PROCEEDINGS OF SCIENCE

The Belle II experiment Status and Prospects

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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 $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the Belle II experiment aims to record $50\,\mathrm{ab}^{-1}$ of data, a factor of 50 more than its predecessor. With this data set, Belle II will be able to measure the elements of the Cabibbo-Kobayashi-Maskawa matrix with unprecedented precision and explore flavor physics with B and D mesons, as well as τ leptons. Belle II also has a unique capability to search for low-mass dark matter and low-mass mediators. Commissioning operations with the full detector, called "Phase 3 run", started in March 2019 and recorded a data sample corresponding to an integrated luminosity of $6.49\,\mathrm{fb}^{-1}$ until June 2019. Here, we report the status of the Belle II detector, the results from the early data, and the prospects for the study of rare decays sensitive to New Physics.

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1. Introduction

The study of B mesons can improve the knowledge of topics such as mixing, rare decays and CP violation (CPV) which are sensitive to New Physics beyond the standard model (SM). Experiments with a high yield of $B\bar{B}$ pairs are termed "B factories", but they also produce large numbers of $D\bar{D}$ meson pairs and $\tau^+\tau^-$ lepton pairs.

The Belle experiment [1] and the BaBar experiment [2] operated from 1999 to late 2000s, and these experiments were the first generation of B factories to produce plenty of B meson pairs at an electron-positron accelerator. In 2001, time-dependent CPV of B meson decay was observed by both experiments [3, 4]. Later, direct CPV was observed in $B^0 \to K^+\pi^-$ decays [5].

Some problems to be addressed by the B factory experiments are: (1) new CPV phases in quark sector, (2) multiple Higgs bosons, (3) flavor-changing neutral current and (4) beyond the SM lepton flavor violation [6]. To solve such problems, an experiment with much higher luminosity than the first generation B factories is needed. The SuperKEKB accelerator [7] and the Belle II experiment [8] have potential to explore the above problems in flavor physics, with a target of recording a data sample of 50 ab^{-1}.

2. SuperKEKB and Belle II

The SuperKEKB accelerators consists of two storage rings: the electron (positron) accelerator operating at energy of 7.007 GeV (4.000 GeV), which is called the high energy ring (low energy ring), or "HER" ("LER"). The SuperKEKB shrinks the vertical beam size (σ_y) to tens of nanometers at the collision point, which is referred to as the "nano-beam" scheme. The currents of each beam are only twice those of KEKB. As a result, the design instantaneous luminosity is $8.0 \times 10^{35}\ cm^{-2}s^{-1}$, which is about 40 times larger than that of the KEKB accelerator. The Belle II detector is the successor of the Belle detector, and the tracking efficiency and particle identification are largely improved by several upgrades of the subdetectors.

2.1 Commissioning runs

On the road to high luminosity, SuperKEKB and Belle II have a commissioning schedule that ensures the stability of beam operation, without exposing subdetectors to undue radiation damage. Phase 1 took place from February to June 2016, and this is the first SuperKEKB beam operation, which was without the Belle II detector. The BEAST detectors [9] were installed to monitor beam background near the interaction point. Phase 2 took place from April to July 2018 with the final-focus magnets at the interaction point and most of the Belle II detector except for the VXD. The beam collisions were first produced during phase 2, and a data sample corresponding to an integrated luminosity of 0.5 fb^{-1} was recorded.

Phase 3 began in March 2019 with the addition of the VXD, less as one layer of the PXD detector. Belle II has recorded 6.49 fb^{-1} of collision data until June, 2019. As the beta function value shrunk to 2 mm, the peak luminosity reached $1.2 \times 10^{34}\ cm^{-2}s^{-1}$. The main targets of this commissioning run are increasing the luminosity under a steady beam condition and recorded data validating the beam stability and the detector performance. Some of the validations are described below.

Figure 1 shows $\sigma_{68}(\Delta d_0)$ distributions from events with two charged tracks. The differences (Δd_0) of measured parameter d_0 of the two tracks distribute within $14.2\pm0.1\,\mu$m at 68% confidence level in data, which is known as the resolution of the impact parameter by PXD, SVD and CDC subdetectors. So, the alignment and the calibration of beam and inner detectors have been proven well. Separation of kaon/pion by the TOP detector is validated using the decay of $D^{*+} \to D^0[K^-\pi^+]\pi^+$. If a criterion on the likelihood ratio $R_{K/\pi} = \frac{L_K}{L_K+L_\pi}$ is set to be greater than 0.6, the pion mis-identification probability is 0.10. The B^0-$\bar{B}^0$ mixing is measured using the decay mode $B^0 \to D^{*-}l^+\nu$. We observe that if charged signs of the two leptons in the final state are different, the B^0-$\bar{B}^0$ is unmixed. The unmixed fraction is observed to have an oscillation as a function of Δt. This observation proves the ability to measure precisely the vertex of B decays, hence the ability to measure time-dependent CPV.

