THE UNIVERSITY *of* EDINBURGH
School of Physics
and Astronomy

Measuring Triple Product Asymmetries in $B_s^0 \to \phi\phi$ Decays

MPhys Project Report

Yusong Tian

Submitted for the 40pt MPhys Project course PHYS11016
2nd April 2019

Abstract

The triple product (TP) asymmetry in $B_s^0 \to \phi\phi$ decays was measured by performing extended maximum likelihood fit to the mass distribution on the datasets collected in the LHCb Run1 and part of Run2 (2011–2017). The CP-violating weak phase in this decay channel comes from the interference between the decay (direct CP-violation) and B_s^0–$\bar{B}_s^0$ mixing (indirect CP-violation), and is predicted to be very small by the Standard Model (SM). The TP asymmetries obtained were $A_U = 0.3 \pm 0.9\%$, $A_V = -0.3 \pm 0.9\%$. This result is consistent with the SM prediction of CP conservation.

Supervisor: Dr Matthew Needham

Personal statement

After an initial meeting with my supervisor at the first day of the 1st semester (17th September 2018), I spent the first week familiarizing with the basics of ROOT and finishing some administrative issue like getting registered as an external user of CERN and installing Ubuntu on my laptop, as it is difficult to use ROOT on Windows system. In the end the most convenient way is to use one of the computers on the 5th floor of JCMB that have everything installed. During this project almost every meeting with my supervisor has been in that room.

Having tried simple things like plotting Gaussian functions with the RooFit package, I moved on to trying to fit different probability distribution functions and compositing models. By the end of the 3rd week, the code can composite model with extended likelihood formalism and fit the model to the data, calculate the likelihood and χ^2 probability, and I started to try to fit some functions to the simulated data that represents the peaking background. Both the data and the code snippets were provided by my supervisor. Within the next two weeks, the code could fit real data with composite model, and I started to read about simultaneous fit and papers about triple product (TP) asymmetry. In order to be better at coding, I tried to go through some C++ tutorials online.

In the 6th week, my supervisor gave me all the data needed in this project and explained how real data and simulated data were acquired. During the next 3 weeks I succeeded in using simultaneous fit to get the number of events and therefore calculate the TP asymmetry, and worked on acquiring errors by combining errors with the derivative method, and by random parameters method. In the 10th week I determined the larger width of one of the Gaussian functions by fitting the Monte Carlo simulated data, finished another code which can run the previous code multiple times to fit data from different years, implemented the snippets of code that fits a constant to the TP asymmetry results from different years and save the results in a data file.

There are two triple products: U and V, previous work was done on U, so the last two weeks of the 1st semester was spent on trying to obtain results on V. I also realized my shortage on knowledge about CP violation. My supervisor lent me a book to read. He also gave me the recipe of generating some "toys" - simulated data in order to test the bias of the code and method.

This is the end of the 1st semester, I worked on this project for 12 weeks and achieved some preliminary results. I went home for Christmas holiday thus did not have access to a computer with LINUX system and ROOT, so I used virtual box to install Ubuntu and ROOT on my laptop and continued to work on generating and analysing toys. (The downside is that the virtual system respond quite slow - there is a delay in just moving the mouse.) I prepared for the trial presentation and tried to read papers to make up for my lack of understanding in the theory.

In the first 3 weeks of the second semester, I tried to read more about CP violation, and cleared up some results, like considering which mass range to fit on and thus settle on the fit result of the peaking background. In the next three weeks I tried to investigate whether the choices of initial value and range of parameters affect the fit result to the background, and how much these results consequentially affect the final result on the asymmetries. Some formatting issue like how to put correct label on the histogram was fixed and toys were generated and analysed. It turned out my previous code on analysing toys did not work due to a subtle mistake: an variable should be defined as double instead of float. Thank my supervisor for spotting errors for me and I hope I'm better at C++ so I could have not bothered him with trivial questions like this.

In the last 3 weeks I did pull analysis on the fit of the real data and analysed the results from the generated toy, settled on range of fit, redid every step and obtained results with the new range, put them together, did simultaneous fit on all data from all years, then spent the last two weeks writing up.

I encountered difficulties several times due to not being familiar enough with C++ in LINUX system and classes defined in ROOT. I did several tutorials on object oriented programming language in my spare time and got more familiar with it. I hope in future projects I would do a better job keeping my lab note book clear, maybe by registering result obtained promptly. Although it is difficult to distinguish which results are important to be written down as this project has lots of fit parameters to be settled and they all contribute to final results. I would also like to review my statistics course, spend more time on reading papers to understand the theory and their approach, and practice more on project-oriented programming so that I could understand the ROOT reference guide better.

Acknowledgments

All the ntuples (".root" data files), including data from the LHCb and the simulated data, were provided by my supervisor. Thank him very much for all the support and guidance during this interesting experimental particle physics project.

Contents

1 Introduction

One of the biggest question in particle physics is why our current universe is dominated by matter despite that equal amount of matter and anti-matter were produced in the big bang.

A physicist Sakharov proposed 3 conditions of producing matter-antimatter asymmetry[1]: baryon number violation (a quark give baryon number $\frac{1}{3}$ and an anti-quark give $-\frac{1}{3}$), C and CP violation, and the previous two conditions happening when the universe is not at thermal equilibrium. Therefore, studies on CP violation are necessary on solving the mystery of matter-antimatter asymmetry.

CP violation is expected in the Standard Model (SM) from the CKM (Cabibbo-Kobayashi-Maskawa) matrix[2], but the amount is too small to explain the matter-antimatter asymmetry in the universe. The $B_s^0 \to \phi\phi$ decay channel was observed in 2005 [3]. In this channel, CP violation arise from the interference between the decay and the $B_s^0 - \bar{B}_s^0$ oscillation. A true triple product (TP) asymmetry is due to a T-violating phase, assuming CPT conservation, having a true triple product asymmetry means that CP is violated. A fake triple product asymmetry comes from the strong phase, which is expected to be very small in the $B_s^0 \to \phi\phi$ decay. In the SM, the CP violation in this decay is predicted to be close to 0, thus finding CP violating TP asymmetry in this decay would indicate physics beyond the SM. [4]

The data were produced in the proton-proton collision in the LHCb detector. The result of analysis on the data obtained in LHCb Run 1 was already published [5, 6], and result for data acquired including later years (to 2016) was presented in conference [7].

In this project, analysing all the data collected from 2012 to 2017, the TP asymmetries was measured by analysing the data in two ways. One way is fitting the data from different years separately to determine the number of events with positive and negative TP, therefore calculate TP asymmetries and obtain final result by taking the average of the result from different years. The other way is combining different data files together, and fit for TP asymmetries directly. The results obtained from these two methods agree with each other, and are consistent with the prediction of the SM of CP conservation.

In this report, the $B_s^0 \to \phi\phi$ decay, TP asymmetries and how the data were analysed would be introduced.

2 Background

2.1 The LHCb [8]

The data used in this project come from the LHCb (Large Hadron Collider beauty) experiment. It is one of the experiments at CERN, Genewa.

CERN was founded in 1954, this well-known acronym stands for "European Council for Nuclear Research" in French (Conseil Européen pour la Recherche Nucléaire). Nowadays, it is one of the biggest laboratory studying fundamental particle physics. [9] There are several accelerators at CERN, the largest one is the Large Hadron Collider (LHC) started up in 2008, whose accelerator ring has 27 km circumference. The beams in the ring collide at four locations that corresponds to four particle detectors: ATLAS, CMS, ALICE and LHCb [10].

The LHCb detector is a single-arm spectrometer aims at looking for new physics in CP violation and rare decays of beauty and charm hadrons (hadrons that contain b or c quarks) [11]. In the collision b and $\bar{b}$ are produced, and B mesons and baryons are formed.

A detector has several layers of subdetectors, each getting different properties of particles produced in collisions, like the speed, mass, charge, etc. and then use these information to identify the particle. The layout of the LHCb detector is shown in figure 1.

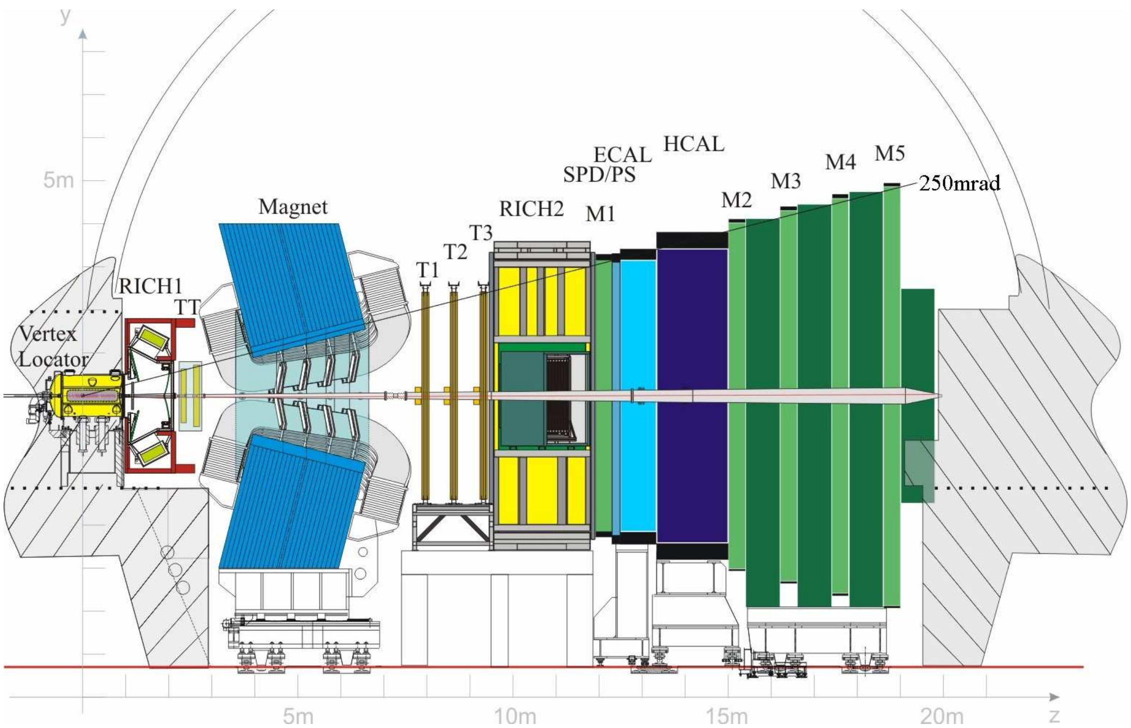


Figure 1. The layout of the detector. The z axis is along one of the proton beams (the other beam come from the opposite direction to collide) and y axis is vertical. The detector has forward angular coverage of about 10 mrad to 250 mrad. It only covers the forward area of one of the beams as at high energy, b and $\bar{b}$ are mostly produced in the forward or backward cone and there is no difference between these two, therefore only one needs to be detected. Starting from the vertex (where the collision happens), the different structures are: the Vertex Locator system (VELO), Ring Imaging Cherencov counter 1 (RICH1), Trigger Tracker (TT), Magnet, three tracking stations (T1, T2, T3), RICH2, M1, Scintillator Pad Detector and Preshower (SPD/PS), electromagnetic calorimeter (ECAL), hadronic calorimeter (HCAL), M2, M3, M4, M5.

