PROCEEDINGS OF SCIENCE

Revisiting $X(3872)$ at Belle II Experiment

PoS(CHARM2020)058

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The Belle II experiment has accumulated data corresponding to 213 fb^{-1} of integrated luminosity at the SuperKEKB asymmetrc-energy e^+e^- accelerator and is performing well. While the data are being collected toward the final goal of 50 ab^{-1}, which will allow searching for rare processes and high precision in spectroscopy, the current data already allow for performing analyses.
We present here the analysis of $B \to KJ/\psi\pi^+\pi^-$ decays using a $\Upsilon(4S)$ data sample of 62.8 fb^{-1}. We find an evidence for a $X(3872)$ signal at a statistical significance of 4.6σ and confirm that the obtained branching fraction of $B \to K\psi(2S)$ agrees with the world average. When larger sample will be available, Belle II plans an even more interesting analysis of $B \to D\bar{D}\pi^0 K$, where $X(3872)$ is reconstructed in the $D\bar{D}\pi^0$ channel in a pursuit for the natural width measurement.

**** 10th International Workshop on Charm Physics (CHARM2020), ****
**** 31 May - 4 June, 2021 ****
**** Mexico City, Mexico - Online ****

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1. Introduction

The $X(3872)$ also as known as $\chi_{c1}(3872)$ was discovered by the Belle collaboration in 2003 in the $B \to KJ/\psi\pi^+\pi^-$ decay [1]. It has sparked a new generation of searches for particles noted as XYZ, requiring new explanations for their structures. Over the years the properties of the $X(3872)$ have been intensely studied: its mass, quantum numbers J^{PC} are well-known with the width also having been measured from a recent lineshape study from LHCb [2].

Table 1: Experimental summary of the $X(3872)$ [3].

Mass	3871.65 ± 0.06 MeV$/c^2$
Width	1.19 ± 0.21 MeV
J^{PC}	1^{++}
Production in	$B \to KX(3872),\ e^+e^- \to \gamma X(3872)\ p\bar{p},\ pp$
Well established decay modes	$J/\psi\pi^+\pi^-,\ J/\psi\pi^+\pi^-\pi^0,\ J/\psi\gamma,\ \psi(2S)\gamma,\ D\bar{D}\pi,\ D\bar{D}\gamma,\ \pi^0\chi_{c1}$

The true nature of the $X(3872)$'s internal structure is still under debate. It is one of the goals of the future experiments to deliver measurements that extend our current knowledge, listed in Table 1.

The Belle II experiment, the Belle successor, aims to perform these measurements with luminosities of up to 50 ab^{-1}, nearly 50 times of what its predecessor has collected. These will include precise determinations of the X(3872) properties with emphasis on its natural width. As a first milestone of this program, the Belle II experiment reports the first reconstruction of the $X(3872)$ in the $B \to KJ/\psi\pi^+\pi^-$ channel with its early phase 62.8 fb^{-1} data taken at the $\Upsilon(4S)$ resonance.

2. SuperKEKB Accelerator and Belle II Detector

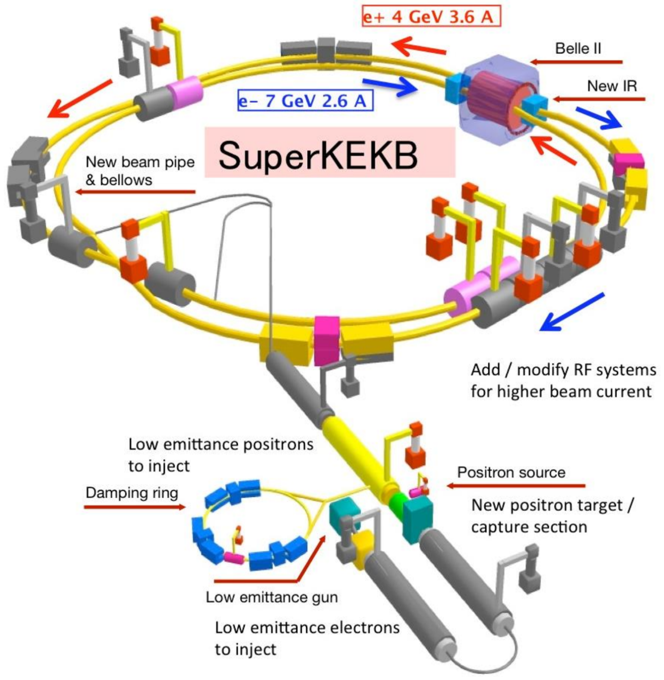

Figure 1: Overview of the SuperKEKB collider.

