

Progress and challenges in the study of direct CP violation and γ determinations: summary of CKM 2018 working group V

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Abstract

Purely hadronic B decays are vital to the study of CP violation within and beyond the Standard Model of particle physics. One key contribution is the determination of the CKM angle γ . In addition, very large direct CP violation has been observed in regions of phase space of multi-body hadronic decays, the description of which remains a significant challenge. In this summary, we discuss the recent results and progress for the determination of γ and direct CP violation in purely hadronic B decays as presented at CKM 2018.

1 Introduction

Within the Standard Model of particle physics (SM), CP violation is accommodated by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The violation of the CP symmetry is a crucial element to explain the imbalance between matter and anti-matter in the universe, and its study forms an important part of the flavour physics program. The goal is to precisely determine the SM CKM parameters, and to obtain insights in possible new sources of CP violation beyond the SM.

Purely hadronic B decays are vital to this endeavour. Decays like $B \rightarrow DK$, allow for a precise determination of the Unitary Triangle (UT) angle γ , which plays an important role in the study of CP violation. At the moment, this angle is the least well known of the three UT angles, however due to significant experimental progress this is expected to change in the near future. From a theoretical point, the study of CP violation in pure (charmless) hadronic B decays is challenging due to the strong decay dynamics of these decays. The incredible amount of data available from LHCb and the B-factories provides a perfect set-up, but requires reliable and precise theoretical predictions and poses experimental challenges. In this summary, we present recent experimental and theoretical progress, and give a brief outlook for the exciting future to come.

2 Determination of γ

One of the key parameters of the CKM matrix is the Unitarity Triangle (UT) angle γ :

$$\gamma = \arg \left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right). \quad (1)$$

It can be determined in a theoretically clean way from tree-level $B \rightarrow D^{(*)}K^{(*)}$ and $B \rightarrow D^{(*)}\pi$ decays using the interference between the $b \rightarrow u\bar{c}s(d)$ and $b \rightarrow c\bar{u}s(d)$ transitions. The theoretical uncertainty on γ determined from these decays is expected to be $\delta\gamma/\gamma \lesssim 10^{-7}$ as no penguin operators contribute to the decay amplitudes, and in addition electroweak box corrections are shown to be tiny [1, 2]. However, it has been pointed out that new physics contributions to the tree-level Wilson coefficients C_1 and C_2 might actually influence the determination of γ from tree decays [3, 4].

Several methods to determine γ have been proposed [5–8], differing in the type of D decays that are probed: the GLW [5, 6] method, exploiting D decays to CP -eigenstates; the ADS [8], using doubly Cabibbo-suppressed decays; the GGSZ [7], which exploits the three-body D decays to self-conjugate modes, such as $D^0 \rightarrow K_s^0 h^+ h^-$ ($h = K, \pi$). The best sensitivity is achieved by combining the various methods and decay modes as each of them has a different sensitivity to γ depending on the CP -conserving parameters entering the decay amplitudes. The latest combination of γ measurements by the LHCb collaboration [9] yield

$$\gamma = (74.0_{-5.8}^{+5.0})^\circ, \quad (2)$$

which is in very good agreement with the world averages $\gamma = (71.1_{-5.3}^{+4.6})^\circ$ [10], $\gamma = (73.5_{-5.1}^{+4.2})^\circ$ [11] and $\gamma = (70.0 \pm 4.2)^\circ$ [12]. The updated LHCb combination includes also three recent LHCb analyses of $B^+ \rightarrow D^{(*)}K^{(*)\pm}$ decays [13–15], all based on data from Run1 and Run2, and corresponding to an integrated luminosity of pp collisions of 1 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$, 2 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, and 2 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$. Particularly interesting is the analysis reported in

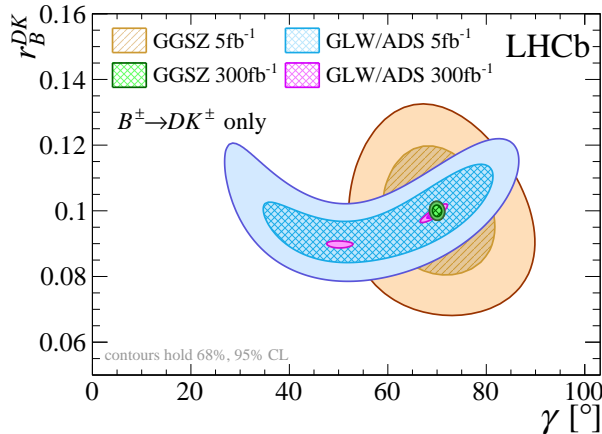


Figure 1: Comparison between the current results of LHCb using the GGSZ and the GLW/ADS methods, alongside with their future projections with 300 fb^{-1} , in the plane of γ vs. r_B^{DK} . Plot taken from [22]. Note: the parameter r_B^{DK} is an additional hadronic parameter quantifying the ratio between the amplitudes of the suppressed $b \rightarrow u$ and favoured $b \rightarrow c$ transitions of the B decay.

Ref. [15], where the $D^{*0} \rightarrow D^0 \pi^0$ and $D^{*0} \rightarrow D^0 \gamma$ decays are exploited without reconstructing the π^0 or the γ . In fact, the invariant-mass distribution of $B^+ \rightarrow D^{*0} h^+$ decays with a partially reconstructed D^{*0} has a peculiar shape, which allow for the separation of the $B^+ \rightarrow D^{*0} h^+$ from backgrounds and fully reconstructed $B^+ \rightarrow D^0 h^+$ decays. With the full LHCb Run 2 data, the attainable uncertainty on γ from this single decay is expected to be between 3° and 4° .

At the moment, the γ combination from LHCb in Eq. (2) is dominated by the results of GLW, ADS and GGSZ analyses, however, also other $B \rightarrow Dh$ modes contribute. Of those modes, very interesting are the tagged time-dependent analyses of the $B_s^0 \rightarrow D_s^- K^+$ [16] and $B^0 \rightarrow D^- \pi^+$ [17] decays. These analyses provide valuable information on both γ and $-2\beta_s$ (for the B_s^0 mode), and on both γ and β (for the B^0 mode) with minimal external inputs [18–21]. In particular, the B_s^0 mode, which can uniquely be probed at LHCb, allows for a determination of γ with a precision of approximately 20° with the current experimental precision using as the only external input the value $-2\beta_s$. Projections show that a precision of 2.5° on γ is achievable at the end of Run3 of LHCb from this channel alone [22].

With the increasing precision of the collected data sets, it will be possible to exploit also new decay modes to determine γ . Nice examples are B^0 and B_s^0 decays to $\bar{D}^0 \pi^+ \pi^-$ and $\bar{D}^0 K^+ K^-$ final states. A time-dependent analysis of the Dalitz plane of these decays provides significant information on γ , β and $-2\beta_s$ [6, 23]. The first observation of the $B_s^0 \rightarrow \bar{D}^0 K^+ K^-$ decay is reported by LHCb analyzing the full Run1 sample [24]. Restricting to the $K^+ K^-$ mass region around the $\phi(1020)$ also the $B_s^0 \rightarrow D^{*0} K^+ K^-$ decay is observed for the first time¹. Even though the statistics are still insufficient to fully exploit the full potential of these decays, the long term prospects are encouraging given the large sensitivity to γ provided by these modes [6, 22].

New analyses of $B \rightarrow Dh$ decays are also available from the Belle experiment [25]. The much cleaner environment of e^+e^- collisions and the fixed centre-of-mass energy allow to work with D -meson decays that involve γ and π^0 in the final state, that are very challenging for LHCb, like $D^0 \rightarrow K^- \pi^+ \pi^0$ or $D^0 \rightarrow K_s^0 \pi^+ \pi^- \pi^0$. This last final state is very interesting given its relatively large branching fraction of 5.2%. A precision on γ of 25° is expected from this

¹The technique of partially reconstructing $D^{*0} \rightarrow D^0 \pi^0$ and $D^{*0} \rightarrow D^0 \gamma$ decays is used.

