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Current challenges and future prospects for γ from $B \to Dhh'$ decays

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Decays of the type $B \to Dhh'$, where a b hadron decays to a neutral charm meson that can be an admixture of D^0 and $\bar{D}^0$ states together with two light particles that are typically a kaon and a pion, have demonstrated potential to enable precise determinations of the angle γ of the CKM Unitarity Triangle. The current status and future prospects of these measurements are reviewed.

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The angle γ of the CKM Unitarity Triangle is a key parameter of quark flavour physics. It is the only *CP*-violating parameter that can be measured using only tree-level decays, and as such is a benchmark Standard Model reference point (for a detailed review, see Ref. [1]). Its precise determination is essential in order to be able to disentangle possible contributions from physics beyond the Standard Model to other *CP*-violating observables that enter the global CKM fit.

The channels that are most commonly used to determine γ are of the type $B \to DK$, where a b hadron decays to a neutral charm meson together with a kaon. When the final state is accessible to both D^0 and $\bar{D}^0$ decays, the neutral D meson is an admixture of the flavour eigenstates. Since these are produced through $b \to u$ and $b \to c$ transitions, their interference is sensitive to the relative weak phase γ [2–5]. By measuring the rates and *CP* asymmetries of such decays, γ can be determined with negligible theoretical uncertainty [6].

The method can be extended to $B \to DK\pi$ decays. In this case, amplitude analysis of the B decay Dalitz plot [7] provides direct information about the relative phases, and therefore can be used to obtain precise information about γ without ambiguities in the solution. In particular, in the Dalitz plot analysis of $B^0 \to DK^+\pi^-$ decays,[1] interference between $B^0 \to DK^*(892)^0$ and $B^0 \to D_2^*(2460)^-K^+$ amplitudes can be used to obtain more information about γ than is available in a quasi-two-body analysis [8, 9]. A key point is that the $D_2^*(2460)^-K^+$ amplitude is flavour-tagged and therefore does not depend on the D decay final state. The method also allows the determination of additional hadronic parameters such as coherence factors that enter the formalism of the quasi-two-body approach [10].

Determination of γ with this method has recently been achieved, for the first time, by LHCb. In the first step, the Dalitz plot distribution of $B^0 \to \bar{D}^0K^+\pi^-$ decays is obtained by fitting a sample reconstructed in the $\bar{D}^0 \to K^+\pi^-$ channel (which is flavour-specific, to a good approximation). With the full LHC run I data sample of $3\,\text{fb}^{-1}$ of pp collision data at centre-of-mass energies of $\sqrt{s} = 7$ and $8\,\text{TeV}$, 2344 ± 66 signal decays are found inside the B^0 signal window [11]. The Dalitz plot analysis provides a model for the $b \to c$ transition, and reveals that the largest resonant contributions are from the $K^*(892)^0$ and $D_2^*(2460)^-$ states, with additional significant components from $K\pi$ and $D\pi$ S-waves. Results on the masses and widths of the $D_0^*(2400)^-$ and $D_2^*(2460)^-$ states are also obtained in the analysis.

With the $b \to c$ model thus established, the analysis is extended to include decays of the D meson to the *CP*-even K^+K^- and $\pi^+\pi^-$ final states, where yields of 339 ± 22 and 168 ± 19 signal events are available inside the B^0 signal window [12], as shown in Fig. 1. A simultaneous Dalitz plot fit, implemented in Laura++ [13] with the *jFit* method [14], is carried out to the samples with $D \to K^+\pi^-$, K^+K^- and $\pi^+\pi^-$ – this is the first such simultaneous Dalitz plot analysis ever performed. The $B^0 \to DK^+\pi^-$, $D \to K^+\pi^-$ sample is fitted with the $b \to c$ model, while the model is modified for the $D \to K^+K^-$ and $\pi^+\pi^-$ samples to account for effect of the $b \to u$ contributions. Specifically, the complex coefficient c_j which describes the relative contribution of the resonance j to the overall amplitude is unchanged for $D\pi^-$ resonances, since the charge of the pion tags the flavour of the resonance, while amplitudes for $K^+\pi^-$ resonances receive additional contributions,

$$c_j \longrightarrow \begin{cases} c_j & \text{for a } D\pi^- \text{ resonance}\,, \\ c_j\,[1 + x_{\pm,j} + iy_{\pm,j}] & \text{for a } K^+\pi^- \text{ resonance}\,, \end{cases} \tag{1}$$

[1] The inclusion of charge conjugate processes is implied throughout unless explicitly stated otherwise.

