New results on the XYZ states and B-decays from Belle

Makoto Takizawa[1,2,3,4]

[1]Showa Pharmaceutical University, Machida, Tokyo, 194-8543, Japan
[2]Theoretical Research Division, Nishina Center, RIKEN, Wako, Saitama 351-0198, Japan
[3]J-PARC Branch, KEK Thery Center, IPNS, KEK, Tokai, Ibaraki, 319-1106, Japan
[4]On behalf of the Belle Collaboration

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We present the recent results on the XYZ states and B-decays measured by the Belle detector at the KEKB e^+e^- collider.

1 Introduction

The Belle experiment ran at the KEKB [1] e^+e^- asymmetric energy collider between 1999 and 2010 and the total integrated luminosity reached 1040 fb^{-1}. Most of the data were taken at the energy of the $\Upsilon(4S)$ resonance in order to study the B physics, but other energy data were taken as listed in Table 1. The physics events were detected by the general purpose Belle spectrometer [2], which consists of a silicon vertex detector, a central drift chamber, an array of aerogel Cherenkov counters, a barrel-like arrangement of time-of-flight scintillation counters and an electromagnetic calorimeter. Arrays of resistive plate counters interspersed in the iron yoke is used for the identification of muons and K_L mesons. The physics achievements from the Belle experiment until 2012 are reviewed in Ref. [3] and the physics results from the B-factories until 2014 are reviewed in Ref. [4].

Concerning the XYZ states, Particle Data Group (PDG) uses the naming X for all XYZ states. On the other hand, in the many literatures, the Y's are used for the states of $J^{PC} = 1^{--}$ with the energy range of the charmonia but seem not to be considered as the charmonia. As for the Z_c's (Z_b's), the Z_c's (Z_b's) are the meson states including $c\bar{c}$ ($b\bar{b}$) with electric charge, and therefore, the minimal quark content for Z_c^+ is $c\bar{c}u\bar{d}$. The Z_c's and Z_b's are considered as isospin 1 states and there exist the neutral states with same isospin multiplet. Such states are also called Z states. We use the X for all other types of the exotic mesons. The recent status of XYZ states is reviewed in Ref. [5].

2 Bottomonium-like hadrons

2.1 Anomalous $\Upsilon(nS)\pi^+\pi^-$ (n=1,2,3) production near $\Upsilon(5S)$ resonance

The $\Upsilon(10860)$ resonance is the $J^{PC} = 1^{--}$ state with the mass of 10876 ± 11 MeV/c^2 and the width of 55 ± 28 MeV. The main component of this resonance is considered as the 5th excited

Resonance	On-peak luminosity (fb^{-1})	Off-peak luminosity (fb^{-1})	Number of resonances
$\Upsilon(1S)$	5.7	1.8	102×10^6
$\Upsilon(2S)$	24.9	1.7	158×10^6
$\Upsilon(3S)$	2.9	0.25	11×10^6
$\Upsilon(4S)$	711.0	89.4	772×10^6
$\Upsilon(5S)$	121.4	1.7	7.1×10^6
Scan		27.6	

Table 1: Summary of the luminosity of the Belle experiment. "On-peak" means the energy is just at the resonance points and "Off-peak" means the energy is 60 MeV below the resonance points. "Scan" means the energy is scanned between the $\Upsilon(4S)$ and $\Upsilon(6S)$ resonances.

state (including the ground state) of the orbital angular moment $L = 0$ bottomonium, and therefore, sometimes called $\Upsilon(5S)$. Its mass is above the open bottom threshold and the decays to $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$ and $B_s\bar{B}_s$ have been observed. In 2008, Belle reported the first observation of $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$ and first evidence for $e^+e^- \to \Upsilon(3S)\pi^+\pi^-$, $\Upsilon(1S)K^+K^-$ near the peak of the $\Upsilon(5S)$ resonance at $\sqrt{s} \sim 10.87$ GeV [6]. The $\Upsilon(nS)$ was detected through the $\Upsilon(nS) \to \mu^+\mu^-$ decay mode. Signal candidates were identified using the kinematic variable ΔM, defined as the difference between $M(\mu^+\mu^-\pi^+\pi^-)$ or $M(\mu^+\mu^-K^+K^-)$ and $M(\mu^+\mu^-)$ for pion or kaon modes. The signal events should be concentrated at $\Delta M = \sqrt{s} - M_{\Upsilon(nS)}$ and results are given in Fig. 1. By analyzing the data and assuming the $\Upsilon(5S)$ to be the sole

