Dear reader,
In the next few pages I would like to introduce you to the world I have been living in for the past few years. This world of mine is inhabited by the smallest of things, the elementary particles. Yet, it is everywhere around us, stretching out to the furthest corners of our Universe. It is an incredibly complex world. The deeper we adventure into it, the more hidden mysteries we uncover, and the more we are drawn in by its spells. To you this world might appear difficult to comprehend, but so it does to us too. And yet, it has not stopped us from exploring. Instead, the challenges and questions drive us ever on. Since, like you, I cannot grasp it all, I have dedicated the four years of my PhD study to one special creature inhabiting this world. It lives in the cold and icy part of my world, and is only rarely seen. Yet we know it must be there, and so we set out to search for it . . .

The Standard Model

Let us start our journey through the realm of particle physics right on the doorstep of our home. The objects you encounter in everyday life might not always seem spectacular to you, but there is more to them than meets the eye. If we were to zoom in on them, and continued to do so, at some point you would notice that they are made out of billions of smaller building blocks: molecules. In turn, molecules are made out of atoms, which themselves consist of a core of protons and neutrons, surrounded by a cloud of electrons. But this is not yet the end of it, because protons and neutrons can again be decomposed into quarks. Specifically two types: the up and the down quark. Together, the electrons and the quarks form the most basic building blocks of our Universe (that we know of).

Although everything around us is made out of electrons, up and down quarks, we have learned over the past hundred years that there are actually many more elementary particles in Nature. Most of the other fundamental particles, however, are very exotic and short-lived\[a\], making it more difficult to observe them. In fact, you need large particle accelerators, either man-made or cosmic in origin, to

\[a\]Neutrinos form an exception. But due to their weak interaction with other matter, they are still very challenging to observe.
reach the energies that are needed to produce them. By studying collisions involving these accelerated particles we have been able to learn a lot about the world of elementary particles. For example, we have so far identified six different quark types. In order of increasing mass, that are the up, down, strange, charm, bottom (or beauty, whatever you prefer) and top. Likewise, we now know of three electron-like particles, the electron, muon and tau. And have found three different ghost-like particles, referred to as neutrinos, that are associated with these electrons, muons and taus. Together, these six particles form the leptons. As if that is not enough, every particle listed above also has a partner, the antiparticle, which functions as its antagonist. Particles and antiparticles have the same mass, but otherwise opposite properties. If, for example, the particle is blue and positively charged, the antiparticle would be anti-blue (or yellow on the colour wheel) and negatively charged. Energy can be used to create a particle–antiparticle pair, and likewise if a particle and its antiparticle meet, they annihilate each other and transform back into energy. Luckily for us, antimatter has become very rare in the Universe, so the annihilation process almost never happens, and especially not on human-size scales. It is nonetheless regularly produced (and exploited by, for example, medical PET scanners), but only in tiny amounts and most of it quickly annihilates again. Studying the relation between particles and their antiparticles forms an important aspect of my research.

Besides the quarks and leptons, we have also discovered a bunch of particles that act as mediators for three of the four fundamental forces of Nature: electromagnetism, and the weak and strong (nuclear) force. The electromagnetic force is responsible for light, electricity and magnetism, and for keeping electrons in orbit around the atom core. Its force carrier is the photon. The strong force acts as glue that keeps the quarks together inside the protons and neutrons, and is mediated by so-called gluons. The weak force is responsible for the decay of unstable particles, for example in radioactivity. Its mediators are the \( W \) and \( Z \) bosons. The strong and weak force only play a role at the length scale of atoms or smaller, and are therefore less prominently visible in our daily lives. And lastly, in addition to the quarks, leptons and force carriers, there is also the Higgs particle. It is related to the mechanism that is responsible for the masses of the fundamental particles. But truly explaining what it is and how it comes about, goes a bit beyond the purpose of this summary.

