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THE SUPERB PROJECT*

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The SuperB project of a new generation flavour factory is presented. An overview of physics programme, together with the description of the conceptual design of the accelerator and detector are given.

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1. Introduction

The SuperB project [1] intends to continue and extend the extremely successful physics programme of so-called B factories *i.e.* the accelerators PEP-II [2] and KEKB [3] together with the respective detectors BaBar [4] and Belle [5]. These two high-luminosity, asymmetric energy e^+e^- colliders collected over the last decade enormous amount of data (1.6 ab^{-1}). As a result, the BaBar and Belle collaborations provided the evidence for the CP violation in the b-quark sector and tested the unitarity of the Cabibbo–Kobayashi–Maskawa (CKM) matrix [6] with the precision of the order of 1%. Moreover, the evidence of the D^0–$\overline{D}^0$ mixing was given, together with observation of several new hadrons and a substantial progress in the studies of τ meson decays.

SuperB is a proposed e^+e^- collider operating with a high luminosity at energies from open charm threshold (corresponding to the $\psi(3770)$ meson) to above the $\Upsilon(5S)$ resonance. The accelerator is to be located either in Laboratori Nazionali di Frascati or on the campus of Tor Vergata University of Rome. The principal goal of SuperB is to collect 75 ab^{-1} of data at the $\Upsilon(4S)$ resonance which would correspond to the world largest samples

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of B, D and τ pairs (75 times the statistics accumulated at any existing experiment). Moreover, large data samples will be collected at other Υ resonances. A similar project is pursued at KEK (Japan) with the plans to upgrade the KEKB/Belle facility to SuperKEKB/Belle-II [7] with the goal to collect $50\,\mathrm{ab}^{-1}$ of data. Apart from the perspective of recording bigger data sample the SuperB facility offers two unique features: longitudinal polarisation of the electron beam and the possibility of running with a high-luminosity at the $\psi(3770)$ resonance. The latter allows for use of quantum correlations between pairs of D–$\overline{D}$ mesons in full analogy with the case of B–$\overline{B}$ pairs at the $\Upsilon(4S)$.

This paper is organised as follows. The basic physics motivation for the SuperB project is presented in the Sec. 2. The next two are devoted to the issues related to the accelerator and detector.

2. Physics potential of the SuperB

2.1. b physics

The continuation of measurements concerning B mesons, performed at the centre-of-mass energy corresponding to the $\Upsilon(4S)$ resonance, comprise an important part of the SuperB physics program. It is expected that data statistics of 75 ab^{-1} would allow for an improvement in the precision of the determination of the apex and angles of the unitarity triangle at the level of an order of magnitude [8] (*cf.* Table I). In particular, it would be possible to perform inclusive measurements of the CKM elements $|V_{cb}|$ and $|V_{ub}|$ with the precision of 1% (5%), respectively [9]. Such an impressive progress in the experimental precision could potentially reveal inconsistencies of the CKM paradigm in the Standard Model (SM) leading to the evidence for New Physics (NP).

TABLE I

Uncertainties of the CKM parameters obtained from the Standard Model fit based on the experimental and theoretical input available today (left) and expected for the SuperB (right) [8].

CKM Parameter	SM fit	
	Current value	Precision expected at SuperB (50 ab^{-1})
$\overline{\rho}$	0.163 ± 0.028	± 0.0028
$\overline{\eta}$	0.344 ± 0.016	± 0.0024
α	$(92.7 \pm 4.2)^\circ$	$\pm 0.45^\circ$
β	$(22.2 \pm 0.9)^\circ$	$\pm 0.17^\circ$
γ	$(64.6 \pm 4.2)^\circ$	$\pm 0.38^\circ$

The sensitivity of direct searches for effects from NP will be qualitatively improved at the SuperB. Most of these studies will refer to measurements of time-dependent CP asymmetries resulting from heavy particles contributing to loops in the respective topologies and NP contributions for tree level processes. The golden channels for the former category are penguin dominated transitions $b \to s$ and $b \to d$, while the $b \to c\bar{c}s$ is the most important among tree level processes. Current measurements of these decay modes together with SuperB expectations are collected in Table II.

