Technische Universität Dortmund

Physics Department

International Master Advanced Methods in Particle Physics

Measurement of matter-antimatter asymmetries with the LHCb experiment

Laboratory report

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Analysis of CP violation with LHCb data

Advanced Laboratory Course: Particle Physics

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Abstract

The goal of this data analysis is to investigate the matter-antimatter asymmetry induced by the CP violation of the weak interaction by studying the three-body decays of B mesons into $K^{\pm}$ and $\pi^{\pm}$. Furthermore, not only the global matter-antimatter asymmetry will be studied but the matter-antimatter asymmetry in local regions of phase space will be analysed, too.

1 Introduction

The CP-symmetry is violated for the weak interaction, where C is the charge conjugation symmetry which changes particles to antiparticles and vice versa and P is the parity symmetry which states that the inversion of the spatial coordinates should leave the physical processes unchanged. It was first discovered in 1964 in the decay of neutral kaons. CP-violation is one of the Sakharov conditions that must be satisfied in the first seconds after the Big Bang to explain the matter-antimatter asymmetry in the universe. The CP-violating decay $B^+ \to K^+K^+K^-$ by the weak interaction will be studied. One of the experiments that allows to study this decay is the LHCb experiment.

2 The LHCb experiment

The LHCb experiment is one of the four large experiments at the Large Hadron Collider (LHC) at Cern. Its main purpose is to study the decay of hadrons that have charm or bottom quarks, investigate the matter-antimatter asymmetry in the universe, and study rare decays. Moreover, it can be used for precision measurements of the standard model. A schematic view of the detector can be seen in Figure 1. The LHCb detector consists of the vertex locator VELO, the two ring-imaging Cherenkov detectors RICH1 and RICH2, a magnet, a tracking system, the electromagnetic and hadronic calorimeters, and the five muon chambers M1-M5. VELO is used to determine the vertex of the event of interest. RICH1 and RICH2 allow the computation of the velocity of the particles. The calorimeters are used to measure the deposited energy and flight direction of the particles. At last, muons are detected in the muon chambers.

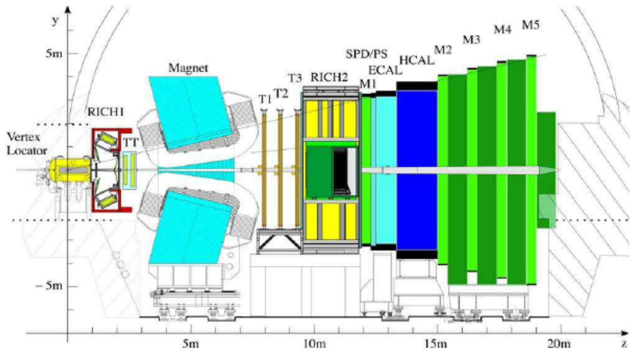


Figure 1: Schematic view of the LHCb detector. [1]

3 Datasets

Three datasets will be used. One that consists of simulated events of the decay $B^\pm \to K^\pm K^+ K^-$ and two other datasets of the decay $B^\pm \to h^\pm h^+ h^-$ where h is a kaon or pion. The events have been reconstructed from data that was taken by the LHCb experiment in 2011. Both datasets differ only in the polarity of the magnet that was used for the measurement.

4 Analysis Strategy

At first, the invariant mass of the B meson will be reconstructed from the energy and momenta of the daughter particles. The mass can be calculated from the energy-momentum relation by

$$E^2 = p^2 + m^2 \,. \tag{1}$$

The momentum of the daughter particles is measured by the detector but the energy must be calculated from the energy-momentum relation by making use of the masses of the daughter particles. This can be achieved by adding up the four momenta of the daughter particles and using the four-momentum conservation.

