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Physics Case at e^+ e^- high luminosity machine

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In this paper we present the Physics program for an e^+ e^- high luminosity asymmetric B Factory. The measurements which can be performed will allow to study in a unique manner the structure of the New Physics beyond the Standard Model, if discovered at LHC, and/or eventually to extent the domain of the New Physics search at energy scales larger and not accessible to the LHC.

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1. Introduction

The search for evidence of physics beyond the Standard Model (SM) is the main goal of particle physics in the next decades. The LHC at CERN will search for New Physics (NP) which has solid theoretical motivations, related to the quantum stabilization of the Fermi scale, to show up around 1 TeV.

However, pushing the high-energy frontier, i.e. increasing the available center-of-mass energy in order to produce and observe new particles, is not the only way to look for NP. New particles could manifest themselves through their virtual effects in processes involving SM particles only. For this kind of searches the production thresholds are not an issue anymore. Since quantum effects become typically smaller as the mass of the virtual particles increases, the name of the game is rather high precision. As a matter of fact, high-precision measurements allow to probe NP energy scales inaccessible at present and next-generation colliders.

Flavour physics is the best candidate as a tool for indirect NP searches for several reasons. First, Flavour Changing Neutral Currents (FCNC), neutral meson-antimeson mixing and CP violation occur at the loop level in the SM and therefore are potentially subject to order one NP virtual corrections. In addition, quark flavour violation in the SM is governed by the weak interaction and suppressed by the small quark mixing angles. Both features are not necessarily shared by NP which, in such cases, could produce very large effects. Indeed, the inclusion in the SM of generic NP flavour-violating terms with natural order one couplings is known to violate present experimental constraints unless the NP scale is pushed up to 10-100 TeV or even more, depending on the flavour sector. The difference between the NP scale emerging from flavour physics and the one suggested by Higgs physics clearly indicates that flavour physics has either the potential to push the explored NP scale in the 100 TeV region or, if the NP scale is indeed close to 1 TeV, that the flavour structure of NP is highly non-trivial and the experimental determination of the flavour-violating couplings is particularly interesting.

There is a consensus in the community that doing so requires a data sample corresponding to an integrated luminosity of 50 to 100 ab^{-1}. A reasonable benchmark for obtaining such a data sample is of the order of five years of running. Meeting both constraints requires a collider luminosity of 10^{36} $\mathrm{cm}^{-2}s^{-1}$ or more, yielding 15 ab^{-1}/Snowmass Year of 1.5 10^7 seconds. It is the needed luminosity for a future Super B-factory.

Reaching this luminosity with a collider design extrapolated from PEP-II or KEKB, such as SuperKEKB, is difficult; beam currents and thus power consumption are very high, and the detector backgrounds difficult to sustain. The low emittance crabbed waist design of SuperB provides a solution to the problem, allowing to reach the needed luminosity with beam currents and power consumption similar to those at PEP-II . The success of the test of the crabbed waist concept at Frascati, shows that is the way to follow [1].

The physics program for a high luminosity SuperB/SuperKEKB factory is described in details in several publications (see for instance [2]).

In the following we show the potentiality of the best possible future Super B-factory (called SuperB in the following), collecting 75 ab^{-1}, with at least one longitudinal polarised beam and with the possibility of running at different threshold energies and in particular at the charm threshold (the $\psi(3770)$ resonance).

The chapter is organized as follows. We concentrate first on B physics at the $\Upsilon(4S)$ (the potential for B_s physics at the $\Upsilon(5S)$ is described in [3]), then we discuss the τ and charm physics and finally we say few words on spectroscopy.

2. Determination of CKM parameters and New Physics

One lesson from the B Factories is that precision is crucial for testing the SM in the flavour sector, as the tests are redundant measurements of the same underlying quantity. In Fig. 1 we show the regions on the $\overline{\rho}$-$\overline{\eta}$ plane selected by different constraints assuming the current measurement precision (left), and that expected at SuperB (right). With the precision reached at SuperB, the current discrepancies would clearly indicate the presence of NP in the flavour sector. It is important to note that for achieving that, several measurements have to be performed at the $\%$ level, among them we mention the three Unitarity Triangle (UT) angles (α, β and γ) and the elements $|V_{ub}|$ and $|V_{cb}|$ measured through semileptonic B decays.

