# Prospects in spectroscopy with Belle II

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

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

## 1 Introduction

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 have been found which can't find place in the conventional spectroscopy. Some states have non-zero charge which suggest that they are tetraquark/molecule-like state. Belle II (with 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 are suggested to go through Belle II Physics book [3].

## 2 Belle to Belle II

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

- Vertex detector (VXD) consists of two-layers DEPFET pixel (PXD) and 4-layers double-sided silicon strips (SVD), with improved resolution (to half) of what we got in Belle.

- A central drift chamber (CDC) with larger volume drift camber, smaller drift cells and faster electronics.
- A complete new particle identification [time of propogation (barrel) and proximity-focusing Aerogel Ring-Imaging Cherenkov detector (endcap)].
- Old 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 endcaps are instrumented with scintillator strips.

## 3 Current status of Belle II

Belle II successfully completed running on Phase II and accumulated 472 $pb^{-1}$ of data at $\Upsilon(4S)$. During Phase II, all the sub-detectors were in except full vertex detector (partial vertex detector for a particular $\phi$ was in).

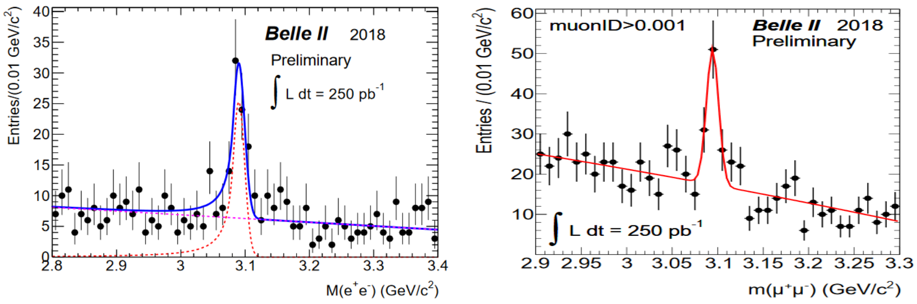

**Fig. 1.** Reconstructed invariant mass of $J/\psi \to e^+e^-$ (left) and $J/\psi \to \mu^+\mu^-$ (right) at Belle II using partial Phase II data. We also have the plots with full data at current date (however, the plots shown here are similar to what was shown at the conference). Plots with full data 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 clear peak of $J/\psi$ 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 $J/\psi$, $D$, and $B$ Belle II detector is working as per expectation.

