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SuperKEKB and SuperB: flavor physics

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Abstract. The paper discusses future experiments at super B factories. It presents the physics motivation and the tools, accelerators and detectors, and reviews the status of the two projects, SuperKEKB/Belle-II in Japan and SuperB in Italy.

1 Introduction

B factories have significantly shaped particle physics in the past decade. They were built with the primary goal of measuring CP violation in the B system. From the discovery of large CP violation in 2001, the B factory results evolved into a precision measurement of the CP violation parameter $\sin 2\phi_1$ in $B \to J/\psi K^0$ decays [1–3]. The constraints from measurements of angles and sides of the unitarity triangle show a remarkable agreement [4, 5], which significantly contributed to the 2008 Nobel prize awarded to Kobayashi and Maskawa. The two B factories also observed direct CP violation in B decays, measured rare decay modes of B mesons, and observed mixing of D^0 mesons. They started with systematic searches for physics beyond the Standard Model (SM) by measuring CP violation in $b \to s$ transitions, with studying of forward-backward asymmetry in $b \to s l^+ l^-$ transition, and with searches for lepton flavor violating τ decays. Last but not least, B factories observed a long list of new hadrons, some of which do not seem to fit into the standard scheme of mesons and baryons. All this was only possible because of constant improvements in the performance of the two accelerators, PEP-II and KEKB, much beyond their design values. In the KEKB case, the peak luminosity reached a world record value of $2.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, exceeding the design value by a factor of more than two. The two collaborations have accumulated data samples corresponding to integrated luminosities of 0.557 ab^{-1} (BaBar) and 1.041 ab^{-1} (Belle).

While the principal goal of B factories was to check whether the SM with the CKM matrix is correct, the emphasis of the next generation of B factories, the super B factories, will be on investigations of physics beyond SM, also known as New Physics (NP). To search for departures from the Standard model, a ≈ 50 times bigger data sample of decays of B and D mesons and τ leptons is needed, corresponding to an integrated luminosity of $\approx 50\ \mathrm{ab}^{-1}$. A substantial upgrade is therefore required both of the accelerator complex as well as of the detector [6, 7]. Of course, by 2016 when the first super B factory starts to take data, there will be serious competition from the LHCb experiment, which is performing extremely well, and has by now published several very interesting results, including the observation of CP violation in D meson decays. Still, an e^+e^- collider operating at (or near) the $\Upsilon(4S)$ resonance will have considerable advantages in several classes of measurements, e.g., with final states involving neutral particles (γ, π^0) and neutrinos, and will be complementary in many more.

In what follows we shall first discuss the physics motivation, the accelerators and detectors, and then review the status of the two projects, SuperKEKB/Belle-II in Japan and SuperB in Italy.

2 Physics motivation

In searches for effects from New Physics, some particularly challenging measurements can only be carried out a B factory, an example being the studies of B meson decays with more than one neutrino in the final state. One of the processes of this type is the leptonic decay $B \to \tau\nu_\tau$ which is followed by the decay of the τ lepton with one or two additional neutrinos in the final state. In the SM, this transition proceeds via W annihilation, but in some NP extensions it could also be mediated by a charged Higgs boson [8]. The measured branching fraction can therefore be used to set limits on the two parameters, the charged Higgs mass and the ratio of vacuum expectation values, $\tan\beta$ [9].

As shown in Fig. 1, with the present measurements (green) it is possible to exclude a sizable part of the parameter space; with a data sample corresponding to a luminosity of 50 ab^{-1}, the five standard deviations discovery region covers a substantial fraction of the parameter space (red). The sensitivity is comparable to direct searches with large data sets at the LHC.

A similar process, $B \to D\tau\bar{\nu}_\tau$ is sensitive to the charged Higgs boson as well [10]. Compared to $B \to \tau\nu_\tau$, it has a smaller theoretical uncertainty, a larger branching fraction [11, 12], and the differential distributions can be

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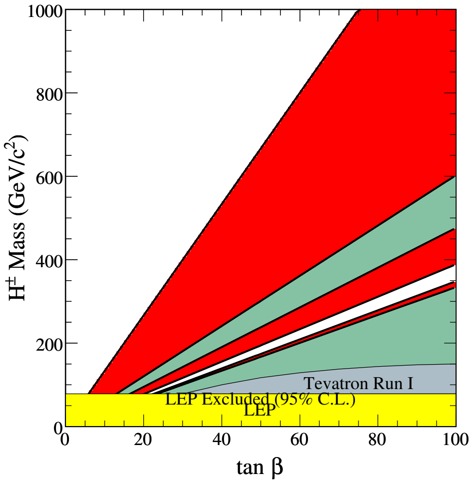

Figure 1. Five standard deviations discovery region (red) for the charged Higgs boson in the $(m_{H^\pm}, \tan\beta)$ plane, from the measurement of $\mathcal{B}(B^+ \to \tau^+\nu)$ with 50 ab^{-1} [9]. Other shaded regions show the current 95% C.L. exclusion region.

used to discriminate the contributions of W^+ and H^+. It is worth noting that while LHC experiments are sensitive to $H-b-t$ coupling, in $B \to \tau\nu_\tau$ and $B \to D\tau\bar{\nu}_\tau$ we probe the $H-b-u$ and $H-b-c$ couplings, respectively.

