Measuring matter-antimatter asymmetries in $B^{\pm}$ meson decays

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This experiment was performed in collaboration with John Cobbledick

Abstract

Using LHCb data, $B^{\pm}$ mesons were studied computationally to find differences between $B^{+} \rightarrow K^{+}K^{+}K^{-}$ and $B^{-} \rightarrow K^{-}K^{+}K^{-}$. The global CP asymmetry found was A_{CP} = -0.043 $\pm$ 0.009 (stat) $\pm$ 0.004 (sys) $\pm$ 0.006 (J/ψ $K^{\pm}$), in which the final uncertainty was from CP asymmetry in the $B^{\pm} \rightarrow J/\psi\ K^{\pm}$ correction channel. With significance of 3.8σ, this is evidence for CP violation in these decays. Larger asymmetries were found in local phase-space regions and global asymmetries for other decays were also measured.

1 Introduction

During the LHC run in 2011, protons were collided at the LHCb detector [1] to produce $B^{\pm}$ mesons. Four $B^{\pm}$ meson decay channels were studied to find asymmetries. These four channels were $B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$, $B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}$. $\pi^{\pm}$ (Pions) and $K^{\pm}$ (Kaons) are mesons, but survive long enough to be detected.

Asymmetry is interesting since it might explain why there was more matter than antimatter at the Big Bang and it is not completely explained in the Standard Model. Asymmetries have been measured in weak decays but this experiment attempted to measure larger asymmetries accurately. Violation means enough asymmetry to be consistent with the fact that there is more matter than antimatter. Significance is defined as measurement/error. A value of 3σ is classed as evidence and 5σ as observation.

The data have also been analysed by the LHCb collaboration [2, 3]. A computational package called ROOT [4] on Linux [5] was used to analyse the data.

2 Theory

Asymmetry, A, is the difference in B^{+} and B^{-} events as a fraction of total events,

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

where $N^{\pm}$ are the number of $B^{\pm}$ events. Asymmetry in Equation 1 is raw since it is uncorrected for experimental bias or production asymmetry due to the colliding protons being positive matter rather than antimatter. CP asymmetry, A_{CP}, is obtained from

$$A_{CP} = A - A_{J/\psi} + 0.003, \tag{2}$$

where A is raw asymmetry, $A_{J/\psi}$ is the measured asymmetry in the $B^{\pm} \rightarrow J/\psi\, K^{\pm}$ correction channel and 0.003 is the accepted $J/\psi\, K^{\pm}$ asymmetry value [6]. Using Equation 2 mitigates analytical bias and production asymmetry. $J/\psi\, K^{\pm}$ is a useful correction as it has a well measured, small asymmetry consistent with 0. The accepted $J/\psi\, K^{\pm}$ asymmetry uncertainty is quoted as final error.

Another error is statistical, σ_{stat}, given by

$$\sigma_{stat} = \sqrt{\frac{1 - A_{CP}^{2}}{N^{-} + N^{+}}}, \tag{3}$$

obtained from error propagation of Equation 1 and taking uncertainties on $N^{\pm}$ as $\sqrt{N^{\pm}}$.

There may also be detector asymmetry, where some chambers have higher efficiencies in detecting one charge compared to the other. Whether a particular charge reaches a chamber depends on magnet polarity. A way to quantify detector asymmetry is taking the largest difference between the whole sample and the sample with the magnet in either up or down polarity as systematic error.

The detector gives probabilities that particles are Kaons or Pions, therefore during analysis one decides which particles to keep. The best probability cut is obtained by maximising the signal to the square root of the background ratio. This can be done by looping over cuts, whilst considering fit convergence and χ^{2}. Figure 1 shows $K^{\pm}K^{+}K^{-}$ optimisation.

