STATUS OF SUPER-KEKB AND BELLE II*

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The status of preparations to Belle II experiment at the SuperKEKB collider is reviewed in this article.

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1. Introduction

The Belle detector [1] has stopped data taking in June 2010. A decade-long operation of the experiment at the asymmetric beam energy electron-positron collider KEKB [2] resulted in a data sample of an integrated luminosity exceeding 1 ab^{-1}. This would not be possible without the excellent performance of the KEKB. The collider has reached the world record instantaneous luminosity of 2.2×10^{34} $cm^{-2}s^{-1}$ (Fig. 1), more than twice the design luminosity. Several technological innovations contributed to this achievement, among them crab cavities developed at KEK and successful implementation of continuous injection.

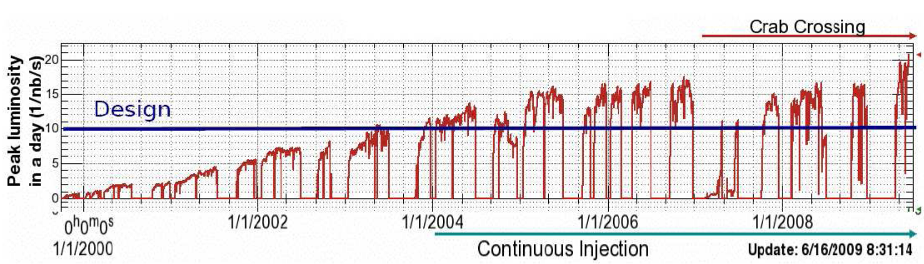

Fig. 1. Time-line of KEKB peak luminosity.

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By the precise measurement of the CKM angle ϕ_1 by Belle and BaBar, its companion B-meson factory experiment at SLAC [3], the Kobayashi–Maskawa mechanism of CP violation [4] has been confirmed. Following the experimental confirmation M. Kobayashi and T. Maskawa were awarded the 2008 Nobel Prize in Physics. Numerous other physics results of B-meson factory experiments further support the hypothesis that the matrix of three-generation quark mixing is the dominant source of CP violation in B- and K-meson decays. However, the current experimental uncertainties of the measurements and the theoretical uncertainties involved in the interpretation of various observables, combine to the overall accuracy of the test of the Standard Model (SM) anzatz at 20% level. This still leaves room for additional sources of CP violation, called New Physics (NP). Almost all extentions of the SM imply that such sources exist. The purpose of proposed experiments at super-luminous B-meson factories is to search for new sources of CP violation.

2. Physics motivations

Despite of tremendous success of the SM in describing all known experimental facts, many fundamental questions remain unanswered within the model. The crucial question for a flavour physics is why there should be only three generations of elementary fermions. The SM in the flavour sector contains free parameters alone: the masses and mixing parameters of the quarks and leptons. All of them must be determined experimentally, there is no principle to govern the Yukawa terms in the SM Lagrangian. Any gauge-invariant and renormalizable Yukawa coupling between two fermions is allowed, irrespectively of the generation they belong to. On the contrary, the measured CKM matrix elements show a clear hierarchy. This hierarchy is a mystery at the time being. It may suggest that some hidden cause exists for it, *e.g.* some new flavour symmetry at a higher energy scale. The SM also fails by several orders of magnitude to explain the asymmetry between matter and anti-matter observed in the universe. This discrepancy suggests that additional sources of CP violation beyond the KM mechanism may exist.

The SM is believed to be a low-energy approximation of a more fundamental theory. Direct searches for new particles of new physics will be done at the LHC. A complementary approach is the search for deviations from the SM predictions, that are due to virtual contributions of new particles, via precision flavour physics measurements. This is the main physics objective of the Belle II experiment at the SuperKEKB collider. The precision flavour physics measurements will provide essential information to identify the kind of NP, even if the direct searches for NP at the LHC are successful. This strategy has been named a DNA test of NP [6]. The mass reach of new particles effects in Belle II can be as high as $\mathcal{O}(100)$ TeV if the couplings are enhanced compared to the SM (Fig. 2).

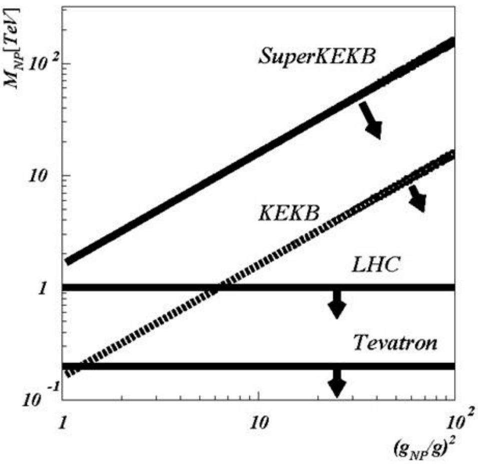

Fig. 2. Sensitivity to NP as a function of the flavour violating couplings (relative to the SM) in the indirect searches at KEKB and SuperKEKB, and direct searches at LHC and Tevatron.

