Future e^+e^- flavour factories: detector challenges and physics expectations

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Prospects of the two future e^+e^- flavour factories are discussed. The detector designs and the technical challenges are described together with the motivating physics background.

I. INTRODUCTION

Since the beginning of the KEKB/Belle and the PEP-II/BaBar experiments, both B-factories have been exploring the luminosity frontier. Both exceeded their design luminosity ($1 \times 10^{34}/cm^2/s$ for KEKB and $3 \times 10^{33}/cm^2/s$ for PEP-II) and continued a steady operation. Two factories integrated more than $1.3\,\text{ab}^{-1}$ of data in total, and have reported a lot of important physics results every year. Some of the measurements reached already precision measurements, however, there are quite a few of unsettled issues. Just as an example, we have measured $\sin 2\phi_1$ with a precision of $4\,\%$ in $B \to J/\psi K^0$ and related decay modes. On the other hand, we found that the effective $\sin 2\phi_1$ measured in the penguin ($b \to sq\bar{q}$) decays such as $B \to \phi K^0$ is possibly slightly smaller than $\sin 2\phi_1$. This possible shift could be explained by a contribution from the new physics (NP) beyond the standard model (SM); to confirm the shift with confidence, much more statistics would be needed. We wish to continue finding answers to those unsettled issues with more data. To accumulate more data in a reasonable time-line, we need to upgrade the accelerator and the detector.

There are three facilities that will study B physics including future projects: the LHCb [2], the KEKB upgrade (Super KEKB [3]), and the Super$B$ [4] in Italy. The LHCb will produce lots of beauty particles including B_s and b-baryons in a hadronic manner. It is good for accumulating data, but the background environment does not allow us to study the modes with neutral particles in the final state. One of the important roles of the Super KEKB and the Super$B$ are to do analyses with neutral particles in the final state in a clean environment of the e^+e^- collider. The complemental roles of the LHCb and the other two is well summarized in the preprint by I. Bigi [1]. The target of this presentation is to describe the common things and the differences of the Super KEKB and the Super$B$.

II. ACCELERATOR AND BEAM BACKGROUND

The approaches to achieve high luminosity are very different in the Super KEKB and the Super$B$. In the Super KEKB, luminosity gain is obtained mainly from the higher beam current. On the other hand, the Super$B$ aims for a high luminosity by squeezing the beam size drastically, while the beam currents are kept at the same level as in the current B-factories. Though both approaches are challenging in the different viewpoints, Super KEKB for the high current operation, and the Super$B$ for the nano beam operation, it is often said that Super KEKB is a brute force but a steady and adiabatic method, and the Super$B$ is a brand-new and more sophisticated method.

The target luminosity of the Super KEKB is $8 \times 10^{35}\,cm^{-2}s^{-1}$, and the integrated luminosity for the discussion of physics is $10\,\text{ab}^{-1}$ as the first target, and then we aim for $50\,\text{ab}^{-1}$. On the other hand, the luminosity of Super$B$ is expected to begin with $1 \times 10^{36}\,cm^{-2}s^{-1}$ and it can be improved by a few times. The integrated luminosity will reach $80\,\text{ab}^{-1}$ in seven years. However, one should be aware that the lattice design and the beam-beam simulation that support the design luminosity is not as matured as in the case of the Super KEKB, which should be improved in the coming years.

In the Super KEKB scheme, the most severe beam-induced background is from the beam-gas scattering. Due to N times higher beam current, the vacuum around the interaction region becomes N times worse, provided the evacuation power is the same; hence, the amount of the beam-gas background will be N^2 times larger than the present level. In total, at the full spec of the machine, we will receive some 20 times more background than the present level. Although there are several ideas to improve the background, the detector is designed so that it works under such high background conditions.

In the case of the Super$B$, one of the biggest worry is in the Touschek background, which is an intra-beam scattering enhanced in the narrow beams of the Super$B$. According to a simulation study, the Touschek background could be reduced by three to four orders of magnitudes with a new lattice and collimator; with which detector designs are feasible.

