Overview of flavor physics results at Belle

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Abstract. We will present recent topics of the flavor physics in decays of the heavy mesons at the Belle experiment. Most of the results are based on a full data set which corresponds to 772 million $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy e^+e^- collider. We also discuss about prospects of the studies in the future B-factory experiment.

1 Introduction

Measurements of various B meson decays induced by interactions of flavor such as CP violations, decay rates with high precision give hints to the new physics beyond the Standard Model (SM). To investigate the difference between several decay modes or deviation from theoretical predictions in the SM with a large statistic data sample will be a good probe to find a tiny effect from the new physics. In this scheme, we can access to the phenomena that appears in a very high energy scale and this analysis scheme is so called a luminosity frontier. In this report, we review recent progress in the Belle experiment.

The results reported herein are based on a data sample containing 772×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector [1] at the KEKB asymmetric energy e^+e^- (3.5 on 8.0 GeV) collider [2]. The Belle detector consists of six types of sub-detectors: a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), a CsI(Tl) crystal-based electromagnetic calorimeter (ECL), and a multilayer structure of resistive plate counters and iron plates to detect K_L mesons and muons (KLM). All the sub-detectors except for the KLM are located inside a 1.5 T solenoidal magnetic field. Two inner detector configurations were used: a 2.0 cm beampipe and a three-layer SVD were used for the first sample of $152 \times 10^6 B\bar{B}$ pairs, while a 1.5 cm beampipe, a four-layer SVD and a small-cell CDC were used to record the remaining $620 \times 10^6 B\bar{B}$ events [3]. The latter sample has been reprocessed with an improved track reconstruction algorithm, which significantly increased the signal reconstruction efficiency especially in the decay modes in which low momentum charged particles are appeared in the final states.

Using information collected with the Belle detector such as particle momentum, charge, energy and so on, we reconstruct the B^0 meson with decay products. We identify B candidates using two kinematic variables: the beam-energy constrained mass, $M_{\mathrm{bc}} \equiv \sqrt{E_{\mathrm{beam}}^2 - |\sum_i \vec{p}_i|^2}$, and the energy difference, $\Delta E \equiv \sum_i E_i - E_{\mathrm{beam}}$, where E_{beam} is the beam energy, and $\vec{p}_i$ and E_i are the momentum and

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energy, respectively, of the i-th daughter of the reconstructed B candidate in the e^+e^- center-of-mass (CM) frame. Signal events typically peak at the nominal B-meson mass for $M_{\rm bc}$ and at zero for ΔE. The dominant background arises from the $e^+e^- \to q\bar{q}$ continuum process, where q denotes u, d, s or c. To suppress this background, we employ continuum suppression variables calculated from shape variables of the B decays. We finally perform a fit with these variables to extract target physics parameters in each decay mode to enhance the signal reconstruction efficiency and background rejection.

2 CP Violation

Measurements of the CP violation in the B meson decays are one of the main target in the B-factory experiment and they achieve great breakthrough in measurements of the parameters such as angles of an unitary triangle of the Cabbibo-Kobayashi-Maskawa (CKM) matrix which describe transition in the quark sector. In the Kobayashi-Maskawa theory [4] in which the quark-mixing matrix has a single irreducible complex phase that gives rise to all CP-violating asymmetries. In the decay sequences $\Upsilon(4S) \to B^0\bar{B}^0 \to f_{CP}f_{\rm tag}$, where one of the B mesons decays at time t_{CP} to a CP eigenstate f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\bar{B}^0$, the decay rate has a time dependence given by

$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big[1 + q \cdot \big[S_f \sin(\Delta m_d \Delta t) + A_f \cos(\Delta m_d \Delta t)\big]\Big]. \tag{1}$$

Here, S_f and A_f are parameters that describe mixing-induced and direct CP violation, respectively, τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t = t_{CP} - t_{\rm tag}$, and the b-flavor charge, $q = +1(-1)$ when the tagged B meson is a $B^0(\bar{B}^0)$. At the KEKB asymmetric-energy e^+e^- collider [2], $\Upsilon(4S)$ is produced with a Lorentz boost. Since B^0 and $\bar{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (CM), the Δt can be determined from the displacement between the f_{CP} and $f_{\rm tag}$ decay vertices along flight direction of $\Upsilon(4S)$, $z : \Delta t \simeq (z_{CP} - z_{\rm tag})/(\beta\gamma c) \equiv \Delta z/(\beta\gamma c)$. Since most of the CP eigenstates are not flavor-specific, q is determined using the information of $f_{\rm tag}$ such as flavor of charged lepton, high momentum kaon and low momentum pion from D^* decay.