Most subdetectors are in two halves, as this is convenient for assembling and maintaining. It also give scientists access to the beampipe, which is a 19 m long vacuum chamber inside the detector made from beryllium and stainless steel, allowing beams to collide in vacuum and the resultant particles to pass through the pipe and get detected and analyzed by the various subsystems. The functions of these subsystems are introduced below.

- The vertex locator system (VELO): measure the track close to the interaction region, help to reconstruct production and decay vertices of hadrons. This helps determining the decay life time and impact parameter of particles.

- Tracking system: apart from VELO, tracking system also consists of Trigger tracer (TT) and three tracking stations (T1, T2 and T3). The tracking system reveals the path of charged particles by recording electrical signals that the particle trigger when they pass through the device and interact with the substances.

- Ring Imaging Cherencov counters (RICH) identify particles by measuring their Cherenkov radiation, which is the radiation that a particle emit when it travels in a medium faster than light. The velocity of the particle can be calculated from the angle that the radiation is emitted with. Combining with the momentum, the mass and thus the identity of the particle can be identified. There are two RICH detectors, RICH1 cover low momentum range and RICH2 cover high momentum range. They can distinguish the resultant particle of B-meson decay, like pions and kaons. This is a special feature of the LHCb.

- Magnet: produce magnetic field which bend the path of the particle. The momentum can be calculated from the curvature.

- Calorimeter system consists of the SPD/PS, ECAL and HCAL. Calorimeters absorb and measure the energy of particles, identify electrons, photons, hadrons, and measure their position and energy. But it cannot stop muons and neutrinos.[5]

- Muon detecting system consists of 5 stations, M1 M2 M3 M4 and M5. They are mostly at the outer layer as muons interact very little with matter.

In LHCb the trigger system consists of the Level-0 (L0) trigger and High Level Trigger (HLT), being the hardware and software trigger systems respectively. Trigger systems select events that are of interest and save their data for analysis. Without the trigger system, the amount of data would be unmanageable. The L0 trigger makes decision in $4\mu s$. The HLT processes the data and do a full reconstruction [12] The $B_s^0 \to \phi\phi$ candidates are selected by the trigger systems by setting constraint on the mass of the final kaons (which ϕ mesons decay into) and p_T (the transverse momentum) [5]. The $B_s^0 - \bar{B}_s^0$ oscillation is very fast, adding high requirements on the trigger systems.

2.2 CP Violation

According to Noether's theorem, continuous symmetry means conservation. But this theorem does not cover discrete symmetries, which include symmetries in Charge (C), parity (P) and time (T). Charge conjugation reverse a particle's charge , parity reverse the particle's spacial coordinates and their product gives CP symmetry.

C and P symmetries are conserved in electromagnetic and strong interactions, but not in weak interactions. In 1956, Lee and Yang found that parity violation has not been tested in weak decays and proposed experiments [13], Wu then conducted experiment [14], where she cooled ^{60}Co (cobalt) to 0.01K and applied a B-field. Then the atomic spins would align and the rate of β decay ($^{60}Co(J=5) \rightarrow^{60} Ni^{*}(J=4) + e^- + \bar{\nu}_e$) with respect to the field direction was studied. It was found that for the emission of β particles, one direction is favoured over the other, which means parity is violated.

This has been a big shock, but then it was believed that CP could be an exact symmetry, until CP violation found in 1964. [15] K_S^0 and K_L^0 (has shorter and longer lifetime respectively) are eigenstates of CP. For K_L^0:

$$|K_L\rangle = |K_2\rangle = \frac{1}{\sqrt{2}}(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle) \tag{1}$$

$$CP\,|K_2\rangle = -1\,|K_2\rangle \tag{2}$$

K_L decays into pions, each pion have CP -1, which means if CP is conserved, K_L must decay into 3 pions. Research found that this is not the case. [16] Experiment was done by bombarding protons on Be target. The detector consists of two spectrometers and the analysis programme calculate the momentum of each charged particle observed in the decay. The angle θ between the vector sum of the two momenta and the direction of the K_2^0 beam would be 0 if it is a two-body decay and different from zero for three-body decays. The result showed an excess of events at $\theta = 0$, therefore CP is violated in weak interaction.

Then the only symmetry left is the CPT symmetry, which remains conserved until today.

CP violation is possible in the Standard Model (SM). There are three generations of quarks, which is the minimum number of generations needed for CP violation to happen[2]. But the amount of CP violation from this is not enough to explain the matter-antimatter asymmetry in the universe. Other sources of CP violation must exist, and finding it would indicate physics beyond the SM.

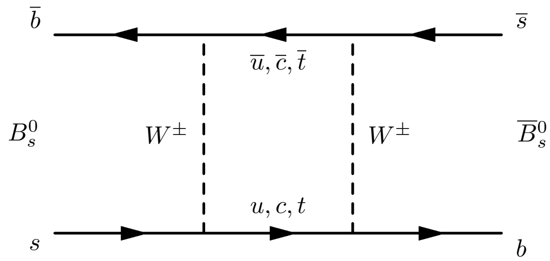
There are three types of CP violations: direct CP violation where particles decay into final particle or anti-particles with different rates, indirect CP violation where particles and anti-particles oscillate back and forth with different rate, and the interference between these two. [17] The $B_s^0 \rightarrow \phi\phi$ decay being investigated in this project falls into the third category.

2.3 The $B_s^0 \rightarrow \phi\phi$ decay

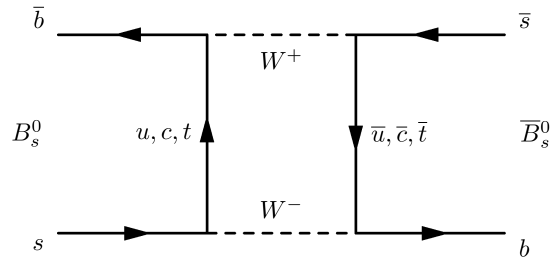
When it comes to CP violation, the B factories has been a popular sector of study. The first detection of the time-dependent CP asymmetry was in 2001 by Belle[18] and BaBar [19] experiments in the $B^0 \rightarrow J/\psi K^0$ decay.

In this project the aim is to measure the TP asymmetry in the $B_s^0 \to \phi\phi$ decay, in order to find out whether there is CP violation or physics beyond the SM. As mentioned in the previous section, in this decay channel the CP violation is from the interference between the decay amplitude and the $B_s^0 - \bar{B}_s^0$ oscillation.

Fast $B_s^0 - \bar{B}_s^0$ oscillations are expected in the SM. Figure 2 shows the leading order box diagrams (the type of Feynman diagram that look like a box) of this oscillation.



(a) intermediate quarks



(b) intermediate W bosons

Figure 2. The two leading order box diagrams for $B_s^0 - \bar{B}_s^0$ oscillation.

The B_s^0 and $\bar{B}_s^0$ oscillates between each other and decays into two ϕ mesons. In the SM, the $B_s^0 \to \phi\phi$ decay is forbidden at tree level (with no loops in the Feynman diagram), and proceeds via a $\bar{b} \to \bar{s}s\bar{s}$ loop described by a penguin diagram (a type of Feynman diagram that describes a one-loop process) shown in figure 3. [7]

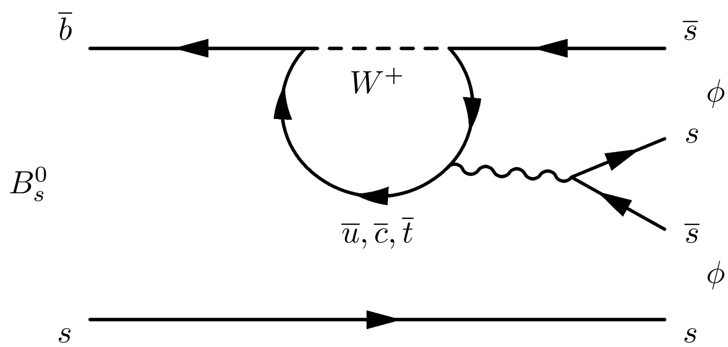


Figure 3. Feynman diagram of the $B_s^0 \to \phi\phi$ decay. The $\bar{B}_s$ also decays into two ϕ mesons, which then decay into two pairs of K^+ and K^- mesons.

This decay is of particular interest because the loop could come from exchange of new virtual massive particles instead of a W boson, which would indicate new physics. Also, the CP-violating weak phase is predicted to be very small (0.02 rad) in the SM, so if CP violation is found, it would also indicate new physics. [20]

2.4 Triple Product Asymmetry [5, 6]

There are two triple product (TP) observables defined by the angle between the two decay planes formed by the four kaons. For a diagram of the spacial configuration of the decay planes see figure 4.

