**CP violation in B mesons**

D. Manuzzi  

on behalf of the LHCb collaboration,  

with results from the Belle and Belle II collaborations.  

*University of Bologna, via Irnerio 46, Bologna, 40126, BO, Italy*

This proceeding reports a selection of recent experimental results concerning CP violation in the sectors of $B^0$ and $B^\pm$ mesons. They were published within the last two years by the Belle, Belle II and LHCb collaborations. The first set of measurements is related to the determination of the angles of the Unitarity Triangle. The second is connected to another crucial test of the SM: the isospin sum rule of $B \to K \pi$ decays. Thirdly, studies of CP violation in the decays charged $B$ mesons to charmless three-body final states are presented. Finally, prospects for the future experimental upgrades of this sector are summarised.

**I. INTRODUCTION**

Several CP-violating phenomena have been observed studying $B^+$ and $B^0$ mesons. Now, CP violation is well established in the decays of both mesons [1]. The CP violation in the $B^0$-$\bar{B}^0$ mixing has not been observed yet. However, the Standard Model (SM) predicts this effect to be suppressed below the current experimental limit [1, 2]. Instead, the CP violation in the interference between mixing and decay of neutral $B$ mesons is well measured [1]. These results strongly corroborate the SM and, in particular, the flavour-mixing mechanism of quarks encoded by the Cabibbo-Kobayashi-Maskawa matrix (CKM) [3]. The investigation of this sector is a very active field. Indeed, the combination of multiple measurements provides crucial SM consistency tests, which are very sensitive to the eventual indirect effects of new physics (NP). Some examples come from the relations called Unitarity Triangle (UT) and Isospin Sum Rule [1, 4]. Besides, the decays of $B$ mesons to more than two particles have a rich CP-violation phenomenology, whose connection with the underlying resonance contributions has to be scrutinised. This proceeding reviews the most recent results on these topics. They have been obtained by the Belle, Belle II, and LHCb collaborations [5]. Due to the large number of publications and the complexity of the analyses, only main aspects are highlighted here. Finally, the programs for the future upgrades of the Belle II and LHCb experiments are summarised, with a focus on the prospects for the measurements introduced above.

$$\alpha \equiv \phi_2 \equiv \arg \left[ -\frac{(V_{td}V_{tb}^*)}{(V_{ud}V_{ub}^*)} \right],$$

$$\beta \equiv \phi_1 \equiv \arg \left[ -\frac{(V_{cd}V_{cb}^*)}{(V_{ud}V_{ub}^*)} \right],$$

$$\gamma \equiv \phi_3 \equiv \arg \left[ -\frac{(V_{ud}V_{ub}^*)}{(V_{cd}V_{cb}^*)} \right].$$

Each of them can be determined either with direct measurements or indirectly through global fits of the CKM parameters, assuming unitarity. Any discrepancy between direct and indirect measurements, or between measurements exploiting different modes, would be a hint of NP. The status of the art of these comparisons is reviewed by another talk at this conference [6].

Exploiting the interference between the Cabibbo-favoured $b \to c$ and the Cabibbo-suppressed $b \to u$ transitions, it is possible to measure $\gamma$ with processes dominated by tree-level Feynman diagrams. This is usually done by studying $B^\pm \to (D \to f_D) h^\pm$ decays, where $h^\pm$ is a charged pion or kaon, and $f_D$ stands for a final state shared by the decays of both $D^0$ and $\bar{D}^0$ mesons. In general, crucial parameters for the achievable precision are the ratio between the magnitudes of the amplitudes of the interfering modes ($R_B$) and the difference between their strong phases ($\delta_B$). Depending on $f_D$, various methods are available in the literature. The GLW [7] method concerns the cases when $f_D$ is a CP eigenstate (e.g. $f_D = K^{+}K^{-}$). The ADS [8] method exploits the interference between Cabibbo-favoured $D^0$ decays and doubly-Cabibbo-suppressed $\bar{D}^0$ decays (e.g. $f_D = K^{+}\pi^{-}$). Another option is using $D^0$ and $\bar{D}^0$ decays CP self-conjugated multi-body final states (e.g. $f_D = K^0_{ud}h^+h^-$). In this case, the $D$-decay phase space has to be considered. A detailed description of the intermediate-resonance structure requires assumptions on the $D$-decay amplitude model. This implies potentially large and difficult-to-determine systematic uncertainties. To overcome this issue a model-independent strategy, called BPGGSZ method [10], was developed. It utilises CP-asymmetry measurements in disjoint regions (bins) of the $D$-decay phase space. Such measurements are then related to $\gamma$ using

