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# Heavy Hadrons – Exotic and Conventional Quarkonium Physics at Belle II *

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## Abstract

The Belle II experiment, now operating at the KEK laboratory in Japan, is a substantial upgrade of both the Belle detector and the KEKB $e^+e^-$accelerator. It aims to collect 50 times more data than existing B-Factory samples. Belle II is uniquely capable to study Charmonium and Bottomonium states and search for heavy exotic hadrons consisting of more than three quarks.

*Keywords:* Belle II, Charmonium, Bottomium, Exotics

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## 1. Introduction

The strong interaction is one of the fundamental forces of nature. It is described by Quantum Chromo Dynamics (QCD) with quarks and gluons as building blocks. Many aspects of this theory have already been explored and yet there are still many more open questions.

Heavy quark-antiquark systems, especially containing charm (Charmonium) and bottom (Bottomonium) quarks, offer a unique opportunity to study the properties of QCD in a non-relativistic approach [1] in a similar way as positronium is used to study QED. Furthermore, QCD allows a multitude of composite particles yet only mesons and baryons, the latter containing three (anti)quarks and the former a quark-antiquark pair, have been observed. Searching for exotic states containing four or more quarks or gluonic degrees of freedom is another way to study the properties of QCD [2].

B-factories, like BaBar and Belle in the past and Belle II now, are an excellent place for these studies as they produce the necessary heavy quark-antiquark pairs in copious numbers.

## 2. SuperKEKB and the Belle II Experiment

The Belle II experiment [3] is located at KEK in Tsukuba, Japan. The goal of the Belle II experiment is to accumulate a data set of 50 $\mathrm{ab}^{-1}$, 50 times larger than that of Belle. This requires a major upgrade of both, the KEKB accelerator and the Belle Detector.

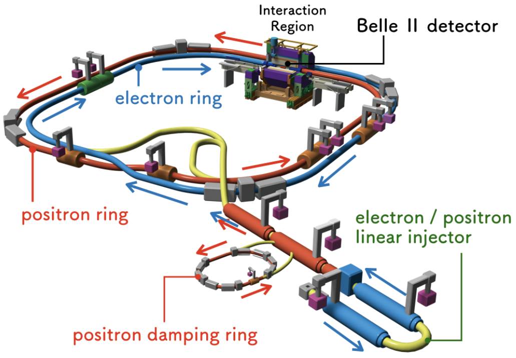

Figure 1: Overview of the SuperKEKB accelerator complex at KEK in Tsukuba, Japan.

The new accelerator, called SuperKEKB [4] (see Fig. 1), has a design luminosity of $8 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, 40 times more than KEKB, and operates at approximately 10.5 GeV center of mass (CM) energy, in the

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Table 1: Design parameters for SuperKEKB in comparison to KEKB.

| | E (GeV) LER/HER | $\beta_y^*$ (mm) LER/HER | $\beta_x^*$ (mm) LER/HER | $\phi$ (mrad) | I (A) LER/HER | L ($cm^{-2}s^{-1}$) |
|---|---|---|---|---|---|---|
| KEKB | 3.5/8.0 | 5.9/5.9 | 120/120 | 11 | 1.6/1.2 | $2.1 \times 10^{34}$ |
| SuperKEKB | 4.0/7.0 | 0.27/0.30 | 3.2/2.5 | 41.5 | 3.6/2.6 | $8.0 \times 10^{35}$ |

proximity of the $\Upsilon(4S)$ resonance. It is an asymmetric collider with beam energies of 7 and 4 GeV for the $e^-$ and $e^+$ beams, respectively, which result in a CM system which is boosted along the beam ($z$) axis, with a factor $\beta\gamma = 0.28$. The largest luminosity increase stems from the novel low-emittance nano-beam scheme which squeezes the beam at the interaction point to 50 nm in the $y$- and 5 $\mu$m along the $x$-direction. For this, a set of superconducting focussing magnets (QCS) has been installed close to the interaction point. A comparison of the most relevant beam parameters for KEKB and SuperKEKB is summarized in Tab 1.

The existing Belle detector would not cope with the anticipated increased background rates. In addition, the reduced boost of the SuperKEKB accelerator requires an improved vertex resolution for the reconstruction of secondary decay vertices of B mesons. Thus, the Belle II detector design has been optimized to address these challenges. The detector components are shown in Fig. 2.

