Abstract

The decay $\bar{B}^0 \rightarrow \phi \gamma$, tagged from the $D^{*\pm} \rightarrow \bar{B}^0 \pi^\pm$ decay, has been studied with the data collected at LHCb with the aim of estimating the error achievable on a direct CP asymmetry measurement in this decay. It has been found that additionally to this decay there is an irreducible background of $D^0 \rightarrow \phi \pi^0$. Their respective proportions have been predicted with Monte Carlo simulations and are expected to be: $N_{D^0 \rightarrow \phi \gamma} = 129 \pm 22$ and $N_{D^0 \rightarrow \phi \pi^0} = 511 \pm 160$. With such proportions, the error on the direct CP asymmetry $\frac{\Gamma_{D^0 \rightarrow \phi \gamma} - \Gamma_{\bar{D}^0 \rightarrow \phi \gamma}}{\Gamma_{D^0 \rightarrow \phi \gamma} + \Gamma_{\bar{D}^0 \rightarrow \phi \gamma}}$ is estimated to be 15.5%.
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1 Introduction

The Large Hadron Collider (LHC) at CERN is the world’s highest energy accelerator. It accelerates two proton beams at an energy of 8 TeV each and collides them in order to create conditions that existed shortly after the big bang. The study of the processes that occur during these collisions is crucial to our understanding of the universe. LHCb is one of the four experiments at the LHC and focuses on $b$-physics and CP violation. One of the main goals of LHCb is to understand why our universe is made of matter rather than anti-matter, by studying differences in behaviour of the matter and anti-matter particles produced by the collisions in the LHC. This master project is focused on the study of the direct CP asymmetry ($A_{CP}$) in the decay $D^0 \rightarrow \phi \gamma$. This measurement will be the first in radiative charm sector and it has been suggested as a way to disentangle Standard Model (SM) and New Physics (NP) contributions to the delta $A_{CP}$ measurement by LHCb [1]. A measurement of this asymmetry needs a perfect understanding of the decay and this project focuses on the analysis of the possible confusions between this decay, which is the interesting signal, and the background, the decay $D^0 \rightarrow \phi \pi^0$. Indeed, the $\pi^0$ can be easily misreconstructed as a photon in the detectors. We need to find out efficient methods to discriminate the two components as well as possible and quantify the remaining $D^0 \rightarrow \phi \pi^0$ contamination as precisely as possible. In this project, we will use Monte Carlo (MC) simulations and analyse the 2012 data. We will look at the two decays, signal and background, separately and try to correct the MC predictions with well known calibration channels in sections 5.2.4 and 5.3.3. We will use the helicity as an independent method in order to discriminate the two components and get their respective proportions in section 7. We will finish by estimating the error we could achieve with the current data on the asymmetry measurement on the signal $D^0 \rightarrow \phi \gamma$.

1.1 The LHCb detector

The LHCb detector is one of the four experiments at the LHC at CERN. It has specifically been designed to study bottom particles and CP violation. It has been shown that the produced $b$-particles are boosted forward and backward, they do not scatter in the whole $4\pi$ solid angle [2]. Therefore LHCb only looks in one of the two preferred directions. LHCb is made of several layers of detectors that all have a specific goal. First the VErtex LOcator (VELO), as its name indicates, locates the decay vertices. It is made of 42 silicon disks that are placed very close to the beam. Then there are two Ring Imaging CHERenkov detectors (RICH), which estimate

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1 the charge conjugated decay is implied for all the decays in the project
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the particles’ speed based on the information from their Cherenkov light cones thus providing particle identification information. The magnet bends the charged particles in two directions depending on their charge and the trackers record the tracks left by these charged particles. The Electromagnetic and the Hadronic CALorimeters (ECal and HCal) stop almost all the particles in order to measure their energy. The muon chambers track the muons produced in the various decay processes.

The $c\bar{c}$ production cross section at LHCb is approximately 20 times higher than the $b\bar{b}$ production cross section (see [3] and [4]), making LHCb an ideal place to study charm physics.

![Figure 1: The LHCb detector with all its layers of sub-detectors.](image)

1.2 The decay $D^0 \rightarrow \phi\gamma$

The decay studied in this project is $D^0 \rightarrow \phi\gamma$. This decay and all decays containing a $D^0$ studied in this project will be tagged decays with a $D^0$ coming from $D^{*+} \rightarrow D^0\pi^+$. The complete decay chain is therefore $D^{*+} \rightarrow (D^0 \rightarrow (\phi \rightarrow K^+K^-)\gamma)\pi^+$ and the branching ratio of $D^0 \rightarrow \phi\gamma$ as reported in the PDG [5] is:

$$BR(D^0 \rightarrow \phi\gamma) = (2.70 \pm 0.35) \times 10^{-5}$$

An interesting question to ask oneself is how is this decay possible and what force is involved in the process. The Feynman diagrams on Fig.2 to 5 are four different possibilities for this decay to realise. Two of them are defined as short range and two of them as long range. It has been shown that the only the weak processes can produce an asymmetry (see [6] and [7]).
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Figure 2: First short range possibility for the decay $D^0 \rightarrow \phi \gamma$ to realise, through a weak loop [7].

Figure 3: Second short range possibility for the decay $D^0 \rightarrow \phi \gamma$ to realise, through a W [7].

Figure 4: First long range possibility for the decay $D^0 \rightarrow \phi \gamma$ to realise, called the pole diagram [7].

Figure 5: Second long range possibility for the decay $D^0 \rightarrow \phi \gamma$ to realise, called the vector meson dominance [7].
1.2.1 Data and simulated samples

In 2012 an integrated luminosity of $(2.0 \pm 0.1) \text{ fb}^{-1}$ was recorded and we use stripping 20. The stripping is a selection procedure that applies some cuts to the data in order to select the decays of interest. The MC simulation samples used in this project are listed in Tab.1. Where possible, we use the version of the MC sample corresponding to the Stripping 20 of the 2012 data.

<table>
<thead>
<tr>
<th>Decay</th>
<th>MC production</th>
<th>$N_{gen}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{*+} \to (D^0 \to \phi \gamma) \pi^+$ $(27163203)$</td>
<td>MC12, Pythia8, Sim08c, R14aS20</td>
<td>3011997</td>
</tr>
<tr>
<td>$D^{*+} \to (D^0 \to \phi \pi^0) \pi^+$ $(27163401)$</td>
<td>MC12, Pythia8, Sim08c, R14aS20</td>
<td>3021992</td>
</tr>
<tr>
<td>$D^{*+} \to (D^0 \to K^- \pi^+) \pi^+$ $(27163003)$</td>
<td>MC12, Pythia8, Sim08a, R14aS20</td>
<td>7033225</td>
</tr>
<tr>
<td>$D^{*+} \to (D^0 \to K^- \pi^+ \pi^0) \pi^+$ $(27163400)$</td>
<td>MC11a, 3.5TeV, Sim05c, R12aS17</td>
<td>10004442</td>
</tr>
<tr>
<td>$B_s \to \phi \gamma$ $(13102202)$</td>
<td>MC12, Pythia8, Sim08a, R14aS20</td>
<td>2981989</td>
</tr>
<tr>
<td>$B_d \to K^+ \gamma$ $(11102202)$</td>
<td>MC12, Pythia8, Sim08a, R14aS20</td>
<td>3003487</td>
</tr>
</tbody>
</table>

Table 1: MC simulation samples used in the project along with the Pythia version and the LHCb simulation settings. The last column shows the number of events that were generated for each decay mode.

1.2.2 Stripping Cuts

The stripping cuts were designed to select the signal candidates by taking into account the fact that the stripping line should take a reasonable amount of time and rate. The stripping cuts are shown in Tab.2. The $D^0 \to \phi \gamma$ candidates are required to have two kaons and a slow pion with tracks of good quality (track $\chi^2$). Only kaons with an impact parameter $\chi^2$ (IP $\chi^2$) (defined as the difference between the $\chi^2$ of the primary vertex (PV) formed with and without the considered tracks) greater than 25 are considered. The kaons, the photon and the $D^0$ have a condition on their transverse momentum. The $\phi$ and the $D^0$ are taken inside a mass window, the deltamass is defined as the difference between the reconstructed mass and the PDG mass. The $\phi$ and the $D^*$ must have a well reconstructed vertex (vertex $\chi^2$). The PIDK variable will be defined and explained specifically in section 5.2.2.
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<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm$ track $\chi^2 &lt;$</td>
<td>2.5</td>
</tr>
<tr>
<td>slow $\pi$ track $\chi^2 &lt;$</td>
<td>5</td>
</tr>
<tr>
<td>$K^\pm$ IP $\chi^2 &gt;$</td>
<td>25</td>
</tr>
<tr>
<td>$K^\pm$ PIDK $&gt;$</td>
<td>2</td>
</tr>
<tr>
<td>$K^\pm$ PT $&gt;$</td>
<td>500 MeV/$c$</td>
</tr>
<tr>
<td>$\phi$ deltamass $&lt;$</td>
<td>50 MeV/$c^2$</td>
</tr>
<tr>
<td>$\phi$ vertex $\chi^2 &lt;$</td>
<td>16</td>
</tr>
<tr>
<td>$\gamma$ PT $&gt;$</td>
<td>1700 MeV/$c$</td>
</tr>
<tr>
<td>$D^0$ deltamass $&lt;$</td>
<td>200 MeV/$c^2$</td>
</tr>
<tr>
<td>$D^0$ PT $&gt;$</td>
<td>1000 MeV/$c$</td>
</tr>
<tr>
<td>$\text{abs}(M(D^{*+})-M(D^0)) &lt;$</td>
<td>160 MeV/$c^2$</td>
</tr>
<tr>
<td>$D^{*+}$ vertex $\chi^2 &lt;$</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2: Stripping cuts used in the stripping 20.

This set of cuts is still very loose, and this can be seen in data. The mass region of the $D^0$ is completely dominated by the background as shown in Fig.6.

