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Prospects for Heavy Quarkonium at SuperB

Elisa Manoni*
Istituto Nazionale di Fisica Nucleare - Sezione di Perugia
E-mail: elisa.manoni@pg.infn.it

In the past few years, the B Factories and the Tevatron have provided evidence for states that do not admit conventional mesonic interpretation and that instead could be made of a larger number of constituents. While this possibility has been considered since the beginning of the quark model, the actual identification of such states would represent a major revolution in our understanding of elementary particles. It would also imply the existence of a large number of additional states that have not yet been observed. This talk reviews the steps needed towards the understanding of this picture and discusses the role of the future SuperB project in it.

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*Speaker.

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1. The SuperB project

The Standard Model (SM) of particle physics has proven to be very successful and experimental measurements have confirmed the theoretical predictions with good accuracy. As of today, there are still open questions on the elementary structure of matter and antimatter and on their interactions and many New Physics (NP) models have been postulated in order to give coherent answers to such issues, accounting for the current experimental knowledge. There are two possible ways to NP discovery: the direct searches and the indirect ones. The firsts are performed at high energy hadronic machines, such as LHC, in which the production of non-standard states as real particles is possible. On the other hand, flavor physics experiments can study NP contributions due to non-standard particles, in their virtual states, contributing to known processes which are predicted to be rare or forbidden in the SM framework. The next generation flavor physics experiments at e^+e^- colliders, SuperB in Italy and Belle-II in Japan, will allow to measure the coupling of new states with already-known particles in order to determine the NP scale and disentangle between different NP scenarios. At the end of their running, the super flavor factories will collect $5-10\times10^{10}$ $b\bar{b}$, $c\bar{c}$, and $\tau^+\tau^-$ pairs, which will be analyzed in the light of the LHC experiment results. If NP will be found at LHC, SuperB and Belle-II will be able to determine the structure of the NP couplings, will study its flavor structure, and will search for indirect signal of heavier states. On the contrary, if the LHC will not found evidence for NP at the investigated energy scales, in the flavor sector one will look for indirect NP signals, will connect them to the theoretical models and exclude regions of the model parameter space.

This contribution will focus on the SuperB project, an asymmetric e^+e^- machine [1] which will mainly run at the $\Upsilon(4S)$ resonance mass. Runs at the $\Psi(3770)$ threshold and a scan above and below the $\Upsilon(4S)$ will also be possible. The design luminosity will be a factor of one hundred higher than at the previous flavor factory experiments (BaBar in the USA and Belle in Japan), aiming to a nominal value for the instantaneous luminosity of 10^{36} cm^{-2} s^{-1} at the $\Upsilon(4S)$ threshold.

The project has been approved by the Italian government in December 2010, the laboratory site, locate in the Tor Vergata campus near Rome, has been chosen in May 2011 and in October of the same year the start-up for the laboratory, named *Cabibbo Lab* in honor of Professor Nicola Cabibbo, has been signed. A detector Technical Design Report is foreseen by the end of 2012 while the construction is expected to start in mid 2013. With the planned luminosity, 75 ab^{-1} at the $\Upsilon(4S)$ threshold will be collected half way through the next decade.

The detector which will allow to study such a big amount of events is a multi-purpose device based on the BaBar detector and described in detail in Ref. [2]. Given the variety of the energy investigated and the amount of data collected for the different samples, the physics case for the SuperB experiment [3] comprises many aspects of the flavor physics, such as B, D, B_s and τ property studies, other than heavy quarkonium searches, as discussed in this contribution.

2. Heavy Quarkonium at SuperB

Heavy quarkonium states, such as charmonium and bottomonium, will be largely produced at the SuperB experiment through different mechanisms.

