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Belle II at SuperKEKB, a SuperB factory

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The two B-factories – BaBar at PEP II (SLAC) and Belle at KEKB – brought during the decade of their operation immense amount of results on the *CP* violation and also hints for the physics beyond the Standard Model. For the latter it is evident, that many interesting measurements are statistically limited and similar machine with much higher intensity would substantially enhance our understanding of the heavy quark sector. This is the key motivation for the upgrade of the KEKB to the SuperKEKB – a high-luminosity asymmetric e^+e^- SuperB-factory together with corresponding upgrade of the detector.

Physics motivation of this upgrade as well as description of the project status is presented in this paper.

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1. Introduction

The Standard Model (SM) – one of the most successful physics theories, namely after recent discovery of Higgs boson – describes elementary particles and their interactions. One of the important ingredients of the SM is the *CP* violation observed in the heavy quark sector. Large part of the experimental results from this area come from two B-factories: PEP-II at SLAC and KEKB at KEK. Here beams of e^+e^- collided with the unprecedented luminosity at the $\Upsilon(4S)$ resonance decaying predominantly to $B\bar{B}$. Due to the energy asymmetry the $B\bar{B}$ system was boosted. This allows to study the time-dependence of the B-meson decays provided the vertex reconstruction is precise enough. Belle and BaBar, the two detectors built at the KEKB and PEP-II, respectively, have accumulated 1500 fb^{-1}, corresponding to over 1 billion $B\bar{B}$ pairs. However, many interesting measurements are still statistically limited and similar machine with much higher intensity would substantially enhance our understanding of the heavy quark sector. Furthermore there are many questions that cannot be explained within the SM and new ideas have to come in. This is the key motivation for the upgrade of the KEKB to the SuperKEKB – a high-luminosity asymmetric e^+e^- SuperB-factory together with a corresponding upgrade of the Belle detector.

2. Physics Case

One of the most fundamental problems of our current understanding is the explanation of the observed matter-antimatter asymmetry of the Universe. Violation of the *CP* symmetry can indeed lead to a matter dominated universe, but the Kobayashi-Maskawa (KM) mechanism cannot explain the observed magnitude of the asymmetry. New sources of the asymmetry must be found: e.g. new flavor symmetries at higher energy scale. There are two key approaches to obtain new experimental data on the relevant processes. One is exploiting the high energy proton beams at the Large Hadron Collider (LHC) at CERN (LHCb, but also ATLAS and CMS experiments), while the other one intends to use the unprecedented intensity electron-positron collisions at the SuperKEKB, which is under construction at KEK, Tsukuba. The energy and intensity frontier approaches are quite complementary and can only together reveal the existence and hopefully also the nature of the new effects.

Because of the precision achieved at the high-luminosity B-factory the sensitivity to the effects of new Physics (NP) goes far beyond the energies used. The mass reach cannot be determined exactly, because it depends on yet unknown strength of the flavor violating couplings, but Belle II can definitely probe effects of particles up to $\mathcal{O}(1\ \text{TeV}/c^2)$ if the Minimal Flavor Violation is the correct description. However, as shown in Ref. [1], Belle II can also reach $\mathcal{O}(100\ \text{TeV}/c^2)$ in case of enhanced couplings.

The reach of the two above mentioned approaches is illustrated in Fig. 1. The most promising processes to be studied at Belle II can be classified into 3 categories: processes with missing energy (E_{miss}), processes where one measures inclusive quantities, and processes with (several) neutral particles in the final states. The individual processes will be discussed in the following sections. However we summarize here only some of the physics capabilities of the Belle II experiment. Detailed information on the physics case can be found in [3, 4, 5]. The detector upgrade is described in the Technical Design Report [3] as well as in other papers in these proceedings [6, 7, 8, 9].

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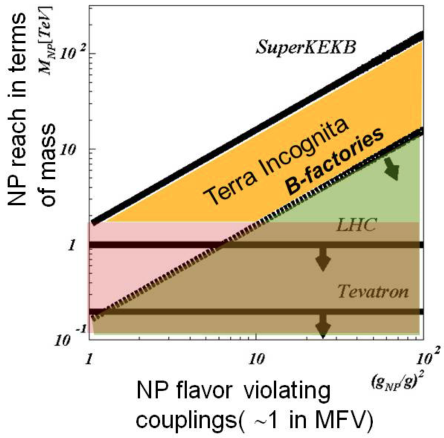

Figure 1: Illustrative region of sensitivity to NP as a function of the flavor violating couplings (relative to the SM) in the indirect searches at KEKB and SuperKEKB, and direct searches at the LHC and the Tevatron.

