PROCEEDINGS OF SCIENCE

Charmonium-like studies at Belle II

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The Belle II experiment has accumulated data corresponding to 213 fb^{-1} integrated luminosity in the past two years. Belle II plans to accumulate 50 ab^{-1} of data which is expected to bring large impact to the field of hadron spectroscopy. We present here the analysis of $B \to KJ/\psi\pi^+\pi^-$ and $B \to K\psi(2S)$ using 62.8 fb^{-1} of data at Belle II. We find evidence of $X(3872) \to J/\psi\pi^+\pi^-$ with a signal yield of 14.4 ± 4.6 and a statistical significance of 4.6 σ. We also present the preliminary results of $e^+e^- \to \pi^+\pi^-J/\psi$ via ISR using 37.8 fb^{-1} of data at Belle II.

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1. Introduction

The Gell-Mann Zweig idea, known as the Constituent Quark Model, [1][2] classifies all known hadrons which is expected to consist of two- (mesons) or three-quark (baryons) combinations. One such possible epitome is quarkonium which is a bound state of heavy quark (b,c) with its anti-quark. This system is explained by various theoretical models based on quantum chromodynamics (QCD), the theory of strong interaction. However, the motivated QCD models predicts the existence of complex structures known as *exotic* states involving more than 3 quarks which became evident with the discovery of $X(3872)$[1] at Belle[3] in 2003. Soon after, $X(3872)$ was confirmed by CDF[4], D∅[5], BaBar[6] and LHCb[7]. More than 30 exotic candidate states have been observed after the discovery of $X(3872)$, mostly found in the charmonium sector accessible via B decays and direct production.

Undoubtedly, the B-factories have made rich contribution to quarkonium spectroscopy. However, some interesting signatures such as $Z_c(3900)$, $Z_c(4430)$, etc. have not been fully established yet. More data are needed to understand and unravel the situation. Belle II is expected to help improve our understanding in this sector.

2. SuperKEKB & Belle II

The Belle II experiment [8] is located at the SuperKEKB asymmetric e^+- e^- collider at KEK in Tsukuba, Japan. SuperKEKB is designed to reach the peak luminosity which is $\sim$ 30 times higher than that of KEKB. The instantaneous luminosity achieved so far is $3.1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. The goal of the Belle II experiment is to accumulate a data set of 50 ab^{-1}, 50 times larger than that of Belle. As compared to Belle, Belle II can provide better vertexing resolution and comparable kaon pion seperation in a higher beam background environment. Figure 1 shows the overview of the SuperKEKB and the Belle II detector.

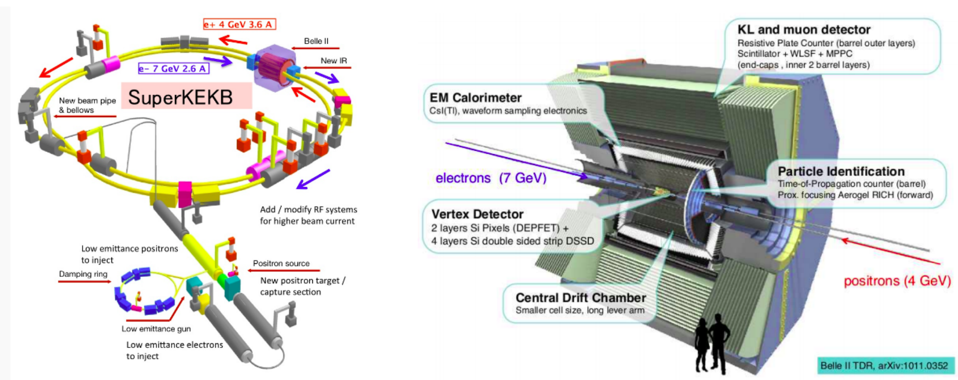

Figure 1: Overview of SuperKEKB and Belle II detector.

[1]It is called $\chi_{c1}(3872)$ in PDG.

3. Study of $X(3872)$ at Belle II

The $X(3872)$ was first discovered at Belle in $B \to KJ/\psi\pi^+\pi^-$. It has been widely studied in various decay modes. However, the complete nature of this state is not fully clear yet.