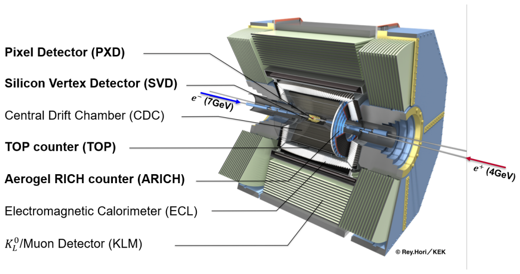

Figure 2: Overview of the Belle II Detector with its components. Bold font indicates newly developed systems, while the other systems have been upgraded substantially.

In several aspects, Belle II will offer considerably better performance than Belle: the vertex resolution is improved by the excellent spatial resolution of the two innermost pixel detector (PXD) layers; the efficiency for reconstructing $K_S$ decays to two charged pions with hits in the silicon strip detector (SVD) is improved because the silicon strip detector occupies a larger volume; the new particle identification devices in the barrel (TOP) and endcap (ARICH) regions extend the very good pion/kaon separation to the kinematic limits of the experiment; the new electronics of the electromagnetic calorimeter (ECL) considerably reduce the noise pile up, which is of particular importance for missing-energy studies.

The commissioning of the experiment is divided into three phases:

**Phase I**, concluded in 2017, consisted in the first commissioning of the SuperKEKB complex, for which the Belle II detector was replaced by the Beast II commissioning detector [5].

**Phase II** ran from January to July 2018. During this phase the final components of the accelerator were commissioned, including the final focusing magnets, and the Belle II detector, with the vertex detector (SVD and PXD) replaced by the Beast II (Phase II configuration) apparatus for beam background measurements, took the first 500 pb$^{-1}$ of SuperKEKB collision data.

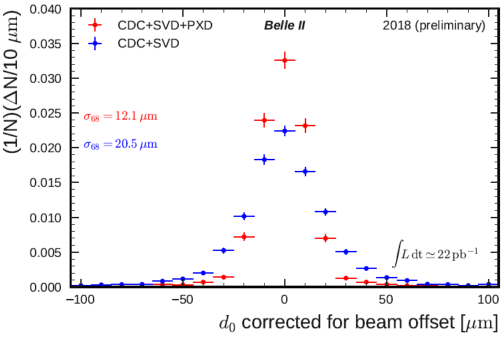

Figure 3: $d_0$ distributions of selected tracks reconstructed with the default reconstruction chain (CDC+SVD+PXD) and the chain excluding the PXD detector (CDC+SVD) for data collected during Phase II. The resolution is estimated using half of the symmetric range around the median containing 68% of the $d_0$ distribution. The distributions are normalised to unit area.

This data was used to perform a preliminary detector calibration and check the reconstruction and analysis algorithms. Fig. 3 shows the vertex resolution $d_0$ for SVD only and PXD and SVD combined. Furthermore, $B$ meson decays were studied and the beam-constrained mass $M_{bc}$ reconstructed (see Fig. 4).

Finally, starting from January 2019, **Phase III** begun

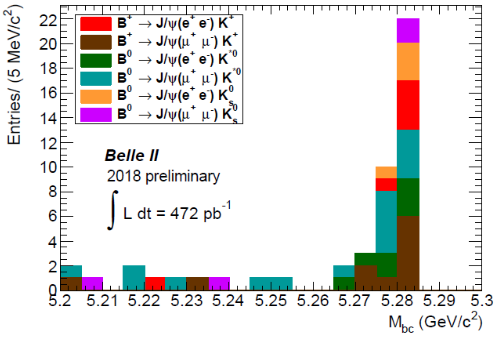

Figure 4: $M_{bc}$ distributions of $B$ candidates in 472 $pb^{-1}$ of collision data, in the mode $B \rightarrow J/\psi K_s^{(*)}$. Events are required to contain at least three good tracks to purify the sample with processes of the type $e^+e^- \rightarrow hadrons$, while rejecting beam induced background, Bhabha scattering, and other low multiplicity background sources.

with the full detector in place and first collisions with the final Belle II detector were recorded in April. The first run period ended after recording approx. 6 $fb^{-1}$ (cf. Fig. 5) in July. The accelerator already achieved a peak luminosity of $4 \cdot 10^{33}$ $cm^{-2}s^{-1}$ in this period.

