X, Y, Z search at Belle II

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Abstract. The Belle II experiment has successfully concluded Phase-2 of data taking in July 2018, and just started Phase-3, with the complete detector setup. Great perspectives and unique physics cases are enhanced in the Belle II physics program. In the sector of charmonium and spectroscopy, Belle II will investigate several physics processes: ISR physics for the vector states, bottomonium search and the study of the X(3872) line shape are some examples where the contribution of the Belle II experiment will help in better understanding QCD, for which several open issues still remain unsolved. First simulations and data analyses will be shown, with the first available dataset (2018), and the plan for spectroscopy search at Belle II will be discussed.

1 Introduction

The Gell-Mann Zweig idea [1] inspired mostly all modern QCD-motivated models. Although developed more than half century ago, when the *t*- and *b*- quarks were still not discovered, it showed to be very performant in classifying all known hadrons, and still now remains valid. The QCD-motivated models have however predicted a world where composite particles are made not only of two or three bound quarks, *e.g.* only mesons and baryons, but the possibility that other complex forms of quark binding, involving more than three quarks, has been brought up. From experimental point of view, the long silence was broken roughly 15 years ago, with the observation of the X(3872) [2], first announced by the Belle collaboration [3]. Quickly the world of "*exotic*" particles got a remarkable boost, with first observations performed at B-factories and subsequent announcements by the BES III collaboration [4], honeying a field which interest has grown up until the most recent announcement of pentaquarks [6, 7] by the LHCb collaboration [5] and di-baryons [8] at WASA-at-COSY [9]. The story still did not come up to the end, yet.

Undoubtely the BaBar [10] and the Belle collaborations have given a great contribution to the field of the charmonium- and bottomonium-like spectroscopy search. However, it is a decade they both ended data-taking, and showed that most of the interesting discoveries in the field, *i.e.* the $Z_c(3900)$, the $Z_c(4430)$, the $Z_b(10610)$ and the $Z_b(10650)$, etc. etc. have been not established yet, even with the full collected integrated luminosity. More data are needed, and the possibility to solve puzzling cases can be given by an e^+e^- collider with up to 50 times more integrated luminosity, such as the upgraded and completed Belle II experiment [11].

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2 The Belle II experiment

The Belle II experiment, located in Tsukuba (Japan) at the High Energy Accelerator Research Organization known as KEK [12], where the old Belle experiment collected $\approx$1 ab^{-1} integrated luminosity, has similar structure than the former Belle experiment. The Belle II detector is structured with an internal vertex detector (VXD), which is made by 2 inner layers of silicon Pixel Detector (PXD) and 4 double-side strips of Silicon Detector (SVD); then a Central Drift Chamber (CDC) is given for tracking purposes and particle identification. A time-of-propagation (TOP) detector is also furnished, surrounded by an electro-magnetic calorimeter (EM), while the outer detector is for muons and K_L^0 detections. As the former Belle detector, it is an asymmetric e^+e^- collider, running at the energy in the center of mass of $\Upsilon(4S)$ for the time being. Below the main differences with the old Belle detector are listed:

- a Pixel detector (PXD) has been installed (one of the 2 planned layers for the Phase-3 starting), with vertex resolution in z-direction a factor 2 better than at Belle: from 50 μm (Belle) to 25 μm (Belle II);
- the Time-of-Propagation (TOP) detector has been installed and properly working for particle identification purposes. The time resolution is 50 ps by design, and the detector surface is polished at nanometer precision;
- KLM detector for K_L and muon detection: 2 inner layers of barrel and all layers in the endcap are replaced by scintillators;
- the electromagnetic calorimeter (ECL) readout electronics has been exchanged: now fast ADCs are used;
- a gain-factor 40 better than Belle luminosity is planned, due to the new value of the beam current (which gives a factor 2) and the nano-beam principle, which gives an improvement of a factor 20. In this way we expect 50 times more data than what was collected at Belle over 11 years, so in 2026 the recorded integrated luminosity is expected to be 50 ab^{-1}. This will be possible thanks to the nano-beam scheme proposed by Pantaleo Raimondi [13, 14].

