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The Super*B* project

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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 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

Observable/mode	Current value	Super$B$ with 75 ab^{-1}	Theory now
BF($B \to X_s\gamma$) ($\times 10^{-4}$)	3.55 ± 0.26	0.11	3.15 ± 0.23
$A_{CP}(B \to X_{(s+d)}\gamma)$	0.06 ± 0.06	0.02	$\sim 10^{-6}$
S in $B \to K_s^0\pi^0\gamma$	-0.15 ± 0.20	0.03	-0.1 to 0.1
$B \to K^*\mu^+\mu^-$ (events)	250	10-15k	—
BF($B \to K^*\mu^+\mu^-$) ($\times 10^{-6}$)	1.15 ± 0.16	0.06	1.19 ± 0.39
$B \to K^*e^+e^-$ (events)	165	10-15k	—
BF($B \to K^*e^+e^-$) ($\times 10^{-6}$)	1.09 ± 0.17	0.05	1.19 ± 0.39
$A_{FB}(B \to K^*l^+l^-)$	0.27 ± 0.14	0.04	-0.089 ± 0.020
$B \to X_s l^+l^-$ (events)	280	8600	—
BF($B \to X_s l^+l^-$) ($\times 10^{-6}$)	3.66 ± 0.77	0.08	1.59 ± 0.11
S in $B \to \eta' K^0$	0.59 ± 0.07	0.01	± 0.015
S in $B \to \phi K^0$	0.56 ± 0.17	0.02	± 0.02
BF($B^+ \to K^{*+}\nu\bar{\nu}$) ($\times 10^{-6}$)	< 80	1.1	6.8 ± 1.1
BF($B \to K^+\nu\bar{\nu}$) ($\times 10^{-6}$)	< 160	0.7	3.6 ± 0.5

Table 1: Current precision and experimental sensitivity expected at Super$B$ for a selection of benchmark B decays [8]. BF, A_{CP}, A_{FB} and S indicate the Branching Fraction, CP asymmetry, forward-backward asymmetry and $\sin 2\beta_{eff}$ discussed in the text, respectively.

observables [13]. As for the $b \to s\gamma$ process previously discussed, the inclusive decays $B \to X_s l^+l^-$ are affected by a smaller theoretical uncertainty compared to the exclusive modes $B \to K^{(*)}l^+l^-$. The LHCb collaboration has shown that the exclusive modes $B^0 \to K^{(*)0}\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$ can be measured precisely at hadron colliders [14]. However, the Super$B$ factories are expected to extend the search to final states which include all the $B \to K^{(*)}\mu^+\mu^-$ and $B \to K^{(*)}e^+e^-$ decays and the inclusive channels $B \to X_s l^+l^-$, thus exploring the $b \to sl^+l^-$ sector with unprecedented precision. Estimates for the expected yields are given in Table 1.

NP might appear also in the measurement of mixing-induced, time-dependent CP asymmetry of processes dominated by $b \to sq\bar{q}$ ($q = u,d,s$) penguin transitions. In the SM $\sin 2\beta$ is measured up to small corrections from the asymmetry, but the presence of NP particles can potentially cause observable deviations. The decays $B^0 \to \phi K^0$, $B^0 \to \eta' K^0$ and $B^0 \to K^0\bar{K}^0K^0$ are among the ones with the smallest theoretical uncertainty. Table 1 reports the expected sensitivities at Super$B$ for $B^0 \to \eta' K^0$ and $B^0 \to \phi K^0$.

Super$B$ can bring the knowledge of the CKM matrix parameters down to the percent level thanks to a wide range of measurements performed with unprecedented precision. These include the measurement of $|V_{cb}|$, $|V_{ub}|$ and the angles α, β and γ of the unitarity triangle, as reported in Table 2. The precise knowledge of the CKM matrix is important per se, but it is also a powerful tool to spot inconsistencies in the SM and to improve the SM prediction, and hence the NP sensitivity, of many other flavor observables (see for example [15]).

