

# Mass and Lifetime measurements at LHCb

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**Abstract.** The data collected at LHCb during the first run of the LHC are analysed to perform precision measurement of mass and lifetime of hadrons containing heavy quarks. I report here about recent mass measurements of the  $\Xi_c^0$ ,  $\Lambda_b^0$ ,  $\Xi_b^-$ , and  $\Omega_b^-$  baryons, and of charged and neutral  $D$  mesons. Recent precision measurements of the lifetime of  $\Lambda_b^0$ ,  $\Xi_b^0$  and  $\Omega_b^-$  baryons are also reported. I conclude this report with an overview on the experimental knowledge of the  $B_{s,H}^0$ ,  $B_{s,L}^0$ , and  $B_s^0$  flavour specific effective lifetimes. LHCb has performed the world best measurements of most of these quantities.

The large amount of hadrons containing heavy quarks produced at the LHC allows to perform measurements of the properties of  $b$ - and  $c$ - hadrons with unprecedented precision. The LHCb detector, described in Ref. [1], offers an excellent resolution on the momentum of charged tracks and on the position of the secondary vertices, and therefore on mass and lifetime of the reconstructed particles.

The recent mass and lifetime measurements summarized in this paper have been obtained analyzing the dataset of  $pp$  collisions collected with the LHCb detector in 2011 and 2012, at 7 and 8 TeV of energy in the center of mass, and corresponding to an integrated luminosity of 1 and 2  $\text{fb}^{-1}$ , respectively.

## 1. Mass measurements

The LHCb Collaboration has recently reported the mass measurements of the charmed mesons  $D^0$ ,  $D^+$  and  $D_s^+$  performed analysing the dataset collected in 2011 [2]. The following decays have been studied:  $D^0 \rightarrow K^+K^-\pi^+\pi^-$ ,  $D^0 \rightarrow K^+K^-K^-\pi^+$ ,  $D^+ \rightarrow K^+K^-\pi^+$ , and  $D_s^+ \rightarrow K^+K^-\pi^+$ ; for which  $4608 \pm 89$ ,  $849 \pm 36$ ,  $68\,787 \pm 321$ , and  $248\,694 \pm 540$  candidates were observed, respectively. The mass measurements are obtained with extended unbinned maximum likelihood fits to the distributions of the invariant mass of the daughters. The  $D^0$  mass measurements obtained with the 3- and 4-body decays are combined to give  $M(D^0) = 1864.75 \pm 0.15 (\text{stat}) \pm 0.11 (\text{syst}) \text{ MeV}/c^2$ , where the systematic uncertainty, correlated between the two channels, is dominated by the limited knowledge of the momentum scale. Such a contribution partially cancels when evaluating mass differences, so that it is preferable to quote the results on  $D^+$  and  $D_s^+$  masses as

$$M(D^+) - M(D^0) = 4.76 \pm 0.12 (\text{stat}) \pm 0.07 (\text{syst}) \text{ MeV}/c^2, \text{ and} \\ M(D_s^+) - M(D^+) = 98.68 \pm 0.03 (\text{stat}) \pm 0.04 (\text{syst}) \text{ MeV}/c^2.$$

To measure the mass of the  $\Xi_c^+$  baryon LHCb has studied the decays  $\Xi_b^0 \rightarrow \Xi_c^+\pi^-$  with  $\Xi_c^+ \rightarrow pK^-\pi^+$ , using the decay  $\Lambda_c^+ \rightarrow pK^-\pi^+$  as control channel [3]. The mass difference

measured using the combined 2011 and 2012 datasets is

$$M(\Xi_c^+) - M(\Lambda_c^+) = 181.51 \pm 0.14 \text{ (stat)} \pm 0.10 \text{ (syst)} \text{ MeV}/c^2.$$

In the same analysis, the mass of the  $\Xi_b^0$  baryon relative to the  $\Lambda_b^0$  mass was measured to be

$$M(\Xi_b^0) - M(\Lambda_b^0) = 172.44 \pm 0.39 \text{ (stat)} \pm 0.17 \text{ (syst)} \text{ MeV}/c^2.$$

