PROCEEDINGS OF SCIENCE

Belle II physics and early measurements

Jing-Ge Shiu[†]
National Taiwan University
E-mail: physjg@hep1.phys.ntu.edu.tw

After the tremendous achievements of the first generation B factories, the new generation B-factory SuperKEKB at KEK is designed to explore the intensity frontier. It has succeeded beam circulation commissioning in 2016. The associated Belle II experiment will start physics data taking within 2 years. The target total integrated luminosity is 50ab^{-1}, which is 50 times larger than the Belle experiment. This offers high data statistics for precision measurements and rare decay studies. In these proceedings, I will highlight some major topics of the Belle II physics, e.g. precision measurements of the CKM parameters, searching for more exotic states, and probing new physics in rare decays. A few possible early measurements will also be discussed.

16th International Conference on B-Physics at Frontier Machines
2-6 May 2016
Marseille, France

[†]Speaker

PoS(BEAUTY2016)055

1. Introduction

The first generation B factories, PEP-II with BaBar and KEKB with Belle, have achieved tremendous success. Decisive confirmation of the CKM mechanism of CP violation (CPV) in the Standard Model (SM) led to the 2008 Nobel Prize in physics to M. Kobayashi and T. Maskawa. Beyond that, they also have great achievements in many other attractive physics topics in flavor physics, including the observation of D^0 mixing, exotics states, and many new particles in the bottomonium spectroscopy (Figure 1).

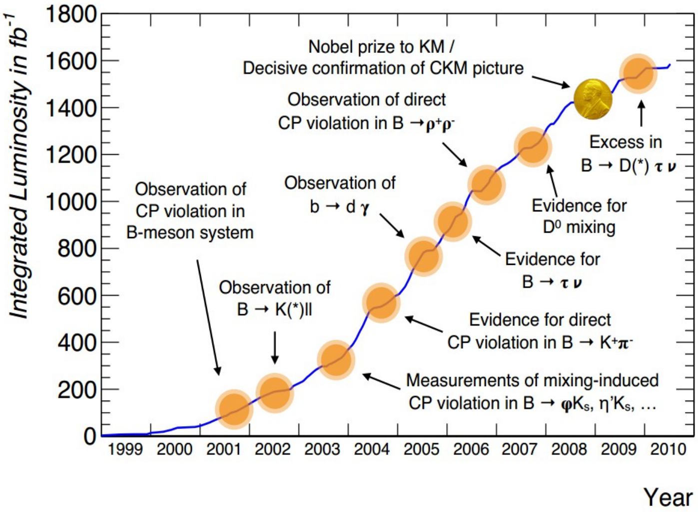

Figure 1: A chronicle of some major observations at the B factories.

However, there are still unsolved puzzles. The measured CPV is not sufficient to explain the huge matter-antimatter asymmetry observed in the Universe. There are indications that the current SM is not the full story of the fundamental physics. Chasing new physics (NP) beyond the SM is always attractive. Many theoretical models have proposed new particles or processes in a wide energy scale to enhance some rare processes in the SM.

The high energy physics research thus moves into two directions. The LHC explores the energy frontier to search for new particles and physics in the highest energy scale currently achievable by man-made facility. Observation of the Higgs boson is the first triumph and was awarded the 2013 Nobel Prize in physics. Complementary to the energy frontier exploration, the new generation B factory, namely Belle II at SuperKEKB, is targeting at the intensity frontier to accumulate high data statistics for precision measurement and rare decay studies.

The SuperKEKB e^+e^- collider at the High Energy Accelerator Research Organization in Japan (KEK) has succeed its first beam circulation commissioning in 2016. The Belle II experiment will start physics commissioning in 2 years, and expect to collect $50ab^{-1}$ data in 7 years operation. With this amount of data and relative clean environment, one can improve the measurement precision in many attracting B and D physics topics and explore rare processes in the SM to probe for NP. In these proceedings, a few promising physics topics in the Belle II experiment will be highlighted [5][7]. The details of analysis strategy and physics process are beyond the scope of these proceedings.

