Search for CP violation in charm baryon decays

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Summary. —
A search for direct CP violation ΔA_{CP} of Λ_c^+ baryon in single-Cabibbo-suppressed decays $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$, using data collected by LHCb during Run 2 (2016-2018) for a total integrated luminosity of 5.57 fb^{-1}. This analysis will improve the uncertainty of ΔA_{CP} of a order of magnitude with respect to the previous measurement performed by LHCb with data collected during Run 1 (2011-2012).

1. – Introduction

The LHCb experiment has been designed to have a predominant role in particle physics and in flavour physics research. Since the start of its data taking in 2011, LHCb has performed several CP violation measurements in decays of hadrons containing a charm quark with extremely high precision, observing for the first time direct CP violation in two-body decays of D^0 meson in 2019 [1]. However, CP violation in baryon decays has never been observed, and this measurement will be complementary to other measurement performed up to these days. These are crucial aspects of Standard Model to understand baryonic asymmetry and to find signatures of New Physics.

The single-Cabibbo-suppressed decays $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$ have been analysed. Those decays are very powerful in CP violation searches thanks to the low background contribution of the Standard Model.

A measurement has already been performed with the data collected by LHCb during Run 1 [2] which resulted in

$$\Delta A_{CP} = A_{CP}(pK^-K^+) - A_{CP}(p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61)\%, \tag{1}$$

where the first uncertainty is statistical and the second systematic.

2. – Analysis strategy

The main goal of this analysis is to measure the difference in CP asymmetry ΔA_{CP} of the decays of the charmed baryon Λ_c^+ as $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$. The

definition of ΔA_{CP} is $\Delta A_{CP} \equiv A_{CP}(pKK) - A_{CP}(p\pi\pi)$ where $A_{CP}(phh)$ is the direct CP asymmetry of each decay. The direct CP asymmetry $A_{CP}(f)$ of a generic final state f can be expressed as

$$A_{CP}(f) = \frac{\Gamma(f) - \Gamma(\overline{f})}{\Gamma(f) + \Gamma(\overline{f})}, \tag{2}$$

where $\Gamma(f)$ is the decay width if the decay into the final state f.

This quantity can be expressed in function of the raw asymmetry A_{raw} and the nuisance asymmetries $A_P(\Lambda_c)$ the production asymmetry of the baryon Λ_c, $A_D(p)$ the detection asymmetry of the proton and $A_D(h^{\pm})$ the detection asymmetries of the hadrons $h^{\pm}$. The raw asymmetry, defined as

$$A_{\text{raw}} = \frac{N(f) - N(\overline{f})}{N(f) + N(\overline{f})}, \tag{3}$$

where $N(f)$ are the number of decay in specific final state f, can be extracted with a simultaneous fit to the data. Finally, the raw asymmetry can then be expressed as

$$A_{\text{raw}} \simeq A_{CP} + A_P(\Lambda_c) + A_D(p) + A_D(h^-) + A_D(h^+). \tag{4}$$

If the two hadrons h^+, h^- have the same kinematic distributions we can assume $A_D(h^-) = -A_D(h^+)$ and after inverting the eq. 4 we can obtain the direct CP asymmetry as

$$A_{CP} \simeq A_{\text{raw}} + A_P(\Lambda_c) + A_D(p). \tag{5}$$

The remaining nuisance asymmetries are dependent on the kinematics of the relevant particle and can be cancelled out with subtraction with another decay channel assuming they have the same kinematic distributions of Λ_c, p. To ensure this the kinematic distributions of the decay channel $\Lambda_c \to p\pi\pi$ are matched to the ones of $\Lambda_c \to pKK$ through a re-weighting procedure.

The resulting quantity, ΔA_{CP} can be expressed as

$$\Delta A_{CP} = A_{CP}(pKK) - A_{CP}(p\pi\pi) \simeq A_{\text{raw}}(pKK) - A_{\text{raw}}(p\pi\pi). \tag{6}$$

3. – Data selection

The data sample analysed for this measurement have been collected by LHCb in pp collision during Run 2 data taking campaign, in 2016-2018, with a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The sample correspond to 5.57 fb^{-1} integrated luminosity.

The selection is divided in two steps:

- A pre-selection where a cut based approach is employed to veto non-CPV resonance, such as $\Lambda_c^+ \to \Lambda^0(\to p\pi^-)\pi^+$ and $\Lambda_c^+ \to pK_0^s(\to \pi^-\pi^+)$, apply Particle Identification requirements on the final states and divide our sample depending on the trigger configuration of the experiment;
- A BDT is trained and optimised based on the pre-selection sample, to reject the combinatorial background using mainly kinematic variables. The BDT is trained separately for each data taking year and magnet polarity period.