CKM observable	Precision	Theory uncertainty
β ($c\bar{c}s$)	$0.1°$	clean
α	$1-2°$	dominant
γ	$1-2°$	clean
$\lvert V_{cb}\rvert$ (inclusive)	0.5%	dominant
$\lvert V_{cb}\rvert$ (exclusive)	1.0%	dominant
$\lvert V_{ub}\rvert$ (inclusive)	2.0%	dominant
$\lvert V_{ub}\rvert$ (exclusive)	3.0%	dominant

Table 2: The expected precision on CKM observables at Super$B$ with 75 ab^{-1}. The third column indicates if the measurement will be theoretically clean or dominated by theory uncertainties [8].

2.2. τ physics

In a modest extension of the SM where the neutrino masses are not null, lepton flavor violating (LFV) decays are allowed through neutrino mixing but are many orders of magnitude below the present and future achievable sensitivity ($BF \approx O(10^{-54})$). On the other hand, the same rates can be of the order of 10^{-6} in some supersymmetric extensions. Therefore, the observation of a LFV process would be a clear signal of NP.

On a dataset of 75 ab^{-1} Super$B$ has a sensitivity over 100 times better than BaBar in low-background decay modes such as $\tau^+ \to l^+l^-l^+$ and over 10 times better for background-dominated channels such as $\tau \to l\gamma$ ($l = e, \mu$). Table 3 shows the expected sensitivity for $\tau \to e\gamma$, $\tau \to \mu\gamma$ and $\tau \to lll$. Many of these decays are difficult or impossible to reconstruct in the hadronic environment of LHC. Super$B$ can exploit the electron beam polarization to further suppress the backgrounds and to better determine the properties of NP from the

Process	Expected 90% CL upper limit	3σ evidence reach
BF($\tau \to \mu\gamma$)	2.4×10^{-9}	5.4×10^{-9}
BF($\tau \to e\gamma$)	3.0×10^{-9}	6.8×10^{-9}
BF($\tau \to lll$)	$2.3 - 8.2 \times 10^{-10}$	$1.2 - 4.0 \times 10^{-9}$

Table 3: Expected 90% CL upper limits and 3σ evidence reach on LFV decays with 75 ab^{-1} and the longitudinally polarized electron beam [8].

Parameter	Current value	Super*B* 75 ab^{-1}	Theory now
x	$(0.63 \pm 0.20)\%$	0.02%	$\sim 10^{-2}$
y	$(0.75 \pm 0.12)\%$	0.01%	$\sim 10^{-2}$
$\|q/p\|$	$(0.88 \pm 0.17)\%$	2.7%	$\sim 10^{-3}$
$\arg(q/p)$ [deg]	-10.1 ± 9.2	1.4×10^{-2}	$\sim 10^{-3}$

Table 4: Current precision [18] on D mixing parameters and expected uncertainty at Super*B* [8].

polarization-dependent angular distribution of the tau decay final state.

There are other areas where Super*B* can significantly lower the current experimental limits on observables that are sensitive to NP in specific SM extensions. These include the measurement of the tau electric dipole moment and anomalous magnetic moment, and the search for CP violation. Also in this case the electron beam polarization provides an additional handle to increase the sensitivity.

2.3. Charm physics

In 5 years of running at the baseline luminosity Super*B* is expected to produce about 9.8×10^{10} $e^+e^- \to c\bar{c}$ events. Such a large dataset represents a powerful tool to look for signs of NP in the charm sector, especially through the measurement of CP asymmetries and the search for rare decays.

The observation of the $D^0 - \bar{D}^0$ mixing first reported by BaBar in 2007 has opened a new window into the search for CP violation in mixing through the time-dependent measurement of the D^0 decays. CP violation in mixing is expected to be negligibly small in the SM, hence its observation would be considered a strong signal of NP. With a dataset of 75 ab^{-1} the errors on the magnitude and phase (expressed in radiants) of the CP-sensitive parameter q/p measured at Super*B* would be $O(0.01)$, an order of magnitude smaller than the current experimental precision.

