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Flavor physics at Super B-factories era

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Abstract. We review numerous results from the B-Factories, obtained last decade. They provide currently strong constraints on New Physics extensions beyond the Standard Model. We discuss the physics program at Super B-factory, a next generation asymmetric collider with the luminosity almost two orders of magnitude higher than those achieved at the existing colliders, and its capability in cooperation with LHC of new insights into New Physics phenomena.

1. Introduction

Up to now the Standard Model (SM) of the particle physics remains one of the best experimentally verified theories. For almost 50 years since its establishment the SM managed to overcome all experimental tests and precisely describes all processes in a wide energy range up to the scale probed at energy frontier experiments at LHC. Moreover, the SM predicted the existence of new processes not only in particle physics but also in cosmology and astrophysics. The observation by Atlas and CMS of the Higgs boson [1], the last fundamental particle of the SM, that escaped the detection for decades, marked a triumph of the Standard Model. Furthermore, by now LHC confirmed measured properties of Higgs boson are consistent with the SM expectations.

Despite the great success in describing the matter and forces of nature, the SM persists to remain a not complete theory. First of all, it is more a theoretical framework built from experimental observations rather than a fundamental theory based on the first principles. Furthermore, it fails to resolve intrinsic problems, such as instability of the fundamental weak scale against radiative corrections, and remains unanswered many fundamental questions, such as origin of gauge groups, fermion masses and mixing hierarchy etc. These suggest that the SM is only an effective theory, which does not remain valid up to an arbitrarily high energy scale. On the contrary, it is widely believed that the New Physics (NP) beyond the SM can be observed at precision or energy frontier experiments in the near future.

The quark sector of the SM is especially rich in puzzles and the largest contributor in terms of number of free parameters. The measuring of quark mixing parameters provides a major test of the Cabibbo-Kobayashi-Maskawa (CKM) description of flavor changing currents and CP violation [2]. Although CKM mixing does provide a source for CP violation – one of the Sakharov's conditions for the Universe evolution [3], the magnitude of the matter-antimatter asymmetry cannot be explained by the CKM mechanism only. This may indicate that some hidden mechanism resulting at larger CP violation exists at higher energies. Flavor Physics is a promising tool for NP searches through quantum loop effects. Rare decays, neutral meson-antimeson mixing and CP violation are potentially subjected to NP virtual corrections.

2. Future Flavor experiments

The major information about CKM matrix is obtained in B meson study, thus providing the stringent test of the CKM mechanism. Carrying out these studies was the main motivation for construction of two B-Factory experiments, Belle and BaBar. Since 1999 both experiments have performed many precise and *independent* measurements of the CKM parameters. The underlying idea was to check the overall consistency of the CKM framework; any discrepancy between measurements could be interpreted as potential NP effects. While with the current precision of data no significant deviations were found, it was demonstrated that Flavor Physics is indeed sensitive to TeV scale effects.

Future experiments are scheduled to address open questions and perform more precise tests:

- At LHC the main contributor into flavor studies is LHCb experiment with luminosity $2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponding the $B\overline{B}$ production rate 10^{12} per year.
- Two projects of asymmetric energy e^+e^- collider to operate at the $\Upsilon(4S)$ resonance, Super KEKB (Japan) and SuperB (Italy), were elaborated, but only the first one survived.
- BEPCII charm factory and discussed Super-c-tau factory will perform searches for NP in charm sector and provide complimentary information required for B physics.

Together with possible direct observation of NP at LHC, these experiments can help to uncover its flavor structure. Furthermore, even if nothing will be found at LHC, the Flavor experiments still have a chance to discover NP, thus perform an important role in the particle physics program.

