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The Super$B$ project

Matteo Rama
INFN Laboratori Nazionali di Frascati, Italy

Abstract

The Super$B$ experiment is a proposed next generation asymmetric e^+e^- flavor factory designed to operate mainly at the $\Upsilon(4S)$ resonance with a baseline luminosity of 10^{36} cm^{-2}s^{-1}, almost two orders of magnitude higher than the peak luminosity reached at previous e^+e^- B-factories. The main purpose of the experiment is searching for physics beyond the Standard Model and possibly investigating its nature through the measurement of rare processes involving b and charm quarks as well as τ leptons. In addition to running data at the $\Upsilon(4S)$, Super$B$ is designed to operate at energies ranging from the $\Psi(3770)$ threshold up to the $\Upsilon(5S)$ and beyond. We present the physics program and an overview of the accelerator and detector design.

Keywords: flavor physics, CKM matrix, beyond Standard Model, B factory

1. Introduction

Despite the extraordinary success of the standard model (SM) of particle physics in describing the electroweak and strong interactions, a number of theoretical considerations and experimental observations suggest that it should be extended. A large experimental effort is ongoing to shed light on the nature of new physics (NP) beyond the SM. Current and future particle accelerators are designed to search for hints of NP using two complementary approaches. One is the 'energy frontier' path, whose main representatives today are the ATLAS and CMS experiments. The second is the 'intensity frontier' path where indirect observation of new particles or processes can be obtained through the precise measurement of flavor physics phenomena at lower energy, searching for deviations from the SM prediction in rare or forbidden particle decays.

The Super$B$ experiment [1][2][3] is designed to search for NP and possibly clarify its nature following the intensity frontier path. It is based on a new generation, high luminosity asymmetric electron-positron collider operating at a nominal CM energy of 10.58 GeV, the $\Upsilon(4S)$ resonance threshold. The accelerator is designed to deliver a baseline luminosity of 1×10^{36} cm^{-2}s^{-1}, nearly two orders of magnitude higher than the peak luminosity achieved at the previous generation B-factories PEP II and KEKB, where the BaBar and Belle experiments have operated. The physics program is further extended thanks to the longitudinal polarization of the electron beam and the possibility to explore additional energy regions from 3.77 GeV (the open charm threshold) up to 11 GeV above the $\Upsilon(5S)$ resonance. In five years at the nominal luminosity Super$B$ will collect a data set of 75 ab^{-1}, corresponding to a sample of about 80×10^9 $B\bar{B}$ pairs, 100×10^9 $e^+e^-\to c\bar{c}$ events and 70×10^9 $\tau^+\tau^-$ pairs: Super$B$ is in fact a "super flavor factory".

2. Physics program

Super$B$ is a unique laboratory to search for evidence of NP because it can access a wide variety of processes including rare decays of b and c quarks, and of tau leptons. LHCb [4][5] and its possible upgrade at CERN, and Belle II [6] under construction in Japan, will also focus on heavy flavor physics. The programs of Super$B$ and LHCb are complementary to a large extent. The low background e^+e^- environment of Super$B$ allows to

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reconstruct final states with several photons or neutrinos: the measurement of such decays is difficult or impossible in the hadronic environment of LHC. On the other hand, LHCb can exploit the large $b\bar{b}$ production cross section and the large boost of B hadrons to perform important complementary measurements. Belle II is an asymmetric e^+e^- flavor factory operating at the $\Upsilon(4S)$ CM energy, designed to reach a target luminosity of 0.8×10^{36} cm^{-2}s^{-1} and to collect a dataset of 50 ab^{-1} in seven years of running. The beams are not polarized and the machine is not designed to run at CM energies significantly below the $\Upsilon(4S)$ threshold.

In the following sections we present a selection of measurements that Super*B* can perform with a dataset of 75 ab^{-1} by exploiting its unique features. We will focus mostly on measurements that are complementary to those accessible at LHCb and its proposed upgrade. The interested reader can refer to [1][7][8] for thorough and exhaustive discussions of the Super*B* physics case.

