THE PHYSICS CASE OF THE SUPERB FACILITY

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Abstract

The physics case of the SuperB facility with design luminosity of $10^{36}$ cm$^{-2}$s$^{-1}$ is compelling. Such a facility has a rich and varied potential to probe physics beyond the Standard Model. These new physics constraints are obtained through the study of the rare or Standard Model forbidden decays of $B_{u,d,s}$, $D$ and $\tau$ particles. The highlights of this wide-ranging physics programme are discussed in these proceedings.

1 Introduction

A conceptual design report of a next generation $e^+e^-$ collider capable of delivering 100 times the luminosity of the current $B$ factories has recently been compiled [1]. This report forms the basis of the physics motivation, detector, and accelerator designs for the next generation $B$ factory at an $e^+e^-$ collider. Details of the accelerator and detector designs are discussed elsewhere [2].
Data taking could commence as early as 2015 if the project is approved in the next few years. By this time, the LHC will have produced the results of direct searches for SUSY, Higgs particles and many other new physics (NP) scenarios, as well as providing precision measurements of CP violation and the CKM mechanism for quark mixing in $B_{u,d,s}$ decays. The focus of high energy physics at that time will either be to understand the nature of any new particles found at the LHC, or to try and indirectly constrain possible high energy new particles by looking for virtual contributions to increasingly rare decays. If new particles exist they can contribute significantly at loop level to many rare $B$, $D$ and $\tau$ decays. If this occurs, we may measure observables that differ from Standard Model (SM) expectations. Precision measurements of branching fractions, CP, and other asymmetries in many different rare decays can be used to elucidate the flavor structure of new particles and distinguish between different NP scenarios. Some NP scenarios introduce new particles at low energies (few GeV) which can be observed directly at SuperB. In short, the main aim of the SuperB facility is to search for and elucidate the behavior of NP.

2 B Physics

2.1 Measurements of $\sin(2\beta_{\text{eff}})$

Since the discovery of CP violation in the decay of B mesons through $b \to c\bar{s}s$ transitions, an industry has developed in performing alternate measurements of $\sin 2\beta$ in other processes (these are measurements of $\sin(2\beta_{\text{eff}})$). In the presence of new physics, one can measure CP asymmetries that are significantly different from the SM expectation which is $\sin 2\beta$ measured in $b \to c\bar{s}s$ transitions. Measurements of $\sin(2\beta_{\text{eff}})$ are performed in decays with $b \to s$ and $b \to d$ transitions. Loop dominated rare decays can receive significant contributions from new physics, and large effects have been ruled out by current measurements (See Figure 1). The general trend of measurements shows that $\sin(2\beta_{\text{eff}}) < \sin(2\beta)$. In addition to the experimental uncertainties on the measurement of $\sin(2\beta_{\text{eff}})$, there are theoretical uncertainties on the SM prediction in each decay mode. The first thing to note when considering theoretical uncertainties is that different decay modes have different expected shifts that are known with different levels of precision. As a result, it is not correct to average all of the $\sin(2\beta_{\text{eff}})$ measurements and compare this average with the reference from $b \to c\bar{s}s$ transitions, although in practice this comparison is often made. You really have to perform a precision measurement for each mode, and then make the comparison. Ideally when you make such a comparison, you want the experimental and theoretical uncertainties to be similar. There is insufficient statistics available at the existing B factories to do this comparison correctly. The most precise estimates of the SM uncertainty on $\Delta S = \sin(2\beta_{\text{eff}}) - \sin(2\beta)$
are of the order of a percent for \( B \rightarrow \eta' K^0 \), \( B \rightarrow K^+ K^- K^0 \), and \( B \rightarrow 3K^0 \) decays. SuperB will be able to experimentally measure \( \sin(2\beta_{\text{eff}}) \) to one percent with 75\( ab^{-1} \), thus enabling a comparison at the few percent level between \( \sin(2\beta_{\text{eff}}) \) and \( \sin(2\beta) \).