SuperKEKB, shown in the Figure 1, is an energy asymmetric collider running at the center-of-mass energy around the $\Upsilon(4S)$ resonance mass. It is designed to reach the peak luminosity of 6.5×10^{35} cm^{-2}s^{-1} which is over 30 times of the previous design by increasing the beam current and reducing the vertical beta function at the interaction point. The instantaneous luminosity record so far was reached on summer of 2021 at 3.1×10^{34} cm^{-2}s^{-1}.

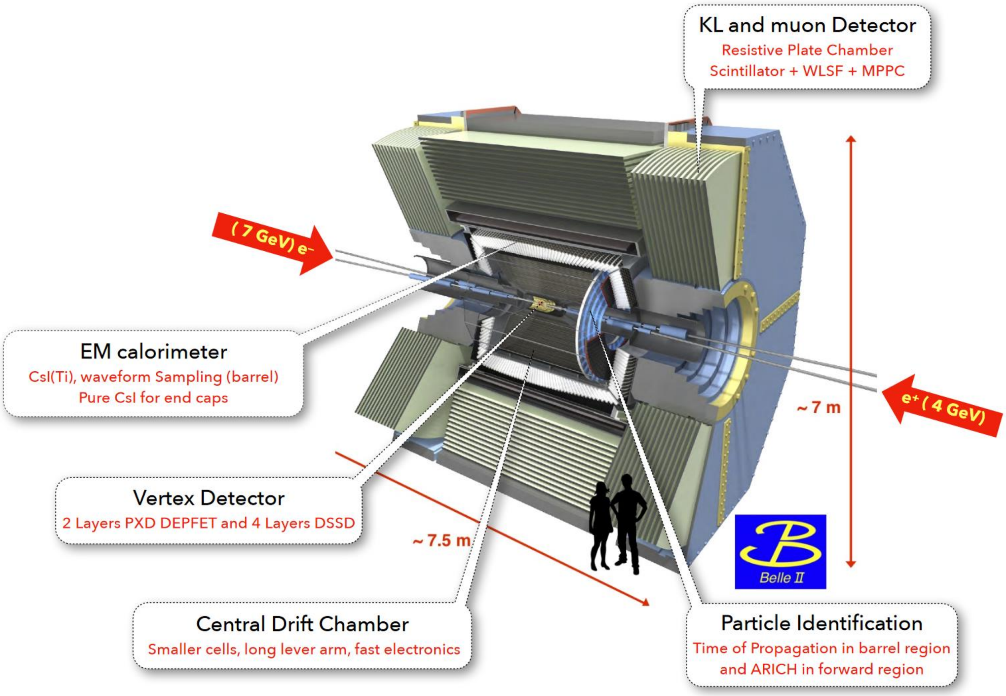

Figure 2: Overview of the Belle II detector.

The Belle II detector is the successor of the Belle detector used to first discover the $X(3872)$. The overall structure is shown in the Figure 2. The new Belle II detector is similar to the Belle detector [4]. It is designed to cope with the higher radiation level and increased beam-related background due to the increase in instantaneous luminosity. The major differences are addition of the pixel detector in the innermost part of the detector to provide better vertexing information and use of the Cherenkov Ring-imaging concept allowing Belle II to reach a comparable level of kaon and pion separation to that of the Belle detector in an environment with higher beam background. A comprehensive detail of the detector can be found in the Ref. [5].

3. Reconstruction and Event Selection

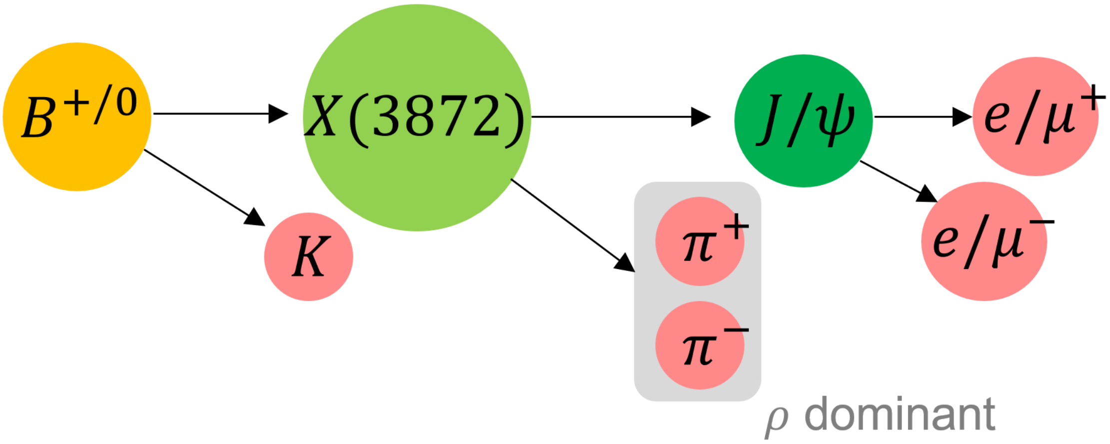

Figure 3: $B \to KX(3872):\ X(3872) \to J/\psi\pi^+\pi^-$ reconstruction scheme.

