# $B$ Physics: Past and Present

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**Abstract**

After recalling the significance of the discovery of $B^0$–$\overline{B}^0$ mixing, we review the current status of flavor physics, starting with measurements pioneered by ARGUS and CLEO, followed by what we learned about $CP$ violation from *BABAR* and Belle. We discuss the implications of the recent discoveries of $B_s^0$–$\overline{B}_s^0$ and $D^0$–$\overline{D}^0$ mixing, and conclude with a brief outlook for flavor physics in the LHC era.

## 1 Introduction: $B^0$–$\overline{B}^0$ mixing in 1987

The discovery of $B^0$–$\overline{B}^0$ mixing [1], which this symposium celebrates, is one of two major breakthroughs that occurred in 1987, which play prominent roles in particle physics to date (the other being Supernova 1987a and the detection of the neutrinos associated with it [2]).[1]

The unexpectedly large value of $\Delta m_B$, i.e., the unexpectedly fast $B^0$–$\overline{B}^0$ oscillation was surprising, because it indicated a much heavier top quark mass than the direct search limits at that time, which was $m_t > 23\,\text{GeV}$. While the first announcement at DESY was in a seminar on February 24 [3], and the ARGUS paper [1] was received by Phys. Lett. B on April 9, the first theory paper analyzing the consequences of the discovery was received and published earlier [4], followed by a number of other studies [5, 6, 7, 8]. (Actually, it was pointed out in 1983 [but not taken too seriously] that if the $B$ lifetime was large, the upper bound on $\Gamma(b \to u)/\Gamma(b \to c)$ and the measured value of $\epsilon_K$ implied a heavy top; for $\tau_B = 1.5\,\text{ps}$, $m_t > 60\,\text{GeV}$ [9].)

In the standard model (SM), once $m_t \gg m_{u,d,s,c,b}$, the dominant contributions to $\Delta m_B$ come from box diagrams with intermediate top quarks

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[1] A few minutes at the beginning of the talk were devoted to events unrelated to physics that also occurred in 1987, which are probably better not put in writing. And the Nobel Prize in physics in 1987 was shared by Bednorz and Müller for their discovery of high-$T_c$ superconductivity, something which we still don't fully understand.

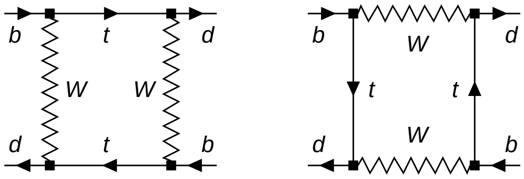

Figure 1: Dominant contributions to $B^0$–$\overline{B}^0$ mixing in the standard model.

shown in Fig. 1. Therefore, $\Delta m_B$ is determined by short-distance physics,

$$\Delta m_B = |V_{tb}V_{td}^*|^2\, \frac{G_F^2}{4\pi^2}\, \frac{m_W^2}{m_B}\, \times S\bigg(\frac{\overline{m}_t^2}{m_W^2}\bigg)\, \eta_B\, b_B(\mu) \times \langle B^0|Q(\mu)|\overline{B}^0\rangle\,, \qquad (1)$$

except for the matrix element of $Q(\mu) = (\bar{b}_L\gamma_\nu d_L)(\bar{b}_L\gamma^\nu d_L)$ in the last term,

$$\langle B^0|Q(\mu)|\overline{B}^0\rangle = \frac{2}{3}\, m_B^2\, f_B^2\, \frac{\widehat{B}_B}{b_B(\mu)}\,, \qquad (2)$$

which is a nonperturbative quantity. In Eq. (1) $S(\overline{m}_t^2/m_W^2)$ is an Inami-Lim function [10], while $\eta_B \simeq 0.55$ and $b_B(\mu)$ contain the QCD corrections that occur in running the effective Hamiltonian down to a low scale and resum the potentially large logarithms of $m_W/\mu$. Hadronic uncertainties enter via $f_B^2\, \widehat{B}_B$, which has to be determined from lattice QCD.

Using the available model predictions of $f_B$ (which tended to be smaller than its currently favored value) and the upper bound on $|V_{td}|$ (which followed from $|V_{cb}|$ and the bound on $|V_{ub}/V_{cb}|$), the ARGUS discovery implied $m_t > 50 - 100\,\text{GeV}$. This was the first indication that the top quark may not be observable at SLC and LEP. It also implied that there would be no top flavored hadrons, and that $B_s$–$\overline{B}_s^0$ mixing had to be maximal.

Of course, if there is beyond SM physics near the electroweak scale, it could modify the conclusions. Simply box diagrams with charged scalars in a two Higgs doublet model could have given rise to “A light top quark after all?” [11] (a scenario later excluded [12]). The lesson from this is that the interpretation of measurements of flavor-changing neutral-current (FCNC) processes in general — due to their sensitivity to physics at high scales — depend on whether one assumes the SM to be valid.

