Measurement of b-flavoured hadron lifetimes at LHCb

CERN Summer Student Project Report

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1 Project description and motivation

The aim of this Summer Student internship is to provide precise lifetime measurements of b-flavored hadrons. Decays of neutral b-mesons provide an ideal laboratory to study CP violation and the time-dependent quantities of these asymmetries require a good knowledge of the lifetime of b-flavored mesons.

The current work focuses on two b-mesons, B_s^0 and B^+, and their corresponding antiparticles. The quark content of those hadrons is as follows

$$B_s^0 = s\bar{b} \qquad \bar{B}_s^0 = \bar{s}b$$
$$B^+ = u\bar{b} \qquad B^- = \bar{u}b$$

During the course of this work, two effects which influence the lifetime estimate are accounted for, namely the decay-time resolution and the decay-time acceptance. Decay-time acceptance is the collective name of all decay-time dependent efficiencies that can be introduced at any stage of the reconstruction, selection and trigger. It is therefore important to check that the origins of all possible time-biasing effects are well understood and their influence on the lifetime is under control. Moreover, a correction for these effects is essential to demonstrate a good understanding of the LHCb detector and plays an important role in other lifetime-dependent measurements such as the CP violating phase ϕ_s in the decay of $B_s^0 \to J/\psi\phi$.

2 Data, decay modes and selection process

The analysis in this work is based on Monte Carlo data simulating Run2 2015 conditions.[1] Two decay modes are processed

$$B_s^0 \to J/\psi[\mu^+\mu^-]\phi[K^+K^-]$$
$$B^+ \to J/\psi[\mu^+\mu^-]K^+$$

Out of all generated events, those that pass the reconstruction, selection and trigger criteria are used for further analysis. The reconstruction requirement is that tracks are reconstructed as Long Tracks such that they traverse the full tracking system and have the most precise momentum resolution. The selection requirements are shown on Table 1. They ensure that decay products pass PID, mass and traverse momentum criteria, have good quality tracks and form a good origin vertex. In addition, the b-mesons are asked to originate from the PV, to have a good quality decay vertex and also to pass mass and decay-time restrictions. The trigger criteria concerning the HLT1 and HLT2 stage aims to select good dimuon candidates.

3 Lifetime measurements

The decay-time, t, of a particle in its rest frame is given by

$$t = \tfrac{L}{\beta\gamma} = L\tfrac{m}{|\vec{p}|} \tag{1}$$

where L is the flight distance traveled by the b-hadron, $\beta = v/c$ is the ratio of the particle velocity v to the speed of light c, γ is the Lorentz factor, p is the reconstructed three-momentum and m_B is the b-hadron reconstructed invariant mass in the laboratory frame. Ignoring the effect of mixing for the B_s^0 candidate, the decay-time follows an exponential distribution and thus, the lifetime can be extracted by an exponential fit to the decay-time data. A simple view of production and decay of a b-hadron is presented in Figure 1.

However, from an experimental point of view, all the quantities that determine the decay-time in Equation 1 need to be measured and therefore suffer from experimental artifacts. In this sense, the main contributions come from decay-time resolution and decay-time acceptance, see Figure 2. Taking them into account, the lifetime τ of a b-hadron can be measured modeling the decay-time distribution in the following way

$$measured\ distribution = \left[e^{-t/\tau} \otimes Res(t,t')\right] \cdot Acc(t'). \tag{2}$$

In the following sections each of these three elements is studied.

3.1 Fit of b-hadron decay-time

The decay-time distribution of a b-hadron candidate is polluted by background events, which should be subtracted from signal events. In order to do it, a 2D unbinned maximum

[1]The MC simulated proton-proton collisions at a center-of-mass energy at $\sqrt{s} = 13\,TeV$ registered by the LHCb detector.

Table 1: Selection criteria used to identify $J/\psi \to \mu^+\mu^-$, $B_s^0 \to J/\psi\phi$ and $B^+ \to J/\psi K^+$ candidates. The selection of J/ψ candidates is common for both decay modes.