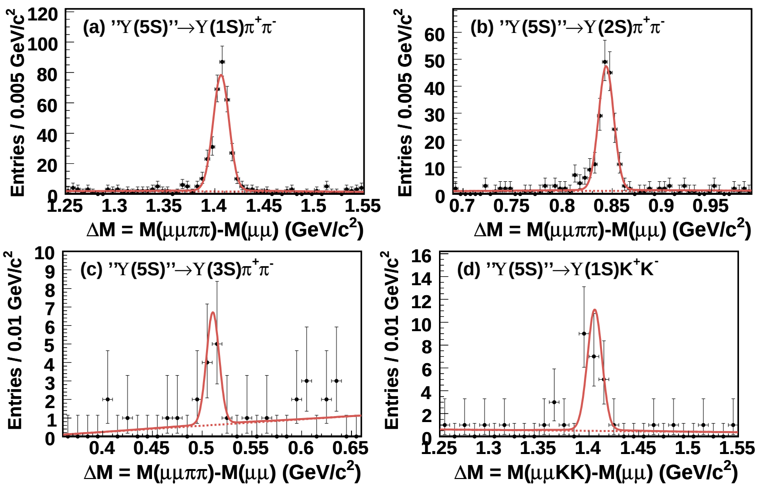

Figure 1: The ΔM distributions for (a) $\Upsilon(1S)\pi^+\pi^-$, (b) $\Upsilon(2S)\pi^+\pi^-$, (c) $\Upsilon(3S)\pi^+\pi^-$, and (d) $\Upsilon(1S)K^+K^-$ with the fit results superimposed. The dashed curves show the background components in the fits. Figures are taken from Ref. [6]

source of the observed events, the partial decay widths have been obtained. The results are summarized in Table 2. The measured partial widths , of order $0.6 - 0.9$ MeV, are more than 2 orders of magnitude larger than the corresponding partial widths for $\Upsilon(4S)$, $\Upsilon(3S)$ or $\Upsilon(2S)$

Process	N_s	Σ	Γ(MeV)
$\Upsilon(1S)\pi^+\pi^-$	325^{+20}_{-19}	20σ	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	186 ± 15	14σ	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$10.5^{+4.0}_{-3.3}$	3.2σ	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(1S)K^+K^-$	$20.2^{+5.2}_{-4.5}$	4.9σ	$0.067^{+0.017}_{-0.015} \pm 0.013$

Table 2: Signal yield (N_s), significance (Σ) and the partial widths (Γ) for $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$ are also given. The first uncertainty is statistical, and the second is systematic.

decays. The unexpectedly large partial widths disagree with the expectation for a pure $b\bar{b}$ state, and therefore, the $\Upsilon(5S)$ is one of the strong candidates for the exotic hadron.

In order to understand the nature of the $\Upsilon(5S)$ state, Belle measured the production cross sections for $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$ and $\Upsilon(3S)\pi^+\pi^-$ as a function of $\sqrt{s}$ between 10.83 GeV and 11.02 GeV [7]. The enhancements of the production cross sections were observed in all three final states. A fit using a Breit-Wigner resonance shape yields a peak mass of $[10888.4^{+2.7}_{-2.6}(\text{stat}) \pm 1.2(\text{syst})]$ MeV/c^2 and a width of $[30.7^{+8.3}_{-7.0}(\text{stat}) \pm 3.1(\text{syst})]$ MeV. Recently, new measurements have been performed with including not only $\Upsilon(10860)$ but also $\Upsilon(11020)$ [8]. The results are $M_{10860} = (10891.1 \pm 3.2^{+0.6}_{-1.7})$ MeV/c^2, $\Gamma_{10860} = (53.7^{+7.1}_{-5.6}{}^{+1.3}_{-5.4})$ MeV, $M_{11020} = (10987.5^{+6.4}_{-2.5}{}^{+9.0}_{-2.1})$ MeV/c^2 and $\Gamma_{11020} = (61^{+9}_{-19}{}^{+2}_{-20})$ MeV.

