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 $8 \times 10^{35}\,cm^{-2}s^{-1}$ 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 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 has also a unique capability to search for low mass dark matter and low mass mediators. Commissioning operations with full detector, called "Phase 3 run", started in March 2019 and recorded data of integrated luminosity of $6.49\,fb^{-1}$ until June 2019. Here, we reported 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 the topics such as mixing, rare decays and CP violation which are sentive to New Physics beyond the standard model (SM). Experiments with a high yield of $B\bar{B}$ pairs are termed "B factory", but 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 a plenty of B meson pairs at an electron-positron accelerator. In 2001, time-dependent CP violation of B meson decay was observed by both experiments [3, 4]. Direct CPV was observed at $B^0 \to K^+\pi^-$ decays in 2004 [5].

There are many problems to be addressed by the B factory experiments: 1. New CPV phases in quark sector; 2. Multiple Higgs bosons; 3. Flavor-changing neutral current and beyond the SM lepton flavor violation; [6] To solve the above problems, an experiment with much higher luminosity than the first generation B factories is needed. SuperKEKB [7] and Belle II [8] have potential to explore the above problems 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 (4.0 GeV) which is called as high energy ring (low energy ring), or "HER" ("LER"). The SuperKEKB shrinks the vertical beam size (σ_y) to tens of nano-meter at the collision point, which is called as "nano-beam". The currents of each beam are only twice than ones of KEKB. As a result, a designed instantaneous luminosity is 8.0×10^{35} $cm^{-2}s^{-1}$, which is about 40 times than one of KEKB accelerator.

The Belle II detector is the successor of the Belle detector, and the track efficiency and particle identification are largely improved by the several updates 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 Febuary to June, 2016, and this is the first SuperKEKB beam operation 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 most of Belle II detector except for the VXD and the QCS magnet. The beam collisions were first produced during at phase 2, and a data sample corresponding to an integrated luminosity of 0.5 fb^{-1} was recorded.

Phase 3 operates from March 2019 with the addition of the VXD less as one layer of the PXD detector. Belle II has have recorded 6.49 fb^{-1} of collision data until June, 2019. As the beta function value is shrinked to 2 mm, the peak luminosity has reached 1.2×10^{34} $cm^{-2}s^{-1}$. The main target of this commisioning run are the increasing the luminosity under a steady beam condition, and the recorded data validated the beam stability and the detector performance. Some of the validations are described below:

Fig.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±0.1 μm at 68% confidence level in data, and this 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 cut on the likelihood ratio $R_{K/\pi} = \frac{L_K}{L_K+L_\pi}$ is set to be 0.6, the pion mis-identification probability is 0.10. The B^0-$\bar{B}^0$ mixing is measured using decay mode of $B^0 \to D^{*-}l^+\nu$. 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 time Δt. This observation proves the ability of precise measurement for vertex of B decays, hence the ability to measure the time-dependent CP violation.

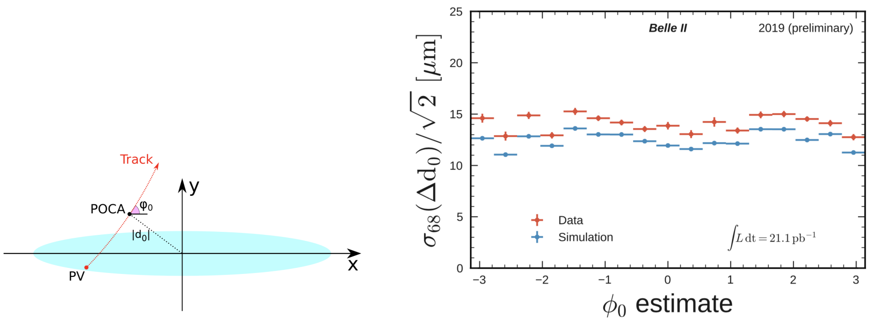

Figure 1: Left figure shows the coordinate system on x-y plane. For a track from primary vertex, the transverse impact parameter (d_0) is the signed distance between the point of closest approach (POCA) and the z axis, and φ_0 is the azimuthal angle of the track momentum at the POCA. Right figure shows the 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 CMS, 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

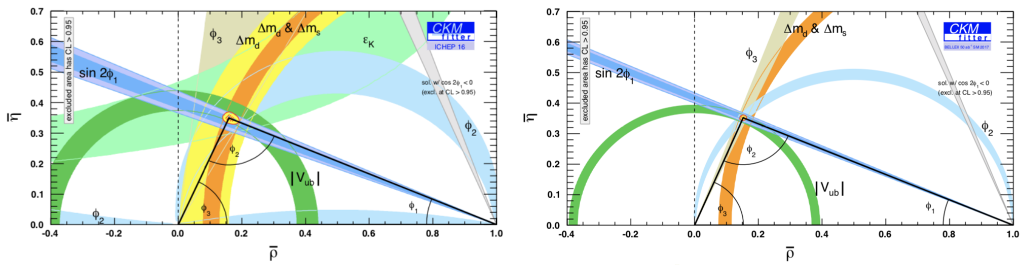

Figure 2: Left: the CKM Unitary Trangle fit today by CKMfitter group [10]. Right: CKM UT fit which is extrapolated to the 50 ab^{-1} luminosity for an SM-like scenario [6].

