THE PHYSICS PROGRAMME AT SUPERB

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Abstract. SuperB is a next generation high luminosity $e^+e^-$ collider that will be built at the Cabibbo Laboratory, Tor Vergata, in Italy. The physics goals of this experiment are to search for signs of physics beyond the Standard Model through precision studies of rare or forbidden processes. While the name suggests that $B$ physics is the main goal, this experiment is a Super Flavour Factory, and precision measurements of $B_{u,d,s}, D, \tau, T$, and $\psi(3770)$ decays as well as spectroscopy and exotica searches form part of a broad physics programme. In addition to searching for new physics (NP) in the form of heavy particles, or violations of laws of physics, data from SuperB will be able to perform precision tests of the Standard Model. I will briefly review of some highlights of the SuperB physics programme.

1 Introduction

Flavour physics has been instrumental in the development of the Standard Model (SM), starting from a combination of results from hyperon decays by Cabibbo [1]. Shortly after this development Glashow, Iliopolus and Maiani [2] proposed the existence of the charm quark to satisfy the observed pattern of branching fractions in kaon decays and establish a four quark model of particle physics. The discovery of CP violation by Cronin, Christenson, Turlay and Fitch in 1964 [3] was another landmark, and in time Kobayashi and Maskawa postulated a six quark model in order to accommodate CP violation naturally within the SM [4]. These developments laid the foundations of our current theory, however we now know that there are a number of features missing, including an understanding of the matter-antimatter asymmetry.

SuperB is a next generation $e^+e^-$ flavour factory designed to operate primarily with a centre of mass energy of the $\Upsilon(4S)$, and at the charm threshold $\psi(3770)$. The project status, accelerator and detector are discussed in the contribution to these proceedings by Francesco Forti [5]. Recent reviews of the physics programme of this project can be found in Refs. [6–8]. The rest of these proceedings discuss a number of physics highlights, and how these can be used to elucidate the structure of physics beyond the SM.

2 $\tau$ Physics

The intrinsic level of charged lepton flavour violation in the $\tau$ sector arising from neutrino oscillations is expected to occur at the level of $10^{-54}$. Given that both quark and neutral lepton number conservation is known to be violated at a small level, it is natural to presume that there may ultimately be

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non-conservation of charged lepton number. Indeed many scenarios of physics beyond the SM predict large (up to $\sim 10^{-9}$) levels of charged lepton flavour violation (LFV). These predictions are model dependent: some models favour large $\mu \to e$ transitions over other possibilities. Other models prefer large $\tau \to \mu$ or $\tau \to e$ transitions. While the quest for a discovery of LFV continues, it is clear that all three sets of transitions need to be measured or well constrained in order to understand the underlying dynamics. SuperB will be able to improve upon existing limits from the $B$ factories by between one and two orders of magnitude. Channels such as $\tau \to \ell \gamma$ will see a factor of ten improvement as these have irreducible SM backgrounds that one will have to contend with, while other channels such as $\tau^\pm \to \ell^+\ell^-\ell^\pm$, which are free of SM backgrounds, will see a factor of one hundred improvement.

The $e^-$ beam at SuperB will be 80% polarised, enabling one to separate contributions from SM-like LFV channels and otherwise irreducible backgrounds as one can use the polarisation of the final state $\tau$ lepton produced in collisions in order to suppress background. This works well for improving limits, or indeed searching for left handed sources of NP. One can verify if there is a right handed component to any underlying NP by comparing results with and without polarised beams. Similarly as one expects some higher theory to undergo symmetry breaking in order to manifest the low energy scenarios we are studying at facilities today, which includes the LHC reach, the different types of fundamental particle may be related to each other. There are models that predict correlated effects between charged leptons decays and processes involving quarks, and of course neutrinos. Hence in order to understand any underlying deviations in any of these sectors one needs to cross check, for example, charged LFV results with neutrino mixing, neutral meson mixing and CP violation measurements in the quark sector. A number of scenarios of physics beyond the SM are discussed in Ref. [7] in order to illustrate this point.