B-meson decays offer a natural place to investigate a wide range of Flavour Changing Neutral Current (FCNC) processes because b quark decay transitions involve all generations of quarks. There are many FCNC decay processes induced by so-called penguin diagrams, suppressed in the SM by the GIM mechanism, in which effects of new physics can be substantially enhanced. Examples of such processes in which new CP-violating phases can be seen include the radiative decay $b \to s\gamma$, the semileptonic decay $b \to sl^+l^-$, and the hadronic decays $b \to dq\overline{q}$ and $b \to sq\overline{q}$.

There are several measurements at both B factory experiments for the penguin processes which disagree with the SM prediction at the level of two-three standard deviations, of too low significance to call them the observation of the discrepancy. Since these measurements are currently limited by their statistical uncertainties, a dataset of $50\,\mathrm{ab}^{-1}$ aimed for at SuperKEKB, would allow to either restrict the parameter space of NP models considerably or to find NP effects. As an example the sensitivity for the measurement of $\sin 2\phi_1$ difference in $b \to sq\overline{q}$ and $b \to c\overline{c}s$ is shown in Fig. 3.

High precision measurements over-constraining the unitarity triangle are an important part of the Belle II physics programme. The anticipated measurement accuracies of the triangle angles achievable with 50 ab^{-1} are 0.012 for $\sin\phi_1$, 1° for ϕ_2 and 1.5° for ϕ_3.

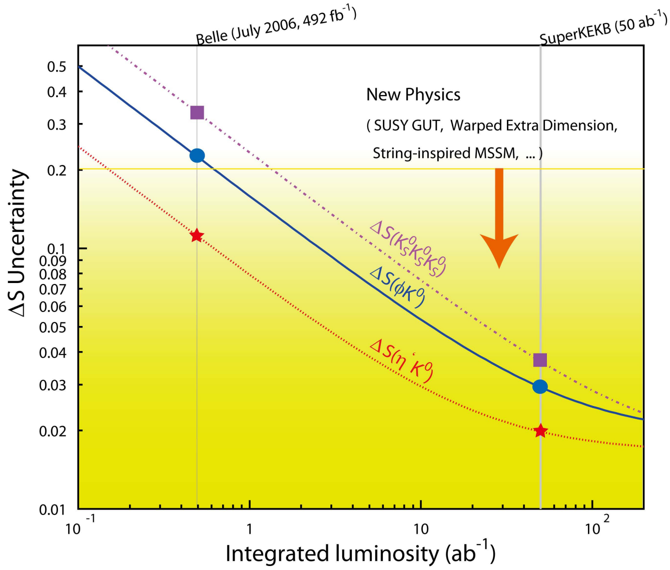

Fig. 3. Expected total uncertainty of ΔS as a function of integrated luminosity.

A possible hint of NP might have been seen in the forward–backward (FB) asymmetry in $B \to K^* l^+ l^-$ decays. BaBar, Belle, and CDF measurements show a trend towards values exceeding the SM prediction. The zero crossing point of the asymmetry as a function of di-lepton invariant mass is less model dependent than the overall shape of the distribution. The zero crossing point can be determined with 5% accuracy with 50 ab^{-1}, that is sufficient to confirm the SM or to establish the evidence for NP.

Another tension has been recently observed in $B^+ \to \tau^+ \nu_\tau$ decays. The branching ratios measured by Belle and BaBar are more than 2 standard deviations higher than the SM expectation. If it were the statistically significant discrepancy, it could be caused by contributions from a charged Higgs. The Belle II discovery potential for $H^\pm$ expected already at 5 ab^{-1} dataset is shown in Fig. 4.

Tremendous improvements in sensitivity are also expected in searches for lepton flavour violation and CP violation in D0 decays.

Finally, unexpected phenomena, those beyond the guidance of models, can show up in a clean experiment with statistics increased by nearly two orders of magnitude.

A detailed discussion of the Belle II physics program can be found in Ref. [5].

