Lay summary

Particle Physics

The laws of physics, at least in principle, underpin all the observations we can make about our world, and thereby also every field of science. To put it very simply, as the cartoon below\(^3\) jokingly does, sociology is just applied psychology, psychology applied biology, biology applied biochemistry, biochemistry applied chemistry and, finally, chemistry just applied physics:

And within the field of physics we may continue this reductionism. We are then eventually led to conclude that all natural phenomena, varying from the weather to the firing of neurons within our brains, can be described in terms of \textit{interactions} between elementary particles. In practice this description relies heavily on mathematics, as the cartoon also points out, but in this chapter we will spare the reader from these details.

An elementary particle is a building block of Nature that we currently believe to be indivisible. For example, in our attempt to understand atoms we have discovered that their nuclei are made of protons and neutrons, and that these, in turn, are composed of particles called \textit{quarks}. As quarks do an adequate job of describing subatomic physics (we will say more about this later), they are an example of what we consider to be elementary particles. Electrons, which bind to the atomic nuclei to complete an atom, are another example.

\(^3\)Taken from xkcd comics [220].
Interactions between elementary particles are mediated by fundamental forces. We currently know of four such forces. Namely, the electromagnetic force, the strong force, the weak force and gravity. Interestingly, these forces can themselves be described in terms of elementary particles, specifically so-called messenger particles. Messenger particles essentially communicate to other particles whether they should attract or repel each other. With respect to the fundamental forces just listed, the associated messenger particles are the photon (responsible for visible light), the gluon, the $W$ and $Z$ bosons and the graviton.

Of the four fundamental forces, the strong and weak nuclear forces are less familiar from an everyday perspective. The strong force is responsible for binding the neutrons and protons (or quarks to be more precise) of an atomic nucleus together. It is called “strong” because at subatomic distances it is stronger than the competing electromagnetic force that tries to push the (positively charged) protons in the nucleus apart. On the other hand, the weak force is so named because the interactions it mediates are relatively weak and seldom. Nonetheless, it is a very interesting force with important physical consequences. One of its most relevant features for this thesis is that it allows quarks to change a characteristic called their fl avour, which we will come back to. A possibly familiar example of the weak force in action is radioactive beta decay, which is caused by a neutron decaying to a proton while releasing an energetic electron (the beta particle) and a neutrino particle.

Our current understanding of particle physics is summed up by the aptly named Standard Model. The Standard Model predicts how all of the known elementary particles behave with respect to each of the fundamental forces (except for gravity$^4$). This model is almost 40 years old and continues to give accurate predictions for particle physics experiments. The state of the art of such experiments is the Large Hadron Collider (LHC) at CERN in Geneva. The LHC is a circular particle accelerator with a 27 km circumference, which can collide protons at close to the speed of light. It began operating in early 2010, and in 2012 it discovered$^5$ what was considered the last missing piece of the Standard Model: the Higgs boson. Although the Standard Model now appears complete, it is not without shortcomings, some of which we will mention in the next section. The LHC could therefore continue to play an important role by uncovering new physical phenomena, which may help us to extend or replace the ageing Standard Model.

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$^4$Einstein's theory of general relativity describes gravitational interactions at long distances. It is challenging, however, to incorporate gravity into the quantum mechanical framework of the Standard Model, which is necessary for an understanding at short, subatomic, distances.

$^5$Technically a particle with properties very similar to the Higgs boson was discovered. Further tests are needed to confirm that it is certainly the Higgs boson.
Stellar motivations

To point out some of the Standard Model’s shortcomings it is sufficient to point at the sky. Given a sufficiently capable telescope, we would observe that the galaxies in our universe are moving away from each other. This observation, that the universe is expanding, is what motivated the popular big bang hypothesis for the beginning of the universe. What is odd, however, is that the rate at which galaxies are currently moving away from each other is not decelerating, as we would expect due to their gravitational attraction, but accelerating! We call the source of this mysterious acceleration dark energy, which accounts for 68% of the total energy budget of the universe\textsuperscript{6}.

Next, if we take a closer look at these galaxies, we observe something else: the outer stars that are in a stable orbit rotate too quickly with respect to the galaxy’s visible inner matter (its other stars). For these rotational speeds to make sense, galaxies must contain a significant amount of invisible matter, called dark matter. The best explanation for this mysterious dark matter, which also agrees with calculations of how the universe was formed, is that galaxies contain a cloud of tiny, very weakly interacting particles. These dark matter particles are estimated to comprise 27% of the total universe energy budget. However, none of the elementary particles described by the Standard Model qualify.

The contribution of ordinary matter to the total energy budget of the universe, as described by the Standard Model, is thus 5%. That the Standard Model only describes a small fraction of our universe is clearly somewhat of a shortcoming for an otherwise very successful model. Inadequacies such as these, among others, lead us to believe that the model is incomplete. We suspect that if we continue to test it by colliding particles at higher energies or making measurement with increasing precision, we must eventually observe a deviation from its predictions. We refer in general to future physical phenomena that will deviate from Standard Model predictions as New Physics. Outlining strategies to hunt for New Physics is one of the main goals of this thesis.