## 2 Flavor physics

In the standard model, the only interaction of quarks that distinguish between the three generations is their Yukawa couplings to the Higgs condensate, which gives rise to quark masses and all flavor changing phenomena described by the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [13, 14]. We do not understand the hierarchy of the masses and mixing angles. Moreover, if there is new physics (NP) at the TeV scale, as suggested by the gauge hierarchy problem, it is puzzling why it has not shown up in flavor physics. For example, the four-quark operator, $(s\bar{d})^2/\Lambda_{\rm NP}^2$, with $\mathcal{O}(1)$ coefficient would give a contribution exceeding the measured value of the $CP$ violating parameter $\epsilon_K$ in the kaon sector [15], unless $\Lambda_{\rm NP} \gtrsim 10^4$ TeV. In fact, most extensions of the SM aimed at solving the hierarchy problem contain new sources of $CP$ and flavor violation. For example, generic SUSY models have 43 new $CP$ violating phases [16, 17], and many of them have to be tiny in order not to contradict the experimental data. Finally, the observed baryon asymmetry of the Universe requires $CP$ violation beyond the SM, however, it need not be in flavor changing processes (may affect electric dipole moments only) and it need not occur in the quark sector (could be in the lepton sector or between new particles only). In any case, flavor physics is an important probe of new physics — if there is new physics at the TeV scale, it has to have a very special structure to avoid violating the bounds imposed by the existing flavor physics data.

## 2.1 Testing the flavor sector

The flavor sector of the SM contains 10 physical quark flavor parameters, the 6 quark masses and the 4 parameters in the CKM matrix, 3 mixing angles and 1 $CP$ violating phase. Therefore, the SM predicts intricate correlations between dozens of different decays of $s$, $c$, $b$, and $t$ quarks, and in particular between $CP$ violating observables. Possible deviations from the CKM paradigm may modify (i) correlations between different measurements (e.g., inconsistent constraints from $B$ and $K$ decays, or $CP$ asymmetries not equal in $B \to \psi K$ and $\phi K$); (ii) predictions for FCNC transition (e.g., $\Delta m_{B_s}$ incompatible with SM, enhanced $B_{(s)} \to \ell^+\ell^-$); (iii) enhanced (or suppressed) $CP$ violation, (e.g., in $B \to K^*\gamma$ or $B_s \to \psi\phi$).

The goal is not only to determine SM parameters as precisely as possible, but to test by many overconstraining measurements whether all observable flavor-changing interactions can be explained by the SM. It is convenient to use the Wolfenstein parameterization [18] of the CKM matrix,

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix}, \tag{3}$$

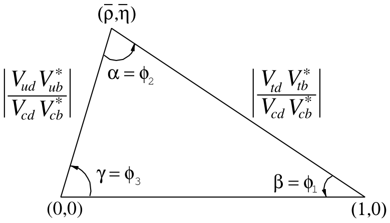

Figure 2: Sketch of the unitarity triangle.

which exhibits its hierarchical structure by expanding in $\lambda \simeq 0.23$, and is valid to order $\lambda^4$. The unitarity of the CKM matrix implies $\sum_i V_{ij} V_{ik}^* = \delta_{jk}$ and $\sum_j V_{ij} V_{kj}^* = \delta_{ik}$, and the six vanishing combinations can be represented by triangles in a complex plane. The ones obtained by taking scalar products of neighboring rows or columns are nearly degenerate, so one usually considers

$$V_{ud}\, V_{ub}^* + V_{cd}\, V_{cb}^* + V_{td}\, V_{tb}^* = 0\,. \tag{4}$$

A graphical representation is the unitarity triangle, obtained by rescaling the best-known side to unit length, see Fig. 2. The sides and angles can be determined in many "redundant" ways, by measuring $CP$ violating and conserving observables. Considering the constraints on $\bar\rho$ and $\bar\eta$ is a convenient way to compare overconstraining measurements (however, some important ones cannot be represented on this plane in a useful way).

The $CP$ violating parameter in the $K$ system, $\epsilon_K$, which has been precisely known for a long time, is at a level compatible with the SM; i.e., it can be accommodated with an $\mathcal{O}(1)$ value of the KM phase. The other observed $CP$ violating quantity in kaon decay, $\epsilon'_K$, is notoriously hard to interpret, because the electromagnetic and gluonic penguin contributions tend to cancel [19], significantly enhancing the hadronic uncertainties.[2] We cannot even rule out yet that NP is responsible for a large part of the measured value of $\epsilon'_K$, so it does not provide a strong test of the KM mechanism. In the kaon sector, precise tests may come from measuring $K \to \pi\nu\bar\nu$ in the future.

## 3 The ARGUS and CLEO era

I focus here on a few semileptonic $B$ decay measurements, for which many experimental techniques and theoretical tools were developed in the late 80's

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[2] Amusingly, the Review of Particle Properties in 1986 [20], just before the ARGUS discovery, was the last edition in which $\epsilon'/\epsilon$ was still within $1\sigma$ of 0. The first results of NA31 at CERN and E731 at Fermilab also appeared in 1987.

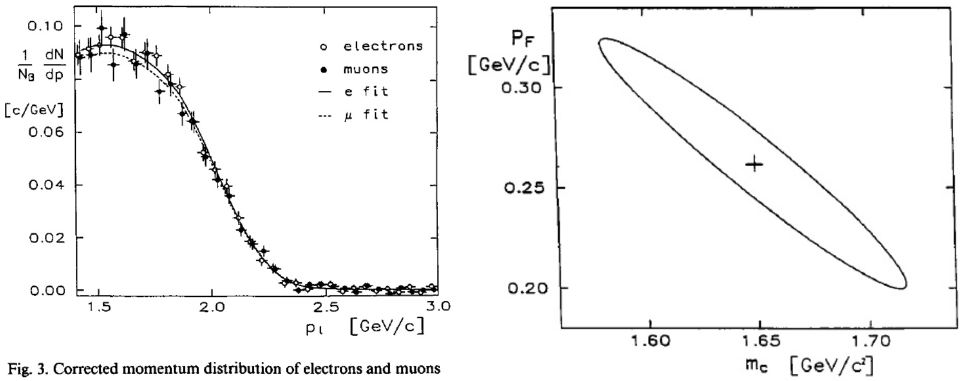


**Fig. 3.** Corrected momentum distribution of electrons and muons from $\Upsilon(4S)$ decays. The solid and dashed lines are the fits of the GISW model to the electron and muon data respectively.