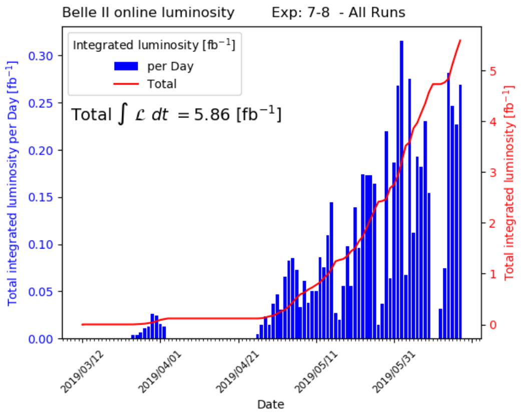

Figure 5: Accumulated data for Phase 3 until summer shutdown 2019.

## 3. Prospects for Quarkonium Physics

The primary physics goals of Belle II are to search for new physics in the flavour sector at the intensity frontier, and to improve the precision of measurements of Standard Model parameters [6]. Thus, most of the data will be taken at the $\Upsilon(4S)$ resonance but substantial data sets at energies above and below this energy (cf. Tab. 2) are also planned. The various opportunities for studying quarkonia in these different energy regimes will be discussed below.

### 3.1. Prospects at $\Upsilon$(4S)

As already mentioned, Belle II will mostly run at the $\Upsilon(4S)$ resonance. The various opportunities for QCD studies in Charmonium(-like) systems will be discussed below.

*B meson decays*

$B$ meson decays in association with a kaon, $B \rightarrow KX_{c\bar{c}}$, have been a rich source of Charmonium(-like) mesons and show a relatively large branching fraction ($10^{-4} - 10^{-3}$) for the production of these states [7].

By now all Charmonium levels below the $D\bar{D}$ threshold are known. Only one more narrow Charmonium level remains unobserved: the $\eta_{c2}(1D)$, a spin-singlet 1D state with $J_{PC} = 2^{-+}$.

Of the 24 known Charmonium-like states 10 have been observed in $B$ decays. With the possible exception of the X(3872), the experimental information on all other states is very incomplete. The determination of absolute branching fractions of the $XYZ$ states (and, thus, partial decay widths) are essential. This can be done at Belle II by identifying their inclusive production in $B \rightarrow KX$ decays via the missing mass recoiling against the kaon. Both the $B$ and the kaon are spinless, therefore the state $X_{c\bar{c}}$ is produced polarised (with $J_Z = 0$ relative to kaon path). This helps to discriminate various spin and parity hypotheses for the $X_{c\bar{c}}$.

Systematic investigations of Charmonium plus light hadron final states, $B \rightarrow K(c\bar{c} + h)$ will be useful both for uncovering new decay channels of known Charmonium-like mesons and for new Charmonium-like meson searches. In this case, all narrow Charmonium states ($\eta_c$, $\eta_c(2S)$, $J/\psi$, $\psi(2S)$, $h_c$, $\chi_{cJ}$ and $\psi_2(1D)$), and light hadron systems (such as: $\pi^0$, $\pi^\pm$, $\eta$, $\omega$, and $\phi$) should be considered.

For many of the above-described measurements, Belle II will have competition from the LHCb experiment. However, for absolute branching fraction measurements and for studies of final states that include neutral particles, Belle II will have considerably lower background.

*Double Charmonium Production*

This production mechanism provides a powerful tool for understanding the interplay between perturbative QCD (pQCD) (and its expansions beyond the leading order) and non-perturbative effects, in particular

Table 2: Current data set sizes in $fb^{-1}$ (millions of events) and proposal for Belle II.

