^{ct}_i) + (1-f_s) \cdot P^b_m(m_i) \cdot T^b_t(ct_i|\sigma^{ct}_i) \cdot S^b_{\sigma^{ct}}(\sigma^{ct}_i)], \tag{1.1}$$

where P_m, T_{ct}, and $S_{\sigma^{ct}}$, and are the normalized probability density functions (PDF) for observables m_i, ct_i and σ^{ct}_i, 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.

The signal mass distribution, P^s_m, is modeled as the sum of two Gaussians centered on the b-hadron mass. The width is determined by σ^m_i multiplied by a scale factor to account for the misestimation of the mass resolutions. The background mass distribution, P^b_m, is modeled as a linear function.

The signal ct distribution, T^s_{ct}, 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 $\mathscr{R}$ to account for backgrounds from prompt J/ψ's originating from the primary vertex, and one exponential for negative proper times and two for positive 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. The detector resolution is based upon a Gaussian with width $s_j \cdot \sigma^{ct}_i$, where s_j is the scale factor that accounts for the misestimation the σ^{ct}_i. Motivated by a study of resolution in an inclusive sample of J/ψ events, where prompt J/ψ events dominate, $\mathscr{R}$ is modeled as $\mathscr{R} = \sum^3_{j=1} f_j/\left(\sqrt{2\pi}s_j\sigma^{ct}_i\right) \cdot \exp\left(-t^2/2(s_j\sigma^{ct}_i)^2\right)$, where $f_1 + f_2 + f_3 = 1$. The Gaussians are centered at zero as no evidence of an offset in the data samples is observed. 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 $\mathscr{R}$ since the background events are primarily expected to originate from the interaction vertex.

After the resolution model parameters are determined from the mass-sideband-only fit, the likelihood is calculated for each candidate and the product is maximized in each of the four channels to extract the lifetime, signal yield and the other parameters required to describe the mass, background decay time, and σ^{ct} distributions. Decay time 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 $\tau(B^+) = [1.639 \pm 0.009(\text{stat}) \pm 0.009(\text{syst})]$ ps and $\tau(B^0) = [1.507 \pm 0.010(\text{stat}) \pm 0.008(\text{syst})]$ ps where the two B^0 measurements have been combined. These results are consistent and of similar precision to the measurements from Belle[3] . The similarities between the decay channels allow for the accurate determination of the ratio $R_+ = [1.088 \pm 0.009\ (\text{stat}) \pm 0.004\ (\text{syst})]$ which favors a slightly higher value than the current average of 1.071 ± 0.009 [4]. These results are consistent with the current HQE predictions [4, 5], giving further confidence in this theoretical framework, and also provide an accurate test for future lattice QCD calcula-

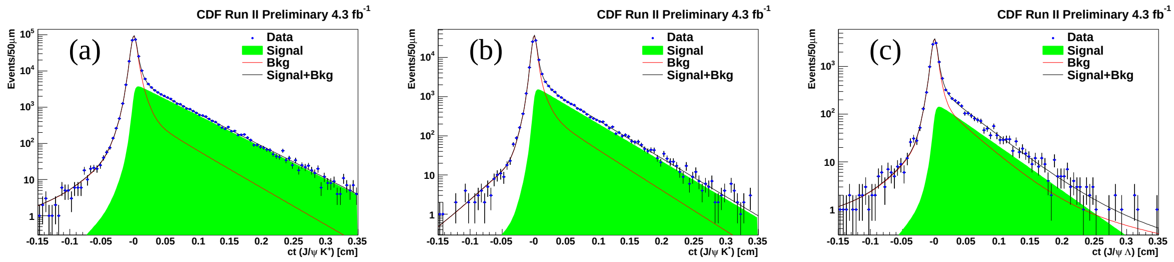

Figure 1: Decay time distributions for (a) $B^+ \to J/\psi K^+$, (b) $B^0 \to J/\psi K^*$, and (c) $\Lambda_b^0 \to J/\psi \Lambda^0$ candidates.

tions. For the Λ_b^0 we measure $\tau(\Lambda_b^0) = [1.537 \pm (\text{stat})0.045 \pm (\text{syst})0.014]$ ps and $R_\Lambda = [1.020 \pm 0.030(\text{stat}) \pm 0.008(\text{syst})]$. This measurement is the most precise measurement of $\tau(\Lambda_b^0)$ and is consistent with the previous CDF measurement in this decay channel of $\tau(\Lambda_b^0) = [1.593^{+0.083}_{-0.078}(\text{stat}) \pm 0.033(\text{syst})]$ ps [6] but is more than 2σ larger than the world average of $1.383^{+0.049}_{-0.048}$ ps and the previous CDF measurement [7], performed on a different decay channel ($\Lambda_c^\pm \pi^\mp$): $[1.401 \pm 0.046(\text{stat}) \pm 0.035(\text{syst})]$ ps . The ratio is also higher than the predicted value of 0.88 ± 0.05 [5] but in agreement with 1.063 ± 0.027 [8]. 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 [9]: $[1.530 \pm 0.025(\text{stat}) \pm 0.012(\text{syst})]$ ps.

