Monte Carlo Independent Lifetime Fitting at LHCb in Lifetime Biased Channels

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Abstract

Lifetime measurements at LHCb will help in detector calibration as well as providing constraints on lifetime differences in the B_s system and other theoretical models. In order to exploit the full range of decays available in LHCb, it is important to have a method for fitting lifetimes in hadronic channels, which are biased by the impact parameter cuts in the trigger. We have investigated a Monte Carlo simulation independent method to take into account the trigger effects. The method is based on calculating event by event acceptance functions from the decay geometry and does not require any external input. This note presents current results with this method for both the full LHCb Monte Carlo for the channel $B_d^0 \to D^-\pi^+$ and a toy Monte Carlo for the same channel, including a discussion of the expected statistical precision on lifetime measurements using this method once LHCb is operational.

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1 Introduction

This note describes a Monte Carlo independent method for measuring the lifetime acceptance function for lifetime dependent triggers, which will allow the measurement of lifetimes in hadronic decay channels at LHCb. The method presented here, and the "UHTFitter" software used, were originally developed at CDF. The basic idea of the acceptance correction is described in [1]. The details of the method, especially the treatment of background, are described in [2], which is currently an internal CDF note. We will update our references once the CDF analysis has been published.

The remainder of this section will motivate the study. Section 2 describes those parts of the LHCb trigger which are relevant to this study. Sections 3 and 4 describe the method for measuring the acceptance function. Section 5 shows fits to signal data. Section 6 shows fits when background events are added. Section 7 discusses the expected statistical precision on lifetimes. Section 8 concludes and discusses what work remains to be done.

1.1 Motivation for measuring B lifetimes at LHCb

LHCb [3] is a dedicated B physics experiment located at the LHC [4] at CERN. It is estimated that $10^{12} b\bar{b}$ pairs will be produced every year at LHCb. In the B_s and b–baryon sectors in particular, LHCb will considerably enhance the available statistics.

The measurement of B lifetimes will be important both for early detector calibration studies, and as a test of theoretical models such as Heavy Quark Expansion theory [5, 6]. A particularly interesting and important measurement is that of lifetime differences [7] in the B_s system. LHCb is expected to quickly improve on the current world lifetimes average.

High yield hadronic channels can make significant contributions to the knowledge of lifetimes, but suffer from the lifetime acceptance bias introduced by the hadronic trigger. B particles are long lived compared to background, and their decay products will therefore have high impact parameters relative to the primary vertex. The LHCb trigger, described more fully in Section 2, cuts on these and in doing so it introduces an acceptance bias in the lifetime distributions.

A possible method for taking these acceptance effects into account is to measure an acceptance function in Monte Carlo events. This is susceptible to systematic effects arising from possible differences between the simulation and the real data. An alternative way that has been proposed is to apply a lower lifetime cut and assume that beyond that lifetime cut, the acceptance is flat. This assumption is not valid for the LHCb trigger at the time of writing this note because the upper impact parameter cuts introduce a downward slope in the acceptance. However, even if these upper lifetime cuts were removed and the acceptance were in fact flat beyond a certain point, this approach would lose a significant number of events below the cut. Here we propose a Monte Carlo independent method for correcting the trigger bias which does not require a life-time cut-off, or a flat acceptance curve beyond a certain point, and which can cope with both lower and upper impact parameter or lifetime cuts.

1.2 The channel $B_d^0 \to D^-(\pi^-\pi^-K^+)\pi^+$

This channel was selected to test the fitting method because its high yield and purity make it a prime candidate among hadronic channels for the actual measurement of the B_d meson lifetime. It also has the same topology as the channel $B_s^0 \to D_s(\pi^-K^+K^+)\pi$, which is the prime candidate among hadronic B_s channels for a measurement of the B_s lifetime. The channel $B_d^0 \to D^-(\pi^-\pi^-K^+)\pi^+$ will [8] have an annual yield of 1.7M fully triggered events, with a signal to background ratio of ~ 6.

1.3 The data set

The LHCb Monte Carlo, which uses the Pythia event generator and includes a full GEANT detector simulation, is used for the study. The data set consists of 350,000 signal events and 40 million $b\bar{b}$ background events, generated in the forward detector acceptance. The events on the signal tape are selected using MC truth information and applying only loose vertex quality cuts on the secondary vertices. This is done in order to prevent offline lifetime dependent cuts from interfering with the study of the trigger acceptance. The events on the background tapes are selected using loose vertex quality and transverse momentum cuts. For reasons of simplicity, only events with a single primary vertex are considered in this study. In the future, this method can be extended to cover multiple interactions.

All fits were performed using ROOT [9] v4.02/00 and the package MINUIT [10].

2 The LHCb lifetime dependent trigger

The current study was performed using the DC04 versions of DaVinci[a] [11], the LHCb analysis software, and the corresponding trigger architecture. During this phase of Monte Carlo studies, aimed at understanding detector performance, there were changes to specific cut values in the trigger, however the overall architecture of the lifetime dependent trigger remained unchanged. In this section, the lifetime dependent part of the trigger will be described. We will also describe a method of associating the particles used in the offline reconstruction to the online tracks used in the trigger which was developed for this study.

It is important to distinguish between the information seen by the trigger, and the information seen by the offline reconstruction. Because it operates under time constraints, the trigger necessarily performs only a partial reconstruction of the event, and quantities such as the momenta and impact parameters of the final state particle tracks are therefore measured with a poorer resolution than that of the offline selection. The term "online" will refer to quantities or tracks as measured by the LHCb high-level trigger, unless otherwise specified. Similarly, the term "offline" will refer to quantities or tracks as measured by the offline event selection. Throughout this document, the term "final state particle" will refer to the three D^- daughters and the π daughter of the B^0.

2.1 Trigger architecture

The trigger architecture relevant to this study [12] consist of three parts. The L0 is a hardware trigger, which searches for events with a high energy or transverse momentum signature and selects them for further reconstruction. It is not lifetime dependent and hence does not concern us further. The L1 trigger is a software trigger, which performs a partial event reconstruction and searches for high transverse momentum and impact parameter signatures in those events passed by the L0 trigger, and is hence lifetime dependent. Events selected by the L1 are then passed to the HLT. This is a software trigger which performs a fuller reconstruction of the event, and is in principle able to cut on any quantity which can be cut on offline. Therefore, the HLT will also be a lifetime dependent trigger. For the purposes of this study, the L1 trigger acceptance will be measured as a proof of principle; measurement of the HLT acceptance is expected to be a straightforward extension of this problem.