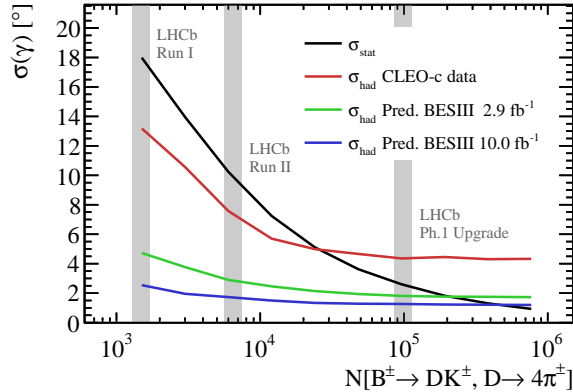


Figure 2: Contribution of CLEO-c and BES-III to the determination of γ from $B^+ \rightarrow D^0 K^+$ decay with the D^0 meson going to $\pi^+ \pi^- \pi^+ \pi^-$ final state. The uncertainty on γ as a function of the signal yields is determined considering different contribution from the charm factories. Plot taken from [28].

channel alone with the full Belle data set, while a 4.4° precision is foreseen if projecting to the 50 ab^{-1} of integrated luminosity of Belle-II [26]. Including all the main $B \rightarrow Dh$ modes, Belle-II is expected to measure the angle γ with a precision of 1° with 50 ab^{-1} of integrated luminosity [27]. The projection for Belle-II are encouragingly supported by the first run of data taking. With an integrated luminosity of approximately 0.5 fb^{-1} B - and D -meson decays have been rediscovered. A promising yield of 254 $B \rightarrow D\pi$ candidates is observed with the D mesons reconstructed using various final states.

As already mentioned, thanks to impressive data set that will be collected by Belle-II and the LHCb upgrade, the determination of the angle γ will reach an impressive precision of about 1° for each experiment in the next few years. Even more impressive are the prospects for a second upgrade of LHCb; collecting an integrated luminosity of 300 fb^{-1} would shrink the uncertainty on γ to 0.35° [22]. Figure 1 shows the comparison between the current determination of γ from LHCb and the expected determination with 300 fb^{-1} of integrated luminosity. However, the analyses that mainly contribute to the γ determination require external inputs, that will soon become the limiting factor to achieve such a precision. The best way to determine these input parameters is to study quantum-correlated charm decays, that can be produced at e^+e^- colliders operating at the $\psi(3770)$ resonance threshold. Decays of $\psi(3770)$ to two neutral charm mesons allow the measurement of the strong phases, the coherence factors and the CP content of multibody charm decays. In this respect the rôle of BES-III, and its predecessor CLEO-c, will be crucial. The current contribution of CLEO-c is quantified in an uncertainty of about 2° on the overall error on γ [29]. Fully exploiting the full sample collected by BES-III, corresponding to about 10 times the integrated luminosity of CLEO-c, will allow to reach a sub-degree precision on γ . As an example, in Figure 2 the contribution of BES-III and CLEO-c to the determination of γ from the $B^+ \rightarrow D^0 K^+$ decay with the D^0 meson going to $\pi^+ \pi^- \pi^+ \pi^-$ final state, is shown [28].

3 CP violation in two-body B decays

Two-body B decays are theoretically challenging to describe as both the initial and final states are purely hadronic. These decays have been studied in various approaches such as QCD factorization (QCDF) [30–32], pQCD [33–35] or by using flavour symmetries of the light quarks [36]. Here we focus on the status and prospects for QCD factorization [37] and recent developments for $B \rightarrow \pi K$ decays using flavour symmetries [38].

QCD factorization makes use of the heavy B meson mass to make a systematic expansion both in Λ/m_b as well as in α_s . Importantly, at leading order in Λ/m_b the strong phases required to generate CP violation are only generated at order α_s , making the study of these contributions crucial. While the topological tree amplitudes are known already at NNLO level [39–48], the leading penguin amplitudes represent the last missing ingredient to establish QCD factorization at the NNLO level to leading power in Λ_{QCD}/m_b . The calculation of the vertex correction to the latter amounts to a genuine two-loop, two-scale problem including a kinematic threshold, and applies state-of-the-art multi-loop techniques. Recently, also the leading penguin amplitudes were calculated [49, 50]. The NNLO correction turns out to be sizable, but there is no breakdown of the perturbative expansion [50]. The sizable NNLO effects in the amplitude gets diluted in quantities like amplitude ratios, direct CP asymmetries and branching ratios.

The key question is how to improve QCDF-based predictions for non-leptonic B-decays in the future [37]. On the perturbative side, the NNLO QCD correction to the power-suppressed but chirally enhanced (and therefore phenomenologically relevant) penguin amplitude a_6 are still missing, as well as NLO QED corrections. Moreover, it could be beneficial to combine insights from two-body decays with the QCDF formulation of three-body decays [51, 52]. The most urgent issue in two-body charmless nonleptonic B-decays in QCDF is, however, improving our poor understanding of power corrections. To date their inclusion amounts to a rather crude parametrisation [53] or to a data-driven approach [54]. An understanding of power corrections in QCDF on field-theoretic grounds is therefore highly desired, and ideas in this direction exist based on the ‘collinear anomaly’ [55, 56] in collider physics. The long-term goal is to obtain a comprehensive QCDF analysis of all channels and observables with a satisfactory treatment of power corrections.

In this respect, phenomenological studies using flavour symmetries can provide valuable insights into the strong decay dynamics of pure hadronic decays and non-perturbative contributions. Specifically interesting are $B \rightarrow \pi K$ decays, which are dominated by QCD penguin topologies due to a CKM suppression of the tree topologies, and which were studied extensively [53, 57–68]. In fact, using an isospin relation between the neutral $B \rightarrow \pi K$ decays, a correlation between the direct and mixing-induced CP asymmetries of $B^0 \rightarrow \pi^0 K_s^0$ is found, which is in tension with the experimental data [57, 58, 68]. Interestingly, this tension has grown stronger over the years in particular due to more precise determination of γ , which emphasizes the importance of improved γ determinations for phenomenological studies. The tension cannot trivially be resolved by a change in the data, as was recently discussed [38, 57, 58]. Here a state-of-the-art analysis of $B \rightarrow \pi K$ using flavour SU(3) symmetry was performed, including the electroweak penguin (EWP) contributions that are at the same level as the tree contribution in these decays. In addition, the angle ϕ_{\pm} between the amplitude $A(B_d^0 \rightarrow \pi^- K^+)$ and its CP -conjugate was studied and found to provide an additional stringent constraint which increases the tension between the SM prediction and the current experimental data. An intriguing possibility is that this discrepancy is signalling New Physics, for which a modified EWP sector is a prime candidate.

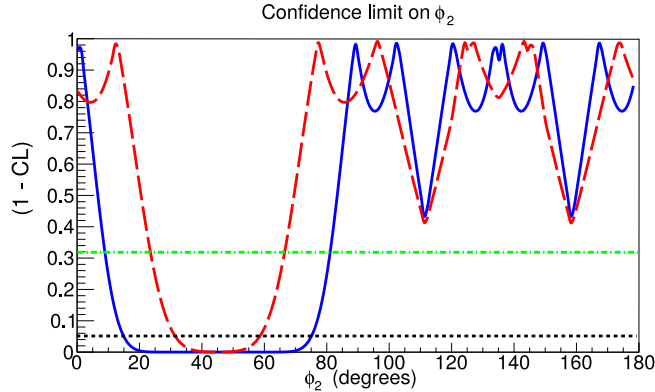


Figure 3: Scan of the confidence level for α/ϕ_2 using only data from $B \rightarrow \pi\pi$ measurements of the Belle experiment. The dashed red curve shows the previous constraint, while the solid blue curve includes the newest measurement of the $B^0 \rightarrow \pi^0\pi^0$ decay. Plot taken from [75].

