Beauty physics in the next 15 years – an itinerary for a long journey towards an essential goal

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Abstract

After re-stating why beauty physics is so special and sketching its present status I attempt to map out an itinerary for the next fifteen years. The basic elements are listed for a research program that allows one to define and probe the KM unitarity triangle in a manner where the numerical uncertainties are reduced to the few percent level. Dedicated experiments at the LHC will be essential in exploiting the discovery guarantee in beauty physics to the fullest.

This paper is dedicated to Prof. H. Kastrup on the occasion of his 60th birthday. I spent five years at his institute at the RWTH Aachen and truly enjoyed the stimulating atmosphere he created by encouraging intellectual exchange unimpeded by hierarchical privileges.

1. Introduction

Approaching Mont Saint Michel one recognizes the church crowning the rock from far away. Getting closer one discovers there is much more structure to the Mont; after having spent a little while here one realizes that these other buildings do more than merely support the church, that they hold their own charm and beauty. At the end of this paper I will return to this image and explain why it provides us which such a fitting allegory on the purpose of our meeting.

I will argue that a satisfactory research program in beauty physics requires and deserves a long term commitment. Before we set out on a long and arduous journey it behooves us to recall past experiences to prepare our souls and spirits for the adventures that lie ahead. So let us remember the main lessons we have learned from the study of the production and decay of strange hadrons: the full relevance of the concepts of flavour quantum numbers and of Cabibbo universality was revealed; the first evidence for parity violation emerged through the \( \theta - \tau \) puzzle; the tremendous suppression of flavour-changing neutral currents became apparent leading to the prediction of a then new quantum number, namely charm, including its mass scale; the discovery of CP violation fundamentally changed our perception of nature’s microscopic design and, on a more practical level, showed the existence of New Physics (NP) even beyond a two-family ansatz. All these insights were essential ingredients in formulating what we call now the Standard Model (SM) – although it has to be said that at first they were often met with considerable skepticism.

While this Standard Model has so far yielded a consistent description, it is generally viewed as incomplete. This is based on the realization that it contains various mysteries. Central among them is the origin of mass in general and of fermions in particular, the existence of families and the very peculiar form of the KM matrix. CP violation is intimately connected with these mysterious features.

My basic contention is: a detailed and comprehensive analysis of beauty decays that includes meaningful studies of CP violation – provides novel and unique perspectives on fundamental mysteries of SM, – will very likely reveal NP and – will possibly be essential in formulating the “New Standard Model”.

In the remainder of the paper I will state “why beauty decays” are so special, summarize the “status quo”, sketch the “next five years”, rhapsodize about the “heroic period” and point to the “ultimate measurements” before concluding with an “outlook”.

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2. Why beauty?

The lifetimes of beauty hadrons are of order 1 ps, i.e. they are “long” according to two criteria: (i) Decay vertices of beauty hadrons can be resolved with available technologies once they move with sufficient velocity. (ii) Beauty decays are much more than Cabibbo suppressed: \[ |V(cb)|^2 \ll \sin^2 \theta_C. \] Since SM tree level transitions are thus reduced, the sensitivity to quantum effects and/or NP is considerably enhanced.

SM quantum effects are actually GIM enhanced since \( m_{top} > M_W \). This generates “speedy” \( B^0 - B^0 \) oscillations – \( \Delta m(B) / \Gamma(B) \geq \mathcal{O}(1) \) – and a relatively large branching ratio for \( B \to K^\ast \gamma. \) As we have heard from Ali at this meeting [1] there exists an extremely rich phenomenology of B decays involving all three families, namely in semi-leptonic, radiative and other rare transitions.

The most fascinating aspect is that SM predicts, as reviewed here by Wyler [2], huge CP asymmetries of order few \( \times 10\% \) in some B decays due to the undiluted interplay of all three families and the high \( B^0 - B^0 \) oscillation rate.