**II. UPDATES TO THE UT ANGLES**

The SM assumes the unitarity of the CKM matrix. This condition implies various relations among its elements. One of them is $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. It can be represented as a triangle in the complex plane,
measurements of $D$-decay parameters available in the literature [11].

The Belle and Belle II collaborations have recently published a joint $\gamma$ determination following the BPG-GSZ method. The full decay chain is $B^{\pm} \rightarrow (D \rightarrow \bar{K}_S^0 h^+ h^-) h^\pm$ where $h \in \{\pi, K\}$ and the integrated luminosity is 711 fb$^{-1}$ from Belle plus 128 fb$^{-1}$ from Belle II. The final result is [12]:

$$\gamma = (78.4 \pm 11.4 \pm 0.5 \pm 1.0) \degree,$$

where the uncertainties are statistical, systematic and due to external inputs, respectively. This is the most precise determination of $\gamma$ at the B-factories. The improvement compared to the previous Belle results is equivalent to doubling the statistics. This was possible thanks to the inclusion of the $D \rightarrow \bar{K}_S^0 K^+ K^-$ decay mode and improvements in the $K_S^0$ selection and background suppression. A further decisive advantage is also taken from the inputs updated by BESIII [11].

In 2021 the LHCb collaboration published the combination of all its direct $\gamma$ measurements. It includes all the procedures cited above, but also methods based on the measurements of time-dependent decay rates to exploit the interference due to the mixing of $B^0_{s} (\pi)$ and $\bar{B}^0_{(\pi)}$ mesons. The data were collected during the Run1 and Run2 of the LHC, with a total integrated luminosity of 9 fb$^{-1}$. The combination follows a frequentist approach [13], with the novel inclusion of inputs from the charm sector. The final results is [14]:

$$\gamma = (65.4^{+3.8}_{-4.2}) \degree.$$

This is the most precise determination of $\gamma$ by a single experiment. It is statistically dominated and agrees with the indirect determinations from global CKM fits. In Fig. 1 the contributions to the LHCb $\gamma$ combination coming from the $B^0_{s}$, $B^+$, and $B^0$ species are compared. A 2$\sigma$ tension between the results from $B^0$ and $B^+$ sectors is observed. The new combination method permitted the simultaneous determination the $D^0$ mixing parameters. In particular, the precision on $y_D \equiv \Delta \Gamma / \Gamma$ was improved by a factor of two with respect to the previous world average.

Despite the release of this combination, the analysis of LHCb data is still ongoing. A more recent $\gamma$ measurement, concerns $B^{\pm} \rightarrow (D \rightarrow h^+ h^- \pi^0) h^\pm$ decays, with $h, h', h'' \in \{\pi, K\}$ [15]. The case with $h = h'$ are treated as “quasi-GLW”, while the channels with $h \neq h'$ are “quasi-ADS”. In the first case, the $D \rightarrow \pi^+ \pi^- \pi^0$ and $D \rightarrow K^+ K^- \pi^0$ final states are admixtures of CP-even and CP-odd eigenstates. In the second case, the interference effects that are sensitive to $\gamma$ vary over the phase space of the $D$ decay due to the strong decays of intermediate resonances. To deal with that, dilution factors determined by measurements of CLEO-c and BESIII [16–18] are exploited. This permits $\gamma$ to be calculated, combining eleven CP observables described in Ref. [15]. They are all measured with world best precision by this analysis. The final results is [15]

$$\gamma = (56^{+24}_{-19}) \degree.$$

It shall be used in future combinations to constrain the angle $\gamma$. The total reported uncertainty is largely dominated by the statistical uncertainty. In addition, the suppressed $B^+ \rightarrow (D \rightarrow \pi^+ K^- \pi^0) K^+$ decay is observed for the first time, with a significance of almost 8 $\sigma$.