**Fig. 4.** Best fit and $1\sigma$ contour for $p_F$ and $m_c$ in the ACM model.

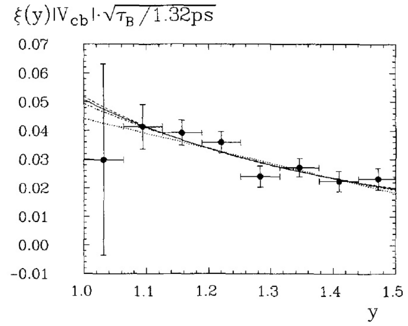
Figure 3: Semileptonic $B \to X_c \ell \bar\nu$ spectrum (left) and constraints on ACM model parameters (right) [21].

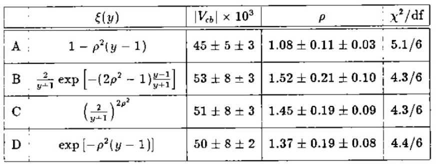
and early 90's. The successors of these yield the best measurements of $|V_{cb}|$ and $|V_{ub}|$ to date. They determine one side of the unitarity triangle and are crucial for the search for new physics, since these are tree-level measurements to which the loop processes sensitive to new physics can be compared.

### 3.1 Inclusive $B \to X_c \ell \bar\nu$ and $|V_{cb}|$

The inclusive semileptonic $B \to X_c \ell \bar\nu$ rate is obviously proportional to $|V_{cb}|^2$, and the "only" question was how to extract $|V_{cb}|$ without relying on models of the strong interaction. The state of the art around 1990 was to measure the charged lepton energy spectrum, and fit it to model predictions [21]; see the left plot in Fig. 3 (curiously, what is now known as the ISGW model was still called GISW [22] in the caption). It was already realized that the shape of the same spectrum can also be used to constrain the parameters of, say, the ACM [23] model, as shown in the right plot in Fig. 3.

Few years after these measurements, it was realized that the semileptonic decay spectra can be computed in a systematic, QCD based, operator product expansion (OPE) [24]. To make the perturbation series well behaved, instead of the pole mass an appropriate short distance mass scheme has to be used, e.g., the $1S$ mass [25]. By now the total rate, as well as moments of the lepton energy and the hadronic invariant mass spectra have been precisely measured and computed to order $\Lambda_{\rm QCD}^3/m_b^3$ and $\alpha_s^2\beta_0$ [26] (very recently the full $\alpha_s^2$ calculation is done [27]). These theoretical predictions are fit to about a hundred measurements from *BABAR*, Belle, and CLEO,





| | $\xi(y)$ | $\lvert V_{cb}\rvert \times 10^3$ | $\rho$ | $\chi^2$/df |
|---|---|---|---|---|
| A | $1-\rho^2(y-1)$ | $45 \pm 5 \pm 3$ | $1.08 \pm 0.11 \pm 0.03$ | 5.1/6 |
| B | $\frac{2}{y+1}\exp\left[-(2\rho^2-1)\frac{y-1}{y+1}\right]$ | $53 \pm 8 \pm 3$ | $1.52 \pm 0.21 \pm 0.10$ | 4.3/6 |
| C | $\left(\frac{2}{y+1}\right)^{2\rho^2}$ | $51 \pm 8 \pm 3$ | $1.45 \pm 0.19 \pm 0.09$ | 4.3/6 |
| D | $\exp\left[-\rho^2(y-1)\right]$ | $50 \pm 8 \pm 2$ | $1.37 \pm 0.19 \pm 0.08$ | 4.4/6 |

Table 5: Results on $|V_{cb}|$ and the "charge radius" $\rho$ from various parametrizations of the Isgur-Wise-function $\xi(y)$ [22] for fitting the $q^2$-distribution

Figure 4: Semileptonic $B \to D^*\ell\bar\nu$ spectrum (left) and parameters of the fits with various functional forms to the $y = v \cdot v'$ distribution (right) [29].

and the fit determines simultaneously $|V_{cb}|$ and the hadronic parameters. Its consistency provides a powerful test of the theory. These fits have been performed in several schemes and give $|V_{cb}|$ and $m_b$ with about 2% and 1% errors, respectively [26],

$$|V_{cb}| = (41.5 \pm 0.7) \times 10^{-3}\,, \qquad m_b^{1S} = (4.68 \pm 0.04)\,\mathrm{GeV}\,. \tag{5}$$

The value of $m_b$ is particularly important for the determination of $|V_{ub}|$ discussed below (this value corresponds to $\overline{m}_b(\overline{m}_b) = (4.18 \pm 0.04)\,\mathrm{GeV}$).