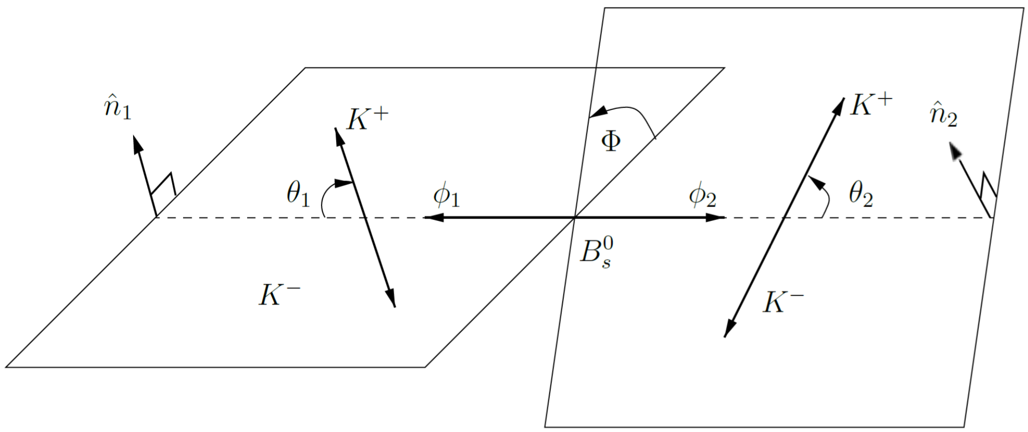


Figure 4. [5] The spacial configuration of the The $B_s^0 \to \phi\phi$ decay. The momentum of ϕ_1 and ϕ_2 are shown in the B_s rest frame. $\phi_{1,2}$ then each decays into a pair of K^+ and K^-, whose momentum are shown in the $\phi_{1,2}$ rest frame. The *phi* meson decay planes are defined by the momentum of the $\phi_{1,2}$ and the momentum of the kaon pairs. Φ is the angle between the two decay planes. $\theta_{1,2}$ are the angle between the momentum of K_+ and $\phi_{1,2}$. $\hat{n}_{1,2}$ are the unit vectors normal to the plane.

The triple products U and V are defined as:

$$U \equiv \sin\Phi\cos\Phi = \sin(2\Phi)/2 = (\hat{n}_1 \cdot \hat{n}_2)(\hat{n}_1 \times \hat{n}_2) \cdot \hat{p}_1 \tag{3}$$

$$V \equiv \sin(\pm\Phi) = (\hat{n}_1 \times \hat{n}_2) \cdot \hat{p}_1 \tag{4}$$

where:

— $\hat{n}_i (i = 1, 2)$ is as in figure 4;

— $\hat{p}_1$ is a unit vector with the direction of the momentum of ϕ_1 in the B_s^0 rest frame.

— For V, the + sign is taken if $\cos\theta_1 \cos\theta_2 \geq 0$ and − sign is taken if otherwise.

The triple product (TP) asymmetry of U is defined as:

$$A_U = \frac{N(U > 0) - N(U < 0)}{N(U > 0) + N(U < 0)} \tag{5}$$

where $N(U > 0)$ is the number of events with U > 0, and $N(U < 0)$ otherwise. A_V is defined in the same way with "U" replaced by "V".

The $B_s^0 \to \phi\phi$ decay belongs to the class $P \to VV$, which is a pseudoscalar meson decaying into two vector particles. [20] The resultant vector mesons could have 3 possible spin configurations that fulfill angular momentum conservation. These form 3 different helicity states, which then defines 3 polarization amplitudes.

Measuring TP asymmetries allows measuring CP violation in a decay time integrated way. The time-dependent differential decay rate can be expressed with equation:

$$\frac{d^4\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi dt} \propto \sum_{i=1}^{15} K_i(t) f_i(\theta_1, \theta_2, \Phi) \tag{6}$$

where the angles θ_1, θ_2 and Φ are the helicity angles as shown in figure 4.

In the SM prediction, the triple products give access to the $K_4(t)$ and $K_6(t)$ terms, and provide a method of probing CP violation without measuring the decay time or the initial flavour of the B_s^0 meson, which is very convenient as the B_s^0 and $\bar{B}_s^0$ oscillation is very fast.

If non-zero TP asymmetries are observed, there can be two possible causes [5, 4]:

1. T-violation. Assuming that CPT is conserved, it means CP is violated. In this case the triple product (TP) asymmetry is a "true" TP asymmetry, and requires no strong phases.
2. Final-state interactions. In this case it is a "fake" TP asymmetry, which is due to strong phases and require no CP violation.

True TP asymmetry have been measured in $K_L \to \pi^+\pi^-e^+e^-$ decay [21, 22]. This is also the case for the $B_s^0 \to \phi\phi$ decay, which is the reason why this decay was chosen to be studied. TP asymmetry $B_s^0 \to \phi\phi$ decay was measured by the Collider Detector at Fermilab (CDF) experimental collaboration in 2011 [23] with $295 \pm 20(stat) \pm 12(syst)$ events identified as signal events. The values of the TP asymmetries are $A_U = -0.7 \pm 6.4(stat) \pm 1.8(syst)\,\%$ and $A_V = -12.0 \pm 6.4(stat) \pm 1.6(syst)\,\%$.

To see results of triple product asymmetries found by previous researches in the LHCb, refer to table 2 in section 2.7.

2.5 Data from the LHCb

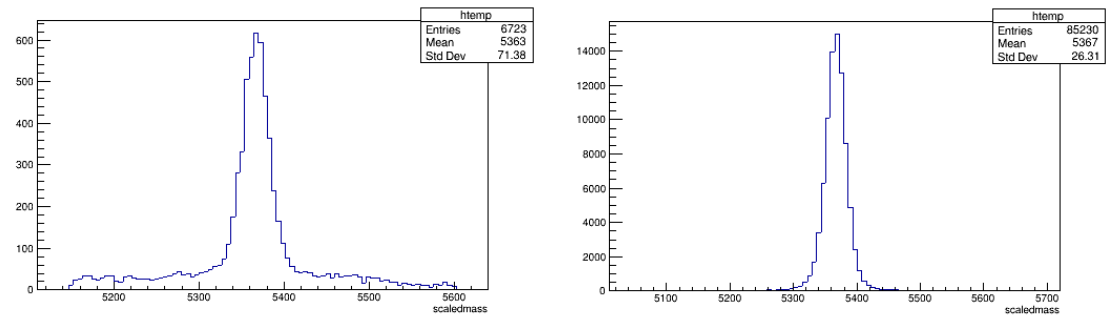
During the proton-proton collisions in the LHCb detector, s and $\bar{s}$ quarks are produced, producing B_s^0 and $\bar{B}_s^0$ mesons. The data from the detector goes into reconstruction where $B_s^0 \to \phi\phi$ decays are selected by a series of structures in the detector like the trigger system, as introduced in section 2.1. The decays are reconstructed with the LHCb reconstruction program BRUNEL, and with assist from simulated data. Then the Data Summary Tapes (DTS) is used and the ROOT files created.

The data used in this project was produced in 5 different years: 2011, 2012, 2015, 2016 and 2017 in the LHCb experiment Run 1 (2010-2012) and Run 2 (2015-2018). Data produced in different years were analysed separately because of different parameters of the collision and the number of events collected. These conditions are summarized in table 1.

Year	Energy (TeV)	Integrated Luminosity (fb^{-1})	Number of Events
2011	7	1	1292
2012	8	2	3292
2015	13	0.3	1062
2016	13	1.6	6723
2017	13	1.7	7027

Table 1. The centre of mass energy $\sqrt{s}$, integrated luminosity and the total number of events collected in different years. The centre of mass energy is the same for year 2015, 2016 and 2017. Data collected in 2015 contain the least number of events.

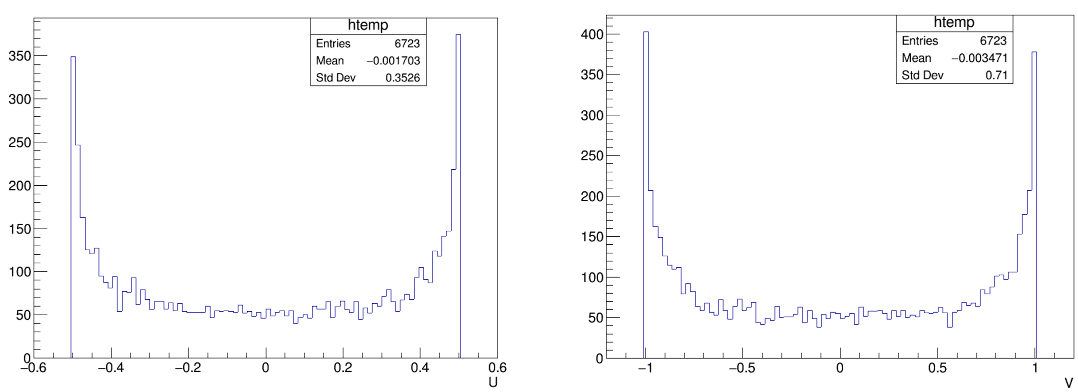
The data files used in this project contains a large number of events. The information stored for each events are the scaled mass of the particle and the triple product: U and V values, which were calculated from the angular observables obtained by the reconstruction and selection process of the detector. Compared with the simulated data used to assist data analysis, these real datasets contains combinational background (noise) and other decays reconstructed as the $B_s^0 \to \phi\phi$ decay by mistake. Figure 5 are histograms of the invariant mass distribution of the B_s^0 meson from real data and simulated data. The histograms of U and V from real data are shown in figure 6.



(a) Real data (b) Simulated data

Figure 5. Histogram of the real and simulated data. x axis is the scaled mass in MeV, y axis is the number of candidates. Each year has different data files, these are from year 2016 as an example. The data are unbinned in the data files, although shown as binned histogram here.

One may notice that in the figure the mass is labelled "Scaled" mass. This is because the masses of the B_s^0 mesons are obtained from reconstruction of the event. They are calculated from the momentum of the final four kaons, and the momentum is from the curvature of the track. The reconstruction is achieved with help of interaction that was already known, which means the results of the masses depend on some other factors and were given with a resolution that depend on the detector and reconstruction method. Thus the mass is called scaled mass.



(a) U (b) V

Figure 6. Histogram of the TPs U and V from data in 2016. U and V are dimensionless and the y axis is the number of candidates. The asymmetry is a measure of the difference between the two peaks.

2.6 Simulated Data

Except for data from real collisions in the LHCb, two types of simulated data were also used to assist the analysis.

Monte Carlo (MC) simulated data (signal)

This data simulates the $B_s^0 \to \phi\phi$ decay without background, although mistakes in reconstruction was also included in the simulation: some events come from other decays mistaken as this decay. It was generated with various software: the collisions were generated by the PYTHIA generator, this generator allows choosing a LHCb configuration. The hadron decays were described by the EVTGEN package, in which final state radiation is generated using PHOTOS. The interaction between the generated particles and the detector was simulated by GEANT4 toolkit [6], which is a toolkit simulating the passage of particles through matter. It can simulate the scattering and magnetic field [24].

The mass distribution is shown in figure 5b. The result from fitting the MC data helped determining one of the parameters in the signal model when fitting the mass distribution from the real data. This is because there are too much background events in the real data and it is difficult to distinguish the signal.