Other interesting LHCb results on  $b$ -baryons include the analysis of the 2011 dataset to measure the mass of the  $\Lambda_b^0$ ,  $\Xi_b^-$ , and  $\Omega_b^-$  baryons [4]. The mass measurements are obtained with maximum likelihood fits on the invariant mass distributions of  $6870 \pm 110 \Lambda_b^0 \rightarrow J/\psi \Lambda^0$ ,  $111 \pm 12 \Xi_b^- \rightarrow J/\psi \Xi^-$ , and  $\Omega_b^- \rightarrow J/\psi \Omega^-$  candidates. The statistical significance of the decay  $\Omega_b^- \rightarrow J/\psi \Omega^-$  is 6 standard deviations. The measured values are

$$\begin{aligned} M(\Lambda_b^0) &= 5619.53 \pm 0.13 \text{ (stat)} \pm 0.45 \text{ (syst)} \text{ MeV}/c^2, \\ M(\Xi_b^-) &= 5795.8 \pm 0.9 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ MeV}/c^2, \\ M(\Omega_b^-) &= 6046.0 \pm 2.2 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ MeV}/c^2. \end{aligned}$$

As for the measurements discussed above, the systematic uncertainty is dominated by the limited knowledge of the momentum scale.

## 2. Measurements of baryon lifetimes

Combining the optical theorem, the operator product expansion, and some results of the Heavy Quark Effective Theory (HQET) leads to a theoretical prediction for the decay width, and hence lifetime, for each heavy hadron, dominated by the “free-quark lifetime” with QCD corrections suppressed by the squared mass of the heavy quark [5]. Testing the theoretical estimates of these corrections is important to validate this approach, named *Heavy Quark Expansion* (HQE).

Historically, HQE could hardly accommodate the LEP experimental results of the  $\Lambda_b^0$  lifetime. Indeed, while the ratio  $\tau(\Lambda_b^0)/\tau(\bar{B}^0)$  was predicted to be larger than  $\sim 0.9$  [6], the world average in 2003 was  $0.798 \pm 0.052$  [7]. Since then, many updates to the experimental average and to the theoretical prediction were made, the latter including modern matrix element calculations with lattice QCD, but inconsistency remained important until the first measurements by LHCb.

The first LHCb analysis, measuring the  $\Lambda_b^0$  lifetime using the decay  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  decay channel was limited by the systematic uncertainty on the time dependence of the efficiency function, due to the trigger requirements on the impact parameter of the daughter tracks [8]. Relative lifetime measurements are much less affected by this uncertainty. If  $B_1$  and  $B_2$  are two generic  $b$  hadrons decaying to the similar final states  $f_1$  and  $f_2$ ;  $\tau_1$  and  $\tau_2$  their lifetimes, and  $\epsilon_1(t)$  and  $\epsilon_2(t)$  the reconstruction efficiency of the two final states dependent on the decay time  $t$ , one can write the number of reconstructed events for  $f_1$  and  $f_2$  as  $N_1(t) = \epsilon_1(t) \exp(-t/\tau_1)$  and  $N_2(t) = \epsilon_2(t) \exp(-t/\tau_2)$ , where the experimental resolution on the decay time is neglected. If the final states are similar, the ratio  $\epsilon_1(t)/\epsilon_2(t)$  is nearly unity, and small corrections can be safely obtained from simulation. A fit to

$$R(t) = \frac{N_1(t)}{N_2(t)} = \frac{\epsilon_1(t)}{\epsilon_2(t)} \exp \left[ \left( \frac{1}{\tau_2} - \frac{1}{\tau_1} \right) t \right]$$

is used to extract  $\tau_1$  known  $\tau_2$  (or vice-versa).

Applying this technique to  $\Lambda_b^0 \rightarrow J/\psi p K^-$  decays in the 2011 dataset [9] before, and then updating the result including the data collected in 2012 [10], LHCb measured the  $\tau(\Lambda_b^0)$  relative to the lifetime  $\tau(\bar{B}^0)$  of the  $\bar{B}^0$  meson as reconstructed in the  $J/\psi \pi^+ K^-$  final state. The results,

$$\frac{\tau(\Lambda_b^0)}{\tau(\bar{B}^0)} = 0.974 \pm 0.006 \text{ (stat)} \pm 0.004 \text{ (syst)}, \quad \text{and} \quad \tau(\Lambda_b^0) = 1.479 \pm 0.009 \text{ (stat)} \pm 0.010 \text{ (syst)} \text{ ps},$$

are well consistent with a modern HQE prediction  $\tau(\Lambda_b^0)^{\text{HQE}} = 1.41 \pm 0.08$  ps [5].

The same method has been applied to the 2011 and 2012 datasets to measure the  $\Xi_b^-$  lifetime using the decay  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  as normalization [4]. The result,  $\tau(\Xi_b^-) = 1.55_{-0.09}^{+0.10}$  (stat)  $\pm$  0.03 (syst) ps, is consistent with the HQE prediction  $\tau(\Xi_b^-)^{\text{HQE}} = 1.56 \pm 0.10$  ps [5].