### 3.2 Exclusive $B \to D^*\ell\bar\nu$ and $|V_{cb}|$

Exclusive $B \to D^{(*)}\ell\bar\nu$ decays provide a determination of $|V_{cb}|$ complementary to inclusive decays, as both the theoretical and experimental uncertainties are different. The discovery of heavy quark symmetry [28] in 1989 opened the way for the model independent determination of $|V_{cb}|$, and the $B \to D^*\ell\bar\nu$ data was first analyzed by ARGUS [29] using the predictions of heavy quark symmetry.

In the $m_b$, $m_c \gg \Lambda_{\mathrm{QCD}}$ limit, heavy quark symmetry relates all $B \to D^{(*)}$ form factors to a single Isgur-Wise function [28]. The relations hold at any value of the recoil parameter, $y = v\cdot v' = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B\, m_{D^{(*)}})$, where $v$ and $v'$ are the four-velocities of the $B$ and $D^{(*)}$, respectively. Moreover, the value of this function is known at zero recoil, $\xi(1) = 1$, and the measured form factor satisfies $F(y) = \xi(y) + \mathcal{O}(\alpha_s,\, \Lambda_{\mathrm{QCD}}/m_{b,c})$. The left plot in Fig. 4 shows $|V_{cb}|\,\xi(y)$, which is how $|V_{cb}|$ is extracted from $B \to D^*\ell\bar\nu$ to date. The calculation of $F(1)$ is now dominated by lattice QCD [30].

As shown in the table in Fig. 4, already in the ARGUS analysis a dominant uncertainty was that from the functional form used to fit the data. This

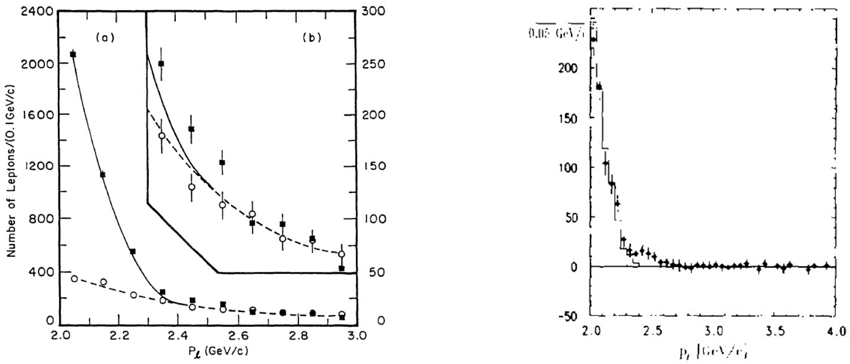


FIG. 1. Sum of the $e$ and $\mu$ momentum spectra for ON data (filled squares), scaled OFF data (open circles), the fit to the OFF data (dashed line), and the fit to the OFF data plus the $b \to c l \nu$ yield (solid line). Note the different vertical scales in (a) and (b).

Fig. 5. Combined lepton momentum spectrum for direct $\Upsilon(4S)$ decays: the histogram is a $b \to c$ contribution normalized in the region 2.0–2.3 GeV/c.

Figure 5: First observation of semileptonic $B \to X_u \ell \bar\nu$ decay from CLEO [32] (left) and ARGUS [33] (right).

was largely reduced by the derivation of model independent constraints on the shape of the form factor [31], following from unitarity and analyticity.

### 3.3 Inclusive $B \to X_u \ell \bar\nu$ and $|V_{ub}|$

Before a nonzero value of $|V_{ub}|$ was established, it was not known whether the $3 \times 3$ CKM matrix contains $CP$ violation, since its complex phase could be eliminated if any of the CKM elements vanished.

The $b \to u$ semileptonic decay was first observed by CLEO [32] and ARGUS [33]. Since one had to study the endpoint region of the $B \to X_u \ell \bar\nu$ spectrum to eliminate the much larger $B \to X_c \ell \bar\nu$ background (see Fig. 5), the hadronic model dependence was even greater than for $|V_{cb}|$, and was the dominant uncertainty. The CLEO paper concluded "$|V_{ub}/V_{cb}|$ … is approximately 0.1; it is sensitive to the theoretical model" [32], while ARGUS was even more cautious, "If interpreted as a signal of $b \to u$ coupling the observed event rate leads to … $|V_{ub}/V_{cb}|$ of about 10%" [33].

The theoretical uncertainties became better controlled when it was realized [34] that the nonperturbative effects that lead to a breakdown of the OPE in the endpoint region of $B \to X_u \ell \bar\nu$ spectra can be related to the photon energy spectrum in $B \to X_s \gamma$, first measured by CLEO [35]. Thus, theoretical uncertainties are suppressed by $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$, but there are several unknown functions at that order, and it is hard to control them below the 10% level. Recently, with the full reconstruction method, the $B$ factories could measure the neutrino momentum, which allowed access to wider kinematic regions and also to parts of phase space in which the $B \to X_c \ell \bar{\nu}$ decay is forbidden, but an OPE is still possible [36].

## 4 The *BABAR* and Belle era

An illustration that the $B$ factories started a new era in the study of $CP$ violation is the fact that for 35 years, from 1964 until 1999, there was only one $CP$ violating quantity, $\epsilon_K$, which was robustly measured. At the time of this Symposium, 19 $CP$ violating quantities with different sensitivities to short distance physics are measured with at least $3\sigma$ significance (i.e., not counting $S_{\psi K_L}$ separately from $S_{\psi K_S}$, but considering $S_{\eta' K_S}$ as independent) [37]. Thus, the important measurements are those which are experimentally most precise and theoretically least uncertain, thereby providing the best sensitivity to constrain possible deviations from the SM. (The experimental techniques and more complete lists of references to the measurements can be found in J. Olsen's contribution.)