Decays $B^0 \to (c\bar{c})K^0$ induced by the $b \to c\bar{c}s$ quark transition are referred to as "golden modes" since these are clean both experimentally and theoretically due to relatively large branching fractions and small background contamination [5]. A color-suppressed tree diagram is a dominant contribution of these mode and $S_f = -\xi_f \sin 2\phi_1$ is predicted in a good approximation in the SM, where $\xi_f = +1(-1)$ corresponds to CP-even (-odd) final states and ϕ_1 is an angle of the unitary triangle defined using CKM matrix elements: $\phi_1 = \arg(V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$. On the other hand, decays induced by the $b \to sq\bar{q}$ ($q = u, ds$) transitions are also th CP-eigenstates of the ϕ_1 but the Feynman diagram so called "penguin diagram" contains a loop so that they are sensitive to the contribution of the new physics. Consequently, search for the extra-CP phase from the new physics is done through the precise measurement of the phi_1 in several B decays.

Among such decays, we recently release the new result in the $B^0 \to \omega K^0$ decay [6]. Figure 1 and 2 are the reconstructed kinematic variables and decay time difference distributions, respectively. From these, we obtain the result $\sin 2\phi_1 = 0.91 \pm 0.32 \pm 0.06$. The statistical uncertainty is still large but evidence of the CP-violation is seen with the significance of 3.1σ. This is consistent with the SM expectation from the precise measurement in decays $B^0 \to (c\bar{c})K^0$ and other decay modes which is induced by the $b \to sq\bar{q}$ penguin process.

$\phi_2(= \arg(V_{ud}V_{ub}^*/V_{td}V_{tb}^*))$ is measured using the decays which induced by $b \to u\bar{u}d$ tree diagram. However, there is contamination from an extra-CP phase in the measured variable due to the $b \to u\bar{u}d$

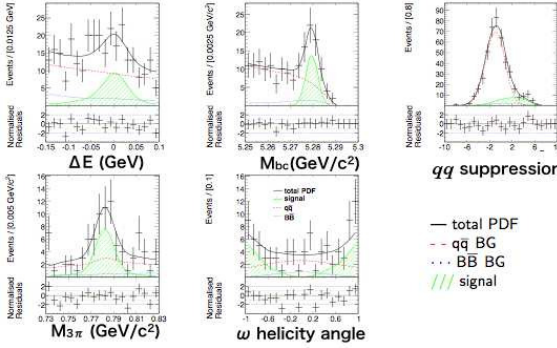**Figure 1.** Reconstructed variables of $B^0 \rightarrow \omega K$: ΔE (top left), M_{bc} (top middle), $q\bar{q}$ suppression (top right), invariant mass of 3π (bottom left) and helicity angle (bottom right) of ω candidates. The solid lines show the fit result of signal extraction, dashed lines for $q\bar{q}$, dotted lines for $B\bar{B}$ background and shaded region for signal.
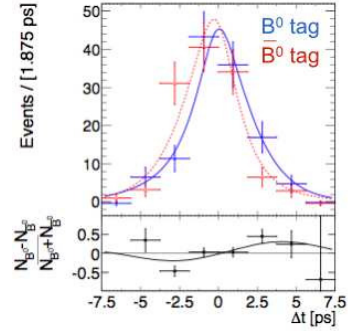
Figure 2. Δt distribution and CP asymmetry of ωK^0.