To make sense of all these different particles and their behaviour, physicists have come up with a theory describing the elementary particles and their interactions: the Standard Model. The only thing missing from this theory is a description of the fourth, and most obvious, fundamental force, gravity. It simply does not fit into the mathematical formulation used to describe the other forces. That is not the only problem we encounter in particle physics. The Standard Model has been (and
continues to be) remarkably successful in describing the experimental data we collected from cosmic ray and accelerator-based experiments, but it cannot explain the origin or nature of some other firmly established experimental observations. Let me illustrate that with a few examples. Cosmological observations contain a lot of information about the content of the Universe and how it evolved from the Big Bang, an enormous explosion of energy that marked the birth of our Universe, to the present day. These observations tell us that the Universe consists for only 4% out of ordinary matter, i.e. atoms and molecules. The remaining 96%, which go under the mysterious names of dark matter and dark energy, are currently unexplained. In addition, the Big Bang created equal amounts of matter and antimatter. Yet in the Universe we observe today, antimatter has largely disappeared. How did that happen? One way to find out more about this puzzling observation is to study the differences in behaviour between particles and their antiparticles.

Because of the shortcomings mentioned above (and others that are more difficult to explain here), physicists consider the Standard Model to be only an approximate theory; a special corner of a more complete, but unknown, theory of particle physics. It is our goal, as a particle physics community, to find evidence for this “grand theory of particle physics”, and gain further insight into its properties. To succeed in that, we explore many different possibilities: we search for new fundamental particles, or new types of interactions, or ... All these phenomena go under the general name of new physics. So far, we have not yet found clear evidence for new physics effects. That means that the deviations from the Standard Model will be small or hard to find, thus requiring further effort from both the experimental and the theoretical particle physics communities.

The Search for New Physics

Our main instruments for searching for experimental evidence of new physics are high-energy particle accelerators, which accelerate electrons and/or protons to nearly the speed of light before smashing them into each other at pre-defined collision points. Around these collision regions, large particle detectors are built. These detectors act as oversized cameras taking pictures of the collision events, millions of times per second. By analysing these pictures, we hope to learn more about what happens at the smallest length scales, which can eventually lead to new findings that cannot be explained by the Standard Model theory. In the quest for new physics, the accelerators are attaining higher and higher energies in order to access yet unexplored territory, where new fundamental particles might abide. The latest and most powerful accelerator taking up this task is the Large Hadron Collider (LHC), located at CERN in Geneva, Switzerland. It has four interaction

[b] As an example, Newtonian gravity is the (s)low-speed limit of Einstein's General Relativity.
points. The large detectors surrounding each one of them are called Atlas, Alice, CMS and LHCb. Together, they have performed many interesting new measurements, but the biggest highlight of the LHC is undoubtedly the discovery of the Higgs particle by the Atlas and CMS experiments.

In my research, the LHCb detector plays a central role. Complementary to the high energy frontier that is explored by Atlas and CMS, it focuses on high precision measurements of known physical processes related to the decay of particles containing beauty and charm quarks. Through these measurements we hope to find indirect evidence for new physics, manifesting itself as deviations from the Standard Model predictions. Given the current situation, such new physics observations can only be claimed when the theoretical precision on the Standard Model prediction for the measured observables at least matches the experimental uncertainty. We therefore need to have a careful look at the theoretical assumptions linking the experiment measurements with the Standard Model parameters.

The tools we have developed to perform theoretical calculations in particle physics are based on a series expansion, where each new term in the series gives a small correction to the previous one. Thus, the more terms in these series we take into account, the more precise our calculation becomes. But each additional term is also increasingly more difficult to compute. For many experimental measurements we therefore only take into account the first (few) term(s) of this series. With the increased experimental precision that can be reached by the LHCb experiment, this approximation will no longer remain sufficient for some of the key observables measured by LHCb.

