

## Measurement of $\gamma$ ( $\phi_3$ ) and first results on CP violation at Belle II

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Flavor physics measurements at high luminosity  $B$ -factories offer a good probe for testing the Standard Model and looking for New Physics. With the first successful  $e^+e^-$  collisions recorded in 2018, the Belle II experiment is accumulating its first physics data. The design peak instantaneous luminosity of the SuperKEKB accelerator is  $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ . The size of the targeted data set is  $50 \text{ ab}^{-1}$ , which will significantly improve the experimental precision on the three angles of the CKM unitarity triangle measured by the first generation of  $B$  factories.. These measurements are based on time-dependent  $CP$  asymmetry analyses for the angles  $\phi_1$  and  $\phi_2$ , and on the measurement of direct  $CP$  violation in the decay channel  $B^- \rightarrow DK^-$  for  $\phi_3$ . In this proceeding, we report the prospects for determining  $\phi_3$ . In addition, we describe the first calibration and performance of the Belle II flavor tagging algorithm. Finally, we present the first time-dependant  $CP$  violation measurement using the channel  $B^0 \rightarrow J/\psi(e^-e^+/\mu^-\mu^+)K_S$  with the  $34.6 \text{ fb}^{-1}$  data set recorded by Belle II so far, which results in the measurement of  $\sin 2\phi_1$  of  $0.55 \pm 0.21 \pm 0.04$  where the first and second uncertainties are statistical and systematic, respectively.

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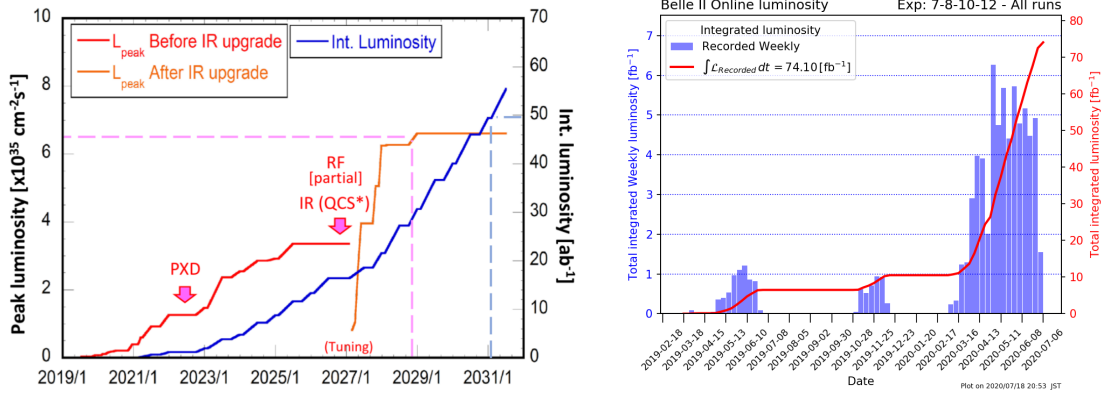
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## 1. Introduction

The Standard Model (SM) is largely successful in explaining the fundamental particles of nature and their interactions. Despite this tremendous success, there are still a few questions unanswered by the SM, such as the matter-antimatter asymmetry, mass and flavor hierarchy of the quarks and leptons and existence of too many parameters in SM. Many New Physics (NP) scenarios have been proposed to explain such blind-spots of the SM. One of the approaches to search for NP is to make measurements of the parameters in the flavor sector to see if they deviate from the SM predictions. Belle II has a unique opportunity to constrain and search for NP at the intensity frontier [1].

