The SuperB Project: Status and the Physics Reach

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Abstract. The SuperB experiment is a next generation Super Flavour Factory expected to accumulate 75 ab$^{-1}$ of data at the Υ(4S) in five years of nominal running, and will be built at the recently established Cabibbo Laboratory on the outskirts of Rome. In addition to running data at the Υ(4S), SuperB will be able to accumulate data from the ψ(3770) up to the Υ(6S). A polarized electron beam enables unique physics opportunities at SuperB. The large samples of B, D and τ decays that will be recorded at SuperB can be used to provide both stringent constraints on new physics scenarios, and over-constraints on the Standard Model. We present the status of the project as well as the physics potential of SuperB.

1. Introduction

The BaBar and BELLE experiments and the B factories (PEP-II and KEKB) at SLAC and KEK were designed and built with the primary goal of performing the first precision tests of the Cabibbo-Kobayashi-Maskawa (CKM) mechanism for flavor mixing and CP violation with 3 generations of quarks. From the unitarity of the CKM quark mixing matrix we obtain the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which is usually represented as a triangle in the complex plane (the “Unitarity Triangle”). BaBar and BELLE have made fundamental contributions to the measurements of the angles and sides of the Unitarity Triangle and have established the success of the CKM paradigm for describing CP violation within the Standard Model (SM).

Kobayashi and Maskawa were awarded of the 2008 Nobel Prize in physics.

However, in flavor physics there are few tensions and puzzles that require larger data samples to be solved. As a lesson from history, I would like to mention an interesting anecdote that I learned at this conference and taken from L. B. Okun [1]: “A special search at Dubna was carried out by E. Okonov and his group. They have not found a single $K^0_L \rightarrow \pi^+\pi^-$ event among 600 decays of $K^0_L$ into charged particles [2]. At that stage the search was terminated by administration of the Lab. The group was unlucky”. It is hard to believe nowadays that we could have missed the discovery of CP violation in the kaon sector by Fitch and Cronin [3] if we had stopped the search at the 1% level of accuracy.

In this Letter I will discuss the perspectives on SuperB, a next generation asymmetric $e^+e^-$ flavor factory with very high peak luminosity ($\mathcal{L} = 10^{36}$ cm$^{-2}$ s$^{-1}$) to be built near Rome, whose main purpose is to search for evidence of physics beyond the SM and investigate its nature. The experiment is designed to collect an integrated luminosity exceeding 75 ab$^{-1}$ at the Υ(4S) mass peak and about 500 fb$^{-1}$ at the Ψ(3770) mass peak in few years of running. The polarization of the electron beam will offer the unique possibility of performing precision...
electroweak measurements and will provide also extra handles for background rejection in lepton flavor violating decay searches, such as $\tau^- \rightarrow \mu^- \gamma$ and $\tau^- \rightarrow e^- \gamma$.

I will also discuss the basic principles of the innovative accelerator scheme and a general overview of the detector.

2. The Physics Program and the Discovery Potential

SuperB is a next generation high luminosity $e^+e^-$ collider that will accumulate a data sample of $75 \text{ ab}^{-1}$ with five years of nominal data taking. This experiment has been approved for funding in 2011 and could start running as early as 2016, by which time the LHC will have accumulated a significant sample of data, and would be reporting the results of searches for or direct measurements of new physics (NP). Those results are limited in that they measure only flavour diagonal processes. In order to fully understand the nature of NP, one also has to measure the off-diagonal terms, in analogy to the CKM mixing matrix. In the scenario that LHC does not find NP particles, SuperB has the possibility to explore NP scale beyond the reach of the LHC (up to 10 TeV or more depending on NP models) looking for indirect signals.

In this sense the SuperB physics reach is complementary to the LHC one. In particular there is also a large complementarity with the flavor physics potential of the LHCb experiment. For example, rare decay modes with one or more neutrinos in the final state such as $B^- \rightarrow l^-\nu\nu$, inclusive analyses of processes such as $b \rightarrow s\gamma$ and $b \rightarrow s\ell^+\ell^-$, measurements of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ and searches for lepton flavor violation such as $\tau^- \rightarrow \mu^-\gamma$ are unique to SuperB, where the environment of the $e^+e^-$ collider is clean and relatively simple compared to the events at the hadronic machine [7].