4.1 Selection

A selection must be applied to the two datasets to reduce the background. The selection cuts are given in Table 1. The considered variables are the momentum p, the momentum in the transverse plane p_T, the mass of the $B^\pm$ candidate $M(K^\pm K^+ K^-)$ calculated from the kaons, and a χ^2 fit of the impact parameter. The impact parameter is defined as the minimal distance between the true origin of the particle and the reconstructed tracks. The χ^2 fit of the impact parameter χ^2_IP is the fit divided by the estimated uncertainty.

Table 1: Selection cuts applied to the variables of the dataset. [2]

Variable	Selection cut
Transverse momentum of the track (p_T)	$> 0.1\,\mathrm{GeV}/c$
Summed p_T of the track	$> 4.5\,\mathrm{GeV}/c$
Momentum of the track (p)	$> 1.5\,\mathrm{GeV}/c$
Mass of the $B^\pm$ candidate ($M(K^\pm K^+ K^-)$) under the assumption that all tracks are $K^\pm$	$5.05 < M_{KKK} < 6.30\,\mathrm{GeV}/c^2$
χ^2_IP of the individual tracks	> 1
sum of the χ^2_IP of all tracks	> 500
$B^\pm$ candidate vertex fit χ^2	< 12

4.2 Global CP-asymmetry

The CP asymmetry can be calculated from

$$A_\mathrm{CP} = \frac{N^- - N^+}{N^- + N^+}\,, \tag{2}$$

where N^+ is the number of decays from B^+ mesons and N^- is the number of decays from B^- mesons into three hadrons. Its uncertainty is given by:

$$\sigma_A = \sqrt{\frac{1 - A^2}{N^+ + N^-}} \tag{3}$$

An important quantity to compute is then the *significance*, which is the ratio between the measurement and the error:

$$s = \frac{A}{\sigma_A} \tag{4}$$

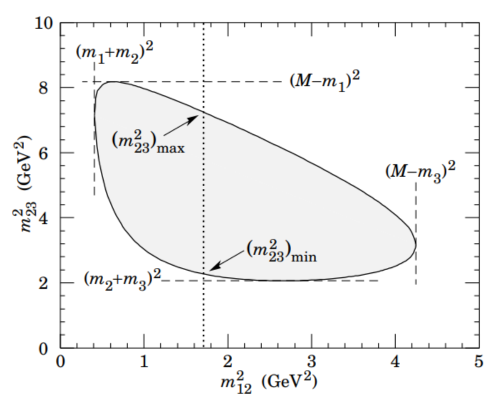
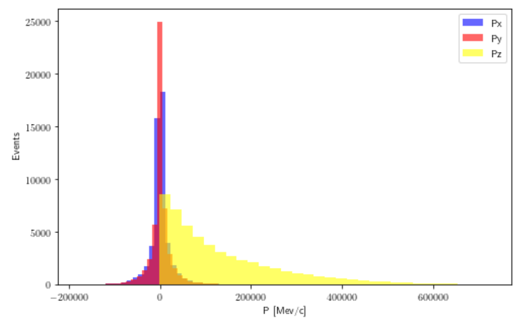


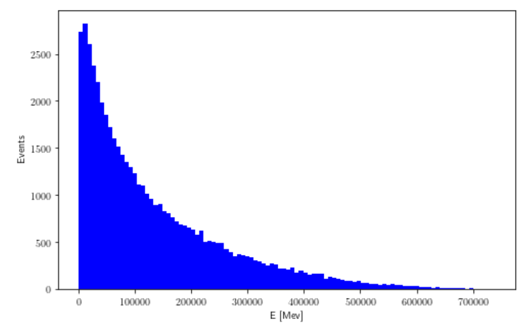
Figure 2: Example of a Dalitz plot. [2]

4.3 Local CP-asymmetry and Dalitz plots

One technique to analyze three-body decays is a Dalitz plot. An example of a Dalitz plot can be seen in Figure 2. By using energy and momentum conservation a three-body decay



(a)



(b)