This exciting phenomenology is predicted with fairly high theoretical reliability in some relevant cases at least. As discussed by Berger [3], production rates for beauty hadrons should be predicted with reasonable accuracy. For some ratios of transition rates one can expect the major part of the hadronic uncertainties to drop out, like in \( \Delta m(B_s) / \Delta m(B_d) \approx |V(ts)|^2 / |V(td)|^2. \) Other decay rates can be expressed in terms of the basic parameters \( V(cb), V(ub), V(td) \) etc. with at least decent accuracy. Furthermore one can translate those parametric predictions into numerical ones by employing \( 1 / m_b \) expansions to extract the values of these parameters from semi-leptonic and radiative decays. However in doing so we better keep the advice of Maitre Le Yaouanc at heart [4]: the quark model is a wonderful device to develop our intuition and check our conjectures; yet at the same time its proper application involves an artful evaluation of past experiences rather than a rigid scientific procedure – exactly like it is with good French cooking!

3. Status quo

One can discuss the status of hadronic beauty production like the well-known story about the optimist/pessimist looking at a half-full/half-empty glass of wine: while CDF measures [5] a larger beauty cross section than predicted, I am not yet convinced that this represents an alarming problem for theory; for proper perspective one should also keep in mind that the observed \( b \to b \) correlations seem to follow the expected pattern.

The “average” beauty lifetime has been measured to be close to 1.5 ps establishing that indeed \( |V(cb)| \sim \mathcal{O}(\sin^2 \theta_C) \) rather than \( \sim \mathcal{O}(\sin \theta_C). \) This is a very important observation with far-reaching implications as mentioned above. Yet it should now assume the place of honour it richly deserves in the “museum of important measurements”. For once you have established that the “typical” beauty lifetime is indeed around 1 ps, any numerically more precise measurement of the average lifetime in an a priori unknown cocktail of beauty hadrons can certainly advance bragging rights, but not our understanding of the physics involved. For that purpose one has to extract the lifetimes of specified beauty hadrons, i.e. charged vs. neutral mesons vs. baryons. In Table 1 juxtapose theoretical predictions obtained within QCD through an expansion in \( 1 / m_b \) with present data [6].

A few comments are in order here:
- To (formal) order \( 1 / m_b \) one predicts unequivocally \( \tau(B^-) > \tau(B_d). \) The quoted uncertainty reflects corrections of order \( 1 / m_b \) that have not been determined; also their sign is uncertain.
- It is very hard to see theoretically how \( \tau(A_h) \) could differ from \( \tau(B_d) \) by more than 10%.
- No theoretical disaster has occurred; i.e., while the data are not sufficiently precise to establish the predictions, they are quite consistent with them. This constitutes a non-trivial semi-quantitative success, since the lifetime differences in the beauty sector indeed are much smaller than in the charm sector.
- If future data establish a significant deviation from the predictions we would be faced with a serious theoretical conundrum. There is no “model” parameter that could freely be adjusted. One would quite naturally suspect that the deficiencies of our expansions arise mainly in the description of non-leptonic decays. There are actually two variants for such a conjecture: (a) \( 1 / m_b \) expansions are of no use in non-leptonic decays in general although they can be employed with profit in semileptonic decays. (b) Alternatively – and a detailed analysis of the concept of quark–hadron duality seems to point in that direction – one would conclude that the \( 1 / m_b \) expansion numerically converges more slowly in non-leptonic \( b \to c \) than in semileptonic \( b \to c \) and in all \( b \to u \) transitions. (One should note that the energy release is larger in \( b \to u \) than in \( b \to c \) transitions.)

Time-dependent manifestations of \( B^0 - B^0 \) oscillations have been analysed at LEP in a most impressive way:

\[
\Delta m(B_b) = 0.509 \pm 0.046 \text{ (ps)}^{-1},
\]

\[
x_s \equiv \frac{\Delta m}{\Gamma}|_{B_b} > 2.5.
\]

VI. SUMMARIES
Once the top quark mass is known with good accuracy one can infer some information on $|V(td)|$ from a measurement of $\Delta m(B_s)$. Yet keeping in mind that $\Delta m(B_d)$ depends roughly linearly on $m_{top}$ in the relevant range and that hadronic uncertainties arise – as expressed through the quantity $B_s f^2_s$ – it seems to me that $\Delta m(B_s)$ is not quite, but almost as well measured as required. Based on the SM bound $x_s > 0.5$ one concludes that improvements in the LEP measurements anticipated for the next two years have the potential to provide strong evidence for the intervention of NP beyond the SM. In the context of $B_s$, $B_c$ oscillations one should also point out that there are actually two lifetime, namely one for a $B_{s,\text{long}}$ and one for a $B_{s,\text{short}}$ with their difference estimated to be [7]

$$\frac{\tau(B_{s,\text{long}}) - \tau(B_{s,\text{short}})}{\tau(B_c)} \simeq 0.18 \left( \frac{f_{B_s}}{200 \text{MeV}} \right)^2. \quad (3)$$