3 B Physics

As much of the NP search potential of SuperB concerns the use of indirect constraints on rare processes to infer the existence or otherwise of some model, one naturally has some sensitivity to the corresponding energy scale $\Lambda_{NP}$ of the NP. The correlation between measurement of the rare decays (a branching fraction or other observable) and the energy scale is non trivial. If one considers the minimal supersymmetric model (MSSM) in the mass insertion hypothesis then for example the measurement of the inclusive branching fractions of $b \to s\gamma$ and $b \to s\ell\ell$, along with the $CP$ asymmetry in $b \to s\gamma$ can be used to constrain the mass insertion parameter $(\delta_{23}^d)_{LR}$. The magnitude of this parameter can be used to infer an upper limit on $\Lambda_{NP}$ to complement the null results obtained so far from the LHC. If generic MSSM was a realistic description of nature then
the fact that the LHC has failed to find a low mass gluino implies that there is a non-trivial coupling $(\delta d^d_{23})_{LR}$, and hence in turn SuperB should be able to observe a non-trivial deviation from the SM when studying the inclusive decays $b \to s\gamma$ and $b \to s\ell\ell$. The magnitude of the observed deviation will benefit the SLHC community as the inferred upper bound on the energy scale obtained will provide useful information on the integrated luminosity required to yield positive results via direct searches. For example if one measured $|\delta d^d_{23}^{LR}| = 0.05$, then the implied upper limit on $\Lambda_{NP}$ is 3.5 TeV, which is also compatible with known constraints on $\tan \beta$ as can be seen from Ref. [7]. Other processes can be used to constrain other mass insertion parameters.

There are a number of golden rare $B$ decay channels at SuperB, including $B \to \ell\nu$, where $\ell = \tau, \mu, e$. In the SM this decay is known up to uncertainties relating to the value of $V_{ub}$ and $f_B$. The rate of these processes can be modified by the existence of charged Higgs particles predicted in a number of extensions of the SM for example two-Higgs Doublet models (2HDM) or SUSY extensions of the SM. Hence the measured rate of these decays can be used to place limits on the inferred mass of any $H^+$ particle, and such constraints are a function of $\tan \beta$. Existing constraints from the $B$ factories from inclusive $b \to s\gamma$ decays exclude masses below $295 GeV/c^2$, and the constraint from $B \to \tau\nu$ excludes higher masses for large $\tan \beta$ scenarios. With $75 ab^{-1}$ of data SuperB will be able to exclude, or detect, a $H^+$ with a mass $1 - 3$ TeV, for $\tan \beta$ between 40 and 100. This constraint results from a combination of $B \to \tau\nu$ (dominates at lower luminosity) and $B \to \mu\nu$ (dominates at high luminosity). Ref. [7] discusses the physics potential of a number of other interesting rare $B$ decays.

Many of the $CP$ asymmetry observables of $B_{u,d}$ decays available at SuperB are dominated by loop contributions and are sensitive to the same sources of NP that can affect many of the interesting rare decays discussed above. The golden modes to use in measuring the angle $\beta$ of the unitarity triangle are $B$ decays to charmonium ($c\bar{c}$), $\eta'$ or $\phi$ and a neutral kaon. SuperB will be able to measure the $CP$ asymmetries in these decays with precisions of 0.002, 0.008, and 0.021, respectively using a data sample of $75 ab^{-1}$. Both tree ($c\bar{c}K^0$) and penguin dominated decays can be affected by the presence of NP.

To complement the $B_{u,d}$ programme at SuperB, there will be a dedicated run at the $\Upsilon(5S)$ resonance which enables the study of a number of $B_s$ related observables that may be affected by physics beyond the SM. These include the semi-leptonic asymmetry and branching fraction $B_s \to \gamma\gamma$.