The $B \rightarrow \pi K$ decays, therefore, provide an excellent opportunity to study the parameters that govern these EWP contributions. Isospin relations between the $B \rightarrow \pi K$ amplitudes can be used to determine them in a theoretically clean way, using only minimal SU(3) assumptions [57, 58, 68]. In this new strategy, the mixing-induced CP asymmetry of $B_d^0 \rightarrow \pi^0 K_S$ plays an important role, offering exciting prospects for Belle II. Although in general, theoretical uncertainties are difficult to control in non-leptonic B decays, in this new method, the theory uncertainty is expected to be at the same level as the experimental precision that can be reached at the end of Belle II [69]. The new strategy offers exciting possibilities for the nearby future and would potentially allow for the observation of new CP -violating physics in the $B \rightarrow \pi K$ system.

From the experimental point of view, charmless non-leptonic B decays are also challenging. Main experimental issues are related to the cross-contamination of the different final states that need to be suppressed with excellent particle identification capabilities. This is complicated by the fact that the typical branching ratios of these decays vary by about three order to magnitudes (between 10^{-5} and 10^{-8}) making some of the decay modes the main source of background to other channels. New results have been shown by LHCb and Belle, plus interesting projections on the capabilities of Belle-II. Updated measurement of CP violation in $B_{(s)}^0$ meson decays to $\pi^+\pi^-$, K^+K^- and $K^+\pi^-$ final states have been reported by LHCb [70]. This includes the measurement of the time-integrated CP asymmetries of the $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ decays, and the time-dependent CP asymmetries of the $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ decays. All the measurements are world's best and the time-integrated CP asymmetries of the $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ decays are also leading the world averages of these quantities. They are used to perform the test of the Standard Model suggested in Ref. [71], finding no evidence of deviations from the Standard Model. The measurement of the CP violation parameters in the $B_s^0 \rightarrow K^+K^-$ decay is unique to LHCb and constitutes the strongest evidence of time-dependent CP violation in the B_s^0 -meson sector to date, with a significance of 4 standard deviations. These new measurements will enable improved constraints to be set on the CKM CP -violating phases, using processes whose amplitudes receive significant contributions from loop diagrams both in the mixing and decay of $B_{(s)}^0$ mesons [72–74].

As already mentioned in Section 2 the much cleaner environment of e^+e^- colliders allows Belle to perform analyses with neutral particles in the final states, that would be very challeng-

ing for LHCb, like $\eta\pi^0$, $\eta\eta$ and $\pi^0\pi^0$. Particularly interesting is the analysis of the $B^0 \rightarrow \pi^0\pi^0$ decay, whose CP asymmetry and branching fraction are relevant input to the determination of the CKM angle α [76] and to the analysis already mentioned in Ref. [73, 74]. The updated result from Belle on the branching ratio and the direct CP asymmetry of this decay [75] provide a relevant contribution to the determination of α , as visualised in Figure 3. However, the real breakthrough is expected with Belle-II, when the much larger statistics will allow to exploit the Dalitz decay $\pi^0 \rightarrow \gamma e^+ e^-$. This makes it possible to perform a time-dependent analysis of the $B^0 \rightarrow \pi^0\pi^0$ decay, measuring both the direct and mixing-induced CP asymmetries. Finally, a precision on α of about 2° is expected using only the $B \rightarrow \pi\pi$ system, while the overall precision on α is expected to be below 1° [27].

Another interesting channel that is challenging for LHCb, given the reduced acceptance of the experiment to the long living K_s^0 , is the $B_s^0 \rightarrow K_s^0 K_s^0$ decay. This decay proceeds through pure penguin topologies and thus the measurement of its branching fraction and CP asymmetries has the potential to probe several scenarios of physics beyond the Standard Model [77–79]. The Belle experiment, using the 121.4 fb^{-1} of luminosity collected at the $\Upsilon(5S)$ resonance, reported the first observation of this decay with a significance of more than 5 standard deviations [80]. Even though the resolution on the decay time achievable by Belle (and Belle-II) is not sufficient to resolve the fast oscillation of the B_s^0 meson, a measurement of its effective lifetime is possible. Thanks to the non-zero decay-width difference $\Delta\Gamma_s$ of the B_s^0 meson, measuring the effective lifetime allows to extract information also on CP violation. Approximately 1000 $B_s^0 \rightarrow K_s^0 K_s^0$ signal candidates are expected with the full Belle-II sample.

4 CP violation in three-body B decays

Multibody decays form a large part of the non-leptonic B -meson branching fraction. Especially, in the study of CP violation they are interesting because due to their non-trivial kinematics, these decays contain more information on strong phases than two-body decays. For charmless $B \rightarrow hhh$ decays, interesting and rich patterns of direct CP violation, (A_{CP}), across the Dalitz distribution were indeed observed [81]. In particular, a clear correlation between the channels $B^\pm \rightarrow K^\pm \pi^+ \pi^-$ and $B^\pm \rightarrow K^\pm K^+ K^-$ decays was observed, where the CP asymmetries carry opposite signs. This is a signature of the rescattering process $\pi^+ \pi^- \rightarrow K^+ K^-$ and a consequence of the CPT symmetry, which requires the equal total decay rates between particles and antiparticles [82]. Theoretically, such three-body decays are challenging to describe and a large variety of approaches are considered (see e.g. [82–84]). Recently, three-body decays were also studied for the first time in a QCD factorization approach [51, 52], which requires new non-perturbative objects as the $B \rightarrow hh$ and $2h$ distribution amplitudes.

To fully understand the different CP patterns and distribution of the strong phases across the Dalitz plot a full amplitude analysis is required. For $B^\pm \rightarrow \pi^- \pi^+ \pi^\pm$ and $B^\pm \rightarrow K^- K^+ \pi^\pm$, new analyses by the LHCb Collaboration are expected to appear soon [85]. Of particular note are the observation of very large direct CP -violation, (approaching 1), in regions of phase space for the $B^\pm \rightarrow K^+ K^- \pi^\pm$ and $B^\pm \rightarrow \pi^+ \pi^- \pi^\pm$ modes [85] [86]. The interpretation of these decays is challenging, given the lack of proper description for all the components (in particular scalar resonances) contributing to the Dalitz plot distributions. The case of the $B^\pm \rightarrow K^+ K^- \pi^\pm$ decay, is particularly challenging as the yield shows an order of magnitude increase above phase space below $M_{KK} < 1.1 \text{ GeV}$ as well as $A_{CP} = -0.90 \pm 0.17 \pm 0.04$ [86]. Thus two amplitudes are required to provide an order of magnitude increase below $M_{KK} < 1.1 \text{ GeV}$. One where the weak phase changes sign between particles and anti-particles and the other

where it does not.

The analysis of $B^\pm \rightarrow K^- K^+ K^\pm$ is ongoing. In this decay, the rescattering of charm penguins might play an important role in the generation of strong phases [87, 88]. In fact, the CP asymmetry of $B^\pm \rightarrow K^- K^+ K^\pm$ changes sign close to the $D\bar{D}$ open threshold around an invariant KK -mass of 4 GeV [81]. Therefore, at these high energies $D\bar{D} \rightarrow K\bar{K}(\pi^-\pi^+)$ may be important, in analogy to $\pi\pi - KK$ rescattering at low energies. The effect of this $D\bar{D}$ rescattering, can be parameterized by a pure hadronic triangle loop [88], which would generate a distinct structure in the Dalitz plot. In particular, the phase of the hadronic amplitude changes sign across the $D\bar{D}$ threshold. This triangle parameterization could be confirmed by data, using amplitude analysis of the $B^\pm \rightarrow K^- K^+ K^\pm$ channel. Interestingly, a similar contribution would also influence the rare $B_c \rightarrow K^- K^+ \pi^+$ decay [89]. New data from LHCb, would be able to test the charm rescattering parametrization.

