Status of the Super B Factory Projects

Riccardo de Sangro

Laboratori Nazionali di Frascati dell’INFN, Via E. Fermi 40, I-00044 Frascati, Italy

Abstract. Two proposals have been presented for the construction of super high luminosity B factories, the SuperB in Italy and SuperKEKB in Japan. We review the physics case for the construction of such facilities in the LHC era and highlight several topics of hadronic physics that can benefit from the high luminosity they will integrate. The present status of the accelerator and detector work toward the Technical Design Reports is also presented.

Keywords: B factory, B meson, B physics, flavour physics, SuperB, SuperKEKB

PACS: 14.20.-c, 14.40.-n, 13.20.-v, 13.25.-k, 13.35.Dx

INTRODUCTION

The search for physics beyond the Standard Model will be the main objective of elementary particle physics in the coming decade. This search has begun a few months ago with the start of LHC operations at CERN, where the search for the Higgs boson will be accompanied by an extended search for new states indicating the presence of “New Physics” (NP), motivated by the expectation that a new scale will make its appearance at energies around 1 TeV, accessible to the LHC.

The production and observation of new particles is not, however, the only way to look for NP, as the new heavy particles can reveal themselves through virtual effects in lower energy processes like the decays of Standard Model particles such as $B$ and $D$ mesons and $\tau$ leptons. Since quantum effects typically become smaller as the mass of the virtual particles increases, high-precision measurements are required to extend the mass reach, and thus a high statistic data sample is needed. There are therefore two complementary approaches in the quest for the discovery of NP: the high energy frontier presently being explored at the LHC, and the high luminosity frontier, which is the path followed by the two super $B$ factories proposals presently under discussion.

The SuperB project [1] in Italy is designed to have a baseline peak luminosity of $10^{36} \text{cm}^{-2}\text{s}^{-1}$, with the possibility to further improve by a factor of 4, and to be able to collect a total of 75 ab$^{-1}$ of integrated luminosity in 5 years of running, starting around 2015; the design also includes the possibility of running with a polarized $e^-$ beam and to operate at lower energies, down to the charm threshold, making this facility truly a flavour factory. Similarly, the SuperKEKB project [2] in Japan will improve on the present KEKB collider peak luminosity by a factor of $\approx 40$ to reach $8 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$, aiming to collect a total of 50 ab$^{-1}$ by the year 2020.

PHYSICS HIGHLIGHTS

In this paper we discuss just a few examples illustrating the physics case for the construction of a super $B$ factory and refer the reader to the SuperB CDR [1] and Valencia Workshop [5] proceedings for a more detailed discussion.

Certainly the most stringent test for NP at the super $B$ factory will be the determination of the CKM parameters with 1% precision, which will open the possibility to look for small differences in the values of CKM parameters obtained with different independent measurements, and test the unitarity of the Unitarity Triangle.

There are a number of processes whose production rates, branching fractions, $CP$ or angular asymmetries are predicted with high precision in the Standard Model (SM) or are completely forbidden, which we call golden as they can give a clear indication of NP. Measurements that can produce evidence of NP are:

- rare $B$ decays
  - leptonic: $B^+ \rightarrow \ell^+ \nu(\gamma), B^0 \rightarrow \ell^+ \ell^-$
  - inclusive and exclusive radiative decays: $B \rightarrow s\gamma, B \rightarrow s\ell^+\ell^-$, $B \rightarrow d\gamma, B \rightarrow d\ell^+\ell^-$
- tests of $CP$, $CPT$, and Lepton Flavour Violation (LFV) in $\tau$ decays (i.e. $\tau \rightarrow \mu(\epsilon)\gamma$)
Indeed, there are different golden channels for the several different NP models that have been proposed \[6\]|\[7\]|\[8\], and processes that display a measurable deviation from Standard Model for a given NP scenario could be uninteresting in a different scenario. In Table 1, we show a selection of golden modes in different NP scenarios. We indicate with “X” the golden channel of a given scenario, and with “O” modes which are not the golden one of a given scenario but can still display a measurable deviation from its Standard Model predicted value. The label CKM denotes golden modes which require the high-precision determination of the CKM parameters achievable at the super \(B\) factory. This table is taken from reference \[5\], where a discussion of this choice of measurements and models can be found. As we do not know what the NP will look like, and which of these models is the correct one, this richness is a very welcome feature.