### 4.1 Mixing and $CP$ violation (again)

The two neutral $B$ meson states form a quantum mechanical two-level system, whose time evolution is described by

$$i \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix} = \Big( M - \frac{i}{2}\, \Gamma \Big) \begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix}, \tag{6}$$

where $M$ and $\Gamma$ are $2 \times 2$ Hermitian matrices. The physical mass eigenstates (labelled heavy and light) are linear superpositions of the flavor eigenstates,

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle \,. \tag{7}$$

The box diagrams in Fig. 1 (with $t, c, u$ quarks) give rise to $M_{12}$ and $\Gamma_{12}$. These in turn determine $q/p$ (see, e.g., [38]), which plays an important role in $CP$ violation,

$$q/p = e^{-2i\beta + (\xi_B + \xi_d - \xi_b)} + \mathcal{O}(10^{-3})\,, \tag{8}$$

where $\beta$ is an angle of the unitarity triangle shown in Fig. 2, and $\xi_{B,d,b}$ are (unphysical) phase conventions for the meson and quark fields. In the SM, $|q/p|$ is very near unity, which means that $CP$ violation in $B^0$–$\overline{B}^0$ mixing is expected to be a small, $\mathcal{O}(10^{-3})$. (Recall that $CP$ is violated in mixing if and only if $\langle B_H|B_L\rangle = |p|^2 - |q|^2 \neq 0$, indicating that $CP$ violation is an intrinsically quantum mechanical phenomenon.)

In some cases it is possible to obtain theoretically clean information on phases in the Lagrangian of the underlying theory from large $CP$ violating phenomena. The simplest examples are $CP$ violation in the interference of decay with and without mixing [39, 40], in particular, when the final state is a $CP$ eigenstate. The interference between $\overline{B}^0 \to f_{CP}$ and $\overline{B}^0 \to B^0 \to f_{CP}$ is described by

$$\lambda_{f_{CP}} = \frac{q}{p}\,\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{f_{CP}}\,\frac{q}{p}\,\frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}\,, \tag{9}$$

where $A_f = \langle f|\mathcal{H}|B\rangle$, $\overline{A}_f = \langle f|\mathcal{H}|\overline{B}\rangle$, and $\eta_{f_{CP}} = \pm 1$ is the $CP$ eigenvalue of $f_{CP}$. Experimentally one can study the time dependent $CP$ asymmetry,

$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\overline{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = S_f \sin(\Delta m_B\, t) - C_f \cos(\Delta m_B\, t)\,, \tag{10}$$

where $t$ is the time difference between the flavor tag of the “other” $B$ meson and the decay, and

$$S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}\,, \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,. \tag{11}$$

If amplitudes with one weak phase dominate a decay, then $a_{f_{CP}}$ measures a phase in the Lagrangian theoretically cleanly. In this case $C_f = 0$ (no direct $CP$ violation), and $S_{f_{CP}} = \mathrm{Im}\,\lambda_{f_{CP}} = \sin(\arg\,\lambda_{f_{CP}})$, where $\arg\lambda_{f_{CP}}$ is the phase difference between the $\overline{B}^0 \to f_{CP}$ and $\overline{B}^0 \to B^0 \to f_{CP}$ amplitudes.

Equation (10) makes it clear that the unexpectedly large value of $\Delta m_B$ discovered by ARGUS was very important to make the precision study of time dependent $CP$ violation feasible.

## 4.2 Some key measurements

The theoretically cleanest $CP$ violation measurement in $B$ decays is $B \to \psi K^0$ (where $\psi = J/\psi,\ \psi'$). While there are tree and penguin contributions to the decay amplitude with different weak phases, the dominant part of the penguin amplitudes have the same weak phase as the tree. Therefore, contributions with the tree amplitude’s weak phase dominate, to an accuracy better than ∼1%. In the usual phase convention $S_{\psi K_{S,L}} = \mp \sin[(B\text{-mixing} = -2\beta) + (\text{decay} = 0) + (K\text{-mixing} = 0)]$, so we expect $S_{\psi K_{S,L}} = \pm \sin 2\beta$ and $C_{\psi K_{S,L}} = 0$ to a similar accuracy. The current world average is [37]

$$\sin 2\beta = 0.681 \pm 0.025\,. \tag{12}$$

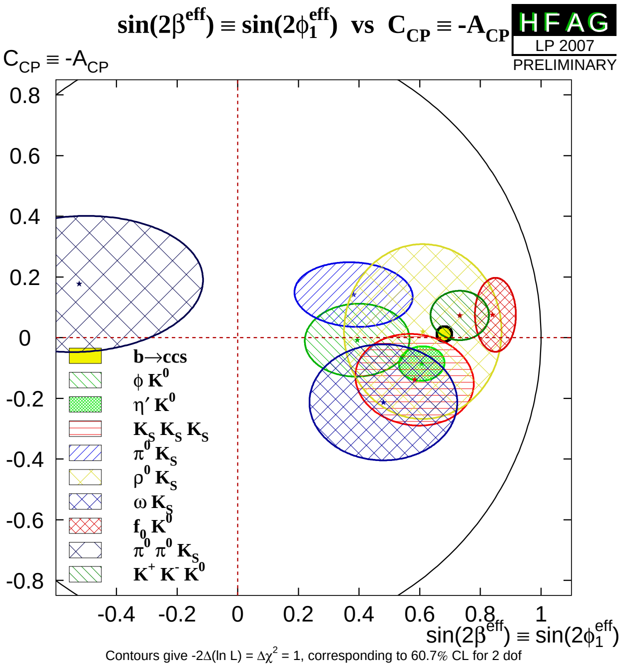


Figure 6: The $CP$ asymmetries in $b \to s$ penguin dominated modes [37].

