Prospects in spectroscopy with Belle II

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Abstract. Belle played a leading role in shaping the spectroscopy sector for last decade. With 50 times more data than Belle, the Belle II experiment also expects to play crucial role in spectroscopy for the next decade. In this talk, a few chosen results one expects from Belle II will be discussed.

Keywords: Belle II, spectroscopy, prospects, quarkonium, exotic

1 Introduction

The Belle II detector [1] is a general purpose detector built to test Standard Model mechanism by doing precision measurements. Belle II also provides a very clean environment and is an ideal place to carry quarkonium $q\bar{q}$ spectroscopy related studies. $q\bar{q}$ are produced through B decays, double charmonium production, two photon production, initial state radiation, and quarkonium decay/transitions.

For the last 15 years Belle [2] (predecessor of the Belle II detector with similar environment) had a very successful program on quarkonium ($q\bar{q}$). Many new $q\bar{q}$ (-like) states such as $\eta_c(2S)$, $X(3872)$, $X(3915)$, $Z(3930)$, $X(3940)$, $Z_1(4050)^+$, $Y(4260)$, $Z(4430)^+$, $Y(4660)$, $Z_b(10610)$, and $Z_b(10650)$ have been found. Many of these states cannot be accomodated by the conventional spectroscopy. Some states have non-zero charge which suggest that they are tetraquark/molecule-like states. Belle II (with the ability to accumulate 50 times more data in comparison to Belle) will be able to play important role in understanding the nature of these states. In this talk, I will try to give brief overview of the Belle II program for quarkonium. I should admit here that I have not done justice in this proceeding. Interested readers should refer to the Belle II Physics book [3].

2 Belle to Belle II

The Belle II experiment (situated in Tsukuba, Japan), is the upgraded successor of Belle. The detector's major upgrades in comparison to Belle are:

- A Vertex detector (VXD) consisting of two layers of DEPFET pixels (PXD) and four layers double-sided silicon strips (SVD), with improved resolution (to half) compared to Belle.

- A central drift chamber (CDC) with larger volume drift chamber, smaller drift cells and faster electronics.
- Completely new particle identification [time of propagation (barrel) and proximity-focusing Aerogel Ring-Imaging Cherenkov detector (end-cap)].
- Belle CsI (Tl) crystals are used for the electro-magentic calorimeter with modified waveform sampling electronics to reject pile-up events.
- Upgraded $K_L - \mu$ detection system (KLM) where resistive plate counter used in Barrel. Because of the projected inefficiency of RPCs at high ambient rate, Belle II end-caps are instrumented with scintillator strips.

3   Current status of Belle II

Belle II successfully completed "Phase II" commissioning runs and accumulated 472 pb^{-1} of data. During Phase II, all the sub-detectors were in except the full vertex detector (partial vertex detector for a particular ϕ was in).
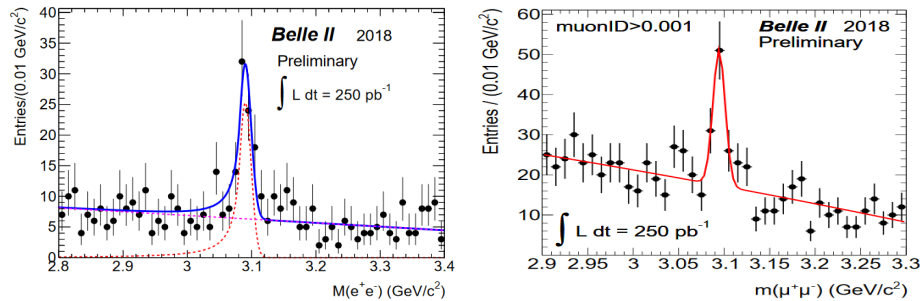

Fig. 1. Reconstructed invariant mass of $J/\psi \to e^+e^-$ (left) and $J/\psi \to \mu^+\mu^-$ (right) at Belle II using partial Phase II data. We also have the plots with full data at current date (however, the plots shown here are similar to what was shown at the conference). Plots with full data set can be found at Ref. [4]

3.1   Re-discovery of "November revolution"

Figure 1 shows the reconstructed $J/\psi \to \ell^+\ell^-$ demonstrating the capability of reconstructing lepton tracks. We see a clear peak of J/ψ to e^+e^- and $\mu^+\mu^-$ reconstruction.

3.2   Re-discovery of D and B mesons

Figure 2-3 shows the reconstructed D and B mesons demonstrating the capability of reconstructing charged and neutral Kaon and pions.

