

Analysis of flavour mixing and CP violation in the strange-beauty meson system using LHCb data

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Abstract

This research analysed the flavour mixing and CP violation in the B_s^0 meson system using LHCb data for the $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow D_s^\mp K^\pm$ decays. The available data was filtered using the available detector reconstruction parameters, and fitted with theoretical functions to extract fundamental parameters of nature. Mass plots for the B_s^0 and $D_s^\mp$ mesons were created, together with decay-time distributions, flavour mixing and CP-asymmetry plots. Δm_s was found to be $(17.732 \pm 0.042) \cdot 10^{12} s^{-1}$ and $\Delta \Gamma_s = (0.00 \pm 0.35) \cdot 10^{12} s^{-1}$, where the natural units $\hbar \equiv c \equiv 1$. The obtained master equation parameters do not deviate significantly from 0, so no CP violation was observed. Further improvements could be the use of more sophisticated fitting software, for example RooFit, and a more extensive background contribution modelling.

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Chapter 1

Introduction

1.1 Historical background

The Standard Model (SM) of particle physics has been around since the 1970's [1, 2, 3, 4] and has been extensively tested experimentally. It includes three generations of fundamental quarks and leptons ($\text{spin} = \frac{1}{2}$), four gauge bosons ($\text{spin} = 1$) covering the electromagnetic, weak and strong interaction, and a scalar Higgs boson ($\text{spin} = 0$). The underlying theory of the SM is quantum field theory (QFT) and the SM is used to explain and predict the behaviour of particle interactions.

Three Generations of Matter (Fermions)				
	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name→	u up	c charm	t top	γ photon
Quarks	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
	<2.2 eV 0 $\frac{1}{2}$ ν_e electron neutrino	<0.17 MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	<15.5 MeV 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV 0 1 Z weak force
	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	80.4 GeV ± 1 1 W weak force
	Leptons			Bosons (Forces)

Figure 1.1: Schematic depiction of the Standard Model of elementary particles [5].

There are, however, physical observations that can not be explained by

the SM. One of the major unexplained phenomena is the baryon asymmetry in the observable universe, which means that there is an imbalance of matter and antimatter, with a surplus of matter [6]. It is generally assumed that at very early times in the universe fast particle-antiparticle production and annihilation were in thermal equilibrium, and that some out-of equilibrium process generated the currently observed baryon asymmetry. This (theoretical) process is known as Baryogenesis. In 1967 Sakharov formulated three conditions, now known as the Sakharov conditions, that have to be satisfied to allow baryon asymmetry to occur [7]. These three conditions are listed below:

1. Baryon number violation must have occurred. Baryon number is a quantum number assigned to quarks. If matter dominates over antimatter, a violating fundamental process must have occurred.
2. Charge (C) and charge-parity (CP) symmetry violation must have occurred in processes. Similarly, these symmetries would lead to perfect annihilation of matter and antimatter, therefore their violation is required.
3. The universe departed from thermal equilibrium. If this was not the case, no net asymmetry could be generated, since the backwards reaction would restore any asymmetry created by a process.

This analysis will focus on the second condition, in particular CP violation. Most readers will be familiar with the concept of charge, but possibly not with parity. The charge operator inverts the sign of the charge of a particle, turning it into its anti-particle. The parity operator (P) flips the signs of the spatial coordinates of a particle; it thus changes a right-handed coordinate system into a left-handed one or vice-versa. Parity conservation implies that any process and its mirror image will proceed exactly the same. For further explanation on the subject of parity, charge, CP, and particle physics in general, 'Modern Particle Physics' provides a more detailed explanation [8].

Originally, however, it was assumed that parity and charge symmetries were conserved in all fundamental processes. In 1957, two experiments were performed that showed that the weak interaction violates parity [9, 10]. By simultaneously performing charge conjugation, however, there was still a combined CP symmetry. This CP symmetry meant that the physics laws for a particle should be the same for its antiparticle in mirror image. Violation of this CP symmetry, and therefore an observable difference between matter and antimatter, was observed for the first time in 1964 with kaon particles. This experiment showed that the weak interaction does not only violate parity or charge, but also, in smaller amounts, the combination of the two [11].

For the theory this means that quantum mechanical processes for particles and antiparticles must be described with complex conjugated amplitudes.

In 1963, when only three quarks were known and before CP violation was discovered, Cabbibo introduced a mixing angle (θ_c), describing mixing between d and s quark eigenstates in the weak interaction [12]. The Cabbibo angle was the only free parameter in a 2×2 unitary, real, mixing matrix. To allow CP violation, the mixing matrix has to contain complex elements, such that $V_{ij} \neq V_{ij}^*$ which introduce a complex phase in quantum amplitudes of particle interactions. This requires at least a 3×3 matrix and therefore the existence of at least three families of quarks. This idea was published in 1973 by Kobayashi and Maskawa, to explain CP violation in the SM [13]. The quark-state mixing matrix was named the Cabbibo-Kobayashi-Maskawa (CKM) matrix, containing all possible mixing parameters. It is a tantalizing fact that indeed our universe contains the minimum number of particle generations required to allow for CP violating processes.

1.2 CP Violation in the B_s^0 meson system

More recent research has focused on CP violation in the B meson systems (particles containing a b quark) and more specifically the B_s^0 ($\bar{b}s$) meson. The weak interaction allows B_s^0 mesons to undergo rapid transitions to their antiparticle, the $\bar{B}_s^0$ meson, and vice-versa. This flavour mixing process can be analysed by solving the two-state Schrödinger equation, which shows that the B_s^0 flavour eigenstates are not equal to their mass eigenstates; the mass eigenstates form a superposition of the flavour eigenstates [14]. Extending the oscillation with a subsequent decay into a final state f , the time-dependent decay rates of the mesons can be obtained. These equations are also known as the master equations. This will be discussed in more detail in the theory section of this thesis.

CP violation in B meson transitions can occur in multiple ways. When the decay rate of a B to a final state f is different from the rate of the $\bar{B}$ to a $\bar{f}$, this is called *CP violation in decay*, the first type. The second type is *CP violation in mixing*, which means that the oscillation probability $B \rightarrow \bar{B}$ is different than $\bar{B} \rightarrow B$. The final type is *CP violation in interference between a decay with and without mixing*. This happens when both B as well as $\bar{B}$, apart from undergoing mixing, can also decay into the same final state f . This implies that two decay amplitudes contribute to the decay to the final state, namely $B \rightarrow f$ and $\bar{B} \rightarrow f$. The two decay amplitudes will interfere with each other, leading to CP violation. This type of CP violation will be studied in this research.

The first experimental observations of CP violation in the B system were performed by the Belle and BaBar experiments [15, 16]. Being located at so-called B-factories they managed to observe sufficient B^0 and $\bar{B}^0$ mesons to obtain a significant CP-violation measurement for the first time with particles different than kaons. More recently, the LHCb detector located at CERN has been studying the CP asymmetry with B_s^0 mesons, for the first time observing direct CP violation with B_s^0 decays [17]. In this research, CP violation in interference is studied using the $B_s^0 \rightarrow D_s^\mp K^\pm$ decays.¹ [18]. Decays involving the B_s^0 meson are particularly interesting, since the oscillation frequency of $B_s^0 \longleftrightarrow \bar{B}_s^0$ is substantially higher than other neutral mesons [19]. Next to this, the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay has the required effect that both final states can come from an initial B_s^0 or $\bar{B}_s^0$. This means that there is the possibility of CP violation in decay with and without mixing.

1.3 Outline

This research focuses on the $B_s^0 \rightarrow D_s^\mp K^\pm$ and $B_s^0 \rightarrow D_s^- \pi^+$ decays. Unlike $B_s^0 \rightarrow D_s^\mp K^\pm$ decays, $B_s^0 \rightarrow D_s^- \pi^+$ decays are flavour specific. Using data collected with the LHCb detector, mixing plots are presented, together with mass plots, decay time distributions and possible CP asymmetry plots. The parameters for the master equations are obtained by fitting the function on the decay-time distribution data. The obtained data is analyzed for the presence of CP violation.

LHCb data is filtered for the relevant decays using the available detector information, which indicate whether the detected particles were pions or kaons, to separate $B_s^0 \rightarrow D_s^- \pi^+$ from $B_s^0 \rightarrow D_s^\mp K^\pm$, and with what certainty that could be determined. Next to this, the available flavour tagging parameters are used to determine whether the initially produced particle was a B_s^0 or $\bar{B}_s^0$. Since every b quark is produced in a pair with a $\bar{b}$, the flavour of the B_s^0 meson can be identified by looking at the flavour of the other, so-called opposite B particle [20]. By looking, amongst other options, at the lepton charge from semileptonic b decays, its flavour (b or $\bar{b}$) can be determined. Data cuts are made around the B_s^0 and the D_s mass, to reduce the amount of background. A Boosted Decision Tree (BDT), which gives an indication of how likely the observed decay is a signal rather than background, will also be used to further reduce the background and reduce the data to only the relevant events [21].

Firstly, the theory involved will be explained and a derivation of the master equations will be provided. Secondly, the LHCb experiment will be

¹The inclusion of the charge conjugated decay is implied throughout the thesis.

described and the used LHCb detector information will be explained. Finally, the obtained results will be shown and discussed.

The SM predicts that the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay will show CP violation, while the $B_s^0 \rightarrow D_s^- \pi^+$ decay will not. This difference is caused by the fact that the $B_s^0 \rightarrow D_s^- \pi^+$ decay is flavour specific, and no amplitude interference can occur, while in the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay both the B_s^0 as well as the $\bar{B}_s^0$ can decay into the same final state. This leads to, as mentioned earlier, interference of the decay amplitudes and therefore to the possibility of CP violation. The mixing frequency, Δm_s , is expected to be around $(17.757 \pm 0.012 \cdot 10^{12}) s^{-1}$, the lifetime parameter $\Delta\Gamma$ $(0.082 \pm 0.007) \cdot 10^{12} s^{-1}$ [22], and the master equation parameters are predicted to be comparable to the Particle Data Group (PDG) values [23]. Throughout this analysis, the natural units are taken as $\hbar \equiv c \equiv 1$. A deviation from these values would imply a falsification of the CKM mechanism for these decays. In other words, it would imply that new particles or forces, beyond the SM parameters, would be involved in the virtual quantum processes.

Chapter 2

Theory

In this chapter the theory framework to analyse B_s^0 decays is reviewed. The first section focuses on the quantum mechanical mixing phenomenology, the second on the requirements for CP violation, and the third and fourth describe the $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow D_s^\mp K^\pm$ decays.

2.1 B_s^0 meson mixing and decay

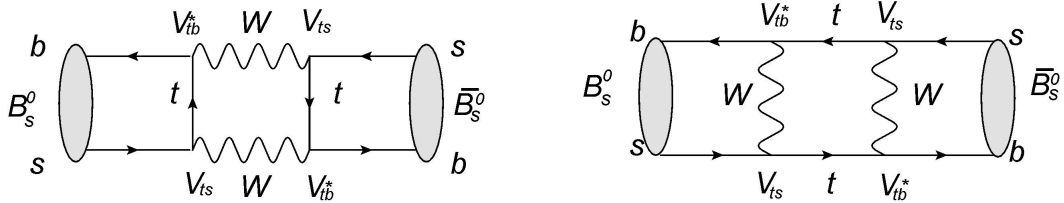


Figure 2.1: The two main B_s^0 flavour mixing Feynman diagrams. The V_{ij} are the CKM parameters, the W -boson is the weak force carrier, and the t represents a virtual top quark.

