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B_s^0 and Λ_b^0 Lifetimes and Branching Ratios at the Tevatron

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We review B_s^0 and Λ_b^0 lifetime and branching ratio measurements from the CDF and DØ experiments at the Tevatron Run II. Using up to 1 fb^{-1} data samples per experiment, Λ_b^0 lifetime in $J/\psi\Lambda^0$ decays, B_s^0 lifetime difference in K^+K^- and $D_s^{(*)+}D_s^{(*)-}$ decays and B_s^0 branching ratio in $D_{s1}^-(2536)\mu^+\nu X$ decays are reported.

1. INTRODUCTION

Since 2001, Tevatron has delivered about 2.0 fb^{-1} of $p\bar{p}$ collision data at $\sqrt{s}$ = 1.96 TeV, which includes decay modes of all B hadron species. Using up to 1 fb^{-1} data per experiment, we review lifetime and branching fractions of B_s^0 meson and Λ_b^0 baryon, which are currently only produced at the Tevatron.

The CDF and DØ detectors at the Tevatron Run II have excellent mass and lifetime resolutions, owing to their tracking systems which include silicon vertex detectors. In addition, DØ has good lepton ID from calorimetry and CDF has good low momentum hadron ID from dE/dx and ToF devices, useful for rejecting backgrounds.

Since $\sigma(b\bar{b}) \ll \sigma(p\bar{p})_{inel}$ both CDF and DØ rely on dedicated triggers to select events of interest from backgrounds. Both CDF and DØ employ single- (di-) lepton triggers where identification of a high p_T lepton (two lower p_T leptons) in an event fires the trigger. The samples collected from these triggers are used to study semi-leptonic B hadron decays or B hadron decays which proceed via a J/ψ. In addition CDF exploits its displaced track reconstruction capability, to trigger at Level 2 on a lepton and a displaced track or two displaced tracks. These triggers are used to select semi-leptonic and fully hadronic B decays, respectively.

2. B HADRON LIFETIMES

In a simple quark spectator model the lifetime of all B hadrons are expected to be the same. However, owing to significant non-spectator effects the B hadron lifetimes follow a hierarchy: $\tau(B^+) \geq \tau(B^0) \approx \tau(B_s^0) > \tau(\Lambda_b^0) \gg \tau(B_c^+)$. This knowledge comes from the Heavy Quark Expansion (HQE) technique[1], which expresses the total decay widths of heavy hadrons as an expansion in inverse powers of the heavy quark mass ($1/m_b$) and predicts B hadron lifetime ratios. There has been a long standing discrepancy between experimental measurements of $\tau(\Lambda_b^0)/\tau(B^0)$ and HQE expection up to $O(1/m_b^3)$. A recent calculation [2] upto $O(1/m_b^4)$, $\frac{\tau(\Lambda_b^0)}{\tau(B^0)}$ = 0.88 $\pm$ 0.05, reduces the disagreement with the current world average, 0.804 $\pm$ 0.049 [3]. Figure 1 shows comparison of current experimental data (curve) and the HQE prediction (histogram) for $\tau(B_s^0)/\tau(B^0)$ and $\tau(\Lambda_b^0)/\tau(B^0)$.

The mixing phenomenon in the B_s^0 meson system is known to arise from second order weak interaction and results in two mass eigenstates, m_H (*heavy*) and m_L (*light*). Assuming a negligible *CP* violating phase in B_s^0-$\bar{B}_s^0$ mixing, they can be regarded as *CP* eigenstates such that, $|B_{sL,H}^0\rangle = \frac{1}{\sqrt{2}}(|B_s^0\rangle \pm |\bar{B}_s^0\rangle)$. Also it is convenient to define average and difference of decay widths of these states as, $\Gamma = (\Gamma_H + \Gamma_L)/2$ and $\Delta\Gamma = \Gamma_L - \Gamma_H$, respectively. The Standard Model prediction for $\Delta\Gamma_s/\Gamma_s$ is (9.3 $\pm$ 4.6)% [4] and the current world average is $0.31\ ^{+0.11}_{-0.13}$ [3].