4.1 Extracting γ from three-body decays

The conventional methods to extract γ from hadronic $B \rightarrow Dh$ decays are theoretically clean because these decays proceed through pure tree-level transitions. Besides, using flavour symmetries, it is also possible to extract γ from penguin dominated charmless two-body B decays [90, 91], but also from three-body B decays [83, 92]. Because of the relevant contributions of penguin topologies to the decay amplitudes, these latter decays might be sensitive to new particles that could enter the loops as virtual contributions, making very interesting to compare extractions of γ from tree- and loop-dominated decays.

The angle γ can be extracted from $B \rightarrow hhh$ decays using a diagrammatic analysis, and by relating the hadronic parameters of the different decays by SU(3) flavour symmetry [83, 92, 93]. In this way, by using the available branching ratios, direct and mixing-induced CP asymmetries, γ can be determined from data [94]. Thanks to the number of observables that over-constrain the system of equations, it is also possible to introduce a parameter that takes into account possible SU(3)-breaking effects, hence relaxing the theoretical assumptions of the method. An implementation of this method using BaBar data for $B^+ \rightarrow K^+ \pi^+ \pi^-$, $B^0 \rightarrow K_S^0 \pi^+ \pi^-$, $B^0 \rightarrow K^+ \pi^- \pi^0$, $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ and $B^0 \rightarrow K_S^0 K^+ K^-$ [95] was first presented in Ref. [92, 94]. In the SU(3) limit, the momentum dependent hadronic parameters are equal in each point in the Dalitz plot, making it possible to extract γ (and the SU(3)-breaking parameter) independently in different regions. The key advantage is that the extracted values of γ can then be averaged over the entire Dalitz plot, and thereby increasing the precision.

Recently, a new analysis using this method was performed, which takes into account several systematic uncertainties [96, 97]. By combining several hundred sets of points on the Dalitz plane, and taking into account the correlations among the different points, six possible solutions for γ with a $\mathcal{O}(10^\circ)$ precision were found. The uncertainty is comparable with measurements of γ from decays including loops processes and allows for a comparison with the world average from measurements obtained with tree-dominated decays [11, 12]. Very interesting is the possibility of the analysis to quantify the strength of SU(3)-breaking effects. Although locally SU(3) breaking might be large, it was found that averaging over a large number of points in the Dalitz plane, the breaking effects are $\mathcal{O}(6\%)$ [96, 97].

Efforts to included anti-symmetric states or mixed states are undertaken, which may help to decrease the statistical uncertainties and reduced the number of solutions. It would be interesting to perform this analysis using LHCb and Belle-II data by extracting γ directly from a simultaneous fit.

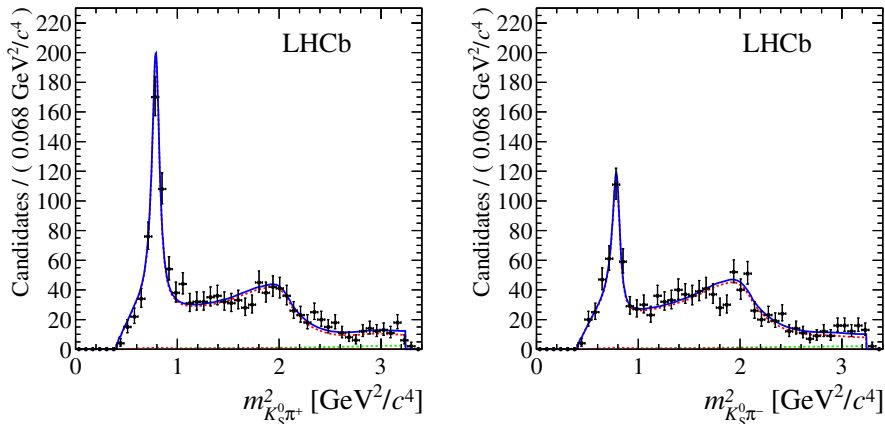


Figure 4: Projections of the $B^0 \rightarrow K_S^0 \pi^+ \pi^-$ data points and best fit result (blue line) onto the Dalitz-plot variables (left) $m_{K_S^0 \pi^+}^2$ and (right) $m_{K_S^0 \pi^-}^2$. Projections are restricted to the two-body low invariant-mass regions. Plot taken from [99].

4.2 Experimental status

From the experimental point of view the study of $B_{(s)}^0$ decays to multibody charmless final states is also challenging. As for the two body decays the low branching fractions and the plethora of different final states makes very difficult to efficiently select the signals. For LHCb, the analyses are further complicated by the low acceptance of the detector with respect to the long lifetime of the K_S^0 . Recent results from LHCb includes the measurement of the branching fractions of the various $B_{(s)}^0 \rightarrow K_S^0 h^+ h'^-$ decays [98] and the untagged time-integrated Dalitz analysis of the $B^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay [99] both performed with the full Run1 sample. The branching fractions are measured relatively to the $B^0 \rightarrow K_S^0 \pi^+ \pi^-$ and report the observation of all the B^0 and B_s^0 modes, except for the $B_s^0 \rightarrow K_S^0 K^+ K^-$ for which only an upper limit is determined. The Dalitz analysis of the $B^0 \rightarrow K_S^0 \pi^+ \pi^-$ is the first amplitude analysis of a any $B_{(s)}^0 \rightarrow K_S^0 h^+ h'^-$ mode at a hadronic machine. It is described using the isobar model, including several intermediate resonances plus a non-resonant component. The $K_S^0 \pi^-$ S-wave is described using the EFKLLM model [100]. The CP -averaged fit fractions of all the components are determined as well as the CP asymmetries of the flavour-specific final states. A very large CP asymmetry is observed for the $B^0 \rightarrow K^{*-} \pi^+$ decay, corresponding to

$$A_{CP}(B^0 \rightarrow K^{*-} \pi^+) = -0.308 \pm 0.062, \quad (3)$$

which is the first observation of CP violation in this channel with a significance of more than 6 standard deviations. The very large CP asymmetry is visible in Figure 4, where the projection on the Dalitz-plot variables $m_{K_S^0 \pi^+}^2$ and (right) $m_{K_S^0 \pi^-}^2$ are shown. The full potential of these decays can only be exploited with flavour-tagged time-dependent Dalitz analyses, that are very challenging and require much larger statistics. Thanks to the much better performances of flavour tagging, Belle-II will be able to remain competitive for the time-dependent measurement of the B^0 modes.

