

Status and prospects of the Belle II experiment

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Abstract. Measurements using the Belle detector at the KEKB collider in Japan have achieved important progress in the flavor structure of the Standard Model of elementary particle physics. Both the collider and the detector are being upgraded to the SuperKEKB collider and the Belle II detector to collect about 40 times higher luminosity of the Belle experiment with several improvements in the detector performance. Using the higher statistics, several measurements with precision comparisons to the predictions in the Standard Model will be performed to search for new physics beyond the Standard Model from a wide range of flavor physics channels. This paper describes the physics prospects and collider/detector construction status of the Belle II experiments.

1. Introduction

The two previous B factory experiments using e^+e^- asymmetric colliders, the Belle experiment [1] at the KEKB collider in KEK [2] and the BaBar experiment [3] at the PEP-II collider in SLAC, collected 1.5 ab^{-1} of integrated luminosity on $\Upsilon(4S)$ resonances, mainly decaying to $B\bar{B}$ meson pairs, in long term operation. Both colliders were designed with asymmetric beam energies of electron and positron to boost the B meson pair and the decay times of the $B\bar{B}$ mesons are measured from the lengths of the two particles. With the accumulated $B\bar{B}$ samples, some of important insights in the flavor structure of the Standard Model have been obtained. The observation of CP violation in the B meson system is one of the memorable results, confirming the structure of the quark flavor sector proposed by N. Cabibo, M. Kobayashi and T. Maskawa [4, 5]. However a lot of interesting measurements are still limited by statistics. To improve statistics, upgrades of both the KEKB collider and the Belle detector to the SuperKEKB collider [6] and the Belle II detector [7], are in progress in order to achieve 50 ab^{-1} of luminosity to search for physics beyond the Standard Model with more precise checks of the predictions of the Standard Model. This paper describes the status and physics prospects of the Belle II experiment in the SuperKEKB facility.

2. Physics prospects

A broad physics program in the heavy-flavor system with much higher statistics on the $\Upsilon(4S)$ resonance at the SuperKEKB collider and the Belle II detector is performed to search for signs of new physics phenomena beyond the Standard Model in the heavy-quark system [8, 9]. The quest is based on indirect searches for contributions from new physics, which are expected to show up as differences between measured values of the observables and the ones predicted in



the Standard Model. Some important topics are selected among the large number of planned measurements and explained in the following paragraphs.

2.1. Search for non-Standard Model CP violation

The CP violation phase ϕ_1 in the Standard Model should be same among measurements of various decay modes while some new physics models such as supersymmetric grand-unified theories with the see-saw mechanism [10, 11, 12] allow deviations from the Standard Model predictions. One of the most promising ways is to compare the CP asymmetry in $b \rightarrow sq\bar{q}$, which is sensitive to possible contribution from the new physics models, with the asymmetry in $B \rightarrow J/\Psi K_S$. The measurements of $\sin \phi_1$ with $b \rightarrow sq\bar{q}$ are still statistically limited in the results of the Belle experiments and it is possible to reach the theoretical limit of 0.03, for the three golden modes ($B \rightarrow \phi K^0$, $B \rightarrow \eta' K^0$ and $B \rightarrow \phi K_S K_S K_S$), with 50 ab^{-1} of the integrated luminosity at the SuperKEKB collider and the Belle II detector [8].

2.2. $B \rightarrow \tau\nu$ measurements

$B \rightarrow \tau\nu$ decay is one of interesting channels for the new physics search since the branching fraction of $B \rightarrow \tau\nu$ is expected to be affected by the contribution from the charged Higgs in the so-called type II Higgs doublet models instead of the contribution of the weak boson in the Standard Model. The first evidence for the $B \rightarrow \tau\nu$ decay has been confirmed by the Belle experiment [13, 14], followed by the BaBar experiment at PEP-II [15, 16]. A small disagreement has been observed between the measured branching fraction of $B \rightarrow \tau\nu$ and the theoretical prediction in the Standard Model but these results are still consistent with the Standard Model prediction within errors. The Belle II experiment is expected to give a better constraint to the charged Higgs mass and to $\tan \beta$.

2.3. τ lepton flavor violation

The lepton-flavor-violating decays such as $\tau \rightarrow \mu\gamma$ could be induced by neutrino oscillation with non-zero neutrino mass but these processes are strongly suppressed due to the small neutrino mass and the branching fractions are far beyond experimental reach. However, the situation can differ if a new particle exists with a mass of the order of the weak scale and couples to leptons. Some extensions of the Standard Model predict enhanced lepton-flavor-violating decays and the branching fractions can be as high as experimentally accessible by the Belle II experiment, reaching at the order of 10^{-9} to 10^{-7} [17, 18].

