RECENT RESULTS FROM BELLE

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Abstract. We report about recent studies of the $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances, charged bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ and their decays at Belle. Study of the $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ with the whole Belle data sample and search for dark photon and dark Higgs boson are also briefly discussed.

1 Introduction

The Belle detector at the asymmetric energy e^+e^- collider KEKB (so called B-factory) collected the world largest data sample of about one inverse attobarn in the region of $\Upsilon(4S)$ resonance and around it [1,2]. Initially, it was designed to search for CP symmetry violation (CPV) in the B meson decays, hence the largest luminosity integral was recorded on or near the $\Upsilon(4S)$ resonance to produce B mesons via $\Upsilon(4S) \to B\bar{B}$ process. Finally, large CPV in B meson system was discovered by Belle and BaBar [3], in good agreement with Cabibbo-Kabayashi-Maskawa mechanism of CPV in the Standard Model [4]. However, Belle also recorded unique data sets at the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances. The data sample in the region of $\Upsilon(10860)$ and $\Upsilon(11020)$ resonances is of particular interest in the bottomonium spectroscopy due to the exotic charged bottomonium-like states $Z_b^\pm$ recently found in the transitions $\Upsilon(10860, 11020) \to b\bar{b}\pi^+\pi^-$ and $\Upsilon(10860) \to B^{(*)}\bar{B}^{(*)}\pi$.

2 Study of bottomonia and charged bottomonium-like states $Z_b^\pm$

Recently Belle observed anomalously large rates (by about two orders of magnitude larger than that of $\Upsilon(2,3,4\text{S}) \to \Upsilon(1\text{S})\pi^+\pi^-$) of the events $e^+e^- \to \Upsilon(n\text{S})\pi^+\pi^-$ ($n = 1, 2, 3$) at the $\Upsilon(10860)$ resonance [5]. The rates of $e^+e^- \to h_b(m\text{P})\pi^+\pi^-$ ($m = 1, 2$) were found to be of the same order of magnitude, although the $\Upsilon(10860) \to h_b(m\text{P})\pi^+\pi^-$ decay should be suppressed due to a b-quark spin-flip [6]. In the study of the dynamics of $\Upsilon(10860) \to \Upsilon(n\text{S})\pi^+\pi^-$ and $\Upsilon(10860) \to h_b(m\text{P})\pi^+\pi^-$ processes Belle discovered two new charged bottomonium-like resonances, $Z_b^\pm(10610)$ and $Z_b^\pm(10650)$, decaying to $\Upsilon(n\text{S})\pi^\pm$ and $h_b(m\text{P})\pi^\pm$ final states [7]. The measured masses of $Z_b^\pm(10610)$ and $Z_b^\pm(10650)$ are close to the thresholds of the open beauty channels $B\bar{B}^*$ and $B^*\bar{B}^*$, and their quantum numbers were unveiled to be $J^P = 1^+$ [8]. The quark structure of the decay products indicates that $Z_b^\pm$ could be interpreted as four-quark state [9–11]. Also the properties of the $Z_b^\pm$ can be naturally explained by the "molecular" structure of these states [12]. Several years ago Belle

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found $Z_b^\pm(10610)$ and $Z_b^\pm(10650)$ states in the analysis of the three-body decay $\Upsilon(10860) \to (B^{(*)}\bar{B}^*)^\mp\pi^\pm$ [13]. The dominating decay of $Z_b^\pm$ into the $B^{(*)}\bar{B}^*$ final state strongly supports the molecular hypothesis. The neutral partner of the charged $Z_b^\pm(10610)$, $Z_b^0(10610)$, has been also observed in the $\Upsilon(10860) \to \Upsilon(2\mathrm{S}, 3\mathrm{S})\pi^0\pi^0$ decay, while the statistics was not enough to resolve $Z_b^0(10650)$ [14].

Although $\Upsilon(10860)$ is usually considered as a radial exitation state of bottomonium, $\Upsilon(5\mathrm{S})$, with the quantum numbers $J^{PC} = 1^{--}$, its decay to the charged exotic states $Z_b^\pm$ and recent results of the energy scan of the $\sigma(e^+e^- \to \Upsilon(n\mathrm{S})\pi^+\pi^-)$ cross section [15] raised questions about the nature of the $\Upsilon(10860)$ state [16]. Conventionally, further we call $\Upsilon(10860)$ and $\Upsilon(11020)$ as $\Upsilon(5\mathrm{S})$ and $\Upsilon(6\mathrm{S})$, respectively.