Simulated data from RapidSim (peaking backgrounds) [25]

Two other simulated data files were used in this project. They were generated by an application called RapidSim, it is an application based on ROOT software package for fast simulation in b and c hadron decays. The MC simulated data was generated with a full detector simulation, which is more precise but takes a relatively long time. RapidSim can simulate potential background decays quicker and easier with properties close to that from a full detector simulation. It uses uses FONLL (fixed-order next-to leading-log) calculations to provide kinematic properties of the hadrons from proton-proton collisions at the LHC, and can mimic the effect of imperfect track reconstruction, mis-identification of final state particles, momentum smearing, etc.

These two data files simulate background signal from another decay $\Lambda_b^0 \to \phi p K^-$, which empirically is more likely be mistaken as the wanted $B_s \to \phi\phi$ decay by the detector. There are two ways that this decay can happen: a two-body decay $\Lambda_b^0 \to \phi\Lambda^*$, where the Λ^* then decays into pK^-, and a direct three-body decay $\Lambda_b^0 \to \phi p K^-$. The detector misidentifies this decay as the $B_s \to \phi\phi$ decay when the p is mistaken as a K^+. Theoretically each decay mode has a branching ratio, and the real condition should be between these two.

When doing analysis, the 2 possibilities were fitted separately with different functions, result of the fits to these simulated data provides values for the parameters which are fixed when fitting the real data. The TP asymmetry result obtained from this two different cases were compared.

2.7 Previous Results from the LHCb

Results from previous study in the LHCb is summarized in figure 2.

Year	No. of Events	A_U	A_V
2011 [5]	801	$-5.5 \pm 3.6\ (stat)$ $\pm 1.8\ (syst)\%$	$1.0 \pm 3.6\ (stat)$ $\pm 1.8\ (syst)\%$
2011 & 2012 [6]	4000	$-0.3 \pm 1.7\ (stat)$ $\pm 0.6\ (syst)\%$	$-1.7 \pm 1.7\ (stat)$ $\pm 0.6\ (syst)\%$
2011–2016 [7]	9000	$0.0 \pm 1.2\ (stat)$ $\pm 0.4\ (syst)\%$	$-0.3 \pm 1.2\ (stat)$ $\pm 0.4\ (syst)\%$

Table 2. Results of the TP asymmetries from the literature. The results are consistent with each other and consistent with the hypothesis of CP conservation.

These researches analysed datasets obtained from earlier years, and with different method of analysis. In the research that uses the LHCb Run1 datasets (2011 and 2012) data [6], a boosted decision tree (BDT) was implemented to separate the signal events from the background. The BDT takes a machine learning approach to analyse the data, the training was done by simulated $B_s^0 \to \phi\phi$ events. Different decay mode was assumed as the peaking background: apart from the decay mode considered in this project, the $B^0 \to \phi K^{*0}$ etc. were also considered as backgrounds for this decay. When doing the fit, the model for the $B_s^0 \to \phi\phi$ signal was a double Gaussian model, the combinational background was described by an exponential function. These are the same as the model used in this project. But the yields of the peaking background contributions were determined beforehand with BDT. And the functions used to describe the background are also different. The background from $B^0 \to \phi K^{*0}$ was described by the sum of a Crystal Ball function and a Gaussian. The background from $\Lambda_b^0 \to \phi p K^-$ decay was fit with a Crystal Ball function.

In the latest literature [7], TP asymmetries in Run1 and Run2 were determined separately and combined by calculating a weighted average. The sum of a Crystal Ball and Student's t functions was used as the signal model, the combinational background component was described by an exponential function and the peaking background by a Crystal Ball function.

In these researches, the decay time acceptance, angular acceptance, and small effect from the mass model, combinational background and peaking background knowledge was treated as systematic uncertainty. Decay time acceptance is from requirements on the impact parameter of the final-state particles. Angular acceptance is due to the geometry of the detector and momentum requirements on the final-state particles, which means the detection have different efficiency for different helicity angles. They were determined by generating simulated signal events with and without angular acceptance. This analysis on systematic uncertainty was not done in this project.

The asymmetries from all literatures are in agreement with 0. No evidence for CP violation was found.

3 Fit Model

The data was analysed with the CERN ROOT toolkit. It is a software toolkit implemented in C++ widely for data analysis and visualization in particle physics. [26]

The TP asymmetries were obtained in two ways. Both way include performing an unbinned extended maximum likelihood fit to the four-kaon invariant mass distributions with a composite model. "Unbinned" refers to that the data are unbinned when performing the fit. This would allow getting a better accuracy, and the result would not depend on the binning of the data. If the data sample is too large, the binned fit would come into use. Composite model allows combining different probability density functions (PDF) for signal and background events to describe the whole data sample. The fit was done with the RooFit package in ROOT. It uses programme MINUIT to minimize the function and also estimate the errors of the parameters. [27]

RooSimultaneous class in ROOT was used to allow different models to be fit on data with different categories and give different yields (number of events).

The datasets used in this project were from different years. As the energy and cross section of the collisions were different for different years, the datasets have to be treated differently. One way is to fit each year separately and obtain different TP asymmetries results by year and then take the average, another way is to combine the datasets from different years but take the year into consideration when performing simultaneous fit. In this section the composite model and the two ways of fitting with simultaneous fit is described.

3.1 The Composite Models

Composite model can be constructed to describe data sample that include different types of events, like the $B_s^0 \to \phi\phi$ signal events, combinational background and peaking background.

In this fit, the $B_s^0 \to \phi\phi$ signal was described by a double Gaussian function, the combinational background by an exponential function, and the peaking background from the three-body decay process $\Lambda_b^0 \to \phi p K^-$ and two-body decay $\Lambda_b^0 \to \phi \Lambda^*$ were described by the Novosibirsk function and Double Crystal Ball function respectively. Fit on the peaking background was done on simulated data, and when fitting real datasets, the contributions from this background were fixed to the shapes found in simulated events by fixing the parameters in the corresponding PDF.

There are two ways of compositing models, both are used in this project. The first way is to express a data model in terms of the fraction of the one type of events (say, signal events) among the total number of events. The second is the extended likelihood formalism: as the result wanted is the number of events instead of fraction, in this case, the data model is expressed in terms of the number of signal and background events directly.

The double Gaussian function that describes the signal was constructed by compositing two Gaussian functions together and the composite model is expressed by fraction. In this case, the two types of events are those described by the 1st Gaussian function and the 2nd Gaussian function.

$$M(x) = fG_1(x) + (1-f)G_2(x) \tag{7}$$

where:

— $M(x)$ is a composite model.

— $G_1(x)$ and $G_2(x)$ are the PDFs for the 1st Gaussian and 2nd Gaussian function respectively.

— f is the fraction of events in the sample that are described by the first Gaussian function.

It is also possible to use several fractions and PDFs, But in this project, this formalism is only used to composite two Gaussian functions.

In the extended likelihood formalism case, the composite model is expressed by equation 8.

$$M(x) = \left(\frac{N_S}{N_S + N_{B_1} + N_{B_2}}\right) S(x) + \left(\frac{N_{B_1}}{N_S + N_{B_1} + N_{B_2}}\right) B_1(x) + \left(\frac{N_{B_2}}{N_S + N_{B_1} + N_{B_2}}\right) B_2(x) \tag{8}$$

where:

— M(x) is the composite model.

— N_S, N_{B_1} and N_{B_2} are the yields of the signal, the combinational background and the peaking background.

— $N_S + N_{B_1} + N_{B_2}$ is the total number of events in the data sample.

— $S(x)$, $B_1(x)$ and $B_2(x)$ are the PDFs that describes the signal and two types of backgrounds.

This formalism does not restrict the number of PDFs. It can be two or more. In this project $M(x)$ is the composite model of three different PDFs.

The probability density functions

The PDFs used in composite model are:

- Signal: double Gaussian function

  The double Gaussian function is composited from two Gaussian functions with a fraction f. The Gaussian distributions are:

  $$G_{1,2} = e^{-\frac{x-\mu^2}{2\sigma_{1,2}^2}} \tag{9}$$

  where:

  — μ is the mean.

  — σ is the width.

  In the fit, the first Gaussian function is chosen to be the one with smaller width.

- Combinational background: Exponential function

  $$B_1 = e^{\lambda x} \tag{10}$$

- Peaking background: Novosibirsk function

  The Novosibirsk function is essentially a Gaussian function with a tail. It is often used as a fitting function in particle physics. [28, 29]

$$P(x) = e^{-0.5^{(\ln q_y)^2/\Lambda^2 + \Lambda^2}} \tag{11}$$

$$q_y = 1 + \Lambda(x - x_0)/\sigma \times \frac{\sinh\left(\Lambda\sqrt{\ln 4}\right)}{\Lambda\sqrt{\ln 4}} \tag{12}$$

  where:

  — x_0 is the peak position.

  — σ is the width of the peak.

  — Λ is a parameter describes the tail of the distribution.

- Peaking background: Double Crystal Ball function (DCB)

  The double crystal ball function is similar to the single crystal ball function developed by the Crystal Ball Collaboration [30, 31], but has power-law tails on both sides of the core Gaussian component.

$$f = \begin{cases} \exp\left[-\frac{1}{2}\left(\frac{x-x_0}{\sigma}\right)^2\right] & \text{if } -\alpha_L \leq \frac{x-x_0}{\sigma} \leq \alpha_R \\ \left(\frac{n_L}{\alpha_L}\right)^{n_L} e^{-\frac{1}{2}\alpha_L^2} \left(\frac{n_L}{\alpha_L} - \alpha_L - \frac{x-x_0}{\sigma}\right)^{-n_L} & \text{if } \frac{x-x_0}{\sigma} < \alpha_L \\ \left(\frac{n_R}{\alpha_R}\right)^{n_R} e^{-\frac{1}{2}\alpha_R^2} \left(\frac{n_R}{\alpha_R} - \alpha_R + \frac{x-x_0}{\sigma}\right)^{-n_R} & \text{otherwise} \end{cases} \tag{13}$$

  where:

  — x_0 is the peak position.

  — σ is the width of the peak.

  — n_L and n_R are the power exponent of the tails on the left and right side of the core Gaussian component.

  — a_L and a_R are the transition points.

For the shape of the Novosibirsk and DCB functions refer to figure 8, which shows the result of fit for the peaking background. The value of the parameters in these two functions were determined by the fit to the simulated data, and kept fixed when fitting the real data.