![Figure 6: $D^0 \rightarrow \phi\gamma$ mass spectrum with the stripping cuts of Tab.2, corresponding to $2 \text{ fb}^{-1}$ of LHCb data.](image)

**1.2.3 Additional Cuts**

Since the stripping cuts were not tight enough in order to get a clean signal peak in data, additional cuts and trigger requirements have been applied and they are listed in Tab.3. The direction angle of the $D^0$ is defined as the angle between the line joining the PV and the secondary vertex (SV)
and the reconstructed momentum of the \(D^0\). The photon related cuts (isPhoton, CL and Veto \(\pi^0 \to \gamma\gamma\)) and the helicity will be explained and detailed in sections 3 and 7 respectively. The ghost probability is multivariate variable provided by the tracking group in order to reduce random background. The LHCb trigger is composed of three levels. Each level reduces the amount of data that needs to be stored, by selecting the interesting events. The level 0 (L0) is a hardware trigger, it looks very quickly at the calorimeter and muon chambers and select the event if it contains clusters of high enough energy. After the L0 come two High Level Triggers (HLT1 and HLT2) which are software triggers. HLT1 reconstructs tracks in the event and select the ones with at least one good quality track. And finally HLT2 reconstructs the whole event and applies decay length and mass cuts in order to achieve a rate of data that is possible to store on hard drives [8].

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^0) lifetime (&gt;)</td>
<td>0 ps</td>
</tr>
<tr>
<td>(D^0) Direction angle (&lt;)</td>
<td>0.02 rad</td>
</tr>
<tr>
<td>(\text{abs}(D^0\text{ helicity}) &lt;)</td>
<td>0.8</td>
</tr>
<tr>
<td>(K^\pm) and slow (\pi) ghost probability (&lt;)</td>
<td>0.3</td>
</tr>
<tr>
<td>(\gamma) isPhoton (&gt;)</td>
<td>0.6</td>
</tr>
<tr>
<td>(\gamma) CL (&gt;)</td>
<td>0.25</td>
</tr>
<tr>
<td>(\gamma) CL (\neq)</td>
<td>0.5</td>
</tr>
<tr>
<td>(\pi^0 \to \gamma\gamma) Veto =</td>
<td>0</td>
</tr>
<tr>
<td>(K^\pm) PIDK (&gt;)</td>
<td>10</td>
</tr>
<tr>
<td>(\phi) delta mass (&lt;)</td>
<td>10 MeV/c²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 Hadron</td>
<td></td>
</tr>
<tr>
<td>HLT1 Photon</td>
<td></td>
</tr>
<tr>
<td>HLT2 Charm (\to) HHX</td>
<td>TOS</td>
</tr>
</tbody>
</table>

Table 3: Additional cuts and trigger requirements applied to clean the signal \(D^0 \to \phi\gamma\).

We make the trigger requirements on our \(D^0 \to \phi\gamma\) candidates using the high PT photon and the hadron tracks from the \(\phi \to K^+K^-\) decay. At L0, we require either the L0Hadron or L0Photon trigger to be fired (TOS, Trigger on signal) by our candidate. At the Hlt1 level, we require either the Hlt1TrackAllL0 or the Hlt1TrackPhoton to be fired by our candidate. Each of the above mentioned trigger lines use only one of the final state particle for its decision. At the Hlt2 level, we use the Hlt2CharmHadD02HHX trigger line which was added at the beginning of the 2012 data taking. This line attempts to reconstruct the \(D^{*+} \to D^0\pi^+\) decay chain, allowing the \(D^0\) to decay to various final states where at least two of the daughter particles are
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hadrons. This trigger line therefore has a very high efficiency on our signal decay. The 2011 data could not be taken into account in this project since no relevant Hlt2 trigger line was present during that period. The result of applying the requirements of Tab.2 and 3 is shown in Fig.7 where a peak with 876 signal candidates is clearly visible.

![Figure 7: $D^0 \to \phi\gamma$ mass spectrum with all the cuts and triggers (Tab.2 and 3) corresponding to 2 fb$^{-1}$ of LHCb data where the fit is a superposition of a Gaussian and a decreasing exponential.](image)

1.2.4 Possible backgrounds

We are interested in isolating the $D^0 \to \phi\gamma$ decay where the narrow $\phi$ meson signal helps reducing the background. However, as it has been pointed out by the study at Babar [9], the backgrounds containing a $\phi$ as well could affect our measurement. We list the branching ratios of the relevant $D^0$ decays containing a $\phi$ meson, [5].

- $BR(D^0 \to \phi X) = (1.05 \pm 0.11)\%$
- $BR(D^0 \to (\phi \to K^+K^-)\rho^0) = (7.0 \pm 0.6) \times 10^{-4}$
- $BR(D^0 \to (\phi \to K^+K^-)(\bar{K}^*(892)^0 \to K^-\pi^+)) = (1.06 \pm 0.20) \times 10^{-4}$
- $BR(D^0 \to (\phi \to K^+K^-)\pi^0) = (6.4 \pm 0.4) \times 10^{-4}$
- $BR(D^0 \to \phi\eta) = (1.4 \pm 0.5) \times 10^{-4}$
- Reminder: $BR(D^0 \to \phi\gamma) = (2.70 \pm 0.35) \times 10^{-5}$
We ran a reconstruction for all of these backgrounds on the CharmCompleteEventDST (0.5 fb$^{-1}$ of LHCb data) in order to see the importance of these decays. We looked at the invariant mass of the $\phi$ and the neutral particle, the plots are shown in appendix A. There is only one background that passes the cuts and still peaks at the $D^0$ mass, it is the $D^0 \rightarrow \phi \pi^0$ decay. We therefore conclude from this that this decay will be a major contribution of the background in data.

We also looked at an inclusive MC sample of $D^0 \rightarrow KKx$, where x is any particle. We reconstructed $D^0 \rightarrow \phi \gamma$ candidates in this sample and applied all stripping cuts. The true ID of the "$\gamma$" candidate reconstructed in this sample is shown in Fig.8, left. On the right of the plot, the mother true ID of the photon is mostly a $\pi^0$. From the results of this study, we see that the major background will be coming from the misreconstruction of the neutral particle.

![Figure 8: Analysis of the $D^{*+} \rightarrow (D^0 \rightarrow K^+ K^- x) \pi^+$ MC sample after stripping cuts (Tab.2). True ID of the photon (left) and true ID v/s the mother ID (right), for the reconstructed $D^0 \rightarrow \phi \gamma$ candidates in this MC sample.](image)

### 2 MC predictions

In order to estimate the real composition of the peak seen on Fig.7, the MC simulations can be used to establish a prediction of the number of events that are expected to be found in data. As seen in the previous section, we expect to have two main components, the $\gamma$ mode : $D^0 \rightarrow \phi \gamma$ and the $\pi^0$ mode : $D^0 \rightarrow \phi \pi^0$.

#### 2.1 The $\gamma$ mode

For the $\gamma$ mode, we have the following MC12 sample :

- Number of generated events : $N_{gen} = 3011997$
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- Number of selected events after all the cuts and triggers: $N_{\text{sel}} = 403$
- The efficiency of this selection is computed below.

$$
\varepsilon = \frac{N_{\text{sel}}}{N_{\text{gen}}} \pm \sqrt{\frac{N_{\text{sel}}}{N_{\text{gen}}}} = (1.34 \pm 0.07) \times 10^{-4}
$$

(2)

The error on the efficiency is taken as an approximation of the Poisson error. This approximation works if $N_{\text{sel}} \neq 0$ and $N_{\text{sel}} \ll N_{\text{gen}}$ [10], which is the case in this project. A first computation of the expected number of events can be done with this efficiency and the result is shown in Eqn.4. The values of the parameters used are shown in Tab.4.

$$
N_{\text{exp}} = L_{2012} \cdot \sigma_{\bar{c}c} \cdot 2 \cdot f_{D^+} \cdot \varepsilon_{\text{gen},D^0 \to \phi \gamma} \cdot \mathcal{B}(D^+ \to D^0 \pi^+) \\
\cdot \mathcal{B}(D^0 \to \phi \gamma) \cdot \mathcal{B}(\phi \to K^- K^+ \gamma) \cdot \varepsilon
$$

(3)

$$
= 497 \pm 76 \text{events}
$$

(4)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity $L_{2012}$</td>
<td>$(2.0 \pm 0.1)$ fb$^{-1}$</td>
<td>[3]</td>
</tr>
<tr>
<td>Production cross section $\sigma_{\bar{c}c}$</td>
<td>$(6.10 \pm 0.93) \times 10^3$ µb</td>
<td>[3]</td>
</tr>
<tr>
<td>Fragmentation fraction $f_{D^+}$</td>
<td>0.229 ± 0.026</td>
<td>[3]</td>
</tr>
<tr>
<td>Decprodcut eff. $\varepsilon_{\text{gen},D^0 \to \phi \gamma}$</td>
<td>0.0731 ± 0.0003</td>
<td>[11]</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \to D^0 \pi^+)$</td>
<td>$(6.77 \pm 0.05) \times 10^{-1}$</td>
<td>[3]</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \to \phi \gamma)$</td>
<td>$(2.70 \pm 0.35) \times 10^{-5}$</td>
<td>[3]</td>
</tr>
<tr>
<td>$\mathcal{B}(\phi \to K^- K^+ \gamma)$</td>
<td>$(4.89 \pm 0.05) \times 10^{-1}$</td>
<td>[3]</td>
</tr>
<tr>
<td>Decprodcut eff. $\varepsilon_{\text{gen},D^0 \to K^- \pi^+}$</td>
<td>0.0823 ± 0.003</td>
<td>[11]</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \to (\phi \to K^- K^+ \gamma) \pi^0)$</td>
<td>$(4.0 \pm 0.4) \times 10^{-4}$</td>
<td>[3]</td>
</tr>
<tr>
<td>Decprodcut eff. $\varepsilon_{\text{gen},D^0 \to K^- \pi^0}$</td>
<td>0.2153 ± 0.0004</td>
<td>[11]</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \to K^- \pi^+)$</td>
<td>$(3.88 \pm 0.05)%$</td>
<td>[5]</td>
</tr>
<tr>
<td>Decprodcut eff. $\varepsilon_{\text{gen},D^0 \to K^- \pi^0 \pi^0}$</td>
<td>0.3526 ± 0.0004</td>
<td>[11]</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \to K^- \pi^+ \pi^0)$</td>
<td>$(13.9 \pm 0.5)%$</td>
<td>[5]</td>
</tr>
<tr>
<td>Production cross section $\sigma_{\bar{b}b}$</td>
<td>$(2.84 \pm 0.53) \times 10^2$ µb</td>
<td>[4]</td>
</tr>
<tr>
<td>Fragmentation fraction $f_s$</td>
<td>0.09 ± 0.02</td>
<td>[12]</td>
</tr>
<tr>
<td>Decprodcut eff. $\varepsilon_{\text{gen},B_s \to \phi \gamma}$</td>
<td>0.2352 ± 0.0008</td>
<td>[11]</td>
</tr>
<tr>
<td>$\mathcal{B}(B_s \to \phi \gamma)$</td>
<td>$(3.6 \pm 0.4) \times 10^{-5}$</td>
<td>[5]</td>
</tr>
<tr>
<td>Fragmentation fraction $f_d$</td>
<td>0.366 ± 0.061</td>
<td>[12]</td>
</tr>
<tr>
<td>Decprodcut eff. $\varepsilon_{\text{gen},B_d \to K^- \gamma}$</td>
<td>0.2150 ± 0.0005</td>
<td>[11]</td>
</tr>
<tr>
<td>$\mathcal{B}(B_d \to K^- \gamma)$</td>
<td>$(4.33 \pm 0.15) \times 10^{-5}$</td>
<td>[5]</td>
</tr>
<tr>
<td>$\mathcal{B}(K^+(892)^0 \to K^+ \pi^-)$</td>
<td>$\sim 100%$</td>
<td>[5]</td>
</tr>
</tbody>
</table>