2.1 $\sigma(e^+e^- \to \Upsilon(1S, 2S, 3S)\pi^+\pi^-)$ and $\sigma(e^+e^- \to b\bar{b})$ in the region of $\Upsilon(5\mathrm{S})$ and $\Upsilon(6\mathrm{S})$ resonances

Recent Belle result on the ratios, $R_{\Upsilon\pi\pi} = \sigma(e^+e^- \to \Upsilon(n\mathrm{S})\pi^+\pi^-)/\sigma^0_{\mu^+\mu^-}$ and $R_b = \sigma(e^+e^- \to b\bar{b})/\sigma^0_{\mu^+\mu^-}$ ($\sigma^0_{\mu^+\mu^-}$ is Born cross section of the $e^+e^- \to \mu^+\mu^-$ process), at six energy points near the $\Upsilon(5\mathrm{S})$ and $\Upsilon(6\mathrm{S})$ resonances showed inconsistency in the $\Upsilon(5\mathrm{S})$ mass of (9 ± 4) MeV/c^2 [15]. To clarify this anomaly Belle repeated this study with the whole available data sample at the center-of-mass (CM) energies, $\sqrt{s}$, between 10.60 and 11.05 GeV in the region of the $\Upsilon(5\mathrm{S})$ and $\Upsilon(6\mathrm{S})$ resonances [17]. Data sample of about 19 fb^{-1} was used to measure R_b. Hadronic $b\bar{b}$ events were required to have at least five good tracks, more than 1 cluster in the electromagnetic calorimeter (ECL) with the energy threshold of 0.1 GeV, ECL total energy in the range $(0.1 \div 0.8)\sqrt{s}$, total energy of the tracks and photons more than $0.5 \times \sqrt{s}$ and the reconstructed event vertex within 1.5 and 3.5 cm of the interaction point in the transversal and longitudinal directions, respectively. The $b\bar{b}$ detection efficiency $\epsilon_{b\bar{b}}$, estimated via Monte Carlo (MC) simulation, increases almost linearly from about 70% up to 74%. Selected sample comprises events of $b\bar{b}$, $q\bar{q}$ continuum, and bottomonia produced via e^+e^- annihilation with initial state radiation (ISR): $e^+e^- \to \gamma_{\mathrm{ISR}}\Upsilon(1\mathrm{S}, 2\mathrm{S}, 3\mathrm{S})$. The number of selected events at the i^{th} CM energy point is $N_i = \mathcal{L}_i(\sigma_{b\bar{b},i}\epsilon_{b\bar{b},i} + \sigma_{q\bar{q},i}\epsilon_{q\bar{q},i} + \sum\limits_{\Upsilon(1,2,3\mathrm{S})} \sigma_{\mathrm{ISR},i}\epsilon_{\mathrm{ISR},i})$ ($\mathcal{L}_i$ - integrated luminosity; detection efficiencies, $\epsilon_{q\bar{q},i}$ and $\epsilon_{\mathrm{ISR},i}$, were evaluated with MC simulation; $\sigma_{q\bar{q},i}$ was estimated from the experimental data; $\sigma_{\mathrm{ISR},i}$ was calculated). As a result the ratios, $R'_{b,i} = \sigma_{b\bar{b},i}/\sigma^0_{\mu^+\mu^-,i}$ and $R_{b,i} = R'_{b,i} + \sum\limits_{\Upsilon(1,2,3\mathrm{S})} \sigma_{\mathrm{ISR},i}/\sigma^0_{\mu^+\mu^-,i}$, were extracted and fitted by the function $\mathcal{F}(s) = |A_{\mathrm{nr}}|^2 + |A_{\mathrm{r}} + A_{5\mathrm{S}}e^{i\phi_{5\mathrm{S}}}f_{5\mathrm{S}} + A_{6\mathrm{S}}e^{i\phi_{6\mathrm{S}}}f_{6\mathrm{S}}|^2$, where $f_{n\mathrm{S}} = M_{n\mathrm{S}}\Gamma_{n\mathrm{S}}/[(s - M^2_{n\mathrm{S}}) + iM_{n\mathrm{S}}\Gamma_{n\mathrm{S}}]$ and A_{r} and A_{nr} are coherent and incoherent continuum amplitudes, respectively. Results of the fits of R'_b and R_b are shown in Table 1.