There are several ways of measuring lifetimes of the *heavy* and *light CP* eigenstates. One way is to measure $\Delta\Gamma$ directly by an angular analysis of the decay $B_s^0 \to J/\psi\phi$ [5] and thereby disentangling *CP even* and *odd* components from this CP-mixed decay mode. Another way is to measure "flavor-specific" lifetime using final states with equal fractions of the

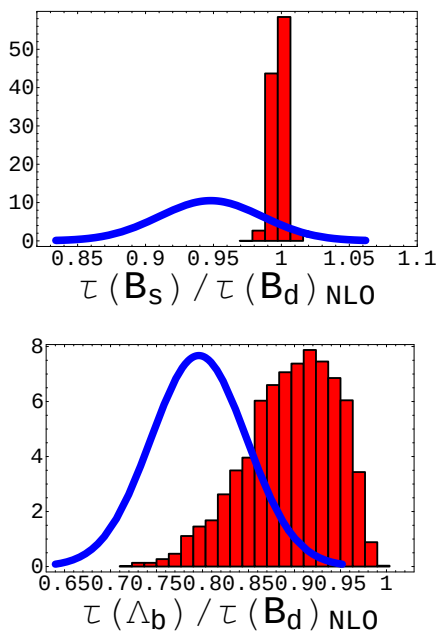

Figure 1. Comparison of experimental data (curve) and the HQE prediction (histogram) for $\tau(B_s^0)/\tau(B^0)$ and $\tau(\Lambda_b^0)/\tau(B^0)$.

heavy and *light* states, given by $\tau(B_s^0)_{\rm fs} = 1/\Gamma(1+(\frac{\Delta\Gamma}{2\Gamma})^2)/(1-(\frac{\Delta\Gamma}{2\Gamma})^2)$. A third way is to measure $\tau_L = 1/\Gamma_L$ from the decay $B_s^0 \to K^+K^-$, which is 95% *CP*-even. Finally, according to the prescription in Ref. [6], $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ decays are predominantly *CP* even and satisfy $2\times BR(B_s^0 \to D_s^{(*)+}D_s^{(*)-}) = \frac{\Delta\Gamma_{CP}}{\Gamma}\left[1+O(\frac{\Delta\Gamma}{\Gamma})\right]$. Neglecting the second term in the brackets, $\frac{\Delta\Gamma_{CP}}{\Gamma} = 2\times BR(B_s^0 \to D_s^{(*)+}D_s^{(*)-})$. In this paper we report results from the latter three methods. Charge conjugate states are always implied throughout this text, wherever applicable.

2.1. Λ_b^0 Lifetime in $\Lambda_b^0 \to J/\psi\Lambda^0$

Using 1 fb^{-1} data each, CDF [7] and DØ [8] have analysed the decay $\Lambda_b^0 \to J/\psi\Lambda^0$ in the di-muon ($J/\psi \to \mu^+\mu^-$) trigger datasets and have found 538 and 174 fully reconstructed events, respectively. Both the analyses perform simultaneous unbinned likelihood fits to mass and proper decay length to extract the Λ_b^0 lifetime.

The reconstructed proper decay length of Λ_b^0 by CDF is shown in Fig. 2. The lifetime is extracted as $\tau(\Lambda_b^0) = 1.593\,^{+0.083}_{-0.078}$ (stat) $\pm$ 0.033 (syst) ps, and using world average value of $\tau(B^0)$ the lifetime ratio is obtained as $\tau(\Lambda_b^0)/\tau(B^0) = 1.041 \pm 0.057$ (stat$\oplus$syst).

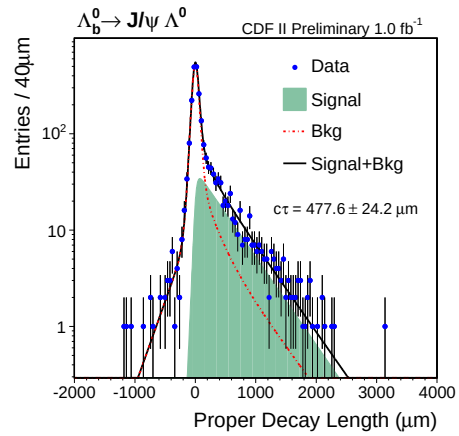

Figure 2. Proper decay length projection of the CDF Λ_b^0 lifetime fit.

