Matter-Antimatter Asymmetry at the Large Hadron Collider

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The CP asymmetry of the charmless three-body decay, $B^{\pm} \to K^{\pm} + \pi^{+} + \pi^{-}$ is investigated through analysis of proton-proton collision data at a CoM energy $\sqrt{s} = 7$ TeV collected by the LHCb in 2011, corresponding to an integrated luminosity of 1.0 fb^{-1}. The global asymmetry was measured to be $-0.021 \pm 0.010(fit) \pm 0.004(syst.) \pm 0.010(J/\psi\mathrm{K}^{\pm})$. Significant local CP asymmetries were discovered, including local CP asymmetry in excess of 3σ in decays paths with the $\rho^0(770)$ resonance.

I. INTRODUCTION

The current understanding of physics cannot explain the abundance of matter that is observed in the universe. Almost all the matter and anti-matter created in the Big Bang annihilated shortly after to produce the cosmic microwave background. The universe seen around us is comprised almost entirely of matter, with very strong constraints on the proportion of antimatter in the universe [1]. CP symmetry violation is one of the three Sakharov conditions required for matter-antimatter asymmetry in the early universe [2]. The Standard Model accounts for some CP asymmetry through the CKM matrix[3], but not enough to explain the matter dominated universe. This indicates that there are other sources of CP asymmetry beyond the Standard Model. Analysis of CP asymmetries is an important method of searching for new physics.

In this experiment, the published data from the 2011 LHCb (Large Hadron Collider beauty) experiment is analysed to investigate the global and local CP asymmetry in the charmless $B^{\pm} \to K^{\pm} + \pi^{+} + \pi^{-}$ decay.

II. THEORY

A. CP Asymmetry

The B meson is a relatively long-lived particle that decays via the weak interaction. The most common decay path is through an intermediate state called a resonance, R^0. The resonance decays quickly through the strong interaction into two of the final-state particles [4]. The dominant resonances, such as D^0 occur through the b quark decaying into a c quark. As this experiment aims to investigate charmless decays, collisions that decay through charm resonances should be excluded.

The CP asymmetry A is defined as

$$A = \frac{(N_{-} - N_{+})}{(N_{-} + N_{+})} \tag{1}$$

where $N_{\pm}$ is the number of $B^{\pm}$ decays. The statistical uncertainty in the asymmetry σ_A is given by

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

where N is the total number of decays. There is also a systematic offset on the measured asymmetry due to the production and detection asymmetries A_{Δ}. This is caused by the collision producing the B-meson, and the detector being made of matter. The true CP asymmetry A_{CP} is given by

$$A_{CP} = A_{\mathrm{raw}} - A_{\Delta}, \tag{3}$$

where A_{raw} is the raw observed CP Asymmetry. The offset can be accounted for by analysing A_{Δ} through a control decay mode.

B. Dataset and Selection

The data for this experiment comes from the 2011 published data for the LHCb. Protons were accelerated to a centre of mass energy of 7 TeV for approximately 10^{14} collisions. The LHCb detector is a single-arm forward spectrometer at the Large Hadron Collider designed for precision measurements of CP violation and rare decays of beauty and charm hadrons [5]. Events are preselected by the LHCb trigger; this is comprised of a hardware stage that selects events with a large transverse energy and a software stage which reconstructs the events and applies several cuts to identify events consistent with the decay of a B meson [6]. After trigger selection, 8.5 million events remain, corresponding to a luminosity of 1.0 fb^{-1}. Final states of $K^{\pm}\pi^{+}\pi^{-}$ are then selected by using the particle identification information from the ring-imaging Cherenkov detectors.

The detector has a greater resolution when measuring the momentum of the final state particles compared to when measuring their energy. Therefore, when calculating the two- and three-body invariant masses the energy E is given by

$$E = \sqrt{m_i^2 + \mathbf{p}^2}, \tag{4}$$

where $\mathbf{p}$ is the momentum and m_i^2 is the mass of the final state particles.