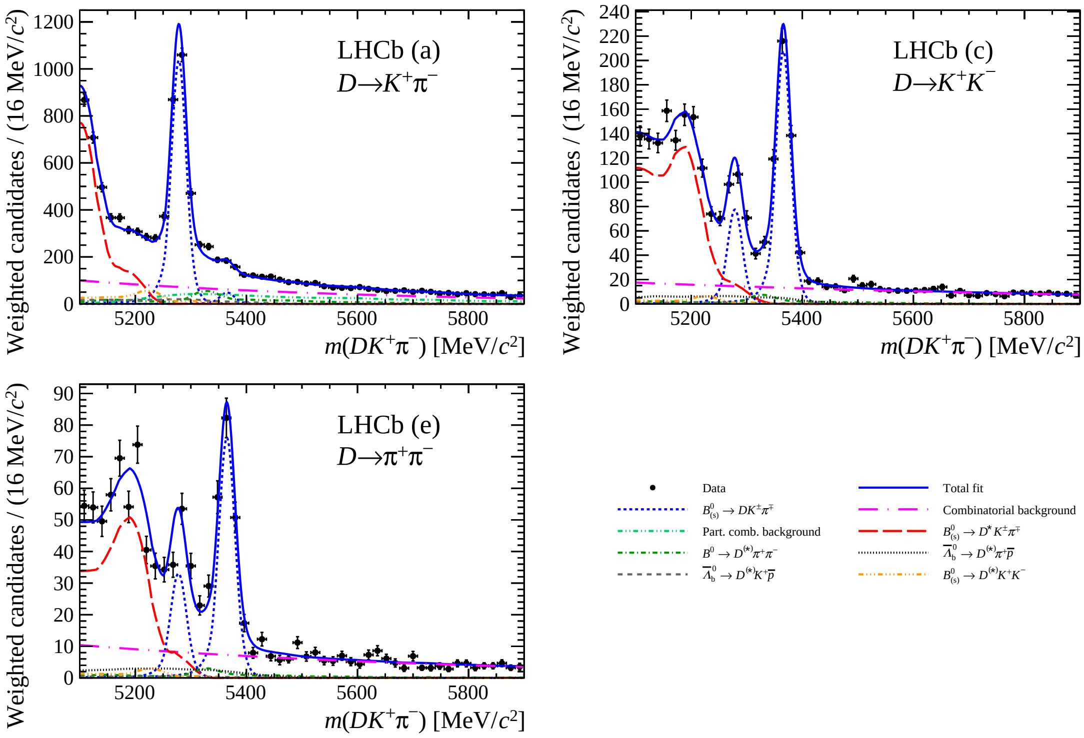

Figure 1: Candidates for $B^0 \to DK^+\pi^-$ decays in the (top left) $D \to K^+\pi^-$, (top right) K^+K^- and (bottom left) $\pi^+\pi^-$ channels [12]. The largest peak in the *CP*-eigenstate modes is due to $B_s^0 \to \bar{D}^0 K^-\pi^+$ decays, with an associated satellite peak (long-dashed red line) from $B_s^0 \to \bar{D}^{*0} K^-\pi^+$ decays. The candidates have been weighted by the signal-to-background fractions in the different samples that are fitted.

with $x_{\pm,j} = r_{B,j}\cos(\delta_{B,j} \pm \gamma)$ and $y_{\pm,j} = r_{B,j}\sin(\delta_{B,j} \pm \gamma)$, where the $+$ and $-$ signs correspond to B^0 and $\bar{B}^0$ decay amplitudes, respectively. Here $r_{B,j}$ and $\delta_{B,j}$ are the relative magnitude and strong phase of the $b \to u$ and $b \to c$ amplitudes for each $K^+\pi^-$ resonance j. A component corresponding to the $B^0 \to D_{s1}^*(2700)^+\pi^-$ decay, which is mediated by the $b \to u$ amplitude alone, is also included.