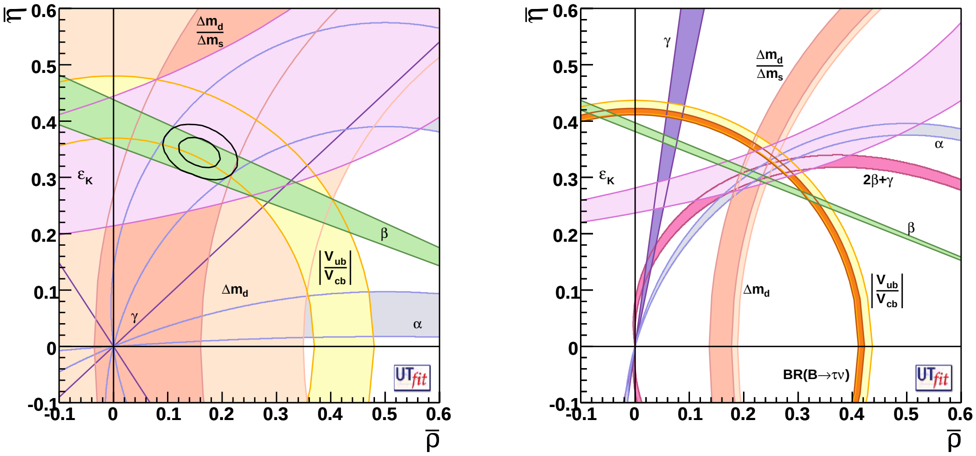

Figure 1: Regions corresponding to 95% probability for $\overline{\rho}$ and $\overline{\eta}$ selected by different constraints, assuming present central values with present errors (left) or the same central values with errors expected at SuperB (right).

3. The New Physics sensitive measurements in B sector

Is it possible to define few golden channels for SuperB ? In fact, at SuperB, a golden channel is any channel that is very well-known in the Standard Model. We thus want to stress that one of the most sensitive searches for NP will be the 1% determination of CKM parameters; the possibility of performing such a precise determination in the presence of NP is a unique feature of SuperB. For that several measurements, at the 1% level precision, as those shown in the previous section have to be performed.

On the other hand SuperB will be able to measure many rare decay processes that are sensitive to different NP scenarios. Each scenario has its own golden channels which together form a golden

	H^+ high $\tan\beta$	MFV	Non-MFV(2-3)	Non-MFV(1-3)	NP Z-penguins	Right-handed currents
$\mathcal{B}(B \to X_s\gamma)$		L	M			M
$\mathcal{A}_{CP}(B \to X_s\gamma)$			L			M
$\mathcal{B}(B \to \tau\nu)$	L-$'CKM'$					
$\mathcal{B}(B \to X_s\ell\ell)$			M		M	M
$\mathcal{B}(B \to K\nu\overline{\nu})$			M		L	
$S_{K_S\pi^0\gamma}$						L
The angle β (ΔS)				L-$'CKM'$		L

Table 1: The golden matrix of observables versus the NP scenarios. L denotes a large effect, M denotes a measurable effect, and CKM denotes a measurement that also requires precise determination of the CKM matrix.

matrix of observables versus models. The golden channels are clear signals for NP in one or more scenarios and by measuring the set of observables for all of these golden channels it is possible to distinguish between many different types of NP. In Table 1 we show the result of our selection of golden modes in different NP scenarios.

In some of the scenarios considered above this list is far from complete; many other measurements are expected to show deviations from their Standard Model values. For example, in the case of non-minimal flavor violation in the transitions between third and second generations, the entire cohort of $b \to s$ penguins-dominated non-leptonic modes could show a deviation in the measured value of time-dependent CP asymmetries compared to those measured in $b \to c\bar{c}s$ transitions.