Figure 3: a) Distribution of the three momentum components for one of the kaons. As xpected P_x and P_y are Gaussian distributed around 0, whereas P_z is boosted forward. b) Energy distribution of the kaon

can be described by the squared masses of the daughter particles defined by

$$m_{12}^2 = (p_1 + p_2)^2 \,, \tag{5}$$
$$m_{23}^2 = (p_2 + p_3)^2 \,, \tag{6}$$

where p_1, p_2, and p_3 are the four momenta of the three daughter particles. The advantage of these plots is that resonances can be seen as bands in the plot. For the B meson decay the masses have been chosen to be $M_{h_1^+ h_3^-}$, and $M_{h_2^+ h_3^-}$. The much smaller CP violation of c quarks will be ignored by removing the c quark resonances from the Dalitz plots. Additionaly, the local CP-asymmetry will be determined by Equation 2 for different regions of the Dalitz plots and classified accordingly to their significance, where 3σ is an "evidence" and 5σ is a "discovery".

5 Analysis

5.1 Simulation

First of all, the simulated data were visualized and analyzed in order to obtain the B^+ meson mass. Consider that the simulated events only contain kaon decays, $B^\pm \to K^\pm K^+ K^-$. In Figure 3, the distribution of the three momentum components of one of the kaons has been plotted, together with its energy distribution, obtained by applying Equation 1. The next step is to compute the invariant mass of the mother particle, the $B^\pm$ meson. In order to do so, the energy of $K^\pm$ is computed using m_K = 493.677 MeV/c^2 from PDG [3]. After that, the 4-momenta are summed up to get the energy and momentum of the $B^\pm$. With the total energy and momentum, using Equation 1, the invariant mass can be reconstructed and shown in Figure 4. The distribution is centered on the value of 5279.25 MeV/c^2, which is indicative of a B^+ initial state. The low width is due to no reconstruction effects applied to the simulation.

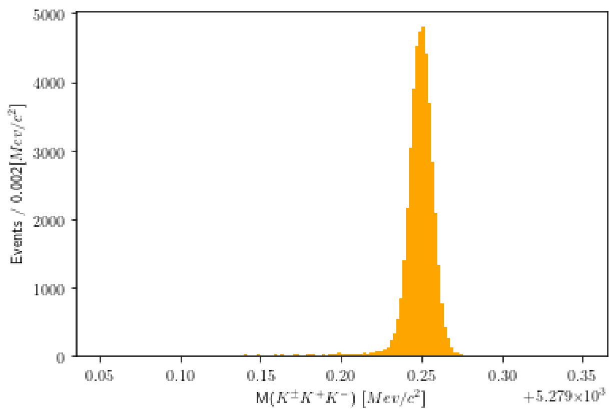
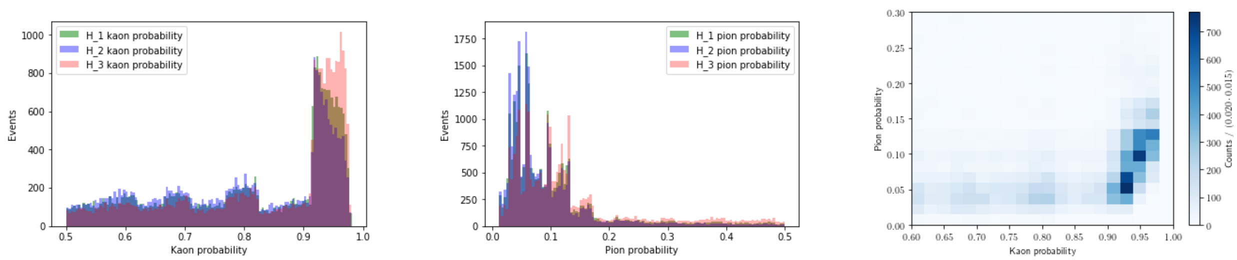


Figure 4: Distribution of the B^+ meson invariant mass



(a) (b) (c)

Figure 5: a) Distribution of the feature *Hi_ProbK* for the three final states after the cut. b) Distribution of the feature *Hi_ProbPi* for the three final states after the cut. c) 2D histogram showing the distribution of the two features in the remaining events