penguin diagram. To determine the ϕ_2 without the extra-phase, several techniques are developed for data analysises in the B decays. Using the isospin relations among the decay amplitudes of $B \rightarrow \pi\pi$ system, the extra-phase is determined with the four-fold ambiguity [7]. We have measured them in the $B^0 \rightarrow \pi^+\pi^-$ [8] and $B^+ \rightarrow \pi^+\pi^0$ [9] precisely with the full data set. Preliminary result of $B^0 \rightarrow \pi^0\pi^0$ is recently obtained with the full data set and new analysis technique using the ECL timing information to remove background. Figure 3 shows the distribution of reconstructed variables for the signal identification. We obtain the branching fraction $\mathcal{B}(B^0 \rightarrow \pi^0\pi^0) = (0.90 \pm 0.12 \pm 0.10) \times 10^{-6}$ with the significance of 6.7σ and the direct CP asymmetry $A_{CP} = -0.054 \pm 0.086$. With this result, the constraint to the ϕ_2 using the isospin relation in the $B \rightarrow \pi\pi$ system will be reevaluated.
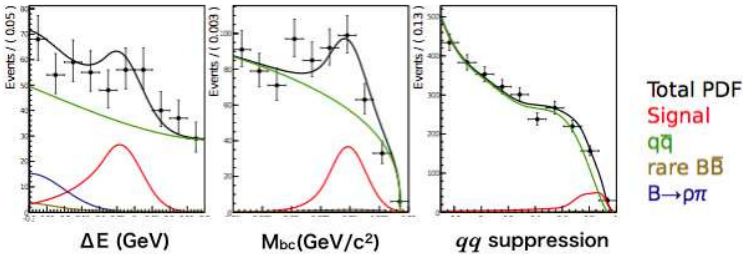

Figure 3. Reconstructed variables of $B^0 \rightarrow \pi^0\pi^0$: ΔE (left) M_{bc} (center) and continuum suppression (right).

Non-zero CP violation is expected from the contribution of new physics in decays induced by the $b \rightarrow s\gamma$ penguin transition such as the decay of $B \rightarrow X_s\gamma$, where the X_s is a meson with a s-quark. In theoretical expectations, uncertainty arise due to the long-range strong interaction. However, it cancels

when performing a combined analysis for the final-states of the X_s and X_d [10]. Figure 4 shows the distribution of the energy of the photon in the decay candidates that are reconstructed inclusively. We obtain the preliminary result $A_{CP} = (2.2\pm4.0\pm0.8)\times10^{-2}$ for the signal enhanced region of $E_\gamma^{CM} > 2.2$ GeV where E_γ^{CM} is an energy of the γ from the B in center-of-mass (CM) system in the e^+e^- collision. This is consistent with zero which is expected from the SM.

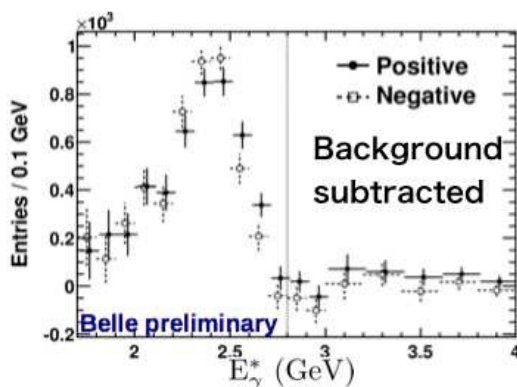**Figure 4.** Energy distribution of $B^0 \to X_{u,d}\gamma$ candidates. Filled circles with solid lines show that of the B^0/B^+ tagged candidates and open circles with dashed lines are that for the B^0/B^+ tagged ones.

3 Branching fraction measurements

Signal from the new physics is also expected to be appeared in the decay rates, especially in the mode which is induced by the diagram with a loop.

Among such decay modes, the decay $B \to X_s\gamma$ is good probe to test the theoretical estimation with the next-next-leading-order (NNLO) and the branching fraction is expected to be $\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23)^{-4}$ for $E_\gamma^{CM} > 1.6$ GeV [11]. To identify the X_s, there are several analysis approaches: full-exclusive in which single photon energy spectrum is observed, semi-inclusive in which as much as reconstructed decay mode of hadrons with s-quark are combined, and exclusive in which a specific decay mode such as $B \to K^*\gamma$ is reconstructed. Due to the QCD uncertainties in the hadronization in the initial- and final-states, a theoretical uncertainty becomes large in the exclusive approach. On the other hand, a signal purity becomes worse due to the background in the inclusive approaches. We recently update the result of the semi-inclusive analysis using 38 X_s decay modes in the invariant mass range of 0.6 GeV $< M_{X_s} <$ 2.8 GeV/c^2 by combinations of the K, π and η which corresponds to about 70% of the total X_s decays. Figure 5 shows the partial branching fraction as a function of the X_s mass. From this data sample, we obtain the branching fraction $\mathcal{B}(B \to X_s\gamma) = (3.74 \pm 0.39) \times 10^{-4}$ and this is consistent with the SM expextation.