The UT angle $\beta$ can be measured using decays of neutral B mesons to CP eigenstates, $f_{CP}$, in common between $B^0$ and $\bar{B}^0$. In these cases, assuming CPT invariance and negligible CP violation in the mixing, the time-dependent CP symmetry can be written as [37]

$$\frac{\Gamma_{B^0 \rightarrow f_{CP} (t)} - \Gamma_{\bar{B}^0 \rightarrow f_{CP} (t)}}{\Gamma_{B^0 \rightarrow f_{CP} (t)} + \Gamma_{\bar{B}^0 \rightarrow f_{CP} (t)}} = +S_{f_{CP}} \sin(\Delta m_d t)$$

$$-C_{f_{CP}} \cos(\Delta m_d t),$$

where $\Delta m_d$ is the $B^0, \bar{B}^0$ oscillation frequency, and the CP violation in the decay and in the interference between mixing and decay are encoded by the parameters $C_{f_{CP}}$ and $S_{f_{CP}}$, respectively. When only one CKM phase is present in the amplitudes which dominates the transition, the SM predicts $C_{f_{CP}} = 0$ and $S_{f_{CP}} = -\sin(2\beta)$. The theoretically cleanest process is $B^0 \rightarrow J/\psi K_S^0$, which proceeds at tree level. However, also channels dominated by a loop-level topology are possible. They are particularly interesting because NP in the loops may have implications on the values of $C_{f_{CP}}$ and $S_{f_{CP}}$. The Belle collaboration recently studied with its full dataset (711 fb$^{-1}$) one of these cases: the $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ decay [19]. The analysis utilises a three-dimensional fit to extract signal and background yields. The latter is mainly due to continuum background, namely $e^+ e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ processes. It is suppressed with a Neural Network classifier. The classifier output is also an observable of the fit. The other ones are the beam-energy-constrained

FIG. 1: One dimensional 1-CL profiles for the LHCb $\gamma$ combinations using inputs from $B^0_{s}$ (light blue), $B^0$ (orange), $B^+$ mesons (red) and all species together (dark blue) [14].
They supersede the previous Belle results thanks for
produced by the process \( \Upsilon(4S) \rightarrow B^0\bar{B}^0 \) are selected, the
quark content of the signal \( B^0 \) can be tagged when a flavour-specific decay of the companion \( \bar{B}^0 \)
reconstructed. The time information derives from the difference, \( \Delta t \), between the decay times of the signal and tagging \( B \), measured in their center-of-mass frame. Fig. 2 displays the time-dependent \( CP \) asymmetry observed in data with the results of the best fit superimposed. The determinations of this analysis are [20]

\[
S_{3K_S^0} = -0.71 \pm 0.23 \text{(stat.)} \pm 0.05 \text{(syst.)}, \]
\[
C_{3K_S^0} = -0.12 \pm 0.16 \text{(stat.)} \pm 0.05 \text{(syst.)}.
\]

