Studies of $D^0 \rightarrow KsK^K$ decays for measuring y_{CP}

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Abstract

The discovery of CP violation in the decay of D^0 mesons by LHCb opens the door for the study of this phenomena in charm mesons. From all the values that describe this effect, this study focuses in the y_{CP} parameter for CP violation. This parameter is defined as the deviation from unity of the ratio of the effective lifetimes of D^0 meson decays to flavor-specific and CP-even final states. The measurement of y_{CP} assuming no CP violation in nature will be done, and the result compared to the tabulated values of the mixing parameter y. The existence of discrepancy between these two values would be the prove of CP violation, and the quantitative value would parametrize its range.

In order to measure y_{CP}, some studies in sensitivity must be done. These sensitivity values are the result of the project.

Contents

1 Introduction

CP violation was first discovered for Kaons, and B mesons. In March 2019, LHCb announced discovery of CP violation in charmed D^0 decays. Having observed direct CP violation in the decays of $D^0 \rightarrow hh$, it is interesting to look for indirect CP violation, arising from the interference in the mixing diagrams (as the one shown in figure 1) or between the mixing and the decay diagrams.

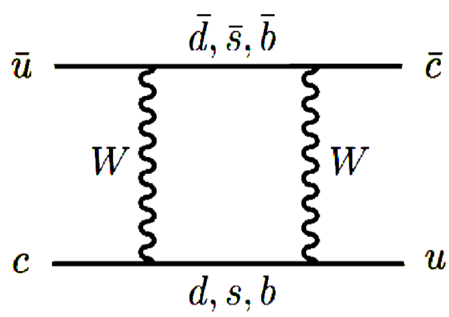

Figure 1: *Box Feynmann diagram for describing the oscillations between particle and antiparticles for D^0 mesons*

One way to do this is by studying the parameter named y_{CP}, defined as the difference between one and the value of the ratio of the effective lifetimes of D^0 decays for the two channels explained in section 2.

The idea of the study is to perform some sensitivity studies that afterwards can be used to extract the y_{CP} parameter. For that, the ratio between ON peak and OFF peak events (see Section 2) will be calculated for the different types of data explained in Section 3. Moreover, the data will be binned for the different decay times of the D^0 (15 bins with equal number of events in each of them). More details in the binning of decay time and the results of the analysis will be presented in section 4. Finally, the conclusions for the project are summarized in section 5.

The data taken for the study is a LHCb sample from 2016, 2017 and 2018.

2 CP violation. On and OFF data

The main decay studied in this project is the following:

$$D^0 \to K^+K^-K^0_S \tag{1}$$

followed by the decay of the K_S in $\pi^+\pi^-$.

If the decay undergoes as mentioned above, the final three body state is an eigenstate of CP with an even eigenvalue. However, the D^0 can decay to a resonance as a primary state, such that the resonance decays almost immediately to the final state particles, as follows:

$$\begin{gathered} D^0 \to \phi\, K^0_S \\ \phi \to K^+K^- \end{gathered} \tag{2}$$

This resonance state has an odd CP value. The fact that the final states have different CP eigenvalues can be used to parametrize the effects of the CP violation in these decays. The study of the ratio of ON resonance data and OFF resonance data is the key goal in the project. By plotting the ratio of the yields of signal for each kind of data, $\frac{N(ON)}{N(OFF)}$, and its variation over time, it's possible to extract the y_{CP} parameter. CP violation is searched for by comparing the y_{CP} parameter (calculated assuming no CP violation) with the world average of y (see hflav.cern.ch).

