The Observation of CP violation in the Charmless B Meson Decay
Third Year Lab Report

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(Dated: December 15, 2025)

In this experiment, LHCb data is used to quantify matter/antimatter asymmetries. A number of selection cuts are applied to the data in order to consider only the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay. 4 body decays, as well as the D meson and J/ψ resonances, are removed. A polynomial fitting procedure is performed on the sideband region of the results, and a Lorentzian curve is fitted to the signal region. By scaling the background fit, and removing excess data points, a positive global asymmetry of $A = +0.057 \pm 0.015$ is found. Using the high and low mass pairs of each event, a Dalitz plot is produced, with a positive local asymmetry of $+0.847 \pm 0.014$ in the $\rho(770)$ channel - an observation of CP violation with a 61σ significance.

1. INTRODUCTION

In the weak interaction, charge conjugation (C) and parity (P) symmetries are maximally violated according to the Standard Model (SM) [1, 2]. Despite this, CP violation is not required to exist since applying both a C and P operation restores symmetry. Some CP violation is accounted for in the SM, but the full extent that we see in the Universe is not [2]. Therefore, identifying sources of CP violation is a large research topic in particle physics. In previous experiments, the global CP violation of the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay has been observed to be $A = +0.090 \pm 0.004$, despite the asymmetry undergoing a sign change across the region of the Dalitz plot [3]. Most known sources of CP violation occur through mesonic decays; however, it is known that the Λ_0^b baryon decays with an asymmetry of $A = (2.45 \pm 0.46 \pm 0.10)\%$, a significance of 5.2σ [4, 5].
In this experiment, LHCb data is subjected to numerous selection cuts which narrow the sample to the pure $B^{+} \to \pi^{+}\pi^{+}\pi^{-}$ decay and its corresponding antimatter equivalent, $B^{-} \to \pi^{-}\pi^{-}\pi^{+}$. This data is fitted using both a scaled polynomial and a Lorentzian in order to remove background data points and count the number of signal events, where a signal event is an event that lies within the peak of the invariant mass distribution. The number of signal events from both the matter and antimatter decay channels is then used to find the global CP asymmetry in the 3 pion decay channel. The data is also used to create Dalitz plots, which are used to obtain values for the local CP violation across the plot.

2. THEORY

2.1. *Decay Width*

The lifetime of a particle affects the uncertainty on the energy measurement due to the Heisenberg uncertainty principle for energy [6]. Since the energy is used in the calculation of the invariant mass, the lifetime of the B meson will have an effect on the minimum measurable width of the invariant mass peak. In this case, the lifetime of the B meson is $(1.638 \pm 0.004) \times 10^{-12}$s [7], which is long enough that the invariant mass peak approximates a delta function. This is, however, not what is observed. The Central Limit Theorem (CLT) states that as the number of samples, n, grows large, the sample mean varies around the population mean with a standard deviation (σ_s) equal to

$$\sigma_s = \frac{\sigma_p}{\sqrt{n}}, \tag{1}$$

where σ_p is the standard deviation of the population. Therefore, as n increases, the sampling distribution tends towards a Gaussian, regardless of the original distribution [8].
In a particle detector, there are many different detection systems which each take multiple measurements for redundancy [9]. Since a large number of measurements are taken for each event, the CLT applies, broadening the peak of the decay beyond a delta function and approximating a Gaussian.

2.2. *Invariant Mass*

In particle physics interactions total 4-momenta, p^{μ}, is conserved. Since particle collisions in the LHC occur at relativistic speeds, invariant quantities of the collisions must be considered. The invariant quantity derived from the 4-momentum is the invariant mass, W, where

$$W^2 = p^{\mu}p_{\mu}. \tag{2}$$

Therefore, if the energies and momentum of the final state particles are known, the invariant mass can be reconstructed using

$$W = \sqrt{\left(\sum_{i=1}^{N} E_i\right)^2 - \sum_{j=1}^{N} (\mathbf{p}_i^2)}, \tag{3}$$

where E_i is the energy of each particle, $\mathbf{p}_i$ is the 3-momenta of each particle, and N is the number of final state particles. Since the initial state only contains 1 particle (the B^{+} or B^{-} meson), the invariant mass of the collision is equal to the mass of the charged B meson [10].

3. SELECTION CUTS

3.1. *Initial Selections*

The particle detector returns a discrete muon probability of either 1 or 0 (True or False). This is used to exclude muon events from the data, where all events with at least 1 particle identified as a muon are removed. Since the lepton number must be conserved within the weak interaction, the decay must result in 2 muons. Therefore, if one muon is misidentified, the erroneous decay will still be removed. The removal of decays with 2 misidentified muons is discussed in Section 3.3.
The kaon and pion probabilities are continually distributed. Therefore, for a desired 3 pion event probability of 70%, the probability for each particle being a pion must be greater than 70%, and it must also have less than a 20% probability of being a kaon. Events with at least one particle falling outside of these ranges are excluded.