The search for $X(3872)$ at Belle II is done by studying $B \to KJ/\psi\pi^+\pi^-$ using 62.8 fb^{-1} of data collected at the Υ(4S) resonance. The charged tracks are required to originate from the interaction point by applying the selection criteria in the r-ϕ plane and along z-axis. K_s^0 mesons are reconstructed by combining two oppositely charged pion candidates, subjecting them to a vertex fit, and constraining the resulting K_s^0 candidate mass $m_{\pi^+\pi^-}$ to be within 490 and 506 MeV/c^2. J/ψ mesons are reconstructed from a pair of oppositely charged electron or muon tracks. After requiring the J/ψ candidate mass to be in between 3.070 and 3.117 GeV/c^2 for candidates reconstructed from $\mu^+\mu^-$, or in between 3.065 and 3.117 GeV/c^2 in the case of e^+e^-, a mass-constrained fit is performed. For the $\pi^+\pi^-$ pair not associated with the K_s^0, the condition $(m_{\pi^+\pi^-}) - (m_{J/\psi\pi^+\pi^-}) + m_{J/\psi} >$ -0.150 GeV/c^2 is applied, where $m_{J/\psi}$ is the nominal mass of J/ψ[13], in order to reduce combinatorial backgrounds and misidentified $\gamma \to e^+e^-$ conversions. To reduce the $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ background events, a selection on the normalized fox-wolfram moments[14] R_2 is applied. The B meson candidates are selected with the energy difference $\Delta E = E_B^{cms} - \sqrt{s}/2$ and the beam-constrained mass $M_{bc} = \sqrt{s/4 - (p_B^{cms})^2}$, where E_B^{cms} and p_B^{cms} are the energy and momentum of the B candidate in the center-of-mass system, respectively. The signal candidates are required to have M_{bc} >5.27 GeV/c^2 and $\Delta E < 0.02$ GeV. The $m_{J/\psi\pi^+\pi^-}$ distribution is used to extract the signal. A histogram PDF generated with signal MC samples assuming the nominal mass of $X(3872)$[9] and the width from the LHCb measurement[10] is used as a PDF for the signal component. A first-order Chebyshev polynomial is used as a PDF for the background component. A simultaneous fit is performed so as to combine the distribution for B^0 decay and that for B^+ decay, where a ratio of the expected signal yields is constraint. Here, $\mathcal{B}(B^0 \to X(3872)K^0)/\mathcal{B}(B^+ \to X(3872)K^+) =$ 0.50 is assumed [11].

The Belle II re-discovered the $X(3872)$ with a 14.4 ± 4.6 signal events with a 4.6 σ statistical significance is shown in Figure 2. This study is validated with the control sample $B \to \psi(2S)K$ as shown in Figure 3. Here, a triple Gaussian with a common mean are used as a probability density function (PDF) for the signal component, where parameters except the mean and scaling factor of the sigmas are determined with the signal Monte-Carlo (MC) samples. A first-order Chebyshev polynomial is used as a PDF for the background component.

The full width measurement at Belle II is planned with $B \to KX(3872)$, $X(3872) \to DD\pi$ due to the low Q-value, and hence, the mass resolution is much better as compared to $J/\psi\pi^+\pi^-$ channel. The Figure 4 shows that 3σ sensitivity on the width is expected to be accessible with 10 ab^{-1} or more data.

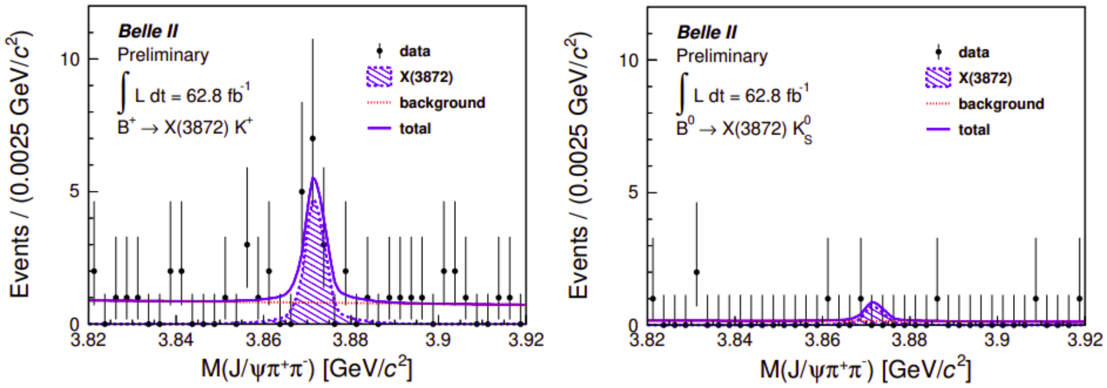

Figure 2: The $m_{J/\psi\pi^+\pi^-}$ distributions on the $X(3872)$ signal region with the real data. Blue solid line shows total fit result.

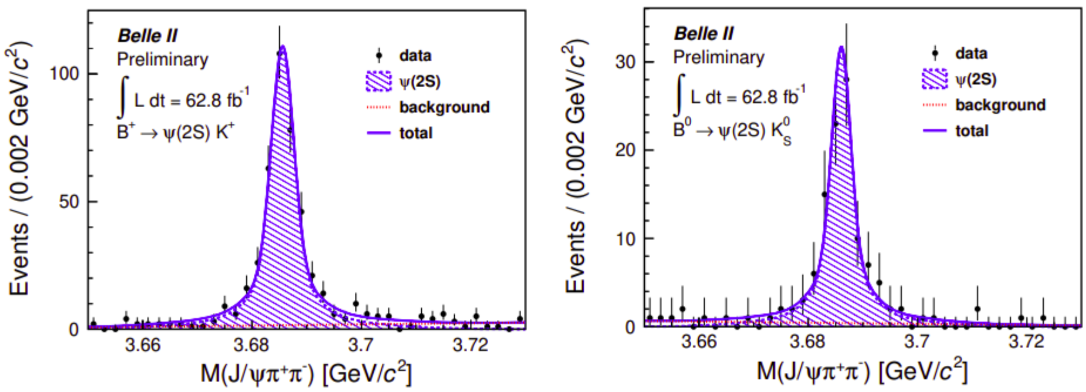

Figure 3: The $m_{J/\psi\pi^+\pi^-}$ distributions on the $\psi(2S)$ signal region with the real data. Blue solid line shows total fit result.

