The Physics of Heavy Flavours at SuperB

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Abstract. This is a review of the SuperB project, covering the accelerator, detector, and highlights of the broad physics programme. SuperB is a flavour factory capable of performing precision measurements and searches for rare and forbidden decays of $B_{u,d,s}$, $D$, $\tau$ and $\Upsilon(nS)$ particles. These results can be used to test fundamental symmetries and expectations of the Standard Model, and to constrain many different hypothesised types of new physics. In some cases these measurements can be used to place constraints on the existence of light dark matter and light Higgs particles with masses below 10 GeV/$c^2$. The potential impact of the measurements that will be made by SuperB on the field of high energy physics is also discussed in the context of data taken at both high energy in the region around the $\Upsilon(4S)$, and near charm threshold.

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1. Introduction

This topical review discusses the potential impact of high luminosity $e^+e^-$ collider experiments, the so-called Super Flavour Factories, on our understanding of high energy physics. In particular this review will focus on the potential of one of these facilities; the SuperB project. This experiment will record billions of $B$, $D$, and $\tau$ decays at various center of mass energies ranging between the $\psi(3770)$ and $\Upsilon(6S)$ in order to search for signs of physics beyond the Standard Model of Particle Physics (SM) and to perform precision measurements of the SM. There are two Super Flavour Factories, one called Belle II which is being constructed at KEK in Japan, and the other called SuperB being built in Italy. The aim of Belle II is to integrate $50\,\text{ab}^{-1}$ of data at a center of mass energy corresponding to the $\Upsilon(4S)$ resonance, while SuperB aims to integrate $75\,\text{ab}^{-1}$ of data at that energy. There are several important differences between these two experiments (i) the electron beam at SuperB will be polarised, enabling superior performance in the study of $\tau$ leptons and other important precision tests of the SM such as the measurement of the weak mixing angle via $\sin^2\theta_W$ and (ii) SuperB will have a dedicated run at the $\psi(3770)$ which corresponds to the charm production threshold.

Before discussing the implications of the many measurements that will be possible at SuperB, and thus the benefits of the additional features of SuperB over Belle II, it is prudent to take a brief look at history (Section 1.1), and our understanding of current popular expectations of physics beyond the SM, which is often referred to as ‘new physics’ (NP) in the literature (Section 1.2). Section 1.3 provides an outline of the rest of the review. Detailed reviews of the physics programmes of SuperB and Belle II can be found in Refs. [1] and [2].

There are two types of measurement that provide the motivation for SuperB. The first type consists of theoretically clean observables that can be measured with high precision. Such observables for a rare or suppressed decay can be sensitive probes of NP. Decay channels related to this type of measurement are often referred to as golden modes in the context of NP searches. The second type of measurement motivating the SuperB experiment are precision CKM or SM measurements, for example the precision measurement of $\sin^2\theta_W$. These measurements have a dual purpose, to provide a precision determination of SM parameters, and in turn to constrain possible NP scenarios.

1.1. Historical look at flavour

The SM provides a mathematical description of all known physical phenomena relating to the interactions between particles and anti-particles. Where the particles are divided into quarks (up-type quarks are $u$, $c$, and $t$, and the down-type quarks are $d$, $s$, and $b$), leptons ($e$, $\mu$, $\tau$ and their respective neutrinos) and gauge bosons ($\gamma$, $g$, $Z^0$, $W^\pm$). The sub-set of phenomena relating to the change of one type of quark or lepton into another type of quark or lepton is referred to as flavour physics. Phenomena pertaining to flavour interactions in quarks are described by the $3 \times 3$ Cabibbo-Kobayashi-Maskawa (CKM)
quark mixing matrix, which encompasses the quark-mixing mechanism postulated by Cabibbo in 1963 \[3\] with the description of CP violation introduced by Kobayashi and Maskawa in 1973 \[4\]. In the SM Lagrangian transitions of up-type \((q_u)\) and down-type \((q_d)\) quarks are mediated by the exchange of a \(W\) boson via \(q_u V_{ij} q_d\), where \(V_{ij}\) represents the CKM matrix with the indices \(i\) and \(j\) corresponding to the quarks. The CKM matrix

\[
V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix},
\]

\(\lambda\), the sine of the Cabibbo angle, and three other parameters \(A\), \(\rho\) and \(\eta\). This description of the CKM matrix is the convention of Wolfenstein \[5\]. When working with the large data samples expected at the next generation of experiments, the above matrix is not expanded to sufficient orders in \(\lambda\), and one obtains a convention dependent solution. The Buras parameterisation of the CKM matrix provides a convenient framework to use at higher orders \[6, 7\]. SuperB is able to probe in detail many aspects of the CKM matrix by making a number of redundant measurements.

There is an equivalent formalism to describe neutrino mixing that is currently being explored by a number of experiments including Daya Bay, Super Kamiokande, and T2K. These measurements are related to elements in a \(3 \times 3\) mixing matrix describing neutrino mixing (for example see the review by B. Kayser in Ref \[8\]). To date there is no evidence for charged lepton flavour violation. SuperB will be able to make significant advances in the search for charged lepton flavour violation in \(\tau\) decays, so transitions from the third, to the second or first generations of charged leptons (see Section 3).

Historically quark mixing was postulated as a way to understand the behavior of hadronic currents in Hyperon decays. This work was completed in an era before the concept of quarks was accepted as a given fact, and the concept of mixing was expressed in terms of currents, that would have corresponded to interactions between the \(u\), \(d\), and \(s\) quarks in today’s terminology. Shortly after this significant step forward, it was realised that attempts to reconcile theory and measurement for the branching fraction of \(K^0_L \rightarrow \mu^+ \mu^-\) decays required the introduction of a fourth quark via the GIM mechanism \[9\]. The discovery of the \(J/\psi\) particle was the confirmation that this fourth quark existed, and we now refer to this as the charm quark. A repeat of this problem was encountered in the study of \(B^0 - \bar{B}^0\) mixing by the ARGUS experiment. The amplitude for \(B^0 - \bar{B}^0\) mixing is dominated by transitions involving the top quark, thus theorists were able to make predictions of the top quark mass based on the experimental knowledge of this mixing observable. It is interesting to note that in both cases (i) the study of a rare kaon decay, leading to the discovery of the charm quark, and (ii) the
use of experimental constraints on $B^0 - \bar{B}^0$ mixing to discover the top quark, one is using a low energy flavour changing process to place stringent constraints on a much higher energy phenomenon. Measurements of flavour changing processes such as the GIM mechanism and mixing in $B^0\bar{B}^0$ decays have shaped our understanding of the SM.

Precision measurements in the flavour sector will continue to provide a detailed set of reference points to test models of NP against. This aspect underpins the importance of many of the measurements that will be made at SuperB. In addition to these particle physics constraints, there are also ramifications for other fields of research such as astrophysics, in terms of searches for Dark Matter candidates, and ultimately cosmology in terms of understanding the evolution of matter and anti-matter in the early universe.

1.2. Expectations for physics beyond the Standard Model

The experimental community has been focusing on the search for evidence of the Higgs particle, which would be added to the Standard Model (SM) in order to make this more self-consistent. Having introduced the SM Higgs to the model, further corrections are required in order to cope with Higgs self coupling interactions. This motivates the search for a richer texture of NP beyond just identifying a SM Higgs candidate. If it turned out that the Higgs did not exist, then something else would have to be introduced into the model in order to address the issues that the Higgs particle was originally postulated for. There is a wide range of scenarios of physics beyond the SM that have been postulated. Many of these scenarios are derived from some higher theory such as M-Theory or subsets such as SUSY, others introduce a variety of different concepts, for example extra spatial dimensions, additional generations of fermions, and additional Higgs particles. These models of new physics are obtained by adding new terms to the SM Lagrangian, and then using existing constraints from experiments to evaluate if such an addition is consistent with nature or not. Some of the most stringent constraints that have guided theorists in the construction of the SM are so-called flavour changing neutral currents (FCNC), and in many cases such constraints are being used to guide the development of theories beyond the SM.

The criteria required to probe the high energy regime are to identify suppressed processes within the SM that are theoretically clean that may have contributions from new heavy particles, and then to perform precision measurements of those processes. Interpretation of the results, in comparison with both SM expectations, and those of the NP scenario can be used to constrain the parameter space of the NP model. One of the parameters that enters into this process is the energy scale for the new physics $\Lambda_{NP}$ (e.g. the particle mass in the case of the charm and top quarks discussed previously). Thus just as flavour changing processes have provided stringent constraints for theorists in understanding and constructing the SM, any theory of physics that goes beyond the scope of the SM will also be strongly constrained by measurements of flavour changing transitions. Hence model builders will be able to partially reconstruct the new physics Lagrangian using the results of Super$B$ and other flavour experiments. In particular if
there are mixing matrices between sets of new particles introduced into the theory, then in general the off-diagonal complex elements may be constrained by rare decays probed in flavour physics experiments.

1.3. The outline of this review

The remainder of this review paper provides a description of the experimental facility (Section 2), followed by a pedagogical overview of the physics potential of SuperB. The following sections discuss the roles of $\tau$ physics in terms of searches for forbidden processes that violate well known symmetries of nature, and tests of the SM (Section 3), the decays of $B_{u,d,s}$ (Section 4), $D$ mesons (Section 5), and precision tests of electroweak physics which are discussed in Section 6. Spectroscopy measurements in terms of direct searches of unknown particles related to new physics (Section 7) is also reviewed. Section 8 briefly mentions some of the other measurements that can be made at Super Flavour Factories. Estimated improvements in the field of Lattice QCD and subsequent impact on the SuperB physics programme are discussed in Ref. [1]. Thus far the LHC experiments have not found evidence for the SM Higgs or any physics beyond the SM. The exclusions obtained using the first few years of data taking suggest that flavour observables can, and will, play an important role in elucidating nature in the coming years. It is important to globally combine information from all possible measurements together in order to optimally decode the signatures of physics beyond the SM. Section 9 reviews the measurements to be made at SuperB in such a global context, highlighting inter-relations between different sets of measurements as a tool to elucidate generic behavior of new physics and of the SM.

2. The SuperB experimental facility

The most up to date detailed review of the SuperB experimental programme is available in the form of a set of progress reports discussing the accelerator [10], detector [11], and physics [1, 12]. Older descriptions of the project can be found in Refs. [13, 14]. The SuperB collaboration is also in the process of preparing a set of Technical Design Reports that will supersede these reports and serve as blue prints for the construction of the experiment. This section provides a brief summary of the aspects of SuperB accelerator and detector as detailed in the aforementioned reports. SuperB will be constructed at the Cabibbo Laboratory, Tor Vergata University near Rome, Italy. First collisions could be as early as 2016, with the first year of nominal data taking starting the following year. After five years of nominal data taking this experiment should have integrated 75 ab$^{-1}$ of data at the $\Upsilon(4S)$, which is 150 times that of $\text{Bab\text{a}r}$, and 75 times that of Belle. On a similar time-scale (early next decade) the competing experiment Belle II will have accumulated 50 ab$^{-1}$ of data.

By the time SuperB starts taking data, the LHCb experiment will have finished much of its physics programme. Any discoveries of new physics from LHCb, or indeed
possible inconsistencies of measurement and SM expectations will be of direct interest to
the SuperB physics programme. This is the case as, aside from FCNC and annihilation
topologies, the difference between $B_{u,d}$ decays and $B_s$ decays is the choice of the light
spectator quark, which does not drive the physics content of a particular decay. Any
FCNC or annihilation topologies that do manifest signs of a deviation from the SM in
$B_s$ decays also have parallels for $B_{u,d}$ decays, although the relative new physics couplings
may in general be different from the $B_s$ case. While hadron collider experiments have
the advantage of vast statistics over experiments at $e^+e^-$ machines, there is a price paid
in terms of triggering systems, backgrounds, and poor neutral reconstruction. Typically
rare charged hadronic final states will be measured well in hadron machines, and hence
good theoretical control of hadronic uncertainties may be required to interpret such
results. Whereas experiments at $e^+e^-$ will excel in final states containing neutrals,
and in particular $\nu'$s that would otherwise be challenging or impossible to study in a
hadronic environment. Final states of this type are generally theoretically much cleaner
that the hadronic ones best accessed in a hadron machine. Many of these latter decays
are vital ingredients for constraining possible sources of NP. A proposal for a potential
upgrade of LHCb is in preparation, and such an experiment could finish taking data as
early as 2030 [15], a number of years after SuperB and Belle II are expected to have
finished accumulating their nominal data sets.

2.1. The accelerator

The SuperB accelerator is designed to collide bunches of electrons and positrons at center
of mass energies between 3.37 GeV and 11 GeV, such that the center of mass system is
boosted in the reference frame of the laboratory. The reason for having a boosted center
of mass frame is in order to facilitate the study of time-dependent $CP$ violation in $B$
and $D$ decays, and this naturally results in a forward-backward asymmetry in the design
of the detector. This requirement has a consequence that asymmetric beam energies
are needed, with a boost factor of the centre of mass relative to the lab $\beta\gamma = 0.23$
in the $\Upsilon(4S)$. While the baseline design for the machine also has a low boost factor for
operation at the $\psi(3770)$, it may be possible to take data at this energy with a with a
boost factor $\beta\gamma$ as large as 0.91. If that were realisable, then this would open up the
possibility of performing a number of quantum correlated time-dependent studies with
charm decays as discussed in Section 5.

The instantaneous luminosity of the accelerator at the $\Upsilon(4S)$ [$\psi(3770)$] will be
$10^{36}[10^{35}]cm^{-2}s^{-1}$, with bunch currents of a few amps in both the low and high energy
rings (LER and HER). This is an increase of two orders of magnitude in luminosity
compared to the operating conditions at PEP II, with similar beam currents in both
rings. The luminosity in a circular collider is given by

$$\mathcal{L} = \frac{N^+N^-f_c}{4\pi\sigma_y\sqrt{\sigma_z\tan(\theta/2)^2 + \sigma_z^2}}$$

(3)

where $N^\pm$ are the number of electrons ($-$) and positrons ($+$) in a bunch, $\sigma_i$ is the
beam size in dimension \(i = x, y, z\) where \(\sigma_{x,y} = \sqrt{\beta_{x,y}^* \epsilon_{x,y}}\). Here \(\beta_{x,y}^*\) is the beta function and \(\epsilon_i\) is the emittance at the interaction point (IP). The angle \(\theta\) is the crossing angle of the two beams, so the \(\sigma_z\) contribution vanishes for beams colliding head on, and the parameter \(f_c\) is the frequency of collision of each bunch. There are two potential routes to increasing the luminosity of a circular collider (i) increase the number of electrons (which is related to the power required to run the machine), or (ii) decrease the transverse size of the bunches in the beam, i.e. decrease the emittance. The main driving force to increasing the luminosity of the SuperB accelerator relative to PEP II is to significantly reduce the emittance of the beam, and as a result to make the bunch sizes smaller than the previous generation of \(e^+e^-\) colliders. There is a second important improvement in the accelerator design related to the interaction region: In order to bring bunches of electrons and positrons into collision, one has to either have a complicated array of magnets to align an incoming \(e^-\) bunch so that it collides head on with a \(e^+\) bunch, or to have a small but finite crossing angle between the two beams. The former approach was adopted by the SLAC B Factory, and has the limitation that there would be a significant level of luminosity related beam backgrounds recorded in the SuperB detector that could obscure some of the rare signals under study if a similar approach was adopted for future machines. The traditional problem with the latter approach results from the fact that bunches of electrons and positrons are ellipsoidal in shape, and by bringing two bunches into collision at a finite angle, and the effective cross sectional area of the collision at the IP is reduced. It was realised by Pantaleo Raimondi that sextupole magnets positioned before and after the interaction region can be used to skew the transverse waists of incoming bunches with a finite crossing angle in such a way that they are pinched optimally at the point of collision. This collision scheme has been termed the ‘crabbed waist’ scheme, and it was successfully tested at LNF Frascati in 2009 (See [10] and references therein).

