Belle II physics prospects, status, and schedule

J. Bennett

Department of Physics, Carnegie Mellon University, 5000 Forbes Ave, Pittsburgh, PA 15213

E-mail: `jvbennett@cmu.edu`

Abstract. The second generation B-factory at the SuperKEKB facility in Tsukuba, Japan is beginning to take shape. The highly anticipated Belle II experiment will have a rich physics program at the intensity frontier, in complement to existing experiments in the energy frontier. Accelerator commissioning has been making good progress, as has the construction and installation of the Belle II detector. An overview of the physics prospects at Belle II, as well as the status and schedule of the experiment, is presented.

1. Introduction

The Belle II experiment inherits a very successful flavor physics program from its progenitors, the Belle and BaBar experiments. The first generation B-factories boasted many important results, including experimental confirmation of the CKM mechanism as the source of CP violation (CPV) in the Standard Model (SM). This decisive evidence lead to the awarding of the 2008 Nobel prize in physics to Makoto Kobayashi and Toshihide Maskawa “for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature” [1].

Together, the Belle and BaBar collaborations recorded a total data sample of over 1.5 ab^{-1}, or about 1.25×10^9 $B\bar{B}$ pairs. Most of this was collected at the center of mass energy of the $\Upsilon(4S)$, which is just above the threshold for B-meson pair production. From the time of the first measurement of the CKM parameter $\sin 2\beta$ that established CPV in the B system in 2001 to the state of the art in 2015, global fits to the data relevant to the CKM unitarity triangle have made a remarkable improvement. Current results show excellent agreement between the SM and results from the B factories and LHCb [2]. Even with the improved precision, however, there is still room for contributions from new physics such as flavor-changing neutral currents (FCNC), lepton flavor violation (LFV), and new sources of CPV. A new physics (NP) amplitude in B_d mixing, on the scale of about 20 (2) TeV for tree-level (one-loop) processes, is perfectly compatible with the current data [3]. With the size of the data samples expected at Belle II, it should be possible to improve the current limits on contributions from NP by a factor of five for all CP violating phases.

In contrast to experiments at the LHC, which search for new physics at the energy frontier, Belle II will search for NP in the flavor sector at the intensity frontier, relying on massive data samples and high precision measurements for its physics program. While LHCb, for example, relies on the direct production of new particles and is limited by beam energy, Belle II will search for signatures of new particles or processes through measurements of suppressed flavor physics reactions or in deviations from SM predictions. Any observed discrepancies could then be interpreted in terms of NP models. Studies like these at the “flavor frontier” will enable searches for NP in virtual particle loops on a scale of up to 100 TeV [3]. Of course, the Belle II physics program is not entirely dedicated to CKM measurements. Dark sector searches, LFV, and studies of QCD exotics are just a few more examples of the rich physics program that will be pursued in the next decade at Belle II.

2. SuperKEKB and Belle II

In order to reach the design goal to collect a 50 ab^{-1} data sample at Belle II, the KEKB accelerator has undergone a significant upgrade. The new SuperKEKB accelerator makes use of nanobeams to reach the design luminosity of 8×10^{35} $\text{cm}^{-2}\text{s}^{-1}$, an impressive 40 times higher than that of KEKB. This improvement is achieved in part by greatly reducing the beam size. Of course, luminosity of this rate will result in much higher background rates, leading to greater detector occupancy, radiation damage, and other effects that must be considered. The data acquisition system (DAQ) and computing resources have also been upgraded to accommodate the burden of a higher event rate.

The Belle II detector builds upon the success of its predecessor in order to enable a strong physics research program at SuperKEKB. The colliding electron and positron beams are slightly asymmetric, resulting in a boosted center of mass (CM) system to enable time-dependent CPV measurements. With a coverage of greater than 90% of 4π, the hermiticity of the Belle II detector is improved relative to that of Belle due to a reduction in the CM boost. Most of the Belle II data will be collected at the $\Upsilon(4S)$ resonance, just above the threshold for B meson pair production, with a goal of collecting 50 ab^{-1} by the year 2024.