The SuperB machine design includes the polarization of the electron beam (about 80% polarization) allowing the unique possibility of performing precision $\sin^2\theta_W$ measurements at $Q^2 = (10.58 \text{ GeV})^2$ with $\mu^+\mu^-$, $\tau^+\tau^-$ and $c\bar{c}$ events, as well as measurements of the neutral current vector coupling of the $b$. Such measurements are sensitive to a $Z'$ and can probe neutral current universality at high precision. Sensitivity on $\sin^2\theta_W$ will be at the level 1%, if the systematic error on polarization is kept under control, which is competitive with the SLC measurement but at a much lower energy. In addition, the production of polarized $\tau$ pairs will allow a better separation between signal and background events for $\tau$ decays, thus improving the experimental sensitivity in lepton flavor violating (LFV) processes. In Table 1 are reported the expected experimental sensitivities (90% upper limits) for $\tau$ LFV processes at SuperB with $75 \text{ ab}^{-1}$ of data along with the present upper limits.

Charm physics also plays an important role in the SuperB physics program. Constraints on flavor-changing neutral currents from NP in the up quark sector are much weaker than in the down quark sector. Thus, high sensitivity studies of rare charm decays offer the possibility of isolating NP effects in $D^0 - \bar{D}^0$ mixing, in CP violation and in rare decay branching fractions. The sensitivity on CP violation asymmetries in decay modes such as $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$ and $D^0 \rightarrow K_S^0\pi^+\pi^-$ is expected to reach the level of $\mathcal{O}(10^{-4})$ with $75 \text{ ab}^{-1}$, which will probe the SM predictions. The machine design includes the possibility to run at different center-of-mass energies, e.g. at the $\Psi(3770)$ for exclusive $D\bar{D}$ production, at the $\Upsilon(5S)$ for $B_s\bar{B}_s$ production and up to the $\Upsilon(6S)$, thus further enriching the physics program.

The SuperB physics case is extensively discussed in refs. [4, 5, 6]. In Table 2 are reported, as an example, the golden modes for different NP scenarios. These decays are very difficult or impossible to reconstruct at the LHC. Even at the clean environment of SuperB the selection is experimentally challenging and to suppress backgrounds to an acceptable level the recoil technique is often necessary, in which the other $B$ in the $B\bar{B}$ event is reconstructed in either a semileptonic or hadronic decay. Table 3 reports the comparison of the experimental sensitivity

\footnote{charge conjugation is implied throughout the paper if not otherwise stated.}
Table 1. Expected 90% CL upper limits on representative LFV $\tau$ lepton decays with 75 ab$^{-1}$ and current upper limits.

| Process                  | Sensitivity at SuperB | Current limit |
|--------------------------|-----------------------|---------------|
| $\mathcal{B}(\tau \to \mu \gamma)$ | $2 \times 10^{-9}$    | $4.5 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to e \gamma)$ | $2 \times 10^{-9}$    | $1.1 \times 10^{-7}$ |
| $\mathcal{B}(\tau \to \mu \mu \mu)$ | $2 \times 10^{-10}$   | $3.2 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to e e e)$ | $2 \times 10^{-10}$   | $3.6 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to \mu \eta)$ | $4 \times 10^{-10}$   | $6.5 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to e \eta)$ | $6 \times 10^{-10}$   | $9.2 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to e K^0_S)$ | $2 \times 10^{-10}$   | $3.3 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to \mu K^0_S)$ | $2 \times 10^{-10}$   | $4.0 \times 10^{-8}$ |

Table 2. Golden modes in different New Physics scenarios. An “X” indicates the golden channel of a given scenario. An “O” marks modes which are not the “golden” one of a given scenario but can still display a measurable deviation from the Standard Model. The label $CKM$ denotes golden modes which require the high-precision determination of the CKM parameters achievable at Super$B$.

| $H^+$ | Minimal FV | Non-Minimal FV | NP Z-penguins currents |
|-------|------------|----------------|------------------------|
| $\mathcal{B}(B \to X_s \gamma)$ | X | O | O |
| $\mathcal{A}_{CP}(B \to X_s \gamma)$ | X | O | O |
| $\mathcal{B}(B \to \tau \nu)$ | X-CKM | X | X |
| $\mathcal{B}(B \to X_s l^+ l^-)$ | O | O | O |
| $\mathcal{B}(B \to K \nu \bar{\nu})$ | X | O | O |
| $S(K_S^0 \pi^0 \gamma)$ | X-CKM | X | O |

today and with 75 ab$^{-1}$, showing that in most cases Super$B$ is able to measure the observables with a few percent accuracy.

