The Belle II Experiment: Status and Prospects

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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 $6 \times 10^{35} cm^{-2}s^{-1}$ 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) and its mechanism. 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 the 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 low background environment and large data samples of B, D, and τ is needed, which will give exclusive advantages to its experiment as compared to the hadronic 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 $6 \times 10^{35} cm^{-2}s^{-1}$ 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 review the status of 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 (figure 1 (left)) is a successor of former KEKB, which has reached to the world record peak luminosity of $2.40 \times 10^{34} cm^{-2}s^{-1}$ for an e^+e^- collider.

The accelerator machine is placed at High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan. The design luminosity of the SuperKEKB accelerator is $6 \times 10^{35} cm^{-2} s^{-1}$, which is 40 times grater than that of the KEKB. The luminosity of

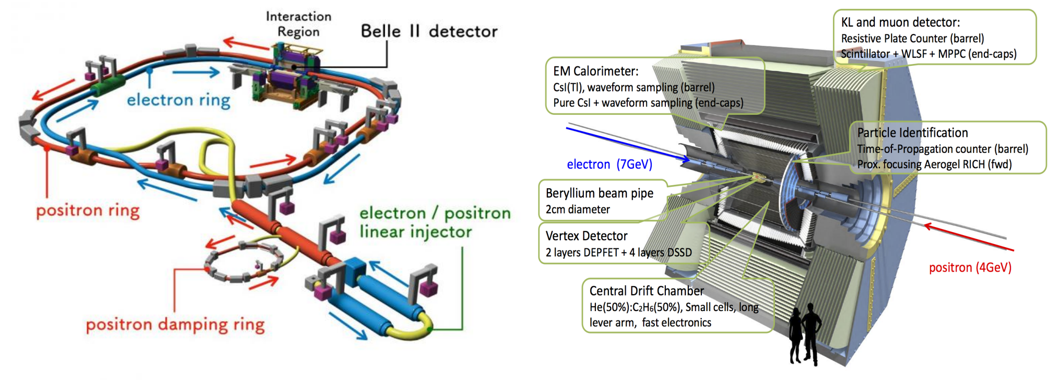

Figure 1: SuperKEKB accelerator (left) and Belle II detector (right).

SuperKEKB is expressed as,

$$\mathcal{L} = \frac{\gamma_{\pm}}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}R_L}{\beta_{y\pm}R_{\xi_y}} \tag{1}$$

where r$_e$, e and γ are respectively the electron classical radius, elementary electric charge and the Lorentz factor. The $\pm$ signs distinguish the positron (+) from the electron (-), while the ratio between the parameters R$_L$ and R$_{\xi_y}$ represents a geometrical reduction factor. In order to achieve this high luminosity, a nano beam scheme [6] is introduced by SuperKEKB, where luminosity is greatly increased by increasing the beam current (by a factor $\sim$ 2) and reducing the vertical beta function at IP (by a factor $\sim$ 20). However with the increase in luminosity, the beam related background also increases, which will be handled with the improved Belle II detector.

3 Belle II Detector

Due to the high luminosity of SuperKEKB, the Belle II detector will be operated in a harsh radiation environment with respect to Belle. In order to cope up with this high background, almost all Belle II sub-detectors have been substantially upgraded. Starting from the interaction point, a new Vertex detector (VXD) consisting of a Pixel Vertex Detector (PXD) and four layers of fast Silicon Vertex Detector (SVD) are developed, which provides the improved vertex resolution by a factor of 2 as compared to Belle. Further, we have a Central Drift Chamber (CDC), which is a main tracking detector and it provides the better charge track reconstruction and dE/dx measurement. It is built with smaller cells to operate with higher event rates. After CDC, we have particle identification system consisting of a Time-of-Propagation Counter (TOP) in barrel region and the Aerogel Ring-Imaging Cherenkov (ARICH) detector in the forward-end-cap region, which is mainly used to distinguish pions from kaons with a fake rate lower than in Belle. After PID, we have a Calorimeter, which is substantially the same as used in Belle detector, with a faster read-out electronics. K_L and μ detector has been improved by substituting all the Resistive Plate Chamber (RPC) layers with scintillators in the end-caps region and the first two layers in the barrel region. The upgraded Belle II detector is expected to provide the improvement on the impact parameter resolution, increase in K_s efficiency, a better K/π separation and good π^0 reconstruction.

4 Performance of Belle II Detector

The performance of the Belle II detector is validated on the basis of working of their sub detector systems. The performance of the charged kaon and pion identification is studied using Phase III data collected at integrated luminosity of $37 fb^{-1}$. The results of kaon efficiency and pion mis-ID 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 laboratory frame momentum and polar angle bins [7]. The tracking efficiency and fake rate are 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 [9] at Belle II is demonstrated by analysing the two photon events coming from π^0 and η [9].