III. DETECTOR DESIGN AND EXPECTED PHYSICS REACH

As discussed in the previous section, in the case of the Super KEKB, the detector (sBelle[10]) must work under typically 20 times higher background; in the case of the Super$B$, the condition is supposed to be

milder because of the lower beam current. What we do in the detector design against the high background is simple in principle: to use faster technology and/or to have smaller segmentation of the sensors. The idea is to avoid the overlap of the particle hits in time and/or in space.

The baseline design of the sBelle sub-detectors is as follows. We will have a 1.5 cm radius beam pipe and 6 layers of silicon vertex detectors (SVD). We will adopt a new readout ASIC, APV25, which has 16 times shorter shaping time than the present readout chip (VA1TA). For the central drift chamber (CDC), we will have a small cell chamber with about 15 thousand sense wires. According to the simulation studies, by improving the tracking algorithm for the CDC, and also with the help of the SVD stand-alone tracking, we can improve the performance of the charged track reconstruction even under 20 times more background. For the particle identification (PID) detector, we will not be able to use the time-of-flight (TOF) counters which are based on the scintillation counters, because of the high counting rate. The possible device should be Cherenkov detectors since they are insensitive to high energy photons. Among several options for the barrel PID detectors, the baseline is the time-of-propagation (TOP) counter, which reconstruct the Cherenkov ring image in one of the spatial coordinates and in time. The PID detector in the forward end-cap is a proximity focusing ring imaging Cherenkov counter with the aerogel radiators (A-RICH). Thallium doped CsI crystals are used for the electromagnetic calorimeter (ECL). The end-caps will be replaced with faster crystals such as pure CsI. The waveforms of the signals are sampled and fitted to resolve the overlap of multiple hits. According to a simulation study, the waveform fitting has an effect to suppress the background clusters by a factor of seven. The K_L and muon detector (KLM) is based on resistive-plate-counter in the barrel and scintillator in the end-caps. More details of the detector design are described elsewhere [5].

The design of the SuperB detector is based on the BaBar detector. The concept of the upgrade is similar to that for the sBelle, but with somewhat milder condition of the beam background. Aged components such as the silicon vertex tracker (SVT), the drift chamber (DCH) are to be renewed. The DIRC counter can be reused as the PID detector, possibly with new photon sensors that allow a smaller stand-off box. The forward end-cap of the electromagnetic calorimeter (EMC) will be replaced with faster crystals such as LYSO. The K_L and muon detection will be based on scintillators. More details of the detector design are described elsewhere [6].

In the following subsections, some of the key features of the detector upgrade are discussed. Possible physics reaches related to the upgrade options are also described.
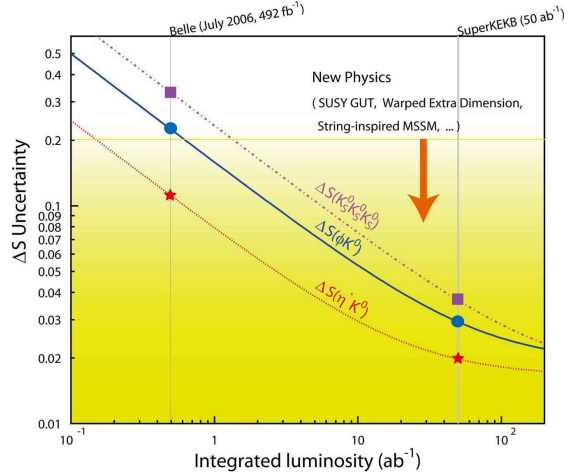

FIG. 1: Expected sensitivity of the $\mathcal{S}_{\phi K^0}$, $\mathcal{S}_{\eta' K^0}$ and $\mathcal{S}_{K^0 K^0 K^0}$ with regard to the accumulated luminosity.

