Measuring matter-antimatter asymmetries at LHC

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The report aims to use and understand data analysis techniques used in modern particle physics, understand the design of a particle physics detector, and observe matter-antimatter differences in the $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ decay. The experiment involves finding an optimal selection cut, calculating the invariant mass with a peak around the B mass, and fitting it. Two-body decays are analysed to observe resonances and remove unwanted charmed resonances. Using a Dalitz plot, local asymmetries can be observed. The resulting global raw asymmetry is measured to be $A_{raw} = 0.11 \pm 0.03$. In addition to this asymmetry, larger asymmetries are observed in localised regions.

I. INTRODUCTION

In 1964, [1] James Cronin and Val Fitch provided clear evidence of a two-pion decay from neutral kaons and thus that CP-symmetry could be broken. CP violation plays an important role in cosmology to explain the dominance of matter over antimatter in the present universe. [2] It is one of the three Sakharov conditions, which must be satisfied simultaneously to observe this asymmetry. The Standard Model of Particle Physics includes this violation, but its magnitude is too small to explain the matter-antimatter imbalance in the universe.
The Large Hadron Collider beauty (LHCb) is one of the four large experiments at the Large Hadron Collider (LHC). It is dedicated to looking for new physics beyond the Standard Model through matter-antimatter asymmetries and CP Violation and rare decays of hadrons containing bottom and charm quarks.
The aims of the experiment are to utilise and understand data analysis techniques used in modern particle physics, to understand the design of a particle physics detector, and how to observe matter-antimatter differences.

II. THEORY

CP violation is a fundamental phenomenon in particle physics that involves the difference in behaviour between matter and antimatter under charge conjugation (C) and parity reversal (P). [3] Charge conjugation is the operation that transforms all particles by their antiparticles in the same state so momenta and position are conserved. Parity refers to symmetry under spatial reflection.
In the Standard Model of particle physics, CP violation is linked through the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which describes the mixing of quark flavours in weak interactions. The CKM matrix predicts a small but measurable CP asymmetry in certain decay processes, such as those involving B mesons. However, it is still not enough the explain the deviance in matter and antimatter. CP asymmetry is defined as the difference in the probability of a particle and its antiparticle decaying into a certain final state. The difference in decay rates is related to CP violation and can be observed experimentally through the analysis of certain decay processes, such as B meson decays. CP asymmetry can be either positive or negative, depending on whether the particle or antiparticle has a higher probability of decaying into a certain final state. The CP asymmetry is defined as

$$A = \frac{N^{-} - N^{+}}{N^{-} + N^{+}}, \tag{1}$$

where N^{+} and N^{-} are the numbers of positive and negative events respectively.
The statistical uncertainty on the asymmetry can be derived from Equation 1 as we see in Equation 2.

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

The experiment uses data from the LHCb, which is located along the direction of the beamline of the LHC and covers a small solid angle of about 10 degrees. The detector is composed of several sub-detectors, each designed to measure different properties of the particles produced in the collisions. [4] The VELO is the innermost detector and consists of two silicon detectors on each side of the interaction point. Its main purpose is to measure the position of the primary collision vertex where the proton-proton collision occurs. It can also measure the position and momentum of charged particles. The tracking system consists of a Trigger Tracker (TT) in front of the spectrometer magnet and three tracking stations behind the magnet (T1, T2, T3). The tracking system provides precise measurements of the momentum and charge of charged particles, allowing for the identification of particles containing the beauty quark. The Ring Imaging Cherenkov (RICH) detectors are used to identify charged particles by measuring the velocity of the particle relative to the speed of light. Each RICH detector consists of a radiator material that produces Cherenkov radiation when

Variable	Selection Cut
Track Transverse Momentum (p_T)	> 0.1 GeV/c
Sum of p_T of Tracks	> 4.5 GeV/c
Track Momentum (p)	> 1.5 GeV/c
B± candidate mass	$5.05 < M < 6.30$ GeV/c^2
Track Impact Parameter (IP) χ^2	> 1
Sum of IP χ^2 of Tracks	> 500
$B^{\pm}$ candidate vertex fit χ^2	< 12
Probability of K	< 0.4
Probability of π	> 0.6

