Measurement of the D^0 meson mean life with the LHCb detector

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Abstract: a measurement of the mean life of the D^0 meson is performed using real $D^0 \to K^+\pi^-$ decay data collected at LHCb and selected according to the decay's specific features. First, the selection algorithm is described. Then, the measurement of the mean life is optimized by changing the acceptance range of the data according to three variables involved in the selection. The value obtained for the mean life is compatible with the worldwide averaged value provided by the Particle Data Group.

I. INTRODUCTION

The D^0 meson is a bound state of a charm quark and an up antiquark. It is the lightest particle containing a charm quark. Therefore, in order to decay it must change the charm quark into an (anti)quark of another type. Since this kind of decay does not conserve charm quantum number, it is only possible via the weak interaction. Thus, D^0 mesons have been historically studied to gain knowledge on the weak interaction.
The charge conjugate of the D^0 is denoted as $\bar{D}^0$. In 2009 it was confirmed that mass eigenstates are $D^0 \leftrightarrow \bar{D}^0$ oscillating states [1]. Thus, a comparison of the D^0 and $\bar{D}^0$ properties can provide valuable information about matter-antimatter asymmetries beyond the Standard Model, which is the reason why D^0 physics is studied at LHCb.
Some properties of the D^0 meson were measured with high precision in previous experiments. However, it is convenient to check that they can be measured precisely at LHCb before starting to do more complex measurements in the complicated environment of a proton-proton collider.
The aim of this project is to measure one of these parameters, the mean life τ, using real $D^0 \to K^+\pi^-$ decay data collected at LHCb and a simplified version of the analysis software. Figure 1 shows the dominating Feynman diagram of the decay.

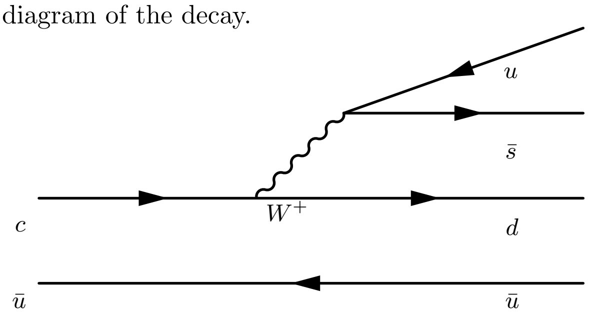

Figure 1: Main Feynman diagram of the $D^0 \to K^+\pi^-$ decay.

The lifetime t' of a D^0 meson is defined as the time, measured in the meson's frame, that the particle takes to decay. It is a random variable which obeys an exponential distribution. Therefore, if we have N_0 D^0 mesons at $t' = 0$, the number of mesons as a function of t' will be

$$N(t') = N_0 e^{-t'/\tau}, \tag{1}$$

where τ is the mean life.

II. THE *LHCb* EXPERIMENT

CERN's Large Hadron Collider (LHC) is the world's largest and most powerful hadron collider. Its aim is to test theoretical predictions of the Standard Model of particle physics, as well as to explore new physics only accessible at very high energies. There are four major detectors at LHC, each designed for a specific kind of research. The LHC beauty experiment (LHCb) is one of these four detectors.
LHCb is devoted to the study of particles containing b and c quarks, with the main purpose of detecting matter-antimatter asymmetries deviating from the Standard Model which could give some indication about the evolution of the universe at its early stages. The particles of interest are produced, together with many background particles, as products of proton-proton (pp) collisions at 7-8 TeV center-of-mass energies.
In order to give an appropiate response to its large pp collision rates, LHCb is capable of pre-analysing online up to 40 million events per second. A sketch of LHCb is displayed in Figure 2.

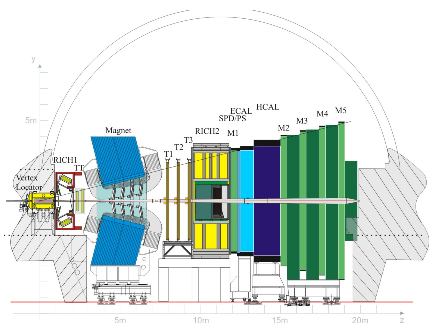

Figure 2: Side view of the LHCb detector.