For example, in the framework of the MSSM with generic squark mass matrices parameterized using the mass insertion (MI) approximation \[8\], the NP flavour violating couplings are the complex MIs \((\delta_i^d)_{AB}\), where \(i,j = 1,2,3\) are the generation indices and \(A,B = L,R\) are the helicities of the SUSY partner quarks. Considering only the dominant gluino contribution, the other relevant parameters in the model are the gluino mass \(m_{\tilde{g}}\) and the squarks average mass \(m_{\tilde{q}}\).

Using Super \(B\) factory measurements as constraints, with a value of \(m_{\tilde{g}} = 1 \text{ TeV}\) allowed from the present upper bound, we can constrain these MI. Examples of this are given in the plots in Fig. 1 which display the allowed region in the plane \(\Re(\delta_{13}^d)_{LL} - \Im(\delta_{13}^d)_{LL}\) for \(m_{\tilde{q}} = m_{\tilde{g}} = 1 \text{ TeV}/c^2\) and \((\delta_{13}^d)_{LL} = 0.085e^{i\pi/4}\) using Super \(B\) measurements with 75 \(ab^{-1}\). Different colours correspond to different constraints: \(A_{CP}\) (green), \(\beta\) (cyan), \(\Delta m_{d}\) (magenta), all together (blue). Right: Same plot for the \((\delta_{23}^d)_{LR}\) MI, assuming \((\delta_{23}^d)_{LR} = 0.28e^{i\pi/4}\). Colors are constraints from: \(B(b \rightarrow Xs\gamma)\) (green), \(B(b \rightarrow Xs\ell^+\ell^-)\) (cyan), \(A_{CP}(b \rightarrow Xs\gamma)\) (magenta), all together (blue).

- measurement of the \(\tau\) anomalous magnetic moment
- search for \(CP\) violation in the \(D\) meson system

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Mode & \(H^+\) & Minimal \ FV \ & Non-Minimal \ FV (1-3) & Non-Minimal \ FV (2-3) & NP \ Z-penguins & Right-Handed \ currents \\
\hline
\(B(B \rightarrow Xs\gamma)\) & X & O & O & O & X-CKM \\
\(A_{CP}(B \rightarrow Xs\gamma)\) & X & O & O & O & X-CKM \\
\(B(B \rightarrow Xe^+\ell^-)\) & X & O & O & O & X-CKM \\
\(B(B \rightarrow K\nu\nu)\) & X & O & O & O & X-CKM \\
\(S(K_S \rightarrow \pi^0\gamma)\) & X & O & O & O & X-CKM \\
\(\beta\) & X-CKM & & & & \\
\hline
\end{tabular}
\caption{Illustrative example of golden modes in different NP scenarios.}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Left: Density plot of the selected region in the \(\Re(\delta_{13}^d)_{LL} - \Im(\delta_{13}^d)_{LL}\) for \(m_{\tilde{q}} = m_{\tilde{g}} = 1 \text{ TeV}/c^2\) and \((\delta_{13}^d)_{LL} = 0.085e^{i\pi/4}\) using Super \(B\) measurements with 75 \(ab^{-1}\). Different colours correspond to different constraints: \(A_{CP}\) (green), \(\beta\) (cyan), \(\Delta m_{d}\) (magenta), all together (blue). Right: Same plot for the \((\delta_{23}^d)_{LR}\) MI, assuming \((\delta_{23}^d)_{LR} = 0.28e^{i\pi/4}\). Colors are constraints from: \(B(b \rightarrow Xs\gamma)\) (green), \(B(b \rightarrow Xs\ell^+\ell^-)\) (cyan), \(A_{CP}(b \rightarrow Xs\gamma)\) (magenta), all together (blue).}
\end{figure}
Fig. 1(right) shows the constrains on their spectroscopy, a measurements with high precision, most notably an extensive search of charmonium and bottomonium states to study \( A \) which is a unique feature of Super factory will have a sensitivities down to \( 10^{−10} \). The longitudinally polarized high energy ring electron beam, which is governed by a theoretical potential models \[13\]. The dots are the experimentally observed states. As one can see from Fig.2(left), the new X,Y,Z states have masses and quantum numbers that hardly fit with the prediction for charmonium states. Also our knowledge of bottomonium spectroscopy is rather limited today, as one can see from