2. X,Y,Z states:

CDF is playing a significant role in the study of exotic X,Y and Z states with the first confirmation of $X(3872)$ [10], the measurements of its quantum numbers[11], the precision mass measurement of $X(3872)$ [12] and the $Y(4140)$ evidence [13].

An update [14] on the search for structures in the $J/\psi\phi$ system produced in exclusive $B^+ \to J/\psi\phi K^+$ decays with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ is reported here. This analysis is based on an integrated luminosity of about 6.0 fb^{-1}. The same requirements applied in [13] are used. The major points of the analysis are the use of L_{xy} to separate B vertex from the primary vertex and the use of kaon particle identification to reduce combinatorial background. Fig. 2 shows the invariant mass of $J/\psi\phi K^+$ after the requirements of [13]. A fit with a Gaussian signal function and a linear background function to the mass spectrum returns a B^+ signal of 115±12 events. We increased the $B^+ \to J/\psi\phi K^+$ statistics by 53 % comparing to previous analysis [13]. The same model described in reference [13] is used as well, in order to examine the $Y(4140)$ structure. The enhancement is modelled by an S-wave relativistic Breit-Wigner function [15] convoluted with a Gaussian resolution function with the r.m.s. fixed to 1.7 MeV/c^2 obtained from MC, and a three-body phase space [4] is used to describe the background shape. An unbinned fit to the $\Delta M = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ distribution, as shown in Fig. 2, returns a yield of 19±6 events, a ΔM of $1046.7^{+2.9}_{-3.0} \pm 0.6$ MeV/c^2, and a width of $15.3^{+10.4}_{-6.1} \pm 2.5$ MeV/c^2. The statistical significance of the signal is over 5σ. The mass of $Y(4140)$ is above open charm production and the width favors a strong decay. The relative branching fraction between $B^+ \to Y(4140)K^+, Y(4140) \to J/\psi\phi$ and $B^+ \to J/\psi\phi K^+$ is 15±5%.

An excess above the three-body phase space background shape appears at approximately 1.18 Gev/c^2 in Fig. 2. Since the significance of Y(4140) is greater than 5σ, we fit to the data assuming

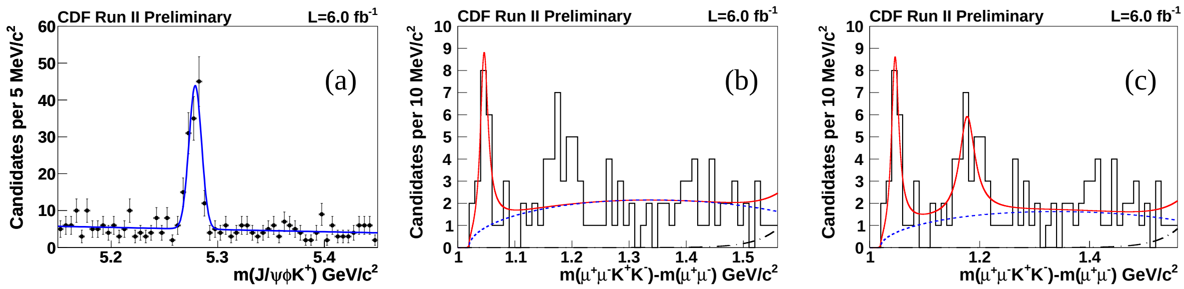

Figure 2: Mass distributions for $B^+ \to J/\psi\phi K^+$ (a) and mass difference ΔM, between $\mu^+\mu^-K^+K^-$ and $\mu^+\mu^-$ in the B^+ mass window together with an unbinned fit of one (b) and two (c) signal hypothesis.

two structures at ΔM of 1.05 and 1.18 GeV/c^2. The new enhancement is modelled by an S-wave relativistic Breit-Wigner function [15] convoluted with a Gaussian resolution function with the r.m.s. fixed to 3.0 MeV/c^2. The fit to the data returns a yield of 22±8 events, a ΔM of $1177.7^{+8.4}_{-6.7} \pm 1.9$ MeV/c^2, and a width of $32.3^{+21.9}_{-15.3} \pm 7.6$ MeV/c^2 for the structure around ΔM of 1.18 GeV/c^2. The statistical significance of the new signal is over 3σ. After including the world-average J/ψ mass, the mass of this structure is $4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV/c^2.

In summary, the increased $B^+ \to J/\psi\phi K^+$ sample at CDF enables us to further investigate the $Y(4140)$ structure and we find that its mass and width are consistent with the previous report [13] with a significance greater than 5σ. A new structure is found at around 4275 MeV/c^2.

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[15] $\frac{dN}{dm} \propto \frac{m\Gamma(m)}{(m^2-m_0^2)^2+m_0^2\Gamma^2(m)}$, where $\Gamma(m) = \Gamma_0 \frac{q}{q_0}\frac{m_0}{m}$, and the 0 subscript indicates the value at m_0, the pole mass.