

Measurements of B hadron lifetimes at CDF

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Using data samples in excess of 1 fb^{-1} collected by the CDF II detector we present several world's best measurements of B hadron lifetimes. They include B_s meson lifetime in a flavor-specific decay mode, combining fully and partially reconstructed hadronic decays, B_c^+ meson lifetimes in semileptonic $B_c^+ \rightarrow J/\psi \ell^+ X, \ell^+ = \mu^+, e^+$ decays and Λ_b baryon lifetime in $\Lambda_c^+ \pi^-$ fully-reconstructed decays. In addition, we introduce a Monte Carlo independent technique for measuring B hadron lifetimes in data samples biased by displaced vertex triggers.

1. INTRODUCTION

In a simple quark spectator model, the lifetimes of all B hadrons are equal, independent of the flavor of the light quark(s) bound to the b quark. However, significant non-spectator effects enter in the third order, $(\Lambda_{QCD}/m_b)^3$, and higher order terms in the Heavy Quark Expansion (HQE) [1] of the decay width, leading to the predicted lifetime hierarchy: $\tau(B^+) \geq \tau(B^0) \sim \tau(B_s^0) > \tau(\Lambda_b) \gg \tau(B_c^+)$. Especially, Pauli Interference terms increase $\tau(B^+)$ by 5% and $\tau(\Lambda_b)$ by 3% and Weak Annihilation and Exchange reduce $\tau(\Lambda_b)$ by 7%. Recent theoretical calculations predict $\tau(B^+)/\tau(B^0) = 1.06 \pm 0.02$, $\tau(B_s)/\tau(B^0) = 1.00 \pm 0.01$ and $\tau(\Lambda_b)/\tau(B^0) = 0.88 \pm 0.05$ [2]. The experimental world averages for these ratios are 1.071 ± 0.009 , 0.939 ± 0.021 and 0.904 ± 0.032 , respectively [3]. While B^+ and B^0 lifetimes are measured precisely at the B -factories, the experimental uncertainty on B_s lifetime is far higher than the theory uncertainty. Prior to 2006 world average of $\tau(\Lambda_b)/\tau(B^0)$ was small compared to the 3rd order HQE prediction, while the value measured by CDF in 2006 [4] is precise but larger than previous results.

The doubly heavy B_c^+ meson decay is an interesting laboratory to probe heavy quark dynamics, where both b and c quarks can decay weakly as well as annihilate. Due to significant contributions from c quark decay and annihilation process, the B_c^+ lifetime is expected to be shorter than the light B mesons. Current theory predictions for $\tau(B_c^+)$ range from 0.47 to 0.59 ps [5].

In this proceeding we present world best measurements of B_s , Λ_b and B_c^+ lifetimes by CDF which will help constrain the theories. In addition, we present a measurement of B^+ lifetime in a decay time biased data sample using a Monte Carlo independent method. It significantly reduces systematic uncertainty on lifetime compared to the traditional Monte Carlo based method and can provide improvements on future measurements of other B hadrons.

2. B_c^+ LIFETIME MEASUREMENTS

The B_c^+ lifetime is measured in $B_c^+ \rightarrow J/\psi \ell^+ X, \ell^+ = e^+, \mu^+$ semileptonic decay channels [6] collected by di-muon trigger in 1.0 fb^{-1} data. Due to the missing neutrino momentum, the observed decay time (ct^*) is corrected by a K -factor as follows: $ct = K \cdot ct^*$ where, $ct^* = \frac{M(B_c^+) L_{xy}(J/\psi \ell^+)}{p_T(J/\psi \ell^+)}$ and $K = p_T(J/\psi \ell^+)/p_T(B_c^+)$, extracted from Monte Carlo.

About 5.6 million signal J/ψ events were reconstructed. The main challenge in the analysis comes from various backgrounds which enter due to using a broad partially reconstructed mass shape. These include real J/ψ plus misidentified lepton, random track pair consistent to be J/ψ plus real lepton, real J/ψ plus real lepton coming from different b quarks, prompt J/ψ plus lepton and residual conversion in $J/\psi e^+$ decays. The decay time distribution shape of all backgrounds are modeled and calibrated carefully both from data and Monte Carlo. The lifetime is extracted from an unbinned maximum likelihood fit where the signal and background normalizations are fixed and $\tau(B_c^+)$ is the only free parameter.

