Summary

The Standard Model, developed over the last forty years, describes the nature of particles and their interactions. Although it is considered to be a fundamental theory of particle interactions, the Standard Model is far from being a complete theory. There are a number of phenomena that remain unexplained; such as the reason why particles have the mass that they have, the nature of dark matter and dark energy, the phenomenon of neutrino oscillations and the origin of the matter-antimatter asymmetry. To find answers to these open questions, physicists are looking for extensions or even alternative models which together are known as Physics Beyond the Standard Model.

Of these unexplained phenomena the research presented in this dissertation falls in the context of understanding the matter-antimatter asymmetry. In fact, the Standard Model includes the assumption that there is only a very small discrepancy between the quantities of matter and antimatter that were created during the Big Bang. However, the world that surrounds us and the universe in general are made exclusively of matter. So where did all the antimatter go? How can we explain the imbalance between matter and antimatter?

To explain this, we need to introduce the concept of CP-symmetry, that corresponds to the combination of two conserved quantities: charge conjugation (C) and parity (P). What CP-symmetry tells us is that the laws of physics should stay the same if each particle is interchanged with its antiparticle and if its spatial coordinates are inverted, or mirrored. The existence of CP violation during the first seconds of our universe, together with Baryon number violation and thermal non-equilibrium, would explain the imbalance between matter and antimatter from an initial condition of balance.

We know that something must have happened to disrupt this initial equilibrium. If it had not, then protons would have cancelled with antiprotons, electrons with positrons and so on, and we would have been left with a universe consisting only of a sea of radiation, which is clearly not the case.

How can we find evidence of CP violation? The Standard Model includes in its predictions three possible sources of CP violation: in weak interactions of the quark and lepton sector and in strong interactions. The fact that CP violation does not occur in strong interactions is considered a fine-tuning problem. CP violation in the lepton sector can manifest itself in neutrino oscillations, which will be studied by future experiments. The LHCb experiment at the LHC has been designed to effectively search for CP violation in the quark sector; it has been optimized to detect the decays of B mesons, in which evidence of CP violation can be observed.

So why are B mesons so special? Neutral B mesons are known to spontaneously oscillate between their particle and antiparticle state before decaying, making these particles particularly interesting for CP violation studies. In particular, the LHCb experiment has observed that $B^0$ and $B^0_s$ mesons decay into matter in different decay rates than they decay into antimatter [77], which could help explain the universe’s imbalance between matter and antimatter.

CP violation studies have been performed in the past at the Tevatron accelerator and at the BaBar and Belle experiments, but the moderate production rate of neutral B mesons makes CP violation measurements of rare decays extremely challenging. However, with the start of the

\[1\text{These are known as Shakharov conditions.}\]
Summary

Large Hadron Collider (LHC) at CERN a new era in High Energy Physics began.

At the LHC, protons collide at a center-of-mass energy of 8 TeV\(^2\); energy that has never been achieved at any particle physics experiment. This makes the LHC the most abundant source of \(b\)-quarks, which can hadronized into different types of long-lived \(B\) hadrons. These hadrons are produced in pairs and, due to their small mass compared to the energy of the LHC, fly predominantly in the forward or backward direction. The LHCb experiment was specifically designed to study beauty (\(b\)-quark) and charm (\(c\)-quark) flavour physics. Unlike the ATLAS and CMS detectors the LHCb spectrometer does not cover the full solid angle, but is developed along the forward direction with respect to the collision point.

Apart from its geometry, developed to accommodate for the large \(b\bar{b}\) cross section, the LHCb detector was optimized to perform flavour physics precision studies. In order to measure the fast \(B^0_{(s)}\) oscillations the measurements of proper decay time must be very precise. This means that, among other things, an excellent vertex resolution is needed to distinguish secondary vertices produced by \(B^0_{(s)}\) mesons from primary vertices produced from \(pp\) interactions.

The mission of identifying the positions of vertices where \(B^0_{(s)}\) mesons are produced and decay is left to the VERTex LOcator (VELO); a silicon detector that, during the normal running of the LHC, sits only 7 mm away from the proton beams.

The work presented in this thesis was divided in two main parts: the first involved commissioning work and data quality analysis for the VELO detector and the second focused on the determination of the flavour of neutral \(B^0_s\) mesons at production, necessary for the study of CP violation in \(B^0_s \rightarrow D_s^\pm K^\pm\) decays.

As mentioned previously, the VELO detector at LHCb is used to measure the positions of vertices where \(B^0_s\) mesons are produced and decay; measurements that must be as precise as possible in order to correctly evaluate the decay times of these particles. To achieve this, not only does the detector need to have an excellent performance but we must make sure that the data that is read out by the detector, on which physics analyses are based, is correct.