It is intriguing to note that this delicate phenomenon is expected to yield the largest lifetime difference among $B$ mesons. This could remain an academic observation since a difference as predicted by Eq. (3) is presumably too small to be observable. On the other hand the calculation underlying this estimate for $\Delta \Gamma(B_s)$ is not “gold-plated” and could conceivably underestimate it significantly. Therefore one should endeavour to search for separate $B_{s,\text{long}}$ and $B_{s,\text{short}}$ lifetimes even if one can attain sensitivity only for a 50% or 100% difference. The cleanest method for such an analysis is probably to determine the $B_s$ lifetime in two different classes of decay channels, e.g.,

$$\tau(B_s \rightarrow \ell \nu D^{(*)}) - \tau(B_s \rightarrow \psi \phi) \simeq \frac{1}{2} \left[ \tau(B_{s,\text{long}}) - \tau(B_{s,\text{short}}) \right]. \quad (4)$$

The KM parameters $|V(cb)|$ and $|V(ub)|$ can best be determined in semileptonic decays. There are two rather reliable methods available:

(a) One can compare the measured inclusive semileptonic width for $B$ mesons with the theoretical expression through order $1/m_c^2$; that way one deduces [8]

$$|V(cb)|_{\text{incl}} \simeq 0.0415 \pm 0.002 \pm \text{experimental errors}, \quad (5)$$

where I have specified the present theoretical uncertainty only. It is so small, since $\Gamma_{\text{SL}}(B_s)$ turns out to depend mainly on the mass difference $m_c - m_s$, rather than on $m_c$ separately; the heavy quark expansion allows the determination of this difference quite precisely from the observed values of the $D^{(*)}$ and $B^{(*)}$ masses.

(b) Measuring the exclusive channel $B_s \rightarrow \ell \nu D^*$ as a function of the energy transfer and extrapolating to the zero recoil point, one extracts $F_{B_{s,\nu D^*}}(0)|V(cb)|$; the most recent CLEO data yield [9]: $F_{B_{s,\nu D^*}}(0)|V(cb)| = 0.0351 \pm 0.0019 \pm 0.0018 \pm 0.0008$. From heavy flavour symmetry one infers: $F_{B_{s,\nu D^*}}(0) = 1 + O(\alpha_s/\pi) + O(1/m_c^2)$. It had been claimed [10] that the non-perturbative corrections reduce this form-factor by merely 2–3%. If true it would be very surprising: for the $1/m_c^2$ terms should be dominated by the charm mass leading to corrections of order $(\mu_{\text{QCD}}/m_c)^2 \sim 10\%$. Very recently it has been shown through an application of $1/m_c$ expansions in the small velocity limit that the pre-asymptotic corrections are actually larger than previously claimed and in agreement with the simple expectation sketched above [11]: $F_{B_{s,\nu D^*}}(0) \approx 0.89 \pm 0.03$ and therefore

$$|V(cb)|_{\text{incl}} \simeq 0.0394 \pm 0.0034, \quad (6)$$

in good agreement with the value obtained from the inclusive analysis, Eq. (5).

The situation is much more uncertain concerning $|V(ub)/V(cb)|$: even once the exclusive mode $B \rightarrow \ell \nu \phi$ has been measured, it will pose a formidable challenge to theory to extract a value for $|V(ub)/V(cb)|$ as emphasized by Le Yaouanc [4]. As far as inclusive semileptonic $B$ decays are concerned, we are in a better position – also because clear evidence for $b \rightarrow u$ transitions has been found there. In analysing the inclusive lepton spectrum there is wide-spread consensus on the procedure to be followed: one picks one’s favourite model – AC$^2$M$^2$, ISGW etc. – , fixes its shape parameters from fitting the spectrum in $B \rightarrow \ell \nu X$, and applies it to the endpoint region from where one extracts $|V(ub)/V(cb)|$. Considerable progress has been made recently in putting this procedure onto a firmer theoretical foundation: it has been noted that a properly re-defined AC$^2$M$^2$ model represents a faithful (though not unique) realization of QCD for $b \rightarrow u$ (but not for $b \rightarrow c$) transitions [12]; furthermore it has been noted that the shape of the lepton spectrum in $B \rightarrow \ell \nu X$ can be deduced from the photon spectrum in radiative $B \rightarrow \gamma X$, decays [13]. Rather reliable extractions of $|V(ub)/V(cb)|$ will thus become possible in the future. Yet for the moment considerable uncertainties exist. I will use