Tracks used to reconstruct the $B \to KJ/\psi\pi^+\pi^-$ decay, as described in Figure 3, are first identified statistically according to the Belle II charged particle identification information [6]. In order to restrict to e^+e^- collisions while suppressing the beam-background events, the tracks' closest point of approach to the interaction point is required to be less than 1 cm in the $r - \phi$ plane and 3 cm along the z-direction. K_s^0 mesons are collected by combining two oppositely charged pion candidates, subjecting them to a vertex fit, and constraining the resulting K_s^0 candidate's mass $m(\pi^+\pi^-)$ to be within 490 and 506 MeV$/c^2$. J/ψ mesons are reconstructed from a pair of oppositely charged electrons or muons. The energies of the bremsstrahlung photons in the vicinity of the travel path of the electron candidates are recovered for the momentum calculation. 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^- reconstruction, 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 [3], in order to reduce combinatorial backgrounds and misidentified $\gamma \to e^+e^-$ conversions. This condition is sufficient for rejecting misidentified pions, thus need for further particle identification. To reduce the level of $e^+e^- \to q\bar{q}$ ($q = u, d, s$ or c-quark) events, normalized Fox-Wolfram moment $R2$ [7] is required to be less than 0.4.

The B meson candidates are selected with the energy difference $\Delta E \equiv E_B^{\text{cms}} - \sqrt{s}/2$ and the beam-constrained mass $M_{\text{bc}} \equiv \sqrt{s/4 - (p_B^{\text{cms}})^2}$, where E_B^{cms} and p_B^{cms} are the energy and momentum of the B candidate in the center-of-mass system. The signal candidates are required to meet $M_{\text{bc}} > 5.27$ GeV$/c^2$ and $|\Delta E| < 0.02$ GeV.

4. Control Sample Study with the $B \to K\psi(2S)$ ($\psi(2S) \to J/\psi\pi^+\pi^-$) Channel

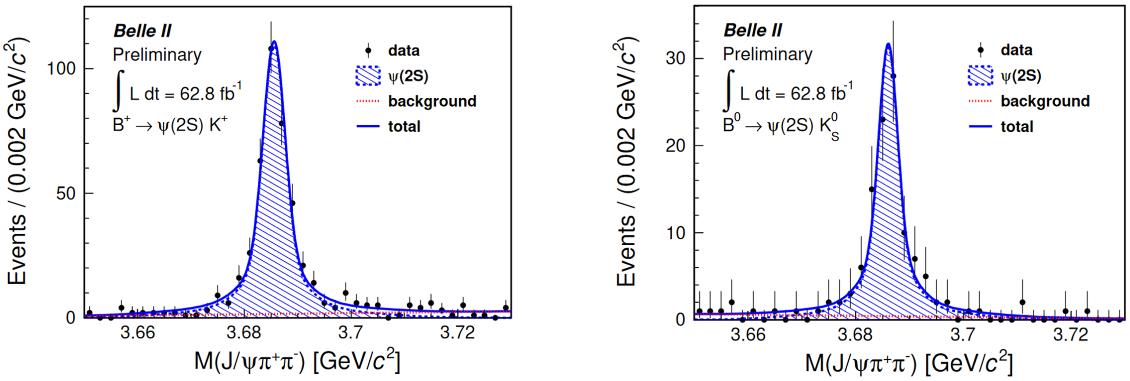

Figure 4: Distribution of $m(J/\psi\pi^+\pi^-)$ for $B^\pm \to K^\pm\psi(2S)$ (left) and $B^0(\bar{B}^0) \to K^0\psi(2S)$ (right) modes with signal-extraction fit overlaid.

A control sample study using the $B \to K\psi(2S)$ ($\psi(2S) \to J/\psi\pi^+\pi^-$) decay is performed as a validation analysis by comparing the obtained branching fraction $\mathcal{B}(B \to K\psi(2S))$ to the world average in the Ref. [3]. The event selection criteria mentioned in the previous section are applied, except the $m(\pi^+\pi^-)$ condition. The observed mass of the $J/\psi\pi^+\pi^-$ system $m(J/\psi\pi^+\pi^-)$ and the projection of an unbinned extended maximum likelihood fits to extract signal events are displayed in the Figure 4. The signal Monte Carlo events are modeled with three Gaussian functions with the same central value and the background is modeled with a first-order Chebyshev polynomial.