Table 1: Υ(5S) and Υ(6S) masses and widths extracted from the fits (the first error is statistical and the second is systematic one).

	M_{5S} (MeV/c^2)	Γ_{5S} (MeV)	M_{6S} (MeV/c^2)	Γ_{6S} (MeV)
R_b	$10881.9 \pm 1.0 \pm 1.2$	$49.8 \pm 1.9\,^{+2.1}_{-2.8}$	$11002.9 \pm 1.1\,^{+0.8}_{-0.9}$	$38.5^{+1.6\,+1.3}_{-1.5\,-2.4}$
R_b'	$10881.8^{+1.0}_{-1.1} \pm 1.2$	$48.5^{+1.9\,+2.0}_{-1.8\,-2.8}$	$11003.0 \pm 1.1\,^{+0.9}_{-1.0}$	$39.3^{+1.7\,+1.3}_{-1.6\,-2.4}$
$R_{\Upsilon\pi\pi}$	$10891.1 \pm 3.2^{+0.6}_{-1.5}$	$53.7^{+7.1\,+0.9}_{-5.6\,-5.4}$	$10987.5^{+6.4\,+9.0}_{-2.5\,-2.1}$	$61^{+9\ \ +2}_{-19\,-20}$

Υ(5S) and Υ(6S) masses and widths from the R_b fit are consistent with those measured by Belle [15] and BABAR [18]. To measure $R_{\Upsilon\pi\pi}$, events of the $e^+e^- \to \Upsilon(n\mathrm{S})[\to \mu^+\mu^-]\pi^+\pi^-$ (n = 1, 2, 3) process were fully reconstructed. Four-track events were selected, with two oppositely-charged tracks identified as muons with the $\mu^+\mu^-$ invariant mass $M(\mu^+\mu^-) > 8$ GeV/c^2 and the remaining oppositely-charged tracks identified as pions. Signal candidates were selected by requiring $|M(\mu^+\mu^-\pi^+\pi^-) - \sqrt{s}_i/c^2| < 200$ MeV/c^2 and $\delta\Delta M \equiv |\Delta M - (\sqrt{s_i}/c^2 - m_\Upsilon)| < 25$ MeV/c^2 ($\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$), sideband events with 50 MeV/c^2 $< |\delta\Delta M| <$ 100 MeV/c^2 were used to evaluate background. Detection efficiencies were estimated from MC simulation, they vary from about 15% up to 45% over the $\sqrt{s}$ range. The distribution of $R_{\Upsilon\pi\pi,i} = N_{\Upsilon\pi\pi,i}/(\mathcal{L}_i\mathcal{B}(\Upsilon(n\mathrm{S}) \to \mu^+\mu^-)\sigma^0_{\mu^+\mu^-}(\sqrt{s}_i))$ was fitted by the function $\mathcal{F}(s)$. A_{nr} and A_{r} were found to be consistent with zero for all channels; obtained Υ(5S) and Υ(6S) masses and widths are shown in Table 1. Figure 1 shows the $R_{\Upsilon\pi\pi}$ data and fit result. The masses and widths of the Υ(5S) and

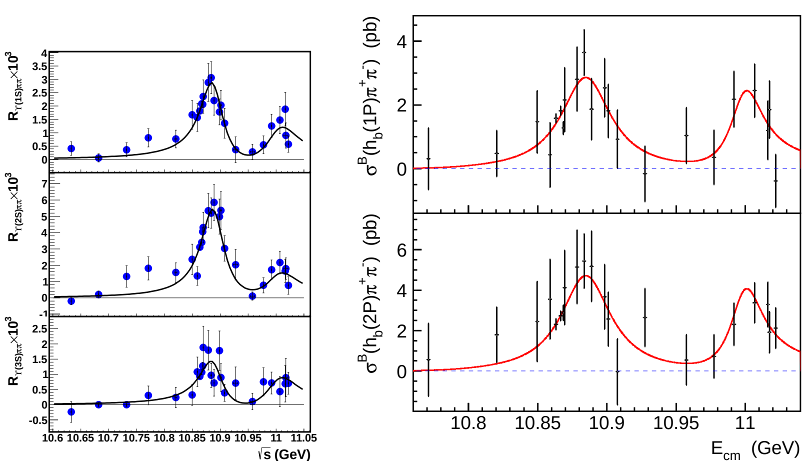

Figure 1: Left: $R_{\Upsilon\pi\pi}$ data for Υ(1S, 2S, 3S) (from top to bottom) with results of fit. Right: $\sigma(e^+e^- \to h_b(1P, 2P)\pi^+\pi^-)$ data (points with error bars) and result of the fit (solid curves).

