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SuperB physics opportunities

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Summary. — The Super$B$ project in Tor Vergata (Italy) aims at investigating flavor physics with a data sample two orders of magnitude larger than the B-Factories that have operated for more than a decade. In the era of LHC this represents a unique opportunity to perform complementary indirect searches for new physics effects. In addition its design characteristics make it a flavor factory with an even broader physics reach. This paper summarizes the host of physics opportunities that will be opened by this experiment and the project status.

PACS `13.66.Jn` – Precision measurements in e^-e^+ interactions.
PACS `11.30.Hv` – Flavor symmetries.
PACS `14.40.Pq` – Heavy quarkonia.

1. – Introduction

The new Super$B$ facility will investigate the consequences for flavor physics of any discoveries at the LHC and search for New Physics (NP) signatures at energy scales that exceed the direct search capabilities of the LHC. A super-flavor factory will also be able to improve the precision and sensitivity of the previous generation of flavor factories by factors of five to ten. The sides and angles of the Unitarity Triangle will be determined to an accuracy of $\sim 1\%$. Limits on Lepton Flavour Violation (LFV) in τ decays will be improved by two orders of magnitude. It will become feasible to search for CP violation (CPV) in charm mixing. Extensive searches for new states in bottomium and charmonium spectroscopy will be achieved. New precision measurements of electroweak properties, such as the running of the weak mixing angle $\sin^2\theta_W$ with energy, should become possible.

Flavor physics is an ideal tool for indirect searches for NP. Both mixing and CPV in B and D mesons occur at the loop level in the Standard Model (SM) and therefore can be subject to NP corrections. New virtual particles occurring in the loops or tree diagrams can also change the predicted branching fractions or angular distributions of rare decays. Current experimental limits indicate NP with trivial flavor couplings has a scale in the 10–100 TeV range, which is much higher than the 1 TeV scale suggested by

TABLE I. – *The golden matrix of observables versus a sample of NP scenarios. H^+ represents the insertion in the model of a charged Higgs Boson; (non-)MFV is a representative (non-)Minimal Flavour Violation model; ZP is NP in Z-penguins; RH corresponds to the introduction of right handed currents. A number of explicit SUSY models are included* [2]. *"L" denotes a large effect, "M" a measurable effect and "CKM" indicates a measurement that requires precise measurement of the CKM matrix.*

	H^+	MFV	non-MFV	ZP	RH	SUSY models			
						AC	RVV2	AKM	δLL
$\mathcal{B}(\tau \to \mu\gamma)$						L	L	M	L
$\mathcal{B}(B \to \tau\nu, \mu\nu)$	CKM								
$\mathcal{B}(B \to K^{(*)}\nu\overline{\nu})$			M	L		M	M	M	M
$S_{K_S^0\pi^0\gamma}$					L				
Angle β (ΔS)			CKM		L	L	M	M	L
$A_{CP}(B \to X_s\gamma)$			L		M	M	M	M	L
$\mathcal{B}(B \to X_s\gamma)$		L	M		M				
$\mathcal{B}(B \to X_s ll)$			M	M	M				
$A_{FB}(B \to K^{(*)}ll)$						M	M	M	L
Charm mixing						L	M	M	M
CPV in Charm	L								L

SM Higgs physics. This means that either the NP scale cannot be seen in direct searches at the LHC or the NP scale is close to 1 TeV and therefore the coupling of NP with flavor must be minimal. In either case, indirect searches provide a way of understanding the new phenomena in great detail.

Super$B$ is an asymmetric e^+e^- collider with a 1.3 km circumference. The design calls for 6.7 GeV positrons colliding with 4.18 GeV electrons at a centre-of-mass energy $\sqrt{s} = 10.58$ GeV. The boost $\beta\gamma = 0.238$ is approximately half the value used at BaBar. The electron beam can be 60%–80% polarized. The design luminosity is $10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and data taking is expected to start in the latter part of this decade with a delivered integrated luminosity of $75\,\mathrm{ab}^{-1}$ over five years.