The signal selection efficiencies and the obtained branching fractions of the control sample study are summarized in the Table 2. Only the statistical component of the uncertainties is shown for branching fractions. No notable discrepancy to the world average is seen.

Table 2: Signal selection efficiencies and comparison of the obtained branching fractions to the world average of the $B \to K\psi(2S)$ study. Only the statistical uncertainty and the uncertainty associated with the finite size of simulated samples are considered.

	$B^\pm \to K^\pm\psi(2S)$	$B^0(\bar{B}^0) \to K^0\psi(2S)$
Signal selection efficiency [%]	22.69 ± 0.16	17.40 ± 0.17
Obtained branching fraction [$\times 10^{-4}$]	6.08 ± 0.37	6.18 ± 0.69
Obtained / world Ave. [3]	0.982 ± 0.069	1.07 ± 0.15

5. $B \to KX(3872)$ Channel Signal Extraction

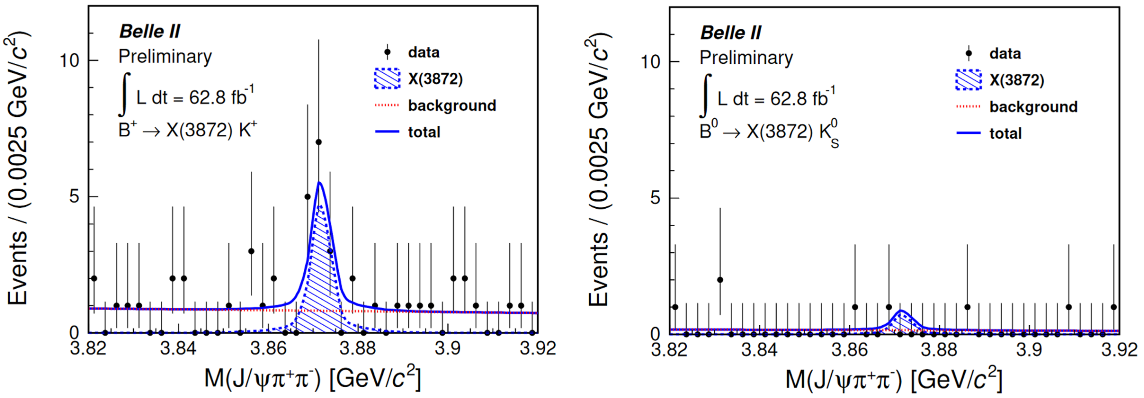

Figure 5: Distribution of $m(J/\psi\pi^+\pi^-)$ for $B^\pm \to K^\pm\psi(2S)$ (left) and $B^0(\bar{B}^0) \to K^0X(3872)$ (right) modes with signal-extraction fit overlaid.

The signal extraction for $B \to KX(3872)$ in the $m(J/\psi\pi^+\pi^-)$ window near the mass of $X(3872)$ is done by performing an unbinned simultaneous extended maximum likelihood fit in order to cope with the small sample size in the neutral B meson mode, where the ratio of the signal yields between the charged and neutral B meson modes is fixed according to $\mathcal{B}(B^0(\bar{B}^0) \to K^0X(3872))/\mathcal{B}(B^+ \to K^+X(3872)) = 0.5$ [8] and their signal selection efficiency information, as shown in Table 3. The fit to the data is displayed in Figure 5, where the signal Monte Carlo events are modeled by assuming the world average mass [3] and the width information from LHCb results [2], and the background distribution is modeled with a first-order Chebyshev polynomial. The statistical significance is determined to be 4.6σ from likelihood ratio between the signal-plus-background and the background-only hypotheses. Obtained signal yield, number of background events, and negative log-likelihood values of the fits are summarized in Table 4.

Table 3: Information used for fixing the ratio between the charged and the neutral mode in the simultaneous fit.

	$B^\pm \to K^\pm X(3872)$	$B^0(\bar{B}^0) \to K^0X(3872)$
$\mathcal{B}(B \to KX(3872)) \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$	8.6×10^{-6}	4.3×10^{-6}
Signal selection efficiency [%]	22.9	17.5
Expected events / fb^{-1}	0.267	0.0484

Table 4: Fit results with and without signal hypothesis and the statistical significance. Uncertanties are statistical only.