They supersede the previous Belle results thanks to the improvements in the \( K_S^0 \) selection, background suppression, vertex reconstruction, and increased statistics. These values agree with the world average for \( -\sin(2\beta) \) [21] and the null SM prediction for \( C_{3K_S^0} \). The significance of \( CP \) violation in this mode is determined to be 2.5 \( \sigma \) from \((0,0)\). The measurement of the UT angle \( \alpha \) relies on \( b \rightarrow u\bar{d}d \) transitions. Due to the Cabibbo suppression of the tree-level topology, loop-level amplitudes may be sizeable. Therefore, hadronic contributions, which are difficult to be precisely measured, complicate the determination of \( \alpha \) from \( B \) decays. A possible approach consists of combining measurements of decays related to isospin symmetries. The complete set of \( B \to \rho\rho \) isospin partners is valuable for this purpose [24]. Belle II is expected to be able to study them jointly and within the same experimental environment. As a first step, it recently exploited the 190 fb\(^{-1} \) data collected so far to analyse the \( B^+ \to \rho^+\rho^0 \) decay. Relevant inputs for the \( \alpha \) determination are its branching ratio, \( CP \) asymmetry, and longitudinal polarization fraction, \( f_L \). The whole reconstructed decay chain includes \( \rho^+ \to \pi^+(\pi^0 \to \gamma\gamma) \) and \( \rho^0 \to \pi^0\pi^0 \) decays. To measure \( f_L \), the helicity angles between the momentum of the positive-charged pions and the direction opposite to the \( B^+ \) momentum are considered. The large continuum background is reduced with multivariate methods. The final fit for the parameter extraction included 6D templates obtained from simulation and corrected with calibration samples, as described in Ref. [23]. The raw charge asymmetry determined by the fit is then corrected for the detection asymmetry due to instrumental effects. It is measured with a \( D^+ \to K_S^0\pi^+ \) control channel. The final results are [23]

\[
A_{CP}(B^+ \to \rho^+\rho^0) = -0.069 \pm 0.068 \pm 0.060, \\
B(B^+ \to \rho^+\rho^0) = (23.2^{+2.2}_{-2.0} \pm 2.7) \times 10^{-6}, \\
f_L = 0.943^{+0.033}_{-0.035} \pm 0.027,
\]

where the first uncertainty is statistical and the second is systematic. The determinations are consistent with the measurements available in the literature [1]. This is the first measurement of \( A_{CP}(B^+ \to \rho^+\rho^0) \) by Belle II. The systematic uncertainties are mainly data-driven, hence they are expected to decrease by exploiting the future datasets.

III. UPDATES TO THE \( K\pi \) PUZZLE

Isospin relations would suggest the same value for the \( CP \) asymmetries of \( B^+ \to K^+\pi^0 \) and \( B^0 \to K^+\pi^- \) decays. However, their world averages, recently updated by LHCb [25], show a 8 \( \sigma \) discrepancy. This peculiarity constitutes the long-standing “\( K\pi \) puzzle”. As explained in Ref. [4], a more accurate examination of this anomaly leads to the following sum rule, which also concerns the \( CP \) asymmetries in the \( B^0 \to K^0\pi^0 \) and \( B^+ \to K^0\pi^+ \) decays:

\[
A_{CP}(B^0 \to K^+\pi^-) B(B^0 \to K^+\pi^-) \tau_{B^+} \\
+ A_{CP}(B^+ \to K^0\pi^+) B(B^+ \to K^0\pi^+) \tau_{B^0} \\
- 2A_{CP}(B^+ \to K^+\pi^0) B(B^+ \to K^+\pi^0) \tau_{B^+} \\
- 2A_{CP}(B^0 \to K^0\pi^0) B(B^0 \to K^0\pi^0) \tau_{B^+} = 0,
\]