The Belle II experiment at the SuperKEKB collider is designed for high precision measurements and studies of rare decays of B mesons, D mesons, and tau leptons [1]. The nominal center-of-mass energy at the SuperKEKB is at the ϒ(4S) resonance, which makes it a clean environment for B meson decay studies. With advanced accelerator technologies, the designed instantaneous luminosity is at 8×10^{35} $cm^{-2}s^{-1}$, 40 times higher than that at KEKB.

2. SuperKEKB and Belle II

The detail description of the Belle II detector (Figure 2) is covered by another presentation in this conference and will not be repeated here [2]. The Belle II experiment is not just a renovation of its predecessor the Belle experiment [3]. Except the ECL crystal, all other sub-detectors are rebuilt. The physics data rate is about 20 kHz at high luminosity. A whole new trigger system is designed to ensure 100% efficiency at maximum 30 kHz trigger rate, and to be flexible for different physics event trigger requirements. A new DAQ system is developed to collect large data sample and capable of doing a prompt reconstruction after data taking.

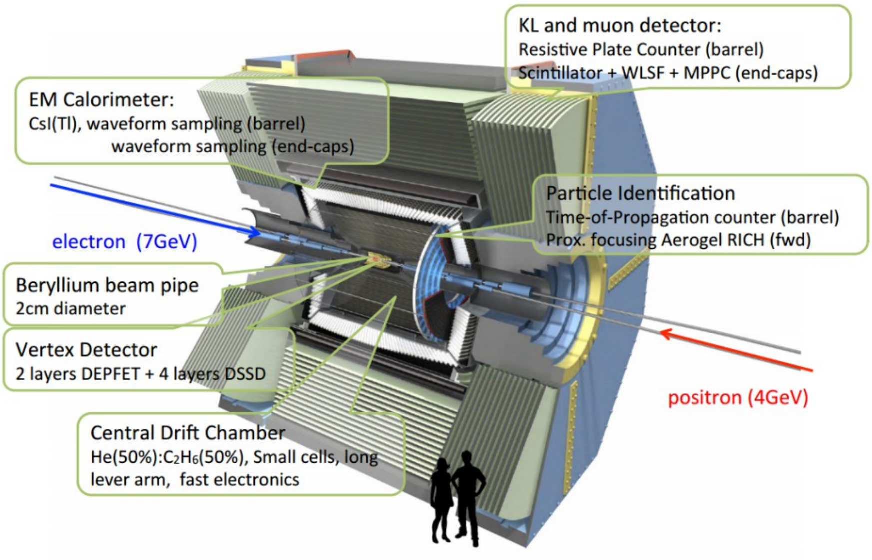

Figure 2: The Belle II detector.

Complementary to the energy frontier, the goal of Belle II experiment is to accumulate large data statistics around specific center-of-mass energy regions. The SuperKEKB has succeeded its phase 1 commission for stable e^+/e^- beam circulation without collision in 2016. The phase 2 operation starting in 2017 will have the first beam collision and the possibility of limited physics data taking. Since 2018, Belle II will start the phase 3 operation for full physics commissioning. The target is to reach $50ab^{-1}$ data by the year 2024. That is about 50 times the total data sample collected by the Belle experiment.

3. Belle II physics prospect

3.1 CKM parameter

The unitarity triangle angles have been measured to a few degrees precision in the B factory and LHCb experiments, and the sum is $\alpha+\beta+\gamma = (175\pm9)^{\circ}$ [4]. Certainly Belle II will keep investigating this important subject. With the full Belle II data sample, it is possible to improve the unitarity triangle angles measurement to a precision of 1 degree level or less [5]. Any deviation from the unitarity triangle may indicate a possible new CP phase and new physics beyond the Standard Model.

Additionally, another probe to search for new physics is to check the CP asymmetries between $b \to s\bar{s}s$ and $b \to c\bar{c}s$ processes (Figure 3), which is sensitive to the sin(2β) of these processes. At first order, the Standard Model predicts no difference between these two processes. However, new physics can add contributions to the loops in the $b \to s\bar{s}s$ process. The current measurement of $\Delta S = S_{J/\psi K_s^0} - S_{\varphi K_s^0}$ is close to 0 but with large statistics uncertainty. Therefore, the precision measurements of sin(2β) remains an important topic to search for new source of CPV. With 50ab^{-1} data, Belle II is capable to improve the significance of these measurements.