Υ(6S) from the R'_b and $R_{\Upsilon\pi\pi}$ fits are in agreement. Large interference of the continuum, A_r (with unknown shape), with the resonance amplitudes results in the unknown systematic errors of the masses and widths, hence $R_{\Upsilon\pi\pi}$ is more suitable to measure Υ(5S) and Υ(6S) properties.

2.2 Energy scan of the $\sigma(e^+e^- \to h_b(1P,2P)\pi^+\pi^-)$ and evidence for the $\Upsilon(11020) \to Z_b^\pm\pi^\mp$ decay

Recently the energy dependence of the $e^+e^- \to h_b(mP)\pi^+\pi^-$ $(m = 1,2)$ cross section in the region of Υ(5S) and Υ(6S) resonances was measured for the first time by Belle [19]. Data sample of about 142 fb^{-1} at the CM energies between 10.77 and 11.02 GeV was analyzed. Signal events were reconstructed inclusively fitting the missing mass of the $\pi^+\pi^-$ pairs, $M_\mathrm{miss}(\pi^+\pi^-)$. The detection efficiency, ϵ, for the $h_b(1P)\pi^+\pi^-$ ($h_b(2P)\pi^+\pi^-$) process varies with CM energy in the range $(40 \div 55)\%$ $((35 \div 50)\%)$. Born cross section is $\sigma^B(e^+e^- \to h_b(mP)\pi^+\pi^-) = N/(L\epsilon|1-\Pi|^2)$, where N is the ISR corrected number of signal events, L is the integrated luminosity at the particular energy point, and $|1-\Pi|^2$ is the vacuum polarization correction. The obtained cross sections, shown in Fig. 1, were fitted simultaneously by the function $\mathcal{F}(s) = A_{h_b(mP)}f(s)|BW(s,M_{5S},\Gamma_{5S}) + ae^{i\phi}BW(s,M_{6S},\Gamma_{6S}) + be^{i\delta}|^2$, where $f(s)$ is the phase space factor, $BW(s,M,\Gamma) = M\Gamma/(s-M^2+iM\Gamma)$, free parameters in the fit are: $A_{h_b(1P)}$, $A_{h_b(2P)}$, M_{5S}, Γ_{5S}, M_{6S}, Γ_{6S}, a, ϕ and (optionally) b, δ. The non-resonant continuum contribution, $be^{i\delta}$, was found to be insignificant and was set to zero in the fits. The optimal masses and widths were found to be $M_{5S} = (10884.7^{+3.2+8.6}_{-2.9-0.6})$ MeV/c^2, $\Gamma_{5S} = (44.2^{+11.9+2.2}_{-7.8\ -15.8})$ MeV, $M_{6S} = (10998.6 \pm 6.1^{+16.1}_{-1.1})$ MeV/c^2, $\Gamma_{6S} = (29^{+20+2}_{-12-7})$ MeV, they agree with the values measured in the $e^+e^- \to \Upsilon(1S,2S,3S)\pi^+\pi^-$ processes. The $\Upsilon(6S) \to h_b(mP)\pi^+\pi^-$ transitions were studied with the data collected at the six highest CM energy points. The first evidence of the $e^+e^- \to h_b(1P)\pi^+\pi^-$ and observation of the $e^+e^- \to h_b(2P)\pi^+\pi^-$ at Υ(6S) were found. By fitting $M_\mathrm{miss}(\pi^+\pi^-)$ distribution in bins of $M_\mathrm{miss}(\pi)$ the dynamics of $\Upsilon(6S) \to h_b(mP)\pi^+\pi^-$ was investigated. An evidence of the $\Upsilon(6S) \to Z_b^\pm\pi^\mp \to h_b(mP)\pi^+\pi^-$ mechanism was found, but the statistics was not enough resolve between $Z_b^\pm(10610)$ and $Z_b^\pm(10650)$ states.