5.2 Real data

5.2.1 Preselection

In the case of real data, the dataset available to us consists of events likely originating from B^+ or B^- mesons decaying into three final state charged particles. However, in this dataset, the final state is not exclusively composed of kaons. The goal of the preselection process is to ensure the selection of events with a high probability of containing three kaons in the final state. Firstly, we excluded muons by selecting events where the feature *isMuon* = *False*. Subsequently, our aim was to maximize the probability of selecting a kaon while minimizing the probability of selecting a pion. In Figure 5, an initial cut is presented with the conditions $Kaon\ Probability > 0.5$ and $Pion\ Probability < 0.5$. This cut is not necessarily optimal for maximizing the signal-to-background ratio, CP asymmetry, or its significance, but it serves as a starting point. A two-dimensional histogram is used to display the distribution of the remaining events. Despite several attempts to find a better cut based on the distribution's shape, it was concluded that the most significant results were obtained around the initial cut.

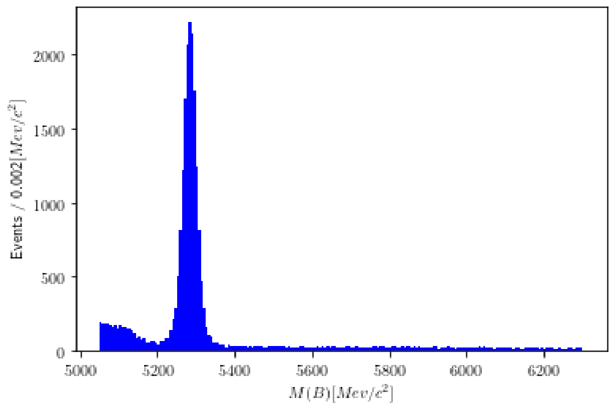
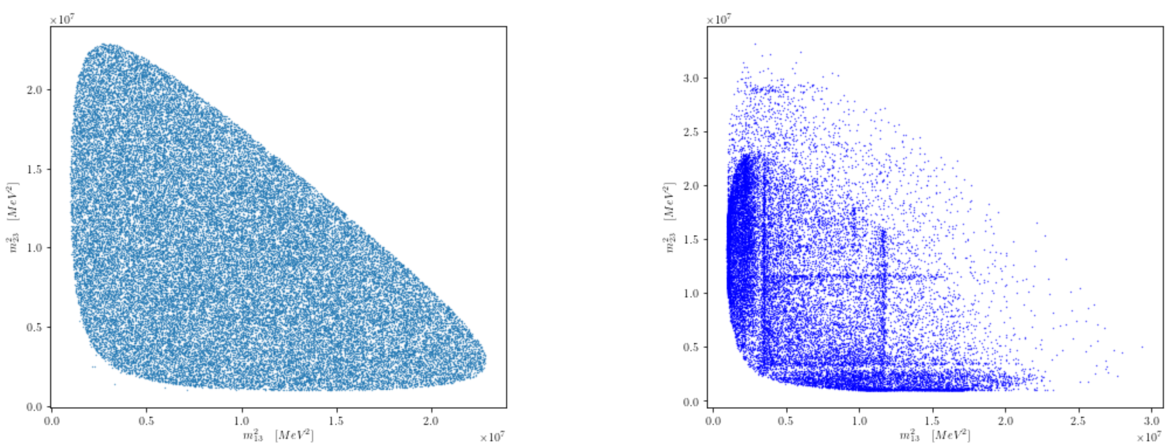


Figure 6: Distribution of the $B^{\pm}$ meson invariant mass in the initial state from the real data.

