PROCEEDINGS OF SCIENCE

Search for CP violation in charm baryon decays

Francesco Zenesini[*]
Università di Bologna,
Via Zamboni 33, Bologna, Italy
INFN Bologna section,
Viale Berti Pichat 6/2, Bologna, Italy
E-mail: zenesini@bo.infn.it

A search for CP violation in charm baryon Λ_c^+ decays is presented. The analysis measures the difference of CP asymmetries ΔA_{CP} of single Cabibbo suppressed decays $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$ from promptly produced Λ_c^+ collected at LHCb during 2016-2018. This measurement will improve both the statistical and systematic uncertainties with respect to the previous measurement performed by LHCb with data collected during Run 1 (2011-2012).

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[*]Speaker

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1. Introduction

The LHCb collaboration plays a crucial role in particle physics, particularly in Flavour Physics research. Since it began collecting data in 2011, LHCb has conducted numerous high-precision measurements of CP violation in the decays of hadrons containing a charm quark. In 2019, the LHCb collaboration reported the first evidence of direct CP violation in D^0 decays [1]. However, CP violation has not yet been observed in baryon decays. Investigating new sources of CP violation in the charm sector, particularly in Λ_c^+ baryons, is then a powerful probe for new physics. This proceeding presents the search for direct CP violation in the singly Cabibbo suppressed decays of the charm baryon $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$ promptly produced in proton-proton collisions with Run 2 data at LHCb. This measurement has been previously performed by LHCb with Run 1 data [2], with $\Lambda_b^0 \to \Lambda_c^+\mu^- X$ decays and found to be

$$\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%, \tag{1}$$

where the first uncertainty is statistical and the second is systematic. The measurement is currently dominated by statistical uncertainty, and, with the high-statistic dataset collected at LHCb during Run 2, it can be greatly improved.

2. Analysis strategy

The goal of this analysis is to measure ΔA_{CP} in $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$ decays. ΔA_{CP} is defined as

$$\Delta A_{CP} = A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}(\Lambda_c^+ \to p\pi^+\pi^-), \tag{2}$$

where the CP asymmetry to the final state f, $A_{CP}(\Lambda_c^+ \to f)$ is defined as

$$A_{CP}(\Lambda_c^+) = \frac{\Gamma(\Lambda_c^+ \to f) - \Gamma(\Lambda_c^- \to \overline{f})}{\Gamma(\Lambda_c^+ \to f) + \Gamma(\Lambda_c^- \to \overline{f})}, \tag{3}$$

with Γ the decay rate of a flavour specific decay. To access this quantity, raw asymmetries A_{raw} are measured, which are defined as

$$A_{\text{raw}}(\Lambda_c^+ \to f) = \frac{N(\Lambda_c^+ \to f) - N(\Lambda_c^- \to \overline{f})}{N(\Lambda_c^+ \to f) + N(\Lambda_c^- \to \overline{f})}, \tag{4}$$

where N is the number of events extracted from a simultaneous fit to the invariant mass distributions of both Λ_c^+ and Λ_c^-. These asymmetries are affected by a number of nuisance asymmetries, i.e. detection asymmetry of the proton $A_D(p)$, production asymmetry of the Λ_c^+, $A_P(\Lambda_c^+)$, detection asymmetries of the pair of hadrons $A_D(K^\pm)$, $A_D(\pi^\pm)$ and trigger asymmetry due to the hardware trigger (L0). Assuming these effects introduce small asymmetries, the raw asymmetries can be expanded as

$$A_{\text{raw}}^{KK} = A_{CP}^{KK} + A_P^{KK}(\Lambda_c^+) + A_D^{KK}(p) + A_D(K^-) + A_D(K^+) + A_{L0}^{KK}(p), \tag{5}$$
$$A_{\text{raw}}^{\pi\pi} = A_{CP}^{\pi\pi} + A_P^{\pi\pi}(\Lambda_c^+) + A_D^{\pi\pi}(p) + A_D(\pi^-) + A_D(\pi^+) + A_{L0}^{\pi\pi}(p), \tag{6}$$

where the superscripts $hh = KK, \pi\pi$ of asymmetries A_i^{hh} refer to the asymmetries in the corresponding decay $A_i^{hh} = A_i(\Lambda_c^+ \to phh)$. This expansion allows to rewrite Equation 2 as

$$\begin{aligned}\Delta A_{CP} =&(A_{\rm raw}^{KK} - A_{\rm raw}^{\pi\pi})+ \\ &+ A_P^{KK}(\Lambda_c^+) + A_D^{KK}(p) + A_{L0}^{KK}(p) - A_P^{\pi\pi}(\Lambda_c^+) - A_D^{\pi\pi}(p) - A_{L0}^{\pi\pi}(p)+ \\ &+ A_D(K^-) + A_D(K^+) - A_D(\pi^-) - A_D(\pi^+).\end{aligned} \tag{7}$$