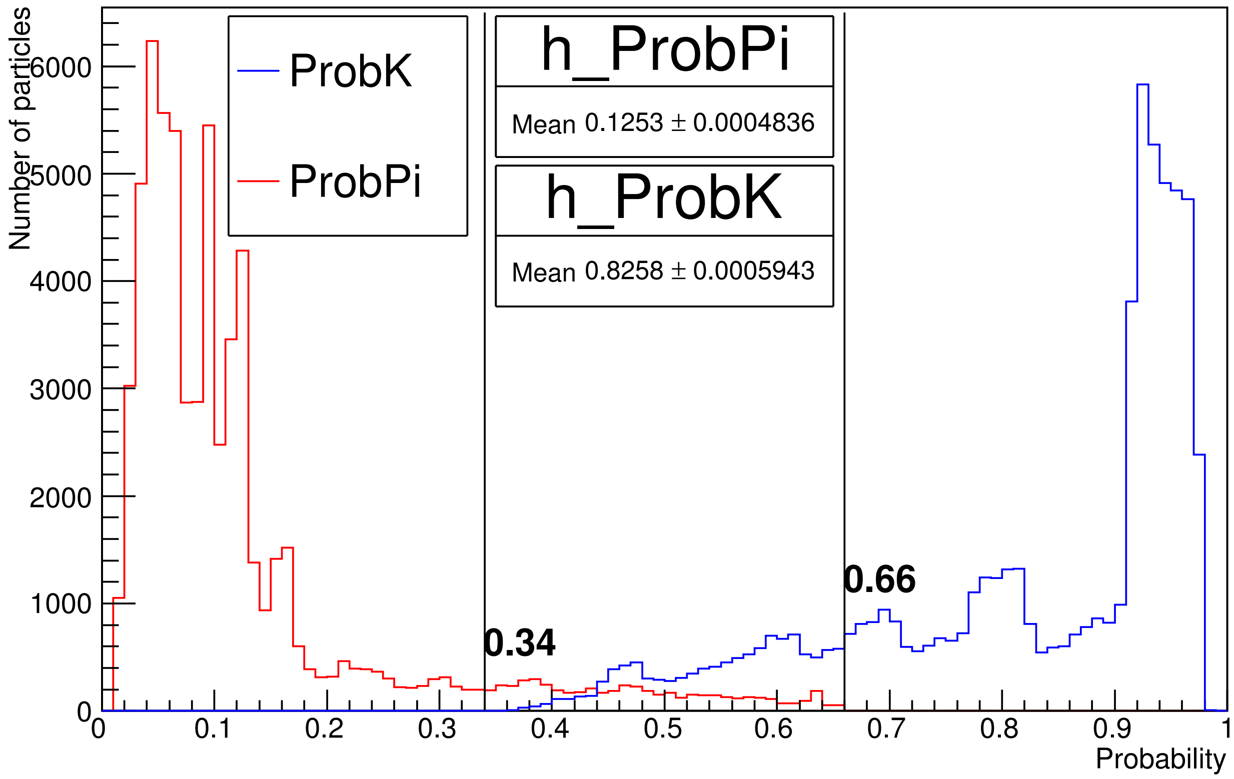


Figure 1: Graph of probability that any particle is a Kaon or Pion on x against number of particles on y. Cuts are 0.34 for Kaons and 0.66 for Pions.

Dalitz plots represent decay phase-spaces by plotting squared invariant masses of particle pairs. The particle with different charge to the B (say 3), is paired with the other two separately to make two variables (1 and 3 would make one, 2 and 3 the other). For decays with 3 particles of the same type, the higher mass pair is plotted against the lower. Dalitz plots allow study of local asymmetries.

Figure 2 illustrates a secondary vertex.

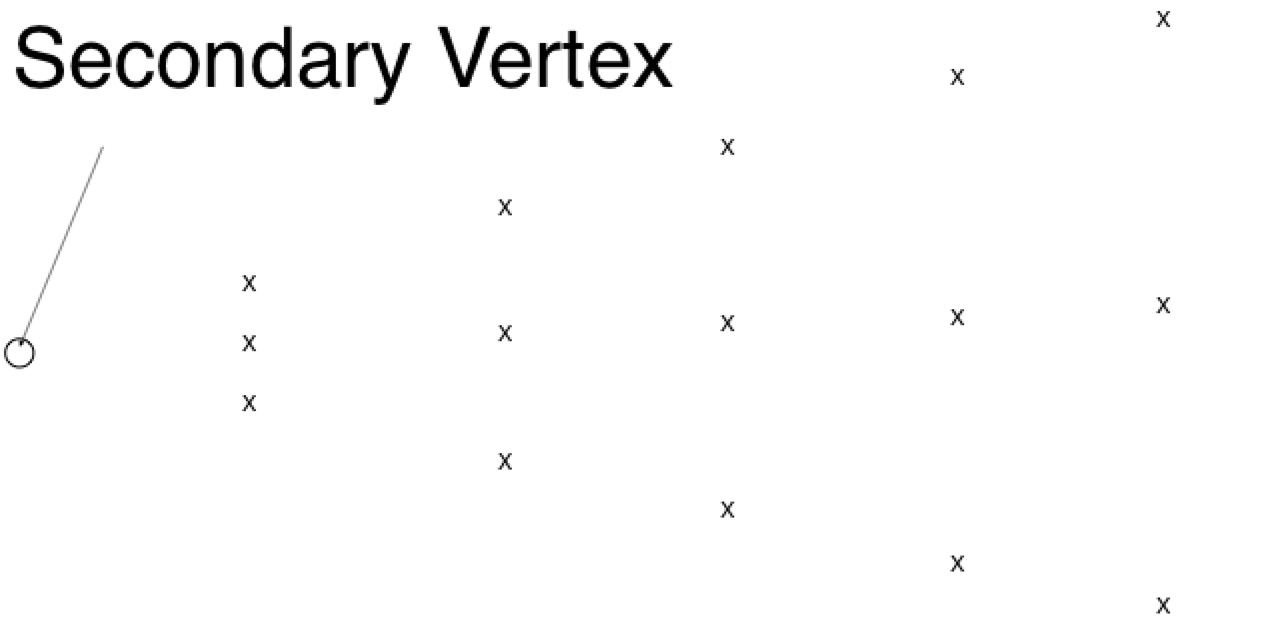


Figure 2: Illustration of 3 particle tracks retraced to find the secondary vertex where the $B^{\pm}$ meson decayed. X indicates a detector strip measurement.

