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Overview of time-dependent *CP* violation in *B* meson decays

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The Belle II and LHCb experiments are currently taking data with the goal of testing the standard model predictions and finding evidence of new physics. Opportunities for probing these theories come from time-dependent *CP* violation measurements in *B* meson decays. Some recent results are presented, covering the CKM angles ϕ_1 (β), ϕ_3 (γ), ϕ_s and other observables of B_s-meson decays. We present some highlights and discuss their experimental challenges, analysis techniques, uncertainties, limitations and future prospects.

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1. Introduction

Two major experiments heavily dedicated to B-meson decays are currently operating. The LHCb experiment [1] is located on the border between France and Switzerland near Geneva and the Belle II experiment [2] is in Tsukuba, Japan.

The Belle II experiment operates at the asymmetric electron-positron collider SuperKEKB. It is a standard high-energy particle detector with cylindrical shape and almost full solid angle coverage. It is designed to record an integrated luminosity of 50 ab^{-1}. In 2022, the SuperKEKB accelerator achieved the world-record instantaneous luminosity, 4.7×10^{34} cm^{-2}s^{-1} and the Belle II collected a data set of 428 fb^{-1} (Fig.1) [3].

The LHCb detector is a single-arm forward spectrometer with 0.01 to 0.3 rad coverage in the horizontal and 0.25 rad in the vertical plane. LHCb operates at the Large Hadron Collider at CERN. The LHCb detector has collected so far a data set of 9 fb^{-1} (Fig.1) [4].

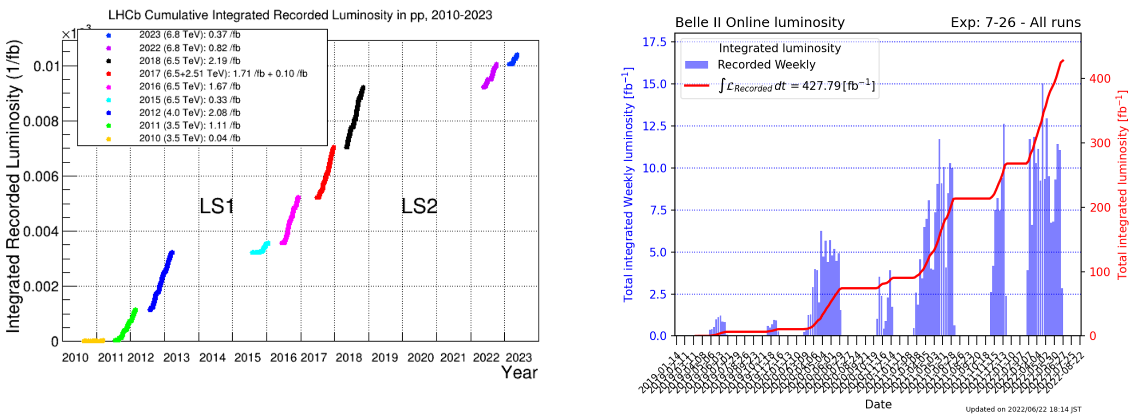

Figure 1: Collected integrated luminosity for LHCb (left) [4] and Belle II (right) [3]

Both detectors have good particle identification capabilities and high vertexing resolution, which translates into resolution of proper time measurements. However, LHCb is typically limited to final states containing only charged particles, while Belle II, operating in the much cleaner environment of the e^+e^- collisions, can also study final states containing neutral particles (π^0, η', K_L^0, ...), which makes them complementary.

2. Flavor taggers

In Belle II, SuperKEKB collides electrons and positrons at the center of mass energy corresponding to the mass of the $\Upsilon(4S)$ resonance, producing a quantum entangled $B\bar{B}$ pairs. On the other hand, the proton-proton collisions at LHCb produce a variety of final states from the hadronization of the $b\bar{b}$ quarks and quantum entanglement is not expected. This difference requires different flavor tagging and time-dependent analysis strategies at the two experiments.