If the nuisance asymmetries depend only on the kinematics of the corresponding particle the ΔA_{CP} asymmetry can be simplified thanks to the cancellation of nuisance asymmetries between different decay channels. This is ensured by applying weights to $\Lambda_c^+ \to p\pi^+\pi^-$ candidate to match the kinematic distributions in the two channels. The irreducible detection asymmetries $A_D(K^\pm)$ and $A_D(\pi^\pm)$ are estimated with the Cabibbo favoured decay $\Lambda_c^+ \to pK^-\pi^+$ and corrected for in the resulting asymmetries. Finally, ΔA_{CP} can be expressed as

$$\Delta A_{CP} \simeq A_{\rm raw}^{KK} - A_{\rm raw}^{\pi\pi} + A_D(K^-) + A_D(K^+) - A_D(\pi^-) - A_D(\pi^+). \tag{8}$$

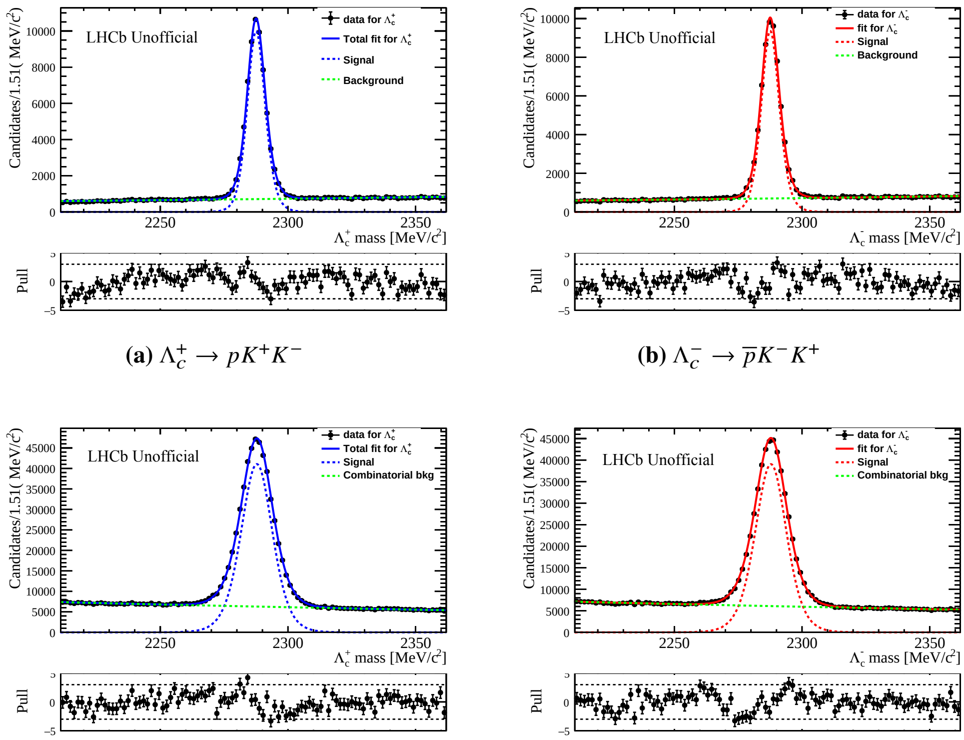
3. Data sample and selection

To measure the CP asymmetries, data taken by LHCb during 2016-2018 from proton-proton collision at a centre-of-mass of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of $\mathcal{L} = 5.4\ \text{fb}^{-1}$, are analysed.

The candidates are selected online with the LHCb trigger and offline, first with a cut-based approach and then they are further filtered with a multivariate algorithm based on boosted decision trees (BDT). The cut-based step is applied to exclude mis-identified background decays, secondary decays, candidates where one or more tracks are clones of each other, and to remove high asymmetry regions and non-CPV resonances. Furthermore, a veto on the position of the hits on the hadron calorimeter of LHCb is applied, since it would introduce an irreducible correlation in the particle kinematics. At this stage the sample is also divided in sub-samples according to the year of data-taking, the magnet polarity and the trigger category. In particular, the two possible categories are TOS (Trigger On Signal), where the candidates are the ones which triggered the event, or TISnotTOS (Trigger Independent of Signal), where the candidates are not the ones responsible of triggering the event and which is complementary to the former category. For each sub-sample, a BDT is trained and optimized independently on each sub-sample. To optimize the BDT cut, Monte Carlo toys are generated from the test sample to find the cut which minimize the uncertainty on the $A_{\rm raw}$ for each case.