2.2 Sub-detectors

LHCb subdetectors of particular importance to the L1 trigger are the VELO [13] and the TT (trigger tracker) station. The VELO is a silicon vertex detector, which is positioned close to the beamline and provides excellent spatial resolution. It is used for the reconstruction of primary vertices, secondary vertices, and tracks in the trigger. The TT station provides limited momentum information to the L1 trigger and allows the hadron trigger to discriminate between tracks based on their transverse momentum.

2.3 The L1 trigger

The L1 trigger contains a lifetime dependent generic hadron trigger. In order to operate at the required speed, the event reconstruction proceeds in two stages. First of all, tracks with hits in the VELO are reconstructed in two dimensions in the rZ plane, where the Z axis is defined along the LHC beamline. Those 2D tracks which pass an impact parameter cut are subsequently reconstructed in 3D, including the TT station which provides a measurement of the track transverse momentum. In order to pass the trigger, the event must contain two

[a] References to the trigger throughout the rest of this document should be taken to mean the DC04 version of the trigger, unless otherwise stated

3D tracks which pass an impact parameter cut and whose transverse momenta satisfy the equation

$$\ln p_t^{(1)}/\text{MeV} + \ln p_t^{(2)}/\text{MeV} > 13.915, \quad (1)$$

where $p_t^{(1)}$ and $p_t^{(2)}$ refer to the transverse momenta of the first and second 3D track respectively.

3 A Monte Carlo independent method for measuring lifetimes

The Monte Carlo independent method for measuring the trigger lifetime acceptance function has been described in detail in [1] and [2]. We give an outline of the method here, and the reader is referred to the above documents for details.

3.1 Overview

The LHCb trigger uses impact parameter cuts which bias the observable lifetime distributions. An overview of the trigger system is given in Section 2.

A B meson or baryon originates at the primary vertex of the event, and its decay position and kinematics determine the subsequent position of its daughter tracks. Specifically, for any given set of kinematics, there is a one-to-one correspondence between the decay vertex of the B and the impact parameter of the final state particle tracks. It follows that for any given set of event kinematics, it is possible to build up the trigger acceptance function for that event by “swimming” the B along its direction of momentum, and adjusting the positions of the final state tracks accordingly. Figure 1 demonstrates the principle of this swimming.

For any given position of the B decay vertex, the event either passes the trigger or it does not; as a result, the value of the acceptance function is always either 1 (accept) or 0 (reject). What makes the acceptance function and likelihood so simple is that the kinematics which translate the impact parameter cuts into a lifetime cut don't depend on the lifetime of the B. In particular, we need to calculate the probability of finding an event with a given lifetime and kinematics:

$$P(c\tau,\text{kin}) = P(c\tau|\text{acc})P(\text{acc}). \quad (2)$$

The term $P(\text{acc})$ is the probability of finding a given acceptance function, as calculated from the event's kinematics. It is independent of the lifetime, and will therefore factor out of the minimization. The term $P(c\tau|\text{acc})$ represents the probability of finding an event with mean lifetime τ given the acceptance function we just measured, and these probabilities can be multiplied to give a likelihood for a mean lifetime τ. For a set of N events, in the absence of any background or detector effects, the likelihood is given by:

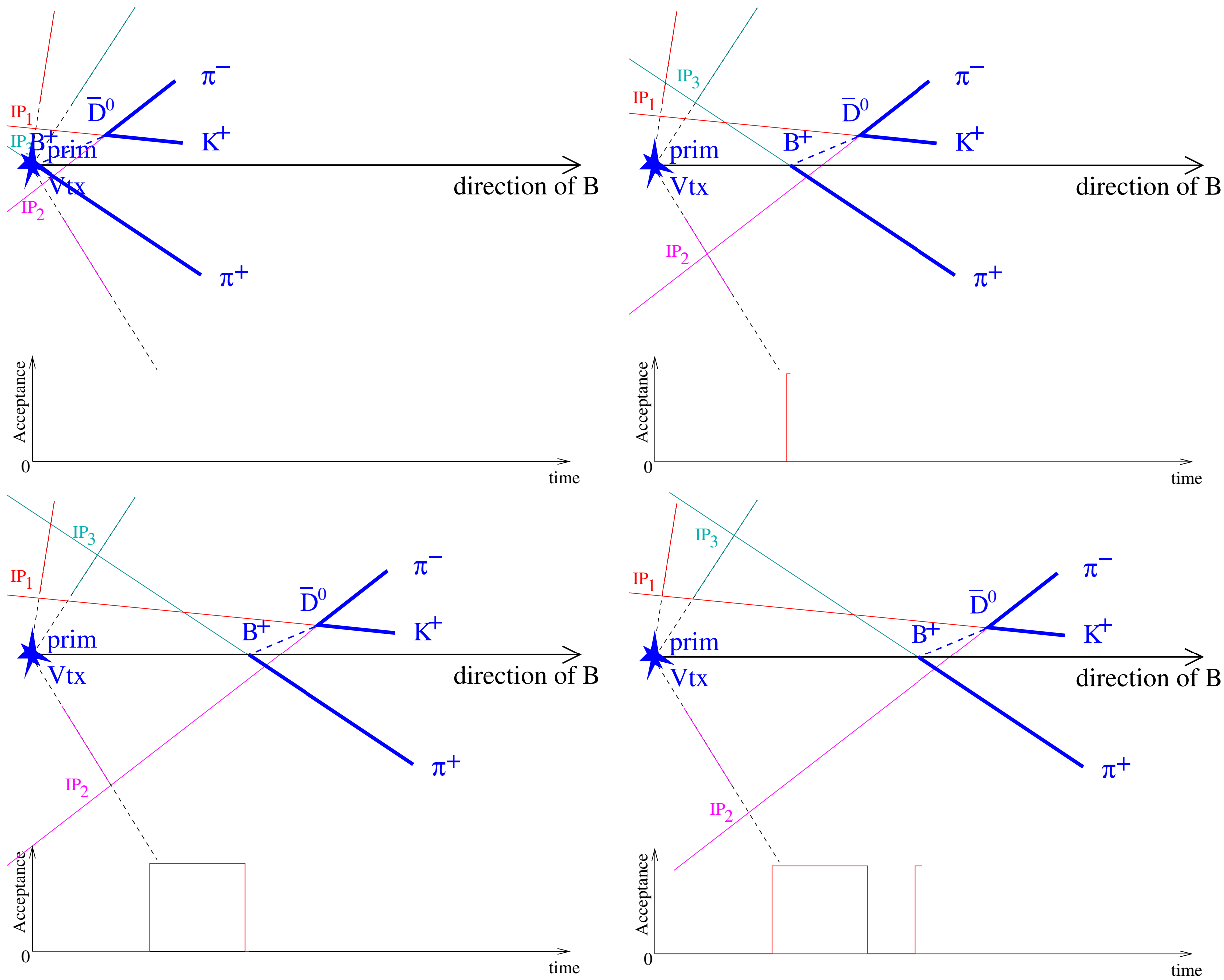
$$\log(L) = -Nlog(\tau) - \sum_{i=1}^{N}\left(\frac{t_i}{\tau} + \log(e^{\frac{-t_{max_i}}{\tau}} - e^{\frac{-t_{min_i}}{\tau}})\right), \quad (3)$$