It has to be noted that most of the golden channels are very challenging from experimental point of view. One of the main characteristics of the SuperB physics program is the possibility of performing inclusive measurements, which are often better under control from theoretical point of view, in addition to exclusive ones; and in addition the possibility of measuring channels with neutrinos, γ, K_L.. in the final states.

It is important to note that for some channels (indicated with the $'CKM'$ tag in the above table) improvements on Lattice calculations are primordial if we want to use these measurements as powerful probes of NP in given scenarios. In the following we will discuss few of these channels.

$B \to K^{(*)}\nu\overline{\nu}$ decay modes

The rare decay $B \to K^{(*)}\nu\overline{\nu}$ is an interesting probe for NP in Z^0 penguins [5], such as chargino-up-squark contributions in a generic supersymmetric theory. Due to presence of two undetected neutrinos the analyses of these decay modes are partciularly challenging. Recent studies have shown that the $B \to K^{(*)}\nu\overline{\nu}$ decay can be observed with the SuperB statistics. In addition the longitudinal polarisation for the channel with K* can also be measured. All these quantities measured at 10% level could be effective probes of NP in this particular scenario.

The branching fraction of $B \to \ell\nu$

Precision measurements of the branching fraction of $B^\pm \to \ell^\pm\nu$ where $\ell = e, \mu, \tau$ can be used to constrain NP. NP contributions can enhance the branching fractions of $B^\pm \to \ell^\pm\nu$, as described in CDR [4]. Fig. 2 shows a comparison of the exclusion plot in the $m(H^+)$–$\tan\beta$ plane coming from a measurement of $\mathcal{B}(B \to \tau\nu)$ and $\mathcal{B}(B \to \mu\nu)$ with different data samples, 2 ab^{-1}, 10 ab^{-1}, 75 ab^{-1} and 200 ab^{-1}, assuming that the result is consistent with the Standard Model.

It is clear that the presence of charged Higgs with mass beyond the TeV could be detected in scenario with high tanβ.

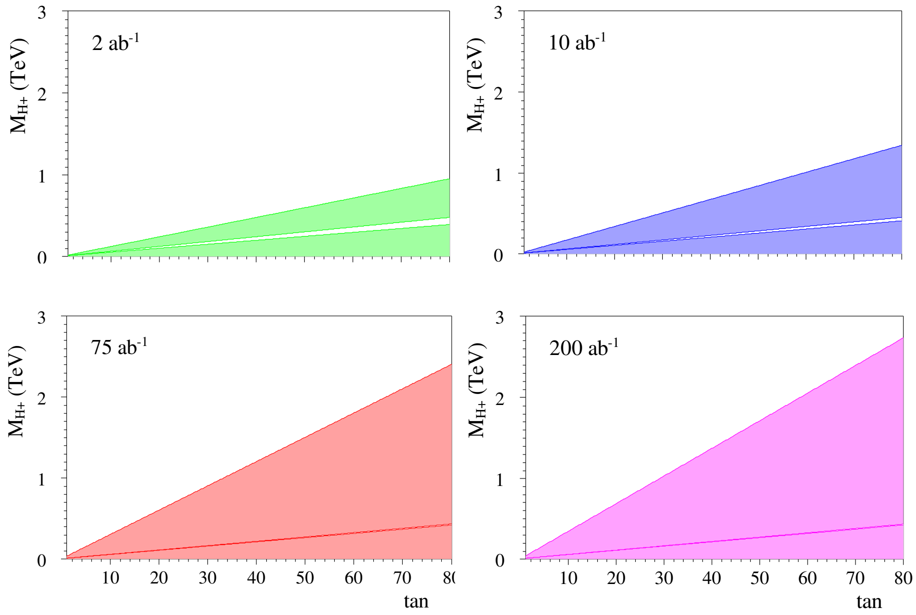

Figure 2: Exclusion regions in the $m(H^+)$–$\tan\beta$ plane arising from the combinations of the measurement of $\mathcal{B}(B \to \tau\nu)$ and $\mathcal{B}(B \to \mu\nu)$ using 2 ab^{-1} (top left), 10 ab^{-1} (top right) 75 ab^{-1} (bottom left) and 200 ab^{-1} (bottom right). We assume that the result is consistent with the Standard Model.