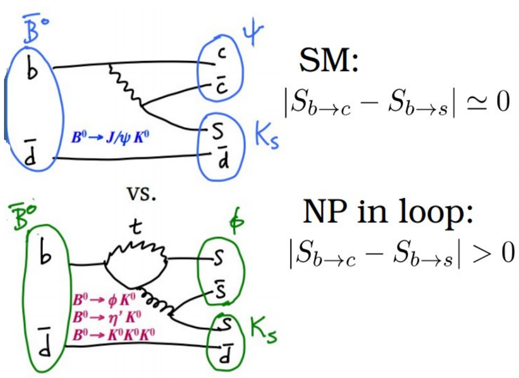

Figure 3: Scratch diagrams of $b \to s\bar{s}s$ and $b \to c\bar{c}s$ transitions.

Another puzzle of the CKM parameter is the discrepancy of $|V_{ub}|$ and $|V_{cb}|$ measured in inclusive and exclusive means, which still remains at the end of the B factory experiments[6]. Belle II will scrutinize these tensions with new techniques and much larger data set.

3.2 Rare B decays

With relative clean environment and high instantaneous luminosity with near 100% trigger efficiency, Belle II is also a good place to study rare events and processes involving neutral particles in the final state.

The $B\to\tau\nu$ leptonic decay is suppressed in the Standard Model with expected branching fraction at 7.58×10^{-5} [8]. In the type II 2HDM model, this process can be enhanced by a charged Higgs boson. The current average measurement by Belle and BaBar is $(1.14\pm0.22)\times10^{-4}$ [9]-[12]. Belle II should be able to reduce the uncertainty to 5% or less with full data set. This will be crucial to test the contribution from this NP model or set limit on the charged Higgs mass.

The $B\to D^{(*)}\tau\nu$ decays can be another benchmark to explore NP like the 2HDM model. These 3-body semileptonic decays have large branching fractions, and provide other observables sensitive to possible NP contributions [5][7][13]-[15]. The ratios $R(D^{(*)}) = BR(B\to D(*)\tau\nu)/\ BR(B\to D(*)\ell\nu)$ with smaller uncertainty provides a better way to probe any contributions beyond the SM. The latest result of R(D*) measurement by Belle has reached

13.8σ statistical significance [16]. The combined result of R(D) and R(D^*) is larger than the SM expectation at 4σ significance. However, the experimental measurement uncertainties are still statistical dominant. Belle II could reduce the relative uncertainty of R(D) and R(D^*) to 3.5% and 2%, respectively, and provide a more decisive result of this study. Another point worth to point out is that Belle II will be sensitive to the H-b-u and H-b-c couplings in these two modes, while LHC will be to H-b-t coupling.

3.3 LFV

The lepton flavor violation decay is highly suppressed in the SM, well below the possible reach of any experiment in the near future. Various NP models predict to enhance the branching fraction to 10^{-8} to 10^{-10} level. For example, the predictions of the branching fraction of $\tau\to\mu\mu\mu$ and $\tau\to\mu\gamma$ decays in a few models are listed in Table 1.

The low background makes Belle II an ideal place for such searches, especially for LFV τ decays such as $\tau\to 3\ell$, $\tau\to h\ell$, or $\tau\to\ell\gamma$. Many LFV τ decays have been studied. The sensitivity has currently reached the level of a few times 10^{-8} (Figure 4)[18]. It is possible to push those limits 1 to 2 orders of magnitude lower with the full Belle II data sample. The result will either favor some models or put tighter constraints on them. This makes Belle II the most promising experiment to test numerous theoretical predictions in the LFV τ decays. For example, the $\tau\to\mu\mu\mu$ mode with 3 muons in the final state is a very clean mode. It is possible to reduce the sensitivity by a factor of 50 with 50 ab^{-1} data. For the $\tau\to\mu\gamma$ search, the main background is from $ee\to\mu\mu\gamma_{ISR}$, we can probably reduce the sensitivity by a factor of 7.