TABLE II

Current experimental precision [10], and that expected at a SuperB experiment with $75\,\mathrm{ab}^{-1}$ of data. The first entry in the table corresponds to the tree level calibration mode, and the next two sections of the table refer to $b \to s$ and $b \to d$ transitions. A long dash '—' denotes that there is no theoretical uncertainty computed yet for a given mode.

Mode	Current precision			Predicted precision (75 ab^{-1})		
	Stat.	Syst.	Theor.	Stat.	Syst.	Theor.
$J/\psi K^0_S$	0.022	0.010	< 0.01	0.002	0.005	< 0.001
$\eta' K^0_S$	0.08	0.02	0.014	0.006	0.005	0.014
$\phi K^0_S \pi^0$	0.28	0.01	—	0.020	0.010	—
$f_0 K^0_S$	0.18	0.04	0.02	0.012	0.003	0.02
$K^0_S K^0_S K^0_S$	0.19	0.03	0.013	0.015	0.020	0.013
ϕK^0_S	0.26	0.03	0.02	0.020	0.010	0.005
$\pi^0 K^0_S$	0.20	0.03	0.025	0.015	0.015	0.025
ωK^0_S	0.28	0.02	0.035	0.020	0.005	0.035
$K^+ K^- K^0_S$	0.08	0.03	0.05	0.006	0.005	0.05
$\pi^0 \pi^0 K^0_S$	0.71	0.08	—	0.038	0.045	—
ρK^0_S	0.28	0.07	0.14	0.020	0.017	0.14
$J/\psi \pi^0$	0.21	0.04	—	0.016	0.005	—
$D^{*+} D^{*-}$	0.16	0.03	—	0.012	0.017	—
$D^+ D^-$	0.36	0.05	—	0.027	0.008	—

SuperB will also offer the possibility to measure observables related to several rare decays of B mesons that are sensitive to different NP scenarios [8,11] (*cf.* Table III). Each of them provides a set of a few golden observables. All relevant scenarios form a so-called golden matrix of observables *versus* models. The measurement of the set of golden observables would allow to decipher the nature of New Physics. All golden observables are related to decay channels with neutral particles (in particular neutrinos) in the final state. The possibilities of reconstruction of such decys are extremely limited for the LHC experiments.

TABLE III

Experimental sensitivities of the golden observables. More details can be found in [12–14].

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

It is generally expected that experiments running at hadronic accelerators will be the main sources of B_s related measurements. However, both CLEO [15] and Belle [16] collaborations have had short periods of data taking at center-of-mass energies corresponding to the $\Upsilon(5S)$ resonances and obtained results that fully confirmed the potential of e^+e^- machines in the domain of B_s physics. The SuperB is expected to play the leading role in the measurements of the angle β_s from penguin dominated rare decays like $B_s \to J/\psi\eta^{(\prime)}$, $B_s \to D^{(*)+}D^{(*)-}$, $B_s \to D^{(*)}K^0_{\mathrm{S}}$, $B_s \to D^{(*)}\phi$, $B_s \to J/\psi K^0_{\mathrm{S}}$, $B_s \to \pi^0 K^0_{\mathrm{S}}$ and $B_s \to \phi\eta^{(\prime)}$. Using the ratio $\mathcal{R}_s = \mathcal{B}(B^0_s \to K^{*0}\gamma)/\mathcal{B}(B^0_d \to K^{*0}_{\mathrm{S}}\gamma)$ it will be also possible to perform a measurement of $|V_{td}/V_{ts}|$ with the precision limited by theoretical uncertainties. Last but not least, the decay $B_s \to \gamma\gamma$ is considered as a golden channel to search for new physics at SuperB. It is expected that 14 signal events on top of 20 background events will be observed in a sample of 1 ab^{-1} assuming a Standard Model branching fraction. With the sample of 30 ab^{-1} the $\mathcal{B}(B_s \to \gamma\gamma)$ is to be measured with the statistical (systematic) error of 5% (7%), respectively.

2.2. τ physics

The physics programme in the sector of the τ lepton would encompass searches for lepton–flavour violating (LFV) decays, experimental investigations on CP violation and measurements of the τ electric dipole moment (EDM), as well as of the anomalous magnetic moment $g-2$. SuperB offers here unique features that make it superior to SuperKEKB/Belle-II. These are: a larger design luminosity and a polarized electron beam.