The SuperKEKB colliding-beam accelerator provides  $e^+e^-$  collisions at an energy corresponding to the mass of the  $\Upsilon(4S)$  resonance, boosted with a boost factor  $\beta\gamma = 0.28$ , which are being recorded by the Belle II detector. It consists of two storage rings of 3.012 km length each, one for the 7 GeV electrons (High Energy Ring, HER) and one for the 4 GeV positrons (Low Energy Ring, LER). The design peak instantaneous luminosity of SuperKEKB is  $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ , approximately thirty times higher than that achieved by the KEKB accelerator [2]. So far Belle II has accumulated  $74 \text{ fb}^{-1}$  physics data, after its first successful commissioning in 2018, and will accumulate a total integrated luminosity of  $50 \text{ ab}^{-1}$  by 2031, as shown in the SuperKEKB road map in fig. 1. With this large data set, we can perform precision measurements of Cabibbo-Kobayashi-Maskawa (CKM) parameters [3], and search for NP, such as  $CP$  violation in charm mesons, lepton-flavor violations in  $\tau$  decays, new particles affecting rare flavor-changing neutral current processes and search for light dark matter candidates [1].



**Figure 1:** SuperKEKB road map for reaching the target luminosity (left) and the Belle II achieved luminosity so far (right).

In this document, we will discuss Belle II readiness for the measurement of the angle  $\phi_3$  and the first time-dependent  $CP$  asymmetry measurements for the angle  $\phi_1$  of the UT triangle using the data set collected by Belle II in 2019 and early 2020, which includes a description the first calibration of the Belle II flavor tagger and its performance.

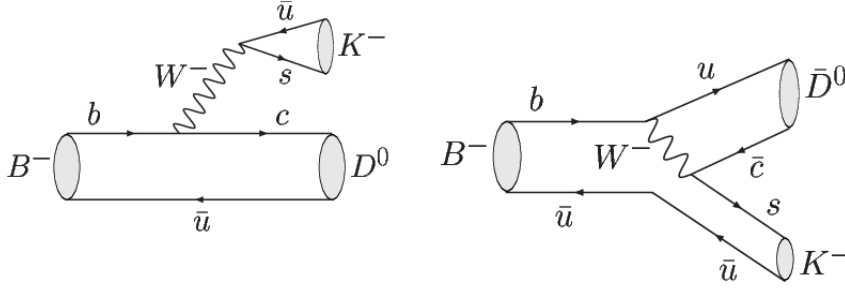
## 2. Measurement of $\gamma$ ( $\phi_3$ )

The more precise determination of the  $CP$ -violating parameter  $\phi_3$  (also called  $\gamma$ ) is the most promising path to a better understanding of the Standard Model (SM) description of  $CP$  violation

and search for contributions from non-standard model physics. It can be extracted via tree-level decays, along with non-perturbative strong interaction parameters, which makes the method free of theoretical uncertainties to  $O(10^{-7})$  [4]. Figure 2 shows the two interfering diagrams for the most commonly used decay channel  $B^\pm \rightarrow DK^\pm$ , where  $D$  indicates a  $D^0$  or  $\bar{D}^0$  meson decaying to the same final state  $f$ ; the weak phase  $\phi_3$  appears in the interference between  $b \rightarrow c\bar{u}s$  and  $b \rightarrow u\bar{c}s$  transitions. The  $b \rightarrow u\bar{c}s$  amplitude ( $\mathcal{A}_{\text{sup}}$ ) is suppressed relative to the  $b \rightarrow c\bar{u}s$  amplitude ( $\mathcal{A}_{\text{fav}}$ ) because of the magnitudes of the CKM matrix elements involved and the requirements of colorless hadrons in the final state. The two amplitudes are related by

$$\frac{\mathcal{A}_{\text{sup}}}{\mathcal{A}_{\text{fav}}} = r_B e^{i(\delta_B - \phi_3)}, \quad (1)$$

where,  $r_B$  is the magnitude of the ratio of amplitudes and  $\delta_B$  is the strong-phase difference between the favoured and suppressed amplitudes. The current world average value of  $r_B$  is  $0.103 \pm 0.005$  [5].



