The Belle II Experiment: Status and Prospects

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August 17, 2021

Abstract

The Belle II experiment at the SuperKEKB energy asymmetric e^+e^- collider is a substantial upgrade of the B factory facility at the Japanese KEK laboratory. The design luminosity of the machine is 6×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than its predecessor. With this data set, Belle II will be able to measure the Cabibbo-Kobayashi-Maskawa (CKM) matrix, the matrix elements and their phases, with unprecedented precision and explore flavor physics with B, charmed mesons, and τ leptons. Belle II has also a unique capability to search for low-mass dark matter and low-mass mediators. In this paper, we will review the status of the Belle II detector, SuperKEKB accelerator and the prospects for physics at Belle II.

1 Introduction

Heavy flavour physics plays a key role in understanding the Standard Model (SM). The first generation of B factories [1], KEKB, PEP-II and their related experiments Belle and BaBar successfully operated for 10 years and achieved substantial physics results. Both experiments provided significant contributions to B physics in finding the first evidence of CP violation outside the kaon system [2] and the experimental confirmation of the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [3]. There are still several SM predictions, which need to be verified, and the investigation of New Physics (NP) processes is extremely important. Therefore, a second generation B factory with a low-background environment and large data samples of B and D mesons, as well as τ leptons is needed, which will have exclusive advantages as compared to experiments at hadron machines. The Belle II experiment [4] at SuperKEKB [5] is the successor to the previous Belle experiment at KEKB. The design luminosity of SuperKEKB is 6×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the Belle II experiment aims to record 50 ab^{-1} of data, which is a factor of 50 more than its predecessor. With this huge data set, Belle II is expected to extend the search for NP in the flavour sector at the precision frontier using a complementary approach with respect to LHC experiments. This paper reviews the status of the Belle II experiment and SuperKEKB. The latest results on B physics, charm physics and τ physics at Belle II are also discussed.

2 SuperKEKB Accelerator

The SuperKEKB accelerator machine is situated at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan. The design luminosity of the SuperKEKB accelerator is 6×10^{35} cm^{-2}s^{-1}, which is 30 times greater than that of KEKB. In order to achieve this high luminosity, a nano-beam scheme [6] is introduced by SuperKEKB, where luminosity is greatly enhanced by increasing the beam current and reducing the vertical beta function at the IP. However with the increase in luminosity, the beam related background also increases, which will be handled with the improved Belle II detector. The SuperKEKB accelerator (figure 1 (left)) reached to the world record peak luminosity of 2.40×10^{34} cm^{-2}s^{-1} for an e^+e^- collider in the summer of 2021.

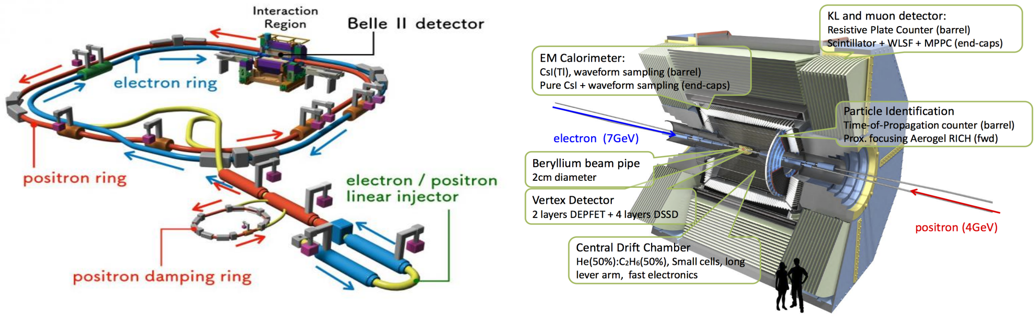

Figure 1: SuperKEKB accelerator (left) and Belle II detector (right).