Figure 3 shows proper decay length of Λ_b^0 by DØ . The lifetime is extracted from a fit as $\tau(\Lambda_b^0) = 1.298 \pm 0.137$ (stat) $\pm$ 0.050 (syst) ps, and using their measurement of $\tau(B^0)$ in the decay $B^0 \to J/\psi K_s^0$ the lifetime ratio is obtained as $\tau(\Lambda_b^0)/\tau(B^0) = 0.870 \pm 0.102$ (stat) $\pm$ 0.041 (syst).

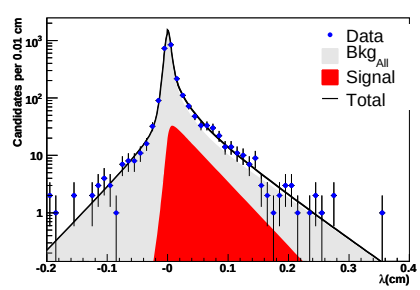

Figure 3. Proper decay length projection of the DØ Λ_b^0 lifetime fit.

The CDF results are current world's best. Both CDF and DØ results for the $\tau(\Lambda_b^0)/\tau(B^0)$ ratio are consistent with an HQE prediction [2] and the current

world average [3], although the former deviates from the HQE prediction by about 1.8σ and the world average by about 3σ. More experimental inputs would be necessary to confirm compatibility between these results. A future CDF measurement of Λ_b^0 lifetime in another fully hadronic decay, $\Lambda_b^0 \to \Lambda_c^+\pi^-$, could shade some light on this.

2.2. B_s^0 Meson Lifetime

The flavor-specific B_s^0 lifetime is measured by CDF and DØ in various decay modes. Using about 1150 $B_s^0 \to D_s^- \ell^+ \nu$ (ell^+=e^+,μ^+) events from 360 pb^{-1} data, collected by single lepton triggers, CDF has measured $\tau(B_s^0)$ = 1.381 ± 0.055 (stat) $^{+0.052}_{-0.046}$ (syst) ps [9]. Figure 4 shows the fitted pseudo-proper decay length distribution.

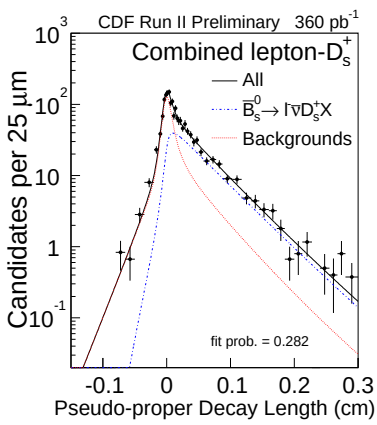

Figure 4. CDF fit of pseudo-proper decay length in semi-leptonic B_s^0 decays.

DØ , on the other hand, has used a low p_T threshold muon trigger sample from 400 pb^{-1} data and has measured B_s^0 lifetime in $B_s^0 \to D_s^- \mu^+ \nu$ decays to be $\tau(B_s^0)$ = 1.398 ± 0.044 (stat) $^{+0.028}_{-0.025}$ (syst) ps [10]. Figure 5 shows the fitted pseudo-proper decay length distribution. This is the current world's best flavor-specific B_s^0 lifetime measurement.

CDF has also measured the flavor-specific B_s^0 lifetime in fully reconstructed hadronic decays, $B_s^0 \to D_s^- \pi^+$ and $D_s^- \pi^+ \pi^- \pi^+$, in 360 pb^{-1} data, collected using the displaced track trigger [11]. This trigger introduces a bias to the B hadron decay length distribution, which is corrected using a Monte Carlo simulation. The flavor-specific B_s^0 lifetime obtained, based

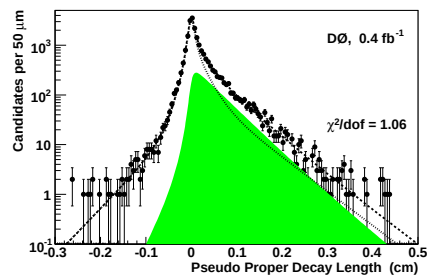

Figure 5. DØ fit of pseudo-proper decay length in semi-leptonic B_s^0 decays.

on a simultaneous fit to mass and decay length, is $\tau(B_s^0)$ = 1.60 ± 0.10 (stat) ± 0.02 (syst) ps. The fitted proper decay length distributions for $D_s^- \pi^+$ and $D_s^- \pi^+ \pi^- \pi^+$ decays are shown in Figs. 6 and 7, respectively.