Particle	Variable	Quantity
$\mu^\pm$	χ^2_{track}/nDoF	< 4
	$\Delta\ln\mathcal{L}_{\mu\pi}$	> 0
	p_T	> 550 MeV/c
$J/\psi \to \mu^+\mu^-$	χ^2_{vtx}/nDOF	< 16
	$m(\mu^+\mu^-)$	$\in [3030, 3150]$ MeV/c^2

Particle	Variable	Quantity
all tracks	χ^2_{track}/nDOF	< 4
$\phi \to K^+K^-$	$\Delta\ln\mathcal{L}_{K\pi}$ $(K^\pm))$	> 0
	$p_T(\phi)$	> 1.0 GeV/c
	$m(K^+K^-)$	$\in [1008, 1032]$ MeV/c^2
$B_s^0 \to J/\psi\phi$	$m(J\psi K^+K^-)$	$\in [5200, 5500]$ MeV/c^2
	χ^2_{IP}	< 25
	χ^2_{DTF}/nDoF	< 5
	t	$\in [0.3, 14.0]$ ps

Particle	Variable	Quantity
all tracks	χ^2_{track}/nDOF	< 4
K^+	$\Delta\ln\mathcal{L}_{K\pi}$	> 0
	p_T	> 1.0 GeV/c
	p	> 10 GeV/c
$B^+ \to J/\psi K^+$	$m(J\psi K^+)$	$\in [5170, 5400]$ MeV/c^2
	χ^2_{IP}	< 25
	χ^2_{DTF}/nDoF	< 5
	t	$\in [0.3, 14.0]$ ps

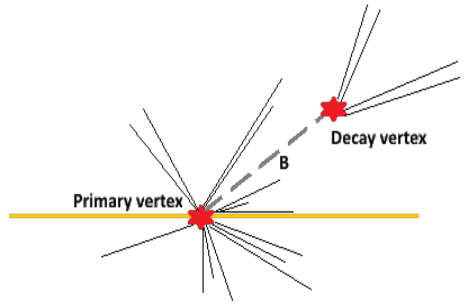


Figure 1: Schematic picture of a b-meson production in the pp interaction point, the PV, and decay in DV.

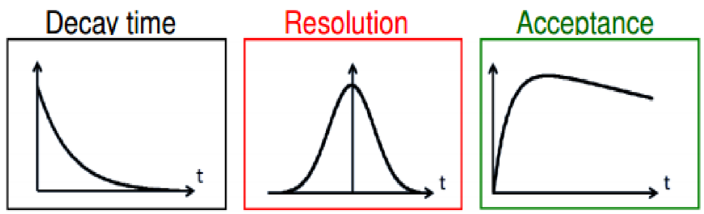


Figure 2: Sketches of a typical decay-time distribution, decay-time resolution, and decay-time dependent acceptance of a b-hadron candidate.

likelihood fit of the mass and the decay-time distribution of the b-hadron is performed. The model used to fit the decay-time distribution in order to extract the lifetime, τ_{sig}, is

$$P(t) = N_{sig} * P_{sig}(t) + N_{bkg} * P_{bkg}(t) = N_{sig} * e^{-t/\tau_{sig}} + N_{bkg} * \sum_{i=1}^{3} e^{-t/\tau_{bkg}}, \tag{3}$$

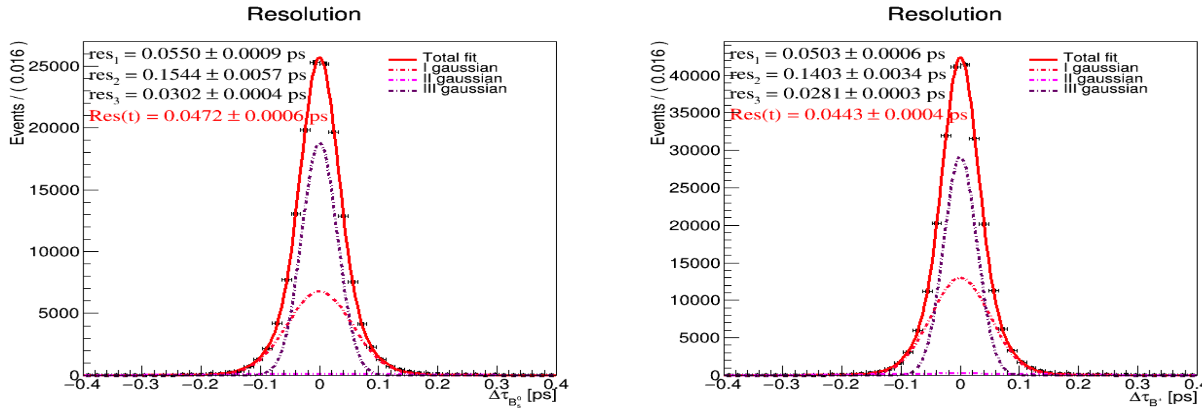
where the background is fitted with three exponents.