Searches for LFV decays constitute one of the most clean and powerful tools to discover New Physics and to elucidate its nature. The lepton–flavour violating effects are considered to scale quadratically with the lepton mass, that together with a large number of decays which can be studied, clearly favours the τ. The branching fractions for LFV decays of charged leptons are negligibly small in the SM (*e.g.* $\mathcal{B}(B \to l\gamma) < 10^{-54}$ and $\mathcal{B}(B \to lll) < 10^{-14}$, $(l = e, \mu)$. They are predicted, however, to be significantly enhanced in many NP models, especially in supersymmetric extensions of the Standard Model. In particular the branching fraction $\tau \to l\gamma$ is then expected at the level 10^{-9} [17] which matches with the sensitivity of the SuperB. Other interesting classes of LFV decays are $\tau \to lP^0$, $(P^0 = \pi^0, \eta^{(\prime)}, K^0_{\rm S})$, $\tau \to lS^0$, $(S^0 = f^0)$, $\tau \to lV^0$, $(V^0 = \rho^0, K^{*0}\phi, \omega)$ and $\tau \to lll$. SuperB will be able to uniquely explore the lepton–flavour-violating transitions between the third and first or second generations, while the MEG experiment [18] will search for the decay $\mu \to e\gamma$ with great sensitivity (Fig. 1).

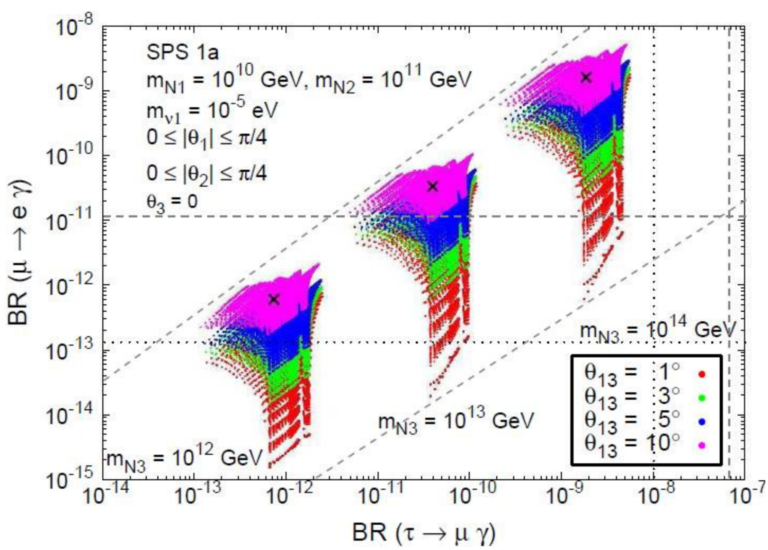

Fig. 1. $\mathcal{B}(\tau \to \mu\gamma)$ *versus* $\mathcal{B}(\mu \to e\gamma)$ (in the constrained Minimal Supersymmetric Model characterized by the set of parameters SPS 1a [17]) for three reference values of the heavy right-handed neutrino mass M_{N3} and several values of the neutrino mixing angle θ_{13}. The horizontal dashed (dotted) line denotes the present experimental bound (future sensitivity) on $\mathcal{B}(\mu \to e\gamma)$. All other relevant parameters are set to the values specified in [17].

The effects of CP violation have not been observed yet in charged lepton decays. In the Standard Model they are predicted to be vanishingly small *e.g.* the CP asymmetry of the decay $\tau^{\pm} \to K^0_{\rm S}\pi^{\pm}\nu_\tau$ is calculated to be of the order of 10^{-12} [19]. Observable CP-violating effects are expected in

R-parity violating supersymmetric models [20] and in specific non-SUSY multi-Higgs models [21]. The first search for CP violation in τ decay has been performed by the CLEO Collaboration [22]. A tau-charge-dependent asymmetry of the angular distribution of the hadronic system produced in the decay $\tau \to K_s^0 \pi \nu_\tau$ has been studied. The mean value of the optimal asymmetry observable $\langle \xi \rangle = (-2.0 \pm 1.8) \times 10^{-3}$ was obtained. It was estimated [9] that SuperB with the data sample of $75\,\mathrm{ab}^{-1}$ would reach an experimental sensitivity of the order of 2.4×10^{-5} for that variable.

