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The Belle II experiment: status and physics prospects

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The Belle II experiment at SuperKEKB e^+/e^- collider, Japan, is aiming at exploring flavour physics in high intensity frontier. The target instantaneous luminosity of SuperKEKB is at $8 \times 10^{35}/s/cm^2$, which is 40 times higher than that at KEKB. The renovated Belle II detectors around the interaction point are expected to collect $50ab^{-1}$ data within 7 years. This gives high data statistics for precision measurements and probing new physics in rare decay studies. The Belle II experiment has successfully recorded the first collision events at SuperKEKB in April 2018, and ready for physics data taking. This presentation will cover the current status of Belle II and highlight its prospects on flavour physics.

Keywords: SuperKEKB; Belle; Belle II.

1. Introduction

The B factories, BaBar at SLAC and Belle at KEKB, have achieved a great success in flavour physics studies in the first decade of this century. Besides the confirmation of the CKM mechanism of CP violation (CPV) in the Standard Model (SM), which led to the 2008 Nobel Prize in physics, they also have first observations of the D^0 mixing, exotics states, and many new particles in the bottomonium spectroscopy.[1]

Currently the accelerator is being upgraded to SuperKEKB[2] for high luminosity machine. The designed instantaneous luminosity of SuperKEKB is at $8 \times 10^{35} cm^{-2} s^{-1}$, which is 40 times higher than that at KEKB. To prusue the physics studies at the high intensity frontier, the Belle detector[3] is also upgraded to Belle II[4] . The Belle II experiment is expected to collect $50ab^{-1}$ data in about 7 years commissioning. This is about 50 times of the data collected at the last generation B factories. With this amount of data, one can make precision measurements of many interesting topics in B, D, and τ physics, and explore possible new physics (NP) beyond the SM.

2. The Belle II detector

In order to achieve the instantaneous luminosity 40 times higher than that at KEKB, two approaches are adopted by the SuperKEKB. One is to squeeze the beam size at the interaction region, so-called nano-beam scheme, which could provide a factor of 20 to the luminosity. In addition, by increasing the beam currents it can push that

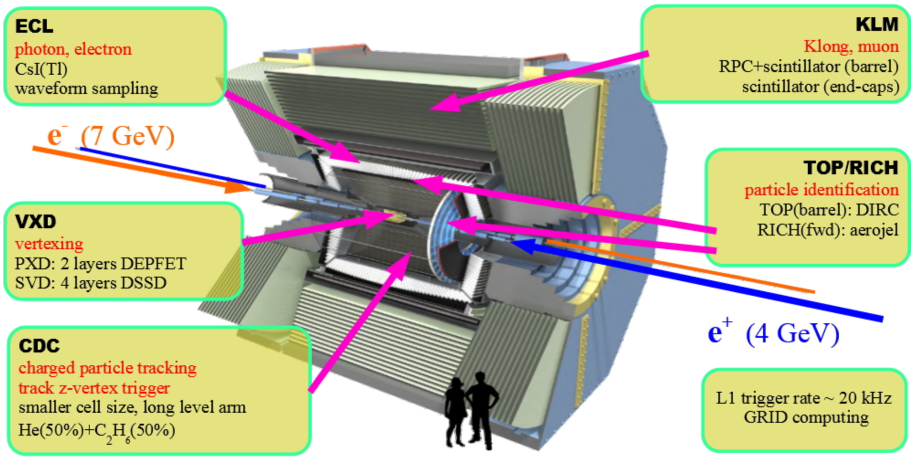

Fig. 1. The Belle II detector.

to another factor of 2. The nano-beam technology also works as a prototype for the future high intensity collider projects. Though, comparing to hadron colliders, the e^+/e^- collider is a relatively clean environment, the much higher beam induced background then that at Belle is expected at Belle II. To work with such higher background and radiation environment, the Belle II detector is upgraded from its predecessor, the Belle detector, with many renovations in detector sensors and fast readout electronics (Fig. 1).