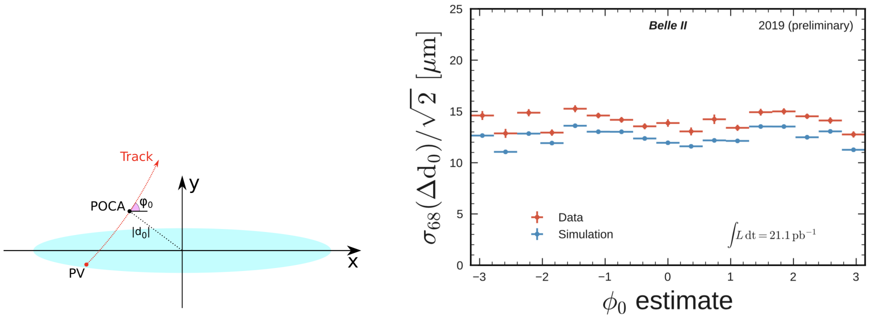

Figure 1: Left: the coordinate system in the x-y plane. For a track from the primary vertex, the transverse impact parameter (d_0) is the signed distance between the point of closest approach (POCA) and the z axis, and φ_0 is the azimuthal angle of the track momentum at the POCA. Right: 68% interval $\sigma_{68}(\Delta d_0)/\sqrt{2}$ of differences Δd_0 of tranverse impact parameters for two tracks. The two tracks t_1, and t_2 at two-track event are produced back-to-back in the center-of-mass frame, and the transverse impact parameters, $d_0(t_1)$ and $d_0(t_2)$ have opposite sign. $\Delta d_0 \equiv d_0(t_1)+d_0(t_2)$ divided by $\sqrt{2}$ is an estimation of d_0 resolution.

3. Physics Prospects

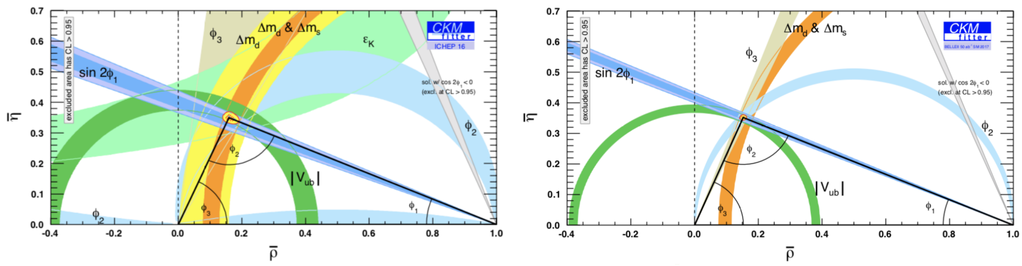

Figure 2: Left: the CKM Unitary Trangle fit today by CKMfitter group [10]. Right: CKM UT fit which is extrapolated to the $50\,\mathrm{ab}^{-1}$ luminosity for an SM-like scenario [6].

Belle II covers the following topics: semi-leptonic and leptonic B decays, radiative and electroweak penguin B decays, time-dependent CP violation in B decays, measurement of the CKM

UT angle φ_3, hadronic B decays, charm physics, quarkonium, tau and low multiplicity physics, dark sector, and beyond the SM and global fit analyses. The details of the physics potential can be found in "The Belle II Physics Book" [6]. In this contribution, we only discuss some selected topics. Figure 2 shows the CKM unitary triangle global fit today and a prediction for the future, assuming Belle II has reached an integrated luminosity of $50\,\mathrm{ab}^{-1}$. Belle II will measure parameters of the UT triangle precisely by observing many of B meson decays. For example, the branching ratio of $B^+ \to \tau^+\nu_\tau$ decay is related to the value of $|V_{ub}|$. Belle II has developed a new analysis tool, which is called "Full Event Interpretation" [11], such that a decay with multiple missing particles like $B^+ \to \tau^+\nu_\tau$ can be reconstructed efficiently with low background contamination. Another example is $B^0 \to \pi^0\pi^0$ decay, in which the direct CP asymmetry A_{CP} is sensitive to φ_2. Belle II has the ability to detect π^0 with lower momentum and higher efficiency than LHCb. The precise measurement of φ_2 from this mode is expected at Belle II. In addition, time-dependent CPV can be studied using converted photons and π^0 Dalitz decays.