	With signal hypothesis	Without signal hypothesis
Signal yield	14.4 ± 4.6	-
Charged B channel background yield	31.6 ± 6.1	45.0 ± 6.7
Neutral B channel background yield	7.0 ± 2.8	8.0 ± 2.8
Negative Log likelihood $-\ln L$	-231.01	-220.33

$-2\ln(L_0/L) = 4.6\sigma$

Table 5 compares the signal yield per fb^{-1} and signal efficiency of the $B \to K\psi(2S)$ and $B \to KX(3872)$ studies to those observed in a similar study at the Belle experiment [8]. Despite increased beam backgrounds, performances are similar to the previous experiment. It should be noted that the signal selection efficiency at Belle II is comparably higher for the $B \to K\psi(2S)$ study as the conditions were not optimized for the corresponding modes.

Table 5: Comparison of the expected signal events and selection efficiencies to the previous comparable Belle analysis [8].

	Belle		This analysis	
	Signal Yield/fb^{-1}	Signal Eff. [%]	Signal Yield/fb^{-1}	Signal Eff. [%]
$B^{\pm} \to K^{\pm}\psi(2S)$	5.027 ± 0.090	17.8 ± 0.2	6.52 ± 0.37	22.7 ± 0.2
$B^0(\bar{B}^0) \to K^0\psi(2S)$	1.145 ± 0.042	14.1 ± 0.2	1.66 ± 0.18	17.4 ± 0.2
$B \to KX(3872)$	0.212 ± 0.021	19.1 ± 0.2	0.194 ± 0.062	22.9

6. Plans for the $X(3872)$ Width Measurement with $X(3872) \to D\bar{D}\pi^0$

The Belle II experiment plans to measure the width of the $X(3872)$ by reconstructing its $D^0\bar{D}^0\pi^0$ final state, which is expected to benefit from a much better mass resolution compared to the $J/\psi\pi^+\pi^-$ channel thanks to the proximity (7 MeV/c^2) to the mass threshold, compared to the 500 MeV/c^2 gap in the $J/\psi\pi^+\pi^-$ final state. Simplified simulations [10] show that 3σ sensitivity on the width is expected to be accessible with 10 ab^{-1} or more data as shown in Figure 6.

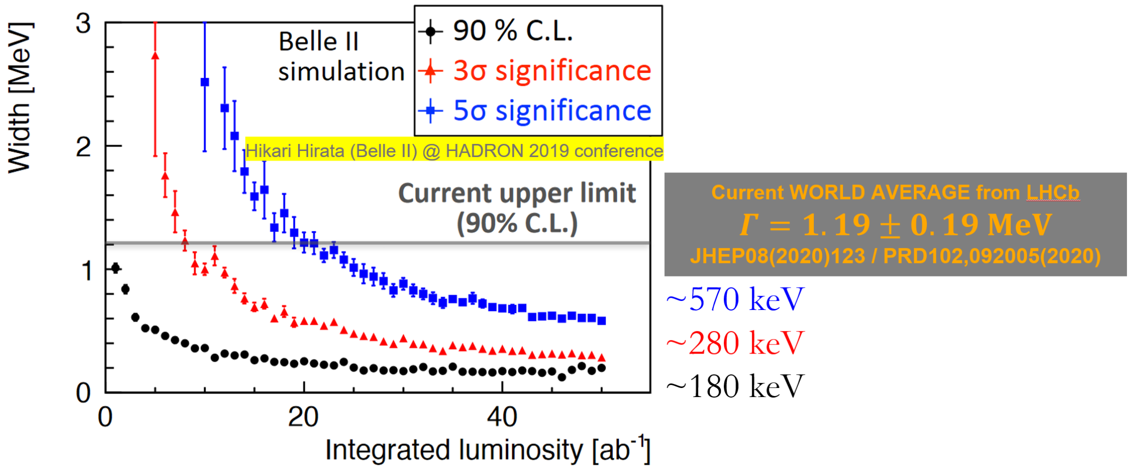

Figure 6: Sensitivity to resolve the X(3872) width at benchmark levels of significance as a function of integrated luminosity in simplified simulated experiments [10].

7. Summary

The Belle II experiment reports the first reconstruction of $X(3872)$ decays in the $J/\psi\pi^+\pi^-$ channel with 62.8 fb^{-1} data taken at the $\Upsilon(4S)$ resonance. The obtained statistical significance is 4.6σ. With constant improvement and smooth operation, Belle II aims to gather data of 50 ab^{-1} and looks forward to contributing towards precision studies of the $X(3872)$ properties, including a

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natural width measurement in the $D^0\bar{D}^0\pi^0$ final state. Furthermore, we look forward to revisiting other sub-channels of the $X(3872)$ as well as expanding the studies towards other charmonia physics.

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