The τ EDM could influence both the angular distributions and the polarization of the taus produced in e^+e^- annihilation. The polarization of the electron beam allows for construction of observables that unambiguosly discriminate between the contribution due to the τ EDM and other effects. Moreover, in the presence of the polarized electron beam, these variables can be reconstructed from the angular distribution of the products of a single τ decay [23]. For SuperB with $75\,\mathrm{ab}^{-1}$ it was estimated [9] that the upper limit sensitivity for the real part of the τ electric dipole moment is $\mathrm{Re}|(d_\tau^\gamma)| \leq 7.2 \times 10^{-20}\ e\,\mathrm{cm}$.

The SuperB can also shed light on the long standing discrepancy between the experimental results and Standard Model predictions for the anomalous magnetic moment of the muon ($\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} \approx (3 \pm 1) \times 10^{-9}$). The scaling of heavy-particle effects on lepton magnetic dipole moments implies $\Delta a_\tau / \Delta a_\mu \sim m_\tau^2 / m_\mu^2$. Assuming that the present muon discrepancy Δa_μ is real, this leads to the expectation that $\Delta a_\tau \approx 10^{-6}$. Both real and imaginary parts of the $g-2$ form factor of the τ lepton can be determined at SuperB ($75\,\mathrm{ab}^{-1}$) with a resolution of the order of 10^{-6} [24]. The polarization of the electron beam again plays here a crucial role. The real part of the $g-2$ form factor can be determined either by fitting just the τ polar angle distribution or by the measurement of the transverse and longitudinal polarization of the τ from the angular distribution of its decay products.

2.3. Charm physics

One of the unique features of the SuperB project is the possibility of collecting data at the charm threshold. The run at the center-of-mass energy corresponding to the $\psi(3770)$ is foreseen with the luminosity of the order of $10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. After a few months of running, a $0.5\ \mathrm{ab}^{-1}$ of data should be available. For such events, tagging those in which one D meson is identified, the other D can be studied with very small background contamination. The $D\overline{D}$ are also produced in the state of quantum entanglement (as $B\overline{B}$ pairs at the $\Upsilon(4S)$). The availability of quantum-correlated D decays allows independent measurement of strong phases like $\delta_{K\pi}$, $\delta_{K\pi\pi}$ *etc.* Their values are used for mixing measurements at the $\Upsilon(4S)$. The data collected at the charm threshold should improve substantially the precision in mixing parameters x_D and y_D to the level of the order of 10^{-4}. Also the asymmetry $\alpha_{\mathrm{SL}} = (\Gamma_{l^-} - \overline{\Gamma}_{l^+})/(\Gamma_{l^-} + \overline{\Gamma}_{l^+})$ is expected to be measured with the precision of 20%. Here $\Gamma_{l^-}(\overline{\Gamma}_{l^+})$ denote decay rates for "wrong-sign" semileptonic $D(\overline{D})$ decays, respectively.

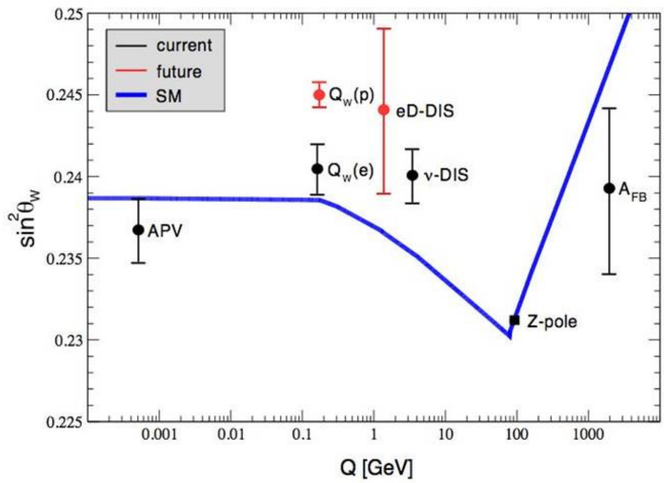

Fig. 2. Summary of experiments that have measured or are proposing to measure $\sin^2\Theta_{\mathrm{W}}$ as compiled in [25]. The standard model running of $\sin^2\Theta_{\mathrm{W}}$ is overlayed on the data points. SuperB will provide a point at $Q^2 \approx (10.58\ \mathrm{GeV})^2$ with an error comparable to that of the measurement at the Z-pole [9].