3 Method

To analyse the vast number of particles, selection cuts were applied to filter possible B candidates, with the most important $K^{\pm}K^{+}K^{-}$ cuts in Table 1. For other decays, the probability cuts change. Figure 3 shows the secondary vertex χ^2 cut. Similarly, Figure 4 shows the B invariant mass range cut, as well as the $K^{\pm}K^{+}K^{-}$ fit. Table 2 describes the functions fitted to each invariant mass plot section for different decays, whilst Table 3 describes the meaning of each fit parameter.

Description	Cut
Kaon probability	> 0.34
Pion probability	< 0.66
$B^{\pm}$ invariant mass, M (MeV/c^2)	$5050 < M < 6300$
Secondary vertex χ^2	< 12

Table 1: The most important selection cuts.

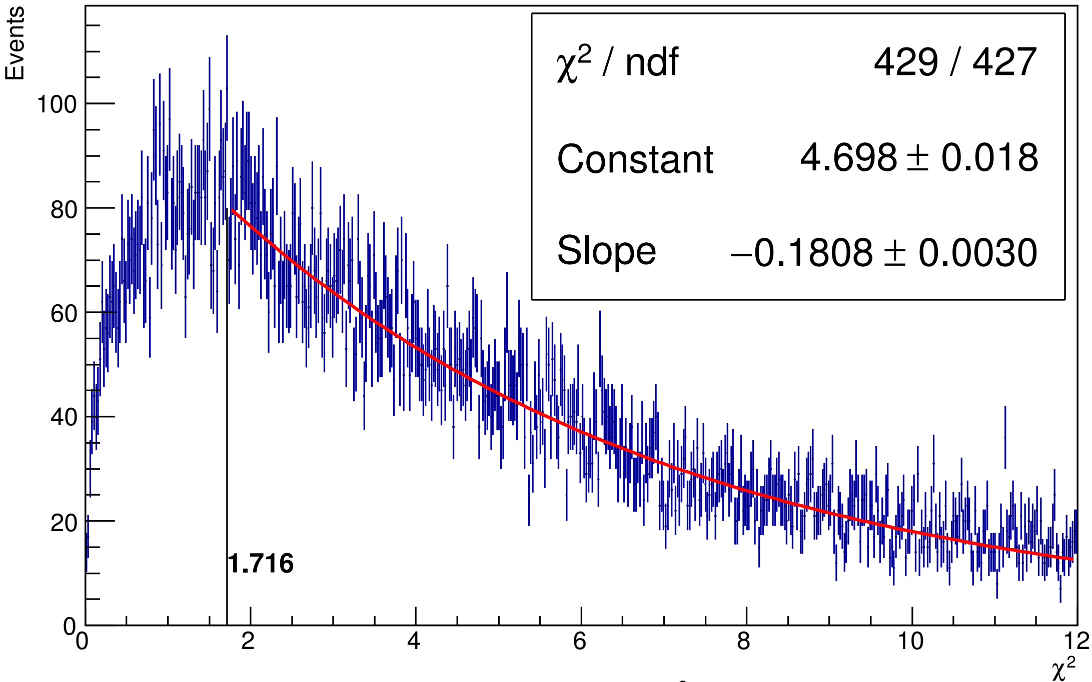


Figure 3: Graph of secondary vertex χ^2 on x against events on y.

$B^{\pm} \rightarrow$	Signal	Background	4-body
$K^{\pm}K^{+}K^{-}$	tall and narrow + short and wide Gaussians	linear	Gaussian
$\pi^{\pm}\pi^{+}\pi^{-}$	single Gaussian	exponential	Gaussian
$K^{\pm}\pi^{+}\pi^{-}$	single Gaussian	linear	Gaussian
$\pi^{\pm}K^{+}K^{-}$	tall and wide + short and narrow Gaussians	exponential	Gaussian

Table 2: Description of functions fitted to invariant mass plot sections.