In some cases, there are no suitable normalization channels to perform a relative lifetime measurement and the determination of the efficiency function as a function of the decay time requires other strategies. The optimization of the simulation reliability has allowed to obtain lifetime precision measurements for the  $\Xi_b^0$  and  $\Omega_b^-$  with a systematic uncertainty smaller than the statistical error. The decays  $\Xi_b^- \rightarrow J/\psi \Xi^-$  and  $\Omega_b^- \rightarrow J/\psi \Omega^-$  have been studied in the 2011 and 2012 datasets.  $313 \pm 20$   $\Xi_b^-$  candidates, and  $58 \pm 8$   $\Omega_b^-$  candidates were used to determine the lifetime of the two heavy baryons:

$$\begin{aligned}\tau(\Xi_b^-) &= 1.55_{-0.09}^{+0.10} \text{ (stat)} \pm 0.03 \text{ (syst) ps,} \\ \tau(\Omega_b^-) &= 1.54_{-0.21}^{+0.26} \text{ (stat)} \pm 0.05 \text{ (syst) ps.}\end{aligned}$$

The HQE prediction for the  $\Xi_b^-$  lifetime [5],  $\tau(\Xi_b^-)^{\text{HQE}} = 1.56 \pm 0.10$  ps is found in good agreement with the experimental result.

### 3. Measurements of the lifetimes of the $B_s^0$ - $\bar{B}_s^0$ system

Experimental techniques similar to those applied to measure the baryon lifetimes can be used to determine the lifetime of  $B_s^0$  states. However, the eigenstates of the hamiltonian and time-evolution operators are not the flavour eigenstates  $B_s^0$  ( $\bar{b}s$ ) and  $\bar{B}_s^0$  ( $b\bar{s}$ ), but rather their combinations  $|B_{s,L}^0\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$ , and  $|B_{s,H}^0\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$ . The  $B_{s,L}^0$  and  $B_{s,H}^0$  eigenstates have decay width  $\Gamma_L$  and  $\Gamma_H$ , respectively. Their average and difference are indicated as  $\Gamma_s = (\Gamma_L + \Gamma_H)/2$  and  $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ . Defining  $A_f$  and  $\bar{A}_f$  as the decay amplitudes to the generic final state  $f$ :  $B_s^0 \rightarrow f$  and  $\bar{B}_s^0 \rightarrow f$ , respectively; and  $\lambda_f = \frac{q\bar{A}_f}{pA_f}$ , one neglects production asymmetries to writes the decay width of a  $B_s^0$  mixture to  $f$  as

$$\Gamma[f, t] = \Gamma(B_s^0(t) \rightarrow f) + \Gamma(\bar{B}_s^0(t) \rightarrow f) \propto e^{-\Gamma_L t} |\langle f|B_{s,L}^0\rangle|^2 + e^{-\Gamma_H t} |\langle f|B_{s,H}^0\rangle|^2, \quad (1)$$

and approximated at the second order in  $\Delta\Gamma_s t$  as [11]

$$\Gamma[f, t] = e^{-\Gamma_s t} \left[ 1 + \frac{1}{2} \left( \frac{\Delta\Gamma_s}{2} t \right)^2 + \frac{-2\text{Re}(\lambda_f)}{1 + |\lambda_f|^2} \left( \frac{\Delta\Gamma_s}{2} t \right) \right]. \quad (2)$$

Neglecting CP violation, measured to be small [12], when  $f$  is an even (odd) CP-eigenstate,  $\langle f|B_{s,H}^0\rangle$  ( $\langle f|B_{s,L}^0\rangle$ ) is null for CP conservation, and time dependence in Equation 1 simplifies into a single exponential whose slope depends on  $\Gamma_L$  ( $\Gamma_H$ ). For “flavour specific”  $B_s^0$  decays, where  $\bar{B}_s^0 \rightarrow \bar{f}$  and  $B_s^0 \rightarrow f$ , the decay is the sum of two exponentials that when fitted with a single exponential allows to evaluate an *effective lifetime* approximated by [13]

$$\tau_{\text{fs}} = \frac{1}{\Gamma_s} \frac{1 + \left( \frac{\Delta\Gamma_s}{2\Gamma_s} \right)^2}{1 - \left( \frac{\Delta\Gamma_s}{2\Gamma_s} \right)^2}.$$

