Measuring \( CP \) violation with \( \Delta A_{CP} \) at LHCb

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1 Introduction

The control of systematic uncertainties is a key component of many analyses performed at the Large Hadron Collider (LHC), and will only become more important as more data are taken during Run II. Many of the \( CP \) measurements performed using the LHCb detector [1] have statistical precisions below the per cent level, and so particular care must be taken in this area. One technique for dealing with the various production and detection asymmetries which can mask the physics asymmetry of interest, and increase the measurement’s systematic uncertainty, is \( \Delta A_{CP} \). The application of \( \Delta A_{CP} \) in three separate LHCb analyses of \( D^0 \) and \( \Lambda^0_b \) decays will be discussed, along with prospects for applying the technique to \( \Lambda^+ \) decays.

2 Measuring direct \( CP \) violation

Violation of charge-parity symmetry in decays mediated by the weak force occur when the matter state decays at a different rate to the antimatter state. This can be observed experimentally by measuring the difference between the partial decay width, \( \Gamma(f) \), of the particle to a final state \( f \) and the partial width of the \( CP \) conjugated process, \( \Gamma(\bar{f}) \),

\[
A_{CP}(f) = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})}.
\]

A non-zero value of \( A_{CP} \) indicates that the particle in question violates \( CP \) symmetry in its decay. Measuring the decay width directly is difficult as it requires computing the absolute efficiencies from production to selection. It is simpler to count the number of decays, \( N \), observed after the full selection

\[
A_{CP}^{\text{Raw}}(f) = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})}.
\]

This is contaminated by several background asymmetries, to first order

\[
A_{CP}^{\text{Raw}}(f) = A_{CP}(f) + A_P + A_D.
\]
The production asymmetry $A_P$ of the decaying particle arises during $q\bar{q}$ hadronisation due to the higher abundance of matter valence quarks available from the interacting protons, whilst $A_D$ is the asymmetry due to the difference in detection and selection efficiencies of the final states $f$ and $\bar{f}$.

By counting the number of decays to two separate final states $f$ and $g$, and by assuming that the background asymmetries are mode independent, one can construct a difference which leaves only the difference between the interesting physics asymmetries

$$\Delta A_{CP} = A_{\text{Raw}}^{CP}(f) - A_{\text{Raw}}^{CP}(g) = A_{CP}(f) - A_{CP}(g).$$

However, it is not true a priori that the background asymmetries are mode independent. The production and detection asymmetries are generally dependent only on the kinematics of the mother particle and the final state respectively, and so if the kinematics are the same between the modes, or can be weighted to be so, then the asymmetries will cancel in the difference. A final state which is its own $CP$ conjugate, such as $\pi^+\pi^-$, will naturally have zero detection asymmetry, whereas a state like $K^-\pi^+$ must be handled more carefully.

The methodologies employed by three separate analyses using the $\Delta A_{CP}$ technique at LHCb will be summarised in the following sections, and then prospects for using $\Delta A_{CP}$ in $\Lambda_c^+$ decays will explored.

### 3 $D^0 \rightarrow h^+h^-$ decays

Under SU(3) flavour symmetry, direct $CP$ asymmetries in the singly Cabibbo-suppressed decays $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ are predicted to be of equal magnitude but opposite sign. This makes $\Delta A_{CP}$ particularly useful for measuring direct $CP$ violation. The Standard Model predictions for direct $CP$ asymmetries in this system can be at the per mille level [5], and this may be enhanced in theories beyond the Standard Model.

In order to construct $A_{\text{Raw}}^{CP}$ for each mode, the flavour of the charm hadron ($D^0$ or $\bar{D}^0$) must be known. This can be inferred by selecting $D^0$ and $\bar{D}^0$ decays originating from $D^{*+} \rightarrow D^0\pi^+$ or $\bar{B} \rightarrow D^0\mu^-\bar{\nu}_\mu X$ decays and their charge conjugates. In the former the flavour is ‘tagged’ by the charge of the pion from the $D^{*+}$ decay, and in the latter the flavour is tagged by the charge of the muon from the $B$ decay.