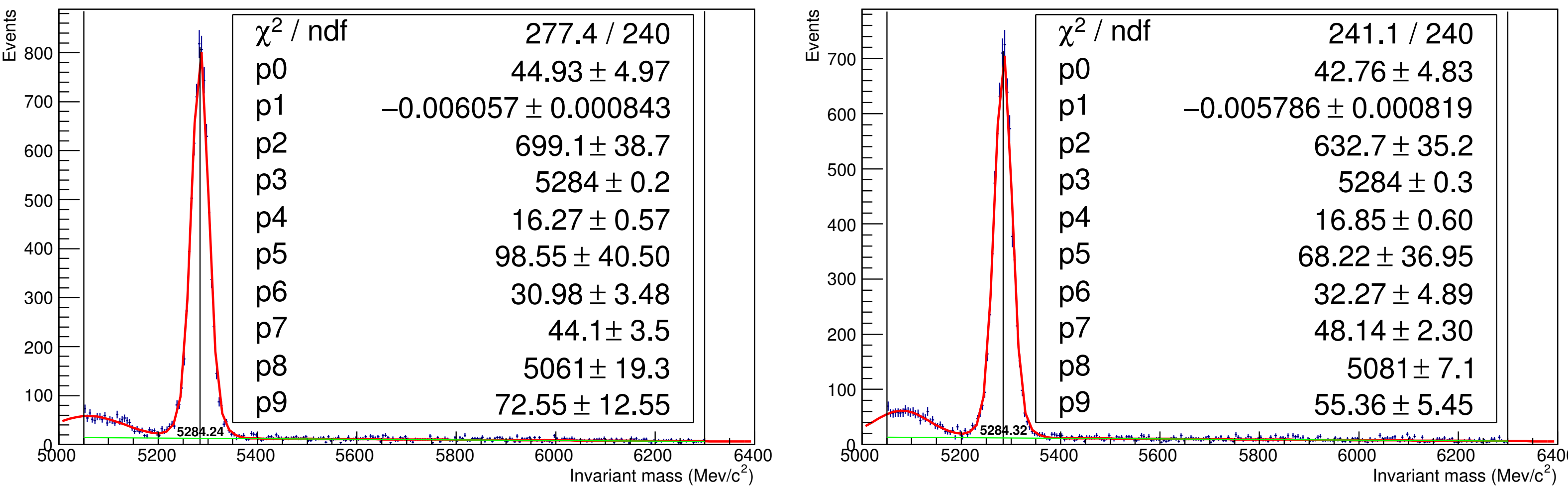
Figures 5, 6 and 7 show respectively the $\pi^{\pm}\pi^{+}\pi^{-}$, $K^{\pm}\pi^{+}\pi^{-}$ and $\pi^{\pm}K^{+}K^{-}$ invariant mass plots.

4 Results

In the intersection of 0.5 GeV^2/c^4 $< m^2_{K^+K^-\ low} <$ 2.75 GeV^2/c^4 and 7.28 GeV^2/c^4 $< m^2_{K^+K^-\ high} <$ 9.67 GeV^2/c^4 in Figure 8, a local asymmetry A_{CP} = -0.195 $\pm$ 0.032 (stat) $\pm$ 0.030 (sys) $\pm$ 0.006 (J/ψ $K^{\pm}$) was measured, giving a significance of 4.4σ. The largest and most significant asymmetry was found in the region $m^2_{\pi\pi} < 2.33$ GeV^2/c^4 and $m^2_{\pi K} < 2.3$ GeV^2/c^4, where A_{CP} = 0.349 $\pm$ 0.036 (stat) $\pm$ 0.044 (sys) $\pm$ 0.006 (J/ψ $K^{\pm}$), meaning a total significance of 6.1σ. Global asymmetries are summarised in Table 4.

Parameter	$K^{\pm}K^{+}K^{-}$	$\pi^{\pm}\pi^{+}\pi^{-}$	$K^{\pm}\pi^{+}\pi^{-}$	$\pi^{\pm}K^{+}K^{-}$
p0	background function y axis intercept	4-body Gaussian constant	background function y axis intercept	background function y axis intercept
p1	background function gradient	4-body Gaussian mean	background function gradient	background function decay length
p2	tall signal Gaussian constant	4-body Gaussian width	signal Gaussian constant	short signal Gaussian constant
p3	signal mean	signal Gaussian constant	signal mean	signal mean
p4	tall signal Gaussian width	signal mean	signal width	short signal Gaussian width
p5	short signal Gaussian constant	signal width	4-body Gaussian constant	tall signal Gaussian constant
p6	short signal Gaussian width	background function y axis intercept	4-body Gaussian mean	tall signal Gaussian width
p7	4-body Gaussian constant	background function decay length	4-body Gaussian width	4-body Gaussian constant
p8	4-body Gaussian mean			4-body Gaussian mean
p9	4-body Gaussian width			4-body Gaussian width

Table 3: Description of parameters in invariant mass plots.



