SuperB, the Super Flavor Factory

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Abstract. Heavy flavor physics measurements, in particular $B$ and $\tau$ physics results from the $B$ Factories, currently provide strong constraints on models of physics beyond the Standard Model. Super$B$, a next generation asymmetric collider with 50 to 100 times the luminosity of existing colliders, can, in a dialog with LHC and ILC, provide unique insights into New Physics phenomena seen at those machines.

1. Introduction
The two asymmetric $B$ Factories, PEP-II and KEKB, and their companion detectors, $BABAR$ and Belle, have produced a wealth of flavor physics results, subjecting the quark and lepton sectors of the Standard Model to a series of stringent tests, all of which, as of this writing, have been passed.

By measuring $CP$-violating asymmetries in the $B$ meson system for the first time, $BABAR[1]$ and Belle[2] have shown that the CKM phase accounts for all $CP$-violating phenomena in $b \rightarrow c$ and $b \rightarrow u$ decays. While the $BABAR$ and Belle measurements, as well as other results on very rare decays, have placed stringent constraints on physics beyond the Standard Model, there is a substantial literature demonstrating that New Physics beyond the Standard Model, be it supersymmetry, extra dimensions, or other Standard Model extensions, can have measurable effects in the flavor sector. Measuring these effects typically requires data samples substantially larger than the current $B$ Factories will provide. Some of these measurements are accessible at the LHC [3], but the most promising approach to this physics would be a very high luminosity asymmetric $B$ Factory, a Super $B$ Factory.

2. Physics Objectives and Capability
The current $B$ Factories will integrate a combined luminosity of less than 2 ab$^{-1}$. At this level of precision, we will improve our present knowledge of SM-related quantities and place more stringent bounds on New Physics (NP) parameters. This precision is not, however, sufficient to cleanly measure NP effects. This shortcoming thus provides the primary for undertaking a new generation of $e^+e^-$ experiments that will allow us to measure effects of New Physics on the decays of heavy quarks and leptons. A detailed picture of the observed pattern of such effects will be crucial to gaining an understanding of any New Physics found at the LHC. Most studies of the capability of the LHC to distinguish between, for example, models of supersymmetry breaking have emphasized information accessible at high $p_T$. Many of the existing constraints on models of New Physics, however, come from flavor physics. Improving limits and teasing out new effects in the flavor sector will be just as important in constraining models after New Physics has been found as it has been in the construction
of viable candidate models in the years before LHC operation. If the relevant scale is 1 TeV or less, 50 to 100 ab$^{-1}$ are required to make measurements precise enough to unambiguously isolate New Physics effects in the flavor sector. This sets the scale for a new $e^+e^-$ initiative: a Super $B$ Factory with a luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$ can collect 15 ab$^{-1}$ in a New Snowmass Year [4], or 75 ab$^{-1}$ in five years. A comprehensive discussion of the physics program of Super$B$ can be found in Refs. [5] and [6]. We briefly summarize the physics capabilities of Super$B$ below.

A primary tool for isolating new physics is the time-dependent analysis of decay channels that can only proceed through penguin diagrams, such as the $b \rightarrow s \bar{s}s$ processes $B^0 \rightarrow \phi K^0$ and $B^0 \rightarrow (K \bar{K})_{CP} K^0$ or the similar $b \rightarrow d \bar{s}s$ transitions $B^0 \rightarrow \eta' K^0$, $B^0 \rightarrow f^0 K^0$, $B^0 \rightarrow \pi^0 K^0$, $B^0 \rightarrow \rho^0 K^0$, and $B^0 \rightarrow \omega K^0$. The dominant contribution to these decays is the combination of CKM elements $V_{tb}V_{ts}$ and $V_{cb}V_{cs}$, with respect to $V_{cb}$. New heavy particles contribute new loop amplitudes with new phases that can contribute to the $CP$ asymmetry, so that the $S$ coefficient of the time-dependent analysis could be substantially different from $\sin2\beta$. For this comparison, one has to take into account a Standard Model uncertainty due to a penguin contribution with an up quark running in the loop, which is expected to be of order $\lambda_{up}^2 \approx 5\%$. The $B$ Factories have explored many of these channels, most with poor statistics; as yet no definite conclusions can be drawn. It is clear, however, that we are potentially at the beginning of a very interesting era in which we can begin to probe New Physics effects beyond the Standard Model in the flavor sector. With 50 ab$^{-1}$, the measurement error on many $b \rightarrow s \bar{s}s$ decays will be at the same level as we have now for $b \rightarrow c \bar{c}s$, which is of the same order as the theoretical uncertainties (see Table 1.)