To separate this two types of events, the variable $m(K^+K^-)$ is studied (see figure 2). In this plot, we can appreciate the peak in the mass corresponding to a resonance. Two regions where defined to separate ON and OFF signal data:

- ON data: $m(K^+K^-) \subset [1015, 1025]\ GeV$
- OFF data: $m(K^+K^-) \subset [2m_K, 1010]\ or\ [1033, 1100]\ GeV$

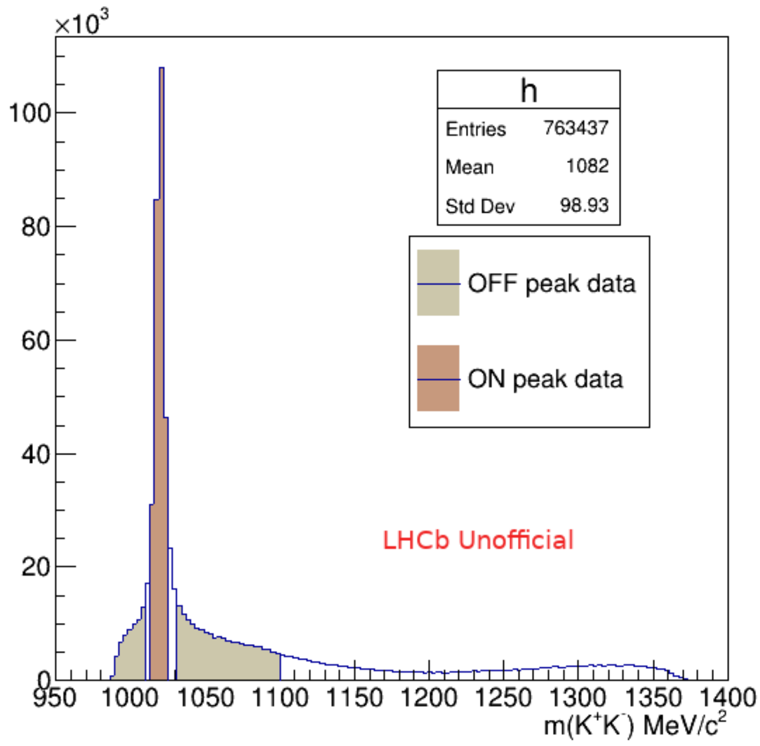

Figure 2: *Variable* $m(K^+K^-)$, with shaded regions for ON and OFF peak data.

3 Samples

For the data taken, I started from a sample made available from the Charm WG at LHCb. Some extra cuts were applied to perform a selection based on Particle Identification (PID) and the topology of the event.

The skimmed data used for the study can be classified according to production mechanism of the D^0 particle, the year of collection of the data and the type of the K_S^0.

There are two types of decay that can produce the D^0 particle needed for the experiment, known as Prompt and Semileptonic decays.

In figure 3, we can see the schematic representation for each event. In the Prompt sample, the collision of the two protons in the LHC produces a D^* meson, which itself decays in the D^0 and a pion, which will be named ”pi soft” to distinguish it from the pions coming from the K_S. Instead, in the Semileptonic decay, the D^0 comes from a B meson, which decay also produces a muon and a muon neutrino (therefore, the name ”Semileptiongic” for this decay channel), and also some extra non-relevant particles, represented by the grey ”X”.

The Prompt decay can be itself subdivided in two modes, namely Prompt and Life Time Unbiased (LTUNB). The difference between them is related to the trigger selection made for the decay events, the latter having an enlarged acceptance at low decay times.