Table 4: Parameters needed in order to compute the expected number of events in each decay
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The $c\bar{c}$ cross section is taken in the whole $4\pi$ angle. This is done because the literature contained different PT and $\eta$ phase space than us and then interpolated their result to $4\pi$ with Pythia. Each of the quark in the $c\bar{c}$ pair can produce a $D^{*+}$, which is why the factor 2 is present. Then we need to account for the proportion of the c quarks that produce a $D^{*+}$, this is the role of the fragmentation fraction $f_{D^{*+}}$. Finally we need to select the events that are in the acceptance of LHCb and this is represented by the decprodcut efficiency $\epsilon_{\text{gen}}$. This efficiency is different for each decay and it is computed by Pythia.

2.2 The $\pi^0$ mode

The same computation is done for the $\pi^0$ mode where we have the following MC12 sample:

- Number of generated events: $N_{\text{gen}} = 3021992$
- Number of selected events after all the cuts: $N_{\text{sel}} = 46$
- The efficiency of this selection is computed below.

$$\epsilon = \frac{N_{\text{sel}}}{N_{\text{gen}}} \pm \sqrt{\frac{N_{\text{sel}}}{N_{\text{gen}}}} = (1.5 \pm 0.2) \times 10^{-5} \quad (5)$$

And again, a first computation of the expected number of events can be made, using the parameters listed in Tab.4.

$$N_{\text{exp}} = L_{2012} \cdot \sigma_{c\bar{c}} \cdot 2 \cdot f_{D^{*+}} \cdot \epsilon_{\text{gen},D^0\rightarrow\phi\pi^0} \cdot BR(D^{*+} \rightarrow D^0 \pi^+) \cdot BR(D^0 \rightarrow (\phi \rightarrow K^+ K^-) \pi^0) \cdot \epsilon$$

$$= 3077 \pm 531 \text{ events} \quad (6)$$

2.3 Incompatible predictions

From this computation, we see that we expect six times more events in the $\pi^0$ mode than in the $\gamma$ mode. However, these two components do not add up to the observed number of events in data.

$$(497)_{\gamma \text{ mode}} + (3077)_{\pi^0 \text{ mode}} \neq (868)_{\text{data}} \quad (7)$$

A likely explanation for the above result is that the simulation does not describe well the efficiencies for neutral particles. This has already been established in radiative B decays (discussed in section5.2.4). This could also be true for the efficiency of the slow pion in the $D^{*+} \rightarrow D^0 \pi^+$ decay. Therefore, we correct the yield predictions from MC by taking more effects into account.
account and calibrating the MC efficiencies with well-known clean signals. The basic idea is to reweight the MC efficiency with information from a calibration channel in order to match the data efficiency as shown in Eqn.9.

\[ \varepsilon_{\text{data}} = \varepsilon_{\text{MC}} \cdot \left( \frac{N_{\text{data}}}{N_{\text{MC}}} \right)_{\text{cal.channel}} \]  

Where \( \varepsilon_{\text{data}} \) is the efficiency in data, \( \varepsilon_{\text{MC}} \) is the efficiency in MC, \( N_{\text{data}} \) is the signal yield of the calibration channel fitted in data and \( N_{\text{MC}} \) is the expected number of signal of the calibration channel computed in MC as shown in Eqn.3 or 6.

3 Photon related cuts

There are three photon related cuts that have been used in this project: the "isPhoton", the "\( \gamma \) Confidence Level (CL)" and the veto \( \pi \rightarrow \gamma \gamma \). They have been optimised for the \( b \)-physics by the calorimeter group, therefore a further analysis needs to be undertaken in order to know whether we can apply the recommended values from the \( b \)-physics or if they need to be adjusted for our own study. Moreover, we need to establish if the efficiency of the cuts on those variables is well modelled in MC.

3.1 isPhoton

The variable "isPhoton" is a composition of many informations coming from the shower created by the photon in the calorimeter. This variable goes from 0 to 1 and the closer a candidate gets to 1, the more chance there is that it is a photon. The recommended cut given by the calorimeter group is to keep everything above 0.6 (\( \gamma \) isPhoton > 0.6). In order to validate the \( \gamma \sim \pi^0 \) separation power of this variable, we compare its distribution for the neutral particle in \( B_s \rightarrow \phi \gamma \) and \( D^0 \rightarrow K^- \pi^+ \pi^0 \) samples from the data. This is shown in Fig.9.

The shape is quite different between the two clean decays \( B_s \rightarrow \phi \gamma \) and \( D^0 \rightarrow K^- \pi^+ \pi^0 \) and this variable has a good discrimination power at low isPhoton values. A cut at 0.6 will remove a lot of background while leaving most of the signal. Since we are comparing the shape of this variable in a B and a D decay, some PT dependence could spoil a fair comparison of these shapes. We looked at the PT dependence of this variable (see appendix B) and found no evidence for this.

We also looked at the difference of the shape of this variable between data and MC. This is shown in Fig.10. Since the data are not background subtracted, there is a reasonable agreement between the two and we can assume we can compute the efficiency of the cut on this variable in MC.
3.2 CL

The variable "CL" is a Confidence Level for being a neutral particle. It also takes information from the ECal and ranges from 0 to 1. Since the calorimeter group recommends to apply two cuts on this variable (CL > 0.25 and CL != 0.5), we need to know the difference between MC and data to see if the efficiency of this cut needs to be handled specifically. This difference is shown for the decay $D^0 \rightarrow K^- \pi^+ \pi^0$ in Fig. 11. We can see that it is rather similar and that therefore a cut in MC or in data will have a similar efficiency. It has also been studied whether this variable shows a PT dependence and the plots are shown in the appendix C. No PT dependence either have been
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found here.

![Diagram](image)

Figure 11: Shape of the variable "CL" for the decay $D^0 \rightarrow K^- \pi^+ \pi^0$ in LHCb data (2 fb$^{-1}$, Stripping 20 production) and MC.

### 3.3 Veto $\pi^0 \rightarrow \gamma\gamma$

The veto is the last photon related variable that can possibly help to identify the photons. The value of this variable is equal to 1 (0) if it was (not) possible to reconstruct a $\pi^0 \rightarrow \gamma\gamma$ candidate in that event, combining the photon in question and any other photon in the calorimeter. Therefore a cut of Veto=0 removes a part of the $\pi^0$ background, specifically the resolved $\pi^0$. There are indeed two kinds of possible reconstruction for a $\pi^0$ in the LHCb detector, either the $\pi^0$ decays into two photons, which in turn create two showers that are detected in the ECal and the invariant mass match the one of a $\pi^0$, in this case the $\pi^0$ is resolved. Or the two photon showers are unresolved, in which case, the candidate is called a merged $\pi^0$. This last component is harder to discriminate from the photons.

We also need to know if the efficiency of the cut on this variable is similar in MC and in data. In order to do this we look at the ratio of the number of merged $\pi^0$ and resolved $\pi^0$ in data and MC. This is shown in Fig.12. We see that there is a good agreement between both and that we can therefore compute the efficiency in MC. We also see that there are much more merged $\pi^0$ than resolved $\pi^0$ and that the higher the PT, the more merged $\pi^0$ there is.
4 \( \pi^0 \) reconstruction as \( \gamma \)

We look now at the efficiency of the reconstruction of a \( \pi^0 \) as a \( \gamma \), which is what is happening in data. From the \( D^{*+} \rightarrow (D^0 \rightarrow \phi \pi^0)\pi^+ \) MC12 sample we reconstructed three different sets: we reconstruct the \( \pi^0 \) of this sample as a \( \gamma \), as a merged \( \pi^0 \) and as a resolved \( \pi^0 \).

4.1 Without photon related cuts

In the \( \gamma \) set, we first apply all the cuts but the three photon related ones discussed previously. There are 188 candidates that passes the selection. From those 188 candidates, we want to know if some of them can also be reconstructed as a merged or a resolved \( \pi^0 \). In order to do this, we look at the \( \phi \) in the three sets by comparing their momentum. If the \( \phi \) candidate of any of the 188 candidates of the \( \gamma \) set has the same momentum as either in the merged or the resolved \( \pi^0 \) sets, we conclude that the event is the same. Here are the result of this comparison between the three sets.

- 188 events pass the cuts in the \( \gamma \) set
- 103 events have the same \( \phi \) as a candidate in the merged \( \pi^0 \) set
- 26 events have the same \( \phi \) as a candidate in the resolved \( \pi^0 \) set

\( \Rightarrow \) 59 events could not be matched to any candidate of the \( \pi^0 \) sets

Those 59 unmatched candidates are coming from a \( D^0 \rightarrow \phi \pi^0 \) sample, so it is strange that the neutral particle cannot be reconstructed as a \( \pi^0 \). A further analysis is therefore undertaken on the 59 unmatched candidates.
They were projected to a 2D plane 12m downstream the primary vertex, which is the location of the ECal of LHCb [2]. This projection has been done in order to see if they were located on the edges of the ECal and that we lost the second photon of the $\pi^0$ decay. But these candidates are not close to the edges of the ECal as we can see on Fig.13. It is therefore not the reason why these candidates cannot be reconstructed as $\pi^0$. We also looked at the PT and the invariant mass of the three sets (see appendix D) in order to spot any discrimination between them, but none were found.

![Figure 13: Projection of the position of the neutral candidate onto the LHCb calorimeter, from the "unmatched" $D^0 \rightarrow \phi \gamma$ candidates (refer to text) in $D^0 \rightarrow \phi \pi^0$ simulated events.](image)

Finally, we looked at the true ID and the true mother ID of those unmatched candidate. And most interestingly, their true ID is the one of a photon, but their mother true ID is the one of a $\pi^0$ in 55 case out of 59 (there are also 2 $\pi^0$ coming from a $D^0$ and 2 non identified particles). We therefore conclude that these candidates were also mis-reconstructions of a true $\pi^0$ as a photon.

