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Belle II early physics program of bottomonium spectroscopy

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The Belle II experiment at the SuperKEKB collider is a major upgrade of the KEK "B factory" facility in Tsukuba, Japan. Phase 1 commissioning of the main ring of SuperKEKB has started in February 2016 and first physics data will be recorded in 2017 during the so-called Phase 2 commissioning, when the partial Belle II detector will be operated still without its vertex detector. In 2018, the full Belle II detector will be rolled in and physics run will start. In this proceeding, a possible physics program for this early data run at different center-of-mass energies is described, in particular at the $\Upsilon(3S)$ and $\Upsilon(6S)$ resonances, amongst other energy points.

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1. Introduction

The so-called B factory is an asymmetric e^+e^- collider mainly running at the $\Upsilon(4S)$ resonance energy of 10.58 GeV to produce B meson pairs. The first generation of B factories are Belle at KEKB in Japan and BaBar at PEP-II in US, which have collected about 1.5ab^{-1} data sets in total (Table. 1). B factories cover fruitful physics program and have made great achievements in intensity frontier. The physics topics include CP violation in beauty and charm sectors, precise measurements of CKM matrix elements, bottomonium spectroscopy and searching for unanticipated new particles such as XYZ hadrons. B factories are also competitive to search for new physics beyond Standard Model (SM), such as study of rare decay of $b \to sl^+l^-$, $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$, lepton flavor violating and searching for light dark matter and dark photon [1].

The Belle II experiment [2], as the upgraded successor of Belle, is under construction at the SuperKEKB collider [3]. Benefiting from the nano-beam technology, the designed peaking luminosity of SuperKEKB reaches 8×10^{35}cm^{-2}s^{-1}. The detector will be upgraded for Belle II apparatus, including the vertex detector (VXD) of two-layers DEPFET pixel (PXD) and 4-layers double-sided silicon strips (SVD), a drift chamber (CDC) with longer arms and smaller cells, a completely new particle identification (PID) system, the upgraded electro-magnetic calorimeter (ECL) and $K_L - \mu$ detection system (KLM). As scheduled, the Belle II detector will be partially commissioned in the so-called BEAST II Phase II in 2017. After full commissioned in 2018, Belle II is expected to accumulate the equivalent data sets of Belle in one year, and 50 ab^{-1} integrated luminosity by 2025. Data collected at different center-of-mass energies during Phase II and the beginning of physics run could yield unique new physics results two years beforehand. Therefore, this period represents opportunity for the Belle II experiment to have an early scientific impact.

In this proceeding, some proposed studies of bottomonium spectroscopy aiming for the early physics program of Belle II experiment are described.

Table 1: Existing e^+e^- datasets collected near Υ resonances.

Experiment	Scans /Off.Res. fb^{-1}	$\Upsilon(5S)$ 10876MeV fb^{-1} 10^6	$\Upsilon(4S)$ 10580MeV fb^{-1} 10^6	$\Upsilon(3S)$ 10355MeV fb^{-1} 10^6	$\Upsilon(2S)$ 10023MeV fb^{-1} 10^6	$\Upsilon(1S)$ 9460MeV fb^{-1} 10^6
CLEO	17.1	0.4 0.1	16 17.1	1.2 5	1.2 10	1.2 21
BaBar	54	R_b scan	433 471	30 122	14 99	-
Belle	100	121 36	711 772	3 12	25 158	6 102

2. Accelerator/Detector Conditions and Early Physics

The proposed commissioning of Belle II detector will take place in the BEAST II (**B**eam **E**xorcism for **A** **ST**able experiment), aiming at characterizing the beam-induced backgrounds near the interaction point (IP). The commissioning scenario will be performed in three stages, they are

Phase 1 (2016.2-6): Beam commissioning without collisions or the Belle II detector.

Phase 2 (2017.11-2018.3): Accelerator tuning and evaluation of beam related background. Partial Belle II detector will be rolled in without full vertex detector. Collision will start.

Phase 3 (2018.10-): Physics run with full Belle II detector.

