Physics potential of SuperB project

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Abstract. In the following we present the physics prospects of SuperB project, a proposed asymmetric $e^+e^-$ collider, projected to have a mean luminosity of $L = 10^{36}$ cm$^{-2}$s$^{-1}$, and the option for an 80% electron beam polarization, which would provide, with a five-year data taking period, a data sample consisting of an integrated luminosity of 75 ab$^{-1}$. Such a large data sample will allow to perform precision measurement in many different sectors. In this paper we will focus on three main topics: the searches for $\tau$ lepton flavor violating decays, with in depth discussion about $\tau \rightarrow \ell \gamma$ and $\tau \rightarrow \ell_1 \ell_2 \ell_3$ (where $\ell_i = e, \mu$); search for CP violation in the charm sector, which has never been observed and if observed would provide a clear hint for new physics; and precision measurements in the Electro-Weak sector, both measuring $\sin^2 \theta_W$ in an energy region previously unexplored, and testing neural current universality in the $\gamma-Z$ interference and $Z-b\bar{b}$ coupling. The Physics program of SuperB project will be vast and the potential reach for new physics discovery great thanks to the many topics that will be studied with the large statistic available and the novel machine techniques expected for SuperB.

1. Introduction

The Standard Model of fundamental interactions (SM) has been tested in the last decades to great extent, without any finding of large discrepancies from theoretical expectations. The great success of SM was confirmed by the measurement on Electroweak sector at hadron and $e^+e^-$ machines, such as LEP results, discovery of the top quark, measurement of CP violation in $K$ and $B$ sectors observed by experiment at CERN, Fermilab and at the B-Factories KEKB and PEP-II. On the other hand SM is not able to explain some physical observations and some crucial questions are still left unanswered as the lack of original antimatter in the Universe or the nature of dark matter. It is a general opinion that physics processes not expected by the SM need to be looked for, and further experimentation is needed to look for new physics (NP). Results from neutrino oscillations [1] from dedicated experiments suggest that NP could be within experimental sensitivities and Lepton Flavor Violation (LFV) would be one of the most clear signals of it. A direct way to look for NP is now pursued by LHC experiments, where the available energy for the interaction is enough to produce particles not predicted by the SM. The other way is to look at the indirect effects of NP in interference processes (as CP violation and Electroweak effects) and in rare or forbidden decays (like in LFV processes in $\mu$ and $\tau$ decays).

The complementarity between the two approaches is based on the fact that NP processes are mainly governed by two parameters: the NP energy scale $\Lambda$ and the effective coupling of the processes $C$, which would have different intensities and different patterns, depending on the particular NP flavor model. Super Flavor Factories, producing $7.9 \times 10^{10}$ pairs of $B$ and $D$ mesons and of $\tau$ leptons, will provide enough statistics to look for NP in both cases whether LHC will produce evidence or not. If NP is found at LCH, such high statistics would provide
precision measurements on the flavor structure of NP, through CPV phases, LFV processes, and electroweak parameters, along with possible hints of heavier states not yet found at LHC. If the NP is to be expected at larger $\Lambda$, the Super Flavor Factories will be able look for indirect searches for NP and constrain the phase space of NP models up to the order of several tens or even hundred of TeV.

In the following we present the physics potential of the SuperB factory, with particular attention to CP violation in the charm sector, searches for LFV in the $\tau$ decays, and precision measurements in the Electroweak sector.

2. Search for Lepton Flavor Violation in $\tau$ decays

The $\tau$ physics will assume great importance to probe new physics beyond the SM. The heavy lepton sector, with the use of larger luminosities available at SuperB, will provide precise measurement of both direct effects, via LFV processes, and indirect effects, visible in g-2 and electron dipole moment (EDM) [2] of $\tau$s.

The SuperB machine is expected to deliver mean luminosities of $10^{36}$ cm$^{-2}$s$^{-1}$, achieving an integrated luminosity ($\mathcal{L}$) of about 75 ab$^{-1}$ during a five year long period of data-taking. Differently from other proposed super flavor factories, SuperB machine design provides the option of a polarized $e^-$ beam, with mean polarization of $\sim 80\%$, which may be used to both reduce backgrounds in LFV searches and shed light on the chiral coupling, and flavor structure of the NP if LFV signal is observed.

