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# Recent results from the $B$ factories and perspectives on Super$B$

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**Summary.** — The BaBar and Belle experiments, running mostly at the center-of-mass energy of about 10.58 GeV at the PEP-II $e^+e^-$ collider at SLAC and at the KEKB $e^+e^-$ collider at KEK, have recorded integrated luminosities exceeding $0.5\,\text{ab}^{-1}$ and $1.0\,\text{ab}^{-1}$, respectively. The results of the two experiments have confirmed the success of the CKM mechanism for flavor mixing and $CP$ violation and are in agreement with the Standard Model predictions. The Super$B$ experiment, a new generation flavor factory with very high luminosity ($\mathcal{L} = 10^{36}\ \text{cm}^{-2}\,\text{s}^{-1}$) will be able to record $75\,\text{ab}^{-1}$ of data in five years of nominal data taking, which is about two orders of magnitude larger than the BaBar and Belle data samples. This new experiment has been proposed for searching for new physics effects in the flavor sector, mainly through precision measurements and searches for forbidden processes in $B$, $D$ and $\tau$ decays. We report on recent results from the BaBar and Belle Collaborations, in particular on the measurement of the CKM angle $\gamma$ and we present the physics reach of the Super$B$ experiment.

PACS 12.15.Hh – Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements.
PACS 13.25.Hw – Decays of bottom mesons.
PACS 13.35.Dx – Decays of taus.

## 1. – Introduction

The BaBar and Belle experiments and the $B$ factories (PEP-II and KEKB) at SLAC and KEK were designed and built with the primary goal of performing the first precision tests of the Cabibbo-Kobayashi-Maskawa (CKM) mechanism for flavor mixing and $CP$ violation with 3 generations of quarks.

From the unitarity of the CKM quark mixing matrix we obtain the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which is usually represented as a triangle in the complex plane (the "Unitarity Triangle"). BaBar and Belle have made fundamental contributions to the measurements of the angles and sides of the Unitarity Triangle. The $CP$ asymmetry measurements from BaBar and Belle can be directly related to the angles of the Unitarity Triangle ($\alpha$, $\beta$, $\gamma$) with little theoretical uncertainty. The constraint on the angle $\beta$, from the amplitude of the time-dependent $CP$ asymmetry of $B^0 \to J/\Psi K_S^0$ and other $b \to c\bar{c}s$

 

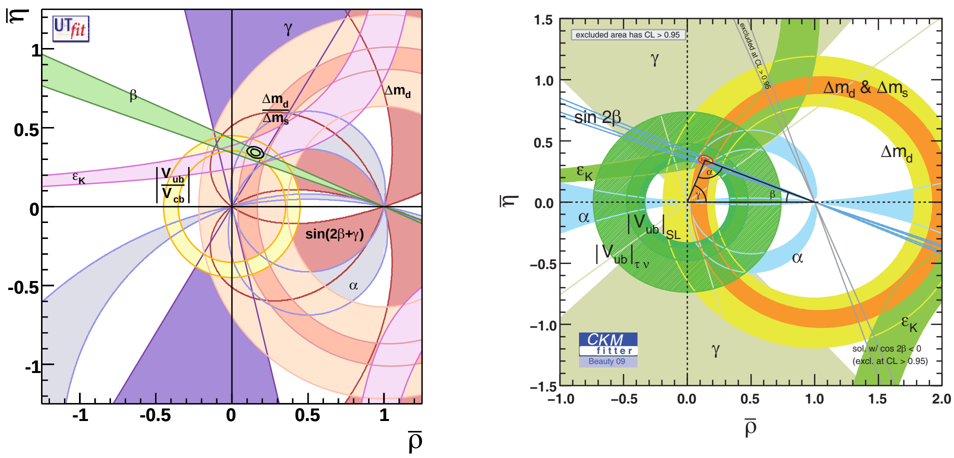


Fig. 1. – Constraints in the $(\bar{\rho}, \bar{\eta})$-plane from a global CKM fit from UTFit [1] (left plot) and CKMFitter [2] (right plot) Collaborations.

decays, is the strongest, with a one standard deviation uncertainty of less than one degree. The most difficult angle to measure is $\gamma$ and significant progress has been made in the past years.