As seen from the re-discovery plots of the J/ψ, D, and B, the Belle II detector is working as per expectation.

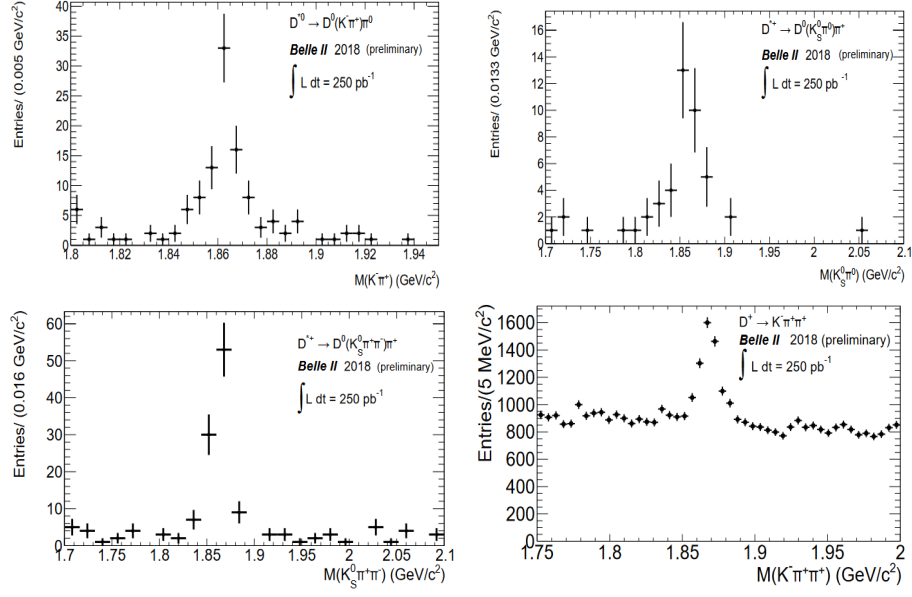**Fig. 2.** Reconstructed invariant mass of D mesons from various decay modes.
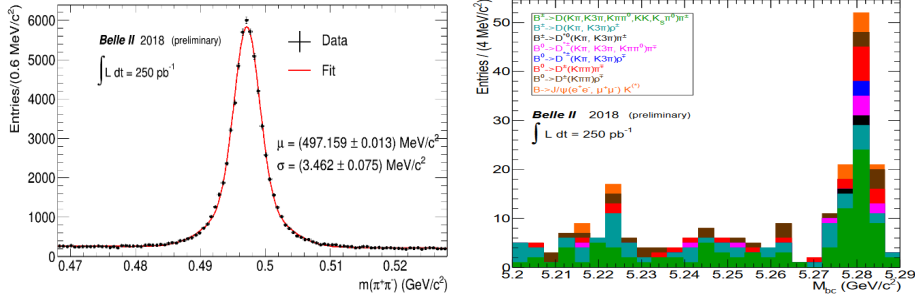

Fig. 3. Invariant mass of reconstructed $K_S^0 \to \pi^+\pi^-$ (left) and M_{bc} for reconstructed B meson from different modes.

4 Prospects for $c\bar{c}$(-like) states

$X(3872)$ was first observed in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ process at Belle [5]. Soon after its discovery, $X(3872)$ was confirmed by CDF [6], D⊘ [7], BaBar [8], LHCb [9] and CDF [10]. A lot of effort went into studying this particle, thanks to which now we know its precise mass, width, and J^{PC} to be (3871.69 ± 0.17) MeV/c^2 [11], < 1.2 MeV [12], and 1^{++} [13], respectively. At Belle II, we expect 1500 signal events with 10 ab^{-1} of data (which is 1/5 of the total data Belle II aims to accumulate). Just to give an idea, the current yield of $B^+ \to \psi'(\to J/\psi\pi\pi)K^+$ is ~3600 signal events at Belle. This will help in measuring precisely $X(3872)$

mass and width. Within the first two years of data taking, one can expect that Belle II will accumulate 5 to 10 ab^{-1} of data.

The narrow width of $X(3872)$ and the proximity of its mass to the $D^0\bar{D}^*$ threshold makes it a good candidate for a $D^0\bar{D}^*$ molecule [14]. Currently the most probable explanation for the $X(3872)$ nature is a molecule with admixture of charmonium.