LFV is indeed one of the clearest signature of NP if detected, in fact SM predicts LFV in the charged sector only at very small rates (less than $\mathcal{O}(10^{-40})$) [3], which are well beyond present (and future) flavor factory sensitivities, on the other hand many NP models predict enhanced branching fractions (BF) for LFV processes as large as $\mathcal{O}(10^{-8})$ [4]. An observation of LFV processes would be a clear signature for NP, and if LFV is observed in more than one channel the ratios between different processes BF$s$ would identify the NP flavor structure [5].

2.1. Search for $\tau^- \rightarrow \ell^- \gamma, \ell = e, \mu$

Most NP model predict $\tau^- \rightarrow \ell^- \gamma, \ell = e, \mu$ to be the LFV process with the largest BF, so the search for this particular decay is of uttermost importance for NP searches since the sensitivity needed for the discovery is smaller than the one needed for other channels. Searches at the B-factories were limited by irreducible backgrounds coming from radiative $\tau$ decays such as $\tau \rightarrow \mu\nu\nu\gamma$. Radiative $\tau$ decays present the same topology, reconstructed neutral energy, and lepton momenta as a signal event when the $\nu$s are produced almost at rest. BaBar, in its analysis [6], performed a blind search for $\tau^- \rightarrow \ell^- \gamma, \ell = e, \mu$ decays, and 5.1 background events were expected in the 2$\sigma$ blinded signal region, among them 1.7 came from lepton tags, 2.0 expected in single hadron tags ($\pi$ and $\rho$), and the rest coming from 3 hadron tags. Most of the background is produced by real $\tau$ decays, and 86% of the total is due to $\tau \rightarrow \mu\nu\nu\gamma$ decays: if no further backgrounds become relevant with the increase in statistics expected at SuperB, the backgrounds predicted at higher luminosities could be extrapolated by a simple scaling. Considering a sample of 75 ab$^{-1}$, SuperB would expect about 300 background events in the signal region, leading to an expected Upper Limit (UL) of $\sim 6.4 \times 10^{-9}$, which would scale as $\sqrt{\mathcal{L}}$ from BaBar ULs. The $\sqrt{\mathcal{L}}$ scaling is expected if background can not be reduced more efficiently than in previous experiment, so if no further handles for signal selection are available the UL improvement would be strongly suppressed.

SuperB machine is expected to have an 80% polarized $e^-$ beam, this would allow to have information on the dynamical properties for the decay, especially if single hadron modes ($\tau \rightarrow \pi\nu$ and $\tau \rightarrow p\nu$) are used in the tagging,with the presence of only one $\nu$ in the final state for signal events. The presence of only one $\nu$ has two main consequences: first of all the event kinematics is fully reconstructed by identifying the missing momentum of the event to be the $\nu$ momentum,
and secondly and more importantly the event helicity is fixed, since the $\nu$ may be considered massless and hence chiral. Angular momentum conservation can be used to reduce backgrounds by looking at the correlation between the signal and tracks helicity angles: the helicity angle is defined as the angle between the track momentum in the parent $\tau$ rest frame and the momentum of the other $\tau$ in the laboratory frame. The correlation is shown for both signal and background in Fig. 1.

![Figure 1. Correlation between signal track and tag track helicity angles for signal events (left) and background events (right) for $\tau \to \pi \nu$ tag. On the horizontal axis the signal helicity angle is plotted while on vertical axis tag helicity angle is shown.](image)

Applying a simple selection on the helicity angle correlation it is possible to strongly reduce backgrounds coming from radiative $\tau$ decays, even by a factor 10, while retaining almost 50\% of the signal. Using only single hadron tags, along with angular momentum conservation the background could be reduced to $\sim 15$ events, making it possible for the UL to scale almost linearly with $L$. The improvement expected with the use of polarized beams would make it possible to reach UL of $3.9 \times 10^{-9}$, corresponding to an increase of $L$ (in the background dominated case, using all tags) of a factor 2.6, albeit using only 25\% of the statistics. Further improvements are expected using the same method on lepton tags, even if the effect is going to be diluted due to the presence of two $\nu$s in the event.

2.2. Search for $\tau^- \to \ell^-_1 \ell^+_2 \ell^-_3$, $\ell_i = e, \mu$

The search for $\tau^- \to \ell^-_1 \ell^+_2 \ell^-_3$ decays allows the simultaneous study of all the six channels compatible with charge conservation. Theoretical models generally predict smaller BF for these channels with respect to $\tau^- \to \ell^- \gamma$ decays, making them an useful, but less important way to discover LFV processes, on the other hand being able to simultaneously measure six channels would make it possible to study the flavor structure of NP and the chiral coupling of the NP particles. Background expectation in previous BaBar analysis [7] were small for all the six channels, so even considering a background increase proportional to $L$, and without considering any improvement in both selection and detection, the ULs are expected to scale almost $\propto L$ as shown in Fig.2. SuperB thanks to its large statistics would reach ULs of $\mathcal{O}(10^{-10})$ for some channels, with an improvement of almost 2 orders of magnitude for all the channels.