The Dalitz plots for candidates in the $B^0 \to DK^+\pi^-$, $D \to K^+K^-$ and $\pi^+\pi^-$ samples combined are shown in Fig. 2, together with projections of the data and the fit result onto $m(K^\mp\pi^\pm)$. Within the available statistics, there is no evidence for *CP* violation. The results for the parameters of the $B^0 \to DK^*(892)^0$ decay are consistent with those of a quasi-two-body analysis based on the same data sample [15]. The determination of the $x_\pm, y_\pm$ parameters of Eq. (1) allows also a comparison with results obtained from the $B^0 \to DK^*(892)^0$, $D \to K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$ mode [16, 17]: the $x_\pm$ results from the $B^0 \to DK^+\pi^-$ Dalitz plot analysis are slightly more precise, while the $y_\pm$ results are slightly less precise; all results are consistent.

Since the central values of the $x_\pm, y_\pm$ parameters are not significantly different from zero, limited precision on γ is obtained using the results of the $B^0 \to DK^+\pi^-$ Dalitz plot analysis alone. However, the analysis also yields information about the hadronic parameters needed to interpret results obtained from quasi-two-body analyses. In particular, the coherence factor κ, which would be unity in the case that the $K^*(892)^0$ selection window contains only contributions from the $K^*(892)^0$

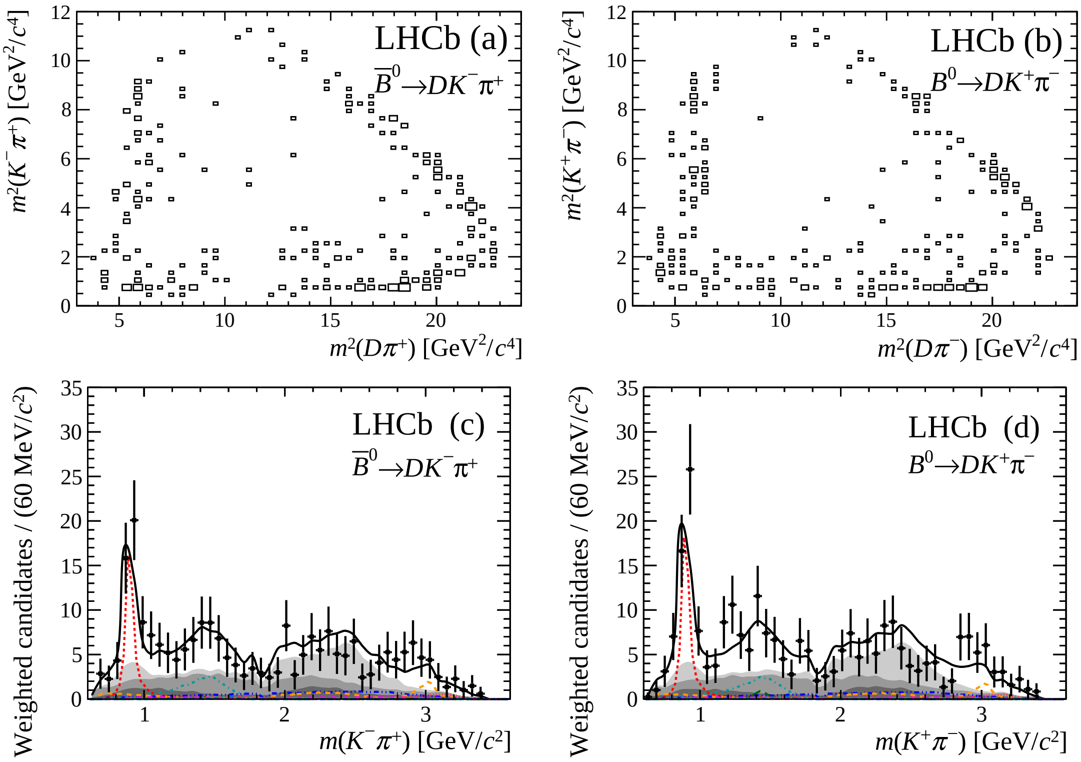

Figure 2: (Top) Dalitz plots for (left) $\bar{B}^0$ and (right) B^0 candidates, together with (bottom) their projections onto $m(K^\mp\pi^\pm)$ with results of the fit superimposed [12]. In the projections the shaded areas indicate backgrounds, while the red dotted line is the contribution from the $\overset{(-)}{K}{}^*(892)^0$ resonance.

