Tightening constraints on $CP$ violation phase in $b$-baryon decays

Shunan Zhang$^1$, Yi Jiang$^2$, Zewen Chen$^2$, Wenbin Qian$^2$

$^1$State Key Laboratory of Nuclear Physics and Technology & School of Physics, Peking University, Beijing, China
$^2$University of Chinese Academy of Sciences, Beijing, China

Abstract

In this paper, a new observable, the decay parameter $\alpha$, is proposed for the measurement of the weak phase $\gamma$ in $\Lambda_0^b \rightarrow D \Lambda$ decays, further tightening our understanding of $CP$ violation in addition to the decay rate asymmetry. Feasibility studies show that adding this observable improves the sensitivity on $\gamma$ by up to 60% and makes the decays one of the most promising places to measure angle $\gamma$ and to search for $CP$ in $b$-baryon decays. This new observable could also be applied to other processes with two or more consequent weak baryon decays.
The current focus on search for \( CP \) violation is observed yet. Finding \( CP \) violation in baryon decays will be an important step towards understanding the large matter-antimatter asymmetry observed in Universe. The current focus on search for \( CP \) violation in baryon decays are in charmless final states, however, a non-zero \( \gamma \) determined in b-baryon decays into charmed particles will also be an unambiguous sign of \( CP \) violation. The ADS decay of \( \Lambda^0 \to D(K^+\pi^-)pK^- \) has recently been observed and \( CP \) violation parameters are measured. Throughout the paper, charge-conjugation is applied if not specified. Extracting the angle \( \gamma \) from \( \Lambda^0 \to DpK^- \) decays are complicated due to many resonances involved. The spin-\(1/2\) nature of \( \Lambda^0 \) and \( p \) baryons makes it even more difficult than the partner decays of \( B^+ \to DK^+ \). Additional strong parameters have to be added to take into account different angular momentum contributions to the decay amplitudes and thus dilute the sensitivity to \( \gamma \).

In this paper, we propose to measure the angle \( \gamma \) in \( \Lambda^0 \to D\Lambda \) decays, which have similar Feynman diagrams as \( \Lambda^0 \to DpK^- \) in the \( \Lambda^* \) region. Unlike \( \Lambda^0 \to DpK^- \), an additional observable can be measured which significantly increases the sensitivity on \( \gamma \).

The angular momentum between \( D \) and \( \Lambda \) could be either \( S \)-wave or \( P \)-wave and one has to take both into account when measuring the angle \( \gamma \). The \( S \)-wave decay amplitudes are written as

\[
A_S(\Lambda^0 \to D\Lambda) = A_{c,S}, \tag{1}
\]

\[
A_S(\Lambda^0 \to \bar{D}^0\Lambda) = A_{c,S}r_{B,S}e^{i(\delta_{B,S} - \gamma)}, \tag{2}
\]

for the \( b \to c \) and \( b \to u \) processes, respectively. The parameters \( r_{B,S} \) and \( \delta_{B,S} \) describe the strong interaction parts of the amplitude ratio between the two processes. The corresponding \( P \)-wave amplitudes are denoted by replacing the subscript of \( S \) into \( P \). For the charge-conjugated decay amplitudes, the weak phase \( \gamma \) changes the sign while other parts remain the same.

The \( D^0 \) and \( \bar{D}^0 \) decay amplitudes into a final state \( f \) are given by \( A_D(f) \) and \( \bar{A}_D(f) \), respectively. Studies in \( B^+ \to DK^+ \) have shown that bias on \( \gamma \) caused by ignoring
$D^0$-$\bar{D}^0$ mixing effect and $CP$ violation in $D$ decays is less than 1° $^{25,27}$. In the recent LHCb $\gamma$ combination $^{28}$, they find that by fitting the $\gamma$ and $D$ mixing and $CP$ violation observables together, additional constraints on the $D$ mixing parameters are obtained. In this study, we neglect these contributions since their effects on $\gamma$ are marginal for the current small statistics of $\Lambda_b^0 \to D\Lambda$ decays and focus more on methodology itself. In the assumption, we have $\bar{A}_D(f) = A_D(f)$ and $\bar{A}_D(f) = A_D(f)$. The full decay amplitude of $S$-wave is