3. CP Violation in charm sector

The recent observation of large $D^0 \bar{D}^0$ oscillation at the B-Factories [8] rise the exciting possibility of finding CP violation in the charm decay, which would be a major hint for physics beyond the SM, in fact no CP violation is expected in the up sector due to the presence of only one phase
in the CKM matrix. SuperB will be able to make comprehensive studies in the charm sector, with the large amount of data taken on the $\Upsilon(4S)$ resonance, SuperB will also be able to run at $\Psi'(3770)$ resonance, featuring a collider designed to run at lower center of mass energies with reduced luminosity of $10^{35}\text{cm}^{-2}\text{s}^{-1}$.

SuperB has many distinctive features useful to study CPV in the charm sector. The experimental environment is very clean, with small background contribution with respect to the great rate at which $D$'s are produced, at $\Upsilon(4S)$ energy the mesons can be tagged through $D^* \rightarrow D\pi$ decay, making it possible to have a flavor tag on the produced $Ds$. On the other hand $D$ production at $\Psi'(3770)$ energy would allow a coherent production of the $D^0\bar{D}^0$ pair, opening novel ways to study CPV in the up sector. While running at threshold would offer lower backgrounds and access to both direct and indirect CPV it comes at the expense of statistics. SuperB great luminosity at $\Upsilon(4S)$ energy make it possible to obtain great results in time dependent measurements: the vertexing detector of SuperB should be able to achieve precisions of few tens of microns, which would make it possible to study the decay lengths of the $D$'s with the beam position known with nm precision allowing time dependent measurements. In Fig. 3 present and future precision for CPV parameters in the $D$ sector are shown.

4. Testing the Electro-Weak sector
The combination of high luminosity and polarized electrons present at SuperB provides a unique opportunity to measure, with precision comparable or better than SLC and LEP, a number of electroweak neutral current parameters at transferred momenta $q^2$ of $(10.58\text{ GeV})^2$. In particular use of polarized beams allows the measurement of $\sin^2\theta_W$, using $\mu$ and $\tau$ pair production differential cross sections, with precision comparable to SLD but at much lower energies. Another important aspect for Electroweak precision tests is the measurement of the neutral current vector coupling to both $\mu$s and $b$ quarks, such measurements are sensitive to a $Z'$ and can prove neutral current universality at high precision.

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**Figure 2.** UL measured at the B-factories and extrapolation at $75 \text{ ab}^{-1}$. The yellow shading presents the background dominated expectation ($\propto \sqrt{L}$) and the green shading the background free expectation ($\propto L$) for the ULs
4.1. Measure of $\sin^2(\theta_W)$ with $e^+e^- \rightarrow \mu^+\mu^-$ processes

With polarization, SuperB will be able to make a relatively straightforward measurement of the left-right asymmetry in the $e^+e^- \rightarrow \mu^+\mu^-$ production in a manner identical to the one used by the SLC collaboration [9], which operated at the Z pole. SuperB will measure the $A_{LR}$ asymmetry defined as

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \frac{1}{<P>},$$

where $<P>$ is the mean polarization of the beams, $\sin^2(\theta_W)$ can be extracted from the $A_{LR}$ parameter since $A_{LR} \propto (T_f^3 - 2Q_f \sin^2(\theta_W))$. SLC measured $\sin^2(\theta_W) = 0.23098 \pm 0.00026$, where the systematic uncertainty (accounting for almost 50% of the error) is due to the 0.5% uncertainty on the polarization.

An analysis made using BaBar sample, and then scaled to the SuperB luminosity, revealed that selection efficiencies of 53% can be achieved with 99.6% sample purity. Considering a sample of 46 billion $\mu$-pairs available after 5 year of data taking at SuperB, and an 80% mean polarization, the statistical error on $A_{LR}$ is expected to be of $\mathcal{O}(10^{-2})$. If the systematic error on polarization measurement can be kept under 1% level the uncertainty on $\sin^2(\theta_W)$ may be as low as 0.0002, competitive to the SLC measurement, but at a different $q^2$. The same $A_{LR}$ can be measured in $\tau$ and charm production, with smaller efficiencies and purities, providing the most stringent test to neutral current universality. Fig. 4 shows the present results and the planned measurement that will be made by SuperB.