One of the most stringent tests of the SM flavor sector come from $CP$ asymmetry measurements in $b \to s$ dominated transitions, such as $B \to \phi K^0$, $\eta' K^0$, $K^+K^-K_S$, etc. These decays are dominated by one-loop (penguin) amplitudes in the SM, and therefore new physics could compete with the SM contributions [41]. Using CKM unitarity, one can write the contributions to such decays as a term proportional to $V_{cb}V_{cs}^*$ and another proportional to $V_{ub}V_{us}^*$. Since the ratio of these CKM elements is $\sim 0.02$, we expect amplitudes with the $V_{cb}V_{cs}^*$ weak phase to dominate, similar to $B \to \psi K^0$. Thus, in the SM, the measurements of $-\eta_f S_f$ should agree with $\sin 2\beta$ (and $C_f$ should vanish) to an accuracy of order a few times 0.02. Figure 6 shows the current measurements, with the tiny circle representing the tree-dominated $B \to \psi K^0$ mode. There is no significant evidence for deviations from the SM, e.g., $S_{\psi K} - S_{\phi K} = 0.29 \pm 0.17$.

The measurements of $\alpha$ and $\gamma$ are less precise, although the results are better than they were foreseen a decade ago; the best modes to measure both are actually new since 2003. (I call a measurement of $\gamma$ the determination of the phase difference between $b \to u$ and $b \to c$ transitions, and $\alpha (\equiv \pi - \beta - \gamma)$ refers to measurements of $\gamma$ in the presence of $B^0$–$\overline{B}^0$ mixing.)

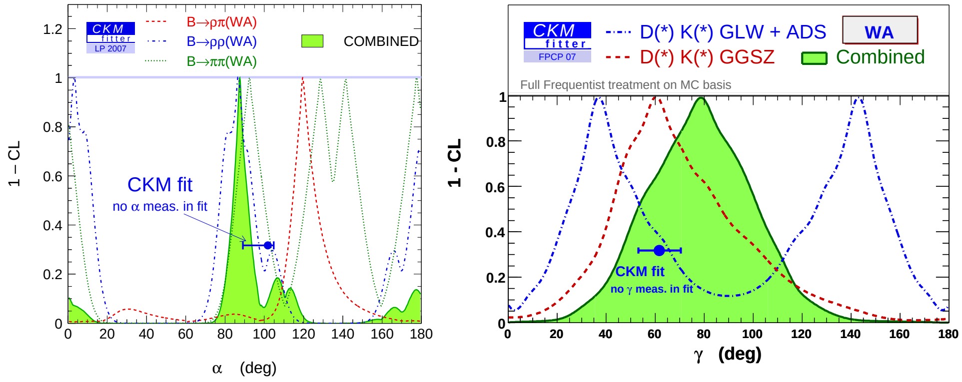


Figure 7: Measurements of the CKM angles $\alpha$ and $\gamma$ [44].

In contrast to $B \to \psi K$, which is dominated by amplitudes with one weak phase, it is known since the CLEO observation of $B \to K\pi$ in 1997 [42] that in $B \to \pi^+\pi^-$ the penguin ($P$) amplitude is not much smaller than the tree ($T$). Before this measurement, one expected $S_{\pi^+\pi^-} = \sin[(B\text{-mixing} = -2\beta) + (\overline{A}/A = -2\gamma + \ldots)] = \sin 2\alpha + \ldots$. The ellipses denote $\mathcal{O}(P/T)$ terms, which are experimentally measured to be sizable. Therefore, to determine $\alpha$ model independently, an isospin analysis of all $B \to \pi\pi$ decay channels is needed [43]. The world average, including the $B \to \rho\rho$ and $\rho\pi$ modes, is shown in the left plot in Fig. 7. The $B \to \rho\rho$ mode dominates, because the data tell us that $|P/T|$ is relatively small in this mode.

The special feature of the measurements of $\gamma$ compared to $\beta$ and $\alpha$ is that $\gamma$ is measured in entirely tree-level processes, in the interference of $b \to c\bar{u}s$ (e.g., $B^- \to D^0K^-$) and $b \to u\bar{c}s$ (e.g., $B^- \to \overline{D}{}^0K^-$) transitions, using common final states of $D^0$ and $\overline{D}{}^0$. Since there are no two identical quarks in these decays, penguin diagrams cannot contribute, so new physics is very unlikely to effect these measurements. The world average, including several $D$ decay modes is shown in the right plot in Fig. 7.

For all these angle measurements one would need much more data to approach the theoretical limitations, and the sensitivity to new physics would increase at least until when the experimental errors get ~10 times smaller.