The $D^0\bar{D}^0$ system is known to undergo mixing [2], allowing indirect $CP$ violation to contribute to $\Delta A_{CP}$. Current experimental sensitivity is too low to measure this contribution directly, however, and it is expected to be mode-independent, leaving $\Delta A_{CP}$ as a pure measurement of direct $CP$ violation.

#### 3.1 Pion tagged analysis

Using an integrated luminosity of $1.0\text{fb}^{-1}$, corresponding to the total data collected by LHCb in 2011, $\Delta A_{CP}$ is measured using $D^{*+}$ tagged $D^0$ decays [3].

Here, the $D^{*+}$ production asymmetry and charged pion detection asymmetry will contaminate $A_{\text{Raw}}^{CP}$. The production asymmetry can be controlled by assuming that the $D^{*+}$ production rates depend only on the kinematics of the particle, then weighting the $D^{*+}$
kinematics distributions between $K^+K^-$ and $\pi^+\pi^-$ modes to be the same. In the same way, the charged pion detection asymmetry is assumed to be dependent on the pion kinematics, and so will cancel in $\Delta A_{CP}$ if the kinematics of the two modes are the same. This is ensured by weighting the $D^{*+}$ kinematics in momentum $|p|$, transverse momentum $p_T$, and azimuthal angle $\phi$. As the final state acceptances are shown to agree within the experimental precision, this also normalises the $D^{*+}$ pion kinematics.

To check for any systematic deviations due to changing detector conditions, the data were split by the magnet polarity with which the data were taken and the decision of the hardware trigger with respect to the selected candidates. The signal yields within each subsample were then computed by a simultaneous fit in reconstructed $D^0$ mass and the mass difference $\delta m$ between the reconstructed $D^{*+}$ and $D^0$. Representative fits are shown in Figures 1a and 1b. The final $\Delta A_{CP}$ value is obtained by a weighted average of the values obtained from the subsamples and found to be

$$\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%,$$

where the first uncertainty is statistical and the second is systematic.

![Figure 1:](a) $D^0$ mass distribution (a) and $\delta m = m(D^{*+}) - m(D^0)$ distribution (b) of fully selected $D^0 \rightarrow \pi^+\pi^-$ candidates, where the flavour of the $D^0$ has been tagged using $D^{*+} \rightarrow D^0\pi^+$ decays.

### 3.2 Muon tagged analysis

Using an integrated luminosity of 3.0 fb$^{-1}$, corresponding to the total data collected by LHCb in 2011 and 2012, $\Delta A_{CP}$ is measured using muon tagged decays from semileptonic $b$-decays [3].

Unlike the pion tagged analysis, the production asymmetry associated with the $b$-hadron and the detection asymmetry of the muon are cancelled using a proxy mode, namely $\bar{B} \rightarrow D^0 \mu^\pm \nu\mu X$ with the $D^0$ decaying to the Cabibbo-favoured $K^-\pi^+$ final state. The contribution from direct $CP$ violation in $A_{CP}^{\text{Raw}}(D^0 \rightarrow K^-\pi^+)$ is greatly suppressed in comparison with the singly Cabibbo-suppressed modes, and is negligible in comparison with the
Experimental sensitivity. However, there is now a contribution from the charged kaon-pion detection asymmetry

\[ A_{\text{Raw}}^{CP}(D^0 \to K^- \pi^+) = A^B_p + A_\mu^p + A^K_{\pi}. \]

Using a combination of the Cabibbo-favoured \( D^+ \to K^- \pi^+ \) and \( D^+ \to \overline{K}^0 \pi^+ \) decays, and the neutral kaon detection asymmetry obtained from simulation, one can measure \( A^K_{\pi} \) directly and extract the pure \( A_{\text{CP}}(K^+K^-) \) and \( A_{\text{CP}}(\pi^+\pi^-) \) asymmetries.