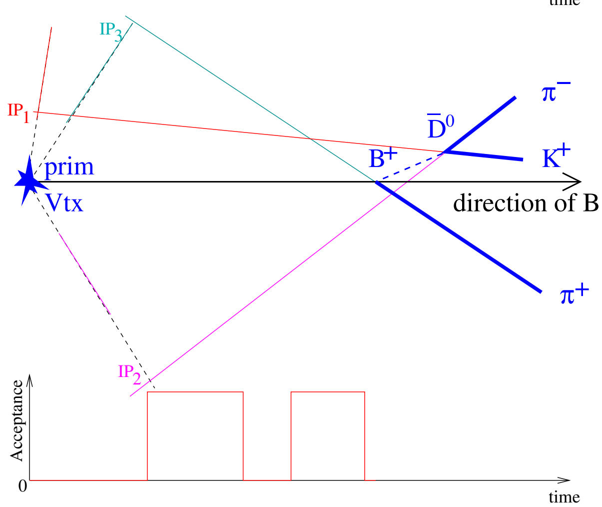
where t_{mini} and t_{maxi} refer to the minimum and maximum lifetime at which the acceptance function equals 1 for event i. For complicated events there may be more than one time interval where the acceptance function equals 1, in which case these intervals are summed together.

3.2 Taking measurement errors into account

In practice, the simple likelihood quoted above will have to be modified to take into account both errors on measured lifetimes and impact parameters. In particular, the fact that the trigger cuts on online quantities, while the swimming is performed using offline data, must be accounted for. Any given track in the event is reconstructed online and offline, as are the primary vertices, and since the two reconstructions are performed with different resolutions

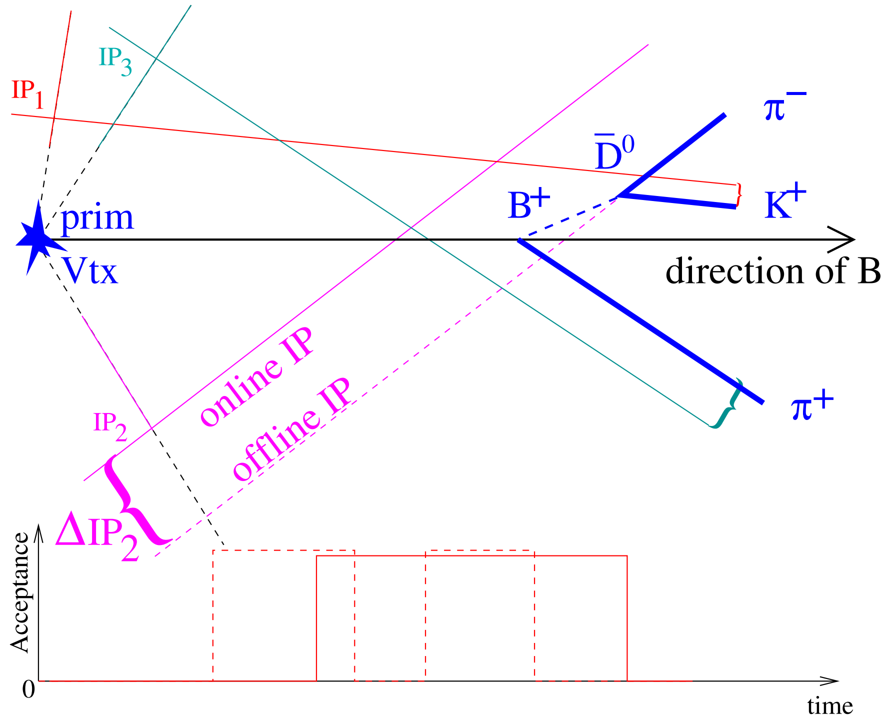
Figure 1 Illustration of the link between impact parameter requirements and cuts on the decay time. Whenever 2 tracks pass the IP requirements, the acceptance is set to one, otherwise zero. (1)





Given the 3-momenta of all particles in the decay, and the decay lengths of particles down the decay chain (here a D^0), the requirements of the hadronic trigger that two particles pass the IP cut translates into an acceptance of one or more intervals.

Figure 2 Re-establishing the direct link between online impact parameter cuts and measured lifetime (measured from offline data). (1)



the online and offline impact parameters will be different for the same track. As a result, although there is a one-to-one correspondence between the lifetime of the B and the offline impact parameters of the final state tracks, there is no longer a one-to-one correspondence between the lifetime of the B and the impact parameters as seen by the trigger.

In order to build up the acceptance function by swimming as before, the offline impact parameters must now be corrected by taking this difference into account. This is possible as long as the difference is not itself lifetime dependent. This assumption can be tested in data.

Figure 2 illustrates the principle. The difference between the online and offline impact parameters is measured at the one point at which it is known, which is the actual decay position of the B. The swimming is then performed using the offline quantities, and the offline impact parameter is converted into an online impact parameter at each point by adjusting for this measured difference.

3.3 Fitting with background

For the purposes of the lifetime fit, the background lifetime distribution is described by a sum of exponentials with different mean lifetimes, which are subject to the same swimming procedure as the signal. A zero lifetime prompt component is also included to take account of any background from the primary vertex.

