Chapter 17
Search for $Y(4260)$ in $B \to Y(4260)K$ Decay Mode at Belle

Renu Garg, Vishal Bhardwaj, and J. B. Singh

Abstract $Y(4260)$ is an exotic charmonium-like state with 4230 ± 8 MeV/c^2 mass and 55 ± 19 MeV width. The $Y(4260)$'s decay to $J/\psi\pi\pi$ suggests, it to be a charmonium ($c\bar{c}$) meson. But its mass is not consistent with any of 1^{--} $c\bar{c}$ state. Several models have been proposed to explain the nature of $Y(4260)$ including $c\bar{c}g$ hybrid model, tetraquark, $D_1 D$, $D^0 D^*$ molecule, $J/\psi f_0(980)$ molecule, and so on. This state is so interesting that a charged state $Z_c(3900)$ is observed in its decay mode and $Z_c(3900)$ is a tetraquark state. Some recent studies suggest $Y(4260)$ be an admixture of tetraquark and charmonium state. It has been suggested that the structure of $Y(4260)$ can be estimated if one measured branching fraction of $B \to Y(4260)K$. Till now, this state has been only produced by ISR or e^+e^- annihilation. We search for $B \to Y(4260)K$, where $Y(4260) \to J/\psi\pi\pi$ decay mode using the full $\Upsilon(4S)$ data collected by the Belle detector at the asymmetric KEKB e^+e^- collider.

17.1 Introduction

The $Y(4260)$ state was first observed in the initial state radiation (ISR) process $e^+e^- \to \gamma_{ISR} J/\psi\pi^+\pi^-$ by the BABAR collaboration [1]. It has been confirmed by the Belle [2] and CLEO [3] collaborations in the same process. J^{PC} of $Y(4260)$ is expected to be 1^{--} as it is produced in ISR and its decay to J/ψ modes indicate the presence of $c\bar{c}$ in its contents. However, its mass and properties are not consistent with any of the $c\bar{c}$ states in the charmonium spectrum as low lying $\psi(3S)$, $\psi(2D)$ and $\psi(4S)$ $c\bar{c}$ states have been assigned to well established states $\psi(4040)$, $\psi(4160)$,

R. Garg (✉) · J. B. Singh
Department of Physics, Panjab University, Chandigarh, India
e-mail: renu92garg@gmail.com

J. B. Singh
e-mail: singhjb@pu.ac.in

V. Bhardwaj
Department of Physical Sciences, IISER, Mohali, India
e-mail: vishstar@gmail.com

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and $\psi(4415)$, respectively, and $\psi(3D)$ has a higher mass (4.520 GeV/c^2) [4]. This results in difficulty to assign $Y(4260)$ as one of the conventional states. Several models have been proposed to explain the nature of $Y(4260)$ including tetraquark [5], hybrid [6], molecule [7, 8] or even charmonium baryonium [9]. Observation of charged charmonium candidate $Z_c(3900)^{\pm}$ by BESIII [10] and Belle [11] collaborations in the $J/\psi\pi^{\pm}$ invariant mass spectrum of $Y(4260) \rightarrow J/\psi\pi^+\pi^-$ decay provides the strong evidence for the $Y(4260)$ being a exotic state.

Measurement of the branching fraction $\mathcal{B}(B \rightarrow Y(4260)K)$ and its decay property can help us to understand the structure of $Y(4260)$. It has been suggested [12] on the basis of QCD sum rules that branching fractions of $\mathcal{B}(B \rightarrow Y(4260)K)$, $\mathcal{B}(Y(4260) \rightarrow J/\psi\pi\pi)$ to be in the range $3.0 \times 10^{-8} - 1.8 \times 10^{-6}$. Till now, only the BABAR collaboration has provided the limit [13] on $\mathcal{B}(B^- \rightarrow Y(4260)K^-)$ with statistical significance of 3.1σ, $1.2 \times 10^{-5} < \mathcal{B}(B^- \rightarrow K^-Y(4260)) \times \mathcal{B}(Y(4260) \rightarrow J/\psi\pi\pi) < 2.9 \times 10^{-5}$ based on $211\, fb^{-1}$ data that contains $(232 \pm 3) \times 10^6 B\bar{B}$ pairs. Due to limited statistics, it is not sufficient to conclude. Our aim is to provide precise measurements of the branching fraction. Recently, BESIII [14] observed two resonances in a fit to the cross section of $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ process, one at $Y(4260)$ resonance and other at $Y(4360)$ resonance. $Y(4360)$ has not been confirmed yet. In the present analysis, we assume $Y(4260)$ to be a single resonance as measured by Belle and BABAR.

