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Rediscovery of $X(3872)$ at Belle II Experiment

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The Belle II experiment has accumulated data corresponding to 89.99 fb^{-1} integrated luminosity in the past 2 years, and is performing very good. Waiting that the full planned data set will be recorded (50 ab^{-1}), which will allow search for rare processes and will have a tremendous impact in the spectroscopy field, the Phase 3 data set allows to already perform analysis with high precision.
We present here the analysis of $B \to KJ/\psi\pi^+\pi^-$ and $B \to K\psi(2S)$: in the former for the first time the evidence for the $X(3872) \to J/\psi\pi^+\pi^-$ has been found at Belle II, which is consistent with the observation at Belle of the same resonant state, performed in 2003. The re-discovery of the $X(3872)$ based on the early Phase3 data includes the efficiency and resolution study, calibration with $B \to K\psi(2S)$, and background check. When higher statistics will be available, Belle II is planning the even more interesting analysis of $B \to D\bar{D}\pi^0 K$, and search for $X(3872) \to D\bar{D}\pi^0$.

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1. Introduction

The $X(3872)$ also as known as $\chi_{c1}(3872)$ was first discovered by 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. Among them, the inaugural discovery, the $X(3872)$ has been most 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 and it is one of the goals of the future experiments to deliver measurements beyond our current knowledge listed in Table 1. Belle II experiment, the successor of the experiment which led to the surprising discovery of the $X(3872)$, aims to measure such with an integrated luminosity goal of 50 ab^{-1}, nearly 50 times of what its predecessor has collected. In the future Belle II experiment plans to provide input on the precise properties of the $X(3872)$, especially with emphasis on its full width, as well as other charmonium physics. As the first milestone to study such, Belle II experiment presents a revisit 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

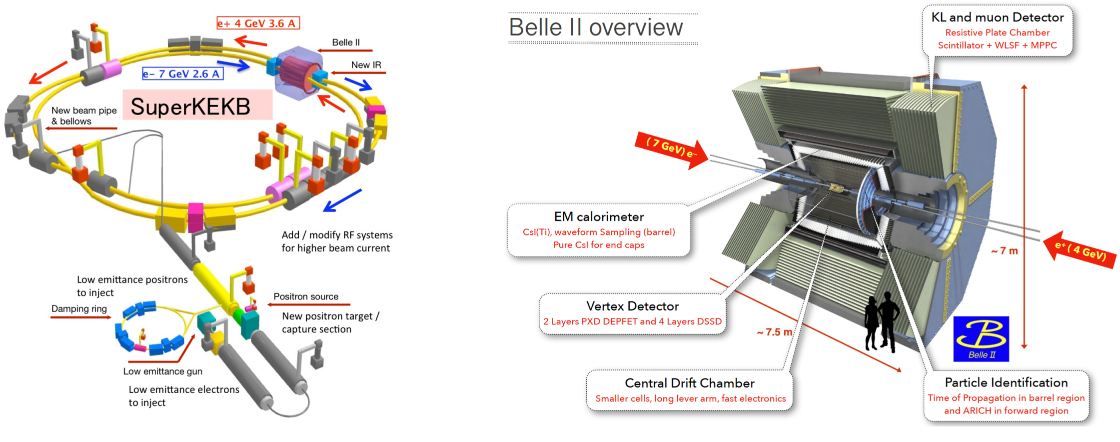

Figure 1: Overview of the SuperKEKB collider (left) and the Belle II detector (right).

The SuperKEKB shown in the left diagram of 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 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 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}.

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 right diagram of Figure 1. In the core the new Belle II detector is similar with the Belle detector [4]. It is designed to cope with the higher radiation level and increased beam related background due to the increase in the instantaneous luminosity. The major differences to the Belle detector 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 allowing the new detector 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

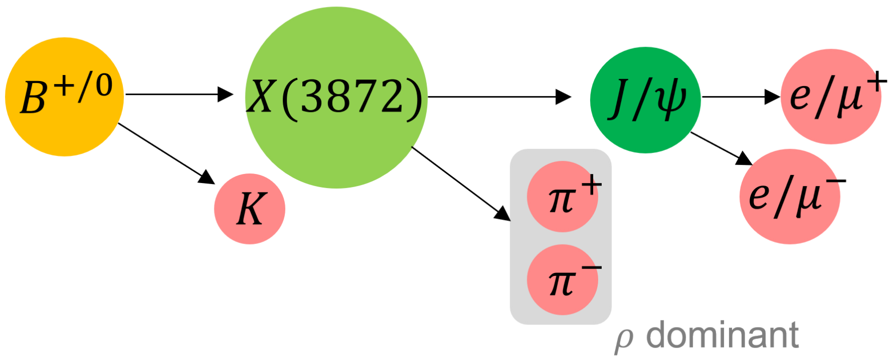

Figure 2: $B \to KX(3872)$: $X(3872) \to J/\psi\pi^+\pi^-$ reconstruction scheme.