The charge of each particle is considered in order to refine the data into B^+ and B^- events. This is done by checking for all combinations of $+/+/-$ charge for B^+ and the antimatter equivalent, $-/-/+$, for B^-. 1.74% of initial events are identified as B^+ decays and 1.73% are identified as B^- decays.

3.2. 4 body decays

This experiment only considers the 3 body pion decay. However, if a 4th, undetected, neutral body is also produced, it will carry away some of the 4-momenta of the decay. The largest value for invariant mass that corresponds to a 4 body decay (D) is that where the 4th body carries away zero energy,

$$D = W - M_{\pi^0}, \tag{4}$$

where M_{π^0} is the mass of a neutral pion. π^0 is chosen as the neutral body since it has a smaller mass than the neutral kaon (the other possible neutral body). This results in a mass deficit of $D \approx 5139$ MeV. In order to exclude the 4 body decays, all the data points with an invariant mass of less than D are removed.

3.3. 2 body resonances

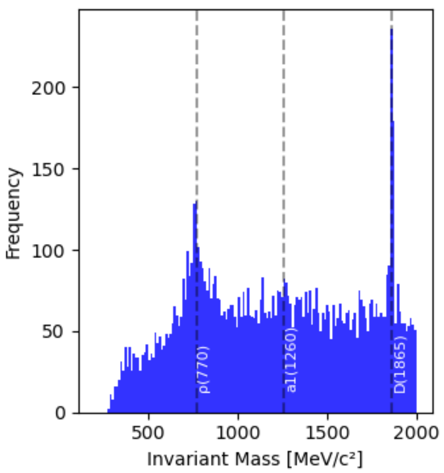

FIG. 1. The two body resonances of the B^+ decay (shown in blue). The identified particle invariant mass is shown as a grey dashed line.

The B meson decay can proceed through a short-lived, intermediary particle (R^0) which quickly decays to the final state products via $B^\pm \to R^0\pi^\pm \to \pi^\pm\pi^+\pi^-$. In order to observe the 2 body resonance state of the decay, the invariant mass of only 2 particles in each event are plotted, as shown in Figure 1. Within this plot, many peaks are observed, including the charmed D^0 meson. This decay path is the most common resonance, but is less CP asymmetric than other resonances. Therefore, all events with a 2 body invariant mass of 1865 ± 20MeV (the mass of a D^0 meson) are excluded [11].
Another possible decay for the B meson is $B^\pm \to J/\Psi \to (\mu^+\mu^-)\pi^\pm$, and, if both muons are misidentified as pions within the detector, a 2 body resonance peak can occur at this point [7]. Therefore, all events with an invariant mass of 3090 ± 20MeV (the J/ψ invariant mass) are also excluded.

4. DATA FITTING

To quantify the background within the data sample, a sideband region far from the signal region is identified. Within this region, a polynomial is fitted to minimise the χ^2_R. This resultant polynomial is then scaled across the full range of data, and subtracted, as shown in Figure 2.

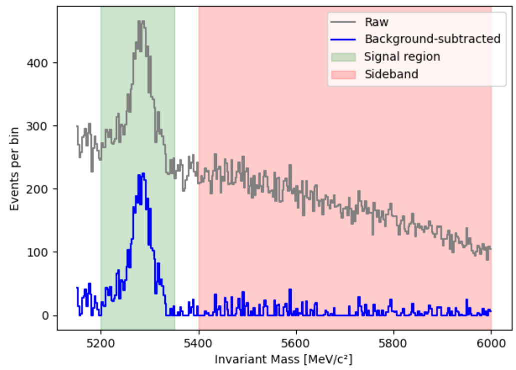

FIG. 2. A graph showing the raw data, the signal and sideband regions, and the resultant data after removing the scaled background polynomial from the data.

Using the background subtracted data, both a Gaussian and a Lorentzian fit are tested to find the minimal error. The Gaussian fit was found to have a χ^2_R of 8.34 for B^+, and 8.03 for B^-, while the Lorentzian was found to have a χ^2_R of 6.67 for B^+ and 5.71 for B^-. Therefore, the Lorentzian fit, as shown in Figure 3, is used when calculating the asymmetry.
When calculating the number of events in the peak from each data sample, the following values are obtained: $N^+ = 4697 \pm 233 \pm 13$, and $N^- = 5293 \pm 232 \pm 13$, where the first error is from the Lorentzian fit, and the second is from the background removal procedure.