\[ \text{TABLE 2. Expected 90\% CL upper limits (sensitivity) on representative LFV } \tau \text{ decays with 75 ab}^{-1} [1]. \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B(\tau \to \mu \gamma) )</td>
<td>( 2 \times 10^{-9} )</td>
</tr>
<tr>
<td>( B(\tau \to e \gamma) )</td>
<td>( 2 \times 10^{-9} )</td>
</tr>
<tr>
<td>( B(\tau \to \mu \mu) )</td>
<td>( 2 \times 10^{-10} )</td>
</tr>
<tr>
<td>( B(\tau \to \gamma \gamma) )</td>
<td>( 2 \times 10^{-10} )</td>
</tr>
<tr>
<td>( B(\tau \to \mu \eta) )</td>
<td>( 4 \times 10^{-10} )</td>
</tr>
<tr>
<td>( B(\tau \to e \eta) )</td>
<td>( 6 \times 10^{-10} )</td>
</tr>
<tr>
<td>( B(\tau \to (K^0_s)^*) )</td>
<td>( 2 \times 10^{-10} )</td>
</tr>
</tbody>
</table>

\[ \text{TABLE 3. Expected precision } (\sigma) \text{ on the mixing and CPV parameters for SuperB with an integrated luminosity of 75 ab}^{-1} \text{ compared to LHCb with 10 fb}^{-1} [11]. \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Observable</th>
<th>( (75 \text{ ab}^{-1}) )</th>
<th>LHCb (10 fb^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^0 \to K\pi )</td>
<td>( x^2 )</td>
<td>( 3 \times 10^{-5} )</td>
<td>( 6 \times 10^{-5} )</td>
</tr>
<tr>
<td></td>
<td>( y' )</td>
<td>( 7 \times 10^{-4} )</td>
<td>( 9 \times 10^{-4} )</td>
</tr>
<tr>
<td>( D^0 \to K^+K^- )</td>
<td>( y_{CP} )</td>
<td>( 5 \times 10^{-4} )</td>
<td>( 5 \times 10^{-4} )</td>
</tr>
<tr>
<td>( D^0 \to K_S\pi^+\pi^- )</td>
<td>( x )</td>
<td>( 4.9 \times 10^{-4} )</td>
<td>( )</td>
</tr>
<tr>
<td></td>
<td>( y )</td>
<td>( 3.5 \times 10^{-4} )</td>
<td>( )</td>
</tr>
<tr>
<td></td>
<td>(</td>
<td></td>
<td>q/p</td>
</tr>
<tr>
<td></td>
<td>( \phi )</td>
<td>( 2^\circ )</td>
<td>( )</td>
</tr>
</tbody>
</table>

Another possibility for the NP effects is the observation of the lepton flavour violating decay \( \tau \to \mu \gamma \), complementary to muon (LFV) searches (e.g., the MEG experiment [9]). With 50−75 ab\(^{-1}\) the Super B factory can cover a significant portion of the parameter space of most New Physics scenarios predictions for LFV in tau decays. The most stringent limits come today’s B factories [10] and are in the range \( B(\tau \to \mu \gamma) < 4.4 \times 10^{-7} \), while super B factory will have a sensitivities down to \( 10^{-9} \) which we have summarized in Table 2. What we call here sensitivity is the expected 90\% CL upper limit assuming no signal. The longitudinally polarized high energy ring electron beam, which is a unique feature of SuperB, is also the key to searching for CP violation in tau production or decay. An asymmetry in production would signal a \( \tau \) EDM, with a sensitivity of \( \sim 10^{-19} \) e·cm, while an unexpected CP-violating asymmetry in decay would be a clear signature of NP.

In Table 3 we show the Super B factory sensitivity for the mixing parameters and for the observation of CPV in the \( D \) system, which is governed by a CPV phase that in the SM is expected to be negligible (\( \phi \approx 2\eta A^2 \lambda^3 / \lambda \approx 10^{-3} \)). Any deviation of \( \phi \) from zero would be a clear indication of NP.