Experimentally, LHCb reported recently an analysis of the 2011 dataset to measure the (effective) lifetimes of the  $B_d^0$  and  $B_s^0$  mesons in charmless 2-body decays [14]. The time-dependent acceptance function was obtained with a data-driven technique named “swimming” already in use at LEP and at TeVatron experiments [15, 16]. It consists of an event-by-event determination of the *turning points* of the efficiency at which the single candidate efficiency

changes from *not-selected* to *selected* by gradually increasing the distance between the production and decay vertices. The  $B_s^0$  decay channels studied are  $B_s^0 \rightarrow K^+K^-$ , yielding the measurement of  $\tau_L$  possibly polluted by penguin-diagram contributions  $\tau_{B_s^0 \rightarrow K^+K^-} = 1.407 \pm 0.016$  (stat)  $\pm$  0.007 (syst) ps, and  $B_s^0 \rightarrow \pi^+K^-$ , yielding the measurement of the flavour specific  $B_s^0$  lifetime  $\tau_{B_s^0 \rightarrow \pi^+K^-} = 1.60 \pm 0.06$  (stat)  $\pm$  0.01 (syst) ps. The lifetime of the  $B_d^0$  meson is also measured using the decay channel  $B_d^0 \rightarrow K^+\pi^-$  to be  $\tau_{B_d^0 \rightarrow K^+\pi^-} = 1.524 \pm 0.011$  (stat)  $\pm$  0.004 (syst) ps.

Some sensitivity to physics beyond the Standard Model is offered by the comparison of the results for  $\tau_{B_s^0 \rightarrow K^+K^-}$  with a previous measurement by LHCb determining the lifetime of the  $B_{s,L}^0$  eigenstate through a decay channel less polluted by penguin contributions:  $B_s^0 \rightarrow D_s^-D_s^+$  [17]. The analysis, performed on the combined 2011 and 2012 datasets, used  $B^- \rightarrow D^-D_s^+$  as normalization channel and obtained the result  $\tau_{B_s^0 \rightarrow D_s^-D_s^+} = 1.379 \pm 0.026$  (stat)  $\pm$  0.017 (syst) fs, in good agreement with  $\tau_{B_s^0 \rightarrow K^+K^-}$ .

In the same paper, LHCb reported the measurement of the flavour specific lifetime  $\tau_{\bar{B}_s^0 \rightarrow D^-D_s^+}$  relative to  $\tau_{B_d^0}$  as measured in the decay channel  $B_d^0 \rightarrow D^-D_s^+$ . The result,  $\tau_{\bar{B}_s^0 \rightarrow D^-D_s^+} = 1.52 \pm 0.15$  (stat)  $\pm$  0.01 (syst) ps, is consistent with a more recent and more precise determination of the flavour specific  $B_s^0$  lifetime obtained analysing the decays  $B_s^0 \rightarrow D_s^- \pi^+$ , followed by  $D_s^- \rightarrow K^+K^- \pi^+$  in the combined 2011 and 2012 LHCb datasets [18]. The  $B_s^0$  lifetime was measured relative to three normalization channels:  $B^- \rightarrow D^0 \pi^-$  with  $D^0 \rightarrow K^- \pi^+$ ,  $B^- \rightarrow D^0 \pi^-$  with  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ , and  $B^0 \rightarrow D^+ \pi^-$  with  $D^+ \rightarrow K^- \pi^+ \pi^+$ . The results obtained with the three normalization channels are perfectly consistent, but have fully correlated uncertainties and therefore they cannot be combined. The best result was obtained using the  $B^0 \rightarrow D^+ \pi^-$  channel as normalization:  $\tau_{\bar{B}_s^0 \rightarrow D_s^+ \pi^-} = 1.535 \pm 0.015$  (stat)  $\pm$  0.012 (syst)  $\pm$  0.007 ( $\tau_{B^-}$ ) ps, with the third uncertainty being on the world average of the lifetime measurements of the  $B^-$  meson.

#### 4. Conclusion

The excellent performance of the LHC and of the LHCb detector has allowed many world leading results on  $b$ - and  $c$ -hadron masses and lifetimes. Consistency with theoretical predictions is good for both these important quantities, and notably for lifetimes where the recent results restore confidence in the HQE formalism.

The future run of LHC will allow to further challenge new physics with lifetime measurements of both mesons and baryons, and to include new heavier probes as  $\Xi_b$ ,  $\Omega_b^-$ , and  $B_c^+$  states.

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