4. Rediscoveries of early Belle II data

During the commissioning run, Belle II re-discovered particles and some B meson decay modes to validate its performance.

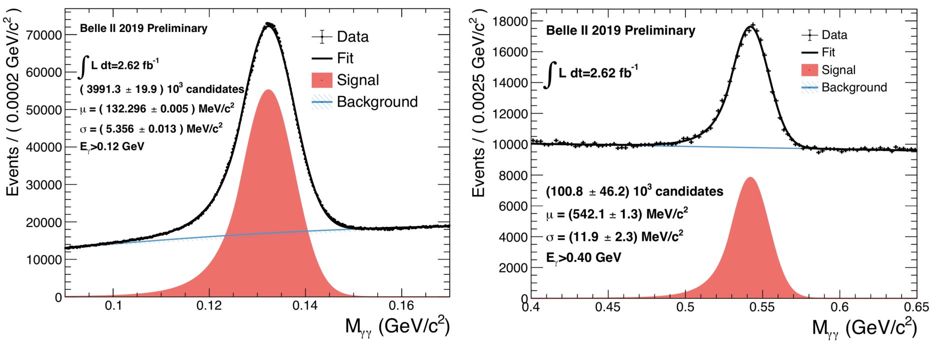

Figure 3: Invariant mass spetra of $\gamma\gamma$ at phase 3 data. Left: a clear peak at the π^0 mass value. Right: a clear peak at η mass value. The signal is fitted to a Crystal Ball function in both distributions, which is shown in read.

In figure 3, we can see that a clear peak of π^0 (left) and a clear peak of η (right) are in the $\gamma\gamma$ invariant-mass spectrum. These distributions show the ability to detect photons in the ECL detector. In addition, other particles such as J/ψ, Λ^0 and D^0 are re-discovered by combinations of particles to yield peaks in the invariant-mass spectra.

Figure 4 shows the B mesons reconstructed from $B^{0/\pm} \to D^{0(*)} + h^{0/\pm}$, where h is π or ρ, and $D^{0(*)}$ is reconstructed from K^0_S, $K^\pm$, $\pi^\pm$, and π^0. There is a clear peak at $\Delta E = 0.0$ GeV and $M_{bc} = 5.28$ GeV/c^2 where $\Delta E \equiv E_B - E_{beam}$ and $M_{bc} \equiv (E^2_{beam} - p^2_B)^{\frac{1}{2}}$ in center-of-mass frame, which shows that B mesons can be reconstructed from neutrals and charged particles efficiently.

5. Conclusion

SuperKEKB and Belle II are on the road to achieving high luminosity, and commisioning runs

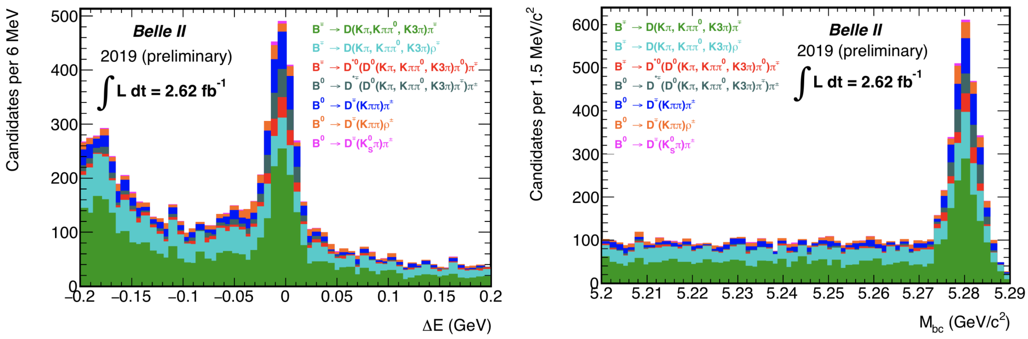

Figure 4: Distribution of ΔE (left) and M_{bc}(right) for all $B^{0/\pm} \to D^{0(*)} + h^{0/\pm}$ candidates in collision data.

started in 2018. During the phase 3 run, luminosity increased by shrinking the beta function value steadily. The analysis of phase 3 data indicates good performance of the SuperKEKB beam and the Belle II detector. Belle II confirmed rediscoveries of some particles, including B mesons, from a data sample corresponding to an integrated luminosity of a few fb^{-1}. Belle II aims to precisely measure CKM UT parameters and search for new physics beyond the SM in the near future.

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