The invariant mass distribution is modeled with a double Gaussian for the signal candidates and an exponential distribution for the background. As a crosscheck, the ${}_sPlot$ technique [1] has been also used.

3.2 Decay-time resolution

In the lifetime formula, Equation 1, the flight distance L depends on the primary vertex, PV, and decay vertex, DV, resolution. Moreover, the resolution of the mass m and the momentum p depend on the momentum resolution of the final state particles. As a result, the decay-time resolution, $Res(t)$, varies for different decay modes.

For the decay modes of interest, see Section 2, the decay-time resolution is estimated and results are shown on Figure 3. In both cases the resolution, around 45 fs, is small enough that it would not have a significant impact on the lifetime measurements. Since it is known that Monte Carlo estimates vary from data at the 10% level [2], the resolution can be taken from simulation and implemented in data analysis without loss of precision. Systematic uncertainties will be applied to the final result to test this assumption.



(a) $B_s^0 \to J/\psi[\mu^+\mu^-]\phi[K^+K^-]$ (b) $B^+ \to J/\psi[\mu^+\mu^-]K^+$

Figure 3: Decay-time resolution in the case of $B_s^0 \to J/\psi\phi$ in (a) and $B^+ \to J/\psi K^+$ in (b). Simulation data is fitted with three Gaussian distributions. Fit results are presented.

3.3 Decay-time acceptance

3.3.1 Origin of decay-time acceptance

In this work absolute measurements of b-meson lifetimes are made and the expected statistical uncertainty on the result is of the order of few femtoseconds. During RunI it was shown that ignoring acceptance effects in MC studies leads to the underestimation of B_s^0 lifetime of about 20 fs [3]. Therefore, decay-time acceptance must be controlled and accounted for.

In order to study the time-biasing effect of different selection, reconstruction and trigger criteria, the lifetime of b-hadrons is estimated after each requirement is applied. This is clearly only possible in Monte Carlo. The requirements used on simulation data are outlined in Section 2. The plots showing the B_s^0 and B^+ lifetime at each step of the selection of candidates are shown on Figure 4.

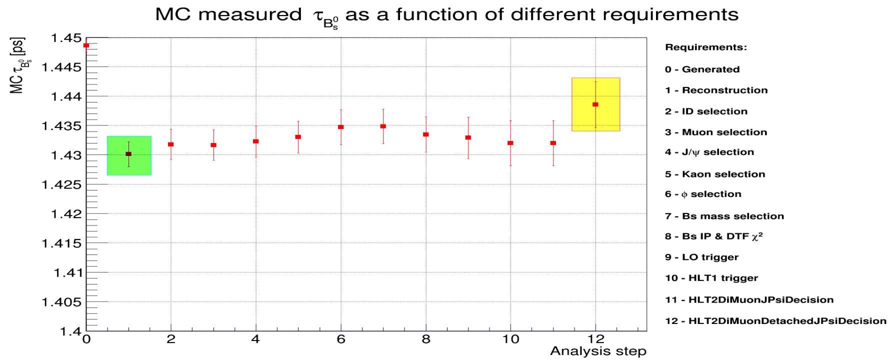
In both cases the total bias on the final lifetime estimate is around 10 fs. The main sources of lifetime bias are the reconstruction of the final-state tracks at step 1 and the trigger requirement on the displacement of the J/ψ candidate from the primary vertex at step 12 for B_s^0 and step 11 for B^+. In the following subsections these two effects are discussed and procedures to correct for them are explained.