A. Time-Dependent CP Analyses and Vertex Detector

In the upgrade, the vertex detector is important for the time-dependent CP (TCP) asymmetry measurements. Especially, the TCP in $b \to s\bar{q}q$ penguin decays should be measured precisely, because it could be affected by the NP. Figure 1 shows the expected sensitivities of the TCP parameters ($\mathcal{S}$) in $B^0 \to \phi K^0$, $B^0 \to \eta' K^0$, and $B^0 \to K^0 K^0 K^0$ decays; the extrapolation is based on the analyses of Belle data [7]. With $50\,\mathrm{ab}^{-1}$, the uncertainty of the measured $\mathcal{S}$ reaches the level of the current theoretical uncertainty (0.03). It also indicates that the measurement will be limited by the systematic uncertainty after $50\,\mathrm{ab}^{-1}$. To go beyond $50\,\mathrm{ab}^{-1}$, we must seriously consider how to reduce the intrinsic systematics from the sources such as the alignment of the vertex detector.

The key issue to improve these analyses is the proper time (Δt) resolution, which is determined from the vertex resolution (Δz) and the boost factor ($\beta\gamma$) of the $\Upsilon(4S)$ rest frame in the laboratory frame as $\Delta t = \Delta z/\beta\gamma c$. We can achieve a better vertex resolution by having the first sensor of the vertex detector as close to the interaction point (IP) as possible. In the SuperB, since the boost factor is small, the desire to put the first sensor closer is ardent. A beam pipe of 1.0 cm radius that allows to place the innermost layer at the radius of 1.2 cm is proposed. The technical challenges for this are (1) higher background at the sensor, (2) the stronger synchrotron radiation fan, and (3) the higher-order-mode heating of the beams.

The TCP in $B^0 \to K_S^0 \pi^0 \gamma$ is also an interesting mode to search for the NP effects from a different aspect [8]. In this decay mode, since there is no charged particle in the final state of the signal B^0 decays that comes from the IP, we need to determine the B^0 decay
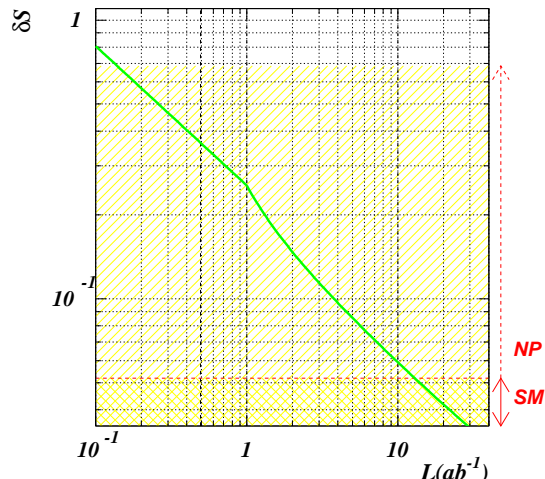
FIG. 2: Expected sensitivity of the $\mathcal{S}_{K^{*0}\gamma}$ with regard to the accumulated luminosity.
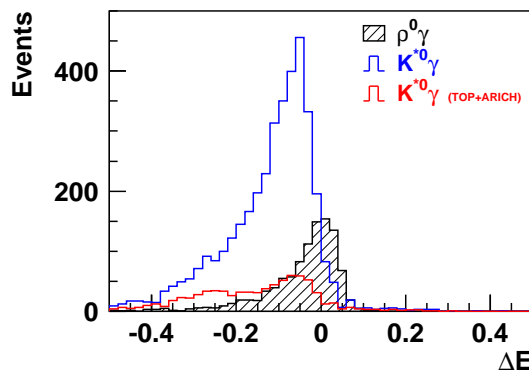

FIG. 3: The ΔE distributions for the $B^0 \rightarrow \rho^0\gamma$ signal (hatched) and the $K^{*0}\gamma$ background. The blue(red) line shows before(after) the upgrade of the PID.

position from the K_S^0 trajectory which is determined from the daughter π^+ and π^- trajectories. Therefore, a larger vertex detector that allows more $K_S^0 \rightarrow \pi^+\pi^-$ decays inside the vertex detector volume is preferred.

From the technical point of view, if we build a larger vertex detector in a conventional ladder structure, the detector capacitance becomes larger ($\gtrsim 60\,pF$), which means a higher noise in the readout chip. Since a faster readout chip, which we need so that the background overlap can be avoided, is in general more susceptible to higher input capacitance, here is a technical difficulty. One way to avoid this dilemma is to abandon the conventional ladder structure and to put the readout chips on the sensor itself to reduce the capacitance. Special care should be taken for the material inside the sensitive area, and also for the cooling and the influence of the heat-cycling on the sensor.