3.1 MSSM with Generic Squark Mass Matrices

We now discuss the impact of SuperB on the parameters of the Minimal Supersymmetric Standard Model (MSSM) with generic squark mass matrices parameterized using the mass insertion (MI) approximation [6]. In this framework, the NP flavour-violating couplings are the complex MIs. For simplicity, we consider only the dominant gluino contribution. The relevant parameters are therefore the gluino mass $m_{\tilde{g}}$, the average squark mass $m_{\tilde{q}}$ and the MIs $(\delta^d_{ij})_{AB}$, where $i, j = 1,2,3$ are generation indices and $A, B = L, R$ refer to the helicity of the SUSY partner quarks.

In Fig. 3 we show an example in case of $(\delta^d_{23})_{LL,LR}$ obtained by requiring that the absolute value of the reconstructed MI is more than 3σ away from zero. From these plots, one can see that SuperB could detect NP effects caused by SUSY masses up to 10–15 TeV, corresponding to $(\delta^d_{23})_{LL} \sim 1$. Here the relevant constraints come from $\mathcal{B}(b \to s\gamma)$, $A_{CP}(b \to s\gamma)$, $\mathcal{B}(b \to s\ell^+\ell^-)$, $A_{CP}(b \to s\ell^+\ell^-)$, Δm_{B_s} and A^s_{SL}.

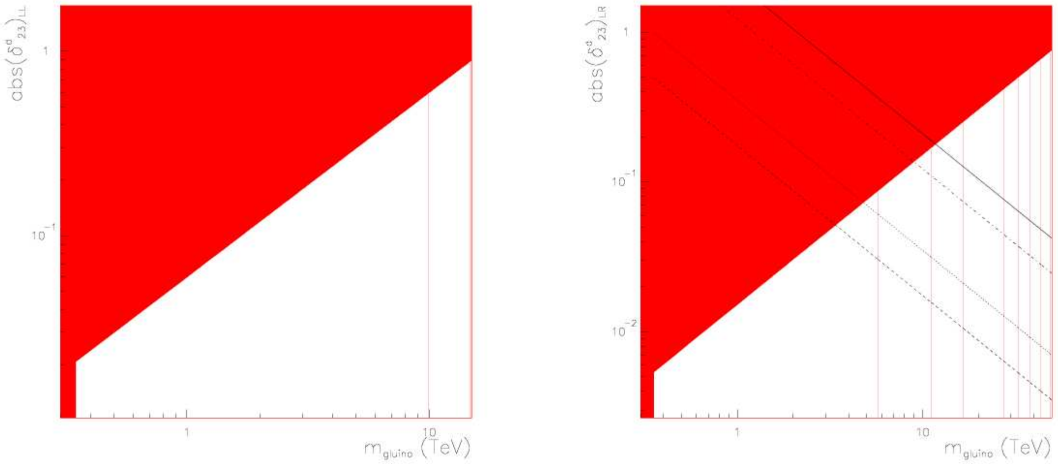

Figure 3: Sensitivity region of SuperB in the plane $m_{\tilde{g}}$–$(\delta^d_{23})_{LL}$ (left) and $m_{\tilde{g}}$–$(\delta^d_{23})_{LR}$ (right). The region is obtained by requiring that the reconstructed MI is 3σ away from zero.

4. NP sensitive measurements in the τ sector

Lepton Flavour Violation (LFV) in τ decay is one of the most theoretically and experimentally clean probe to search for NP. This search at SuperB is complementary with the existing neutrino experiments aiming at measuring θ_{13} and the MEG experiment at PSI searching for $\mu \to e\gamma$. With an integrated luminosity of 75 ab^{-1} SuperB can gain an order of magnitude on several LFV in τ decays (see Table 2), exploring a significant portion of the parameter space of various NP scenarios by searching for LFV in τ decays.