$$A_S = A_{c,s}[A_D(f) + r_{B,S}e^{i(\delta_{B,S} - \gamma)}\bar{A}_D(f)],$$

and the decay rate of $\Lambda_b^0 \to D(f)\Lambda$ is given by

$$\Gamma(\Lambda_b^0 \to D(f)\Lambda) = |A_S|^2 + |A_P|^2 \propto (1 + r^2)|A_D(f)|^2 + (r_{B,S}^2 + r_{B,P}^2)|\bar{A}_D(f)|^2 + 2[r_{B,S}\Re(e^{i(\delta_{B,S} - \gamma)}\bar{A}_DA_D^*) + r_{B,P}r_{P}\Re(e^{i(\delta_{B,P} - \gamma)}\bar{A}_DA_D^*)].$$

The factor $|A_{c,s}|^2$ is omitted for simplicity and $A_{c,P}$ is replaced by $re^{i\alpha}A_{c,s}$. The parameters $r$ and $\delta$ are to be determined from data. Comparing Eq. [4] with that in $B^+ \to DK^+$ decays $^{28}$, one can immediately find the decay rate in $\Lambda_b^0$ decays are more complicated and have three additional strong parameters, $r$, $r_{B,P}$ and $\delta_{B,P}$, to be introduced to take into account contributions from $P$-wave. The subsequent decay of $\Lambda \to p\pi^-$ only contributes an overall factor of $|A_S|^2 + |A_P|^2$ to the decay rate, where $A_S$ and $A_P$ are the $S$- and $P$-wave amplitudes of $\Lambda \to p\pi^-$, respectively, and are not listed.

There are other variables proposed to study $CP$ violation in hyperon decays $^{29,30}$, the decay parameters. The decay parameters contain interference information between $S$- and $P$-waves. As $\Lambda_b^0$ produced in $pp$ collisions at LHC is found to be unpolarized $^{31}$, the only relevant decay parameter for $\Lambda_b^0 \to D\Lambda$ is

$$\alpha_- = \frac{2\Re(A_{S}^*A_P)}{|A_S|^2 + |A_P|^2},$$

which can be measured using angular distributions

$$\frac{d\Gamma(\Lambda_b^0 \to D\Lambda(p\pi^-))}{d\Phi} \propto 1 + \alpha_- \alpha_+ \cos \theta.$$  

Here $\theta$ is the helicity angle of the $\Lambda \to p\pi^-$ decay, defined as the direction of $\pi^-$ with respect to the direction of $D$ in the rest frame of $\Lambda$. The $\alpha_{-\Lambda}$ and $\alpha_{\Lambda}^\Lambda$ are the decay parameters of the $\Lambda_b^0$ and $\Lambda$ decays. The $\alpha_{-\Lambda}^\Lambda$ has been measured very precisely $^{32}$ and $\alpha_{-\Lambda}^\Lambda$ is determined uniquely. This offers us additional observables to constrain the angle $\gamma$ as

$$\Re(A_{S}^*A_P) \propto r[|A_P|^2 \cos \delta + r_{B,S}r_{B,P} \cos(\delta + \delta_{B,P} - \delta_{B,S})|\bar{A}_D|^2 + \Re[r_{B,S}e^{i(\delta_{B,S} - \gamma - \delta)}A_D\bar{A}_D + r_{B,P}e^{i(\delta_{B,P} - \gamma + \delta)}A_D^*\bar{A}_D]].$$

Combing Eq.[7] and Eq.[4], the formula for $\alpha_{-\Lambda}^\Lambda$ is obtained. In the above formula, despite the additional parameter $\delta$, there are more observables when considering the many decays in this study and their charge-conjugated ones. When $\alpha$ in different $D$ decays are the same, one obtains $r_{B,S} = r_{B,P}$ and $\delta_{B,S} = \delta_{B,P}$, the complications of $\Lambda_b^0$ decays degenerate and the sensitivity on $\gamma$ from $\Lambda_b^0 \to D\Lambda$ can be considered in a similar way as in $B^+ \to DK^+$. 