The addition of background complicates the likelihood function because the term $P(\mathrm{acc})$, representing the probability of finding an event with a given acceptance function calculated from its kinematics, no longer factors out. Defining $P(s)$ as the probability that an event is signal, and $P(b) = 1 - P(s)$ as the probability that an event is background, the probability of finding an event with a lifetime and a given acceptance function can be written as:

$$P(c\tau,\mathrm{acceptance}) = P(\mathrm{s})P(c\tau|\mathrm{acc,s})P(\mathrm{acc|s}) + P(\mathrm{b})P(c\tau|\mathrm{acc,b})P(\mathrm{acc|b}). \quad (4)$$

We can rewrite this equation as:

$$P(c\tau,\text{acceptance}) = P(\text{s}|\text{acc})P(c\tau|\text{acc,s})P(\text{acc}) + P(\text{b}|\text{acc})P(c\tau|\text{acc,b})P(\text{acc}). \quad (5)$$

The factor $P(\text{acc})$ now factors out, while the terms $P(\text{s}|\text{acc})$ and $P(\text{b}|\text{acc})$ will have to be taken into account. A particular difficulty is that to calculate the probability that an event is signal given its acceptance function requires calculating a probability given a function, as opposed to a parameter. It will be easiest if the acceptance function is reduced to a single number, but this must be done in a manner which minimizes the associated loss of information. The number which is calculated is the value of a Fisher discriminant, an outline of which is given in the next section.

In order to discriminate between signal and background, the fitter needs to know what the background looks like in the absence of signal. The background can be modeled by events in the mass sidebands, and a simultaneous mass and lifetime fit is performed using this information to determine the probability that an event is signal. Such an approach assumes that the lifetime profile of the background under the mass peak is the same as that in the sidebands, and is a possible source of systematic error in the fit.

4 The Fisher discriminant

In order to calculate the full likelihood with background in Equation 5, we need to parameterize the signal fraction as a function of the acceptance function, $P(\text{s}|\text{acc})$. To facilitate this parameterization we associate a characteristic number to each acceptance function and parameterize $P(\text{s}|\text{number(acc)})$ instead of $P(\text{s}|\text{acc})$. To ensure that $P(\text{s}|\text{number(acc)})$ is in fact a good approximation to $P(\text{s}|\text{acc})$ we need to associate this characteristic number in a way that minimizes the information loss regarding the "signal-ness" of the acceptance function, i.e. a number that discriminates well between signal and background.

Fisher discriminants provide a reasonably simple way to provide very good signal and background discrimination. A set of parameters describing each event is projected down to a single number, the Fisher scalar, that provides optimal signal-background separation. The input parameters in our case are those describing the acceptance functions. Since the number of parameters describing the acceptance functions is unclear because we can have 1, 2, ... n distinct top-hat function, we chose a brute-force approach and split the time axis into a number of bins. The value of an acceptance function at a given bin is one parameter in the parameter set, the number of parameters is the number of bins. The details of this approach are described fully in [2].

An example of a Fisher scalar distribution for a sample containing $\sim 3,000$ signal and $\sim 3,000$ background events can be seen in Figure 3. Figure 4 shows the probability of an event being signal fitted for the values of the scalar Fisher discriminant. We see that the probability of an event being signal increases smoothly with the value of the scalar Fisher discriminant, and that most of the events have high values of this discriminant, as would be expected in a sample in which the majority of events are signal.

4.1 Associating online and offline tracks

In order to correct for the resolution difference between online and offline impact parameters when swimming the event, an association has to be made between online and offline tracks in the event. After investigating a χ^2 based method of association, it was decided to match the tracks based on the number of hits they have in common in the VELO sub-detector; two tracks were considered a match if they shared more than 70% of hits in the VELO. A publically available DaVinci tool was written which enabled this association to be performed, and is documented more fully in [14].

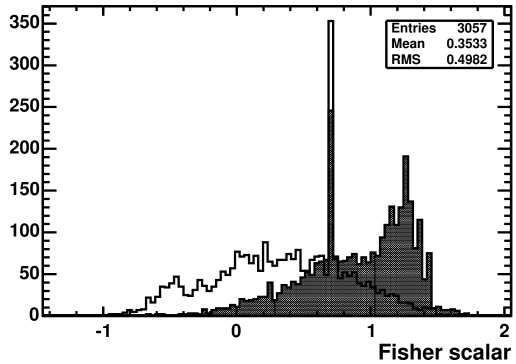


Figure 3 Fisher scalar distribution for a sample of $\sim 3,000$ signal (shaded) and $\sim 3,000$ background (unshaded) events.

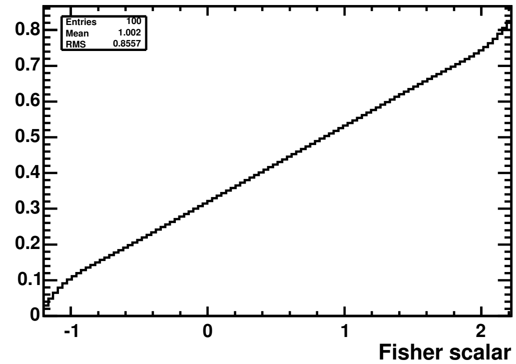


Figure 4 The signal probability associated with a value of the scalar Fisher discriminant in Figure 3

As mentioned above, the L1 trigger uses two types of track: ones reconstructed in 2D, and ones reconstructed in 3D. Compared to offline tracks, which are reconstructed using the full detector information, 2D tracks are reconstructed using only the VELO R-segments. The 3D tracks add the VELO ϕ-sensors, and the four-layer TT station to the reconstruction. The limited amount of information available to the online reconstruction and the use of a "fast" pattern recognition both contribute to the resolution difference between the online and offline impact parameters.

4.2 Trigger emulation

Since it is not currently possible to re-run the online trigger in order to swim an event[b], an offline emulation is required. This emulation has to reproduce only the lifetime dependent parts of the trigger. Following [15, 16], three types of event are distinguished:

- TIS: Events which were triggered by tracks which are not part of the signal. These events are lifetimes unbiased by definition, since swimming the signal has no impact on the trigger decision.
- TOS: Events which were triggered by signal tracks only. These events are lifetime biased, and their acceptance functions have to be measured by swimming them.
- TOB: Events which were triggered by a mixture of signal and non-signal tracks. These events cannot be accounted for at present, but they represent a small fraction of the overall sample.

The trigger emulation runs on the offline final state particles for all TOS events, demanding that two tracks satisfy the L1 impact parameter cuts and satisfy 1.

5 Fitting to signal events

This section shows results obtained by fitting the B_d^0 lifetime to a pure signal sample, both in the case of the full LHCb Monte Carlo for the channel $B_d^0 \to D^-\pi^+$, and in the case of a toy Monte Carlo created for the same channel. The expected yearly yield for this channel is 1730k events once all triggers have been taken into account. However only around 20k fully reconstructed events are available from the full Monte Carlo once the L1 trigger is applied, and far less if the L0 and HLT triggers are also applied. This is why a toy Monte Carlo is needed to estimate the expected statistical precision of this method.