During Phase II, all the outer sub-detectors and one octant of VXD will be present, while the remaining area of VXD will be populated with the FANGS, CLAWS and PLUME detectors. Nominal operating energy is at $\Upsilon(4S)$, while larger energy range from $\Upsilon(1S)$ to 11.25 GeV should be capable. The instantaneous luminosity is expected to reach $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the beam energy spread is expected to be close to the nominal value of about 5 MeV. Majority of the time in Phase II will be spent for accelerator commissioning and tuning. If the machine commissioning are accomplished in a good time manner, there will be opportunity for 2 months physics data collection. The estimated integrated luminosity during Phase II is 20 ± 20 fb^{-1}.

During the early running phase, the luminosity will be relatively low, and therefore the triggers could be configured to be looser than at nominal. The lack of the VXD detector is expected to result in tracking efficiency losses in low p_t region since these tracks can not reach or produce sufficient hits to be reconstructed in CDC . Preliminary studies of photon efficiency indicate that no appreciable difference is expected between Phase II and Phase III due to nearly equivalent amount of material contributed in VXD area. As a result, early physics analyses relying on photon detection will be as effective in Phase II as in Phase III.

3. Bottomonium Spectroscopy

Heavy quarkonium presents an ideal laboratory for testing the interplay between perturbative and nonperturbative QCD [4]. Bottomonium spectroscopy focuses on the existence, quantum numbers, masses and widths of bottomonia states. Of late, progress has occurred mostly at e^+e^- colliders with the capability to obtain large data sets at bottomonia masses with well-known initial-state quantum numbers and kinematics. Although bottomonium spectroscopy has been detailed explored by the first generation of B-factories and other experiments, there are still open questions, for example the unobserved states such as $\Upsilon(1D)$ and some unpredicted observations such as XYZ hadrons. Quite a few of these analyses are limited by statistics. From the view of event reconstruction in detector, transitions involving another bottomonium state especially the radiative transitions from onresonance data sets do not strongly rely on the vertex determination and PID. All these properties offer achievable opportunities of early physics at Belle II in bottomonium spectroscopy.

4. Bottomonium bellow $\Upsilon(4S)$

A significant increase in scientific potential at $\Upsilon(3S)$ could be achieved with about 200 fb^{-1} of data (7× Babar data size). Within a shorter time of data collection, it offers unique early physics that would not necessarily be achieved with an equivalent size of Belle data at $\Upsilon(4S)$ (711fb^{-1}). Meanwhile, from the standpoint of machine operation, it may also be desirable to begin at lower energy.

4.1 Study of $\eta_b(1S,2S)$ at $\Upsilon(3S)$

With the 109M $\Upsilon(3S)$ radiative decays, the Babar Collaboration observed the bottomonium ground state $\eta_b(1S)$ [5]. Subsequent analysis at Belle from $\Upsilon(5S)$ provided further measurement of $\eta_b(1S)$ and evidence of $\eta_b(2S)$ via $\Upsilon(5S) \to h_b(nP)\pi^+\pi^- \to \eta_b(mS)\gamma$ [7]. Despite many measurements in different experiments, there is conflict in $\eta_b(1S)$ mass at about 3.5σ between the combined Babar [5, 8] and CLEO [6] results of 9391.1±2.9 MeV/c^2 from radiative decays and Belle results of 9403.4±1.9 MeV/c^2 from $h_b(nP) \to \gamma\eta_b(1S)$. Further measurements with large increase in available statistics are needed.

Verification of the $\eta_b(1S)$ mass from $\Upsilon(3S) \to \gamma\eta_b(1S)$ in the inclusive photon spectrum should be straightforward with a large statistics from early Belle II data set. Given the branching fraction of 5×10^{-4}, one expects roughly 800 $\eta_b(1S)$ per fb^{-1}, assuming an efficiency of about 40%. The decay of $\Upsilon(3S) \to \pi^0 h_b(1P) \to \gamma\eta_b(1S)$ for which 3σ evidence was seen at Babar [9], may also provide complement on $\eta_b(1S)$. Based on the branching fraction and efficiency from Babar of 4×10^{-4} and 20%, this process is expected to represent about 350 events per fb^{-1} at Belle II. In both processes $\eta_b(1S)$ are inclusively reconstructed and large background is expected. Another potential pathway well-suited to the initial running conditions of Belle II would be via $\Upsilon(3S) \to \gamma\chi_{b0}(2P) \to \eta\eta_b(1S)$. The branching fraction of $\mathscr{B}(\chi_{b0}(2P) \to \eta\eta_b(1S))$ is expected to be as large as 10^{-3} [10]. One can expect about 2000 events with a 200 fb^{-1} $\Upsilon(3S)$ sample assuming the efficiency of 5%.