4.3 CP violation in beauty baryons at LHCb

In contrast to meson decays, CP violation in the baryon sector has never been observed. In this quest, the study of beauty-baryon decays, and in particular those without charm quark in the final state, provides excellent opportunities. In fact, these decays might have large CP asymmetries, as the tree-level and loop-level transitions are comparable in magnitude which allows for large interference effects. Thanks to the large production cross-section of beauty baryons in pp collisions at the LHC, the LHCb experiment is the only active experiment capable of expanding our knowledge in this sector, as these decays are not accessible at the e^+e^- KEK collider. The only measurement of CP violation in b -baryon decays previous to LHCb was the measurement of the direct CP asymmetries of $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decays performed by CDF [101] with precision of $\mathcal{O}(0.1)$. Using the full Run1 data sample, corresponding to integrated luminosities of 1 fb^{-1} and 2 fb^{-1} of pp collisions collected as $\sqrt{s}=7\text{ TeV}$ and $\sqrt{s}=8\text{ TeV}$, respectively, LHCb measured the same quantities with uncertainties reduced by approximately a factor 4 [102]

$$\begin{aligned} A_{CP}(\Lambda_b^0 \rightarrow pK^-) &= -0.020 \pm 0.013 \pm 0.019, \\ A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) &= -0.035 \pm 0.017 \pm 0.020, \end{aligned}$$

where the first uncertainty is statistics and the second systematics. A measurement of the difference between the two CP asymmetries is also performed, in which the main systematic uncertainties, being the asymmetry of detection efficiency between p and \bar{p} , and the asymmetry between the production cross-section of Λ_b^0 and $\bar{\Lambda}_b^0$, cancel:

$$A_{CP}(\Lambda_b^0 \rightarrow pK^-) - A_{CP}(\Lambda_b^0 \rightarrow p\pi^-) = 0.014 \pm 0.022 \pm 0.013.$$

In addition, the LHCb collaboration also studies b -hadron decays with multibody final states. Recently evidence for CP violation in the $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decay [103] with a significance exceeding the 3 standard deviations was reported. The analysis is based on the full Run1 statistics, corresponding to integrated luminosities of 1 fb^{-1} and 2 fb^{-1} of pp collisions collected as $\sqrt{s}=7\text{ TeV}$ and $\sqrt{s}=8\text{ TeV}$, respectively, and the experiment has the potential to establish a first observation of CP violation in a baryon decays when including also the Run2 data. In the analysis, triple products of the momenta of the final-state particles are used to build observables that are sensitive to the violation of the P and CP symmetry [104, 105]. These observables have the advantage of being almost insensitive to spurious asymmetries, like the detection asymmetry of charge-conjugate final states or the imbalance between the production cross sections between Λ_b^0 and $\bar{\Lambda}_b^0$ baryons in pp collisions. The validity of this consideration is nevertheless tested by performing the analysis on the control mode $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ in which CP violation is expected to be negligible. The search for P and CP violation is also performed in different regions of the phase space of the decay. Two splitting scheme are used: one designated to isolate regions according to the dominant intermediate resonances and one designated to separate the sample in bins of the angle between the $p-\pi^-$ and the $\pi^+-\pi^-$ decay planes, as suggested in Refs. [104, 105]. Also, the $\Lambda_b^0 \rightarrow p\pi^-K^+K^-$ decay was studied by LHCb, finding no evidence of P and CP violation [103]. More recently the same technique has been applied to $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$, $\Lambda_b^0 \rightarrow pK^+K^-K^+$ and $\Xi_b^0 \rightarrow pK^-K^+\pi^-$ decays, reconstructed using the Run1 data [106]. Again, no evidence of P or CP violation is observed for these decay modes. Moreover, inspecting the phase space of the $pK^-\pi^+\pi^-$ and $pK^-K^+K^-$ final states the decay $\Lambda_b^0 \rightarrow pK^-\chi_{c0}$ is observed for the first time. The branching ratios of several Λ_b^0 and Ξ_b^0 decays to $p3h$ final states (with h being charged kaons or pions) have also been measured relatively to the branching ratios of the $\Lambda_b^0 \rightarrow \Lambda_c^+(pK^-\pi^+)\pi^-$, using the same data sample [107]. Given that

the sector of beauty baryon decays is almost unexplored, the many results expected in the near future will require a joined effort both on the experimental and on the theory side to provide reliable interpretation of the experimental results.

5 Conclusion

The search for new sources of CP violation in B decays remains an interesting but challenging enterprise. With the start of Belle-II and the continued analyses at LHCb, many exciting new results will surface in the near future. Among these are determination of γ from single experiments at the few degree level and an expected combined precision of an impressive 1° . In addition, with Belle-II running also the decays with neutral particles (like photons and π^0) in the final states will be updated and new CP asymmetries measured, which provide also important guidance to stimulate theoretical progress. Finally, especially in the three- and multibody B decays exciting results are expected in the nearby future. Most importantly, the full exploitation of this incredible amount of data, requires continued efforts and synergies between theorists and experimentalists. Theoretically, there are still the power-corrections and the description of three-body decays that require further investigations and many interesting avenues can still be explored, especially when making use of the available data. We look forward to the many interesting new analysis and theoretical progress that will be presented at the next CKM workshop.

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References

- [1] J. Brod and J. Zupan, *The ultimate theoretical error on γ from $B \rightarrow DK$ decays*, JHEP **01** (2014) 051, [arXiv:1308.5663](#).
- [2] J. Brod, *Electroweak effects in the extraction of the CKM angle γ from $B \rightarrow D\pi$ decays*, Phys. Lett. **B743** (2015) 56, [arXiv:1412.3173](#).
- [3] J. Brod, A. Lenz, G. Tetlalmatzi-Xolocotzi, and M. Wiebusch, *New physics effects in tree-level decays and the precision in the determination of the quark mixing angle γ* , Phys. Rev. **D92** (2015) 033002, [arXiv:1412.1446](#).
- [4] G. Tetlalmatzi-Xolocotzi. talk at 10th conference of the CKM matrix (CKM 2018), these proceedings.
- [5] M. Gronau and D. Wyler, *On determining a weak phase from CP asymmetries in charged B decays*, Phys. Lett. **B265** (1991) 172.

- [6] M. Gronau and D. London, *How to determine all the angles of the unitarity triangle from $B_d^0 \rightarrow DK_S^0$ and $B_s^0 \rightarrow D\phi$* , Phys. Lett. **B253** (1991) 483.
- [7] A. Giri, Y. Grossman, A. Soffer, and J. Zupan, *Determining γ using $B^\pm \rightarrow DK^\pm$ with multibody D decays*, Phys. Rev. **D68** (2003) 054018, [arXiv:hep-ph/0303187](https://arxiv.org/abs/hep-ph/0303187).
- [8] D. Atwood, I. Dunietz, and A. Soni, *Enhanced CP violation with $B \rightarrow KD^0(\bar{D}^0)$ modes and extraction of the CKM angle γ* , Phys. Rev. Lett. **78** (1997) 3257, [arXiv:hep-ph/9612433](https://arxiv.org/abs/hep-ph/9612433); D. Atwood, I. Dunietz, and A. Soni, *Improved methods for observing CP violation in $B^\pm \rightarrow KD$ and measuring the CKM phase γ* , Phys. Rev. **D63** (2001) 036005, [arXiv:hep-ph/0008090](https://arxiv.org/abs/hep-ph/0008090).
- [9] LHCb collaboration, *Update of the LHCb combination of the CKM angle γ using $B \rightarrow DK$ decays*, LHCb-CONF-2018-002.
- [10] Heavy Flavor Averaging Group, Y. Amhis *et al.*, *Averages of b -hadron, c -hadron, and τ -lepton properties as of summer 2016*, Eur. Phys. J. **C77** (2017) 895, [arXiv:1612.07233](https://arxiv.org/abs/1612.07233), updated results and plots available at <https://hflav.web.cern.ch>.
- [11] 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](https://arxiv.org/abs/1501.05013), updated results and plots available at <http://ckmfitter.in2p3.fr/>.
- [12] 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 Δm_s and $BR(B \rightarrow \tau\nu_\tau)$* , JHEP **10** (2006) 081, [arXiv:hep-ph/0606167](https://arxiv.org/abs/hep-ph/0606167), updated results and plots available at <http://www.utfit.org/>.
- [13] LHCb collaboration, R. Aaij *et al.*, *Measurement of the CKM angle γ using $B^\pm \rightarrow DK^\pm$ with $D \rightarrow K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$ decays*, JHEP **08** (2018) 176, Erratum *ibid.* **10** (2018) 107, [arXiv:1806.01202](https://arxiv.org/abs/1806.01202).
- [14] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP observables in $B^\pm \rightarrow DK^{*\pm}$ decays using two- and four-body D final states*, JHEP **11** (2017) 156, Erratum *ibid.* **05** (2018) 067, [arXiv:1709.05855](https://arxiv.org/abs/1709.05855).
- [15] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP observables in $B^\pm \rightarrow D^{(*)}K^\pm$ and $B^\pm \rightarrow D^{(*)}\pi^\pm$ decays*, Phys. Lett. **B777** (2018) 16, [arXiv:1708.06370](https://arxiv.org/abs/1708.06370).
- [16] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP asymmetry in $B_s^0 \rightarrow D_s^\mp K^\pm$ decays*, JHEP **03** (2018) 059, [arXiv:1712.07428](https://arxiv.org/abs/1712.07428).
- [17] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP violation in $B^0 \rightarrow D^\mp\pi^\pm$ decays*, JHEP **06** (2018) 084, [arXiv:1805.03448](https://arxiv.org/abs/1805.03448).
- [18] R. Fleischer, *New strategies to obtain insights into CP violation through $B_s^0 \rightarrow D_s^\pm K^\mp$, $D_s^{*\pm} K^\mp$, ... $B^0 \rightarrow D^\pm\pi^\mp$, $D^{*\pm}\pi^\mp$, ... decays*, Nucl. Phys. **B671** (2003) 459, [arXiv:hep-ph/0304027](https://arxiv.org/abs/hep-ph/0304027).
- [19] I. Dunietz and R. G. Sachs, *Asymmetry between inclusive charmed and anticharmed modes in B^0 , \bar{B}^0 decay as a measure of CP violation*, Phys. Rev. **D37** (1988) 3186, Erratum *ibid.* **D39** (1989) 3515.