This section will provide an explanation of the theory involved in the B_s^0 mixing and decay. B_s^0 mesons undergo flavour oscillations, also known as mixing, to their antiparticle $\bar{B}_s^0$, and vice-versa $\bar{B}_s^0$ to B_s^0 . Feynman diagrams for the two most contributing topologies of the flavour mixing are shown in figure 2.1, where the coupling constants at the vertex points are the CKM matrix parameters, which relate the mass eigenstates of the quarks to the weak interaction eigenstates:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}; V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (2.1)$$

Flavour mixing is a result of quantum mechanics and described by the time-dependent Schrödinger equation:

$$i \frac{\partial}{\partial t} \psi = H \psi, \text{ where } \psi = a(t)|B_s^0\rangle + b(t)|\bar{B}_s^0\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} \quad (2.2)$$

A stepwise derivation and explanation of the mixing will be provided on the following pages. Equation 2.2 implements that the wave function is a superposition of the B_s^0 and the $\bar{B}_s^0$ state. Hence, the wave function can be written as a 2-dimensional vector with components $a(t)$ and $b(t)$, and therefore the Hamiltonian can be represented as a 2x2 complex matrix:

$$H = M - \frac{i}{2}\Gamma = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix} \quad (2.3)$$

In equation 2.3, M provides a 'mass' term and Γ the exponential decay. The off-diagonal elements of the matrix both describe flavour mixing, although in different ways. The M_{12} describes the mixing via so-called *off-shell* states, for example the two Feynman diagrams shown in figure 2.1. The Γ_{12} term describes the *on-shell* states, representing flavour mixing via a virtual, intermediate decay, for example $f = \pi^+\pi^-$. Substituting equation 2.3 into equation 2.2 leads to the following expression for the Schrödinger equation:

$$i \frac{\partial}{\partial t} \psi(t) = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix} \psi(t) \quad (2.4)$$

Solving the Schrödinger equation yields the eigenvalues: (where m corresponds to the mass and Γ the lifetime of the particle. The subscripts H and L indicate respectively the heavy and light eigenvalue.)

$$\begin{aligned} \lambda_- \equiv \lambda_L &\equiv m_1 + \frac{i}{2}\Gamma_1 \\ \lambda_+ \equiv \lambda_H &\equiv m_2 + \frac{i}{2}\Gamma_2 \end{aligned} \quad (2.5)$$

From the equation above, the difference in mass and lifetime of the eigenvalues can be expressed as:

$$\begin{aligned} \Delta m &= m_2 - m_1 = m_H - m_L \\ \Delta \Gamma &= \Gamma_1 - \Gamma_2 = \Gamma_L - \Gamma_H \end{aligned} \quad (2.6)$$

where the chosen sign convention is taken from the PDG. We can now define the two mass eigenstates of the B_s^0 meson as the heavy and light eigenstate, which are superpositions of the B_s^0 and $\bar{B}_s^0$ states with the complex parameters p and q :

$$\begin{aligned} |B_H\rangle &= p|B_s^0\rangle + q|\bar{B}_s^0\rangle \\ |B_L\rangle &= p|B_s^0\rangle - q|\bar{B}_s^0\rangle \end{aligned} \quad (2.7)$$

In reverse, the flavour eigenstates can then be written as a superposition of the mass eigenstates.

$$\begin{aligned} |B_s^0\rangle &= \frac{1}{2p}(|B_H\rangle + |B_L\rangle) \\ |\bar{B}_s^0\rangle &= \frac{1}{2q}(|B_H\rangle - |B_L\rangle) \end{aligned} \quad (2.8)$$

The ratio between p and q is found by solving for the eigenvalues:

$$\begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix} \begin{pmatrix} p \\ q \end{pmatrix} = \lambda_{\pm} \begin{pmatrix} p \\ q \end{pmatrix} \quad (2.9)$$

By defining Δm to be positive, we select the positive eigenvalue, which, after some mathematics, yields:

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \quad (2.10)$$

Using the Schrödinger equation, the time dependent wave functions of the mass eigenstates are obtained:

$$\begin{aligned} |B_H(t)\rangle &= e^{-i\omega_+ t} |B_H\rangle \\ |B_L(t)\rangle &= e^{-i\omega_- t} |B_L\rangle \end{aligned}$$

where $\omega_+ = M + \frac{\Delta m}{2} - \frac{i}{2}\left(\Gamma + \frac{\Delta\Gamma}{2}\right)$ (2.11)

and $\omega_- = M - \frac{\Delta m}{2} - \frac{i}{2}\left(\Gamma - \frac{\Delta\Gamma}{2}\right)$

By combining equations 2.7, 2.8 and 2.11, assuming that at $t = 0$ a $|B_s^0\rangle$ state is produced, the initial amplitudes $|B_H(0)\rangle$ and $|B_L(0)\rangle$ can be computed and

the time dependent wave function is obtained:

$$\begin{aligned}
|B_s^0(t)\rangle &= \frac{1}{2p} \left\{ e^{-im_H t - \frac{1}{2}\Gamma_H t} |B_H(0)\rangle + e^{-im_L t - \frac{1}{2}\Gamma_L t} |B_L(0)\rangle \right\} \\
&= \frac{1}{2p} \left\{ e^{-im_H t - \frac{1}{2}\Gamma_H t} (p|B_s^0\rangle + q|\bar{B}_s^0\rangle) + e^{-im_L t - \frac{1}{2}\Gamma_L t} (p|B_s^0\rangle - q|\bar{B}_s^0\rangle) \right\} \\
&= \frac{1}{2} \left(e^{-im_H t - \frac{1}{2}\Gamma_H t} + e^{-im_L t - \frac{1}{2}\Gamma_L t} \right) |B_s^0\rangle + \frac{q}{2p} \left(e^{-im_H t - \frac{1}{2}\Gamma_H t} + e^{-im_L t - \frac{1}{2}\Gamma_L t} \right) |\bar{B}_s^0\rangle \\
&= g_+(t) |B_s^0\rangle + \left(\frac{q}{p} \right) g_-(t) |\bar{B}_s^0\rangle
\end{aligned} \tag{2.12}$$

where $M = (m_H + m_L)/2$ and Δm as defined as in equation 2.6, and $g_+(t)$ and $g_-(t)$ are defined as:

$$\begin{aligned}
g_+(t) &= \frac{1}{2} \left(e^{-im_H t - \frac{1}{2}\Gamma_H t} + e^{-im_L t - \frac{1}{2}\Gamma_L t} \right) = \frac{1}{2} e^{-iMt} \left(e^{\frac{-i}{2}\Delta m t - \frac{1}{2}\Gamma_H t} + e^{\frac{+i}{2}\Delta m t - \frac{1}{2}\Gamma_L t} \right) \\
g_-(t) &= \frac{1}{2} \left(e^{-im_H t - \frac{1}{2}\Gamma_H t} - e^{-im_L t - \frac{1}{2}\Gamma_L t} \right) = \frac{1}{2} e^{-iMt} \left(e^{\frac{-i}{2}\Delta m t - \frac{1}{2}\Gamma_H t} - e^{\frac{+i}{2}\Delta m t - \frac{1}{2}\Gamma_L t} \right)
\end{aligned}$$

The same process can be followed for an initially produced $\bar{B}_s^0$, yielding:

$$|\bar{B}_s^0(t)\rangle = g_-(t) \left(\frac{p}{q} \right) |B_s^0\rangle + g_+(t) |\bar{B}_s^0\rangle \tag{2.13}$$

From equations 2.12 and 2.13 it can be seen that B_s^0 changes into a $\bar{B}_s^0$, and back again to B_s^0 , over time. At production ($t = 0$), the particle is still a pure flavour eigenstate, i.e. B_s^0 or $\bar{B}_s^0$. When $t > 0$ the particle is in a superposition of the two flavour eigenstates, and the flavour mixing occurs. The wave function can be extended with a subsequent decay into a final state f , obtaining the transition amplitude for $B_s^0(t) \rightarrow f$:

$$\begin{aligned}
\langle f|T|B_s^0(t)\rangle &= g_+(t) \langle f|T|B_s^0\rangle + \left(\frac{q}{p} \right) g_-(t) \langle f|T|\bar{B}_s^0\rangle \\
&= g_+(t) A(f) + \left(\frac{q}{p} \right) g_-(t) \bar{A}(f)
\end{aligned} \tag{2.14}$$

where we define $A(f) \equiv \langle f|T|B_s^0\rangle$ and $\bar{A}(f) \equiv \langle f|T|\bar{B}_s^0\rangle$

The time dependent decay rate can then be obtained by taking the square of the amplitude of the wave function, as is shown on the next page.

$$\begin{aligned}
\Gamma_{B_s^0 \rightarrow f}(t) &= |\langle f|T|B_s^0(t)\rangle|^2 \\
&= \left[g_+(t) A(f) + \left(\frac{q}{p} \right) g_-(t) \bar{A}(f) \right] \left[g_+^*(t) A(f) + \left(\frac{q}{p} \right) g_-^*(t) \bar{A}(f) \right] \\
&= |g_+(t)|^2 |A(f)|^2 + \left(\frac{q^2}{p^2} \right) |g_-(t)|^2 |\bar{A}(f)|^2 + \\
&\quad \left(\frac{q}{p} \right) |A(f)| |\bar{A}(f)| \left[|g_+(t)| |g_-^*(t)| + |g_+^*(t)| |g_-(t)| \right] \\
&= |A(f)|^2 \left[|g_+(t)|^2 + \left(\frac{q^2}{p^2} \right) |g_-(t)|^2 \frac{|\bar{A}(f)|^2}{|A(f)|^2} + \right. \\
&\quad \left. \left(\frac{q}{p} \right) \frac{|\bar{A}(f)|}{|A(f)|} (|g_+(t)| |g_-^*(t)| + |g_+^*(t)| |g_-(t)|) \right] \\
&= |A(f)|^2 \left[|g_+(t)|^2 + |\lambda_f|^2 |g_-(t)|^2 + 2\Re(|\lambda_f| g_+^*(t) g_-(t)) \right]
\end{aligned}$$

where the parameter $\lambda_f = \frac{q \bar{A}(f)}{p A(f)}$ has been introduced for readability.

(2.15)

It is convenient to write $|g_+(t)|^2$ using equation 2.11 as:

$$\begin{aligned}
|g_+(t)|^2 &= \left(\frac{e^{-i\omega_+ t} + e^{-i\omega_- t}}{2} \right) \left(\frac{e^{-i\omega_+^* t} + e^{-i\omega_-^* t}}{2} \right) \\
&= \frac{e^{-it(-i\Gamma - \frac{i}{2}\Delta\Gamma)} + e^{-it(\Delta m - i\Gamma)} + e^{-it(-\Delta m - i\Gamma)} + e^{-it(-i\Gamma + \frac{i}{2}\Delta\Gamma)}}{4} \\
&= \left(e^{-t\frac{\Delta\Gamma}{2}} + e^{-it\Delta m} + e^{it\Delta m} + e^{t\frac{\Delta\Gamma}{2}} \right) \frac{e^{-t\Gamma}}{4} \\
&= \left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos(\Delta m t) \right] \frac{e^{-t\Gamma}}{2}
\end{aligned}$$

(2.16)

Similarly, $|g_-(t)|^2$ and $|g_+^*(t)| |g_-(t)|$ can be written as:

$$\begin{aligned}
|g_-(t)|^2 &= \left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\Delta m t) \right] \frac{e^{-t\Gamma}}{2} \\
|g_+^*(t)| |g_-(t)| &= \left[\sinh\left(\frac{\Delta\Gamma}{2}t\right) + i \sin(\Delta m t) \right] \frac{-e^{-t\Gamma}}{2}
\end{aligned}$$

(2.17)

By combining equations 2.15, 2.16 and 2.17, the time dependent decay rate master equation can be obtained:

$$\begin{aligned}
\Gamma_{B_s^0 \rightarrow f}(t) &= |A(f)|^2 \frac{e^{-t\Gamma}}{2} \left[\cos(\Delta m t) + \cosh\left(\frac{\Delta\Gamma}{2}t\right) + |\lambda_f|^2 \left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\Delta m t) \right) \right. \\
&\quad \left. + 2\Re|\lambda_f| \left(\sinh\left(\frac{\Delta\Gamma}{2}t\right) + i \sin(\Delta m t) \right) \right] \\
&= |A(f)|^2 \frac{e^{-t\Gamma}}{2} \left[(1 + |\lambda_f|^2) \cosh\left(\frac{\Delta\Gamma}{2}t\right) + (1 - |\lambda_f|^2) \cos(\Delta m t) \right. \\
&\quad \left. - 2\Re|\lambda_f| \left(\sinh\left(\frac{\Delta\Gamma}{2}t\right) \right) - 2i|\lambda_f| \sin(\Delta m t) \right] \\
&= |A(f)|^2 \frac{e^{-t\Gamma}}{2} (1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \frac{(1 - |\lambda_f|^2)}{(1 + |\lambda_f|^2)} \cos(\Delta m t) \right. \\
&\quad \left. - \frac{2\Re|\lambda_f|}{(1 + |\lambda_f|^2)} \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \frac{2i|\lambda_f|}{(1 + |\lambda_f|^2)} \sin(\Delta m t) \right]
\end{aligned} \tag{2.18}$$

The experimentally observable parameters C_f , D_f and S_f are defined in terms of the CP parameters as follows:

$$C_f = \frac{(1 - |\lambda_f|^2)}{(1 + |\lambda_f|^2)}, \quad D_f = \frac{2\Re\lambda_f}{(1 + |\lambda_f|^2)} \quad \text{and} \quad S_f = \frac{2i\lambda_f}{(1 + |\lambda_f|^2)}$$

This derivation is valid for both B^0 and B_s^0 particles. For B_s^0 we take $\Delta m \rightarrow \Delta m_s$; $\Gamma \rightarrow \Gamma_s$ and $\Delta\Gamma \rightarrow \Delta\Gamma_s$, to finally obtain the decay rate formula:

$$\begin{aligned}
\Gamma_{B_s^0 \rightarrow f}(t) &= |A(f)|^2 \frac{e^{-t\Gamma_s}}{2} (1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + C_f \cos(\Delta m_s t) + D_f \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) \right. \\
&\quad \left. - S_f \sin(\Delta m_s t) \right]
\end{aligned} \tag{2.19}$$

Similarly, the equations for $\bar{B}_s^0$ can be derived as:

$$\Gamma_{\bar{B}_s^0 \rightarrow f}(t) = |A(f)|^2 \frac{e^{-t\Gamma_s}}{2} (1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - C_f \cos(\Delta m_s t) + D_f \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + S_f \sin(\Delta m_s t) \right] \quad (2.20)$$

and the equivalent decay rates for the antiparticle final state $\bar{f}$

$$\Gamma_{\bar{B}_s^0 \rightarrow \bar{f}}(t) = |\bar{A}(\bar{f})|^2 \frac{e^{-t\Gamma_s}}{2} (1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + C_{\bar{f}} \cos(\Delta m_s t) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (2.21)$$

$$\Gamma_{B_s^0 \rightarrow \bar{f}}(t) = |\bar{A}(\bar{f})|^2 \frac{e^{-t\Gamma_s}}{2} (1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - C_{\bar{f}} \cos(\Delta m_s t) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (2.22)$$

where $\bar{\lambda}_{\bar{f}} = \frac{p}{q} \frac{A(\bar{f})}{\bar{A}(\bar{f})}$, equivalent to equation 2.19.