A unique feature of the machine is that the bunches of electrons will be polarised, which translates into significant benefits for the SuperB physics programme. The polarisation is designed to be \(\sim 80\%\). Two particular benefits of this feature are (i) this provides an additional kinematic variable in studying rare \(\tau\) decays and is useful for both \(\tau\) EDM and \(g - 2\) measurements, as one is able to reconstruct the polarisation of the \(\tau\) in the final state and use this as a background suppression tool, and (ii) one can perform precision electroweak tests of the SM, such as measuring \(\sin^2 \theta_W\) using left-right asymmetries in \(e^+e^- \rightarrow f \bar{f}\) transitions, where \(f\) is a fermion, in addition to being able to measure forward-backward asymmetries that would be accessible without a polarised beam. The asymmetry for the \(b\bar{b}\) final state can be measured as precisely as the SLC/LEP measurements at the \(Z\) pole, but at an energy that is free from hadronisation uncertainties. Details of the intended scheme to be used in order to obtain a polarised electron beam can be found in Ref. [10]. In order to use the polarisation information in precision measurements one needs to have a sub \(1\%\) measurement of the value of the polarisation, which is achievable using a Compton polarimeter.

A number of parameter sets have been developed for use at SuperB for both
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operation at a center of mass energy corresponding to the $\Upsilon(4S)$, and to operate at the $\psi(3770)$. In addition to being able to operate the machine at these two resonances, it will be possible to scan the machine from the $\Upsilon(1S)$ to the $\Upsilon(6S)$ resonance. The physics programme for prolonged running at one of the other $\Upsilon$ resonances rests in direct searches for light dark matter and Higgs particles, tests of lepton flavour universality, and the study of $B_s$ mesons in the case of the $\Upsilon(5S)$. Table 1 shows some of the parameters for the different configurations of the accelerator. All of the three $\Upsilon(4S)$ configurations are able to reach the desired luminosity of $10^{36} \text{cm}^{-2}\text{s}^{-1}$, and while the collection of machine parameters may look difficult to achieve, each of these has been demonstrated at an operating machine somewhere in the world. The challenge on the accelerator side is to construct a machine that can simultaneously achieve all of these. The $\psi(3770)$ configuration should reach an instantaneous luminosity of $10^{35} \text{cm}^{-2}\text{s}^{-1}$. All other resonances of interest near the $\Upsilon(4S)$ and $\psi(3770)$ energies can be reached by tuning the machine lattice from one of the two optimal working points. A more detailed description of the SuperB accelerator can be found in Ref. [10].

**Table 1.** Machine parameters for different configurations of the accelerator. There are three configurations for operating at the $\Upsilon(4S)$, and one for the $\psi(3770)$.

| Parameter                          | Nominal | Low emittance | High Current | $\psi(3770)$ |
|------------------------------------|---------|---------------|--------------|-------------|
| $e^- / \text{LER energy (GeV)}$    | 4.18    | 4.18          | 4.18         | 1.61        |
| $e^+ / \text{HER energy (GeV)}$    | 6.7     | 6.7           | 6.7          | 2.58        |
| $\epsilon_y (\text{HER}) (\text{pm})$ | 5.0     | 2.5           | 10           | 13          |
| $\epsilon_x (\text{HER}) (\text{nm})$ | 2.0     | 1.0           | 2.0          | 5.2         |
| $\epsilon_y (\text{LER}) (\text{pm})$ | 6.15    | 3.08          | 12.3         | 16          |
| $\epsilon_x (\text{LER}) (\text{nm})$ | 2.46    | 1.23          | 2.46         | 6.4         |
| $\sigma_y (\text{HER}) (\mu m)$   | 0.036   | 0.021         | 0.054        | 0.092       |
| $\sigma_x \text{effective (HER)} (\mu m)$ | 165.22  | 165.22        | 145.60       | 166.67      |
| $\sigma_y (\text{LER}) (\mu m)$   | 0.036   | 0.021         | 0.0254       | 0.092       |
| $\sigma_x \text{effective (LER)} (\mu m)$ | 165.30  | 165.30        | 145.78       | 166.67      |
| Total Power (MW)                   | 16.38   | 12.37         | 28.83        | 2.81        |
| $e^- \text{Polarisation (\%)}$    | 80.0    | 80.0          | 80.0         | —           |
| $\mathcal{L} (\text{cm}^{-2}\text{s}^{-1})$    | $10^{36}$ | $10^{36}$   | $10^{36}$    | $10^{35}$   |

While the primary goal of SuperB is the pursuit of knowledge that will hopefully elucidate our understanding of physics beyond the SM, it has also been realised that the small emittance of the SuperB machine means that this facility will be an extremely bright synchrotron light source. In fact this machine will be thirty times brighter than the Diamond facility at RAL, UK and the ESRF facility at Grenoble, France. While this is an interesting subject in itself, it is not the focus of this review, and will not be discussed further here.
2.2. The detector

Working from the inner to outermost components, the SuperB detector consists of a Silicon Vertex Tracker (SVT) surrounded by a Drift Chamber (DCH), both of which are used to detect the passage of charged particles through the detector. The Particle Identification (PID) system is comprised of a next generation Detector of Internally Reflected Cherenkov radiation (FDIRC) which surrounds the DCH. There is also a forward PID system under investigation to provide particle identification over a larger solid angle than that covered by the FDIRC. Surrounding the PID system is an Electromagnetic Calorimeter (EMC) which is used primarily to provide measurements of photon and electron energies. All of the aforementioned components will be situated in a super-conducting solenoid magnet capable of producing a solenoidal magnetic field of 1.5T. This is the same solenoid magnet that was used for the BaBar experiment. The field strength for charm threshold running may be lower than 1.5T, and studies are ongoing in order to determine the strength required for signal reconstruction versus background suppression. The outermost part of the detector is the so-called Instrumented Flux Return (IFR) which is used to identify muons and $K^0_L$ mesons. Figure 1, taken from Ref. [11], shows a schematic of the SuperB detector. The top half of the Figure illustrates the baseline detector design, while the bottom half shows various options such as forward PID system and backward calorimeter. The main components of the detector are described in more detail in the following (A more detailed discussion can be found in Ref. [11]).

Figure 1. A schematic of the SuperB detector concept.
**SVT**: The SuperB SVT consists of two types of detector. The first is a highly segmented device close to the beam pipe (referred to as Layer 0), and the second is a **Babar**-like multi-layer double sided silicon strip detector. There are several choices of technology for Layer 0, and the baseline choice for low luminosity operation of the machine (data taking during the first few years) is a double-sided silicon strip based detector with short strips at $45^\circ$ to the direction of the beam, with a stereo angle of $90^\circ$ between strips on both sides of the sensor. This iteration of Layer 0 will be at an average radius of 1.6 cm from the IP. There are several Monolithic Active Pixel Sensor and Hybrid Pixel Sensor technology options under investigation, all of which will be suitable for use in the high luminosity running that corresponds to nominal data taking. The amount of material in Layer 0 depends on the technology chosen, but is expected to be between 0.4 and 1.0% of a radiation length. The outer part of the SVT will consist of several layers of double sided strip sensors arranged in a configuration similar to the **Babar** SVT [16]. The use of the SVT is not anticipated in the trigger, and triggers formed using information from the DCH will be required in order to read out the SVT.

**DCH**: The SuperB drift chamber will be the primary sub-system for providing measurement information on tracks with momenta larger than $\sim 100 \text{ MeV}/c$. The DCH design for SuperB is similar to the **Babar** one, with 40 layers of cells, the cross-section of each cell being $1 \text{ cm}^2$. Studies are underway to determine the optimal gas mixture to use for the DCH, and the overall layout, with either spherical or stepped end plates. The choice of gas mixture will be driven by the desire to minimize the overall occupancy of the sub detector, estimated to be 3.5%. There is also an ongoing effort to understand if it is possible to benefit from the use of cluster counting in order to improve the $dE/dx$ resolution by a factor of two [17, 18]. No experiment has yet managed to utilize this technique, so the potential use of cluster counting is considered an interesting option for improving the DCH performance beyond an acceptable design level. The DCH will provide fast trigger information for events with charged tracks in the final state.

**PID**: A next generation Detector of Internally Reflected Cherenkov radiation (FDIRC) surrounds the DCH tracking volume, and is used to distinguish between different types of charged particle. The fused silica bars of the **Babar** DIRC will be re-used in SuperB, and combined with a segmented fused silica focusing block system read out by semiconductor sensors. This next generation DIRC will have superior particle identification performance and tolerance to backgrounds than the first generation **Babar** DIRC. The reason for replacing the water based focusing system with a fused silica one is to produce a radiation hard device that has a much smaller instrumented area than the **Babar** DIRC, in order to be able to cope with increased levels of backgrounds that are expected at SuperB. There is an option for a forward PID system, which is motivated by the desire to increase the angular coverage of the PID system and there are several technologies under study for a potential device. The additional material required to implement such a system would not significantly
The Physics of Heavy Flavours at SuperB degrade the performance of the calorimeter end-cap.

**EMC**: The primary purpose of the EMC is to measure the energy deposited by photons and electrons that have traversed the inner regions of the detector. There are two parts to the EMC, a barrel and an end-cap. SuperB will reuse the BaBar CsI(Tl) crystal calorimeter barrel as the crystals themselves are adequate for the rates, and fluence of particles expected at SuperB, however the readout electronics will be updated in order to operate at a suitable rate. The end-cap part of the calorimeter needs to be replaced with a faster and more highly segmented solution than that used for BaBar. The baseline choice of crystal in the SuperB end-cap calorimeter is Cerium doped Lutetium Yttrium Orthosilicate (LYSO) which provides a superior performance over all other materials currently available. Different options are being considered as alternate solutions, such as CsI, PbWO, BGO. All of these crystals have significant lower light yield than LYSO, but studies are ongoing to evaluate if they can provide acceptable operational performance. The amount of material in the barrel of the EMC is between 16.0 and 17.5 radiation lengths, and will be 17.5 radiation lengths for the end cap.

**IFR**: The purpose of the IFR is twofold; to detect and positively identify muons, and to detect $K_L$ mesons that would have passed through the inner part of the detector and typically interact in absorber material between the active layers of this sub-system. The baseline technology chosen for the high rate environment expected at SuperB is based on wavelength shifting scintillating fibres that are read out by avalanche pixel photo-diodes operating in Geiger mode. Studies are ongoing in order to determine the amount of iron required for optimal muon identification performance at SuperB. It was recognised that there was insufficient material used at BaBar to optimally detect muons, and it is intended that more material will be used in the SuperB IFR. The amount of material in the IFR will be about 5.5 radiation lengths.

**Trigger**: Unlike a hadron experiment, most of the interactions occurring at an $e^+e^-$ collider like SuperB are of interest. One would only want to record a small fraction of the Bhabha scattering events that occur, given the large cross-section for this process, relative to other events of interest. As a result there is a strong constraint on the trigger performance. The experiment must be able to trigger on as many interesting events as possible, in the first instance (Level 1), so that a subsequent software filtering system can be applied to events at the so-called Level 3 trigger stage. Currently there is no intention to introduce a Level 2 trigger in SuperB. Events that pass the Level 3 trigger are stored for full event reconstruction and offline analysis. A Level 4 trigger, a higher level software trigger used to make decisions to reduce the volume of data permanently stored, may be implemented if required. At this time however the intention is to implement an open trigger system that records almost all of the interesting physics events occurring in the detector. The present expectations of the trigger system are to have a Level 1 accept rate of
150kHz, with an event size of 75kb, and an anticipated dead time of less than 1%.

As with any modern particle physics experiment, SuperB will produce hundreds of petabytes of data during its lifetime, equivalent to an LHC experiment. Thus in order to be able to record and subsequently analyse data in an efficient way, this experiment is already using the latest GRID technology. There are two Monte Carlo simulation programmes available for SuperB. The first is based on GEANT4 [19], and the second is a third generation Fast Simulation (FastSim) with track fitting and other advanced capabilities [20]. A more detailed description of the SuperB detector can be found in Ref. [11]. Both of these simulations are used in order to compute the projected sensitivities discussed in the remainder of this document.

3. \( \tau \) physics

The Super Flavour Factories will record vast quantities of \( \tau \) lepton decays that can be used to probe our understanding of a number of areas. These include searches for charged Lepton Flavour Violation, otherwise referred to as LFV (Section 3.1), \( CP \) violation (Section 3.2), precision measurements of the electric dipole moment and \( g - 2 \) of the \( \tau \) (Section 3.3), as well as precision measurements of SM quantities such as \( V_{us} \) (Section 3.4). The polarised electron beam at SuperB provides a statistical advantage over experiments with unpolarised beams. With polarised electrons, one can reconstruct the \( \tau \) helicity distribution and thus use information on the polarised \( \tau \) final states to suppress backgrounds. This can be particularly relevant when searching for forbidden or rare processes, but is also useful for measurements of the electric dipole moment and \( g - 2 \).