4.2 $\Upsilon(nD)$ studies

The $\Upsilon(1D)$ is the lowest-lying D-wave triplet of the $b\bar{b}$ system. CLEO first made the observation of $\Upsilon(1^3D_2)$ using the four-photon cascade of $\Upsilon(3S) \to \gamma\chi_{bJ}(2P) \to \gamma\Upsilon(1D) \to \gamma\chi_{bJ}(1P) \to \gamma\Upsilon(1S) \to l^+l^-$, where $l^\pm = e^\pm/\mu^\pm$ [11], and Babar observed $\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_2) \to \pi^+\pi^-\Upsilon(1S)$ with the significance of 5.8 σ [12]. Theoretical calculations predict the J=1, 3 masses around 10150, 10170 GeV/c^2, the $\Upsilon(2^3D_2)$ mass is predicted to be in the range of 10420 to 10460 MeV/c^2. They are expected to be narrow, and predominantly decay to $\gamma\chi_{bJ}(nP)$. Opportunities are open to Belle II with larger statistics $\Upsilon(3S)$ samples. Meanwhile, $\Upsilon(n^3D_1)$ states can be produced directly via a beam energy scan. Assuming a value of instantaneous luminosity of 2×10^{-34}cm^{-2}s^{-1}, a 7-10 steps scan centered on 10.150 (10.435) GeV with 2 (1.4) fb^{-1} per point would take about one week for each J=1 states, to achieve a 5σ observation.

4.3 $h_b(1P)$ studies

First evidence (3.1σ) of $h_b(1P)$ came from Babar by selecting the soft pion and radiative photon restricted to $\eta_b(1S)$ mass in $\Upsilon(3S) \to \pi^0 h_b(1P) \to \gamma\eta_b(1S)$, with the multiplied branching fraction of $(4.3\pm1.4)\times10^{-4}$ [9]. No evidence of dipion transition $\Upsilon(3S) \to \pi^+\pi^- h_b(1P)$ was found, the upper limit of branching fraction was determined to be 1.2×10^{-4} [13]. An increase by a factor of >3 in statistics could provide an observation of $h_b(1P)$. This analysis mainly relies on photon detection, which would be advantageous in early running scenarios of Belle II.

4.4 Analysis with converted photons

An improvement in photon energy resolution can be achieved using the e^+e^- pair from photon conversion in detector material, although the efficiency for reconstruction is much lower than that for calorimeter. Babar attempted to perform a study of bottomonium radiative transitions using converted photons. Precise measurements of $\mathscr{B}(\chi_{b1,2}(1P,2P) \to \gamma\Upsilon(1S))$ and $\mathscr{B}(\chi_{b1,2}(2P) \to \gamma\Upsilon(2S))$

were made, and the searches for $\eta_b(1S, 2S)$ states were inconclusive [14]. The advantage of the improved resolution from a converted photon technique offers chances to make a definitive measurement of $\eta_b(1S)$ mass and width in future B-factories with more data.

4.5 Hadronic/Radiative transitions

With sufficient statistics, the dipion transitions amongst bottomonia such as $\Upsilon(3S) \to \pi\pi\Upsilon(1S, 2S)$, $\chi_b(2P) \to \pi\pi\chi_b(1P)$ can be studied in detail. Other hadronic transitions that have been attempted include $\Upsilon(2S, 3S) \to \gamma\Upsilon(1S)$ and $\chi_b(2P) \to \omega\Upsilon(1S)$. Studies involving ρ transitions need to be complemented. Regarding these radiative transitions between Υ and χ_b, the $\chi_{b0}(2P) \to \gamma\Upsilon(1S)$ could only reach a significance of 2.2σ from recent measurement of Babar, the $\Upsilon(3S) \to \gamma\chi_{bJ}(1P)$ observation is difficult to measure due to the overlapping photon transition energies and theoretically difficult to calculate due to the effects of higher-order corrections.

