# Measuring asymmetry in strange beauty

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# Summary

## WHAT?

This thesis is dedicated to the measurement of the CP violating phase $\phi_s$ which arises in $B_s^0 \to J/\psi\phi$ and $\overline{B}_s^0 \to J/\psi\phi$ decays. Sounds complicated, so let's first start with a brief overview of the universe and what we know about it. Everything we see around is made of several types of fundamental particles of different masses and charges. They interact with each other by means of fundamental forces. Under the C (charge)-transformation, each particle converts into an associated anti-particle, which has the same mass but opposite charges. The P (parity)-transformation inverts all space coordinates and therefore reverts the direction of particle momentum. If we look in a special mirror, which reverts both C and P, then the reflection in such a mirror would behave slightly differently from the original. This is what is called CP violation.

Elementary particles are bound together to form other particles, such as $B_s^0$ mesons which are combinations of two quarks, namely bottom, $\overline{b}$, and strange, s. The $B_s^0$ particle is unstable with a lifetime of only around $1.5 \times 10^{-12}$ seconds! It can decay to various other particles, but the ones that we will search for are the $J/\psi$ and $\phi$ mesons. The $J/\psi$ is made of charm, c, and anti-charm, $\overline{c}$, quarks; it is also an unstable particle. Among other possibilities, it can decay to two leptons, $\mu^+$ and $\mu^-$, and that's what is looked for. The $\phi$ is made of s, and $\overline{s}$ quarks, and is an unstable particle as well. The decay $\phi \to K^+K^-$ is of interest, where $K^\pm$ is a hadron composed of up, u ($\overline{u}$), and $\overline{s}$ (s) quarks. An additional complication arises due to the fact that $B_s^0$ meson during its lifetime can transition into $\overline{B}_s^0$ meson and vice-versa. This interchange happens on average 27 times before the decay. So, there are two possible processes that can happen, a $B_s^0$ meson can decay to $J/\psi\phi$ or it first transitions into its anti-particle, $\overline{B}_s^0$, and then decays to $J/\psi$ and $\phi$ particles. If we look at the $B_s^0 \to J/\psi\phi$ decay in our special CP mirror, we will see the $\overline{B}_s^0$ decaying to $J/\psi$ and $\phi$ particles, which are their own anti-particles. A $\overline{B}_s^0$ meson can also either decay directly to $J/\psi\phi$ or first turn into a $B_s^0$ meson. After having a careful look, we will be able to tell if the mirror image is different from the original, e.g. if the probabilities for the processes and anti-processes are the same. The parameter which characterises this difference is called $\phi_s$. In the Standard Model of elementary particles, this parameter is expected to be very small, $-0.03698^{+0.00081}_{-0.00070}$ rad, meaning that the $B_s^0 \to J/\psi\phi$ and $\overline{B}_s^0 \to J/\psi\phi$ decays proceed in an almost identical way.

## WHY?

Why is the measurement of $\phi_s$ important? If the measured value for $\phi_s$ would be different from the expected one, then it would mean that there are new, unknown effects appearing in the $B^0_s \to J/\psi\phi$ and $\overline{B}^0_s \to J/\psi\phi$ decays. In particular, there can be a new fundamental particle that enters the processes of $B^0_s$-$\overline{B}^0_s$ transition and which modifies the prediction of $\phi_s$. Such an approach to search for new particles is called an indirect search, where only the consequences of a particle are observed rather then the particle itself. If the mass of a new particle is much larger than the energies accessible experimentally, then it cannot be produced and detected in a direct search. However, this new particle will most likely modify a number of distinct processes and therefore can be observed indirectly and some of its properties can be derived. This increased reach is a great advantage of the indirect approach.