The measured lifetimes from the electron and muon channels are $c\tau = 121.7_{-16.3}^{+18.0} \mu\text{m}$ and $c\tau = 179.1_{-27.2}^{+32.6} \mu\text{m}$ and the combined result is $\tau(B_c^+) = 0.475_{-0.049}^{+0.052}(\text{stat}) \pm 0.018(\text{syst})\text{ps}$ which is the world best measurement to date. Figure 1 (left) shows the combined likelihood as a function of the $c\tau(B_c^+)$. Combining with the DØ measurements [3] the Tevatron weighted average is $\tau = 0.459 \pm 0.037 \text{ ps}$. A comparison of our B_c^+ lifetime result with Run I CDF and DØ results is shown in Figure 1 (right). A good agreement is seen between all the measurements.

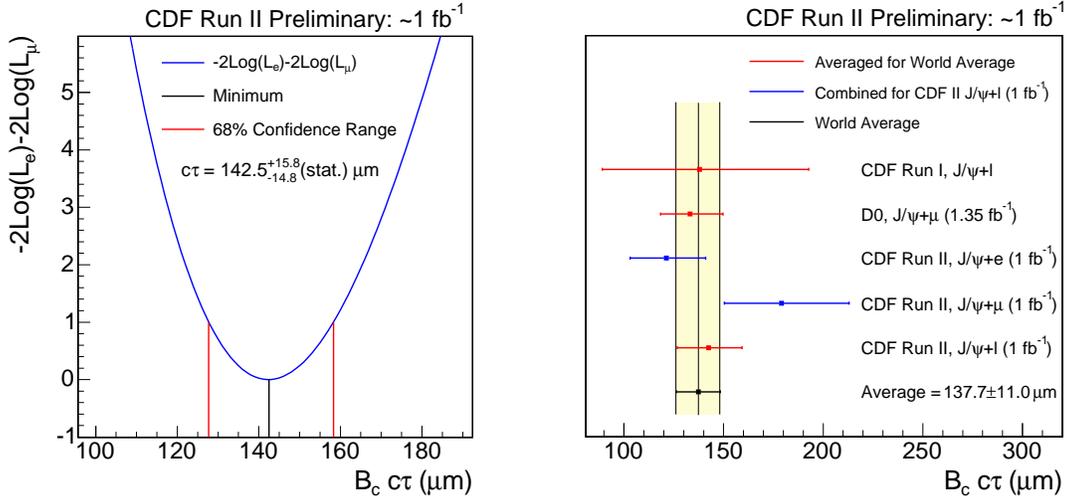


Figure 1: The combined likelihood in muon and electron channels as a function of the $\tau(B_c^+)$ (left). Comparison of B_c^+ lifetime with CDF Run I result and CDF and DØ Run II results (right). A weighted average is made assuming no correlation among these measurements.

3. B_s LIFETIME MEASUREMENT

The B_s lifetime is measured in the flavor-specific $B_s \rightarrow D_s^- \pi^+ X$ decays [7], with $D_s^- \rightarrow \phi \pi^-$ collected using CDF displaced vertex trigger in a 1.3 fb^{-1} data sample. In addition to about 1100 fully reconstructed $D_s^- \pi^+$ events this analysis uses about 2000 partially reconstructed $D_s^* \pi^+$ and $D_s^- \rho^+ (\pi^+ \pi^0)$ events to increase the statistics significantly. The latter type events involve missing particles (e.g. a π^0 in the $D_s^- \rho^+$ mode) which result in mis-reconstructed mass and transverse momentum. A K -factor is introduced to correct the lifetime: $ct = \frac{L_{xy} \cdot m_{B_s}^{rec}}{p_T} \cdot K$.

The B_s lifetime is determined from two sequential fits. The first is a binned maximum likelihood fit of the invariant mass distribution of the $D_s^- \pi^+$ candidates to determine the signal and background composition. The second is a unbinned maximum likelihood fit of ct to extract the B_s lifetime where all the other parameters are fixed. Decay time bias due to trigger acceptance is modeled in the final fit by an efficiency curve, extracted from Monte Carlo. Extensive tests of the fit procedure have been performed on B^+ and B^0 control samples which yield lifetime results in good agreement with the corresponding world average values. Figure 2 (left) shows the lifetime fit projection. We obtain the flavor-specific B_s lifetime $\tau(B_s) = 1.518 \pm 0.041(\text{stat}) \pm 0.025(\text{syst})$ ps.