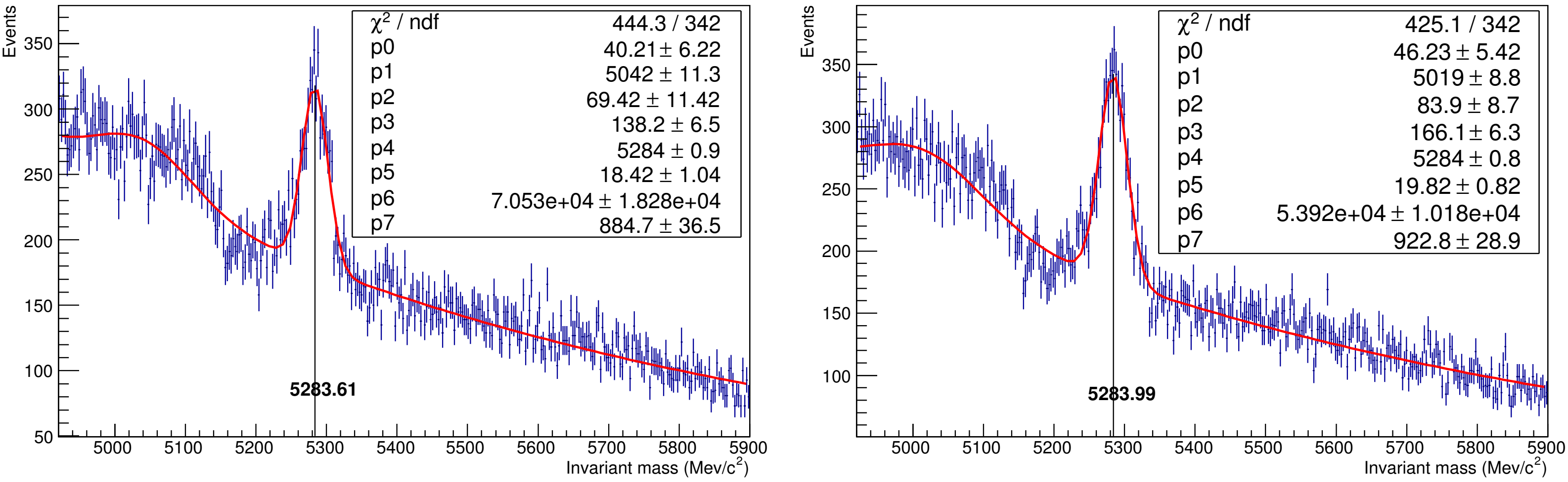
(a) $B^{+} \rightarrow K^{+}K^{+}K^{-}$.

(b) $B^{-} \rightarrow K^{-}K^{+}K^{-}$.

Figure 4: Graph of $B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}$ candidate invariant mass in MeV/c^2 on x axis against events on y axis.

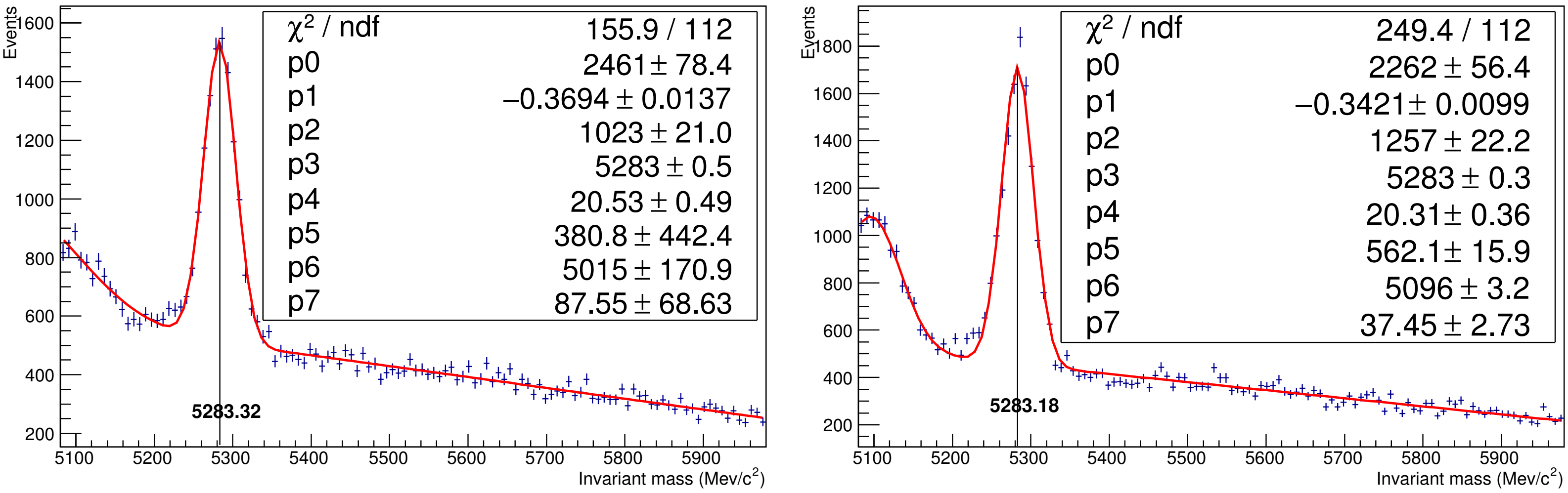
$B^{\pm} \rightarrow$	A_{CP}	± stat	± sys	± $J/\psi\ K^{\pm}$	σ_{total}
$K^{\pm}K^{+}K^{-}$	-0.043	0.009	0.004	0.006	3.8
$\pi^{\pm}\pi^{+}\pi^{-}$	0.144	0.014	0.050	0.006	2.7
$K^{\pm}\pi^{+}\pi^{-}$	0.127	0.008	0.067	0.006	1.9
$\pi^{\pm}K^{+}K^{-}$	-0.020	0.011	0.051	0.006	0.4