Although the typical lifetimes of particles such as the D^0 meson are of the order of fs, the relativistic time dilation effect allows their decays to be detected at LHCb as secondary vertices displaced about 1 mm from the primary pp collision vertex, as shown in Figure 3.

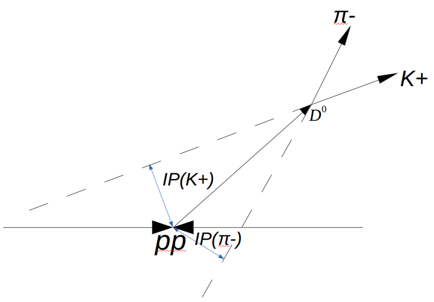

Figure 3: Schematic representation of the particles and vertices involved in a D^0 creation and decay.

The impact parameter IP, defined as the distance of closest approach between the track of a particle and the pp collision vertex, will play an important role in the optimization of the mean life measurement. From Figure 3, it is clear that the D^0 candidates should ideally have a null impact parameter, whereas the particles resulting from their decays are expected to have a large impact parameter.

These are the crucial elements of LHCb for the detection of signal decays:

- VELO (VErtex LOcator): its function is to locate accurately both the primary pp collision vertices and the vertices corresponding to the decays of particles containing b and c quarks. It is sensitive to 50 fs lifetime differences, so that the primary and secondary vertex can be differentiated even if the particle takes a very short time to decay.
  It consists of 21 silicon stations placed very close to the beam: 40 mm when the acceleration is in process and 8 mm during collisions. It provides a 10 μm spatial resolution [2].
- RICH (Ring Imaging Cherenkov): its function is to determine whether a particle resulting from a decay of interest is a kaon or a pion. To do so, it measures the velocity of the particle, so that knowing its momentum (measured with the tracking system) it is possible to deduce its mass and thus determine which kind of particle it is.
  The velocity is measured using the Cherenkov radiation, which is emitted when a charged particle travels through a medium of refractive index n at a speed faster than the speed of light in such medium. This radiation is emitted at a characteristic angle given by
  $$\theta = \arccos \frac{1}{\frac{v}{c}n} \tag{2}$$
  By measuring this angle it is possible to determine the velocity of the particle, v. The RICH consists of two measuring centers provided with materials of different refractive indices so that a wide momentum range can be covered.
- Tracking system: its function is to track the charged particles produced as a result of the decays and to measure their momentum. LHCb's tracking system consists of four tracking stations, each of which has an outer part made of straw chambers and an inner part made of silicon detectors.
  With the track reconstructed, knowing the magnetic field distribution, it is possible to determine the momentum of the particle by studying the deflection of the trajectory caused by the field.

III. MEASUREMENT OF THE D^0 MEAN LIFE

The subdetectors described in the previous section allow measuring, for a single particle and in the lab frame, the distance between its production and decay vertexs d, the invariant mass m, and the momentum p. Once these quantities are known, the lifetime of the particle can be calculated as

$$t' = \frac{dm}{p} \tag{3}$$

The data used for this study was recorded at LHCb during 2011. The integrated luminosity of the original sample is 0.3 fb^{-1}, which corresponds approximately to one third of the total data collected that year. However, due to the large D^0 production rate, the trigger line selected only one in every 160 events.
The data has been selected according to the following criteria:

- The tracking system must provide a well reconstructed track for all daughter candidates.
- The RICH system must identify clearly a daughter candidate as a kaon and the other as a pion.
- The daughter candidates must have a transverse momentum $p_T > 750$ MeV/c.
- The impact parameter of the daughter candidates must be large.
- The two daughter candidates must form a good vertex, being the distance of closest approach between their two tracks shorter than 1mm.
- The invariant mass of the combination must not differ more than 50 GeV/c^2 from the accepted value for the D^0 mass provided by [3].
- The transverse momentum of the reconstructed D^0 meson must be in the range
  $$2.5\,\text{GeV/c} < p_T < 20.0\,\text{GeV}/c$$

- The lifetime of the reconstructed D^0 meson must be in the range

$$0.15\,\text{ps} < t' < 10.15\,\text{ps}$$

- The impact parameter of the reconstructed D^0 meson must be in the range

$$-4.0 < \log(IP/\mu m) < 1.5$$

A significant amount of background events is present in the data after these criteria are applied. Hence, it is necessary to correct their effect in the measurement. The main source of background is the so-called combinatorial background, due to uncorrelated pairs of pions and kaons.