We report on the MC study for $B \rightarrow Y(4260)K$ decay. Monte Carlo (MC) sample for each decay mode is generated using EvtGen [15] and radiative effects are taken into account using PHOTOS [16]. Detector response is added by detector simulation software based on GEANT3.4 [17] software tool.

17.2 Particle Selection and Reconstruction

The charged tracks like kaons, pions, and protons are required to originate from the interaction point (IP). The closest approach w.r.t IP is required to be within 3.5 cm in the beam direction (z) and 1.0 cm in the transverse plane (xy-plane). Charged kaon and pion selections are based on the information from aerogel Cerenkov counters (number of Cherenkov photons), time-of-flight, and central drift chamber (dE/dx measurement) detectors.

The J/ψ is reconstructed via its decay mode $J/\psi \rightarrow \ell^+\ell^-$, where ℓ stands for e or μ. There is a loss of energy from a electron in the form of emission of bremsstrahlung photons. In $J/\psi \rightarrow e^+e^-$, the four momenta of the photons within 0.05 radian of e^+ or e^- direction are included in the invariant mass calculation [hereinafter denoted as $e^+e^-(\gamma)$]. The invariant mass of the J/ψ is required to be within 3.05 GeV/c^2 $\leq M_{ee(\gamma)} \leq$ 3.13 GeV/c^2 or 3.07 GeV/c^2 $\leq M_{\mu\mu} \leq$ 3.13 GeV/c^2 as shown in Fig. 17.1. The asymmetric interval is taken for $e^+e^-(\gamma)$ to include the radiative tail. The vertex- and mass-constrained fit is performed to the selected J/ψ candidates.

ψ', $X(3872)$, and $Y(4260)$ candidates are formed by combining the selected J/ψ candidate with a $\pi^+\pi^-$ pair. The invariant mass of ψ', $X(3872)$, and $Y(4260)$ is

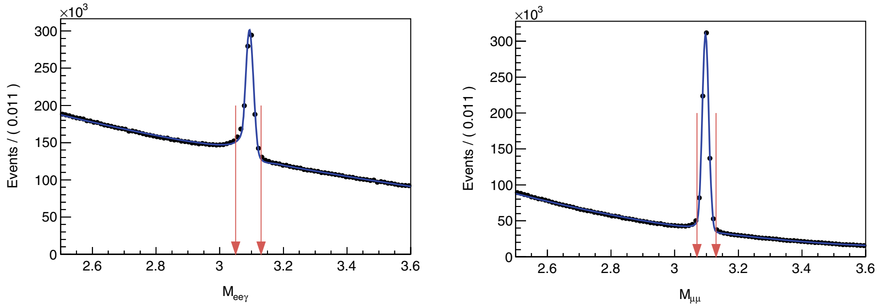

Fig. 17.1 Fit to $M_{\ell\ell}$ invariant mass of J/ψ, $J/\psi \to e^+e^-$ [left] and $J/\psi \to \mu^+\mu^-$ [right]

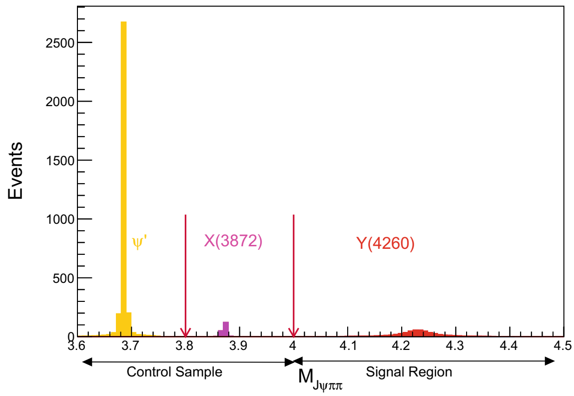

Fig. 17.2 Comparison of ψ', $X(3872)$, and $Y(4260)$ signal

required to be in the range $3.67\ \text{GeV}/c^2 \leq M_{J/\psi\pi\pi} \leq 3.70\ \text{GeV}/c^2$, $3.835\ \text{GeV}/c^2 \leq M_{J/\psi\pi\pi} \leq 3.910\ \text{GeV}/c^2$, and $4.0\ \text{GeV}/c^2 \leq M_{J/\psi\pi\pi} \leq 4.6\ \text{GeV}/c^2$, respectively. Then, finally B candidates are formed by combining ψ', $X(3872)$ and $Y(4260)$ candidate with K candidates. As $B \to \psi' K$ and $B \to X(3872)K$ decay modes have the same topology and are well established, we used them as our control sample to validate and calibrate our MC simulations. Comparison of ψ', $X(3872)$, and $Y(4260)$ signal is shown in Fig. 17.2.