Figure 2 shows the expected sensitivity of the TCP parameter ($\mathcal{S}$) in the $B^0 \rightarrow K^*(K_S^0\pi^0)\gamma$ decay based on the analysis of Belle data [9]. Thanks to the detector upgrade that appears as a kink at $1\,ab^{-1}$, we can reach sensitivities close to the level of the SM theoretical uncertainty with some $10\,ab^{-1}$.

B. Particle Identification

The PID of the Belle detector has been working without any serious troubles from the very beginning until now. The performance is good enough so that we could pursue many analyses by discriminating kaons from pions and vice versa. One pity is that the kaon fake rate in the pion candidates is higher than the case of the BaBar. This makes the analyses that require kaon veto more difficult; $B^0 \rightarrow \rho^0(\rightarrow \pi^+\pi^-)\gamma$ is one of

such analyses where the $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\gamma$ decay with the K^+ misidentified as the π^+ contributes as a severe background. To improve the performance, we will completely renew the PID detectors both in the barrel and in the forward end-cap. Two additional reasons to replace the PID detectors are: because the TOF will not work under high background condition of the Super KEKB, and because the ACC container and the photomultiplier are massive which is bad for the photon reconstruction in the calorimeter.

The baseline option of the barrel PID is the TOP counter, which measures one spatial coordinate with a few mm precision and the time of Cherenkov light arrival with the time resolution of $\lesssim 40\,ps$. In addition to the excellent time resolution, the photo-sensor is required to work under $1.5\,T$ magnetic field. A micro-channel-plate PMT (MCP-PMT) is a promising candidate for such a purpose.

The baseline option of the end-cap PID is the A-RICH. The three candidate photo-sensors, the hybrid avalanche photo-diode, the MCP-PMT, and the multi-pixel photon counter (MPPC) have been extensively tested at the test-beam line at KEK. In the test, clear ring images are successfully observed. In the case we use the MCP-PMT, additional discrimination power is obtained because the time resolution is good enough to measure the TOF difference of kaons and pions.

Figure 3 shows the ΔE distributions for the $\rho^0\gamma$ signal and the $K^{*0}\gamma$ background in the $B^0 \rightarrow \rho^0\gamma$ analysis. By the upgrade of the PID detector, we can significantly reduce the $K^{*0}\gamma$ background. The sensitivity gain with this improvement is equivalent to $83\,\%$ more luminosity.
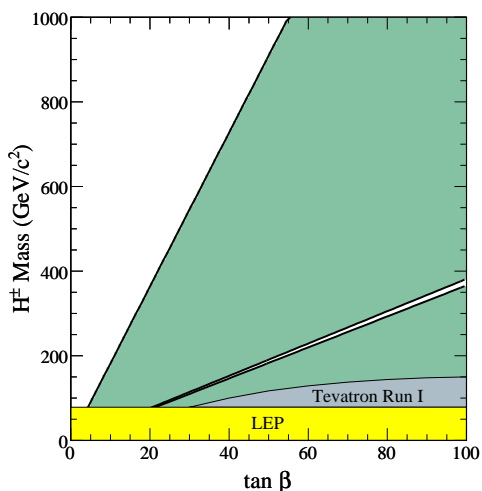
FIG. 4: Exclusion region in the $\tan\beta$ vs. $H^{\pm}$ mass plane with $50\,\text{ab}^{-1}$ of data. Pale sea-green region would be excluded by $B \to \tau\nu$.
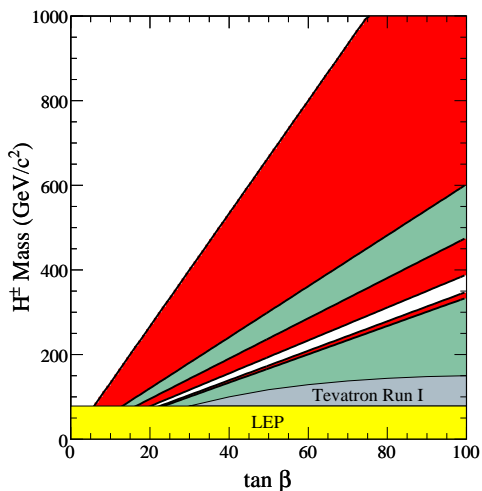

FIG. 5: Discovery region in the $\tan\beta$ vs. $H^{\pm}$ mass plane with $50\,\text{ab}^{-1}$ of data. Red region is where we could discover a charged Higgs with $5\,\sigma$, pale sea-green region has already been excluded.