In order to realize the Belle II experiment and get it running, also the KEK facility got an upgrade, so now the era of SUPERKEKB started [15]. The Belle II collaboration can count on 950 members from 26 countries. The Phase-3 of data taking started on March 11, 2019, and will finish at the end of June 2019. The plan is to collect up to 60 fb^{-1} data, of which an integrated luminosity of at least 10 fb^{-1} should be collected at the energy in the center of mass of the $\Upsilon(4)$, and at least 1 fb^{-1} are planned to be "off-peak" data for background study. It has required a lot of effort from many expert physicists and technicians. Figure 1(left) shows the detector design and Fig. 1(right) shows the first event recorded with Phase-3, on March 25, 2019 [16].

3 Spectroscopy studies at Belle II

3.1 Physics with ISR processes

Initial State Radiation (ISR) processes were first studied at BaBar [17], then confirmed and continued by Belle [18–20]. The most prominent case is the Y(4260), which was observed in the $J/\psi\pi^+\pi^-$ invariant mass system in the $e^+e^- \to \gamma J/\psi\pi^+\pi^-$ process. The $J/\psi\pi^+\pi^-$ invariant mass distribution has been studied on the recoil of the ISR photon, therefore its quantum numbers are those of the ISR photon: $\mathrm{J^{PC}} = 1^{--}$. This is a clear signature for such events. By studying also the invariant mass system of $\psi(2S)\pi^+\pi^-$, more of these resonances have been found, still without a clear interpretation, except all of them are vector states seen in a

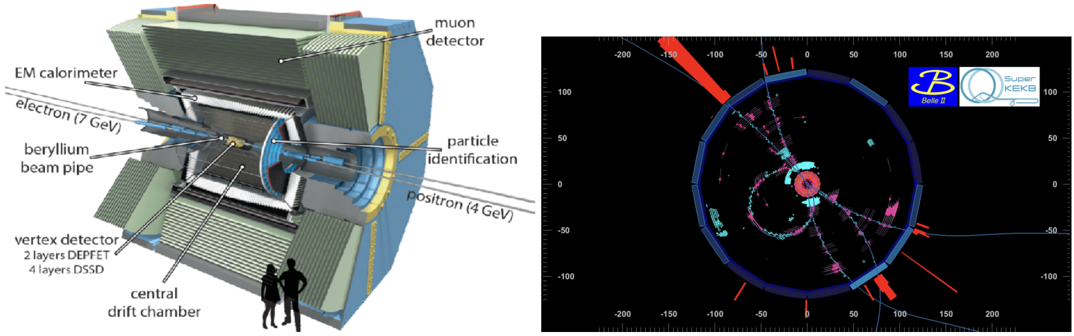

Figure 1. Schematic view of the Belle II detector (Left) and first Phase-3 data recorded events [16] (Right).

very rare process. In fact, with full data set only a yield of a couple of hundreds events was observed. This is not sufficient to full investigate *e.g.* their line shape, other decay products, etc. etc. It is also surprising that several of those states were observed, quite large, in a mass range of 1 GeV/c^2, but they do not mix. Further investigation of states like the Y(4260), the Y(4360), the Y(4660) should be performed with much higher statistics, such as at Belle II. The study of ISR processes and the investigation of the so-called Y states (old nomenclature) represents a unique physics case for Belle II, which is going to be the most performant e^+e^- collider in the world for the next years. Table 1 gives information on the expected statistical errors on the yield measurements of the most known Y-family states, which have been observed by the Belle experiment: high precision is expected when Belle II will collect 50 ab^{-1}.

3.2 Physics with Z states

The so-called Z states (old nomenclature) are definitively exotic states, since they are charged states with $c\bar{c}$ quark content, while all Charmonium states are neutral states by definition. The $Z_c(4430)^+$ was first observed at Belle [21] in the invariant mass system of $\psi(2S)\pi^+$ through B decays. After a decade of investigation in this field, where the BES III and LHCb experiments gave also an important contribution, we undestood that Z-charged states can be classified in two main categories: those with larger widths, not connected to $\bar{D}^{(*)}D^{(*)}$ threshold, seen in B decays; and those with narrower widths, seen directly in e^+e^- collisions or ISR processes. In any case, Belle II is in a unique position to look for both Z-charged state categories in only one experiment, while the first can be seen only at LHCb and Belle/Belle II, and the latter only at BES III or Belle/Belle II.