Except the ECL crystals and the magnet, all the sub-detectors are brand new ones. The most inner part, VXD, consists of a Pixel Vertex Detector (PXD) and a double-sided Silicon strip Vertex Detector (SVD) for vertexing and inner tracking. The new VXD system can improve the vertex resolution by a factor of 2, compared to the Belle detector, which leads to an advantage in time dependent physics studies. Outside the VXD, there is a new Central Drift Chamber (CDC) with smaller cell and larger volume for main tracking system, together with ECL and new particle identification systems. Though the ECL crystals are recycled for Belle II, the readout system is redesigned to have better performance for high event rate and background rejection. A new Time of Propagation (TOP) detector in the barrel and a new RICH detector in the forward end-cap, as well as upgraded K_ℓ and muon (KLM) detector give better performance of particle identifications. In order to catch the targeted physics events at high luminosity, a whole new trigger system is designed to ensure 100% efficiency at maximum 30 kHz rate,[5] as well as a new DAQ system and software platform to collect large data sample and to proceed a prompt reconstruction for quick physics analyses. Two new features are designed for the Belle II level 1 trigger system. One is to have a 3-dimensional track reconstruction using CDC hits, which improves the power to reject tracks from beam induced background mostly not from the interaction point. Another is to implement a global reconstruction login (GRL) to match the charged tracks with ECL and KLM clusters. This gives the capability to have more flexibility in trigger for specific physics studies.

3. Physics prospects

Complementary to the LHC experiments, the goal of Belle II experiment is to focus on precision measurements and exploration of new physics in rare physics events, with large data statistics around the center-of-mass energy of $\Upsilon(4S)$.[6,7] One joint theory-experiment "Belle II Theory Interface Platform" (B2TiP)[8] is organized to study the potential physics topics for Belle II. A few of them are highlighted here.

3.1. *CKM parameters*

Precision measurement of the CKM parameters is one way to check any possible new NP beyond the SM. The current global results give the sum of the unitarity triangle angles $\alpha + \beta + \gamma = (183^{+7}_{-8})^{\circ}$.[9] With the full Belle II data, it is feasible to surpress the precision of those angles to 1 degree level or less. A significant deviation from the unitarity triangle will be an indication of new CP phase beyond the current CKM mechanism.

Another example of probing NP at Belle II is to check the CP asymmetries between $b \to s\bar{s}s$ and $b \to c\bar{c}s$ processes. Though the SM predict similar strength in both processes, additional contributions from NP can enhance the penguin dominated $b \to s\bar{s}s$ process. For example, the current word average of the measurement $\Delta S = sin2\beta_{J/\psi K_s^0} - sin2\beta_{\phi K_s^0}$ is close to 0 but with large statistics uncertainty. By more precise measurement of the $sin(2\beta)$ with larger data statistics at Belle II, this statistics limited significance can be improved.

3.2. *Rare B decays*

The environment at an e^+/e^- collider is relative clean compared to that at a hadron collider. With high luminosity and close to 100% trigger efficiency, Belle II is a good place to study rare events and processes involving neutral particles in the final state. To give an instance, the 3-body semileptonic decays $B \to D^{(*)}\tau\nu$, whose large branching fractions provide observables to probe NP contributions.[10–12] In addition, the ratio $R(D^{(*)}) = \mathfrak{B}(B \to D^{(*)}\tau\nu)/\mathfrak{B}(B \to D^{(*)}\ell\nu)$ is even a better probe for any contributions beyond the SM due to its smaller theoretical uncertainty. The current result of $R(D)$ and $R(D^*)$ is off from the SM expectation at 4σ significance. While the measurement uncertainties are still statistical dominate, Belle II could give a more conclusive result by reducing the relative uncertainties to 3.5% and 2% for $R(D)$ and $R(D^*)$ with full data sample.