While there is a general consensus that the observation of CP violation in charm mixing would be an indication of physics beyond the SM, the situation is less clear concerning CP violation not related to mixing. LHCb has recently reported evidence of CP violation in the time-integrated measurement of $D^0 \to h^+h^-$ decays ($h = \pi$, K), quoting $A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%$ [16]. Better theoretical understanding and more experimental data are necessary to establish the origin of the observed asymmetry. In particular, useful information can come from a number of related channels such as $D \to \pi\pi$, $D \to \rho\rho$ and $D_{(s)} \to$ multibody decays [17]. Super*B* is an ideal laboratory to precisely measure $D^0 \to h^+h^-$ and the related decay modes, including the ones with neutral pions in the final state whose reconstruction at LHC is very challenging.

An additional opportunity to look for physics beyond the SM is provided by the search for rare or forbidden charm decays. For example, the branching ratio of $D^0 \to \mu^+\mu^-$ is negligibly small in the SM ($O(10^{-13})$) but can be enhanced significantly in some NP models. Super*B* can lower the current experimental limit by at least one order of magnitude, down to $O(10^{-8})$. Similar considerations and experimental limits apply to $D^0 \to e^+e^-$ and to the LFV decay $D^0 \to e^+\mu^-$.

The accelerator is designed to possibly run at the $D\bar{D}$ threshold with a luminosity of 10^{35} cm^{-2}s^{-1}, producing about 3×10^9 $\psi(3770) \to D\bar{D}$ decays in a 1-year run (about 1 ab^{-1}). Operating at charm threshold has several advantages. The quantum correlation of the D meson pairs allows the measurement of the strong phase difference between the amplitudes of $D^0 \to f$ and $\bar{D}^0 \to f$, where f is a generic final state. This is of interest both for the measurement of the mixing and CPV D mixing parameters, and for the measurement of the angle gamma of the unitarity triangle using $B \to DK$ decays. In addition it's possible to use a recoil analysis technique in the search for very rare D decays, as done for B decays at the $\Upsilon(4S)$: events are selected where one D meson is reconstructed, and the other D is studied to search for rare decays in a very clean environment. Measurements of some specific leptonic or semileptonic decay channels at charm threshold have uncertainties comparable to those based on 2-3 orders of magnitude more data at the $\Upsilon(4S)$ [18].

2.4. Other topics

The Super*B* physics program includes a number of other topics that are not discussed in this article. The list includes spectroscopy measurements, a B_s physics program complementary to that available at the LHC, the search for light Dark Matter and light Higgs candidates, the precise measurement of $\sin^2\theta_W$ at q^2 =

$(10.58\ GeV)^2$, plus other measurements that the interested reader can find in [1][7].

3. The accelerator

The Super*B* e^+e^- collider is to be constructed on an area of 30 hectares of the campus of Rome Tor Vergata University, 5 km away from the Laboratori Nazionali di Frascati (LNF) of the Istituto Nazionale di Fisica Nucleare (INFN). The project is managed by Cabibbo Lab[1], a newly formed consortium between the University of Tor Vergata and INFN. The collider design comprises two rings with a 1.25 km circumference, one for electrons at a nominal energy of 4.2 GeV and one for positrons of 6.7 GeV. There is one interaction point where the colliding beams are squeezed down to a vertical rms size of 36 nm. Electrons are longitudinally polarized with a polarization fraction of 65-85%. The machine design is the result of a balance between three main requirements: high luminosity, relatively low backgrounds and electric power consumption comparable with previous generation B-factories.

In high luminosity colliders with conventional collision schemes the key requirements to increase the luminosity are very small vertical beta function β_y^* at the interaction point, high beam intensity and large horizontal beam size σ_x. However, in these schemes the luminosity is limited because β_y^* cannot be much smaller than σ_z without incurring the "hourglass" effect (the dependence of the vertical beam size on the longitudinal position along the crossing region), and σ_z cannot be made too small without introducing other problems which, in turn, would limit the luminosity and increase dramatically the power consumption. The solution chosen by Super*B* is based on the crab waist (CW) scheme [19][20][21] and aims at increasing the luminosity without longitudinal bunch length reduction and with moderate power consumption.