3.1. Lepton Flavour Violation

Lepton flavour changing processes were traditionally forbidden in the SM, however since the discovery of neutrino oscillations, one has had to account for not only lepton number violation in the neutrino sector, but also the intrinsic possibility that charged lepton number should also be violated. If neutrino oscillations are the sole source of charged lepton number violation, then it is unlikely that any experiment would be able to reach the required sensitivities to probe such effects in the foreseeable future. Given that both quark and neutrino flavour numbers are already known to be violated at a small level, it is reasonable to assume that the corresponding scenario could also be true in the charged lepton sector. In fact many scenarios of physics beyond the SM allow for large enhancements of charged LFV, and as in the case of the neutrino sector affecting expectations in the charged lepton sector, many models of charged LFV are dependent also on the neutrino mixing parameters. In order to full determine the underlying nature of any NP affecting the lepton sector one will have to combine results from both \( \tau \) and \( \mu \) decay studies with results from the neutrino sector.
In terms of charged LFV, one needs to constrain all three sets of possible transitions between generations ($2 \rightarrow 1$, $3 \rightarrow 1$, and $3 \rightarrow 2$), in analogy with the programme of experiments studying neutrino oscillations currently underway. Tests of LFV transitions from the second to first generation can be performed by searching for the decay $\mu \rightarrow e\gamma$, or through searches for $\mu \rightarrow e$ conversion in the presence of nuclear material. The MEG experiment at the Paul Scherrer Institut (PSI) in Switzerland is searching for $\mu \rightarrow e\gamma$ transitions [21], and the most precise constraint on $\mu \rightarrow e$ conversion comes from the Sindrum II experiment [22], which was also based at PSI. Two new $\mu \rightarrow e$ conversion experiments, COMET and PRISM, are being planned. Searches for charged LFV using $\tau$ decays focus on transitions from the third to the first and second generations of charged leptons. There are a number of different models of NP that generally predict which set of measurements will provide the most stringent constraints on charged LFV. While these models are a useful guide to follow, one should remember that historically in the neutrino sector, oscillation results have often been contrary to the most popular scenarios initially proposed, and secondly it is not simply good enough to observe LFV in one physical process. In order to understand the structure of NP in a detailed way, one needs to over constrain couplings related to LFV transitions, and hence to study the full set of possible lepton flavor transitions. SuperB is able to contribute to this area by searching for charged LFV in the decay of $\tau$ leptons. The combination of results from Super Flavour Factories with those from MEG and future $\mu \rightarrow e$ conversion experiments, will provide a powerful set of constraints on the sets of charged LFV transitions.

In the SM, neglecting the tiny contribution from neutrino mixing, the decay of a $\tau$ lepton necessarily results in at least one neutrino in the final state via the decay of a $\tau$ into a virtual $W$ boson and a $\nu_\tau$. The virtual $W$ boson subsequently decays into either a hadronic state or a lepton-neutrino pair. A Lepton Flavour Violating (LFV) decay involves the direct transition of the initial $\tau$ to a final state devoid of a neutrino. The two most important examples of LFV decays to be studied at SuperB are

\begin{align*}
\tau^\pm &\rightarrow \ell^\pm \gamma, \\
\tau^\pm &\rightarrow \ell^\pm \ell^+ \ell^-, 
\end{align*}

where $\ell = e, \mu$. As neutrinos are known to change flavour, it is possible for a $\tau$ to decay into one of the above final states, without emitting a neutrino. However the SM expectations for such a LFV branching fraction is well beyond current experimental reach, for example the branching fraction for $\tau \rightarrow \mu \gamma$ or $\mu \rightarrow e\gamma < 10^{-40}$ [23], where current knowledge of neutrino mixing places this limit closer to $\sim 10^{-54}$. In many popular scenarios of new physics these LFV branching fractions can be enhanced to the level of $10^{-9}$ [24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38], for example by introduction loop contributions containing sparticles, where experimental bounds limit the parameter space of the models.

The $\ell\gamma$ and $3\ell$ decays are golden channels for SuperB and the experimental reach for these modes is given in Table 2 where the results from $\text{BABAR}$ and Belle come from Refs. [39, 40, 41, 42]. In $75 \text{ ab}^{-1}$ of data collected at the $\Upsilon(4S)$ SuperB expects to record
70 \times 10^9 \tau \text{ leptons pairs. A further } \sim 1.2 \times 10^9 \tau \text{ pairs should be accumulated during the 500 fb}^{-1} \text{ run at charm threshold. As one can see, the experimental sensitivity of these golden modes will be able to constrain NP models between one and two orders of magnitude better than current bounds, and interpretation of limits from data in the context of such models is discussed in Section 3.1.1. The expected limits achievable by Belle II are slightly worse than those indicated for SuperB for two reasons, firstly Belle II will accumulate slightly less data than SuperB, and secondly the electron beam will be longitudinally polarised in SuperB, introducing an additional kinematic variable: the polarisation of the \tau. The utilisation of this information when analysing data will provide SuperB with an additional variable to suppress background relative to the signal that is not available at other proposed or existing experiments.

It should also be noted that the relative difference between the existing \(B\) factory limits for \(\ell\gamma\) and \(3\ell\), and expectations for SuperB are similar for many other LFV \(\tau\) decay measurements that SuperB will be able to perform.

| Mode               | \(B\) (\times 10^{-8}) | Belle (\times 10^{-8}) | SuperB (\times 10^{-8}) |
|--------------------|-------------------------|-------------------------|-------------------------|
| \(\tau^\pm \rightarrow e^\pm\gamma\) | 3.3                     | 12                      | 0.3                     |
| \(\tau^\pm \rightarrow \mu^\pm\gamma\) | 4.4                     | 4.5                     | 0.2                     |
| \(\tau^\pm \rightarrow \mu^\pm\mu^+\mu^-\) | 3.3                     | 2.1                     | 0.08                    |
| \(\tau^\pm \rightarrow e^+e^-\) | 2.9                     | 2.7                     | 0.02                    |

The LHCb experiment may ultimately be able to reach a similar sensitivity to the current limits from \(B\) and Belle in the \(\tau \rightarrow 3\mu\) channel, but will not be competitive with other channels. There is also a possible upgrade to LHCb that is under consideration [15], however it is clear that even in the best case scenario any LHCb upgrade will be an order of magnitude less sensitive than the searches from the Super Flavour Factories, based on the results presented in [43]. The relatively poor performance from LHCb is a direct result of the hadronic environment at LHC, where there are no primary vertex constraints available to kinematically separate signal from background as cleanly as one can at a Super Flavour Factory.

### 3.1.1. New physics scenarios and LFV

Any evidence found at existing or planned experiments for charged LFV would be a clear sign of physics beyond the SM, which in itself would be a significant milestone in particle physics. However one can go beyond this binary test and try to elucidate the dynamics of possible new physics scenarios, both in the presence and absence of a signal. Given that the interpretation of LFV is highly model dependent, one needs to identify realistic benchmark models to test using data, and a number of observables that can be used to distinguish between the benchmarks. A lot of work has been
done in this area, which include CMSSM and NUHM SUSY as specific variants of a more generalised SUSY model, as well as little Higgs models (LTH) and SUSY GUT models. By piecing together different experimental observations one can distinguish between different types of model. For example the channel $\tau^{\pm} \rightarrow \ell^{\pm}\gamma$ can be significantly enhanced in SUSY based models relative to $\ell^{\pm}\ell^{\mp}\ell^{\pm}$, whereas $\tau^{\pm} \rightarrow \ell^{\pm}\ell^{\mp}\ell^{\pm}$ can have a corresponding enhancement in LTH models relative to $\ell^{\pm}\gamma$. Hence a measurement of the ratio of the rates of these two channels could be used to distinguish between these sets of models. A recent analysis of the correlation between the $\mu\gamma$ and $3\mu$ branching fractions (shown in Figure 2) for Little Higgs models with T parity can be found in Ref. [44]. SuperB will be able to exclude all but the bottom left quadrant of the phase space shown in the Figure.

![Figure 2](image)

**Figure 2.** The branching fraction for $\tau \rightarrow \mu\gamma$ vs. $\tau \rightarrow 3\mu$ in Little Higgs model with T parity, shown with the expected sensitivity reach from SuperB (solid lines), from Ref. [44].

Two examples of how results from SuperB and other experiments can be combined are given in the following. If one considers the $SU(5) \times T'$ model of Ref. [45], there is a definite prediction that lepton flavour violation in the MSW sector arises from charged leptons and that $\nu$'s only mix. Other models can be built where this is not the case. This model also has well defined predictions for CP violation in $B$ and $D$ decays. Hence it is important to make as complete a set of measurements as possible in the charged lepton and quark sectors, and consider the relationship between such measurements and the $\nu$ sector to verify or refute this prediction. Similarly in the model of Antusch et al. [30], the rates of $\tau^{\pm} \rightarrow \ell^{\pm}\gamma$, $\mu \rightarrow e\gamma$, and the neutrino mixing parameter $\sin \theta_{13}$ are correlated, once again highlighting the need for a global approach to interpreting results. The recent $\nu_e$ appearance result from the T2K experiment [46] is an important step forward in neutrino physics, and future updates of that result will be of interest when considering possible new physics scenarios in the context of charged lepton flavour.
violation. If $\theta_{13}$ turns out to be large as currently suggested by data, then according to this model SuperB should not see $\tau \rightarrow \mu \gamma$. The corollary of this is that if one were to observe a large signal for this channel, then this model would be ruled out.

3.2. CP violation

In the SM $\tau$ decays proceed via a single amplitude, and hence there is no $CP$ violation. The exceptions to this rule are decays to final states including kaons, where the well known level of $CP$ violation in kaon decay may be manifest when reconstructing the final state. Any significant deviation found in a measurement of a $CP$ asymmetry in the decay of a $\tau$ lepton would be an unequivocal sign of NP. Models of NP that can naturally manifest $CP$ violation in $\tau$ decays include multi-Higgs models [47], which could modify the angular distributions of decaying $\tau$ leptons relative to SM expectations. This area has been largely unexplored, and so far results are only available for $\tau^\pm \rightarrow K^0_s \pi^\pm \nu$ decays [48, 49], where the SM expectation of the $CP$ asymmetry is $(0.33 \pm 0.01)\%$ [50]. The $\BaB$ result is $(-0.45 \pm 0.24 \pm 0.11)\%$, and Belle report results as a function of the $K^0_s \pi$ mass that are compatible with zero.

The extraction of $CP$ asymmetry parameters is complicated by having to understand matter-antimatter effects in the detector. The reason for this is that both matter and antimatter have slightly different cross sections for interaction within the detector, which is constructed entirely of matter. A detailed understanding of this difference is straightforward and can be modeled in simulation. Another way to understand the magnitude of such a matter-antimatter asymmetry effect is to use a calibration sample of data. The advantage of this is that one can remove reliance of these important measurements on any simulation, and this route has been taken with existing searches for $CP$ violation. It will be possible for SuperB to significantly improve upon the precision of $CP$ violation searches in $\tau$ decays. In the case of the $\tau^\pm \rightarrow K^0_s \pi^\pm \nu$ decay, where there is an intrinsic $CP$ asymmetry resulting from kaons in the final state, SuperB should be able to reduce current upper limits to the level where this SM background effect becomes measurable. One can use the channel $\tau^\pm \rightarrow \pi^+ \pi^- \pi^\pm \nu$ in a region where the signal $K^0_s$ has been vetoed to control systematic uncertainties arising from any detector asymmetry for the $K^0_s \pi^\pm \nu$ channel. Indeed the existing experiments are approaching that sensitivity now, and the $\BaB$ result of almost $3\sigma$ deviation from the SM motivates higher statistics searches. The ultimate precision achievable for $CP$ asymmetry measurements in $\tau$ decays needs to be evaluated, both in terms of integrated rate measurements and in terms of angular distributions.

3.3. Electric dipole moment and $g - 2$ of the $\tau$ lepton

The electric dipole moments (EDMs) of charged leptons $d_\ell$ are sensitive to different models of new physics including MSSM, generic SUSY, and multi-Higgs extensions of the SM. As is the case with lepton flavor violation measurements it is necessary to measure all three of the EDMs in order to understand which model or underlying mechanism
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may be at play in physics beyond the SM. For example the different values of \(d_\ell\) scale with lepton mass in the case of MSSM, where any new CP phases are independent of flavour \([35]\), whereas more general models of SUSY could produce large effects for the \(d_\tau\), and small effects for both \(d_e\) and \(d_\mu\) \([51]\). The values of \(d_\ell\) in multi-Higgs models scale as \(m_\ell^3\) \([52]\).

One can measure the \(\tau\) EDM using an angular asymmetry in \(e^+e^- \rightarrow \tau^+\tau^-\) transitions. The current limit on the \(|\tau|\) EDM is \(\leq 5 \times 10^{-17}\)\,e\,cm and comes from the Belle Collaboration \([53]\), using a data sample of 29.5 fb\(^{-1}\). The anticipated reach for SuperB using 75 ab\(^{-1}\) of data is \(d_\tau \leq 17 - 34 \times 10^{-20}\)\,e\,cm without a polarised electron beam. One can improve the sensitivity by almost a factor of two beyond this with 80% electron beam polarisation.

The anomalous magnetic moment measured for the muon is not in good agreement with the SM. The difference between the SM and experimental measurement is \(\Delta a_\mu = a_\mu^{\text{expt}} - a_\mu^{\text{SM}} = (3 \pm 1) \times 10^{-9}\). A measurement of the anomalous magnetic moment for the \(\tau\) would enable us to understand if \(\Delta a_\mu\) is the result of NP, or simply a statistical fluctuation in data. In NP scenarios one expects \(\Delta a_{\mu,\tau}\) to scale with the lepton mass squared, and so one would anticipate \(\Delta a_\tau \sim 10^{-6}\) if the muon signal was an indication of NP. In fact \(\Delta a_\tau\) can be as large as \(10^{-5}\) in some NP scenarios. With a polarised electron beam at SuperB one will be able to measure \(\Delta a_\mu\) to a statistical precision of \(2.4 \times 10^{-6}\) from \(e^+e^- \rightarrow \tau^+\tau^-\) transitions \([1]\).

3.4. Measurement of \(|V_{us}|\)

Up until recently knowledge of \(|V_{us}|\) has been dominated by results from studies of kaon decays. This approach is limited by theoretical uncertainty, and \(|V_{us}|\) has been measured to \(\sim 0.8\%\) \([8]\), where the experimental contribution is \(\sim 0.2\%\). The opposite scenario is encountered in \(\tau\) decays, where the theoretical uncertainty is relatively small, and the experimental uncertainty dominates \([54]\). It will be possible to produce a more precise constraint on this SM parameter using \(\tau^\pm \rightarrow K^\pm \nu\) decays at SuperB and the potential for this is currently under study. The current determination of \(|V_{us}|\) from kaon and \(\tau\) decays is \([8, 54]\)

\[
V_{us}(K) = 0.2255 \pm 0.0004(\text{expt.}) \pm 0.0019(\text{th.}),
\]

\[
V_{us}(\tau) = 0.2165 \pm 0.0026(\text{expt.}) \pm 0.0005(\text{th.}).
\]

A precision measurement of \(|V_{us}|\) feeds into testing a unitarity constraint on the CKM mechanism. In fact this element also plays a role in the charm \(cu\) triangle, that has yet to be tested directly (see Section 5). While \(|V_{us}|\) is not the limiting constraint on this test of CKM unitarity, it is apparent that an improved precision on this quantity will be desirable on the time scale of the Super Flavour Factories.
4. B physics

B physics at SuperB is divided into the study of the decays of $B^0_u$ and $B^+_u$ mesons produced via $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, and the study of $B^0_d$, $B^{+}_d$ and $B^0_s$ mesons as well as excited states via $e^+e^- \rightarrow \Upsilon(5S) \rightarrow B^{(*)}\bar{B}^{(*)}$. Selected highlights of $\Upsilon(4S)$ and $\Upsilon(5S)$ programmes are discussed in Sections 4.1 and 4.2 respectively.