In charmless hadronic B decays, loop appears in the penguin diagram with the first order of the decay process and its effect is appeared in the branching fraction, polarization, direct CP violation and so on. We recently report the branching fraction measurements in $B^+ \to \bar{K}^*(892)^0K^*(892)^+$ induced by the $b \to d$ penguin and $B^0 \to \eta'K^*(892)^0$ induced by the $b \to s$ penguin.

In the $B^+ \to \bar{K}^*(892)^0K^*(892)^+$ decay, a longitudinal polarization of the B decay to two vector meson state f_L is also measured to validation of the SM in which $f_L \simeq 1$ is expected from
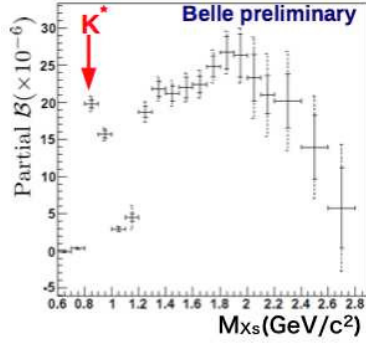
Figure 5. The partial branching fraction as a function of M_{X_s} in $B^0 \to X_s \gamma$ candidates in semi-inclusive reconstruction.

the QCD. Figure 6 shows the fit result to the seven-dimensional variables. From this, we obtained the branching fraction $\mathcal{B}(B^+ \to \bar{K}^*(892)^0 K^*(892)^+) = (0.77^{+0.35}_{-0.30} \pm 0.12) \times 10^{-6}$ and polarization $f_L(B^+ \to \bar{K}^*(892)^0 K^*(892)^+) = 1.06 \pm 0.30 \pm 0.14$, where the significance of the non-zero branching fraction is 2.7σ.

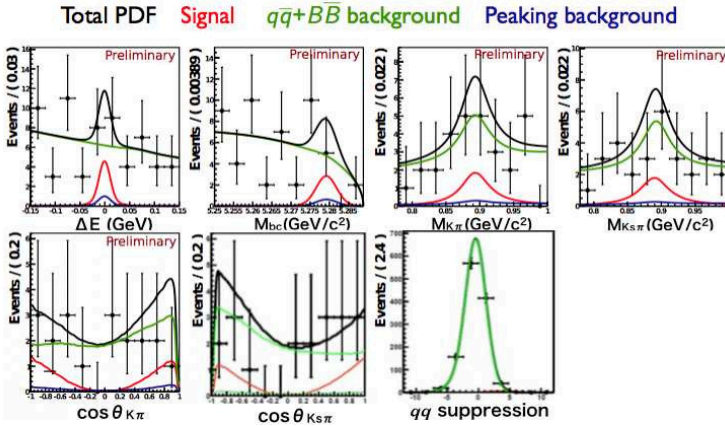**Figure 6.** Reconstructed variables for $B^+ \to \bar{K}^*(892)^0 K^*(892)^+$ identification, points with error bars is the data distribution and lines are the fit results: ΔE (top left), M_{bc} (top second from left), $M_{K\pi}$ (top third from left), $M_{K_S\pi}$ (top right), $\cos(K\pi)$ (bottom left), $\cos(K_S\pi)$ (bottom middle) and $q\bar{q}$ suppression (bottom right).

In the $B^0 \to \eta' K^*(892)^0$ decay, a large CP violation is expected from the interference of $b \to s$ penguin and $b \to u$ tree diagrams and an evidence is seen in the $B^0 \to \eta K^0$ decay, in which same interference is considered, in both of the Belle and BABAR [12, 13]. We recently release the result of $B^0 \to \eta' K^*(892)^0$ decay. Figure 7 shows the fit result for the four-dimensional variables to extract the signal yield. From the extracted signal, we obtain the branching fraction $\mathcal{B}(B^0 \to \eta' K^*(892)^0) =$

$(2.6 \pm 0.7 \pm 0.2) \times 10^{-6}$ and direct CP violation $A_{CP}(B^0 \rightarrow \eta' K^*(892)^0) = -0.22 \pm 0.29^{+0.02}_{-0.03}$, where the significance of the branching fraction measurement including the systematic uncertainty is 5.0σ [14].