| Mode                  | Current | Expected (75 ab$^{-1}$) |
|-----------------------|---------|-------------------------|
| $\mathcal{B}(B \to X_s \gamma)$ | 7%      | 3%                      |
| $\mathcal{A}_{CP}(B \to X_s \gamma)$ | 0.037   | 0.004-0.005             |
| $\mathcal{B}(B^+ \to \tau^+ \nu)$ | 30%     | 3-4%                    |
| $\mathcal{B}(B^+ \to \mu^+ \nu)$ | not measured | 5-6%         |
| $\mathcal{B}(B \to X_s l^+ l^-)$ | 23%     | 4-6%                    |
| $\mathcal{A}_{FB}(B \to X_s l^+ l^-)_{s_0}$ | not measured | 4-6%         |
| $\mathcal{B}(B \to K \nu \bar{\nu})$ | not measured | 16-20%     |
| $S(K_S^0 \pi^0 \gamma)$ | 0.24    | 0.02-0.03               |

Table 3. Comparison of current experimental sensitivities with those expected at Super$B$ (75 ab$^{-1}$). Only a small selection of observables is shown. Quoted sensitivities are relative uncertainties if given as a percentage, and absolute uncertainties otherwise. For more details, see Refs. [4, 5, 6, 7].
3. The Accelerator: the Innovative Scheme

SuperB is a second generation flavor factory aiming for a luminosity of $10^{36}$ cm$^{-2}$s$^{-1}$. This represents a step forward of about two order of magnitudes in luminosity with respect to the first generation $B$ factories. The key advances in the design of this accelerator come from recent successes at the DAFNE collider at INFN in Frascati, Italy, at PEP-II at SLAC in California, USA, and at KEKB at KEK in Tsukuba Japan, and from new concepts in beam manipulation at the interaction region (IP) called “crab waist”. This new collider comprises of two beam rings, one at 4.2 GeV and one at 6.7 GeV, a common interaction region, a new injection system at full beam energies, and one of the two beams longitudinally polarized at the IP. Most of the new accelerator techniques needed for this collider have been achieved at other recently completed accelerators including the new PETRA-3 light source at DESY in Hamburg (Germany) and the upgraded DAFNE collider at the INFN laboratory at Frascati (Italy), or during design studies of CLIC or the International Linear Collider (ILC).

The very high luminosity is obtained increasing the density of the bunches at the IP by demagnifying their vertical size to about 30 nm. To reach this goal the amplitude of the betatron oscillation must be kept at minimum. This requires optimal ring lattice design, precise magnet alignment and machine tuning, small emittance damping ring (about 5 pm × Rad) and a “crab waist” collision scheme in order to overcome the beam-beam luminosity limit. The first ingredient of the “crab waist” collision scheme is the large Piwinsky angle $\phi$ defined as:

$$\phi = \frac{\sigma_z \tan \frac{\theta}{2}}{\sigma_x}.$$  \hspace{1cm} (1)

$\sigma_x$ being the horizontal rms bunch size, $\sigma_z$ the rms bunch length. It is worth noting that the luminosity of an $e^+e^-$ collider is given by the expression:

$$\mathcal{L} = \frac{N^+N^-}{4\pi \sigma_y \sqrt{(\sigma_z \tan \frac{\theta}{2})^2 + \sigma_y^2}} f_c = \frac{N^+N^-}{4\pi \sigma_y \sigma_x \sqrt{\phi^2 + 1}} f_c.$$  \hspace{1cm} (2)

In SuperB, $N^+ = 5.1 \times 10^{10}$ ($N^- = 6.6 \times 10^{10}$) is the number of positrons (electrons) per bunch, $\sigma_y = 36$ nm the vertical rms size and $f_c = 233$ MHz is the collision frequency. In the limit of small collision angle $\theta = 66 \cdot 10^{-3} \ll 1$ and large Piwinsky angle $\phi \gg 1$ can be approximated by:

$$\mathcal{L} = \frac{N^+N^-}{2\pi \sigma_y \sigma_z \theta} f_c \simeq 1 \cdot 10^{36} \text{cm}^{-2} \text{s}^{-1}.$$  \hspace{1cm} (3)