Consistency checks are also performed by computing \( \Delta A_{\text{CP}} \) in various data taking periods in 2011 and 2012 and in the different magnet polarities the data were taken with. The final measured values of the asymmetries, made on the full dataset, are

\[ \Delta A_{\text{CP}} = (+0.14 \pm 0.16 \pm 0.08)\%, \]
\[ A_{\text{CP}}(K^-K^+) = (-0.06 \pm 0.15 \pm 0.10)\%, \]
\[ A_{\text{CP}}(\pi^-\pi^+) = (-0.20 \pm 0.19 \pm 0.10)\%, \]

where in each case the first uncertainty is statistical and the second is systematic.

4 \( \Lambda^0_b \to J/\psi ph^- \) decays

Probing baryon decays for CP violation is complementary to that in meson decays, and links directly to the puzzle of the observable baryon asymmetry in the universe.

The \( \Lambda^0_b \) baryon, the lightest of the beauty baryons, has a similar lifetime to the neutral \( B \) mesons. Given the relatively recent discovery of direct CP violation in \( B^0 \) and \( B^0_s \) decays [6, 7, 8], it is pertinent to check if the \( \Lambda^0_b \) also shares this property.

As part of an analysis on the full 3 fb\(^{-1} \) dataset which made the first observation of the Cabibbo-suppressed \( \Lambda^0_b \to J/\psi p\pi^- \) decay, \( \Delta A_{\text{CP}} \) is measured as the difference in \( A_{\text{Raw}}^{\text{CP}} \) between this decay and \( \Lambda^0_b \to J/\psi pK^- \) [9]. Unlike the aforementioned \( D^0 \) decays, the \( \Lambda^0_b \) final states tag the flavour of the mother by baryon number conservation, and so the sample of \( \Lambda^0_b \) is taken as those originating directly from the pp interaction region.

The \( \Lambda^0_b \) and proton kinematics were found to be identical between the modes after full selection, and so the respective production and selection asymmetries cancel in \( \Delta A_{\text{CP}} \). The remaining relative charged kaon-pion detection asymmetry is measured directly using \( \overline{B}^\to J/\psi\overline{K}^* \) decays. Yields for each mode are measured by a fit to the reconstructed \( \Lambda^0_b \) mass, shown in Figures 2a and 2b, and combined with the \( A^K_{\pi} \) measurement to give

\[ \Delta A_{\text{CP}} = (+5.7 \pm 2.4 \pm 1.2)\%, \]

where the first uncertainty is statistical and the second is systematic.

5 \( \Lambda^+_c \to ph^-h^+ \) decays

Future prospects for using \( \Delta A_{\text{CP}} \) at LHCb include the study of the Cabibbo-suppressed \( \Lambda^+_c \to pK^-K^+ \) and \( \Lambda^+_c \to p\pi^-\pi^+ \), and the two-body \( \Lambda^+_c \to p\phi \) and \( \Lambda^+_c \to p\overline{K}^0 \) decays. This
as yet unexplored avenue in the charm sector is complementary to the $D^0$ decays [10], which has seen a revival of interest within the theoretical community. Experimental challenges are similar to the other $\Delta A_{CP}$ measurements, namely controlling the production and final state detection asymmetries. This analysis is currently under way, with an expected sensitivity on $\Delta A_{CP}$ of approximately 1%.

6 Summary

Since the discovery of $CP$ violation over 50 years ago, experimental searches continue to produce important results in an attempt to explain the matter-antimatter imbalance in our universe. New techniques must be created to reduce systematic uncertainties and enhance sensitivity for future measurements on ever larger datasets.

By using two decay modes of the same particle, $\Delta A_{CP}$ allows the cancellation of background asymmetries common to both modes, but requires careful treatment of the kinematic differences between the modes. LHCb has used this technique to great effect, yet clearly there is still much more to explore.

References