Rare processes with several neutrinos in the final state, such as $B \to \tau\nu_\tau$, are searched for in the following way [13]. First, one of the B mesons is fully reconstructed in a number of exclusive decay channels like $B \to D^{(*)}\pi$. Because of the exclusive associated production of B meson pairs in a B factory, the remaining particles in the event must be the decay products of the associated B. In the $B^- \to \tau^-\bar{\nu}_\tau$, $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu, e^-\nu_\tau\bar{\nu}_e, \pi^-\nu_\tau$, decay sequences, only one charged particle is detected. To exclude background events with additional neutral particles (π^0 or γ) in the final state, we use the remaining energy in the calorimeter which is not associated with reconstructed charged tracks. In this measurement we greatly profit from the excellent hermeticity of the spectrometers of the B factories.

The decays $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ have a similar event topology as $B^- \to \tau^-\bar{\nu}_\tau$, and a similar event analysis can be applied to it as well. By simultaneously measuring the branching fractions for the two decay types and comparing them to the SM predictions (4×10^{-6} for $K\nu\bar{\nu}$ and 6.8×10^{-6} for $K^*\nu\bar{\nu}$, with contribution from penguin box diagrams) it is possible to determine the contributions of anomalous right-handed and left-handed couplings [9, 14, 15].

Yet another example of a decay which cannot be studied at LHCb is a measurement of CP violation in $B \to K_S\pi^0\gamma$ decays in a search for right-handed currents. The present uncertainty in the time-dependent CP violation parameter S is about 0.2, and should be reduced to a few percent level with 50 ab^{-1} of data.

Super B factories will also be used to search for lepton flavour violating decays of τ leptons, in particular in the $\mu\gamma$ and $\ell\ell\ell$ final state. Theoretical predictions for branching fractions of these two decay modes are between 10^{-10} and 10^{-7} for various extensions of SM (mSUGRA+seesaw, SUSY+SO(10), SM+seesaw, non-universal Z^0, SUSY+Higgs). The reach of super B factories (from 10^{-9} to 10^{-8}, depending on the decay mode) will allow probing of these predictions and discrimination between the different NP theories [16].

The physics potential of a super B factory [9, 15] can be summarized as follows. There is a good chance to see new phenomena, such as CP violation in B decays from new physics sources, or lepton flavor violation in τ decays. The Super B factory results will help to diagnose or constrain new physics models. $B \to \tau\bar{\nu}_\tau$ and $B \to D^{(*)}\tau\bar{\nu}_\tau$ decays can probe the charged Higgs contribution in the large $\tan\beta$ region. The physics motivation for a super B factory is independent of LHC. If LHC experiments find new physics phenomena, precision flavour physics is compulsory to understand it; if no new physics is found at LHC, high statistics B and τ decays would be a unique way to search for new physics above the TeV scale (or at the TeV scale in case of the minimal flavour violation scenario). Needless to say that there are many more topics to explore, including CP violation searches for charmed hadrons, searches for new hadrons etc.

3 Accelerators

For an increase in the data sample size by a factor of ≈ 50, needed in searches for departures from the SM, a sizable upgrade of the B factory accelerator complex is required leading to a 40 times larger peak luminosity. These next generation accelerators are known as super B factories. At KEK, a super B factory project known as SuperKEKB foresees a substantial redesign of elements of the existing KEKB accelerator complex while retaining the same tunnel and related infrastructure. After 11 years of successful operation, KEKB stopped operation in June 2010. This opened the way for the construction of SuperKEKB. To increase the luminosity by a factor of 40 the plan is to modestly increase the current (by a factor of 2) with respect to the KEKB values, and dramatically shrink the beam size at the collision point, while the beam beam parameter is kept at the KEKB value (Table 1). In this 'nano-beam' scheme which was invented by Pantaleo Raimondi for the Italian SuperB project [17], the beams collide at a rather large angle of 83 mrad (compared to 22 mrad in KEKB). In addition, a lower beam energy asymmetry of 7 GeV and 4 GeV instead of 8 GeV and 3.5 GeV is needed to reduce the beam losses due to Touschek scattering in the lower energy beam.