3.3.2 Anatomy of decay-time acceptance

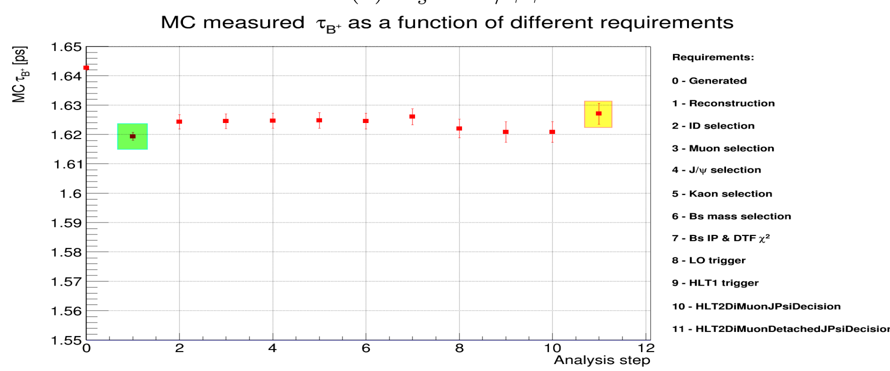
An overview of the decay-time acceptance is shown in Figure 5. These curves are produced dividing the decay-time distribution after all reconstruction, selection and trigger criteria are applied by the generated one. Two regions of interest can be identified in this plot. The first one is at short decay-times and is conveniently called Lower acceptance. The second has impact on long-living candidates and is called Upper acceptance.

3.3.3 Upper acceptance

A closer look at Upper acceptance is given on Figure 6. It is obtained dividing the decay-time distribution of b-hadron candidates that pass all reconstruction, selection and trigger criteria

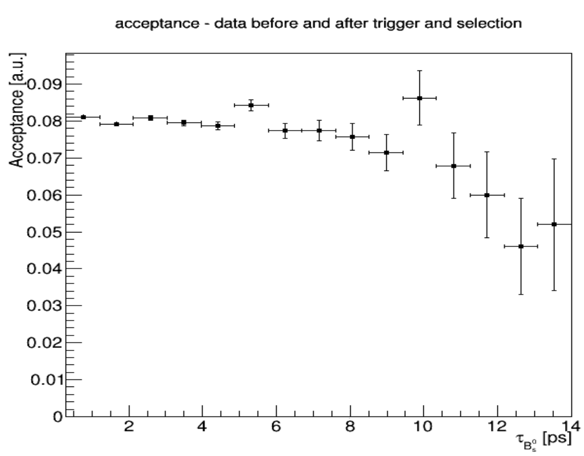


(a) $B_s^0 \to J/\psi\phi$

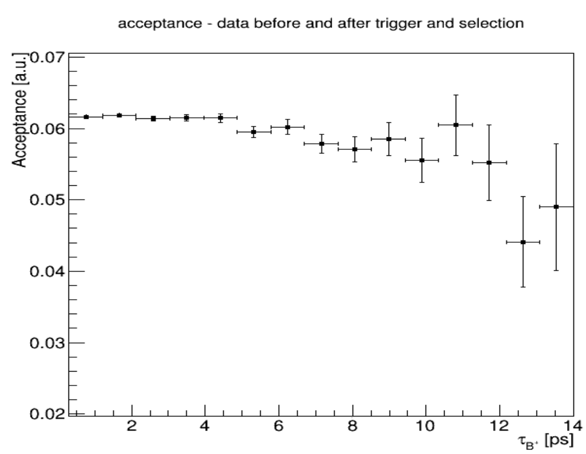


(b) $B^+ \to J/\psi K^+$

Figure 4: Measured lifetime in MC of $B_s^0 \to J/\psi\phi$ (a) and $B^+ \to J/\psi K^+$ (b) decay channels as a function of the different reconstruction, selection and trigger criteria used in the analysis.