TABLE I. Pre-selection and selection cuts applied to the data sample

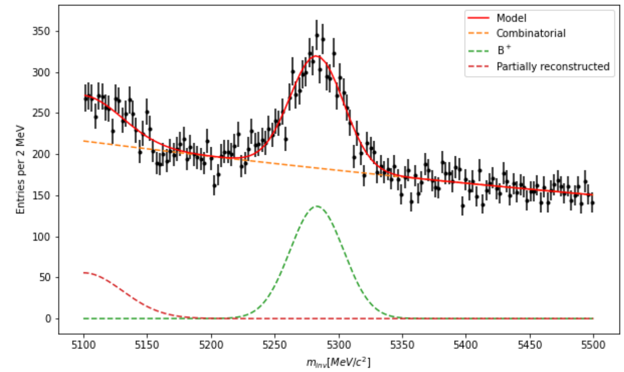

FIG. 1. Invariant mass fit of $B^+ \to \pi^+\pi^-\pi^+$ decay. The χ^2_{red} is 0.98.

charged particles pass through it, and a detector that measures the angle and intensity of the Cherenkov light. The LHCb has two types of calorimeters, the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). The ECAL measures the energy of electrons and photons, while the HCAL measures the energy of hadrons, such as protons and neutrons. Finally, the muon system is located furthest away and is in charge of detecting muons, which with the neutrinos, are the only particles that get through.
The B decay analysed in this experiment is the $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$. This decay process involves weak interaction, which changes the flavour of the quarks in the B meson. [5] It is a rare decay with a branching fraction of around 10^{-6}, which makes it a challenging process to study.

III. METHOD

To begin with the experiment, a series of pre-selection cuts were done to the raw data as we can observe in Table 1. 1D and 2D histograms were then plotted for the probability of being a kaon and pion for all three hadrons in the data. By observing the probability distributions, an optimal selection cut, which included the maximum number of events possible, was found for the probabilities, as we observed in Table 1. Once these cuts are applied, new 1D and 2D histograms are plotted for the regions for a higher probability of being a pion.

The invariant mass is found by using the relativistic formula with the sum of energies and the sum of p_x, p_y, and p_z. The invariant mass is then plotted in a histogram with a peak around the B mass at 5.279 GeV/c^2 [6].
Using the previous histogram and with the help of two Gaussians and an exponential, a fit is created in the region of the B meson (5.1 - 5.5 GeV/c^2). The fit parameters are estimated and optimised to obtain the fit with the χ^2_{red} closest to 1. The fit is then repeated for the negative (B^-) and positive (B^+) invariant mass. Using the positive and negative normalisation constants and Equation 1, the global CP asymmetry is calculated.
After finding the region for the B peak, two-body resonances are plotted combining H1, H2, and H3 hadrons with the condition of having a neutral charge. H2 and H3 have charge and so have no neutral resonances. Charmed resonances have to be removed as they involve another type of CP violation. The D^0 is removed manually from the data, while J/ψ is removed by setting the muon probability to zero. Other particles such as misidentified kaons are also removed.
A Dalitz plot is an important technique for analysing three-body decays. It is plotted by squaring the two-body masses in the B meson region and grouping them into low (m^2_{low}) and high (m^2_{high}) regions.
The combinatorial background is then removed from the Dalitz plot by creating a new plot with only the background and subtracting it from the initial plot. The process is then repeated for B^+ and B^-. The local CP asymmetry Dalitz plot is found using Equation 1, assigning N^+ and N^- to the positive and negative Dalitz plots respectively. The CP asymmetries are further studied in the regions where large raw asymmetries are found by selecting the regions and fitting their invariant masses.

IV. RESULTS AND DATA ANALYSIS

In both Figure 1 and Figure 2 we can observe a $B^{\pm}$ peak represented by a Gaussian with an exponential that goes underneath, which is combinatorial background. The semi-gaussian is a partially reconstructed 4-body. The raw global CP asymmetry is found to be $A_{raw} = 0.11 \pm 0.03$ with a significance of 3.01.
The statistical uncertainty of the asymmetry was found using Equation 2 and the significance was by dividing A_{raw} over the uncertainty. The systematic uncertainties in this experiment come from the combinatorial background and from the detector asymmetries (A_D) and production asymmetries (A_P). The production asymmetry comes from the raw asymmetry of the $B^{\pm} \to J/\psi K^{\pm}$ mode.