This is the current world best measurement in flavor-specific mode. Figure 2 (right) compares this result with all published results from flavor-specific channels. A good overall agreement with the PDG 2007 [3] result is seen.

4. Λ_b LIFETIME MEASUREMENT

The Λ_b lifetime is measured in $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ fully reconstructed decays [8] obtained from the CDF displaced vertex trigger where Λ_c is reconstructed from its decay to a proton, kaon and a pion. About 2900 signal events are reconstructed from a data sample of 1.1 fb^{-1} . A blind analysis is performed where all analysis procedures are finalized with the signal region $(m(\Lambda_b) \in [5.565, 5.670] \text{ GeV}/c^2)$ in data blinded. As in Section 3 a two-step fit of invariant mass and lifetime is performed to extract the Λ_b lifetime. As before, the trigger efficiency curve, obtained from Monte Carlo, is introduced in the lifetime fit to model decay time bias. The fit procedure is validated using input lifetime (τ) values in Monte Carlo between 325 and 500 μm .

Figure 3 (left) shows the lifetime fit projection. We measure the Λ_b lifetime $\tau(\Lambda_b) = 1.410 \pm 0.046(\text{stat}) \pm 0.029(\text{syst})$ ps. This is the current world best measurement. Using world average B^0 lifetime [3] we obtain $\tau(\Lambda_b)/\tau(B^0) = 0.922 \pm 0.039$. The leading sources of systematic error to this measurement come from modeling of the displaced vertex trigger, Λ_c^+ Dalitz structure and decay time distribution of combinatorial background. Figure 3 (right) compares this result with the current world average

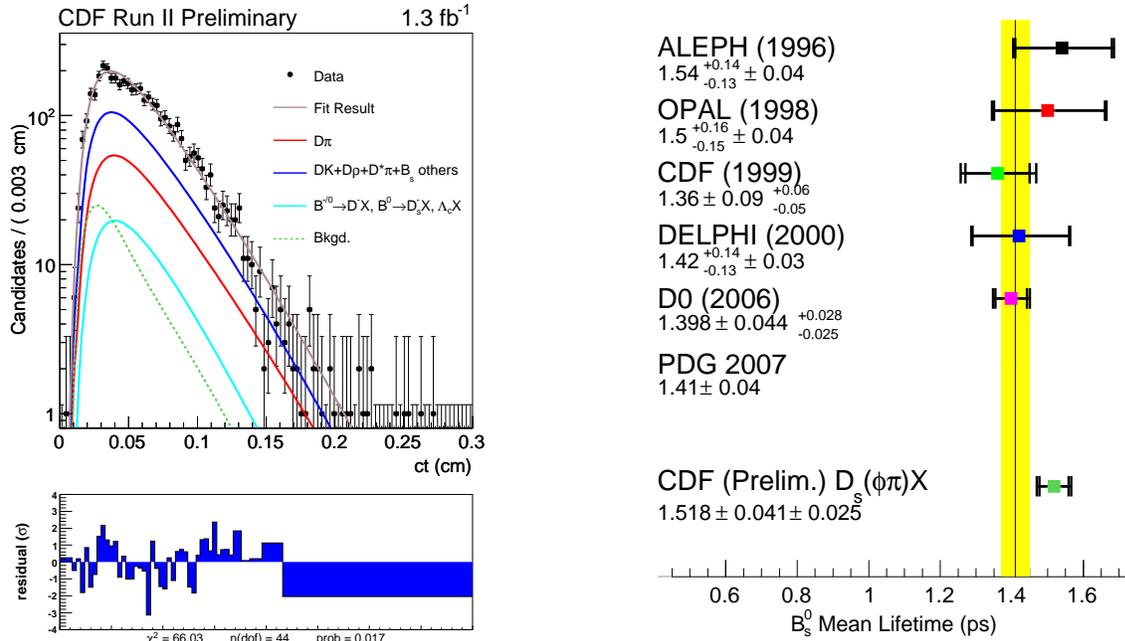


Figure 2: Lifetime fit projection of $B_s \rightarrow D_s^-(\phi\pi^-)\pi^+X$ (left). B_s lifetime results from flavor-specific channels (right).