- [20] R. Aleksan, I. Dunietz, and B. Kayser, *Determining the CP violating phase γ* , Z. Phys. **C54** (1992) 653.
- [21] K. De Bruyn *et al.*, *Exploring $B_s \rightarrow D_s^{(*)\pm} K^\mp$ Decays in the Presence of a Sizable Width Difference $\Delta\Gamma_s$* , Nucl. Phys. **B868** (2013) 351, [arXiv:1208.6463](#).
- [22] LHCb collaboration, R. Aaij *et al.*, *Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era*, [arXiv:1808.08865](#).
- [23] S. Nandi and D. London, *$B_s(\bar{B}_s) \rightarrow D_{CP}^0 K\bar{K}$: detecting and discriminating new physics in B_s - \bar{B}_s mixing*, Phys. Rev. **D85** (2012) 114015, [arXiv:1108.5769](#).
- [24] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay $B_s^0 \rightarrow \bar{D}^0 K^+ K^-$* , Phys. Rev. **D98** (2018), no. 7 072006, [arXiv:1807.01891](#).
- [25] Belle collaboration, P. K. Resmi, *Latest results on $B \rightarrow DK/D\pi$ decays from Belle*, in *10th International Workshop on the CKM Unitarity Triangle (CKM 2018) Heidelberg, Germany, September 17-21, 2018*, 2018. [arXiv:1812.03440](#). in these proceedings.
- [26] P. K. Resmi, J. Libby, S. Malde, and G. Wilkinson, *Quantum-correlated measurements of $D \rightarrow K_S^0 \pi^+ \pi^- \pi^0$ decays and consequences for the determination of the CKM angle γ* , JHEP **01** (2018) 082, [arXiv:1710.10086](#).
- [27] Belle-II collaboration, W. Altmannshofer *et al.*, *The Belle-II physics book*, [arXiv:1808.10567](#).
- [28] S. Harnew *et al.*, *Model-independent determination of the strong phase difference between D^0 and $\bar{D}^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ amplitudes*, JHEP **01** (2018) 144, [arXiv:1709.03467](#).
- [29] S. S. Malde, *Synergy of BES-III and LHCb physics programmes*, LHCb-PUB-2016-025. CERN-LHCb-PUB-2016-025.
- [30] M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, *QCD factorization for $B \rightarrow \pi\pi$ decays: strong phases and CP violation in the heavy quark limit*, Phys. Rev. Lett. **83** (1999) 1914, [arXiv:hep-ph/9905312](#).
- [31] M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, *QCD factorization for exclusive, nonleptonic B meson decays: general arguments and the case of heavy light final states*, Nucl. Phys. **B591** (2000) 313, [arXiv:hep-ph/0006124](#).
- [32] M. Beneke and M. Neubert, *QCD factorization for $B \rightarrow PP$ and $B \rightarrow PV$ decays*, Nucl. Phys. **B675** (2003) 333, [arXiv:hep-ph/0308039](#).
- [33] Y. Y. Keum, H. n. Li, and A. I. Sanda, *Fat penguins and imaginary penguins in perturbative QCD*, Phys. Lett. **B504** (2001) 6, [arXiv:hep-ph/0004004](#).
- [34] Y. Y. Keum, H. n. Li, and A. I. Sanda, *Penguin enhancement and $B \rightarrow K\pi$ decays in perturbative QCD*, Phys. Rev. **D63** (2001) 054008, [arXiv:hep-ph/0004173](#).
- [35] C. D. Lu, K. Ukai, and M. Z. Yang, *Branching ratio and CP violation of $B \rightarrow \pi\pi$ decays in perturbative QCD approach*, Phys. Rev. **D63** (2001) 074009, [arXiv:hep-ph/0004213](#).

- [36] D. Zeppenfeld, *SU(3) relations for B meson decays*, Z. Phys. **C8** (1981) 77.
- [37] T. Huber. talk at 10th conference of the CKM matrix (CKM 2018), these proceedings.
- [38] R. Fleischer, R. Jaarsma, E. Malami, and K. K. Vos, *Probing New Physics in $B \rightarrow \pi K$ Decays*, in *10th International Workshop on the CKM Unitarity Triangle (CKM 2018) Heidelberg, Germany, September 17-21, 2018*, 2018. [arXiv:1812.02672](#).
- [39] G. Bell, *NNLO vertex corrections in charmless hadronic B decays: imaginary part*, Nucl. Phys. **B795** (2008) 1, [arXiv:0705.3127](#).
- [40] G. Bell, *NNLO vertex corrections in charmless hadronic B decays: real part*, Nucl. Phys. **B822** (2009) 172, [arXiv:0902.1915](#).
- [41] G. Bell and V. Pilipp, *$B^- \rightarrow \pi^- \pi^0 / \rho^0$ to NNLO in QCD factorization*, Phys. Rev. **D80** (2009) 054024, [arXiv:0907.1016](#).
- [42] M. Beneke, T. Huber, and X. Q. Li, *NNLO vertex corrections to non-leptonic B decays: tree amplitudes*, Nucl. Phys. **B832** (2010) 109, [arXiv:0911.3655](#).
- [43] M. Beneke and S. Jager, *Spectator scattering at NLO in non-leptonic B decays: tree amplitudes*, Nucl. Phys. **B751** (2006) 160, [arXiv:hep-ph/0512351](#).
- [44] N. Kivel, *Radiative corrections to hard spectator scattering in $B \rightarrow \pi\pi$ decays*, JHEP **05** (2007) 019, [arXiv:hep-ph/0608291](#).
- [45] M. Beneke and S. Jager, *Spectator scattering at NLO in non-leptonic B decays: leading penguin amplitudes*, Nucl. Phys. **B768** (2007) 51, [arXiv:hep-ph/0610322](#).
- [46] A. Jain, , I. Z. Rothstein, and I. W. Stewart, *Penguin loops for nonleptonic B Decays in the standard model: is there a penguin puzzle?*, [arXiv:0706.3399](#).
- [47] V. Pilipp, *Hard spectator interactions in $B \rightarrow \pi\pi$ at order α_s^2* , Nucl. Phys. **B794** (2008) 154, [arXiv:0709.3214](#).
- [48] C. S. Kim and Y. W. Yoon, *Order α_s^2 magnetic penguin correction for B decay to light mesons*, JHEP **11** (2011) 003, [arXiv:1107.1601](#).
- [49] G. Bell and T. Huber, *Master integrals for the two-loop penguin contribution in nonleptonic B decays*, JHEP **12** (2014) 129, [arXiv:1410.2804](#).
- [50] G. Bell, M. Beneke, T. Huber, and X. Q. Li, *Two-loop current-current operator contribution to the non-leptonic QCD penguin amplitude*, Phys. Lett. **B750** (2015) 348, [arXiv:1507.03700](#).
- [51] S. Kränkl, T. Mannel, and J. Virto, *Three-body non-leptonic B decays and QCD factorization*, Nucl. Phys. **B899** (2015) 247, [arXiv:1505.04111](#).
- [52] R. Klein, T. Mannel, J. Virto, and K. K. Vos, *CP Violation in Multibody B Decays from QCD Factorization*, JHEP **10** (2017) 117, [arXiv:1708.02047](#).
- [53] M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, *QCD factorization in $B \rightarrow \pi K, \pi\pi$ decays and extraction of Wolfenstein parameters*, Nucl. Phys. **B606** (2001) 245, [arXiv:hep-ph/0104110](#).