About Trees and Penguins

This thesis reports my study on the impact of such higher order corrections for two specific processes. These processes deal with the decay of so-called neutral $B$ mesons. $B$ mesons are heavy particles consisting of a bottom antiquark and either a down ($B^0$) or a strange ($B^0_s$) quark. They are unstable, and only live for a very short period of time (a few trillionths of a second), after which they decay into a number of lighter particles. We have found well over 250 different possible combinations of decay products, but of interest for this thesis are the two decay channels $B^0 \rightarrow J/\psi K_S^0$ (to be pronounced as B-zero-to-jay-psi-K-short) and $B^0_s \rightarrow J/\psi \phi$ (B-s-to-jay-psi-fi). In these modes, the $B$ meson decays into a $J/\psi$ particle, consisting of a charm and an anticharm quark, and either a $K_S^0$ particle, consisting of a strange antiquark and a down quark, or a $\phi$ particle, consisting of a strange and an antistrange quark. But you may also see it as cryptic code which particle physicists use to talk about certain decay processes.

The leading order process with which the $B^0 \rightarrow J/\psi K_S^0$ and $B^0_s \rightarrow J/\psi \phi$ decays take place, is referred to as the tree amplitude because of the forked graphical rep-
representation of this mechanism. In addition, the decays can also occur via more complicated decay paths known as penguin diagrams, which are illustrated in Fig. S.1. In the $B^0 \rightarrow J/\psi K^0_S$ and $B^0_s \rightarrow J/\psi \phi$ decay channels, the contributions from these penguin diagrams are strongly suppressed compared to the more prominent tree amplitude. Nonetheless, we are reaching experimental precisions on the observables associated with the $B^0 \rightarrow J/\psi K^0_S$ and $B^0_s \rightarrow J/\psi \phi$ decays where even these small corrections start to become noticeable, and thus need to be controlled. The main goal of this thesis is to explore methods to do just that.

Because of low-energy strong interactions between the quarks involved in the decay process, direct theoretical calculations of these penguin contributions are difficult. The low-energy dynamics between quarks and gluons cannot be fully described using our standard tools. To nonetheless get a handle on these effects, we need to rely on alternative methods which can estimate them directly from the experimental data. Here symmetries play an important role.

**Symmetries and CP Violation**

The corrections we are after can be determined from observables associated with the difference in behaviour between particles and antiparticles. Particles and their antiparticles are related to each other by simultaneously applying the charge symmetry and parity transformations. The charge symmetry ($C$) transformation interchanges the positive and negative charges of the fundamental particles, while parity ($P$) inverts the spatial directions, i.e. it makes the simultaneous transformation $x \rightarrow -x$, $y \rightarrow -y$ and $z \rightarrow -z$. Although the Universe started out $CP$ symmetric, with equal amounts of matter and antimatter, the world around us is now exclusively made out of matter, and antimatter has become very scarce. This can only
be explained if particles do not exactly behave in the same way as antiparticles, i.e. the \( CP \) symmetry between them is broken. As it turns out, the strong\(^{[c]} \) and electromagnetic interactions are invariant under \( CP \) transformations, but the weak interaction is not. The amount of \( CP \) violation measured in weak interactions is not sufficient to explain the observed imbalance between matter and antimatter in the Universe. Hence, there must be additional sources of \( CP \) violation not yet described by the Standard Model. By studying weak decay processes, like \( B^0 \to J/\psi K^0_s \) and \( B^0_s \to J/\psi \phi \), we hope to find new physics that can help us understand all the details regarding \( CP \) violation in our Universe.