3.3. *Charm physics*

Besides the B physics, Belle II is also good for studies in charm and τ physics. The B factories had first observed the evidence of $D^0 - \overline{D^0}$ mixing in 2007.[13] With the better vertexing capability at Belle II, the proper time resolution for D^0 decay is expected to reach 0.14ps, about a factor of 2 better than that at BaBar experiment. This will provide an opportunity to probe CPV in D^0 mixing with more precise measurement. In the rare charm decay studies, Belle has measured the $\mathfrak{B}(D^0 \to \gamma\gamma) = 8.5 \times 10^{-7}@90\%CL$.[14] The predicted branching fraction is at 10^{-8} level in SM, but can be booted to above 10^{-6} in some extensions, e.g. MSSM. With full Belle II data, we should be able to reach to 10^{-7} level or below, which can not only probe the contribution from possible NP, but also check the SM prediction.

3.4. *Lepton flavour violation decays*

Searching for charged lepton flavour (LFV) has a long history since 1940s. An observation of any LFV decays will be a smoking gun of NP. The predicted branching fractions of LFV in the SM are well below the possible reach of any existing experiments. Belle II will be very competitive to explore NP in this field for its relatively low background.

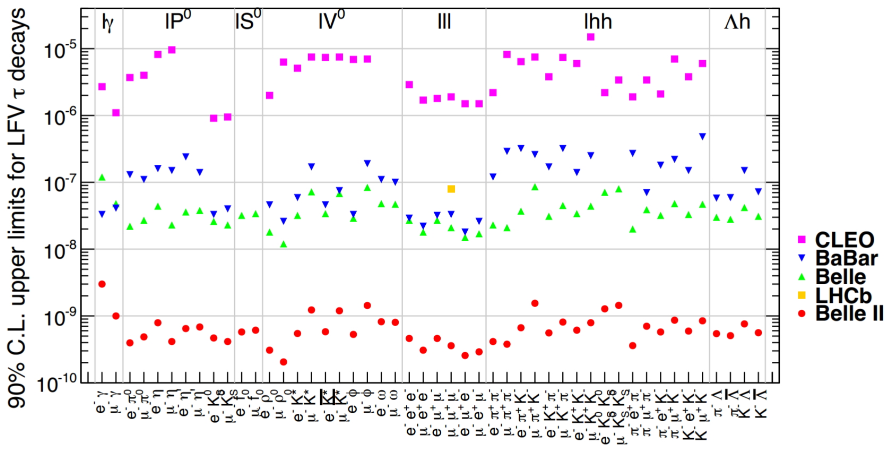

Fig. 2. The current experiment limit of LFV τ decays and the expected limit with full Belle II data sample.

Many LFV τ decays have been studied, such as $\tau \to 3\ell$, $\tau \to h\ell$, and $\tau \to \ell\gamma$. The current experiment results set uplimits around the order of 10^{-8}.[15] Several NP models claim enhancement of the branching fractions to 10^{-8} to 10^{-10} level, which is feasible with the full Belle II data sample (Fig. 2). The result of the studies on LFV search at Belle II will certainly make important feedback to those theoretical models, either finding indication of NP or applying tighter constraints on them.

For example, the predictions of $\mathfrak{B}(\tau \to \mu\gamma)$ and $\mathfrak{B}(\tau \to \mu\mu\mu)$ from several theoretical models are list in Table 1. For the $\tau \to \mu\gamma$ mode, the main background will be from the initial state radiation, we can probably reduce the sensitivity by a factor of 7 with 50 ab^{-1} full Belle II data. For the $\tau \to \mu\mu\mu$ mode with 3 muons in the final state, it is a relatively clean mode and we can probably reduce the sensitivity by a factor of 50.

Table 1. Prediction of the $\mathfrak{B}(\tau \to \mu\mu\mu)$ and $\mathfrak{B}(\tau \to \mu\gamma)$.