$$|V(ub)/V(cb)| \sim 0.05 - 0.11, \quad (7)$$

however I am not convinced that even this range properly reflects the uncertainty.

The quantity $\sin 2\beta$ with $\beta$ denoting one of the angles in the KM triangle determines the SM CP asymmetry in the decay $B_d/B_s \rightarrow \psi K_s$. Its size can be inferred from the measured value for the ratio $\epsilon_K/\Delta m(B_d)$ with fairly little sensitivity to the value of $m_\tau$, albeit with considerable theoretical uncertainties concerning the size of $\Delta S = 2$ (and $\Delta S = 1$) matrix elements:

$$\sin 2\beta \simeq 0.33 \times \text{UNC,} \quad (8a)$$

$$\text{UNC} \simeq \left( \frac{0.045}{|V(cb)|} \right)^2 \left( \frac{0.72}{x_\phi} \right) \left( \frac{\epsilon_K}{\epsilon_{\text{QCD}}} \right) \left( \frac{0.62}{\eta_{\text{QCD}}} \right) \times \left( \frac{2B_B}{3B_K} \right) \left( \frac{f_B}{160 \text{MeV}} \right)^2, \quad (8b)$$
with $\chi_d \equiv \Delta m(B_d)/\Gamma_B$. Our present information on the shape of the KM triangle is summarized in Fig. 1: the top of the triangle has to lie in the shaded area. One reads off without ado that none of the three angles is particularly small; the corresponding CP asymmetries are then predicted to fall in the range of few $\times 10\%$.

4. The next five years

Several actors will carry the drama of beauty physics during that period, namely CLEO II, the LEP experiments, CDF and maybe D0.

At the FNAL collider hadronic $b$ production in the central region will be studied more precisely and conclusively. Lifetime measurements will be refined and extended where the following levels of accuracy might be attained:

$$
\delta[\tau(B^0) / \tau(B_d)] = \pm (5 - 7)\%,
\delta[\tau(B_s) / \tau(B_d)] = \pm (3 - 5)\%,
\delta[\tau(\Xi_b) / \tau(\Lambda_b)] = \pm (5 - 7)\%,
\delta[\tau(\Xi_b^0) / \tau(\Xi_b^-)] = \pm (20)\%,
\delta[\tau(\Xi_b^0) / \tau(\Xi_b^-)] = \pm (20)\%.
$$

While the precision of these measurements presumably will not suffice to firmly establish the lifetime pattern as predicted in QCD, they will at the very least be valuable in that they probe for potential trouble.

Let me make a side remark on a "cute" system, namely $B_c \equiv (b\bar{c})$. It provides a rich spectrum of excitations that are calculable; the Isgur-Wise function for the decay $B_c \to \ell^+\psi$ can be computed as well; its overall decays reflect an intriguing interplay of three classes of transitions, namely the decay of the $b$ quark, that of the $\epsilon$ (anti)quark and the "weak annihilation" of $b$ and $c$ Ignoring the latter one would naively expect the $\epsilon$ decay to dominate: $\Gamma(B_c \to B + X_c) / \Gamma(D^0) \approx (4 \times 10^{-13})s^{-1} > \Gamma(B_c \to X_c) / \Gamma(B) \approx (1.5 \times 10^{-12})s^{-1}$. It has been suggested [14] that for a tightly bound system like $B_c$ the decay width should be expressed not in terms of the usual quark masses $m_b$ and $m_c$, but instead in terms of effective quark masses reduced by the binding energy $\mu_{BE}$. If so, then the $B_c$ decay width would be reduced significantly since due to $\Gamma \propto m^2_{c}$ one would find $\Delta \Gamma / \Gamma \sim (\mu_{BE} / m_{bc})^2$ even more significantly, beauty decays would become more frequent among $B_c$ decays than charm decays since the binding energy constitutes a higher fraction of $m_c$ than of $m_b$. However such a conjecture is fallacious! For it has been shown [15] that the leading non-perturbative corrections arise at the $1/m_{bc} \lesssim 10\%$ level; the naive estimate is thus basically correct, i.e. $\tau(B_c) \approx 3 \times 10^{-13}$s with charm decays dominating over beauty decays.