2.2 First observation of the P-wave spin-singlet bottomonium states

The $h_b(nP)$ states are the P-wave spin-singlet bottomonium. In 2012, Belle reported the first observations of the $h_b(1P)$ and $h_b(2P)$ produced via $e^+e^- \to \pi^+\pi^- h_b(nP)$ using a 121.4 fb^{-1} data sample collected at energies near the $\Upsilon(5S)$ resonance [9]. The $h_b(nP)$ states were observed in the $\pi^+\pi^-$ missing mass spectrum defined as $M^2_{miss} \equiv (P_{\Upsilon(5S)} - P_{\pi^+\pi^-})^2$, where $P_{\Upsilon(5S)}$ is the 4-momentum of the $\Upsilon(5S)$ determined from the beam momenta and $P_{\pi^+\pi^-}$ is the 4-momentum of the $\pi^+\pi^-$ system. The M_{miss} spectrum is divided into three adjacent regions with boundaries at $M_{miss} = 9.3$, 9.8, 10.1, and 10.45 GeV/c^2 and fitted separately in each region. In the third region, prior to fitting, the contribution due to the $K^0_S \to \pi^+\pi^-$ is subtracted. In Fig. 2, the M_{miss} spectrum after subtraction of both the combinatoric and $K^0_S \to \pi^+\pi^-$ contributions is shown with the fitted signal functions. The measured masses of $h_b(1P)$ and $h_b(2P)$ are $M = (9898.2^{+1.1}_{-1.0}{}^{+1.0}_{-1.1})$ MeV/c^2 and $M = (10259.8 \pm 0.6^{+1.4}_{-1.0})$ MeV/c^2, respectively. Using the world average masses of the $\chi_{bJ}(nP)$ states, the P-wave hyperfine splittings are determined to be $\Delta M_{\text{HF}} = (+1.7 \pm 1.5)$ and $(+0.5^{+1.6}_{-1.2})$ MeV/c^2, respectively. The significances of the $h_b(1P)$ and $h_b(2P)$ are 5.5 σ and 11.2 σ, respectively.

The hadronic transition $\Upsilon(4S) \to \eta h_b(1P)$ and the radiative decay $h_b(1P) \to \gamma\eta_b(1S)$ have been observed [10]. The measured branching fractions are $\mathcal{B}[\Upsilon(4S) \to \eta h_b(1P)] = (2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$ and $\mathcal{B}[h_b(1P) \to \gamma\eta_b(1S)] = (56 \pm 8 \pm 4)\%$.

2.3 First observation of two charged bottomonium-like resonances; $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$

In 2012, Belle reported the first observations of two narrow charged bottomonium-like resonances in the mass spectra of the $\pi^\pm\Upsilon(nS)$ ($n = 1, 2, 3$) and $\pi^\pm h_b(mP)$ ($m = 1, 2$) pairs