The current experimental constraints on the Wolfenstein parameters $\bar{\rho}$ and $\bar{\eta}$, which give the coordinates of the apex of the Unitarity Triangle, are shown in fig. 1. The $CP$ violation parameters of the CKM matrix are overconstrained and the CKM theory has been experimentally confirmed. Kobayashi and Maskawa were awarded of the 2008 Nobel Prize in physics.

In this paper I will focus on recent results from the $B$ factories, such as the measurement of the CKM angle $\gamma$ in $B^\pm \to D^{(*)}K^{(*)\pm}$ decays. I will also discuss the perspectives on Super$B$, a next generation asymmetric $e^+e^-$ flavor factory with very high peak luminosity ($\mathcal{L} = 10^{36}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) proposed to be built near Rome, whose main purpose is to search for evidence of physics beyond the SM and investigate its nature.

## 2. – Recent results from $B$ factories

**2**$\cdot$1. *Measurement of the CKM angle* $\gamma$ *in* $B^\pm \to D^{(*)}K^{(*)\pm}$ *decays.* – The measurement of the angle $\gamma = \arg(-(V_{ud}V^*_{ub})/(V_{cd}V^*_{cb}))$ is an example of a measurement of unexpected success at the $B$ factories. The methods [3-5] that currently give the strongest constraints on $\gamma$ use decays of the type $B^\pm \to D^{(*)}K^{(*)\pm}$(1), where the neutral $D$ meson decays to a final state that is accessible to both $D^0$ and $\bar{D}^0$. The final state can be reached through two different quark-level processes, $b \to c\bar{u}s$ and $b \to u\bar{c}s$ (respectively $B^- \to D^{(*)0}K^{(*)-}$ and $B^- \to \bar{D}^{(*)0}K^{(*)-}$). The sensitivity to $\gamma$ comes from the interference between $b \to u\bar{c}s$ and the $b \to c\bar{u}s$ amplitudes which introduces a relative phase $\gamma$ in the decay amplitude. These are both tree level $b$ decays, so the interpretation of the measurements in terms of $\gamma$ is theoretically extremely clean.

(1) In what follows, the symbol $D$ refers to either $D^0$ or $\bar{D}^0$.

The most precise measurement of the angle $\gamma$ comes from the analysis of $B^{\pm} \to D^{(*)}K^{(*)\pm}$ decays where the $D$ decays to three-body final states such as $K_S^0\pi^+\pi^-$ or $K_S^0K^+K^-$. The main advantage of the method [5] is that it involves the entire resonant structure of the three-body decay of the $D$ meson, with interference between doubly-Cabibbo-suppressed, Cabibbo-allowed and $CP$-eigenstate amplitudes, all providing the sensitivity to $\gamma$. The price to pay is that it requires a detailed study of the resonances and their interference through a Dalitz plot analysis technique, where a phenomenological parameterization of the $D$ decay amplitude is assumed.

Using a data sample of 435 fb$^{-1}$ BaBar measures $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$ [6] in a combined fit of $B^{\pm} \to DK^{\pm}$, $B^{\pm} \to D^*K^{\pm}$ and $B^{\pm} \to DK^{*\pm}$ decays where $D$ decays to $K_S^0\pi^+\pi^-$ or $K_S^0K^+K^-$. Belle using a data sample of 605 fb$^{-1}$ measures $\gamma = (78.4^{+10.4}_{-11.6} \pm 3.6 \pm 8.9)^\circ$ [7] in a combined fit of $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D^*K^{\pm}$ decays with $D \to K_S^0\pi^+\pi^-$. The first error is statistical, the second systematic and the third is due to the $D$ decay amplitude model.

Both the BaBar and Belle measurements are statistics limited and would benefit from a larger data sample. At Super$B$, with 75 ab$^{-1}$, it is expected that Dalitz model independent approaches [5, 8] will be viable, rendering any controversy over the true Dalitz model systematic error on $\gamma$ irrelevant and turning $\gamma$ into a precision measurement with an estimated sensitivity of about one degree.

## 3. – The Super$B$ experiment

Super$B$ is a next generation high-luminosity $e^+e^-$ collider that will accumulate a data sample of 75 ab$^{-1}$ with five years of nominal data taking. This experiment could start running as early as 2015, by which time the LHC will have accumulated a significant sample of data, and would be reporting the results of searches for or direct measurements of New Physics (NP). Those results are limited in that they measure only flavor diagonal processes. In order to fully understand the nature of NP, one also has to measure the off-diagonal terms, in analogy to the CKM mixing matrix. In the scenario that LHC does not find NP particles, Super$B$ has the possibility to explore NP scale beyond the reach of the LHC (up to 10 TeV or more depending on NP models) looking for indirect signals.