However, \( r_B \sim 0.4 \) in \( \Lambda_b^0 \to DpK \) is larger than that in \( B^+ \sim 0.1 \) \cite{28} and results in larger \( CP \) violation effects.

Sensitivities on \( \gamma \) are studied using the decay rates, with and without the decay parameter \( \alpha \). The decay channels of \( D \) mesons considered are \( D \to K^+K^- \), \( D \to \pi^+\pi^- \), \( D \to K^+_0\pi^+\pi^- \) and \( D \to K^{±}\pi^±\pi^+\pi^- \). For multi-body final states, amplitude variations over the phase space needs to be taken into account. It could be done either by using an amplitude model to describe the \( D \) decays or by a model-independent method where the \( D \) decay information is obtained from charm factories using quantum correlated \( D \) samples from \( \psi(3770) \to D^0D^0 \). The model-independent method has the advantage of small systematic uncertainties and is more preferred for precise measurements. In this paper, we take the model-independent strategy where the phase space of \( D \) decays is divided into different bins and only the integrated information in these bins is used. The strong phase parameters \( c_i \) and \( s_i \) of \( D \to K^0\pi^+\pi^- \) decays are measured by CLEO-c and BESIII experiments \cite{33,35} and the coherent factors \( R_D \) and effective strong phase difference \( \delta_D^i \) for \( D \to K^±\pi^±\pi^+\pi^- \) are measured using CLEO-c data \cite{36}.

The \( \Lambda^0_b \to D\Lambda \) has not been observed yet. Predictions based on factorization approach \cite{37,39} indicates that the branching fraction of \( \Lambda^0_b \to D\Lambda \) is about 200 times smaller than that of \( \Lambda^0_b \to J/\psi\Lambda \). Around 300 \( \Lambda^0_b \to D(K^±\pi^±)\Lambda \) events are expected to be reconstructed based on the data collected by LHCb in the years 2011-2018 \cite{31}, and is used for the sensitivity estimation. The numbers for the other channels are scaled accordingly based on the formalism described previously. However, the yields of \( D \to K^0\pi^+\pi^- \) and \( D \to K^±\pi^±\pi^+\pi^- \) are further scaled by a factor of 0.16 and 0.18 \cite{40,42} to take into account their efficiency differences with respect to the two-body decays.

In the study, \( r_{B,S} \) and \( r_{B,P} \) are set to 0.4 and 0.3, respectively, as both \( \Lambda^0_b \to D^0\Lambda \) and \( \Lambda^0_b \to D^0\Lambda \) decays are color suppressed. The \( r \) value describes the amplitude ratio between \( S \)- and \( P \)-waves and three sets of values (0.5, 1 or 2) are chosen. The three phases, \( \delta \), \( \delta_{B,S} \) and \( \delta_{B,P} \), are also set to three different values, \( 0^\circ \), \( 60^\circ \) and \( 150^\circ \). The \( \gamma \) input value is chosen to be \( 65^\circ \) and the charm inputs are taken from their averaged values \cite{32} or from those measured with CLEO-c or BESIII data \cite{33,36}.

Pseudo data samples are generated according to the yields and \( \alpha \) obtained from a set of parameters. A \( \chi^2 \) fit is then performed, where yields and \( \alpha \) are considered to be independent as is shown in toys. In addition to the physical parameters, normalization factors are also considered as free parameters. The two-body \( D \) decays share the same normalization factor following what has been done in real measurements, while the \( K^0\pi^+\pi^- \) and \( K^±\pi^±\pi^+\pi^- \) have standalone normalization factors. This procedure is performed 1000 times for each set of inputs, and the uncertainty of \( \gamma \) is obtained by a Gaussian fit to its distribution from the toy samples. No bias is found in all the parameter settings. The procedures have been validated using parameters found in \( B^+ \to DK^+ \) decays \cite{28} with \( r = 0 \). An uncertainty of 2.4\(^\circ \) for the angle \( \gamma \) is achieved. The slightly better precision is due to ignoring background contributions.