Variable	Cut
ProbNNp(p)	> 0.85
$IP(\Lambda_c)$	< 0.05
ProbNNh(h^+)	> 0.6
ProbNNh(h^-)	> 0.6
Open angle θ	$\theta_{Phm} > 0.0008$
	$\theta_{Php} > 0.0008$
	$\theta_{hmhp} > 0.0008$
Fiducial cut 1	$\|\|p_x(d)\|\| \leq 0.317(\|\|p_z(d)\|\| - 2000\text{MeV/c})$
Fiducial cut 2 excluding:	$\|\|p_y(d)/p_z(d)\|\| < 0.02$ and $\|\|p_x(d)\|\| > (418 - 0.01397 \cdot p_z(d))$ and $\|\|p_x(d)\|\| < (497 + 0.01605 \cdot p_z(d))$
Trigger TIS	Lc_L0Global_TIS==1 and Lc_L0Global_TOS==0 and (Lc_Hlt1TrackMVADecision_TOS==1 or Lc_Hlt1TwoTrackMVADecision_TOS==1)
Trigger TOS	Lc_L0Global_TOS==1 and (Lc_Hlt1TrackMVADecision_TOS==1 or Lc_Hlt1TwoTrackMVADecision_TOS==1)

TABLE I.: Summary of cuts applied during the pre-selecction step for both samples. h represents either a pion or a kaon in their respective decays $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$ while d represents a generic daughter in these decays. ProbNN is a Particle Identification observable based on neural networks.

3˙1. *Pre-selection.* – During the pre-selection, a cut-based approach is applied to exclude mis-id events, reduce combinatorial background and exclude high asymmetry regions in order to increase our sensibility to CP asymmetry. The summary of cuts is reported in Table I. During this step the sample is also divided in TIS (Trigger Independent of Signal) and TOS (Trigger On Signal) samples based on the respective trigger mode. TIS sample is composed of those events where the final states used to reconstruct the candidate are not actively participating in the trigger decision, but it is the rest of the event responsible to trigger the event. TOS candidates are instead those candidates where the final states are actively participating in the trigger decision. This is done to better analyse and understand effects that are highly dependent on the trigger procedure, such as the induced trigger asymmetry related to detection asymmetry of the proton that prefers antiproton events with respect to proton events.

On the $\Lambda_c^+ \to p\pi^-\pi^+$ sample two additional cuts are applied to excluded non-CPV resonance present in the sample namely $\Lambda_c \to \Lambda\pi$ and $\Lambda_c \to pK_s^0$.

3˙2. *BDT training and optimisation.* – The samples, after the pre-selecction, are also selected with multivariate classifier, namely a BDT (Boosted Decision Tree). In order to do so, a BDT is trained on each sub-sample (year, magnet polarity and trigger configuration) independently. The variables used to train the BDT are reported in Table II. The multivariate classifier has been optimised to minimise the uncertainty on the asymmetry.

4. – Re-weighting and fit procedure

In order to ensure that the nuisance asymmetries are properly cancelled, the kinematic distributions of proton and of Λ_c^+ need to be equivalent in the two different decay channel. To do so kinematic weights are applied to the $\Lambda_c^+ \to p\pi^-\pi^+$ sample. These weights are evaluated using an iterative procedure. The variables involved in the procedure are:

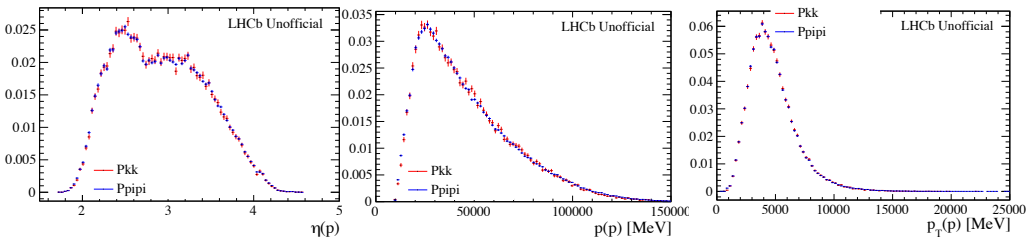
Λ_c variables	p variables	$h^{\pm}$ variables
$\chi^2_{IP}(\Lambda_c)$	$IP(p)$	$IP(h^{\pm})$
$\eta(\Lambda_c)$	$p_T(p)$	$p_T(h^{\pm})$
$p_T(\Lambda_c)$	ProbNNghost(p)	ProbNNghost(h^+) $\cdot$ ProbNNghost(h^-)
$\phi(\Lambda_c)$		
$\chi^2_{\text{ENDVERTEX}}(\Lambda_c)$		
$DIRA(\Lambda_c)$		