2.1. Advantages of Super B-factory

Although LHCb experiment successfully started data taking and produced by now many excellent results in B physics, there are strong arguments to push for the next generation of unprecedented high luminosity e^+e^- machine, Super KEKB. The number of produced and triggered $B\overline{B}$ pairs at LHCb exceeds those expected at Super KEKB, however e^+e^- machine provides very clean environment and minimal trigger bias, which is essential for many important observables. Belle II experiment at Super KEKB has advantages in a study of the decays that involve reconstruction of photons and K_L, which are the key modes for many measurements. Even more important are neutrino modes, such as $B\to\tau\nu$, $B\to D^{(*)}\tau\nu$, $B\to K^{(*)}\nu\bar{\nu}$. They probe charged Higgs and SUSY and can be studied at e^+e^- machines only. The measurement of $|V_{ub}|$ through the decay $b\to u\ell^+\nu$ is also important task to constrain the CKM mechanism.

The flavor tagging is more efficient at Super B-Factory which compensates lower production rate in indirect CP violation studies. The high reconstruction efficiency and low trigger bias help to reduce substantially systematic uncertainties in many types of measurements, such as Dalitz analysis. At last, e^+e^- machine allows to accumulate huge statistics of $\tau^+\tau^-$ data.

Evidently, Super B-Factory has a complementary physics program, and is required in addition to LHCb to cover fully the flavor sector. We illustrate methods to measure the key observables using Belle results, and extrapolate the sensitivity for Belle II. The target SuperKEKB luminosity is $8\times10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, corresponding to $50\,\mathrm{ab}^{-1}$ data sample accumulated within 5 years of operation.

3. Unitarity Triangle measurements at Super B-factory

The unitary relations of the CKM matrix can be represented as Unitarity Triangles (UT) in the complex plane. One of these triangles, that visualizes the relation between the first and third columns of the CKM matrix, $V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0$, is the most important for CP violation studies in B_d decays. Many important results described below can be depicted as constraints in this UT. The main questions addressed to these measurements: are the measured angles consistent with sides? are the angle from loop and tree decays consistent? By now the consistency is good, but the present accuracy can not excludes the NP effects at 1% level.

3.1. β from $B^0 \to (c\bar{c})K^0$ decays

The most precise determination of the angle β is provided by the measurement of the mixing-induced CP violation in $B^0 \to (c\bar{c})K^0$ decays:

$$A_{CP}(\Delta t) = \frac{N(\overline{B}^0 \to (c\bar{c})K^0) - N(B^0 \to (c\bar{c})K^0)}{N(\overline{B}^0 \to (c\bar{c})K^0) + N(B^0 \to (c\bar{c})K^0)} = \sin 2\beta \sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t)\,. \quad (1)$$

These modes are dominated by the $b \to c\bar{c}s$ tree diagram. The penguin contribution has the same weak phase within few per cent accuracy, which makes direct CP violation vanishing to a very good approximation. Besides theoretical clarity, these channels also offer experimental advantages because of the large branching fractions and the presence of narrow resonances in the final state, which provides a powerful suppression of combinatorial background.

The most precise determination of mixing-induced CP violation in $B^0 \to (c\bar{c})K^0$ decay was provided by Belle [4]. Figure 1 shows time-dependent asymmetries for both CP-odd and CP-even final states at Belle. The sign of the asymmetry for opposite CP eigenvalues is flipped, as expected. The measured parameters, $\sin 2\beta = 0.667 \pm 0.023 \pm 0.012$ and $A = 0.006 \pm 0.016 \pm 0.012$, are consistent with the SM expectations, in particular with zero direct CP violation. It is expected that similar reconstruction and flavor tagging efficiencies, and similar vertex resolution will be achieved by Belle II. As the systematic errors are well under control using the control samples, they are expected to scale with statistics. Belle II can achieve accuracy of 0.3° [5] in measurement of β, which will provide a solid reference point to search for evidence of NP.