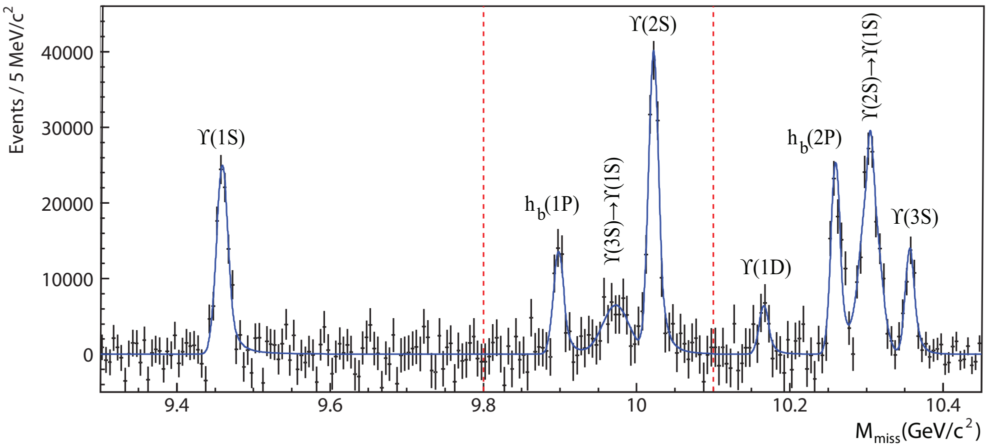

Figure 2: The M_{miss} spectrum with the combinatoric background and K_S^0 contribution subtracted (points with errors) and signal component of the fit function overlaid (smooth curve). The vertical lines indicate boundaries of the fit regions. Figure is taken from Ref. [9]

that were produced in association with a single charged pion in $\Upsilon(5S)$ decays [11]. Amplitude analyses of the three-body $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ decays were performed by means of unbinned maximum likelihood fits to two-dimensional $M^2[\Upsilon(nS)\pi^+]$ vs $M^2[\Upsilon(nS)\pi^-]$ Dalitz distributions. Two peaks were observed in the $\Upsilon(nS)\pi^\pm$ system near 10.61 GeV/c^2 and 10.65 GeV/c^2. The statistical significance of the two peaks exceeded 10σ for all $\Upsilon(nS)\pi^+\pi^-$ channels. Similarly, two peaks were observed in the $h_b(mP)\pi^\pm$ system. The significance of the $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ is 16.0σ [5.6σ] for the $h_b(1P)$ [$h_b(2P)$]. Weighted averages of the mass and width are $M = 10607.2 \pm 2.0$ MeV/c^2, $\Gamma = 18.4 \pm 2.4$ MeV for the $Z_b(10610)^\pm$ and $M = 10652.2 \pm 1.5$ MeV/c^2, $\Gamma = 11.5 \pm 2.2$ MeV for the $Z_b(10650)^\pm$, where statistical and systematic errors are added in quadrature. Recent amplitude analysis of the three-body $\Upsilon(nS)\pi^+\pi^-$ final states strongly favored $I^G(J^P) = 1^+(1^+)$ quantum-number assignments [12]. Since the minimal quark content is $b\bar{b}u\bar{d}$ [$b\bar{b}d\bar{u}$] for the Z_b^+ [Z_b^-], the $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ are the genuine exotic hadrons. The measured masses of two states are a few MeV/c^2 above the thresholds for the open bottom channels $B^*\bar{B}$ (10604.46 MeV/c^2) and $B^*\bar{B}^*$ (10650.2 MeV/c^2). This suggests that these states have a hadronic molecular-type structure.

2.4 First observation of $Z_b(10610)^0$

Belle reported the first observation of the neutral partner of the $Z_b(10610)^\pm$, the $Z_b(10610)^0$ decaying to $\Upsilon(2,3S)\pi^0$ with a 6.5σ significance using a Dalits analysis of $\Upsilon(5S) \to \Upsilon(2,3S)\pi^0\pi^0$ decays [13]. The measured mass of the $Z_b(10610)^0$ is $M = (10609 \pm 4 \pm 4)$ MeV/c^2, that is consistent with the mass of the corresponding charged state, the $Z_b(10610)^\pm$. This suggests that the isospin symmetry breaking is small for $Z_b(10610)$'s and an admixture of the $b\bar{b}$ component in $Z_b(10610)^0$ is small.

3 Charmonium-like hadrons

3.1 $Y(4260)$, $Y(4360)$ and $Y(4660)$

The $Y(4260)$ state was first observed by the BaBar Collaboration in the initial-state-radiation (ISR) process $e^+e^- \to \gamma_{\text{ISR}}\pi^+\pi^- J/\psi$ [14] and then confirmed by the CLEO [15] and Belle experiments [16, 17] using the same technique. The cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ are given in Fig. 3 The quantum number of the $Y(4260)$ resonances is $J^{PC} = 1^{--}$. However, the