TABLE II.: Variables provided to the BDT to perform the training and compute the BDT variable. $h^{\pm}$ is either the pion or the kaon, depending on the decay channel.

p_T, η, ϕ of the Λ_c^+ baryon and of the proton. During each iteration, the weights are evaluated for the 1-D distribution of a variable and applied to the distribution of the next variable in the list. The procedure iterates over the list several times, keeping the order of the variables fixed at each cycle. For the TOS sample there is a different fraction of protons that triggered the event in the two channels, so this fraction is also re-weighted. An example of resulting kinematic distributions are reported in fig. 1. After this procedure, a simultaneous fit on both charges is performed on the invariant mass distribution of the sample with the resulting weights from the previous step applied. The fit model is

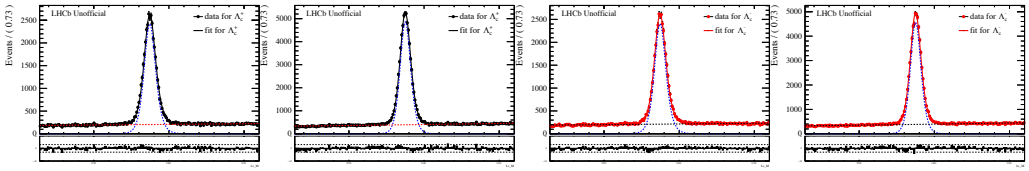
$$
\begin{aligned}
f(M) = & \frac{1}{2} n_{sig}[(1+A_{raw})(a \cdot J_+ + (1-a)G_+) + (1-A_{raw})(a \cdot J_- + (1-a)G_-)] + \\
& \frac{1}{2} n_{bkg}[(1+A_{bkg})E_+ + (1-A_{bkg})E_-],
\end{aligned} \tag{7}
$$

where n_{sig}, n_{bkg} are respectively the number of events of signal and background, $J_{\pm}$ and $G_{\pm}$ are johnson and gaussians functions with the mean parameter shared for the two charges but with the others shape parameters not shared between different charges, $E_{\pm}$ are exponential functions to model the background, and A_{bkg} is the raw asymmetry of background events. An example of fits for a sub-sample are reported in fig. 2.

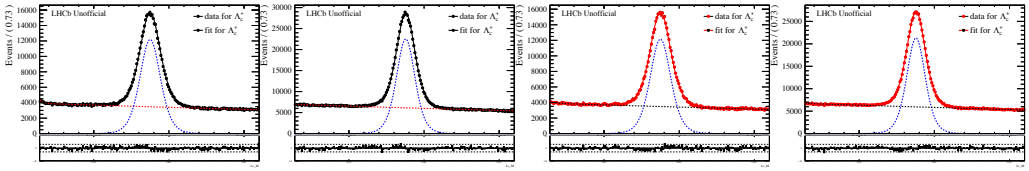


(a) (b) (c)

Fig. 1.: Examples of kinematic distributions of the proton after the reweighting procedure, for both decay channels overlapped. The kinematics are compatible, so that the procedure of removing nuisance asymmetries can be performed.



(a) $\Lambda_c^+ \to pK^-K^+$ TOS positive charge (b) $\Lambda_c^+ \to pK^-K^+$ TIS positive charge (c) $\Lambda_c^+ \to pK^-K^+$ TOS negative charge (d) $\Lambda_c^+ \to pK^-K^+$ TIS negative charge



(e) $\Lambda_c^+ \to p\pi^-\pi^+$ TOS positive charge (f) $\Lambda_c^+ \to p\pi^-\pi^+$ TIS positive charge (g) $\Lambda_c^+ \to p\pi^-\pi^+$ TOS negative charge (h) $\Lambda_c^+ \to p\pi^-\pi^+$ TIS negative charge

Fig. 2.: Invariant mass distribution with their respective fit for the 2018 Magnet Down sample for both decays.

