Future Belle II experiment at the KEK laboratory

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The Belle II experiment at the SuperKEKB collider in Tsukuba, Japan, is a next generation flavour factory that will search for New Physics in the flavour sector at the precision frontier. 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. The physics data taking will start in the year 2018 and we aim at accumulating 50 ab^{-1} of e^+e^- collision data, about 50 times the data set of the previous Belle experiment. In this article, we review the current state of Belle II construction and describe the main physics opportunities at this future facility.

1 Introduction

Belle II experiment at SuperKEKB collider is a new facility to study the decays of B, charm mesons and τ in order to search for New Physic (NP) i.e. physics beyond the Standard Model (SM). SuperKEKB, as an upgraded KEKB machine, is an asymmetric electron positron collider in Tsukuba (Japan), which provides a clean environment for producing $B\bar{B}$ meson pairs via $\Upsilon(4S)$ resonance decay and its designed luminosity is $L = 8 \times 10^{35} cm^{-2}s^{-1}$. Belle II detector is a new apparatus based on previous Belle detector, which is planned to collect a data sample of overall integrated luminosity of 50 ab^{-1}, what is around 50 times of data collected by Belle experiment

Generally, there are two approaches in search of New Physics. We can observe new phenomena directly (Atlas or CMS experiments at LHC), as new particles could be produced in high energy collisions (so called “energy frontier”), where the main limitation arises from the energy of the beam. An alternative way is to search for the NP effects at the precise indirect studies (“flavour frontier”), which may reveal new virtual particles appearing in the loops(“B factories”, LHCb). In the latter case, much higher energies (above 10 TeV) can be probed. Here appears the complementarity of these two physical aspects: potential New Physics discovered in direct searches implies the existence of the indirect NP effects in B, D and τ decays. That, consequently, may shed some light on the flavour structure of NP, or lead to the discovery of new source of CP violation.

There is also a complementarity between Belle II and LHCb experiments in the flavour frontier approach. Belle II, due to well defined initial state, is better to handle final states with missing energy like $\tau\nu$ or $D^{(*)}\tau\nu$ or inclusive modes, e.g. $B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$ etc. Furthermore, we can study decays with neutral final states $\pi^0\pi^0$, $K_S\pi^0(\gamma)$, $K_SK_SK_S$ much more efficiently. 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 $B \to \mu\mu$.

2 “B factories”, their features and achievements

Main advantage of “B factory” is related to the fully known initial state, as there are only two B mesons in the final state from $\Upsilon(4S)$ decay, without additional particles. Therefore, 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 B meson may be fully reconstructed in hadronic modes, or partially reconstructed in semileptonic modes. This is crucial for performing studies on the channels with missing energy like $B \to D^{(*)}\tau\nu$ [1, 2] or $B \to \tau\nu$ [3]. It also gives the possibilities for inclusive measurements (e.g. “missing mass” analyses).

Another feature, related to the clear experimental environment, is low background level and thus easier reconstruction of the channels with γ, π^0, ρ and η in the final state. Low track multiplicities and detector occupancy gives high reconstruction efficiency for B, D and τ, along with rather low 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 possibility 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 successful operation of last decade “B Factories”: Belle at KEKB in KEK and BaBar at PEP2 in SLAC. Among their many achievements, 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

The future studies of New Physics require the experiment of higher intensity and precision. Many parts of KEKB are upgraded for SuperKEKB collider. One of the most important improvements is significantly squeezing the beams to obtain so called nano-beams. Along with increasing the beam current by the factor of two, it allows to achieve forty 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.

Belle detector is being upgraded accordingly for Belle II apparatus [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 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 address numerous questions regarding New Physics. Below we discuss selected points out of very rich Belle II physics program.

There are several decays like $B \to D^{(*)}\tau\nu$ or $B \to \tau\nu$[5, 6], which are sensitive for a charged scalars (e.g. charged Higgs boson), that can be exchanged in some NP models. 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. $B \to D^*\tau\nu$ channel is also a good scope for testing leptoquarks models. Very important observable is the ratio of branching fractions of the decays with tauon and the similar channel with lighter leptons:

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B^+ \to D^{(*)}\tau\nu)}{\mathcal{B}(B^+ \to D^{(*)}\ell\nu)}.$$

We already see 4σ deviation from the SM and the full data sample of Belle II can provide 3% sensitivity for this ratio. Also, we will be able to measure D^* and τ polarization, and this information combined with $\mathcal{R}(D^{(*)})$ result can shed some light to potential nature of NP.