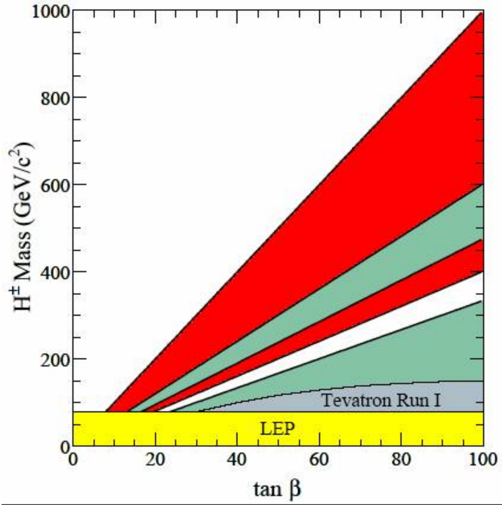

Fig. 4. Excluded masses of charged Higgs as a function of $\tan\beta$ — lihgt grey (yellow), grey, pale grey (green) and 5σ discovery sensitivity region — dark grey (red) in $B^+ \to \tau^+\nu_\tau$ for 5 ab^{-1} dataset.

3. SuperKEKB collider

A large statistics data set required to reach the physics goals of Belle II experiment can only be achieved with a new generation e^+e^- collider. The collider design luminosity of 8×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is needed to accumulate 50 ab^{-1} in five years of operation. The design instantaneous and integrated luminosity of the SuperKEKB in a function of operation time is shown in Fig. 5.

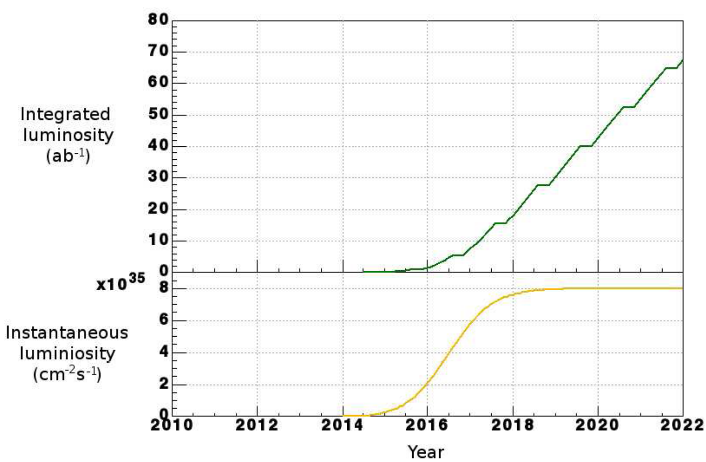

Fig. 5. SuperKEKB integrated and instantaneous design luminosity.

The luminosity $\mathcal{L}$ of a collider can be expressed, assuming flat beams and equal horizontal and vertical beam sizes of two beams at the interaction point, by

$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)\left(\frac{R_{\mathrm{L}}}{R_{\xi_y}}\right), \tag{1}$$

where γ, e, r_e are the Lorentz factor, the beam particle elementary electric charge and the classical radius, I is the beam current, $\beta^*_{y\pm}$ the vertical beta function at the interaction point, $\xi_{y\pm}$ the beam–beam interaction parameter and R_{L}/R_{ξ_y} — a geometrical factor related to beam crossing angle and hourglass effect. The subscript $\pm$ denotes the product of the corresponding quantities for the low energy positron (LER) and high energy electron (HER) beams.

A combination of several improvement factors for parameters in (1) is needed to reach a forty times higher luminosity than the present KEKB luminosity. The main increase in luminosity comes from an extremely small beam size at the interaction point — so-called Nano-Beam scheme, which was first proposed for the Super B factory in Italy. The beta functions are reduced as compared to KEKB: in y direction (β_{y^*}) from 5.9 mm to 0.27/0.42 mm for HER/LER, and in x direction (β_{x^*}) from 120 cm to 3.2/2.5 cm. This requires designing a new Interaction Region (IR) with new focusing quadrupole magnets.

Since the beam–beam interaction parameter is proportional to $\sqrt{\beta^*/\epsilon}$, the emittance ϵ has to be reduced to keep the beam–beam parameter at the similar level as at KEKB. A reduction of the emittance from 18/24 nm to 3.2/1.7 nm is obtained by installing a new electron source and a new damping ring, in addition to a redesign of the HER arcs. The last contribution to the luminosity gain comes from higher beam currents. They are increased from 1.6/1.2 A to 3.6/2.6 A.