5. – Preliminary results

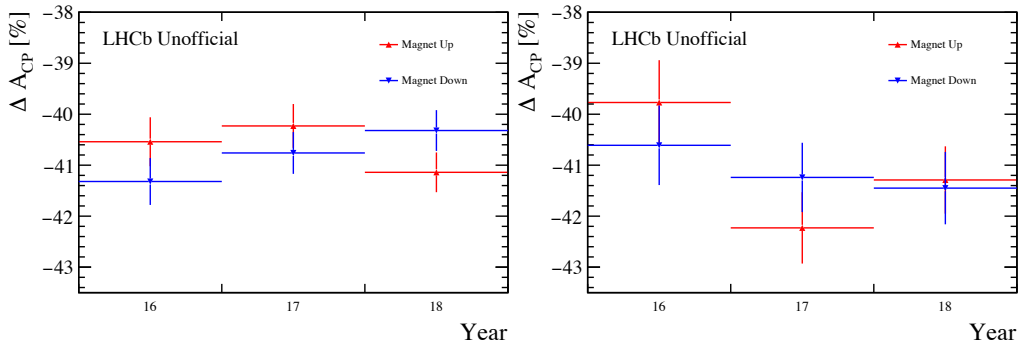
The resulting value for ΔA_{CP} are extracted from the simultaneous fits. For the TIS samples the results are compatible between magnet polarities while for TOS samples there is an inconsistency in 2018 magnet up and magnet down samples. This is due to a correlation between kinematics of the particles that is due to the hadron calorimeter at the trigger level that induce an asymmetry which is not properly cancelled with eq. 4. To eliminate this additional asymmetry, events with two particles in a cluster are excluded from the analysis. For each sub-sample, the blinded results are reported in fig. 3. The centre value of the result is blinded with a random shift on both the $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$ raw asymmetries, different in the two channels, but identical in each sub-sample, while uncertainties are not blinded. Statistical uncertainties are smaller with respect to Run 1 measurement and are estimated to be between 0.39% and 0.84% depending on the sub-sample. The resulting combination of each sub-sample is

$$\Delta A_{CP} = (-\mathrm{XX.XX} \pm 0.15_{stat})\%, \tag{8}$$

resulting in a statistical uncertainty that is six times smaller with respect to Run 1 result [2].

6. – Preliminary systematic studies

Preliminary systematic studies has also been performed to ensure that the approximation of eq. 4 is reasonable. To do so, the Cabibbo favoured decay $\Lambda_c^+ \to pK^-\pi^+$, which is used as control channel, is employed to estimate the detection asymmetries $A_D(K^-K^+)$ and $A_D(\pi^-\pi^+)$. Two different methods have been used. A data-driven technique, that estimate this uncertainty with a similar approach to the ΔA_{CP} measurement employed in this analysis, reports detection asymmetries of $A_D(KK) = (0.006 \pm 0.057)\%$ and



(a) TIS samples (b) TOS samples

Fig. 3.: ΔA_{CP} results for each sub-sample analysed. The centre value is blinded while uncertainties are not, as described in Section **5**.

$A_D = (0.019 \pm 0.061)\%$ well below statistical uncertainties. The other method is based on a previous analysis of LHCb [3] that also has measured detection asymmetry of both the pion and the kaon as function of momentum. With this method, the contribution of each event is computed based on the momentum of the daughters from the detection asymmetry tables provided by the previous analysis [3]. The final detection asymmetries are then the sum of each event contribution and result in lower asymmetries.

7. – Conclusions

The combination of preliminary results of all the sub-sample ΔA_{CP} is

$$\Delta A_{CP} = (-\mathrm{XX.XX} \pm 0.15_{stat} \pm 0.05_{syst})\%, \tag{9}$$

and it will greatly increase precision on this measurement with respect to Run 1. The systematic uncertainties are only preliminary estimated and are well below the statistical uncertainty. Up to now, this analysis only considers prompt produced Λ_c^+ but in the future it is planned to include Λ_c produced by Λ_b^0 decays. This will increase the statistic power of the analysis.

REFERENCES

[1] *Observation of CP Violation in Charm Decays* The LHCb Collaboration, *Phys. Rev. Lett.*, **122** (2019) 211803
[2] *A measurement of the CP asymmetry difference in* $\Lambda_c^+ \to pK^-K^+$ *and* $p\pi^-\pi^+$ *decays.* The LHCb Collaboration, *JHEP*, **03** (2018) 182
[3] *A search for CP violation in* $\Lambda_b^0 \to pK^-$ *and* $\Lambda_b^0 \to p\pi^-$ *decays.* The LHCb Collaboration, *Phys. Lett. B*, **787** (2018) 124-133