Super$B$ Report

Intensity Frontier Workshop

1 Introduction

The Standard Model (SM) has been very successful in explaining a wide range of electroweak and strong processes with high precision. In the flavor sector, observation of CP violation in B decays at *BABAR* and Belle, and the extraordinary consistency between the CKM matrix elements, established the SM as the primary source of CP violation in nature (leading to the 2008 Nobel Prize in physics). However, the remarkable success of the SM in describing all known flavor-physics measurements presents a puzzle to the search for New Physics (NP) at the LHC. New particles below the TeV scale should contribute to low-energy processes through virtual loop diagrams and cause observable effects in the flavor sector. The lack of any such effects suggests that either the NP mass scale is much higher than the TeV scale, or that NP flavor-violating operators are suppressed. In either scenario, flavor physics at the intensity frontier is poised to remain a central element of particle physics research in the coming decades.

The INFN-sponsored Super$B$ project [1–3] in Italy is an asymmetric-energy electron-positron collider in the 10 GeV energy region with an initial design average luminosity of $10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which will deliver up to $75\,\mathrm{ab}^{-1}$ in five years of operation (see Fig. 1 for details) to a new Super$B$ detector derived from the existing *BABAR*. A new innovative concept in accelerator design, employing very low-emittance beams and a "crab waist" final focus, makes possible this large increase (100-fold) in instantaneous luminosity over present B Factory colliders with no corresponding increase in power consumption, and similar backgrounds for the detector. The increased luminosity, in a clean environment, greatly expands the science horizon of the Super$B$ facility beyond that of the B Factory experiments

Physics opportunities at Super$B$ span a wide range of topics, with the primary goal being observation of NP in processes involving bottom and charm mesons, lepton-flavor violation, and in the direct search for light exotic particles that could go unnoticed at the energy frontier. The remainder of this report describes in more detail the potential physics impact of Super$B$ concentrating on the heavy-quark sector (see Ref. [4] for a recent summary).

Parameter	Goal	Remark
Integrated Luminosity @ Υ(4S) (5 years)	75 ab^{-1}	1 year = 1.5 x 10^7 seconds (from PEP-II experience)
Average Luminosity (Top-up mode)	10^{36} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Flexible parameter space. Peak Lumi, upgradable to 4 x 10^{36} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Wall Plug Power	< 20 MW	Similar to PEP-II (22 MW)
Energy Range	Charm Threshold to above Υ(5S)	
Boost	$\beta\gamma$ = 0.23	Need 1 cm radius beampipe with first measurement at 1.5 cm
Longitudinal Polarization (e^-)	~80%	Enables τ CPT studies and improves LPV sensitivities

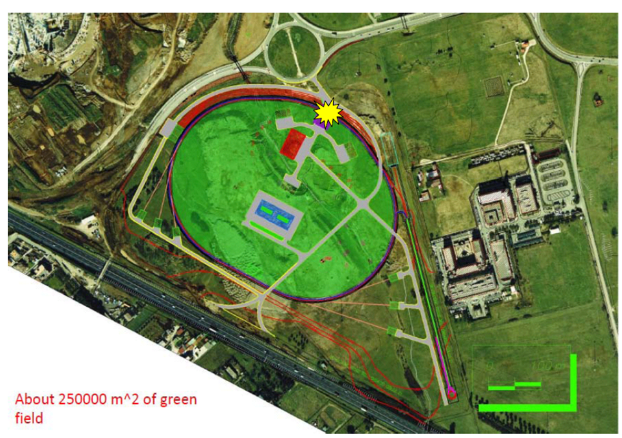

Figure 1: Super$B$ machine parameters (left) and a photo of the site (right) with a schematic layout of the machine overlaid.

2 B Physics

Super$B$ is expected to accumulate a sample of approximately 1.65×10^{11} B decays in five years. This will allow the study of rare B decays in experimentally clean e^+e^- collisions with unprecedented precision. The primary focus of the program is to search for signs of new physics in these decays, in particular those involving "penguin loops" that could include new high-mass particles. A set of theoretically well understood decays have been identified as the "Golden Modes" of the B physics program at Super$B$ (Table 1). Each of them are sensitive to NP at different levels, and to different types of NP, so that the suite of measurements is complementary. Examples of the NP models include an extended Higgs sector with charged Higgs Bosons (as occurs in SUSY), new interactions that either respect the CKM flavor structure (minimal flavor violating (MFV)) or not (non-MFV), and NP with righthanded currents. The NP Lagrangian can then be deduced from the matrix of observables. Essentially any significant new flavor couplings in the mass scale up to 10 TeV, and in some scenarios to 100 TeV, can be mapped out in this way.