As today’s B factories have already shown, many measurements have been performed in the clean environment of \( e^+e^- \to \gamma(4S) \to BB \) that are statistically limited and therefore worth to be studied with the 50 to 75 ab\(^{-1}\) the Super B factory will collect. With such a high statistic sample, many systematic uncertainties will also be greatly reduced. Improvement in the theoretical calculations of long distance effects due to strong interaction and lattice QCD predictions, together with improved measurements of leptonic and semi-leptonic \( B,D \) decay branching fractions, will improve our knowledge of key hadronic physics parameters such as \( f_{D_s} \), the ratio \( \tilde{\xi} = f_{B_s} / f_{B_s} / f_{B_s} / f_{B_s} / f_{B_s} / f_{B_s} \), etc. up to the level of \( \sim 1\% \) [5].

The large data samples of the super B factory offer the possibility to perform a wealth of hadronic physics measurements with high precision, most notably an extensive search of charmonium and bottomonium states to study their spectroscopy, a field which has recently seen a renovated interest with the discovery of new charmonium-like states (X, Y, Z) by BaBar and Belle [12].

In Fig. 2 we show the present status of our knowledge of charmonium (left) and bottomonium (right) spectroscopy. The white and yellow boxes in these plots represent states that are expected to exist and whose masses are predicted by the most widely used theoretical potential models [13]. The dots are the experimentally observed states. As one can see from Fig.2(left), the new X,Y,Z states have masses and quantum numbers that hardly fit with the prediction for charmonium states. Also our knowledge of bottomonium spectroscopy is rather limited today, as one can see from
Fig. 2(right) showing that many bottomonium states are still to be observed. At a Super B factory, these gaps could be filled, and bottomonium analogs of the charmonium-like X, Y, Z states could be discovered if they exist.

The present schedules of the proposed Super B factories call for their physics run to occur between 2015 and 2020, that is concurrently with LHC data taking. The LHCb experiment [16] which is devoted to the study of B physics at LHC, will have collected by then 10 fb$^{-1}$ of data and will therefore compete with the Super B factory on many important measurements. It is therefore important to briefly discuss how the two physics program overlap.

It is clear that LHCb will perform much better than Super B factory in all the B related quantities ($\sin(\Phi_1)$, $B(B \rightarrow \mu\mu)$, $\gamma(B_s \rightarrow KK)$, $\gamma(B_s \rightarrow D_s K)$). However, there is a substantial complementarity between the two, as the LHCb will have only limited reconstruction of final states containing several neutral particle or large missing energy, offering no competition in the study of several important channels like $B \rightarrow s\gamma$, $B \rightarrow d\gamma$, $\tau \rightarrow \mu\gamma$ etc. There are other measurements, like $\sin2\beta$, $\alpha(\rho\pi)$, $\gamma(DK^*)$, $A_{CP}(B \rightarrow s\gamma)$, for which the two experiments will reach comparable precision.

### THE ACCELERATORS

The luminosity formula for $e^+e^-$ beams colliding with an horizontal crossing angle $\theta$ can be expressed [14] in terms of the vertical tune shift parameter $\xi_y$, the vertical beta function at the IP $\beta_y$ and the number of particles per bunch $N$ ($\propto$ the beam current)

$$L \propto \frac{N \cdot \xi_y}{\beta_y^2};$$

where $\xi_x, \xi_y, \xi_z$ are the r.m.s. bunch sizes, $\epsilon_x$ is the horizontal betatron emittance and $\phi$ is the Piwinsky angle $\phi \approx \sigma_x/\sigma_y\theta$. An increase in luminosity has traditionally been obtained by substantially increasing the beams currents (higher $N$) and decreasing the beam transverse dimensions (increase $\xi_y/\beta_y$). This was KEKB original upgrade plan, the so called “High Current Scheme”.

However, it was soon realized that following this path would not be practical to reach the desired factor of 100 gain in luminosity, as the backgrounds generated and the operating costs of a machine with currents of the order of 10 A per beam would be prohibitive ($\approx 100$ MS/year for electricity only).

