Measurement of matter-antimatter asymmetries with the LHCb experiment

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Submission / Prediscussion?: DATE

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Contents

1 Motivation

In our universe, we observe a surplus of particles over antiparticles that is called *baryon asymmetry*. A key aspect of this matter-antimatter problem is the violation of the *CP* symmetry that occures in the weak interaction. In this experiment, the decays of B mesons measured by the LHCb experiment are analyzed to calculate the *CP* asymmetry.

2 Theory

In 1964, *CP* violation was observed in the decay of neutral Kaons by Cronin and Fitch [4]. At this time, the Standard Model of particle physics did not provide methods to describe *CP* violation. This chapter focuses on establishing a connection between the baryon asymmetry and the violation of the *CP* symmetry. Moreover, the theory behind *CP* violation is explained.

2.1 Sakharov conditions

For a higher production rate of matter over antimatter, three conditions must be fullfilled. These conditions are referred to as the *Sakharov conditions*, named after the physicist Andrei Sakharov who proposed these criteria in 1966 [8]. First, a violation of the baryon number B is needed. This is in disagreement with the Standard Model as we know it today but extenstions of it could allow for baryon number violation.
Second, both the charge symmetry C and the combination of the charge and parity symmetries *CP* need to be violated. The *CP* violation is the topic of this lab course and is explained in detail in the following sections.
The third conditon states that the violation of the baryon number (first conditon) needs to occur out of thermal equilibrium. If this was not the true, any baryon number asymmetry would lead to a corresponding reverse process and thus no overall asymmetry could be observed. Consequently, the universe is not in a state of thermal equilibrium.

2.2 *CP* violation in the weak interaction

Before 1970, the weak interaction theory was based on Nicola Cabibbo's notation of the unitary symmetry [3] leading to quark mixing via the Cabibbo angle. This notation described how the weak interaction causes transitions between different quark flavors via

$$u \leftrightarrow d \cdot \cos(\theta_{\mathrm{C}}) \quad \text{and} \quad u \leftrightarrow s \cdot \sin(\theta_{\mathrm{C}}).$$

At this time, only three quarks (u,d,s) were know to be part of the Standard Model. This theory faced issues with renormalizability, failing to adequately describe certain decays or particle interactions. In 1970, Glashow, Iliopoulos, and Maiani proposed a new weak interaction theory [5], introducing a fourth quark (charm) and one vector boson (Z_0). This model helped address these problems and allowed for the integration of the previously predicted boson and the unification with the electroweak interaction. A few years later, in 1973, Kobayashi and Maskawa further refined the theory of the weak interaction by postullating a third generation of quarks [6]. By introducing the quarks now known as *top* and *bottom* quarks, they also extended the theory to a total of three mixing angles θ_i and a *CP* violating phase δ. In summary, the quark mixing matrix is written as

$$\begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}.$$

This unitary matrix is referred to as the *Cabibbo-Kobayashi-Maskawa* matrix or the *CKM* matrix and can be parameterized in different manners, for example

$$\begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_2c_2c_3 - s_2s_3\mathrm{e}^{\mathrm{i}\delta} & c_1c_2s_3 + s_2c_3\mathrm{e}^{\mathrm{i}\delta} \\ s_1s_2 & c_1s_2c_3 + c_2s_3\mathrm{e}^{\mathrm{i}\delta} & c_1s_2s_3 - c_2c_3\mathrm{e}^{\mathrm{i}\delta} \end{pmatrix}.$$

Here, s_i and c_i are abbreviations for sines and cosines of the mixing angles θ_i, e.g. $s_1 = \sin\theta_1$. Another representation of the *CKM* matrix is a form with Euler angles, where $\theta_1 2$ denotes the Cabibbo angle θ_{C}. The result is

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\mathrm{e}^{-\mathrm{i}\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta_{13}} & c_{23}c_{13} \end{pmatrix}.$$

In another representation of the matrix, the parameters are chosen such that the unity matrix is obtained in the absence of quark mixing. The four degrees-of-freedom are expressed as

$$\lambda = s_{12} \qquad A = \frac{s_{23}}{s_{12}^2}$$
$$\rho = \Re\left(\frac{s_{13}\mathrm{e}^{-\mathrm{i}\delta}}{s_{12}s_{23}}\right) \qquad \eta = -\Im\left(\frac{s_{13}\mathrm{e}^{-\mathrm{i}\delta}}{s_{12}s_{23}}\right).$$

Inserting these parameters into the *CKM* matrix leads to an approximation to the order λ^3. It follows that

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - \mathrm{i}\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-\mathrm{i}\eta) & -A\lambda^2 & 1 \end{pmatrix}.$$

In this form, the violation of the *CP* symmetry is found in the parameter ρ and η.