- [54] C. Bobeth, M. Gorbahn, and S. Vickers, *Weak annihilation and new physics in charmless $B \rightarrow MM$ decays*, Eur. Phys. J. **C75** (2015) 340, arXiv:1409.3252.
- [55] T. Becher and M. Neubert, *Drell-Yan production at small q_T , transverse parton distributions and the collinear anomaly*, Eur. Phys. J. **C71** (2011) 1665, arXiv:1007.4005.
- [56] J. Y. Chiu, A. Jain, D. Neill, and I. Z. Rothstein, *A formalism for the systematic treatment of rapidity logarithms in quantum field theory*, JHEP **05** (2012) 084, arXiv:1202.0814.
- [57] R. Fleischer, R. Jaarsma, and K. K. Vos, *Towards new frontiers with $B \rightarrow \pi K$ decays*, Phys. Lett. **B785** (2018) 525, arXiv:1712.02323.
- [58] R. Fleischer, R. Jaarsma, E. Malami, and K. K. Vos, *Exploring $B \rightarrow \pi\pi, \pi K$ decays at the high-precision frontier*, Eur. Phys. J. **C78** (2018), no. 11 943, arXiv:1806.08783.
- [59] M. Gronau, J. L. Rosner, and D. London, *Weak coupling phase from decays of charged B mesons to πK and $\pi\pi$* , Phys. Rev. Lett. **73** (1994) 21, arXiv:hep-ph/9404282.
- [60] R. Fleischer, *Strategies for fixing the CKM angle γ and obtaining experimental insights into the world of electroweak penguins*, Phys. Lett. **B365** (1996) 399, arXiv:hep-ph/9509204.
- [61] M. Neubert and J. L. Rosner, *New bound on γ from $B^\pm \rightarrow \pi K$ decays*, Phys. Lett. **B441** (1998) 403, arXiv:hep-ph/9808493.
- [62] M. Neubert and J. L. Rosner, *Determination of the weak phase γ from rate measurements in $B^\pm \rightarrow \pi K, \pi\pi$ decays*, Phys. Rev. Lett. **81** (1998) 5076, arXiv:hep-ph/9809311.
- [63] A. J. Buras and R. Fleischer, *A general analysis of γ determinations from $B \rightarrow \pi K$ decays*, Eur. Phys. J. **C11** (1999) 93, arXiv:hep-ph/9810260.
- [64] A. J. Buras, R. Fleischer, S. Recksiegel, and F. Schwab, *$B \rightarrow \pi\pi, \pi K$ and implications for rare K and B decays*, Phys. Rev. Lett. **92** (2004) 101804, arXiv:hep-ph/0312259.
- [65] A. J. Buras, R. Fleischer, S. Recksiegel, and F. Schwab, *Anatomy of prominent B and K decays and signatures of CP violating new physics in the electroweak penguin sector*, Nucl. Phys. **B697** (2004) 133, arXiv:hep-ph/0402112.
- [66] M. Gronau, *A precise sum rule among four $B \rightarrow K\pi$ CP asymmetries*, Phys. Lett. **B627** (2005) 82, arXiv:hep-ph/0508047.
- [67] M. Gronau and J. L. Rosner, *Rate and CP asymmetry sum rules in $B \rightarrow K\pi$* , Phys. Rev. **D74** (2006) 057503, arXiv:hep-ph/0608040.
- [68] R. Fleischer, S. Jager, D. Pirjol, and J. Zupan, *Benchmarks for the New-Physics search through CP violation in $B^0 \rightarrow \pi^0 K_S^0$* , Phys. Rev. **D78** (2008) 111501, arXiv:0806.2900.
- [69] Belle-II collaboration, T. Abe *et al.*, *Belle II technical design report*, arXiv:1011.0352.
- [70] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP asymmetries in two-body $B_{(s)}^0$ -meson decays to charged pions and kaons*, Phys. Rev. **D98** (2018), no. 3 032004, arXiv:1805.06759.

- [71] H. J. Lipkin, *Is observed direct CP violation in $B^0 \rightarrow K^+\pi^-$ due to new physics? Check standard model prediction of equal violation in $B_s^0 \rightarrow \pi^+K^-$* , Phys. Lett. **B621** (2005) 126, [arXiv:hep-ph/0503022](#).
- [72] R. Fleischer and R. Knegjens, *In pursuit of new physics With $B_s^0 \rightarrow K^+K^-$* , Eur. Phys. J. **C71** (2011) 1532, [arXiv:1011.1096](#).
- [73] M. Ciuchini, E. Franco, S. Mishima, and L. Silvestrini, *Testing the Standard Model and searching for new physics with $B_d \rightarrow \pi\pi$ and $B_s \rightarrow KK$ decays*, JHEP **10** (2012) 029, [arXiv:1205.4948](#).
- [74] LHCb collaboration, R. Aaij *et al.*, *Determination of γ and $-2\beta_s$ from charmless two-body decays of beauty mesons*, Phys. Lett. **B741** (2015) 1, [arXiv:1408.4368](#).
- [75] Belle collaboration, T. Julius *et al.*, *Measurement of the branching fraction and CP asymmetry in $B^0 \rightarrow \pi^0\pi^0$ decays, and an improved constraint on ϕ_2* , Phys. Rev. **D96** (2017) 032007, [arXiv:1705.02083](#).
- [76] M. Gronau and D. London, *Isospin analysis of CP asymmetries in B decays*, Phys. Rev. Lett. **65** (1990) 3381.
- [77] Q. Chang, X.-Q. Li, and Y.-D. Yang, *A comprehensive analysis of hadronic $b \rightarrow s$ transitions in a family non-universal Z' model*, J. Phys. **G41** (2014) 105002, [arXiv:1312.1302](#).
- [78] S. Baek, D. London, J. Matias, and J. Virto, *$B_s^0 \rightarrow K^+K^-$ and $B_s^0 \rightarrow K^0\bar{K}^0$ decays within supersymmetry*, JHEP **12** (2006) 019, [arXiv:hep-ph/0610109](#).
- [79] A. Hayakawa, Y. Shimizu, M. Tanimoto, and K. Yamamoto, *Searching for the squark flavor mixing in CP violations of $B_s^0 \rightarrow K^+K^-$ and $K^0\bar{K}^0$ decays*, PTEP **2014** (2014) 023B04, [arXiv:1311.5974](#).
- [80] Belle collaboration, B. Pal *et al.*, *Observation of the decay $B_s^0 \rightarrow K^0\bar{K}^0$* , Phys. Rev. Lett. **116** (2016) 161801, [arXiv:1512.02145](#).
- [81] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP violation in the three-body phase space of charmless B^\pm decays*, Phys. Rev. **D90** (2014) 112004, [arXiv:1408.5373](#).
- [82] I. Bediaga, T. Frederico, and O. Lourenço, *CP violation and CPT invariance in B^\pm decays with final state interactions*, Phys. Rev. **D89** (2014) 094013, [arXiv:1307.8164](#).
- [83] B. Bhattacharya and D. London, *Using U-spin to extract γ from charmless $B \rightarrow PPP$ decays*, JHEP **04** (2015) 154, [arXiv:1503.00737](#).
- [84] D. Boito *et al.*, *Parametrizations of three-body hadronic B- and D-decay amplitudes in terms of analytic and unitary meson-meson form factors*, Phys. Rev. **D96** (2017), no. 11 113003, [arXiv:1709.09739](#).
- [85] A. C. dos Reis. talk at 10th conference of the CKM matrix (CKM 2018), these proceedings.
- [86] Belle collaboration, C.-L. Hsu *et al.*, *Measurement of branching fraction and direct CP asymmetry in charmless $B^\pm \rightarrow K^+K^-\pi^\pm$ decays at Belle*, Phys. Rev. **D96** (2017) 031101(R), [arXiv:1705.02640](#).