Another hot topic is related to the FCNC semileptonic $b \to sll$ processes, where we can measure certain observables for different values of dilepton mass - q^2. The first one is a ratio

$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)},$$

for which LHCb sees 2.6σ deviation from the SM. Belle II can do this measurement with better electron efficiency then LHCb, for wide q^2 region. The other interesting point is a known tension for P_5' parameter (for $B \to K\mu\mu$ channel) firstly observed by LHCb and recently also by Belle in the lepton-flavor-dependent angular analysis [7]. Prospects for Belle II include the isospin comparison of charged and neutral K^* as well as the ground kaon states. Here, we can also perform inclusive studies, resulting in less theoretical uncertainty.

One of the unsolved puzzle is a tension between SM prediction and measurement for $B \to K\pi$ channel [8]. 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 [9, 10],

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

which includes challenging channel with neutral particles in final state, $B^0 \to K^0\pi^0$. Such study is available only at "B factories" experiments like Belle II. For the $B \to K^0\pi^0$ asymmetry Belle II can obtain uncertainty of the order of 4%.

Next, we can mention missing energy modes like $B \to h^{(*)}\nu\nu$, which is possible window to light dark matter, not accessible in direct searches. Such channels may be also sensitive to Supersymmetry. There is a big potential for Belle II to surpass the current Belle constrains [11] by an order of magnitude.

One can address a question about the 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 significantly expanded. Belle has reached a good sensitivity for such studies [12, 13], but no trace of NP has been found so far. For this physics case, Belle II sensitivity will be highly increased, varying for several LFV decays. Overall, we expect the branching fraction of the order of 10^{-8} to be within the capability of this experiment.

Another interesting point is a consideration of the right-handed currents coming from New Physics. Here we can perform an intriguing measurement on time-dependent CP Violation in $B \to K^{*0}\gamma$ channel [14, 15], where K^{*0} decays into $K_S^0\pi^0$ neutral CP eigenstate. This kind of

TCPV may occur only if we have an interference between left- and right-handed photon emitted from b quark. However, the latter is suppressed in the SM by the factor of respective quark masses ratio (m_s/m_b). This mode is also accessible 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.

Finally, 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 sensitivities 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 Unitary Triangle is found, this will be a signature of New Physics.

5 Status and schedule

In general, there are three phases in commissioning and operation of Belle II. We have successfully proceeded with Phase 1 which involves start of the beams circulation, commissioning of the main ring and installation of the outer detector. We also proceed with vacuum scrubbing and beam background studies with BEASTII. In Phase 2 (it is scheduled to begin in autumn 2017) we plan to start the beam collisions and take first physics runs with Belle II, however, still without the vertex detector. Finally, in Phase 3 scheduled for the end of 2018, Belle II will be fully operational. We anticipate to collect 50 inverse attobarns of data by 2025.

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-charged final state decays, studied on high sample of B and B_s mesons.

References

1. A. Matyja et al., Phys. Rev. Lett.99 191807 (2007).
2. A. Bozek et al., Phys. Rev. D82 072005 (2010).
3. B. Kronenbitter, M. Heck, P. Goldenzweig, T. Kuhr et al., arXiv:1503.05613v2 (2015).
4. T. Abe et al., KEK Report 2010-1 (2010), arXiv:1011.0352v1.
5. B. Grzadkowski, W. S. Hou, Phys. Lett. B 283, 427 (1992).
6. W. S. Hou, Phys. Rev. D48, 2342 (1993).
7. S. Wehle et al., Phys. Rev. Lett. 118, 111801 (2017).
8. S.-W. Lin et al., Nature 452, p332 (2008).
9. M. Gronau, Phys. Lett. B 627 82 (2005).
10. D. Atwood, A. Soni, Phys. Rev. D58, 036005 (1998).
11. O. Lutz et al., Phys. Rev. D87 111103 (2013).
12. K. Hayasaka, et al., Phys. Lett. B 666 16-22 (2008).
13. K. Hayasaka, K. Inami, Y. Miyazaki et al., Phys. Lett. B 687 139-143 (2010).
14. D. Atwood, M. Gronau, A. Soni, Phys. Rev. Lett.79, 185 (1997).
15. D. Atwood, T. Gershon, M. Hazumi, A. Soni, Phys. Rev. D71, 076003 (2005).