The method for correcting the effect of the combinatorial background is based on the distribution of the invariant mass of the D^0 candidates. For signal, the invariant mass is distributed as a gaussian function with a mean value corresponding to the true D^0 mass. On the other hand, the combinatorial background has an invariant mass that can be modelled as a linear distribution.

First, a linear function is fitted using the information contained at the edges of the histogram, where all the events are assumed to be background. Then, the approximation that the background properties are independent of the region of the histogram is assumed, so the signal distribution can be found by subtracting the previously fitted background distribution to the total histogram distribution.

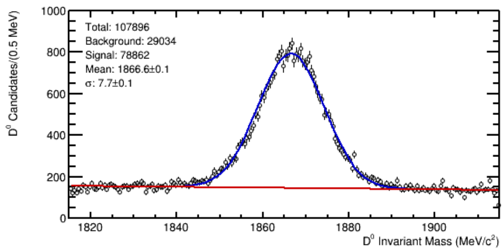

Figure 4: Invariant mass histogram of the total data sample with the background (red) and signal (blue) distributions fitted.

Since a gaussian distribution contains the 99,7% of its events within 3 standard deviations of the mean, once the signal distribution has been fitted, the signal region is taken as the 3 σ region around the mean.

The cuts in the p_T, IP and t' of the particle will be crucial to optimize the mean life measurement. Figures 5-7 show the signal and background distributions of the total data sample for these variables.

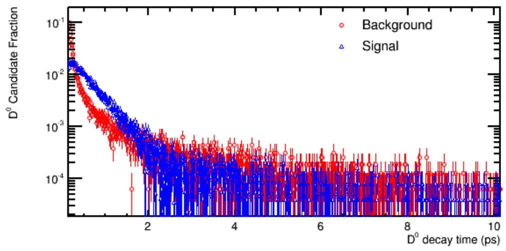

Figure 5: Signal and background lifetime distributions of the total data sample

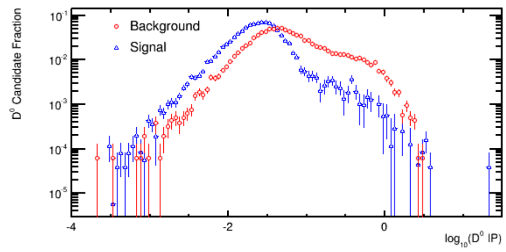

Figure 6: Signal and background impact parameter distributions of the total data sample.

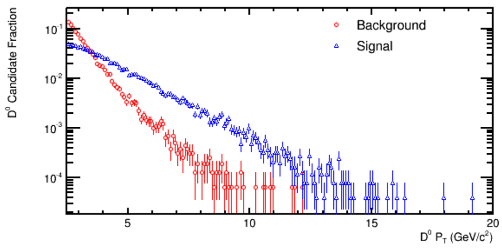

Figure 7: Signal and background transverse momentum distributions of the total data sample.

With the signal events identified, according to (1) τ can be measured by representing a histogram of the decay time in a logarithmic scale and fitting a linear function. Figure 8 shows the fit of the mean life obtained with the total data sample.

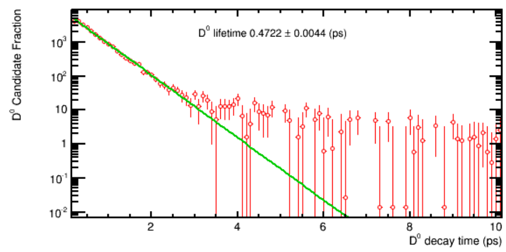

Figure 8: Mean life fit based on the signal events of the total data sample.