If $X(3872)$ is charmonium then one expects it to be χ'_{c1}. If so then it should decay to $\chi_{c1}\pi^+\pi^-$. Current search by the Belle has a negative result [15]. One can measure or expect a tighter constraint from Belle II.

Performing the study of $X(3872) \to \bar{D}^0 D^{*0}$ [16] with the full Belle II data will bring more information. Measuring the ratios of radiative decays [17] $\mathcal{B}(X(3872) \to \psi'\gamma)/\mathcal{B}(X(3872) \to J/\psi\gamma)$ with more data is what Belle II should do, as it is crucial for understanding the nature of $X(3872)$. If $X(3872)$ is a $D^0\bar{D}^{*0}$ molecule, then one expects that there may be other "X-like" particles with different quantum numbers that are bound states of $D^{(*)}$ mesons, such as a $(D^0\bar{D}^{*0} - \bar{D}^0 D^{*0})$ combination as the C-odd partner of $X(3872)$ with J^{PC} of 1^{+-}. C-odd search has been negative till now [18]. Searching for the the charged $X(3872) \to J/\psi\pi^+\pi^0$ [12] and C-odd partners such as $J\psi\eta$ at Belle II is interesting. If found, it will suggest a molecular/tetraquark nature of the $X(3872)$ [19]. On the other side, absence of charged partners suggest $X(3872)$ to be an iso-singlet state. This suggests $X(3872) \to J/\psi\pi^+\pi^-$ to be an iso-spin violating decay. BaBar has measured the ratio $\mathcal{B}(X(3872) \to J/\psi\omega(\to \pi^+\pi^-\pi^0))/\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)) = 0.8\pm0.3$. Belle II can improve this ratio with much precision.

Absolute $\mathcal{B}(B \to X(3872)K^+)$ helps in measuring $\mathcal{B}(X(3872) \to$ final states). This measurement is only possible at the e^+e^- B factories. One has to reconstruct the missing mass recoiling against the K^+,

$$M_{\mathrm{miss}} = \sqrt{(p^*_{e^+e^-} - p^*_{\mathrm{tag}} - p^*_K)^2}/c \tag{1}$$

where M_{miss} is the missing mass recoiling against the K^+, and $p^*_{e^+e^-}$, p^*_{tag}, and p^*_K are the four-momenta of the electron-positron initial state, B_{tag} (full reconstruction of one of the two charged B mesons via hadronic states) and kaon, respectively, in the center-of-mass frame. The M_{miss} peaks around the mass of the signal. Belle measured $\mathcal{B}(B^+ \to X(3872)K^+) < 2.6 \times 10^{-4}$ (@ 90% CL) [20]. With 50 times more data, Belle II can measure the branching fraction till 10^{-5} or less due to the improvement [21] in the full reconstruction algorithm (in comparison to Belle).

Not only decays, but also production of $X(3872)$ in the B decay provide information about the nature of $X(3872)$. Belle observed the $B^0 \to X(3872)K^+\pi^-$ decay mode having 7σ significance. In their study of the production dynamics of $B^0 \to X(3872)K^+\pi^-$, they found that $B^0 \to X(3872)K^*(892)^0$ does not dominate the $B^0 \to X(3872)K^+\pi^-$ decay, which is in contrast to the normal charmonium states (where $K^*(892)^0$ dominates) [22]. This suggest that $X(3872)$ doesn't behave like normal charmonium states. With 10 ab^{-1} of data collected with Belle II, we expect $B \to X(3872)K\pi$ to have the same number of events to

what Belle has accumulated for $B \to \psi' K \pi$. Therefore, one can expect to have a more precise measurement.

In the two photon process, $\gamma\gamma \to J/\psi\phi$, Belle observed $X(4350)$ [23]. However, recently in the amplitude analysis of $B \to J/\psi\phi K$, LHCb found several structures ($Y(4140)$, $Y(4274)$, $X(4500)$, and $X(4700)$) but did not found $X(4350)$ [24]. Belle II should revisit with more data. Another area where Belle II can contribute is the $Y(4260)$ study. Belle II will compliment BESIII here. We expects improvement in mass resolution due to CDC improvements. Belle II with 50 ab^{-1} should be able to study the line-shape of $Y(4260)$. Another possible study one can think of is $e^+e^- \to Y(4260)(\to J/\psi\pi^0\pi^0)\gamma_{ISR}$ to search for a neutral partner. Also, measuring $\mathcal{B}(B \to Y(4260)K)$ at Belle II is an important in step to understand the nature of $Y(4260)$. The first charged $Z(4430)^+$ state was seen by Belle in the $B^0 \to (\psi'\pi^+)K^-$ decay mode [25]. Till recently this state was not well established due to non observation in other experiments. Recently, LHCb confirmed $Z(4430)^+$ and using an Argand diagram, they supported the resonance nature of this state [26]. Belle II can perform amplitude analyses with more statistics (similar to the one done at Belle [27,28]) and help in understanding these states with precision. Other modes not feasible at Belle are also accessible at Belle II. For example only with 10 ab^{-1} of data at Belle II, one expects the yield of the $B^0 \to (\chi_{c2}\pi^-)K^+$ decay mode to become comparable to what Belle accumulated for $B^0 \to (\chi_{c1}\pi^-)K^+$ [29]. Not only that but Belle II can also search for the neutral partners using π^0 modes ($B^0 \to (c\bar{c})\pi^0 K^+$).