The Golden B-decay modes include the leptonic decays $B \to \tau\nu, B \to \mu\nu$, in which the b and u quarks of the $B^\pm$ annihilate to a $W^\pm$. They are particularly sensitive to mass-dependent couplings, such as a charged Higgs, and the observation of $B \to \tau\nu$ at the existing B Factories already provides stringent constraints. Experimentally, the presence of neutrinos in the final state makes the measurements challenging. The recoil tagging technique in which the non-signal B of the $B\overline{B}$ pair is identified by a lepton from a semi-leptonic decay, or fully reconstructed in a hadronic decay, is effective in reducing backgrounds. These methods require that the detector be highly efficient and as hermetic as possible. It also requires the high statistics possible at Super$B$ to challenge the precision of the SM prediction.

Similarly the electroweak penguin decays with neutrinos in the final state $B \to K^{(*)}\nu\bar{\nu}$ are accessible with the recoil tagging technique, and sensitive to up-squark contributions in generic SUSY models. The companion electroweak penguin decays with electrons or muons in the final state $B \to K^{(*)}\mu^+(e^+)\mu^-(e^-)$ have been the subject of intense study at the B Factories, where hints of NP in the forward-backward asymmetry are being put to the test. A sample of 100,000 $B \to K^{(*)}\mu^+\mu^-$ events to be collected at Super$B$ will definitively find NP in these decays if it exists. The inclusive electroweak penguin process $B \to X_s l^+ l^-$ will also be studied with unprecedented precision, while enjoying similarly precise theoretical predictions. The electromagnetic and electroweak penguins are complementary in their sensitivity to NP, and the combination will provide a stringent test of the SM.

The electromagnetic penguin decay $B \to X_s\gamma$ has long been known to be highly sensitive to NP, with over 500 theoretical papers devoted to this possibility. The principal observables are the decay rates for inclusive and exclusive channels, direct CP asymmetries and the photon helicity via the mixing-induced CP asymmetry in $B^0 \to K^0_S\pi^0\gamma$ decays ($S_{K^0_S\pi^0\gamma}$). The photon helicity is particularly interesting, since it is sensitive to possible righthanded currents in the decay, whereas the SM predicts that the photon is strictly lefthanded. An intense collaborative theoretical effort has led to a precise SM prediction for $\mathcal{B}(B \to X_s\gamma)$ up to the four-loop level, which makes it an important test for physics beyond the SM. At Super$B$ it will be possible to measure this rate to a few percent, and the joint asymmetry $A_{cp}(B \to X_{s+d}\gamma)$ will also provide a clean observable to detect non-MFV couplings since it

Table 1: Experimental sensitivities for Super$B$ Golden Modes in the B sector: current results, Super$B$ sensitivity with $75\,\mathrm{ab}^{-1}$, and present theoretical estimate.

Observable	Now	Super$B$ Sensitivity	Theory (2011)
$\mathcal{B}(B \to \tau\nu)$ $(\times 10^{-4})$	1.64 ± 0.34	0.05	1.1 ± 0.2
$\mathcal{B}(B \to \mu\nu)$ $(\times 10^{-6})$	< 1.0	0.02	0.47 ± 0.08
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 80	1.1	6.8 ± 1.1
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 160	0.7	3.6 ± 0.5
$\mathcal{B}(B \to K^{*}\mu^+\mu^-)$ $(\times 10^{-6})$	1.15 ± 0.16	0.06	1.19 ± 0.39
$\mathcal{B}(B \to K^{*}e^+e^-)$ $(\times 10^{-6})$	1.09 ± 0.17	0.05	1.19 ± 0.39
$\mathcal{B}(B \to X_s\ell^+\ell^-)$ $(\times 10^{-6})$	3.66 ± 0.77	0.08	1.59 ± 0.11
$A_{\mathrm{FB}}(B \to K^{*}\ell^+\ell^-$	0.27 ± 0.14	0.04	-0.089 ± 0.020
$\mathcal{B}(B \to X_s\gamma)$ $(\times 10^{-4})$	3.55 ± 0.26	0.11	3.15 ± 0.23
$A_{\mathrm{CP}}(B \to X_{s+d}\gamma)$	0.060 ± 0.060	0.02	$\sim 10^{-6}$
S in $B^0 \to K^0_S\pi^0\gamma$	-0.15 ± 0.20	0.03	$\sigma_S \sim 0.10$
S in $B \to \eta' K^0$	0.59 ± 0.07	0.01	$\sigma_S \sim 0.015$
S in $B \to \phi K^0$	0.56 ± 0.17	0.02	$\sigma_S \sim 0.02$