3.2 Simultaneous Fit

Simultaneous fit was performed with the RooSimultaneous class in RooFit. This allows labelling events in the data sample by defined categories, and to split the models and parameters by these categories. This allows some parameters in the model, like the peak of the mass, the parameters in the Gaussian, exponential and Novosibirsk (DCB) to be shared (some of these parameters are fixed to the value obtained from fitting the simulated data), but some other parameters like the yields for positive and negative triple products to be different.

Fit different years separately

As mentioned, one way of obtaining the TP asymmetries is by fitting datasets from each years separately with the composite model. For each year, separate the candidates according to whether their TP is positive or negative, then perform simultaneous fit to the mass distributions with different models. I. e. there are two different composite models $M_{positive}$ and $M_{negative}$. They have common parameters and parameters that are uniquely defined for themselves. The common parameters for these models are the parameters in the Gaussian, exponential and Novosibirsk (or DCB) functions. The different parameters split into different categories are the yields for the signal and backgrounds. I.e. instead of having N_S, N_{B_1} and N_{B_2} as in equation 8, the $M_{positive}$ model has parameters $N_S(U > 0)$, $N_{B_1}(U > 0)$, $N_{B_2}(U > 0)$, and $M_{negative}$ has $N_S(U < 0)$, $N_{B_1}(U < 0))$, $N_{B_2}(U < 0)$. They are all allowed to vary independently to fit events with positive U and negative U.

From the fit, the yields (number of events) for the $B_s^0 \to \phi\phi$ signal events with $U > 0$ and < 0 can be determined, and the TP asymmetry A_U can be calculated with equation 5. Then by taking the average of the TP asymmetries of each year, the overall TP asymmetry of all datasets can be calculated. The asymmetry of V A_V was calculated in the same way.

Combining datasets

The other way is to combine the datasets for different years together. But when performing a simultaneous fit, apart from splitting the events according to the sign of U and V observables, they are also split according to which year the event was detected. I.e. ten different categories $2011(U > 0)$, $2011(U < 0)$, $2012(U > 0)$, $2012(U < 0)$ etc. were created.

Correspond to the ten categories, ten models with combination of 2 types of TP value (positive and negative) and 5 different years were composited. In this case, the common parameters are also those in the Gaussian, Exponential, etc. PDFs. The different parameters are the asymmetries for the signal, combinational background and the peaking background, as well as the total yields for signal and the two types of backgrounds in different years.

Note that in this case instead of fitting for the yield, the asymmetries were left as free parameters and fitted for directly in the simultaneous fit. As well as total yields for signal (background) events for different years. The yields with different signs of TP were determined from the relation between the total yields in that year and the asymmetry with equation 14 and 15. These relations come from inverting equation 5.

$$N_{sig}^{2011}(U > 0) = \frac{N_{sig}^{2011}(total) \times (A_{U_{sig}} + 1)}{2} \tag{14}$$

for negative U:

$$N_{sig}^{2011}(U < 0) = \frac{N_{sig}^{2011}(total) \times (A_{U_{sig}} - 1)}{2} \tag{15}$$

where $N_{sig}^{2011}(U > 0)$ is the yield with positive U that come from the year 2011, $N_{sig}^{2011}(total) = N_{sig}^{2011}(U > 0) + N_{sig}^{2011}(U < 0)$ is the total yields in the year 2011.

3.3 Uncertainty

When fitting datasets from different years separately, error of TP asymmetry can be calculated with the standard way of propagating errors with derivative, while as the parameters are correlated, this method is no longer accurate.

Thus the errors of the asymmetries were determined by "random parameters method". In this method, the parameters were set to be a value that deviates from the result of the fitting by a randomly sampled amount within the covariance matrix. From these parameters, the number of signal events with U (or V) larger or smaller than 0 was determined and the asymmetries calculated. Doing this a number of times gives a histogram of the value of the asymmetries. Then the value and error of the asymmetry can be obtained from the mean and the root mean square value respectively.

In the way of combining all datasets and fit together, the asymmetries were fit directly, thus the uncertainties were also given directly from the fit.

4 Fit Validation

The RooFit package also allows generating "toy" Monte Carlo events. A large number of toys were generated with parameters set as the values from the fit on the real data, in order to mimic a large number of experiments. The asymmetry were set to be 0. Then the toys were analysed with the methods as used on the data to test whether there is any bias in this method.

The distribution of the pull of toys $\frac{A_{fit} - V_{gen}}{\Delta A}$ should have a Gaussian distribution. If the method is unbiased, the mean should =0 and the standard deviation should = 1.

The fit result on 2015 and 2016 data were chosen to be used to generate toys, because dataset in 2015 have the smallest number of events and 2016 has a standard number of events. The relative error $\propto \frac{1}{\sqrt{N}}$, which means the error of the 2015 data should be larger than that of 2016.

5 Results and Discussion

5.1 Fit on Simulated Data

MC data - the $B_s^0 \to \phi\phi$ signal

A double Gaussian function was fit to the MC data. The two Gaussian functions in the composited double Gaussian model have the same mean μ but different width σ.

Three different MC data simulated for different years were used to assist the analysis. They are MC2011, MC2012 and MC2016. An example of the fit on MC2016 is shown in figure 7.

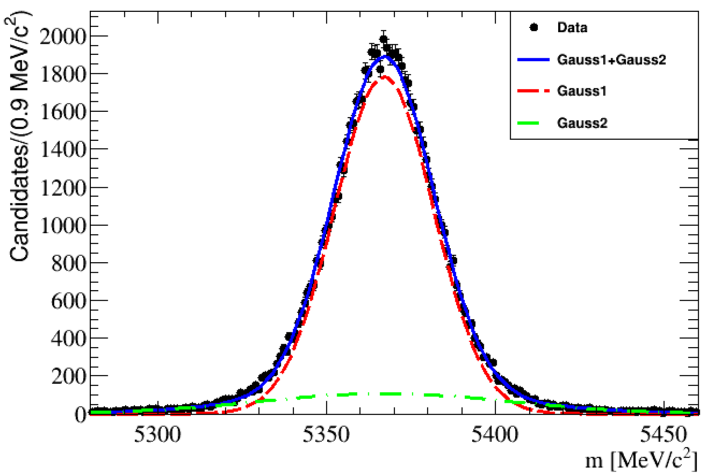


Figure 7. Fit result on MC data. This is on the data simulated for the year 2016, the fit on the other two years are similar. This is a histogram of the data, but the data themselves and the fit were unbinned. The double Gaussian function (solid blue line) fits the data well.

The range of parameters, result and the χ^2 probability of the fit are shown in table 3.

The fit gives uncertainties but they are small and not of particular importance thus not included in the table. The χ^2 probability shows that the fit is good for 2011 and 2012. For year 2016, it can be seen from the figure of the fit that the model describes the data well, thus although the χ^2 probability is not good, the result can still be used.

The fit was done on the mass in the range 5280 to 5460. This range is smaller than that chosen to fit the real data, as the MC data is more "clean" (very small background) and thus spread less. The value for B_s^0 invariant mass from the Particle Data Group (PDG) is 5366.84 ± 0.30 MeV [32], so the initial value of μ is chosen to be 5366. The fit result is close to the value from PDG.

The ranges for σ_1 and σ_2 were set to be different, this is for convenience: it makes sure that σ_2 is the larger one.

Parameters	Range of Parameters			Results		
	Initial Value	Lower Bound	Upper Bound	2011	2012	2016
μ (MeV)	5366	5280	5460	5368.3	5368.5	5367.0
σ_1	20	0	30	13.7	13.8	14.7
σ_2	30	20	200	34.4	35.3	37.4
f	0.7	0	1	0.9	0.9	0.9
χ^2 probability				0.12	0.50	0.00004
No. of Events				56491	53033	85230

Table 3. The initial values and ranges of the parameters used to fit the MC data, the fit result and χ^2 probability for each years and the number of events in each MC data file. f is the fraction of the first (narrower) Gaussian function.

The results for σ_2 were used when fitting the real data. This value is more accurate as the MC data has much lower backgrounds. If the double Gaussian function was fitted directly on the real data, instead of describing the signal, the programme would misfit the second Gaussian to the background, resulting to a very large σ_2 value and the signal would not be very well described. Thus this parameter has to be fixed when fitting the real data. The result for MC data from 2011 and 2012 were used when fitting the data for the year 2011 and 2012, and the result from 2016 was used on 2015, 2016 and 2017, as they were produced with similar collision condition.

The fit is stable, the result do vary with the mass range, but this range is suitable and the resultant change on σ would not give a big impact on the result of the asymmetries.

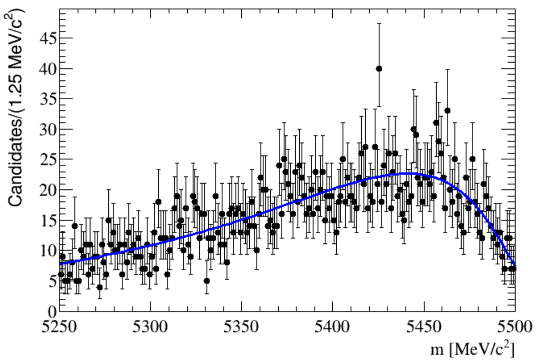
Peaking Background

The simulated data of the background signal from the $\Lambda_b^0 \to \phi p K^-$ decay was fitted with the Novosibirsk function, and the background from $\Lambda_b^0 \to \phi \Lambda^* \to \phi p K^-$ was fitted with the DCB function. The fits are shown in figure 8.

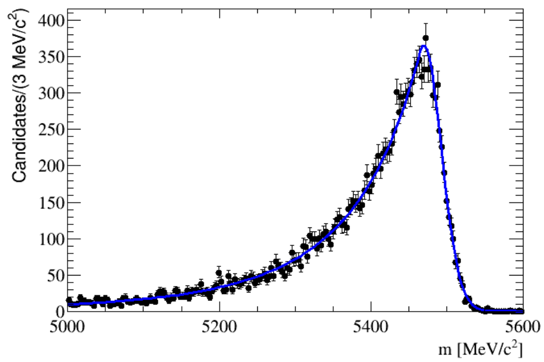
The range and results of the parameters are shown in tables 4 and 5.

Parameter	Initial Value	Lower Bound	Upper Bound	Result
m_0 (peak position) (MeV)	5400	5250	5500	5441
Λ	0.1	-1	2	0.94
σ	100	0	200	78.98
χ^2 probability				0.99

Table 4. The range of the parameters in the Novosibirsk function and the results of the fit. For the function and meaning of the parameters refer to equation 11. The variable x in the equation 11 is the invariant mass m here.