Belle II covers the following physical 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 can be found in "The Belle II Physics Book" [6]. In this contribution, we only discussed about some selected topics. Fig. 2 shows the CKM unitary triangle global fit today and the future assuming Belle II has reached an integrated luminosity of $50\,\mathrm{ab}^{-1}$. Belle II will measure parameters of UT triangle precisely by observing a plenty of B meson decays. For example, the branching ratio of $B^+ \to \tau^+\nu_\tau$ decay relates to value of $|V_{ub}|$. Belle II has developed a new analysis tool, which is called "Full Event Interpretation" [11], an decay with multiple missing particles like $B^+ \to \tau^+\nu_\tau$ can be reconstructed well with lower 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 the mode is expected at Belle II. In addition, time-dependent CP violation 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.

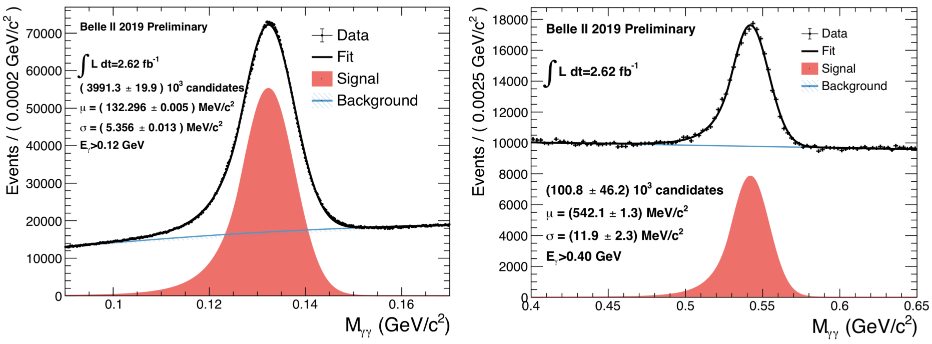

Figure 3: Invariant mass spetra of $\gamma\gamma$ at phase 3 data. Left: a clear peak at the π^0 mass value. Right: a clear peak at η mass value. The signal is fitted to a Crystal Ball function in both distributions, which is shown in read.

In Fig. 3 , we can see that a clear peak of π^0 (left) and a clear peak of η(right) are at the $\gamma\gamma$ invariant mass spectrum. This shows an ability of γ-ray detection of the ECL detector. In addition, other particles such as J/ψ, Λ^0 and D^0 are re-discovered by combinations of charged particles to yield peaks in the invariant mass spectra.

Fig.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 $M_{bc} = 5.28\ \mathrm{GeV/c^2}$ where $\Delta E \equiv E_B - E_{beam}$ and $M_{bc} \equiv (E^2_{beam} - p^2_B)^{\frac{1}{2}}$ in CM 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 started in 2018. During phase 3 run, luminosity increased by shrinking the beta function value steadily. The collected data of phase 3 indicate good performance of the SuperKEKB beam and the

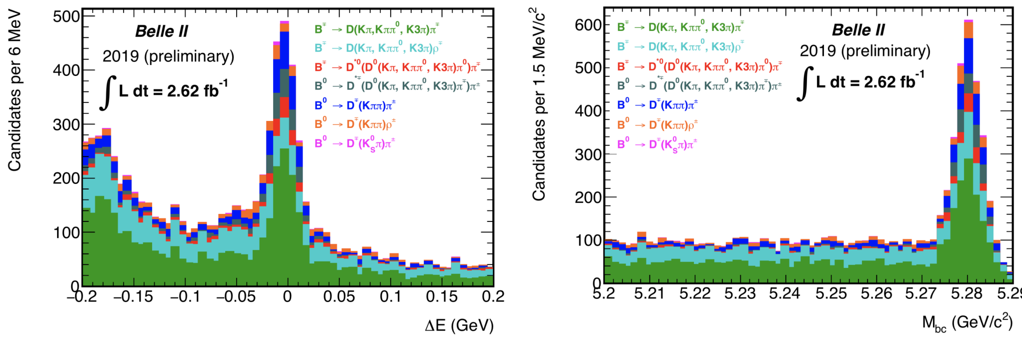

Figure 4: Distribution of ΔE (left) and M_{bc}(right) for all $B^{0/\pm} \to D^{0(*)} + h^{0/\pm}$ candidates in collision data.

Belle II detector. Belle II confirmed rediscoveries of some particles including B mesons, from data sample correspond 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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