is CKM suppressed.

Measurements of *CP*-violating asymmetries in decays to flavor eigenstates that are dominated by penguin processes probe NP effects in the interference of mixing and decay diagrams. In particular, the angle β will be measured precisely at Super$B$ with gluonic penguin modes such as $B \to \phi K^0$ and $B \to \eta' K^0$. The comparison to the extraction of β from the tree level $B^0 \to J/\psi K^0$ decay may reveal new *CP*-violating phases present in the penguin loop. Super$B$ will also accumulate an unprecedented dataset of $1\,\mathrm{ab}^{-1}$ at the $\Upsilon(5S)$, allowing for comprehensive studies of the decay rates for the B_s meson that are comparable in precision to the currently available results for $B_{u,d}$ meson. In addition, the semi-leptonic asymmetry $A^{\mathrm{s}}_{\mathrm{SL}}$ can be measured with high precision, and searches for rare B_s decays to neutral final states, such as $B_s \to \gamma\gamma$, could reach NP sensitivity. Such measurements can only be performed in the clean environment of a Super Flavor Factory.

Outside of the core program there is also a broad spectrum of interesting topics. Searches for extremely rare decays of B mesons that violate fundamental symmetries could reveal NP in a completely unexpected way. B mesons also provide a wonderful testing ground for low energy QCD. In particular the technology for lattice calculations has advanced significantly in recent years. The interplay of these calculations with experimental data may eventually make the reliable calculation of form factors routine. This would open up a new class of observables sensitive to NP.

3 Charm Physics

It has been pointed out many times [5-7] that detailed studies of CP invariance in charm decays, unique in having the only neutral system comprised of up-type quarks, can act as virtually zero-background searches for NP. The primary goals of the Super$B$ charm program are the observation of CP violation and the search for NP in decays that are highly suppressed in the SM. The clean environment at Super$B$, with $\sim 150\times$ the BABAR sample at $\Upsilon(4S)$ and (uniquely) $\sim 1,200\times$ the CLEOc sample at the $\psi(3770)$ will allow for detailed studies of charm processes, including both charged and neutral particles, which will be critical in building a complete understanding of any NP effects that may be reported. CP violation can be detected down to the tiny SM levels expected.

CP violation in charm processes can be observed in either time-averaged or time-dependent decay rate asymmetries [8]. Evidence for the former has recently been reported [9] by LHCb at the $\sim 1\%$ level in the difference between K^+K^- and $\pi^+\pi^-$ modes. Precise studies using more modes, some only open to Super$B$ or BelleII, will be required to understand this more fully. Asymmetries in D^0–$\overline{D}^0$ mixing can be parametrized by $|q/p|$ and $\phi_M = \arg(q/p)$, where q and p relate D^0 flavor and mass eigenstates. Measurements of these parameters across different decay modes can indicate whether CP asymmetry also arises in mixing. So far, all measurements are consistent with no such CP violation ($q = p = 1/\sqrt{2}$).

All mixing measurements to date have studied decays to final states accessible to either D^0 or $\overline{D}^0$ via the parameter $\lambda_f = (q/p)(\bar{\mathcal{A}}_f/\mathcal{A}_f)$. In general, the strong phase $\delta_f = \arg[\bar{\mathcal{A}}_f/\mathcal{A}_f]$ limits the precision of ϕ_M. It can be measured from quantum correlated (QC) decays at charm threshold. Such measurements from CLEOc and from the BES III experiment will be available but, to achieve a precision in ϕ_M of $\sim 1^\circ$ will require the $1\,\mathrm{ab}^{-1}$ data sample at the $\psi(3770)$. To date, measurements of decay rate asymmetries for D^0 mesons have been integrated over decay time, which means that contributions from mixing are included. It has recently been pointed out that time-dependent CP asymmetry measurements (TDCPV) of D^0 decays to CP eigenstates (such as K^+K^- or $\pi^+\pi^-$) can be used to measure the overall weak phase of λ_f, as was done by the B factories for B^0 decays. LHCb should be able to make an excellent measurement of ϕ_M, but interpretation of weak decay phases will require similar measurements in many other channels uniquely accessible to an e^+e^- environment.

