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Measurement of γ (ϕ_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 instantaneous luminosity of the SuperKEKB accelerator is 6×10^{35} cm^{-2}s^{-1}. The size of the targeted data set is 50 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 ϕ_1 and ϕ_2, and on the measurement of direct CP violation in the decay channel $B^- \to DK^-$ for ϕ_3. In this proceeding, we report the prospects for determining ϕ_3. In addition, we describe the first calibration and performance of the Belle II flavour tagging algorithm. Finally, we present the first time-dependant CP violation measurement using the channel $B^0 \to J/\psi(e^-e^+/\mu^-\mu^+)K_S$ with the 34.6 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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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, 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 6×10^{35} cm^{-2}s^{-1}, approximately thirty times higher than that achieved by the KEKB accelerator [2]. So far Belle II has accumulated 74 fb^{-1} physics data, after its first successful commissioning in 2018, and will accumulate a total integrated luminosity of 50 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 τ decays, new particles affecting rare flavor-changing neutral current processes and search for light dark matter candidates [1].

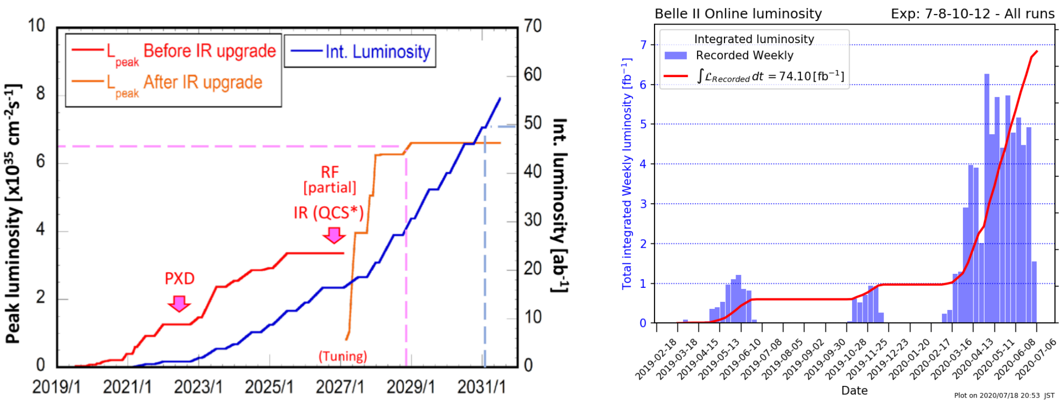

Figure 1: SuperKEKB road map for reaching the target luminosity (left) and the Belle II achived luminosity so far (right).

In this document, we will discuss Belle II readiness for the measurement of the angle ϕ_3 and the first time-dependent CP asymmetry measurements for the angle ϕ_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 γ (ϕ_3)

The more precise determination of the CP-violating parameter ϕ_3 (also called γ) 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 $O\left(10^{-7}\right)$ [4]. Figure 2 shows the two interfering diagrams for the most commonly used decay channel $B^{\pm} \to DK^{\pm}$, where D indicates a D^0 or $\overline{D^0}$ meson decaying to the same final state f; the weak phase ϕ_3 appears in the interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions. The $b \to u\bar{c}s$ amplitude ($\mathcal{A}_{\text{sup}}$) is suppressed relative to the $b \to u\bar{c}s$ 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

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

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

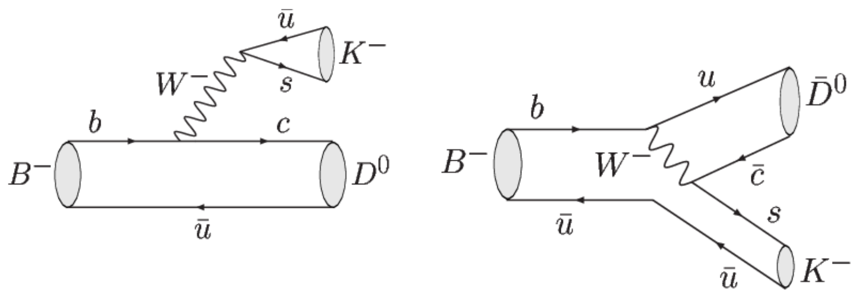

Figure 2: Leading order quark flow diagrams for the decay channel $B^- \to DK^-$.

Using the early Belle II data set, corresponding to an integrated luminosity of 5.15 fb^{-1}, we rediscovered the channel $B^{\pm} \to DK^{\pm}$ with 5.2σ 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 ΔE variable, which is defined as $\Delta E = \Sigma E_i - E_{\text{beam}}$, where E_{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 ± 9 signal candidates are obtained for this channel. Figure 3 shows the ΔE distributions, with and without the PID criteria on the prompt track, along with the fit projections.

Currently, the experimental precision on ϕ_3 is $\sim 5^{\circ}$ [5], which provides a lot of room for improvement. A combined sensitivity of 1.6° is expected when all Belle results are extrapolated to a 50 ab^{-1} data set [1]. Accounting for current constraints on new physics in tree-level amplitudes, a shift of up to 4° on the SM value of ϕ_3 is possible [6]. This is one of the strongest motivations for the 1° precision being pursued by Belle II.