Based on the above settings, the sensitivity of \( \gamma \) in \( \Lambda^0_b \to D\Lambda \) decays is found to be around \( 12 - 36^\circ \) as shown in Fig. \ref{fig:1}. Dependence on the input values of \( r, \delta_{B,S} \) and \( \delta_{B,P} \) are found, while little on \( \delta \). The sensitivity on \( \gamma \) is improved by up to 60\% when including the
Figure 1: Statistical uncertainties of $\gamma$ from feasibility studies (left) with and (right) without the decay parameter $\alpha$. The parameters $r_{B,S}$, $r_{B,P}$ and $\delta$ are set to be 0.4, 0.3 and 60°, respectively, for all toy samples.

proposed observable $\alpha$. Using the current data collected by the LHCb experiment, there are chances to observe $CP$ violation in $\Lambda_0^b \to D \Lambda$ decays while it is almost guaranteed to obtain a non-zero $\gamma$ with the data collected in the LHCb upgrade I period [43]. We strongly suggest the LHCb experiment performing the measurements proposed in this paper.

Acknowledgements

This work is partially supported by National Natural Science Foundation of China (NSFC) under grant No. 11975015, the Fundamental Research Funds for the Central Universities. We thank Yuehong Xie and Yuming Wang for useful discussions on the topic.

References

[1] N. Cabibbo, Unitary symmetry and leptonic decays, Phys. Rev. Lett. 10 (1963) 531.

[2] M. Kobayashi and T. Maskawa, CP-Violation in the Renormalizable Theory of Weak Interaction, Progress of Theoretical Physics 49 (1973) 652, arXiv:https://academic.oup.com/ptp/article-pdf/49/2/652/5257692/49-2-652.pdf.

[3] CKMfitter group, J. Charles et al., Current status of the standard model CKM fit and constraints on $\Delta F = 2$ new physics, Phys. Rev. D91 (2015) 073007, arXiv:1501.05013, updated results and plots available at http://ckmfitter.in2p3.fr/.

[4] UTfit collaboration, M. Bona et al., The unitarity triangle fit in the standard model and hadronic parameters from lattice QCD: A reappraisal after the measurements of $\Delta m_s$ and $BR(B \to \tau \nu)$, JHEP 10 (2006) 081, arXiv:hep-ph/0606167, updated results and plots available at http://www.utfit.org/.

[5] J. Brod and J. Zupan, The ultimate theoretical error on $\gamma$ from $B \to DK$ decays, JHEP 01 (2014) 051, arXiv:1308.5663.
[6] M. Gronau and D. Wyler, *On determining a weak phase from CP asymmetries in charged B decays*, Phys. Lett. B 265 (1991) 172.

[7] M. Gronau and D. London, *How to determine all the angles of the unitarity triangle from $B^0_d \to DK_s$ and $B^0 \to D\phi$*, Phys. Lett. B 253 (1991) 483.

[8] D. Atwood, I. Dunietz, and A. Soni, *Enhanced CP violation with $B \to K D^0(D^0)$ modes and extraction of the Cabibbo-Kobayashi-Maskawa angle $\gamma$*, Phys. Rev. Lett. 78 (1997) 3257, arXiv:hep-ph/9612433.

[9] A. Giri, Y. Grossman, A. Soffer, and J. Zupan, *Determining $\gamma$ using $B^\pm \to DK^\pm$ with multibody $D$ decays*, Phys. Rev. D 68 (2003) 054018, arXiv:hep-ph/0303187.

[10] A. Bondar and A. Poluektov, *Feasibility study of model-independent approach to $\phi^3$ measurement using Dalitz plot analysis*, Eur. Phys. J. C 47 (2006) 347, arXiv:hep-ph/0510246.

[11] A. Bondar and A. Poluektov, *The use of quantum-correlated $D^0$ decays for $\phi^3$ measurement*, Eur. Phys. J. C 55 (2008) 51, arXiv:0801.0840.