## HOW?

How can one possibly measure the value of $\phi_s$? First of all, particles such as $B^0_s$ are not present in the usual matter around us, so they have to be created. One of the main factories for particle production is the LHC accelerator at CERN, where protons are accelerated to speeds approximately 0.999999997 times the speed of light. They are then collided with each other and some of the energy of the collision is transformed into particles. In some of these collisions a $B^0_s$ meson is produced, which decays shortly after. To catch it and its decay products, detectors are build around the collision points. The detector that is specifically designed to look at particles containing bottom quarks is LHCb. The unique design of the experiment is chosen to maximally cover the forward region, thus catching most of the decay products of the b quark. Inside LHCb, proton collisions happen around 30 million times every second. A dedicated system of the experiment, the trigger, is designed to select "interesting" events from the enormous amount of pp collisions. In this particular case, "interesting" events are those that contain the $B^0_s \to J/\psi\phi$ or $\overline{B}^0_s \to J/\psi\phi$ decay. The trigger system is a sophisticated architecture that has to operate extremely fast and efficiently select interesting events. The more relevant events are selected, the more precise the measurement of $\phi_s$ will be.

Detecting all the decay products, $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$, allows the reconstruction of the original $B^0_s$ or $\overline{B}^0_s$ meson. Specific algorithms distinguish whether this meson was a $B^0_s$ or $\overline{B}^0_s$. The meson travels, on average, a distance of approximately 1 cm inside the LHCb detector. The measurement of this distance allows the calculation of the decay time for each found $B^0_s$ ($\overline{B}^0_s$) particle. Comparing the probability of their decays to the same $J/\psi\phi$ final state then leads to the measurement of $\phi_s$. In case the processes in the CP mirror is identical, $\phi_s$ would be exactly zero. The more different the CP image is, the larger the value of $\phi_s$ would be.

## RESULT

What's is the result of the measurement? For the measurement of the CP violation described in this thesis, proton-proton collisions which happened at LHCb in 2015 and 2016 are used. In around 117 000 events out of these collisions either a $B_s^0 \to J/\psi\phi$ or $\overline{B}_s^0 \to J/\psi\phi$ decay was found. These are used to determine $\phi_s$, which is measured to be

$$\phi_s = -0.083 \pm 0.041 \pm 0.006\,\text{rad}$$

where the first uncertainty is due to the limited number of $B_s^0$ decays found and the second one is due to the imperfect methods used to perform the measurement. Within uncertainties, the result is consistent with the expected value. The $\phi_s$ parameter describes CP violation not only in the decays of $B_s^0$-$\overline{B}_s^0$ system to the $J/\psi\phi$ final state, but also in other decays such as $B_s^0 \to J/\psi\pi^+\pi^-$, $B_s^0 \to J/\psi K^+K^-$ for the $m_{KK}$ region above $1.05\,\text{GeV}/c^2$, $B_s^0 \to \psi(2S)\phi$ and $B_s^0 \to D_s^+D_s^-$. The results of the $\phi_s$ measurements using all of these decays performed at LHCb are combined, yielding the following value:

$$\phi_s = -0.042 \pm 0.025\,\text{rad}$$

where uncertainty reflects both the limited number of $B_s^0$ decays found and the imperfect tools for the measurements.

## WHAT'S NEXT?

The indirect determination, assuming the validity of the Standard Model, of the value of $\phi_s$ is much more precise than the current experimental determination, which means that there is still possibility for new particles to show up. To catch them or to make sure that they are not there, it is essential to decrease the uncertainty on the measurement, which means to collect more data, while keeping improving the methods and tools of the measurement. In the following years, the data collected in LHCb in 2017 and 2018 will be analysed and the statistical uncertainty on the measured value of $\phi_s$ will decrease by a factor of around 1.7, bringing us closer to unravelling possible sources of New Physics. This measurement will be followed with one performed on data that will be collected at the upgraded version of the LHCb experiment, where major parts of the detector will be replaced to get an optimal performance. The hunt for New Physics with $B_s^0 \to J/\psi\phi$ decays will continue until it will become clear whether there are, or are not, new particles hiding in the process.