2.4. Electroweak neutral current measurements

The combination of high luminosity and the polarization of electron beam offers a unique opportunity to measure at SuperB electroweak neutral current parameters with the precision comparable to the one obtained at SLC and LEP but at $Q^2 \approx (10.58\,\mathrm{GeV})^2$. It exploits the fact that cross-sections for $e^+e^- \to f\overline{f}$ (where f denotes the fermion) are sensitive to the beam polarization through $Z-\gamma$ interference. The $\sin^2\Theta_{\mathrm{W}}$ will be measured at SuperB using $\mu^+\mu^-$, $\tau^+\tau^-$ and $c\overline{c}$ pairs in the final state. For the muon pairs and an integrated luminosity of $75\,\mathrm{ab}^{-1}$ and for 80% polarization of the electron beam, the statistical error on the left–right asymmetry is expected to be of 5×10^{-6} which corresponds to a relative error of $\mathcal{O}(1\%)$. SuperB running at the $\Upsilon(4S)$ can also provide a measurement of the b-quark neutral coupling g_{V}^b with the precision compatible with the results of LEP and SLC, but at lower Q^2.

2.5. Spectroscopy

Since 2003 the B factories have observed several new charmonium-like states. Among them are $X(3872)$, $Y(4260)$, $Y(4350)$, $Y(4660)$, $Z^+(4050)$ and $Z^+(4430)$. The properties of most of these new resonances do not fit into the picture of standard mesons [26]. These states could be individually interpreted as hybrids (bound states of a quark–antiquark pair and a number of constituent gluons), molecules (bound states of two mesons, usually denoted as $[Q\overline{q}][q'\overline{Q}]$ where Q is the heavy quark) or tetraquarks (a system composed of two bound pairs; the first is composed of quarks, the second of antiquarks $[Qq][\overline{q}'\overline{Q}]$). Current evidence for all the new states, apart from the $X(3872)$, is based on observation in a single decay channel and with a significance only slightly exceeding five standard deviations. Therefore, the SuperB is expected to clarify the above picture by providing a unique interpretation for the abovementioned resonances. The observation of other new states seems to be very likely.

The SuperB can run with a high luminosity also at the center-of-mass energies corresponding to $\Upsilon(nS)$, $n \neq 4$ and thus is expected to improve qualitatively the knowledge about bottomonia. In particular the spectrum of their singlet states (parabottomonia) and of the D-wave narrow resonances is largely unknown. The ground state of this family of states, the η_b, has been observed recently by BaBar [27].

2.6. Direct searches

Several NP scenarios [28] predict a rather light Higgs boson (Wilczek mechanism [29]) with a mass less than twice the b-quark mass. Similarly, the particles of Dark Matter can also be that light in some models [30] (the most promising searches could be performed in the mode $\Upsilon(3S) \to \pi^+\pi^- invisible$). Finally, low interacting light particles that couple mostly to photons are also expected in the new paradigm of Dark Forces [31]. The SuperB will be able to discover and determine masses and couplings of almost any such light non-SM particle.

3. The accelerator

The design of the SuperB accelerator is based on a new collision scheme. Its basic features are: a small collision area, very small beta function at the interaction point (β_y^*) large Piwinski angle and "crab waist" correction scheme [1, 32]. This concept allows to reach the required luminosity of 10^{36} cm^{-2}s^{-1} with beam currents, and thus also wall plug power, at the same level as those of the current B factories. The basic parameters of the SuperB accelerator are collected in Table IV.

TABLE IV

SuperB nominal beam parameters. The acronym LER (HER) refers to the Low (High) Energy Ring, respectively.