3 Belle II Detector

Due to the high luminosity of SuperKEKB, the Belle II detector will be operated in a harsher radiation environment compared to Belle. In order to cope with this high background, almost all Belle II sub-detectors have been substantially upgraded. A new vertex detector consisting of a pixel vertex detector and four layers of fast silicon vertex detector is introduced, which provides the improved vertex resolution by a factor of two as compared to Belle. Further, we have a new central drift chamber (CDC), which is the main tracking detector and it provides better charge track reconstruction and dE/dx measurement. It is built with smaller cells than Belle's to operate with higher event rates. Outside the CDC, we have a particle identification (PID) system consisting of a time-of-propagation counter in the barrel region and the aerogel ring-imaging Cherenkov detector in the forward-end-cap region, which are mainly used to distinguish pions from kaons with a fake rate lower than in Belle. After the PID sustem, we have an electromagnetic calorimeter, which is substantially the same as used in Belle, but with faster readout electronics. A K_L meson and μ detector has been improved by substituting all the resistive plate chamber layers with scintillators in the end-cap region and the first two layers in the barrel region. The upgraded Belle II detector (figure 1 (right)) is expected to provide improved impact parameter resolution, increased K_S efficiency, a better K/π separation and good π^0 reconstruction. Belle II has recorded data corresponding to an integrated luminosity of 213 fb^{-1}.

4 Performance of the Belle II Detector

The performance of the Belle II detector is validated using various control samples. The performance of the charged kaon and pion identification is studied using data corresponding to at integrated luminosity of 37 fb^{-1}. The results of kaon efficiency and pion misidentification rates for different PID criteria using the decay $D^{*+} \to D^0[K^-\pi^+]\pi^+$ are shown in figure 2 (left). This study is performed in several bins of laboratory-frame momentum and polar angle [7]. The tracking efficiency is measured using $e^+e^- \to \tau^+\tau^-$ events in e^+e^- collision data collected in 2019 at Belle II, where one tau lepton decays leptonically ($\tau \to \ell^\pm \nu_\ell \bar{\nu_\tau}, \ell = e, \mu$), while the other decays hadronically into three charged pions ($\tau \to 3\pi^\pm\nu_\tau + n\pi^0$) [8] as shown in figure 2 (right). Further, reconstruction performance of neutral particles at Belle II is demonstrated by analysing the two photon events coming from π^0 and η [9].

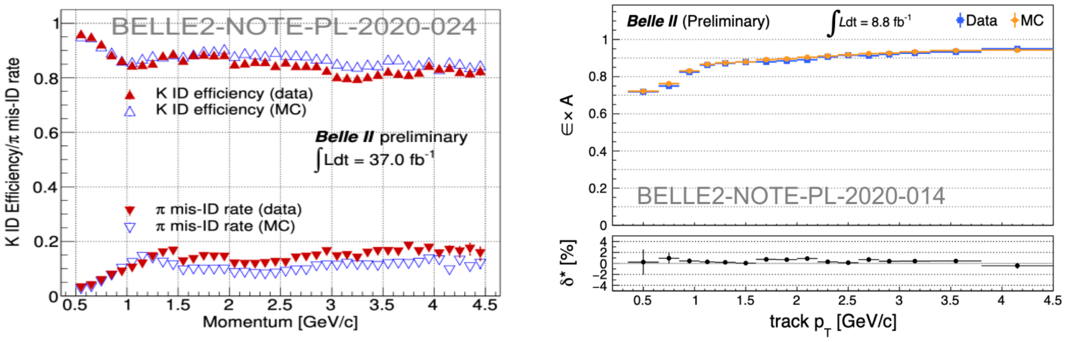

Figure 2: K-identification efficiencies and π-misidentification rates for different PID criteria using the decay $D^{*+} \to D^0[K^-\pi^+]\pi^+$ (left), measured tracking efficiency times detector acceptance ($\epsilon \times A$) and calibrated data-MC discrepancy (δ^*) for the combined channels as a function of the 1-prong track p_T (right).

5 Physics Programme at Belle II

The Belle II experiment aims to investigate heavy flavour physics with high precision. The physics programme at Belle II covers wide range of physics, which includes B, D mesons and τ leptons along with dark sector searches and spectroscopy. In this paper, important highlights on limited physics studies such as measurement of the CKM angles, time integrated CP asymmetry using charmless B decays, D^0 lifetime along with τ-mass measurement will be discussed.