[b]An interface which would allow this is currently under discussion and is expected to be available in the near future as part of the LHCb offline analysis framework.

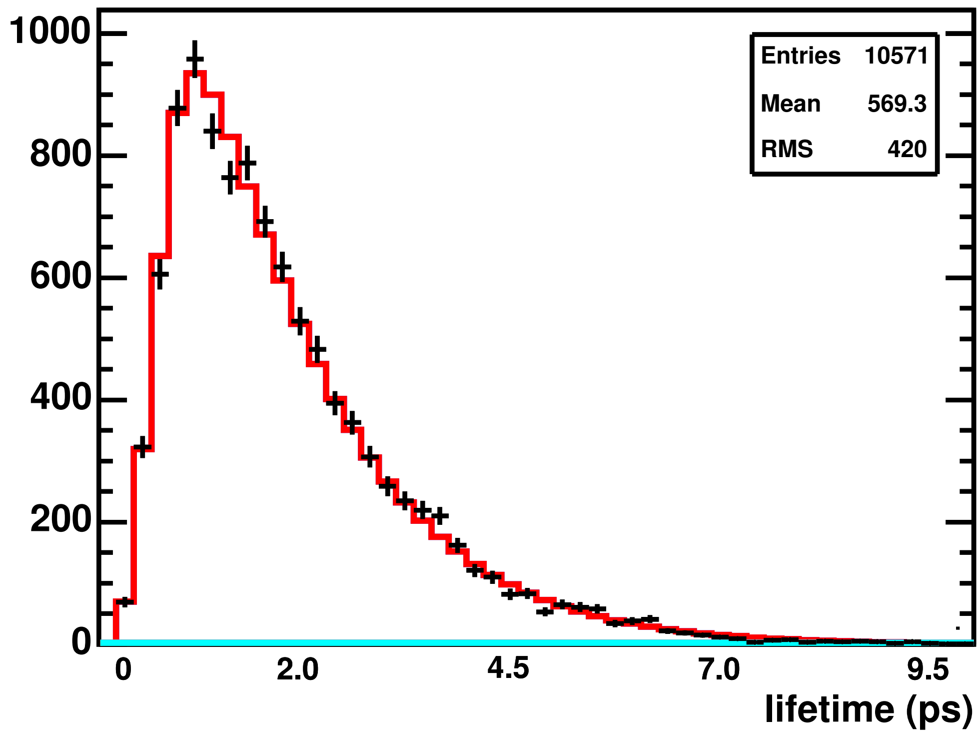


Figure 5 Lifetime fit for 10571 full Monte Carlo signal events

5.1 Full Monte Carlo fit

The signal fit in 5 was created using a sample of 10571 signal events which passed the online LHCb L1 trigger. The generator value of the mean B lifetime is 1.534ps. The fit result is:

$$\text{lifetime} = 1.532 \pm 0.017\text{ps}$$
$$\frac{\chi^2}{ndof} = 1.35 \tag{6}$$
$$\chi^2 \text{ probability} = 2.9\%$$

which is in good agreement with the input value, and has a reasonable $\frac{\chi^2}{ndof}$.

5.2 A toy Monte Carlo for $B_d^0 \to D^- \pi^+$

Because the fitter measures the acceptance function on an event by event basis, any toy Monte Carlo has to contain all the information required to measure such a function for each event. This means generating not only the lifetime distribution, but also the other variables used in the fit, such as the momenta of the final state particles, decay vertex positions, B and D lifetimes, and so on.

The method adopted here is to start with a list of variables which are assumed to be independent of each other. The B, D masses and lifetimes are generated according with the relevant distributions (Gaussian and exponential respectively), using the current world average values [17], and resolutions measured from the full Monte Carlo data. The B lifetime used in the generation is 1.534ps. The rest of the independent variables are generated from their corresponding distributions as measured on the full Monte Carlo. All other variables in the event are then calculated from these initial values. We list all the dependent and independent variables used in the toy Monte Carlo below.

- Independent variables: Primary Vertex position, B lifetime, B mass, B momentum, B vertex χ^2, D mass, D lifetime, D vertex χ^2, errors on measured impact parameters
- Dependent variables: B vertex position, D vertex position, D momentum, D impact parameter, final state particle momenta, final state particle impact parameters, online quantities (discussed further below)

The process is perhaps best illustrated by working through the generation of an event. The primary vertex position and B momentum, are generated from their measured distributions in the full Monte Carlo, while the B mass and lifetime are generated from Gaussian and exponential distributions respectively. Next, the D mass is generated from a Gaussian distribution, and the four momenta of the D and the bachelor pion from the B daughters is calculated by taking the B four momentum and decaying it with the ROOT package TGenPhaseSpace. The B decay vertex is calculated from the primary vertex position, B lifetime and B momentum, and is assigned a χ^2 value based on the measured distribution in the full Monte Carlo. The D is assigned a lifetime according to an exponential distribution, and the D decay vertex position is similarly calculated. Finally the four momenta of the D daughters are calculated, and the impact parameters of all the final state particles are calculated. All impact parameters are assigned an error, which is generated from the measured distribution of impact parameter errors in the full Monte Carlo.

The fact that "online quantities" are listed as a dependent variable requires further explanation. In order to perform a realistic swimming, and mimic the L1 trigger decision, the online impact parameters and momenta for the final state particles in this decay must be generated. The first step is to measure the distribution of the difference between these online and offline quantities on the full Monte Carlo. We then smear the offline quantities generated for the toy Monte Carlo by these distributions. As the L1 trigger only uses one tracking station, it has a probability of 79.2% of measuring an online momentum for a given online track. This probability is not lifetime dependent and is applied to the online momenta, with an online momentum of 400MeV being assigned to those tracks which fail the test. This is the default momentum assigned to such tracks in the online L1 trigger.