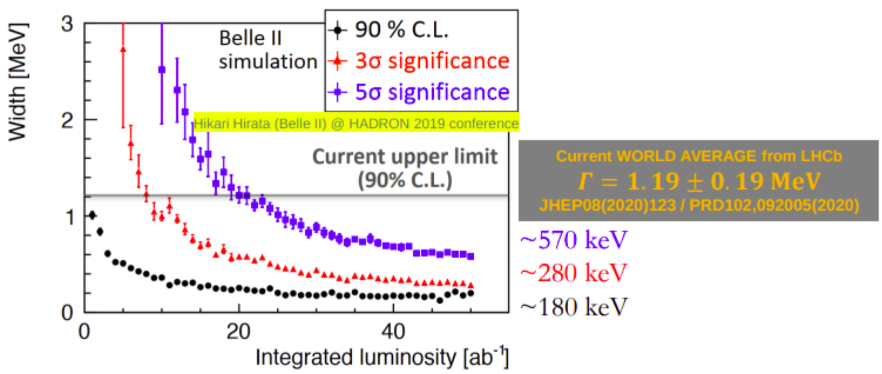

Figure 4: Width of the $X(3872)$ as a function of the expected integrated luminosity at Belle II. The plot shows MC simulations of the estimated upper limit at 90% C.L. (black dots), at 3σ (red dots) & at 5σ (blue dots) of the measured $X(3872)$ width at Belle II. The horizontal black line is fixed to the current upper limit of 1.2 MeV for comparison[12].

4. ISR preliminary results at Belle II

Initial State Radiation (ISR) is a useful tool to study $J^{PC} = 1^{--}$ states below the center-of-mass energy. The advantage of ISR is that the whole hadron spectrum is visible so that the line shape of the resonance and fine structures can be investigated.

The decay $e^+e^- \to \pi^+\pi^- J/\psi$ via ISR is studied using 37.8 fb^{-1} of data collected at Υ(4S) resonance. The J/ψ meson is reconstructed from e^+e^- or $\mu^+\mu^-$ within a mass range of 75 MeV/c^2 from the nominal value. A selection on the missing mass squared ($|MM^2(J/\psi\pi^+\pi^-)| < 2$ GeV/c^2) is required. A clear signal of ISR $\psi(2S)$ is seen as shown in Figure 5.

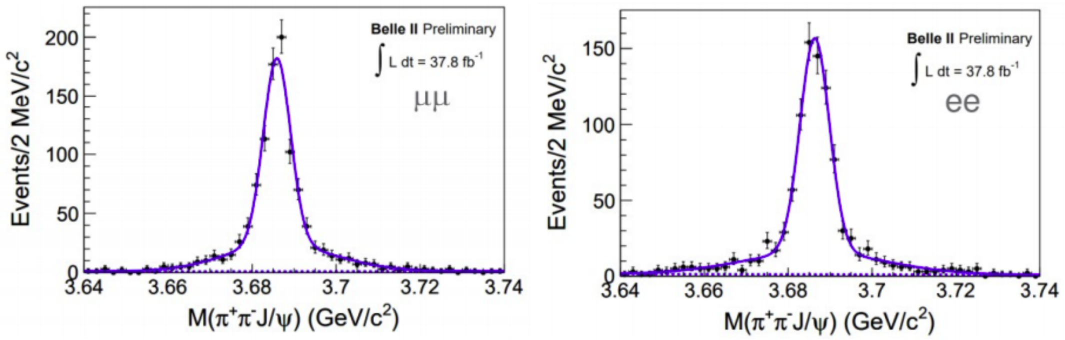

Figure 5: The $J/\psi\pi^+\pi^-$ invariant mass distribution for the ISR process $e^+e^- \to \pi^+\pi^- J/\psi$. A clear $\psi(2S)$ peak is observed.

5. Summary

The Belle II experiment is already in a good shape and will soon accumulate the dataset similar to BaBar or Belle. With the significant increase of statistics compared to Belle, Belle II can improve for sure some of the measurements alreay performed by Belle, and look for new states still undisclosed forms of exotic states. Belle II can measure more precisely the line shapes of the states, determine their spin-parities and search for new decay channels. Quarkonium/XYZ is one of the main components of the physics program. One of the unique aspects of the XYZ program at Belle II is the ability to study Z states in both B meson decays and in direct production via ISR. It is expected that Belle II will make a significant impact on exotic quarkonium spectroscopy.

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