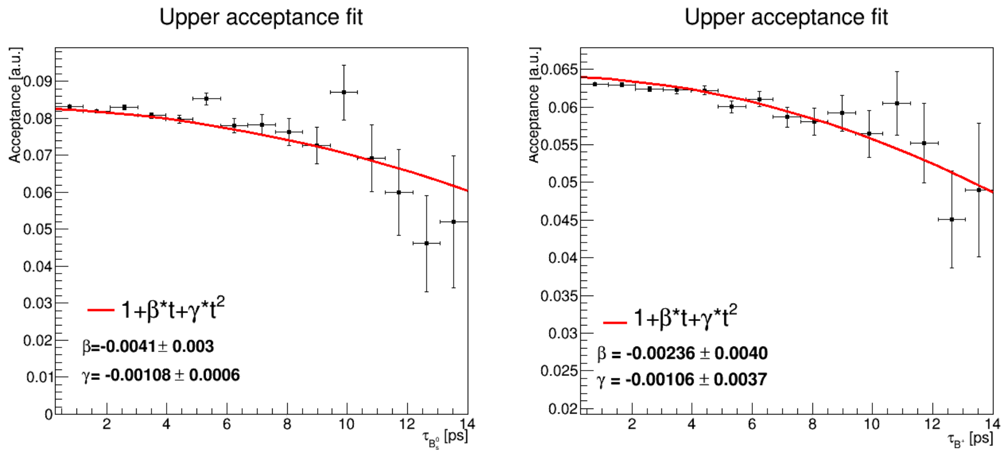


(a) $B_s^0 \to J/\psi\phi$



(b) $B^+ \to J/\psi K^+$

Figure 5: Decay-time acceptance of all the reconstruction, selection and trigger requirements in $B_s^0 \to J/\psi\phi$ (a) and $B^+ \to J/\psi K^+$ (b) MC samples.



(a) $B_s^0 \to J/\psi\phi$ (b) $B^+ \to J/\psi K^+$

Figure 6: Decay-time acceptance of all the reconstruction, selection and trigger requirements but the displacement of the J/ψ candidate from the PV in $B_s^0 \to J/\psi\phi$ (a) and $B^+ \to J/\psi K^+$ (b) MC samples. Superimposed in red there are the results of a fit with a parabolic function, see Equation 4.

but the displacement of the J/ψ candidate by the generated one. The Upper acceptance is mainly introduced by the track reconstruction in the vertex locator VELO. This acceptance shows a parabolic behavior and is fitted with the quadratic function

$$PDF(t) \propto (1 + \beta t + \gamma t^2), \tag{4}$$

where t is the decay-time and β and γ parameterise the observed decay-time acceptance. The values of these parameters, shown in Figure 6, are similar to those obtained using RunI data [2].

3.3.4 Lower acceptance

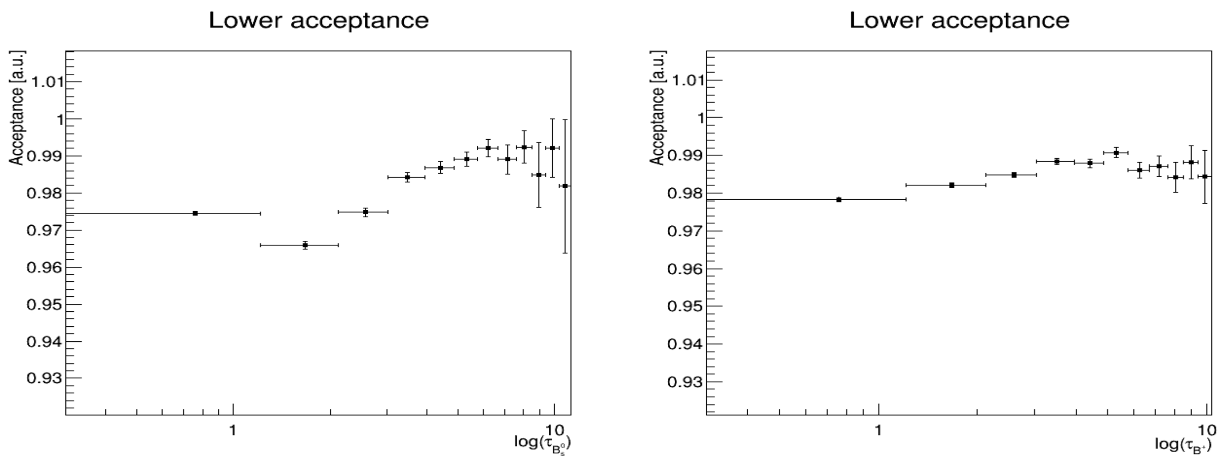
The Lower acceptance is shown in Figure 7. It is introduced by the requirement of displacement of the J/ψ candidate from the PV used in the HLT2 selection. The plot is produced dividing the decay-time distributions before and after the displacement criterion is applied. It shows a drop for small values of the decay-time as the detached requirement removes short-lived b-mesons.