2.1. B physics

The physics program includes observables accessible through the decays of neutral and charged B mesons produced in the process $e^+e^- \to \Upsilon(4S)$ and the subsequent decay of $\Upsilon(4S)$ to $B^0\bar{B}^0$ and B^+B^- pairs, each with a fraction of about 50%. Super*B* will collect about 16×10^9 $B\bar{B}$ pairs per year at the design luminosity of 10^{36} cm^{-2}s^{-1}. The machine can also run near the $\Upsilon(5S)$ resonance, beyond the $B_s^{(*)}\bar{B}_s^{(*)}$ threshold. Even though the experiments running at hadronic machines will produce larger amounts of $B_s^{(*)}$ decays, final states with neutral particles can best or only be measured in the much cleaner enviornment of the e^+e^- colliders.

The first class of processes that we consider includes the decays $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ and $B^- \to \tau^-\bar{\nu}_\tau$. In the SM these transitions are mediated at first order by a virtual W boson and are potentially sensitive to the existence of NP charged particles, such as the charged Higgs predicted in the type II Two Higgs Doublet Model (2HDM) [9][10] or in the minimal supersymmetric SM (MSSM) extension. On a dataset of about 0.5 ab^{-1} BaBar has measured the ratios $R(D^{(*)}) = BF(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)/BF(\bar{B} \to D^{(*)}l^-\bar{\nu}_\tau)$ ($l = e, \mu$) and found values exceeding the SM expectations by 2.0 and 2.7 standard deviations for the D and D^* channels, respectively. When the results are combined, the disagreement grows up to 3.4σ. At the same time, from the measured $R(D)$ and $R(D^*)$ the type II 2HDM yields inconsistent values for $\tan\beta/m_{H^+}$, where $\tan\beta \equiv v_2/v_1$ is the ratio of the vacuum expectation values and m_{H^+} is the mass of the charged Higgs. As a result, the model is excluded with a 99.8% CL for any value of $\tan\beta/m_{H^+}$ [11]. Even though more data are necessary to confirm these results, this is an example of how the SM and its extensions can be probed through precise measurements in the flavor sector. The expected precision of $BF(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)$ at Super*B* is about 2%, five times smaller than the current precision. Also in the case of $B^+ \to l^+\nu_l$ a precise measurement of the branching ratio can test NP models and constrain their parameters. For example, in the type II 2HDM the branching ratio is scaled by the factor $(1-\tan\beta^2 m_B^2/m_H^2)^2$ compared to the SM value (a similar scale factor applies in the case of MSSM). Assuming a dataset of 75 ab^{-1} and the SM prediction, the branching ratios for the τ and μ channels can be measured at Super*B* with an error of 4-5%, making these channels sensitive probes of NP. This kind of measurement cannot be performed at the LHC because of the presence of at least two neutrinos in the final state that makes the combinatorial background too large.

In the SM the radiative flavor changing neutral current (FCNC) decays $b \to s\gamma$ and $b \to d\gamma$ proceed through loop diagrams and are sensitive to the presence of NP particles. A number of observables can be measured, such as the rates and CP asymmetries. This can be done either inclusively by selecting all products of the s quark fragmentation, or by reconstructing exclusive final states. Inclusive measurements are experimentally more challenging but theoretically cleaner, and in general more sensitive in the detection and interpretation of NP effects. While some specific decay channels (e.g. $B^0 \to K^{*0}[\to K^+\pi^-]\gamma$) can be measured precisely at hadron machines, as recently proven by the LHCb collaboration, final states with several K_S or photons and the inclusive mode $B \to X_s\gamma$ can only be measured in the clean environment of the e^+e^- B-factories.

While photons in radiative $b \to d\gamma$ and $b \to s\gamma$ decays are predominantly left-handed in the SM, in some of its extensions (see for example [12]) the amplitude of right-handed photons is proportional to the mass of the virtual NP fermion mass. As a consequence, mixing induced CP asymmetries in $b \to q\gamma$ decays are suppressed by m_q/m_b in the SM but might be enhanced up to visible levels due to the presence of NP. The photon polarization can be measured for instance in the decay $B \to K_S\pi^0\gamma$, where Super*B* is expected to improve the current precision of the time-dependent CP asymmetry measurement by an order of magnitude (see Table 1).

The decays $b \to ql^+l^-$ ($q = d,s$) are also sensitive probes of NP through the measurement of an extensive set of observables. The list includes the rate and direct CP asymmetries, the isospin and forward-backward asymmetries, the ratio of the rate of the muon channel to the rate of the electron channel, plus other angular