4.2 With photon related cuts

We recreate the three sets but by applying all the cuts including the photon related ones in order to see the effect of these three cuts. The new numbers obtained are listed below:

- 46 events pass the cuts in the $\gamma$ set
- 22 events have the same $\phi$ as a candidate in the merged $\pi^0$ set
- 0 events have the same $\phi$ as a candidate in the resolved $\pi^0$ set

$\Rightarrow$ 24 events could not be matched to any candidate in the $\pi^0$ sets
The first immediate conclusion to draw is that the three variables remove almost 3/4 of the 188 mismatched candidates from the previous section, they are quite efficient. Moreover, the veto works as expected, it takes care of all the resolved $\pi^0$. From this we can conclude that our real background in data will mostly be merged $\pi^0$.

5 Efficiency calibration

5.1 Procedure

We apply now the calibration of the MC in order to correct the predictions we made in section 2. In order to apply this calibration, the efficiency of the selection $\varepsilon$ used in Eq.3 is split in two parts, the MC efficiency and the Particle IDentification (PID) efficiency. Moreover, some corrections are applied in order to make the MC predictions match the data more precisely.

1. The MC efficiency is computed as in Eq.2 but without applying any PID cuts: $\varepsilon_{MC}^{\prime}$

2. The PID cut efficiency is computed by re-weighting the tracks according to the efficiencies measured in data in the decay $D^0 \to K^- \pi^+$: $\varepsilon_{PID}$

3. We look at the tracking efficiency correction given by the tracking group of LHCb: $\varepsilon_{Tr}^{\prime}$

4. We compute the efficiency correction coming from the calibration channel: $\varepsilon_{N}^{\prime}$, where N stands for the neutral particle, either the photon or the $\pi^0$.

5. Finally we compute the efficiency correction coming from the $D^{*+}$ tagging and the slow pion: $\varepsilon_{slow\pi}^{\prime}$

The "$\varepsilon$" account for real efficiencies as the "$\varepsilon^{\prime}$" account for the corrections. These corrections are computed as the ratio between data and MC: $N_{data}/N_{MC}$. This procedure will be applied on the $\gamma$ and $\pi^0$ mode in the next sections.

5.2 The $\gamma$ mode

The calibration is first applied on the $D^0 \to \phi\gamma$ mode in order to get a reliable prediction of the number of events one can expect to find in data.
5.2.1 MC efficiency

As mentioned above, in order to compute the MC efficiency, all the cuts but the PID ones are applied. The number of events left after these cuts is $N_{sel} = 466$. Then the computation is the same as in Eq.2 and this gives an efficiency: $\epsilon_{MC} = (1.55 \pm 0.07) \times 10^{-4}$.

5.2.2 PID efficiency

The particle identification is using information from all the detectors of LHCb. The trackers measure the bending radius (due to the magnet) and the charge of the particle, the RICH measure the velocity and the calorimeters measure the total energy. The small differences between MC and data will therefore add up and result in a significant error on the identification of the particle. Therefore the PID efficiency needs to be computed in data. In order to be able to compute this efficiency correctly, we need clean tracks without applying any PID cuts. This is the case in the decay $D^0 \rightarrow K^- \pi^+$. The PID is based on the comparison between two particle hypotheses and is represented by the difference in logarithms of the likelihoods (DLL) between the two hypotheses. Kaons are required to have $DLL_K(\pi) > x$ while pions are required to have $DLL_K(\pi) < x$. The methods used to compute the efficiency of the PID cuts are explained in the appendix E.

In the decay $D^0 \rightarrow \phi \gamma$, there are two relevant tracks, the two kaons coming from the $\phi$. We apply the cut $PID_K > 10$ on each track. The PID efficiency has to be computed on both particles. However, they are not independent as they are the two daughter particles of a two body decay. In order to take this correlation into account, we use a toy method. First, the efficiency is computed in data on the kaon of the decay $D^0 \rightarrow K^- \pi^+$ in P and PT bins (see Fig.14).

For each of those bins, a random Gaussian with mean 0 and sigma 1 is built with N numbers, where N is the number of toys, typically 10000. For each event of the MC sample $D^0 \rightarrow \phi \gamma$, we need to know in which bin the two tracks are located and then create an array of N values containing the product of the two corresponding efficiencies shifted by its error times the random number of the Gaussian. And these N values are saved in a histogram which is fitted with a Gaussian. Its mean and the sigma are taken as the PID efficiency and its error. The correlation is taken into account by the fact that every time a track falls in the same bin, the N values will be shifted by the same random number. The resulting histogram is shown on Fig.15.

$$\epsilon_{PID} = 0.8444 \pm 0.0004$$ (10)
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Figure 14: Efficiency of the cut PIDK > 10 applied on the kaon, computed in the 2 fb$^{-1}$ data sample of $D^0 \to K \pi$ decays in $P$ and PT bins of the kaon.

Figure 15: Result of the toy method (refer to text) to estimate the efficiency of PIDK > 10 cut on the kaons from $D^0 \to \phi \gamma$ decay.

5.2.3 Tracking efficiency correction

The tracking group has provided corrections in order to match the tracking efficiencies between data and MC. These corrections are given in momentum and pseudorapidity bins as shown in Fig.16.

The same procedure as explained for the PID efficiency is used here. A random Gaussian is generated with N numbers for each bin, the two bins in which the tracks are located are found, the product of the two corrections is taken by shifting each component by its error multiplied by the random number of the Gaussian and this is done for each event of the MC sample. Finally the average is taken and the result is shown on Fig.17.

\[ \chi^2 / \text{ndf} = 10.63 / 13 \]

\[ \text{Constant} = 1888 \pm 23.3 \]

\[ \text{Mean} = 0.8444 \pm 0.0000 \]

\[ \text{Sigma} = 0.0004221 \pm 0.0000031 \]
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1.04186 1.0107 1.0067 1.00812 1.02354
1.0732 1.00311 0.991312 0.987473 0.994748

Momentum $P$ (GeV/c)

$\eta$ Pseudorapidity

2 2.5 3 3.5 4 4.5

Figure 16: Correction factors for the tracking efficiency in momentum and pseudorapidity bins, LHCb tracking group [13].

We can observe that the correction that has to be applied for the tracking efficiencies is:

$$\epsilon_{Tr}' = 1.004 \pm 0.002$$  \hspace{1cm} (11)

This correction is smaller than one percent. Therefore we conclude that the MC describes well the tracking in our case and we neglect this correction, it will not be applied in the following sections.
5.2.4 Photon efficiency correction

The correction for the photon reconstruction efficiency is the major part of the correction. It comes from the calibration channel $B_s \to \phi \gamma$. It is computed as the ratio between the expected number of events coming from the MC prediction and the observed number of events in data. However, the $B_s$ and the $D^0$ do not have the same photon PT spectrum (see Fig. 18). We need to know the dependence in PT of the photon efficiency correction. We will therefore compute this efficiency correction in PT bins. In order to obtain correct values, the MC of the $B_s$ needs to have its PID efficiency computed as explained in the section 5.2.2 in order to match the efficiency of the data. We do not correct for the tracking since we saw that this efficiency is well modelled by the MC.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure18.png}
\caption{PT spectrum of three different decays, LHCb MC.}
\end{figure}

5.2.4.1 $B_s \to \phi \gamma$ In order to visualise the dependence in photon PT of the correction factor we compute the number of expected events from MC and fit the data in each PT bin $i$. $N_{\text{exp}}$ is computed without any PID cuts applied and the PID efficiency is computed in the $D^0 \to K^- \pi^+$ data.

\begin{align}
\epsilon'_{\gamma,i} &= \frac{N_{\text{obs},i}}{N'_{\text{exp},i}} \quad (12) \\
\text{where} \quad N'_{\text{exp},i} &= N_{\text{exp},i} \cdot \epsilon_{\text{PID}} \quad (13)
\end{align}

In order to be sure that all kinematics effects are taken into account, we do this computation for three different PIDK cuts, two different methods and different binnings in P-PT and P-$\eta$ (the pseudorapidity). The three cuts, PIDK > 0, PIDK > 5 and PIDK > 10, are applied on both kaons. The two different methods (normal and background subtracted) used are explained.
in the appendix E. These six results are shown in Fig.19 and they should be identical if we really have only the contribution of the photon efficiency. The binning used for this figure is 11 bins in P and 4 bins in PT. The other binnings gave compatible results.

Figure 19: Efficiency correction for the photon in the $B_s \rightarrow \phi \gamma$ for three different PID cuts and two different PID efficiency computation methods.

A disturbing feature of these six results is that they are actually different. The two different PID computation methods are compatible, but the points for the cut "PIDK > 10" are almost always higher than the other. The tighter the PIDK cut is, the lower is the PID efficiency and the closer $N_{\text{exp}}$ gets to $N_{\text{obs}}$. This differences can be understood by the fact that the PID cuts select a particular phase space for the tracks and consequently for the photon. If we look at the polar angle of the photon, we can see that it is different for different cuts (see Fig.20). Therefore if the photon phase space is different, it is not a surprise that the efficiency correction is different. For now, these differences are taken as systematics but if the real measurement of the CP asymmetry is being done, it would be necessary to dig further into this in order to know if there is a way to quantify the effect of the phase space and if it is possible to isolate completely the contribution of the photon. It is also important to know if we can apply the correction computed in the $B_s$ to the $D^0$. We look therefore at the difference of the photon phase space between the decays. We see on Fig.21 that there are some difference but they are of the same order than the one between PID cuts, on Fig.20. Therefore these differences are also taken into account in the systematics that we have chosen.

The goal of this computation was to detect any PT dependence for the photon efficiency correction. From Fig.19, no PT dependence is suggested, which means that we would not need to cut the sample in PT bins in order to apply the correction. There are however a little number of bins. It is
Direct CP asymmetry in $D^0 \to \phi \gamma$

Figure 20: Polar angle of the photon with (blue) and without (red) PID cuts (PIDK $> 10$) for $\gamma$ PT $< 3500$ for simulated $B_s \to \phi \gamma$ events.

Figure 21: Polar angle of the photon for different decays without any PID cuts, LHCb MC.

limited by the fact that in order to be able to fit the data, we need enough statistics in each bin.