5. Bottomonium above $\Upsilon(4S)$

The upper limit of Belle II/Super-KEKB facilities can reach $\sqrt{s}$ of 11.25 GeV/c^2, which would allow for data collection across $\Upsilon(6S)(\Upsilon(11020))$. The proposed physics program for bottomonia above $\Upsilon(4S)$ includes the energy scan and searches for bottomonium-like states.

5.1 $\sqrt{s}$ scan

Scans in e^+e^- center-of-mass energy ($\sqrt{s}$) can map out vector resonances via either inclusive hadronic-event counting (R scan) and/or exclusive final states (*e.g.*, $B\bar{B}$, $\pi\pi\Upsilon(nS)$). Up to date, sparing studies of energy range of 10.6 to 11.25 GeV have been done. In 2008, Babar published the results of $e^+e^- \to b\bar{b}$ cross section measurements based on the 3.3 fb^{-1} data from 10.54 to 11.20GeV and 600 pb^{-1} at $\Upsilon(6S)$ region, parameters of $\Upsilon(5S)$ and $\Upsilon(6S)$ are measured [15]. Subsequently, Belle measured the production cross section for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ using the 8.1 fb^{-1} data between 10.83 and 11.02GeV, followed by a high-luminosity scan for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ and $e^+e^- \to b\bar{b}$ [16]. For early running period of Belle II, one proposal is doing a scan extending to the energy beyond $\Upsilon(6S)$ or even close to Λ_b pair threshold, which is close to the maximum energy of facilities.

5.2 Charged Bottomonium-like states: $Z_b^\pm$

The bottomonium-like $Z_b^\pm(10610)$ and $Z_b^\pm(10650)$ states are of special interest since their properties do not fit the potential model predictions. The minimal quark substructure of $b\bar{b}u\bar{d}$ would be necessary and therefore be manifestly exotic. They were first observed by Belle in $\Upsilon(nS)\pi^\pm$ and $h_b(mP)\pi^\pm$ $(n = 1, 2, 3; m = 1, 2)$ channels produced in $\Upsilon(5S) \to Z_b^\pm\pi^\mp$, using the 121 fb^{-1} sample [17]. The $J^P = 1^+$ is favored from angular analyses. Corresponding neutral state of $Z_b^0(10610)$ produced in $\Upsilon(5S) \to \Upsilon(2S, 3S)\pi^0\pi^0$ decays at a consistent mass [18] indicates isospin 1 is favored.

Given proximity to the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds and finite widths, it's natural to expect the rates of $Z_b(10610) \to B\bar{B}^*$ and $Z_b(10650) \to B^*\bar{B}^*$ are substantial in the molecular picture. The $\pi^\pm$ missing mass spectrum in $\Upsilon(5S) \to B\bar{B}^*\pi$ decays shows clear excess (8σ) of events over background which is interpreted as $Z_b^\pm(10610)$ signal, while $\Upsilon(5S) \to B^*\bar{B}^*\pi$ shows $Z_b^\pm(10650)$ signal with 6.8σ [19]. Belle measurements indicated the $B^{(*)}\bar{B}^{*}$ decays is dominant and accounts for a branching fraction of about 80% assuming so far observed Z_b decays are saturated.

Belle also studied the processes of $e^+e^- \to h_b(1P,2P)\pi^+\pi^-$ with 6 fb^{-1} $\Upsilon(6S)$ sample. Evidence of $Z_b^{\pm}(10610)$ and $Z_b^{\pm}(10650)$ were reported [20], while the information of Z_bs on $\pi\Upsilon(mS)$ and $B^{(*)}\bar{B}^{*}$ from $\Upsilon(6S)$ decay are still absent. Larger statistics $\Upsilon(5S,6S)$ samples are necessary for a better understanding of Z_b states.

6. Summary

The Belle II experiment will be the next generation of B-factory with ultra high luminosity. The physics data taking will start in 2018, while first data with partial detector will come in 2017. Various bottomonia spectroscopy topics that could be considered in the early data taking phase for Belle II are covered. Considering the detector condition, the proposed analyses here are more related to the photon reconstruction but not to PID, nor vertex finding precision. Most of these analyses are limited to existing sample sizes at specific collision energies, especially at $\Upsilon(3S)$ and $\Upsilon(6S)$.

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