4.1. $B$ physics at the $\Upsilon(4S)$

One might feel justified in asking, why bother with a second generation Super Flavour Factory programme of $B$ physics given the successes of $BaBar$ and Belle, and the potential of the CERN based LHCb experiment. It is true that the CKM mechanism has been verified at the 10\% level, resulting the Kobayashi and Maskawa being awarded the Nobel Prize for physics in 2008 for their innovative work on a three generation quark mixing matrix to introduce $CP$ violation into the SM. However one should not overlook the fact that new possibilities present themselves with one hundred times more data than existing experiments. Super$B$ will accumulate $75 \times 10^9$ neutral and charged $B$ mesons in a data sample of $75 \text{ab}^{-1}$, compared with $0.4 - 1.0 \times 10^9$ accumulated by $BaBar$ and Belle. With this increase in data it will be possible to perform a % level test of the CKM mechanism, and substantially improve a number of constraints on NP. The LHCb experiment will make a number of important measurements in the coming years, however as previously mentioned there are complementary advantages (and disadvantages) for experiments operating in $e^+e^-$ environments versus hadronic ones that mean LHCb is complementary to Super$B$, as opposed to a natural competitor. The true strength of these two experimental programmes comes when one combines the total set of observables that they will be able to measure. Here we concentrate on the contributions that Super$B$ will make to understanding new physics. One should also note that there are a number of issues that have recently been raised with regard to existing measurements of $B$ decays that need to be explored in greater detail, as these may already be indications of problems with the SM:

\textbf{sin}2$\beta$: The measured value of this quantity from $B$ meson decays to final states including a neutral kaon and charmonium ($\psi\bar{\psi}$) is $3.2\sigma$ from the SM preferred value as highlighted in Ref. \cite{55}.

$|V_{ub}|$ and $|V_{cb}|$: There are disagreements between inclusive and exclusive results for $|V_{ub}|$ and $|V_{cb}|$. These are only resolvable with a more thorough analysis provided by increased data samples, and improvements in theoretical understanding.

\textbf{CPT}: The CPT asymmetry measurement as a function of sidereal time made by $BaBar$ is $2.8\sigma$ from SM expectations and could indicate NP \cite{56}.

\textbf{ASL}: Semi-leptonic asymmetry measurement made recently by the D0 experiment is $3.9\sigma$ from SM expectations \cite{57}.

$B_s \rightarrow \mu^+\mu^-$: The Tevatron reports an excess of $B_s \rightarrow \mu^+\mu^-$ well above the expected SM branching fraction \cite{58}, however data from CMS and LHCb presented at EPS
2011 [39] suggest that the Tevatron data is probably the result of a background fluctuation.

**New physics energy scale:** $\Lambda_{NP}$ is widely believed to be $\sim 1$TeV, in order to resolve the so-called hierarchy problem. This is a regime that is currently being probed by the LHC. Flavour observables indicate that $\Lambda_{NP}$ may be significantly higher than the TeV scale, where the scale indicated is model dependent. Recent results from the LHC are placing considerable constraints on the NP parameter space, and it is looking increasingly likely that any new physics discovery may not be just around the corner as was once believed to be the case. If this is indeed the case, then one needs to either (i) build an energy upgrade to the LHC, (ii) a sufficiently high energy $e^+e^-$ linear collider, or (iii) use indirect constraints to constrain new physics. Neither of the first two options will be easy or quick to achieve. The third option is based on the role Belle II, SuperB, and other flavour physics experiments can play in placing model dependent constraints on high energy physics. However, if NP is discovered at the LHC, a similar indirect methodology can probe the mixing couplings of particles related to the NP sector. More details of this route can be found in Refs. [1, 60].

These discrepancies may ultimately turn out to be statistical fluctuations, or in some cases the result of some mis-understanding in the SM description of the observable, however it is clear that there are a number of unresolved issues in $B$ physics that need to be pursued, and some of these can only be addressed using experiments at an $e^+e^-$ collider.

The $B_{u,d}$ physics programme at SuperB is large, and for brevity, the following discussion is confined to the study of rare $B$ decays (Section 4.1.1), precision angle and sides measurements (Section 4.1.2) of the $bd$ unitarity triangle. The forthcoming Physics of the B Factories book currently in preparation [61] will describe many of the additional measurements of interest.

4.1.1. Rare $B$ decays

There are a number of rare $B$ decays of interest at SuperB. Most of the interesting final states contain neutral particles such as photons that are best studied in an $e^+e^-$ environment and final states with neutrinos, which can only be studied in an $e^+e^-$ environment. Only a selection of these decays are discussed in the following: $B \to K^{(*)}\nu\bar{\nu}, B \to \ell\nu, b \to s\ell\ell$, and $b \to (s,d)\gamma$ (where $\ell = e, \mu, \tau$) and more information can be found in Ref [1].

$B \to K^{(*)}\nu\bar{\nu}$: Decays to final states with $\nu\bar{\nu}$ allow one to study $Z$ penguin transitions. In the SM the $K^* (K^+)$ channel has a branching fraction of $6.8 \times 10^{-6} (3.6 \times 10^{-6})$ [62, 63]. The cleanest theoretical observables are the inclusive branching fraction measurement $B \to X_s\nu\bar{\nu}$ and the fraction of longitudinally $f_L$ polarised events in $B \to K^*\nu\bar{\nu}$ decays, however the former is a challenging measurement, while measurement of the latter first requires one to observe the decay mode. The branching
fractions and $f_L$ in the $B \to K^*\nu\bar{\nu}$ mode are sensitive to NP. Large effects could result from models with right handed currents, $Z'$ bosons, and models with light scalar particles \cite{64, 65, 66, 67, 68}. In contrast, only small effects are found in models of minimal flavor violation such as MSSM \cite{62, 69}. These decays can be parameterised in terms of left and right handed Wilson coefficients, $C_{\nu L}^\nu$, via $\epsilon$ and $\eta$, where

$$\epsilon = \sqrt{|C_{\nu L}^\nu|^2 + |C_{\nu R}^\nu|^2} \quad \text{and} \quad \eta = -\frac{\text{Re}(C_{\nu L}^\nu C_{\nu R}^\nu)}{|C_{\nu L}^\nu|^2 + |C_{\nu R}^\nu|^2}. \quad (7)$$

The branching fractions and $f_L$, relative to their SM expectations, can be parameterised in terms of $\epsilon$ and $\eta$, where $(\epsilon, \eta)_{\text{SM}} = (1, 0)$.

With 75 ab$^{-1}$ of data at SuperB one should be able to make measurements of the branching fractions of the exclusive modes at the 16-20% level. Figure 3 shows the constraint expected on the $(\epsilon, \eta)$ plane using exclusive branching fraction and $f_L$ measurements at SuperB. In order to achieve this level of precision one has to have a good hermiticity of the detector, to limit the level of background. Given that only a rudimentary measurement of $f_L$ will have been made with this data sample, one could envisage the desire to perform a high precision study of these decays with data samples of hundreds of ab$^{-1}$ in the longer term. Such a measurement would greatly improve the constraint on $\eta$.

**Figure 3.** The constraint on $\epsilon$ and $\eta$ expected using exclusive branching fraction and $f_L$ measurements made with data sample of 75 ab$^{-1}$ at SuperB (from Ref. \cite{12}). The central two contours represent the 68% and 95% confidence level (C.L.) constraint obtained at SuperB, while the light (green) contour indicates the existing constraint obtained using limits on the $B \to K^{(*)}\nu\bar{\nu}$ modes.

**$B \to \ell\nu$:** In the SM the branching ratio of the set of leptonic decay modes $b \to \ell\nu$ is related to $|V_{ub}|$, and can be computed using Lattice input on the parameter $f_B$. Hence this channel can be combined with other determinations of CKM parameters in order to test the SM. If one considers NP scenarios with Higgs multiplets, then one can replace
the $W$ boson in the SM amplitude for this decay with a charged Higgs particle. The modification to the expected rate for this decay depends on both the charged Higgs mass $m_{H^+}$, and on the ratio of Higgs vacuum expectation values, $\tan \beta$. In this scenario it is possible to use a branching fraction measurement to indirectly constrain the $m_{H^+} - \tan \beta$ plane. For a two Higgs doublet model (2HDM) the branching fraction can be modified by a scale factor $r_H$ relative to the SM rate, where \cite{70}

$$r_H = \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta\right).$$

(8)

The corresponding constraint on the $m_{H^+} - \tan \beta$ plane resulting from measurements of $b \rightarrow \ell \nu$ decays expected from SuperB is shown in Fig. 4 (taken from Ref. \cite{12}). The expectations of direct searches using 14TeV collision data at the LHC is also shown on this plot for the ATLAS experiment \cite{71}. While there is a region at low values of $\tan \beta$ that will not be excluded using $b \rightarrow \ell \nu$ decays, one should remember that existing constraints from measurements of the $CP$ asymmetry in $b \rightarrow s\gamma$ events already excludes charged Higgs particles with masses less than 295 GeV$/c^2$. More recently LHC direct searches have increasingly ruled out the low $\tan \beta$ scenario. It is worth noting that the constraints will be dominated by $B \rightarrow \tau \nu$ at low luminosity, however at some point the branching fraction measurement of that mode will become systematically limited. As a result the high luminosity constraints will be dominated by the contribution from $B \rightarrow \mu \nu$.

![Figure 4](image_url)

**Figure 4.** The constraint on the $m_{H^+} - \tan \beta$ plane from $b \rightarrow \ell \nu$ branching fraction measurements at SuperB, compared with the expectations of direct searches at the LHC. The shaded region will be excluded by $b \rightarrow \ell \nu$ decays. Measurements from $b \rightarrow s\gamma$ already exclude values of $m_{H^+} < 295$ GeV$/c^2$.

If one considers more complicated extensions, such as SUSY variants, then the bounds on the $m_{H^+} - \tan \beta$ plane do change, as does the functional dependence of $r_H$ on $m_{H^+}$ and $\tan \beta$. However the correction arising from the addition of SUSY particles...
does not alter the conclusion drawn that the indirect constraints on searches for charged Higgs particles from $b \rightarrow \ell \nu$ can exclude a larger parameter space than direct searches from the LHC. While it is possible to use measurements of rare kaon decays in a similar way, additional model dependence has to be introduced in order to interpret kaon bounds on $m_{H^\pm}$ and $\tan \beta$, hence the $b \rightarrow \ell \nu$ bounds are both more general and more rigorous than the kaon ones.

$b \rightarrow s \ell \ell$: Existing measurements from BABAR and Belle on the forward backward asymmetry in these decays, while consistent with the SM, are more compatible with possible NP scenarios. The NP phenomenology that is possible with these decays is extremely rich, and beyond the scope of this review, however Ref. [11] discusses many of the relevant issues. Both inclusive and exclusive decays can be measured at SuperB, in both $e$ and $\mu$ final states. The advantage of being able to perform this full set of measurements is that one can constrain all NP sensitive observables. The set of NP sensitive observables includes forward-backward and isospin asymmetries as well as ratios of the different leptonic final states. Recently a number of additional asymmetries have been added to the list, for example see [72]. The theoretical issues associated with interpretation of inclusive and exclusive measurements are different, so if a deviation from the SM were to be found one would want to confirm that the two types of measurement (inclusive and exclusive) both exhibited this behavior in order to identify the underlying cause. It is expected that SuperB will collect $10,000 - 15,000$ $B \rightarrow K^\ast \ell^+ \ell^-$ events. LHCb has recently started producing results on the di-muon channel, and expects to accumulate 8,000 events in a data sample of 5 fb$^{-1}$. The $e^+e^-$ mode is more challenging in a hadronic environment, and SuperB is expected to accumulate twenty times the number of $K^\ast e^+e^-$ events than LHCb.

In addition to these exclusive measurements, Super Flavour Factories will be able to perform precision measurements of inclusive modes, where the attainable precision is under investigation. The inclusive modes are of interest as one can use the measured branching fraction to constrain the NP energy scale in MSSM with mass insertions (Section 9.2). For example if one assumes that the squark and gluino masses are the same, then by combining inclusive measurements of $b \rightarrow s \ell^+ \ell^-$ with inclusive measurements of $b \rightarrow s \gamma$ (see below), one is able to measure both the real and imaginary part of the mass insertion parameter $(\delta_{23}^d)_{LR}$, a coupling of 2$^{nd}$ to 3$^{rd}$ left-right squark transitions. This parameter in turn is related to $\Lambda_{NP}$.

In addition to studying the opposite charge $b \rightarrow s \ell \ell$ decays, one can search for same sign lepton events, so $b \rightarrow s \ell^\pm \ell^\pm$, which would be manifest through transitions involving Majorana neutrinos. The search potential for such a measurement is greater in an $e^+e^-$ environment compared to a hadronic one, as there are smaller backgrounds and a complete set of leptonic final states can be studied. In order to constrain couplings for each of the hypothetical Majorana neutrino generations in this scenario, one needs to measure all of these different final states.

$b \rightarrow (s,d)\gamma$:

The inclusive branching fractions, and $CP$ asymmetries, of $B$ mesons decaying into
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$X_{s,d}\gamma$ can be used to constrain new physics scenarios. Currently one of the most precise limits on the mass of a charged Higgs particle in a 2HDM comes from $B \to X_s\gamma$, where $m_{H^+} > 295 \text{GeV}/c^2$ at 95% C.L. This is the most stringent constraint available on $m_{H^+}$ for low values of tan$\beta$. The current constraint obtained from this channel, when combined with existing results from $B \to \ell\nu$, is able to exclude the possibility of finding a charged Higgs particle at the LHC for at least the next few years. The inclusive branching fraction can also be used to constrain the compactification scale $R$ in minimal models of universal extra dimension scenarios. The current data give $1/R > 600 \text{GeV}$ at 95% C.L. Constraints from $X_d\gamma$ complement the information obtained from $X_s\gamma$, and for example if one combines information on the direct CP asymmetries measured in these two inclusive decays it is possible to determine NP scenarios based on Minimal Flavour Violation (MFV) from more generic models.

Experimentally one will be able to measure the inclusive $X_s\gamma$ branching fraction to a precision of about 3% with 75 ab$^{-1}$ of data at Super$B$. The corresponding precision on the direct CP asymmetry is expected to be $\sim 0.02$. It is also worth noting that the related channel $B \to K^0\pi^0\gamma$ can also be used as a null test of the SM, where Super$B$ will reach a precision of 0.03 on the time dependent CP asymmetry parameter $S$ (see Section 4.1.2). If one observes a large time-dependent CP asymmetry in this decay, this would be a clear sign of NP. This radiative mode is sensitive to right handed currents and so complements studies of $B \to K^{(*)}\nu\nu$ discussed previously.

4.1.2. Precision CKM: Angles and Sides of the Unitarity Triangle

Unitarity of the CKM matrix given by Eq. (2) leads to six triangles that can be represented in a complex plane. One of these is related to $B_{u,d}$ transitions and can be studied in great detail at a Super Flavour Factory. This relation is generally known as the “unitarity triangle” and is given by

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0.$$  \hspace{1cm} (9)

Here we refer to this triangle as the $bd$ unitarity triangle to avoid possible confusion with the $cu$ triangle discussed in Section 5. The triangle itself is shown in Figure 5, where the base is normalised to unity, so that any two measurements of the triangle may be used to constrain it completely.