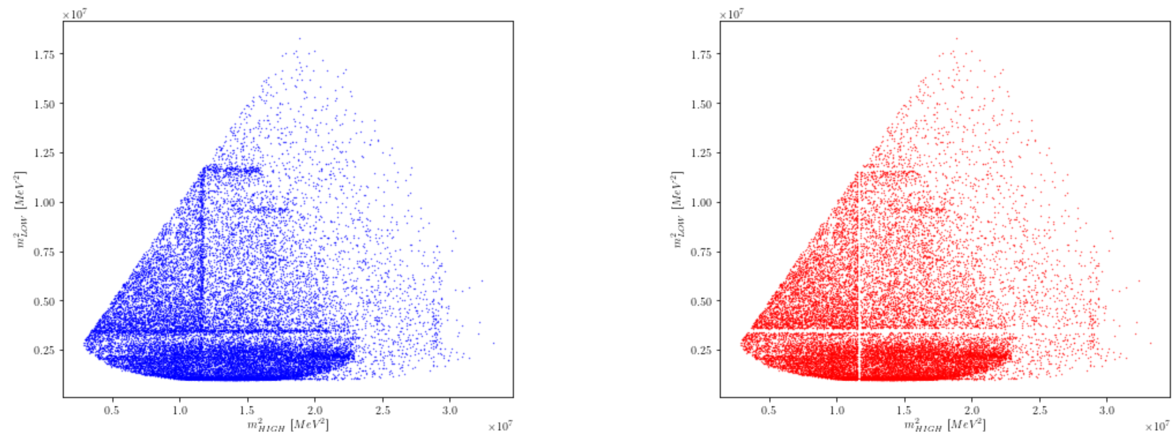
5.2.2 Global CP asymmetry

Following the procedure applied in 5.1, the $B^{\pm}$ meson invariant mass is computed from the real data. The obtained distribution is shown in Figure 6. The mass estimation from the distribution is $m_{B^{\pm}} = 5284.37$ MeV/c^2 which is consistent with what displayed in the PDG. The next step is to compute the global CP asymmetry. By using Equation 2, we obtain a global asymmetry of $A = 0.0370$. Its associated statistical uncertainty, computed by Equation 3, is $\sigma_A = 0.0065$. Finally we can obtain the significance of our CP asymmetry applying Equation 4. The result is $s = 5.73$. This is also the parameter used to optimise the cut during the preprocessing process.



(a) (b)

Figure 7: a) Dalitz plot of the simulation data, the surface is completely homogeneous as expected because there are no intermediate resonances in that dataset. b) Dalitz plot of the real data. Some high-density bands are visible, they represent intermediate resonances in the decay process.



(a) (b)

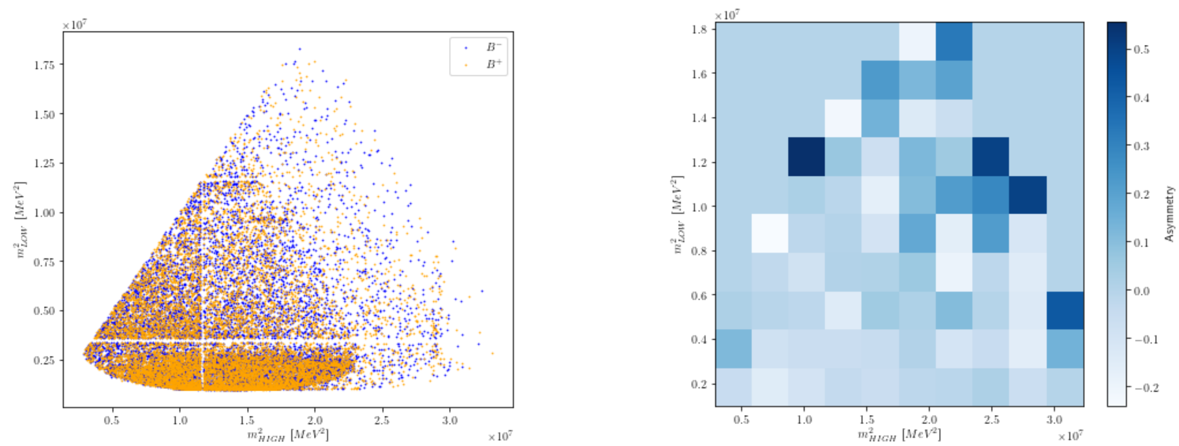
Figure 8: a) Dalitz plot with m_{LOW} and m_{HIGH} on the axes. By reducing the kinematic region while maintaining the same statistics, the event density increases, making resonances more visible. Notably, two high-density bands are distinctly recognizable. b) Since we are interested in the *charmless* B meson decay, the charm resonances have been removed.