4.2. $Z-b\bar{b}$ coupling and $g_V^b$ measure

As SuperB will be running mostly at $\Upsilon(4S)$ energy, the left right asymmetry for B mesons will be sensitive to the product of the electron neutral current axial coupling and b quark neutral current vector coupling $g_V^b$, the same formalism adopted for measuring $g_V^e$ at $\Phi$ factories can be used and is described elsewhere [10]. Using $10^9 BB$ pairs produced at the $\Upsilon(4S)$ energy, with an 80% $e^-$ polarized beam, SuperB will provide a measurement of $g_V^b$ competitive with the measurement from LEP and SLC, but at smaller $q^2$ values. Present measurement have a relative error of about 2.4% with the statistics available at SuperB a 0.3% error could be achieved if the systematics error on polarization are kept under control. The main concern comes from the non resonant production of B-mesons, however the problem has been studied and results prove that...
Figure 4. Summary of experiments that have measured $\sin^2(\theta_W)$. SM predictions and uncertainty are presented as the solid line and gray area respectively. SuperB will provide a point at $q = 10.58$ GeV, a region previously unexplored.

$A_{LR}$ from $B \bar{B}$ at $\Upsilon(4S)$ give access to the $Z - b \bar{b}$ coupling in a manner independent from the production process. Such high precision measurement can be obtained at SuperB thanks to the fact that no QCD corrections are needed at such low energy, and that the coupling between the final states and the parent pseudo scalars couple directly without any hadronization processes.

It is also possible to measure the ratio between the left right asymmetry measured in muon and b-quark production, testing the universality of neutral vector coupling with great precision, since polarization systematics cancel out in the ratio, giving another robust way to test neutral current universality. In addition to probing NP, this measurement will shed light on the long standing $3\sigma$ difference between the measurement of $\sin^2(\theta_W)$ obtained from the forward backward asymmetry of b-quarks and the leptons. In Fig.5 the present status of $g^b_V$ and $g^h_A$ measurement is shown along with the expected precision of the measurement made at SuperB.

Figure 5. Present status of measurement of $g^b_V$ and $g^h_A$, contours represent experimental uncertainties, the red cross represent SM prediction, the pink shaded area is the expected error obtained by SuperB measurement.
4.3. Open issues in Electroweak test at SuperB
The main issues for Electroweak testing at SuperB come from the systematic error on polarization, which are dominated by the luminosity dependent polarization: it is of great importance to know $<P>$ at a level better than 1% in order to reach sensitivities competitive to those of previous experiment. SuperB with its great luminosity could in principle have a great knowledge of the polarization value for each bunch, and new ways to measure $<P>$ with great precision are under study. On the other hand in order to compare the SuperB results with LEP and SLC results $g_V^b$ should be run to larger $q^2$ values, which is a huge theoretical effort. The last issues comes from the possibility to use $\Psi'(3770)$ running to make the same measurement for charm as it was done for strange and bottom coupling, however large polarization at lower energy is needed along with sufficient luminosity, the reach of charm running and the systematics associated are still under study by SuperB collaboration.

5. Conclusions
SuperB machine with its large luminosity and the possibility to have a polarized electron beam will have clear edges in the search for NP in the near future. Its design and physics case is complimentary to LHC experiments, and SuperB seeks NP in an indirect way, looking for discrepancies from SM predictions and rare decays. SuperB has a strong physics case in the search for LFV in the $\tau$ sector being able with its polarized beams to reduce UL of $\tau \rightarrow \ell \gamma$ of almost two order of magnitude, albeit the present searches are background dominated, and the same will happen for $\tau \rightarrow \ell \ell \ell$ LFV decays. The nanometric beams and the large statistics, along with the possibility to run at $\Psi'(3770)$ will allow to look for CPV in the charm sector in both direct CPV and in the mixing, or even with time dependent measurement. On the precision frontier, SuperB will be able to measure Electroweak parameters in $q^2$ regions previously unexplored and probably shedding light on discrepancies observed by previous experiments such as LEP and SLC. SuperB has a vast physics case ranging from B-physics to electroweak precision test and its sensitivity to such processes is a great tool for NP discovery and for NP flavor study, if NP is going to be observed at LHC.

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