2.1 Processes with E_{miss}

- $B \to \tau\nu$

The purely leptonic decay $B \to \tau\nu$ is of particular interest since it provides a unique opportunity to test the SM and its extensions. Physics beyond the SM could significantly suppress or enhance $\mathscr{B}(B \to \tau\nu)$ via exchange of new charged particles such as a charged Higgs boson from supersymmetry or other two-Higgs doublet models.

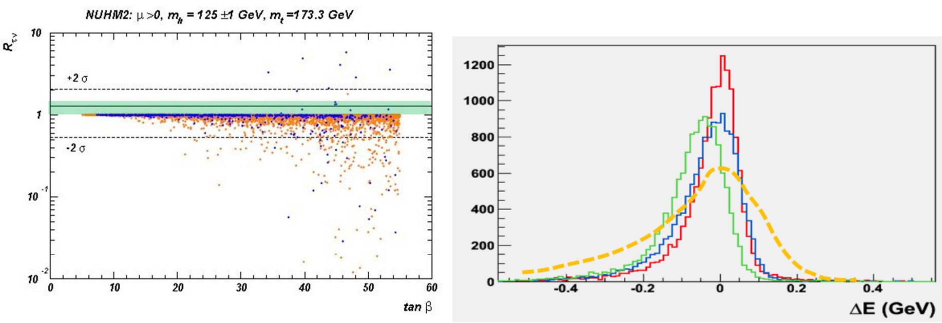

Figure 2: Left: Allowed $R_{\tau\nu} = \mathscr{B}(B \to \tau\nu)^{MSSM}/\mathscr{B}(B \to \tau\nu)^{SM}$ and $\tan\beta$ space in NUHM2 model [10] with the assumption of a Higgs boson with a mass around 125 GeV/c^2. The solid line shows the central experimental value from [11], the dashed lines the $\pm 2\sigma$ interval, and the light shaded band the expected precision with 50 ab^{-1} of data at Belle II. Right: Full simulation of the Belle II ECL performance in terms of the energy difference $\Delta E = E_{\text{B}}^{\text{CMS}} - E_{\text{beam}}^{\text{CMS}}$. Green: default γ energy, blue: after rough calibration, red: after calibration and D^0 mass fit. Yellow dashed line: Belle ECL for a comparison.

The accuracy achievable with 50 ab^{-1} is 3 % (extrapolated from a previous Belle measurement, and using both hadronic and semileptonic tagging). Such a precise measurement of $\mathscr{B}(B \to \tau\nu)$ would be an important input for the determination of $|V_{ub}|$ and would put constraints on many

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models of NP. Recent discovery of a Higgs boson implies severe constraints on the parameter space of SUSY, specifically rather high masses of sleptons and squarks. Then it is interesting to choose as an example a particular model that includes such a Higgs boson. This is shown in Fig. 2 for the NUHM2 model [10]. Clearly such a measurement could yield interesting insights especially if the central value does not coincide with the SM expectation.

These measurements rely strongly on the Electromagnetic Calorimeter (ECL) consisting of the barrel and two endcaps, in total 8736 30 cm long CsI(Tl) counters with PIN diode readout. While the counters are kept from Belle detector, new electronics that provides fast shaping digitization and pipe-line readout with the following wave shape analysis is being developed. For the next stage replacement of the endcap CsI(Tl) with pure CsI counters is assumed. The performance improvement can be illustrated in Fig. 2 right.

Long-lived kaon and muon detector is also an essential component for these studies. Large part will be reused from Belle, but inner two barrel layers as well as endcaps will be upgraded from currently used RPCs to scintillators read out by Geiger mode APDs.

- $B \to D^{(*)}\tau\nu$

This decay shows also certain sensitivity to the exchange of a charged Higgs boson as expected in the Minimal Supersymmetric Standard Model (MSSM), since the amplitude is roughly proportional to $m_\tau m_b \tan\beta$. All four $B \to D^{(*)}\tau\nu$ decays have been observed recently by both BaBar and Belle. However, the current world average values of $\mathscr{B}(B \to D^{(*)}\tau\nu)$ seem to deviate from the SM predictions as well as from the type II 2HDM model. Future measurements of branching ratios with a relative accuracy of 3 %, are needed to clarify the deviations.