The measurement is further optimized to take into account experimental effects and specific backgrounds by modifying the value of the selection cuts in p_T, t' and IP.

Optimization of the mean life measurement.

- Lifetime: one of the selection criteria is that the daughter particles have a large impact parameter. This prevents many D^0 mesons with very short lifetimes to be included in the signal data sample. As a consequence of this lack of data in the short lifetime range, the theoretical lifetime distribution is not well reproduced and the mean life is overestimated.
  A way to avoid this problem is to set a longer lifetime lower cut so that this region is kept out of the fit. Figure 9 shows the dependence of the mean life and its uncertainty on the lower lifetime cut. The upper cut on the lifetime is 10.15 ps, while the other cuts are the loosest possible according to the selection criteria.

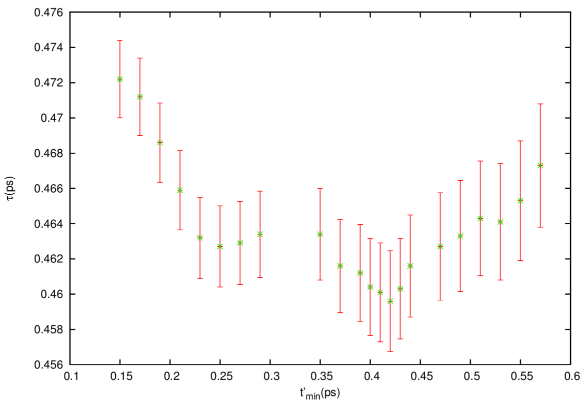

Figure 9: Mean life as a function of the lower t' cut.

  Figure 9 shows that the mean life estimation decreases as the lower t' cut increases until the region given approximately by $0.2 < t' < 0.3$, where it remains steady within statistical uncertainties. Therefore, a value of t' belonging to this region has been chosen as the optimal lower t' cut

$$t'_{min} = 0.25\,\text{ps} \qquad (4)$$

- Impact parameter: there is a subset of background events whose mass distribution does not obey a linear distribution but rather has a peak in the same position as the signal events. It is therefore impossible to subtract this kind of background from the total histogram by the usual process of fitting a function at the edges of the histogram and assume that the background has the same properties in all the regions of the histogram.
  This background corresponds to the decay of D^0 mesons which are the product of B particles decays and therefore do not come directly from the primary pp collision vertex. These D^0 mesons are measured decaying further from the primary vertex than the ones that come directly from there, causing an overestimation of the mean life.
  Most likely, these background D^0 candidates have a very large IP because the vertex in which their decay takes place already comes from the secondary vertex of a B particle decay. Therefore, they can be subtracted from the signal events imposing a more stringent IP upper cut.
  In figure 10 the dependence of the mean life and its uncertainty on the upper IP cut is represented. The lower cut on the impact parameter is $\log(IP/\mu m) = -4$, the optimal value for the lifetime lower cut (4) is used and the rest of the cuts are the loosest possible according to the selection criteria

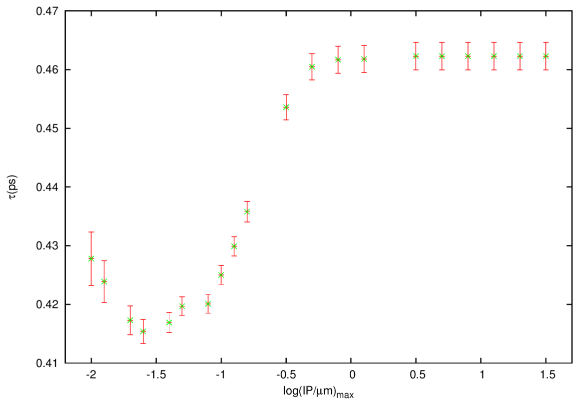

Figure 10: Mean life as a function of the upper IP cut.