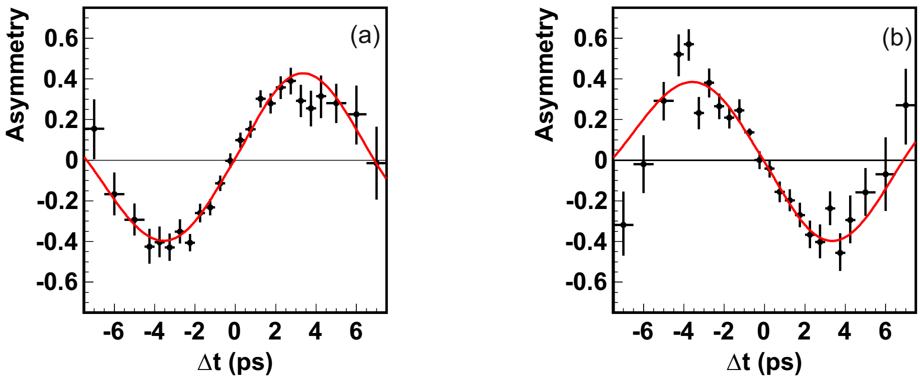

Figure 1. The asymmetry for all CP-odd modes (a) and the CP-even mode (b) at Belle.

3.2. Measurement of the angle α

The angle α can be determined from a time-dependent CP asymmetry in charmless $b \to u\bar{u}d$ decays. The weak decay phase of $b \to u$ transition (figure 2a) is related to V_{ub}, thus CP asymmetry in a pure $b \to u$ modes is equal to $\sin 2\alpha$. However, a penguin diagram (figure 2b) contributes with a different phase. This causes a deviation of the magnitude of indirect CP asymmetry from $\sin 2\alpha$ and a non-zero direct CP asymmetry. Following the idea of M. Gronau and D. London [6] the angle α is extracted using the isospin relation among branching fractions and CP asymmetries of $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$, and $B^+ \to \pi^+\pi^0$ decays. The method allows to constrain the contribution from the penguin amplitude generally with an eight-fold ambiguity.

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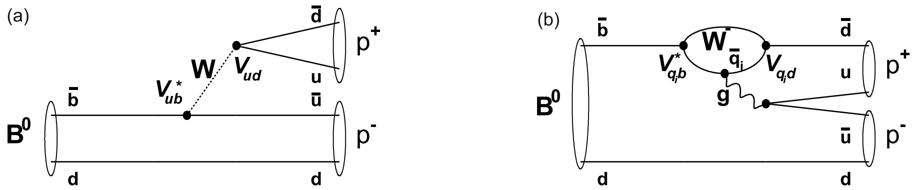

Figure 2. Feynman diagrams for $B^0 \to \pi^+\pi^-$ decays.

The decay $B \to \pi\pi$ has the simplest two-body topology, however, the large observed direct CP violation, and large branching fraction for $B^0 \to \pi^0\pi^0$ [7] suggest that penguin contribution to this final state is large, thus complicating the extraction of α. Using the full data set Belle measured the CP asymmetry in $B^0 \to \pi^+\pi^-$ quite precisely [8]: $A = 0.33 \pm 0.06 \pm 0.03$ and $S = -0.64 \pm 0.08 \pm 0.03$ (the world's most precise measurement!), but, because of trigonometrical ambiguities in extraction of α this mode allows only to exclude some intervals (figure 3, red line).

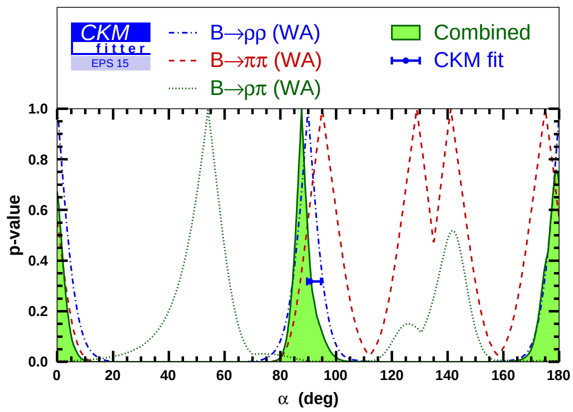

Figure 3. Difference $1 - CL$ for a range of α from $\pi\pi$, $\rho\rho$ and $\rho\pi$ analyses as averaged by CKMfitter Group [10].