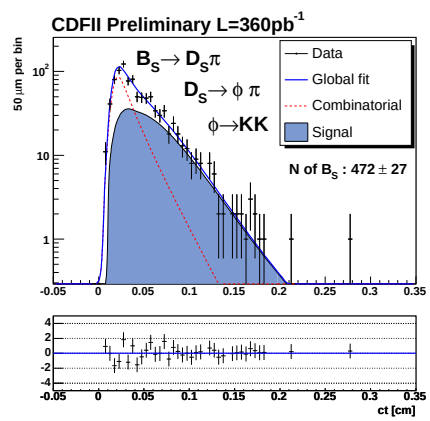

Figure 6. CDF fit of proper decay length in $B_s^0 \to D_s^- \pi^+$ decays.

Using a 360 pb^{-1} data sample collected from the displaced track trigger CDF has measured $\tau_L(B_s^0)$ [12]. The two-body charmless decays are analysed and the four $B \to h^+h^-$ components namely, $B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^-\pi^+$ and $B_s^0 \to K^+K^-$, are resolved using a multidimensional unbinned likelihood fit to invariant mass, kinematics and particle ID informations. Constraining the B^0 lifetime to the world average, $\tau_L(B_s^0)$ is measured to be $\tau(B_s^0 \to K^+K^-)$ = 1.53 ± 0.18 (stat) ± 0.02 (syst). Figure 8 shows the decay length distribution of

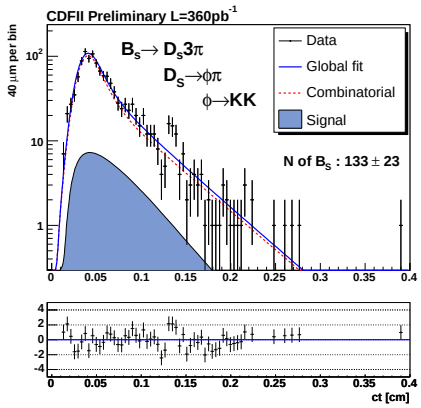

Figure 7. CDF fit of proper decay length in $B_s^0 \to D_s^- \pi^+ \pi^- \pi^+$ decays.

the h^+h^- sample with various components and background overlaid.

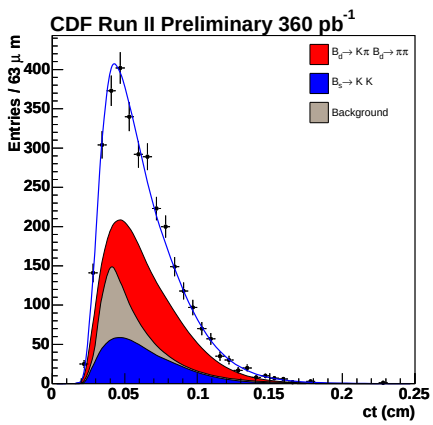

Figure 8. Fit to proper decay length of two-body hadronic decays.

Using world average of flavor specific $\tau(B_s^0)$, lifetime difference is measured to be $\frac{\Delta\Gamma_{CP}}{\Gamma_{CP}}$ = -0.08 ± 0.23 (stat) ± 0.03 (syst).

DØ has obtained $\frac{\Delta\Gamma_{CP}}{\Gamma}$ in the B_s^0 system by measuring the $BR(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$ from an 1 fb^{-1} muon triggered data sample [13]. One of the $D_s^\pm$ is reconstructed from $\phi\pi^\pm$ and the other from $\mu^\pm\phi\nu$. Firstly events containing a muon and a $D_s^- \to \phi\pi^-$ are made into a μD_s sample. Then an additional ϕ meson is searched in the μD_s sample which makes the $\mu\phi D_s$ sample. The D_s^- invariant mass is fit to extract $N(\mu D_s)$. Figure 9 shows the D_s^- invariant mass distribution, with the fit overlaid.