In order to make the toy Monte Carlo more realistic, several detector resolution effects are included:

- Momentum resolution: The measured momenta are obtained by smearing the generator level momenta with a resolution of 0.37%, taken from [3].
- Momentum acceptance: For all generated final state particle momenta, the measured detector reconstruction efficiency [3] is applied to determine if the particle with this momentum was reconstructed by the detector. If not, the event is discarded.
- Kaon Momentum cut: Any event with a Kaon whose momentum exceeds 100GeV/c is discarded, in order to improve K–π separation.
- Angular acceptance: All four final state particles are required to lie in the detector's angular acceptance of $300mrad$ [3].
- Vertex resolution: The measured vertex positions are obtained by smearing the generator level vertex positions by the appropriate resolution. In this case, the following resolutions are used: primary vertex X resolution of $0.013\mu m$, primary vertex Z resolution of $0.063\mu m$, secondary vertex X resolution of $0.011\mu m$, secondary vertex Z resolution of $0.090\mu m$. For the purposes of this toy Monte Carlo, all secondary vertices are taken to have the same resolution.

Figures 7 and 6 show the lifetime distributions for signal events in the full and toy Monte Carlo datasets respectively. We can see that the toy Monte Carlo models the correct behavior here[c], and the same is seen across other parameters.

[c] The ToyMC introduces extra background at low lifetimes after the trigger, but this is not a significant discrepancy.

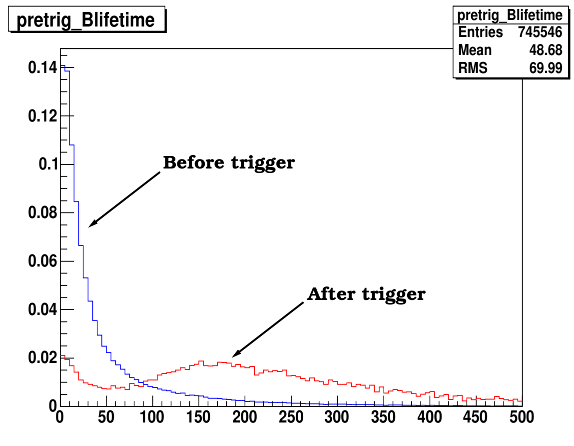


Figure 6 The pre and post trigger lifetime distributions for the toy Monte Carlo

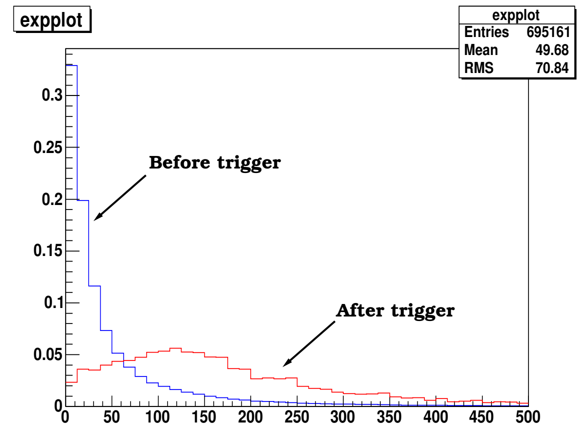


Figure 7 The pre and post trigger lifetime distributions for the full Monte Carlo

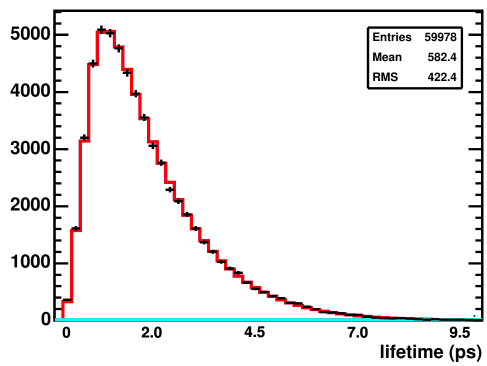


Figure 8 Lifetime fit to 60,000 toy Monte Carlo signal events

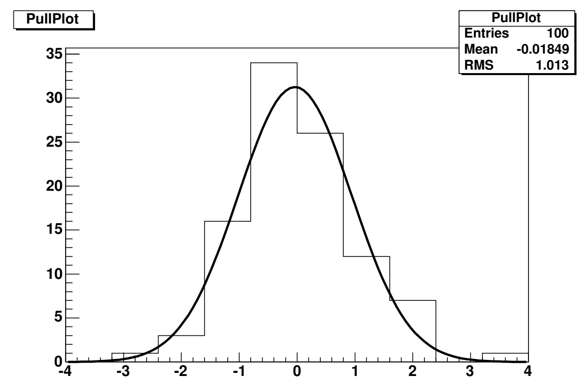


Figure 9 Pull plot of 100 lifetime fits of 500 events each. Mean = -0.04, σ = 0.98

5.3 Toy Monte Carlo fit

The fit in Figure 8 was created using 60k signal events. The fit result is:

$$\begin{aligned} \text{lifetime} &= 1.528 \pm 0.007\text{ps} \\ \frac{\chi^2}{ndof} &= 0.91 \\ \chi^2 \text{ probability} &= 71.7\% \end{aligned} \tag{7}$$

The reason the fit was performed with 60k events and not a full one year sample of 1560k toy Monte Carlo events is the time required to fit such a number of events. Comparing the statistical precision of this fit to the 0.017ps precision of the full Monte Carlo fit in Figure 5, it is seen to scale as expected with the square root of the number of events. Hence the yearly statistical precision is expected to be approximately five times better than the value quoted in Equation 7, or 0.0014ps.

Figure 9 shows a pull plot obtained by generating 100 samples of 500 events each and fitting to them, which is unbiased.

6 Including background

We use a sample of background events obtained from $b\bar{b}$ inclusive tapes in order to estimate the degradation in the statistical precision, as well as potential systematic errors, in the

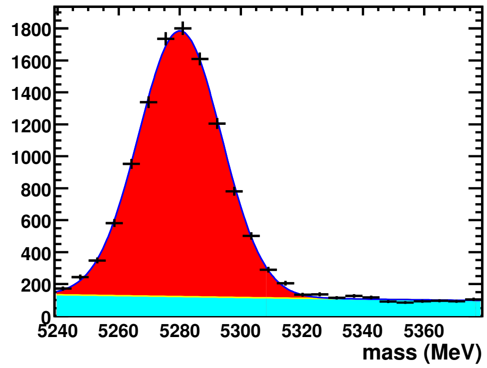


Figure 10 The mass fit for signal and background events

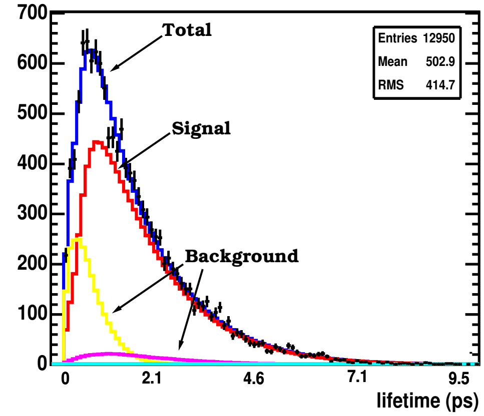


Figure 11 Lifetimes fit to signal and background full Monte Carlo events

presence of a background. However, only around 25 background events pass both the L1 trigger and the offline cuts, as opposed to $\sim 10,000$ signal events. Since we expect a $\frac{S}{B}$ of 6 under the signal peak, we require more background in our Monte Carlo sample to be able to produce realistic fits.