\[
\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_1) \quad \text{H F A G}
\]

| b \rightarrow cs | World Average | 0.68 \pm 0.03 |
|------------------|--------------|---------------|
| \( \eta'K^0 \)  | Average      | 0.39 \pm 0.17 |
| \( \eta K^0 \)   | Average      | 0.61 \pm 0.07 |
| \( \phi K^0 \)   | Average      | 0.58 \pm 0.30 |
| \( \phi K^0 \)   | Average      | 0.38 \pm 0.19 |
| \( \phi K^0 \)   | Average      | 0.61 \pm 0.24 |
| \( \phi K^0 \)   | Average      | 0.35 \pm 0.20 |
| \( \phi K^0 \)   | Average      | 0.95 \pm 0.07 |
| \( \phi K^0 \)   | Average      | 0.70 \pm 0.45 |

Figure 1: The distribution of \( \sin(2\beta_{\text{eff}}) \) measured in \( b \rightarrow s \) penguin decays, along with the reference measurement of \( \sin(2\beta) \) from \( b \rightarrow c\bar{c}s \) decays.

2.2 New Physics in Mixing

In the SM we know that \( B_d \) and \( B_s \) mesons mix. It is possible to model new physics in mixing by allowing for an arbitrary NP amplitude to also contribute to the box diagram, and search for the effect of NP by comparing data to the ratio of the NP+SM contribution to that of the SM, i.e.

\[
C_{B_d} e^{i\phi_{B_d}} = \frac{< B^0 | H_{NP+SM} | B^0 >}{< B^0 | H_{SM} | B^0 >}. \tag{1}
\]

The SM prediction is for \( C_{B_d} = 1 \) and \( \phi_{B_d} = 0 \), so any deviation from this would signify NP. It is possible to constrain \( C_{B_d} \) and \( \phi_{B_d} \) using the available data, and extrapolate to SuperB as shown in Figure 2.
2.3 Minimal Flavor Violation

One set of NP models that is popular assumes that there are no new flavor couplings. The corollary of this is that all CP violation is described by the SM Yukawa couplings. Models of this type are called Minimal Flavor Violation (MFV) models, examples of these are Higgs doublet, MSSM and large extra dimension models. Within the realm of MFV models we can still use the SuperB experiment to tell us about the nature of NP. For example, it is possible to use $B^+ \to \tau^+\nu$ decays to constrain the mass of the charged Higgs $m_{H^+}$ as a function of the Higgs vacuum expectation value, $\tan \beta$ in 2HDM or MSSM (See Figure 3). In 2HDM, the branching fraction of $B^+ \to \tau^+\nu$ can be enhanced or suppressed by a factor $r_H$ which has the form $(1 - \tan^2 \beta [m_B^2/m_{H^+}^2]^{1/2})^2$ [5], and the corresponding factor for MSSM is $(1 - \tan^2 \beta [m_B^2/m_{H^+}^2]/[1 + \epsilon_0 \tan \beta])^2$ where $\epsilon_0 \sim 0.01$ [6]. Other decay modes, including $D^+ \to \tau^+\nu$, $\mu^+\nu_e$ and $b \to s\gamma$ can be used to constrain the charged Higgs mass in a similar way. The worst case scenario of MFV suggests that SuperB would be sensitive to new particles with masses up to 600 GeV.
Figure 3: The distribution the mass of the charged Higgs vs \( \tan \beta \) in a) 2HDM and b) MSSM. The red band is what could be excluded by the current \( B \) factories with a data sample of \( 2ab^{-1} \), and the green band is what could be excluded using \( 75ab^{-1} \) of data from a SuperB factory assuming that the measured \( B^+ \rightarrow \tau^+ \nu \) branching fraction has the standard model value.