We use two kinematical variables to identify the B meson: the beam constrained mass ($M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - \sum_i p_i^{*2}}$) and the energy difference ($\Delta E = \sum_i E_i^* - E_{\text{beam}}$). Here, E_{beam} is the beam energy in the center of mass (CM) frame and p_i^* (E_i^*) is the momentum (energy) of the ith particle in the CM frame of the $\Upsilon(4S)$. There are multiple reconstructed B candidates in an event due to wrong combination of selected particles. We have to select best B meson in an event which has least χ^2

$$\chi^2 = \chi^2_{\text{vtx}} + \left(\frac{M_{J/\psi} - m_{PDG}^{J/\psi}}{\sigma_{J/\psi}}\right)^2 + \left(\frac{M_{\text{bc}} - m_B^{PDG}}{\sigma_{M_{\text{bc}}}}\right)^2 \qquad (17.1)$$

where $\sigma_{J/\psi}$ and $\sigma_{M_{bc}}$ represent the $M_{J/\psi}$ and M_{bc} resolutions, respectively, and are taken to be 9.835 MeV/c^2 and 2.59 MeV/c^2 , respectively, from a fit to the $B \to \psi' K$ events. χ^2_{vtx} represents vertex fit for all the charged particles. This procedure to select most probable B candidate is called the best candidate selection. The best candidate selection chooses true candidate 76% of the time for $B^+ \to Y(4260)K^+$.

17.3 Background Study

Continuum events $e^+e^- \to q\bar{q}$ (where $q = u, d, s$ or c) are suppressed by requiring $R_2 = H_2/H_0 < 0.5$, where R_2 is the ratio of the second- to zeroth-order Fox-Wolfram moments [18]. The main background contribution is expected to be arise from inclusive B decays to J/ψ. With the above selection criteria, we didn't find any peaking structure in the signal region for $B \to \psi' K$, $B \to X(3872)K$, and $B \to Y(4260)K$ decay modes. We expect negligible contribution from J/ψ mass sidebands (2.54 GeV/c^2 $< M_{J/\psi} <$ 2.72 GeV/c^2 and 3.32 GeV/c^2 $< M_{J/\psi} <$ 3.5 GeV/c^2).

17.4 Signal Extraction

We performed unbinned extended maximum likelihood (UML) fit to the ΔE variable for each mode and get the background subtracted ${}_s\mathcal{P}$lot [19] distribution of $M_{J/\psi\pi\pi}$. The likelihood function used is

$$\mathcal{L}(N_S, N_B) = \frac{e^{-(N_S+N_B)}}{N!} \prod_{i=1}^{N} (N_S \times P_S + N_B \times P_B) \tag{17.2}$$

where N is the total number of events. N_S and N_B are the signal events and background events, respectively. P_S (P_B) is the signal (background) probability density function (PDF) model. Signal PDF (P_S) for ΔE is modeled by a sum of two Gaussians and bifurcated Gaussian for the $B \to \psi' K$ and $B \to X(3872)K$ decay mode. Background PDF (P_B) is modeled by the first order polynomial for $\psi' K$, while second order polynomial is used for $X(3872)K$. We extract the signal yield from a UML fit to the ${}_s\mathcal{P}$lot distribution of $M_{J/\psi\pi\pi}$. Here also, the PDF comprises of signal (P_S) and a flat background (P_B). P_S for $M_{J/\psi\pi\pi}$ is a sum of two Gaussians for $\psi' K$, and a sum of two Gaussians plus bifurcated Gaussian for $X(3872)K$. P_B for $M_{J/\psi\pi\pi}$ is second order polynomial for $\psi' K$, while the first order polynomial is used for $X(3872)K$. The mean and width of the core Gaussian are varied and remaining parameters are fixed according to the MC. The results of the fit for the control samples $B \to \psi' K$ and $B \to X(3872)K$ are shown in Fig. 17.3 and Fig. 17.4, respectively.