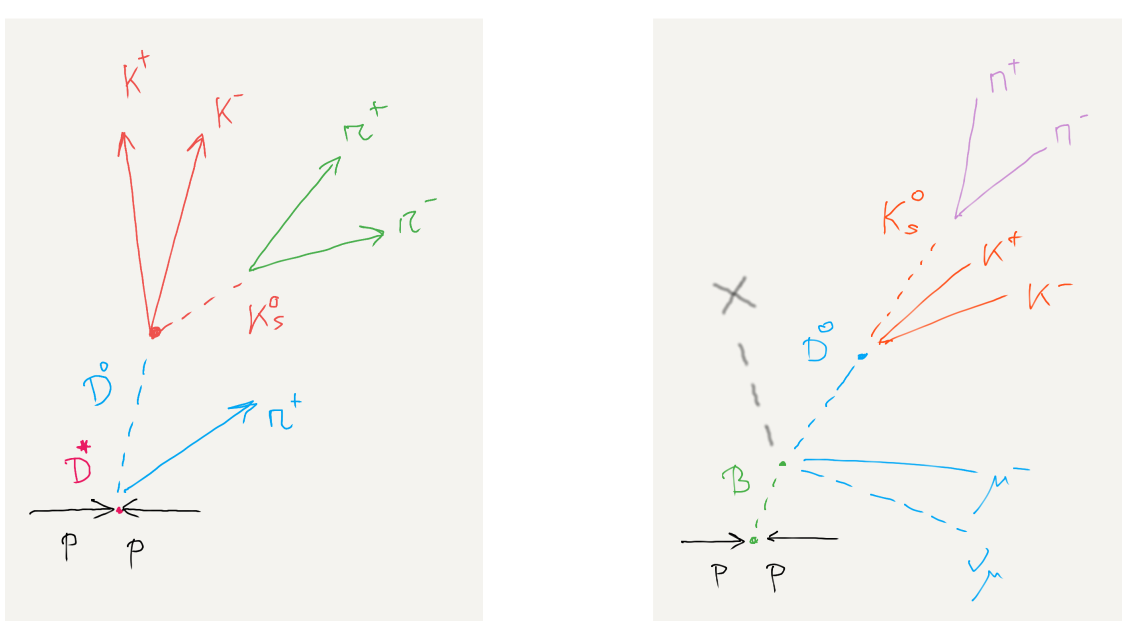

Figure 3: a) Schematic representation of the decay channel for Prompt and LTUNB samples. b) Same for the Semileptonic decay channel.

The data used for the study was collected in the years 2016, 2017 and 2018, and the results will also be classified per year.

Lastly, the data can be classified according to the type of the K_S^0 produced. This classification refers to the part of the detector where the decay of the K_S in the two pions take place. In the figure 4 we can differentiate two types of tracks: Long and Downstream tracks. The long tracks start in the Vertex locator (Velo), the inner part of the detector. The Downstream tracks instead have their beginnig outside the Velo. The tracks refer to the pions, in this case. A long track is created when the K_S decays in the Velo, and a downstream track corresponds to the K_S decaying outside the Velo. As the result of the decay of the K_S is two pions, the data can be classified between LL and DD (two long or two downstream tracks, respectively).

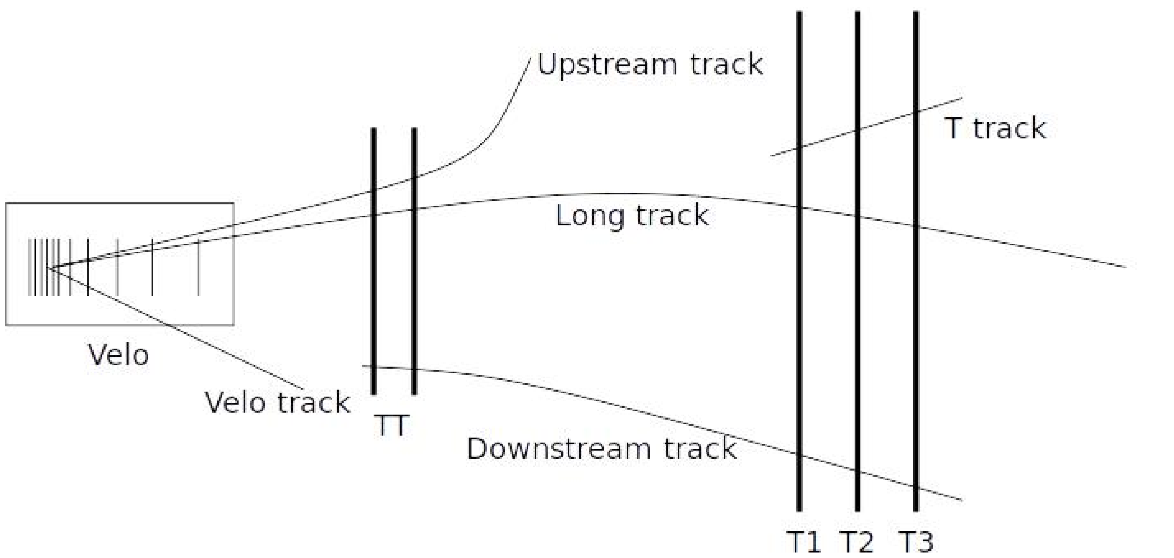

Figure 4: *Schematic tracks of particles detected in LHCb. In the picture, the difference between Long tracks (coming from the Velo) and Downstream tracks (starting after the Velo) can be appreciated.*

4 Results

As mentioned in the introduction, the skimmed data was binned according to the decay time of the D^0 meson. A code to separate the data in 15 bins with similar number of events was written. The results will be classified with the sample types mentioned in section three and also in the bin number of the decay time.