Table 4: Measured global asymmetries for decays studied, listed in order of significance.



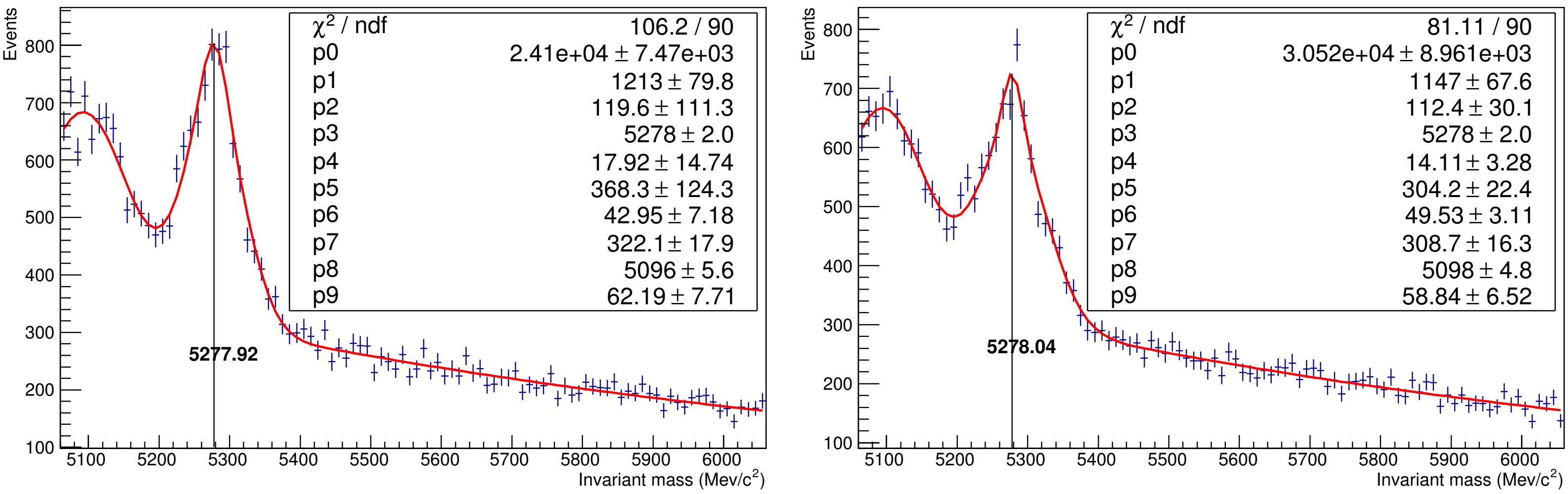
(a) $B^+ \to \pi^+\pi^+\pi^-$. (b) $B^- \to \pi^-\pi^+\pi^-$.

Figure 5: Graph of $B^\pm \to \pi^\pm\pi^+\pi^-$ candidate invariant mass in MeV/c^2 on x axis against events on y axis.



(a) $B^+ \to K^+\pi^+\pi^-$. (b) $B^- \to K^-\pi^+\pi^-$.

Figure 6: Graph of $B^\pm \to K^\pm\pi^+\pi^-$ candidate invariant mass in MeV/c^2 on x axis against events on y axis.



(a) $B^+ \to \pi^+K^+K^-$. (b) $B^- \to \pi^-K^+K^-$.

Figure 7: Graph of $B^\pm \to \pi^\pm K^+K^-$ candidate invariant mass in MeV/c^2 on x axis against events on y axis.