2.3 Study of $e^+e^- \to B^{(*)}\bar{B}^{(*)}\pi$ at the Υ(5S) resonance

To clarify the nature of the $Z_b^\pm$ states an analysis of the three-body $e^+e^- \to B\bar{B}\pi$, $e^+e^- \to B\bar{B}^*\pi$ and $e^+e^- \to B^*\bar{B}^*\pi$ processes has been performed recently at Belle [20]. Data sample with an integrated luminosity of 121.4 fb^{-1} collected at the Υ(5S) resonance was used. B mesons were reconstructed in the eighteen decay modes: $B^+ \to J/\psi K^{(*)+}$, $B^+ \to \bar{D}^{(*)0}\pi^+$, $B^0 \to J/\psi K^{(*)0}$, $B^0 \to D^{(*)-}\pi^+$. The number of B candidates, $N_B = 12263 \pm 168$, was determined from the fit of the reconstructed invariant mass ($M(B)$) distribution. After that B^+ or $\bar{B}^0$ were combined with the π^- candidates (right-sign combinations) and the modified missing mass to $B\pi$ system, $M^*_{\rm miss}(B\pi) = M_{\rm miss}(B\pi)+M(B)-m_B$, was analyzed. Wrong-sign combinaions with π^+ were used to estimate the combinatorial background. The $M^*_{\rm miss}$ distribution was approximated and numbers of signal events were extracted: $N_{B\bar{B}\pi} = 13 \pm 25$, $N_{B\bar{B}^*\pi} = 357 \pm 30$ (9.3σ) and $N_{B^*\bar{B}^*\pi} = 161 \pm 21$ (8.1σ). To study dynamics of the $B^{(*)}\bar{B}^*\pi$ production, events satisfying $|M^*_{\rm miss} - m_{B^*}| < 15$ MeV$/c^2$ ($B\bar{B}^*\pi$) and $|M^*_{\rm miss} - (2m_{B^*} - m_B)| < 12$ MeV$/c^2$ ($B^*\bar{B}^*\pi$) criteria were selected, and the recoil mass against primary pion, $M_{\rm miss}(\pi)$, was analyzed, see Fig. 2. The $m \equiv M_{\rm miss}(\pi)$ distribution was approximated by the function $F(m) =$

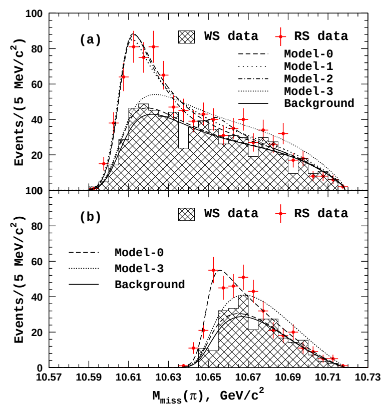

Figure 2: The $M_{\rm miss}(\pi)$ distribution for the (a) $B\bar{B}^*\pi$ and (b) $B^*\bar{B}^*\pi$ candidate events.

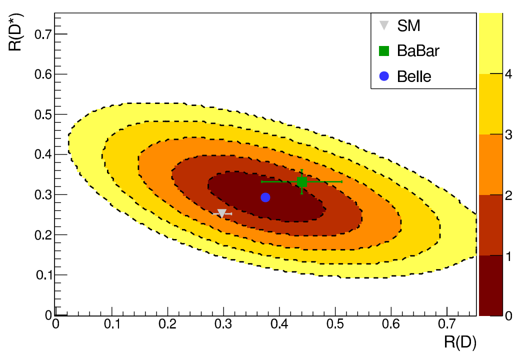

Figure 3: Exclusion levels of the $R(D)$ vs. $R(D^*)$ values in the units of the standard deviations.