The modifications of the KEKB complex include: improvements in electron injection, a new positron target and damping ring, redesign of the lattices of the low energy (LER) and high energy (HER) rings, replacing short dipoles with longer ones (LER), installing TiN-coated beam pipe with ante-chambers, modifications of

	LER (e^+)	HER (e^-)	
Energy	4.0	7.0	GeV
Half crossing angle	41.5		mrad
Horizontal emittance	3.2	4.3	nm
Emittance ratio	0.27	0.25	%
Beta functions at IP (x/y)	32 / 0.27	25 / 0.31	mm
Beam currents	3.6	2.6	A
Beam-beam parameter	0.0886	0.0830	
Luminosity	8×10^{35}		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Table 1. SuperKEKB: parameters of the low energy (LER) and high energy (HER) accelerator rings.

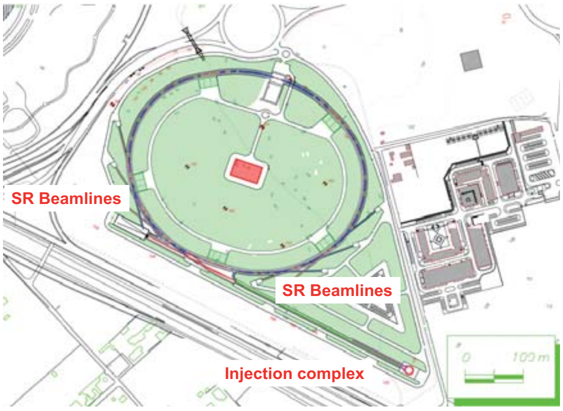

Figure 2. The SuperB accelerator complex

the RF system, and a completely redesigned interaction region [18].

Another approach to the design of a super B factory was exploited in the Italian SuperB project [19]. Here it was foreseen that a new tunnel would be built on the campus of the Tor Vergata university near Rome. Parts of the beam elements of the PEP-II accelerator complex would be reused in the construction. In addition to the nano-beam scheme, an essential feature of the SuperB accelerator was the crab waist collision of two beams in which special sextupoles are used close to the interaction region to maximize the overlap of the two beams. This scheme was successfully tested at the DAΦNE ring by Pantaleo Raimondi and his team [20]. The SuperB accelerator was designed in such a way that it could be modified to run at the $\psi(3770)$ resonance close to charm threshold, where pairs of D^0 mesons are produced in a coherent $L = 1$ state. Data accumulated at charm threshold would allow precision charm mixing, CP violation and CPT violation studies. Another feature of the SuperB accelerator was the polarization of the low energy (electron) beam. This could increase the sensitivity to lepton flavour violating τ decays and CP violation in τ decays through a reduction of backgrounds [15]. It would also enable a precise $\sin^2 \Theta_W$ measurement.

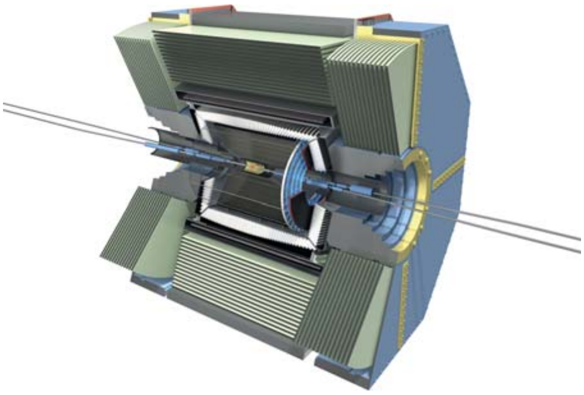

Figure 3. The Belle II spectrometer

4 Detectors

A careful design of the detector is required for operation with an accelerator with a 40 times bigger luminosity [18]. To maintain the excellent performance of the spectrometer, the critical issues will be to mitigate the effects of higher backgrounds (by a factor of 10 to 20), leading to an increase in occupancy and radiation damage, as well as fake hits and pile-up noise in the electromagnetic calorimeter, and neutron induced hits in the muon detection system. Higher event rates require substantial modifications in the trigger scheme, DAQ and computing with respect to the current experiments. In addition, improved hadron identification is needed, and similarly good (or better) hermeticity is required.

For the Belle-II detector [18], shown in Fig. 3, some solutions are listed in what follows. The new vertex detector will have two pixel layers, at r = 14 mm and r = 22 m around a 10 mm radius Be beam pipe, and four double-sided strip sensors at radii of 38 mm, 80 mm, 115 mm, and 140 mm. The pixel detector will be based on DEPFET sensors [21]. A significant improvement in vertex resolution is expected with respect to Belle, both for low momentum particles (by a factor of two) because of reduced Coulomb scattering, as well as for high momentum particles because the high resolution pixel detector is closer to the beam pipe and interaction point. Another important feature is a significant improvement in K_S^0 reconstruction efficiency (by about 30%) and vertex resolution because of a larger volume covered by the vertex detector.