**Figure 2:** Leading order quark flow diagrams for the decay channel  $B^- \rightarrow DK^-$ .

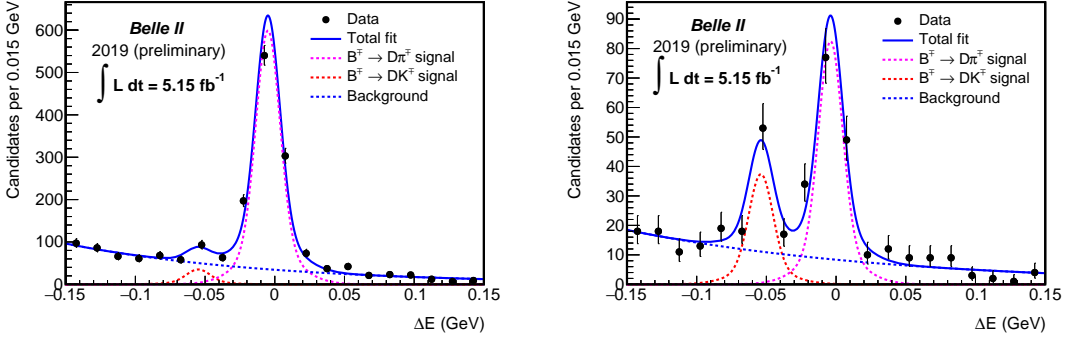
Using the early Belle II data set, corresponding to an integrated luminosity of  $5.15 \text{ fb}^{-1}$ , we rediscovered the channel  $B^\pm \rightarrow DK^\pm$  with  $5.2\sigma$  significance. The analysis uses a continuum suppression technique and particle identification (PID) criteria to isolate the signal decays; the signal yield is determined by performing a one-dimensional maximum likelihood fit to the  $\Delta E$  variable, which is defined as  $\Delta E = \Sigma E_i - E_{\text{beam}}$ , where  $E_{\text{beam}}$  and  $E_i$  are the beam energy and the energy of  $B$  daughter particles in the center-of-mass frame. A total of  $53 \pm 9$  signal candidates are obtained for this channel. Figure 3 shows the  $\Delta E$  distributions, with and without the PID criteria on the prompt track, along with the fit projections.

Currently, the experimental precision on  $\phi_3$  is  $\sim 5^\circ$  [5], which provides a lot of room for improvement. A combined sensitivity of  $1.6^\circ$  is expected when all Belle results are extrapolated to a  $50 \text{ ab}^{-1}$  data set [1]. Accounting for current constraints on new physics in tree-level amplitudes, a shift of up to  $4^\circ$  on the SM value of  $\phi_3$  is possible [6]. This is one of the strongest motivations for the  $1^\circ$  precision being pursued by Belle II.

### 3. Time-dependant $CP$ -violation (TDCPV) at Belle II

Generally, to measure the time-dependant  $CP$ -asymmetries, neutral  $B$  mesons are fully reconstructed when decaying into  $CP$ -eigenstates. The time-dependent decay rate of the neutral  $B$  meson to the  $CP$ - eigenstate is given by [7]

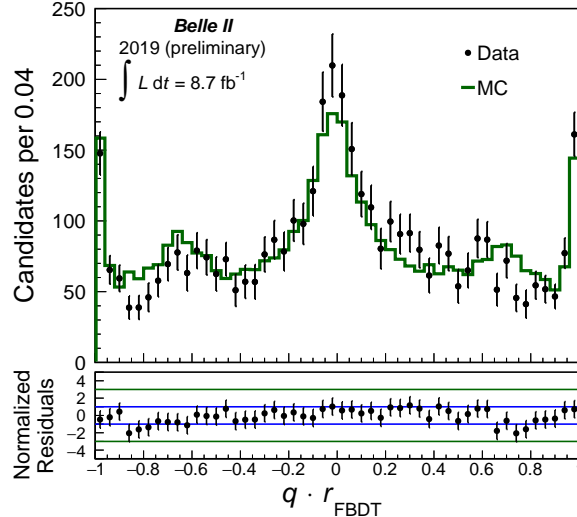
$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \left[ S \sin(\Delta m_d \Delta t) + \mathcal{A} \cos(\Delta m_d \Delta t) \right] \right\}, \quad (2)$$