Tracks used to reconstruct the $B \to KJ/\psi\pi^+\pi^-$ decay, as described in Figure 2, is first identified according to the Belle II charged particle identification likelihood selectors [6]. In order to only collect events originating near the interaction point, 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 and performing vertex fit and requiring condition on the K_s^0 candidate's mass (M_{K_s}) 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, a condition $M_{\pi^+\pi^-} - M_{J/\psi\pi^+\pi^-} + m_{J/\psi} > -0.150$ GeV$/c^2$ where M stands for the measured mass of respective systems noted in the subscripts and m stands for the nominal mass, is applied in order to reduce combinatorial backgrounds and misidentified $\gamma \to e^+e^-$ conversion. This condition is sufficient for rejecting misidentified pions, thus for $B \to KX(3872)$ analysis the Belle II particle identification for the pion is not applied.

To reduce the level of $e^+e^- \to q\bar{q}$ ($q = u, d, s$ or c-quark), normalized Fox-Wolfram moment $R2$ [7] is required to be less than 0.4.

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

The event selection criteria mentioned so far are summarized in Table 2.

Table 2: Summary of event selection criteria.

Track selection	Belle 2 Particle Identification Point of closest approach to the interaction point in $r - \phi$ (along $\hat{z}$)< 1.0 (3.0) cm
K_s^0	Vertex fit with two oppositely charged pions $490 < M_{K_s} < 506$ MeV$/c^2$
J/ψ	$3.070\ (3.065) < M_{J/\psi \to e^+e^-(\mu^+\mu^-)} < 3.117$ GeV$/c^2$ Mass-constrained fit
$\pi^+\pi^-$ system	$M_{\pi^+\pi^-} - M_{J/\psi\pi^+\pi^-} + m_{J/\psi} > -0.150$ GeV$/c^2$
Continuum suppression	$R2 < 0.4$
B meson selection	$M_{\rm bc} > 5.27$ GeV$/c^2$, $|\Delta E| < 0.02$ GeV

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

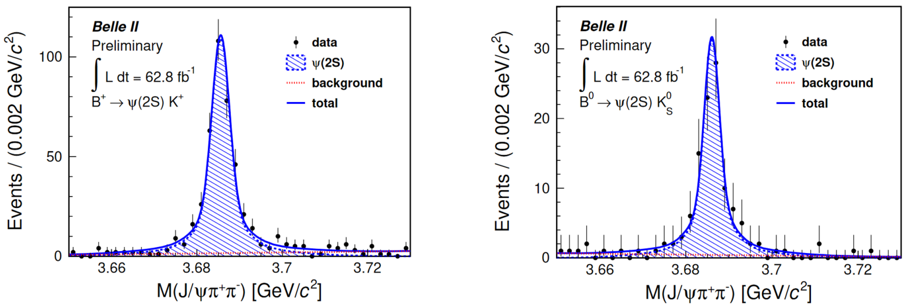

Figure 3: Extraction of signal in $M_{J/\psi\pi^+\pi^-}$ for $B^\pm \to K^\pm\psi(2S)$ (left) and $B^0(\bar{B}^0) \to K^0\psi(2S)$ (right) modes.

A control sample study using $B \to K\psi(2S)$ ($\psi(2S) \to J/\psi\pi^+\pi^-$) decay chain 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 except the condition for the $\pi^+\pi^-$ pair are applied. The measured mass of the $J/\psi\pi^+\pi^-$ system ($M_{J/\psi\pi^+\pi^-}$) and unbinned extended maximum likelihood fits to extract signal events are displayed in the Figure 3. The signal Monte Carlo events are modeled in three Gaussian functions with the same central value and the background is modeled in a first order Chebyshev polynomial.

The signal selection efficiencies and the obtained branching fractions of the control sample study is summarized in the Table 3. The uncertainties in the table regarding the branching fractions are statistical only. No notable discrepancy to the world average is seen.

Table 3: Signal selection efficiencies and comparison of the obtained branching fractions to the world average of the $B \to K\psi(2S)$ study. Statistical uncertainty and signal Monte Carlo statistics as systematic uncertainty are considered in calculation.