[12] Heavy Flavor Averaging Group, Y. Amhis et al., *Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of 2018*, Eur. Phys. J. C81 (2021) 226, arXiv:1909.12524, updated results and plots available at https://hflav.web.cern.ch.

[13] LHCb collaboration, R. Aaij et al., *Search for CP violation in $\Xi^-_b \to pK^-K^-$ decays*, Phys. Rev. D104 (2021) 052010, arXiv:2104.15074.

[14] LHCb collaboration, R. Aaij et al., *Search for CP violation and observation of P violation in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ decays*, Phys. Rev. D102 (2020) 051101, arXiv:1912.10741.

[15] LHCb collaboration, R. Aaij et al., *Measurement of CP asymmetries in charmless four-body $\Lambda^0_b$ and $\Xi^0_b$ decays*, Eur. Phys. J. C79 (2019) 745, arXiv:1903.06792.

[16] LHCb collaboration, R. Aaij et al., *Search for CP violation in $\Lambda^0_b \to pK^-$ and $\Lambda^0_b \to p\pi^-$ decays*, Phys. Lett. B784 (2018) 101, arXiv:1807.06544.

[17] LHCb collaboration, R. Aaij et al., *Search for CP violation using triple product asymmetries in $\Lambda^0_b \to pK^-\pi^+\pi^-$, $\Lambda^0_b \to pK^-K^+K^-$, and $\Xi^0_b \to pK^-K^-\pi^+$ decays*, JHEP 08 (2018) 039, arXiv:1805.03941.

[18] LHCb collaboration, R. Aaij et al., *Search for CP violation in $\Xi^+_c \to pK^-\pi^+$ decays with model-independent techniques*, Eur. Phys. J. C80 (2020) 986, arXiv:2006.03145.

[19] LHCb collaboration, R. Aaij et al., *Search for CP violation in $\Lambda^+_c \to pK^-K^+$ and $\Lambda^+_c \to p\pi^-\pi^+$ decays*, JHEP 03 (2018) 182, arXiv:1712.07051.

[20] BESIII collaboration, M. Ablikim et al., *Polarization and entanglement in baryon-antibaryon pair production in electron-positron annihilation*, Nature Phys. 15 (2019) 631, arXiv:1808.08917.

[21] BESIII collaboration, M. Ablikim et al., *$\Sigma^+$ and $\Sigma^-$ polarization in the $J/\psi$ and $\psi(3686)$ decays*, Phys. Rev. Lett. 125 (2020) 052004, arXiv:2004.07701.
[22] HyperCP collaboration, T. Holmstrom et al., Search for CP violation in charged-Ξ and Λ hyperon decays, Phys. Rev. Lett. 93 (2004) 262001, arXiv:hep-ex/0412038.

[23] M. B. Gavela, P. Hernandez, J. Orloff, and O. Pène, Standard model CP violation and baryon asymmetry, Mod. Phys. Lett. A9 (1994) 795, arXiv:hep-ph/9312215.

[24] LHCb collaboration, R. Aaij et al., Observation of the suppressed Λ_{b}^{0} \rightarrow DpK^{-} decay with D \rightarrow K^{+}\pi^{-} and measurement of its CP asymmetry, arXiv:2109.02621, submitted to PRD.

[25] Y. Grossman, A. Soffer, and J. Zupan, The Effect of D−\overline{D} mixing on the measurement of γ in B \rightarrow DK decays, Phys. Rev. D 72 (2005) 031501, arXiv:hep-ph/0505270.

[26] M. Rama, Effect of D−\overline{D} mixing in the extraction of γ with B_{-}^{0} \rightarrow D_{0}^{0}\pi^{-} and B^{-} \rightarrow D_{0}^{0}\pi^{-} decays, Phys. Rev. D 89 (2014) 014021, arXiv:1307.4384.

[27] W. Wang, CP violation effects on the measurement of the Cabibbo-Kobayashi-Maskawa angle γ from B \rightarrow DK, Phys. Rev. Lett. 110 (2013) 061802, arXiv:1211.4539.