The LHCb flavor tagger is based on two independent strategies: same and opposite side (Fig.2) [5]. The opposite side (OS) algorithms determine the flavor of the signal B meson from the decay products of the hadron produced by the other b ($\bar{b}$) quark produced in the collision. The OS algorithm provides the tagging decision q and mistag probability η combining information from

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the charge of the decay products of semileptonic, $b \to c \to s$ decays, secondary vertex of the other b-hadron decay and secondary charm hadrons, which are weighted based on their transverse momentum. The same side algorithm determines q and η from the properties of the particles produced during hadronisation of the b ($\bar{b}$) quark producing the signal $B_{(s)}$ candidate. Because branching fractions are inconsistent in simulations, all flavor tagger algorithms require calibration. The calibration results of same and opposite side algorithms can be found in Fig.3 for the specific case of the $B_s^0 \to J/\psi\phi$ decay. The tagging power of the combined OS and SS flavor taggers for different data taking periods is: $(4.18 \pm 0.15)\%$ for years 2015 and 2016, $(4.22 \pm 0.16)\%$ for 2017, and $(4.36 \pm 0.16)\%$ for 2018.

The Belle II flavor tagger algorithm is based on opposite side only [6]. Older category (i.e. flavor-specific decays) based algorithm exploits single particles properties (e.g. charge of daughters). A newly developed algorithm (called GFlaT) based on Graph Neutral Networks that better exploits the correlations among the properties of the particles produced by the decay of the other B meson in the event has been developed. The calibration results can be found in Fig.3. The tagging power is $(31.68 \pm 0.38)\%$ for the category based algorithm and $(37.39 \pm 0.39)\%$ for GFlaT. The new algorithm increases the tagging efficiency by about 18% and reduces the statistical uncertainty in time-dependent results by about 8%.

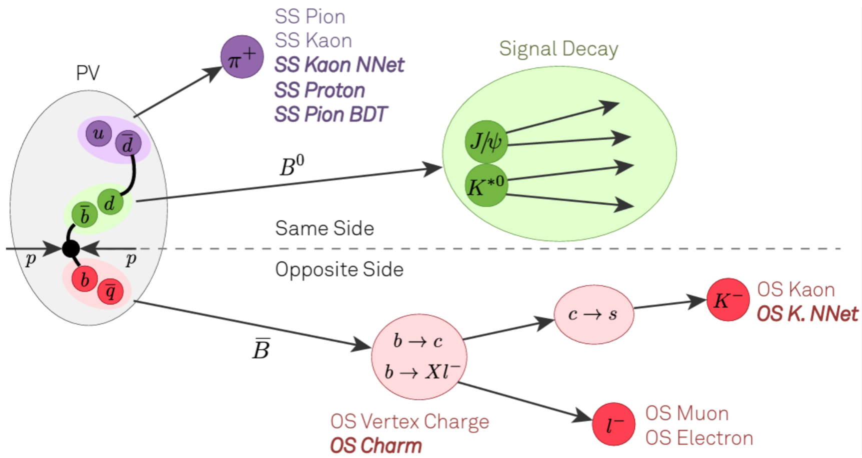

Figure 2: Schematic overview of the underlying principles of LHCb's flavour tagging algorithms [7]

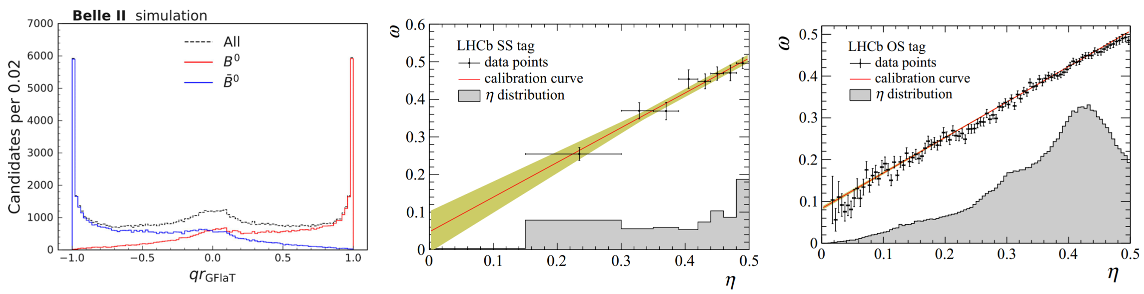

Figure 3: Calibration of flavor taggers: the Belle II (left) [6], same side (center) and opposite side (right) at the LHCb with shadow distributions of mistag probability η in background substracted $B_s^0 \to J/\psi\phi$ sample [5]

