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The Belle II experiment at the SuperKEKB collider

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The Belle II experiment at the SuperKEKB collider in Tsukuba, Japan, will start physics data taking in the year 2018 and aims at accumulating 50 ab^{-1} of e^+e^- collision data, about 50 times the data set of the previous Belle experiment. The physics program provides simultaneous studies of a wide range of areas in b-quark, c-quark, τ-lepton, two-photon, quarkonium and exotic physics. Belle II, as a next generation flavour factory, will search for New Physics in the flavour sector at the precision frontier, and further reveal the nature of QCD in describing matter. In this article, we review the current state of Belle II construction and describe the main physics opportunities at this future facility.

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1. Introduction

Belle II experiment at SuperKEKB collider is a new facility to search for physics beyond the Standard Model (SM), so called New Physics (NP), by studying B, charm and τ decays.

SuperKEKB is an asymmetric electron positron collider in Tsukuba (Japan) and is an upgrade of the previous KEKB collider. It provides a clean enviroment for producing $B\bar{B}$ meson pairs via $\Upsilon(4S)$ resonance decay and it is designed to reach the luminosity of $L = 8 \times 10^{35} cm^{-2} s^{-1}$. We plan to collect the data sample of overall integrated luminosity around 50 ab^{-1} with Belle II detector (upgraded Belle detector), which will be 50 times of data collected at Belle. This correspons to 55 billion of $B\bar{B}$ pairs, 47 billion of $\tau^+\tau^-$ pairs and about 65 billion $c\bar{c}$ states (from $e^+e^- \to c\bar{c}$).

There are generally two approaches in search of New Physics. At the energy frontier we can observe new phenomena directly, if new particles are produced in high energy collisions, but these kind of studies are limited by the beam energy (Atlas or CMS experiments at LHC). Alternatively, at the flavour frontier, we can find NP indirectly as new virtual particles in loops may probe much higher energies, above 10 TeV ("B factories", LHCb).

These two approaches are complementary: if New Physics is found in direct searches, it is reasonable to expect indirect NP effects in B, D and τ decays. The latter studies may than give an answer to some fundamental questions like: what is the flavour structure of New Physics or is there a new CP violation source in NP.

There is also a complementarity between Belle II and LHCb experiments on the field of indirect searches. At Belle II, due to well defined initial state, we can better handle modes with neutral final states: $\pi^0\pi^0$, $K_S\pi^0(\gamma)$, $K_SK_SK_S$, as well as final states with missing energy like $\tau\nu$ or $D^{(*)}\tau\nu$. Furthermore, we can study inclusive modes, e.g. $B \to X_S\gamma$, $B \to X_S\ell^+\ell^-$ etc. On the contrary, large B, B_s and charm statistics collected by LHCb experiment makes it specializes in (very) rare decays to rather clean final states, for example $B \to K^*\mu\mu$ or $B \to \mu\mu$.

However, these two experiments are not only complemetary but also competitive. For example, on the field of determination of sin(2β) from the channels like $B \to J/\psi K_S$ or $B \to \phi K_S$, Belle II sensivity is expected to be of the order of magnitude higher than LHCb can measure with its current data sample.

2. "B factories", their features and achievments

"B factory" has several advantages as we have only two B mesons in the final state from $\Upsilon(4S)$ decay, without additional particles. As the initial state is fully known, the reconstruction of one B meson constrains the four-momentum and flavour of the other one. This feature is commonly used for tagging method, where the first meson is either fully reconstructed in hadronic modes, or partialy reconstructed in semileptonic modes. It is crusial for inclusive measurements like "missing mass" analyses, and also allow us to perform studies on the channels with missing energy like $B \to D^{(*)}\tau\nu$ [1, 2] or $B \to \tau\nu$ [3].

Another advatage is clear experimental enviroment - low background level results with easier reconstruction of the channels with γ, π^0, ρ and η in the final state. Also, low track multiplicities and detector occupancy gives high reconstruction efficiency for B, D and τ, along with rather low

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trigger bias. This reduces corrections and systematic uncertainties in many types of measurements, in particular Dalitz plot analyses or the dark sector searches.

One of the exceptional features of the "B factories" is the possibilty to do an "energy scan", where the beam energy can be set to the different values, corresponding to the specific Υ state. Hence, apart from the large $\Upsilon(4S)$ data sets, we can also record samples at the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(5S)$ resonances. The last case is a unique way for studying B_s decays in the clean environment.

Discussed features resulted in a great operation of last decade "B Factories": Belle at KEKB in KEK and BaBar at PEP2 in SLAC. Among their many achievments, one of the crucial result was the discovery of CP Violation in B decays, in particular, time-dependent CP Violation (TCPV) in $B^0 \to J/\psi K^0$, $B^0 \to K^{*0}\gamma$ etc., and Direct CP Violation (DCPV) in $B \to \pi\pi$ or $B \to K\pi$ decays. These kind of studies also gave contribution to the determination of sides and angles of Unitary Triangle, which is one of the most precise test of Standard Model. Furthermore, many rare B decay have been studied, including highly suppressed transitions like $b \to d\gamma$ and $b \to s\ell^+\ell^-$, whose existence was established by Belle. There are also exciting highlights in the charm sector. Namely, $D^0 - \bar{D}^0$ mixing has been found and many new interesting states has been discovered, some of which were unexpected from the theoretical point of view. Good examples are charmonium(like) states X(3872) and Z(4430)$^+$, which were observed by Belle above the open charm threshold and may give an additional insight into our understanding of QCD.