(a) Novosibirsk



(b) DCB

Figure 8. Fit of the simulated data that represent the shape of the peaking background. The one fitted with Novosibirsk represents the case of a three-body decay. The two-body decay case fitted with the DCB function has a much sharper peak. (Note that the range of the mass is different.)

Parameter	Initial Value	Lower Bound	Upper Bound	Result
m_0 (MeV)	5366	5000	5600	5470
σ	20	0	200	23.32
α_L	0.1	0.1	15	0.27
α_R	5	0.1	15	3.10
n_L	10	0	100	5.18
n_R	10	0	100	2.01
χ^2 probability				0.91

Table 5. Fit range and result of the DCB function. For the function and parameters refer to equation 13.

The errors of the fit results are again omitted. And the χ^2 probability values indicate that these are good fits. The result of the parameters in the DCB function do vary with the initial value and range, especially n_L. The fit result for n_L varies much larger than the other ones but has a big error. The variation of these results are not enough to hugely affect the result of asymmetries.

The range of mass that was fitted is different for Novosibirsk function and DCB function, being 5250 – 5500 MeV and 5200 – 5600 MeV respectively. This is because the peak in the two-body decay case (fitted with DCB) is at a higher mass. If the fit range is too small, it would not cover the peak fully and the fit would fail.

The mass of Λ_b^0 is 5619.60 ± 0.17 MeV, when a final proton was mistaken as a K^+ and reconstructed as the $B_s^0 \to \phi\phi$ decay, the K^+ mass (about 494 MeV) is assigned to the proton (proton mass is about 938 MeV). So the peak is at a larger mass than the B_s^0 mass, but smaller than the Λ_b^0 mass. Note that the peak cannot be calculated directly by subtracting the difference between the proton mass and K^+ mass from the Λ_b^0 mass as the mass are calculated from energy and momentum with $E^2 = m^2 + p^2$ during the reconstruction, and cannot be added or subtracted linearly. (The invariant mass values are from Particle Data Group [32].)

5.2 TP Asymmetry

With all the parameters settled from the simulated data (σ_2 from MC data, shape of the peaking background from the data generated with RapidSim), the fit were done on the real data. The initial value and range of the parameters that remained free are listed in table 6, and the fit results for year 2015 and 2016 are shown in figure 7. Same ranges were used when fitting data from different years. Only events with mass within the range 5250 – 5500 MeV were fitted when using the model with Novosibirsk function as peaking background. When using DCB function, the mass range is larger: 5250 – 5550 MeV, as the peak of the DCB shape obtained from fitting MC data is much larger than the peak of Novosibirsk (as shown in table 4 and 5). If a small mass range is fitted, the whole range of the peak would not be covered, and the fit would fail.

Parameters	Initial Value	Lower Bound	Upper Bound
μ (MeV)	5366	5250	5500
σ_1	20	10	100
f	0.7	0	1
λ	0	-5	5
$N_{sig}\,(TP>0)$	1000	0	1.1× Number of entries
$N_{sig}\,(TP<0)$	1000	0	1.1× Number of entries
$N_{exp}\,(TP>0)$	500	0	1.1× Number of entries
$N_{exp}\,(TP<0)$	500	0	1.1× Number of entries
$N_{peak}\,(TP>0)$	500	0	1.1× Number of entries
$N_{peak}\,(TP<0)$	500	0	1.1× Number of entries

Table 6. Initial values and range of the parameters in the composite model that are left free during the fit. N with different subscripts are the yields. $N_{sig}\,(TP>0)$ is the yield of signal with positive triple product, etc.

Parameters	2015		2016	
	Value	Error	Value	Error
μ (MeV)	5368	1	5367	0
σ_1	13.00	0.67	14.62	0.33
f	0.75	0.06	0.85	0.03
λ	-0.01	0.01	-0.0007	0.0005
$N_{sig}\,(V>0)$	395	26	2509	63
$N_{sig}\,(V<0)$	428	27	2549	62
$N_{exp}\,(V>0)$	40	19	704	106
$N_{exp}\,(V<0)$	62	25	827	70
$N_{Novo}\,(V>0)$	80	20	134	109
$N_{Novo}\,(V<0)$	57	21	0	32
χ^2 probability	1		0.66	

Table 7. Fit result of triple product V with Novosibirsk function as the peaking background.

χ^2 probabilities show that the fits are good. Result for other years, for U and result obtained using DCB function are similar thus not shown. The peak position μ is consistent with the invariant mass of the B_s^0 meson from PDG. Although the yields for the peaking background (N_{Novo}) are very different for V>0 and V<0, it does not mean that there is an asymmetry as they have large uncertainties. These data were used to generate toys for fit validation. The result for year 2015 and 2016 are chosen as in 2015 the total number of candidates is the smallest among all years, and year 2016 has a standard number of candidates and collision condition.

The fit yields 823 ± 53 and 5058 ± 125 $B_s^0 \to \phi\phi$ events in year 2015 and 2016 respectively. All the yields add up to 1062 and 6723, consistent with the total number of events in the data files shown in table 1.

The fit and data sample of 2016 are shown in figure 9.

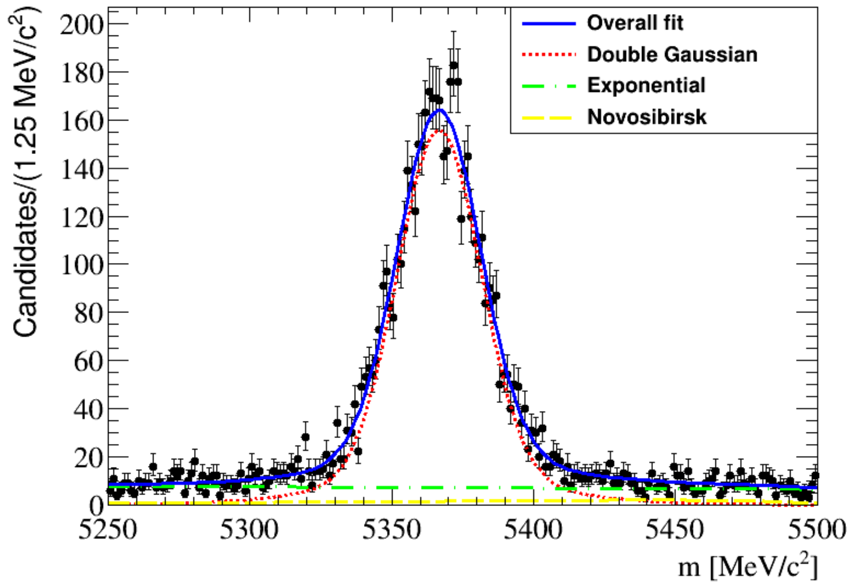


Figure 9. The fit on 2016 data. Remember that two models with different yields for positive and negative V were fitted simultaneously. The models for positive and negative V are very similar and would almost overlap if both shown on the plot, thus only models with positive V are shown.

The pull of the fit is shown in figure 10. It is defined as $pull = \frac{data - fit}{\text{fit uncertainty}}$, where the fit uncertainty $= \sqrt{number\, of\, events}$ is the poisson error on the data.

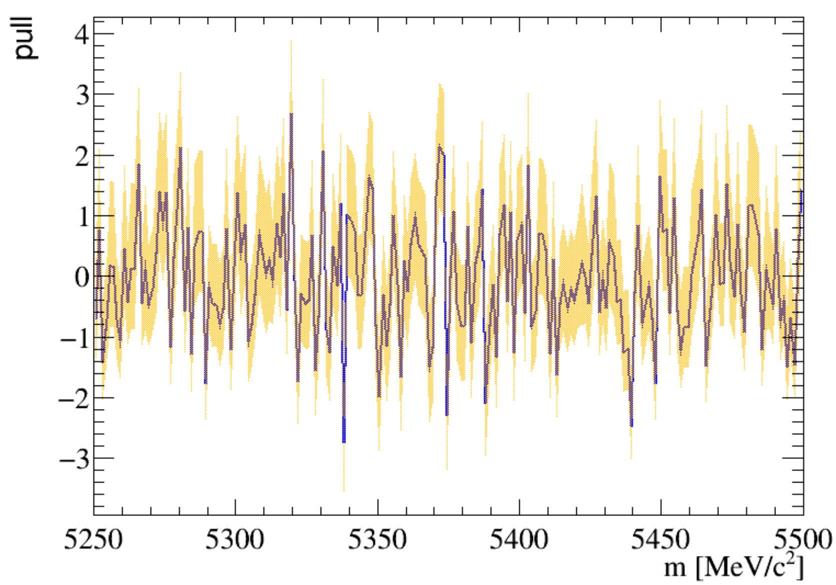
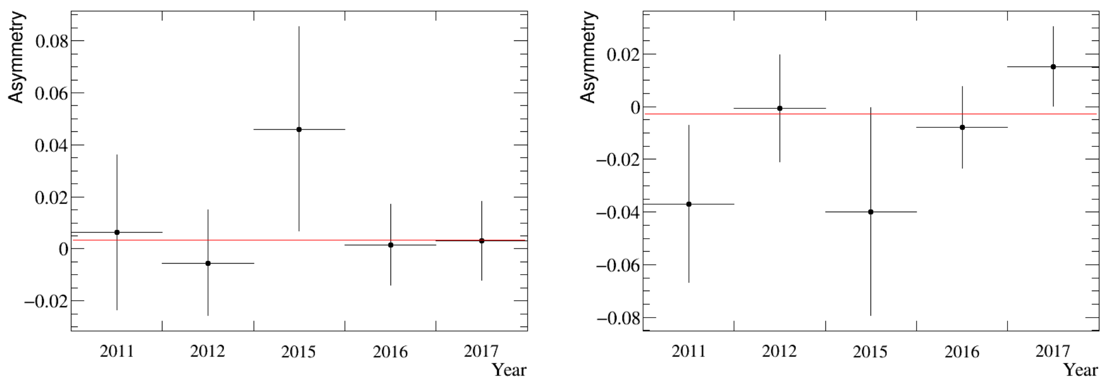


Figure 10. The pull versus mass. The pull is mostly within 3, which means the fit is good.

The TP asymmetries were calculated from the yields. The results for both A_U and A_V from fitting the composite model with Novosibirsk function as the peaking background (the 3-body decay case) to different years are shown in figure 11. The result from DCB function is very similar.