Equations 2.19-2.22 are usually called the master equations. It is interesting to note that the sinh and sin terms are associated with the interference between decays with and without oscillation. By finding the expression for λ_f , a full description of the decay of the B_s^0 meson can be obtained. Possible CP violation can be found by comparing the decay rates of the B_s^0 and the $\bar{B}_s^0$. The following section will extend on this.

2.2 CP violation

2.2.1 CP violation in the SM

CP violation means the breaking of the charge-parity symmetry [24]. To see where CP violation originates from within the SM, it is useful to write the CKM matrix using the approximate Wolfenstein parametrization, where γ , β and β_s are the so-called angles of the complex phases:

$$V_{CKM, \text{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} \quad (2.23)$$

Measuring CP violation effectively means performing a measurement that is sensitive to a complex phase of the CKM matrix. This is not straightforward,

and since the probability for a decay with e.g. an amplitude of order V_{ub} , the amplitude has to be multiplied by its complex conjugate, such that the sensitivity to the complex phase disappears. In decays with more than a single Feynman diagram, however, multiple amplitudes of the form $A_i = |A_i|e^{i\phi_i}$ can contribute to the total decay amplitude. Each of these amplitudes has a phase ϕ_i that consists of a CP-odd phase φ_i that originates from the complex coupling constants, and a CP-even phase δ_i that originates from the strong interaction or from the mixing formalism. Since the CP-even phase is always CP-conserving, the CP-conjugated amplitude has the form $\overline{A}_i = |A_i|e^{i(-\varphi_i+\delta_i)}$. For decays with two amplitudes this leads to:

$$\begin{aligned}
A_1 &= |A_1|e^{i(\varphi_1+\delta_1)}, \\
A_2 &= |A_2|e^{i(\varphi_2+\delta_2)}, \\
|A|^2 &= |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + |A_1||A_2|(e^{i((\varphi_1+\delta_1)-(\varphi_2+\delta_2))} + e^{i(-(\varphi_1+\delta_1)+(\varphi_2+\delta_2))}) \\
&= |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\Delta\varphi + \Delta\delta),
\end{aligned} \tag{2.24}$$

where $\Delta\varphi = (\varphi_1 - \varphi_2)$ and $\Delta\delta = (\delta_1 - \delta_2)$. Similarly, the CP conjugated process ($A \rightarrow \overline{A}$) can be compared as:

$$\begin{aligned}
|A|^2 &= |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2|A_1A_2|\cos(\Delta\varphi + \Delta\delta) \\
|\overline{A}|^2 &= |\overline{A}_1 + \overline{A}_2|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(-\Delta\varphi + \Delta\delta).
\end{aligned}$$

showing that the difference of the particle and antiparticle process require both a non-zero CP-odd phase $\Delta\varphi$ and a CP even phase $\Delta\delta$. The amount of CP violation can then be found by calculating the difference between the amplitude and its CP conjugate.

2.2.2 CP violation in neutral mesons

Three different types of CP violation can be classified. The types are commonly known as:

1. CP violation in decay,
2. CP violation in mixing,
3. CP violation in interference between a decay with and without mixing.

The following subsections provide a general explanation of these types of CP violation. Since only the latter type is potentially present in the studied decays, the first two types will only be briefly discussed. After this, a more detailed explanation of CP violation in interference between a decay with and without mixing will be provided.

CP violation in decay and CP violation in mixing

CP violation in decay is present when the instantaneous decay probability from B to a final state f is not equal to the decay rate of $\bar{B}$ to $\bar{f}$:

$$\left| \frac{\bar{A}(f)}{A(f)} \right| \neq 1 \quad (2.25)$$

CP violation in decay is the only possible type of CP violation for charged meson and baryon decays. Direct CP violation with B_s^0 particles was discovered by LHCb [17].

CP violation in mixing occurs when the oscillation probability from anti-meson to meson is different from that of meson to anti-meson:

$$P(B \rightarrow \bar{B}) \neq P(\bar{B} \rightarrow B)$$

This type of CP violation is present when $|\frac{q}{p}| \neq 1$, see section 2.1. This is not observed to be in the B_s^0 system, so this type of decay is not present to high accuracy [19].

CP violation in interference between a decay with and without mixing

This form of CP violation is sometimes also called CP violation involving oscillations. It is measured in decays that have a common final state for the meson and the anti-meson. CP violation occurs when

$$\Gamma(B_{(\rightsquigarrow \bar{B})} \rightarrow f)(t) \neq \Gamma(\bar{B}_{(\rightsquigarrow B)} \rightarrow \bar{f})(t)$$

Since both B and $\bar{B}$ can decay to f and $\bar{f}$, two amplitudes will contribute to the transition amplitude from $|B\rangle$ to final state f : $A(B \rightarrow f)$ and $A(B \rightarrow \bar{B} \rightarrow f)$. For B mesons we consider the case that $|q/p| \approx 1$, since CP violation in mixing is not observed. The CP violation asymmetry is obtained as

$$A_{CP}(t) = \frac{\Gamma_{B_s^0 \rightarrow f}(t) - \Gamma_{\bar{B}_s^0 \rightarrow \bar{f}}(t)}{\Gamma_{B_s^0 \rightarrow f}(t) + \Gamma_{\bar{B}_s^0 \rightarrow \bar{f}}(t)} \quad (2.26)$$

It is experimentally more common, however, to look at the flavour mixing asymmetries, given as:

$$A_{mix}^f(t) = \frac{\Gamma_{B_s^0 \rightarrow f}(t) - \Gamma_{\bar{B}_s^0 \rightarrow f}(t)}{\Gamma_{B_s^0 \rightarrow f}(t) + \Gamma_{\bar{B}_s^0 \rightarrow f}(t)} \quad (2.27)$$

for both A_{mix}^f and $A_{mix}^{\bar{f}}$ and compare them to work out the amount of CP asymmetry. Looking at the equations mentioned above, it can be seen that the $B_s^0 \rightarrow D_s^- \pi^+$ decay can not have CP violation involving oscillations, since the decay is flavour specific ($B_s^0 \rightarrow D_s^+ \pi^-$ does not occur). The $B_s^0 \rightarrow D_s^- K^+$, however, is not flavour specific and both B_s^0 and $\bar{B}_s^0$ can decay into the same final state, leading to the possibility of CP violation involving oscillations. This will be further explained below.

2.3 The $B_s^0 \rightarrow D_s^- \pi^+$ decay

The first analysed decay is the $B_s^0 \rightarrow D_s^- \pi^+$ decay. The decay is flavour specific, which means that B_s^0 and $\bar{B}_s^0$ decay into a different final state; they are charge conjugated. The Feynman diagram for $B_s^0 \rightarrow D_s^- \pi^+$ is shown in figure 2.2.

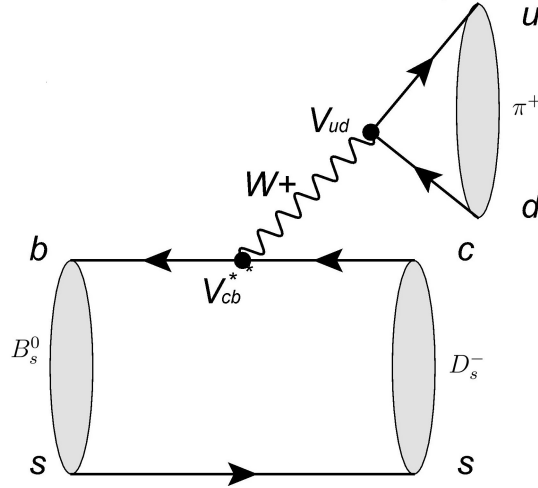


Figure 2.2: Feynman diagram for the $B_s^0 \rightarrow D_s^- \pi^+$ decay.

Since the decay is flavour specific, $A(\bar{f}) = \bar{A}(f) = 0$ and therefore $\lambda_f = 0$ and $\bar{\lambda}_{\bar{f}} = 0$, leading to the coefficients $C_f = 1$, $D_f = S_f = 0$ using equation 2.19, and since $|q/p| \approx 1$, the master equations can be simplified as:

$$\begin{aligned}
\Gamma_{B_s^0 \rightarrow D_s^- \pi^+}(t) &= |A(f)|^2 \frac{e^{-t\Gamma_s}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos(\Delta m_s t) \right] \\
\Gamma_{\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+}(t) &= |A(f)|^2 \frac{e^{-t\Gamma_s}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos(\Delta m_s t) \right] \\
\Gamma_{B_s^0 \rightarrow \bar{B}_s^0 \rightarrow D_s^+ \pi^-}(t) &= |A(\bar{f})|^2 \frac{e^{-t\Gamma_s}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos(\Delta m_s t) \right] \\
\Gamma_{\bar{B}_s^0 \rightarrow D_s^+ \pi^-}(t) &= |\bar{A}(\bar{f})|^2 \frac{e^{-t\Gamma_s}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos(\Delta m_s t) \right]
\end{aligned} \tag{2.28}$$

The flavour mixing asymmetry can be found by looking at the rate difference between $B_s^0 \rightarrow D_s^- \pi^+$ and $\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+$:

$$\begin{aligned}
A_{mix}(t) &= \frac{\Gamma_{B_s^0 \rightarrow D_s^- \pi^+}(t) - \Gamma_{\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+}(t)}{\Gamma_{B_s^0 \rightarrow D_s^- \pi^+}(t) + \Gamma_{\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+}(t)} \\
&= \frac{|A(f)|^2 \frac{e^{-t\Gamma_s}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos(\Delta m_s t) \right] - |A(f)|^2 \frac{e^{-t\Gamma_s}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos(\Delta m_s t) \right]}{|A(f)|^2 \frac{e^{-t\Gamma_s}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + \cos(\Delta m_s t) \right] + |A(f)|^2 \frac{e^{-t\Gamma_s}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \cos(\Delta m_s t) \right]} \\
&= \frac{\cos(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s}{2}t\right)}
\end{aligned} \tag{2.29}$$

Since the decay is flavour specific, the CP asymmetry $A_{CP}(t)$ in equation 2.26 is expected to be 0, which is caused by the fact that no decay amplitude interference is present.

2.4 The $B_s^0 \rightarrow D_s^\mp K^\pm$ decay

The second set of analysed decays consists of the $B_s^0 \rightarrow D_s^- K^+$ and $B_s^0 \rightarrow D_s^+ K^-$ decays and similar for $\bar{B}_s^0$. Feynman diagrams for both decays are shown in figures 2.3 and 2.4.