While many components of the Belle II detector are based on the design of the Belle detector, many improvements have been made to cope with the conditions at SuperKEKB and to improve the expected performance. Immediately surrounding the beam-pipe are upgraded silicon vertex detectors, including two pixel layers (PXD) based on DEPFET sensors and four layers of double-sided silicon strip sensors (SVD). A large central drift chamber (CDC) will provide tracking with precise momentum measurements as well as particle identification (PID) through measurements of ionization energy loss. Surrounding the CDC is the upgraded barrel PID system, which consists of an imaging time of propagation counter (TOP). A focusing aerogel ring imaging cherenkov detector (ARICH) provides PID measurements in the endcap region. The electromagnetic calorimeter (ECL) has been equipped with upgraded electronics to suppress the much higher beam-related backgrounds expected at SuperKEKB. The barrel region of the K_L and muon detector (KLM) consists primarily of resistive plate chambers. The innermost layers of the barrel region and the entirety of the endcap region is made up of plastic scintillators to cope with the high neutron flux both from the interaction point and from the beamline. A schematic view of the Belle II detector is given in Fig. 1.

3. Physics prospects

There are several significant advantages of pursuing a physics program at Belle II. For instance, Belle II will operate in a lower background environment relative to hadron machines like LHCb. The flavor tagging efficiency at Belle II is also superior to that at LHCb by about an order of magnitude. Belle II can measure K_S and K_L particles, which has an impact on most time-dependent CPV measurements. A large sample of τ leptons will enable studies of rare decays and searches for LFV in a low background environment. Interestingly, the systematics of Belle II will be quite different from those of LHCb. This allows for important confirmation by one experiment of any hints of NP observed by the other.

One of the most important advantages of SuperKEKB and Belle II is the ability to collect very clean samples of quantum-correlated $B\bar{B}$ pairs by running at the $\Upsilon(4S)$ resonance. By fully reconstructing one of the B mesons, it is possible to tag the flavor of the other B, determine its momentum, and isolate the tracks of its decay particles. In particular, this allows for a study of reactions with final state neutrinos. Due to the low efficiency of full reconstruction tagging (on