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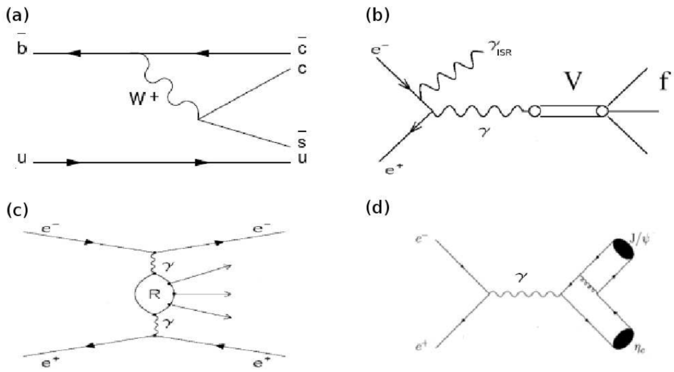

Figure 1: Production mechanisms of $c\bar{c}$ states at the flavor factories: B meson decay to $(c\bar{c})$ plus a strange meson (top left), initial state radiation (top right), two-photon fusion (borrow left), and double charmonium production (bottom right).

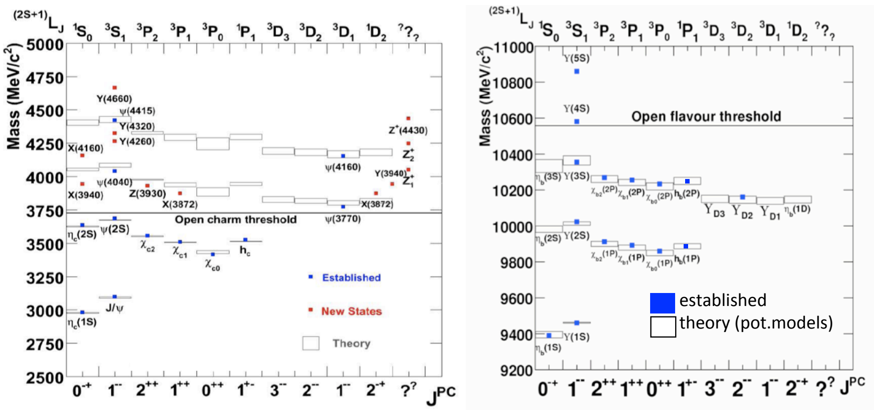

Figure 2: Spectra of charmonium (left) and bottomonium (right) systems. The blue (red) dots represent the established (new) states, the black boxes show the theoretical predictions for the mass states in the context of the potential model [4].

As for the charmonium, Fig. 1 shows four mechanisms by which a $c\bar{c}$ state can be produced: (a) through a B decay and in association with a $K^{(*)}$, (b) as a final product of a e^+e^- collision where one of the two leptons has emitted an initial state photon, (c) through the fusion of two photons exchanged by the two colliding leptons, and (d) in e^+e^- final states composed by two $c\bar{c}$ states.

Mesons composed by $b\bar{b}$ quarks are produced using $\Upsilon(nS)$ samples (where n= 2, 3, 4 in the BaBar searches, similarly to what will be done in SuperB) and looking for lower mass states reached through the decay $\Upsilon(nS) \rightarrow (b\bar{b})\gamma/n\pi$.

The reconstructed samples will allow to complete the knowledge of the below-threshold states and investigate the properties, and in some cases confirm the existence, of exotic particles studied at the b factories.

Reviews of the current knowledge on heavy quarkonium are given in Refs. [4] [5], where the relevant references for theoretical models, experimental results and their interpretation are listed.

2.1 Regular and exotic charmonium states

In the charmonium system, the observation of states below the open charm threshold is in good agreement with the theoretical predictions, as can be also seen in the left plot of Fig. 2. As for the above-threshold region, some unexpected narrow states have been observed by BaBar and Belle.

The first exotic state, $X(3872)$, was observed by Belle [6] in 2003 in the $B \to (J/\Psi\pi\pi)K$ decay and was soon confirmed by other experiments [4]. The quantum numbers of such states have not been determined yet and the studied decay modes leave two possibilities open: $J^{PC} = 1^{++}, 2^{-+}$. The nature of the $X(3872)$ particle is already debated and the most favorite explanations are a new charmonium state, a tetraquark or a $D\bar{D}^*$ molecule. With an integrated luminosity of 50 ab^{-1}, SuperB will provide $3-11 \times 10^3$ fully reconstructed $B \to X(3872)K$, depending on the X(3872) final state. With such samples, a detailed study of the decay dynamics and of the line-shape, to give possible evidence of non $q\bar{q}$-composition, will be feasible.