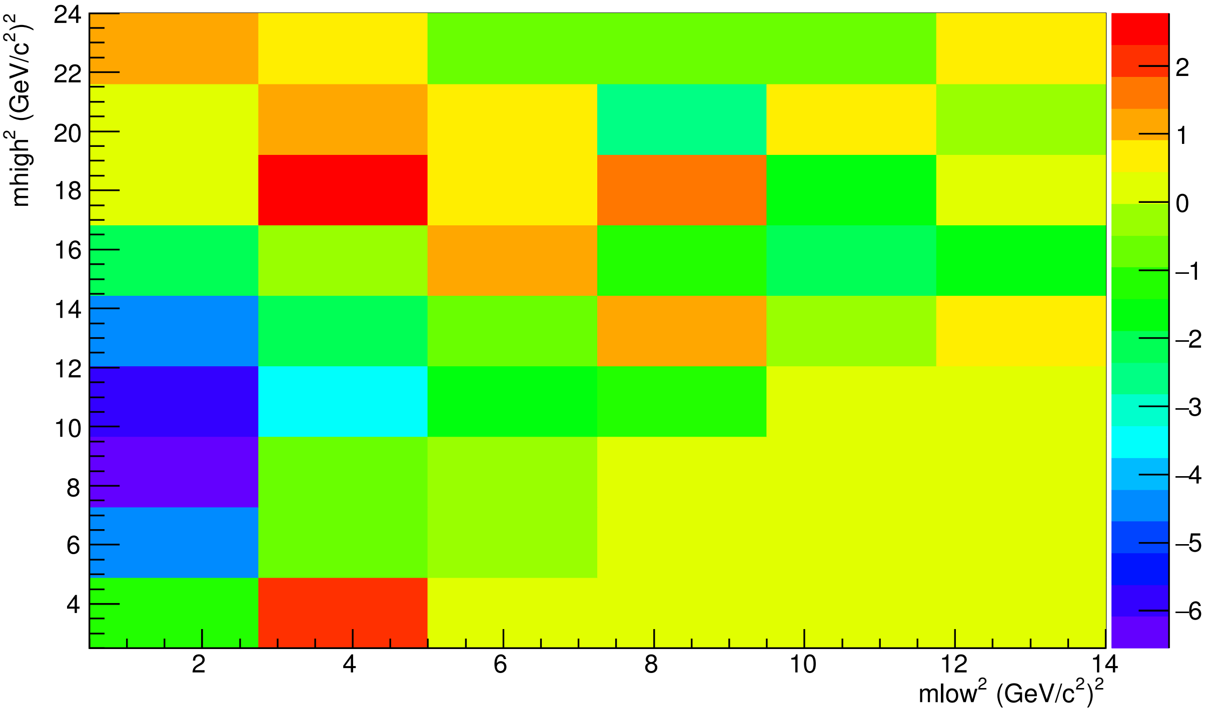


Figure 8: Dalitz plot of $m^2{}_{K^+K^-\,low}$ on x axis against $m^2{}_{K^+K^-\,high}$ on y axis, both in GeV^2/c^4, for asymmetry statistical significance. It is the significance magnitude on the colour scale that matters, the sign shows whether asymmetry is negative or positive. The most asymmetric region is where 0.5 GeV^2/c^4 $< m^2{}_{K^+K^-\,low} <$ 2.75 GeV^2/c^4 and 7.28 GeV^2/c^4 $< m^2{}_{K^+K^-\,high} <$ 9.67 GeV^2/c^4, where the asymmetry statistical significance is 6.1σ.