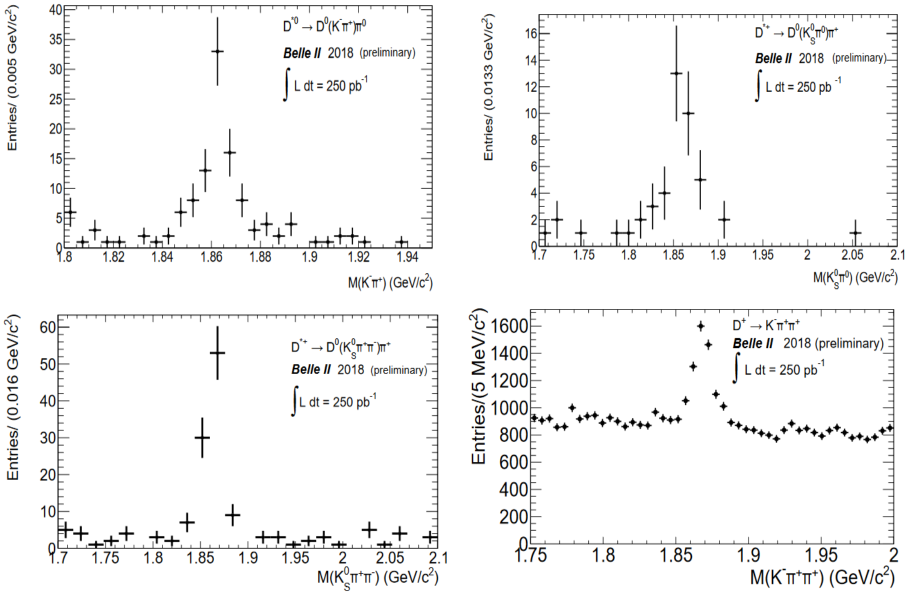

**Fig. 2.** Reconstructed invariant mass of $D$ mesons from various decay modes.

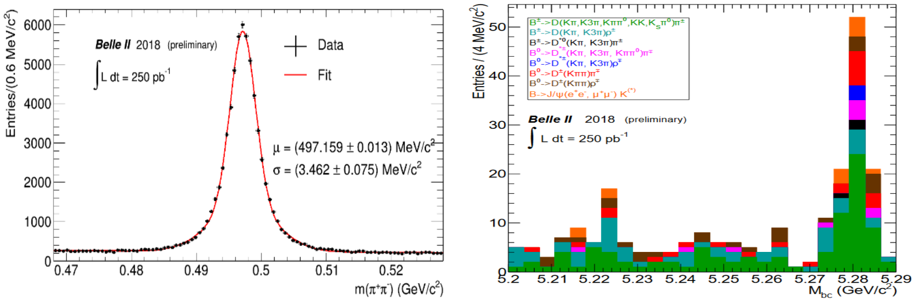

**Fig. 3.** Invariant mass of reconstructed $K^0_S \to \pi^+\pi^-$ (left) and beam constrained mass $M_{\rm bc}$ for reconstructed $B$ meson from different modes.

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

$X(3872)$ was first observed in the $B^+ \to (J/\psi\pi^+\pi^-)K^+$ at Belle [5]. Soon after its discovery, $X(3872)$ was confirmed by CDF [6], DO [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 $(3871.69\pm0.17)$ 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 total data Belle II aim to accumulate). Just to give an idea current yield of $B^+ \to \psi'(\to J/\psi\pi\pi)K^+$ is 3600 signal events at Belle. This will help in measuring precisely its' mass and width.

Within first two years of data taking one can expect that Belle II will accumulate 5 to 10 $\mathrm{ab}^{-1}$ 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]. Current most probable explanation for the $X(3872)$ nature is: molecule with admixture of charmonium.

If $X(3872)$ is charmonium then one expect it to be $\chi'_{c1}$. If so then it should decay to $\chi_{c1}\pi^+\pi^-$. Current search by the Belle has negative result [15]. One can measure or expect tighter constraint from the 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 expect that there may be other "$X$-like" particles with different quantum numbers that are bound states of $D^{(*)}$ mesons. Such as $(D^0\bar{D}^{*0} - \bar{D}^0 D^{*0})$ combination is a $C$-odd partner of $X(3872)$ having $J^{PC}$ 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 molecular/tetraquark nature of the $X(3872)$ [19]. On the other side, absence of charged partner suggest $X(3872)$ to be an iso-singlet state. This suggest $X(3872) \to J/\psi\pi^+\pi^-$ to be iso-spin violating decay. Babar has measured the ratio $\mathcal{B}(X(3872) \to J/\psi\omega(\to \pi^+\pi^-\pi^0))/\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-))$ $= 0.8 \pm 0.3$. Belle II can improve this ratio with much precision.

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

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

where $M_{\mathrm{miss}}$ is the missing mass recoiling against the $K^+$, and $p^*_{e^+e^-}$, $p^*_{\mathrm{tag}}$, and $p^*_K$ are the four-momenta of the electron-positron initial state, $B_{\mathrm{tag}}$ (full reconstruct one of the two charged $B$ mesons via hadronic states) and kaon, respectively, in the center-of-mass frame. The $M_{\mathrm{miss}}$ 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 scan 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 $B^0 \to X(3872)K^+\pi^-$ decay mode having $7\sigma$ 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 $\mathrm{ab}^{-1}$ of data collected with Belle II, we expect $B \to X(3872)K\pi$ to have same number of events to what Belle has accumulated for $B \rightarrow \psi' K\pi$. Therefore, one can expect to have more precise measurement.