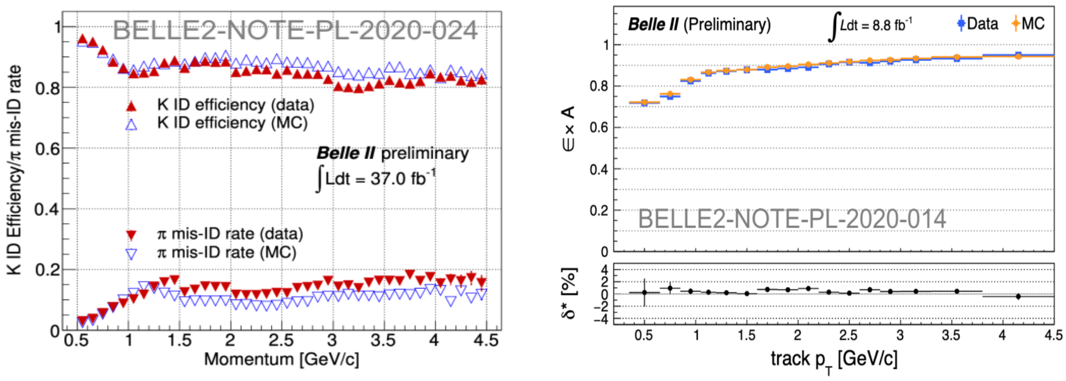

Figure 2: K-efficiencies and π-mis-ID rates for different PID criteria using the decay $D^{*+} \to D^0[K^-\pi^+]\pi^+$ (left), measured tracking efficiency times detector acceptance ($\epsilon \times A$) and calibrated Data-MC discrepancy (δ^*) for the combined channels as a function of the 1-prong track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

5 Physics Program at Belle II

The Belle II experiment aims to investigate heavy flavour physics with high precision as a B factory. Physics program at Belle II covers wide range of physics, which includes B, D and τ leptons along with dark sector searches. 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 life time 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 a unique opportunity to study the CP violation by measuring the CKM angles through various B decays using two important variables ΔE 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 taken at 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 taken at 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 unique decay of Belle II, as it has four photon in final state. This decay is important to measure the measure the CKM angle (ϕ_2). Figure 3 (bottom: right) shows ΔE distribution for $B^0 \to D^0 h^-$, where h is Kaon and pion. This study is aimed to measure the CKM angle (ϕ_3) with higher precision.

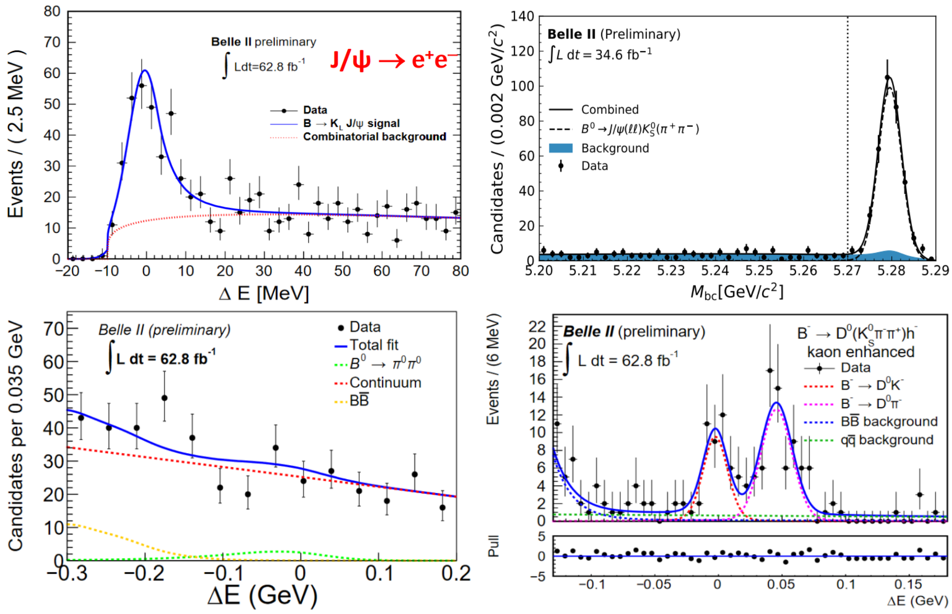

Figure 3: ΔE distribution for $B^0 \to J/\psi K^0_L$ (top: left), M_{bc} distribution for $B^0 \to J/\psi K^0_s$ (top: right), ΔE distribution for $B^0 \to \pi^0\pi^0$ (bottom: left), and ΔE distribution for $B^0 \to D^0 h^-$, where h is Kaon and pion (bottom: right).