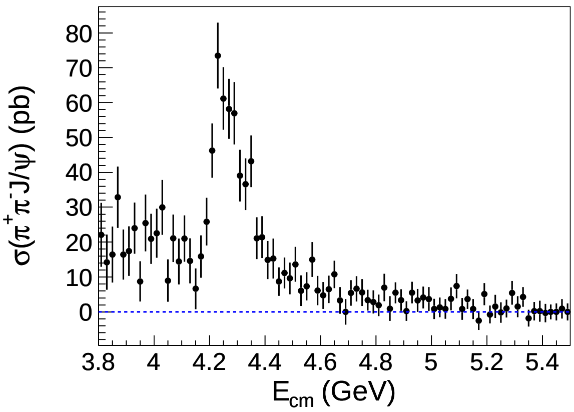

Figure 3: The measured $e^+e^- \to \pi^+\pi^- J/\psi$ cross section for c.m. energies between 3.8 and 5.5 GeV after background subtraction. The errors are statistical only. Figure is taken from Ref. [17]

properties of the $Y(4260)$ resonance are rather different from those of other known $J^{PC} = 1^{--}$ charmonium states in the same mass range. Since it is well above the $D\bar{D}$ threshold, it is expected to decay into $D^{(*)}\bar{D}^{(*)}$ dominantly. In fact, no significant enhancement is observed in $D^{(*)}\bar{D}^{(*)}$ final states. On the other hand, $\Gamma(Y(4260) \to \pi^+\pi^- J/\psi) > 1.6$ MeV at 90% CL, which is much larger than the typical charmonium state, i.e., $\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) = 53 \pm 8$ keV.

In 2007, Belle reported the observation of two resonance structures in $e^+e^- \to \pi^+\pi^-\psi(2S)$ via initial-state radiation [18]. The masses and widths of the two resonances ($Y(4360)$ and $Y(4660)$) are $M_1 = 4361 \pm 9 \pm 9$ MeV/c^2, $\Gamma_1 = 74 \pm 15 \pm 10$ MeV and $M_2 = 4664 \pm 11 \pm 5$ MeV/c^2, $\Gamma_2 = 48 \pm 15 \pm 3$ MeV, respectively, if the mass spectrum is parametrized with the coherent sum of two Breit-Wigner functions. The statistical significance of the first peak is more than 8σ and that of the second peak is 5.8σ. In 2015, using full data sample of the Belle experiment, $Y(4360)$ and $Y(4660)$ states have been studied [19] and the measured cross section is given in Fig. 4. Likewise $Y(4260)$, $Y(4360)$ and $Y(4660)$ are not observed in $D^{(*)}\bar{D}^{(*)}$ channels. $Y(4260)$ has rather large partial decay width to the $\pi^+\pi^- J/\psi$ final state, but has quite small partial decay width to the $\pi^+\pi^-\psi(2S)$ final state. Conversely, $Y(4360)$ and $Y(4660)$ have large partial decay width to the $\pi^+\pi^-\psi(2S)$ final state, but have small partial decay width to the $\pi^+\pi^- J/\psi$ final state. These facts suggest that $Y(4260)$, $Y(4360)$ and $Y(4660)$ are not simple charmonium states, and therefore, are the candidates for the exotic hadrons.

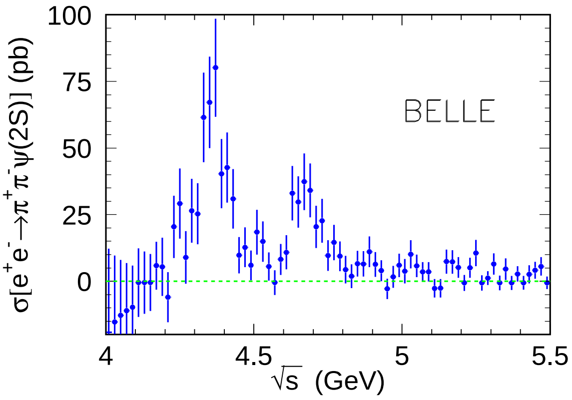

Figure 4: The measured $e^+e^- \to \pi^+\pi^-\psi(2S)$ cross section for c.m. energies between 4.0 and 5.5 GeV after background subtraction. Figure is taken from Ref. [19]