Another classification for the data was performed, in this case, regarding to the kind of trigger that the event fired. The two triggers considered are:

- Trigger 1: Hlt1 trigger with one kaon from the D^0 candidate.
- Trigger 2: Hlt1 trigger with two kaons from the D^0 candidate.

With respect to these triggers, we selected two groups of data: events that fired trigger one and events that fired trigger 1 and 2.

The primary idea is to find the signal yields for ON and OFF distribution and calculate the ratios. To define the signal region, two different variables were plot, according to if the event is a Prompt decay or a Semileptonic one. For the Semileptonic events, the invariant mass of the D^0 particle is plot. For the Prompt sample, the variable plot is ΔM, defined as:

$$\Delta M = M(D^*) - M(D^0) \tag{3}$$

This value has a lowest kinematic limit, which is the mass of the pion created in the decay of the D^*.
Fits of this variables were created for each sample, year and KS Type, and also separating the data for ON and OFF peak regions. Two examples are shown in figure 5.

The signal region was fit to a Johnson distribution for both kinds of samples. This distribution is like a tip over gaussian, and requires four parameters for its description. The distribution for the background was different depending on the sample: for the Prompt sample, a kinematic Threshold distribution was selected. For the Semileptionic decays, the background was fit to a first order Chebyshev polynomial.

The fit for the Semileptonic sample was problematic, because the number of events for this kind of decay was notably lower than for the Prompt sample. This lower yields require a different binning, and due to the duration of the program was not possible to perform them on time, so no results will be shown for SL samples.

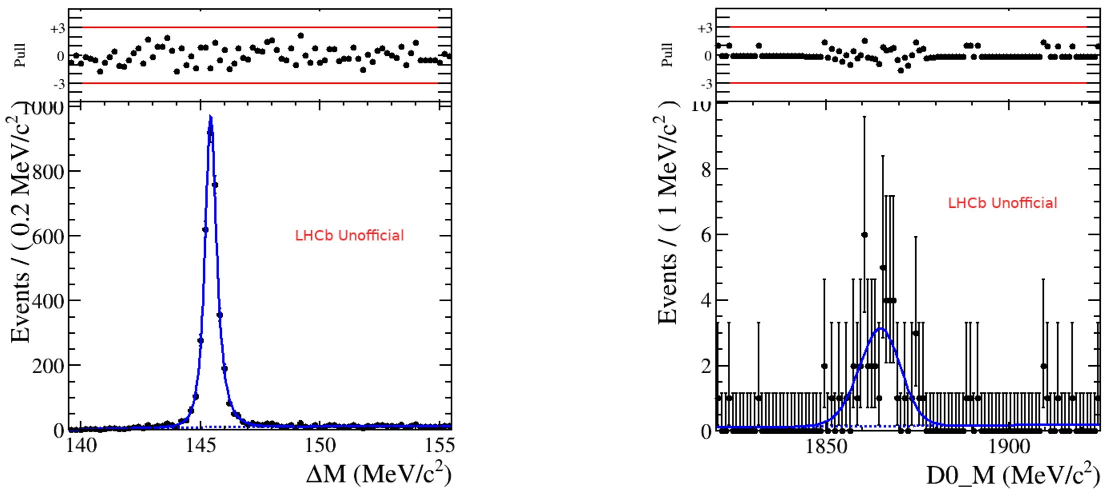

Figure 5: Fits to a Johnson ditribution for: a) Prompt sample of 2016 with KSType LL b) Semileptonic sample of 2016 with KSType LL. The small number of events for the Semileptonic group of decays leads to the big uncertainties in the plot, and therefore, the results of the Semileptonic fits are not used further.