In order to correct for the Lower acceptance effect several approaches were studied. Firstly, an attempt was made to model the Lower acceptance distribution as a function of type

$$PDF(t) \propto (1 - e^{-(t+s)/\alpha}), \tag{5}$$

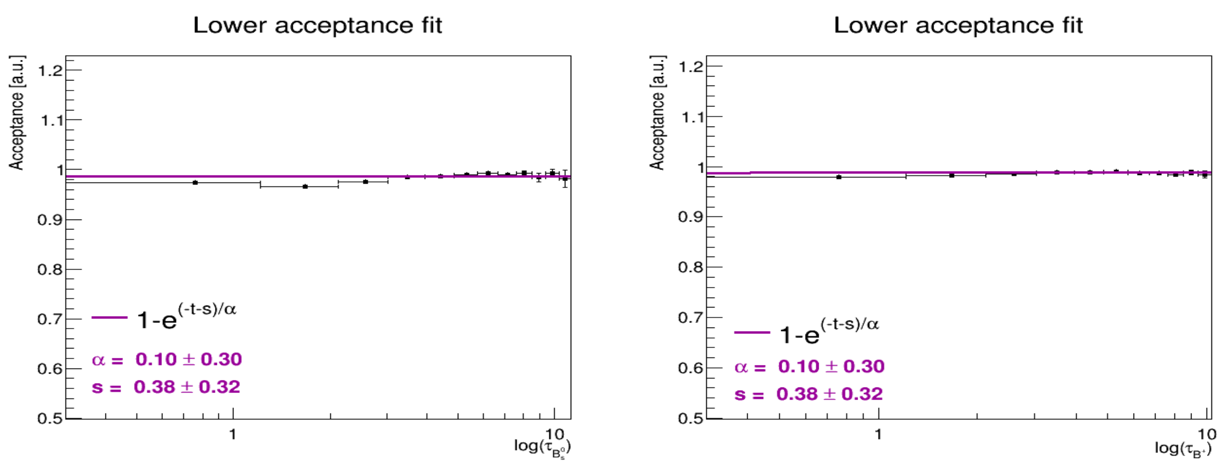
where t is the decay-time and s and α are parameters. This function does not fit well the MC data as shown in Figure 8 where parameters' values are also available.

Then, the Lower acceptance distribution is used as weight and applied to decay-time data to correct for the displacement requirement. For every candidate the inverse of the corresponding bin content in the Lower acceptance histogram is taken as the weight. The resulting weighted data set is fitted using a simple exponential fit as background is already removed.