In this sense the Super$B$ physics reach is complementary to the LHC one. In particular there is also a large complementarity with the flavor physics potential of the LHCb experiment. For example, rare decay modes with one or more neutrinos in the final state such as $B^+ \to l^+\nu$ and $B^+ \to K^{(*)+}\nu\bar{\nu}$, inclusive analyses of processes such as $b \to s\gamma$ and $b \to sl^+l^-$, measurements of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ and searches for lepton flavor violation such as $\tau^- \to \mu^-\gamma$ are unique to Super$B$, where the environment of the $e^+e^-$ collider is clean and relatively simple compared to the events at the hadronic machine [9]. In addition, the Super$B$ machine design includes the polarization of the electron beam (85% polarization) for the production of polarized $\tau$ pairs, allowing a better separation between signal and background events for $\tau$ decays, thus improving the experimental sensitivity in lepton flavor violating (LFV) processes. In table I are reported the expected experimental sensitivities (90% upper limits) for $\tau$ LFV processes at Super$B$ with 75 ab$^{-1}$ of data along with the present upper limits.

Charm physics also plays an important role in the Super$B$ physics program. Constraints on flavor-changing neutral currents from NP in the up-quark sector are much weaker than in the down-quark sector. Thus, high-sensitivity studies of rare charm decays offer the possibility of isolating NP effects in $D^0 - \bar{D}^0$ mixing, in $CP$ violation and

TABLE I. – *Expected* 90% CL *upper limits on representative LFV* $\tau$ *lepton decays with* $75\,\mathrm{ab}^{-1}$ *and current upper limits.*

| Process | Sensitivity at Super$B$ | Current limit |
|---|---|---|
| $\mathcal{B}(\tau \to \mu\gamma)$ | $2 \times 10^{-9}$ | $4.5 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to e\gamma)$ | $2 \times 10^{-9}$ | $1.1 \times 10^{-7}$ |
| $\mathcal{B}(\tau \to \mu\mu\mu)$ | $2 \times 10^{-10}$ | $3.2 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to eee)$ | $2 \times 10^{-10}$ | $3.6 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to \mu\eta)$ | $4 \times 10^{-10}$ | $6.5 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to e\eta)$ | $6 \times 10^{-10}$ | $9.2 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to eK^0_S)$ | $2 \times 10^{-10}$ | $3.3 \times 10^{-8}$ |
| $\mathcal{B}(\tau \to \mu K^0_S)$ | $2 \times 10^{-10}$ | $4.0 \times 10^{-8}$ |

in rare decay branching fractions. The sensitivity on $CP$ violation asymmetries in decay modes such as $D^0 \to K^+K^-,\ \pi^+\pi^-$ and $D^0 \to K^0_S\pi^+\pi^-$ is expected to reach the level of $\mathcal{O}(10^{-4})$ with $75\,\mathrm{ab}^{-1}$, which will probe the SM predictions. The machine design includes the possibility to run at different center-of-mass energies, *e.g.* at the $\Psi(3770)$ for exclusive $D\bar{D}$ production and at the $\Upsilon(5S)$ for $B_s\bar{B}_s$ production, thus further enriching the physics program.

The Super$B$ physics case is extensively discussed in refs. [10, 11]. In table II are reported, as an example, the golden modes for different NP scenarios. These decays are very difficult or impossible to reconstruct at the LHC. Even at the clean environment of Super$B$ the selection is experimentally challenging and to suppress backgrounds to an acceptable level the recoil technique is often necessary, in which the other $B$ in the $B\bar{B}$ event is reconstructed in either a semileptonic or hadronic decay. Table III reports the comparison of the experimental sensitivity today and with $75\,\mathrm{ab}^{-1}$, showing that in most cases Super$B$ is able to measure the observables with a few percent accuracy.