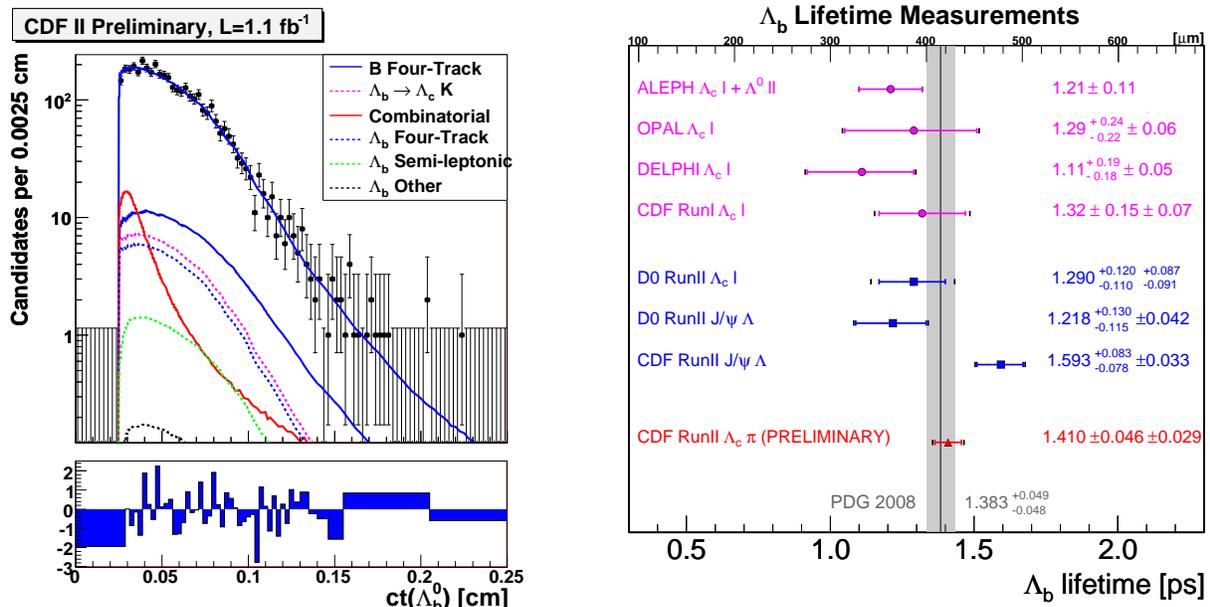


Figure 3: Lifetime fit projection of $\Lambda_b \rightarrow \Lambda_c^+\pi^-$ decays (left). Λ_b lifetime result compared with PDG 2008 and other measurements contributing to it (right).

and all measurements contributing to it, where a good agreement is seen. This result is also compatible with the HQE prediction of the lifetime ratio, $\tau(\Lambda_b)/\tau(B^0)$.