From the fits, the signal yields were extracted, and the ratio $\frac{N(ON)}{N(OFF)}$ calculated for each type of data. One example of the blinded data can be observed in figure 6. In the x axis, the average value of the decay time of D^0 for each of the 15 bins is plot, normalized to the standard decay time of the D^0.

The blinding of the data was performed by generating one random value with a gaussian distribution with mean = 0 and sigma = 0.1 (with seed for python number 13) and adding these same value to every point times the value of the x. The process is like generating a random slope for the points.

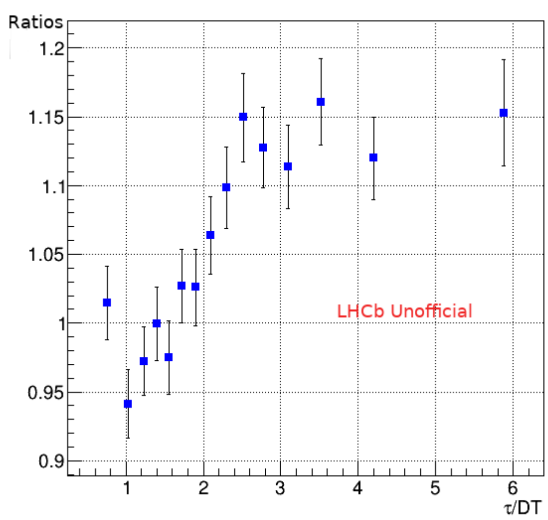

Figure 6: *Ratio* $\frac{N(ON)}{N(OFF)}$ *for data of the sample Prompt, 2016, LL and that fired only the trigger 1.*

As a final step, the blinded data for the fits was fit again and the y parameter was extracted from the fit. The sensitivity that the project aimed to calculate can be computed as the sum in quadrature the uncertainties. For this final step, the data of every year and every sample has been averaged together, but the difference KS Type is maintained, as well as the trigger separation. The results for the sensitivity can be seen in table 1.

	Trigger selection 1	Trigger selection 1 + 2
LL	0.00387	0.00326
DD	0.00469	0.00365

Table 1: *Values of the sensitivity obtained for the different Trigger Selection and KS type.*

5 Conclusions

The sensitivity values for measurements of the y_{CP} parameters are presented in the previous section. With these results, the calculation of the y_{CP} can be performed.

If we calculate the total expected sensitivity given by the sum in quadrature for LL and DD data for each of our triggers, we get the following results:

- Trigger 1: 0.00430
- Triggers 1+2: 0.003460

The obtained value for the y parameter obtained by the LHCb 2019 measurement using $D^0 \rightarrow hh$ is (see reference [3]):

$$y = 0.57 \pm 0.13\,(stat) \pm 0.09\,(syst) \tag{4}$$

To allow a fair comparison, we need to add that our result for the sensitivity could be an optimistic evaluation. Significant systematic effects, such as the contamination from secondary decays in the prompt sample and acceptance effects, need to be accounted in the final measurement, resulting in a potentially larger total uncertainty. Nevertheless, the studies hereby reported are promising and suggest that a complete study of this decay mode is worth pursuing.

Moreover, different binning should be applied for the Semileptonic decay, in order to increase the quality of the fits and be able to extract some results. Overall, further studies are necessary in the topic.

The following step would be to calculate the value of y_{CP} assuming no CP violation. Afterwards, this value will be compared with the standard value of y for this type of decays, and a discrepancy between these two values would indicate CP violation in this fenomena, and its effects could be studied deeply.

References

[1] Belle, A. Zupancet et al. *Measurament of y_{CP} in D^0 meson decays to $K^+K^-K_S^0$ final state. Phys.Rev.D80 (2009) 052006, arXiv:0905.4185. http://arxiv.org/abs/0905.4185*

[2] Thompson, M. *Modern Particle Physics. Cambridge University Press. University of Cambridge, 2013*

[3] Roel Aaij et al. *Measurement of the Charm-Mixing Parameter y_{CP}. LHCb collaboration, CERN (Geneva). DOI: 10.1103/PhysRevLett.122.011802 CERN-EP-2018-270 and LHCb-PAPER-2018-038, LHCb-PAPER-2018-038, CERN-EP-2018-270 e-Print: arXiv:1810.06874 [*