Looking for an alternative solution for the SuperB machine parameters, in 2006 P. Raimondi [14] proposed a scheme in which beams with ultra low emittance (sub-μm transverse size) and relatively small (2-3 A) currents can be successfully collided with large Piwinsky angle thanks to the adoption of an innovative final focus optic (crabbed waist, CW) which very effectively reduces the beam-beam instabilities that would otherwise render this solution unwieldy. This idea has been very recently adopted also by the KEKB accelerator team, which defined a new set of parameters very similar to that of the SuperB, as Table 4 shows.
In Fig. 3 we show the plot of a luminosity scan vs vertical ($Q_y$) and horizontal ($Q_x$) betatron tunes from simulated data for the Siddharta experiment at DAΦNE, showing the beneficial effect obtained when the CW sextupoles are turned on; these plots clearly show that when CW is on, the regions of low luminosity (in blue) are very much reduced with respect to those of high luminosity (in red). This scheme has been successfully tested at DAΦNE in 2009: the luminosity as a function of the product of the beam currents in Fig. 3(right) is indeed ≈ 3 times better with the CW sextupoles on. The SuperB solution is built on the successes of past accelerators and accelerator R&D such as that for the Linear Collider. These have demonstrated the feasibility of all the individual critical components of the project: ultra low emittance lattices were tested for the ILC dumping rings, KEK and PEP-II have stored 2-3 A of beam currents, the CW concept has been tested at the DAΦNE storage ring in Frascati; polarized beams have been successfully produced at the SLC; continuous injection with live detectors has worked very well at PEP-II and KEK, and so have the the asymmetric interaction regions. The SuperB and SuperKEKB teams will have the difficult but not impossible task to make all these components work together at their best. If this is achieved, the goal of increasing the luminosity of $e^+e^-$ colliders by a factor of 100 will be accomplished while keeping backgrounds and operating costs at the level of today’s B factories, which would really be a remarkable feat.
FIGURE 4. BaBar is the baseline for the SuperB detector. The green areas are the parts of BaBar that will need replacement: the vertex detector, central drift chamber, forward EM calorimeter and parts of the muon detector.

THE DETECTORS

The present Belle [4] and BaBar [3] detectors have proven to be very effective for B factory physics. Based on this success, the two groups are following the same ideas for their Super B detectors, using BaBar and Belle as their baseline design and planning to reuse as much as possible of the existing (expensive) hardware.

The main issues to be faced are the higher data acquisition and background rates (and radiation doses), especially for the components closer to the beams and/or in the forward region. As the beam energy asymmetry will be smaller, the separation of the B decay vertices will also be smaller due to the lower boost, and so the vertex resolution needs to be improved. All these aspects are the focus of the R&D studies the groups are carrying on.

SuperB. Simulation studies [1] have shown that the CsI central electromagnetic calorimeter can operate in the SuperB environment, therefore it can be reused together with its mechanical structure. Also the quartz bars of the DIRC barrel particle ID system and the expensive super-conducting coil and flux return yoke may (with some redesign) be reused. The parts that will instead need to be improved or replaced, represented by the green areas in Fig. 4 showing the BaBar detector, are the silicon vertex tracker, central drift chamber, forward end cap electromagnetic calorimeter and the muon chambers.

To improve the vertex resolution to compensate for the lower boost, the addition of a small radius inner layer to a BaBar-like 5 layer vertex detector is under study, together with a new 1.5 cm beam pipe. The favoured technical solution for the so called Layer-0 is based on the use of hybrid pixels. There are several issues to be addressed to match the SuperB requirements: the realization of a device with (50 × 50 µm²) pixels and fast readout, extremely light mechanical supports and cooling system, and a suitable interface to take the signals out. In parallel to this work, R&D continues on an alternative solution based on the less mature technology of thin pixels. In Fig. 5 we show the error on the B mesons time separation as a function of cms boost, for different beam pipe radii.