3. Time-dependent CP violation results

Time dependent CP violation analyses can be performed using tree-level (e.g. $b \to sc\bar{c}$ transitions) and loop-dominated (e.g. $b \to sq\bar{q}$) B-meson decays. The latter, being suppressed, may be sensitive to physics beyond the standard model. Effects of new physics can be detected by measuring a significant difference in the results of the time dependent CP asymmetry $S \approx \sin 2\phi_1$ ($\sin 2\beta$) between tree-dominated and loop-dominated channels. Another test is provided by B_s meson decays from which the mixing-induced CP asymmetry $S \approx \sin \phi_s$ can be determined. The consistency of the standard model can be tested also from the measurement of the difference between the decay widths of the heavy and light mass eigenstates $\Delta\Gamma_s$ or the measurement of the $\phi_3(\gamma)$ angle.

The latest measurements of time-dependent charge-parity (CP) asymmetry in tree-dominated B meson decays have been done by the LHCb and the Belle II experiments. The LHCb collaboration published the results of an analysis using the Run 2 data sample in $B^0 \to J/\psi K_S^0$ and $B^0 \to \psi(2S)K_S^0$ decays, where the direct CP violation parameter C is consistent with zero and the mixing-induced CP asymmetry is measured to be $\sin 2\phi_1 = 0.717 \pm 0.013 \pm 0.008$ [8], which is compatible with the world average $\sin 2\phi_1 = 0.699 \pm 0.017$. Including the result obtained in the Run 1 data set, $\sin 2\phi_1 = 0.760 \pm 0.034$ [9], the updated LHCb average is $\sin 2\phi_1 = 0.724 \pm 0.014$ [8], which is more precise than the world average. The Belle II collaboration published the result $\sin 2\phi_1 = 0.724 \pm 0.035 \pm 0.014$ [6] with the direct CP violation parameter being compatible with zero in $B^0 \to J/\psi K_S^0$ decays. Both results are compared with the world average in Fig. 4.

The Belle II collaboration measured time-dependent asymmetries in several loop-dominated final states: $\pi^0 K_S^0$, ϕK_S^0, $\eta' K_S^0$, and $K_S^0 K_S^0 K_S^0$. In the $\pi^0 K_S^0$ channel, Belle II measured the mixing-induced CP asymmetry $\sin 2{\phi_1}^{\text{eff}} = 0.75\ ^{+0.20}_{-0.20} \pm 0.04$ [10] and direct CP violation parameter consistent with zero. Using the ϕK_S^0 final state, the time-dependent asymmetry is measured to be $\sin 2{\phi_1}^{\text{eff}} = 0.54 \pm 0.26\ ^{+0.06}_{-0.08}$ [11] and the direct asymmetry is consistent with previous measurements. A new measurement using the $\eta' K_S^0$ channel reports mixing-induced CP asymmetry to be $\sin 2{\phi_1}^{\text{eff}} = 0.67 \pm 0.10 \pm 0.04$ [6] and direct CP violation parameter compatible with previous measurements. In the last of the mentioned measurements, using the $K_S^0 K_S^0 K_S^0$ mode, Belle II reports the mixing-induced CP asymmetry to be $\sin 2{\phi_1}^{\text{eff}} = -1.37\ ^{+0.35}_{-0.45} \pm 0.03$ [6] and direct CP violation parameter consistent with zero. In summary, measurements using loop-dominated B meson decays are consistent with world averages and their results are compared in Fig. 4.

The LHCb collaboration updated the measurement of time-dependent CP asymmetry in $B_s^0 \to J/\psi \phi$ decays using the full Run 2 data set, where no evidence of CP violation has been observed, with the mixing-induced CP asymmetry being equal to $\phi_s = -0.039 \pm 0.022 \pm 0.006$ rad [12]. Combining the Run 1 and the Run 2 samples, the LHCb averaged value is $\phi_s = -0.031 \pm 0.018$ rad [12]. Another measurement of ϕ_s^{sss} has been reported using the $B_s^0 \to \phi\phi$ mode, where the combined result of the Run 1 and Run 2 data samples is $\phi_s^{sss} = -0.074 \pm 0.069$ rad [13], that is the most precise measurement to date. The CP violation is also measured for different polarisation states of $\phi\phi$, and no sign of polarization dependence is observed. Combining the Run 1 and Run 2 results, the difference between the decay widths of the heavy and light mass eigenstates $\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009\ \text{ps}^{-1}$ [12] is measured, using the $B_s^0 \to J/\psi \eta'$ and $B_s^0 \to J/\psi \pi^+\pi^-$ modes. The time-dependent CP asymmetry measurement of the ϕ_3 angle using $B_s^0 \to D_s^\pm K^\mp$