The angles of the $bd$ unitarity triangle $\alpha$, $\beta$, and $\gamma$ are given by

$$\alpha = \arg \left[ -V_{td} V_{tb}^* / V_{ud} V_{ub}^* \right],$$  \hspace{1cm} (10)

$$\beta = \arg \left[ -V_{cd} V_{cb}^* / V_{td} V_{tb}^* \right],$$  \hspace{1cm} (11)

$$\gamma = \arg \left[ -V_{ud} V_{ub}^* / V_{cd} V_{cb}^* \right],$$ \hspace{1cm} (12)

and have been measured with precisions of 6.1$^\circ$, 0.8$^\circ$, and 11$^\circ$ by the $B$ Factories\footnote{One can find an alternate notation in the literature, where $(\alpha, \beta, \gamma) = (\phi_2, \phi_1, \phi_3)$, for example in results reported by the Belle experiment.} 73, 76. In addition to precision tests of the angles of the $bd$ unitarity triangle, there are...
measurements of the sides, where the limiting factors are knowledge of the semi-leptonic decays $b \to u\ell\nu$ and $b \to c\ell\nu$ which are related to $|V_{ub}|$ and $|V_{cb}|$. As things currently stand, there is an experimental controversy between inclusive and exclusive measurements of these quantities, and there is a tension between the measurements of $\sin 2\beta$, $|V_{ub}|$, and the branching fraction of $B \to \tau\nu$. If one artificially moves any one of these parameters to try and mitigate the discrepancy for that observable, the discrepancy associated with the other parameters becomes significant. More precise measurements of all of these parameters are required in order to clarify if there is an underlying experimental issue that needs to be resolved, or if this is a sign of physics beyond the SM.

Prior to SuperB starting to take data the LHCb experiment should improve the precision on $\beta$ to about $0.5^\circ$, and on $\gamma$ by a factor of $2-3$ relative to the current state of the art, which may go some way to understanding the current tension in the constraints on the $bd$ unitarity triangle. The CERN based NA62 experiment will measure the CKM parameter $\eta$ (the height of the triangle), using $100 K^+ \to \pi^+\nu\bar{\nu}$ events placing a new constraint on the height of the $bd$ unitarity triangle [77].

SuperB will be able to reduce uncertainties on $\alpha$, $\beta$, and $\gamma$ to the level of $1^\circ$, $0.1^\circ$, and $1^\circ$, respectively to facilitate a precision CKM determination, and also improve the precision with which $|V_{ub}|$ and $|V_{cb}|$ are measured. The latter two observables are discussed below. As pointed out in Ref. [7], it will be necessary to improve constraints on $\Delta\Gamma_{B_d}$ in order to achieve these goals. The set of precision CKM angle constraints can be used to test the SM description of quark mixing and CP violation to the level of 1%. SuperB will also produce a precision measurement of the branching fraction of $B \to \tau\nu$, and thus will also be able to probe the issue of current tensions observed in the SM. One should not forget that the process of making a precision test of the CKM matrix through measurement of these observables also improves the SM reference point that many other NP searches require. Thus it is imperative that SuperB performs precision direct and indirect measurement of the $bd$ unitarity triangle outlined here.

The most interesting $B$ decays that can manifest $CP$ violation at SuperB are dominated either by tree or loop (penguin) transitions. A number of these are known

**Figure 5.** The $bd$ unitarity triangle related to decays of $B_{u,d}$ mesons.
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to be theoretically clean, and calculations of SM uncertainties for a number of the other modes can be improved over the coming decade. Time-dependent $CP$ asymmetries are given by

$$A(\Delta t) = -C \cos \Delta M \Delta t + S \sin \Delta M \Delta t,$$

(13)

where $\Delta M$ is the $B^0 - \bar{B}^0$ mixing frequency, $\Delta t$ is the proper time difference between the decay of two correlated $B^0$ mesons produced in $\Upsilon(4S)$ collisions, and both $S$ and $C$ are parameters related to $CP$ violating effects. These are discussed in detail in Ref. [7]. Collectively the measured differences in the antisymmetric $CP$ asymmetry, parameterised by $S$, in penguin decays and the benchmark $B^0 \to J\psi K_S$ channel are known as $\Delta S$ measurements. In addition to the SM penguin amplitude new heavy particles could contribute additional amplitudes to these final states, and the interference between SM and NP contributions could be detectable as an observable deviation from the tree $\sin 2\beta$ value. More recently however the focus of these measurements has been extended to compare the tree measurement of $\sin 2\beta$ against the inferred indirect constraint on this parameter. Thus this class of time-dependent $CP$ violation mode serves as a set of sensitive interferometers for NP contributions from both tree and loop amplitudes. The modes under study, and corresponding theoretical and experimental sensitivities achievable are listed in Table 3 (reproduced from Ref. [7]). The channels are grouped into common physical final states: $b \to c\bar{c}s$ charmonium decays, $b \to s$ penguin dominated decays, and $b \to d$ penguin dominated decays.

While it is also possible to measure direct $CP$ asymmetries in a large number of modes at SuperB, in general these are of limited use in terms of constraining theory. One exception is the $CP$ asymmetry in $b \to s\gamma$ decays discussed above. The fundamental problem is that many of these measured observables are not theoretically clean, thus it is difficult to translate a direct $CP$ measurement into an unambiguous constraint on a SM parameter. This is the $B$ physics analog of the issue associated with interpreting the measurement of direct $CP$ violation in kaon decays, $\epsilon'/\epsilon$, beyond establishing that such an effect exists, which in itself was an important goal. It may be possible to combine many Charmless $B$ decay modes to test the SM using direct $CP$ asymmetries, however such tests will probably never be as clean a set of observables as some of the time-dependent $CP$ asymmetries discussed previously. A prime example of this situation can be seen in terms of the difference between the direct $CP$ asymmetry measurements in $B \to K\pi$ decays. Some authors have advocated that the discrepancy is clear evidence for NP, however over the last few years there have been a number of SM-based theoretical calculations that are able to explain this phenomenon. For this reason it is unlikely that direct $CP$ violation measurements in Charmless hadronic $B$ decays will play a leading role in future experiments. In Ref. [81] Gronau proposed a sum rule that could be used to correlate the measured asymmetries in $K\pi$ decays.

As mentioned above, it is also important to measure the sides of the $bd$ unitarity triangle, using semi-leptonic decays. The motivation for these measurements is two-fold: firstly to resolve the experimental discrepancy between inclusive and exclusive
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Table 3. Current experimental precision of $S$ [76], and that expected at a SuperB experiment with 75 ab$^{-1}$ of data. The 3σ and 5σ discovery limits at 75 ab$^{-1}$ are also listed. The first entry in the table corresponds to the tree level reference mode, and the next two sections of the table refer to $b \to s$ and $b \to d$ transitions, respectively. Theoretical estimates of $\Delta S$ are taken from Refs. [78, 79, 80]. A long dash ‘−’ denotes that there is no theoretical estimate of $\Delta S$ computed yet for a given mode, thus the corresponding discovery limits are not evaluated.

| Mode | Current Precision | Expected Precision (75 ab$^{-1}$) | Discovery Potential |
|------|-------------------|-----------------------------------|---------------------|
|      | Stat. | Syst. | $\Delta S^f$(Th.) | Stat. | Syst. | $\Delta S^f$(Th.) | 3σ | 5σ |
| $J/\psi K^0_S$ | 0.018 | 0.009 | 0 ± 0.01 | 0.002 | 0.005 | 0 ± 0.001 | 0.02 | 0.03 |
| $\eta K^0_S$ | 0.08 | 0.02 | 0.015 ± 0.015 | 0.006 | 0.005 | 0.015 ± 0.015 | 0.05 | 0.08 |
| $\phi K^0_S \pi^0$ | 0.28 | 0.01 | − | 0.020 | 0.010 | − | − | − |
| $f_0 K^0_S$ | 0.18 | 0.04 | 0 ± 0.02 | 0.012 | 0.003 | 0 ± 0.02 | 0.07 | 0.12 |
| $K^0_S K^0_S K_S^0$ | 0.19 | 0.03 | 0.02 ± 0.01 | 0.015 | 0.020 | 0.02 ± 0.01 | 0.08 | 0.14 |
| $\phi K^0_S$ | 0.26 | 0.03 | 0.03 ± 0.02 | 0.020 | 0.005 | 0.03 ± 0.02 | 0.09 | 0.14 |
| $\pi^0 K^0_S$ | 0.20 | 0.03 | 0.09 ± 0.07 | 0.015 | 0.015 | 0.09 ± 0.07 | 0.21 | 0.34 |
| $\omega K^0_S$ | 0.28 | 0.02 | 0.1 ± 0.1 | 0.020 | 0.005 | 0.1 ± 0.1 | 0.31 | 0.51 |
| $K^+ K^- K^0_S$ | 0.08 | 0.03 | 0.05 ± 0.05 | 0.006 | 0.005 | 0.05 ± 0.05 | 0.15 | 0.26 |
| $\pi^0 \pi^0 K^0_S$ | 0.71 | 0.08 | − | 0.038 | 0.045 | − | − | − |
| $\rho K^0_S$ | 0.28 | 0.07 | −0.13 ± 0.16 | 0.020 | 0.017 | −0.13 ± 0.16 | 0.41 | 0.69 |
| $J/\psi \pi^0$ | 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 | − | − | − |

measurements left as a legacy of BABAR and Belle, and secondly to try and resolve the current tension between $\sin 2\beta$, $V_{ub}$, and the branching fraction of the decay $B \to \tau \nu$.

The uncertainty on the indirect constraint of the location of the apex of the $bd$ unitarity triangle is dominated by the experimental constraint on $|V_{ub}|$. The constraint obtained from $b \to u \ell \nu$ decays on $|V_{ub}|$ has a precision of $\sim 11\%$, whereas measurements of $|V_{cb}|$, $|V_{cd}|$, and $|V_{cs}|$ have uncertainties between 3 and 5%. In the longer term, SuperB is expected to be able to improve the precision on $|V_{ub}|$ to 2(3)% for an inclusive (exclusive) measurement. The precision on $|V_{cb}|$ obtained using $b \to c \ell \nu$ decays could be improved from the current level of 3.5% to $\sim 1\%$ for both inclusive and exclusive measurements. The increase in the precision of $|V_{ub}|$ and $|V_{cb}|$ require some improvement in the precision of Lattice QCD input parameters. The remaining quantities, $|V_{cd}|$ and $|V_{cs}|$, can be measured using the charm decays $D \to \pi \ell \nu$, and $D_s \to \ell \nu$, respectively. It is likely that the most precise measurements that can be made of these quantities at SuperB will use data accumulated at $D \overline{D}$ and above $D_s$ thresholds.

The potential precisions outlined here require improvements in Lattice QCD, that have been predicted up to 2015, and these are discussed in detail in Refs. [13, 1]. Until now all but one of these expected improvements in precision of Lattice quantities has proceeded at the anticipated rate, and in many case surpassed [1]. Thus it is expected
that future improvements in Lattice QCD will be made by the time that SuperB starts taking data, and hence that the estimates discussed in this section will be achievable.

4.2. B physics at the $\Upsilon(5S)$

One of the motivations of studying the $B_s$ system at SuperB is that the $e^+e^-$ environment is extremely clean, so decays involving neutrinos or many neutral particles, that would be inaccessible to an experiment at a hadron collider, can be studied in detail. It is not possible to study $B_s$ mixing or time-dependent asymmetries in the $B_s$ system at existing or proposed $e^+e^-$ colliders because of the large mixing frequency, $\Delta m_s$. Current detector technology would be unable to resolve oscillations in this decay, without having an extreme boost for the center of mass system, relative to the laboratory frame of reference. However it will be possible to measure a number of interesting decays, including the semi-leptonic asymmetry $a_{SL}$ discussed in Section 4.2.1 and $B_s \rightarrow \gamma\gamma$ (see Section 4.2.2). In addition, the increased knowledge of branching fractions obtained via measurements at $e^+e^-$ facilities will help improve the precision of absolute rates of $B_s$ decay modes, as LHCb reports branching ratio measurements, as opposed to branching fractions and will be limited by the absolute results given in the PDG for the normalisation modes used. More details on the $\Upsilon(5S)$ programme at SuperB can be found in Ref. [1].

4.2.1. Semi-leptonic asymmetry

The semi-leptonic asymmetry measured in $B_s$ decays is of potential interest for NP searches. The asymmetry itself is given by

$$A_{SL}^s = \frac{B(B_s \rightarrow \overline{B}_s \rightarrow X^+\ell^+\nu_\ell) - B(\overline{B}_s \rightarrow B_s \rightarrow X^-\ell^-\nu_\ell)}{B(B_s \rightarrow \overline{B}_s \rightarrow X^-\ell^-\nu_\ell) + B(\overline{B}_s \rightarrow B_s \rightarrow X^+\ell^+\nu_\ell)} = 1 - \frac{|q/p|^4}{1 + |q/p|^4}.$$  

While this can be measured in hadronic environments, there is an intrinsic charge asymmetry that needs to be understood, and controlled to high precision [82]. One way for hadronic experiments to control this factor is to measure the difference in asymmetries between $B_d$ and $B_s$ decays $\Delta A_{LS}^d = A_{SL}^d - A_{SL}^s$. The corresponding measurement in an $e^+e^-$ environment would enable a direct measurement of $A_{SL}^s$ with smaller systematic uncertainties, as well as having a different production environment that could be useful in order to understand any deviations from SM expectations obtained. The anticipated precision for a measurement of $A_{SL}^s$ with 1 ab$^{-1}$ of data at SuperB is 0.006. It would also be possible to make an inclusive measurement of the asymmetry for both $B_s$ and $B_d$ decays, $A_{CH}$, with a precision of 0.004. The current measurement of the semi-leptonic asymmetry measured for a combination of $B_0^d$ and $B_0^s$ mesons from the D0 experiment is $3.9\sigma$ from SM expectations [57], where the asymmetry $A_{SL}^b = (-0.78 \pm 0.17 \pm 0.09)\%$, and one expects $(-0.028 \pm 0.005)\%$ in the SM.

4.2.2. $B_s \rightarrow \gamma\gamma$
The SM branching fraction for $B_s \rightarrow \gamma\gamma$ is expected to be $0.5 - 1.5 \times 10^{-6}$ (see for example see Ref. [83], and references therein), and the decay proceeds via a $b \rightarrow s\gamma\gamma$ FCNC loop transition. Hence the NP that can affect possible $b \rightarrow s$ penguin measurements of time-dependent $CP$ asymmetries or other kinematic quantities may also be at play in this decay. This channel benefits from the lack of hadronic particles in the final state, when compared to the $\Delta S$ measurements discussed in Section 4.1.2 and is also related to similar $B_d$ channels.