5.2.4.2 Cross-check with $B_d \to K^* \gamma$ In order to have a better idea of the PT dependence, we need more bins, we therefore do the same computation for the decay $B_d \to K^* \gamma$ where there is a lot more statistics. The computation is also made for the three different PID cuts and the two different PID computation methods. The result is shown on Fig. 22. We can observed that the difference between the PID cuts is also present, it is a real effect. There is also another strange effect, if we had completely isolated the contribution of the photon, the correction would be the same if we compute it on the $B_s$ or the $B_d$. But it is not, the average is around 0.65 for the $B_s$ and around
0.55 for the $B_d$. This difference is not understood. Possible sources of this difference could be an error on the fragmentation fractions $f_s$ and $f_d$ or on the branching ratios of the two decays.

This result is however still reassuring for the PT dependence, for all the six different computations, a fit with a straight line gave a slope compatible with zero. Based on those results, we conclude that the photon efficiency correction is independent of the photon PT.

![Efficiency correction for the photon in the $B_d \to K^{*} \gamma$ for three different PID cuts and two different PID efficiency computation methods.](image)

**Figure 22:** Efficiency correction for the photon in the $B_d \to K^{*} \gamma$ for three different PID cuts and two different PID efficiency computation methods.

### 5.2.4.3 Final result for $\epsilon'_{\gamma}$

As we saw in the previous sections, the efficiency correction for the photon is independent of the photon PT, but it is different for the $B_s$ and the $B_d$ and it is different for each PID cuts. For this project, we decide to take the value from the $B_s$ because this decay is closer to the $D^0 \to \phi \gamma$ that we are interested in, it also has a $\phi$. We take the same PID cut as it is applied on the $D^0$: "PIDK > 10" and we choose one of the two methods since they are compatible (we take the background subtracted one). Finally, we fit a flat line through all the points and take the offset as the final value for the correction (see Fig.23). For its error, since we chose to take as systematics the difference between the PID cuts, we also fit with a flat line the graph for the cut "PIDK > 0" which has the lowest correction (see Fig.24). The difference between those two values is taken as the error on the correction:

\[
\epsilon'_{\gamma,\text{PIDK}>10} - \epsilon'_{\gamma,\text{PIDK}>0} = 0.6449 - 0.6102 = 0.0347 \tag{14}
\]

\[
\Rightarrow \epsilon'_{\gamma} = 0.6449 \pm 0.0347 \tag{15}
\]
5.2.5 Slow pion efficiency correction

The slow pion efficiency correction represents the efficiency of the reconstruction of the pion in the decay $D^{*+} \rightarrow D^0 \pi^+$. This pion is defined as slow since it has very little energy because the decay of the $D^*$ is at threshold. In order to correct this efficiency in the estimation of the expected number of events, we take again the $D^0 \rightarrow K^- \pi^+$ decay as a calibration. No PID cuts are applied in order to do this computation, so we do not need to take care of its efficiency. This decay is tagged, so it contains the slow pion efficiency and we assume it is the only contribution present in this decay. A sample of 123.8 pb$^{-1}$ is used and on Fig.25, one can see that the fit
of the data gives $N_{\text{sig}} = (1.371 \pm 0.001) \times 10^6$. There is a prescale of 0.8 in the stripping line and therefore we have to divide $N_{\text{sig}}$ by this prescale in order to obtain $N_{\text{obs}} = (1.714 \pm 0.002) \times 10^6$.

Figure 25: Fit to the $D^0 \to K^- \pi^+$ mass spectrum in 123.8 pb$^{-1}$ of LHCb data, Stripping 20 production.

The parameters needed for the computation are listed in Fig.4 but the luminosity is different, we used a small sample of $L_{K\pi} = 123.8 \pm 6.2$ pb$^{-1}$.

$$N_{\text{exp}} = L_{K\pi} \cdot \sigma_{ct} \cdot 2 \cdot f_{D^{*+}} \cdot \epsilon_{\text{gen},D^*\to K^-\pi^+} \cdot \mathcal{B}(D^{*+} \to D^0 \pi^+) \cdot \mathcal{B}(D^0 \to K^- \pi^+) \cdot \epsilon$$

$$= (2.93 \pm 0.19) \times 10^6$$

The efficiency of the decay $D^0 \to K\pi$ and therefore the slow pion efficiency correction is computed as:

$$\epsilon'_{\text{slow,}\pi} = \frac{N_{\text{obs}}}{N_{\text{exp}}} = 0.58 \pm 0.04$$
5.3 The $\pi^0$ mode

The same calibration procedure is applied to the mode $D^0 \rightarrow \phi \pi^0$. The selection efficiency $\epsilon$ from Eq.5 is split into two parts, the MC efficiency and the PID efficiency. We neglect the correction for the tracking, as explained in the section 5.2.3. And for this mode, we use the decay $D^0 \rightarrow K^- \pi^+ \pi^0$ as calibration channel. Unlike the decay $B_s \rightarrow \phi \gamma$, this decay is tagged, therefore we can get the slow pion efficiency correction together with the correction for the neutral particle.

5.3.1 MC efficiency

As for the $\gamma$ mode, the MC efficiency is computed with all the cuts applied but the PID ones. We do the same computation as done at Eq.5 but with $N_{sel} = 54$. This gives an efficiency of $\epsilon_{MC} = (1.8 \pm 0.2) \times 10^{-5}$.

5.3.2 PID efficiency

For this mode, we use again the computation with the random Gaussian. Since the tracks are also two kaons coming from the $\phi$, we use the same method as explained in section 5.2.2 which result is shown below.

$\epsilon_{PID} = 0.7795 \pm 0.0002 \ (19)$

5.3.3 $\pi^0$ and slow $\pi$ efficiency correction

As explained before, the two corrections, ie the $\pi^0$ component coming from the calibration channel and the one for the slow pion, could be computed in the same decay, $D^0 \rightarrow K^- \pi^+ \pi^0$. In this decay some PID cuts have been applied. In order to compute the expected number of events in MC, we need to do the same procedure as in the other decays. We need to compute the MC efficiency without any PID cuts and multiply it by the PID efficiency computed in data. However, we do not possess any sample of the decay $D^0 \rightarrow K^- \pi^+ \pi^0$ without any PID cuts, they are already applied in the stripping. The stripping cuts and the additional cuts that have been applied are listed in the appendix F. We found a workaround by assuming that the tracks of $D^0 \rightarrow K^- \pi^+ \pi^0$ have similar spectra than the $D^0 \rightarrow K^- \pi^+$. In the $D^0 \rightarrow K^- \pi^+$ we do not have any PID cuts applied, so we can compute the PID efficiency in MC and in data in this decay in order to correct the one in $D^0 \rightarrow K^- \pi^+ \pi^0$, as shown in Eq.20.

$$\epsilon'_{\pi^0} \cdot \epsilon'_{\text{slow} \pi} = \left( \frac{N_{\text{obs}}}{N_{\text{exp}}} \right)_{K\pi\pi^0} \cdot \left( \frac{\epsilon_{PID, \text{MC}}}{\epsilon_{PID, \text{data}}} \right)_{D^0 \rightarrow K\pi}$$

(20)
The first step is to get the observed number of events in data of $D^0 \to K^- \pi^+ \pi^0$ through the fit of the $D^0$ mass. This is done in Fig. 26 but there is a prescale of 0.083 in the stripping. This means that $N_{\text{obs}} = (3.8 \pm 0.1) \times 10^5$.

![Figure 26: Fit to the $D^0 \to K^- \pi^+ \pi^0$ mass spectrum in 2 fb$^{-1}$ of LHCb data, Stripping 20 production.](image)

Then the expected number of events from MC is computed with the PID efficiency computed in MC since we cannot do differently in this decay with the current stripping. The parameters needed are listed in Tab. 4 and the efficiency is computed to be $\epsilon = (4.168 \pm 0.200) \times 10^{-5}$, it contains $\epsilon_{\text{MC}}$ and $\epsilon_{\text{PID}}$. The result is shown at Eqn. 22.

$$N_{\text{exp}} = L_{2012} \cdot \sigma c \cdot 2 \cdot f_{D^+} \cdot \epsilon_{\text{gen}, D^0 \to K^- \pi^+ \pi^0} \cdot BR(D^{+} \to D^0 \pi^+) \cdot BR(D^0 \to K^- \pi^+ \pi^0) \cdot \epsilon$$

$$= (2.9 \pm 0.6) \times 10^6$$

And finally we need the PID efficiencies in data and in MC for the decay $D^0 \to K^- \pi^+$ in order to rescale the expected number of events of $D^0 \to K^- \pi^+ \pi^0$. In order to do this, we need to know the number of signal with and without the PID cut. The PID cuts are the following:

- on the kaon: PIDK $> 10$
- on the pion: PIDK $< -10$

For the MC, we cut and count the Ntuple since it is all signal, but for the data we need to do a mass fit. The fit without the PID cut has already been done on Fig. 25 and it is done on Fig. 27 with the PID cut. We need to take into account again that there is a prescale of 0.8 in data.
• Number of signal in MC without PID cut: 10582 ± 103
• Number of signal in MC with PID cut: 4216 ± 65
⇒ PID efficiency in MC: \( \epsilon_{\text{PID, MC}} = 0.398 \pm 0.007 \)
• Number of signal in data without PID cut: \( (1.714 \pm 0.002) \times 10^6 \)
• Number of signal in data with PID cut: \( (4.991 \pm 0.008) \times 10^5 \)
⇒ PID efficiency in data: \( \epsilon_{\text{PID, data}} = 0.2912 \pm 0.0006 \)

All parameters of Eqt.20 have been computed, the result is shown below.

\[
\epsilon'_{\pi^0} \cdot \epsilon'_{\text{slow}\pi} = 0.18 \pm 0.05
\]  

Figure 27: Fit to the \( D^0 \rightarrow K^-\pi^+ \) mass spectrum in 123.8 pb\(^{-1}\) of LHCb data, Stripping 20 production.