3. 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]

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

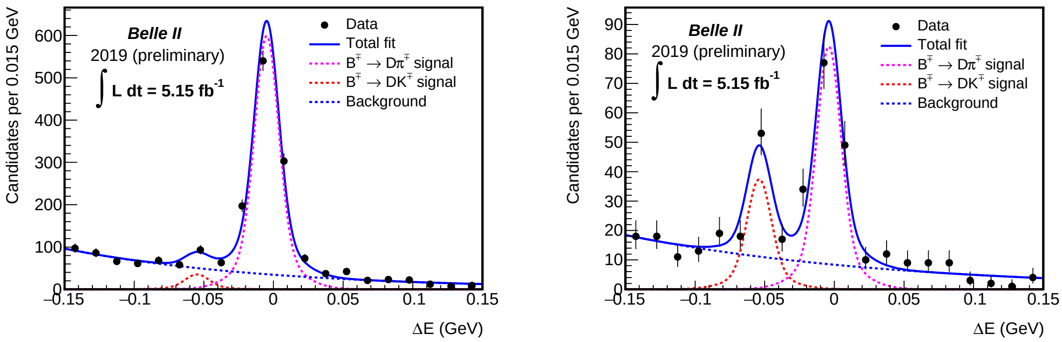

Figure 3: Distributions of ΔE for $B^- \to D^0 h^-$ without PID criteria (left) and with PID requirement (right) ($h = \pi$ or K) candidates reconstructed in 5.15 fb^{-1} of collision data with the projection of an unbinned maximum likelihood fit overlaid.

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

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

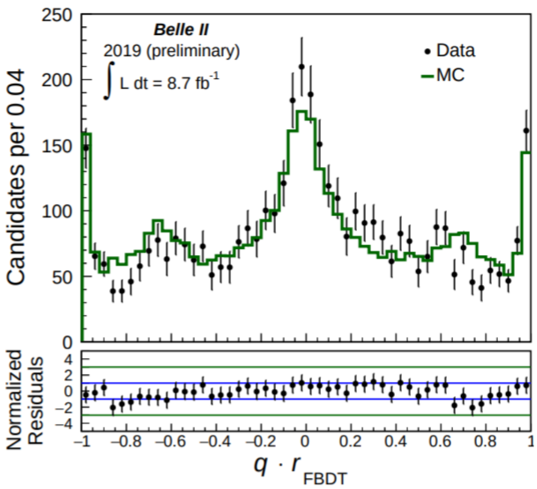

Figure 4: Normalized FT output distributions in data and MC simulation for neutral B candidates.

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 Δz and Δt are related by $\Delta z = \beta\gamma\Delta t$. As a result, one could expect a lower Δt 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 μm where as it is 200 μm 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 $b \to c$ processes, dominated by the decay $B^0 \to J/\psi K^0$. These channels are referred to as the golden channels for $\sin 2\phi_1$ measurement because of its relatively large branching fraction and small theoretical uncertainties [9]. These modes are dominated by color-suppressed $b \to c\bar{c}s$ 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.

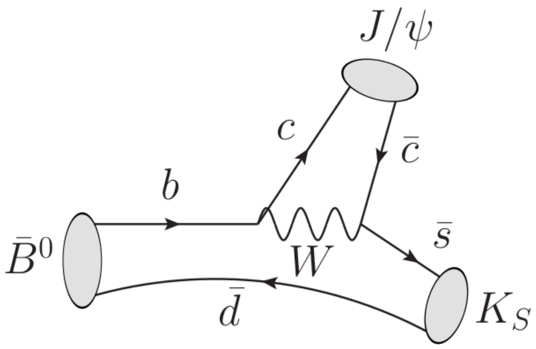

Figure 5: Tree diagram for the channel $B^0 \to J/\psi K^0$

Belle II performed a preliminary measurement of $\sin 2\phi_1$ using a 34.6 fb^{-1} of data set. The fit to the beam-constrained mass ($M_{\rm bc}$) and Δt distribution for $B^0 \to J/\psi(e^-e^+/\mu^-\mu^+)K_S$ candidates reconstructed in the same data set is shown in fig. 6. 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 Δt, only the asymmetry of the Δt 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 ϕ_1 with the full Belle II data set [1] is expected to be better than 0.1°, which can be compared to the 0.7° 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 $B^+ \to DK^+$

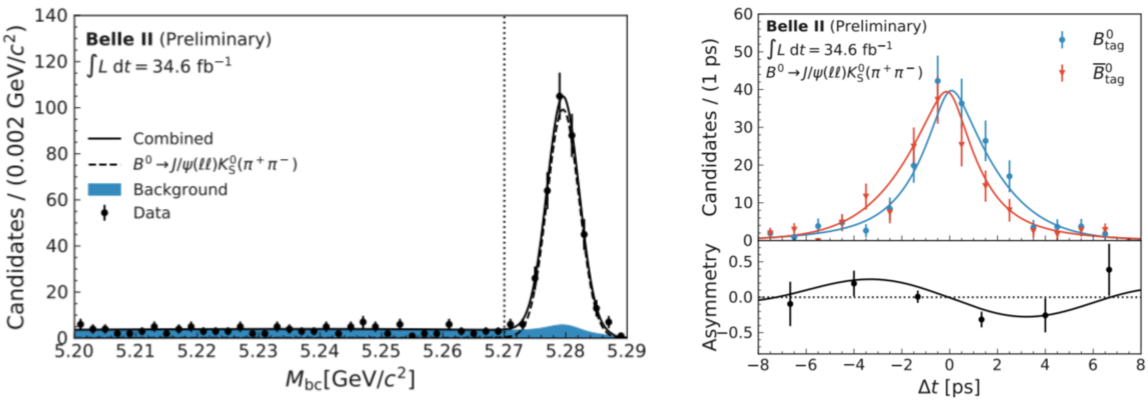

Figure 6: M_{bc} distribution with fit projection (left) and background subtracted Δt distribution and asymmetry as a function of Δt (right) for the channel $B^0 \to J/\psi K^0$.

decays and first measurement of time-dependent CP violation at Belle II, using $B^0 \to J/\psi K^0_S$, 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 ab^{-1} data sets.

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