The high luminosity design also leads to higher beam background levels. Touschek scattering becomes the dominant background source at SuperKEKB. Furthermore, the design requires reduction of the beam energy asymmetry from 3.6/8 GeV to 4/7 GeV and the increase of beam crossing angle from 22 mrad to 83 mrad. SuperKEKB will be hosted in the same tunnel as KEKB. The dismounting of the KEKB has already started. Detailed description of the SuperKEKB can be found in Ref. [7]

4. Belle II detector

Because of the increased background level at the SuperKEKB, the Belle II detector has to be designed to cope with higher occupancy and to withstand radiation damage. Moreover, the increased event rate puts high demands on trigger, data acquisition, and computing. To cope with the conditions at the SuperKEKB collider, the components of the Belle detector are either upgraded or replaced by new ones. Fig. 6 shows a comparison of the Belle and Belle II detectors.

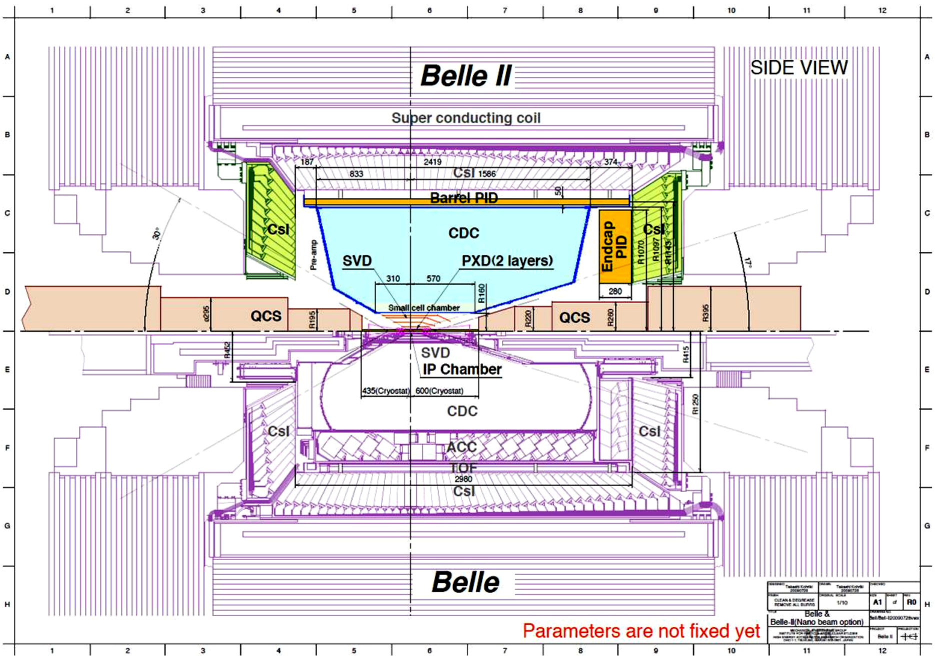

Fig. 6. The Belle II detector (top half) compared to the current Belle detector (bottom half).

The innermost part of the tracking system consists of two layers of monolithic silicon pixel sensors (PXD) based on the DEPFET technology. It is surrounded by four layers of double sided silicon strip detectors (SVD). With the excellent spatial resolution of the PXD an impact parameter resolution of $\sim 20\ \mu$m along the beam direction can be achieved, leading to an improved determination of the vertex position. The larger outer radius of the SVD compared to Belle gives an increase in efficiency of about 30% for the reconstruction of $K^0_S \to \pi^+\pi^-$. A precise measurement of the momentum of charged tracks is provided by the central drift chamber (CDC). Improvements in the momentum resolution compared to the Belle CDC are achieved by employing a smaller cell size and increased outer radius.

The Time-Of-Flight detector and Aerogel Cherenkov Counter of the Belle, used for identification of charged hadrons, is replaced by a Time-Of-Propagation counter (TOP). The usage of timing information of internally reflected Cherekov light allows for a compact design of this particle identification device in the barrel part. The forward region is instrumented with new RICH detectors (ARICH) using aerogel layers with varying refractive index to generate Cherekov rings with the same radius for each layer. A kaon identification efficiency of 99% (96%) at a pion mis-identification rate of $< 0.5\%$ (1%) is expected for $B \to \rho\gamma$ events reconstructed in the TOP counter (4 GeV particles reconstructed in the ARICH), respectively.

The CsI crystals of the Belle electromagnetic calorimeter (ECL) will be reused in Belle II detector. A replacement with faster signal and more radiation tolerant crystals in the endcap region is considered as upgrade option. The readout electronics will be upgraded to enable a wave form sampling, that improves the signal to background separation under the higher background conditions at SuperKEKB.

Muons and $K^0_{\rm L}$ mesons are identified by resistive plate chambers in the outer part of the Belle detector (KLM). For Belle II the endcap regions will be upgraded with scintillator strips to cope with the higher background rates.