3. SuperKEKB collider and Belle II detector

For the future studies of New Physics we need even more powerful machine. Many parts of KEKB are upgraded for SuperKEKB collider. The most important thing is that we significantly squeze the beams to obtain so called nano-beams (Figure 1). Along with incrising the beam current by the factor of two, it allows to achieve fourty times higher luminosity than it was at KEKB. Also, the beam energies will be slightly changed resulting in less boost to the center-of-mass system. This will increase the hermeticity of the detector, which is advantageous for the channels with neutrinos in the final state.

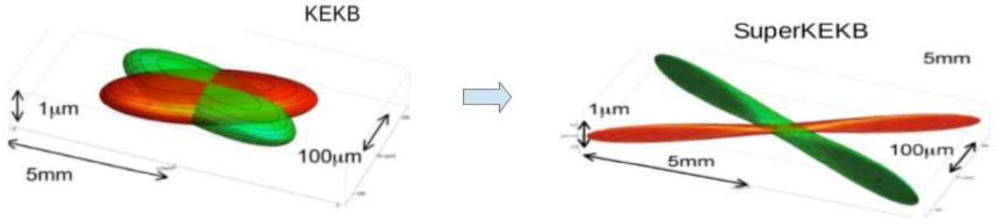

Figure 1: Comparison of beamspots for KEKB beams (left) and SuperKEKB "nano-beams" (right).

Belle detector is being upgraded accordingly for Belle II aparatus [4]. Better hermeticity will be achieved by adding kaon/pion identification and muon identification to the endcaps. Also, K_S efficiency will be significantly increased. As for the less boost compared to KEKB, the interaction point (IP) and secondary vertex resolution will be improved. Another advantage is a better π/K separation and improved π^0 reconstruction, especially important for the neutrals in the final

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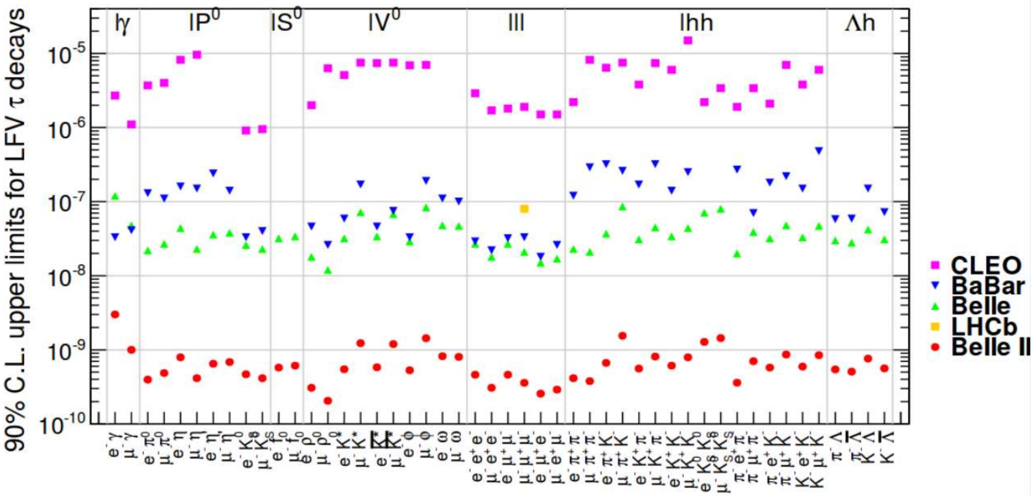

Figure 2: Sensitivity of CLEO, BaBar, Belle, LHCb and Belle II experiments for measurements of τ decays to several Lepton Flavour Violation final states.

states. As for higher luminosity designed for the superKEKB collider, its radiation intensity will be much higher than for KEKB. Therefore, Belle II must be capable to handle higher beam related background.

4. Belle II physics program

With such experiment at hand, we can adress numerous questions regarding New Physics. Below we discuss selected points out of very rich Belle II physics program.

- **Does nature have multiple Higgs bosons?** There are several decays like $B \to D^{(*)}\tau\nu$ or $B \to \tau\nu$[5, 6], which are very sensitive for a charged Higgs, that can be exchanged in some NP models in addition to the exchange of charged W boson. Such case would lead to the modifications of the branching fractions and differential characteristics of these decays, and this can be checked with large Belle II data sample.

- **Are there sources of Lepton Flavor Violation (LFV) beyond the Standard Model?** Decays like $\tau \to \nu\gamma$ or $\tau \to eee$ are highly suppressed in SM but in some New Physics scenarios their branching fractions may be highly expanded. Belle has reached a good sensivity for such studies [7, 8], but no trace of NP has been found so far.