[28] LHCb collaboration, R. Aaij et al., First simultaneous determination of CKM angle γ and charm mixing parameters from a combination of LHCb measurements, arXiv:2110.02350, submitted to JHEP.

[29] T. D. Lee et al., Possible Detection of Parity Nonconservation in Hyperon Decay, Phys. Rev. 106 (1957) 1367.

[30] T. D. Lee and C.-N. Yang, General Partial Wave Analysis of the Decay of a Hyperon of Spin 1/2, Phys. Rev. 108 (1957) 1645.

[31] LHCb collaboration, R. Aaij et al., Measurement of the Λ_{b}^{0} \rightarrow J/\psiΛ angular distribution and the Λ polarization in pp collisions, JHEP 06 (2020) 110, arXiv:2004.10563.

[32] Particle Data Group, P. A. Zyla et al., Review of particle physics, Prog. Theor. Exp. Phys. 2020 (2020) 083C01.

[33] CLEO collaboration, J. Libby et al., Model-independent determination of the strong-phase difference between D^{0} and D^{0} \rightarrow K_{S,L}^{0}h^{+}h^{-} (h = π,K) and its impact on the measurement of the CKM angle γ/φ_{3}, Phys. Rev. D 82 (2010) 112006, arXiv:1010.2817.

[34] BESIII collaboration, M. Ablikim et al., Determination of Strong-Phase Parameters in D \rightarrow K_{S,L}^{0}\pi^{+}\pi^{-}, Phys. Rev. Lett. 124 (2020) 241802, arXiv:2002.12791.

[35] BESIII collaboration, M. Ablikim et al., Model-independent determination of the relative strong-phase difference between D^{0} and D^{0} \rightarrow K_{S,L}^{0}\pi^{+}\pi^{-} and its impact on the measurement of the CKM angle γ/φ_{3}, Phys. Rev. D 101 (2020) 112002, arXiv:2003.00091.

[36] T. Evans, J. Libby, S. Malde, and G. Wilkinson, Improved sensitivity to the CKM phase γ through binning phase space in B^{-} \rightarrow DK^{-}, D \rightarrow K^{+}π^{-}π^{−}π^{+} decays, Phys. Lett. B 802 (2020) 135188, arXiv:1909.10196.
[37] Y. K. Hsiao, P. Y. Lin, C. C. Lih, and C. Q. Geng, *Charmful two-body anti-triplet b-baryon decays*, Phys. Rev. D 92 (2015) 114013, arXiv:1509.05603.

[38] Y.-M. Wang, Y. Li, and C.-D. Lu, *Rare Decays of $Λ_b \to Λ + γ$ and $Λ_b \to Λ + l^+l^−$ in the Light-cone Sum Rules*, Eur. Phys. J. C 59 (2009) 861, arXiv:0804.0648.

[39] Y.-M. Wang and Y.-L. Shen, *Perturbative Corrections to $Λ_b \to Λ$ Form Factors from QCD Light-Cone Sum Rules*, JHEP 02 (2016) 179, arXiv:1511.09036.

[40] LHCb collaboration, R. Aaij et al., *Measurement of CP observables in $B^± \to D(±)K^±$ and $B^± \to D(±)π^±$ decays using two-body $D$ final states*, JHEP 04 (2021) 081, arXiv:2012.09903.

[41] LHCb collaboration, R. Aaij et al., *Measurement of the CKM angle $γ$ in $B^± \to DK^±$ and $B^± \to Dπ^±$ decays with $D \to K_S h^+ h^−$*, JHEP 02 (2021) 0169, arXiv:2010.08483.

[42] LHCb collaboration, R. Aaij et al., *Measurement of CP observables in $B^± \to DK^±$ and $B^± \to Dπ^±$ with two- and four-body $D$ decays*, Phys. Lett. B760 (2016) 117, arXiv:1603.08993.

[43] LHCb collaboration, *Framework TDR for the LHCb Upgrade: Technical Design Report*, CERN-LHCC-2012-007, 2012.