6 Total expected yields

All the efficiencies and the corrections have been computed and they are summarised in Tab.5. We can use them in order to get a realistic expected number of events for the \( \gamma \) and the \( \pi^0 \) mode. We apply all these changes to Eqt.3 and 6 and the result is shown at Eqt.25 and 27, using the relevant parameters from Tab.5.
Direct CP asymmetry in $D^0 \rightarrow \phi \gamma$

M. Schubiger

<table>
<thead>
<tr>
<th>$D^0 \rightarrow \phi \gamma$</th>
<th>$D^0 \rightarrow \phi \pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{MC}$</td>
<td>$(1.55 \pm 0.07) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\epsilon_{PID}$</td>
<td>0.8444 ± 0.0004</td>
</tr>
<tr>
<td>$\epsilon'_{\gamma}$</td>
<td>0.6449 ± 0.0347</td>
</tr>
<tr>
<td>$\epsilon'_{\text{slow} \pi}$</td>
<td>0.58 ± 0.04</td>
</tr>
<tr>
<td>$\epsilon_{MC}$</td>
<td>$(1.8 \pm 0.2) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\epsilon_{PID}$</td>
<td>0.7795 ± 0.0002</td>
</tr>
<tr>
<td>$\epsilon'<em>{\pi^0} \cdot \epsilon'</em>{\text{slow} \pi}$</td>
<td>0.18 ± 0.05</td>
</tr>
</tbody>
</table>

Table 5: Summary table of all efficiencies and efficiency corrections computed in the previous sections for the $\gamma$ and the $\pi^0$ mode.

$$N_{exp,D^0\rightarrow\phi\gamma} = L_{2012} \cdot \sigma_{c\bar{c}} \cdot 2 \cdot f_{D^{*+}} \cdot \epsilon_{gen,D^0\rightarrow\phi\gamma} \cdot BR(D^{*+} \rightarrow D^0 \pi^+) \cdot BR(D^0 \rightarrow \phi \gamma) \cdot BR(\phi \rightarrow K^- K^+) \cdot \epsilon_{MC} \cdot \epsilon_{PID} \cdot \epsilon'_{\gamma} \cdot \epsilon'_{\text{slow} \pi}$$ (24)

$$= 129 \pm 22 \text{ events}$$ (25)

$$N_{exp,D^0\rightarrow\phi\pi^0} = L_{2012} \cdot \sigma_{c\bar{c}} \cdot 2 \cdot f_{D^{*+}} \cdot \epsilon_{gen,D^0\rightarrow\phi\pi^0} \cdot BR(D^{*+} \rightarrow D^0 \pi^+) \cdot BR(D^0 \rightarrow (\phi \rightarrow K^- K^+) \pi^0) \cdot \epsilon_{MC} \cdot \epsilon_{PID} \cdot \epsilon'_{\pi^0} \cdot \epsilon'_{\text{slow} \pi}$$ (26)

$$= 511 \pm 160 \text{ events}$$ (27)

Having corrected the predictions of the MC for the expected number of events of the $\gamma$ and the $\pi^0$ mode, we can compare the total number of events expected to the observed number of events in data. The expected numbers of the two modes have a correlated part, they both contain the luminosity, the $c\bar{c}$ cross section, the $D^{*+}$ fragmentation fraction and the branching ratio $BR(D^{*+} \rightarrow D^0 \pi^+)$. Therefore the error on the total number of expected events takes this correlation into account.

$$\Rightarrow N_{exp,tot} = 640 \pm 163$$

- Compared to data : $N_{obs} = 876 \pm 61$

- Ratio of the signal : $\frac{N_{exp,D^0\rightarrow\phi\gamma}}{N_{exp,tot}} = 0.20 \pm 0.05$

These corrected predictions are compatible within errors. But it could be that there are some other modes present in the data that we did not take into account such as partially reconstructed decays.
7 Discrimination with helicity

The helicity provides a totally independent way to get the proportions of the two modes \( D^0 \rightarrow \phi \gamma \) and \( D^0 \rightarrow \phi \pi^0 \) present in data. The helicity is defined here as the cosine of the angle (that we will call \( \theta \)) between the \( D^0 \) and one of the kaons coming from the \( \phi \) in the rest frame of the \( \phi \). It has a discriminant power since the two main components are of different kinds. The \( D^0 \) is a scalar, the \( \phi \) is a vector meson, the photon is a vector boson and the \( \pi^0 \) is a pseudoscalar meson. Therefore the mode \( D^0 \rightarrow \phi \gamma \) has a combination Scalar going to Vector-Vector (S \( \rightarrow \) \( VV \)) as the mode \( D^0 \rightarrow \phi \pi^0 \) has a combination Scalar going to Vector-Pseudoscalar (S \( \rightarrow \) \( VP \)). Those two configurations have a totally different shape in helicity (see Fig.28). We will use a two dimensional fit on the helicity and the \( D^0 \) mass in order to get informations on the proportions of the two components we are interested in. We will therefore validate the 2D fit on toy MC and then use it to make an sPlot on data.

![Figure 28: Shape of the helicity for a VV and a VP configurations of the daughter particles in a two body decay of a scalar particle.](image)

7.1 2D Fit

First, we build the 2D fit with the \( D^0 \) mass and the helicity. We need to take into account the combinatorial background that we see in the sidebands on Fig.7. We build therefore two probability density functions (PDF) for the helicity, one is a combination of the helicity shape of \( D^0 \rightarrow \phi \gamma \) and \( D^0 \rightarrow \phi \pi^0 \), Eqn.28, and one for the combinatorial background, Eqn.29. The helicity shapes for the \( \gamma \) and \( \pi^0 \) mode are shown in Fig.28 and for the com-
binatorial background the shape is taken from the sidebands in data. The sidebands are defined as the whole range at disposal for the $D^0$ minus the signal region, taken as the $D^0$ mass $\pm 3\sigma$ (where $\sigma$ is taken from the fit on Fig.7). This means that the left sideband ranges from 1680 MeV/$c^2$ to 1762 MeV/$c^2$ and the right sideband from 1966 MeV/$c^2$ to 2020 MeV/$c^2$. The PDF is then built with the RooFit function RooKeysPdf, which approximates any type of data with multiple Gaussians [14]. As the left and right sidebands could be different we look on Fig.29 at them separately. It seems that the left sideband has a similar shape in helicity as the $\pi^0$ mode. This indicates that there might be some partially reconstructed decays with a $\pi^0$ in that sideband. We however do not take these additional backgrounds into account for now, this could be the subject of a further analysis.

For the signal and the background helicity PDFs, we will use the sum of the two components with a floating fraction, as shown below.

\[
PDF_{\text{sig}} = f_{\text{gam}} \cdot PDF_{\sin^2} + (1 - f_{\text{gam}}) \cdot PDF_{\cos^2} \quad (28)
\]
\[
PDF_{\text{bkg}} = f_{\text{left}} \cdot PDF_{\text{left}} + (1 - f_{\text{left}}) \cdot PDF_{\text{right}} \quad (29)
\]

Figure 29: Shape of the helicity in the sidebands (left : [1680-1762] MeV/$c^2$, right : [1966-2020] MeV/$c^2$) of the decay $D^0 \to \phi\gamma$ with all the cuts and triggers (Tab.2 and 3) applied to 2 fb$^{-1}$ of LHCb data, Stripping 20 production.

So we have the following 2D PDFs :

- The signal containing the $\gamma$ mode and the $\pi^0$ mode
  - a Gaussian for the $D^0$ mass
  - The PDF from Eqt.28 for the helicity
• The combinatorial background
  – a decreasing exponential for the $D^0$ mass (fixed from the fit in Fig.7)
  – The PDF from Eqt.29

In order to know if the fit works we build a toy MC, so that we can input the yields we want and see if the fit can retrieve them. We fix all the shapes of the PDFs from fits in MC with the true ID cuts applied. We let only the yields for each component float. We input the following yields in the toy:

• Signal : $129 + 511 = 640$ (MC predictions from section 6)
• Background = 2432 (yield of combinatorial background in Fig.7)

Figure 30: Example of a 2D fit for the helicity, toy MC.

Figure 31: Example of a 2D fit for the $D^0$ mass, toy MC.
The toys comprise of a 2D fit of the mass and the helicity, an example is shown in Fig.30 and 31. We perform 10000 toys by saving each time the yields and the fraction between the $\gamma$ and the $\pi^0$ mode in a histogram. The result is shown in Fig.32 and 33. These figures show the difference between the result of the fit and the input value. The three histograms are fitted with a Gaussian and their parameters are summarised in Tab.6. This study has also been done with different yields and the fit was also able to retrieve extreme values (very low signal or very low background). It has been checked also that the fit errors scale with statistics. We therefore conclude that the fit is unbiased for a range of signal and background proportions and total number of candidates.

![Figure 32: Resulting histograms of the 10000 2D fits for the yields of signal and background, toy MC.](image1)

![Figure 33: Resulting histogram of the 10000 2D fits for the fraction of the $\gamma$ mode in the signal mass peak, toy MC.](image2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal $\mu$</td>
<td>$0.14 \pm 0.35$</td>
</tr>
<tr>
<td>Signal $\sigma$</td>
<td>$34.5 \pm 0.3$</td>
</tr>
<tr>
<td>Background $\mu$</td>
<td>$-0.11 \pm 0.35$</td>
</tr>
<tr>
<td>Background $\sigma$</td>
<td>$34.5 \pm 0.3$</td>
</tr>
<tr>
<td>Fraction $\mu$</td>
<td>$(7 \pm 4) \times 10^{-4}$</td>
</tr>
<tr>
<td>Fraction $\sigma$</td>
<td>$(4.75 \pm 0.30) \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Table 6: Parameters of the Gaussians shown on Fig.32.
7.2 sPlot in data

Now that the 2D fit has been validated on toy MC, we can build an sPlot with the helicity and the $D^0$ mass. An sPlot is a function in RooFit that unfolds two distributions by adding weight to each bin in the histogram according to a discriminant variable [14]. In our case, the sPlot will use the $D^0$ mass as the discriminant variable and will separate the combinatorial background from the mass peak. The result shown on Fig.34, shows the yields found with this method. We can look at the ratio of the $\gamma$ mode and compare it to the one predicted by MC in section 6. As a reminder, in MC we predicted that $(20 \pm 5)\%$ of the peak was the $\gamma$ mode. Here we can see that $(23 \pm 5)\%$ of the yield $nSig$ is the $\gamma$ mode. These two predictions are absolutely compatible.