Taking a closer look at the ordinary matter in the universe, with the 5% energy budget, another mystery presents itself: why is it all made of matter and none of it of antimatter? This question may seem odd at first because antimatter (not to be confused with the dark matter we defined above) sounds like an exotic substance. However, antimatter is actually perfectly normal stuff. Every matter particle is automatically paired with an antimatter particle that has the same mass but opposite charge. The electron, for example, is paired with the positron, a “positive” electron, which is used in everyday things like medical PET (Positron Emission Tomography) scans. The catch is that when a particle and an anti-particle meet, they annihilate each other and release energy. For this reason it is clear why the Earth has only one kind of each stable particle, and of course these are the ones we initially chose to label as matter. However, it could just have easily been made out of stable antimatter particles.

\textsuperscript{6}The total energy budget of the universe was recently updated by the new Planck satellite results [221].
So the Earth is made of matter, but the strange thing is that every galaxy we observe in our universe also appears to be. We would expect that at the beginning of a neutral universe, during the big bang, matter and antimatter were created in equal amounts. So it is a mystery how the antimatter disappeared while matter stuck around. The laws of physics seem to have shown a bias towards matter over antimatter during the evolution of the universe.

In 1967 the Soviet physicist Andrei Sakharov published a paper discussing the conditions that must have been present during the evolution of the universe to explain the current matter–antimatter asymmetry. One requirement is that certain symmetries of the laws of physics, which used to be taken for granted, must be broken. As we will soon explain, it turns out that in the Standard Model these symmetries are in indeed broken. However, they are not broken “enough” to explain the huge difference between matter and antimatter we see today. Therefore our quest for New Physics also includes a quest for symmetry violation.

Symmetry violation and mesons

According to Sakharov, two symmetries of Nature that must be broken in order to explain the matter–antimatter asymmetry of the universe are Charge symmetry (C) and the combination of charge symmetry with Parity symmetry (P), known as CP symmetry. Charge symmetry intuitively states that if we flip the charges of all particles, for instance make electrons positive and positrons negative, the laws of physics describing their interactions stay the same. Parity symmetry, on the other hand, requires the same laws of physics to hold after flipping every spatial direction. Essentially parity symmetry states that a physical process viewed through a mirror should still behave like a valid physical process.

The charge and parity symmetries seem intuitive, and they are respected by almost all of the fundamental forces. The only exception is the weak force, which violates both symmetries separately and, as it turns out, also their combination: CP symmetry. Thus, as far as we currently know, it is the weak force that is responsible for Nature’s bias for matter versus antimatter.

In the Standard Model it is specifically the interaction of quarks via the weak force that violates CP symmetry. As we already mentioned above, quarks are the elementary building blocks of composite particles called hadrons, such as neutrons and protons, and they come in different flavours. There are six flavours in total, and these are labeled up, down, strange, charm, beauty\(^7\) and top. Neutrons and protons, for instance, are made from up and down quarks, the two lightest flavours. They are examples of a subgroup of hadrons called baryons, each consisting of three quarks. It is also possible for a quark to bind together with an antiquark, due to the strong force, to form a composite particle called a meson. Mesons are all unstable and decay quickly, but by studying their decays we can learn a lot about quark interactions.

\(^7\)The beauty quark is also called the bottom quark.
The unique feature of the weak force is that it allows a quark of one flavour to change into another. Furthermore, CP symmetry can be violated if, loosely speaking, the chance that a beauty quark transforms into an up quark is not identical to the chance that a beauty antiquark transforms into an up antiquark, for example. Due to the strength of the strong force, however, it is impossible to isolate individual quarks to study them independently. Therefore, as we just mentioned, we can instead study such flavour-changing quark interactions indirectly by observing the transformations and decays of composite meson particles.

Mesons can be studied using particle detector experiments, like the LHC at CERN. By comparing the behaviour of mesons with anti-mesons we can probe how CP symmetry is violated in the underlying quark processes. Furthermore, by measuring such processes very precisely, we can also make a comparison with what the Standard Model predicts to occur. In this way we can probe New Physics. Specifically, the quantum mechanical nature of these processes allows heavy, as of yet undiscovered, new particles to contribute in a subtle way. In order to discover them, however, we need both precise experimental measurements and precise theoretical predictions.

Strange beauty mesons

Certain pairs of neutral mesons can transform into each other before they decay due to a phenomenon called mixing. The violation of CP symmetry was in fact first discovered in 1964 due to the mixing of neutral kaons, which are mesons made from combinations of down and strange quarks. The amount of violation observed was, however, very small. It was later discovered that mesons that contain a beauty quark exhibit much more CP symmetry violation, both in their mixing and their decay. In the previous decade neutral mesons comprised of a beauty quark together with a down quark, or an up quark for charged beauty mesons, were extensively studied at particle detectors called \textit{B–factories}. This greatly helped in building a picture of the amount of CP symmetry violation present in the Standard Model. Unfortunately, as we already mentioned earlier, this is not enough to solve the matter–antimatter asymmetry puzzle present in our universe.