(a) A_U (b) A_V

Figure 11. Result of asymmetries. This result is the one obtained from the composite model with Novosibirsk function as peaking backgrounds. The result from using DCB function give very similar result. Constants was fitted to the results, which is shown as the red line, and this gives the average.

From figure 11 it can be observed that the asymmetries are very small. A_U is positive and A_V is negative for most of the years. The results for year 2015 have the largest error and the error on 2016 and 2017 are relatively smaller than the others. This is because the dataset in year 2015 has the smallest number of events and datasets in year 2016 and 2017 have larger number of events. The uncertainties shown in the figure are from random parameters method. Although not shown, the uncertainties from derivatives were calculated as well and the difference between the uncertainties obtained with these two methods are small. For the exact value of these results refer to table 8.

Apart from fitting the data from different years separately, combining all datasets and fitting for asymmetries was also achieved. The fit is shown in figure 12. Instead of plotting all data together, the data from different year were projected and plotted, and the corresponding model with positive and negative TPs are shown.

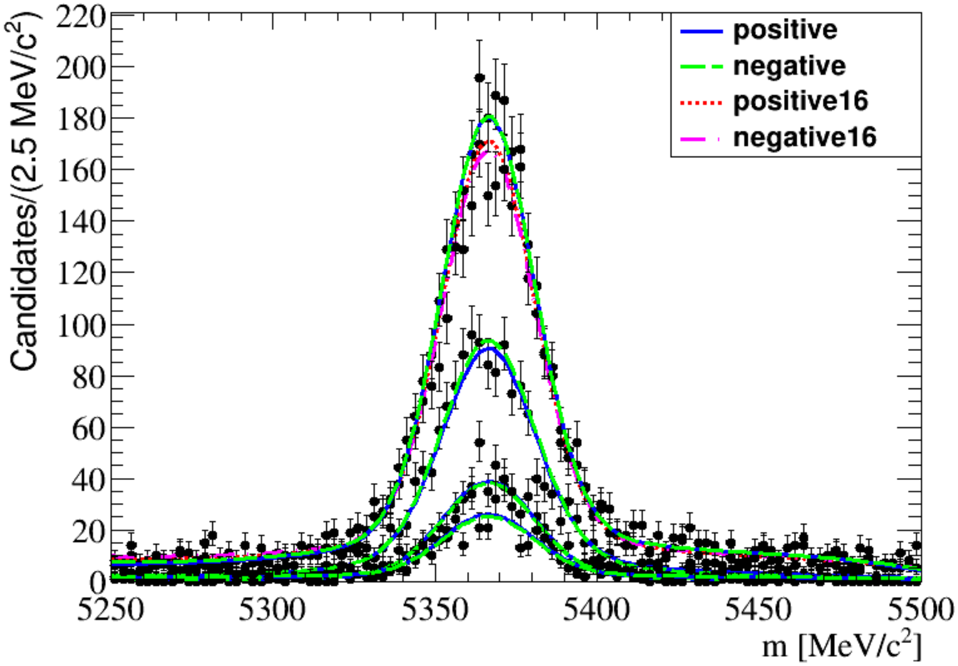


Figure 12. The fit on the combined datasets contain data from every year. The model used in this fit is the one with Novosibirsk Function and the fit is on U. The result for using DCB function or on V are similar to this one. As this is a very crowded plot, only data with positive U is plotted for simplicity of the graph. From the least to the most number of candidates, the data are for year 2015, 2011, 2012, 2016 and 2017. Models for data in year 2016 are marked with different line and colour to be distinguished from that of 2017, as they have similar number of candidates and are difficult to distinguish.

The fit with Novosibirsk function yields 15129 ± 373 signal events, there are 19396 events in total in all the data files.

The results of TP asymmetries A_U and A_V from fitting different years separately and combining all datasets, as well as using different functions as peaking background, are summarized in table 8. The average of the results for different years are also shown.

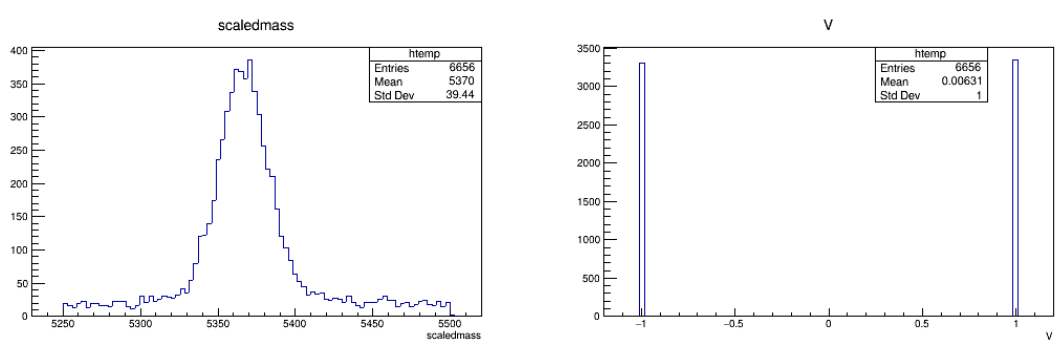
	Novosibirsk		Double Crystal Ball	
	A_U	A_V	A_U	A_V
2011	$0.6 \pm 3.0\,\%$	$-3.7 \pm 3.0\,\%$	$0.6 \pm 2.9\,\%$	$-2.9 \pm 2.9\,\%$
2012	$-0.6 \pm 2.0\,\%$	$-0.1 \pm 2.0\,\%$	$-0.5 \pm 1.9\,\%$	$-0.1 \pm 1.9\,\%$
2015	$4.6 \pm 3.9\,\%$	$-4.0 \pm 4.0\,\%$	$2.6 \pm 3.9\,\%$	$-4.1 \pm 3.9\,\%$
2016	$0.2 \pm 1.6\,\%$	$-0.8 \pm 1.6\,\%$	$0.3 \pm 1.6\,\%$	$-0.8 \pm 1.6\,\%$
2017	$0.3 \pm 1.5\,\%$	$1.5 \pm 1.5\,\%$	$0.7 \pm 1.5\,\%$	$1.6 \pm 1.5\,\%$
Average	$0.3 \pm 0.9\,\%$	$-0.3 \pm 0.9\,\%$	$0.4 \pm 0.9\,\%$	$-0.2 \pm 0.9\,\%$
All	$0.3 \pm 0.9\,\%$	$-0.3 \pm 0.9\,\%$	$0.4 \pm 0.9\,\%$	$-0.3 \pm 0.9\,\%$

Table 8. The result of TP asymmetries. A_U is mostly positive and A_V negative. Note the average of the TP asymmetries from different years and the result from fitting the all combined data. The results from these two methods are exactly the same except for that of A_V fitted with the DCB function. There are only minor differences between the result obtained from fitting different peaking backgrounds.

The results from different fit methods and different models agree with each other and are also consistent with results from literature (as shown in table 2 in section 2.7). The results show no sign of CP violation.

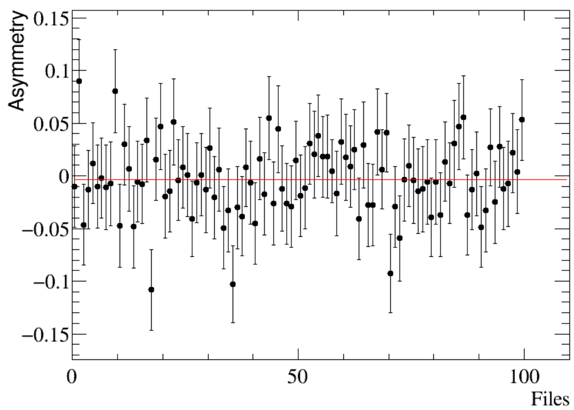
5.3 Result of Fit Validation

100 toys were generated with parameters set to the result from the fits on the real data. See figure 13 for an example of the generated toys. Then the toys were analysed in the same way as analysing the data for each year separately. The TP asymmetry results are shown in figure 14.



(a) mass distribution (b) triple product distribution

Figure 13. The histogram of the mass and triple product for one of the generated toy data file.

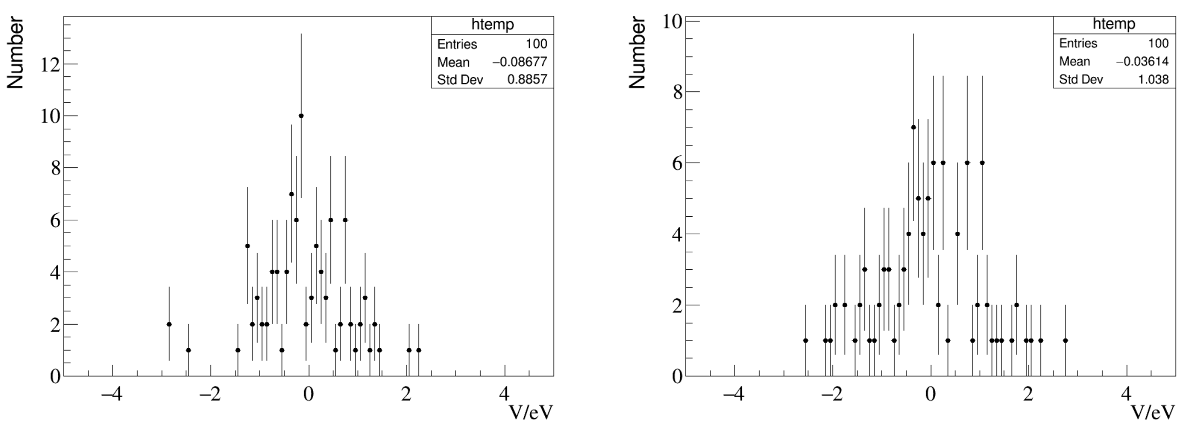


(a) 2015 (b) 2016

Figure 14. The results of the TP asymmetries. The toys were generated with parameter from the fit on 2015 data and 2016 data. 100 toys were generated for each year.

The average of the TP asymmetries are $A = -0.4 \pm 0.4\,\%$ for 2015 and $A = -0.1 \pm 0.2\,\%$ for 2016. The uncertainty of year 2015 is larger than that of 2016 as the later has a larger data sample. This relation is qualitatively correct.

Figure 15 shows the histogram of $\frac{A_{fit}-A_{gen}}{error}$, where A_{fit} is the asymmetry from analysing the toy data, $A_{gen} = 0$ is the asymmetry was set to be 0 when generating the toys.