Final State	Sensitivity $/10^{-10}$
$\mu\gamma$	20
$e\gamma$	20
3μ	2
$3e$	2
$\mu\eta$	4
$e\eta$	6
ℓK^0_S	2

Table 2: The experimental sensitivities (in units of 10^{-10}) expected for LFV searches in τ decay.

Longitudinally-polarized electron beam (at the level of about 85%) is the key to the study of the structure of lepton-flavor-violating couplings in τ decay. Recent studies have shown that the polarisation gives new handles to discriminate between signal and background and thus probably allow to push even further the SuperB sensitivity on LFV measurements. Polarisation opens also the possibility to search for a τ EDM, or for CP violation in τ decay.

5. Charm Physics

Charm physics could play an important role on the NP searches. In fact, among the up-type quarks, only charm allows to probe for FCNC and thus NP in oscillation phenomena and in particular those involving CP violation. It is an unique opportunity since FCNC could be much less suppressed in the up-type than in the down-type quark sectors. It is important to note that in the Standard Model direct CP violation in charm transitions only occur in Cabibbo-suppressed modes at an observable level $\sim \mathcal{O}(10^{-3})$ and time dependent CP asymmetries could reach the 10^{-5} [10^{-4}] level in Cabibbo-allowed and once [doubly]-suppressed modes. The recent observation of $D^0\overline{D}^0$ oscillations, with $x_D, y_D \simeq$ 0.005–0.01, has clearly open the space on which the observation of CP violation could be a manifestation of NP.

SuperB can perform studies on the charm sector in a comprehensive manner, with high luminosity data sample in the $\Upsilon(4S)$ region and at the $\psi(3770)$ resonance. In fact the collider is designed to run at lower center-of-mass energies, at reduced luminosity. With very short low-energy runs, a data sample an order of magnitude greater than that of the final BES-III sample can readily be obtained. Running at the charm threshold should allow to precisely measure the D decay form factor on semileptonic decays and the decay constant on the leptonic decay. These are important measurements which have to be compared with Lattice QCD calculations. Dalitz analyses with high statistics could provide inputs to the measurement of the UT angle γ. Finally, FCNC searches are better performed at the charm threshold.

6. Spectroscopy

The recent results from the B-factories provide evidence for the renaissance of hadronic spectroscopy. Although past performances provide no guarantee of future success, new particles have been discovered by the B Factories at a rate of more than one per year, and there is no reason to believe that this should not continue into multi-ab^{-1} territory. SuperB will open a unique window on this physics because it allows a high statistics study in a clean e^+e^- environment ideal for the complicated analyses necessary to pin down the nature of these new hadrons. Particles can be searched for in exclusive decays, or by using inclusive techniques, such as recoil analysis. The possibility of running at different center-of-mass energies (as at $\Upsilon(3S)$) extends the reach of this branch of the physics program.

The studies of lower Υ resonances would allow tests of extensions of the Standard Model in a manner complementary to the physics program of a classic B Factory and to the LHC. Among the possibility, we mention the one to detect the presence of a light pseudoscalar Higgs produced in the decay $\Upsilon(n\mathrm{S}) \to ll\gamma$ ($n = 1,2,3$) as an intermediate state (in models like NMSSM) [7].

In addition the study of $\Upsilon(n\mathrm{S}) \to$ invisible decays allows independent constraints on models with light dark matter (LDM) to be obtained [8].

7. Conclusions

The next high luminosity asymmetric collider has to be programmed to be capable to reach a luminosity exceeding $10^{36} cm^{-2} sec^{-1}$ at the energy of the $\Upsilon(4S)$ production and capable to run at lower threshold energies. This will be a discovery machine. The measurements which can be performed will allow to study in a unique manner the structure of the NP beyond the Standard Model, if discovered at LHC, and/or eventually to extent the domain of the NP search at energy scales larger and not accessible to the LHC. This ambitious goal is possible thanks to the unpercented precision on several measurements on B, charm and τ sector. In addition SuperB is the ideal machine with which to study hadronic spectroscopy over a large mass range, and to discover new particles, both conventional and exotic.

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