In initial state radiation events, BaBar [7] has found evidence for two exotic $J^{PC} = 1^{--}$ states in the following final states: $Y(4260) \to J/\Psi\pi\pi$ and $Y(4360) \to \Psi(2S)\pi\pi$. In the latter final state, Belle discovered another $J^{PC} = 1^{--}$ state: $Y(4660)$ [8] . The results of such measurements are puzzling since conventional $J^{PC} = 1^{--}$ charmonium states were already known and understood before these evidences, moreover the branching fraction to open charm final states is suppressed with respect to the $J/\Psi\pi\pi$ decay mode. Several hypothesis on the nature of such states have been postulated such as hybrids, tetraquarks, or hadrocharmonium. SuperB, with an integrated luminosity of 50 ab^{-1}, will collect 30×10^3 events for $Y(4260) \to J/\Psi\pi\pi$ and 3×10^3 events for $Y(4360)$, $Y(4660) \to \Psi(2S)\pi\pi$ aiming for a detailed study of line-shapes, partial width ratios, and $\pi\pi$ invariant mass spectra. The inclusions of other Y exclusive decays to charmonium, such as $J/\Psi\eta/\pi^0$, $\Psi(2S)\eta/\pi^0$, $\chi_{cJ}\pi\pi$, $J/\Psi\gamma$, $\Psi(2S)\gamma$, will also be possible.

The most debated states, in the exotic charmonium scenario, are the charged Z particles, observed by Belle and not confirmed by BaBar [4] [9]. Three states have been observed by Belle so far: $Z_1(4050)^+$, $Z_2(4250)^+$ and $Z(4430)^+$ and they can be interpreted as tetraquarks while, in the case of $Z(4430)^+$, also hypothesis of a molecule or a threshold effects have been postulated. With 50 ab^{-1} of SuperB data, 100×10^3 to 1.5×10^4 reconstructed $B \to J/\Psi\pi K$, $\Psi(2S)K\pi$, $\chi_{cJ}K\pi$ candidates will be available, unambiguously establishing the Z^+ existence with a detailed study of their properties.

2.2 Regular and exotic bottomonium states

The bottomonium spectrum below the $B\bar{B}$ production threshold is incomplete and the states $\eta_b(2S, 3S)$ and the three D-states have not been observed yet. The $\eta_b(1S)$ has been recently discovered [10] but it is poorly known. SuperB will provide higher statistic samples in order to complete the below-threshold spectrum, and make a detailed study of the established states in terms of exclusive decay modes and partial widths.

Above-$\Upsilon(4S)$ data have been collected by both BaBar and Belle. BaBar performed an inclusive scan above the $B\bar{B}$ production threshold [11] and the analyzed data did not show any exotic structure. Belle made an exclusive analysis of its $\Upsilon(5S)$ sample [12], claiming for the evidence of two new states, $Z_b^+(10610)$ and $Z_b^+(10650)$, in the decay chains $\Upsilon(5S) \to Z_b^+\pi^-$ with $Z_b^+ \to \Upsilon(1S, 2S, 3S)\pi^+\pi^-$, $h_b(1P, 2P)\pi^+\pi^-$. It is worth to mention that the $\Upsilon(5S)$ mass and the