4. Reweighting and fit model

To ensure the proper cancellation of nuisance asymmetries, kinematic weights are applied to the $\Lambda_c^+ \to p\pi^+\pi^-$ candidates. These weights are computed with an iterative procedure. Starting from s-weighted one dimensional kinematic distributions of a variable, ratios between $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$ distributions are computed and for each candidate a weight is assigned. These weights are then applied to next kinematic distribution and the procedure is repeated up to 100 times to ensure a proper matching of the distributions in the two channels. The variables on which



(a) $\Lambda_c^+ \to pK^+K^-$ **(b)** $\Lambda_c^- \to \overline{p}K^-K^+$

(c) $\Lambda_c^+ \to p\pi^+\pi^-$ **(d)** $\Lambda_c^- \to \overline{p}\pi^-\pi^+$

Figure 1: Fits to the invariant mass distribution of $\Lambda_c^+ \to pK^+K^-$ (top) and $\Lambda_c^+ \to p\pi^+\pi^-$ (bottom) divided by charge, i.e. Λ_c^+ in blue, Λ_c^- in red. The reported distributions are for the 2018 magnet down TISnotTOS sample.

this procedure is applied are $p_T(\Lambda_c)$, $\eta(\Lambda_c)$, $\phi(\Lambda_c)$, $p_T(p)$, $\eta(p)$, $\phi(p)$, the fraction of events in which the proton triggered the event (only in TOS samples) and $\log(\chi^2_{IP}(\Lambda_c))$.

These weights are then applied to the invariant mass of $p\pi^+\pi^-$ and simultaneous fits for both the modes are performed. For the $\Lambda_c^+ \to pK^+K^-$ channel the fit model is composed of a Johnson function for the signal component while the background component is described by an exponential function. The fit model for the $\Lambda_c^+ \to p\pi^+\pi^-$ channel is similar to the previous model with the addition of a Gaussian function to model mis-identified events from the $\Lambda_c^+ \to pK^-\pi^+$ decay in the TOS sample. Examples of fits for the two channels are reported in Figure 1 for 2018 magnet down TISnotTOS sample.

5. Preliminary results

Raw asymmetries are extracted from the simultaneous fit to the invariant mass distributions. These raw asymmetries are corrected for detection asymmetries of the pairs of hadrons, as shown in Equation 8, which are estimated with a data driven technique with the Cabibbo favoured decay $\Lambda_c^+ \to pK^-\pi^+$. The resulting values are reported in Table 1 and shown in Figure 2 where a random shift is applied to the central value to blind the results. Combining these results across the different

Year and magnet polarity	TISnotTOS ΔA_{CP} [%]	TOS ΔA_{CP} [%]
2016 Magnet Down	−40.08 ± 0.44	−39.47 ± 0.86
2016 Magnet Up	−41.11 ± 0.43	−40.04 ± 0.81
2017 Magnet Down	−41.35 ± 0.39	−40.95 ± 0.68
2017 Magnet Up	−40.45 ± 0.39	−42.35 ± 0.70
2018 Magnet Down	−40.42 ± 0.37	−41.38 ± 0.69
2018 Magnet Up	−41.19 ± 0.35	−41.69 ± 0.67

Table 1: Measured values for ΔA_{CP} for all the sub-samples, i.e. year, magnet polarity and trigger configuration. The reported errors are statistical.

sub-samples, the result is

$$\Delta A_{CP} = (-40.87 \pm 0.14)\%. \tag{9}$$

Additionally, to check whether the resonances across the Dalitz plot enhance or dilutes ΔA_{CP}, the analysis is also performed in bins of the Dalitz plot around the $\Lambda, \Sigma(1670)$ and ϕ resonances for the $\Lambda_c^+ \to pK^+K^-$ decay and around the f_0, ω_0, $\Lambda, \Sigma(1385)$ and $\Lambda, \Sigma(1670)$ resonances for the $\Lambda_c^+ \to p\pi^+\pi^-$ decay. The results are shown in Figure 3 and are compatible with each other.