5 Prospects for $b\bar{b}$(-like) states

The bottomonium spectrum has found to be different from what we have understood in charmonium spectrum. Belle II is a unique place to carry out bottomonium related studies due to the energy accessible by SuperKEKB (expecting to reach $\Upsilon(5,6S)$ energy). We know that Z_b states were found in the $\Upsilon(5S)$ decays by Belle and are clear signature of exotic states. Belle [30] found that

$$\frac{\Gamma(\Upsilon(5S) \to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.45 \pm 0.08^{+0.07}_{-0.12}, \text{ for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17}, \text{ for } h_b(2P) \end{cases} . (2)$$

While one expected the decay to h_b should be suppressed due to spin flip, its higher rate was something puzzling. The $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ decay mechanism seems to be exotic. Belle found that $\Upsilon(5S) \to Z_b^+\pi^-$, then Z_b^+ decays to $h_b\pi^+$. $Z_b(10610)$ and $Z_b(10650)$ were found in $\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$, $h_b(1P)\pi^+\pi^-$, and $h_b(2P)\pi^+\pi^-$ decay with masses around the B^*B and B^*B^* thresholds [31]. With more data, Belle II expects to measure the mass and width more precisely. Further, Belle II can study neutral Z_b^0 in $\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ [32] and confirm in other modes also.

Another study of interest to be done at Belle II is an energy scan. A previous energy scan of the $e + e^- \to h_b(nP)\pi^+\pi^-$ ($n = 1, 2$) cross sections by Belle gave first evidence for $\Upsilon(6S) \to h_b(1P)\pi^+\pi^-$ and observation of $\Upsilon(6S) \to h_b(2P)\pi^+\pi^-$. While studying the resonant structure, they found evidence that it

proceeds entirely via the intermediate iso-vector states $Z_b(10610)$ and $Z_b(10650)$ [33]. Currently only Belle II has the capability to do an $\Upsilon(nS)$ scan.

With a unique data set at $\Upsilon(6S)$, Belle II can study $\Upsilon(6S) \to h_b(nP)\pi^+\pi^-$, $\Upsilon(6S) \to \Upsilon(mS)\pi^+\pi^-$ ($n = 1$, 2; $m = 1$, 2, 3). If Z_b is a molecular state, then Heavy Quark Spin symmetry suggests there should be 2 or 4 molecular partner bottomonium-like states (W_b): $\Upsilon(5S, 6S) \to W_{b0}\gamma$, and $\Upsilon(6S) \to W_{b0}\pi^+\pi^-$, where $W_{b0} \to \eta_b\pi, \to \chi_b\pi, \Upsilon\rho$. Fig. 5 summarizes the possible decays via which one can access the molecular partners of bottomonium-like states [34]
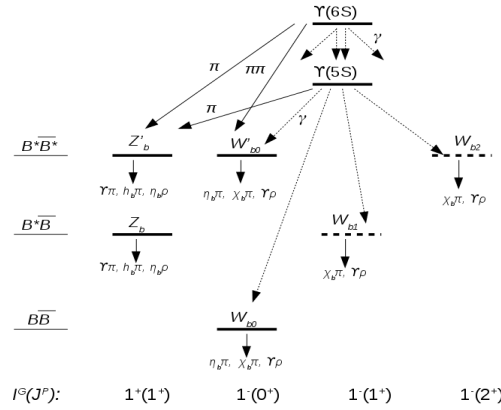

Fig. 4. Accessing molecular partner bottomonium-like states (W_b) via transitions from $\Upsilon(5, 6S)$.

Acknowledgement

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