### 4.3 Constraints on new physics in $B^0$–$\overline{B}{}^0$ mixing

In a large class of models the dominant NP effect in $B$ physics is to modify the $B^0$–$\overline{B}{}^0$ mixing amplitude [45]. Assuming that the $3 \times 3$ CKM matrix is unitary and tree-level decays are SM dominated imply that there are two

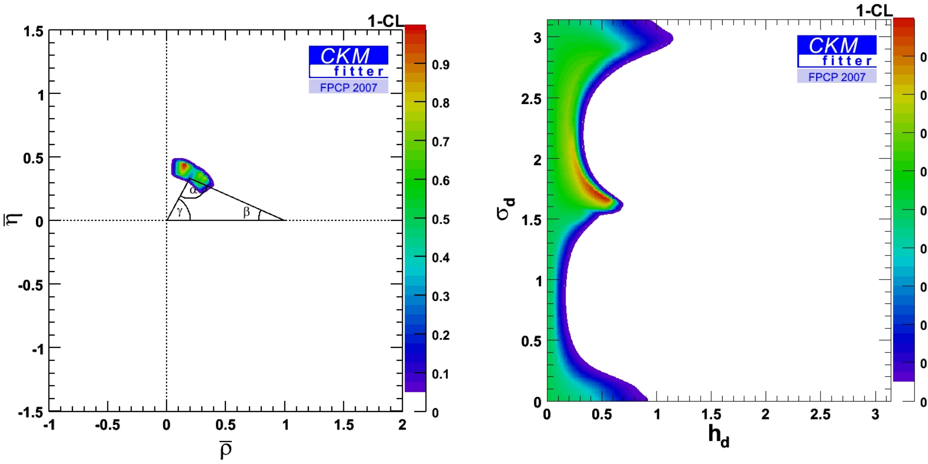


Figure 8: Allowed $\bar{\rho} - \bar{\eta}$ region in the presence of new physics in $B^0$–$\overline{B}^0$ mixing (left), and the allowed $h_d - \sigma_d$ region (right) [44].

new parameters for each meson mixing amplitude,

$$M_{12} = M_{12}^{(\mathrm{SM})}\, r^2\, e^{2i\theta} = M_{12}^{\mathrm{SM}}\, (1 + h\, e^{2i\sigma})\,. \tag{13}$$

The $(h, \sigma)$ parameterization is more physical, since any new physics model gives an additive (and not a multiplicative) correction to $M_{12}$. To constrain new physics, it is crucial to have measurements of both new physics independent tree-level processes, such as $|V_{ub}/V_{cb}|$ and $\gamma$ (or $\pi - \beta - \alpha$), and mixing dependent processes, which include $\Delta m$, $S_{f_i}$, $A_{\mathrm{SL}}$ [46].

It is a remarkable result of the $B$ factories that the allowed $\bar{\rho}-\bar{\eta}$ region in the presence of new physics in mixing has become similarly small as it is in the SM, as shown in the left plot in Fig. 8. The right plot shows the allowed $h_d - \sigma_d$ region, indicating that new contributions to $B^0$–$\overline{B}^0$ mixing at the level of $20 - 30\%$ of the SM without a fine tuned phase are still allowed.

### 4.4 $B_s^0$–$\overline{B}_s^0$ mixing

As mentioned in the introduction, the ARGUS discovery of $B^0$–$\overline{B}^0$ mixing immediately implied that $B_s$ mixing is near maximal in the SM, due to the hierarchical structure of the CKM matrix. [Eq. (1) applies for $B_s$ mixing as well, replacing $V_{td} \to V_{ts}$, $m_{B_d} \to m_{B_s}$, $f_{B_d} \to f_{B_s}$, and $\widehat{B}_{B_d} \to \widehat{B}_{B_s}$.] This made resolving the oscillations very challenging. The CDF measurement [47]

$$\Delta m_{B_s} = (17.77 \pm 0.10 \pm 0.07)\, \mathrm{ps}^{-1}\,, \tag{14}$$

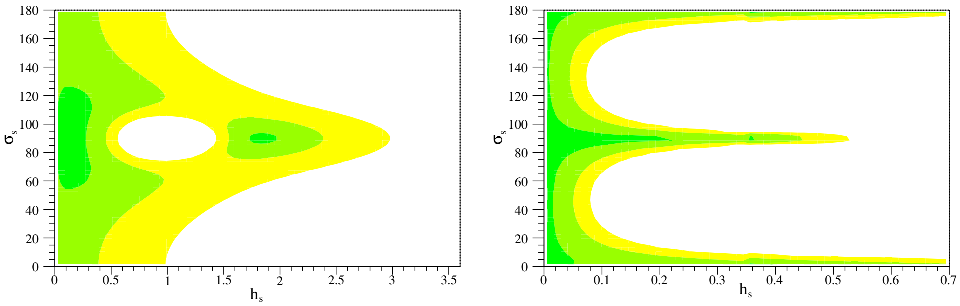


Figure 9: Constraints on the NP parameters $(h_s,\, \sigma_s)$ in $B_s$ mixing, after the measurement of $\Delta m_{B_s}$ (left) and after a nominal year at LHCb (right) [48].

indicates that $B_s^0$ and $\overline{B}{}_s^0$ mesons oscillate about 25 times before they decay. Amusingly, once the oscillation could be resolved, the experimental uncertainty $\sigma(\Delta m_{B_s}) = 0.7\%$ is already smaller than $\sigma(\Delta m_{B_d}) = 0.8\%$. In the $B_s$ system the lifetime difference is $1/\lambda^2$ enhanced compared to $B_d$, since decays to common final states of $B_s^0$ and $\overline{B}{}_s^0$ are Cabibbo allowed. Thus one expected $\Delta\Gamma_{B_s}/\Gamma_{B_s} \sim 0.1$, and the world average is $0.104^{+0.076}_{-0.084}$ [37].