TABLE II. – *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 | NP Z-penguins | Right-handed currents |
|---|---|---|---|---|---|
| $\mathcal{B}(B \to X_s\gamma)$ | | X | O | | O |
| $A_{CP}(B \to X_s\gamma)$ | | | X | | O |
| $\mathcal{B}(B \to \tau\nu)$ | X-CKM | | | | |
| $\mathcal{B}(B \to X_s l^+l^-)$ | | | O | O | O |
| $\mathcal{B}(B \to K\nu\overline{\nu})$ | | | O | X | |
| $S(K_S\pi^0\gamma)$ | | | | | X |
| $\beta$ | | | X-CKM | | O |

TABLE III. – *Comparison of current experimental sensitivities with those expected at SuperB* ($75\,\mathrm{ab}^{-1}$). *Only a small selection of observables is shown. Quoted sensitivities are relative uncertainties if given as a percentage, and absolute uncertainties otherwise. For more details, see refs.* [9-11].

| Mode | Sensitivity | |
|---|---|---|
| | Current | Expected ($75\,\mathrm{ab}^{-1}$) |
| $\mathcal{B}(B \to X_s\gamma)$ | 7% | 3% |
| $A_{CP}(B \to X_s\gamma)$ | 0.037 | 0.004–0.005 |
| $\mathcal{B}(B^+ \to \tau^+\nu)$ | 30% | 3–4% |
| $\mathcal{B}(B^+ \to \mu^+\nu)$ | not measured | 5–6% |
| $\mathcal{B}(B \to X_s l^+ l^-)$ | 23% | 4–6% |
| $A_{\mathrm{FB}}(B \to X_s l^+ l^-)_{s0}$ | not measured | 4–6% |
| $\mathcal{B}(B \to K\nu\overline{\nu})$ | not measured | 16–20% |
| $S(K^0_S\pi^0\gamma)$ | 0.24 | 0.02–0.03 |

## 4. – Conclusions

The $B$ factories have confirmed the success of the CKM mechanism for flavor mixing and $CP$ violation with three generations of quark. Their results went well beyond the original goal. As an example, the measurement of the CKM angle $\gamma$ in $B^\pm \to D^{(*)}K^{(*)\pm}$ decays has reached a precision which was not predicted at the beginning of the BaBar and Belle experiments: $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$ (BaBar) and $\gamma = (78.4^{+10.4}_{-11.6} \pm 3.6 \pm 8.9)^\circ$ (Belle). Flavor physics still offers a unique opportunity for searching for NP and understanding its origin. The most sensitive measurements to NP are reported in tables I and III and are currently statistics dominated. Super$B$, a new generation super flavor factory, will accumulate a data sample of $75\,\mathrm{ab}^{-1}$ with five years of nominal data taking. The physics program is focused on the study of the flavor structure of NP by measuring the flavor couplings and also by exploring the NP scale beyond the LHC reach (up to 10 TeV or more), by looking for indirect signals. The golden modes for different NP scenarios, reported in table II, are difficult or even impossible to reconstruct at LHC. In this sense, the Super$B$ experiment can be considered as an alternative path for discovering NP with respect to the LHC.

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REFERENCES

[1] CIUCHINI M. *et al.* (UTFIT GROUP), *JHEP*, **0107** (2001) 013.
[2] CHARLES J. *et al.* (CKMFITTER GROUP), *Eur. Phys. J. C*, **41** (2005) 1.
[3] GRONAU M. and LONDON D., *Phys. Lett. B*, **253** (1991) 483.
[4] ATWOOD D., DUNIETZ I. and SONI A., *Phys. Rev. Lett.*, **78** (1997) 3257; *Phys. Rev. D*, **63** (2001) 036005.

[5] Giri A., Grossman Y., Soffer A. and Zupan J., *Phys. Rev. D*, **68** (2003) 054018.
[6] del Amo Sanchez P. *et al.* (the BABAR Collaboration), *Phys. Rev. Lett.*, **105** (2010) 121801.
[7] Poluektov A. *et al.* (the Belle Collaboration), *Phys. Rev. D*, **81** (2010) 112002.
[8] Bondar A. and Poluektov A., *Eur. Phys. J. C*, **47** (2006) 347.
[9] Browder T. E., Gershon T., Pirjol D., Soni A. and Zupan J., *Rev. Mod. Phys.*, **81** (2009) 1887.
[10] Bona M. *et al.*, arXiv:0709.0451 [hep-ex].
[11] Hitlin D. G. *et al.*, arXiv:0810.1312 [hep-ph].