where \( \tau_{B^+} \) (\( \tau_{B^0} \)) is the lifetime of the \( B^+ \) (\( B^0 \)) meson. Deviations above the 1% level from this crucial condition are not allowed within the SM. The observable with higher uncertainty is the \( CP \) asymmetry of the \( B^0 \to K^0\pi^0 \) decay. Currently, the sum-rule predicts \( A_{CP}(B^0 \to K^0\pi^0) = -0.138 \pm 0.025 \), using the world averages of the other quantities [21]. Instead, the combination of the direct measurements by Belle and BaBar returns \( A_{CP}(B^0 \to K^0\pi^0) = 0.01 \pm 0.10 \), strongly requiring further inputs [1]. The Belle II collaboration recently updated this value using the 190
The measurement analyses the decays of $B$ mesons to the $K^0_S\pi^0$ final states. The signal $B$ vertex is obtained by projecting back to the interaction region the flight direction of the $K^0_S$ candidate. This provides a good approximation of the signal $B$ decay vertex since both the transverse flight length of the $B^0$ meson and the transverse size of the interaction region are small compared to the $B^0$ flight length along the boost direction. Another challenge is the suppression of the continuum background. A Boost Decision Tree algorithm is trained for this purpose. The $K^0_S\pi^0$ final state cannot be used to tag the $B$ flavour at the decay. Therefore, the time-dependent $CP$ asymmetry is considered. The tagging information is obtained from the companion $B$ meson produced by the primary $\Upsilon(4S)$ resonance. The values of the $\tau_{B^+}$, $\Delta m_d$, and $S_{K^0_S\pi^0}$ are fixed to their world average to maximise the sensitivity on $A_{CP}(B^0 \rightarrow K^0_S\pi^0)$. The $\Delta t$ resolution and bias are calibrated with $B^0 \rightarrow J/\psi K^0_S$ decays. Fig. 3 illustrates the projections of the fit on the $\Delta E$ and $\Delta t$ axes. The final results are [26]

\[
A_{CP}(B^0 \rightarrow K^0_S\pi^0) = -0.41^{+0.30}_{-0.32} \pm 0.09, \\
B(B^0 \rightarrow K^0_S\pi^0) = (11.0 \pm 1.2 \pm 1.0) \times 10^{-6}
\]

This is the first determination of $A_{CP}(B^0 \rightarrow K^0_S\pi^0)$ using a time-dependent analysis at Belle II. The results agree with the previous measurements [21, 27].

IV. $B$ Decays to Charmless 3-Body Final States

A long-standing debate about the role of short- and long-distance contributions to the generation of the strong-phase differences, needed for direct CP violation to occur, is ongoing in literature. The three-body decays of $B$ mesons offer a way to solve it [29]. Using Run1 data LHCb showed evidence of global direct CP-violation and high localised CP asymmetries across the Dalitz plot in charmless 3-body $B$ decays [28]. Amplitude analysis of $B^\pm \rightarrow \pi^\pm\pi^+\pi^-$ connected the large CP violation to the interference between S- and P-waves. A similar analysis related the $\pi^+\pi^- \rightarrow K^+K^-$ rescattering [30] to the large CP violation observed in $B^\pm \rightarrow \pi^\pm K^\pm K^-$ decays. LHCb has just updated these results with the data collected during the Run2 (6 fb$^{-1}$). The $B^\pm \rightarrow K^\pm\pi^+\pi^-$ and $B^\pm \rightarrow K^\pm K^\mp K^-$ are also included. The raw asymmetries between the yields of the $B^+$ and $B^-$ mesons are determined with a simultaneous fit to invariant mass spectra of the eight final states. This permits the cross-feed backgrounds due to misidentification of the final state mesons to be better handled. This background source is particularly relevant because it peaks close to the signal. After that, corrections for the experimental effect are applied. The asymmetry due to the different detection efficiency of the charge conjugated final states is estimated with simulated candidates, calibrated with data-driven techniques. The proton-proton collisions of the LHC cause a slight difference between the production rates of $B^+$ and $B^-$ mesons. This production asymmetry is estimated as the difference between the raw asymmetry of the $B^\pm \rightarrow J/\psi K^\pm$ decay and the world average of its CP asymmetry, which is treated as an external input. The global CP asymmetries of the signal decay modes are determined to be [31]

\[
A_{CP}(B^\pm \rightarrow K^\mp\pi^+\pi^-) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003 \\
A_{CP}(B^\pm \rightarrow \pi^\mp K^+K^-) = -0.144 \pm 0.007 \pm 0.003 \pm 0.003 \\
A_{CP}(B^\pm \rightarrow K^\pm K^\mp K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003 \\
A_{CP}(B^\pm \rightarrow \pi^\pm\pi^+\pi^-) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003
\]