This is an experimentally challenging final state to isolate and extract, and it is only possible to isolate this channel at an $e^+e^-$ collider based experiment. The two-photon invariant mass distribution will have a significant background from high energy combinatoric photons, as has been seen in previous searches for this decay [84]. The current upper limit for this channel is $< 8.7 \times 10^{-6}$ at 90% C.L. obtained by Belle from a data sample of $23.4 \text{fb}^{-1}$ recorded at the $\Upsilon(5S)$. However care should be taken when extrapolating this number to higher luminosities as this limit is obtained from a downward fluctuation, resulting from a slightly negative event yield obtained from the fit to data. The challenge here for SuperB is to isolate as clean a signal as possible, using only information from the EMC to provide a positive identification for $B_s \rightarrow \gamma\gamma$, and the other sub-detectors as an elaborate veto system. The other $B$ meson in the final state can be used to provide sufficient kinematic information to help reduce the background level. The SM rate should be attainable at SuperB where it is expected that sensitivities of the order of $3 \times 10^{-7}$ can be reached. Thus if the signal were manifest at the upper end of expectations, SuperB should be able to observe it, and if the true branching fraction were at the lower end, then it would be challenging to establish evidence for the existence of this decay.

The $\gamma\gamma$ branching fraction can be affected by NP scenarios in a similar way to $B_{d,u} \rightarrow X\gamma, \gamma\gamma$, and $X\gamma\gamma$, where significant enhancements above the SM rate are possible [85, 86]. In addition to the scenarios where the $B_{d,u}$ decays are correlated with $B_s \rightarrow \gamma\gamma$, there are also specific models where there is no correlation and this decay can be significantly enhanced by NP, whereas the $B_{d,u}$ counterparts remain unaffected [83, 87]. This makes $B_s \rightarrow \gamma\gamma$ an important decay to measure in order to provide an independent cross check of any deviation observed in a $B_{u,d}$ mode.

5. D physics

Charm analyses at SuperB are broadly split into two categories, those using data collected at the $\Upsilon(4S)$, and those collected at or near charm threshold, the $\psi(3770)$. The $\Upsilon(4S)$ data results from $D$ mesons being produced from $e^+e^-$ continuum events, where the cross-section for $c\bar{c}$ is comparable to that for $b\bar{b}$. In general one reconstructs tagged $D$ mesons from a $D^* \rightarrow D\pi_s$ transition where $\pi_s$ denotes a slow (low-momentum) pion. The advantage of studying charm in SuperB at this energy is the vast data sample that can be collected in a clean environment where one expects to accumulate $90 \times 10^9$ $D^0$ meson pairs in $75 \text{ab}^{-1}$ of data. The drawback is that the data, while clean, are not
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background free, and for example one must restrict the momentum range of $D$ mesons to exclude events originating from $B$ decay. In some measurements systematic uncertainties from background may be a critical issue, and for these having access to data collected at the $\psi(3770)$ resonance may provide a distinct advantage. In addition to having smaller background, neutral $D$ meson pairs produced at charm threshold are quantum correlated where one always has a $D^0$ and a $\bar{D}^0$ until one of the mesons decays. In essence one can repeat the $B$ factory experiment at the $\Upsilon(4S)$, with a $D$ factory experiment at charm threshold. In order to exploit the full potential of the quantum correlated neutral meson pair one needs to have a boosted centre of mass system, and this may be achievable with $\beta\gamma$ up to 0.91 at SuperB. The baseline boost for SuperB is currently somewhat smaller than this value. The drawback of running at charm threshold, with respect to the $\Upsilon(4S)$, will be that the accumulated luminosity at the $\psi(3770)$ is expected to only be of the order of $500\,fb^{-1}$. This will result in only $\sim 1.8 \times 10^9$ $D$ meson pairs being produced, however these data are extremely clean, and kinematics of the initial state $e^+e^-$ pair and the ‘other’ $D$ meson in the event can be used to essentially select samples of almost pure $D$ mesons. A number of observables measured using the data collected in a few months at the $\psi(3770)$ will be competitive with results from the $\Upsilon(4S)$ sample accumulated over the lifetime of SuperB, and some will help control systematic uncertainties in measurements made using $\Upsilon(4S)$ data at Belle II and SuperB, and also help reduce uncertainties for the corresponding measurements at LHCb. Many observables can be accessed using both samples of data, and are discussed according to topic in the following.

5.1. Charm Mixing

The last largely uncharted area of neutral meson mixing that remains to be explored is that of the charm sector. The $B$ Factories found evidence for charm mixing in 2007 using studies of $D \to K^+\pi^-\pi^-\pi^+$ decays [88], and subsequently using $D \to h^+h^-\pi^0$ decays [89] (where $h = \pi, K$), and have started the search for time-integrated $CP$ violation in charm transitions. While both neutral $B$ and $K$ mesons have been studied in detail, one should recall that these involve flavour changing transitions of down type quarks. The study of mixing and $CP$ violation in the charm sector corresponds to the study of an up-type quark, where any large manifestation of $CP$ violation would constitute a sign of NP. It should also be noted that as the amount of data accumulated increase, additional observables will become accessible to experimentalists. An example of this very situation can be seen in terms of time-dependent $CP$ asymmetry measurements, discussed in Section 5.2.

Neutral $D$ mesons mixing can be described by a Hamiltonian consisting of a $2 \times 2$ matrix of elements given by $M + i\Gamma/2$, where $M$ and $\Gamma$ are themselves $2 \times 2$ matrices [90]. The weak eigenstates of neutral $D$ mesons can be expressed as admixtures of the strong states

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle,$$

(14)
where $q^2 + p^2 = 1$. The characteristic mixing frequency is given by $\Delta M$, which is given by the mass difference of the weak eigenstates. The other relevant observable is $\Delta \Gamma$, given by the width difference of those eigenstates. Experimentally one measures mixing via the parameters $x_D$ and $y_D$ (or related parameters) where

$$x_D = \frac{\Delta M}{\Gamma}, \quad \text{and} \quad y_D = \frac{\Delta \Gamma}{2\Gamma}. \quad (15)$$

Given the small values of $x_D$ and $y_D$ an approximation is used for the time-dependence of the evolving neutral meson state including only quadratic and linear terms of these parameters. A further complication enters the measurement as in general all final states $f$ have a relative strong phase $\delta_f$ (invariant under CP) that needs to be determined, neglecting the weak phases that are expected to be small in the SM. Hence in general one measures parameters in a rotated basis that are related to $x_D$ and $y_D$ given by

$$x'_f = x_D \cos \delta_f + y_D \sin \delta_f, \quad y'_f = y_D \cos \delta_f - x_D \sin \delta_f. \quad (16)$$

A number of final states have been studied in order to determine the $D$ meson mixing parameters, these include wrong sign $D \to K\pi$ [88, 91], $hh$ [89, 92], $K\pi\pi^0$ [93] and $K^0_{sh}\bar{h}h$ [94, 95] decays. Experimentally $x_D$ and $y_D$ are found to be small, where $x \sim 0.005$ and $y \sim 0.01$ [76], thus both $\Delta M$ and $\Delta \Gamma$ are small for neutral $D$ mesons. The dominant contribution to these measurements currently comes from the time-dependent Dalitz Plot (DP) analysis of $D^0 \to K^0_{sh}h^+h^-$ final states as one is able to determine the value of $\delta_f$ as a function of position in the DP, and hence extract $x_D$ and $y_D$ directly for this mode. The other channels measure $x_D$ and $y_D$ up to a rotation corresponding to the strong phase measured in the final state according to Eq. (16). There is an intrinsic limit to the precision of any measurement using the $K^0_{sh}h^+h^-$ final state that comes from the DP model used for the decay. It will be possible to control this contribution to a charm mixing analysis by performing a detailed study of this decay using data collected at charm threshold (see Section 5.4). Table 4 summarises the expected precisions obtainable on mixing parameters using existing methods and data from SuperB. The impact of charm threshold running on the determination of these parameters is clearly evident. On inclusion of the improved DP information one will be able to halve the total uncertainty on $x_D$ and reduce the uncertainty on $y_D$ by 30% and Figure 6 shows the different constraints obtainable using all data from SuperB. More importantly these results will change from being systematically to statistically limited, allowing for further improvements. The SuperB results from threshold running will impact upon the ultimate precision of mixing parameters determined by the Belle II and LHCb experiments. It will also be possible to place model dependent constraints on $|q/p|$ and the phase of charm mixing with precisions better than $1 - 2\%$ and $1.4^\circ$, respectively.

An alternate method of studying charm mixing has been proposed using time-dependent CP asymmetry measurements which is discussed in Section 5.2. One will be able to measure the phase of mixing with a statistical precision of $\mathcal{O}(1.3^\circ)$ using $D^0 \to K^+K^-$, and one may be able to achieve sub-degree level measurements using
Table 4. Expected precision on charm mixing parameters using \( \Upsilon(4S) \) data from SuperB with existing methods from the \( B \) factories. The estimates given in the first two rows include only data from the \( \Upsilon(4S) \), while the results in the last two rows combine the \( \Upsilon(4S) \) expectations with an improved \( K_S^0 \pi \pi \) DP model resulting from a charm threshold run.

| Parameter | \( x \times 10^3 \) | \( y \times 10^3 \) | \( \delta_{K_\pi} (^{\circ}) \) | \( \delta_{K_{\pi\pi}} (^{\circ}) \) |
|-----------|-------------------|-------------------|-----------------|-----------------|
| \( \sigma \) (stat.) | 0.18 | 0.11 | 1.3 | 2.7 |
| \( \sigma \) (stat.) +(syst.) | 0.42 | 0.17 | 2.2 | \(+3.3^{+3.4}_{-3.4}\) |
| \( \sigma \) (stat.) | 0.17 | 0.10 | 0.9 | 1.1 |
| \( \sigma \) (stat.) +(syst.) | 0.20 | 0.12 | 1.0 | 1.1 |

Figure 6. The constraints obtained on the charm mixing parameters \( x_D \) and \( y_D \) using \( \Upsilon(4S) \) and \( \psi(3770) \) data from SuperB (Ref. [1]).

more copious decays such as \( K_S \pi^0 \) [7].

5.2. Time-dependent CP violation

It is possible to perform time-dependent \( CP \) asymmetry measurements in \( D \) decays, both at threshold and using data collected at the \( \Upsilon(4S) \). The motivation and formalism for doing so has been discussed recently in Ref. [7] in the context of testing the \( cu \) unitarity triangle. An important issue to raise is that in order to understand the phenomenology of \( CP \) violation one has to choose a convention for the four parameters of the CKM
matrix, and the order to which one expands the matrix elements in terms of this basis. Until recently the Wolfenstein parameterisation of the CKM matrix \[5\] has been used by default. Here the four expansion parameters of the matrix are \(\lambda = \sin \theta_c \sim 0.22\), \(A\), \(\rho\) and \(\eta\), and the description of the matrix has been given up to \(\mathcal{O}(\lambda^3)\) in Eq. (2). An alternative parameterisation using the same four parameters has been proposed by Buras et al. in Ref. [6] which has the advantage that the unitarity triangle is unitary to any order of the expansion in terms of \(\lambda\). At \(\mathcal{O}(\lambda^3)\), both conventions are equivalent, however in the charm sector one needs to consider additional terms, to at least \(\mathcal{O}(\lambda^5)\), to understand the CKM structure and \(CP\) violation potential of charm decays.

The charm ‘\(cu\)’ triangle given by
\[
V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0,
\]
has been known for some time [96], however thus far there have been no direct tests of unitarity for this triangle. Ref. [7] outlines the procedure to measure the mixing phase using time-dependent \(CP\) asymmetries of \(CP\) eigenstates such as \(D \to K^+ K^-\) and one of the angles of the \(cu\) triangle, \(\beta_c\), using a combination of \(D \to K^+ K^-\) and \(D \to \pi\pi\) final states. The phase difference measured between these two modes is related to the observable \(-2\beta_{c,\text{eff}}\) measured in the time-dependence of \(D^0 \to \pi^+ \pi^-\) decays. The subscript ‘\(\text{eff}\)’ indicates that while this parameter is related to the angle \(\beta_c\) of the \(cu\) triangle, there are theoretical uncertainties that may cause \(\beta_c\) to differ from \(\beta_{c,\text{eff}}\). Ref. [7] discusses this issue, highlighting in particular that one can perform an Isospin analysis of \(D \to \pi\pi\) final states in order to disentangle the effect of penguin amplitudes that contribute to \(D^0 \to \pi^+ \pi^-\) with a different weak phase than the leading tree contribution. As this Isospin analysis requires input from \(D^0 \to \pi^0 \pi^0\) and \(D^+ \to \pi^+ \pi^0\), it will not be possible to perform a self-consistent measurement of \(\beta_{c,\text{eff}}\), correcting for penguins in a hadronic environment. While hadron experiments may provide input to help solve this problem one will require data from a Super Flavour Factory to complete the picture. It has been estimated that it will be possible to constrain \(\beta_{c,\text{eff}}\) to a precision of 1° at SuperB before taking into account penguin contributions [7] on combining data from threshold and the \(\Upsilon(4S)\). As \(\beta_c\) is estimated to be \(\sim 0.035°\), SuperB will be able to constrain large NP effects in time-dependent \(CP\) asymmetry measurements in charm decays, but will lack the precision to perform a direct test of the SM. Nonetheless, it will be important to verify that \(\beta_{c,\text{eff}}\) is consistent with zero. One should also note that time-dependent measurements will also be able to provide model dependent constraints on \(|q/p|\), and so one can search for both direct and indirect \(CP\) violation, in addition to measuring the phase of neutral \(D\) meson mixing.

Some of the systematic uncertainties in time-dependent \(CP\) asymmetry measurements made using data collected at the \(\psi(3770)\) resonance will be different from those at the \(\Upsilon(4S)\). This provides a potential advantage to SuperB as one can perform an independent cross check of any phase measurement for consistency. While the precision of \(\beta_{c,\text{eff}}\) using 500 fb\(^{-1}\) of data from the \(\psi(3770)\) is expected to be slightly worse than that from 75 ab\(^{-1}\) at the \(\Upsilon(4S)\), the average of these two results may approach
the level of 1°. Studies are ongoing in this area.

In addition to direct tests of the CKM matrix via measurements of an angle of the 
$cu$ triangle, one can indirectly test this using constraints on the magnitudes of $V_{ub}$, $V_{cb}$, $V_{us}$, $V_{cb}$, and $V_{cs}$. In principle these quantities can be measured using a combination of 
data collected at the $\Upsilon(4S)$ ($V_{ub}$ and $V_{cb}$), in the vicinity of the $\psi(3770)$ ($V_{cb}$ and $V_{cs}$), and any energy using $\tau$ decays ($V_{us}$). The other CKM matrix element that is required as 
an input for an indirect side constraint is $V_{ud}$, however this is already precisely known [8].