![Figure 34: sPlot of the helicity and the $D^0$ mass with a helicity cut at $< 0.8$ on 2 fb$^{-1}$ of LHCb data, Stripping 20 production. Top left figure is the result of the 2D fit for the discriminant variable, the $D^0$ mass. Top right figure is the result of the 2D fit for the helicity. Bottom left figure is the weighted helicity shape for the $\gamma$ and $\pi^0$ mode, result of the sPlot. Bottom right figure is the weighted helicity shape for the combinatorial background, result of the sPlot.](image-url)
8 Feasibility of the asymmetry measurement

The goal of this project was to understand the signal that we see in data for the decay $D^0 \rightarrow \phi \gamma$. We can therefore now predict the error of an asymmetry measurement if it was done on the current data. The direct CP asymmetry is composed of different parts shown in Eqt.30.

$$A_{CP,raw} = A_{CP,phys} + A_{CP,slow \pi} + A_{CP,D^{*+} prod}$$  \hspace{1cm} (30)

The physical asymmetry is the one we are interested in but in data we can only get the raw asymmetry. We need to compute the asymmetry due to the slow pion detection and reconstruction and the $D^{*+}$ production elsewhere in order to be able to subtract them. For now, in this project, we assume that the effect of these two asymmetries is much smaller than the statistical precision.

The principle of the raw asymmetry measurement is to separate the data in two, the positive and the negative part. Since the decay is tagged this is easily done, we define the positive component as the one coming from the $D^{*+}$ and the negative component as the one coming from the $D^{*-}$. We assume that we only have the two modes studied in this report, the $\gamma$ mode (S) and the $\pi^0$ mode (B), we do not take into account the combinatorial background. We will therefore have the following yields:

- $N_+ = S_+ + B_+$
- $N_- = S_- + B_-$

The diluted CP asymmetry is the one that can be measured in data and it is defined as:

$$A^{D}_{CP} = \frac{N_+ - N_-}{N_+ + N_-}$$  \hspace{1cm} (31)

In order to compute the error we would get on the diluted asymmetry, we separate the predicted yields from section 6 into two and make them fluctuate with a Poisson error. Moreover, we need to artificially create an asymmetry. We halve the yields exactly in two and then add different asymmetries in order to get a feeling of the error. We compute the asymmetry 10000 times for each different asymmetry, each time with a different random Poisson fluctuation on the yields. We fill a histogram with the results and fit with a Gaussian. An example of this Gaussian fit is shown at Fig.35. The mean of the Gaussian is the artificial CP asymmetry that we inputted and the $\sigma$ is the error on the measurement.
Direct CP asymmetry in $D^0 \rightarrow \phi \gamma$

Fig. 35 shows the error we would get on the diluted asymmetry. The error we could achieve with the current data and the current cuts, represented by the full black points, is 4% and it has almost no dependence in the asymmetry. An interesting information as well is the error on the asymmetry we could get if we double the statistics but keep the same selection, ie. the background and the signal discrimination would still be the same. We would achieve an error of 2.8% on the diluted asymmetry, represented by the empty circles on the figure.

Fig. 36 shows the error we would get on the diluted asymmetry. The error we could achieve with the current data and the current cuts, represented by the full black points, is 4% and it has almost no dependence in the asymmetry. An interesting information as well is the error on the asymmetry we could get if we double the statistics but keep the same selection, ie. the background and the signal discrimination would still be the same. We would achieve an error of 2.8% on the diluted asymmetry, represented by the empty circles on the figure.

Figure 35: Example of one of the toys of the diluted asymmetry with input value $A_{CP}^D = 0.01$.

Figure 36: Measurement of the error on the diluted asymmetry for a helicity cut at 0.8, ie. with the yields found in section 6, LHCb MC.
Direct CP asymmetry in $D^0 \rightarrow \phi \gamma$

M. Schubiger

These results are also achievable via the analytical computation of the asymmetry and its error. The definition of the diluted asymmetry is shown in Eqn.31. The full computation to get to its error is shown in appendix G and the result is shown below.

$$\sigma_{A_{CP}} = \frac{1}{\sqrt{N}} \sqrt{1 - (A_{CP})^2}$$  \hspace{1cm} (32)

We can see with this analytical result the low dependence in the asymmetry. For a zero asymmetry, the error is equal to 3.953% and for an asymmetry of 0.04, the error is equal to 3.950%. And this analytical computation give also the result for twice the current statistics if we divide the above results by $\sqrt{2}$. The error for the zero asymmetry is 2.795%. Our toy is therefore fully compatible with the analytical computation.

The diluted asymmetry is what can be measured in data, however, the interesting asymmetry to know is the one on the signal, the non diluted one. In order to get the non diluted asymmetry from the diluted asymmetry we need to do some computations (see appendix G). The result is shown in Eqn.33 in function of the signal fraction (number of $D^0 \rightarrow \phi \gamma$ candidates in the signal peak). The error on this fraction is taken as 25% as computed from the MC predictions in section 6.

$$A_{CP}^{ND} = \frac{A_{CP}}{f}, \text{where } f = \frac{S}{S+B}$$  \hspace{1cm} (33)

Therefore, the error we could achieve on the non diluted asymmetry is computed as the propagation of the errors from the diluted asymmetry and the signal fraction, as shown below.

$$\sigma_{A_{CP}^{ND}} = A_{CP}^{ND} \sqrt{\left(\frac{\sigma_{A_{CP}}}{A_{CP}}\right)^2 + \left(\frac{\sigma_f}{f}\right)^2}$$  \hspace{1cm} (34)

Knowing the error on the non diluted asymmetry, we are able to make another study, an optimisation of the cut on the helicity. Indeed, the cut used in this project was $|\text{helicity}| < 0.8$, however we could look now at the influence of this cut on the error we would achieve on an asymmetry measurement. The yields are different for each helicity cut, they have been computed as in Eqn.24 for the $\gamma$ mode and Eqn.26 for the $\pi^0$ mode, but by estimating the efficiency of each helicity cut from the theoretical PDF of each mode shown in Fig.28. This method had to be used because of the really low statistics in the MC samples that prevented us to cut and count the numbers of events left for each cut. The yields found are listed in Tab.7. The optimisation of the cut is done on the error on the non diluted asymmetry in Fig.37. The best achievable error is 15.5% with a cut on the helicity at 0.4.
Direct CP asymmetry in $D^0 \rightarrow \phi\gamma$

M. Schubiger

<table>
<thead>
<tr>
<th>Helicity cut</th>
<th>Signal S</th>
<th>Background B</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>136</td>
<td>1024</td>
<td>0.12</td>
</tr>
<tr>
<td>0.9</td>
<td>134</td>
<td>747</td>
<td>0.15</td>
</tr>
<tr>
<td>0.8</td>
<td>128</td>
<td>525</td>
<td>0.20</td>
</tr>
<tr>
<td>0.7</td>
<td>119</td>
<td>351</td>
<td>0.25</td>
</tr>
<tr>
<td>0.6</td>
<td>107</td>
<td>221</td>
<td>0.33</td>
</tr>
<tr>
<td>0.5</td>
<td>93</td>
<td>128</td>
<td>0.42</td>
</tr>
<tr>
<td>0.4</td>
<td>77</td>
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<td>0.3</td>
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<td>0.83</td>
</tr>
<tr>
<td>0.1</td>
<td>20</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7: Expected number of events for the $\gamma$ mode (Signal) and $\pi^0$ mode (Background) for different helicity cut along with the signal fraction (f).

Figure 37: Optimisation of the helicity cut on the error on the non diluted asymmetry, LHCb MC

9 Conclusion

The goal of this project was to analyse and understand the decay $D^0 \rightarrow \phi\gamma$ in order to make a prediction on the error one could get if a CP asymmetry measurement was done on this decay. This has been done by predicting the number of events we expect from MC simulations for the two main components. These two main components are the $\gamma$ mode which is really the decay $D^0 \rightarrow \phi\gamma$ and the $\pi^0$ mode is the decay $D^0 \rightarrow \phi\pi^0$. This $\pi^0$ mode is a background mode that is hard to discriminate from the signal. Nevertheless, if we know the proportions of both modes we know the dilution coming from the $\pi^0$ and we can still do the CP asymmetry measurement. The MC simulations were overestimating the efficiencies, so we computed
the PID efficiency in data for all the decays we used. In MC, we corrected as well the slow pion efficiency and we used a calibration channel in order to correct for efficiency coming from the reconstruction of the neutral particle ($\gamma$ or $\pi^0$). The final predictions for the two modes are the following:

- $D^0 \rightarrow \phi \gamma$ : $129 \pm 22$
- $D^0 \rightarrow \phi \pi^0$ : $511 \pm 160$

$\Rightarrow$ Total number of expected events : $640 \pm 163$

With such yields, we saw that we would achieve an error of 4% on the diluted direct CP asymmetry. From this asymmetry we have computed the error on the non diluted asymmetry. In order to get the best achievable measurement, we optimised the helicity cut. The cut giving the best result was $|\text{helicity}| < 0.4$ and the error on the non diluted asymmetry is 15.5%. Therefore the measurement is feasible but we have to keep in mind that we would have an error of this order on the result.

In order to get to a real measurement of the direct CP asymmetry in the decay $D^0 \rightarrow \phi \gamma$, there are a few points that need to be taken care of. First, as shown in Tab.1, the MC sample for the decay $D^0 \rightarrow K^- \pi^+ \pi^0$ is an old one without any resonances in the invariant mass of the daughter particles. In data, we see some resonances which could alter our measurements. We need to get a MC12 sample as well for this decay. Then, we have seen that the total number of expected events is lower than the observed number of events in data. We need to investigate if there are indeed partially reconstructed backgrounds that pass our selection. We need also to compute two asymmetries that we have been neglecting here, the slow pion and the $D^+$ production asymmetries. In order to get a correct measurement, we need to know these two parameters precisely. And finally there might also be some $D^*$ coming from B mesons. As the B mesons have their own asymmetry it could influence our measurement. However as it has been shown in the analysis [15], the contribution expected from those events is much smaller than our current statistical errors.

10 Acknowledgements

I would like to thank first Tatsuya Nakada for allowing me to do my master project at the LPHE with him and for his comments and suggestions on the various subjects addressed in this project. Many thanks to Fatima Soomro for introducing me to the subject of radiative decays, for answering my questions throughout the semester and for the proofreading of the report. I would also like to thank Olivier Schneider for the helpful discussions along the project that helped to move it forward.
A Plots of possible backgrounds

The stripped $D^0 \to \phi\gamma$ events are stored in the CharmCompleteEventDst. In order to check if the backgrounds listed in section 1.2.4 make a large contribution to our signal peak (Fig.7) by providing a good $\phi$ candidate, we looked for those backgrounds in this sample (we use 0.5 fb$^{-1}$) and applied all $D^0 \to \phi\gamma$ cuts except the cuts on the $\gamma$ related variables. The idea was to reject events which peaked in one of these backgrounds as well, namely $D^0 \to \phi(\rho^0 \to \pi^+\pi^-)$, $D^0 \to \phi(K^*(892)^0 \to \bar{K}^-\pi^+)$ and $D^0 \to \phi(\eta \to \gamma\gamma)$. The $D^0$ mass for these candidates is shown in Fig.38 to 41 and we observe that only the $D^0 \to \phi\pi^0$ mode exhibits a clear signal peak.