5.2.3 Dalitz plots

As explained in subsection 4.3, Dalitz plots are a very useful technique for analyzing three-body decays. In this case, the B meson decay can proceed either directly to the three-body final state or via an intermediate resonance. The goal of Dalitz plots is to identify those resonances, which appear as high-density bands. We first create this plot for the simulation data, where there are no intermediate resonances, and thus, we expect a homogeneous surface. Subsequently, we apply the same method to the real data. The resulting plots are shown in Figure 7. Since the resonances are composed of the same particle types, we can improve their visualization in the plots by imposing an ordering that distinguishes them. We sort the two combined invariant masses used, in this case m_{13} and m_{23}, and select the lower and higher values, denoted as m^2_{LOW} and m^2_{HIGH} respectively. By using these new parameters on the axes, we effectively "fold" our Dalitz plot so that one axis always has a higher value than the other. This reduces the energy range but maintains the same statistics. This plot is depicted in Figure 8a. Two high-density bands are clearly visible. The first is around the value of 1860 MeV and corresponds to the D^0 and $\bar{D}^0$ mesons with a mass of 1864.84 ± 0.5 MeV. The other line is situated at a mass value of around 3420 MeV and could be attributed to the $\chi_{c0}(1P)$ particle, an excited $c\bar{c}$ meson with a mass of 3414.71 ± 0.30 MeV [3].

5.2.4 Local CP asymmetry

Previously, CP violation was investigated in the entire kinematic region (*globally*). Now, the interest is in checking if it could vary in different kinematic regions. First, since CP violation in *charmless* B meson decays to kaons is being studied, all processes involving a c quark need to be discarded. This has been done in Figure 8b, where the resonances identified in the previous analysis were removed. CP violation will show up as an asymmetry between



(a) (b)

Figure 9: a) Dalitz plot comparing B^+ and B^- charmless decays. b) Binned Dalitz plot picturing the asymmetry between the two decays.

matter and antimatter, hence as an asymmetry between the B^+ and B^- decays. In Figure 9, a Dalitz plot comparing the B^+ and B^- results is depicted, together with a binned Dalitz plot representing the asymmetry. In the latter, simply observing a large asymmetry in specific regions doesn't definitively indicate the presence of CP violation. If there are only a few events in those regions, the uncertainty surrounding such a significant asymmetry could be substantial, making the observed value still consistent with zero. For each bin, the uncertainty and the significance must be computed. These results are shown in Figure 10. This analysis allowed the selection of a region where the CP violation significance is higher. Therefore, local CP violation in the region of interest can be observed by selecting the corresponding kinematic region that has just been found. The chosen domain is contained in the range $0.6 \cdot 10^7 \text{MeV}^2 < m_{\text{HIGH}} < 1.8 \cdot 10^7 \text{MeV}^2$ and $0 \text{MeV}^2 < m_{\text{LOW}} < 3 \cdot 10^6 \text{MeV}^2$. In Figure 11, the distributions of B^+ and B^- invariant masses in the above-mentioned region are presented. Following the same steps as before, an asymmetry $A = 0.0733 \pm 0.0100$ and a local CP violation significance $s = 7.28$, which is above the 5σ needed for the discovery, are found.