2.3 *B* meson decay

The *B* system is of particular interest for the research of *CP* violation because of the oscillation of the neutral mesons. Here, B_d^0 mesons oscillate into their antiparticle $\bar{B}_d^0$

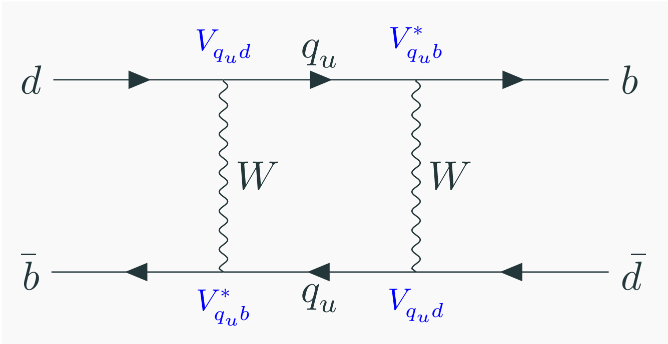

Figure 1: Transition of a B_d^0 meson into a $\bar{B}_d^0$ meson.

and vice versa. The leading order Feynman diagram for this oscillation is depicted in Figure 1.

In the context of this analysis, the CP asymmetry is calculated for the decay of B^+ and B^- mesons. In the absence of CP violation, the production rates of these two mesons are expected to be identical. Hence, a value for the CP violation can be determined by

$$A_{\mathrm{CP}} = \frac{N^- - N^+}{N^- + N^+}. \tag{1}$$

The number of observed $B^+ \to h^+h^+h^-$ is denoted as N^+, while the matching number of $B^- \to h^+h^-h^-$ is N^-.

3 The LHCb detector

Alongside ALICE, ATLAS and CMS, LHCb is one of the four main experiments located at the Large Hadron Collider (LHC) at Cern. At the LHC, opposing proton beams are brought to collision at the four main interaction points with a bunch collision rate of 40 MHz. The resulting particle cascades can then be measured and analysed using the different experiments. LHCb is designed to measure decays including b and c quarks which play an important role in the field of CPV.

The detector is a single-arm forward spectrometer with an acceptance of $2 \leq \eta \leq 5$ in the pseudorapidity range. A schematic view of the apparatus as used in the data taking period relevant for this analysis can be seen in Figure 2. The interaction point of the proton-proton collisions is located at the very left of the graphic, at the Vertex Locator (VELO). The VELO's primary purpose is to measure the primary and secondary vertices of decays. It therefore needs to provide a high spatial resolution. This information can then be used to reconstruct the lifetime and impact paramter (IP) of the decays. B-mesons, for example, typically decay after a few mm to cm and can therefore be measured in the VELO. The tracking stations TT (Tracker Turicensis) and T1-T3 are used to reconstruct tracks of (charged) particles deflected by the dipole magnet, which has an integrated field strength of 4 T m. The information from the tracking stations can be used to calculate momentum and charge of a particle. The Ring Imaging Cherenkov

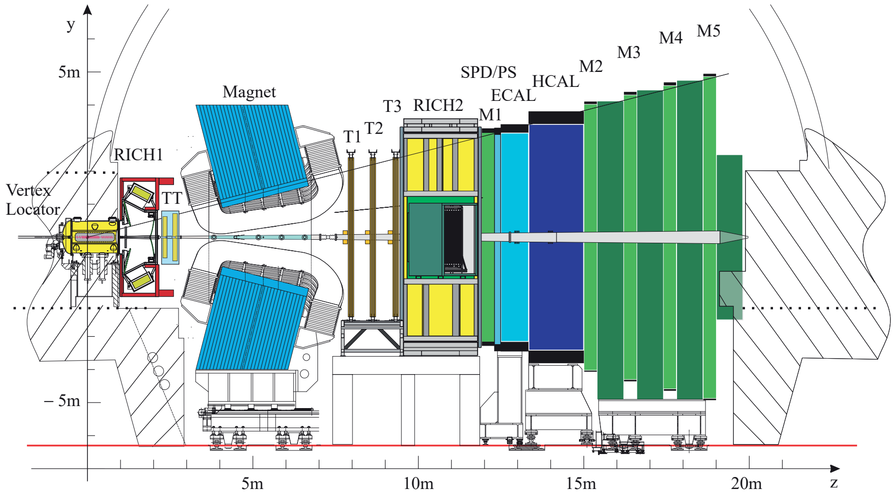

Figure 2: The setup of the Large Hadron Collider beauty experiment as used in Run 1 [1]. The collision point of the protons is on the left. The Vertex Locator (VELO), the tracking stations (TT, T1-T3), the Ring Imaging Cherenkov detectors (RICH1-2), as well as the calorimeters (SPD/PS, ECAL, HCAL) and the muon chambers (M1-M5) can be seen.

detectors RICH 1 and 2 lie upstream and downstream of the tracking stations, respectively. Here, the velocity of traversing particles is calculated from diameter measurements of light cones caused by the Cherenkov effect. Together with the momentum information, this contributes to the particle identification (PID) and can be used to determine kaons from pions. Further downstream, the calorimeter system consisting of the Scintillating Pad Detector (SPD), the Preshower detector (PS) and the electromagnetic- (ECAL) and hadronic (HCAL) calorimeters is located. The calorimeters are utilised to measure the particles energy deposition and also contribute to PID. At the very end of the detector, the muon chambers (M1-M5) measure muons which do not interact much with the aforementioned detector parts.
Events measured by the detector are triggered and preprocessed by a three-level trigger system. The reconstructed decays of interest are then saved to storage for further offline analysis.