2.2 Inclusive processes

- $B \to s\gamma$

Measurements of inclusive $\mathscr{B}(B \to s\gamma)$ can help in determining the direct CP violation asymmetry, A_{CP}. Summing up a large number of exclusive modes (semi-inclusive reconstruction) with up to two neutral pions and a high energy photon may yield in the precision of few 10^{-3} (thus comparable to the SM prediction of $(4.4^{+2.4}_{-1.4}) \times 10^{-3}$[12]).

2.3 Decays with neutral particles in the final state

- $B \to K_S^0\pi^0\gamma$

This mode is interesting for its sensitivity to potential indirect CPV that is heavily suppressed in the SM due to the helicity structure of the Hamiltonian, but it can be enhanced in some NP models [13]. The expected accuracy on S_{CP} with 50 ab^{-1} is around 0.03. In the Left-Right Symmetric Models S_{CP} can be as large as 0.5 (in contrast to the SM prediction of -0.04); here the sensitivity with 50 ab^{-1} of data can reach the SM central value.

For this vertex detector performance is essential. A schematic view of the future vertex detector of Belle II is shown in Fig. 3. The detector is composed of two layers of pixel detectors followed by four layers of double-sided silicon strip detectors. The new detector brings two-fold improvement: better spatial resolution of the vertex determination (around a 25% improvement in

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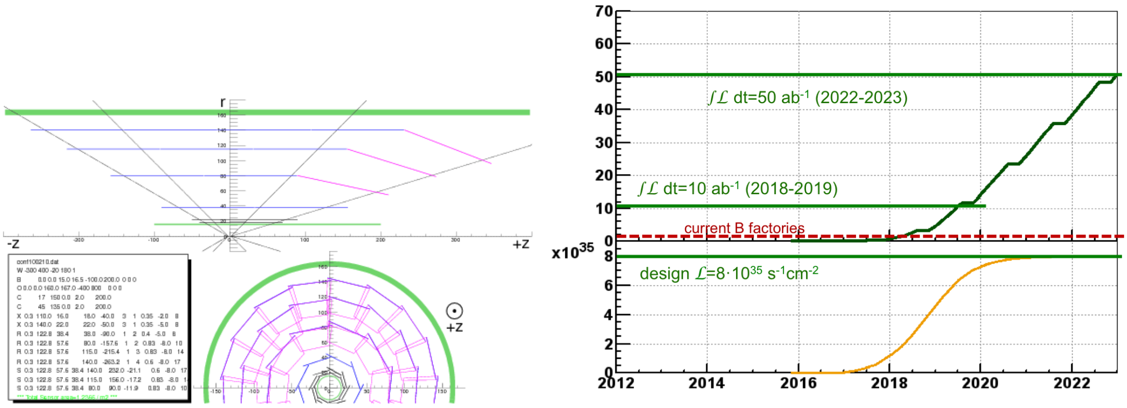

Figure 3: Left: Configuration of the four strip layers, with slanted sensors in the forward region, and two PXD layers. All dimensions are in mm. Right: Planned SuperKEKB peak and integrated luminosities

the case of the $B \to J/\psi K_S$ vertex), and improved high-precision vertex reconstruction efficiency for $K_S \to \pi^+\pi^-$ decays, due to the increased radii of the silicon strip detector layers.

- $B \to K\pi$

This process provides another example how the physics performance can benefit from the upgraded detector components. Here the interesting measurements are related to the so-called direct *CPV* puzzle [14], which arises from the observed difference between the direct *CPV* asymmetry in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays. While in the explicit calculations of the asymmetries $A_{K\pi}$ several model uncertainties are present, a model independent sum rule was proposed [15] to test the consistency of the SM. It relates the asymmetries and the branching fractions of several $B \to K\pi$ decay modes.