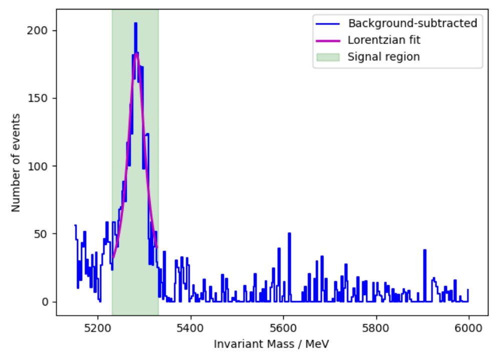

FIG. 3. The background subtracted data with the Lorentzian curve fit overlayed in the signal region.

5. SYSTEMATIC UNCERTAINTIES

There are small sources of systematic uncertainty due to the design of the detector. The production asymmetry arises since the LHCb is a proton-proton collider, an initial state that is not matter-antimatter symmetric. The LHCb estimates that the production asymmetry error is ± 0.011 [3]. There are also physical effects that can impact the results. The different orientations of the dipole magnet can lead to systematic errors, where the detector has a higher efficiency in a certain orientation. This error is avoided by using data from two samples, one in the magnet 'up' orientation, and one in the magnet 'down' orientation.

6. GLOBAL CP ASYMMETRY

The results obtained from performing the background removal and Lorentzian peak fit, discussed in Section 4, are used to find the global CP asymmetry (A) using

$$A = \frac{N^- - N^+}{N^- + N^+}, \tag{5}$$

where N^+ is the number of B^+ decays and N^- is the number of B^- decays within the peak. The global asymmetry is found to be $A = +0.05966$, where the positive result indicates that the 3 pion decay channel has an anti-matter preference.

6.1. *Statistical Uncertainty*

The statistical uncertainty (σ_A) on the asymmetry value is given by

$$\sigma_A = \sqrt{\frac{1 - A^2}{N^- + N^+}}, \tag{6}$$

and is found to be $\sigma_A = 0.01$.
Propagating the fit errors gives a total error of 3×10^-6 which is insignificant compared to the other errors, which compound to give $\sigma = \pm 0.015$.
The significance (Z) of the result can be calculated using

$$Z = \frac{A}{\sigma_A}. \tag{7}$$

Therefore, the global CP violation of the charged B meson decay is found to be $A = +0.057 \pm 0.015$, a 3.8σ significance.

7. LOCAL CP ASYMMETRY

7.1. *Dalitz Plots*

The Dalitz plots are generated using the upper and lower mass pairs from each event. That is, the 2 body invariant mass is calculated for all pairs of particles in each event, and the highest mass is plotted against the lowest mass for all events. In order to reduce erroneous results, a background selection is performed. This is done by sampling the background in a region far from the signal region, and scaling it to remove background events from the full sample.

7.2. *Local CP asymmetry*

Using the Dalitz plots discussed in Section 7.1, the local asymmetry is found using Equation 5 on each bin. The statistical significance of each bin is calculated using Equation 6, and then the significance of the result for each bin is calculated using Equation 7, as shown in Figure 4. There is a region of high statistical significance in the lower left, with a mean positive asymmetry of $A = +0.847 \pm 0.014$, a 61σ significance. This region corresponds to the $\rho(770)$ decay channel.
The region of apparent strong negative asymmetry towards the top of the plot is a false positive, and arises due to the low statistical error from a sufficiently small dataset in that region.

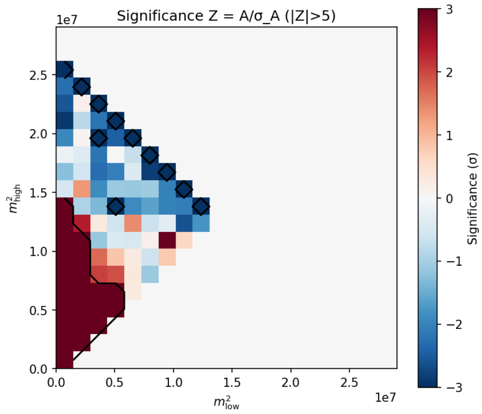

FIG. 4. The bin-by-bin significance of asymmetry with a black outline highlighting regions with a significance, $Z \geq 3$. Red bins have a positive asymmetry and blue bins have a negative asymmetry. The darker the bin, the larger the significance.

8. CONCLUSION

To conclude, the original dataset has been subjected to numerous selection cuts, resulting in a near pure 3 pion sample for the charged B meson decay. In addition, any remaining J/ψ resonances from misidentified muons have been removed, along with the charmed D meson resonances, in order to improve the significance of the results. A scaled background fit has been performed in order to further purify the data, and a Lorentzian curve fitted around the peak. Using these selections and fitting procedures, evidence for a global CP asymmetry of 0.057 ± 0.015 has been found in the 3 pion decay channel of the B meson. Additionally, a local CP asymmetry of 0.847 ± 0.014 has been observed in the $\rho(770)$ resonance channel of the B meson decay, a 61σ significance.

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