	$\mathfrak{B}(\tau \to \mu\mu\mu)$	$\mathfrak{B}(\tau \to \mu\gamma)$	
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

3.5. *Other physics topics*

The B factory experiments had also made great achievements in other fields, for example, the studies of the bottomonium spectroscopy and the observation of exotic states. After the first observation of an exotic state at Belle in 2003,[16] many such new state have been found. The detail structure of those exotic states is still yet fully understood, since they can not be explained by quark model of pure meson or baryon. This opens a new page for the exotic state studies and more experimental results are certainly needed for further scrutinization.

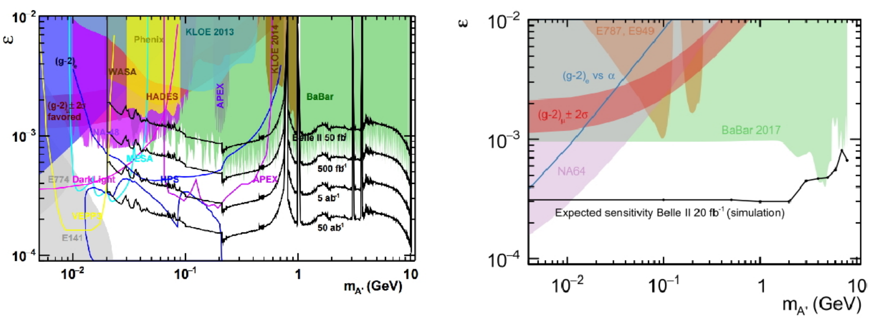

Fig. 3. The expected sensitivity of ε at Belle II projected at different data size. Left one is for $A' \to \ell^+\ell^-$ and the right for $A' \to$ *invisible states*. The color regions are excluded by current experiment results.

On the other hand, the search for dark sector candidates in low mass region (below 10 GeV) gets more and more attention in recently years. Belle II will be one of the experiments appropriate to engage in this research. Unlike most of other NP search to look for branching fraction enhancement due to extra intermediate processes from NP, the search for dark sectors could be directly looking on the final states. For example, the e^+e^- convers to $\gamma A'$, a regular photon and a dark photon A'. The dark photon can decay to $\ell^+\ell^-$ or a pair of invisible light dark matter particles. This study will require high efficiency for single photon trigger, which is possible to achieve by the GRL of L1 trigger. Figure 3 shows the current uplimit of ε as a function of A' mass, where ε is the mixing strength between the SM photon and A', and the projection of what Belle II can reach with different data size. Notice that even with 20 fb^{-1} data, Belle II can already make contribution to the case of A' to invisible states.

4. Current status

The Belle II detector has been moved to commissioning position in April 2017 with all sub-detectors except the VXD. The integration of global DAQ and trigger systems started right after that and the whole systems were validated by cosmic ray tests in 2017 summer. In April 2018, Belle II has successfully recorded the first e^+/e^- beam collision events of SuperKEKB.[17] This is the most important milestone for not only Belle II but also high intensity collider physics experiments. The plan is to reach the recorded KEKB peak luminosity, $2 \times 10^{34} cm^{-2}s^{-1}$, or even higher in 2018 and gradually increase that to the SuperKEKB designed value within another 4 years. After integration of the VXD in 2018 summer, Belle II will have the full detectors ready for physics commissioning since 2019. It is expected to collect data equivalent to what Belle experiment had by the end of 2019. Even with this limited amount of data, it has been assessed for possible early physics studies, such as bottomonium spectrum, searching for more exotic states, and probing candidates in the dark sector.

5. Summary

SuperKEKB has achieved its first e^+/e^- beam collisions with Belle II detectors in April 2018. The achievement of the nano-beam technology lays down a road for future high intensity collider projects. Complementary to the LHC experiments, the Belle II experiment is to explore the physics studies in the intensity frontier. The target is to collect 50 ab^{-1} integrated luminosity in about 7 years.

On account of the relatively clean environment and high preformance detector systems, Belle II will make significant contributions to the precision measurements in flavour physics and the search for new physics, such as improving precision in the CKM parameters, probing new physics in rare B events, LFV τ decays, and dark sectors, as well as studies in charm physics and exotic states, ... etc.

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