- [87] P. C. Magalhães. talk at 10th conference of the CKM matrix (CKM 2018), these proceedings.
- [88] I. Bediaga, T. Frederico, and P. C. Magalhães, *Charm penguin in $B^\pm \rightarrow K^\pm K^+ K^-$: partonic and hadronic loops*, Phys. Lett. **B780** (2018) 357, [arXiv:1712.01230](#).
- [89] I. Bediaga, T. Frederico, and P. C. Magalhães, *Charm rescattering contribution in rare $B_c^+ \rightarrow K^+ K^- \pi^+$ decay*, Phys. Lett. **B785** (2018) 581, [arXiv:1808.02945](#).
- [90] R. Fleischer, *New strategies to extract β and γ from $B^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow K^+ K^-$* , Phys. Lett. **B459** (1999) 306, [arXiv:hep-ph/9903456](#).
- [91] R. Fleischer, R. Jaarsma, and K. K. Vos, *Towards New Frontiers in the Exploration of Charmless Non-Leptonic B Decays*, JHEP **03** (2017) 055, [arXiv:1612.07342](#).
- [92] B. Bhattacharya and D. London, *Extracting γ from three-body B-meson decays*, in *10th International Workshop on the CKM Unitarity Triangle (CKM 2018) Heidelberg, Germany, September 17-21, 2018*, 2018. [arXiv:1811.10671](#).
- [93] B. Bhattacharya *et al.*, *Charmless $B \rightarrow PPP$ decays: the fully-symmetric final state*, Phys. Rev. **D89** (2014) 074043, [arXiv:1402.2909](#).
- [94] B. Bhattacharya, M. Imbeault, and D. London, *Extraction of the CP-violating phase γ using $B \rightarrow K\pi\pi$ and $B \rightarrow KK\bar{K}$ decays*, Phys. Lett. **B728** (2014) 206, [arXiv:1303.0846](#).
- [95] BaBar collaboration, J. P. Lees *et al.*, *Amplitude analysis of $B^0 \rightarrow K^+ \pi^- \pi^0$ and evidence of direct CP violation in $B \rightarrow K^* \pi$ decays*, Phys. Rev. **D83** (2011) 112010, [arXiv:1105.0125](#); BaBar collaboration, B. Aubert *et al.*, *Time-dependent amplitude analysis of $B^0 \rightarrow K_S^0 \pi^+ \pi^-$* , Phys. Rev. **D80** (2009) 112001, [arXiv:0905.3615](#); BaBar collaboration, B. Aubert *et al.*, *Evidence for direct CP violation from Dalitz-plot analysis of $B^\pm \rightarrow K^\pm \pi^\mp \pi^\pm$* , Phys. Rev. **D78** (2009) 012004, [arXiv:0803.4451](#); BaBar collaboration, J. P. Lees *et al.*, *Study of CP violation in Dalitz-plot analyses of $B^0 \rightarrow K^+ K^- K_S^0$, $B^+ \rightarrow K^+ K^- K^+$, and $B^+ \rightarrow K_S^0 K_S^0 K^+$* , Phys. Rev. **D85** (2012) 112010, [arXiv:1201.5897](#).
- [96] E. Bertholet. talk at 10th conference of the CKM matrix (CKM 2018), these proceedings.
- [97] E. Bertholet *et al.*, *Extraction of the CKM phase γ using charmless 3-body decays of B mesons*, [arXiv:1812.06194](#).
- [98] LHCb collaboration, R. Aaij *et al.*, *Updated branching fraction measurements of $B_{(s)}^0 \rightarrow K_S^0 h^+ h'^-$ decays*, JHEP **11** (2017) 027, [arXiv:1707.01665](#).
- [99] LHCb collaboration, R. Aaij *et al.*, *Amplitude analysis of the decay $\bar{B}^0 \rightarrow K_S^0 \pi^+ \pi^-$ and first observation of CP asymmetry in $\bar{B}^0 \rightarrow K^*(892)^- \pi^+$* , Phys. Rev. Lett. **120** (2018) 261801, [arXiv:1712.09320](#).
- [100] B. El-Bennich *et al.*, *CP violation and kaon-pion interactions in $B \rightarrow K\pi^+\pi^-$ decays*, Phys. Rev. **D79** (2009) 094005, Erratum *ibid.* **D83** (2011) 039903, [arXiv:0902.3645](#).
- [101] CDF collaboration, T. Aaltonen *et al.*, *Measurements of direct CP-violating asymmetries in charmless decays of bottom baryons*, Phys. Rev. Lett. **113** (2014) 242001, [arXiv:1403.5586](#).

- [102] LHCb collaboration, R. Aaij *et al.*, *Search for CP violation in $\Lambda_b^0 \rightarrow pK^-$ and $\Lambda_b^0 \rightarrow p\pi^-$ decays*, Phys. Lett. **B787** (2018) 124, [arXiv:1807.06544](#).
- [103] LHCb collaboration, R. Aaij *et al.*, *Measurement of matter-antimatter differences in beauty baryon decays*, Nature Phys. **13** (2017) 391, [arXiv:1609.05216](#).
- [104] G. Durieux and Y. Grossman, *Probing CP violation systematically in differential distributions*, Phys. Rev. **D92** (2015) 076013, [arXiv:1508.03054](#).
- [105] G. Durieux, *CP violation in multibody decays of beauty baryons*, JHEP **10** (2016) 005, [arXiv:1608.03288](#).
- [106] LHCb collaboration, R. Aaij *et al.*, *Search for CP violation using triple product asymmetries in $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$, $\Lambda_b^0 \rightarrow pK^-K^+K^-$ and $\Xi_b^0 \rightarrow pK^-K^-\pi^+$ decays*, JHEP **08** (2018) 039, [arXiv:1805.03941](#).
- [107] LHCb collaboration, R. Aaij *et al.*, *Measurement of branching fractions of charmless four-body Λ_b^0 and Ξ_b^0 decays*, JHEP **02** (2018) 098, [arXiv:1711.05490](#).