Super$B$ will produce large numbers of $D\bar{D}$ pairs in a pristine environment: approximately $1.15\times 10^9/\,\mathrm{ab}^{-1}$ at the $\Upsilon(4S)$ and $4\times 10^9/\,\mathrm{ab}^{-1}$ at the $\psi(3770)$. Such large samples will allow searches for rare charm decays that are complementary to what can be achieved at the LHC. For example, decays to $\ell^\pm\ell'^\mp X$, where X is a charged or neutral π or K or vector hadron, can reveal the need for new particles and/or lepton flavor violation. Inclusive $\ell^+\ell^-$ rates have been estimated in the few times 10^{-8} region, while current limits from BABAR, D0 and CLEOc indicate that Super$B$ can probe rates below 10^{-7} running at the $\Upsilon(4S)$, and to somewhat lower levels running at the $\psi(3770)$. For $X = \pi^0$, limits an order of magnitude lower are foreseen. In addition, "Invisible" modes such as $D^0 \to X\gamma$ where X is undetected can be very heavily suppressed in the SM. For $X = \nu\bar{\nu}$, the rate is $\sim 10^{-30}$. Here, data from Super$B$ operating at the $\psi(3770)$ can be especially important, since a D^0 recoil can be used together with a photon to eliminate most of the obvious backgrounds that dominate at the $\Upsilon(4S)$. The decays $D^0 \to \mu^+\mu^-$, estimated in the SM at $\sim 10^{-13}$, are an interesting place to search for NP. Rates down to the 10^{-8} range can be measured by Super$B$ or LHCb, but long-distance effects are not well understood. A measurement (possible only at Super$B$) of the QED-related $D^0 \to \gamma\gamma$ decay rate could help to pin these down.

4 Direct Searches for New Particles

Bottomonium decays allow for direct searches for NP. A Higgs boson h with $M_h < M_\Upsilon$ can be produced in $\Upsilon(nS)$ decays via the Wilczek mechanism with subsequent decay $\Upsilon(nS) \to \gamma h$. In this scenario, new physics can appear in the form of a monochromatic photon in the decay $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to \gamma\tau^+\tau^-$. This decay chain has a relatively small branching fraction of 4.5%, but has low background. Another decay mode to consider is $\Upsilon(3S) \to \gamma\tau^+\tau^-$ which has a rate that is more than a factor of ten higher than the previous channel but suffers from a larger background arising from $e^+e^- \to \tau^+\tau^-\gamma$ events. Both modes will provide discovery potential for a very light Higgs that could be missed at the LHC.

If Dark Matter is lighter than 5 GeV, it will require a Super Flavor Factory to determine its properties. Generally, in this mass region one needs two particles: the dark matter candidate, χ, and a boson U that couples it to the SM. The most promising searches are in invisible and radiative decays of the Υ, such as the mode $\Upsilon(3S) \to \pi^+\pi^- +$ invisible, which receives a SM contribution from $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to \nu\bar{\nu}$, but could also be sensitive to a vector U. Existing best limits, from the *BABAR* experiment, are still an order of magnitude above the SM prediction. A second promising signature is the radiative decay $\Upsilon(1S) \to \gamma+$ invisible. This is probably the most favored mode theoretically, and is sensitive to a scalar or pseudoscalar U.

The most general searches for dark forces are in direct e^+e^- production. The primary model-independent signature is $e^+e^- \to \gamma A' \to \gamma l^+l^-$, where A' is the gauge boson of the dark force (the "dark photon") with a mass $\sim 1\mathrm{GeV/c}^2$. Super$B$ should be able to improve on limits from existing searches for narrow resonances in $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \tau^+\tau^-\gamma$ by nearly an order of magnitude. Extended searches involving final states with 4, 8, or even 12 or more leptons can also be conducted at Super$B$. While these final states may be harder to use to extract limits on the dark photon, any sign of a narrow resonance in this context would be evidence for new physics.