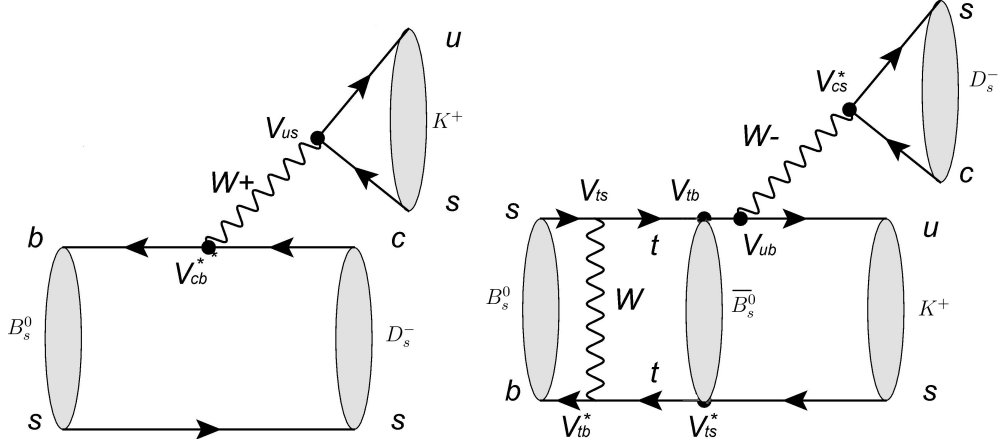


Figure 2.3: The two interfering Feynman diagrams of the $B_s^0 \rightarrow D_s^- K^+$ decay. Left: direct decay $B_s^0 \rightarrow D_s^- K^+$; right: mixing and decay $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow D_s^- K^+$

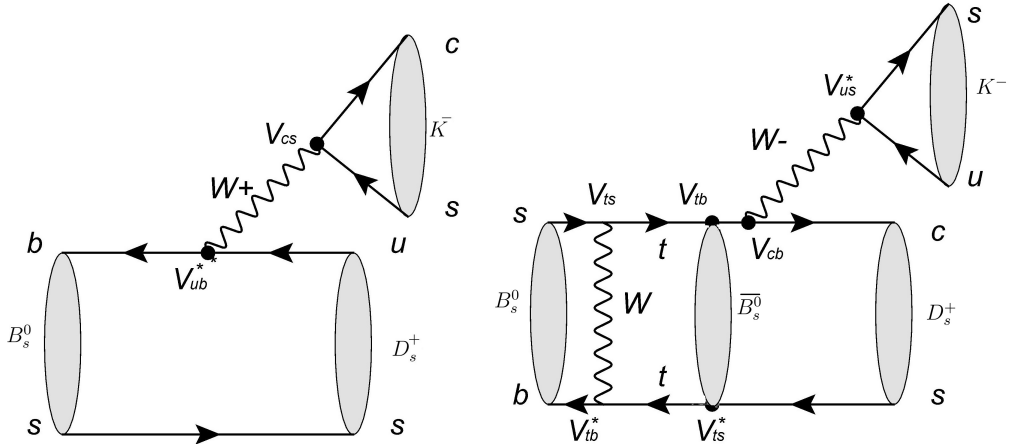


Figure 2.4: The two interfering Feynman diagrams of the $B_s^0 \rightarrow D_s^+ K^-$ decay. Left: direct decay $B_s^0 \rightarrow D_s^+ K^-$; right: mixing and decay $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow D_s^+ K^-$

The decay rates are given by the master equations shown in equations 2.19, 2.20, 2.21 and 2.22. Both the B_s^0 as well as the $\bar{B}_s^0$ can decay into the same final states, leading to the possibility for CP violation in interference between a decay with and without mixing. Since, contrary to the $B_s^0 \rightarrow D_s^- \pi^+$ decay

the parameter $\lambda_f \neq 0$, the equation is more involved. By combining equations 2.26, 2.19 and 2.20 the mixing asymmetry can be written as:

$$A_{mix}^f(t) = \frac{\Gamma_{B_s^0 \rightarrow D_s^- K^+}(t) - \Gamma_{\bar{B}_s^0 \rightarrow D_s^- K^+}(t)}{\Gamma_{B_s^0 \rightarrow D_s^- K^+}(t) + \Gamma_{\bar{B}_s^0 \rightarrow D_s^- K^+}(t)} = \frac{C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t)}{\cosh(\frac{1}{2} \Delta \Gamma_s t) + D_f \sinh(\frac{1}{2} \Delta \Gamma_s t)} \quad (2.30)$$

and similar for $A_{mix}^{\bar{f}}$. By looking at the left of figure 2.3 it can be seen that $B_s^0 \rightarrow D_s^- K^+$ has an amplitude $A_{D_s^- K^+} \sim V_{cb}^* V_{us}$, while $\bar{B}_s^0 \rightarrow D_s^- K^+$ has $\bar{A}_{D_s^- K^+} \sim V_{ub} V_{cs}^*$, as shown on the right side of figure 2.3. Both amplitudes are Cabbibo suppressed, however $|A_{D_s^- K^+}| \neq |\bar{A}_{D_s^- K^+}|$. By splitting the weak coupling part of the amplitude and introducing the amplitude of the strong interactions in the final state as A_1 and A_2 , the ratio of the amplitudes can be written as:

$$\frac{\bar{A}_{D_s^- K^+}}{A_{D_s^- K^+}} = \left(\frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}} \right) \frac{A_2}{A_1} \quad (2.31)$$

Both amplitudes differ by a phase γ originating from V_{ub} in equation 2.23, and as explained in section 2.2.1, an extra phase δ_s from the strong interaction:

$$\frac{A_{D_s^- K^+}}{\bar{A}_{D_s^- K^+}} = \frac{|A_{D_s^- K^+}|}{|\bar{A}_{D_s^- K^+}|} e^{i(\delta_s - \gamma)} \quad (2.32)$$

and similarly

$$\frac{A_{D_s^+ K^-}}{\bar{A}_{D_s^+ K^-}} = \frac{|A_{D_s^+ K^-}|}{|\bar{A}_{D_s^+ K^-}|} e^{i(\delta_s + \gamma)} \quad (2.33)$$

From equation 2.32 an expression for $\lambda_{D_s^- K^+}$ is obtained, which combined with equation 2.19 gives a full description of the $B_s^0 \rightarrow D_s^- K^+$ decay.

$$\lambda_{D_s^- K^+} = \left(\frac{q}{p} \right)_{B_s^0} \left(\frac{\bar{A}_{D_s^- K^+}}{A_{D_s^- K^+}} \right) = \left| \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \right| \left| \frac{V_{ub} V_{cs}^*}{V_{cb}^* V_{us}} \right| \left| \frac{A_2}{A_1} \right| e^{-2\beta_s - \gamma + \delta_s} \quad (2.34)$$

where $\left(\frac{q}{p} \right)_{B_s^0} = \left| \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \right|$ can be read off from the mixing diagram in figure 2.3. The same can be done for the $B_s^0 \rightarrow D_s^+ K^-$ and $\bar{B}_s^0 \rightarrow D_s^+ K^-$ decays, assuming $|A_{D_s^- K^+}| = |\bar{A}_{D_s^+ K^-}| \sim A_1$, yielding:

$$\lambda_{D_s^+ K^-} = \left(\frac{q}{p} \right)_{B_s^0} \left(\frac{\bar{A}_{D_s^+ K^-}}{A_{D_s^+ K^-}} \right) = \left| \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \right| \left| \frac{V_{us} V_{cb}}{V_{cs} V_{ub}^*} \right| \left| \frac{A_1}{A_2} \right| e^{2\beta_s + \gamma + \delta_s} \quad (2.35)$$

A measurement of the parameters $\lambda_{D_s^- K^+}$ and $\lambda_{D_s^+ K^-}$ allows the determination of the mixing angle β_s as well as γ from the CKM matrix in equation 2.23.

Chapter 3

LHC and the LHCb experiment

3.1 LHC

The Large Hadron Collider (LHC) is a large particle collider located at CERN in the France-Switzerland border area close to Geneva. The LHC accelerates protons to close to the speed of light ($0.999999990c$), at energies of 7 TeV per nucleon [25]. The collider has a circumference of about 27 kilometres and lies in a tunnel 50 - 175 metres underground. An aerial view is shown in figure 3.1.

The protons move in opposite directions in two 6.3 cm diameter beampipes, containing an ultra high vacuum between 10^{-7} and 10^{-9} Pa. Superconducting magnets of 8.3 T are used to bend and guide the beam along the ring [25]. This strong magnetic field is achieved by cooling electromagnets to 1.9K using liquid helium, such that they become superconducting.

At multiple points in the tunnel, the beams cross and the protons collide with a frequency of 40 million times per second. The four major detector experiments at CERN (CMS, ATLAS, ALICE and LHCb) are located at these crosspoints, shown in figure 3.1. During the LHC run 1 the collisions had a center of mass energy of $\sqrt{s} = 7$ TeV in 2011 and $\sqrt{s} = 8$ TeV in 2012.



Figure 3.1: Aerial view of the region close to Geneva, with a sketch of the LHC and the location of the four major experiments marked [26].

3.2 LHCb

The LHCb detector is a single-arm forward detector covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks [27]. A schematic overview of the detector is shown in figure 3.2. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector (TT) located upstream of a dipole magnet, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet (T1, T2, T3) [28]. The tracking system provides a measurement of the momentum of charged particles produced in the collision.

Different types of charged hadrons are identified using information from two ring-imaging Cherenkov detectors (RICH1 and RICH2). Photons, electrons and hadrons are distinguished by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL). Muons are identified by a system (M1-M5) composed of alternating layers of iron and multiwire proportional chambers. The initial event selection is performed by a trigger system, which consists of both a hardware stage, which is based on information from the calorimeter and muon systems, and a software stage, which applies a full event reconstruction.

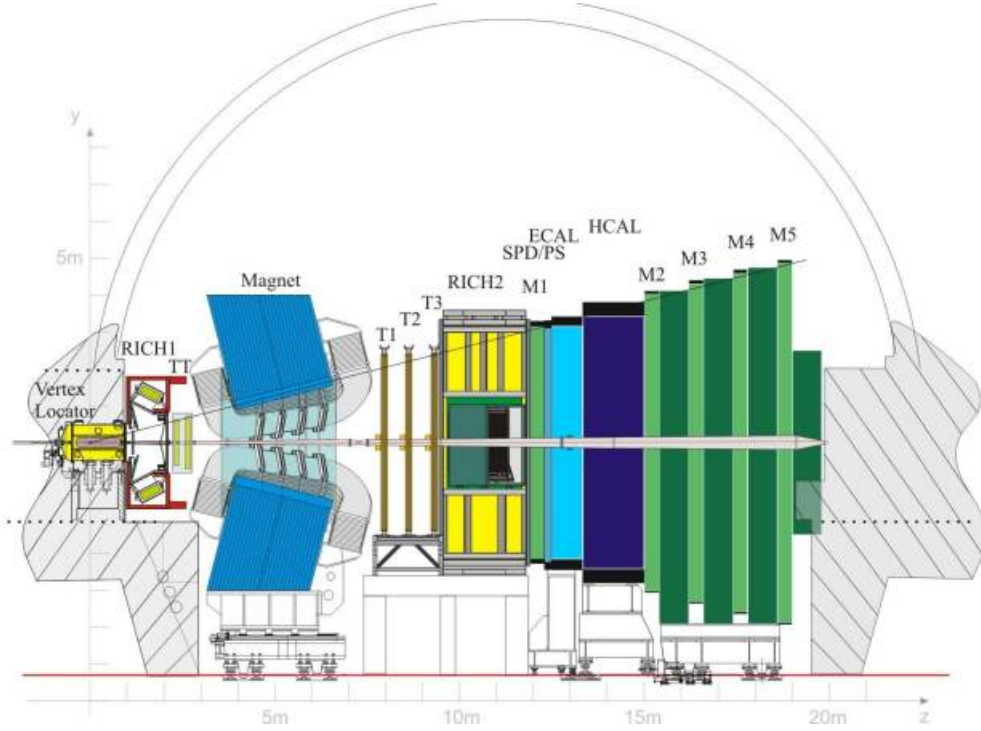


Figure 3.2: Schematic overview of the LHCb detector and its multiple subdetectors [29]. The proton collisions occur on the left side, inside the Vertex Locator. From there on the small angle decay products travel towards the right through the detector.

3.2.1 Tracking

The charged decay products are tracked with high precision using the Vertex Locator (VELO), in combination with the Tracker Turicensis (TT), Inner Tracker (IT) and Outer Tracker (OT). The VELO, shown in figure 3.3, is made of 2 arrays of semi-circular silicon strip detector modules. The modules consist of 2 pieces, attached back-to-back, one of which is responsible for azimuthal angle measurements while the other is used for radial measurements. The arrays are placed around the beam on both sides, so that they overlap and form a cylindrical shape. The VELO has a resolution varying about 25-50 μm , which in the studied particle decays leads to a decay-time resolution of about 40 ps.