modes reports $\phi_3 = (74 \pm 11)^\circ$ [12], which is compatible with the more precise time-integrated measurements. All reported measurements are compatible with their world averages and their comparisons can be found in Fig. 4.

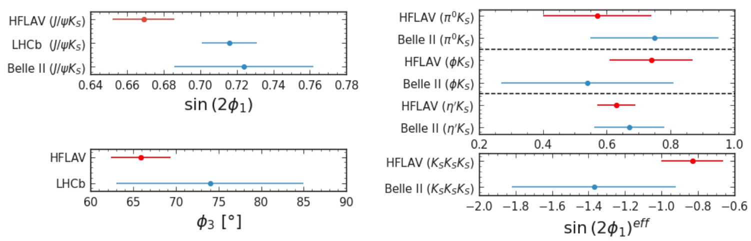

Figure 4: The latest time-dependent CP violation results: $\sin 2\phi_1$ (top left), $\sin 2\phi_1{}^{\text{eff}}$ (center), ϕ_s (top right), $\Delta\Gamma_s$ (bottom right) and ϕ_3 (bottom left); the red and blue markers with error bars represent the current HFLAV value [14] and experimental results, respectively; the y axis labels show the experiment which provided the result, with the used channel within parentheses.

4. Systematic uncertainties

The dominant contributions to the systematic uncertainties in LHCb and Belle II are different, mostly due to the different environment and experimental setup. For LHCb, the main contributions to systematic uncertainty of mixing-induced CP asymmetry $\sin 2\phi_1$ are the $\Delta\Gamma_d$ uncertainty and the portability of the flavor tagger calibration. In the same measurements by Belle II, the tag-side interference is the major contribution to the systematic uncertainty, and this does not scale with the statistics. Its possible reduction, restricting the flavor tagger to using only semileptonic decays, will decrease the available statistics. For time-dependent analyses using loop-dominated B meson decays, the main contributions to systematic uncertainty are the resolution model and background modeling, which do not scale with the statistics, but can be improved in the future. For the angular analyses, the main contributions come from mass factorization, time resolution, and flavor tagging, which do not scale with statistics. Reducing those will not be simple.

5. Perspective for future measurements

The integrated luminosity collected so far for LHCb and Belle II is 9 fb^{-1} and 428 fb^{-1}, respectively. Compared to the size of the expected final data sets, this corresponds to 1% for Belle II. On the other hand, LHCb is planning to collect about 50 fb^{-1} by the end of the Run 4, and is planning an additional Upgrade-II of the detecor to collectt up to 300 fb^{-1} by the end of the Run 6 of LHC. The next runs finishing in 2032 for LHCb and 2029 for Belle II will increase the collected samples to 59 fb^{-1} and 5 ab^{-1}, respectively.

For LHCb in tree-level B meson decays, we can expect the error on the mixing-induced CP asymmetry $\sin 2\phi_1$ to be reduced by a factor 2 and by a factor 4 using the full expected data sample. More details can be found in Tab.1. The current Belle II result is 3 times worse than the LHCb result. The precision at Belle II can be reduced by including additional ψ resonances and the K_L^0 modes. Using the full Belle II data sample and applying all possible improvements, its precision will be

1.5 times worse than precision of the LHCb using their full sample, so the main contribution to the world average will come from LHCb in tree-dominated decays. The projection of the uncertainty on $\sin 2\phi_1$ measurements at LHCb is shown in Fig.5 and Tab.1.