| Experiment | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ | $\Upsilon(4S)$ | $\Upsilon(5S)$ | $\Upsilon(6S)$ | $\frac{\Upsilon(nS)}{\Upsilon(4S)}$ |
|---|---|---|---|---|---|---|---|
| CLEO | 1.2 (21) | 1.2 (10) | 1.2 (5) | 16 (17.1) | 0.1 (0.4) | – | 23% |
| BaBar | – | 14 (99) | 30 (122) | 433 (471) | $R_b$ scan | $R_b$ scan | 11% |
| Belle | 6 (102) | 25 (158) | 3 (12) | 711 (772) | 121 (36) | 5.5 | 23% |
| Belle II | – | – | 300 (1200) | $5 \times 10^4 (5.4 \times 10^4)$ | 1000 (300) | 100 + 400 (scan) | 3.6% |

with application of the light-cone approximation and the non-relativistic QCD (NRQCD) factorisation approaches. For the moment the production of $J/\psi$ and $\psi(2S)$ with spin-0 Charmonia is established with a very high significance [9, 10]. The processes $e^+e^- \to J/\psi X$ are identified from peaks in the mass spectrum of the system recoiling against the reconstructed $J/\psi$ in inclusive $e^+e^- \to J/\psi X$ events.

At Belle II it is likely that the full list of possible Charmonium pairs can be measured with good accuracy, which can be used to verify the Charmonium production models. Another important topic for Belle II is to perform angular analyses (e.g. to measure the $J/\psi$ production and $J/\psi$ helicity angle distributions for $e^+e^- \to J/\psi X$) that gives access to the ratio of different orbital momentum contributions in the two body process, which also allows to check the consistency of the models with the experimental data.

This process can also serve as an efficient tool to study the Charmonium decays, in particular to measure their absolute branching fractions. With a 50 times higher data set Belle II can measure the absolute branching fractions for $\eta_c$, $\eta_c(2S) \to K_S K\pi$ with a 1% accuracy. Furthermore, the double-Charmonium production mechanism offers a unique opportunity to search for and study new $C$-even Charmonium states, produced in association with the effectively reconstructed $C$-odd Charmonia such as $J/\psi$ or $\psi(2S)$.

### *Initial State Radiation (ISR)*

Although dramatic progress has been made on the study of the XYZ states and the conventional Charmonium states, there are still many questions to be answered. States with $J_{PC} = 1^{--}$ can be studied with the ISR technique using the huge Belle II data sample. Compared to the current BESIII experiment, with ISR events the whole hadron spectrum is visible so that the line shape of the resonance and fine structures can be investigated. The disadvantage is that the effective luminosity and detection efficiency are relatively low. Of course, the ISR analyses have a lower efficiency than in direct $e^+e^-$ collisions because of the extra ISR photons and the boost given to events along the beam direction. Even taking these effects into account, the full Belle II data sample will result in similar statistics as BESIII [11] for modes like $e^+e^- \to \pi^+\pi^- J/\psi$. Also Belle II will get access to events above 4.6 GeV, which is currently the maximum energy of BEPCII. With a data sample larger than 10 ab$^{-1}$ at Belle II several ISR processes can be studied, especially these golden modes: $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, $K^+K^- J/\psi$, $\pi^+\pi^- h_c$, $\omega\chi_{c0}$.

### *Two Photon Interactions*

This process gives access to the resonances with $J_{PC} = 0^{++}, 0^{-+}, 2^{++}, 2^{-+}$. At Belle II with higher statistics, the $\gamma\gamma \to D\bar{D}$ process needs to be analysed carefully to give more precise parameters of the $\chi_{c2}(2P)$. Another important two-photon process is $\gamma\gamma \to \phi J/\psi$. With the full amplitude analysis of $B^+ \to K^+\phi J/\psi$ performed by LHCb, four $\phi J/\psi$ structures are observed [12]. Two of these states ($X(4500)$ and $X(4700)$) can be investigated with this method.

## *3.2. Above Υ(4S)*

While in the Charmonium sector many exotica are known, only two states have been observed in Bottomonium, closely related to each other: $Z_b(10610)$ and $Z_b(10650)$ [13]. For the former, the neutral partner has been observed as well. Despite the lack of experimental observation, a rich spectrum of states is predicted by all the effective theories [14] used to model the light-quark contributions to the heavy meson spectra, like the tetraquark and the molecular model.

The investigation of these new states is experimentally challenging since they can be produced only by hadronic or radiative transitions from higher vector states, predicted in the primary $e^+e^-$ collision. In either case, running at the highest possible center of mass energy of 11.24 GeV is preferable. However, in the current configuration the SuperKEKB complex can deliver $e^+e^-$ collisions with an energy of 11.02 GeV just above the $\Upsilon(6S)$ mass.