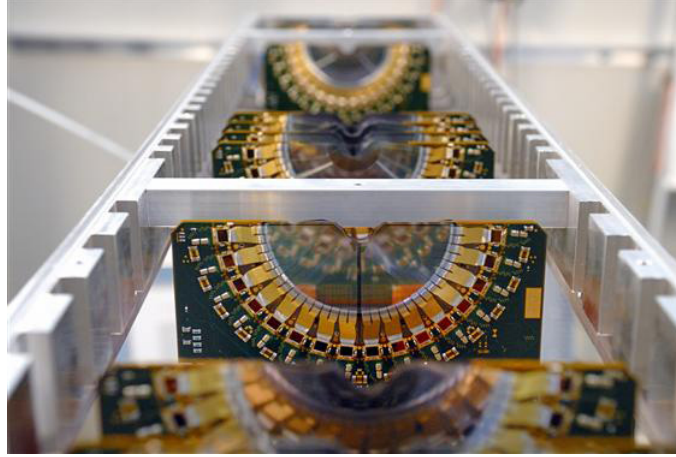


Figure 3.3: Image of a VELO array before installation into the detector [30].

The IT and TT detectors are located both upstream and downstream from the magnet. The TT forms an intermediate detection layer between the VELO and T stations to reduce the number of fake track combinations. Downstream of the magnet the IT is positioned, consisting of three tracking stations surrounded by the straw-tube drift cells of the OT modules. The total tracking system provides a momentum resolution of 0.4% at 100 GeV/ c to 0.6% at 100 GeV/ c , leading to a mass resolution of around 18 MeV for the studied decays.

3.2.2 Particle identification

Particle identification (PID) is required to distinguish the charged hadronic final states. The PID is done using a combination of multiple detectors: the Electromagnetic and Hadronic Calorimeters, the Ring Imaging Cherenkov Detectors (shown in figure 3.4) and the Muon system. The two RICH detectors use, as their name implies, Cherenkov radiation to detect the type of charged particle. Cherenkov radiation is electromagnetic radiation that is emitted when particles that traverse a medium are travelling faster than the speed of light in that medium. The angle of the cone of the emitted radiation is a measure of its velocity, which together with the measured momentum leads to a measurement of the particle mass, and hence its identity. By combining the reconstructed tracks from all the different detectors, a delta log-likelihood (DLL) for each particle ID is created. The DLL used for π and K equals 0 when the probability of the particle being a π is equal to being a K . A positive PID indicates that the particle was more likely to be a K , negative PID a π .

Neutral hadrons, electrons and photons are identified with the calorimeter system. The muon system consists of a layer of iron, to stop all particles except muons, and a multiwire to measure the muons.



Figure 3.4: Photomultiplier tubes in the upper box of the LHCb RICH 1 detector [31].

3.2.3 Boosted Decision Trees

To distinguish background from signal, Boosted Decision Trees (BDTs) are used. A BDT is a machine learning technique that is trained on a set of N variable distributions in a signal and a background sample. It uses a 'tree' of yes/no decisions to build a one-dimensional classifier on which a cut can be placed. [32]. Boosting means the use of multiple Decision Trees, a so-called forest, and combining them into a single classifier. At LHCb, this classifier is used, in combination with efficiency plots to return the probability for an event being background (-1) ranging to being signal (1). An example LHCb event display is shown in figure 3.5.

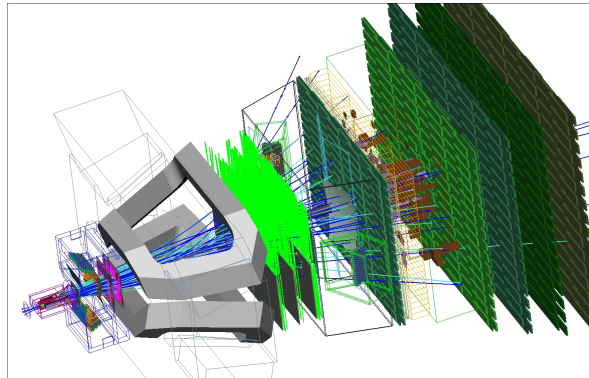


Figure 3.5: An example LHCb event display [33].

Chapter 4

Performed analysis

The following section describes the methods that were used to analyse the data, how the data was selected and which fits were used to extract the observables of interest.

4.1 Used software

The data was analysed and graphed using Python 3.6 with the NumPy, SciPy, Pandas and Matplotlib libraries [34]. The LHCb data that was used consisted of LHC run 1 (2011 and 2012) data with centre-of-mass energies $\sqrt{s} = 7$ TeV for 2011 and 8 TeV for 2012. Python was selected as a novel analysis approach, instead of the commonly used ROOT framework.

Before the analysis was started, the ROOT Ntuples containing the relevant detector information were converted to Hierarchical Data Format (H5) files [35], so that they could easily be opened in Python using the Pandas library. The various detector reconstruction parameters are labelled and described in table 4.1. A download link to all the used code is provided in Appendix A.

Parameter name in code	Description
lab0_LifetimeFit_M	The measured B_s^0 mass of the event in MeV/c^2
lab0_LifetimeFit_MERR	The error on the measured B_s^0 mass in MeV/c^2
lab0_LifetimeFit_ctau	The distance the particle travelled in ps
lab0_TAGDECISION	B_s^0 or $\bar{B}_s^0$ tagging
TaggingTool_TAGOMEGA	How certain the tagging is
lab1_ID	Mass hypothesis of the bachelor particle, either K or π
lab1_PIDK	How certain the particle ID is
lab2_MM	The measured D_s^+ mass
lab3_ID	Type of the first final decay product, either K or π
lab3_PIDK	How certain the particle ID is
lab4_ID	Type of the second final decay product, either K or π
lab4_PIDK	How certain the particle ID is
lab5_ID	Type of the third final decay product, either K or π
lab5_PIDK	How certain the particle ID is
BDTGRresponse_2/3	The BDT classifier, as explained in section 3.2.3

Table 4.1: The LHCb detector reconstruction parameters and their description.

4.2 Data selection and analysis

Firstly, the data was filtered for the relevant decays using the particle ID values. The particle ID numbers and their corresponding particles are shown in the table below:

$B_s^0/\bar{B}_s^0 \rightarrow$	$(D_s^\pm$	$\pi^\mp$ or $K^\mp)$	$D_s^\pm \rightarrow$	$(K^\pm$	$K^\mp$	$\pi^\pm)$
lab0	lab2	lab1	lab3	lab4	lab5	

The lab3_ID, lab4_ID and the lab5_ID were used to filter for the decay $D_s^\pm \rightarrow K^\pm K^\mp \pi^\pm$. For all lab_IDs, a value of 211 or -211 means respectively a π^+ or π^- , while the values 321 and -321 indicate K^+ and K^- . By looking at the charge of the lab5 pion, the D_s charge can be determined; they have to be equal. Secondly, the lab1_ID was used to filter for either the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay or the $B_s^0 \rightarrow D_s^- \pi^+$ decay. The filtered data was saved as a new file.

After this, mass plots for the B_s^0 and the D_s were created using the filtered data. The mass plots were created by selection on the lab0_LifetimeFit_M and lab2_MM parameters. A histogram was created in the mass range $5000 - 5600$ MeV, around the PDG B_s^0 mass of 5366 MeV [22]. The same was done for the $D_s^\pm$ around its PDG mass, 1968 MeV, in the mass range $1920 - 2010$ MeV [22]. By looking at the mass plots and identifying the B_s^0

and $D_s^\pm$ peaks, the mass-window values for further selection were selected. The data was further filtered using the parameters shown in table 4.2.

Parameter	Value	Selection reason
lab1_ID	211/-211 or 321/-321	Select for either the $\pi^\pm$ or $K^\pm$
BDTGResponse_2/3	> 0.6	Relative likelihood of signal being an event
lab1_PIDK	< 0 or > 5	Selecting relative certain pion/kaon
lab3_PIDK	> 5	Selecting relative certain kaon
lab4_PIDK	> 5	Selecting relative certain kaon
lab5_PIDK	< 0	Selecting relative certain pion
TAGDECISION	1 or -1	Selecting B_s^0 or $\bar{B}_s^0$
TAGOMEGA	< 0.35	Wrong tag fraction
lab0_LifetimeFit_M	$5326 < M < 5406$	Cut around the B_s^0 mass peak
lab2_MM	$1950 < M < 1990$	Cut around the $D_s^\pm$ mass peak

Table 4.2: The parameters used for filtering, their selected values and the reason why these values were selected.

To display the decay time distributions and the mixing plots, the data was divided into the different (charge conjugated) decays using the available particle IDs. The decay time distributions were plotted using PyPlot's `errorbar` function. The errors for $B_s^0 \rightarrow D_s^- \pi^+$ were calculated by finding the 1σ boundaries and the error for $B_s^0 \rightarrow D_s^\mp K^\pm$ by taking the square root of the amount of events. The flavour mixing plots were created according to equation (2.29) for $B_s^0 \rightarrow D_s^- K^+$ and equation (2.30) for $B_s^0 \rightarrow D_s^\mp K^\pm$. CP-violation plots were created in a similar way using equation (2.26).

4.3 Fitting

Data fitting was done using Scipy's `optimize.curve_fit` function. As input it requires a fitting function, initial values for the free parameters and the error values of the data. For the $B_s^0 \rightarrow D_s^- \pi^+$ decay, the decay time distributions are fitted using equation (2.28), in combination with an acceptance function based on the LHCb detector performance [36]. This acceptance function adapts the function to the trigger and reconstruction efficiency at low lifetime values:

$$\alpha(t) = \frac{(1 + b^{t-t_0}) a(t-t_0)^n}{1 + a(t-t_0)^n} \quad (4.1)$$

where $a = 1.382$, $b = -0.0494$, $t_0 = 0.07742$ ps, $n = 1.771$ and t is the measured B_s^0 lifetime. This function takes into account the capability to

distinguish between a production and a decay point of a B_s^0 meson in the vertex detector. A plot of the acceptance function is shown in figure 4.1. Looking at the graph, it can be seen that at low lifetimes the acceptance function has a big effect, while at longer lifetimes the scaling factor is close to 1.

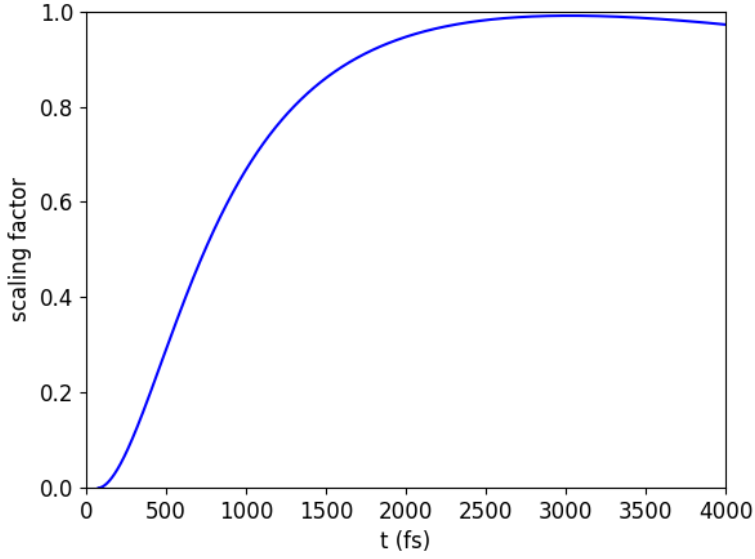


Figure 4.1: Plot of the used LHCb acceptance function between 0 and 4 ps, shown in equation (4.1).

The initial parameters for the fit were obtained from SM theory and earlier experimental measurements. The total lifetime Γ_s was fitted as an exponential function of the form $A e^{-\Gamma_s t/2}$, in combination with the acceptance function. The same process was repeated for the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay. Chi-squared values were calculated to see how well the curves fitted on the data. The decay time distribution fit functions for the individual $B_s^0 \rightarrow D_s^- \pi^+$ were the master equations, shown in equation (2.28), in combination with the acceptance function shown in equation (4.1). Similarly, for the $B_s^0 \rightarrow D_s^\pm K^\mp$ the master equations (2.19-2.22) were used as fit.