  Figure 10 shows that the mean life estimation decreases with the upper $\log(IP)$ cut until a minimum value around $\log(IP)$=-1.5. The optimal value for the $\log(IP)$ upper cut has been chosen as the one in the region of the minimum with the lowest uncertainty

$$\log(IP/\mu m)_{max} = -1.4 \qquad (5)$$

- Transverse momentum: figure 11 shows the dependence of the mean life on the p_T upper cut. The lower lifetime cut and the upper impact parameter cut are the optimal ones from (4) and (5), while the rest of the cuts are the loosest possible according to the selection criteria. The same cuts apply for figure 12, where the dependence of the mean life on the p_T lower cut is shown.

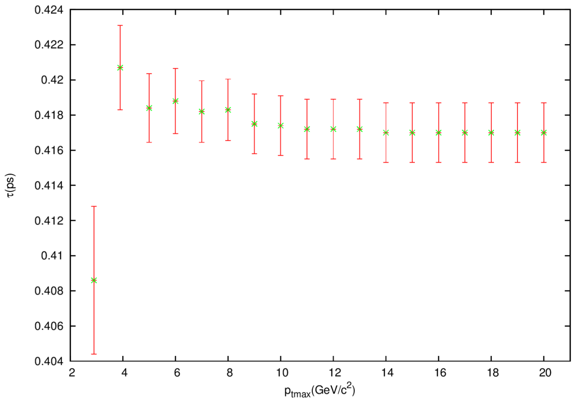

Figure 11: Mean life as a function of the upper p_T cut.

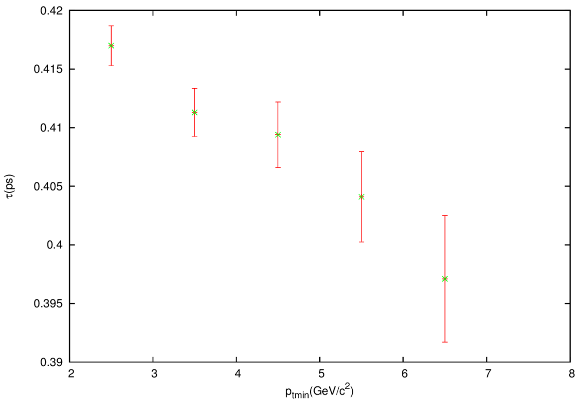

Figure 12: Mean life as a function of the lower P_t cut.

Figure 11 shows that the mean life estimation does not change with the upper p_T cut, except for very small values of this cut for which there is an important loss of statistical significance. From figure 12, it is clear that as the lower p_T cut increases, statistical significance is rapidly lost and the mean life estimation decreases. The variations of the mean life observed are consistent with statistical fluctuations. In any case, the p_T cuts do not play a significant role in the optimization of the mean life measurement, so in the optimal range of the selection variables they are taken as the loosest permitted by the selection criteria.

The optimal cuts have been found to be

$$\begin{array}{l} 2.5\,\mathrm{GeV/c} < p_T < 20.0\,\mathrm{GeV/c} \\ 0.25\,\mathrm{ps} < t' < 10.15\,\mathrm{ps} \\ -4.0 < \log(IP/\mu m) < -1.4 \end{array} \tag{6}$$

The value for the mean life measured for the cuts in (6) is

$$\tau = 417 \pm 4.4\,\mathrm{fs} \tag{7}$$

The Particle Data Group [3] provides an independent value for the D^0 mean life which comes from the average of thousands of measurements made by research groups all around the world

$$\tau_{PDG} = 410.1 \pm 1.5\,\mathrm{fs} \tag{8}$$

Results (7) and (8) are compatible within a 2σ uncertainty. Their mean values differ a 1,68%.

IV. CONCLUSIONS

The D^0 meson mean life could be measured successfully. The selection variable that has the greatest influence on the lifetime estimation is the impact parameter, which highlights the important fraction of D^0 mesons coming from B particles in the data sample.

The success in this simple measurement is a first step to assure that more sophisticated measurements can be made at LHCb in spite of the enormous complexity of the pp collisions, in which hundreds of particles are produced simultaneously.

Acknowledgments

I would like to thank my supervisor Hugo Ruiz for his guidance and help in all the phases of this project.
I would also like to thank my family and friends for their support and encouragement not only with this project, but also during all the years that I took to complete my bachelor's degree.

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