Figure 38: Invariant mass of the sample $D^0 \to \phi\rho^0$, LHCb data, Stripping 20, 0.5 fb$^{-1}$. Figure 39: Invariant mass of the sample $D^0 \to \phi\pi^0$, LHCb data, Stripping 20, 0.5 fb$^{-1}$.

Figure 40: Invariant mass of the sample $D^0 \to \phi\bar{K}^*(892)^0$, LHCb data, Stripping 20, 0.5 fb$^{-1}$. Figure 41: Invariant mass of the sample $D^0 \to \phi\eta$, LHCb data, Stripping 20, 0.5 fb$^{-1}$.
B  isPhoton vs PT

As mentioned in the section 3.1, we wanted to see the dependence of the isPhoton variable in the neutral PT. We therefore plotted this variable for the three interesting decays, $B_s \rightarrow \phi \gamma$, $D^0 \rightarrow K^- \pi^+ \pi^0$ and $D^0 \rightarrow \phi \gamma$, in PT bins. No strong dependence can be deduced from this study since the shape of the variable is similar for all the bins.

![Figure 42: Shape of the variable isPhoton for a photon in the decay $B_s \rightarrow \phi \gamma$, LHCb data, Stripping 20, 2 fb$^{-1}$.](image1)

![Figure 43: Shape of the variable isPhoton for a $\pi^0$ in the decay $D^0 \rightarrow K^- \pi^+ \pi^0$, LHCb data, Stripping 20, 2 fb$^{-1}$.](image2)
Direct CP asymmetry in $D^0 \to \phi\gamma$

M. Schubiger

The three following plots show the variable CL for the decays $B_s \to \phi\gamma$, $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to \phi\gamma$ in PT bins. No dependence have been found.

Figure 44: Shape of the variable isPhoton for a $\pi^0$ in the decay $D^0 \to \phi\gamma$, LHCb data, Stripping 20, 2 fb$^{-1}$.

C CL vs PT

Figure 45: Shape of the variable CL for a photon in the decay $B_s \to \phi\gamma$, LHCb data, Stripping 20, 2 fb$^{-1}$.
Direct CP asymmetry in $D^0 \to \phi \gamma$

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Figure 46: Shape of the variable CL for a $\pi^0$ in the decay $D^0 \to K^- \pi^+ \pi^0$, LHCb data, Stripping 20, 2 fb$^{-1}$.

Figure 47: Shape of the variable CL for the neutral particle in the decay $D^0 \to \phi \gamma$, LHCb data, Stripping 20, 2 fb$^{-1}$.

D Further analysis on the $\pi^0$ reconstruction

A further analysis has been done on the 188 candidates coming from the $D^0 \to \phi \pi^0$ sample with a $\pi^0$ reconstructed as a photon. A comparison has been done between the three components for their PT spectrum (Fig.48) and between the invariant mass of the neutral candidate and the $\phi$ (Fig.49). The point of this small analysis was to find any discrimination between the three sets but none could be found.
E PID cuts efficiency computation

Efficiencies for the various PID cuts made on the tracks (kaons and pions in our case) have been measured using a sample of $D^{*+} \rightarrow (D^0 \rightarrow K\pi)\pi^+$ decay extracted from the NoPIDDstarWithD02RSKPiLine of Stripping20. To avoid any biases arising from the trigger, the probe track (kaon or pion) is required to be TIS with respect the L0Global and the HLT1Phys lines while no requirement on the HLT2 level has been set. This does not bias the results because these decays are selected by HLT2 lines without any
PID requirements. To further clean the sample after the stripping selection, the track of the $D_0$ decay that is not used to evaluate the fake rate (the tag track), is required to be well identified with a cut of $\text{DLL}_k > 10$ and $\text{DLL}_k < 0$ for the kaon and pion tag respectively.

The DLL cut efficiencies are evaluated by binning the sample in the kinematics of the probe track and fitting the $D_0$ mass. The number of signal and background events in a suitable mass window around the $D_0$ peak are extracted. The efficiency to identify a real kaon (pion) as a kaon (pion) by requiring a certain DLL cut is related to the “total” efficiency evaluated in a signal mass window of $\pm 15 \text{MeV}/c^2$ around the peak ($\epsilon_{S+B}$) and the “background efficiency” ($\epsilon_B$), evaluated in the mass sidebands ($|M - M_{D^0}| > 25 \text{MeV}/c^2$), by

$$\epsilon_S = \frac{B + S}{S} \left( \epsilon_{S+B} - \frac{B}{S + B} \epsilon_B \right) \quad (35)$$

This method is referred in the text as "background subtraction" method. An alternate method is used, again binning the sample in the kinematics of the probe track, and in each bin extracting the number of signal events without and with the relevant DLL cut, and dividing the latter by the former. The fitting model used in both methods consists of the sum of a Crystal Ball and a Gaussian (mean constrained to be the same) for the signal peak, and a straight line for the background.

### F $D_0 \rightarrow K^- \pi^+ \pi^0$ Cuts

<table>
<thead>
<tr>
<th>$\pi^0$</th>
<th>StdLooseMergedPi0, StdLooseResolvedPi0 PT $&gt; 800 \text{ MeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^- (\pi^+)$</td>
<td>StdAllNoPI0sPions, DLLk $&gt; 0$ ($&lt; 0$) PT $&gt; 500 \text{ MeV}$, $P &gt; 5 \text{ GeV}$ IP $\chi^2 &gt; 4$, track $\chi^2 &lt; 5$</td>
</tr>
<tr>
<td>$D_0$</td>
<td>$(m_{\text{pdg}}) &lt; 200$, DOCA $&lt; 1.5 \text{ mm}$, DIRA $&lt; 450 \text{ mrad}$, PT $&gt; 2.5 \text{ GeV}$, vertex $\chi^2 &lt; 10$, vertex distance $\chi^2 &gt; 36$</td>
</tr>
<tr>
<td>slow $\pi$</td>
<td>$P &gt; 170 \text{ MeV}$, IP $&lt; 0.5 \text{ mm}$</td>
</tr>
<tr>
<td>$D^{*+}$</td>
<td>$</td>
</tr>
</tbody>
</table>

Table 8: Stripping cuts of the decay $D_0 \rightarrow K^- \pi^+ \pi^0$. 

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Direct CP asymmetry in $D^0 \to \phi \gamma$

| $\pi^0$ | PT $> 1700$ MeV |
| $K^- (\pi^+)$ | PIDk $> 10$ ($< -10$) |
| $\pi^0$ | IP $\chi^2 > 25$, track $\chi^2 < 2.5$ |
| $D^0 (|M-pdg| < 160$ MeV) | DIRA $< 20$ mrad |
| slow $\pi$ | track $\chi^2 < 5$ |

Table 9: Harder cuts in order to clean the signal peak in the decay $D^0 \to K^- \pi^+ \pi^0$.

**G Analytical computations**

First we show the computation of the error on the diluted asymmetry.

\[
\frac{\partial A_{\text{CP}}^{D}}{\partial N_{+}} = \frac{(N_{+} - N_{-}) + N_{-}}{N_{+} + N_{-}} = \frac{2N_{-}}{N_{+}} \quad (36)
\]

\[
\frac{\partial A_{\text{CP}}^{D}}{\partial N_{-}} = \frac{-(N_{+} + N_{-}) - N_{+} + N_{-}}{N_{+} + N_{-}} = \frac{2N_{+}}{N_{-}} \quad (37)
\]

\[
\sigma_{A_{\text{CP}}^{D}}^{2} = \frac{4N_{+}^{2}}{N_{+}^{2}} \sigma_{N_{+}}^{2} + \frac{4N_{-}^{2}}{N_{-}^{2}} \sigma_{N_{-}}^{2} = \frac{4N_{+}N_{-}}{N_{+}N_{-}} \quad (38)
\]

\[
1 - (A_{\text{CP}}^{D})^{2} = (1 + A_{\text{CP}}^{D})(1 - A_{\text{CP}}^{D}) = \frac{2N_{+}N_{-}}{N_{+}N_{-}} = \frac{4N_{+}N_{-}}{N_{+}N_{-}} \quad (39)
\]

\[
\sigma_{A_{\text{CP}}^{D}}^{2} = \frac{1 - (A_{\text{CP}}^{D})^{2}}{N} \quad (40)
\]

\[
\sigma_{A_{\text{CP}}^{D}} = \frac{1}{\sqrt{N}} \sqrt{1 - (A_{\text{CP}}^{D})^{2}} \quad (41)
\]

Then we show the computation to get the expression of the diluted asymmetry in function of the asymmetry on the signal.

We define the total numbers: $S = S_+ + S_-$, $B = B_+ + B_-$

the asymmetry on the signal: $A_{\text{CP}}^{S} = \frac{S_+ - S_-}{S_+ + S_-}$

and the asymmetry on the background: $A_{\text{CP}}^{B} = \frac{B_+ - B_-}{B_+ + B_-}$

\[\Rightarrow S_+ = \frac{S}{2}(1 + A_{\text{CP}}^{S}), \quad S_- = \frac{S}{2}(1 - A_{\text{CP}}^{S}) \quad (45)\]

\[\Rightarrow B_+ = \frac{B}{2}(1 + A_{\text{CP}}^{B}), \quad B_- = \frac{B}{2}(1 - A_{\text{CP}}^{B}) \quad (46)\]
Direct CP asymmetry in $D^0 \rightarrow \phi\gamma$

\( A_{CP}^D = \frac{S_+ + B_+ - S_- - B_-}{S_+ + B_+ + S_- + B_-} \) 

\( = \frac{\frac{1}{2}(S(1 + A_{CP}^S) + B(1 + A_{CP}^B) - S(1 - A_{CP}^S) - B(1 - A_{CP}^B))}{S + B} \) 

\( = \frac{SA_{CP}^S + BA_{CP}^B}{S + B} \) 

\( = \frac{S}{S + B} A_{CP}^S + \frac{B}{S + B} A_{CP}^B \)

assuming a zero asymmetry on the background:

\( \Rightarrow A_{CP}^D = \frac{S}{S + B} A_{CP}^S \)
Direct CP asymmetry in $D^0 \rightarrow \phi \gamma$  
M. Schubiger

References


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