### Table 1. Measurement precision for $CP$ asymmetries in rare decays sensitive to New Physics.

| CPV in Rare Decays | $e^+e^-$ Precision (%) |
|-------------------|------------------------|
| $S(B^0 \rightarrow \phi K_S^0)$ | $\approx 5\%$ | 19.6 | 7.1 | 3.2 |
| $S(B^0 \rightarrow \eta' K_S^0)$ | $\approx 5\%$ | 7 | 2.5 | 1 |
| $S(B^0 \rightarrow K_S^0 \pi^0)$ | | 10 | 3.7 | 1.6 |
| $S(B^0 \rightarrow K_S^0 \pi^0 \gamma)$ | SM: $\approx 2\%$ | 13.5 | 4.9 | 2.2 |
| $A_{CP}(b \rightarrow s\gamma)$ | SM: $\approx 0.5\%$ | 1.2 | 0.4 | 0.2 |
| $A_{CP}(B \rightarrow K^\ast \gamma)$ | SM: $\approx 0.5\%$ | 0.7 | 0.3 | 0.1 |

This precise measurement of channels mediated by loop diagrams, both in $b \rightarrow s \bar{s}s$ and $b \rightarrow d \bar{s}s$ transitions, will allow the determination of the couplings for New Physics contributions, such as the mass insertion parameters $\delta_{23}$ and $\delta_{13}$ in SUSY scenarios [5]. For instance, a mass insertion $\delta_{23}$ with an imaginary part of $\sim 2\%$, with an average squark mass in the range $\sim 350$ to $450$ GeV can produce a deviation of $S(\phi K_S)$ of the order of $20\%$ with respect to $S(J/\psi K_S)$. In order to establish a $20\%$ difference at the $3\sigma$ level, i.e. measuring $A_{CP}(\phi K_S) = 0.50 \pm 0.03$, and assuming the current per event sensitivity, we need to a statistical precision corresponding to at least 30 ab$^{-1}$. Other constraints on NP can be obtained by studying similar channels. For instance, the radiative penguin decays $b \rightarrow s\gamma$ provide a particularly clean environment. Direct $CP$ violation in these decays is expected to be $< 0.5\%$ in the Standard Model, but could be enhanced by New Physics contributions to the penguin loop. Recent inclusive and exclusive measurements are just beginning to constrain such contributions. The information they provide at this point exclude the possibility of huge variations respect to the Standard Model expectations. However, because of the limited statistics, the possibility of observing an
enhancement of an order of magnitude still exists; only SuperB can provide the statistics required to resolve the question. With larger samples it would be interesting to measure the direct CP asymmetry in $b \to d$ decays. New Physics couplings with opposite helicity can be explored by studying the photon polarization in the $b \to s \gamma$ transition, measuring, for example, time-dependent CP violation in $B^0 \to K^0\pi^0 \gamma$, or the Dalitz plot distribution of the $K\pi\pi$ system in $B^0 \to K\pi\pi\gamma$. Both measurements will continue to be statistically limited even at $75 \text{ ab}^{-1}$. Table 2 summarizes several of the crucial measurements to be made in $b$ decays, specifying the various NP scenarios in which these measurements could be decisive.