resonance, is determined to be $\kappa = 0.958\,^{+0.005}_{-0.010}\,^{+0.002}_{-0.045}$, where the uncertainties are statistical and systematic. The results therefore have an important impact on the combined determination of γ using results from all $B \to DK$ type processes [18, 19]. The LHCb combination [18] gives for the ratio of magnitudes of $b \to u$ and $b \to c$ amplitudes, $r_B(DK^*(892)^0) = 0.218\,^{+0.045}_{-0.047}$, smaller than but consistent with the expected value of ~ 0.3. Analyses with larger data samples will therefore be important to see if this value increases, in which case $B^0 \to DK^*(892)^0$ decays will have an even larger impact on the overall combination than now. In addition to increasing the size of the sample, it will be important to improve understanding on $K\pi$ and $D\pi$ S-wave amplitudes (for which good progress has been reported recently [20, 21]) and to control background contributions from $B^0_s \to \bar{D}^{*0}K^-\pi^+$ decays (the $B^0_s \to \bar{D}^0K^-\pi^+$ Dalitz plot has already been studied [22, 23]). More D meson decay modes can also be added, including the possibility of a model-independent $B^0 \to DK^+\pi^-, D \to K^0_S\pi^+\pi^-$ double Dalitz plot analysis [24].

Given the success of the $B \to DK\pi$ Dalitz plot analysis, it is reasonable to ask whether similar approaches can be applied for other $B \to Dhh'$ modes. The isospin partner $B^+ \to DK^+\pi^0$ would be more challenging experimentally, due to the presence of a neutral pion in the final state. A further challenge in this channel is that $D\pi^0$ resonances are not flavour tagged by the charge of the pion, so the associated amplitudes can differ depending on the D meson final state. While this complicates the formalism, it also means that in principle there may be more interference between

$b \to u$ and $b \to c$ amplitudes, and therefore better sensitivity to γ. Although this mode has been investigated in the past [25], a more detailed investigation taking into account the latest knowledge is warranted [26].

A further potential advantage of the $B^+ \to DK^+\pi^0$ mode is that for many $D\pi$ resonances, the relative magnitude of the contributing amplitudes r_B can be known independently from studies of the $B^+ \to D^+K^+\pi^-$ and $B^+ \to D^-K^+\pi^+$ decays [27]. (This is not the case for the $D^*(2007)^0$ resonance, which is below threshold for decay to $D^+\pi^-$, but has other advantages [28]. The quasi-two-body approach is preferable for analysis of decays involving this narrow resonance.) Both these modes have recently been observed by LHCb [29,30]. A large $D_2^*(2460)^0$ component in seen in the Dalitz plot analysis of the favoured mode. In the suppressed mode, the available statistics are not sufficient for amplitude analysis, so instead a novel method involving weighting data by angular moments is used to set a limit on the $\bar{D}_2^*(2460)^0$ contribution. These results give an upper limit $r_B(D_2^*(2460)K^+) < 0.30$ (0.36) at 90 (95) % confidence level.

Extending to four-body decays, similar methods could potentially be used to determine γ from the interference of $b \to u$ and $b \to c$ amplitudes in $B^+ \to D_1(2420)K^+$ decays. A possible sign of the $b \to c$ decay was seen in early LHCb data [31], in the $\bar{D}_1(2420)^0 \to \bar{D}^0\pi^+\pi^-$ channel. In the case that the ground state D meson is reconstructed as a *CP* eigenstate, it is possible that decays of $D_1(2420)$ to the $D^{*+}\pi^-$ and $D(\pi^+\pi^-)$ would allow interference between flavour-tagged and untagged D mesons in the same final state. However, a full four-body amplitude analysis may be necessary, as there is also a significant contribution from $B^+ \to DK_1^+ \to DK^+\pi^+\pi^-$, which has been used to determine γ with a quasi-two-body approach [32]. Further studies will be necessary to establish by how much such an analysis would benefit the sensitivity to γ.

All b hadron species are produced in pp collisions, and LHCb has recorded large samples of B_s^0 and Λ_b^0 decays. Hence, possibilities to determine γ in $B_s^0 \to DK^+K^-$ and $\Lambda_b^0 \to DpK^-$ decays can also be considered. Both of these modes have been observed in LHCb data [33–35], but with modest yields. Moreover, a full analysis of $B_s^0 \to DK^+K^-$ decays requires tagging of the initial B meson flavour, which leads to a reduction of sensitivity. In the case of $\Lambda_b^0 \to DpK^-$ decays, the kinematic boundary of the phase space (due to the proton mass) limits overlap between Dp and pK^- amplitudes, and thus it is unclear how much gain in sensitivity may be possible compared to the quasi-two-body analysis. A detailed study of the amplitude structure of $\Lambda_b^0 \to DpK^-$ decays, similar to that recently performed for the related $\Lambda_b^0 \to Dp\pi^-$ channel [36] will be needed to address this issue.