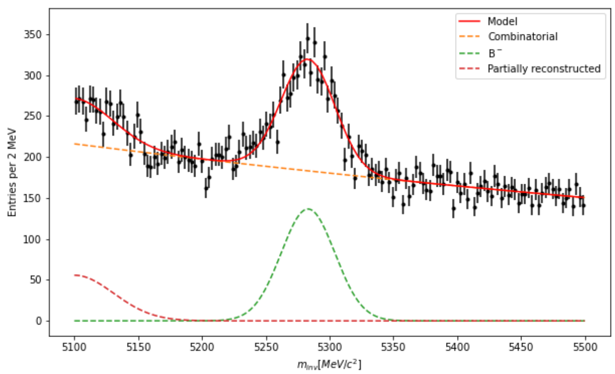

FIG. 2. Invariant mass fit of $B^- \to \pi^+\pi^-\pi^-$ decay. The χ^2_{red} is 1.02.

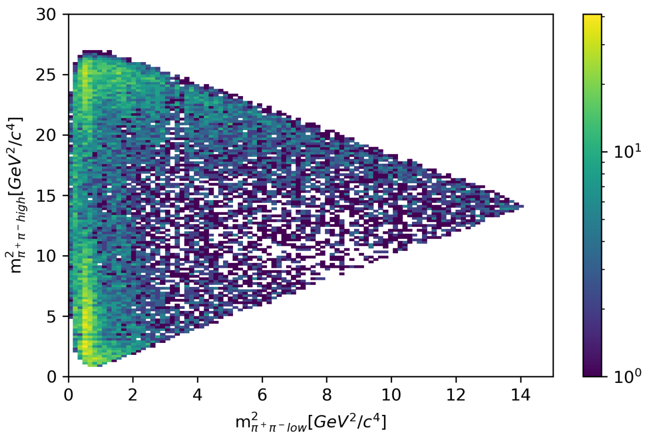

FIG. 3. Dalitz plot with fine binning showing the $\rho(770)$ meson resonance.

In Figure 3 we can observe two vertical lobes, which show the resonance state of the $B^{\pm}$ decay, a $\rho(770)$ meson. The two lobes show a spin of 1.
The local CP asymmetry is shown in Figure 4, which has variable bin widths. Large bins are needed to keep the uncertainties small and varying them in the areas where there is less data also reduces them. An asymmetry uncertainty Dalitz plot is created using Equation 2. A significance plot is made by diving the events in the bins in the local asymmetry by the uncertainties. The regions of high significance, where there are large raw local asymmetries, are defined as $4GeV^2/c^4 < m^2_{\pi^+\pi^- low} < 8.25GeV^2/c^4$ and $18.33GeV^2/c^4 < m^2_{\pi^+\pi^- high} < 20GeV^2/c^4$. The value for the raw asymmetry is $A_{raw} = 0.54 \pm 0.09$, with a significance of 6.

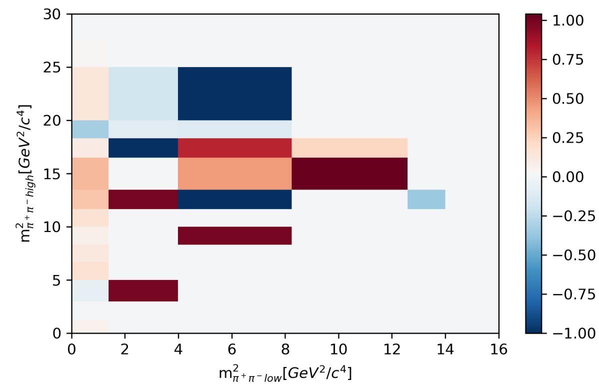

FIG. 4. Local asymmetries of the number of events in bins of the Dalitz plot

V. CONCLUSION

The global CP asymmetry calculated was $A_{raw} = 0.11 \pm 0.03$ with a significance of 3.01. The raw value is in the range of the experimental values from [7]. These suggest that the experiment was accurate and could be used to observe CP asymmetries in the $B^- \to \pi^+\pi^-\pi^-$ decay. The B^+ fit has a $\chi^2_{red} = 0.98$ and the B^- fit a $\chi^2_{red} = 1.02$, meaning the errors were well estimated and the invariant mass was well fit. The localised asymmetry for high-significance regions was $A_{raw} = 0.54 \pm 0.09$, with a significance of 6.
To improve the experiment, systematic uncertainties like the detector and production asymmetries should have been considered to find the proper CP asymmetry value. A significance of 3.01 suggests evidence of a global CP asymmetry.

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