We are lucky to get much higher sensitivity in α from the $B \to \rho\rho$ decays, where the penguin contribution turns out to be small. While this final state is more difficult for experimental study because of two wide vector mesons in the final state, it provides in the moment the best constrain on α (figure 3, blue line). Determination of α is also possible using the decays $B \to \pi\rho$, in spite of the final state is not CP eigenstate. The measurement of four isospin amplitudes is required which leads to 12 unknowns in the isospin pentagon. The problem is simplified and (what is more important) the ambiguity introduced by geometry of isospin triangles is removed with the time-dependent Dalitz analysis of the $B^0 \to (\pi\rho)^0$ decays. Belle performed such study using part of the available data and obtained the constraint $68° < \alpha < 95°$ at 68% CL [9].

The current world average of α including measurements of these three modes from Belle and BaBar, $(87.6^{+3.5}_{-3.3})°$ [10], is quite precise (figure 3). The α measurements necessarily involve neutral modes, thus LHCb can hardly improve the accuracy solely. On the contrary, Belle II can reduce significantly the α errors as they are predominantly reducible. The expected accuracy is better than $2°$ using the $\pi\pi$ and $\rho\rho$ modes with $50\,\mathrm{ab}^{-1}$ data (though with two-fold ambiguity) [5]. Even better precision ($\sim 1°$) with a single solution can be achieved with $\pi\rho$ mode.

3.3. Measurement of the angle γ

The angle γ relies on the measurement of direct CP violation in $B^+ \to D^0 K^+$ decays caused by interference between the two amplitudes with different CKM phases (figure 4). The interference

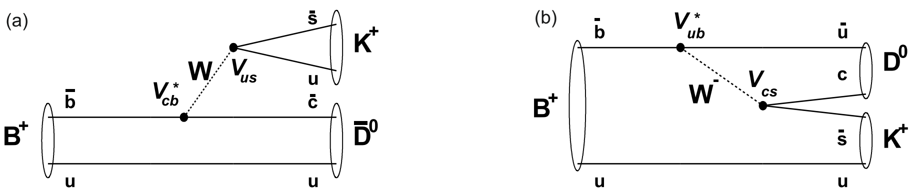

Figure 4. Feynman diagrams for $B^+ \to D^0 K^+$ decays.

appear only if both D^0 and $\overline{D}^0$ mesons decay to a common final state. The method is theoretically clean due to absence of loop contributions. However, the color suppressed amplitude (figure 4b) is a factor of ~ 10 smaller, hence resulting in a small CP asymmetry. There are three methods to measure γ: GLW method [11] uses D^0 decays in CP-eigenstates like K^+K^-; ADS method [12] is based on doubly-Cabibbo suppressed decays like $D^0 \to K^+\pi^-$; GGSZ method [13] is based on a Dalitz analysis of three body D^0 decays such as $D^0 \to K_S\pi^+\pi^-$.

The GGSZ method provides the highest statistical power. Here the amplitude for $B^\pm \to D^0(K_S\pi^+\pi^-)K^+$ decay as a function of Dalitz plot variables $m^2_\pm = m^2(K_S\pi^\pm)$ is given by

$$f_{B^\pm} = f_D(m^2_\pm, m^2_\mp) + r_B e^{\pm\gamma + i\delta} f_D(m^2_\mp, m^2_\pm), \tag{2}$$

where $f_D(m^2_+, m^2_-)$ is the amplitude of the $D^0 \to K_S\pi^+\pi^-$ decay, r_B is two amplitudes ratio, and δ is a strong phase difference. Once f_D is fixed, a simultaneous fit to $B^\pm$ data allows to extract γ, r_B and δ separately. The f_D can be determined from a large sample of flavor-tagged $D^{*+} \to D^0\pi^+$ decays produced in e^+e^- annihilation. However, with this approach the description of f_D is based on a model, that includes interfering resonances in $K_S\pi^+$, $K_S\pi^-$ and $\pi^+\pi^-$ systems. Using GGSZ method with a model-dependent f_D description Belle's measurement [14] yielded $\gamma = (78.4\,^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$, where the last error comes from the model uncertainty.