All of the results of charmless hadronic B decays are consistent with the SM expectations and world averages.
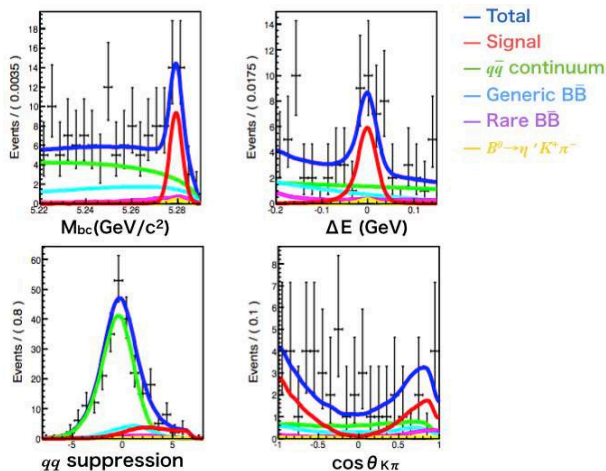

Figure 7. Reconstructed variables for $B^0 \rightarrow \eta' K^*(892)^0$ identification, points with error bars is the data distribution and lines are the fit results: M_{bc} (top left), ΔE (top right), $q\bar{q}$ suppression (bottom left) and $\cos(K\pi)$ (bottom right).

4 CKM matrix elements

In the semi-leptonic decay $B \rightarrow \bar{D}^{(*)} \ell \nu$ induced by the $b \rightarrow c \ell \nu$ tree diagram exchanging W boson, a CKM matrix element V_{cb} is measured from the differential decay width for kinematic variables w, inner product of the B and D velocities. However due to the initial- and final-state hadronization, measured variable includes a form factor. We recently update the result of semi-inclusive analysis in which $\bar{B}^0 \rightarrow D^+ \ell \nu$ with seven D^+ decay modes and $B^- \rightarrow \bar{D}^0 \ell \nu$ with eight $\bar{D}^0$ modes is reconstructed to reduce the uncertainty from the form factor. We measure the signal yields from subdivided data sample respected to the w and measure V_{cb} from its spectrum. Figure 8 shows the signal extraction in a w range and spectrum of the signal yield as a function of the w. From the distribution, we obtained the results of $\eta_{EW}\mathcal{G}(1)|V_{cb}| = 42.63 \pm 0.96 \pm 1.39$ where η_{EW} is an electroweak correction and $\mathcal{G}(1)$ is a form factor. This is consistent with the world average of other measurements.

5 Summary

Using the full data sample accumulated in the Belle experiment which corresponds to the 772 million $B\bar{B}$, we have been investigating a signal of the new physics beyond the SM in various B decays. We recently release the results of the measurements in CP violation, branching fraction and so on. Most of the results are obtained with the best accuracy in the world but evidence of the new physics has not seen. We need further accuracy to access the new physics in higher energy scale from the view point
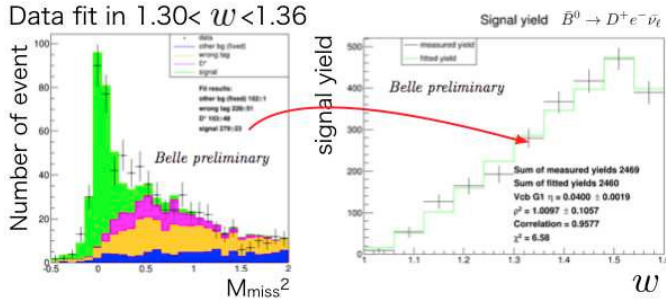
Figure 8. The M_{miss} fit result of $B \to \bar{D}^{(*)}\ell\nu$ candidates in semi-inclusive reconstruction in range of $1.30 < w < 1.36$ (left) and signal yield from the fit as a function of w.

of a flavor physics and upgrade to the super-KEKB and Belle II is ongoing now aiming for 40 times higher luminosity and improvement of the detector performance [15].

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