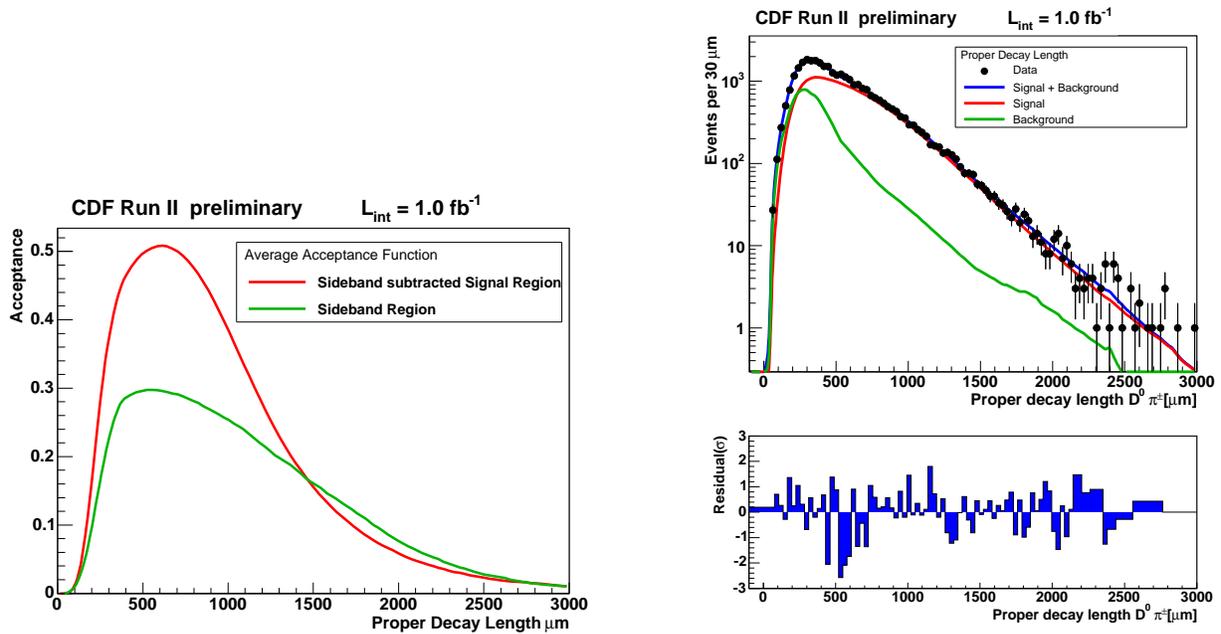


Figure 4: Comparison of averaged acceptance functions for signal and background data (left). Lifetime fit projection of $B^+ \rightarrow \bar{D}^0 \pi^+$ decays (right).

5. B^+ LIFETIME MEASUREMENT USING A MONTE CARLO INDEPENDENT METHOD

The CDF displaced vertex trigger provides heavy-flavor enriched data sample crucial for many B physics analyses, two of which are presented in Sections 3 and 4. The decay time distributions from this sample are biased which B_s and Λ_b lifetime analyses correct for, employing Monte Carlo based efficiency functions. This method, however, serves as the dominant source of systematic error in both these analyses.

A Monte Carlo independent method has been developed which exploits the decay kinematics in data to correct for the trigger bias on a per event basis. It completely avoids Monte Carlo modeling of the trigger effect and thus promises to improve uncertainty involved in future lifetime measurements in trigger biased samples.

As a proof of principle, we present a measurement of B^+ lifetime measured in the fully reconstructed $B^+ \rightarrow \bar{D}^0(K^+\pi^-)\pi^+$ decays [9]. About 24200 signal events are reconstructed in 1 fb⁻¹ data. The CDF displaced vertex trigger requires a pair of tracks with large impact parameters. The Monte Carlo independent method “slides” the events along the B meson flight direction and evaluates trigger acceptance as a function of proper decay length. The resulting averaged trigger acceptance functions for signal and sideband regions are shown in Figure 4 (left). Since the per event acceptance is a function and not a scalar variable it greatly complicates the fit. To circumvent this, a Fisher Discriminant analysis is performed to transform the acceptance into a variable which is easier to handle. The following three step method is adopted to extract the B^+ lifetime. Firstly the mass distribution is fitted which defines the signal and sideband regions and provides the sample composition. Secondly, using the signal and sideband regions the Fisher variable is computed from the trigger acceptance. Finally a maximum likelihood fit is performed on the lifetime and the signal dependent Fisher variable to extract the lifetime.

Figure 4 (right) shows the lifetime fit projection. We measure the B^+ lifetime $\tau(B^+) = 1.662 \pm 0.023(\text{stat}) \pm 0.015(\text{syst})$ ps. This is in good agreement with the current world average of 1.638 ± 0.011 ps [3]. The small systematic error of this measurement makes the Monte Carlo independent method promising for future lifetime measurements of, e.g. B_s and Λ_b hadrons. The dominant sources of systematic uncertainties are impact parameter and transverse momentum dependence of track finding efficiency and correlation between mass and decay time in the background.

6. SUMMARY

Using data samples in excess of 1 fb^{-1} collected by the CDF detector we present world best measurements of B_c^+ , B_s and Λ_b hadron lifetimes. They are in good agreement with the corresponding experimental world averages and HQE predictions. A Monte Carlo independent method is used to measure the B^+ lifetime in a trigger biased data sample which agrees with the current world average and is expected to be used in future measurements of other B hadron lifetimes. It is to be noted that all the measurements presented in this proceeding are from about $1/4^{\text{th}}$ of the current CDF dataset. We expect significant improvements to these results in the near future as more data are analyzed.

References

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