C. Neutrinos and Hermeticity

Another important type of measurements in the future $e^{+}e^{-}$ B-factories are the studies of the decay channels that contain neutrinos in the final state. Figure 4 shows the possible exclusion region in the $\tan\beta$ vs. $H^{\pm}$ mass plane with $50\,\text{ab}^{-1}$ of data, where $B^{0} \to \tau\nu$ provides a very powerful constraint as shown in the pale sea-green region. It could result in a $5\,\sigma$ discovery of the charged Higgs for some cases as shown

in the red region in Fig. 5.

In this type of analyses, one of the most important issues for the detector is the hermeticity. If the daughter particles are not detected because they pass through the insensitive region of the spectrometer, we can not distinguish those missing particles and the signal neutrinos; thus we suffer from a peaking type of background. One idea to improve the detector hermeticity is to place detectors around the forward and the backward beam holes. From the simulation study of the $B \to K^{(*)}\nu\nu$ decays, by reconstructing tracks by three layers of the pixel disks that cover the beam hole, we could eliminate $68.5\,\%$ of the peaking background while sacrificing only $0.3\,\%$ of the signal. The technical challenges for this are: (1) high background as it is close to the beam, (2) very limited space for the detector and the cables, and (3) to understand the magnetic field well despite it is close to the final focusing magnets.

IV.   CONCLUSION

Two future $e^{+}e^{-}$ flavour factories, the Super KEKB and the Super$B$, aim to improve the measurements that have been performed by the Belle and the BaBar collaborations. The Super KEKB will increase the beam currents to increase the luminosity, while the Super$B$ will squeeze the beam size to increase the luminosity even higher than the Super KEKB. The detectors must handle higher background than the detectors of the present B-factories; in the case of Super KEKB, 20 times higher background is expected at the final design luminosity of the machine. A careful design of the detector and the machine is essential for both cases. Further improvements in the detector performance such as the vertex resolution, the K_{S}^{0} reconstruction efficiency with the vertex information, the PID, the hermeticity are foreseen, although each of the improvements is technically challenging. Two projects aim for the higher luminosity in very different approaches, which is good as a strategy to diversify the risk.

[1] I. I. Bigi, "'Ceterum censeo Fabricam Super Saporis esse faciendam' ('Moreover I advise a Super-Flavour Factory has to be built')," arXiv:0804.4612 [hep-ph].

[2] http://lhcb.web.cern.ch/lhcb/

[3] http://superb.kek.jp/

[4] http://www.pi.infn.it/SuperB/

[5] K. Abe *et al.*, KEK Report 2004-4, "Letter of Intent for KEK Super B Factory", (2004).

[6] M. Bona *et al.*, "SuperB: A High-Luminosity Asymmetric e+ e- Super Flavor Factory. Conceptual Design Report," arXiv:0709.0451 [hep-ex].

[7] K. F. Chen *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 031802 (2007) [arXiv:hep-ex/0608039].

[8] D. Atwood, M. Gronau and A. Soni, "Mixing-induced CP asymmetries in radiative B decays in and beyond the standard model," Phys. Rev. Lett. **79**, 185 (1997) [arXiv:hep-ph/9704272];

[9] Y. Ushiroda *et al.* [Belle Collaboration], "Time-dependent CP asymmetries in $B^0 \rightarrow K_S^0 \pi^0 \gamma$ transitions," Phys. Rev. D **74**, 111104 (2006) [arXiv:hep-ex/0608017].

[10] The name of the detector is to be determined. The 'sBelle' is not an authorized name, used only within this proceedings for convenience.