In the Standard Model, \( CP \) violation is parametrised by complex phases. To avoid a whole introduction into the mathematics of complex numbers, just imagine that for the mathematical formulation of the Standard Model we work with numbers which in addition to their size also acquires a compass direction: a phase. By measuring observables that quantify the \( (CP) \) asymmetry between the decay process of the \( B^0 \) and \( B^0_s \) mesons on the one hand, and the \( \bar{B}^0 \) and \( \bar{B}^0_s \) antimesons on the other, these compass directions can be determined. With the decays \( B^0 \to J/\psi K^0_s \) and \( B^0_s \to J/\psi \phi \) we experimentally measure two of the \( CP \) violating complex phases, referred to as \( \phi_d \) and \( \phi_s \). If we ignore the tiny penguin contributions, and assume that these two decays only proceed via the tree diagram, the relation between the measured \( CP \) asymmetries and the phases \( \phi_d \) and \( \phi_s \) is rather straightforward. But if we also include the penguin effects, the relations get modified and corrections, which we parametrise as shifts \( \Delta \phi_d \) and \( \Delta \phi_s \) in this thesis, need to be taken into account. These corrections modify the value of the measured \( CP \) asymmetries, so these asymmetries might also hold the key to controlling the corrections. In \( B^0 \to J/\psi K^0_s \) and \( B^0_s \to J/\psi \phi \) the influence of the penguin amplitudes is small, so the impact on the \( CP \) asymmetries is difficult to notice. Therefore we search for other decay modes where the effect on the \( CP \) asymmetries is magnified.

At this point yet another symmetry comes into play: the flavour symmetry of the strong interaction. Assuming the up, down and strange quark are massless, which is an approximation, the strong interaction cannot distinguish between these three quarks. As far as the strong interaction is concerned, these particles then all look the same, and thus behave in the same way. That is an interesting feature to exploit, especially in view of our problems to calculate the low-energy dynamics between quarks and gluons. This symmetry allows us to relate one decay path to another by interchanging up, down or strange quarks, without affecting the low-energy strong dynamics involved in these modes. So instead of performing explicit calculations, we use flavour symmetry to relate the quantities we want to know to similar quantities in other decay modes where they can be constrained.

\(^{[c]}\)The strong interaction needs not be invariant under \( CP \) transformations, but experimental measurements suggest that it is. This puzzling situation is known as the strong \( CP \) problem.
with experimental data. Of course quarks are not massless, so this symmetry is not realised exactly in Nature. But the masses of the up, down and strange quarks are much smaller than the typical energy scale at which strong interaction processes take place, and thus effectively appear massless to them. The flavour symmetry of the strong interaction therefore is an excellent tool in the study of $B^0$ and $B_s^0$ meson decays.

**Hunting Penguins**

Let me illustrate the use of flavour symmetry in a bit more detail. By interchanging all down and strange quarks with one another, the $B^0 \rightarrow J/\psi K_s^0$ decay transforms into the $B_s^0 \rightarrow J/\psi K_s^0$ decay mode. In the flavour symmetry limit, the strong interaction effects involved in these two decay paths are identical. However, the weak interaction still causes differences between the two decays. As a result the relative contributions of the tree and penguin amplitudes in $B_s^0 \rightarrow J/\psi K_s^0$ are different from those in $B^0 \rightarrow J/\psi K_s^0$; the penguin amplitudes are enhanced in $B_s^0 \rightarrow J/\psi K_s^0$. As a consequence, the $B_s^0 \rightarrow J/\psi K_s^0$ decay is much more sensitive to penguin effects, and can in fact be used to constrain their impact in $B^0 \rightarrow J/\psi K_s^0$, i.e. to quantify the shift $\Delta \phi_d$.

Our main strategy is as follows: We measure the $CP$ asymmetries in $B_s^0 \rightarrow J/\psi K_s^0$, and use them to determine the size of the penguin contributions. Then we invoke the flavour symmetry argument to relate the penguin contributions in $B_s^0 \rightarrow J/\psi K_s^0$ to those in $B^0 \rightarrow J/\psi K_s^0$. With knowledge on the size of the penguin effects in $B^0 \rightarrow J/\psi K_s^0$, we can quantify the shift $\Delta \phi_d$, and thus improve the measurement of $\phi_d$ from the $CP$ asymmetries in $B^0 \rightarrow J/\psi K_s^0$. That may sound like we have everything under control now, but of course nothing is that simple. The penguin contributions might be enhanced in $B_s^0 \rightarrow J/\psi K_s^0$, but the overall decay amplitude is suppressed compared to $B^0 \rightarrow J/\psi K_s^0$, making this mode experimentally more challenging to study. At the moment, we do not yet have high precision measurements of the $B_s^0 \rightarrow J/\psi K_s^0$ $CP$ asymmetries, and therefore cannot yet execute the above described strategy.