In summary, $B \to Dhh'$ decays provide many interesting ways to determine γ, with Dalitz plot analysis methods being particularly sensitive in certain cases. The results from these methods on the $B^0 \to DK^*(892)^0$ mode give competitive sensitivity to those from $B^+ \to DK^+$, with the precision expected to improve further as results with additional D decay modes become available. Other $B \to Dhh'$ decays, which have not yet been used to determine γ, are well worth pursuing, since in addition to helping to improve the overall knowledge of *CP* violation, these channels can also provide interesting results in charm meson spectroscopy.

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References

[1] T. Gershon and V. V. Gligorov, *CP violation in the B system*, Rep. Prog. Phys. (2017) , arXiv:1607.06746.

[2] M. Gronau and D. London, *How to determine all the angles of the unitarity triangle from $B^0 \to DK^0_S$ and $B^0_s \to D\phi$*, Phys. Lett. **B253** (1991) 483.

[3] M. Gronau and D. Wyler, *On determining a weak phase from charged B decay asymmetries*, Phys. Lett. **B265** (1991) 172.

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

[5] D. Atwood, I. Dunietz, and A. Soni, *Improved methods for observing CP violation in $B^\pm \to K^\pm D$ and measuring the CKM phase γ*, Phys. Rev. **D63** (2001) 036005, arXiv:hep-ph/0008090.

[6] J. Brod and J. Zupan, *The ultimate theoretical error on γ from $B \to DK$ decays*, JHEP **01** (2014) 051, arXiv:1308.5663.

[7] R. H. Dalitz, *On the analysis of τ-meson data and the nature of the τ-meson*, Phil. Mag. **44** (1953) 1068.

[8] T. Gershon, *On the measurement of the unitarity triangle angle γ from $B^0 \to DK^{*0}$ decays*, Phys. Rev. **D79** (2009) 051301, arXiv:0810.2706.

[9] T. Gershon and M. Williams, *Prospects for the measurement of the unitarity triangle angle γ from $B^0 \to DK^+\pi^-$ decays*, Phys. Rev. **D80** (2009) 092002, arXiv:0909.1495.

[10] M. Gronau, *Improving bounds on γ in $B^\pm \to DK^\pm$ and $B^{\pm,0} \to DX_s^{\pm,0}$*, Phys. Lett. **B557** (2003) 198, arXiv:hep-ph/0211282.

[11] LHCb collaboration, R. Aaij *et al.*, *Amplitude analysis of $B^0 \to \bar{D}^0K^+\pi^-$ decays*, Phys. Rev. **D92** (2015) 012012, arXiv:1505.01505.

[12] LHCb collaboration, R. Aaij *et al.*, *Constraints on the unitarity triangle angle γ from Dalitz plot analysis of $B^0 \to DK^+\pi^-$ decays*, Phys. Rev. **D93** (2016) 112018, arXiv:1602.03455.

[13] Laura++ Dalitz plot fitting package, http://laura.hepforge.org/, University of Warwick.

[14] E. Ben-Haim, R. Brun, B. Echenard, and T. E. Latham, *JFIT: A framework to obtain combined experimental results through joint fits*, arXiv:1409.5080.

[15] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP violation parameters in $B^0 \to DK^{*0}$ decays*, Phys. Rev. **D90** (2014) 112002, arXiv:1407.8136.

[16] LHCb collaboration, R. Aaij *et al.*, *Model-independent measurement of the CKM angle γ using $B^0 \to DK^{*0}$ decays with $D \to K^0_S\pi^+\pi^-$ and $K^0_SK^+K^-$*, JHEP **06** (2016) 131, arXiv:1604.01525.

[17] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CKM angle γ using $B^0 \to DK^{*0}$ with $D \to K^0_S\pi^+\pi^-$ decays*, JHEP **08** (2016) 137, arXiv:1605.01082.

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[18] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CKM angle γ from a combination of LHCb results*, JHEP **12** (2016) 087, arXiv:1611.03076.