The central tracking device will have to withstand very high rates in its innermost layers, therefore it will be replaced with one with smaller size cells and operated with a faster gas mixture. The new chamber will have a carbon fiber mechanical structure and lighter electronics to ensure better transparency. A new readout system for the fused silica bars of the DIRC is also under study and the possibility to add particle identification capability in the forward detector. The forward calorimeter will have to be replaced with a more radiation hard one, based on the use of LYSO crystals, and a veto calorimetric system will be installed in the backward region. Finally, for the muon detector a device based on scintillators read out with silicon photo-multipliers à la MINOS is being designed, and improved readout and trigger electronics as well. This activity, finalized to the completion of a Technical Design Report by the end of 2010, has
FIGURE 5. Left: $\Delta$ resolution as a function of the cms boost $\beta'\gamma$ for SuperB, showing that with the addition of one layer of vertex detector at 1.5 cm radius the resolution is similar to BaBar. Right: Space resolution in the $R\phi$ plane showing the big improvement over Belle obtained by Belle II (SuperBelle) with the addition of two vertex detector layers.

FIGURE 6. Belle is the baseline for the SuperBelle detector. The vertex detector will be replaced and so will the end caps EM calorimeters, the central drift chamber, the particle identification system and the muon detector. These upgrades have been fully funded by INFN.

Belle II. Similarly to SuperB, Belle II takes as a baseline the present Belle detector, shown in Fig. 6 with the parts that will be upgraded or changed in color. Improvements under study are the addition of two layers of silicon detector very close to the beam pipe, whose significant beneficial effect can be seen in Fig. 5(right), where the $R\phi$ spatial resolution is shown as a function of transverse momentum. As the Belle vertex detector only has 4 layers, the addition of these two will also add the benefit of making this detector an independent tracking device, like the SuperB SVT.

Other important improvements are the upgrade of the particle identification system (PID); the barrel section, a scintillator based time of flight, will be replaced with a new Time of Propagation (TOP) detector [17] while in the end cap a forward proximity focus RICH with silica aerogel will be added. These upgrades will increase the total PID solid angle coverage and improve the $K/\pi$ separation from the present 3$\sigma$ to 4$\sigma$ up to 4 GeV. The entire barrel electromagnetic calorimeter will be reused, with improved waveform sampling readout electronics, while in the end...
caps it will be replaced with pure CsI crystals, that are more radiation tolerant.

The central drift chamber (CDC) and the $K_L$ and $\mu$ identification system (KLM) will also be upgraded. Solutions similar to those taken into account by the SuperB detector are being studied. The DC will use faster gas and have smaller cells in the inner layers, while the end cap KLM will have the present glass RPC system replaced by plastic scintillator bars read out with silicon photo-multipliers.

CONCLUSIONS

Whether or not the LHC will find NP phenomena, the super $B$ factories can play a fundamental role in the understanding of its nature. If NP is found at the LHC and its scale $\Lambda_{NP}$ is measured, super $B$ factories will study its flavour structure; if it is not found, then they will give us the possibility to find indirect evidence for NP, as their sensitivity extends well beyond the energy scale of LHC (up to $\approx 10$ TeV for some models).

To achieve this sensitivity much higher precision is needed, therefore a much larger (a factor 100) data sample, than the one available today: the proposed Super $B$ factories are designed to achieve this goal in a time of about 5 years. Super $B$ factories have NP discovery potential and a physics program complementary to LHC as they will reach unprecedented $< 1\%$ precision on CKM parameters measurements and rare $B$ and $\tau$ decays, improving present accuracy by more than a factor of 10. Also a significant improvement in the knowledge of Charmonium and Bottomonium spectroscopy can be expected, together with the understanding of the nature of the many exotic states found today, still to be clarified. The discovery of additional new states is also a possibility.

Presently both projects have been submitted to their respective ministries of Science and Education, and are waiting final approval and funding from the Japanese and Italian governments.

ACKNOWLEDGMENTS

This talk was prepared with the contribution of many people from the SuperB and SuperKEKB groups. The author would like to give special thanks to M. Biagini, P. Krizan, D. Leith, R. Faccini, G. Finocchiaro, S. Pacetti, F. Renga, E. Solodov, A. Stocchi, for use of some of their material and useful discussions.

REFERENCES

10. B. Aubert et al., arXiv:hep-ex/0908.2381v1
    [arXiv:0711.1661 [hep-ex]].