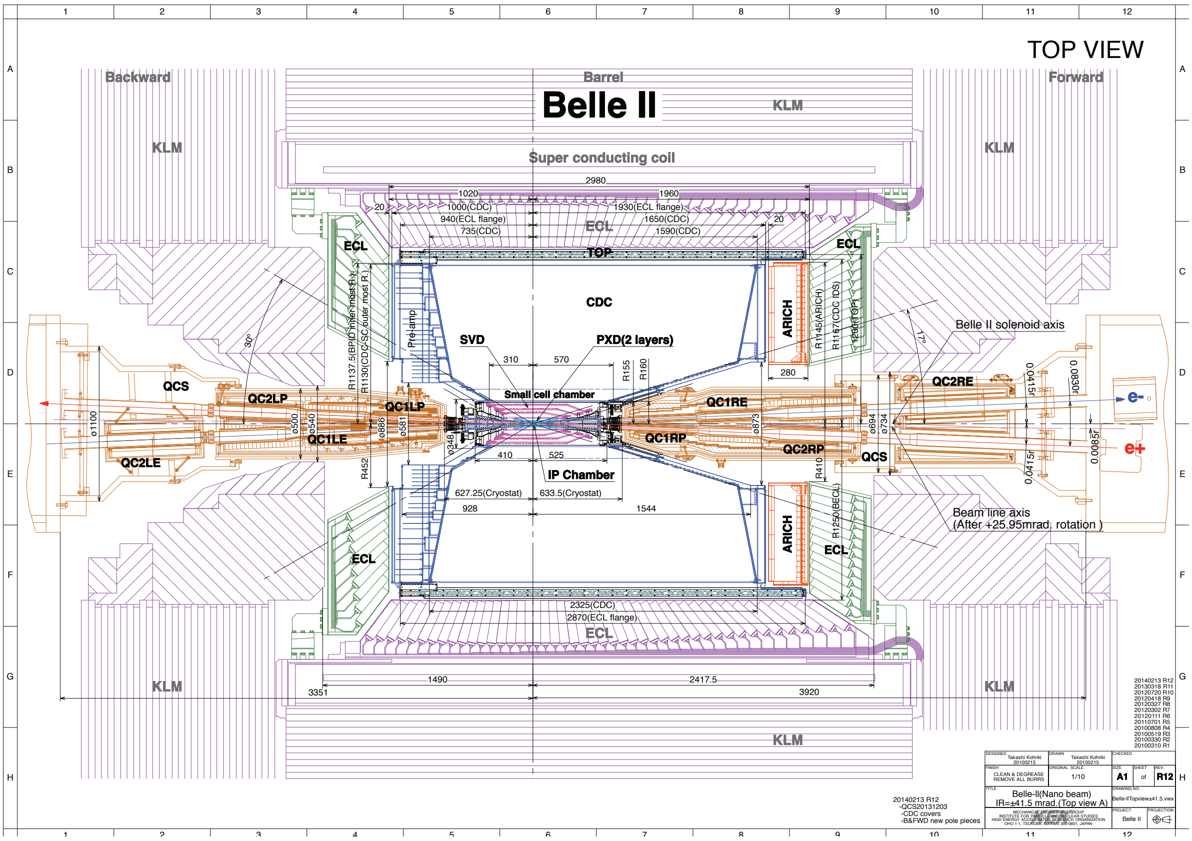

Figure 1. A schematic view of the Belle II detector.

the order of 0.1%), the first generation B factories did not make extensive use of this method. However, given the high statistics samples that will be available at Belle II, this analysis method will be used for precision measurements of CKM elements and searches for NP.

Some of the earliest physics results to come out of Belle II could be in the area of bottomonium spectroscopy. There has been considerable progress recently in Lattice QCD [4] and Belle II has the opportunity to search for some of the missing states. The clean environment at Belle II allows for inclusive searches for new states by reconstructing a single resonance and searching the recoil system. This method of study was successful at Belle and BaBar, for example in the study of P-wave spin-singlet states and the discovery of the Z_b states [5, 6]. Indeed XYZ spectroscopy provides an interesting area of research with much still to be done to quantify and confirm the plethora of states that have been observed recently.

One of the biggest questions that Belle II will seek to explore is whether or not there are any new CP-violating phases, which are included in most theories involving NP. Some of these theories allow for large deviations from SM predictions for B-meson decays. Additional sources of CPV may be important to understand the origin of the observed matter–antimatter asymmetry of the universe. Therefore, it will be important to search for new sources of CPV by comparing the mixing-induced CP asymmetries in penguin transitions with tree-dominated modes. One example of this is in the study of time-dependent CPV in B decays to ϕK^0, $\eta' K^0$, and $K^0 K^0 K^0$, similar to the Belle analysis of the same reactions [7]. With the full Belle II data sample, the uncertainty on these measurements will be on the order of 1-3% [8]. This level of precision will be important to search for any discrepancies with respect to B decays to $J/\psi K^0$. Any such discrepancies would be an important potential source of evidence for NP.

Belle II will also employ other probes for NP, including studies of radiative and electroweak processes like $b \to s\gamma$, $b \to d\gamma$, and $b \to sll$. In helicity-changing NP models like the left-right symmetric model, the helicity-suppressed amplitude could be enhanced in transitions like $B^0 \to K_S^0\pi^0\gamma$ [9], leading to a sizable CP asymmetry. With the improved vertex position resolution and reconstruction efficiency of K_S^0 decays at Belle II, the precision of measurements of this reaction could reach about 3.5%.

Leptonic B decays provide an experimentally challenging environment to test some NP models. The final states contain one or more neutrinos and the signal sides include only a single charged track. The average branching fraction measurement of B decays to $\tau\nu$ using hadronic [10, 11] and semileptonic [12, 13] tags at Belle and BaBar is $(1.14 \pm 0.22) \times 10^{-4}$, slightly higher than the SM prediction of 7.58×10^{-5} [2]. Decays like these are useful for placing constraints on models that include a charged Higgs. Using fully reconstructed hadronic and semileptonic tags at Belle II, it should be possible to measure the branching fraction of B decays to $\tau\nu$ with a precision of 3-5%. Interestingly, leptonic B decays should also provide a competitive measurement of $|V_{ub}|$ with the 50 ab^{-1} data sample.

Another useful avenue to study the two-Higgs-doublet model, one of the simplest possible extensions of the SM, is in semileptonic B decays, which proceed via first-order electroweak interactions. Reactions of this type involving electrons and muons are less sensitive to non-SM contributions, but can be used to measure the CKM elements $|V_{cb}|$ and $|V_{ub}|$. Experimentally challenging decays involving a τ lepton are sensitive to additional amplitudes and provide a means to search for NP. The most recent measurements of $\mathrm{R}(D)$ and $\mathrm{R}(D^*)$ pose a combined significance of 4.0 σ disagreement with the SM [14]. With only a 5 ab^{-1} sample, Belle II should also be able to confirm the excess in the $\mathrm{R}(D^*)$ flavor anomaly [15, 16]. With the full 50 ab^{-1}, Belle II should be able to measure $\mathrm{R}(D)$ and $\mathrm{R}(D^*)$ with a precision of 3.5% and 2%, respectively.