4 Charm Physics

Charm mixing has been established by the $B$ factories and is parameterised by two small numbers: $x = \Delta m_D/\Gamma$ and $y = \Delta \Gamma/2\Gamma$. These are currently measured as $x = (0.65^{+0.18}_{-0.19})\%$, and $y = (0.74 \pm 0.12)\%$ [9]. The precision with
which these mixing parameters can be improved upon is dominated by inputs from $D^0 \rightarrow K_S h^+ h^-$ decays, where $h = \pi, K$. At large integrated luminosities one of the limiting factors of this analysis will be the knowledge of the strong phase variation across the $K_S h^+ h^-$ Dalitz plot. This can be measured using data collected at charm threshold, where $e^+e^- \rightarrow \psi(3770) \rightarrow D^0 D^0$ transitions result in pairs of quantum correlated neutral $D$ mesons. These correlated mesons can be used to precisely determine the required map of the strong phase difference required for charm mixing measurements. With this input from a data sample of $500 fb^{-1}$ the mixing measurements at Super$B$ will still be statistics limited, and one should be able to achieve precisions of 0.02% and 0.01% on $x$ and $y$, respectively. The strong phase difference map measured at charm threshold will also be an important input used for the determination of the unitarity triangle angle $\gamma$ for Super$B$, Belle II and LHCb.

It has often been said that $CP$ violation in charm will provide a unique test of the SM. The reason for this is that one expects only very small effects in the SM, and so any large measured deviation from zero would be a clear sign of NP. Just like the $B_{u,d}$ system, charm has a unitarity triangle that needs to be tested. The physics potential of Super$B$ in this area has recently been outlined in Ref. [10]. In the months following the Lomonosov conference an intriguing hint of $CP$ violation in charm decays was produced by the LHCb experiment [11]. This relates to a difference in direct $CP$ asymmetry parameters measured in $D \rightarrow KK$ and $D \rightarrow \pi\pi$. If this is a real effect one will have to perform the measurements outlined in [10] in order to understand the underlying physics.

A number of charm rare decay analogues of the $B$ physics programme are of interest in constraining NP and elucidating the underlying decay dynamics in charm. The complication with charm is the presence of long distance dynamics that dominate the final states. The combination of charm threshold and $\Upsilon(4S)$ running naturally complement each other when studying rare charm decays.

5 Precision Electroweak Physics

In terms of precision electroweak physics, the polarised electron beam at Super$B$ facilitates the measurement of $\sin^2 \theta_W$ at centre of mass energy corresponding to the $\Upsilon(4S)$ resonance. Super$B$ will be able to measure this quantity with the same precision as the LEP/SLC measurements made at the $Z^0$ pole. However the advantage of the Super$B$ measurement is the fact that the $e^+e^- \rightarrow b\bar{b}$ result will be free from fragmentation uncertainties that limit the interpretation of the LEP/SLC measurements. The Super$B$ measurements will be complementary to other low energy $\sin^2 \theta_W$ measurements from the QWeak Collaboration (JLab), and at the proposed MESA experiment (Mainz).

Super$B$ is expected to accumulate twice this luminosity at charm threshold
6 Interplay Between Measurements and Summary

The power of SuperB comes from the ability to study a diverse set of modes that are sensitive to different types of NP. Through the pattern of deviations from SM expectations for observables one will be able to identify viable NP scenarios and reject those that are not compatible with the data. This goes beyond the motivation of simply discovering some sign of NP and is a step toward developing a detailed understanding of NP. If no significant deviations are uncovered then this in turn can be used to constrain parameter space and reject models that are no longer viable. Given that many of the observables that SuperB will measure are not accessible directly at the LHC, these results will complement the direct and indirect searches being performed at CERN. Detailed discussions on the interplay problem can be found in Refs. [6, 7].

In summary the physics programme at SuperB is varied, and the unique features of the facility: polarised electron beams and a dedicated charm threshold run add to its strengths via versatility. The charm threshold run in particular, in addition to facilitating a number of NP searches, will provide several measurements required to control systematic uncertainties for measurements of charm mixing and the unitarity triangle angle $\gamma$. Results from SuperB will be able to play a role in elucidating any NP discovered at the LHC and indirectly probe to higher energy than the LHC will be able to directly access.

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