In the following sections, the physics potential of Super$B$ will be reviewed separating the "Golden Modes" from the broader set of physics possible at a flavour factory. Finally, a comparison with the competitors and the future perspectives will be reported.

2. – Physics potential: Golden Modes

Contrarily to the B-Factories, there is not a single mode that drives the design of the experiment. Table I summarizes the impact on several "Golden Modes" of possibile NP models, impact that is here briefly detailed.

Both BaBar and Belle have successfully measured the CKM Unitarity Triangle angles α, β and γ [1]. There is an overall agreement with Standard Model expectations although there are a few tensions that might prove to be signs of NP but need smaller statistical uncertainties for confirmation. To this aim Super$B$ is designed to measure the angles α and γ to 1–2%, and β to 0.1%. $|V_{cb}|$ and $|V_{ub}|$ can be measured to 1% and 2% accuracy, respectively, in both inclusive and exclusive semileptonic decays. Figure 1 shows the

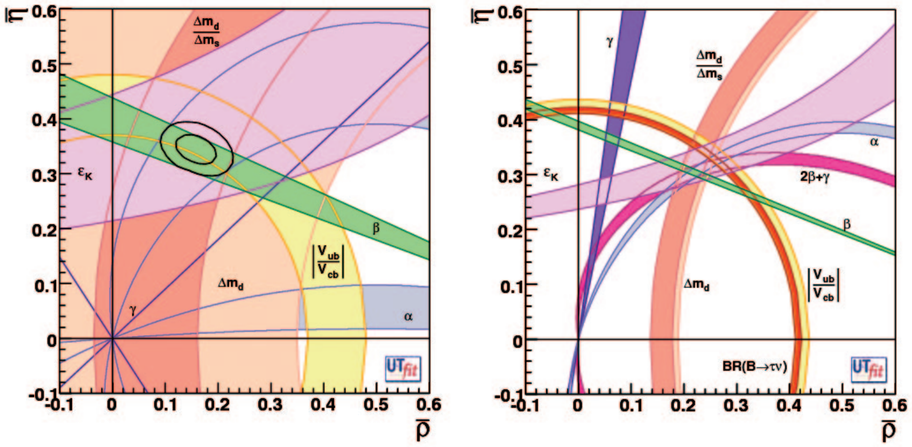

Fig. 1. – Regions corresponding to 95% probability for $\overline{\rho}$ and $\overline{\eta}$ with current measurements (left) and with Super$B$ precision assuming the current central values (right).

$\overline{\rho}$-$\overline{\eta}$ plane with current and predicted experimental measurements, assuming the current measurements maintain their central values.

NP can be probed also by comparing the measurements of CKM angles within several modes, leading to a precision measurement of what is traditionally called "ΔS", *i.e.* the difference in the angle β between $b \rightarrow s$ penguin-dominated transitions and $b \rightarrow c\bar{c}s$ decays.

In 2-Higgs-doublet (2HDM-II) and Minimal SuperSymmetric (MSSM) models, the decay $B \rightarrow \tau\nu$ is sensitive to the presence of a charged Higgs H^- replacing the SM W^-. Super$B$ will be able to exclude masses up to ~ 2–3 TeV for values of $\tan\beta$ up to 80.

Super$B$ can access the off-diagonal elements of generic squark mass matrices in the MSSM model using the mass insertion approximation. These cannot be seen by the LHC general purpose detectors. As an example, Super$B$ is sensitive to non-zero values of the matrix element $(\delta^d_{23})_{LL,LR}$ for gluino masses in the 1–10 TeV range through decays such as $b \rightarrow s\gamma$ and $b \rightarrow sl^+l^-$.