**Table 2:** Golden modes in different New Physics scenarios. An X indicates the golden channel of a given scenario. An O marks modes which are not the “golden” one of a given scenario but can still display a measurable deviation from the Standard Model. The label CKM denotes golden modes which require the high-precision determination of the CKM parameters achievable at SuperB.

| $H^+$ high tan$\beta$ | Minimal FV | Non-Minimal FV (1-3) | Non-Minimal FV (2-3) | NP Z-penguins | Right-Handed currents |
|------------------------|------------|----------------------|----------------------|---------------|-----------------------|
| $B(B \to X_s \gamma)$  | X          | O                    | O                    |               |                      |
| $A_{CP}(B \to X_s \gamma)$ | X          | O                    | O                    |               |                      |
| $B(B \to \tau\nu)$   | X-CKM      | O        | O                    | O             |                      |
| $B(B \to X_s \bar{\ell}\ell)$ | O        | O        | O                    | O             |                      |
| $B(B \to K\nu\nu)$ | O          | X        |                      |               |                      |
| $S(K_S\pi^0 \gamma)$ | X          |                      |                      |               |                      |
| $\beta$                | X-CKM      | O        |                      |               |                      |

It is clear that $\tau$ physics will assume great importance as a probe of physics beyond the Standard Model. SuperB includes in the baseline design an 85% longitudinally polarized electron beam and spin rotators to facilitate the production of polarized $\tau$ pairs. This polarization is the key to the study of the structure of lepton-flavor-violating couplings in $\tau$ decay, as well as the search for a $\tau$ EDM, or for CP violation in $\tau$ decay. Charged lepton flavor-violating $t$ decays are unobservably small in the Standard Model, but many NP extensions predict decays such as $\tau \to \ell\gamma$ or $\tau \to \ell\ell\ell$ at the $10^{-9}$ to $10^{-10}$ level, which should be measurable at SuperB. In these reactions, the polarization serves to reduce backgrounds, and can also be used to determine the Lorentz structure of the lepton flavor-violating coupling in the event that the decay is found [7].

The recent observation of large $D^0\bar{D}^0$ mixing raises the exciting possibility of finding CP violation in charm decay, which would almost certainly indicate physics beyond the Standard Model. SuperB can attack this problem in a comprehensive manner, with high luminosity data samples in the $\Upsilon(4S)$ region and at the $\psi(3770)$ resonance, as the collider is designed to run at lower center-of-mass energies, at reduced luminosity. With very short duration low energy runs, a data sample an order of magnitude greater than that of the final BES-III sample can readily be obtained.
3. The SuperB Machine Design

Reaching a luminosity of $10^{36}$ with a conventional collider design extrapolated from PEP-II or KEKB is difficult; beam currents and thus power consumption are very high, and the resulting detector backgrounds are formidable. The design of SuperB provides an elegant solution to the problem; SuperB can reach unprecedented luminosity with beam currents and power consumption comparable to those at PEP-II. Table 3 shows a selection of machine parameters for SuperB, compared with the recently abandoned SuperKEK-B design.

| LER/HER | Unit | SuperB [5,8] | SuperKEK-B [9] |
|---------|------|--------------|----------------|
| $E^+ / E^-$ | GeV | 4/7 | 3.5/8 |
| Circumference | m | 1800 | 3016 |
| Luminosity | cm$^{-2}$ s$^{-1}$ | $1 \times 10^{36}$ | $4 \times 10^{35}$ |
| $I_+/I_-$ | amperes | 2.00/2.00 | 9.4/4.1 |
| $N^+$ particles | $10^6$ | 6/6 | 11.8/5.1 |
| $N^-$ bunches | 1250 | 5018 |
| $I^+$ bunch | mA | 1.6 | 1.9/0.82 |
| Crossing angle $\theta/2$ | mrad | 30 | 15 |
| $\beta_x^*$ | mm | 35/20 | 200 |
| $\beta_y^*$ | mm | 0.21/0.37 | 3 |
| $\epsilon_x$ | nm | 2.8/1.6 | 24 |
| $\epsilon_y$ | pm | 7/4 | 45 |
| $\sigma_x$ | mm | 9.9/5.7 | 42 |
| $\sigma_y$ | nm | 38/38 | 367 |
| $\sigma_z$ | mm | 5/5 | 3 |
| $\xi_x$ x tune shift | 0.005/0.0017 | 0.36 |
| $\xi_y$ y tune shift | 0.125/0.126 | 0.43 |
| RF wall plug power | MW | 18 | 65 |

