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 $\tau$, 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.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{feynman_diagram.png}
\caption{Main Feynman diagram of the $D^0 \to K^+\pi^-$ decay.}
\end{figure}

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

\[ N(t') = N_0 e^{-t'/\tau}, \]

where $\tau$ 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 appropriate 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.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{lhc_detector.png}
\caption{Side view of the LHCb detector.}
\end{figure}
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.](image)

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 vertex $d$, the invariant mass $m$, and the momentum $p$. Once these quantities are known, the lifetime of the particle can be calculated as

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

The data used for this study was recorded at LHCb during 2011. The integrated luminosity of the original sample is $0.3 \text{ fb}^{-1}$, 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 $p_T > 750 \text{ MeV}/c$.
- 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 1 mm.
- The invariant mass of the combination must not differ more than $50 \text{ GeV}/c^2$ 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.

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 $3\sigma$ 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.
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.

  \[
  t'_{\text{min}} = 0.25 \text{ ps} \quad (4)
  \]

- **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.

  \[
  \log(IP/\mu m)_{\text{max}} = -1.4 \quad (5)
  \]

- **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.
The optimal cuts have been found to be

\[
2.5 \text{ GeV/c} < p_T < 20.0 \text{ GeV/c} \\
0.25 \text{ ps} < t' < 10.15 \text{ ps} \\
-4.0 < \log(IP/\mu m) < -1.4
\]  

(6)

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

\[
\tau = 417 \pm 4.4 \text{ fs}
\]  

(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

\[
\tau_{PDG} = 410.1 \pm 1.5 \text{ fs}
\]  

(8)

Results (7) and (8) are compatible within a 2\(\sigma\) 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.

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[1] R.Aaij et al. Measurement of \(D^0 - \bar{D}^0\) Mixing Parameters and Search for CP Violation Using \(D^0 \rightarrow K^+\pi^-\) Decays, PRL 111, 251801 (2013).