3. SuperKEKB collider

The designed centre-of-mass energy for the SuperKEKB collider on the $\Upsilon(4S)$ resonance is the same as for the KEKB collider while the designed luminosity for the SuperKEKB collider is $8.0 \times 10^{43} \text{ cm}^{-2}\text{s}^{-1}$, 40 times larger than 2.1×10^{34} achieved by the KEKB collider. Parameters of KEKB and SuperKEKB colliders are summarized in Table 1. The upgrade to the SuperKEKB collider is based on the "nano-beam" scheme proposed by P. Raimondi from Frascati [19]. The narrow beam size reduces the vertical beta function at the interaction point by a factor of 1/20, improving luminosity by a factor of 20. In order to achieve this improvement, the final focusing magnets are located closer to the interaction point enlarging the beam crossing angle from 22 mrad to 83 mrad. The other major contribution to the luminosity improvement is from the increase of the beam current which doubles the luminosity. The construction of the SuperKEKB facility is expected to be completed by the end of 2014 Japanese fiscal year, March 2015, and commissioning of the SuperKEKB collider will start in 2015.

Table 1. Parameters of the design values of SuperKEKB and the achieved values of KEKB. The two values separated by a slash indicate the values for positron and electron beams, respectively.

Parameters	SuperKEKB	KEKB
Beam energy (GeV)	4.0/7.0	3.5/8.0
Half crossing angle (mrad)	11	41.5
Vertical beta functions at IP (mm)	5.9	0/0.31
Beam currents (A)	1.64/1.19	3.60/2.60
Luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	2.1×10^{34}	8×10^{35}

4. Belle II detector

The Belle detector is also being upgraded to the Belle II detector against an increase of background occupancy and radiation damages due to a rise in the beam related background, 20 times higher than the Belle experiment. The effects of the background in the detector performance are estimated with the results of the operation of the KEKB collider and the Belle detector by accounting for scaling for each component of the background. Furthermore, to exploit the physics potential of the Belle II experiment, identification capabilities of hadron and muon, especially with low momentum, are also considered in the detector design. Figure 1 shows the dimensions of the Belle II detector compared with the Belle detector. The Belle II detector is under construction and expected to start physics run in 2017. The status of each part of the Belle II detector are described below.

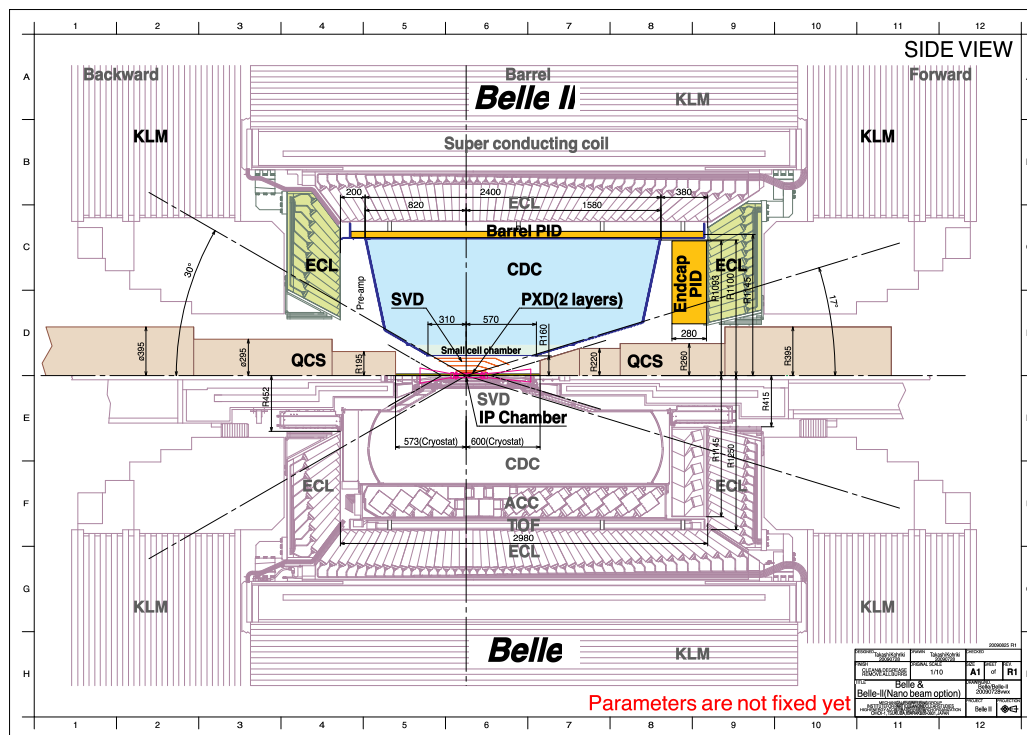


Figure 1. The Belle II detector (top half) compared with the Belle detector (bottom half).