While the statistical errors of GGSZ method will be reduced with increased data sample at Super KEKB, the accuracy will be still limited by the model uncertainty. The new approach was tested by Belle [15] to fight this seeming irreducible limitation of the method. Instead of using parametrized f_D function, Belle substituted the Dalitz plot distribution taken directly from the data obtained by CLEO [16] from the decays of quantum-correlated $D^0\overline{D}^0$ pairs produced in the $\psi(3770)$. Belle obtained $\gamma = (77.3\,^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$, where the last error is due to limited precision of CLEO sample. The large model uncertainty is replaced by purely statistical error of CLEO data, which in future can be reduced with the BESIII or Super-c-tau factory data.

The model-independent approach offers an perspective course for studies at Belle II and LHCb. Here the final state is charged and LHCb has an advantage of larger statistics, while Belle II will contribute to the improved systematics. The expected accuracy at Belle II is 2° [5].

3.4. UT summary

Belle and BaBar performed a plenty of analysis to constrain the UT sides as well. The most important Belle II contribution is to constrain V_{ub} from the $b \to u\ell^+\nu$ studies. To improve the accuracy here the contribution from theory, in particular from the lattice QCD, is also critical.

The present status of the UT studies is illustrated with figure 5 produced by the CKMfitter group [10]. Each colored band corresponds to a different kind of process, and looking closely we can see quite nice agreement between independent constrains. Thanks to Belle, BaBar and

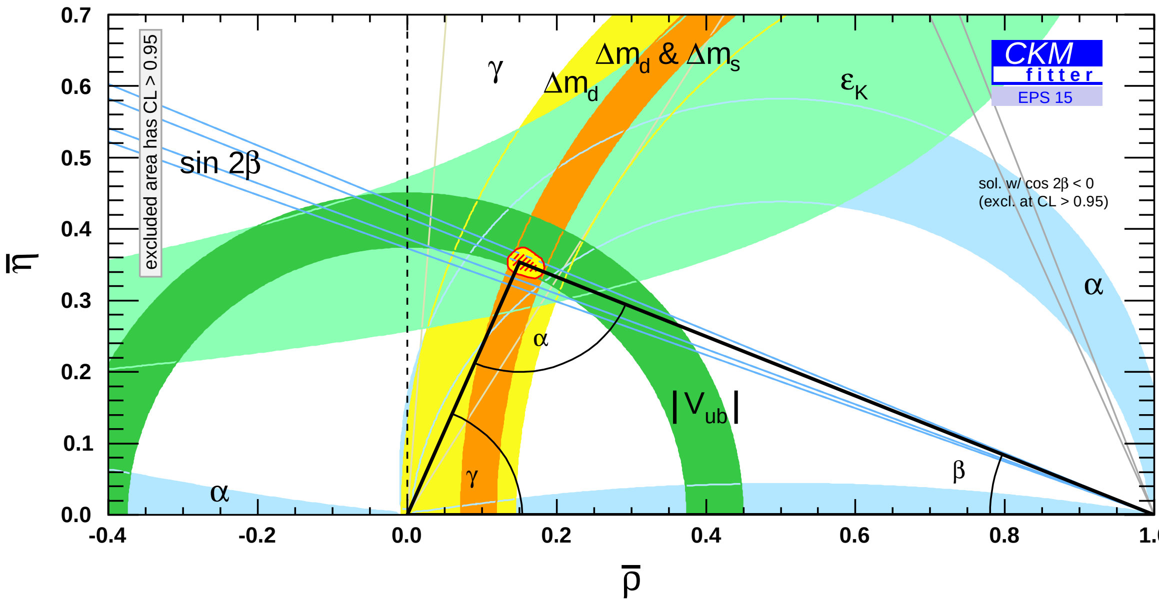

Figure 5. Constraints on the UT as compiled by CKMfitter group [10].