5 Discussion

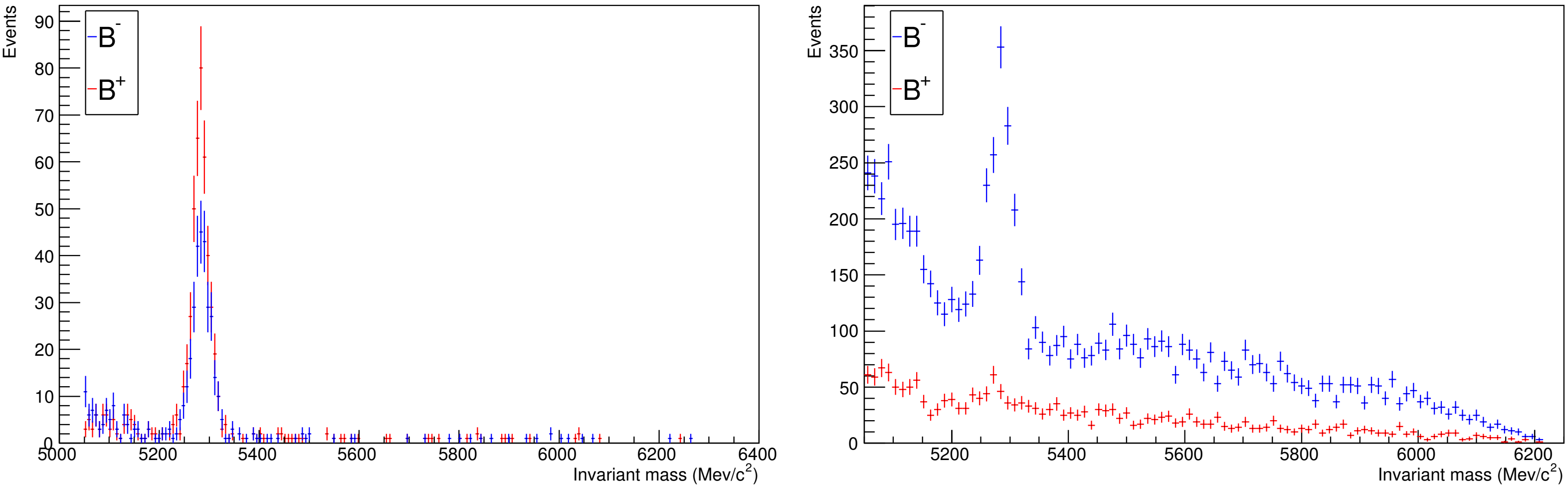
For comparison, the LHCb quoted values are in Table 5, showing that the LHCb values for $K^{\pm}K^+K^-$ and $\pi^{\pm}\pi^+\pi^-$ are within the errors of this experiment, but the other two are not. The decays become harder to analyse in the order given in Tables 4 and 5, as the amount of background increases.

$B^{\pm} \rightarrow$	A_{CP}	$\pm$ stat	$\pm$ sys	$\pm$ J/ψ $K^{\pm}$	σ_{total}
$K^{\pm}K^+K^-$	-0.043	0.009	0.003	0.007	3.7
$\pi^{\pm}\pi^+\pi^-$	0.117	0.021	0.009	0.007	4.9
$K^{\pm}\pi^+\pi^-$	0.032	0.008	0.004	0.007	2.8
$\pi^{\pm}K^+K^-$	-0.141	0.040	0.018	0.007	3.2

Table 5: LHCb quoted global asymmetries for decays studied.

The signal regions might be better fitted by functions other than a Gaussian, such as a Lorentzian, Breit-Wigner, Voigt, Crystal Ball or sums or convolutions of these. These were all attempted but did not give a χ^2 as good as Gaussians. Generally, two Gaussians are better than one because the error from each detector part is Gaussian. More Gaussians may have been better, but fit convergence would become harder. For the decays where only one Gaussian was fitted, a second was attempted but the resulting fit was not as good as with a single Gaussian.

Figure 9 displays asymmetry in the most asymmetric region of the $K^{\pm}K^+K^-$ Dalitz plot and of all decays. A visual difference is seen between B^+ and B^- plots in this region, as opposed to subtle differences between B^+ and B^- globally. The local systematic error is higher than the global for the same channel since no J/ψ decays were found in this region, therefore the same J/ψ correction was applied, but the error was increased accordingly.



(a) $K^{\pm}K^{+}K^{-}$.

(b) $K^{\pm}\pi^{+}\pi^{-}$.

Figure 9: Graph of $B^{\pm}$ candidate invariant mass in MeV/c^2 on x axis against events on y axis in the most asymmetric region of the channel Dalitz plot. B^{+} is in red and B^{-} in blue.

6 Conclusion

The best evidence for CP violation was found in $B^{\pm} \to K^{\pm}K^{+}K^{-}$ decays, where the total significance is 3.8σ. A larger total significance of 4.4σ was found in a local phase-space region of this decay. An observation of local violation in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ was made, where the total significance was 6.1σ. Other decays may also display global violation, but their significance in this experiment was not high enough to be classed as evidence.

References

[1] LHCb collaboration, Alves Jr, A, A. et al, "The LHCb detector at the LHC", *Journal of Instrumentation*, Volume 3, Issue 8, page i, 2008, `hyper link`.

[2] LHCb collaboration, Aaji, R. et al, "Measurement of CP violation in the phase space of $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ decays", *Physical Review Letters*, Volume 111, Issue 10, pages 1-5, 2013, `hyper link`.

[3] LHCb collaboration, Aaji, R. et al, "Measurement of CP violation in the phase space of $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ and $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ decays", *Physical Review Letters*, Volume 112, Issue 1, pages 3-8, 2014, `hyper link`.

[4] ROOT, Version 6, CERN, Geneva, Switzerland, CH-1211, `hyper link`.

[5] Linux, Version 4, `hyper link`.

[6] Particle Data Group, Patrignani, C. et al, "Review of Particle Physics", *Chinese Physics C*, Volume 40, Issue 10, pages 54-60, 2016, `hyper link`.

Appendix

The number of words in this document is 1884.