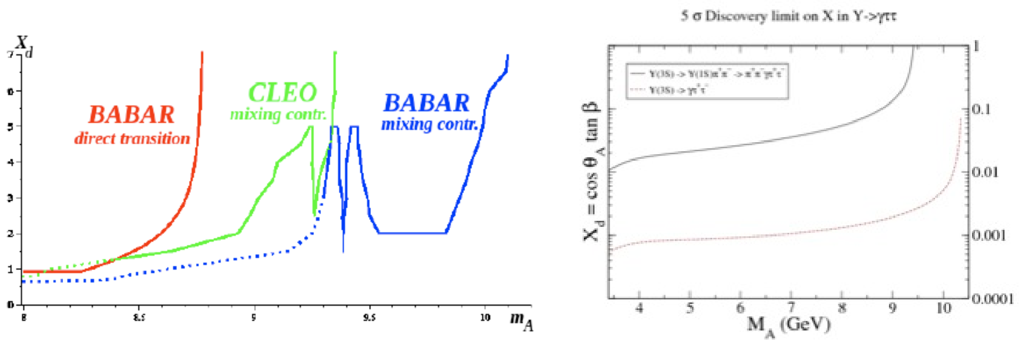

Figure 3: Left: Upper bounds on X_d for A_0 in the mass-range 8-10.1 GeV, using the current experimental results, details on the plot are given in Ref. [16] . Right: 5 σ discovery potential of SuperB at $1ab^{-1}$ with $\Upsilon(3S)$ data, in the modes $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S) \to \pi^+\pi^-\tau^+\tau^-\gamma$ (solid) and $\Upsilon(3S) \to \tau^+\tau^-\gamma$ (dashed)

width measured by BaBar and Belle disagree from the PDG values [13] and the interpretation of this state is still controversial. The above-$\Upsilon(4S)$ data collectable at SuperB will allow to have large data sample on which perform inclusive analysis of $(b\bar{b})$ decays and study in detail the nature of the $\Upsilon(5S)$.

2.3 Little Higgs searches in $(b\bar{b})$ samples

Some NP models, such as Next-to-MSSM, predict the existence of light CP-odd Higgs (A_0) [14] with mass below $2m_b$, being m_b the b quark mass. Such state is the result of the mixing of a singlet and a MSSM-like Higgs through the relation: $A_0 = A_{MSSM} cos\theta_A + A_{singlet} sin\theta_A$, being θ_A a parameter which quantifies the mixing between the two components. Such a boson could be produced in decays of the $\Upsilon(2S,3S)$ mesons, accompanied by a radiated photon. The theory predicts that the A_0 decays predominantly into the heaviest kinematically available down-type fermion pair, so, depending on its mass, the dominant decay mode can be to hadrons, μ or τ pairs, or to completely invisible final states. For its predicted mass, such state is not constrained by LEP analyses. Moreover, the considered low momentum final states are not accessible to the LHC experiments. BaBar performed several searches for the light Higgs boson [15]. The current Υ branching fraction measurements, based on an exclusive reconstruction of final states in which the A^0 may be produced as an intermediate state, are limited by systematics and a 1% precision is foreseen at SuperB. Alternative analyses can be performed, for example, searching for monochromatic photons in the $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ decay with $\Upsilon(1S) \to \gamma\tau^+\tau^-$, which has a small branching fraction (4.5%) but also a low background contamination. The second decay mode would be $\Upsilon(3S) \to \gamma\tau^+\tau^-$, which has a higher branching fraction but also a higher background level. The 5 σ discovery potential of SuperB at an integrated luminosity of 1 ab^{-1} with $\Upsilon(3S)$ data, in the mode $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S) \to \pi^+\pi^-\tau^+\tau^-\gamma$ and $\Upsilon(3S) \to \tau^+\tau^-\gamma$ is presented in the right plot of Fig. 3 [3]. Here, the upper limit on $X_d = cos\theta_A tan_\beta$ as a function of the A^0 mass is shown. It can be noticed that the upper limit ranges from $X_d = 1$ to $X_d = 0.0001$. This can be compared with the same plot obtained by using the current experimental knowledges (Fig. 3, left panel) and it can be noticed how the constraints on X_d are much less stringent with respect to the SuperB reaches.

3. Conclusions

SuperB will be one of the next generation super flavor factories. A dataset of 75 ab^{-1} at the $\Upsilon(4S)$, foreseen half way through the next decade, will be collected in 5 years of data taking. Runs at the $\Psi(3770)$ and a scan above and below the $\Upsilon(4S)$will also be possible. With such samples, precision measurements and indirect searches for NP in the flavor sector, complementary to direct searches at LHC, will be performed. In the heavy quarkonium sector, exotic charmonium state properties will be investigated. The search for the missing regular bottomonium states will be performed; data from the energy scan will be used to investigate the existence of higher bottomonium mass states. Decays of $\Upsilon(nS)$ states will be also used to search for light Higgs, not observable at the LHC experiments. A detailed simulation study of the SuperB reach in those fields is underway.

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