The main systematic uncertainty in $A_{K^0\pi^0}$, which is the least precisely known asymmetry in the $K\pi$ system, can be reduced with a larger data sample; with $\int \mathscr{L} dt = 50$ ab^{-1} an accuracy of 0.03 is expected. Assuming the current central values a discrepancy between the measurements and the sum rule would then become significant (Fig. 4). The key condition for this measurement is very good particle identification which will rely on the time-of-propagation (TOP) [16] counter in the barrel, and an ARICH detector in the forward region [17] (Fig. 5). The TOP detector will consist of quartz bars with mirrors on one side and micro-channel plate photomultipliers on the other. For high momentum (3 GeV/c) kaons we expect better efficiency, typical values can be in the range 90 %-95 % in the barrel with a misidentification probability of 5 %. The improvement is more dramatic at lower momentum.

3. Project status

Both SuperKEKB collider and Belle II detector are in the advanced stage of component production and construction. First beam commissioning is planned for 2015, while physics data should be collected from 2016. Belle II collaboration is composed of 560 members from 94 institutes. Sig-

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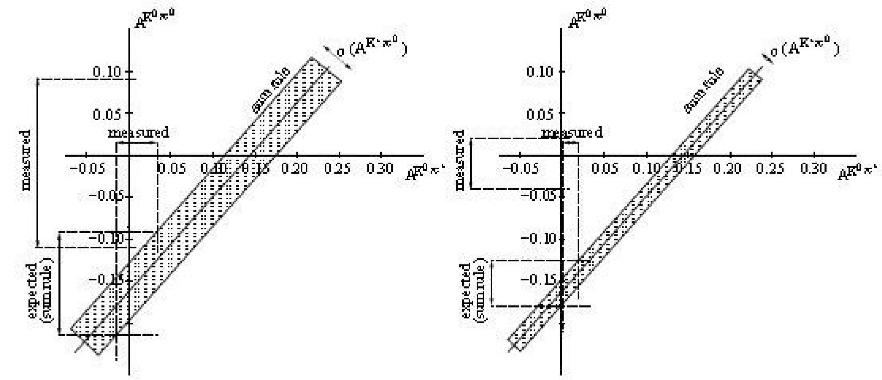

Figure 4: Left: Current directly determined values of $A_{K^0\pi^0}$ and $A_{K^0\pi^+}$ (measured) compared to the prediction from the isospin rule [15] (expected). Right: same with the accuracies on the variables entering the sum rule reduced to the expected values with 50 ab^{-1} of data at Belle II.

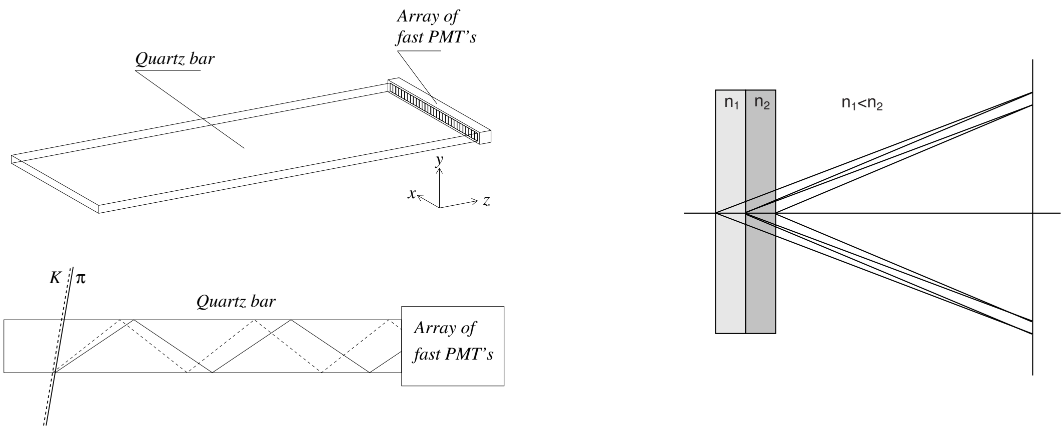

Figure 5: Left: A schematic view of a TOP counter module (top) and of its principle of operation (bottom); right: proximity focusing RICH with a two layer focusing aerogel radiator.

nificant contribution to the project comes from Europe (30 % of all members are from European institutions).

4. Summary

Belle II experiment at the SuperKEKB e$^+$e$^-$ collider aims to discover and understand New Physics Beyond the Standard Model. With its target luminosity of 8×10^{35} cm^{-2}s^{-1} it is supposed to deliver 50 ab^{-1} by 2023, which should allow probing significant part of the New Physics parameter space, complementary to the experiments on the High Energy frontier.

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