$[S(m)+B(m)]\epsilon(m)F_{\rm PHSP}(m)$, where $S(m)$ and $B(m)$ are the signal and background probability density functions, $\epsilon(m)$ is detection efficiency, $F_{\rm PHSP}(m)$ is the phase space factor. $S(m) = |\mathcal{A}_{Z_b(10610)} + \mathcal{A}_{Z_b(10650)} + a_{\rm nr}e^{i\phi_{\rm nr}}|^2$, where $\mathcal{A}_{Z_b} = a_Z e^{i\phi_Z}/(m^2 - m_Z^2 - i\Gamma_Z m_Z)$, masses and widths of the Z_b's are fixed at the values obtained in [7,8]. Results of the fit of the $B\bar{B}^*\pi(B^*\bar{B}^*\pi)$ events by the model including only $Z_b(10610)(Z_b(10650))$ contribution are shown in Fig. 2. The non-resonant contribution, $a_{\rm nr}e^{i\phi_{\rm nr}}$, was found to be insignificant, the production of the $B\bar{B}^*\pi$ and $B^*\bar{B}^*\pi$ are dominated by the intermediate $Z_b(10610)^\pm\pi^\mp$ and $Z_b(10650)^\pm\pi^\mp$, respectively. Visible cross sections were measured to be $\sigma_{\rm vis}(e^+e^- \to B\bar{B}^*\pi) = (11.2 \pm 1.0 \pm 1.2)$ pb, $\sigma_{\rm vis}(e^+e^- \to B^*\bar{B}^*\pi) = (5.61 \pm 0.73 \pm 0.66)$ pb, $\sigma_{\rm vis}(e^+e^- \to B\bar{B}\pi) < 2.1$ pb (90% C.L.).

3 Search for New Physics in $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$

New measurement of the branching fraction ratios $R(D^{(*)}) = \mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)$ (where $\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell) = [\mathcal{B}(\bar{B} \to D^{(*)}e^-\bar{\nu}_e)+\mathcal{B}(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu)]/2$) has been recently published by Belle [21]. The whole data sample of $772 \times 10^6 B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance was analyzed. One of the B mesons, $B_{\rm tag}$, was identified using hadronic full reconstruction algorithm, which includes 1149 B final states. The τ is reconstructed in the leptonic decays $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ ($\ell = e, \mu$), so in the events with $B_{\rm tag}$ the $D^{(*)}\ell$ combination ($D^+\ell^-$, $D^0\ell^-$, $D^{*+}\ell^-$, $D^{*0}\ell^-$) was reconstructed among the remaining charged and neutral particles. The signal mode (with three neutrinos) was distinguished from the normalization mode (with one neutrino) with help of the missing mass squared $M^2_{\rm miss} = (p_{\rm CM} - p_{\rm tag} - p_{D^{(*)}} - p_\ell)^2/c^2$ (where $p_{\rm CM}$, $p_{\rm tag}$, $p_{D^{(*)}}$, and p_ℓ are the four-momenta of the initial e^+e^- system, the $B_{\rm tag}$ candidate, and the signal-B daughters, respectively), which peaks at (above) zero for the normalization (signal) events. The $M^2_{\rm miss}$ range was split into two regions: $M^2_{\rm miss} < 0.85$ GeV$^2/c^4$, populated mostly by normalization $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ events; $M^2_{\rm miss} > 0.85$ GeV$^2/c^4$, enriched by signal $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ events, both subsamples were approximated simultaneously. In the low-$M^2_{\rm miss}$ region, the $M^2_{\rm miss}$ distribution was fitted to evaluate $\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)$, while in the high-$M^2_{\rm miss}$ region, contaminated by background with multiple missing particles, the neural-network output, $O'_{\rm NB}$, was approximated to extract $\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)$. The measured ratios $R(D) = 0.375 \pm 0.064(\text{stat.}) \pm 0.026(\text{syst.})$ and $R(D^*) = 0.293 \pm 0.038(\text{stat.}) \pm 0.015(\text{syst.})$ are shown in Fig. 3. The results agree with the previous measurements as well as with the Standard Model expectation. They are also compatible with the 2HDM(type II) model in the region around $\tan\beta/m_{H^+} = 0.5\ c^2/$GeV [22].

4 Search for dark photon and dark Higgs boson

The dark photon, A', and the dark Higgs boson, h', are introduced in the Dark Sector Models [23]. Recently Belle performed a search for their production in the Higgs-strahlung channel, $e^+e^- \to A'h'$ ($h' \to A'A'$) using full data sample of 977 fb^{-1} [24]. Ten exclusive final-states with $A' \to e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-$, and three inclusive final-states, $2(e^+e^-)X$, $2(\mu^+\mu^-)X$, and $(e^+e^-)(\mu^+\mu^-)X$ (where X denotes A' candidate detected via missing mass) were investigated. No significant signal was observed. Upper limits on the dark photon coupling to the dark Higgs boson (α_D) times the kinetic mixing (ϵ) between the Standard Model photon and the dark photon squared, $\alpha_D \times \epsilon^2$ were obtained. These limits improve upon results of the previous measurements, $3(\pi^+\pi^-)$ and $2(e^+e^-)X$ final states were studied for the first time.

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