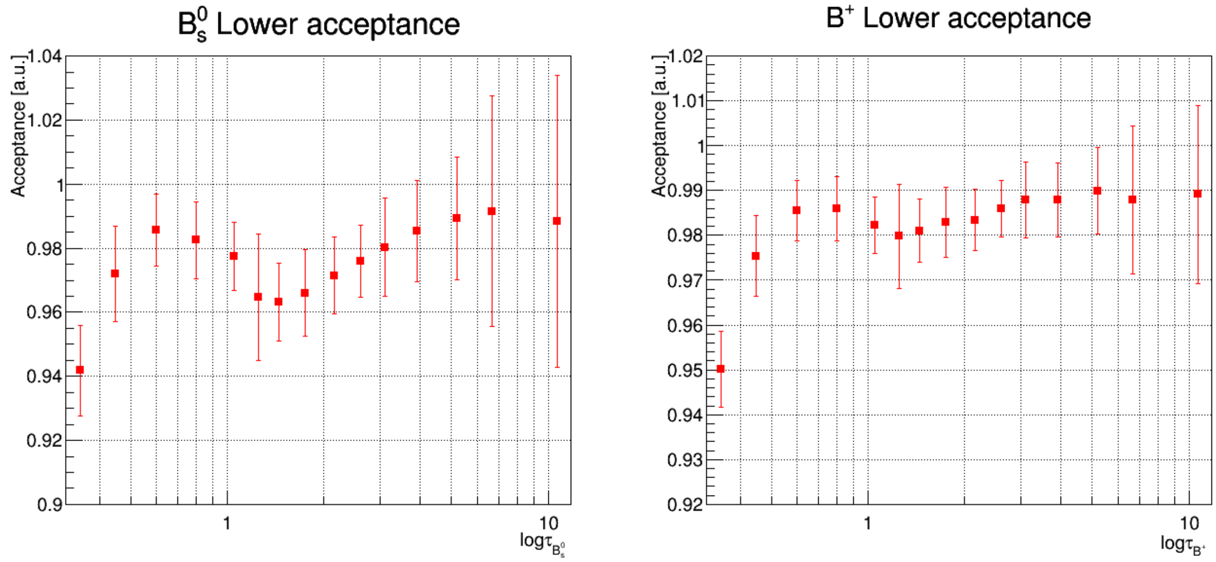
(a) $B_s^0 \to J/\psi\phi$ (b) $B^+ \to J/\psi K^+$

Figure 7: Decay-time acceptance introduced by the requirement on the displacement of the J/ψ candidate from the PV used in the $HLT2DiMuonDetachedJPsiDecision\_TOS$ trigger line in the case of $B_s^0 \to J/\psi\phi$ (a) and $B^+ \to J/\psi K^+$ (b) MC candidates. Note the logarithmic scale on the x axis.



(a) $B_s^0 \to J/\psi\phi$ (b) $B^+ \to J/\psi K^+$

Figure 8: Decay-time acceptance introduced by the requirement on the displacement of the J/ψ candidate from the PV used in the $HLT2DiMuonDetachedJPsiDecision\_TOS$ trigger line. Superimposed in violet there are the results of a fit with the function defined in Equation 5 for $B_s^0 \to J/\psi\phi$ (a) and $B^+ \to J/\psi K^+$ (b) MC samples, respectively. Note the logarithmic scale on the x axis.



(a) $B_s^0 \to J/\psi\phi$ (b) $B^+ \to J/\psi K^+$

Figure 9: Decay-time acceptance introduced by the requirement on the displacement of the J/ψ candidate from the PV used in the *HLT2DiMuonDetachedJPsiDecision_TOS* trigger line. The acceptance is estimated using Equation 6 for $B_s^0 \to J/\psi\phi$ (a) and $B^+ \to J/\psi K^+$ (b) MC samples. Note the logarithmic scale on the x axis.

In the end, a more realistic approach is taken [3]. It is applicable not only in simulation, but in data as well. In this case the mass distribution of b-hadrons is used to determine the number of signal events before, N_B, and after, N_A, the J/ψ displacement criterion is applied. Then, the acceptance, ε, is estimated as

$$\varepsilon = \frac{N_A}{N_B}. \tag{6}$$

The resultant Lower acceptance plots for B_s^0 and B^+ are presented on Figure 9. They have the same characteristic drop at short decay-times.

4 Conclusions

In order to summarize the results of all correction techniques, Figure 10 is presented. As expected, the lifetime bias introduced at step 12 for B_s^0 and step 11 for B^+ is more or less removed for every correction technique. As a result, one can conclude that the same methods can be implemented on data.