To obtain a bigger sample, the offline cuts used in the selection have been loosened. The background after the full offline cuts is dominated by events with a mis-identified pion or kaon and other partially reconstructed B decays, while the background after the trigger is dominated by combinatorics. Hence the background events with looser offline cuts will not be representative of the background which is likely to be seen once the experiment starts. The background from partially reconstructed decays and mis-identification is especially dangerous because the fitter assumes the lifetime behaviour of the background is the same in the mass sidebands and under the peak. Clearly a background from real B mesons lying under the peak makes this assumption problematic. Any such background in the sidebands is also problematic, and it is expected to be found in the left sideband because partially reconstructing a B decay or mis-identifying one of its daughters will systematically decrease the mass of the reconstructed B. For this reason, the lower mass sideband is not used in the fit. As explained in Section 3.3, the background is described by a sum of exponentials, as well as a prompt component.

6.1 Fits to the full Monte Carlo

Figure 11 shows a fit to the same signal sample as in Figure 5, with approximately 2300 background events added. The background level corresponds to $\frac{S}{B} = 7$ within a 3σ window around the B mass. The fit result is:

$$\begin{aligned} \text{lifetime} &= 1.549 \pm 0.019\text{ps} \\ \frac{\chi^2}{ndof} &= 1.49 \\ \chi^2 \text{ probability} &= 0.6\% \end{aligned} \tag{8}$$

The fitted value is in good agreement with the input value. A pull study is required to determine whether the shift relative to the signal-only fit is systematic or statistical.

Figure 10 shows the fit to the B mass distribution which is performed simultaneously with the lifetime fit.

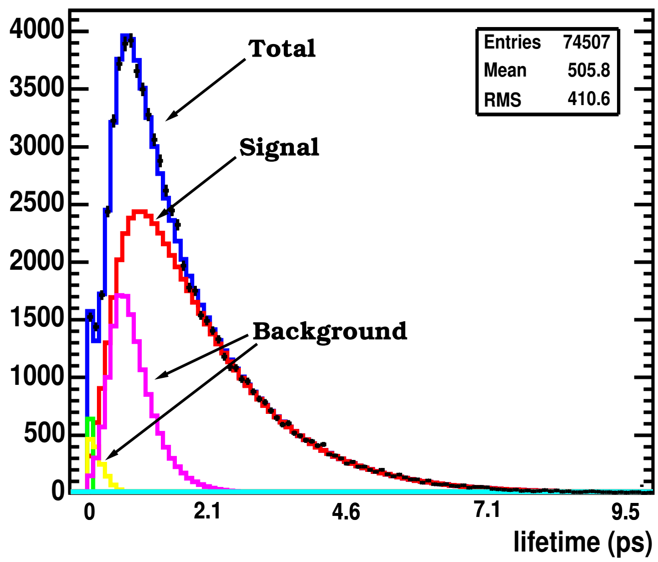


Figure 12 Lifetime fit to signal and background toy Monte Carlo events

6.2 Toy Monte Carlo fit

As with the signal, a toy Monte Carlo can be developed for the background. The background toy Monte Carlo is created using the same method as the signal toy Monte Carlo, with the following modifications:

- Detector effects: the vertex resolution was not included.
- Masses: the B and D masses were generated from the distributions of these parameters on the full background Monte Carlo.
- Lifetimes: the B and D lifetimes were generated from the distributions of these parameters on the full background Monte Carlo.

Figure 12 shows a fit to the same signal sample as in Figure 8, with $15,000$ background events added. The fit result is:

$$\begin{aligned} \text{lifetime} &= 1.552 \pm 0.007\text{ps} \\ \frac{\chi^2}{ndof} &= 1.26 \\ \chi^2 \text{ probability} &= 4.7\% \end{aligned} \quad (9)$$

The fit is in good agreement with the input value, and the $\frac{\chi^2}{ndof}$ of the fit is reasonable. A pull study is required to evaluate any systematic biases in the fitted lifetime when background is added.

6.3 Using a measured average acceptance function

Instead of using the individual event-by-event acceptance functions in the fit, one can also use the event-by-event acceptance functions of all events to build up an average acceptance function. The same average acceptance function is then used for all (signal) decays. In this approach we do not require the troublesome $P(\text{sg}|\text{acc})$ and $P(\text{bg}|\text{acc})$ terms in the likelihood anymore, although we cannot completely dispense with them as we shall see below. A benefit of this method is that it allows for a more flexible background parametrisation:

$$\sum_i n_{weight\ i}(t-b_i)^2(\exp(-t/\tau_i)\otimes gauss(t,\sigma_i))\theta(b-t). \tag{10}$$

This is essentially a generic Gaussian convoluted with an exponential.

In order to use this background parametrization, the signal must be described with an average acceptance function. This is still calculated from the event by event acceptance functions, however:

$$AAF = \sum acc_i, \tag{11}$$

where AAF is the average acceptance function, and acc_i represent the individual event by event acceptance functions for signal events.

There is an additional complication. For any given value of the mean lifetime, an event by event acceptance function gives the probability of accepting an event, and this probability itself varies with the mean lifetime. To give a simple example, if the fit has set the mean lifetime to 0.5ps and the event by event acceptance function in question does not become 1 until 2ps, it would be much less likely to pass events than an event by event acceptance function which is 1 between 0.1ps and 0.9ps, simply because there would be so many more events that fall within the latter. As a result each event by event acceptance function must be normalized before they are added, and this has to be done every time the mean lifetime changes. The formula becomes:

$$AAF = \sum_i \frac{P(\mathrm{s}|acc_i)\times acc_i}{P(\mathrm{trigger}|acc_i,\mathrm{s},\tau)}, \tag{12}$$

where:

- $P(\mathrm{s}|acc_i)$ is the probability that an event is signal, given an event by event acceptance.
- $P(\mathrm{trigger}|acc_i,\mathrm{s},\tau)$ is the probability that a signal event passes the trigger, given the acceptance and the mean lifetime τ as currently set in the fit.
- acc_i is the event by event acceptance.