The Belle II Charmonium official program in Y- and Z-search is summarized in Table 1.

3.3 Total width measurement of the X(3872)

A special session is here dedicated to the new proposal for the measurement of the total width of the X(3872). Up to now, about this very narrow state a bunch of information has already been released [22]. We know about several accessible decay modes of the X(3872), in different production mechanism [23–32], and its quantum numbers are actually measured: $I^G(J^{PC}) = 0^+(1^{++})$ [33, 34]. But its width is unknown, due to the limitation of present and past experiments. Attempts to measure the X(3872) width were performed in the invariant mass

Table 1. Golden channels of the Charmonium in ISR physics program at Belle II. The predicted statistics erroros are given in percentage, assuming Belle II will run over 10 (50) ab^{-1} integrated luminosity at the indicated energy in the center of mass values (E_{cm}).

Golden channels	E_{cm} (GeV)	Statistical error (%)	XYZ
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	Y(4008), Y(4260), Z_c(3900)
$\pi^+\pi^-\psi(2S)$	4.36	12 (5.0)	Y(4260), Y(4360), Y(4660),Z_c(4050)
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	Y(4220), Y(4390), Z_c(4020), Z_c(4025)
$\omega\chi_{c0}$	4.23	35 (15)	Y(4220)

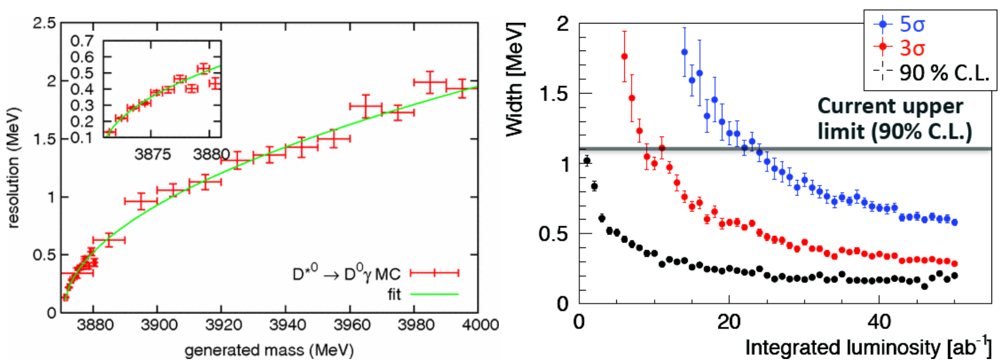

Figure 2. (Left) X(3872) mass resolutiom as a function of the X(3872) mass in the $D^0\gamma$ channel, obtained from Belle MC simulations with a X(3872) mass spectrum generated for a continuous range of masses from threshold to 4.0 GeV/c^2. Crosses are Gaussian resolutions for various generated $\bar{D}^{*0}D^0$ masses; the curve is the result of a fit with square root function. Very simlar results are obtained for the $D^0\pi^0$ channel [30]. (Right) 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 (black dots), evidence (red dots) and observation (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.

systems of $J\psi\pi^+\pi^-$ and $D^{(*)}\bar{D}^{(*)}$, for the latter by studying the decay of X(3872)→ $D^0\bar{D}^{*0}$ through B decays. The small available statistics, due to the rare process under exam, did not allow to improve the current best limit set up by Belle at 1.2 MeV [30]. In fact, in the latter decay mode the width was measured to be 3 MeV by BaBar [28] and 3.9 MeV by Belle [29]. The current best upper limit of the total width was indeed performed by using the full data set collected by Belle at the energy in the center of mass of $\Upsilon(4S)$, corresponding to 772 million $B\bar{B}$ pairs, in the $J\psi\pi^+\pi^-$ invariant mass system [30].