The study of hadronic transitions can also shed light onto the spectrum of conventional quarkonia. Several narrow states which are still missing can be reached via hadronic transitions from the $\Upsilon(6S)$: $\Upsilon_J(2D)$, $\eta_b(1D)$, $h_b(3P)$, $h_{b3}(1F)$, $\Upsilon_J(2D)$ are all reachable with $\pi\pi$, $\eta$ or $\omega$ transitions from the $\Upsilon(6S)$.

In addition to the search for exotica with data taking at a fixed energy at the $\Upsilon(6S)$, another issue that must be addressed by Belle II is the nature of the $\Upsilon(5S)$ and $\Upsilon(6S)$ themselves and the general structure of the hadronic cross section in the threshold region. Being located at the $B_s\bar{B}_s$ threshold, the $\Upsilon(5S)$ could be an admixture of conventional and molecular Bottomonium. In addition to that, several vector tetraquark are predicted in the region between the $\Upsilon(5S)$ and $\Upsilon(6S)$.

### 3.3. *Below $\Upsilon$(4S)*

Having to focus a narrow-quarkonia physics program on one energy only, the $\Upsilon(3S)$ is the more suitable. While the physics at $\Upsilon(2S)$ and $\Upsilon(1S)$ has been largely explored by BaBar and Belle and their datasets can still provide important results, as the BaBar studies of $\Upsilon(3S)$ transitions left few important, unresolved points. The two most outstanding ones are the isospin-violating transition $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$, for which an unexpected evidence has been reported [15], and the $\Upsilon(3S) \rightarrow \eta\Upsilon(1S)$, which despite the theoretical predictions has not been observed yet.

## 4. Beyond Quarkonia

Running at the $\Upsilon(3S)$ offers the possibility to further test QCD. $\Upsilon(3S)$ annihilations have not yet been studied in details, but it has already shown few peculiar characteristics. The CLEO collaboration reported an unexplained enhancement of strangeness production [16], a phenomenon well known to the heavy ion community, which causes a large production rate of hyperons. Bottomonium annihilations are therefore preferable over $e^+e^- \rightarrow q\bar{q}$ and B decays to study the spectrum of these states. The large production rate would allow to study not only the production, but also the the hyperon-hyperon and hyperon-proton correlations: a pilot study made by Belle produced stringent limits on the existence of the H-dibaryon [17], but the goal for Belle II would be to extend this study to the correlation function and to the search for long-lived or stable dibaryons, using fully reconstructed events with missing energy.

Finally, with 1.2 Billions of $\Upsilon(3S)$ annihilations Belle II plans to study the spectrum of anti-deuterons produced in the annihilation [18, 19] with unprecedented precision. This study will allow to investigate the basic mechanism for the production of anti-nuclei in hadronic events, without involving the corrections for final state interaction needed in heavy ion collisions. The understanding of the $\bar{d}$ production mechanism is fundamental for the interpretation of the results on the anti-matter content in cosmic rays expected by the AMS-02 [20] and GAPS [21] collaborations.

## 5. Outlook

Belle II has successfully started taking data earlier this year. With the planned data set of 50 ab$^{-1}$ (cf. Fig. 6), mostly at the $\Upsilon(4S)$ but also up to 11.02 GeV, which is the current limit of SuperKEKB covering the $\Upsilon(6S)$, and down to $\Upsilon(3S)$, many detailed studies and new discoveries in the Charmonium and Bottomonium sector can be expected.

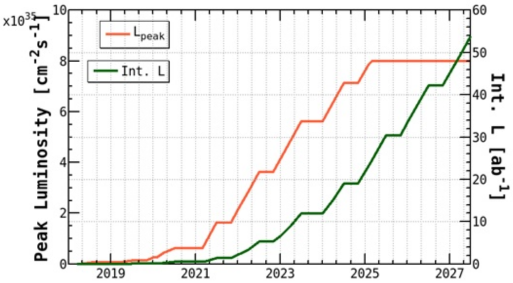

Figure 6: Projected luminosity and accumulated statistics development for Phase III.

## Acknowledgements

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