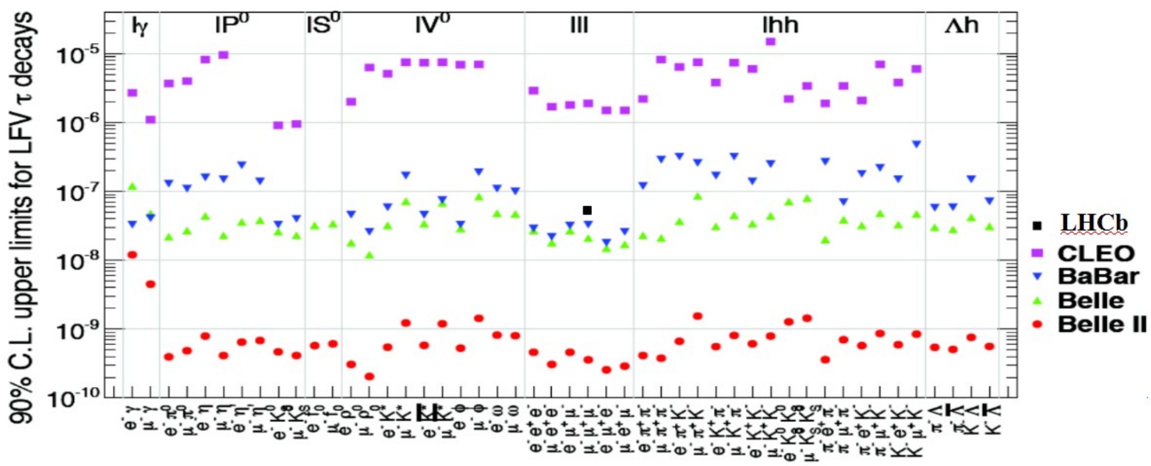

Figure 4: The current experiment limit of various LFV τ decays and the expected limit with full Belle II data sample. The latest result of 3μ decays is also marked [17].

	$\mathcal{B}(\tau\to\mu\gamma)$	$\mathcal{B}(\tau\to\mu\mu\mu)$	
mSUGRA+seesaw	10^{-7}	10^{-9}	PRD 66(2002) 115013
SUSY+SO(10)	10^{-8}	10^{-10}	PRD 68(2003) 033012
SM+seesaw	10^{-9}	10^{-10}	PRD 66(2002) 034008
Non-Universal Z'	10^{-9}	10^{-8}	PLB 547(2002) 252
SUSY+Higgs	10^{-10}	10^{-7}	PLB 566(2003) 217

Table 1: Prediction of the BF($\tau\to\mu\mu\mu$) and BF($\tau\to\mu\gamma$) by several theoretical models.

3.4 Hadron spectroscopy

Besides the major achievement in the CPV studies, many new particles are found at the B factory experiments. Some of the new states could not fit in the traditional quark model for meson and baryon. The observation of exotic state is a big bonus of the B factories. After the first exotic state observed at Belle in 2003 [19], many such new states are observed at Belle and BaBar. The detail structure of these states is still to be identified. More exotic states are expected in Belle II, leading to a new era for exotic state studies. The detail review of the exotic state study can be found in another presentation of this conference [20].

4. Early measurements

SuperKEKB will start beam collision in phase 2 commissioning with nominal designed beam energies, while capable of tuning the energy from Υ(1S) up to 11.25 GeV. Besides the accelerator tuning and beam related background study, it also has an opportunity for physics data collection during the phase 2 operation, which is scheduled starting in 2017. The expected integrated luminosity is about 20 fb^{-1}.

Except the innermost vertex and tracking detectors (VXD), the full Belle II detector will be installed before the phase 2 operation for detector and reconstruction software commissioning. The lack of VXD will certainly affect the tracking efficiency and the charged track identification in phase 2 period. However, this does not have a big impact on the photon efficiency from preliminary studies. The data collected in phase 2 and early phase 3 physics run could be a unique opportunity for early physics study at Belle II.