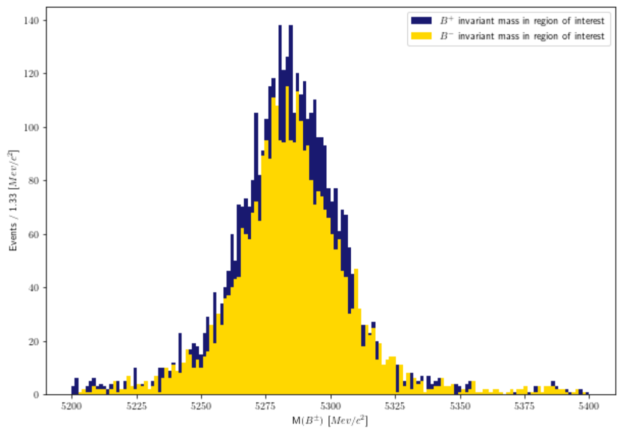
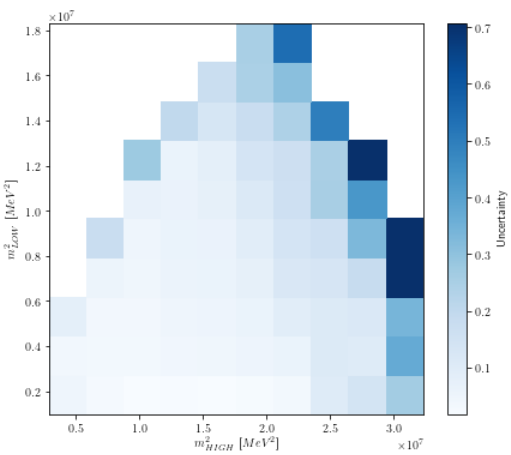
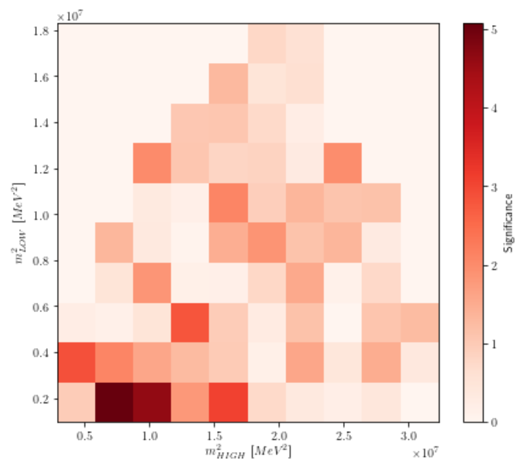


Figure 11: Invariant mass distributions of the reconstructed B^+ and B^- mesons, in the selected kinematic region for the most significant CP-asymmetry.



(a)



(b)

Figure 10: a) Binned Dalitz plot showing the asymmetry uncertainty. b) Binned Dalitz plot showing the CP significance.

6 Discussion and Conclusion

LHCb data has been used to measure CP violation in charmless B meson decays through the decay mode $B^+ \to K^+K^+K^-$. Event selection has been optimized to remove several background contributions. After the initial analysis, possible resonances have also been discarded. The measured value of the global CP asymmetry is:

$$A_{\text{global}} = 0.0370 \pm 0.0065$$

corresponding to a significance of:

$$S_{\text{global}} = 5.73$$

Regarding the local CP asymmetry, a high-significance domain of interest has been isolated between the values $0.6 \cdot 10^7\text{MeV}^2 < m_{\text{HIGH}} < 1.8 \cdot 10^7\text{MeV}^2$ and $0\text{MeV}^2 < m_{\text{LOW}} < 3 \cdot 10^6\text{MeV}^2$. In this region, the asymmetry was found to be:

$$A_{\text{local}} = 0.0733 \pm 0.0100$$

with a significance of:

$$S_{\text{local}} = 7.28$$

The analysis has thus been successful, providing significant evidence of CP violation. Both global and local asymmetry measurements achieved high statistical significance, surpassing the 5σ discovery threshold.

References

[1] Burkhard Schmidt. The lhcb detector-global status. 01 2009.

[2] TU Dortmund University, AG Albrecht. *Measurement of matter-antimatter asymmetries with the LHCb experiment*, 2022.

[3] R.L. Workman et al. (Particle Data Group). Review of particle physics. *Prog. Theor. Exp. Phys.*, 2022(8):083C01, 2022.