LHCb the square of allowed area for the UT upper apex position is reduced by two order of magnitudes compared to the pre B-factory era. Almost the same factor of improvement in precision is expected after joint efforts of LHCb and Belle II, which hopefully reveals the inconsistency and indicates on NP effects.

4. *CP* violation in penguin dominated modes

It is widely believed that B penguin decays can serve as one of the most sensitive probe for NP due to possible non-SM contribution (*e.g.* from SUSY) in the loop diagram. In particular, manifestations of NP contribution in the penguin modes can be revealed as deviations of CP violation parameters from the SM expectations. In $b \to s\bar{s}s$ hadronic decays the SM weak phase is the same as in the $B^0 \to (c\bar{c})K^0$ transition. Therefore, the main task is to check whether the penguin CP violation parameter $\beta^{\rm eff}$ is equal to β, and the direct CP violation is absent ($A = 0$). The SM corrections to these relations are expected to be very small, $\sim 1\%$.

Earlier Belle CP measurements in $B^0 \to \phi K_S$ [17] showed an exciting $3.5\,\sigma$ deviation of $\beta^{\rm eff}$ from β. The later update [18] showed already quite good but disappointing agreement. Now all penguin modes agree well with the SM expectations, and the precision of $\sin 2\beta^{\rm eff}$ is still statistically limited, typically $0.1 - 0.2$ for different mode. The most precise measurement is obtained with $B^0 \to \eta' K_S$ decay. Obtaining of 1% level sensitivity which provides already a real probe for the NP requires studies at Super KEKB and LHCb. Again, because of a photon in the final state, Belle II has an advantage over LHCb to achieve better sensitivity in $B^0 \to \eta' K_S$.

5. Rare *B* decays

Precise measurements of rare decays, *i.e.* processes suppressed in the SM, are sensitive to NP at scales exceeding those achievable at LHC. This is demonstrated by the following studies involving both loop and tree decay diagrams.

5.1. Radiative penguin decays

The dominant SM contribution to $b \to s\gamma$ decays is from a loop involving the t-quark and W^+. The measurement of inclusive $\mathcal{B}(b \to s\gamma)$ gives access to the value of V_{ts}, but, what is more important, provides a tool to search for and constrain physics beyond the SM. Indeed, the SM particles in the loop may be replaced by hypothetical particles such as charged Higgs or SUSY particles resulting in observable deviation of the decay rate.

The inclusive $b \to s\gamma$ rate suffers from the minimal theoretical uncertainty. The SM $\mathcal{B}(b \to s\gamma)$ is calculated including NNLO corrections with a $\sim 7\%$ precision. Ideally, the inclusive photon spectrum should be measured over the entire energy range, but practically, its lower part is hardly accessible due to insurmountably large background. The world average for $E_\gamma > 1.6\,\text{GeV}$, $\mathcal{B}(b \to s\gamma) = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$ [20], is consistent with the theoretical prediction, and have been used to constrain NP scenarios, *e.g.*, the charged Higgs is bounded from this measurement to be heavier than 295 GeV. At Belle II one could expect a measurement of $\mathcal{B}(b \to s\gamma)$ with a relative accuracy of 6% [5], which matches the anticipated precision of the theoretical predictions. Belle II can also measure $\mathcal{B}(b \to d\gamma)$ with $\sim 25\%$ accuracy that can serve to check consistency of the $|V_{td}/V_{ts}|$ value obtained in this measurement and in the ratio of B_s and B_d mixing strengths.

5.2. $B \to \tau\nu$

The pure leptonic $B \to \tau\nu$ decay is sensitive to the NP including the SM extensions with charged Higgs, that could significantly suppress or enhance the branching ratios for these decays. Experimentally it is a real challenge to identify modes with τ lepton due to multiple neutrinos in the final state. At the (Super) B-factories, the exclusive production of a B meson pair with no extra particles allows to tag the signal decay by reconstruction of all particles originating from the accompanying B meson. Using the hermecity of the detector it is possible to identify the signal as absence of the energy deposited in the detector not associated with the tag and signal particles (see figure 6). This mode is hardly accessed at LHCb.