5.2 Charmless B decays

The $K\pi$ isospin sum rule [10] offers a stringent null test of the SM, and is expressed in terms of direct CP asymmetries and $\mathcal{B}$ 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 $\mathcal{B}(B^0 \to K^0\pi^0) = (8.5^{+1.7}_{-1.6} \pm 1.2) \times 10^{-6}$. As this decay is a CP eigen-state, based on the output of flavor tagger, time integrated CP asymmetry is determined to be $[-0.40^{+0.46}_{-0.44} \pm 0.04]$.

5.3 Measurement of D^0 life time

The lifetime measurement of D^0 meson is performed with data collected at 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 $D^{*+} \to D^0\pi_s^+$ [11]. The D^0 lifetime is measured by performing a two-dimensional unbinned ML fit to distributions of proper time and its uncertainty. The average lifetime of D^0 meson is measured to be $(412.3 \pm 2.0) fs$. With 72 fb^{-1} of Belle II data, the lifetime measurement of D^0 is expected to be competitive with the world-averages.

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-

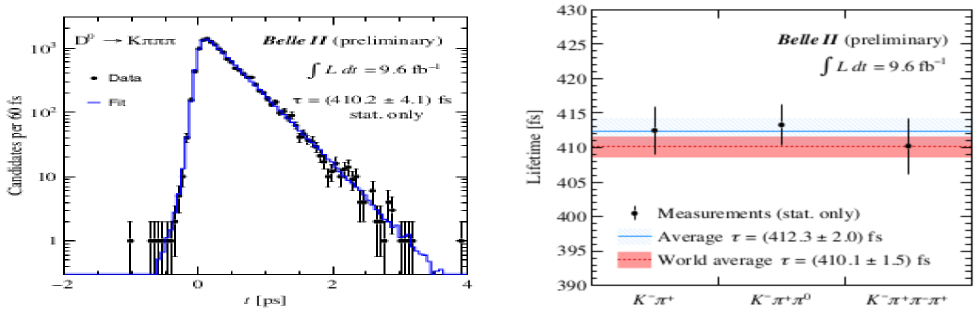

Figure 4: Proper-time distribution of the D^* tagged candidates in the $D^0 \to K^-\pi^+$ channel (left), comparison of the D^0 life time at Belle II with the world average values (right).

integrated Dalitz plot analysis of $D^{*+} \to D^0[\to \pi^+\pi^-\pi^0]\pi^+$ mode could be used to search for CPV in the decay of D. The signal yield of of about $305 \pm 15(stat.)$ is extracted using the distribution ΔM, where ΔM = m(D^*) - m(D^0) with data taken at integrated luminosity of $72 fb^{-1}$ [12] as shown in figure 5 (left).

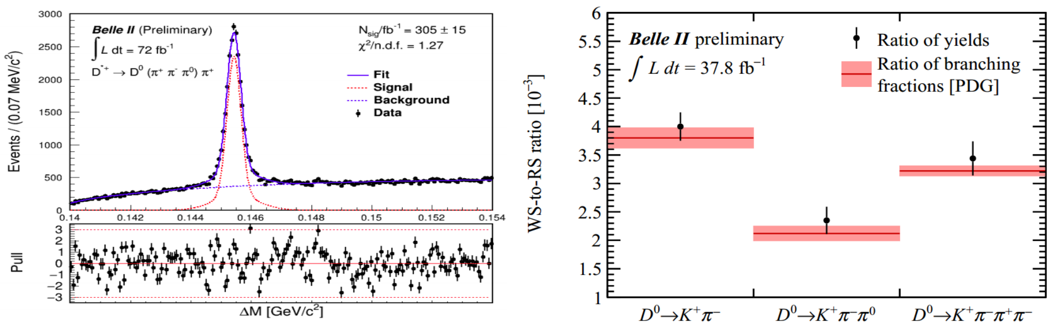

Figure 5: ΔM distribution of $D^{*+} \to D^0[\to \pi^+\pi^-\pi^0]\pi^+$ (left) and ratio of WS to RS yield (right).

In addition, rediscovery of Singly Cabibbo Suppressed (SCS) decay $D^0 \to K_s K_s$ is also carried out at Belle II and detail can be found in [13]. Further, the ratio 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 [14] as shown in figure 5 (right).

5.5 Tau mass measurement

The measurement of mass of τ lepton is carried out at Belle II with data taken at integrated luminosity of 8.8 fb^{-1} [15]. the tau mass is measured to be $\tau = 1777.28 \pm 0.75(stat.) \pm 0.33(syst.) MeV$. The precision of this measurement is limited by the size of the data that was used, but the systematical uncertainties are comparable to those at Belle.

6 Summary

Belle II has been running continuously and collecting the data despite the Covid-19 pandemic. Its aim to reach and record the data at integrated luminosity of 50 ab^{-1} in e^+e^-

collision. 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 detector performance results and physics analysis results reported in this paper are based on early Belle II data, and are obtained as expected.

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