**Searching for Penguins Footprints**

So where does my research come into this game? Well, at two points: it consists both of a theoretical and an experimental part. For the experimental half of my research project, I studied the $B_s^0 \rightarrow J/\psi K_s^0$ decay using data collected by the LHCb experiment. This study was performed in three stages, with each new stage adding another layer of complexity to the analysis. In the first stage, my copromotor and I focused on separating the $B_s^0 \rightarrow J/\psi K_s^0$ events from the much larger background contribution in the data sample. To do this artificial neural networks were
used. This initial analysis resulted in a measurement of the $B^0_s \to J/\psi K^0_S$ branching fraction, i.e. the number of times a $B^0_s$ meson decays into the specific $J/\psi K^0_S$ final state. In the second stage, we also looked at the distribution of decay times of the $B^0_s \to J/\psi K^0_S$ events and measured their lifetime. In the final stage, the $CP$ asymmetries of the $B^0_s \to J/\psi K^0_S$ decay were measured. Unfortunately, the uncertainties on these parameters are still too large to execute the above described strategy, but it nonetheless offers interesting information regarding the future prospects for this decay channel.

On the theoretical side I explored the flavour symmetry method sketched above to determine the penguin effects in $B^0 \to J/\psi K^0_S$ and $B^0 \to J/\psi \phi$. As the necessary information is not yet available for the $B^0_s \to J/\psi K^0_S$ decay, my promotor and I looked at other decay modes that can also be related by the flavour symmetry to $B^0 \to J/\psi K^0_S$ and $B^0 \to J/\psi \phi$. To control the penguin shift $\Delta \phi_d$ affecting $B^0 \to J/\psi K^0_S$, a combined analysis of the $B^0 \to J/\psi K^0_S$, $B^0 \to J/\psi K^0_S$, $B^+ \to J/\psi K^+$, $B^+ \to J/\psi \pi^+$ and $B^0 \to J/\psi \pi^0$ modes was performed. All five modes have similar decay dynamics as the $B^0 \to J/\psi K^0_S$ decay, and can thus be used to constrain the penguin contributions affecting the $B^0 \to J/\psi K^0_S$ channel. In addition to the analysis of the currently available data, we also illustrated the potential of the $B^0_s \to J/\psi K^0_S$ mode for the future LHCb upgrade era using a benchmark scenario, and discussed a strategy to probe corrections to the flavour symmetry method relating the strong interaction dynamics between the $B^0 \to J/\psi K^0_S$ and $B^0 \to J/\psi K^0_S$ decays.

The decay channels that can be used to control the penguin shift $\Delta \phi_s$ affecting $B^0 \to J/\psi \phi$ are $B^0 \to J/\psi \rho^0$ and $B^0 \to J/\psi \bar{K}^*0$. Also for these modes we explored the currently available data and determined the resulting constraints on $\Delta \phi_s$. In addition, a new combined analysis was suggested, which would offer interesting information on the corrections to the flavour symmetry method relating the strong interaction dynamics between $B^0_s \to J/\psi \phi$, $B^0 \to J/\psi \rho^0$ and $B^0_s \to J/\psi \bar{K}^*0$.

Congratulations! You have survived this long and perilous journey through the realm of trees and penguins. I hope you got a brief glimpse of what my research has been about, and what I have been doing for the past four years. At least you now understand why I continue talking about penguins, even though I am not a biologist.

Amsterdam 2015,
Kristof