Further details of the Belle II apparatus can be found in Ref. [7].

5. Belle II computing model

The Belle II physics events rate will be almost two orders of magnitude higher than that at Belle. This requires a substantial upgrade of the data acquisition system and the offline reconstruction software. Both will use a common software framework with ROOT as persistency layer, that is fully object-oriented. A new framework named roobasf is being developed for this purpose. This framework is designed to meet the requirements of real-time processing; the socket I/O interface can be easily implemented as one of the selectable I/O packages for roobasf.

With 10^{10} events per year recorded in Belle II, the centralised computing model of Belle has to be replaced by a distributed computing model. That vast amount of data has to be processed without any delay to the experiment data acquisition, in addition to the production of MC events corresponding to at least 3 times of real data. Moreover, computing power for physics analysis has to be provided. A distributed computing model based on the grid computing will be adopted. The scheme of the model is shown in Fig. 7. The KEK, where the data stream from the detector is recorded, will host the main centre that is responsible for raw data processing. Regional grid sites, located in Asia, Europe and US, will allow users to produce ntuples from skimmed datasets and they take care of the MC production. Finally, users will analyse ntuples on institution's local clusters resources. To keep the grid based system as simple as possible, the key ideas of the model are: a meta-data data-base and a project server structure (like in D0 and CDF experiments) and the use of gLite services as much as possible.

The grid sites in the Belle II computing system will be complemented by Cloud Computing facilities, mainly to absorb surges in demand for computing power in the experiment, that exceed the available installed computing resources. Cloud Computing resources include commercial providers, like Amazon's EC2, and emerging academic cloud facilities, like the facility being developed at the IFJ PAN in Kraków.

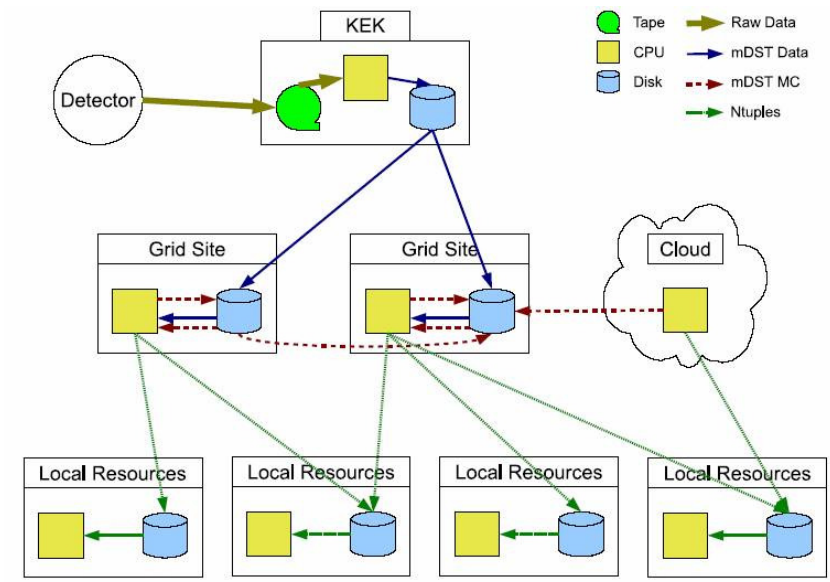

Fig. 7. Belle II computing model.

6. Project status

In March 2008 a first proto collaboration meeting was held. In December of the same year the Belle II Collaboration was officially founded. Currently it has about 300 members from nearly 50 institutions and it is steadily growing. It is a truly international project with members from 13 different countries in Asia, Europe, US and Australia. European groups from Austria, Czech Republic, Germany, Poland and Slovenia constitute $\sim 30\%$ of the collaboration.

After a preliminary approval of the SuperKEKB upgrade by the Japanese Government in January 2010, the Ministry of Science and Technology assigned in June 2010 funds of 100 oku-yen ($\sim$ 110 million dollars) to the project from Very Advanced Research Support Program. This covers about one third of the total project cost. The remaining funds allocation is expected in April 2011.

The Belle experiment has stopped data taking and the KEKB accelerator was switched off on June 30th 2010 to start the upgrade. Dismounting of the KEKB and Belle detector has started, the construction of the damping ring and some other SuperKEKB components has begun. The Belle II detector components are either in advanced prototyping or material purchase and design stages. First data taking with Belle II at SuperKEKB is planned in 2014. The design luminosity should be reached in 2018 so that a total data sample of $50\,\mathrm{ab}^{-1}$ can be accumulated until 2020.

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