Parameter	LER	HER
Particle type	e^+	e^-
Energy [GeV]	4.2	6.7
Center-of-mass boost ($\beta\gamma$)	0.28	
Luminosity [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1×10^{36}	
Circumference [m]	1258	
Full crossing angle [mrad]	66	
Piwinski angle [rad]	18.6	22.9
Longitudinal polarization [%]	0	80
Beam current [A]	2.45	1.89
RF power [MW]	17.1	
β_y^* [cm]	0.0205	0.0253
β_x^* [cm]	3.2	2.6
ϵ_y^* [pm]	6.15	5
ϵ_x^* [nm]	2.0	2.5
σ_y^* [μm]	0.036	
σ_x^* [μm]	7.5	

4. The detector

The concept of the SuperB detector is based on the existing BaBar apparatus (Fig. 3). However, some modifications are necessary to operate at higher event rates (higher beam related backgrounds) and with a reduced center-of-mass-boost $\beta\gamma$ (slightly different topology of events). The BaBar

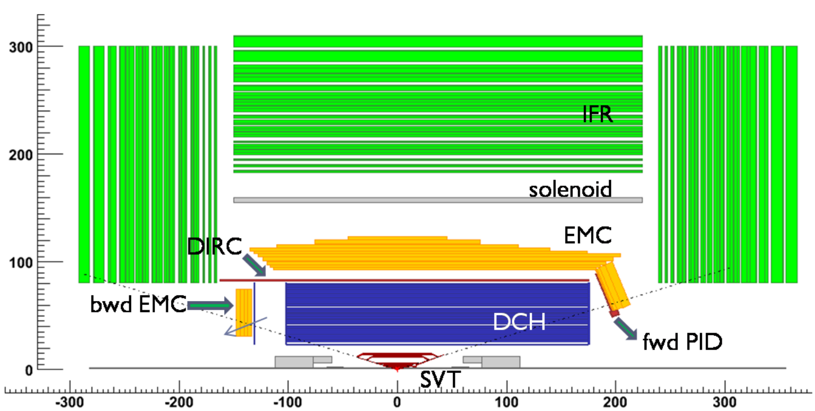

Fig. 3. Concept for the SuperB detector.

detector [4] is composed of a tracking system with a five layer double-sided silicon strip vertex detector (SVT), a 40 layer drift chamber (DCH) inside a 1.5 T magnetic field, a Cherenkov detector with fused silica bar radiators (DIRC), an electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals and an instrumented flux return (IFR) for $K_{\rm L}^0$ detection and μ identification. The following components can be reused at the SuperB: the superconducting solenoid, the barrel part of the EMC, the fused silica bars of the DIRC and the flux-return steel.

The silicon vertex detector of the SuperB will be composed of the innermost layer of striplets (layer0) and five external layers (1–5) of double-sided silicon strip sensors. The radius of the layer0 would be very small (1.5 cm), thus providing sufficient Δt resolution for time-dependent CP violation measurements with the reduced SuperB boost. Options based on pixel sensors are also being developed with specific R&D programs offering the possibility of the installation in the upgraded setup of the experiment [33]. The drift chamber layout will be similar to BaBar's DCH with the optimization of gas mixture and geometry and electronics of this detector. The Cherenkov detector will make use of the radiator quartz bars of the BaBar DIRC with the new fast highly-pixelated photomultiplier tubes.

Two additional subdetectors are considered in order to improve the overall performace of the apparatus: a backward electromagnetic calorimeter and a forward particle identification device. The principal goal of a backward EMC would be to improve the hermeticity of the SuperB. The proposed relatively simple device is based on a multi-layer lead-scintillator stack with longitudinal segmentation providing capability for π/e separation. Two options for the forward particle identification detector are considered: an aerogel radiator RICH and a time-of-flight system.

5. Summary

SuperB is a second generation asymmetric energy e^+e^- planned to operate in a wide range of energies spanning from the charm threshold up to the $\Upsilon(5S)$. The main set of data will be collected at the center-of-mass energy corresponding to the $\Upsilon(4S)$ with the baseline luminosity of 10^{36} cm^{-2} s^{-1}. It is expected that SuperB can collect 75 ab^{-1} of data in five years. Such dataset would allow to test the flavour sector of the Standard Model with unprecidented precision with the potential to elucidate effects of New Physics. The project is currently in the phase of preparation of the Technical Design Report and awaits the final approval. The first collisions at the SuperB are expected in 2016.

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