An almost equal number of $\tau^+\tau^-$ pairs are produced as $B\overline{B}$ pairs at the $\Upsilon(4S)$ resonance. Current experimental 90% confidence level upper limits on τ LFV are in the 10^{-8}–10^{-7} range, depending on the decay. In the very clean environment of Super$B$, upper limits on τ LFV can be achieved down to a level of 2×10^{-10} for $\tau \rightarrow \mu\mu\mu$ and Super$B$ can measure the upper limits in ~ 50 other τ decay modes. Background-free modes should scale with the luminosity (L) while other modes will scale with $\sqrt{\mathcal{L}}$ or better, thanks to re-optimized analysis techniques. In $\tau \rightarrow \mu\gamma$ for example, LFV is predicted at the level 10^{-10}–10^{-7} depending on the NP model. SU(5) SUSY GUT models predict $\tau \rightarrow \mu\gamma$ branching fractions between 10^{-7} and 10^{-9} depending on the NP phase, so the majority of the parameter space is within the expected Super$B$ sensitivity of 2×10^{-9}.

CPV in charm decays is expected to be very low in the SM ($< 1\%$) so its detection would be a clear indicator of NP. Current values for the mixing parameters x and y from HFAG [1] fits give $(0.63 \pm 0.20)\%$ and $(0.75 \pm 0.12)\%$, respectively, allowing for CPV [3]. At Super$B$, the errors should reduce to 0.07% and 0.02%, respectively. If the results are

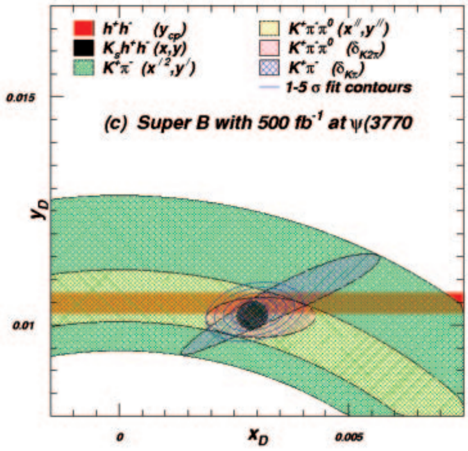

Fig. 2. – Tthe expected precision on charm mixing parameters from combining BES-III and Super$B$ $\psi(3770)$ and $\Upsilon(4S)$ data.

combined with expected results from BES-III and a dedicated Super$B$ 500 fb^{-1} run (~ 4 months running) at the $D\,\overline{D}$ threshold, the BES-III/CLEO-c physics programme can be repeated leading to a further reduction in these errors to 0.02% and 0.01%, respectively. This is shown in fig. 2.

3. – Physics potential: opportunities from a flavour factory

If a polarised electron beam is available, many of the upper limits on τ LFV modes can be improved by an additional factor of two. The polarisation also allows the search for the τ EDM at a level of $2 \times 10^{-19} e\,\text{cm}$ and the measurement of the τ anomalous magnetic moment $\Delta\alpha_\tau$ with an error of 10^{-6}. The value of $\sin^2\theta_w$ can be measured with an accuracy $\pm 1.8 \times 10^{-4}$ at $Q = 10.58\,\text{GeV}$ and so help understand the discrepancy in the measurements from LEP, SLD and NuTev [4]. This is shown in the left-hand plot of fig. 3 where the size of the bar at $Q = 10.58\,\text{GeV}$ represents the expected error on the Super$B$ measurement. It may even be possible to measure $\sin^2\theta_w$ at the $\psi(3770)$ mass if polarisation can be achieved.

The B-Factories and the Tevatron have discovered bound states with a $c\bar{c}$ or a $b\bar{b}$ pair that do not fit into the conventional meson interpretation (see for instance [5] for a review). However, apart from some exceptions like the $X(3872)$, they have only been observed in a single decay channel with a significance only just above 5σ. The right-hand plot of fig. 3 shows some of the newly discovered states. Possible explanations include hybrids, molecules, tetraquarks and threshold effects. Super$B$'s ability to run at the $\Upsilon(nS)$ resonances and charm threshold provides a unique opportunity for testing low- and high-energy QCD predictions. Predicting the expected rates for poorly measured resonances is of course hard and work is on-going to improve the extrapolations. The $B \to X(3872)K$ decays should produce $\sim 2k - 10k$ events in each of their main decay channels. $Y(4260) \to J/\psi\pi^+\pi^-$ will have $\sim 45k$ events, while $\sim 4.5k$ events can be expected for both $Y(4350)$ and $Y(4660)$ decaying to $\psi(2S)\pi^+\pi^-$. It should be possible to confirm the existence of the $Z_1^+(4050)$, $Z^+(4430)$ and $Z_2^+(4430)$ as Super$B$ will collect between $150k - 2M$ events of the relevant fully reconstructed final states $J/\psi\pi^+K$, $\psi(2S)\pi^+K$, and $\chi_{cJ}\pi^+K$.