The loop-dominated B meson decays have been measured in several decay modes by the Belle II detector using the current collected data sample. The most precise measurement of mixing-induced CP asymmetry $\sin 2\phi_1{}^{\text{eff}}$ comes from using the $B^0 \to \eta' K^0$ decay mode. Current results using this mode do not include all possible η' modes, the K^0_L mode, and they are still based on the older category based flavor tagger. Including all modes, new tools, and collecting more data in the next runs, the Belle II collaboration expects to improve the precision by a factor of 4 compared to the current precision. For illustration, the precision of loop-dominated measurements is projected in Tab.1 using $B^0 \to \eta' K^0$ channel only. In other modes, similar improvements are expected.

Year	Integrated luminosity [fb^{-1}]		$\delta \sin 2\phi_1$	$\delta \sin 2\phi_1{}^{\text{eff}}$
	LHCb	Belle II		
2018	3	0	0.017	0.00
2023	9	362	0.011	0.11
2032	59	5 000	0.006	0.03
2041	359	50 000	0.003	0.02

Table 1: Summed integrated luminosity, uncertainty of $\sin 2\phi_1$ [12] and $\sin 2\phi_1{}^{\text{eff}}$ [15] measurements using their dominant channels $J/\psi K_S$ and $\eta' K_S$, respectively, in the next decades

Time-dependent CP asymmetry measurements in $B^0_s \to J/\psi\phi$ and $B^0_s \to \phi\phi$ channels aim at measuring CP violation and its polarization dependence. The standard model does not predict large CP violation for the $J/\psi\phi$ and $\phi\phi$ final states. For the $J/\psi\phi$ channel, the LHCb collaboration expects a precision on the ϕ_s measurement at the level of 0.003 rad. The ϕ_s precision projected to the integrated luminosity of the LHC experiments can be found in Fig.5.

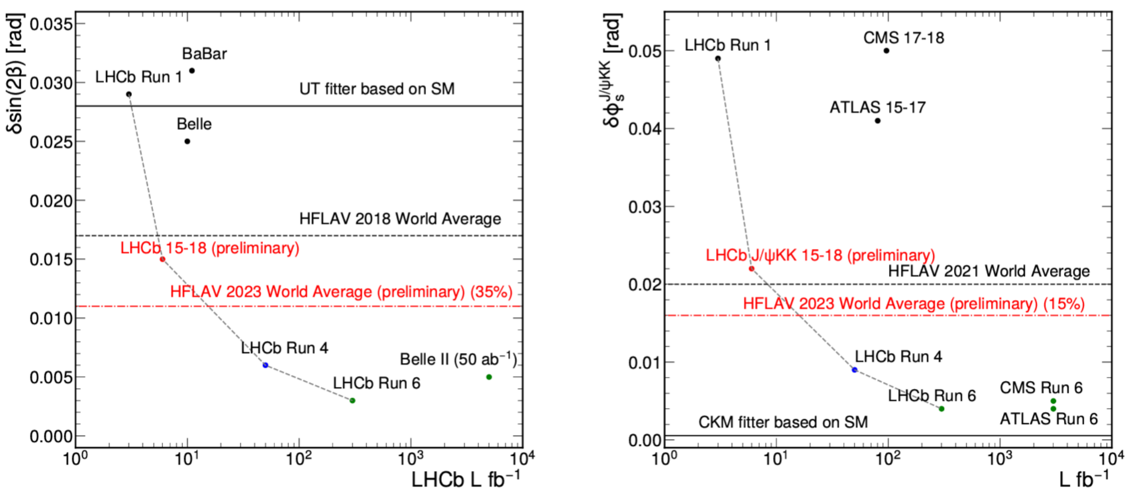

Figure 5: Statistical uncertainty as function of (LHCb's) integrated luminosity for $\sin 2\phi_1$ (left) and ϕ_s (right) measurements [12]

6. Conclusion

Belle II and LHCb, two experiments with key roles in B physics nowadays, are collecting a large amount of data and delivering new results with the goal of improving the current understanding of the standard model and test many new physics models. Using different types of collisions, experimental setups, and analysis techniques, they are providing world leading results or achieving the precision of their predecessors on mixing-induced CP asymmetry measurements in tree-level and loop-dominated B-meson decays and B_s-meson to vector-vector decays. Both collaborations bring competitive and complementary results in different areas. They are able to develop new analysis tools or to enhance the sensitivity of the existing ones in order to improve their results. The results shown demonstrate the current limitations. The main sources of systematic uncertainties are discussed and expectations for the future are presented.

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