The large Piwinsky angle is obtained by decreasing the horizontal beam size and increasing the crossing angle. Several advantages follow: higher luminosity, reduction of the vertical tune shift and suppression of vertical synchro-betatron resonances. The “crab waist” scheme is realized by a couple of sextupole magnets on the two sides of the IP. The waist of the beam moves to the axis of the other beam. As a consequence, each beam collides with the other in the minimum waist region, with a net luminosity gain. Besides the geometrical gain just mentioned, because of the “crab waist” transformation the non linear component of the beam-beam forces decreases, hence reducing the emittance growth due to the collision.

The present machine design is based on a circumference of about 1.2 Km with beam currents of about 2 A and a relatively low power consumption of 16 MW. The estimated construction time for this collider is a total of about four years and will be built in Rome close to the “Laboratori Nazionali di Frascati” of INFN. The name of the new laboratory will be “Cabibbo Laboratory” in honor of Nicola Cabibbo.
4. The Detector: a General Overview

The SuperB detector is based on the BaBar “prototype” and reuses several parts of it: fused silica bars and bar boxes of the Cherenkov detector (DIRC), the CsI(Tl) crystals for the barrel part of the electromagnetic calorimeter (EMC), and the superconducting coil and flux return yoke of the axial magnetic field. However, the detector requires moderate design improvement and R&D to cope with new machine interaction region, the higher luminosity and the high DAQ rates. A brief description of the detector novelties is reported below. A more detailed description of the SuperB detector can be found elsewhere [4, 9].

The drift chamber will be using He as ionizing medium but the gas mixture and the cell size will be optimized for operating at higher rates. The DIRC will replace the photon camera with a twelve-fold modular camera using multi-channel plate photon detectors in a focusing configuration using fused silica optics to reduce the impact of beam related backgrounds and improve performance. The forward EMC will feature cerium-doped LYSO (lutetium yttrium orthosilicate) crystals, which have a much shorter scintillation time constant, a lower Moliere radius and better radiation hardness than the current CsI(Tl) crystals, again for reduced sensitivity to beam backgrounds and better position resolution. The hermeticity of the SuperB detector, and, thus, its performance for certain physics channels will be improved by including a backwards “veto-quality” EMC detector comprising a lead-scintillator stack. The flux-return will be augmented with additional absorber to increase the number of interaction lengths for muons to roughly $7\lambda$.

The smaller center-of-mass boost ($\beta\gamma = 0.24$) with respect to BaBar ($\beta\gamma = 0.55$) imposes improvements in decay vertex reconstruction in order to maintain adequate proper time resolution for time-dependent $CP$ violation measurements. The vertex resolution will be improved by reducing the radius of the beam pipe, placing the innermost layer of the silicon vertex tracker (SVT) at a radius of roughly 1.5 cm, with a material budget less that 1% of $X_0$ and intrinsic resolution of about 10 - 15 $\mu$m.

According to the baseline design this innermost layer of the SVT will be constructed of silicon striplets. Other solutions based on Monolithic Active Pixel Sensors (MAPS) or other pixelated sensors are currently considered as options for detector upgrades, representing more robust solutions against possible high occupancy from beam-related backgrounds.

5. Conclusions

The case for Flavor physics in the LHC era is still compelling. It offers a unique opportunity for searching for NP and understanding its origin. The most sensitive measurements to NP are reported in Tables 1, 3 and are currently statistics dominated.

SuperB, a new generation super flavor factory, will accumulate a data sample of 75 ab$^{-1}$ with five years of nominal data taking. The new facility has been recently approved for funding and is going to be built in Rome. The SuperB detector will be based on the BaBar one and it will reuse part of it for the DIRC, the EMC and the superconducting coil. However the detector will require some improvements and R&D to cope with the new machine design and the higher luminosity.

The physics program is focused on the study of the flavor structure of NP by measuring the flavor couplings and also by exploring the NP scale beyond the LHC reach (up to 10 TeV or more), by looking for indirect signals. The golden modes for different NP scenarios, reported in Table 2, are difficult or even impossible to reconstruct at LHC. In this sense, the SuperB experiment can be considered as an alternative path for discovering NP with respect to the LHC.
References

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