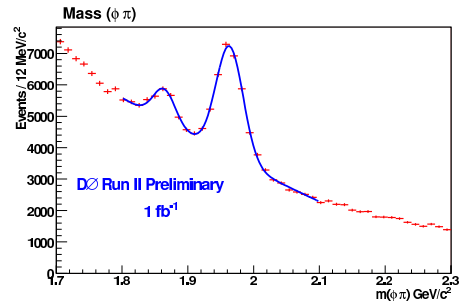

Figure 9. The D_s^- invariant mass distribution. The overlaid fit function is composed of two Gaussians for $D_s^\pm$ and $D^\pm$ signals and a second order polynomial for background.

The yield $N(\mu\phi D_s)$ is extracted by a simultaneous unbinned likelihood fit to D_s^- and ϕ invariant masses. The yield $N(B_s^0 \to \mu^+ D_s^{(*)-}\nu)$ and $N(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$ are then extracted from $N(\mu D_s)$ and $N(\mu\phi D_s)$, respectively. Using these together with PDG values of $BR(D_s^- \to \mu^-\phi\nu)$, $BR(B_s^0 \to \mu^+ D_s^{(*)-}\nu)$ and $BR(D_s^- \to \phi\pi^-)$, $BR(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$ is measured to be 0.071 ± 0.032 (stat) $^{+0.029}_{-0.025}$ (syst). This leads to a lifetime difference of $\frac{\Delta\Gamma_{CP}}{\Gamma}$ = 2×BR = 0.142 ± 0.064 (stat) $^{+0.058}_{-0.050}$ (syst).

Figure 10 summarizes Tevatron measurements of B_s^0 lifetime and $\Delta\Gamma$ measurements. The DØ 2006 $B_s^0 \to J/\psi\phi$ angular analysis result is shown with one-σ contour. The CDF 2004 result of the same is shown with error bars. Also shown are, flavour specific world average (WA), SM theoretical prediction [4], DØ $BR(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$ and CDF K^+K^- results with one-σ bands.

3. B_s^0 BRANCHING FRACTION IN $B_s^0 \to D_{s1}^-(2536)\mu^+\nu X$

The orbitally excited D_s^{**-} state, $D_{s1}^-(2536)$, is composed of a strange-charm quark pair in $L = 1$ (P-

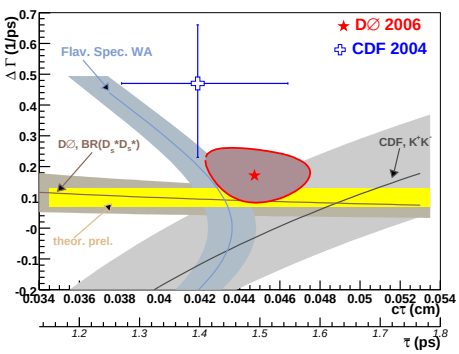

Figure 10. DØ (2006) and CDF (2004) $B_s^0 \to J/\psi\phi$ angular analysis results of $\Delta\Gamma$ are shown with one-σ contour and error bars, respectively. Also shown superimposed are various other measurements discussed in this paper with one-σ bands.

wave) state. A significant fraction of semileptonic B_s^0 decays is made of decay into this state. Thus it is important to compare exclusive and inclusive decay rates, extract CKM matrix elements and serve as an additional channel for B_s^0 mixing. Also, since heavy excited charm states produced in B semileptonic decays are at zero recoil, the Heavy Quark Effective Theory (HQET) corrections become important in predicting their decay rates.