In two photon process, $\gamma\gamma \rightarrow J/\psi\phi$, Belle observed $X(4350)$ [23]. However, recently in the amplitude analysis of $B \rightarrow J/\psi\phi K$ LHCb found several structures ($Y(4140)$, $Y(4274)$, $X(4500)$, and $X(4700)$) but didn't 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 longer CDC. Belle II with 50 ab$^{-1}$ should be able to study the lineshape of $Y(4260)$. Another possible study one can think of is $e^+e^- \rightarrow Y(4260)(\rightarrow J/\psi\pi^0\pi^0)\gamma_{ISR}$ for neutral partner. Also, measuring $\mathcal{B}(B \rightarrow Y(4260)K)$ at Belle II is important in step to understand the nature of $Y(4260)$. First charged $Z(4430)^+$ state was seen by Belle in $B^0 \rightarrow (\psi'\pi^+)K^-$ 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 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 precisions. 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 expect the yield of $B^0 \rightarrow (\chi_{c2}\pi^-)K^+$ decay mode to become comparable to what Belle accumulated for $B^0 \rightarrow (\chi_{c1}\pi^-)K^+$ [29]. Not only that but Belle II can also search for the neutral partners using $\pi^0$ modes ($B^0 \rightarrow (c\bar{c})\pi^0 K^+$).

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

Bottomonium spectrum has been found to be different from what we have understood in charmonium spectrum. Belle II is unique place to carry bottomonium related studies due to the energy accessible by SuperKEKB ( expect 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 state. Belle [30] found that

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

While one expected the decay to $h_b$ should be suppressed due to spin flip, its higher rate was something puzzling. $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$ decay mechanism seems to be exotic. Belle found that $\Upsilon(5S) \rightarrow Z_b^+\pi^-$, then $Z_b^+$ decays to $h_b\pi^+$. $Z_b(10610)$ and $Z_b(10650)$ was 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 mass around $B^*B$ threshold and $B^*B^*$ threshold [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 $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$ [32] and confirm in other modes also.

Another study of interest to be done at Belle II is the energy scan. Recent energy scan of the $e+e^- \rightarrow h_b(nP)\pi^+\pi^-$ (n=1,2) cross sections by Belle gave first evidence for $\Upsilon(6S) \rightarrow h_b(1P)\pi^+\pi^-$ and observation for $\Upsilon(6S) \rightarrow h_b(2P)\pi^+\pi^-$. While studying the resonant structure, they found evidence that they proceed entirely via the intermediate isovector states $Z_b(10610)$ and $Z_b(10650)$ [33]. Currently only Belle II has the capability to do $\Upsilon(nS)$ scan.

With 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 molecular state, then Heavy Quark Spin symmetry suggest there should be 2 or 4 molecular partner bottomonium-like state $(W_b)$: $\Upsilon(5S, 6S) \to W_{b0}\gamma$, 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 partner of bottomonium-like states [34]

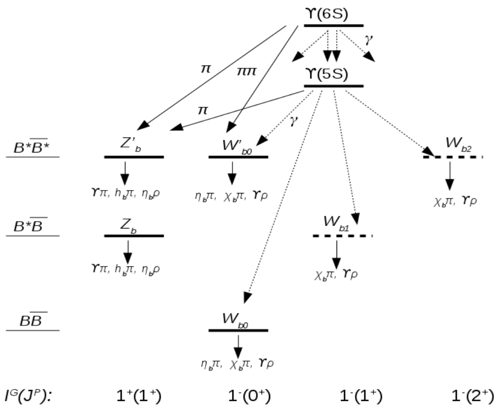

**Fig. 4.** Accessing molecular partner bottomonium-like state $(W_b)$ via transtion from $\Upsilon(5, 6S)$.

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