2.4 Other Searches for New Physics

In contrast to the MFV scenario described above, we can think of a more generalized SUSY scenario. Given that quarks and neutrinos can change type or mix, it is natural to consider that their super-partners would also have non-trivial flavor couplings and would mix. If this is not true, then the NP extension to the SM would have a fine-tuned and unnatural behavior. We can already rule out large new physics contributions to \( B \) and kaon physics, but CP violation is small in the SM, so we should not expect to see large \( \mathcal{O}(1) \) NP effects, and should be content to search for small CP violation effects from NP. The simplest model of this type is MSSM with squark mixing matrices. Combinations of observables measurable at SuperB can be combined to provide non-trivial constraints on the real and imaginary parts of these squark mixing parameters. For example, Figure 4 shows the constraint that SuperB can put on the complex parameter \( (\delta d_{2,3})_{LR} \) with a data sample of \( 75ab^{-1} \), where the \( d \) indicates a quark, the indices 2, 3 indicate mixing between the second and third squark generations and the \( LR \) indicates a left-right helicity for the SUSY partner quarks. The measurements of the branching fractions of \( b \rightarrow s\gamma \) (green) and \( b \rightarrow sl^+l^- \) (cyan), with the CP asymmetry in \( b \rightarrow s\gamma \) (magenta) are
combined (blue) to constrain the real and imaginary parts of \((\delta_{2,3}^d)^{LR}\). SuperB has a sensitivity > 100 TeV for this type of NP model \(^7\). Other examples of constraints squark mixing parameters are described in \(^1\).

![Figure 4: The distribution constraint on the real vs imaginary part of \((\delta_{2,3}^d)^{LR}\) obtainable at SuperB using the constraints described in the text.](image)

There are also models of NP that predict light new particles (Higgs or dark matter candidates). If such particles exist, then it would be possible to create them directly at a SuperB factory. Some of these models are described further in \(^1\).

3 D Physics

Given the recent observation that \(D^0\) mesons mix, we now know that the plethora of observables that one can use to search for CP violation in \(B\) decays also exists in \(D\) decays. As with \(B\) meson decays, the pattern of observables (the branching fractions, CP asymmetries and other observables) in the decays of charm decays can be used to constrain NP scenarios. Work is ongoing to understand how to use these correlations in charm decays to constrain NP.
4  τ Physics

Many NP scenarios have couplings that represent lepton flavor violation (LFV). Such a decay would give an unmistakable signal in the detector, and would mark the start of a new era in particle physics. The current best limits from searches for signals of LFV are $\mathcal{O}(10^{-7})$. These limits are an order of magnitude away from upper bounds in many new physics scenarios. A SuperB facility would provide sufficient statistics to find LFV at the level of such predictions, or push upper limits down to $\mathcal{O}(10^{-9}$ to $10^{-10}$).

The decays of τ leptons proceed via a single amplitude. If a non-zero CP asymmetry is measured in any τ decay, then this is a clear signal of new physics. There have been many proposed searches for CP violation in τ decays. When doing such searches, one has to decouple the possible effects of CP violation in any final state kaons, and the difference between $K^+$ and $K^-$ interactions in the detector.

It is possible to test CPT by comparing the ratio of lifetimes of the $\tau^+$ and $\tau^-$. Any deviation from one would indicate CPT violation. The expected statistical precision of such a test is at the level of $\mathcal{O}(10^{-4})$. If this precision were to be achieved, then the lifetime ratio test in τ decays would be comparable to that in μ decays.

5  Conclusion

The SuperB facility has the potential to indirectly search for NP at energy scales far beyond the reach of the direct searches at the LHC. The ability to probe flavor couplings in NP scenarios up to several hundred TeV means that results from SuperB will be of general interest, and complimentary to the LHC physics programme over the next few decades. There are two possible scenarios: (i) If the LHC discovers new particles, it will be possible to measure their basic properties such as mass and width at ATLAS and CMS. However, in order to fully understand these new particles, one needs to understand their flavor dynamics as well. The flavor dynamics of new physics can be probed well above the TeV scale at SuperB. (ii) If the LHC doesn’t discover any new particles, then it is important to probe ever increasing energy scales. Again, SuperB can probe well above the TeV scale while indirectly searching for new physics. The correlations of flavor related observables measured at SuperB can help us distinguish between the multitude of NP scenarios being proposed today. Without this set of measurements from SuperB, we may not be able to resolve between many of the plausible NP scenarios that exist. These proceedings discuss the core of the physics programme of SuperB, and the interested
reader will find a more comprehensive treatment in Ref. 1. More discussion on exploiting correlations between measurements of flavor observables to distinguish between NP models can be found in Ref 12.

References

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