Belle II will analyze the $B^+ \to D^0\bar{D}^0\pi^0K^+$ decay process, and look for the $X(3872) \to D^0\bar{D}^0\pi^0$. By the former study performed by Belle [30] only a bunch of yield could be measured, equal to 50. It can be proven that the mass resolution of X(3872)→ $D^0\bar{D}^0\pi^0$ is extremely good, due to the fact that the Q value, defined as the difference between the X(3872) mass and the mass of its daughter particles, is very small, in this particular case equal to 7 MeV, while if one considers the decay of X(3872)→ $J/\psi\pi^+\pi^-$ the Q value is equal to 497 MeV. The mass resolution study performed and published by Belle is given in Fig. 2 (left), where it is clearly shown the strong dependence of the X(3872) mass resolution on the generated mass values.

In the preliminary study performed at Belle II, the X(3827)→ $D^0\bar{D}^0\pi^0$ decay chain has been simulated using the PHSP mode. This is an ongoing work, where still systematics effects must be evaluated. Figure 2 (right) shows in particular that the precision reachable by Belle II in the measurement of the X(3872) width can go down to 280 keV (evidence, 3σ) and 570 keV (observation, 5σ) with 50 ab^{-1} integrated luminosity. The results of this MC simulations is quite impressive and very promising, since it shows that in analyzing the invariant mass system of $D^0\bar{D}^0\pi^0$, peaking at the mass of the X(3872) throught B decays, the measurement of the X(3827) width could be performed with excellent performance, or eventually a new limit can be fixed down 180 keV with the full available statistics. The reason why Belle II decided to analyze the decay channel $D^0\bar{D}^0\pi^0$ (Q≈7 MeV) instead of the more promising $D^0\bar{D}^{*0}$ (Q≈1 MeV), with $D^{*0} \to D^0\pi^0$ and $D^{*0} \to D^0\gamma$, is that the pole position of the X(3872) is not exactly known, below or above the $D^0\bar{D}^{*0}$ threshold; therefore it is decided to analyze the $D^0\bar{D}^0\pi^0$ decay channel not to exclude any possibility.

3.4 Bottomonium studies at Belle II

Bottomonium studies are feasible at Belle II, since Belle II could in principle run at the energy in the center of mass of the $\Upsilon(6S)$. In fact, SUPERKEKB can reach the energy of 11 GeV. In analogy with charmonium, meaning bound states with $c\bar{c}$ quark content, bottomonium search is related to resonant states and transitions involving $b\bar{b}$ quark couples. Actually working at the energy in the center of mass of the $\Upsilon(6S)$ is not only possible, but a unique physics case for Belle II, since radiative transitions between bottomonium states will be accessible for the first time, which were suppressed by 1/137 at Belle, and statistics issues did not allow this kind of data analyses.

Search at the energy in the center of mass of the $\Upsilon(5S)$ and $\Upsilon(6S)$ at Belle II has several advantages: for example, one could search for new, predicted or unpredicted states, and the scan of those for a better understanding of the nature of the $Z_b(10650)$ [35]. An exploratory run is planned at the $\Upsilon(6S)$ energy in the center of mass equal to 100 fb^{-1}, and up to 1 ab^{-1} integrated luminosity at the $\Upsilon(5S)$ energy in the center of mass.

A physics program by analyzing the $\Upsilon(3S)$ transition has been also presented at Belle II, including the search for exotic transitions and charmonia in production. Rare χ_b decays and deuteron production mechanism investigation will be also possible at that energy.

The search at the energy of the $\Upsilon(3S)$ will be complimentary to that of the $\Upsilon(5S)$ and $\Upsilon(6S)$. With a run of 300 fb^{-1} integrated luminosity, we could get a factor 5 times better resolution than previous studies performed at Belle, and up to 15 times better in double charmonium study.

Analyzing the $J/\psi K^+K^-$ invariant mass is part of the Belle II physics program, and the plan is to analyze this invariant mass system in every possible decay mechanims for further investigation, since still puzzling questions are not solved concerning the interpretation of the resonant states found in such invariant mass system through B decays.