	$B^{\pm} \to K^{\pm}\psi(2S)$	$B^0(\bar{B}^0) \to K^0\psi(2S)$
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

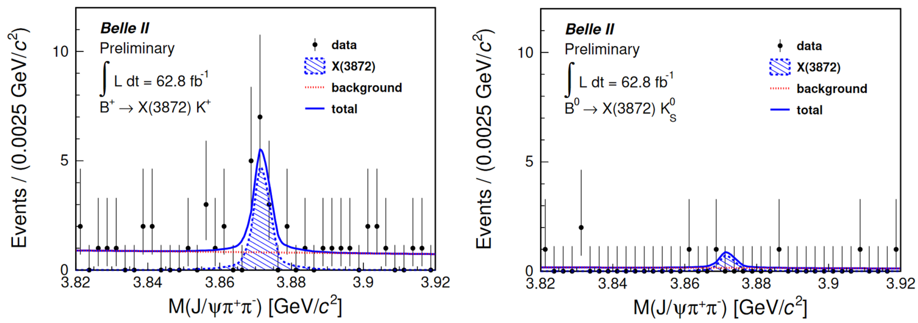

Figure 4: Extraction of signal in $M_{J/\psi\pi^+\pi^-}$ for $B^{\pm} \to K^{\pm}X(3872)$ (left) and $B^0(\bar{B}^0) \to K^0X(3872)$ (right) modes.

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 unbinned simultaneous extended maximum likelihood fit in order to cope with the low statistics in the neutral B meson mode, where the ratio of the signal yields between the charged and neutral B meson modes are 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 in the Table 4. The fit to the data is displayed in the Figure 4, 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 in a first order Chebyshev polynomial. The statistical significance is determined to be 4.6σ from log-likelihood ratio between the signal inclusion and null hypothesis. Studies for the systematic uncertainties in tracking efficiency and K_s^0 reconstruction rate is under progress. Obtained signal yield, number of background events, and log-likelihood of the fits are summarized in Table 5.

Table 4: 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 5: Fit results with and without signal hypothesis and the statistical significance. Uncertanties are statistical uncertainty 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
Log likelihood	$L = -231.01$	$L_0 = -220.33$
$-2\ln(L_0/L) = 4.6\sigma$		

The Table 6 compares the signal yield per fb^{-1} and signal efficiency of the $B \to K\psi(2S)$ and $B \to KX(3872)$ studies to a comparable study at the Belle experiment [8]. It shows that despite of the increased beam backgrounds the order of the signal efficiency and number of signals are approximately at the same level 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. Also in the $B \to KX(3872)$ Belle II study, charged *pi* identification likelihood condition was not applied as the condition on $M_{\pi^+\pi^-} - M_{J/\psi\pi^+\pi^-} + m_{J/\psi}$ is sufficient to handle the fake pion candidates.

Table 6: 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 $X(3872)$ from $D^0\bar{D}^0\pi^0$ channel, which is expected to benefit in a much better mass resolution compared to the $J/\psi\pi^+\pi^-$ channel thanks to its mass threshold being only under 7 MeV/c^2 to the $X(3872)$ mass while the gap widens to approximately 500 MeV/c^2 in the case of $J/\psi\pi^+\pi^-$. A toy Monte Carlo study [10] has already been performed regarding the study and it is expected for the Belle II experiment to be able to measure the width at 3σ significance around the point where the data collection reaches 10 ab^{-1} as shown in the Figure 5.

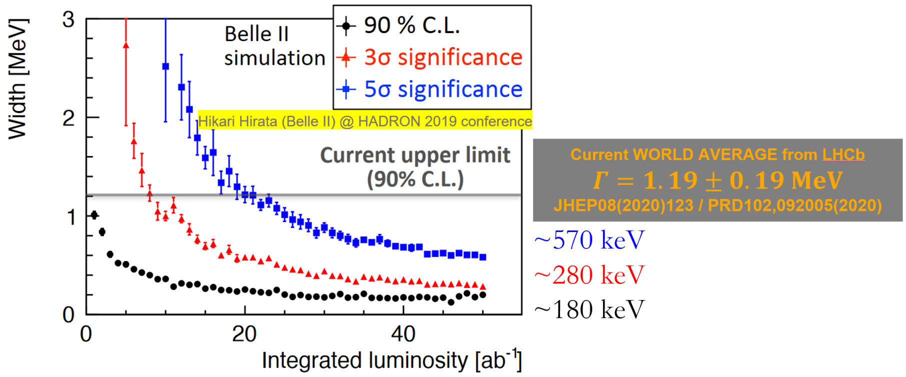

Figure 5: Monte Carlo estimation of the sensitivity towards width measurement of $X(3872)$ reconstructing from $D^0\bar{D}^0\pi^0$ channel. [10]

7. Summary

The Belle II experiment, as its first exotic hadron study, has revisited and observed $X(3872)$ in the $J/\psi\pi^+\pi^-$ channel with 62.8 fb^{-1} data taken at the $\Upsilon(4S)$ resonance. The obtained statistical significance was 4.6σ. With constant upgrade and smooth operation, the Belle II aims to gather data of 50 ab^{-1} and looks forward to contributing towards providing inputs regarding the $X(3872)$ such as its total width using the $D^0\bar{D}^0\pi^0$ channel. 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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