The flavour mixing and CP mixing plots were also fitted using the `optimize.curve_fit` function. The plots were obtained using fitting equations (2.26) and (2.27) as input function. The initial parameters were automatically guessed using an algorithm: a Fourier transform was used to find the Δm_s frequency of the cos and sin functions, the amplitude was guessed as $\sqrt{2}$ standard deviation around 0, the offset from 0 as the mean of the asym-

metry, and the $\Delta\Gamma_s$ in the cosh and sinh was taken from SM theory. Data at low lifetimes ($t < 350$ ps) was removed, since that data was too inaccurate to work in the algorithm. For the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay, the Δm_s and $\Delta\Gamma_s$ were fixed to the values of the $D_s^- \pi^+$ measurements to obtain better fitting results. The error on the asymmetries was calculated using the standard error calculation formula, obtaining:

$$\sigma_{mix} = \sqrt{\frac{4n_2^2}{(n_1 + n_2)^4} \sigma_{n1}^2 + \frac{4n_1^2}{(n_1 + n_2)^4} \sigma_{n2}^2} \quad (4.2)$$

where n_1 and σ_{n1} are the number of events and error for the first decay, n_2 and σ_{n2} the number of events and error for the second decay. The errors on the fit parameters were calculated by taking the square root of the diagonal of the covariance matrix provided by the `optimize.curve_fit` function.

Chapter 5

Results

The following sections show the obtained fits and the corresponding values for the fitted parameters. Firstly the results for the $B_s^0 \rightarrow D_s^- \pi^+$ decay will be shown, secondly the $B_s^0 \rightarrow D_s^\mp K^\pm$ results will be displayed.

5.1 The $B_s^0 \rightarrow D_s^- \pi^+$ decay

Figure 5.1 shows the mass plot for the $B_s^0 \rightarrow D_s^- \pi^+$ decay. It shows a clear peak around 5365 MeV, which is similar to the PDG mass of the B_s^0 meson [22]. Figure 5.2 shows the mass plot for the $D_s^\mp$ meson. It shows a clear peak around 1968 MeV.

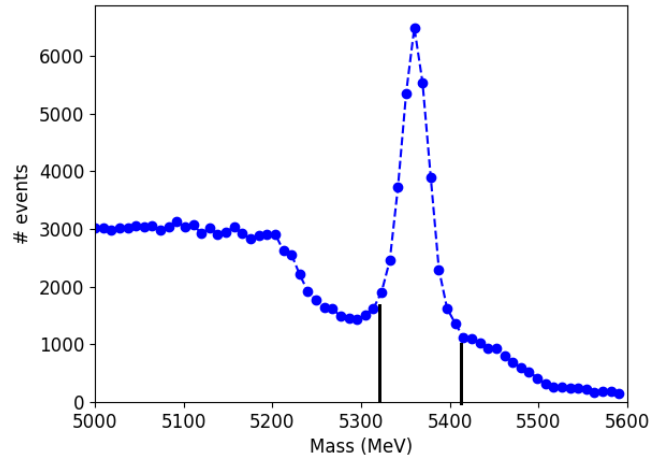


Figure 5.1: The B_s^0 mass plot for the $B_s^0 \rightarrow D_s^- \pi^+$. The error bars are not visible, due to their small size. The two black lines indicate the mass selection values, 5326-5406 MeV.

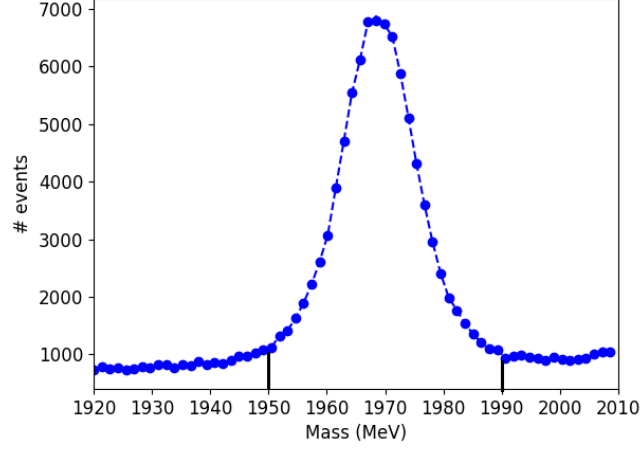


Figure 5.2: The $D_s^\mp$ mass plot for the $B_s^0 \rightarrow D_s^- \pi^+$ and $\bar{B}_s^0 \rightarrow D_s^+ \pi^-$ decays. The two black lines indicate the mass selection values, 1950-1990 MeV

The overall decay time distribution for $B_s^0 \rightarrow D_s^- \pi^+$ is shown in figure 5.3. The graph follows an exponential decaying function, while in the beginning the efficiency is lower due to LHCb trigger limitation at very low lifetimes. This is compensated in the fit by using the earlier mentioned acceptance function (equation 4.1), in the beginning the curve follows the same shape. The B_s^0 lifetime was obtained as 1.488 ± 0.009 ps.

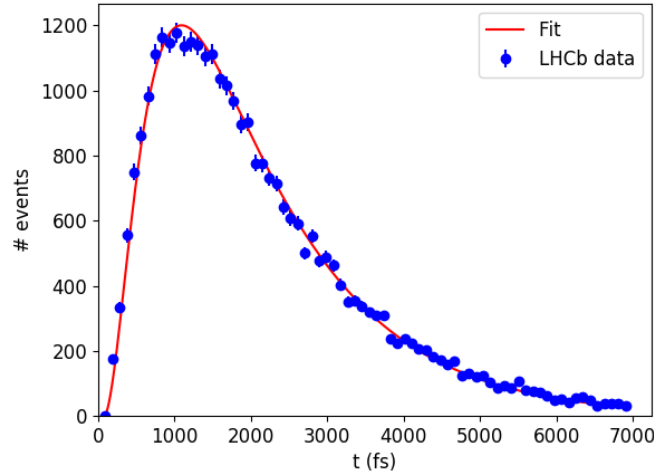


Figure 5.3: The overall decay time distribution and the fitted curve ($\chi^2 = 174.63$ for 70 df). An exponentially decaying function on top of an acceptance curve can be seen.

The decay-time distributions for the individual decays are shown in figure 5.4. All four graphs follow an exponential decaying function, with an added oscillation due to flavour mixing.

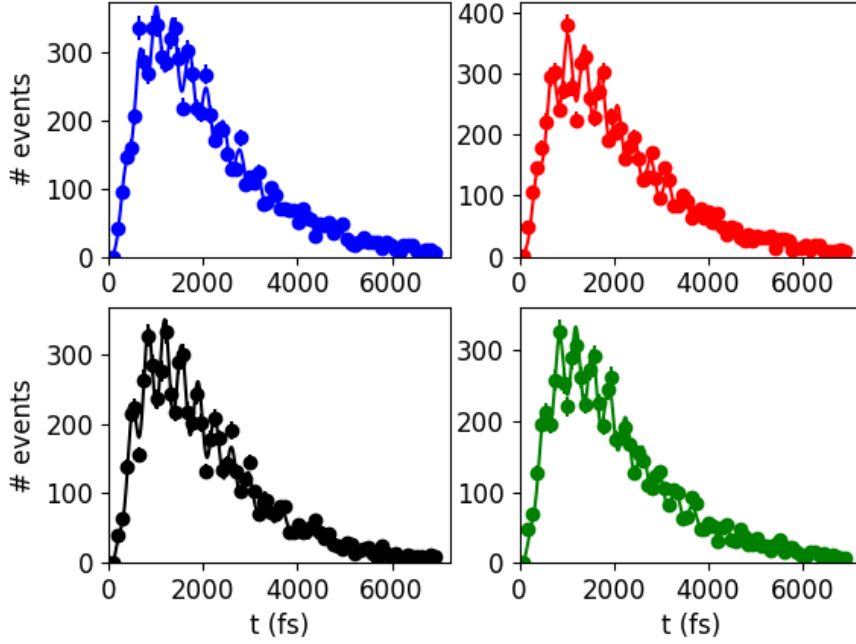


Figure 5.4: The separated decay time distributions. From top to bottom, left to right, the blue line represents the fitted $\bar{B}_s^0 \rightarrow D_s^+ \pi^-$ decay ($\chi^2 = 98.32$ for 68 df), the red $B_s^0 \rightarrow D_s^- \pi^+$ ($\chi^2 = 100.72$), the black $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow D_s^+ \pi^-$ ($\chi^2 = 99.45$) and the green $\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+$ ($\chi^2 = 102.12$). All of them have the form of an exponential decay, with an added oscillation, and the LHCb acceptance function.

The flavour mixing effect, i.e. the matter-antimatter oscillation, can be seen clearer in figure 5.5, which displays the even ($B_s^0 \rightarrow D_s^- \pi^+$ and $\bar{B}_s^0 \rightarrow D_s^+ \pi^-$) and odd ($B_s^0 \rightarrow \bar{B}_s^0 \rightarrow D_s^+ \pi^-$ and $\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+$) oscillated mesons. The two graphs are half a period out of phase; when one is at its maximum the other is at its minimum.

An even clearer image of the flavour mixing was obtained by normalising the two graphs from figure 5.5 using equation (2.29). The resulting data and fitted curve are shown in figure 5.6: the graph shows a clear cosine oscillation with an amplitude of about 0.2. The frequency of this oscillation, Δm_s , was obtained as $(17.732 \pm 0.042) \cdot 10^{12} \text{ s}^{-1}$ and the $\Delta \Gamma_s$ as $0.00 \pm 0.350 \cdot 10^{12} \text{ s}^{-1}$. The error on $\Delta \Gamma_s$ is big compared to the measured value, most likely due to the limitations of the fitting implementation in SciPy.

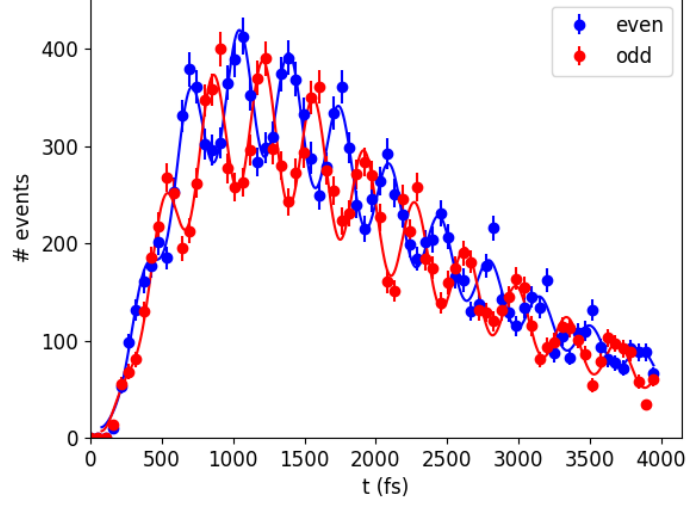


Figure 5.5: The decay-time distribution of the even ($\chi^2 = 110.26$ for 68 df) and odd ($\chi^2 = 112.78$ for 68 df) oscillated B_s^0 and $\bar{B}_s^0$ mesons. Flavour mixing can clearly be seen from both graphs, an oscillation is visible on top of the exponential decay and the LHCb acceptance function.

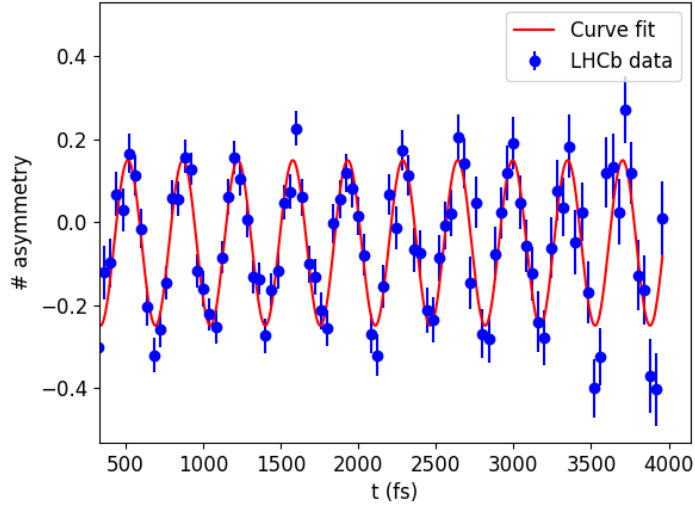


Figure 5.6: The normalized flavour mixing graph and fit ($\chi^2 = 125.93$ for 86 df). It follows a cosine shape with an amplitude of around 0.2, divided by a slowly varying cosh-like shape.

In addition to the flavour mixing asymmetry graph, the CP asymmetry was plotted together with a fit function, equation (2.26). The resulting data and fit are shown in figure 5.7. From the graph it can be seen that the fit seems to not properly match the data. The χ^2 value for the line $y = 0$, the expected CP-asymmetry value, was found to be 126.74 for 88 degrees of freedom, only slightly higher than the fit. The fitted function has an amplitude of 0.031 ± 0.147 , so it is concluded that no CP violation is observed in this decay.