As with $B$ decays it is possible to search for direct $CP$ violation in charm decays 
where the interference between two or more such amplitudes can manifest a $CP$ asymmetry. It is expected that the direct $CP$ asymmetry in $D \to hh$ decays could be as large as $10^{-4}$, which would be manifest in a time-dependent $CP$ asymmetry measurement. As is the case with $K$ and $B$ decays, different strong phases are required in order to manifest a non-trivial effect, and as these are difficult to theoretically calculate, any measurement of a small level of direct $CP$ violation in charm would most probably be of limited use in testing the SM beyond establishing the existence of such an effect.

5.3. Rare decays

Rare $D$ decays are sensitive to NP scenarios, and can provide an important test of the 
SM. A number of possible NP probes are being studied however it is clear that there are several important measurements to be made at Super$B$, including searches for $D \to \gamma\gamma$, $\ell^+\ell^-$, and $\nu\nu(\gamma)$. 

$D \to \ell^+\ell^-$: The SM expectation of the branching fraction of $D \to \mu^+\mu^-$ is dominated 
by a long-distance contribution which is related to the $D^0 \to \gamma\gamma$ rate via 

$$B(D \to \mu^+\mu^-)_{LD} = 3.0 \times 10^{-5} \cdot B(D^0 \to \gamma\gamma).$$

(18)

The expectation is that this decay proceeds at the level of $3 \times 10^{-13}$ which can be inferred from the expected rate of $D^0 \to \gamma\gamma$ discussed below. Significant enhancements to the branching fraction can be obtained in models of NP. The current experimental bound is $< 1.4 \times 10^{-7}$ [97] which is about an order of magnitude larger than possible enhancements from R parity violating SUSY. 

Super$B$ should be able to improve upon these limits and reach a sensitivity an 
order of magnitude better than the current constraints, and in doing so may start to constrain NP parameter space, however it is likely that LHCb will be able to place a more stringent constraint on this mode. Having measured the branching 
fraction from data, one is limited in terms of interpretation of this result in the 
context of NP by the lack of knowledge on the long-distance rate. The related 
channel discussed below can help elucidate this situation, and is an example of the 
natural synergy between hadron and $e^+e^-$ environments.

The di-electron mode is also of interest, however it is more difficult to trigger on 
electrons in a hadronic environment. The Super Flavour Factories will produce 
competitive limits on $B(D \to e^+e^-)$. Currently the most stringent limit on this 
decay is $7.9 \times 10^{-8}$ from Belle [97].
**D^0 \rightarrow \gamma\gamma:** The two-photon channel is expected to have a branching fraction of $(1.0 \pm 0.5) \times 10^{-8}$ in the SM [98]. The current experimental limit [99] on this decay comes from CLEO and is $< 2.9 \times 10^{-5}$. An improved limit on this channel can be used to constrain the long-distance contribution to the di-lepton final states. It is expected that SuperB will be able to achieve a sensitivity of a few $\times 10^{-7}$ in this channel, and while an order of magnitude larger than the SM expectation, this result would be able to constrain possible enhancements in the $D \rightarrow \mu^+\mu^-$ channel at a useful level. The corresponding limit on $B(D \rightarrow \mu^+\mu^-)_{LD}$ obtained from SuperB could reach the expected SM level for this decay, i.e. $3 \times 10^{-13}$. Thus by combining results from hadron experiments on $D \rightarrow \mu^+\mu^-$ with a limit on $D^0 \rightarrow \gamma\gamma$ from an $e^+e^-$ experiment, one will be able to search for NP.

**D \rightarrow \nu\bar{\nu}(\gamma):** Decays of heavy mesons into invisible final states, or $\gamma$+invisible states can be used to probe for signs of light Dark Matter [100]. The SM decay into $\nu\bar{\nu}$ is helicity suppressed, hence any signal found would provide a clear indication of NP. Such a measurement at SuperB would complement the corresponding studies performed in $B$ and $\Upsilon$ decays. In order to perform such an analysis one would have to use data collected at charm threshold, so that the kinematics of the final state $D^0 \rightarrow \nu\bar{\nu}$ can be constrained by measurement of the recoil $D$ meson and knowledge of the initial $e^+e^-$ kinematics in the decay chain $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$. Unlike $B$ decays where the sum of branching fractions for fully reconstructed final states is a few percent, here a $D$ recoil analysis would utilise over half of the available final state $D$ decays. With a total of $1.8 \times 10^9$ $D$ mesons produced at threshold it is feasible to assume that SuperB will be able to perform a detailed search for both of these decays. While the implied single event sensitivity would be $(\mathcal{O}(few \times 10^{-9}))$, one should expect that there might be a significant level of residual background resulting from the lack of hermiticity of the detector, but any background would be less than that found in the corresponding searches for $B$ to invisible final states. The sensitivity achievable is under study, and it is likely that $D^0 \rightarrow \nu\bar{\nu}$ will suffer from an irreducible background from $D \rightarrow K\pi$ decays, where the final state particles go down the beam pipe. There is a similar interest in searching for $B_{d,s} \rightarrow invisible(\gamma)$ decays where the SM and light Dark Matter expectations are also discussed in [100].

### 5.3.1. CPT with charm

CPT can be tested using decays of pairs of neutral $K$, $D$ and $B$ meson created in a quantum correlated state via decays at centre of mass energies corresponding to the $\phi$, $\psi(3770)$, and $\Upsilon(4S)$ respectively. It is possible to perform a precise test of CPT using $D^0\bar{D}^0$ pairs from the data sample collected at $\psi(3770)$, where both $D$ mesons decay into a semi-leptonic final state (e.g. see [101]). The interpretation of any potential CPT violating effect is model dependent, so it is important to test this fundamental symmetry for all neutral meson systems. Existing measurements are compatible with CPT being an exact symmetry, however it is interesting to note that the BaBar experiment reported
a 2.8σ deviation from CPT conservation when studying a large sample of di-lepton events as a function of sidereal time \[56\]. As SuperB expects to accumulate 50 times more statistics than BES III at threshold, it is expected that any constraint on CPT produced would be a significant improvement over previous results, and complement the corresponding measurements made at the \(\Upsilon(4S)\), as well as results expected to be made by the KLOE-2 experiment over the next few years \[102\].

5.4. Other Measurements at Charm Threshold

SuperB will have a dedicated run at the \(\psi(3770)\) (charm threshold) in order to benefit from the extremely clean environment obtained by the use of D-recoil methods that partially or fully reconstruct the other D meson in the event, and the quantum correlated \(D^0 \bar{D}^0\) system. The power of identifying an almost pure sample of charm mesons at threshold to analyse can be seen by comparing the precision of many CLEO-c results to those from the \(B\) Factories. In a number of cases, especially form factors, CLEO-c has been able to out perform the \(B\) Factories, and in some cases the measurements are unique to CLEO-c.

A total of 500 fb\(^{-1}\) of data will be collected at the \(\psi(3770)\), and runs at adjacent resonances may also be performed to include samples of \(D_s^+\) mesons. In comparison CLEO-c accumulated 0.8 fb\(^{-1}\) of data at the \(\psi(3770)\), and 0.6 fb\(^{-1}\) with a centre of mass energy of 4.17 GeV. BES III is expected to accumulate 10 fb\(^{-1}\) of data at threshold during the coming few years. Hence SuperB is expected to accumulate 50 times the data of BES III and over 500 times the data of CLEO-c. This opens up the potential to cleanly search for, and measure a number of rare decays that would otherwise be inaccessible.

A number of important measurements rely on a detailed understanding of charm decays. One such example is the \(D \rightarrow K_S \pi \pi\) final state \[103\], which feeds into both the measurement of \(\gamma\) via the GGSZ method and traditional charm mixing analyses as discussed in Section 5.1. There is an intrinsic model uncertainty associated with the use of this decay, which arises from the amplitudes considered in the DP model and thus the values of strong phases extracted as a function of the DP. CLEO-c have shown that one can use quantum correlated \(D\) mesons produced at the \(\psi(3770)\) in order to perform a measurement of the strong phase in \(K_S \pi \pi\) decays as a function of position in the DP \[104\]. At the time this result came out, it was used to halve the model uncertainty on \(\gamma\) for the \(B\) factory results. In order for the GGSZ method to remain a viable approach for the measurement of \(\gamma\) in the Super Flavour Factory era, one will need an improved measurement of the Dalitz model for \(K_S \pi \pi\) decays. As mentioned in Section 5.1 the inclusion of this result will significantly impact the measurements of charm mixing parameters at SuperB, Belle II and LHCb, and make future studies of these parameters meaningful. A number of other potential uses of charm decays to quantum correlated final states are under investigation within the SuperB Collaboration.
6. Precision electroweak decays

As discussed in Section 2.1, one of the unique features of SuperB is that the longitudinal polarisation of the electron beam. This enables one to study left-right asymmetries in $e^+e^-$ interactions that can be used to perform precision measurements of $\sin^2\theta_W$. There are two reasons why it is interesting to measure this parameter at SuperB; firstly this would provide a measurement of $\sin^2\theta_W$ at an energy of 10.58 GeV, a region where the coupling is changing and there is no measurement so far. Secondly the $e^+e^- \rightarrow b\bar{b}$ measurement made at this energy would be devoid of the $b$ fragmentation uncertainties that theoretically limit interpretation of results from SLC/LEP measurements. The left-right asymmetry $A_{LR}$ is constructed from measurements of the cross-section of events with left and right helicities

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{2a_v a_e}{a_v^2 + a_e^2} = \frac{2[1 - 4 \sin^2 \theta_W^{eff}]}{1 + [1 - 4 \sin^2 \theta_W^{eff}]}$$

where $a_v$ ($a_e$) is a vector (electron neutral current axial) coupling related to the decay. The anticipated precision for $\sin^2\theta_W$ SuperB is $\sim 2 \times 10^{-4}$, and it should be possible to measure the $b-$quark vector coupling with a comparable precision to the SLC/LEP measurement [1].

There are other experiments either performing or proposing to make measurements of $\sin^2\theta_W$ in the coming years. These include the JLab based QWeak experiment ($\sqrt{s} = 0.173$ GeV), and the LHCb upgrade ($Z$ pole). Belle II does not have a polarised beam, and so it won’t be possible to make a measurement of $\sin^2\theta_W$, however that experiment will be able to improve our knowledge of the axial coupling related to this fundamental parameter by measuring the forward-backward asymmetry. This will be a useful input to the Super Flavour Factory precision electroweak physics programme. Improved measurements of $\sin^2\theta_W$ can be used to improve our understanding of precision electroweak predictions based on the SM, or alternatively as constraints on scenarios of physics beyond the SM. In particular precision measurements are sensitive to models of NP with $Z'$ bosons.

7. Direct searches and exotica

Most of the NP searches at SuperB are indirect, where it is not possible to manifest the new particles in the laboratory. However there are models where it would be possible to directly produce NP particles in low energy $e^+e^-$ interactions, and infer something about the type of new physics leading to their existence. This area is briefly discussed here, and more details can be found in [1].

**Dark Matter** The expectation that Dark Matter exists is well known to be motivated by models of the rotation of spiral galaxies, where significant amounts of undetected matter must exist in order to explain the visible part of the galaxies. As a result there are a number of experiments dedicated to searches for signs of the halo dark
matter postulated to exist in the Milky Way, some of which should be local to the Earth. While SuperB is unable to contribute to searches for halo dark matter, it is possible that small amounts of Dark Matter could be created in low energy $e^+e^-$ collisions. These would be manifest through the enhancement of rates for decays to final states with invisible particles such as those discussed in Section 5.3 and analogues in $B_d$ and $B_s$ decays.

**Dark Forces** A relatively recent theoretical development is the scenario that there could be a scalar field related to the so-called ‘Dark Sector’. One of the predictions of these scenarios is a GeV scale particle that decays into dark photons, which can subsequently affect the kinematic distributions and rates of rare processes. Experimental signatures that can be used to search for evidence of the dark sector include meson decays into multi-lepton final states. A recent review of these results can be found in Ref. [105].

**Light Scalar Higgs** The SM Higgs is known to have a mass above $114 \text{ GeV}/c^2$, and both the Tevatron and LHC are actively searching for the existence of such a particle. However if or when the Higgs is found, this particle itself introduces problems into the theory via self-coupling, and would motivate some NP scenario that could involve the introduction of supersymmetric particles, or multiplets of Higgs particles. In many scenarios of new physics with multiple Higgs', where one of these may be a light neutral particle that has not yet been ruled out by data from LEP and the $B$ Factories. In this scenario light means $< 10 \text{ GeV}/c^2$. This light scalar Higgs is denoted by $A^0$ is expected to decay predominantly into charged lepton pairs, where the most probably final state would be $\tau^+\tau^-$. There have been a number of recent searches for such particles by the $B$ factories [106, 107].

Many direct searches for NP have been made by the current $B$ factories, and it will possible for SuperB to make significant improvements on the limits obtained, where for example one would typically assume an order of magnitude improvement on searches for dark matter candidates. The improvement on $A^0 \rightarrow \ell^+\ell^-$ transitions in decays of $\Upsilon$ mesons will depend on the integrated luminosity obtained for the various $\Upsilon(nS)$ resonances.

7.1. Lepton Universality

Using the same experimental signatures of light mesons $M^0$ decaying into di-lepton final states that are required for light Higgs searches to test Lepton universality (LU). In the SM the coupling strength associated with lepton vertices is common and the branching fractions of some $M^0$ into a di-lepton final state are equal up to factors related to the masses of leptons in the final state. The set of measurements comparing ratios of branching fractions, corrected for the lepton mass-difference therefore provides a measure of the lepton coupling, and any deviation from a common value could indicate a violation of LU. As the lighter leptons can undergo bremsstrahlung, it is
necessary to ensure that radiative effects are properly accounted for when performing such measurements. The results of recent tests of LU in $\Upsilon(1S)$ decays provides a test at the percent level $^{[108]}$. Tests at the sub-per mille level using $\tau$ decays have also been reported $^{[109]}$.

8. Other measurements

There is a vast potential to perform other measurements that are not classified as either a golden mode, precision CKM, or SM measurement. These other measurements include hundreds of possible decays of $B$, $D$, $\tau$, $\Upsilon$, and $\psi(3770)$ as well as studies of initial state radiation processes, and both conventional and exotic spectroscopy not discussed here. It should be noted that the physics programme at other resonances above the $\psi(3770)$ is under study, and has not been discussed here. A partial description of many of these possibilities can be found in Refs. $^{[1]} [13][14]$, and a more comprehensive summary will be discussed in the context of results of existing experiments in the forthcoming Physics of the B Factories book currently in preparation $^{[61]}$. SuperB will integrate 150 (75) times the data of $BaBar$ and Belle enabling a significant improvement in precision of these other measurements, and it is expected that during the lifetime of this experiment a number of new areas will be developed.