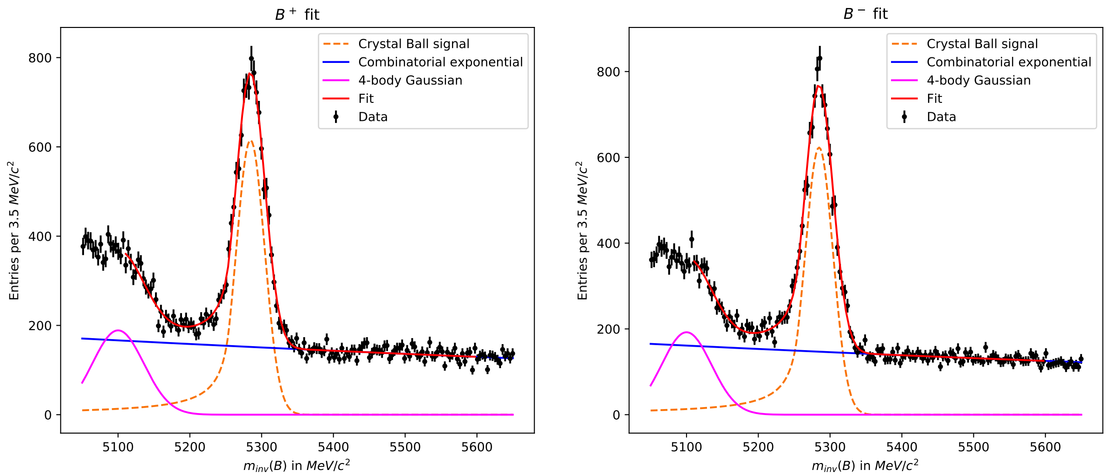

FIG. 1: Three-body invariant mass fits for B$^+$ and B$^-$. The fits have a reduced χ^2 of 1.19 and 0.91 respectively, with a spread σ in the signal of 19.57 ± 0.22 MeV/c^2. There are 13714 ± 202 and 13654 ± 199 signal events for B$^+$ and B$^-$ respectively.

III. METHOD

A. Global CP Asymmetry

The resonances present in the decay are identified by calculating the three-body invariant mass and selecting events with a three-body invariant mass of $5180 < m_B < 5380$ MeV/c^2. The two-body resonances $m_{K^\pm\pi^\mp}$ and $m_{\pi^+\pi^-}$ are then plotted in a histogram. Two decays proceeding via a charm quark are identified, from a D_0 signal at 1864 MeV/c^2 and a χ_{c0} signal at 3414 MeV/c^2. They are removed by making mass cuts of $\pm$60 MeV/c^2 around the D_0 mass in $m_{K^\pm\pi^\mp}$ and $\pm$30 MeV/c^2 around the χ_{c0} mass in $m_{\pi^\pm\pi^\mp}$. The J/ψ resonance at 3096 MeV/c^2 is also present due to misidentification of muons as pions, as they have similar rest masses, and is removed with a mass cut of $\pm$20 MeV/c^2 in $m_{K^\pm\pi^\mp}$.

The three-body rest masses are then plotted in a histogram and fitted using least squares regression as shown in Fig. 1. The error on each bin is given by the square root of the events in that bin as it is a Poisson distribution. A Crystal Ball function is used to model the signal as the final state particles lose energy through Bremsstrahlung radiation. The background that is caused by partially reconstructed 4-body decays is modelled by a Gaussian. An exponential is used to model the combinatorial background. This gives the total number of signal events as 27368 ± 284 and an $A_{\rm raw}$ of -0.0022 ± 0.0010. The control decay mode chosen to find A_Δ is $B \to J/\psi + K^\pm \to K^\pm + \mu^+ + \mu^-$.

The selection cuts are changed to select the relevant decays and a mass cut is made on $m_{\mu\mu}$ to select events within 3096 ± 60 MeV/c^2. The raw CP asymmetry of this decay mode is found by fitting the three-body invariant mass as described above. This gave an $A_{\rm raw}(J/\psi)$ of -0.022 ± 0.007 and a total of 92290 ± 340 events. The published world average of $A_{CP}(J/\psi)$ is $1 \pm 7 \times 10^{-4}$ [4], and using this with Eq. 3 gives A_Δ as -0.023 ± 0.010.

The true global CP asymmetry of the $B^\pm \to K^\pm + \pi^+ + \pi^-$ decay is then calculated using Eq. 3 to give $A_{CP} = -0.021 \pm 0.010 \pm 0.004 \pm 0.010$.
The first uncertainty is obtained by propagating the uncertainties in $N^\pm$ as determined by the fit and adding in quadrature to the statistical uncertainty. The second uncertainty is the systematic uncertainty caused by the trigger event selection [6] and the third uncertainty is due to the J/ψK$^\pm$ control mode. This value is consistent with other published values [4, 6].

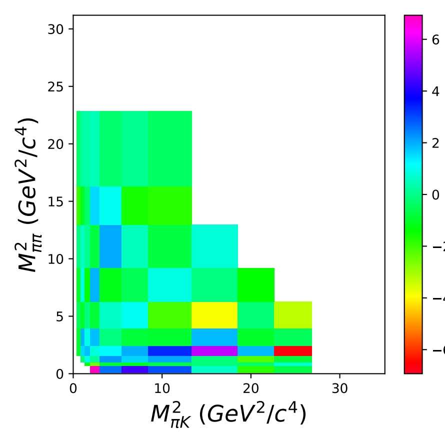

FIG. 2: A variable bin Dalitz plot showing the CP asymmetry significance of events within 4σ of the signal peak.