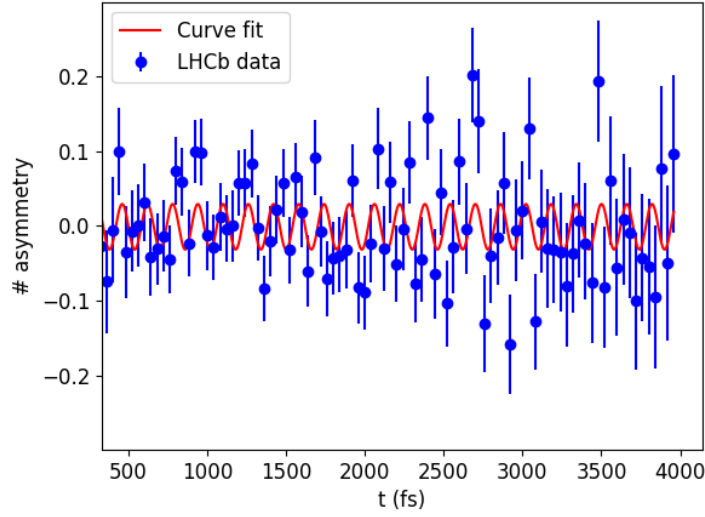


Figure 5.7: The normalized CP-violation graph and fit ($\chi^2 = 114.54$ for 88 df). The data appears to be centered around 0.

5.2 The $B_s^0 \rightarrow D_s^\mp K^\pm$ decay

Figure 5.8 shows the B_s^0 mass plot obtained from the filtered data. Similar to the $B_s^0 \rightarrow D_s^- \pi^+$ decay, it shows a clear peak around the SM B_s^0 mass at 5365 MeV. Next to this, the graph shows a larger peak at around 5275 MeV, the mass of the B^0 meson. Smaller fluctuations are visible in the 5000–5250 MeV range. These are most likely caused by decays into excited states of the $D_s^\mp$ and $K^\mp$ mesons. The $D_s^\mp$ mass plot is shown in figure 5.9. A peak is visible around the PDG mass of the $D_s^\mp$ meson, 1968 MeV [22].

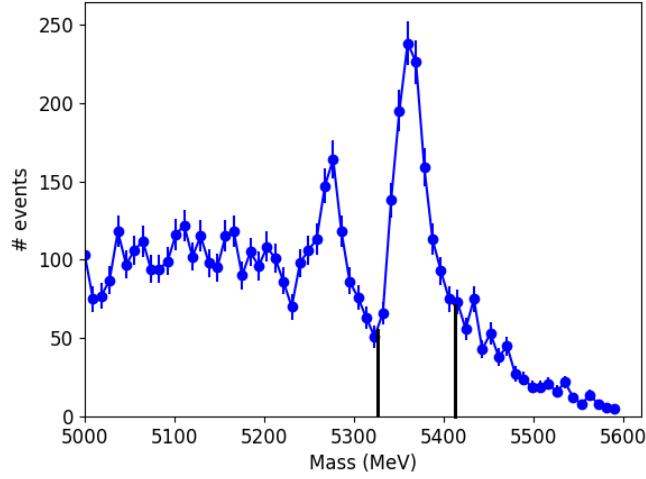


Figure 5.8: The B_s^0 mass plot for the $B_s^0 \rightarrow D_s^\mp K^\pm$ and $\bar{B}_s^0 \rightarrow D_s^\mp K^\pm$ decays. Two clear peaks can be seen, corresponding to the masses of the B_s^0 and B^0 particles. The two black lines indicate the mass selection values, 5326-5406 MeV.

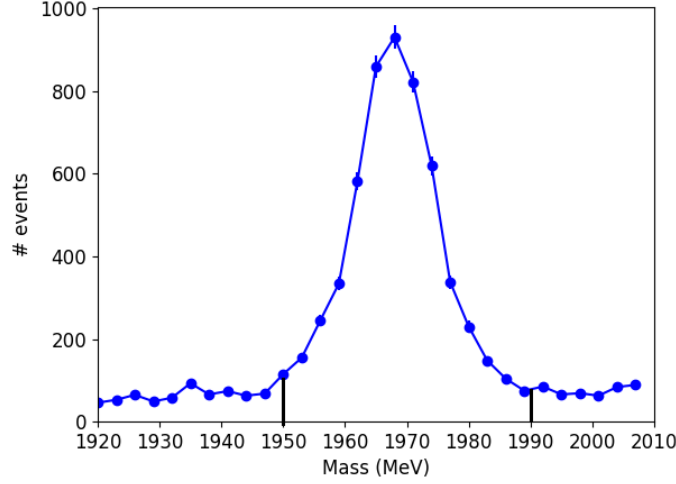


Figure 5.9: The $D_s^\mp$ mass plot for the $B_s^0 \rightarrow D_s^\mp K^\pm$ and $\bar{B}_s^0 \rightarrow D_s^\mp K^\pm$ decays. The two black lines indicate the mass selection values, 1950-1990 MeV

The overall decay time for the decays is shown in figure 5.10. The graph is very similar to figure 5.3, although due to the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay having a smaller branching fraction, there are fewer events. The B_s^0 lifetime was obtained as (1.451 ± 0.030) ps, consistent with the results for $B_s^0 \rightarrow D_s^- \pi^+$.

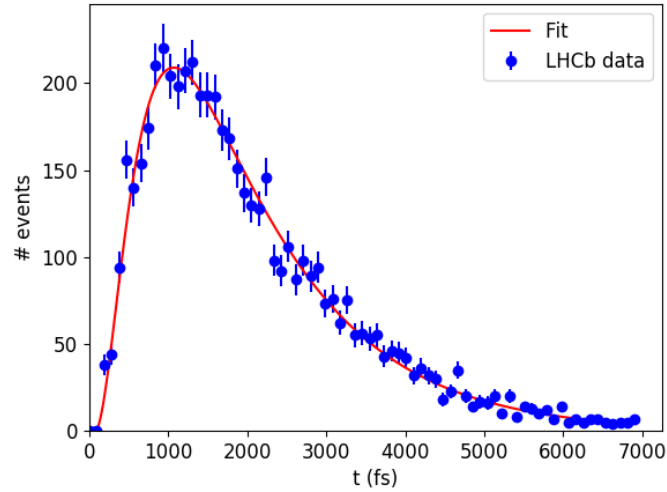


Figure 5.10: The overall decay time distribution and the fitted curve ($\chi^2 = 103.90$ for 70 df). An exponential decaying function was fitted on the data, in combination with the LHCb acceptance function, shown in equation 4.1.

The normalised flavour asymmetry graphs, $A_{mix}^{D_s^- K^+}$ and $A_{mix}^{D_s^+ K^-}$ from equation (2.27), are shown in figure 5.11, and their folded counterparts in figure 5.12. The graphs are folded using $T = \frac{2\pi}{\Delta m_s}$, which corresponds to one period of the flavour mixing oscillation. This means that the data will be added and combined into one oscillation, leading to more events per bin, and therefore potentially better χ^2 fit results. The obtained fit parameters (C_f, S_f, D_f and $C_{\bar{f}}, S_{\bar{f}}, D_{\bar{f}}$) and their associated errors are shown in table 5.1. It can be seen that the D_f and $D_{\bar{f}}$ values have a relatively big error compared to the other parameters. Similarly to the $B_s^0 \rightarrow D_s^- \pi^+$ events, it turns out that the $\Delta\Gamma_s$ influence is difficult to observe.

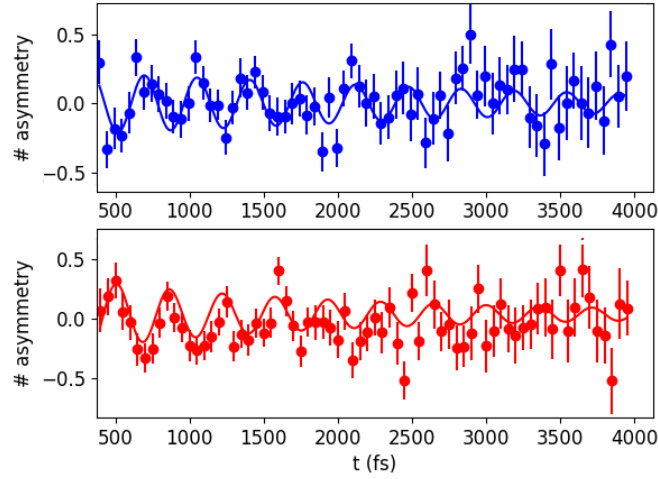


Figure 5.11: The two flavour mixing graphs. The top, blue graph ($\chi^2 = 94.54$ for 88 df) corresponds with the final state $D_s^- K^+$ and the bottom, red graph ($\chi^2 = 112.35$ for 88 df) with the final state $D_s^+ K^-$. The fit consists of a dampened cosine function, corresponding to the expectation.

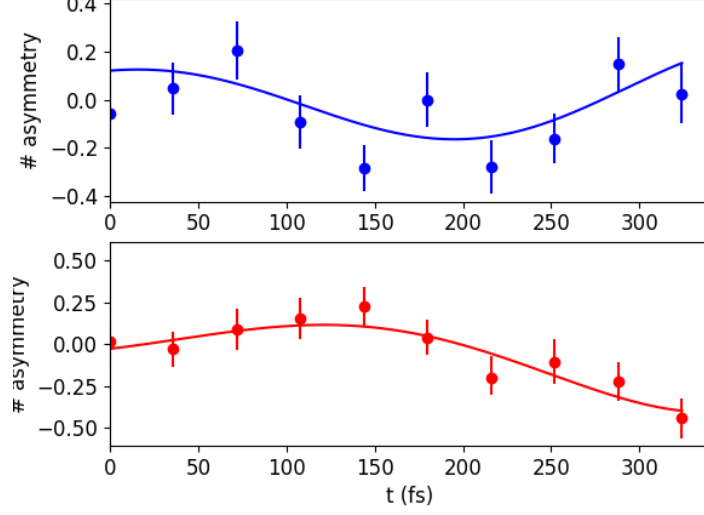


Figure 5.12: Folded flavour mixing graphs for the two final states. The top graph ($\chi^2 = 13.34$ for 7 df) corresponds to the final state $D_s^- K^+$, and the bottom graph ($\chi^2 = 4.31$ for 7 df) to $D_s^+ K^-$.

Parameter	Flavour mixing fit
C_f	0.242 ± 0.216
S_f	-0.021 ± 0.068
D_f	0.456 ± 2.188
$C_{\bar{f}}$	-0.377 ± 0.691
$S_{\bar{f}}$	-0.412 ± 0.770
$D_{\bar{f}}$	3.616 ± 10.973

Table 5.1: The obtained flavour mixing fit parameters and their associated errors.

From these values, using equation (2.19), the value of $|\lambda|$, $\Re(\lambda)$ and $\Im(\lambda)$ can be determined, and hence using equations (2.34) and (2.35) the values of the weak phase $2\beta_s + \varphi$ and the strong phase δ_s . However since all the obtained parameters are not significantly different from 0, and therefore no CP violation is present, this would most likely yield an insignificant result. It was therefore decided, in combination with the limited time frame for this research, that this would not be done.

The CP asymmetry graphs are shown in figure 5.13. No good fit using equation 2.30 could be made, the data does not significantly deviate from 0, since the χ^2 values for a horizontal line $y = 0$ are 29.69 and 39.00 for both the respective $D_s^- K^+$ and $D_s^+ K^-$ final states.

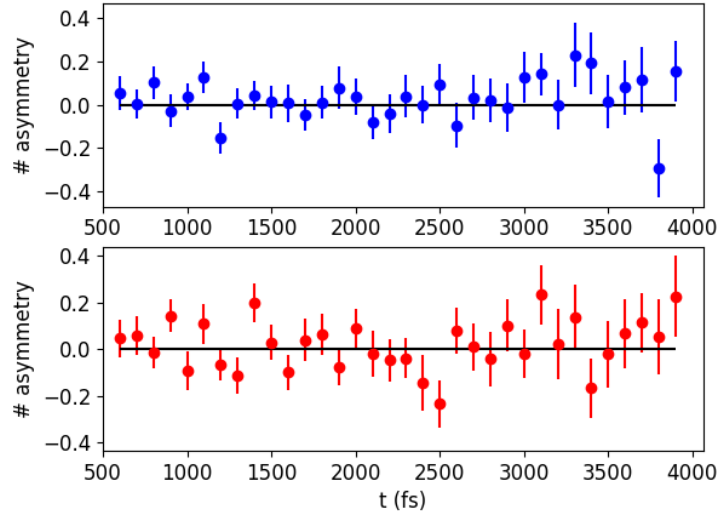


Figure 5.13: The obtained CP asymmetry graphs. The top, blue graph ($\chi^2 = 29.69$ for 38 df) shows the $B_s^0 \rightarrow D_s^- K^+$ and $\bar{B}_s^0 \rightarrow D_s^+ K^-$ asymmetry, and the bottom, red graph ($\chi^2 = 39.00$ for 38 df) the $B_s^0 \rightarrow D_s^+ K^-$ and $\bar{B}_s^0 \rightarrow D_s^- K^+$ asymmetry.