The charm sector provides a unique environment to probe for NP since CP violating effects are expected to be small in this sector. Mixing in heavy flavor systems is dominated by short-distance effects, which are suppressed in the charm system. This makes $D^0 - \bar{D}^0$ mixing a promising avenue for NP searches. However, the sizable effects of hadronic interactions pose a challenge to studies in the charm sector. Belle II will make significant contributions to searches for CPV in charm decays by measuring final states containing neutral particles, which are necessary for isospin analyses to isolate penguin contributions.

Lepton flavor violation is highly suppressed in the SM. Various NP models yield branching ratios for these processes on the order of 10^{-7}-10^{-10} [17, 18, 19, 20, 21]. The hadron machines are generally not competitive with Belle II for τ decay measurements due to trigger and other limitations. With the full data sample, Belle II can access LFV decay rates of over 100 times smaller than those of Belle for the cleanest channels.

4. SuperKEKB status and schedule

The tentative schedule for SuperKEKB indicates that physics quality data should be available in the fall of 2018. Construction and installation of the Belle II detector is currently ongoing. The simple background-conditioning "BEAST" detector was used for phase 1 commissioning starting in February of 2016. Phase 2 commissioning is scheduled to begin in the fall of 2017 and will consist of a more elaborate inner background commissioning detector and the full Belle II outer detector. Full superconducting final focus will be available, so it is possible that early physics results could be available during phase 2. However, the vertex detector will not be installed, so the phase 2 physics program will be limited. Phase 3 running with the full detector is expected to begin in the fall of 2018, with a sample of about 300 fb^{-1} during the first run. An overview of the SuperKEKB schedule is given in Fig. 2.