The four layer silicon strip detector is replaced by a two-layer silicon pixel detector (PXD) based on the DEPFET (DEpleted P-channel Field Effect Transistor) and a four layer silicon strip detector (SVD). The impact parameter resolution in the beam direction is improved mainly by the PXD by a factor of about 2 for momenta below 1 GeV and the improvement of the resolution is also contributed by bringing the detector closer to the interaction point. On the other hand, the SVD contributes in the improvement of reconstruction efficiency of K_S decays to two charged pions thanks to the larger outer radius coverage. Prototypes of the PXD and SVD were tested at an electron test beam facility of Deutsches Elektronen-Synchrotron (DESY) in January 2014. The prototypes were operated with the CO2 detector cooling system and the minimum set of the Belle II data acquisition system, resulting in adequate performance of vertex resolution and data readout with online data reduction.

The central drift chamber (CDC) has smaller drift cells near the beam pipe, extended outer radius coverage, and faster readout electronics compared with the one in the Belle detector to provide better performance of momentum and dE/dx resolution. The faster readout electronics achieves less dead time from several μs to 200 ns with higher event rate by adapting waveform sampling instead of charge-to-time converter.

The particle identification systems (PID) for charged pion and kaon in both the barrel and forward end cap regions of the Belle II detector are based on Cherenkov ring imaging detectors, upgraded from the Cherenkov threshold detectors. The probability of misidentifying a charged pion (kaon) as a charged kaon (pion) is improved from about 10 % to 1 % for selection efficiencies of about 95% at the maximum kinematic momentum of 4 GeV/ c . Both PID systems reconstruct the Cherenkov radiation angles and identify the particle types from the differences in radiation angles. The barrel PID system, called TOP, is made of highly pure quartz radiator and two dimensional MCP-PMT, which measures both hit patterns and time-of-flight of the Cherenkov photons in the quartz material, internally reflected in the quartz module. On the other hand, the forward end cap PID system consists in aerogel radiators and HAPDs, called A-RICH, recording distribution of the Cherenkov photons as 2-D ring images on an array of HAPDs.

The electromagnetic calorimeter (ECL) is based on CsI crystal in the Belle detector and the Belle II detector reuses the material of the Belle detector in the barrel region while the material in the end cap regions is replaced by pure CsI crystal to increase radiation hardness and to improve performance against pileup problems. In addition to the replacement of the material, the readout electronics are also replaced to a 2MHz waveform sampling readout to suppress beam background contamination and improve energy resolution.

The outermost detector for the measurement of K_L and muon (KLM) in the Belle II detector is mainly based on reusing the RPCs of the Belle detector, partially replaced by plastic scintillator strips and optical fibers for the innermost two layers.

The increase of the beam luminosity causes much higher trigger rates up to 30 kHz at the first level trigger of the data acquisition (DAQ) system and the event data size also increases especially in the PXD to improve better performance in the high background environment with the finer granularity and more readout channels in the front end electronics. 30 GB/s of event data are read out in the PXD front end electronics and 3 GB/s are collected from the other detector electronics at the first level trigger. Several software codes for offline analysis are performed in the DAQ backend PC farm to generate the second level software trigger and the region of interest (RoI) on the PXD to reduce data size by squeezing limited data containing physics interests with reconstructed particle tracks. Finally, 3GB/s of event sample are stored on disk. The full readout chain from front end electronics to storage were tested at DESY during the beam test of the PXD and SVD prototypes in January 2014.

5. Summary

The Belle II detector at SuperKEKB is the upgrade of the previous Belle detector at the KEKB collider, expected to achieve about 40 times higher luminosity with several improvements of the detector performance. The Belle II experiment has a broad physics program to search for new physics beyond the Standard Model in the heavy flavor sector. The SuperKEKB facility is expected to complete the construction by the end of Japanese fiscal year 2014 and the accelerator commissioning will start in 2015 while the construction of the Belle II detector is now ongoing and expected to start taking physics data in 2017.

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