When the LHC started up in 2010, and coincidently also this thesis, mesons composed of a beauty quark together with a strange quark, “strange beauty mesons”, had not been extensively studied. Since then the particle detectors at the LHC, namely LHCb, ATLAS and CMS, have begun to sharpen this picture. It is therefore conceivable that we will see evidence for New Physics, in the form of new CP symmetry violation or new particles, in the near future. Consequently, the theoretical analysis of these particles is very relevant, because in order to see a deviation from the Standard Model we first require precise theoretical predictions.

\footnote{We are actually referring here to the coupling strength of these two quarks. The “chance” of this process occurring is the magnitude squared of the coupling strength. CP violation manifests itself as a complex coupling strength, so it is only observable if there is interference between multiple couplings present.}
The combination of a beauty antiquark with a strange quark is denoted by $B_s$ and a beauty quark with a strange antiquark as $\overline{B}_s$. Because both of these particles are neutral they can mix into each other as we mentioned above. Such mixing transitions are typically depicted by Feynman diagrams, which we use extensively throughout this thesis. Here is an example Feynman diagram showing the mixing of a $B_s$ meson into a $\overline{B}_s$ meson:

![Feynman diagram](image_url)

Note in particular that the $W$ bosons, the messenger particles of the weak force, are responsible for mediating such a transition in the Standard Model. In models of New Physics also other particles can contribute to this mixing.

The $B_s$ and $\overline{B}_s$ can be considered each other’s anti-particles. One way to study CP symmetry violation is to identify decay processes beginning with one or the other and comparing their results for differences. From an experimental perspective this act of distinguishing between the so-called flavour states, $B_s$ and $\overline{B}_s$, is known as flavour tagging. Measurements involving this technique can be very sensitive to New Physics. However, the technique is challenging and as a result it only works for a small fraction of events.

A key focus of this thesis is how to search for New Physics using results from experimental measurements that did not rely on flavour tagging. To this end, we can describe the $B_s$ and $\overline{B}_s$ mesons in a different formalism in which they do not mix with each other. In this other formalism the particles are labeled by their relative masses, $B_{s,H}$ and $B_{s,L}$ for the heavier and lighter one, respectively, and are referred to as mass-eigenstates. Because the particles described in this way do not mix, it is possible to define a lifetime for each particle, which is the duration it lives on average before it decays (about a trillionth of a second). What is special about the strange beauty meson system is that the lifetimes of the two particles differ by a small amount. An experiment can in principle hereby distinguish between the two mass-eigenstates, which can also offer a sensitive probe of New Physics. Typically an experiment measures a single effective lifetime for a given strange beauty meson decay, from which interesting physical information has to be decoded.

**Strategies to hunt for New Physics**

The goal of this thesis is to hunt for New Physics using strange beauty meson decays. We have chosen to focus on these mesons because the underlying quark transitions that
mediate their decays may reveal new CP symmetry violation or give indirect evidence for the existence of new particles. Furthermore, such decays are currently being probed by the LHC experiment at CERN. Currently no large signals of New Physics have been observed, but as the experimental precision improves in the years to come we may very well discover smaller signals. In order to be able to identify such signals as New Physics, it is important to have a precise theoretical understanding of what is being measured. In this thesis we discuss strategies for combining experimental measurements in such a way as to minimise the theoretical uncertainty, and thereby maximise our sensitivity to New Physics.

Our ability to theoretically describe the binding of quarks inside a meson due to the nuclear strong force is not perfect. Specifically, although various calculational tools have been developed to this end, their estimates typically have a sizable theoretical uncertainty. To minimise our dependence on this uncertainty, our strategies typically make use of an approximate symmetry of the strong force called flavour symmetry. This symmetry essentially states that the three lightest quark flavours – up, down and strange – are approximately indistinguishable from the perspective of the strong force’s messenger particles. It thereby allows us to relate different meson decay processes to each other, using experimental measurements from one to fix uncertain parameters in another.

One way to search for New Physics is to test if the violation of CP symmetry predicted by the Standard Model is consistent, particularly the lesser constrained corners of this model. We have proposed strategies to do this using several different strange beauty meson decays. In particular we have chosen decays that can be related by flavour symmetry to other meson decays, such as those already studied by the B–factories as we mentioned earlier. We have found that effective lifetime measurements can be particularly useful in these strategies. Once sufficiently precise experimental data becomes available our strategies should be competitive with existing strategies, and can thereby complement the hunt for new sources of CP symmetry violation.

Another way to search for New Physics is by looking at strange beauty meson decays that the Standard Model predicts to be very rare. A notable example is their decay to two muons, which is predicted to occur only one in 300 million times. On the other hand, in some models of New Physics the chance of this decay occurring is predicted to be far higher. This makes measuring the decay rate a priority for experiments at the LHC. A recent measurement has ruled out a large New Physics signal, however a smaller signal could still be present. In this thesis we have discussed an important correction to the theoretical calculation of this decay rate. We have also highlighted the usefulness of measuring the effective lifetime for this decay, which is sensitive to different New Physics features.

\footnote{These “corners” are actually the “angles” of triangles in the complex plane that describe the unitarity of quark flavour changing transitions. See Chapter 3 for further details.}