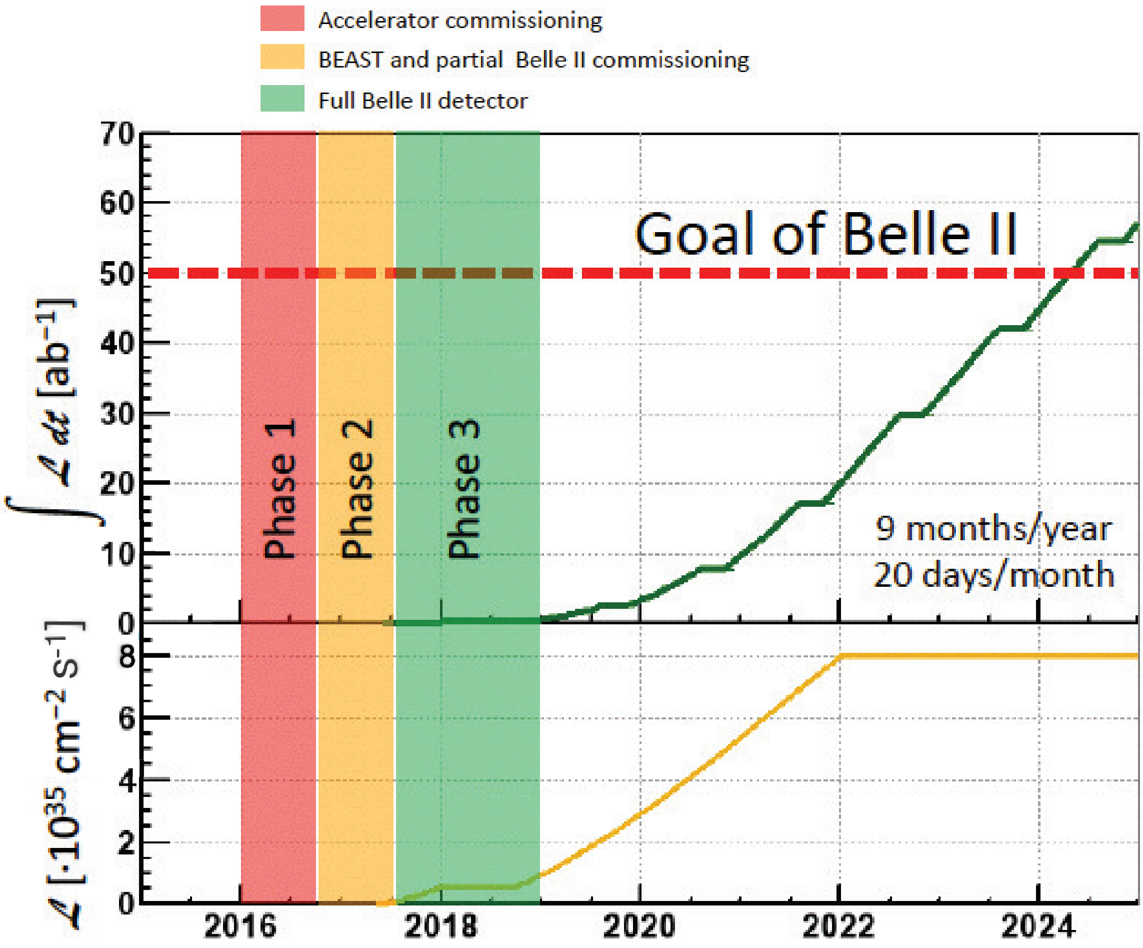

Figure 2. An overview of the projected luminosity and operation at SuperKEKB.

5. Summary

The major upgrades at KEK represent an essentially new experiment as SuperKEKB succeeds KEKB and Belle II takes the reigns from the first generation B-factories. Many detector and electronic components have been replaced in the transition from Belle to Belle II. Significant efforts have also led to improvements in the available software and analysis tools. With these improvements, Belle II is expected to pursue a rich physics program, complementary to that of existing experiments and the energy frontier program. SuperKEKB commissioning is ongoing in 2016 and first physics are possible as early as 2017. With a goal of collecting 50 ab^{-1} by 2024, Belle II is expected to make a significant impact on flavor physics and the search for new physics.

References

[1] "The 2008 Nobel Prize in Physics - Press Release". Nobelprize.org. Nobel Media AB 2014. Web. 17 Aug 2016.
`http://www.nobelprize.org/nobel_prizes/physics/laureates/2008/press.html`
[2] CKMFitter Group (J. Charles et al.), Phys. Rev. D **91**, 073007 (2015).
[3] CKMFitter Group (J. Charles et al.), Phys. Rev. D **89**, 033016 (2014).
[4] S. Godfrey and K. Moats, Phys. Rev. D **92**, 054034 (2015).
[5] I. Adachi et al. (Belle Collaboration), Phys. Rev. Lett. **108**, 032001 (2012).

[6] A. Bondar et al. (Belle Collaboration), Phys. Rev. Lett. **108**, 122001 (2012).
[7] K. F. Chen et al. (Belle Collaboration), Phys. Rev. Lett. **98**, 031802 (2007).
[8] P. Urquijo, Nucl. Phys. B. **263-264** 15-23 (2015).
[9] Y. Ushiroda et al. (Belle Collaboration), Phys. Rev. D **74**, 111104(R) (2006).
[10] K. Hara et al. (Belle Collaboration), Phys. Rev. Lett. **110**, 131801 (2013).
[11] J. P. Lees et al. (BABAR Collaboration), Phys. Rev. D **88**, 031102(R) (2013).
[12] K. Hara et al. (Belle Collaboration), Phys. Rev. D **82**, 071101(R) (2010).
[13] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D **81**, 051101(R) (2010).
[14] Heavy Flavour Averaging Group `http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html`
[15] J. P. Lees et al. (BABAR Collaboration), Phys. Rev. Lett. **109**, 101802 (2012).
[16] A. Abdesselam et al. (Belle Collaboration), arXiv:1603.06711.
[17] G. Cveti, C. Dib, C. S. Kim, and J. D. Kim, Phys. Rev. D **66**, 034008 (2002).
[18] C. Yue, Y. Zhang, and L. Liu, Phys. Lett. B **547**, 252 (2002).
[19] T. Fukuyama, T. Kikuchi, and N. Okada, Phys. Rev. D **68**, 033012 (2003).
[20] J. Ellis, J. Hisano, M. Raidal, and Y. Shimizu, Phys. Rev. D **66**, 115013 (2003).
[21] A. Brignole and A. Rossi, Phys. Lett. B **566** 217 (2003).