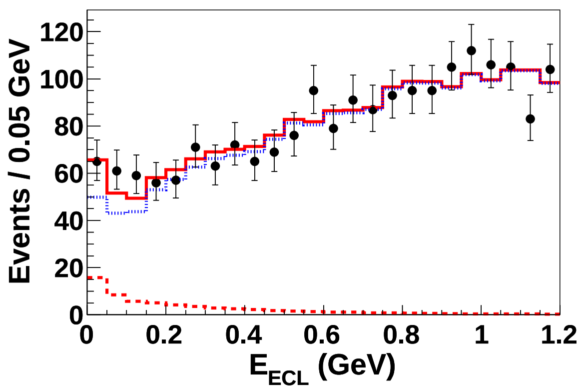

Figure 6. Distributions of deposited energy in the electromagnetic calorimeter at Belle for $B \to \tau\nu$ candidates [21]. The signal is seen as an excess of events with low energy deposition.

The first evidence for $B \to \tau\nu$ was reported by Belle [21] in 2006 and now Belle can see this decay with a $4.6\,\sigma$ significance [22]. The measured by Belle branching ratio with hadronic and semileptonic tag, $\mathcal{B}(B \to \tau\nu) = (0.91 \pm 0.19 \pm 0.11) \times 10^{-4}$ [22], sets constraints on the parameters of various models involving charged Higgs bosons. For large $\tan\beta$ the excluded region are more stringent than those obtained from the direct searched at LHC. At Belle II accumulation of luminosity helps to reduce both statistical and systematic errors by a factor of ~ 7 and bound further the constrain on the charged Higgs mass provided that the SM calculations will be also improved with the help of lattice QCD.

5.3. Semileptonic decays with τ

The SM predicts $B \to D^{(*)}\tau\nu$ branching fractions to be $\gtrsim 1\%$, *i.e.* strictly speaking these modes are not rare. The results are usually presented in terms of $R(D^{(*)}) \equiv \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu)$, which is independent of the V_{cb} and form factor parameterization and can be compared with the SM expectations.

The decays $B \to D^{(*)}\tau\nu$ are observed now at Belle and BaBar with high significance, and their $R(D^{(*)})$ values are consistent [23]. Recently LHCb also reported the measurement of $R(D^{*+})$. The world averaged results, $R(D^*) = 0.322 \pm 0.018 \pm 0.012$ and $R(D) = 0.391 \pm 0.041 \pm 0.028$, show a $3.9\,\sigma$ disagreement with the SM [20]. It is worth to mention that they also disfavor the type II two-Higgs doublet model. With larger statistics of Super KEKB besides the improved accuracy of $R(D^{(*)})$ ($\sim 2\%$), the q^2 and the angular distributions of the τ and $D^{(*)}$ decays could also provide useful information for testing the SM and constraining NP models.

6. Conclusion

The Belle II experiment has an important mission to search for NP in the flavor sector exploiting a huge jump in luminosity and a plenty of independent measurements. If the NP will be observed at LHC before the start of Belle II, the flavor sector of NP still need to be constrained, which is only possible with both LHCb and Super B-factory complimentary programs. The Belle II experiment has a broad physics program uncovered by LHCb, as many important measurements can not be made at hadronic machines.

The SuperKEKB commissioning will start in 2016 while the construction of the Belle II detector is ongoing and expected to start data taking 2017. The aim of the Belle II project is to accumulate $50\,\text{ab}^{-1}$, corresponding to about 55 billion $B\overline{B}$ pairs by the year 2023. The projected sensitivities with this data are below 1° for β, and $\sim 1^\circ$ for α and γ. The accuracy in CP violation studies, branching fractions and kinematics characteristics in rare B decays will be also improved by an order of magnitude. The examples described above are only a small part of possible measurements to be performed with the Belle II experiment. A more detailed overview can be found in Ref. [5].

Acknowledgments

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