**Figure 3:** Distributions of  $\Delta E$  for  $B^- \rightarrow D^0 h^-$  without PID criteria (left) and with PID requirement (right) ( $h = \pi$  or  $K$ ) candidates reconstructed in  $5.15 \text{ fb}^{-1}$  of collision data with the projection of an unbinned maximum likelihood fit overlaid.

where  $q = +1(-1)$  when the other  $B$  meson in the event decay is a  $B^0(\bar{B}^0)$ ,  $\Delta t$  is the proper time difference between the two decays,  $\tau_{B^0}$  is the neutral  $B$  lifetime,  $\Delta m_d$  is the mass difference between the two  $B^0$  mass eigenstates and  $S$  and  $\mathcal{A}$  are the  $CP$ -violating parameters. Hence, the two key elements in the analysis are the vertex position measurement to determine  $\Delta t$  and the  $B$  meson flavor tagging to determine  $q$ .

The Belle II flavor tagger (FT) uses an algorithm where many multivariate classifiers are combined into a single fast boosted decision tree (FBDT). It identifies the flavor  $q$  of the signal  $B$  candidates with an effective tagging efficiency expressed as  $\sum \varepsilon_i \times (1 - 2w_i)^2$ , where  $\varepsilon_i$  represents the efficiency of the  $i^{\text{th}}$  classifier and  $w_i$  is the flavor mistag fraction [8]. The value of effective tagging efficiency obtained from an  $8.7 \text{ fb}^{-1}$  data set is  $(33.8 \pm 3.9)\%$ . This effective tagging efficiency is comparable with the largest values obtained by Belle and Babar [8]. Figure 4 shows the normalized FT output  $qr_{\text{FBDT}}$  distributions for neutral  $B$  signal candidates, we observe good agreement between data and simulation samples.



**Figure 4:** Normalized FT output distributions in data and MC simulation for neutral  $B$  candidates.

Reconstruction of the  $B$  meson decay vertex with good accuracy is a key ingredient of time-dependent analyses. The SuperKEKB accelerator has a lower beam asymmetry than its predecessor,

KEKB, thus providing a lower boost factor  $\beta\gamma = 0.28$ , which is about 2/3 of the KEKB value. The vertex spatial distance  $\Delta z$  and  $\Delta t$  are related by  $\Delta z = \beta\gamma\Delta t$ . As a result, one could expect a lower  $\Delta t$  resolution for Belle II. However, due to better silicon vertex detector configuration at Belle II, it is better than Belle and the resolution is  $130 \mu\text{m}$  where as it is  $200 \mu\text{m}$  at Belle [1].

#### 4. Measurement of $\sin 2\phi_1$

The most precise determination of  $\sin 2\phi_1$  is obtained from TDCPV measurement of the tree mediated  $b \rightarrow c$  processes, dominated by the decay  $B^0 \rightarrow J/\psi K^0$ . These channels are referred to as the golden channels for  $\sin 2\phi_1$  measurement because of their relatively large branching fraction and small theoretical uncertainties [9]. These modes are dominated by color-suppressed  $b \rightarrow c\bar{c}s$  tree diagram. Therefore, the prediction  $\mathcal{S} \approx -\sin 2\phi_1$  and  $\mathcal{A} = 0$  is valid to a good accuracy. Because of the high experimental precision and the low theoretical uncertainty these modes serve as a benchmark in the SM, which means that any other measurement of  $\sin 2\phi_1$  that has a significant deviation, beyond the usual small SM corrections, indicates evidence for New Physics.