The hadron particle identification will be provided by a time-of-propagation (TOP) counter in the barrel part, and a RICH with a focusing aerogel radiator in the forward region of the spectrometer. The TOP counter [22] is a special kind of DIRC counter with quartz radiator bars in which the two dimensional information from a Cherenkov ring image is represented by the time of arrival and impact position of the Cherenkov photons at the photon detector. Compared to the BaBar DIRC, the TOP counter construction is more compact, since the large expansion volume is not needed, and the photon detectors can be coupled directly to the quartz bar exit window via a very short expan-

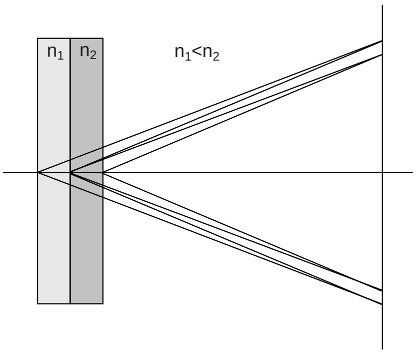

Figure 4. Belle-II PID system in the forward direction: principle of operation of the proximity focusing RICH with a non-homogeneous aerogel radiator in the focusing configuration.

sion wedge. On the other hand, the TOP counter demands photon detectors with single photon time resolution below 100 ps. A 16-channel MCP PMT as developed by Hamamatsu [22] with a very challenging read-out system will be used for this purpose. For the end-cap region a novel type of a proximity focusing RICH with aerogel as radiator is being constructed. The key issue in the performance of this type of RICH counter is to improve the Cherenkov angle resolution per track by increasing the number of detected photons. With a thicker radiator, the number of detected photons increases, but in a proximity focusing RICH the single photon resolution degrades because of the emission point uncertainty. However, this limitation can be overcome in a proximity focusing RICH with a non-homogeneous radiator [23], where one may achieve overlapping of the corresponding Cherenkov rings on the photon detector (Fig. 4). This represents a sort of focusing of the photons within the radiator, and eliminates or at least considerably reduces the spread due to the emission point uncertainty. Both detectors, the time-of-propagation counter and the aerogel RICH detector, are expected to considerably improve the particle identification efficiency if compared to Belle; the end-cap RICH will provide a 4 σ π/K separation up to kinematic limits, and the barrel TOP counter will identify kaons with an efficiency exceeding 90% at a few percent pion fake probability.

The SuperB detector [24] planed to reuse several components of the BaBar spectrometer. In the baseline version two major changes were foreseen, replacing CsI(Tl) crystals in the forward calorimeter with LYSO crystals, and a modification of the particle identification device, the DIRC counter. Options include a pixel detector layer, a RICH as the forward PID device and a veto electromagnetic calorimeter in the backward region to improve the hermeticity of the spectrometer.

In the new type of DIRC counter, a focusing DIRC detector, the large stand-off box with single-channel PMTs is replaced by a compact focusing quartz block and multi-anode PMTs as photon sensors. By measuring the time of arrival of Cherenkov photons, the fast photon detectors allow to correct for the chromatic error, i.e., variation of Cherenkov angle with wavelength [25]. The focusing DIRC counter is expected to extend the π/K separation range by improving the angular resolution by about 10%. At the same time, the order-of-magnitude lower mass of the expansion volume should considerably reduce the level of beam induced backgrounds.

5 Status of the projects

The SuperKEKB/Belle-II project has received initial construction funding in 2010 for the positron damping ring, and with the Japanese 'Very Advanced Research Support Program' a sizable fraction of funds for the main ring upgrade (exceeding 100M EUR) for the period 2010-2012. In 2011, KEK and collaborating institutions also managed to secure additional funds to complete the construction as scheduled, i.e., start the SuperKEKB commissioning in early in 2015, and start data taking in 2016. It is expected that the full data sample of 50 ab^{-1} will be reached in 2022/2023.

The SuperB project was selected as the first in the list of flagship projects of the new Italian national research plan over the next few years. The Italian government has delivered an initial funding as a part of a multi-annual funding program, and a new laboratory was founded. The aim of the project was to accumulate 75 ab^{-1} on a time scale similar to SuperKEKB/Belle-II. After a cost review in autumn 2012, the Italian government decided that it cannot cover the significant cost increase, and decided, quite unfortunately, to cancel the SuperB project.

6 Summary

B factories have proven to be an excellent tool for flavour physics, with reliable long term operation, constant improvement of operation, achieving and surpassing design performance. A major upgrade has started at KEK to construct the SuperKEKB accelerator and the Belle-II detector, and be ready for data taking by 2016. Analysis of the physics reach suggests that we can expect a new and exciting era of discoveries, complementary to the LHC.

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