4 Preliminary results using Phase-2 data at Belle II

During the Phase-2 of data taking, performed from April 26th until July 17th 2018, 509 pb^{-1} integrated luminosity data were collected, without being the vertex detector installed. It was possible however to reconstruct some basic test channels for calibration and detector studies. Figures 3−5 show some of the preliminary achievements reached with Phase-2 data. These plots, showing “re-discovery” channels, testify the good status of the detector performace.

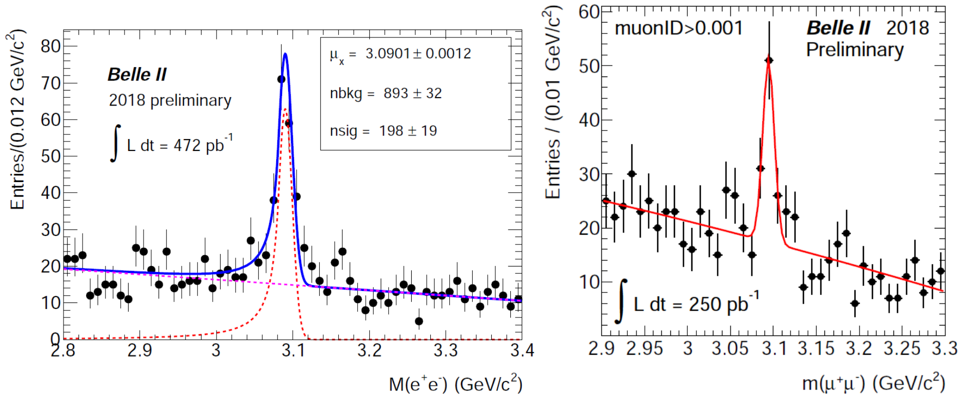

Figure 3. Reconstruction of $J/\psi \to e^+e^-$ (Left) and $J/\psi \to \mu^+\mu^-$ (Right) using different Phase-2 data sets at Belle II. PID is applied in this tests. The dotted red line (Left) refers to MC simualtions; the continuum line is the fit to the data.

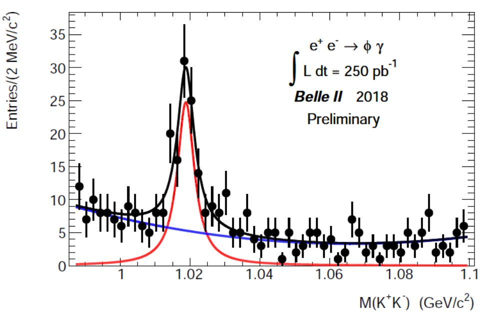

Figure 4. Reconstruction of the K^+K^- invariant mass distribution in the ISR process $e^+e^- \to \phi\gamma$ at Belle II, using 250 pb^{-1} Phase-2 data. The red line refers to the MC simulations, the black line is the fit to data, the blue line is a polynomial parameterization of the background.

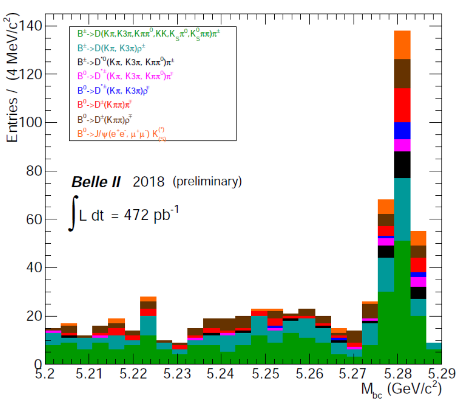

Figure 5. Reconstruction of several channels using the Phase-2 first data set. The variable shown in this plot is the so-called M_{bc}, which is peaking at the B meson mass and easy parametrizable with a Gaussian function, while for the background shape an Argus function can be used.

5 Summary

The Belle II experiment is in a good shape, and now that also the VXD detector is introduced inside the detector good achievements are expected for the year 2019. For the time being, only one over two PXD planned layers is used. An approved physics program for Charmonium and Bottomonium search exists, which requires high statistics. However, golden channels are already prioritized in our analysis program, and this year we plan to perform investigation for rediscovery channels involving the presence of J/ψ, D^*, K^*. Some example have been given in this report, clearly showing also the good status of our software analysis tools [36, 37].

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