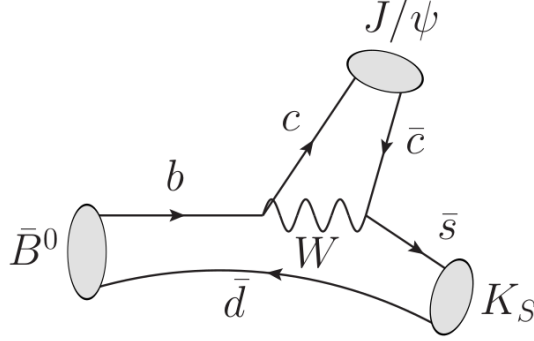


Figure 5: Tree diagram for the channel  $B^0 \rightarrow J/\psi K^0$

Belle II performed a preliminary measurement of  $\sin 2\phi_1$  using a  $34.6 \text{ fb}^{-1}$  of data. The fit to the beam-constrained mass ( $M_{bc}$ ) and  $\Delta t$  distribution for  $B^0 \rightarrow J/\psi(e^-e^+/\mu^-\mu^+)K_S$  candidates reconstructed in the same data set is shown in fig. 6. The variable  $M_{bc}$  is defined as  $\sqrt{E_{\text{beam}}^2 - (\Sigma \vec{p}_i)^2}$ , where  $E_{\text{beam}}$  and  $\vec{p}_i$  are the beam energy and momenta of  $B$  daughter particles in the center-of-mass frame. The fit is performed assuming no direct CP-violation ( $\mathcal{A}$  fixed to zero in the fit), as well as the same reconstruction efficiency and wrong-tag fraction for  $B^0$  and  $\bar{B}^0$  tags. With these assumptions, the asymmetry is a quasi-odd function of  $\Delta t$ , only the asymmetry of the  $\Delta t$  resolution function breaks its oddness. The value obtained for the time-dependent CP-violation parameter is

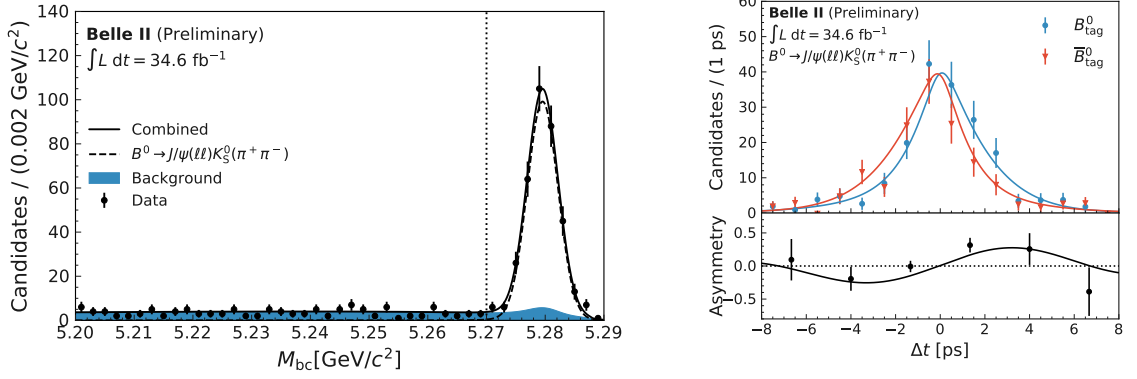
$$\mathcal{S} \approx \sin 2\phi_1 = 0.55 \pm 0.21 \text{ (stat.)} \pm 0.04 \text{ (syst.)},$$

which is in agreement with the world average  $S = 0.691 \pm 0.017$  [5].

The uncertainty reached on  $\phi_1$  with the full Belle II data set [1] is expected to be better than  $0.3^\circ$ , which can be compared to the  $0.7^\circ$  precision on the current world average [5].

#### 5. Summary

Belle II should play a key role in particle physics given the precedent of its predecessors, Belle and Babar. Also, it provides a very good complementarity to LHCb. The rediscovery of  $B^+ \rightarrow DK^+$



**Figure 6:**  $M_{bc}$  distribution with fit projection (left) and background subtracted  $\Delta t$  distribution and asymmetry as a function of  $\Delta t$  (right) for the channel  $B^0 \rightarrow J/\psi K^0$ .

decays and first measurement of time-dependent CP violation at Belle II, using  $B^0 \rightarrow J/\psi K_S^0$ , are reported. The flavor-tagging algorithm has also been validated. The CKM angle uncertainties are expected to improve significantly in the coming years with just 5-10  $\text{ab}^{-1}$  data sets.

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