SuperB achieves its very luminosity with currents comparable to those at the existing B Factories. The feat is accomplished by having very low emittance beams, such as those required for the damping rings of the ILC. This allows the beams to be focused to a very small spot size at the interaction.
region, resulting in high luminosity. In addition, a new final focus configuration, called a ‘‘crab waist’’ is employed. This increases the achievable luminosity, but, more importantly, produces a rather stable tune plane. The recently completed test of the crabbed waist concept at the DAΦNE collider at Frascati was very successful. With the final focus rebuilt to incorporate a crabbed waist, it has been clearly demonstrated that beam sizes at collision can be reduced and luminosity thereby increased by more than a factor of two, with no reduction in specific luminosity.

Aside from higher luminosity at much lower power consumption, SuperB also offers a polarized electron beam and is capable of running at lower center-of-mass energies, both of which significantly increase the physics reach of the project.

SuperB will be built on the campus of the second Rome University at Tor Vergata, close to the INFN Frascati laboratory. A free electron laser, SPARX, is already in an early phase of construction on this site. The SuperB design incorporates a large number of PEP-II and BABAR components; discussions with DOE and SLAC on the details of such a transfer are ongoing. The project has already produced a Conceptual Design Report [5], an update of the physics section of that report, in response to questions from a review committee, and is presently hard at work on a Technical Design Report, that will provide additional details on the accelerator and detector design and on physics opportunities.

4. Conclusion

The new SuperB collider promises to provide the unprecedentedly high luminosity, an increase of nearly two orders of magnitude over current colliders, that will enable a series of unique measurements in $b$, $c$ and $\tau$ decay that have sensitivity to New Physics effects in the flavor sector. These measurements complement results anticipated from the LHC experiments and will be crucial in arriving at a detailed understanding of New Physics uncovered at the LHC.

References

[1] B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 99 171803 (2007).
[2] K.-F. Chen et al. (Belle Collaboration), Phys. Rev. Lett. 98 031802 (2008).
[3] S. Vecchi (LHCb Collaboration), Proceedings of the Second Workshop on Theory, Phenomenology and Experiments in Heavy Flavour Physics, Nucl. Phys. B - Proceedings Supplements, 185, 213, (2008).
[4] The New Snowmass Year is an updating of the convention that multiplying peak luminosity by a ‘‘year’’ containing $10^7$ seconds provides a good measure of actual running time, the effects of accelerator and detector down time, dead time effects and the difference between peak and average luminosity. The PEP-II/ BABAR experience is well-described by a "New Snowmass Year" having $1.5 \times 10^7$ seconds.
[5] SuperB Conceptual Design Report, arXiv:0709.0451v2 [hep-ex].
[6] Proceedings of SuperB Workshop VI: New Physics at the Super Flavor Factory, arXiv:0810.1312v2 [hep-ph].
[7] B.M. Dassinger, Th. Feldmann, Th. Mannel and S. Turczyk, JHEP 0710:039 (2007). A. Matsuzaki and A.I. Sanda, Phys.Rev. D77, 073003 (2008).
[8] See Ref. [5] and updated parameters at http://agenda.infn.it/materialDisplay.py?contribId=1&amp;sessionId=1&amp;materialId=slides&amp;confId=959.
[9] Letter of Intent for KEK Super B Factory, J. W. Flanagan and Y. Ohnishi, eds. (2004). See also updated parameters at http://superb.kek.jp/.