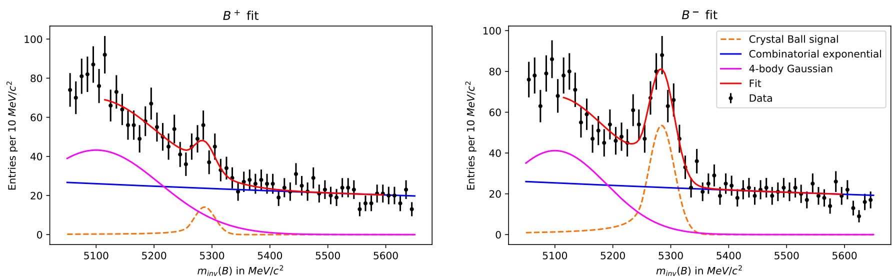

FIG. 3: Three-body invariant mass fits for B^+ and B^- of the events near the ρ^0 resonance. The fits have a reduced χ^2 of 1.02 and 0.73 respectively. There are 114.6 ± 63.9 and 532.5 ± 74.7 signal events for B^+ and B^- respectively.

B. Local CP Asymmetry

For three-body decays, Dalitz plots are used to analyse the 2D phase space of the two-body invariant masses. This is done by plotting the data as a 2D histogram. Variable bin sizes are used to ensure each bin has approximately the same number of events; this minimizes the statistical uncertainty which is the dominant source of uncertainty. Events around the $B^{\pm}$ peak are selected by making a cut of $\pm 4\sigma$, as determined by the global CP asymmetry fit.

A region consisting mainly of background events, 5400-5800 MeV/c^2, is extrapolated and subtracted from the signal by considering the relative strength of the background in the signal region. The CP asymmetry and the statistical uncertainty for each bin is then calculated. The significance of each bin S_{CP} is calculated as A_{CP}/σ_{CP} as shown in Fig. 2. There are very significant asymmetries observed, notably around the $\rho^0(770)$ resonance.

To test for whether the local CP asymmetries observed are statistical fluctuations, the significances are plotted on a histogram and a Gaussian is fitted using least squares regression. The mean is consistent with A_{raw}, and the normalisation was consistent with the number of bins.

In the case of no underlying CP asymmetry, the Gaussian is expected to have a spread of 1. The spread, as determined by the fit, is 1.404 ± 0.061 which is 6.2 sigma above what would be expected if the CP asymmetry was caused by statistical fluctuations.

The events with high S_{CP} around ρ^0 resonance are selected by applying cuts to the two body invariant masses at $400 < m_{\pi\pi} < 950 <$ MeV/c^2 and $m_{K\pi} <$ 3750 MeV/c^2. These events are then fitted as described in Section III A as shown in Fig. 3.

The resulting CP asymmetry is $A_{CP} = 0.669 \pm 0.184$, a 3.6 sigma result. The main source of uncertainty comes from the large fractional uncertainties in $N^{\pm}$ as determined by the fit. This is caused by the low number of signal events in this region. The other sources of uncertainty were negligible.

IV. CONCLUSION

The CP asymmetry of the charmless decay of $K^{\pm}\pi^+\pi^-$ are analysed by selecting relevant events in the published 2011 LHCb dataset. Two-body resonances are identified to exclude charmed decays and muons misidentified as pions. The control group $\mathrm{J}/\psi\mathrm{K}^{\pm}$ is used to find the production and detection asymmetry.

The global CP asymmetry is investigated by fitting a three-body invariant mass graph to find $B^{\pm}$ signal events. The obtained value for the global CP asymmetry is $A_{CP} = -0.021 \pm 0.010 \pm 0.004(\mathrm{syst}) \pm 0.010(J/\psi K^{\pm})$. This value is consistent with the literature.

The local CP asymmetry is investigated by plotting the significance of the CP asymmetry in a background subtracted Dalitz plot with variable bin sizes. Significant local CP asymmetries are observed, particularly near the ρ^0 resonance. The observed asymmetries have a spread of 6.2 sigma above what would be expected from statistical fluctuations.

Events around the ρ^0 resonance are selected and fitted to calculate the local CP asymmetry to obtain a value of $A_{CP} = 0.669 \pm 0.184$, a 3.6 sigma result.

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