Chapter 6

Discussion and Conclusion

6.1 Discussion

6.1.1 The $B_s^0 \rightarrow D_s^- \pi^+$ decay

The B_s^0 mass plot of the filtered data, shown in figure 5.1, shows a clear peak around the SM B_s^0 mass of 5366 MeV. Even though the data was filtered, there are still background events visible. The events above 5420 MeV consist of combinatorial background, while the events between 5000 and 5300 MeV are a the result of both combinatorial background, as well as excited state decays and misidentified particles. Fluctuations are visible between 5100 and 5160 MeV, caused by the presence of partially reconstructed decays. This means that either the $D_s^\mp$ or the bachelor $\pi^\pm$ was in an excited state, and therefore emitted a photon. This photon was not picked up by the LHCb detector, leading to a downwards shift in the detected mass of the B_s^0 particle. By looking at figure 5.1, the mass cut-off values for the filtering were selected as 5326 and 5406 MeV. This mass cut removes a lot of these background events, leading to a more pure data sample. Another interesting observation that can be made from the mass plot, is the visibility of the experimental dilutions. The full width at half maximum (FWHM) of the B_s^0 mass plot corresponds with the mass resolution of the LHCb detector mentioned in section 3.2.1, around 18 MeV. Similar observations can be made from the $D_s^\mp$ mass plot, shown in figure 5.2. It shows a peak around the SM mass, 1968 MeV, of the $D_s^\mp$ meson. Using the obtained mass plot, the $D_s^\mp$ mass cut values to reduce the amount of background were selected as 1950 and 1990 MeV. The mass resolution of the LHCb detector is again visible in this plot as the FWHM value, which is here 18 MeV.

The combined lifetime distribution for the $B_s^0 \rightarrow D_s^- \pi^+$ decay is shown in figure 5.3. The curve corresponds to the expectation. It follows an expo-

ponential decay of the form $A\frac{1}{2}e^{-\Gamma_s t}$. The obtained fit value for the lifetime, Γ_s , is (1.488 ± 0.009) ps, which is a deviation of 3σ from the PDG value, (1.510 ± 0.005) ps [22]. This difference is potentially caused by the presence of background events and the used lifetime acceptance function not being an exact representation of the actual LHCb acceptance for this decay. Figure 5.4 shows the separate decay-time distributions for the four decays. They show a trend comparable to the total decay-time distribution, an exponential decay, with an added cosine oscillation on top. The graphs correspond with the expected decay-time distributions, as shown in equation (2.28). The fits have a mean Γ_s value of (1.437 ± 0.025) ps, which is also 3σ lower than the PDG value. To obtain a more accurate fit value for Γ_s , a possible solution could be applying a decay time cut at $t = 1$ ps, which removes the majority of the background, as well as the dependence on the acceptance function from the fit, leading to a less complicated fit, and therefore potentially a better Γ_s value.

The flavour mixing asymmetry described in section 2.1 can clearly be seen in the obtained graphs. Figure 5.5 shows the decay-time distribution for the even and odd mixed decays. The two curves follow an exponential decay with an added oscillation, the flavour mixing. The oscillations on both curves are half a period out of phase, caused by the minus sign that follows from the $B_s^0 \rightarrow D_s^- \pi^+$ master equations for the odd-mixed mesons, shown in equation 2.28. Figure 5.6 shows the normalised flavour mixing graph, with equation 2.29 fitted. The value for Δm_s used in the fit is $(17.732 \pm 0.042) \cdot 10^{12} s^{-1}$ and $\Delta \Gamma_s$ is $(0.00 \pm 0.35) \cdot 10^{12} s^{-1}$; it could not be determined. The amplitude of the function is not 1, due to detector limitations such as imperfect tagging and the finite decay time resolution. Both values are within one standard deviation of the expected PDG values mentioned in section 1.3, however the inaccuracy of the $\Delta \Gamma_s$ is several orders of magnitude larger than the measured value. This large error is likely caused by the limited fitting sensitivity of the used SciPy `optimize.curve_fit` function, in combination with the relatively small value of $\Delta \Gamma_s$. The Δm_s value, however, has a small error and is similar to the expected value. This difference in error magnitude is likely caused by the expected size difference between the two parameters, and therefore Δm_s having a larger influence on the fit function. The small difference between the obtained Δm_s and the predicted value indicates that the applied data cuts yield a comparable result to the previously performed analysis by the LHCb collaboration [18]. It should be noted, however, that both this analysis as well as the LHCb analysis use the same run 1 data, leading to a potential correlation.

The obtained CP asymmetry is shown in figure 5.7. The fitted function has an amplitude of (0.031 ± 0.147) , so no significant deviation from

0 is present; no CP violation is present. This is in agreement with the SM prediction, as explained in section 2.3.

6.1.2 The $B_s^0 \rightarrow D_s^\mp K^\pm$ decay

The obtained mass B_s^0 mass plot for the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay, shown in figure 5.8, is comparable to the mass plot obtained for the $B_s^0 \rightarrow D_s^- \pi^+$ decay. A peak is clearly visible at the B_s^0 PDG mass of 5366 MeV. At 5275 MeV, another peak can be seen. This peak corresponds to the $B^0 \rightarrow D_s^\mp K^\pm$ mass. This peak is not visible in the $B_s^0 \rightarrow D_s^- \pi^+$ mass plot, since that decay has relatively more (combinatorial) background and more partially reconstructed decays, leading to the peak disappearing in the general background. In addition, similar fluctuations can be seen as in figure 5.1, corresponding to the partially reconstructed decays. The same mass cut values as used for the $B_s^0 \rightarrow D_s^- \pi^+$ decay, 5326 and 5406 MeV, were selected. Similar experimental dilution effects, as explained in section 6.1.1, are also visible in this mass plot. The $D_s^\mp$ mass plot is shown in figure 5.9, and yields comparable results to the $B_s^0 \rightarrow D_s^- \pi^+$ plot (figure 5.2), described in section 6.1.1. Just as for the B_s^0 mass, the same $D_s^\mp$ mass cut values were selected.

The decay-time distribution of all the $B_s^0 \rightarrow D_s^\mp K^\pm$ decays is shown in figure 5.10. It follows an exponential decay, with fitted $\Gamma_s = (1.426 \pm 0.019)$ ps. This is more than 4σ removed from the PDG value mentioned in section 6.1.1. The difference between this Γ_s value and the value obtained for the $B_s^0 \rightarrow D_s^- \pi^+$ decay could be explained by the lower number of candidate events for $B_s^0 \rightarrow D_s^\mp K^\pm$, since it has a lower branching fraction, leading to a lower accuracy. Another possible explanation could be the fact that the sample is less pure, due more background contributions relative to the $B_s^0 \rightarrow D_s^- \pi^+$ decay.

As explained in chapter 2, $B_s^0 \rightarrow D_s^- \pi^+$ is a flavour-specific decay and therefore has no decay amplitude interference. This results in simplified master equations, as shown in equation 2.28, which do not contain the CP-violation parameters D_f and S_f . The $B_s^0 \rightarrow D_s^\mp K^\pm$ master equations (equations 2.19, 2.20 2.21 and 2.22), however, do contain these parameters and their associated sin and sinh terms, leading to a different shape of the curve and the possibility of CP violation. Looking at the flavour mixing graph in figure 5.11, the flavour mixing is again clearly visible. Comparing the graphs with figure 5.6, the earlier explained difference can be seen. Both graphs in figure 5.11 follow the shape of a dampened sinusoidal function, which is caused by the sinh term in the fitted master equation. The folded flavour mixing graphs are shown in figure 5.12. The graphs are folded using $T = \frac{2\pi}{\Delta m_s}$, one period of the flavour mixing oscillation, and show a clearer

image of one oscillation period.

The fitted master equation parameters, corresponding to the fit in figure 5.11, are shown in table 5.1. All the parameters have a relatively large associated error and fall within 1σ of 0. Since the parameters are not significantly different from 0, no evidence for CP violation has been found in this analysis. This is supported by the CP asymmetry plot, shown in figure 5.13. It was not possible to obtain a good fit for the CP asymmetry, and has a low χ^2 for $y = 0$. An important factor is the less extensive background rejection performed in this analysis, compared to the LHCb analysis, leading to more background events and therefore a less clear signal. In addition, SciPy’s limited fitting functionality does not allow for per event likelihood fits, leading to less accurate fits.

6.1.3 Possible improvements, research implications, and further research

An upcoming improvement of the analysis is the use of LHCb run 2 data, which was not available at the time of this analysis. This would lead to more events, about twice the current amount, and therefore more statistical significance in the data. Another improvement could be the further optimisation of the available detector reconstruction parameter values, used in the data filtering. This could possibly further reduce the amount of background, and lead to a purer data sample. Furthermore, due to the relatively low amount of events for the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay, the use of a likelihood fit could lead to better results than a χ^2 fit, since this would remove the need for binning and allow the use of the per-event error. In addition, the used SciPy fitting package appears to be the limiting factor in multiple fits. The use of different fitting software, for example RooFit, could potentially lead to better fitting results with smaller, or at least better defined errors.

The performed research has not found experimental evidence for the expected CP violation in the B_s^0 meson system. It has shown, however, that SciPy is not an ideal tool to use for fitting purposes in the field of meson physics, and that it is better to use more commonly used software, such as Root, for this type of analysis. Furthermore, flavour- and CP-asymmetry plots were created that have never been published before, which can potentially be used as publicity plots for the LHCb collaboration.

Further research in the search for beyond-SM physics to explain Baryogenesis can be done by looking at other B_s^0 decay channels, e.g. $B_s^0 \rightarrow J/\psi \phi$, and continuing the study on the $B_s^0 \rightarrow D_s^\mp K^\pm$ decay using more data. Another possible research direction for beyond-the-SM physics is the search for

CP violation in the strong interaction, which has not yet been observed.

6.2 Conclusion

This research analysed the decay-time dependent flavour mixing and CP violation in the B_s^0 meson system using LHCb data. Both the $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow D_s^\mp K^\pm$ decay data were analysed and filtered using the available detector reconstruction parameters. Mass plots for the B_s^0 and $D_s^\mp$ mesons were created to find the mass cut values. Fits for the expected theory equations were made for the decay-time distributions, flavour mixing and CP-asymmetry plots. Δm_s was found to be $(17.732 \pm 0.042) \cdot 10^{12} \text{ } \hbar s^{-1}$ and the parameter $\Delta \Gamma_s$ could not be accurately determined. The obtained master equation parameters, shown in table 5.1, do not deviate significantly from 0, so no CP violation was observed. Further improvements could be the use of more sophisticated fitting software, for example RooFit, and a more extensive background rejection.

Chapter 7

Self reflection

During the four months I spent on this bachelor thesis research, I have mastered multiple new skills. I have become more proficient in the use of the Python programming language for data analysis. Before I started my thesis, I already had some experience in Python, and followed multiple programming courses at the Maastricht Science Programme (MSP). Although these courses provided me with a good basis, a small learning curve was still present for the use of the NumPy, SciPy, Pandas and PyPlot libraries. I believe I mastered the packages relatively fast, and learned on-the-go how to apply them on the LHCb data.

Besides the programming aspect, the theory was the most complicated part of the performed research. The major part of the first month was spend on understanding the involved theory, using the lecture notes of the UvA Particle Physics 2 master course and following several of its lectures. The MSP PHY3006 course provided me with a decent general knowledge about particle physics, however the increase in difficulty was still substantial. Despite this, I believe I managed to obtain a good understanding of the involved theory and the experimental details of LHCb over the course of this thesis.

There are, however, also some aspects that could be improved next time. In general, my code could have been more structured. Sometimes the changing of a single parameter had to be implemented on multiple locations in the code, while this could have been easily prevented by using a single variable. Also the choice of using Python instead of Root for the analysis turned out to be the suboptimal one, since the fit sensitivity of SciPy is substantially lower than e.g. RooFit. Next time it might be better to use Root.

Overall I am happy with the results of my thesis, especially since I also missed two weeks due to illness. I learned a lot, both about the involved theory and the LHCb experiment, and am very grateful to Nikhef (especially Prof. dr. Marcel Merk) for this great opportunity.

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Appendix A

Code

The code used in this analysis can be found at <https://gitlab.cern.ch/lhcb-dsh-plotting/plotting/tree/master>. The code is sorted for the $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow D_s^\mp K^\pm$ decays.