3.2 $Z_c(3900)$

The $J^{PC} = 1^{--}$ state $Y(4260)$ has rather large decay width to the $\pi^+\pi^-J/\psi$ and it is similar to the $J^{PC} = 1^{--}$ state $\Upsilon(10860)$ has rather large decay width to the $\pi^+\pi^-\Upsilon(1S)$. In the $\Upsilon(10860)$ decay, the charged bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ were observed as described in Sect. 2.3. Likewise $\Upsilon(10860)$, whether the $Y(4260)$ decay to the charged charmonium-like state was the issue of the discussion. Recently, BESIII reported [20], and Belle confirmed [17], the observation of a charged resonance-like structure in the π^+J/ψ invariant mass distribution for $e^+e^- \to \pi^+\pi^-J/\psi$ events collected at $\sqrt{s} = 4.26$ GeV, dubbed the $Z_c(3900)$. The mass and width determined by BESIII are $M = (3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and $\Gamma = (46 \pm 10 \pm 20)$ MeV, respectively with more than 8σ statistical significance. Those by Belle are $M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2 and $\Gamma = (63 \pm 24 \pm 26)$ MeV, respectively with 5.2σ significance. The fit results of the distribution of $M_{\rm max}(\pi J/\psi)$, the maximum of $M(\pi^+J/\psi)$ and $M(\pi^-J/\psi)$ by Belle are given in Fig. 5. Recently, BESIII reported on a study of the process $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ at $\sqrt{s} = 4.26$ GeV using a 525 pb^{-1} data sample collected with the BESIII detector at BEPCII storage ring. A distinct charged structure dubbed $Z_c(3885)$ is observed with more than 18σ significance [21]. The measured mass and width are $M = (3883.9 \pm 1.5 \pm 4.2)$MeV/c^2 and $\Gamma = (24.8 \pm 3.3 \pm 11.0)$ MeV, respectively. The fitted $Z_c(3885)$ mass is marginally (2σ) inconsistent with that of the $Z_c(3900)$, and therefore, it is an issue of the discussion whether the $Z_c(3885)$ structure is identical with the $Z_c(3900)$ structure.

Since the mass of $Z_c(3885)$ or $Z_c(3900)$ is close to the $D^0\bar{D}^{*-}$ threshold, there are suggestions that these states are the virtual $D\bar{D}^*$ molecule-like structure, i,e., a charmed-sector analog of the $Z_b(10610)$. However, the situation is not so simple. Because of the heavy quark symmetry, the interaction between $B^{(*)}$ and $\bar{B}^{(*)}$ is considered to be similar to that between $D^{(*)}$ and $\bar{D}^{(*)}$. On the other hand, the size of the kinetic energy term of the $D\bar{D}^*$ system is about 2.7 times larger than that of the $B\bar{B}^*$ system due to the reduced mass difference. Therefore, simultaneous explanation of the $Z_b(10610)$ and $Z_c(3900)$ structures are rather difficult.

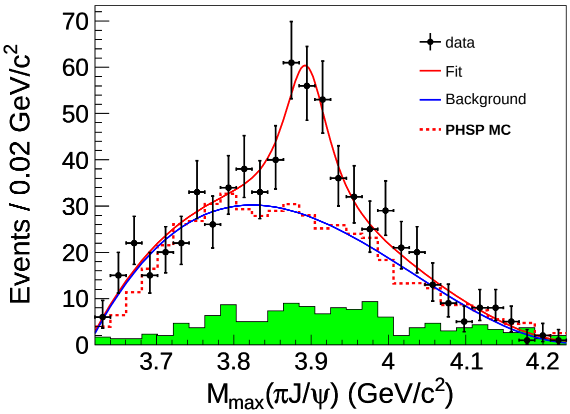

Figure 5: Unbinned maximum likelihood fit to the distribution of the $M_{\max}(\pi J/\psi)$. Points with error bars are data, the curves are the best fit, the dashed histogram is the phase space distribution and the shaded histogram is the non-$\pi^+\pi^- J/\psi$ background estimated from the normalized J/ψ sidebands. Figure is taken from Ref. [17]

4 B decays

The B-meson properties have been studied for understanding the CP violation phenomena and the results from the B-factories have been summarized in Ref. [4]. The energy frontier experiment the Large Hadron Collider (LHC) at CERN started the $\sqrt{s} = 7$ TeV operation in 2010. Then, the observation of the boson has been reported on July 4th, 2012 and later it was identified as the Standard Model (SM) Higgs boson. In 2015, the $\sqrt{s} = 13$ TeV operation at LHC started. However, up to now, no new phenomena beyond the SM (BSM) have been observed.