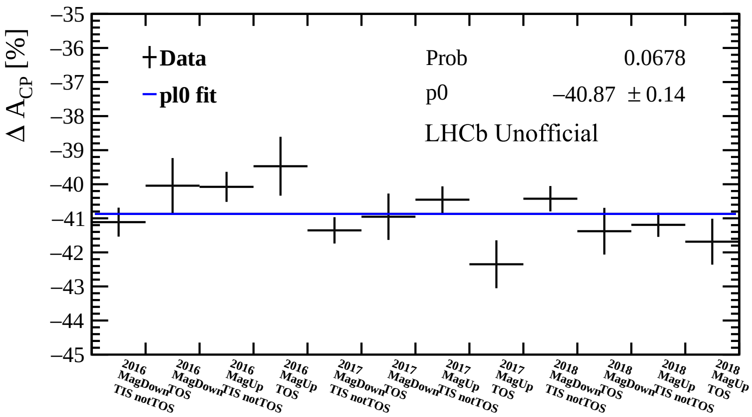
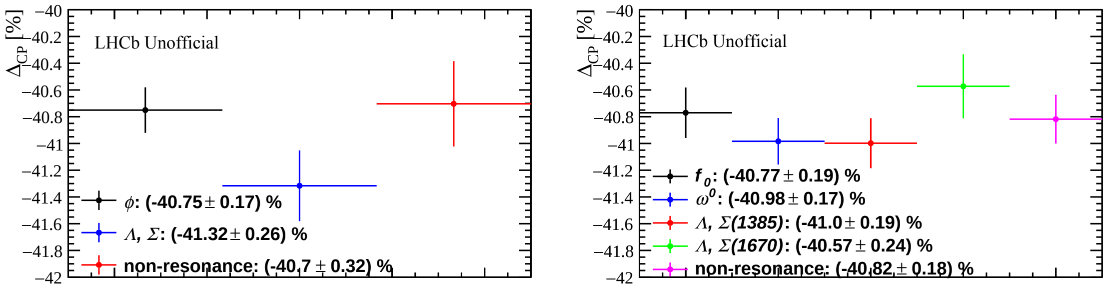


Figure 2: Measured values for ΔA_{CP} for all the sub-samples, i.e. year magnet polarity and trigger configuration. The reported error is statistical. The resulting values are compatible with the hypothesis of no dependence of the data taking conditions.

6. Systematic uncertainties

The main sources of systematic uncertainties have been estimated. In particular, the fit model might not describe correctly the signal, thus a different parametrization has been studied. The rewighting procedure does not account for correlations between variables, hence an alternative two dimensional iterative reweighting is studied. The contribution from residual secondary decays that might contaminate the sample is estimated with a sample with a stricter cut on the impact parameter.



(a) $\Lambda_c^+ \to pK^+K^-$ **(b)** $\Lambda_c^+ \to p\pi^+\pi^-$

Figure 3: Measured values for ΔA_{CP} in bins of the Dalitz plot for $\Lambda_c^+ \to pK^+K^-$, on the left, and for $\Lambda_c^+ \to p\pi^+\pi^-$ on the right.

Finally, the residual asymmetry determined with the data driven technique to estimate the detection asymmetry of pion is accounted for. The resulting systematic uncertainties associated with these effects are reported in Table 2.

Source	Uncertainty [%]
Fit model	0.020
Variables correlation	0.070
Secondary Λ_c^+	0.003
Residual detection asymmetry	0.002
Total	0.080

Table 2: Summary of the systematic uncertainties on ΔA_{CP} for the full combination of all years, magnet polarities and triggers.

7. Conclusions

In this proceeding, the search for CP violation in $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$ decays using data collected by LHCb during 2016-2018 has been presented. The measured ΔA_{CP} is found to be $\Delta A_{CP} = (-40.87 \pm 0.14 \pm 0.08)\%$, where the first uncertainty is statistical and the second systematic and the central value has been shifted by a random quantity to blind the analysis.

References

[1] R. Aaij *et al* (LHCb Collaboration), *Observation of CP Violation in Charm Decays*, Phys. Rev. Lett. **122** (2019) 211803 [arXiv:1903.08726].

[2] R. Aaij *et al* (LHCb Collaboration), *A measurement of the CP asymmetry difference in* $\Lambda_c^+ \to pK^+K^-$ *and* $p\pi^+\pi^-$ *decays*, JHEP 03 (2018), 182 [arXiv:1712.07051].