[19] Y. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016*, arXiv:1612.07233.

[20] LHCb collaboration, R. Aaij *et al.*, *Amplitude analysis of $B^- \to D^+\pi^+\pi^-$ decays*, Phys. Rev. **D94** (2016) 072001, arXiv:1608.01289.

[21] A. Palano and M. R. Pennington, *$K\pi$ $I = 1/2$ S-wave from η_c decay data at BaBar and classic meson-meson scattering from LASS*, arXiv:1701.04881.

[22] LHCb collaboration, R. Aaij *et al.*, *Observation of overlapping spin-1 and spin-3 $\bar{D}^0K^-$ resonances at mass $2.86\,\mathrm{GeV}/c^2$*, Phys. Rev. Lett. **113** (2014) 162001, arXiv:1407.7574.

[23] LHCb collaboration, R. Aaij *et al.*, *Dalitz plot analysis of $B_s^0 \to \bar{D}^0K^-\pi^+$ decays*, Phys. Rev. **D90** (2014) 072003, arXiv:1407.7712.

[24] T. Gershon and A. Poluektov, *Double Dalitz Plot analysis of the decay $B^0 \to DK^+\pi^-$, $D \to K_S^0\pi^+\pi^-$*, Phys. Rev. **D81** (2010) 014025, arXiv:0910.5437.

[25] R. Aleksan, T. C. Petersen, and A. Soffer, *Measuring the weak phase γ in color allowed $B \to DK\pi$ decays*, Phys. Rev. **D67** (2003) 096002, arXiv:hep-ph/0209194.

[26] T. Gershon, T. Latham, C. Wallace, and M. Whitehead, *Prospects for the determination of the CKM angle γ from Dalitz plot analysis of $B^\pm \to DK^\pm\pi^0$ decays*, 2016. Talk given at ICHEP2016, available at https://indico.cern.ch/event/432527/contributions/1071700/.

[27] N. Sinha, *Determining γ using $B \to D^{**}K$*, Phys. Rev. **D70** (2004) 097501, arXiv:hep-ph/0405061.

[28] A. Bondar and T. Gershon, *On ϕ_3 measurements using $B^- \to D^*K^-$ decays*, Phys. Rev. **D70** (2004) 091503, arXiv:hep-ph/0409281.

[29] LHCb collaboration, R. Aaij *et al.*, *First observation and amplitude analysis of the $B^- \to D^+K^-\pi^-$ decay*, Phys. Rev. **D91** (2015) 092002, Erratum ibid. **D93** (2016) 119901, arXiv:1503.02995.

[30] LHCb collaboration, R. Aaij *et al.*, *First observation of the rare $B^+ \to D^+K^+\pi^-$ decay*, Phys. Rev. **D93** (2016) 051101(R), Erratum ibid. **D93** (2016) 119902, arXiv:1512.02494.

[31] LHCb collaboration, R. Aaij *et al.*, *First observation of the decays $\bar{B}^0 \to D^+K^-\pi^+\pi^-$ and $B^- \to D^0K^-\pi^+\pi^-$*, Phys. Rev. Lett. **108** (2012) 161801, arXiv:1201.4402.

[32] LHCb collaboration, R. Aaij *et al.*, *Study of $B^- \to DK^-\pi^+\pi^-$ and $B^- \to D\pi^-\pi^+\pi^-$ decays and determination of the CKM angle γ*, Phys. Rev. **D92** (2015) 112005, arXiv:1505.07044.

[33] LHCb collaboration, R. Aaij *et al.*, *Observation of $B^0 \to \bar{D}^0K^+K^-$ and evidence for $B_s^0 \to \bar{D}^0K^+K^-$*, Phys. Rev. Lett. **109** (2012) 131801, arXiv:1207.5991.

[34] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay $B_s^0 \to \bar{D}^0\phi$*, Phys. Lett. **B727** (2013) 403, arXiv:1308.4583.

[35] LHCb collaboration, R. Aaij *et al.*, *Study of beauty baryon decays to D^0ph^- and $\Lambda_c^+h^-$ final states*, Phys. Rev. **D89** (2014) 032001, arXiv:1311.4823.

[36] LHCb collaboration, R. Aaij *et al.*, *Study of the D^0p amplitude in $\Lambda_b^0 \to D^0p\pi^-$ decays*, arXiv:1701.07873, submitted to JHEP.

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