In such a situation, the intensity frontier experiments are attracting attention since such experiments may have the possibility to access to much higher energy scale phenomena. The deviations from the SM predictions have been measured in the semileptonic B decays to τ leptons and the angular observables of the $B \to K^*\ell^+\ell^-$ decays with $\ell = e, \mu$. In order to observe the BSM phenomena, the observables should be predicted very accurately in the SM. Otherwise the small contributions from the BSM phenomena are easily masked by the uncertainties of the SM predictions. The uncertainties of the SM predictions are mostly come from the strong interaction parts. In this two B-decay modes in question, there is single hadron in the initial and final states and therefore no initial and final state interactions by the strong interaction exist.

4.1 $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$

The ratio $\mathcal{R}(D^{(*)}) = \mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)$, with $\ell = e, \mu$ has much attention since it is sensitive to the Charged Higgs boson contributions, which is the BSM phenomena. It is naively understood that the Charged Higgs boson coupling to the τ lepton is stronger than that to the electron or muon because of the large mass of the τ lepton. By taking the ratio of the branching fractions, the theoretical as well as experimental uncertainties have been reduced. The SM predictions are $\mathcal{R}(D^*) = 0.252 \pm 0.003$ [22] and $\mathcal{R}(D) = 0.300 \pm 0.008$ [23]. On the other hand, experimental results are as follows. *BABAR* reported $\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018$ and $\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042$ with a semileptonic tagging method [24]. Belle used a hadronic tagging method and the results are $\mathcal{R}(D^*) = 0.293 \pm 0.038 \pm 0.015$ and $\mathcal{R}(D) = 0.375 \pm 0.064 \pm 0.026$ [25]. In LHCb experiment, the multidimensional fit to kinematics distributions of the candidate $\bar{B}^0$ decays gave $\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$ [26]. Recently Belle performed the measurement of $\mathcal{R}(D^*)$ using the semileptonic tagging method and the result was $\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$ [27]. In the experimental results, the first errors are statistical ones and the second errors are systematical ones. All the experimental results are consistent with each other.

The Heavy Flavor Averaging Group (HFAG) summarized these results and reported them on their web page. The averages are $\mathcal{R}(D^*) = 0.316 \pm 0.016 \pm 0.010$ and $\mathcal{R}(D) = 0.397 \pm 0.040 \pm 0.028$, which exceed the SM predictions by 1.9σ and 3.3σ, respectively. The combined analysis shows that the deviation from the SM prediction is 4σ, which is summarized in Fig. 6.

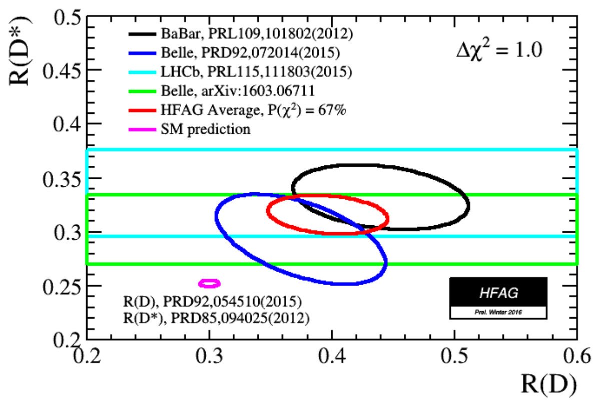

Figure 6: Summary of the theoretical as well as experimental results of $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$. Figure is taken from HFAG web site http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html

4.2 τ lepton polarization in $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ decay

Although I did not mention this subject on my lecture at the summer school, in this subsection, I would like to report Belle's new results on the τ lepton polarization and $\mathcal{R}(D^*)$ in $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ decay with $\tau \to \pi\nu_\tau$ and $\tau \to \rho\nu_\tau$ using the hadronic tagging method [28]. The τ lepton polarization is defined as $P_\tau(D^*) = [\Gamma^+(D^*) - \Gamma^-(D^*)]/[\Gamma^+(D^*) + \Gamma^-(D^*)]$, where $\Gamma^\pm(D^*)$ denotes the decay rate of $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ with a τ helicity of $\pm 1/2$. The $P_\tau(D^*)$ is considered to be sensitive to the BSM physics. The $P_\tau(D^*)$ can be measured from the angular distributions in the two-body hadronic τ decays.