where the uncertainties are statistical, systematic, and due to external inputs, respectively. Large global CP violation is measured for the latter three decay modes. In the last two cases, it is observed for the first time. Besides, the analysis was replicated in different regions (bins) of the Dalitz plot, as shown in Fig. 4. The CP asymmetries are not uniformly distributed in the phase space, with positive and negative $A_{CP}$ appearing in the same charged B decay channel.
significant CP violation is present for all the analysed channels in the range $1 \leq m^{\pi^+\pi^-} < 2.25$ GeV/$c^2$ in both $\pi^+\pi^-$ and $K^+K^-$ invariant masses. The combination of the present $A_{CP}$ results with the recent LHCb results of the previous LHCb analysis are confirmed.

Significant CP violation is present for all the analysed channels in the $\pi^+\pi^- \rightarrow K^+K^-$ rescattering region, namely between 1 and 2.25 GeV/$c^2$ in both $\pi^+\pi^-$ and $K^+K^-$ invariant masses. The combination of the present $A_{CP}$ results with the recent LHCb results shows good agreement with the U-spin symmetry proposed in Ref. [32].

V. PROSPECTS

Many of the CP violation observables in the $B$ sector are dominated by statistical uncertainty. This is one of the motivations leading to the foreseen upgrades of the LHCb and Belle II detectors. LHCb is expected to increase its dataset to 23 fb$^{-1}$ before the end of 2026, touching 50 fb$^{-1}$ within 2032. In the same period, the target of Belle II is collecting a total of 50 ab$^{-1}$. Several studies have already started for the next phase, setting the LHCb goal to 300 fb$^{-1}$ and the Belle II target to 250 ab$^{-1}$. Details about the experiments are documented in Ref. [33, 34]. Table 5 summarises the expected uncertainties in the direct measurements of the UT angles. LHCb and Belle II will provide comparable contributions to the determination of $\sin 2\beta$. LHCb is expected to be more competitive for the $\gamma$ measurement, whereas Belle II will achieve the most precise determinations of $\alpha$. The comparison between the current and future accuracy of the UT tests is illustrated in Fig. 5 by the plots from the CKMfitter collaboration.

The further CP violation features cited above will be also deeply investigated. Belle II is expected to dominate the measurement of $A_{CP}(B^0 \rightarrow K^0\pi^0)$, testing the isospin sum rule at 3% level with 50 ab$^{-1}$. Instead, concerning $B$ decays to charmless three-body final states, LHCb is expected to collect far larger yields with a much better signal-to-noise ratio.

In conclusion, this proceeding presented a selection of novel experimental results about the CP violation in the $B$ sector. They are just examples of the intense work ongoing in this field. It can provide powerful tests of the SM consistency. They currently corroborate the SM, but a much higher level of precision is expected for the years to come. This challenge will benefit from the competition and complementarity of the LHCb and Belle II physics programmes.

| Dataset          | $\alpha$ | $\sin 2\beta$ | $\gamma$ |
|------------------|----------|----------------|----------|
| Current world average | $4.8^\circ$ | 0.017          | $3.5^\circ$ |
| LHCb, 23 fb$^{-1}$ | 0.006    | 1.5$^\circ$    |          |
| Belle II, 50 ab$^{-1}$ | 0.005    | 1.5$^\circ$    |          |
| LHCb, 300 fb$^{-1}$ | 0.003    | 0.35$^\circ$   |          |
| Belle II, 250 ab$^{-1}$ | 0.002    | 0.8$^\circ$    |          |

TABLE I: Current and expected uncertainty on the direct determinations of the UT angles [21, 33, 34].
FIG. 5: Allowed parameter ranges for the UT parameters [35]. The left plot is the current status of the art. The right plot assumes the current central values and includes the precision improvement foreseen for the future for both experiment and theory inputs.

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