The collision scheme based on large Piwinski angle and crab waist has been successfully tested at DAFNE in 2009 [22], observing a factor 3 luminosity increase when the crab waist sextupoles were switched on, in good agreement with the simulations. The test was done in the absence of the solenoidal magnetic field of a detector. Further tests are currently in progress at DAFNE, where the detector KLOE -2 immersed in a 0.52 T magnetic field is now installed and operational.

The present design comprises beam currents of about 2A and a power consumption of the radio frequency units of about 16 MW. The Technical Design Report of the accelerator is in preparation.

[1]`www.cabibbolab.it`

4. The detector

The Super*B* detector design inherits from the BaBar detector concept, with some modifications mostly introduced to deal with the increased particle rate (originating from the $\times 10^3$ increase of the instantaneous luminosity) and the lower CM boost ($\beta\gamma = 0.24$ instead of 0.56). The detector includes a tracking system composed of a silicon vertex tracker (SVT) and a drift chamber (DCH), a Cherenkov detector with fused silica bar radiators (FDIRC) for charged kaon/pion particle identification, an electromagnetic calorimeter (EMC) for energy and direction measurement of photons and electrons, a superconducting solenoid coil providing a 1.5 T magnetic field for the tracking system, and an instrumented flux-return (IFR) for the detection of muons and K_L. A number of components are reused from BaBar: the flux-return steel, the superconducting coil, the barrel part of the EMC and the fused silica bars of the DIRC. A brief overview of the main differences with respect to the BaBar detector is reported below. The reader is referred to [2] for more detailed discussions.

The reduced boost at Super*B* compared to BaBar implies a reduction of the average separation of the two *B* decay vertexes, to be compensated with a corresponding reduction of the reconstructed vertex resolutions in order not to affect the time-dependent measurements. This is achieved by reducing the beam pipe radius and adding an additional layer of SVT placed at 1.5 cm from the interaction point. The baseline technology for this layer is silicon striplets, though other solutions based on pixelated sensors are being considered. The drift chamber is similar in design and performance to the BaBar chamber, with the inner radius constrained to be a few cm larger for the presence of a tungsten shield surrounding the final focus cooling system. R&D is ongoing to evaluate the use of the cluster counting technique together with the dE/dx measurement to improve the particle identification performance. The FDIRC is conceptually similar to the BaBar DIRC and reuses the same quartz bars as Cherenkov light radiatior, but the photon camera is replaced by a much smaller one combined with faster photon detectors. This solution allows to have a performance similar to BaBar in terms of particle identification while at the same time being about 100 times less sensitive to backgrounds. The barrel part of the EMC reuses the BaBar barrel CsI(Tl) crystals read by PIN diodes, with new readout electronics. Two main options are being considered for the forward EMC technology. One is a hybrid solution where the crystals closer to the barrel are recycled from the CsI(Tl) BaBar forward calorimeter and the remaining part is made of LYSO crystals to deal with the higher particle rate in this region; the other solution is made of pure CsI crystals. The IFR uses the steel flux return of the magnet as muon filter and hadron absorber. Compared to BaBar, the absorber is increased and redistributed to optimize the identification of muons and K_L, and extruded plastic scintillator replaces the much slower gaseous detectors (RPC and LST).

Two detector options are still under discussion: a veto-quality EMC made of lead and scintillator installed in the backward region to increase the angular coverage, and a time-of-flight detector placed between the DCH forward endcap and the EMC to enhance the particle identification capability in the forward region.

The Technical Design Report of the detector is in preparation.

5. Summary

In the present situation where the nature of NP is unknown, it is necessary to look for its signs in as many different observables as possible. Flavor physics is a powerful tool to search for physics beyond the standard model and possibly understand its origin, in a way which is complementary to the direct searches. Super*B* is a new generation super flavor factory designed to collect 75 ab^{-1} in five years at the baseline luminosity of 10^{36} cm^{-2}s^{-1}. Such a large data sample allows to reach unprecedented sensitivity not only in the B sector but also in charm as well as in tau lepton physics. The physics program is largely complementary to the flavor physics studies foreseen at the LHC in the next decade.

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