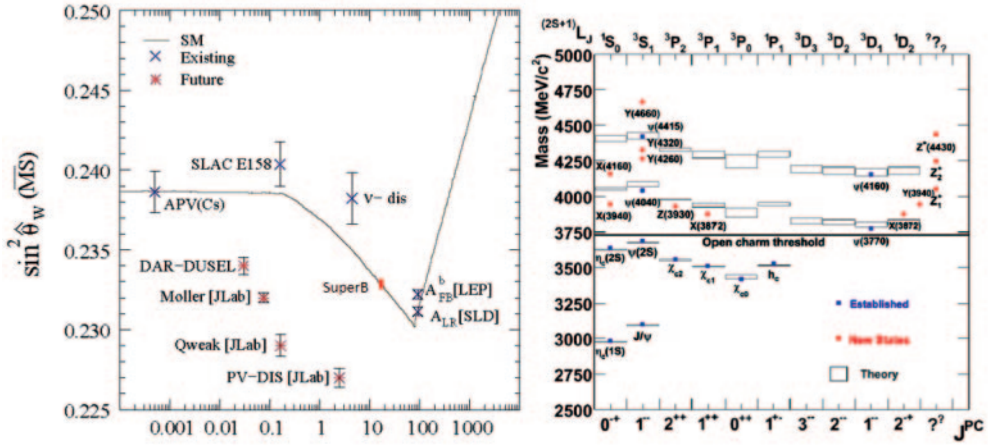

Fig. 3. – Left: measurements of $\sin^2\theta_w$ as a function of the center-of-mass energy ($\sqrt{s}$ in GeV). The size of the bar at $\sqrt{s}\sim 10.6$ GeV representing the Super$B$ measurement is approximately the same size as the error. Right: measured masses of newly observed states positioned according to their most likely quantum numbers.

Other physics opportunities that cannot be detailed here include B_s physics running at the $\Upsilon(5S)$, light meson studies in Initial State Radiation events, $\gamma\gamma$ physics, direct searches for little higgs, Dark Matter, Dark Forces.

4. – Competition and status of the project

The strength of Super$B$ is in the breadth of the physics potential and, in order to achieve it, several features need to be in the design: very high luminosity, possibility to scan from the charm threshold to at least $\sqrt{s}=11$ GeV, polarized beams at least at the $\Upsilon(4S)$, better if also during the scan, and triggers suited for exotic searches. Table II summarized which research line requires each feature and which are the competitors. It is to be noted that nobody competes on all features.

The physics potential [2], and the detector [6] and accelerator [7] plans have been extensively documented and the activity is currently concentrated on writing a Technical Design Report first and a Physics Book next. The Italian government included the

Table II. – *Features required by each research stream and competitors.*

Feature	Physics goal	Competitors
high luminosity	Precision CKM physics, rare B decays	Belle II (slightly lower luminosity but start earlier)/ LHCb (dirty environment)
Beam Polarization	Rare τ decays, EW physics	–
Energy Scan	Exotic Spectroscopy, Charm Physics at threshold	BESIII (up to 4 GeV), Panda (different production)
Devoted Triggers	ISR, $\gamma\gamma$, direct searches	–

experiment among the top priorities of its funded research plan, and the campus of Tor Vergata University, Rome, was chosen as the site. The new laboratory devoted to host this facility (called "Cabibbo Lab") was created. Data taking should begin five to six years after construction begins.

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