5.1 Measurement of the CKM Angles

Due to good flavor tagging efficiency at Belle II, it provides an opportunity to study CP violation by measuring the CKM angles through various B decays; discrimination of signal from background utilizes two important variables ΔE (beam-energy difference) and M_{bc} (beam-constrained mass). The decay $B^0 \to J/\psi K_L^0$ provides an independent measurement of CKM angle $\sin(2\phi_1)$, where J/ψ is reconstructed from e^+e^- and $\mu^+\mu^-$, and $K_L^0$is reconstructed as a hadronic neutral cluster in KLM. Figure 3 (top: left) shows ΔE distribution for $B^0 \to J/\psi K_L^0$ with data corresponding to an integrated luminosity of 62.8 fb^{-1}. Figure 3 (top: right) shows M_{bc} distribution for $B^0 \to J/\psi K_S^0$ with data corresponding to an integrated luminosity of 34.6 fb^{-1}. Further, ΔE distribution for $B^0 \to \pi^0\pi^0$ is shown in figure 3 (bottom: left), which is difficult to reconstruct, as it has four photons in final state. This decay is important to measure the CKM angle (ϕ_2). Figure 3 (bottom: right) shows the ΔE distribution for $B^0 \to D^0 h^-$, where h is either a kaon or a pion. This study is aimed to measure the CKM angle (ϕ_3) with higher precision [10].

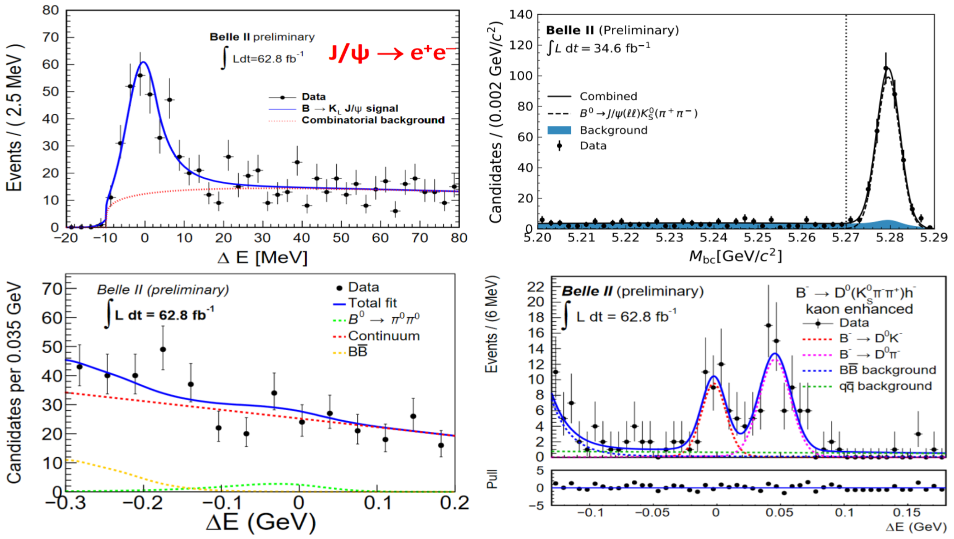

Figure 3: ΔE distribution for $B^0 \to J/\psi K^0_L$ (top: left), M_{bc} distribution for $B^0 \to J/\psi K^0_s$ (top: right), ΔE distribution for $B^0 \to \pi^0\pi^0$ (bottom: left), and ΔE distribution for $B^0 \to D^0 h^-$, where h is either a kaon or a pion (bottom: right).

5.2 $B \to K\pi$ decays

The $K\pi$ isospin sum rule [11] offers a stringent null test of the SM, and is expressed in terms of direct CP asymmetries and branching fractions of the four $B \to K\pi$ decay modes. We observed 45^{+9}_{-8} signal events from the fitting of ΔE and M_{bc} distributions of $B^0 \to K^0\pi^0$, which is translated to $\mathcal{B}(B^0 \to K^0\pi^0) = (8.5^{+1.7}_{-1.6} \pm 1.2) \times 10^{-6}$ [12]. As this decay is a CP eigen-state, we use the output of the flavor tagger to determine the time integrated CP asymmetry $[-0.40^{+0.46}_{-0.44} \pm 0.04]$ [12].

5.3 Measurement of D^0 life time

The lifetime measurement of the D^0 meson is performed with data corresponding to an integrated luminosity of 9.6 fb^{-1} using the three decays modes, namely, $D^0 \to K^-\pi^+, D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-\pi^+\pi^-\pi^+$ coming from $D^{*+} \to D^0\pi^+$ [13]. The D^0 lifetime is measured by performing a two-dimensional unbinned ML fit to distributions of proper time and its uncertainty (figure 4 (left)). The average lifetime of the D^0 meson is measured to be (412.3 ± 2.0)fs (figure 4 (right)). With 72 fb^{-1} of Belle II data, the lifetime measurement of the D^0 meson is expected to be competitive with the world average.