One proposed topic is for bottomonium spectrum study, especially to search for $\Upsilon(1D_1)$ and Υ(2D), which are still missing in the spectrum. Another might be interesting topic is to search for more exotic states above Υ(4S). The 4-quark state Zb(10610) is found by Belle in anomalous $\Upsilon(5S)\to\pi\pi\Upsilon(nS)$ transitions [21], but similar anomaly in Υ(6S) decay has not been confirmed yet.

These proceedings only cover a small part of the Belle II physics topics. There are many other interesting ones to study, e.g. a bunch of subjects in the charm sector, many other rare B decay modes, modes contributing to QCD fragmentation, … etc, and last but not least, search for NP in dark sectors.

Models related to the dark sector predict NP particle at the MeV to GeV scale. Not like most of the NP searches at Belle II, which looking for new intermediate processes or states to enhance the branching fraction of specific decays, the search for dark sectors can be direct. The simplest decay could be $e^+e^- \to \gamma A'$, where A' is a dark photon which can decay to $\ell^+\ell^-$ or invisible states (a pair of light dark matter particles). The cross section of this process is proportional to the square of the mixing strength, ε, between A' and the SM photon. Figure 5 shows the upper limit of ε as a function of A' mass, set by various experiments and the projections at Belle II with different data size. Even with the small data set in the early measurement, it is possible with Belle II to set a limit compatible with or lower than the current experimental result.

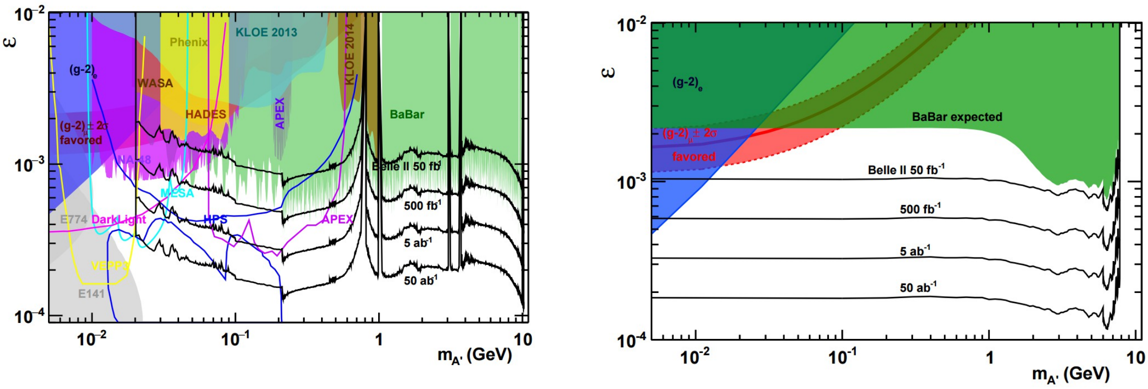

Figure 5: The expected sensitivity of ε at Belle II projected at different data size. Left one is for A' to $\ell^+\ell^-$ and the right for A' to invisible states. The color regions are excluded by various experiments.

5. Summary

The next generation B factory, the SuperKEKB and Belle II experiment, is becoming real. Complementary to the LHC experiments at the energy frontier, the Belle II experiment is to explore the physics studies in the intensity frontier. It will start the first beam collision in 2017 and plan to reach $50ab^{-1}$ integrated luminosity in less than 10 years.

With a relative clean environment and high performance detector systems, Belle II will make a significant contributions to the precision measurements in flavor physics and the search for new physics in rare processes. A few of those proposed topics are highlighted in these proceedings: improving precision in the CKM parameters, probing new physics in rare B events, LFV τ decays, and dark sector, searching for more exotic states, and possible early physics studies.

Serving as a friendly competitor and complementarity with other experiments, Belle II will soon join a new and exciting era to explore the physics frontier

References

[1] T. Abe, *et al.*, *Belle II Technical Design Report*, arXiv:1011.0352 [physics.ins-det]

[2] M. Nayak, Belle II collaboration, "*SuperKEKB, BEAST, and Belle II*", in the proceedings of *BEAUTY 2016 conference*, PoS(BEAUTY2016)

[3] A. Abashian *et al.*. Belle Collaboration, "The Belle detector", *Nucl. Instrum. Mechods A*, vol. 479, pp. 117-232, 2002.