The first part of the research described in this thesis consisted in setting up the error monitoring for the VELO detector. For particle tracks to be reconstructed without any bias from the VELO, the digital representation of the signal charge deposited in the sensors and collected

\(^2\)This energy will increase to up to 14 TeV in future years.
at the silicon strips must be accurate. The possible sources of error that may occur at various stages of the data acquisition chain were studied, isolating the individual problems. Once the different types of errors had been identified, these errors were fixed where possible and problematic outputs were labeled, such that the data coming from them would not be used for physics analysis. In addition, an online error monitoring was set up; meaning that errors are checked for and recorded on the fly, as data is being taken.

While analysing and setting up the error monitoring for the VELO detector, we observed negative signals from the silicon sensors. Part of the research was dedicated to the study of these negative signals and aimed at understanding their source. Although the large number of instrumental effects makes it difficult to determine what the individual negative signals are due to, their overall origin was found to be the coupling between strips that are connected via a routing line. In fact, a negative signal observed on one strip appears to be generated by high signals present on strips with a routing line passing over the strip where the negative hit was observed.

Since one of the main goals of the LHCb experiment is to observe evidence of CP violation in the decays of $B$ mesons, the third part of this thesis focuses on the analysis of $B^0_s \rightarrow D^- \pi^+$ and $B^0_s \rightarrow D^+ K^-$ decays. In order to obtain unbiased measurements a precise understanding of various experimental aspects is required. One of these aspects when trying to observe an oscillation signal is the mistag probability of flavour tagging procedures; i.e. the number of times that an initial $B^0_s$ ($B^0_s$) meson is wrongly identified as a $B^0_s$ ($B^0_s$) meson.

The decay $B^0_s \rightarrow D^+ K^-$ can occur directly or via mixing (the $B$ meson oscillates into its antiparticle before decaying). The presence of a direct tree diagram and a tree diagram with mixing means that CP violation can occur in this channel, from the interference between the two decay amplitudes.

In order to determine the difference between the $B^0_s$ and $B^0_s$ decay rates the initial particle flavour ($B^0_s$ or $B^0_s$) must be measured. For a correct measurement it is of particular importance to determine the probability that a wrong result is produced: the wrong tag fraction.

For this reason, in this analysis $B^0_s \rightarrow D^- \pi^+$ data collected at LHCb was used to precisely measure the mistag probability. Although this decay is topologically similar to the $B^0_s \rightarrow D^+ K^-$ decay, the $B^0_s \rightarrow D^- \pi^+$ decay is flavour specific, meaning that a $B^0_s$ can only decay to a $D^- \pi^+$ final state and a $B^0_s$ can only decay to a $D^+ \pi^-$ final state. Therefore, the oscillation amplitude of the time dependent decay rate is a measure of the tagging purity.
Summary

The value of the mistag probability measured using $B_s^0 \rightarrow D_s^- \pi^+$ data was then used to study the sensitivity of LHCb to carry out CP violation measurements. A measurement of the weak phase $\gamma$ on simulated $B_s^0 \rightarrow D_s^\pm K^\mp$ events was obtained, through which evidence of CP violation can be found. This measurement was performed on two different MC data samples of 10 and 50 fb$^{-1}$, representing respectively the data that is expected to be collected at LHCb before and after the upgrade, using the current and the newly calibrated value of the mistag probability.

The results presented in this dissertation on 10 fb$^{-1}$ of simulated data show that a precise calibration of the mistag probability leads to an improvement in the sensitivity of $\gamma$ of about 10%, from $\gamma = (71.1 \pm 10.7)\degree$ to $\gamma = (71.1 \pm 9.9)\degree$. The studies performed on 50 fb$^{-1}$ show that with larger statistics and a precise value of the mistag probability the uncertainty on $\gamma$ is further reduced to about 2\degree. The precision level of just a few degrees with which the weak phase $\gamma$ can be measured provides a stringent test when searching for evidence of CP violation in the Standard Model.

The first measurement of the CKM angle $\gamma$ from $B_s^0 \rightarrow D_s^\pm K^\mp$ decays was recently obtained at the LHCb experiment. The analysis used 1 fb$^{-1}$ of $B_s^0 \rightarrow D_s^\pm K^\mp$ data, and yields $\gamma = (122^{+25}_{-30})\degree$. Although the measurement of the angle $\gamma$ has not been published yet, this result has been presented at the 2014 ICHEP conference.