5.4 Preliminary analysis of charm meson decays

Due to the large data sample of charm mesons produced at Belle II, it is a good opportunity to investigate the CP violation (CPV) in the charm sector as well. In particular, the time-integrated Dalitz plot analysis of $D^{*+} \to D^0[\to \pi^+\pi^-\pi^0]\pi^+$ mode could be used to

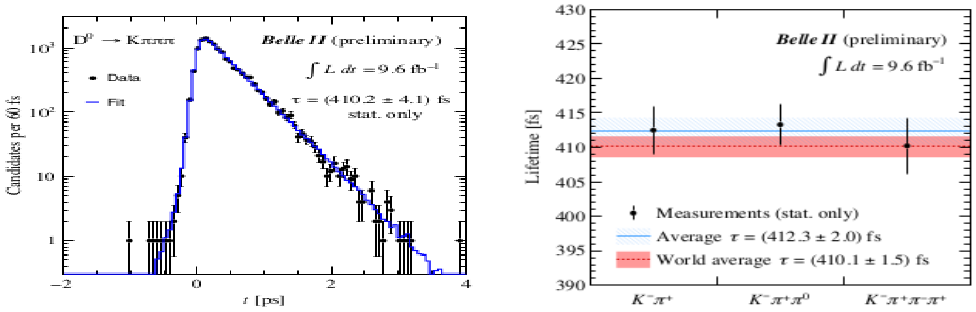

Figure 4: Proper-time distribution of the D^* tagged candidates in the $D^0 \to K^-\pi^+$ channel (left), comparison of the D^0 lifetime at Belle II with the world average values (right).

search for CPV. A signal yield of 305 ± 15 (stat.) is extracted using the distribution of $\Delta M = m(D^*) - m(D^0)$ with data corresponding to an integrated luminosity of 72 fb^{-1} [14] as shown in figure 5 (left). In addition, rediscovery of Singly Cabibbo-Suppressed (SCS) decay $D^0 \to K_s K_s$ is also carried out at Belle II [15]. Further, the ratios of wrong side to right side (WS to RS) yield of three decay modes ($D^0 \to K^+\pi^-, D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$) are also measured and results are in agreement with PDG values [16] as shown in figure 5 (right).

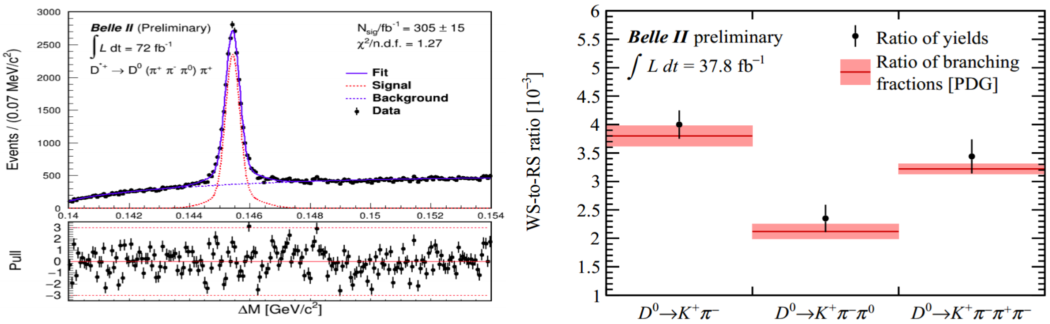

Figure 5: ΔM distribution of $D^{*+} \to D^0[\to \pi^+\pi^-\pi^0]\pi^+$ (left) and ratio of WS to RS yield (right).

5.5 Tau mass measurement

The measurement of mass of τ lepton is carried out at Belle II with data corresponding to an integrated luminosity of 8.8 fb^{-1} [17]. The tau mass is measured to be $1777.28 \pm 0.75(\text{stat.}) \pm 0.33(\text{syst.})\text{MeV}$. The precision of this measurement is limited by the size of the data that was used, but the systematic uncertainty is comparable to that at Belle. With further data provided by the Belle II experiment, the statistical uncertainty will further decrease.

6 Summary

Belle II has been running continuously and collecting data despite the Covid-19 pandemic. Its aim is to record an integrated luminosity of 50 ab^{-1}. This upcoming large and clean data samples of B and D mesons (and τ leptons) will allow Belle II to search for NP and improve the measurements of various SM parameters. The results reported in this paper are based on early Belle II data and show the Belle II's performance is as expected.

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