The result is $P_\tau(D^*) = -0.36 \pm 0.51^{+0.21}_{-0.16}$, which is consistent with the SM prediction $P_\tau(D^*) = -0.497 \pm 0.013$ [29]. This analysis gave the independent measurement of the $\mathcal{R}(D^*)$ in the two-body hadronic τ decay modes. The result $\mathcal{R}(D^*) = 0.27 \pm 0.035^{+0.028}_{-0.025}$ is consistent with the SM prediction.

4.3 Lepton-flavor-dependent angular analysis of $B \to K^* \ell^+ \ell^-$

The $B \to K^* \ell^+ \ell^-$ decay involves the quark transition $b \to s \ell^+ \ell^-$, a flavor-changing neutral current that is forbidden at tree level in the SM. There may be sizable contributions from the BSM phenomena and the LHCb reported the 3.4σ deviation from the SM prediction in the angular dependent observable P'_5 measured by the $B^0 \to K^{*0} \mu^+ \mu^-$ decay [30]. The definition of P'_5 is given in Ref. [30]. Recently, Belle performed the measurements of these angular dependent observables in not only the $B^0 \to K^{*0} \mu^+ \mu^-$, but also the $B^\pm \to K^{*\pm} \mu^+ \mu^-$, $B^0 \to K^{*0} e^+ e^-$ and $B^\pm \to K^{*\pm} e^+ e^-$ decay modes [31]. The results are compatible with SM predictions, where the largest discrepancy is 2.6σ in P'_5 for the muon channels as shown in Fig. 7.

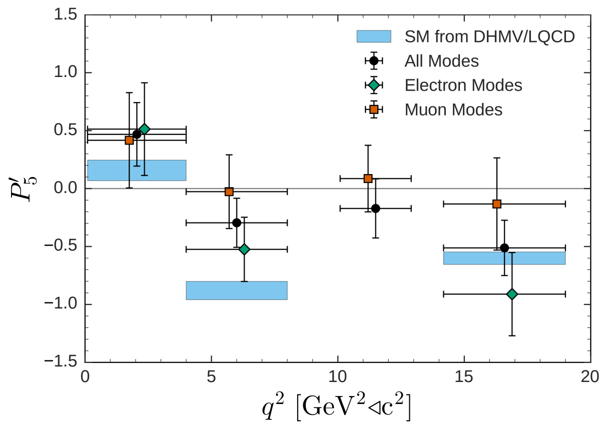

Figure 7: The theoretical as well as experimental results of P'_5. Figure is taken from Ref. [31].

5 Summary

The recent results on the hadron spectroscopy measured by the Belle detector at the KEKB e^+e^- collider have been reviewed. We have focused on the bottomonium-like and charmonium-like mesons having the unanticipated properties from the $q\bar{q}$ structures.

Although the data taking of the Belle experiment was finished on June 30, 2010, there may be rich hadron physics to be analyzed in Belle data. Quantum numbers, production rates, decay rates, etc. have not been to be determined for many higher resonance states, which should be measured. As discussed in this talk, many states may not have the simple quark-gluon structures but have the rich structures. In order to clarify the structures of such exotic hadrons, any suggestion from the theorists is very welcome.

So far, physics beyond the Standard Model has not been observed. In order to observe BSM phenomena, the more accurate and less uncertain SM predictions of the observables as well as the more precise experimental measurements are necessary.

The SuperKEKB/Belle II experiment will start data taking on the end of 2017. The designed luminosity is 40 times bigger than the KEKB-factory/Belle. Please await our new data from the SuperKEKB-/Belle II.

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