This normalization produces a measured average acceptance function which can be used in the fit. As before, a simultaneous mass and lifetime fit is performed, and use the mass sidebands to help determine the background shape. The term $P(\mathrm{s}|\mathrm{acc})$, which caused so many complications, is now not part of the probability density function anymore. However, as we have seen, it is still needed in the calculation of the average acceptance function.

6.3.1 Signal fit

Figure 13 shows the fit to ~ 3000 full Monte Carlo signal events. The fit result is:

$$\begin{aligned} \mathrm{lifetime} &= 1.531 \pm 0.034\mathrm{ps} \\ \frac{\chi^2}{ndof} &= 1.30 \\ \chi^2\ \mathrm{probability} &= 12.2\% \end{aligned} \tag{13}$$

The fit is in good agreement with the input value, and has a reasonable $\frac{\chi^2}{ndof}$.

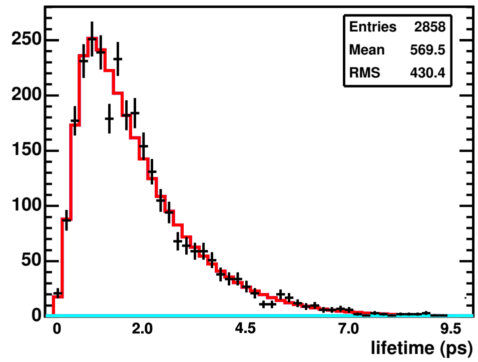


Figure 13 Lifetimes fit to $\sim$ 3000 full Monte Carlo signal events with an average acceptance function

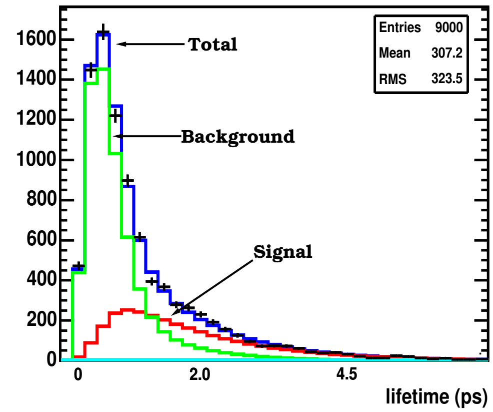


Figure 14 Lifetimes fit to $\sim$ 3000 signal and $\sim$ 6000 background full Monte Carlo events with an average acceptance function

6.3.2 Signal and background fit

Figure 14 shows a fit to the signal sample from Figure 13, with ~ 6000 background events added, corresponding to a $\frac{S}{B}$ ratio of ~ 3 underneath the mass peak. The fit result is:

$$\text{lifetime} = 1.535 \pm 0.037\text{ps}$$
$$\frac{\chi^2}{ndof} = 1.43 \quad (14)$$
$$\chi^2 \text{ probability} = 5.1\%$$

The fit has a reasonable $\frac{\chi^2}{ndof}$, and the fit result matches what was measured with only the signal events. The statistical precision has not worsened considerably compared to the signal only fit. As before, a pull study will be necessary to evaluate any systematic errors arising from background events.

It should be noted that the current version of the average acceptance fitting package exhibits stability problems when fitting with signal and background events at the same time. Work is ongoing to fix this.

7 Expected statistical precision

A summary of the fit results in this study is shown in Table 1. The decay $B_d^0 \to D^-\pi^+$ has an expected yearly yield of 1730k fully triggered and untagged events, with a $\frac{S}{B}$ ratio of ~ 6. Fitting the lifetime with 60k toy Monte Carlo signal events achieves a statistical precision of 0.007ps, while fitting to 60k signal and 15k background events achieves a precision of 0.009ps. A similar result is seen in data generated with the full LHCb detector simulation. For 3000 signal events the fit result is 1.531 ± 0.034 for an input value of 1.534ps. Adding 6000 background events in a mass window of -100GeV, +400GeV ($\frac{S}{B} \sim 4$ within $\pm$ 3 sigma of the mass peak) a result of 1.535 ± 0.037ps is obtained. It is seen that the presence of background does not lead to an undue deterioration in performance. Therefore, although the systematic errors associated with this method are unknown at the moment, a precision comparable with the current world average of 0.009ps [17] can be expected within the first nominal year of running, corresponding to 2fb^{-1} of data.

In the B_s^0 sector, the decay $B_s^0 \to D_s\pi$ [18] has the same topology and is hence expected to have equivalent statistical performance. A yearly yield of 160k $B_s^0 \to D_s\pi$ events and a $\frac{S}{B}$ of ~ 3, allows us to achieve a statistical precision comparable with the current world average of 0.057ps [17] within the first couple of weeks of running at full LHCb design luminosity of $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$.

Table 1 A summary of the fit results presented in this study. A central lifetime value of 1.534ps was used for all fits in this table. FMC refers to full Monte Carlo events, TMC refers to toy Monte Carlo events. AAC refers to fitting with an average acceptance function, EEAC refers to fitting with an event-by-event acceptance function.

Fit data	Fit Method	Fit result (ps)	Fit σ (ps)	χ^2 of fit	χ^2 prob.
10,571 signal (FMC)	EEAC	1.532	0.017	1.35	2.9%
10,571 signal and 2300 background (FMC)	EEAC	1.549	0.019	1.49	0.6%
60,000 TMC signal	EEAC	1.528	0.007	0.91	71.7%
60,000 signal and 15,000 background (TMC)	EEAC	1.552	0.007	1.26	4.7%
3,000 signal (FMC)	AAC	1.531	0.034	1.30	12.2%
3,000 signal and 6,000 background (FMC)	AAC	1.535	0.037	1.43	5.1%

8 Conclusion and future work

A Monte Carlo independent method for measuring lifetime acceptance functions at LHCb has been developed and tested on Monte Carlo data for the channel $B_d^0 \to D^-\pi^+$. We find that the method works with signal data, and that the expected statistical precision will outperform the current world average in the B_s and B_d sectors within the first few months of running.

We have been able to fit to lifetimes in the presence of background data, and find no significant increase in statistical uncertainties in this configuration. A pull plot study is under way to test possible systematic errors stemming from the addition of background data. We have shown first results with an alternative fitting method, using a measured average acceptance function, which may improve the performance when fitting to both signal and background. The fitter exhibits certain stability problems when fitting to signal and background at the same time, and work is ongoing to fix these.

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