9. Interplay between measurements

A priori we don’t know the structure of physics beyond the SM, and we only have model-based lower limits on the possible energy scale of new particles based on naturalness arguments. The basis of naturalness is to assume that couplings in a model of nature are not fine tuned to small values, but may take arbitrary values as large as $O(1)$. Such arguments are used set a scale of electroweak symmetry breaking at 1TeV. On considering the historical development of the SM as described in Section $^{[11]}$ it is also possible to use flavour changing processes to probe higher energies via the contribution of virtual effects to the total amplitude of a rare process. In the case of $B^0$-$\bar{B}^0$ mixing a system with an energy of 5.28 GeV was used to detect the presence of the top quark, which is now known to have a mass of $172 \pm 0.9 \pm 1.3 \, GeV/c^2$ $^{[8]}$. One can perform a similar exercise to constrain possible a NP energy scale $\Lambda_{NP}$, again using rare decays and flavour changing processes. Such constraints are model dependent, and depending on the model, the scale of new physics can be placed between 10 and 100TeV. An energy scale of 1TeV or below can only be obtained by setting flavour parameters in the NP sector to zero. Such models are known as Minimal Flavour Violation (MFV) models. The sources of CPV in a MFV model are the same Yukawa couplings from the Higgs sector that result in the CKM matrix. Given that there is a rich texture in nature related to the flavour changing processes, for both quarks and neutrinos, it may seem improbable that any complex NP sector, such as SUSY would be completely flavour blind, with all new CP violating phases arbitrarily set to zero. Thus there is a
tension between well motivated naturalness arguments giving an energy scale of 1 TeV for the electroweak symmetry breaking, and our expectation that new physics might have a rich texture related to flavour changing processes in analogy with what we have observed so far in the SM. Experimental input is required in order to move forward on both the high-energy and flavour fronts. At the time of writing this report, there has been no significant signature for NP encountered at the LHC in order to guide this exploration. The lack of a discovery has already started to have ramifications for flavour blind scenarios of NP.

In analogy with the pioneering work of Cabibbo in developing quark-mixing phenomenology [3], if we are to determine the structure of any underlying new physics scenario that may provide a realistic description of nature at high energy, we must combine constraints from a number of different measurements. Thus in order to optimise our progress in this endeavor, we need to make as many independent measurements of theoretically clean observables that might be affected by NP as possible. Section 9.1 discusses some of the ways currently envisaged to elucidate the structure of the NP Lagrangian from rare processes based on both observed deviations from SM expectations and results consistent with the SM. Section 9.2 discusses the mass-insertion hypothesis and how one can relate flavour observables to $\Lambda_{NP}$. The three generation mixing matrix can be used as a reference point to search new NP as discussed in Section 9.3.

9.1. Reconstructing the new physics Lagrangian

The main purpose of SuperB is to try and elucidate the structure of new physics at a level that goes beyond anything currently possible. Not only can the existence of an unknown heavy particle directly modify expectations for many of the modes to be studied, but the way that such a particle interacts with the quarks and charged leptons can be used to infer something about coupling constants associated with such interactions. The phenomenology that is possible using data from SuperB is far richer in terms of understanding flavour couplings, than is possible at the energy frontier machines, whereas the latter excel when it comes to direct probes of NP. Given the centre of mass at SuperB is of the order of either 3.8 or 10.6 GeV, it is not possible to directly produce high energy particles in this experiment, however it should be noted that the indirect sensitivity of many processes goes up to $\sim 100$ TeV. In contrast the LHC is capable of directly probing up to energies of $\sim 1$ TeV. To complement its indirect search capability, SuperB will be able to make direct searches for light Higgs and Dark Matter particles (with masses below 10 GeV/c$^2$) that would be unobservable at the LHC. In all of these respects the physics programme of the LHC and SuperB complement each other greatly in the search for a deep understanding of new physics.

The path to enlightenment taken will depend on the outcome of a set of measurements rather than by a single channel. As a result we are faced with a response matrix of measurements versus new physics scenarios. The reason for this is that a
priori we do not know which model of NP best describes nature, and so one must look at both positive and negative signatures of a given model in order to identify or reject it. The collection of observables and models forms a golden matrix, a subset of which is shown in Table 5. While any existing new physics scenarios can be considered as part of this matrix, these are limited to a few specific benchmark examples to illustrate the process.

### 9.2. The new physics energy scale: $\Lambda_{NP}$ and mass insertions

As briefly mentioned in Section 4, flavour observables can be used to infer the energy scale of NP in different models. In terms of a general SUSY scenario with mass insertions (MI), one has a set of squark mixing matrices for interactions with different helicities (left or right-handed). These are analogues of the CKM matrix where the off-diagonal terms describe transitions from the $i$th to the $j$th generation generation of squark. These are parameterised by $(\Delta_{ij})_{kl}$, where the $k,l = L,R$ indices denote which combination of left or right handed interactions are described. In general one can constrain a number of the $(\delta_{ij})_{LR}$ parameters using flavour observables where

$$
(\delta_{ij})_{LR} = (\Delta_{ij})_{LR}/\Lambda_{NP}.
$$

(20)

Here the parameters $\delta$ are simply constrained to be less than one. This raises an interesting point related to the use of results from the intensity and high energy frontier experiments, as illustrated by the following example.

One can combine inclusive measurements of the branching fractions of $b \to s\gamma$ and $b \to s\ell^+\ell^-$ with the direct $CP$ asymmetry in $b \to s\gamma$ decays at SuperB to constrain the

| Observable/mode | $H^+$ high tan $\beta$ | MFV | non-MFV | NP $Z$ penguins | Right-handed currents | LTH | SUSY |
|-----------------|---------------------|-----|--------|-----------------|------------------------|-----|------|
| $\tau \to \mu\gamma$ | $\tau \to \ell\ell\ell$ | $\beta$ | $A_{CP}(B \to Xs\gamma)$ | $BR(B \to Xs\gamma)$ | $BR(B \to Xs\ell\ell)$ | $B \to K^{(*)}\ell\ell$ | $a_{sl}$ $(B_s \to D^{(*)}\ell\nu)$ |
| $B \to \tau\nu, \mu\nu$ | $B \to K^{(*)}\ell\ell$ | $S$ in $B \to K^{(*)}_0\pi^0\gamma$ | $\beta$ | $A_{CP}(B \to Xs\gamma)$ | $BR(B \to Xs\gamma)$ | $BR(B \to Xs\ell\ell)$ | $B \to K^{(*)}\ell\ell$ | $a_{sl}$ $(B_s \to D^{(*)}\ell\nu)$ |

Table 5. Golden matrix of some of the observables/modes that can be measured at SuperB. The effect of a given model is indicated by the number of stars: $\star\star\star$, $\star\star$, $\star$. The more stars the larger the effect. Entries with $\dagger$ indicate that precision measurement of CKM is required. This table has been compiled based on Refs. [12] and [110].
The Physics of Heavy Flavours at SuperB

complex MI parameter \((\delta_{23})_{LR}\) as discussed in Refs [III 112]. If one assumes squark and gluino masses are similar, then one can relate the magnitude of this coupling to the SUSY mass scale in a straightforward way as shown in Figure 7. Light SUSY has been ruled out by the LHC, which as one can see from the figure, implies a non-trivial value for \((\delta_{23})_{LR}\). The LHC should be able to probe up to masses of a few TeV by the end of this decade. If \(\Lambda_{NP}\) is ultimately fixed to a given value by a direct discovery on this time-scale, the combination of flavour observables from SuperB can be used to make a precision measurement of the real and imaginary parts of \((\delta_{23})_{LR}\) and teach us some of the details of the corresponding model. If however the LHC fails to find SUSY, the same combination of flavour observables places an orthogonal constraint on the \((\delta_{23})_{LR} - m_{\tilde{g}}\) plane, and in effect would place an upper limit on \(\Lambda_{NP}\). For example a 5\% \((\delta_{23})_{LR}\) constraint bounds \(\Lambda_{NP} \leq 3.5\text{TeV}\). In such a scenario, results from SuperB could be used as a guide the physics programme of the general purpose LHC upgrade experiments, in terms of data samples required to have sufficient energy reach for a direct discovery. This interplay requires both high energy, and high intensity inputs in order to obtain the maximal level of information to understand the model. One can typically access scales of \(\Lambda_{NP} \sim 10\text{TeV}\) using flavour observables in this scenario.

![Figure 7](image)

**Figure 7.** The constraint on the \((\delta_{23})_{LR} - \text{gluino mass plane}\) obtained using the MI hypothesis in SUSY (figure from Ref [13]).
9.3. Precision SM constraints

In 1972 Kobayashi and Maskawa [4] extended Cabibbo’s quark-mixing model to three generations. On doing this they realised that $CP$ violation could be naturally introduced into theoretical descriptions of particle physics. The experimental confirmation of this extended theory, i.e. the CKM mechanism, by the $BaBar$ experiment at SLAC in the USA, and the Belle experiment at the KEK laboratory in Japan, resulted in Kobayashi and Maskawa being awarded a Nobel Prize in 2008. This experimental determination was the completion of a set of direct tests of the CKM mechanism with a precision of about 10%. The tests were measurements of the angles $\alpha$, $\beta$, and $\gamma$ of the unitarity triangle, and they were complemented by a number of indirect tests. This work established that the leading order contribution to $CP$ violation in the quark sector of the SM is a result of the CKM matrix but can not rule out NP effects below this level. The observed amount of $CP$ violation in the SM is not sufficient to describe the required matter-antimatter asymmetry in the Universe, motivating new sources of $CP$ violation in quark or lepton sectors. Indeed there are a number of models that can accommodate generic NP contributions that would affect the SM picture of the Unitarity Triangle. Super Flavour Factories will be able to over constrain the CKM matrix through both direct and indirect measurements, to a precision of about 1% as indicated in Fig. 8 (from Ref. [1]). Trivial extensions of the SM that one can test in a straightforward way, includes SM4: models where a fourth generation of fermions are introduced to the SM. On doing this one introduces five new parameters to the CKM matrix, two of which are additional $CP$ violating phases. The SuperB and Belle II experiments are the most versatile of all of the existing and proposed flavour physics experiments for performing such a test. Looking at current data, there are several tensions between measured observables at the level of $2.5\sigma$, and it is impossible to simultaneously bring all of these constraints into agreement with each other and the SM expectation [113, 114]. These observables are $\sin 2\beta$, $|V_{ub}|$, and the measured branching fraction of the rare decay $B \rightarrow \tau \nu$. Furthermore, there are discrepancies between inclusive and exclusive measurements of $|V_{ub}|$ and $|V_{cb}|$ that can only be investigated experimentally to a higher precision at a Super Flavour Factory. While LHCb is expected to improve the precision of our knowledge of $\sin 2\beta$ from the current precision of $0.8^\circ$ to $0.5^\circ$, unfortunately that experiment will not be able to study these other problematic observables as they are all final states containing a neutrino. Thus a Super Flavour Factory is needed to resolve if these discrepancies are a first manifestation of NP or simply the result of statistical fluctuations.

SuperB will be able to perform a precision test of the electroweak sector through the measurement of $\sin^2 \theta_W$ at a centre of mass energy of 10.58 GeV. The precision with which this measurement can be made is comparable to the LEP/SLC constraint. At SuperB the $e^+e^- \rightarrow b\bar{b}$ measurement is in a region free from hadronic uncertainties related to $b$ fragmentation unlike measurements at the $Z$ pole. This measurement will feed into the the precision electroweak fits that are currently used to predict the Higgs
mass in the framework of the SM. Thus the Super$B$ measurement will feed into both Higgs searches, and any subsequent attempts to interpret Higgs candidates found at the LHC.

10. Summary

The great challenges in fundamental physics of today range from understanding the evolution of the Universe from the Big Bang to the present day through the study of sub-atomic particles and forces at play during that time. New effects are expected to be uncovered while studying energy densities that existed in the fleeting moments after the Big Bang, and these may be related to our understanding of matter-antimatter asymmetries, Dark Matter, and the existence of unknown particles. In order to improve our understanding of nature these different issues should not be treated as disparate strands each with their own distinct motivation, but rather as distinct constraints on nature, that when combined may yield a more lucid view of the laws of both particle physics and of the Universe. By understanding any of these issues at a deeper level in
nature, physics would take one step toward a Grand Unified Theory.

This process starts with the need to reconstruct a viable Lagrangian for new physics that not only includes the physical particles that are the main building blocks of the Universe, but also the underlying rules defining the behavior of the underlying forces, and hence how these building blocks interact. Many ingredients will be required to start reconstructing the new physics Lagrangian and these will come from a number of different experiments, including terrestrial and satellite based astronomy, intensity frontier experiments like SuperB, and energy frontier experiments at the Tevatron and LHC. There are a number of precision flavour physics experiments taking data, or in construction around the world that will also play a role in elucidating the structure of physics beyond the SM.

SuperB is one of these experiments and it will provide many of the necessary ingredients required to start reconstructing the detailed texture of new physics, and in turn will play a vital role in advancing us toward a higher theory of nature. Physics topics that will be studied at SuperB range from flavour changing quark interactions, and searches for new phenomena like charged lepton flavour violation and CP violation in the lepton sector, to searches for Dark Matter candidates and indirect searches for new particles at energy scales far beyond the reach of the Tevatron and the LHC. These topics cover many aspects of physics, and have implications in areas beyond particle physics. It is interesting to note that this conclusion holds true irrespective of the findings of SuperB: if no deviations from the Standard Model are found, the structure of the Lagrangian is strongly constrained, which is also the case if clear discoveries of new physics were to be made. In this sense SuperB is a discovery experiment – not necessarily discovery of new particles, but discovery of fragments of the underlying structure of the theory. Consequently, in addition to placing stringent constraints on the type of new physics that could be possible in nature, measurements from SuperB will be able to perform many precision tests of the Standard Model of particle physics.

In summary the SuperB experiment could start taking data as early as 2016, and make a diverse set of measurements of flavour related observables. It is expected that SuperB will have recorded 75 fb\(^{-1}\) in five years of nominal data taking, corresponding to 75 billion \(B\), 90 billion \(D\), and 70 billion \(\tau\) pairs for analysis. The sensitivities that one will be able to reach with such data samples can be as low as \(\mathcal{O}(\text{few} \times 10^{-10})\) for clean processes. It is worth noting that there are also important measurements that will be made at SuperB that impact the physics reach of other experiments. Two examples of such a measurement is the strong phase as a function of position in the Dalitz plot for decays such as \(D^0 \rightarrow K^0_S \pi^+ \pi^-\) that feed into \(D\) mixing and \(\gamma\) measurements, and the branching fraction of \(D^0 \rightarrow \gamma \gamma\), which is required in order to disentangle long distance SM contributions from NP enhancements of \(D^0 \rightarrow \mu^+ \mu^-\). The precision CKM measurements that will be performed at SuperB can be used to open over-constrain the SM, and if one finds measurement consistent with theory, then this also provides the gateway for NP searches at other experiments. For example the rare kaon decay experiments searching for \(K \rightarrow \pi \nu \bar{\nu}\) will be able to use their results to test
the SM, however if CKM uncertainties are reduced, one could improve the sensitivity of those channels to NP. Ref. \[12\] contains a succinct summary of the expected precisions obtainable for the core measurements to be made at SuperB.

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