5 Precision Measurements of CKM Parameters

A principal goal of Super$B$ is to improve the accuracy of the CKM parameters by an order-of-magnitude (to 1% precision). This would significantly enhance the predictive power of the SM, and consequently the sensitivity of flavor physics observables to new physics contributions. Table 2 shows the current precision of the important observables that contribute to the determination of the CKM parameters, as well as the expected precision of these observables with a Super$B$ dataset of $75\,\mathrm{ab}^{-1}$. In addition to the improved precision of the experimental observables, reaching this goal will require substantial improvement in the

Table 2: Current precision on CKM parameters, and expected sensitivity of Super$B$.

Observable	Now	Super$B$ ($75\,\mathrm{ab}^{-1}$)
$\sin 2\beta$ ($B^0 \to J/\psi K^0_S$)	0.018	~ 0.005
CKM angle α	$\sim 4^\circ$	1–2°
CKM angle γ	$\sim 10^\circ$	1–2°
$\lvert V_{cb}\rvert$ (exclusive)	4%	1–2%
$\lvert V_{cb}\rvert$ (inclusive)	1.5%	0.5%
$\lvert V_{ub}\rvert$ (exclusive)	10%	$< 5\%$
$\lvert V_{ub}\rvert$ (inclusive)	10%	$< 5\%$

precision of theoretical inputs, which are obtained primarily from lattice QCD calculations. Recent technical advances, together with a significant expansion of the available computing resources, should lead to the required improvement in precision of the calculations on the time scale of Super$B$.

6 Tau Physics and Measurement of $\sin^2\theta_W$

Lepton flavor violation is highly suppressed in the SM, making it one of the most sensitive probes for NP effects.[1] Super$B$ will push the sensitivity of clean final states such as $\tau \to 3\ell$ lower by a factor of 100 relative to existing limits, and by an order of magnitude for modes such as $\tau \to \ell\gamma$ that have irreducible background. The polarized electron beam at Super$B$ will provide additional experimental observables for background suppression, and will enable superior sensitivity to CP violation in the lepton sector, as well as measurements of the τ electric dipole and anomalous magnetic moments.

The combination of high luminosity and polarized electrons at Super$B$ provides a unique opportunity to measure a number of electroweak neutral current parameters with precisions comparable to those obtained at SLC and LEP, but at a Q^2 of $(10.58\mathrm{GeV})^2$. This physics program includes precision $\sin^2\theta_W$ measurements with $\mu^+\mu^-$, $\tau^+\tau^-$, and $c\bar{c}$ events, as well as measurements of the neutral current vector coupling of the b quark. Such measurements are sensitive to a Z' and can probe neutral current universality at high precision. In addition to probing new physics, the measurement of the b-quark neutral current vector coupling will shed light on the long-standing 3σ difference between the measurements of $\sin^2\theta_W$ obtained from the forward-backward asymmetry of b-quarks and those of leptons.

References

[1] M. E. Biagini *et al.* [SuperB Collaboration], [arXiv:1009.6178].

[1]More details can be found in the summary report of the Charged Leptons Working Group.

[2] E. Grauges *et al.* [SuperB Collaboration], [arXiv:1007.4241].

[3] B. O'Leary *et al.* [SuperB Collaboration], [arXiv:1008.1541].

[4] B. Meadows, M. Blanke, A. Stocchi, A. Drutskoy, A. Cervelli, M. Giorgi, A. Lusiani, A. Perez *et al.*, [arXiv:1109.5028 [hep-ex]].

[5] Alexey A. Petrov, arXiv:1101.3822 (2011).

[6] G. Burdman, I. Shipsey, Ann. Rev. Nucl. Part. Sci. **53**, 431-499 (2003). [hep-ph/0310076].

[7] S. Bianco, F. L. Fabbri, D. Benson, I. Bigi, Riv. Nuovo Cim. **26N7**, 1-200 (2003). [hep-ex/0309021].

[8] A. Bevan, G. Inguglia, B. Meadows, [arXiv:1106.5075 [hep-ph]].

[9] LHCb Collaboration, LHC-CONF-2011-061 (2011).