4 Analysis strategy

The data used for this analysis was taken in 2011 at a center of mass energy of 7 TeV. It includes 3.4(5.1) million events of $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays ($h^{\pm}$: hadron; kaon $K^{\pm}$/ pion $\pi^{\pm}$) with dipole magnet polarity up (down), corresponding to an integrated luminosity of $434\,\mathrm{pb}^{-1}$ ($584\,\mathrm{pb}^{-1}$) [7]. Here, only the decay into three kaons ($h^{\pm} = K^{\pm}$) is considered. A dataset of simulated $B^{\pm} \to K^{\pm}K^{+}K^{-}$ decays is also available.
At first, the data is read from the provided `.root` files using the python extension *pyROOT* of the software package *ROOT* [2]. Histograms of the distributions of the

variables listed in the file are to be created for the simulated and measured data. Next, the energy of the kaons in the simulated data is calculated using the known kaon mass and its momentum. From this, the invariant mass of the B-mesons can be calculated and histogrammed. The same is done for the measured data after decays with only kaons in the final state are selected using PID information from the variables listed in the dataframe. A high efficiency should be maintained. The differences between the mass distributions of the measured- and simulated data are to be described. Following that, the global CP-asymmetry, its uncertainty and significance are calculated. In the next step, Dalitz plots are created for the simulated and experimental data. Using the Dalitz diagrams, charm resonances that are present in the measured data can be identified and removed. Finally, the local CP violation in different areas of the Dalitz plot is to plotted. The areas with the most significant evidence of CP violation should be identified and the significance of CPV in this areas should be calculated.

5 Analysis

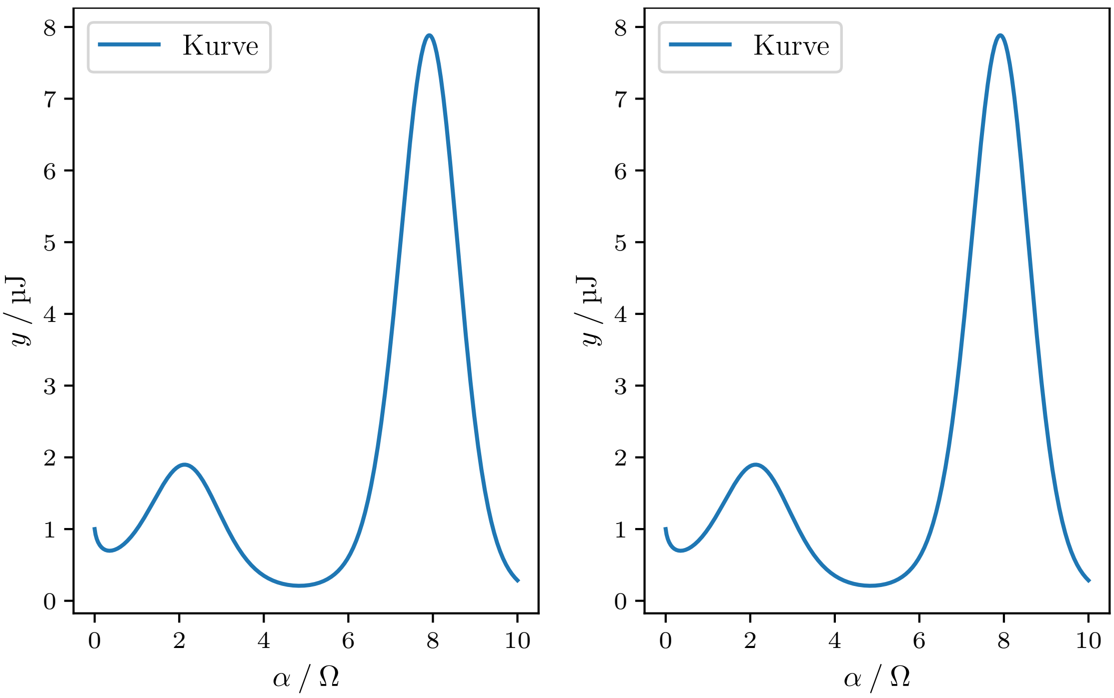

Figure 3: Plot.

Siehe Figure 3!

6 Diskussion

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