Acknowledgments

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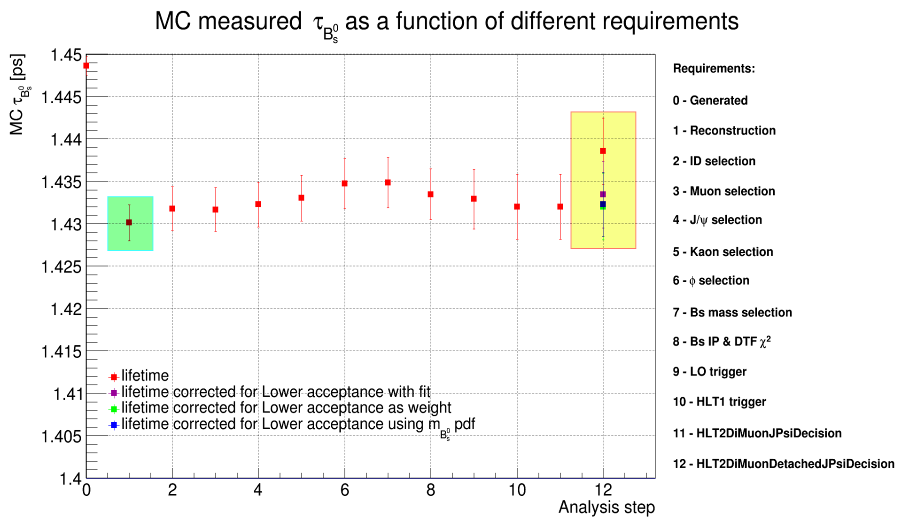
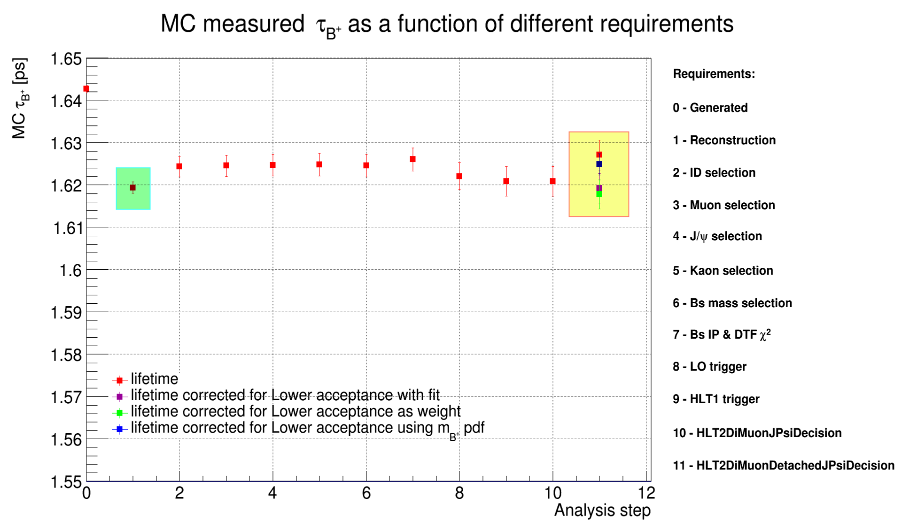


(a) $B_s^0 \to J/\psi\phi$



(b) $B^+ \to J/\psi K^+$

Figure 10: Decay-time acceptance of all the reconstruction, selection and trigger requirements in $B_s^0 \to J/\psi\phi$ (a) and $B^+ \to J/\psi K^+$ (b) MC samples. The lifetime measurement corrected for Lower acceptance is stressed in the yellow box. The corrections made using the function in Equation 5, the Lower acceptance as weight and the mass distribution of b-hadrons are presented in violet, green and blue respectively.

References

[1] M. Pivk and F.R. Le Diberder, *$_s$Plot a statistical tool to unfold data distributions*, arXiv:physics/0402083

[2] F. Dordei et al., *Lifetime measurements of beauty hadrons at the LHCb experiment*, CERN-THESIS-2014-361

[3] Y. Amhis; G. Cowan; F. Dordei; S. Hansmann-Menzemer; R. Märki and T. Nikodem, *b-hadrons absolute lifetime measurements*, LHCb-ANA-2011-055 ; CERN-LHCb-ANA-2011-055