[4] K.A. Olive, *Particle Data Group*, Chin. Phys. C, **38**, 090001 (2014).

[5] P. Urquijo, *Physics prospects at the Belle II experiment,* Nucl. Part. Phys. Proc. 263-264 (2015) 15-23.

[6] A. J. Bevan, B. Golob, Th. Mannel, S. Prell, B. D. Yabsley, H. Aihara, F. Anulli, N. Arnaud,T. Aushev, M. Beneke *et al.*, "*The Physics of the B Factories*", Eur. Pys. J. C, **74**, 3026 (2014).

[7] P. Krizan, *Flavour physics at B factories,* Phys. Sci. T158 (2013) 014024

[8] J. Charles *et al.*, CKMFitter Group, Phys. Rev. D. **91**, 073007 (2015).

[9] K. Hara *et al.*, Belle Collaboration, "*Evidence for* $B^-\to\tau\bar{\nu}_\tau$ *with a Hadronic Tagging Method Using the Full Data Sample of Belle"*, Phys. Rev. Lett. **110**, 131801 (2013).

[10] J. P. Lee *et al.*, BaBar Collaboration, "*Evidence fo* $B^+\to\tau^+\nu$ *decays with hadronic B tags*", Phys. Rev. D **88**, 031102(R) (2013).

[11] K. Hara *et al.*, Belle Collaboration, "*Evidence fo* $B^-\to\tau\bar{\nu}_\tau$ *with a semileptonic tagging method*", Phys. Rev. D **82**, 071101(R) (2010).

[12] B. Aubert *et al.*, BaBar Collaboration, "*Search for* $B^+\to\ell^+\nu_\ell$ *recoiling against* $B^-\to D^0\ell\bar{\nu}X$", Rev. D **81**, 051101(R) (2010).

[13] B. Aubert *et al.*, BABAR Collaboration, "Measurement of the semileptonic decays $\bar{B}\to D\tau^-\bar{\nu}_\tau$ *and* $\bar{B}\to D^*\tau^-\bar{\nu}_\tau$", Phys. Rev. D **79,** 092002 (2009).

[14] A. Bozek et al., Belle Collaboration, "*Observation of* $B^+\to\bar{D}^{*0}\tau^+\nu_\tau$ *and evidence for* $B^+\to\bar{D}^0\tau^+\nu_\tau$ *at Belle*", Phys. Rev. D **82**, 072005 (2010).

[15] R. Garisto, "CP-violating polarizations in semileptonic heavy meson decays", Phys. Rev. D **51**, 1107 (1995).

[16] A. Abdesselam, et al., Belle collaboration, *"Measurement of the branching ratio of* $\bar{B}^0\to D^{*+}\tau^-\bar{\nu}_\tau$ *relative to* $\bar{B}^0\to D^{*+}\ell\bar{\nu}_\ell$ *decays with a semileptonic tagging method"*, [hep-ex/1603.06711v1] .

[17] R. Aaji *et al.*, LHCb collaboration, "Search for the lepton flavour violating decay τ-→μ-μ+μ-", JHEP **02** (2015) 121.

[18] M. Barrett, Belle II collaboration, "*The Belle II Experiment*", in the proceedings of *FPCP conference*, PoS(FPCP2015)049.

[19] S.-K. Choi et al., Belle Collaboration, "*Observation of a Narrow Charmoniumlike State in Exclusive* $B^\pm\to K^\pm\pi^+\pi^- J/\psi$ *Decays*", Phy. Rev. Lett. **91**, 262001 (2003)

[20] R. Lebed, "*Theoretical review on spectroscopy including exotic states*", in the proceedings of *BEAUTY 2016 conference*, PoS(BEAUTY2016)

[21] M.B. Voloshin, "*Radiative transitions from Υ(5S) to molecular bottomonium*", Phys. Rev. D **84**, 031502(R) (2011)