Using a 1 fb$^-$ data sample collected from single muon trigger DØ has made a first ever measurement of the product branching ratio $f(\bar{b} \to B_s^0) \cdot BR(B_s^0 \to D_{s1}^-(2536)\mu^+\nu X) \cdot BR(D_{s1}^-(2536) \to D^{*-}K_s^0)$ [14]. Events compatible with the decay chain $B_s^0 \to D_{s1}^-(2536)\mu^+\nu X$ with $D_{s1}^-(2536) \to D^{*-}K_s^0$ followed by $D^{*-} \to \bar{D}^0\pi^-$, $\bar{D}^0 \to K^+\pi^-$ and $K_s^0 \to \pi^+\pi^-$ are reconstructed and the product branching ratio is extracted using the formula $f(\bar{b} \to B_s^0) \cdot BR(B_s^0 \to D_{s1}^-(2536)\mu^+\nu X) \cdot BR(D_{s1}^-(2536) \to D^{*-}K_s^0) = BR(\bar{b} \to D^{*-}\mu^+\nu X) \cdot \frac{N_{D_{s1}^-(2536)}}{N_{D^*\mu}} \cdot \frac{1}{R_{D^*}^{gen} \cdot \varepsilon_{K_s^0}}$. The fraction, $R_{D^*}^{gen} = \varepsilon(B_s^0 \to D_{s1}^-(2536)\mu \to D^{*-}\mu)/\varepsilon(\bar{b} \to D^{*-}\mu^+)$, denotes the ratio of efficiencies for reconstructing all possible $(D^*\mu)$ final states versus reconstructing the same through a $(D_{s1}^-(2536)\mu)$ intermediate state. The factor $\varepsilon_{K_s^0}$ is the efficiency in signal channel to additionally reconstruct and vertex a K_s^0 to form a $D_{s1}^-(2536)$ once a $(D^*\mu)$ has already been reconstructed. Both $R_{D^*}^{gen}$ and $\varepsilon_{K_s^0}$ are obtained from Monte Carlo simulation. The $BR(\bar{b} \to D^{*-}\mu^+\nu X)$ is taken from PDG. The $N_{D^*\mu}$ and $N_{D_{s1}^-(2536)}$ yields are obtained from data from $M(D^*) - M(D^0)$ and $D^*K_s^0$ invariant mass distributions, respectively, as 82130 $\pm$ 463 (stat) and 43.8 $\pm$ 8.3. Figure 11 shows the $D_{s1}^-(2536)$ invariant mass distribution with a 5.2σ signal.

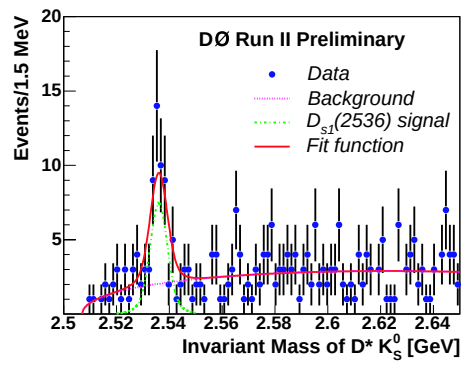

Figure 11. $D_{s1}^-(2536)$ invariant mass with a 5.2σ signal.

The product branching fraction is then measured as $f(\bar{b} \to B_s^0) \cdot BR(B_s^0 \to D_{s1}^-(2536)\mu^+\nu X) \cdot BR(D_{s1}^-(2536) \to D^{*-}K_s^0) = (2.29 \pm 0.43\ (\text{stat}) \pm 0.36\ (\text{syst})) \times 10^{-4}$. Using $f(\bar{b} \to B_s^0)$ from PDG and $BR(D_{s1}^-(2536) \to D^{*-}K_s^0))$ from the EvtGen heavy flavor decay package the first experimental measurement of $BR(B_s^0 \to D_{s1}^-(2536)\mu^+\nu X)$ is (0.86 $\pm$ 0.16 (stat) $\pm$ 0.13 (syst) $\pm$ 0.09 (prod. frac.)) %, where the last error is due to current uncertainty on $f(\bar{b} \to B_s^0)$. It is compared with several theoretical predictions, ISGW2 0.53%, RQM 0.39% and HQET & QCD sum rules 0.195% [14].

4. CONCLUSION

The Tevatron is a unique place to study properties of all B hadron species. With about 2 fb^{-1} data on tape per experiment, and much more to come, heavy flavor physics is entering a precision era. Using largest B_s^0 and Λ_b^0 samples, lifetime measurements from CDF and DØ have put theoretical predictions to stringent tests. These include several world best results. An upcoming Λ_b^0 lifetime measurement by CDF

in $\Lambda_b^0 \to \Lambda_c^+ \pi^+$ is expected to shade some light on the long standing discrepancy between the $\tau(\Lambda_b^0)/\tau(B^0)$ world average and the HQE prediction.

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