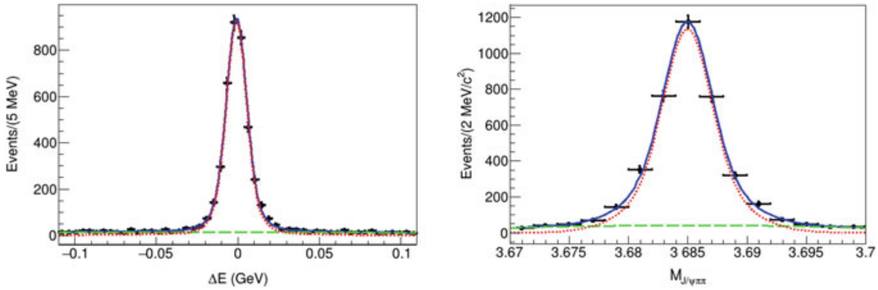

Fig. 17.3 Fit to the ΔE and ${}_s\mathcal{P}lot$ of $M_{J/\psi\pi\pi}$ distributions for $B^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)K^+$

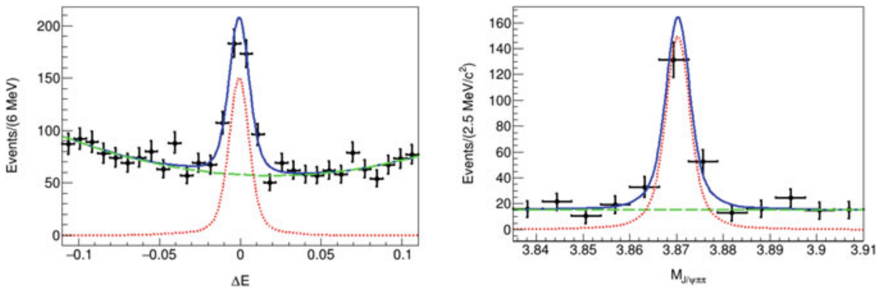

Fig. 17.4 Fit to the ΔE and ${}_s\mathcal{P}lot$ of $M_{J/\psi\pi\pi}$ distributions for $B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$

17.5 Branching Fraction

We determine the branching fraction, $\mathcal{B}(B \to \psi' K)$ and $\mathcal{B}(B \to X(3872)K) \times \mathcal{B}(X(3872) \to J/\psi\pi\pi)$ via relation

$$\mathcal{B} = \frac{N_{\text{event}}}{N_{B\bar{B}} \times \epsilon \times \mathcal{B}_{\text{secondary}}} \tag{17.3}$$

where N_{event} is the number of events for a particular mode, $N_{B\bar{B}} = (772 \pm 11) \times 10^6$ is the number of $B\bar{B}$ events in the data, $\mathcal{B}_{\text{secondary}}$ is the secondary branching fractions ($\mathcal{B}(\psi' \to J/\psi\pi\pi) = 0.3449 \pm 0.0030$ [20] and $\mathcal{B}(J/\psi \to \ell\ell) = 0.119 \pm 0.001$ [20]) based on the mode, ϵ is the efficiency estimated from the signal MC after MC/data correction. Results are summarized in Table 17.1 and agrees well with previous results [21].

Table 17.1 Summary of the reconstruction efficiency (ϵ), signal yield (N_S), branching fraction ($\mathcal{B}$) measured and PDG branching fraction ($\mathcal{B}_{PDG}$) for the $B \to \psi(2S)K$ and $B \to X(3872)K,\ X(3872) \to J/\psi\pi^+\pi^-$ decays

Decay	$B^+ \to \psi(2S)K^+$	$B^+ \to X(3872)K^+,\ X(3872) \to J/\psi\pi^+\pi^-$
ϵ (%)	16.8	22.2
N_S	3481 ± 95	185 ± 13
$\mathcal{B}$	$(6.54 \pm 0.18) \times 10^{-4}$	$(9.07 \pm 0.64) \times 10^{-6}$
$\mathcal{B}_{PDG}$	$(6.21 \pm 0.23) \times 10^{-4}$	$(8.6 \pm 0.8) \times 10^{-6}$

17.6 Summary

In summary, a search for $B \to Y(4260)K$ is crucial to understand the structure of $Y(4260)$. This study is performed using $B\bar{B}$ pairs collected at $\Upsilon(4S)$ resonance by the Belle at KEKB. The branching fractions obtained for $B \to \psi' K$ and $B \to X(3872)K$ are $(6.54 \pm 0.18) \times 10^{-4}$ and $(9.07 \pm 0.64) \times 10^{-6}$, respectively, and found to be consistent with the previous results [21]. Final results for $B \to Y(4260)K$ are obtained and published [22].

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