With the measurement of $\Delta m_{B_s}$, the CKM picture passed another stringent test. Many models with TeV-scale new particles could have given rise to significant deviations from the SM prediction, without altering the agreement with data in the $B_d$ sector. However, as shown in Fig. 9, even after the measurement of $\Delta m_{B_s}$ (and initial data on $\Delta\Gamma_{B_s}$) new physics comparable to the SM contribution may still be present in $B_s^0$–$\overline{B}{}_s^0$ mixing. The next key measurement will come from the time dependent $CP$ asymmetry in $B_s \to \psi\phi$ (i.e., that in the $CP$-even partial waves, the analog of measuring $\sin 2\beta$ in $B \to \psi K$), for which the SM predicts $\sin 2\beta_s = 0.0368^{+0.0017}_{-0.0018}$ [44]. As can be seen from the right plot in Fig. 9, the expected LHCb precision with even one year of nominal data, $\sigma(\sin 2\beta_s) = 0.03$, will make a huge improvement in the sensitivity to NP in $B_s^0$–$\overline{B}{}_s^0$ mixing. (While this writeup was in preparation, the first results from CDF and DØ appeared [49].)

## 4.5 $D^0$–$\overline{D}{}^0$ mixing

There are other fascinating developments in flavor physics. Just this past year, the observation for $D^0$–$\overline{D}{}^0$ mixing is becoming conclusive, which is discussed in detail in K. Schubert's contribution. The $D^0$ system is special in that it is the only neutral meson in which mixing is generated by box diagrams with down (rather than up) type quarks. Unfortunately, it is not possible to rule out that the SM could account for the observed central values of $x_D = \Delta m_D/\Gamma_D$ and $y_D = \Delta\Gamma_D/2\Gamma_D$ [50]. The evidence for $(x_D, y_D) \neq (0,0)$ is $\sim 5\sigma$, but their separate measurements are only at the $\sim 3\sigma$ level. However, the measurements viewed as an upper bound on $\Delta m_D$ already provide strong constraints on new physics (similar to $\epsilon'/\epsilon$). For example, the smallness of $\Delta m_D$ implies that quark-squark alignment models [51] without other suppression mechanisms are no longer viable (if $m_{\tilde g,\tilde q} \lesssim 1\,\text{TeV}$). Thus, it is important to improve the constraints on both $x_D$ and $y_D$, and to look for $CP$ violation, for which there is no hint yet, but it remains a potentially robust signal of new physics.

## 5 Final comments

With the $B_s^0$ and $D^0$ mixing measurements, we now know a lot more about the correspondence between the lifetimes, $CP$ eigenstates, and mass eigenstates of the neutral mesons. Neglecting $CP$ violation in mixing [38]

$$\begin{aligned}
K^0 &: \text{long-lived} = CP\text{-odd} = \text{heavy}\,,\\
D^0 &: \text{long-lived} = CP\text{-odd}\ (3.5\sigma) = \text{light}\ (2\sigma)\,,\\
B_s^0 &: \text{long-lived} = CP\text{-odd}\ (1.5\sigma) = \text{heavy in the SM}\,,\\
B_d^0 &: \text{yet unknown; same as } B_s \text{ in SM for } m_b \gg \Lambda_{\text{QCD}}\,. \qquad (15)
\end{aligned}$$

In all four systems the long-lived state seems to be the $CP$-odd, and it is also the heavier state with the exception of $D$ mesons. Curiously, before 2006 we only knew experimentally the first line in Eq. (15), and it is only the $B_d^0$ system for which we still lack experimental evidence for the correspondence between the heavy-light, even-odd, long-short states. (It may be impossible to identify the $CP$-even and -odd $B_d^0$ states, since it may not have any decay to a $CP$ eigenstate final state in which $CP$ violation is negligible.)

With the imminent start of the LHC, we are at the verge of an exciting era. We will soon probe directly the mechanism of electroweak symmetry breaking. At the same time, the lack of deviations from the SM in flavor physics experiments poses a problem for many TeV-scale new physics scenarios. One possibility to avoid fine tuning in the presence of TeV-scale new physics is to assume minimal flavor violation (MFV), which is the assertion that Yukawa couplings are the only source of flavor and $CP$ violation, even in the presence of new physics. In the context of SUSY, for example, MFV implies to a good approximation that the first two generation superpartners are degenerate and that the decays of new heavy particles are flavor diagonal. These can be probed at the LHC, so the spectra and decay channels of possible new particles will also teach us about flavor.

In conclusion, tremendous progress has been made in $B$ physics over the last couple of decades. The SM flavor sector has been tested with increasing precision, and we now know that the CKM phase is the dominant source of $CP$ violation in flavor changing processes. Deviations from the SM in $B_{d,s}$ mixing, in $b \to s$ and even $b \to d$ decays are being constrained. The scales probed by these measurements are at the hundreds of TeV level, so if there is new physics at the TeV scale, it must incorporate some mechanism(s) to suppress FCNC processes. If beyond SM flavor physics is seen at the $B$ factories or at LHCb, then we will certainly want to study it in as many different processes as possible. In the absence of new discoveries, flavor physics will still provide important constraints, similar to the LEP tests of the gauge sector of the SM. In either case, flavor physics will give powerful constraints on model building in the LHC era.

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