(a) 2015 (b) 2016

Figure 15. The histogram of the pull of asymmetry from generated toys. Note that the mean is close to 0 and the standard deviation is close to 1.

When fitting the real data, analysing one data file gives one result of asymmetries. Generating and analysing 100 toys is like doing 100 experiments, and the distribution of the results shows whether the fit is biased. From figure 15 it can be seen that the mean of these distributions are close to 0 and the standard deviation are 1. This shows that the procedure of the analysis is unbiased.

6 Conclusion

In this project the triple product asymmetries of the $B_s^0 \to \phi\phi$ decay was measured to be $A_U = 0.3 \pm 0.9\,\%$ and $A_V = -0.3 \pm 0.9\,\%$. This result is consistent with previous analysis from the literature [5, 6, 7], and is consistent with the hypothesis of CP conservation.

There are several possible improvements could be done. For example, in this project the combinational background and peaking background from $\Lambda_b^0 \to \phi p K^-$ was taken into consideration. But there are also other possibilities. Several other decay modes have been considered in the literature [6]. Thus the decay mode of the peaking backgrounds could be studied more. As discussed at the end of section 2.7, in previous researches the systematic error was obtained from various source. In this project, although the results from two different methods and composite models were compared, a more extended analysis on the systematical error was not done due to the scope and length of this project. This means the uncertainty could be even larger. Although with the current precision of the result, adding more systematic error does not give more insight on CP violation. When more precise analysis is being done in the future, the systematic uncertainty from acceptance, etc. should be considered.

As the SM prediction of CP violation in this decay is very small, the current precision of the result is not enough to distinguish if the result differs from prediction of the SM. But more data can be taken and added for analysis. Like the data just produced in 2018. The LHCb Upgrade I will begin in 2020, producing Run3, Run4 data in 2022 and 2028. As more data are added, the precision of the TP asymmetry would be increased, the uncertainty would be smaller, then whether the result differ from the SM prediction can be determined.

LHCb Upgrade II would be installed during the long shutdown 4 of the LHC in 2030, bringing high luminosity LHC (HL-LHC). Trigger system would be improved by getting rid of the hardware trigger, the luminosity would also increase. This upgrade would allow CP asymmetries to be measured with larger precision. [33]

References

[1] A. D. Sakharov. *Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry.* 1967.

[2] Makoto Kobayashi and Toshihide Maskawa. "CP Violation in the Renormalizable Theory of Weak Interaction". In: *Prog. Theor. Phys.* 49 (1973), pp. 652–657. DOI: 10.1143/PTP.49.652.

[3] D. Acosta et al. "Evidence for $B_s^0 \to \phi\phi$ Decay and Measurements of Branching Ratio and A_{CP} for $B^+ \to \phi K^+$". In: *Phys. Rev. Lett.* 95 (3 2005), p. 031801. DOI: 10.1103/PhysRevLett.95.031801. URL: https://link.aps.org/doi/10.1103/PhysRevLett.95.031801.

[4] Michael Gronau and Jonathan L. Rosner. "Triple-product asymmetries in K, $D_{(s)}$, and $B_{(s)}$ decays". In: *Phys. Rev. D* 84 (9 2011), p. 096013. DOI: 10.1103/PhysRevD.84.096013. URL: https://link.aps.org/doi/10.1103/PhysRevD.84.096013.

[5] R. Aaij et al. "Measurement of the polarization amplitudes and triple product asymmetries in the Bs0→ decay". In: *Physics Letters B* 713.4 (2012), pp. 369 –377. ISSN: 0370-2693. DOI: https://doi.org/10.1016/j.physletb.2012.06.012. URL: http://www.sciencedirect.com/science/article/pii/S0370269312006387.

[6] R. Aaij et al. "Measurement of CP violation in $B_s^0 \to \phi\phi$ decays". In: *Phys. Rev. D* 90 (5 2014), p. 052011. DOI: 10.1103/PhysRevD.90.052011. URL: https://link.aps.org/doi/10.1103/PhysRevD.90.052011.

[7] The LHCb Collaboration. "Measurement of CP violation in the $B_s^0 \to \phi\phi$ decay and search for the $B^0 \to \phi\phi$ decay". In: CERN. Geneva: CERN, 2018.

[8] A. Augusto Alves Jr. et al. "The LHCb Detector at the LHC". In: *JINST* 3 (2008), S08005. DOI: 10.1088/1748-0221/3/08/S08005.

[9] CERN collaboration. *About CERN*. 2019. URL: https://home.cern/about (visited on 18/03/2019).

[10] CERN collaboration. *The Large Hadron Collider*. 2019. URL: https://home.cern/science/accelerators/large-hadron-collider (visited on 18/03/2019).

[11] Roel Aaij et al. "LHCb Detector Performance". In: *Int. J. Mod. Phys. A* 30.LHCB-DP-2014-002. CERN-PH-EP-2014-290. LHCB-DP-2014-002. CERN-LHCB-DP-2014-002 (2014), 1530022. 73 p. URL: https://cds.cern.ch/record/1978280.

[12] R. Aaij et al. "Performance of the LHCb trigger and full real-time reconstruction in Run 2 of the LHC". In: (2018). arXiv: 1812.10790. URL: http://arxiv.org/abs/1812.10790.

[13] T. D. Lee and C. N. Yang. "Question of Parity Conservation in Weak Interactions". In: *Phys. Rev.* 104 (1 1956), pp. 254–258. DOI: 10.1103/PhysRev.104.254. URL: https://link.aps.org/doi/10.1103/PhysRev.104.254.

[14] C. S. Wu et al. "Experimental Test of Parity Conservation in Beta Decay". In: *Phys. Rev.* 105 (4 1957), pp. 1413–1415. DOI: 10.1103/PhysRev.105.1413. URL: https://link.aps.org/doi/10.1103/PhysRev.105.1413.

[15] Marco S. Sozzi. *Discrete Symmetries and CP Violation From Experiment to Theory*. Oxford University Press, 2012. ISBN: 978-0-19-965542-7.

[16] J. H. Christenson et al. "Evidence for the 2π Decay of the K_2^0 Meson". In: *Phys. Rev. Lett.* 13 (4 1964), pp. 138–140. DOI: 10.1103/PhysRevLett.13.138. URL: https://link.aps.org/doi/10.1103/PhysRevLett.13.138.

[17] Gustavo Castelo Branco, Luis Lavoura and Joao Paulo Silva. *CP Violation*. Clarendon Press Oxford, 1999. ISBN: 0 19 850399 7.

[18] A. Abashian et al. "Measurement of the CP Violation Parameter sin2φ_1 in B_d^0 Meson Decays". In: *Phys. Rev. Lett.* 86 (12 2001), pp. 2509–2514. DOI: 10.1103/PhysRevLett.86.2509. URL: https://link.aps.org/doi/10.1103/PhysRevLett.86.2509.

[19] B. Aubert et al. "Observation of CP Violation in the B^0 Meson System". In: *Phys. Rev. Lett.* 87 (9 2001), p. 091801. DOI: 10.1103/PhysRevLett.87.091801. URL: https://link.aps.org/doi/10.1103/PhysRevLett.87.091801.

[20] Mirco Dorigo. "Suppressed B_s^0 decays at CDF". In: (2011). arXiv: arXiv:1105.4437v1.

[21] A. Alavi-Harati et al. "Observation of CP Violation in $K_L \to \pi^+\pi^-e^+e^-$ Decays". In: *Phys. Rev. Lett.* 84 (3 2000), pp. 408–411. DOI: 10.1103/PhysRevLett.84.408. URL: https://link.aps.org/doi/10.1103/PhysRevLett.84.408.

[22] E. Abouzaid et al. "Measurement of the K^0 Charge Radius and a CP-Violating Asymmetry and a Search for CP-Violating $E1$ Direct Photon Emission in the Rare Decay $K_L \to \pi^+\pi^-e^+e^-$". In: *Phys. Rev. Lett.* 96 (10 2006), p. 101801. DOI: 10.1103/PhysRevLett.96.101801. URL: https://link.aps.org/doi/10.1103/PhysRevLett.96.101801.

[23] T. Aaltonen et al. "Measurement of Polarization and Search for CP Violation in $B_s^0 \to \phi\phi$ Decays". In: *Phys. Rev. Lett.* 107 (26 2011), p. 261802. DOI: 10.1103/PhysRevLett.107.261802. URL: https://link.aps.org/doi/10.1103/PhysRevLett.107.261802.

[24] S. Agostinelli et al. "GEANT4 - A simulation toolkit". In: *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 506.3 (2003), pp. 250–303. ISSN: 01689002. DOI: 10.1016/S0168-9002(03)01368-8.

[25] G.A. Cowan, D.C. Craik and M.D. Needham. "RapidSim: An application for the fast simulation of heavy-quark hadron decays". In: *Computer Physics Communications* 214 (2017), pp. 239 –246. ISSN: 0010-4655. DOI: https://doi.org/10.1016/j.cpc.2017.01.029. URL: http://www.sciencedirect.com/science/article/pii/S0010465517300413.

[26] CERN. *ROOT*. 2014. URL: https://root.cern.ch/ (visited on 24/03/2019).

[27] W Verkerke and D Kirkby. *RooFit Users Manual*. v2.91. 2008, pp. 1–134. URL: https://root.cern.ch/download/doc/RooFit{_}Users{_}Manual{_}2.91-33.pdf.

[28] H. Ikeda et al. "A detailed test of the CsI(Tl) calorimeter for BELLE with photon beams of energy between 20-MeV and 5.4-GeV". In: *Nucl. Instrum. Meth.* A441 (2000), pp. 401–426. DOI: 10.1016/S0168-9002(99)00992-4.

[29] Adrian Bevan and Fergus Wilson. "AFit User Guide". In: (2010), pp. 1–57.

[30] Tomasz Skwarnicki. "A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances". DESY-F31-86-02. PhD thesis. Institute of Nuclear Physics, Krakow, 1986.

[31] Souvik Das. "A simple alternative to the Crystal Ball function". In: (Mar. 2016).

[32] M. Tanabashi et al. "Review of Particle Physics". In: *Physical Review D* 98.3 (2018), p. 030001. ISSN: 2470-0010. DOI: 10.1103/PhysRevD.98.030001. URL: https://link.aps.org/doi/10.1103/PhysRevD.98.030001.

[33] LHCb collaboration et al. "Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era". In: *arXiv e-prints* (Aug. 2018). arXiv: 1808.08865 [hep-ex].