  Red dots in the Figure 2 represent the Belle II sensitivity for several LFV decays. In particular, it can be noticed that the branching fraction of the order of 10^{-8} is within the capability of this experiment.

- **Are there quark Flavour Changing Neutral Currents (FCNC) beyond the Standard Model ?** The insight into this problem can be gained by studying electroweak penguin processes with missing energy, $B \to K^{(*)}\nu\nu$, which are possible window to light dark matter that is not accessible in direct searches. There is a big potential for Belle II to surpass the

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Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\text{Backg.}}$ 711 fb^{-1} Belle	$N_{\text{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\text{Backg.}}$ 50 ab^{-1} Belle II	$N_{\text{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+ \nu\bar{\nu}$	3.98	5.68	21	3.5	2960	245	23%	24%
$B^0 \to K^0_S \nu\bar{\nu}$	1.85	0.84	4	0.24	560	22	110%	110%
$B^+ \to K^{*+} \nu\bar{\nu}$	9.91	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0} \nu\bar{\nu}$	9.19	1.44	5	2.0	704	143	20%	22%
$B \to K^* \nu\bar{\nu}$ combined							15%	17%

Figure 3: Efficiencies, uncertainties and signal/background yields for Belle, as well as respective expectation for Belle II experiment, for various $B \to h^{(*)}\nu\nu$ channels.

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current Belle constrains [9] by an order of magnitude. Fig. 3 sumarises some numbers of expected signal, background and uncertainties for Belle and Belle II, for several channels with hadron and two neutrinos in the final state.

- Another related point is a puzzling tension between SM prediction and measurement for $B \to K\pi$ channel [10]. The CP asymmetry difference A_{CP} between $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ modes has been found to be deviated from zero (predicted by Standard Model). This might be a hint of New Physics, however, the conclusive answer might be provided by model independent sum rule [11, 12],

$$A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+} \frac{\mathscr{B}(B^+ \to K^0\pi^+)\tau_{B^0}}{\mathscr{B}(B^0 \to K^+\pi^-)\tau_{B^+}} = A_{CP}^{K^+\pi^0} \frac{2\,\mathscr{B}(B^+ \to K^+\pi^0)\tau_{B^0}}{\mathscr{B}(B^0 \to K^+\pi^-)\tau_{B^+}} + A_{CP}^{K^0\pi^0} \frac{2\,\mathscr{B}(B^0 \to K^0\pi^0)}{\mathscr{B}(B^0 \to K^+\pi^-)},$$

  which includes challenging channel with neutral particles in final state, $B^0 \to K^0\pi^0$. Such study is avaliable only at “B factories” experiments like Belle II.

- **Are there right-handed currents from New Physics?** Here we can perform an intriguing mesurement on time-dependent CP Violation in $B \to K^{*0}\gamma$ channel [13, 14], where K^{*0} decays into $K^0_S\pi^0$ neutral CP eigenstate. This kind of TCPV may occur only if we have an interference between left- and right-handed photon emmited from b quark. However, the latter is suppressed in the SM by the factor of resepective quark masses ratio (m_s/m_b). This mode is also accesible only at “B factories”, since in this case there are no charged tracks from B meson decay to reconstruct the vertex. Instead, in Belle II the vertex can be determined by extrapolation of the K_S momentum into the Interaction Region, which is highly squeezed in the x-y direction.

- Finaly, it is also very important to determine the Unitary Triangle parameters more precisely as current results still give 10% room for the New Physics. The expected sensivities for angles determination reachable in Belle II, assuming full data sample of 50 ab^-1, are 1^0, 0.3^0 and 1.5^0 for α, β and γ angles, respectively. If any inconsistency between angles and/or sides of the Untary Trianlge is found, this will be a signature of New Physics.

5. Status and schedule

SuperKEKB accelerator is now at the final construction stage and start of beams circulations is scheduled for 2016. In general, there are three phases in commissioning/operation of Belle II. In phase 1, planned for the early 2016, we are going to start commissioning of various components without rolling-in the detector. In particular, vacum scrubbing and beam-related background studies will be performed. Then, in phase 2 scheduled for middle 2017, Belle II detector will take its place for beam collisions. However, the vertex detector still will not be installed as a background level must be examined near the Interaction Region. Finally, in phase 3, the full Belle II aparatus is going to start taking first physics data, which is expected at the end of 2018. We plan to collect the full data sample of 50 ab^{-1} by 2024.

6. Summary

"B factories" proved their excellent tools for flavour physics, which will continue to play a fundamental role in the process of understanding Nature in the next decade. Belle II experiment at SuperKEKB collider, as a continuation of Belle, has a rich physics program, which will shed some light on New Physics in the flavour sector at the precision frontier. This may reveal the nature of NP (if it is found in direct searches at LHC) or, alternatively, probe it far beyond TeV scale. Belle II allows for studying many channels with missing energy and neutral particles in the final states, unlike the complementary LHCb experiment, which specializes in all-charded final state decays, studied on high sample of B and B_s mesons.

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