$B_c \to B_s$ oscillations will be probed with a sensitivity for $x_s$ up to $\sim 5-10$. A positive signal, at least in the lower range, would signal the intervention of NP. Furthermore a $\sim 30\%$ difference in $\tau(B_c \to \psi \phi)$ vs. $\tau(B_c \to \ell^+\ell^-$) can be searched for. If found, it would presumably provide us with a valuable lesson on QCD rather than on NP.

The SM parameters will be determined with improved accuracy: $\delta m_t \approx 10\text{GeV}$, $\delta|V(|cb)| < 5\%$, $\delta|V(|ub)| \approx 20\%$ and $\delta|V(|td)| < 30\%$ seem to be achievable. It is assumed here that $|V(|td)|$ has been extracted from a measurement of $BR(K^+ \to \pi^+\nu\bar{\nu})$.

Measurements or bounds on $B \to \pi\pi$ vs. $B \to K\pi$ vs. $B \to KK$ will yield some clues on the weight of final state interactions, penguins etc.

The hadronic parameters $f_D$ and $f_D$ might be extracted from $D^* \to D \to \mu^+\mu^-$ with "useful" errors. This would allow us to calibrate the findings of QCD simulations on the lattice and to extrapolate to $f_B$ in a controlled way.

Fig. 2 shows the KM triangle resulting from $m_t = 160 \pm 10\text{GeV}$, $|V(ub)|/[V(|cb)| = 0.08 \pm 0.01$ and $f_B = 140-240\text{MeV}$. There emerge two disjoint shaded areas now, i.e. there are two disjoint allowed regions in parameter space – unless one can decide between $f_B \lesssim 170\text{MeV}$ and $f_B \geq 210\text{MeV}$ (for the assumed values of the SM parameters). Those two regions lead to quite different predictions on $x_s$ namely $x_s \approx 8-10$ for the left shaded region and $x_s \approx 17-25$ for the right one (where I have assumed $(f_B/f_{B_d})^2 = 1.1$).

$B \to K^*\pi^-\pi^+\pi^-$ might be observed, $B \to \gamma + higher K$ resonances will be studied and the inclusive reaction $B \to \gamma X$, measured, the last item by CLEO II; they will search also for direct CP violation in $B_d \to K^*\pi^-\pi^+$ vs. $B_d \to K^-\pi^+$ etc.

VI. SUMMARIES
5. The heroic period

Great heroic deeds – in particular in uncovering CP violation – are waiting to be achieved by the bold one, and there is a considerable list of potential heroes: HERA-B, the SLAC and KEK asymmetric B factories, CDF/D0 in the Main Injector era and CLEO III. Of course we all understand that when you see a list of potential heroes, you are at the same time looking at scapegoat candidates. Picture yourself in a big European football match: regulation time is almost over, the score is tied and you get a penalty kick. While you trot over to the penalty box to take the kick you realize that there are only two extreme outcomes for your undertaking: you score, you are the hero and get carried off the field on the shoulders of your peers – or you miss, you are the scapegoat and will always be remembered by your failure, irrespective of your achievements before or after. It seems to me that HERA-B and the two asymmetric B factories are in that precarious situation.

Yet before addressing the quest for heroism, let me evaluate less romantic endeavours.

Hadronic beauty production in the forward region might be studied with one eye on the topic of diffraction [16] and the other on a search for asymmetries in $B$ vs. $B$ production. Lifetime will be determined with high accuracy, say of order 1% or so. This will allow one to establish and measure the lifetime differences as predicted in QCD.

$B_s - B$ oscillations will be probed further with the sensitivity in $x_s$ reaching values of $\sim 15$ and maybe even 20. While present SM phenomenology admits $x_s$ in this whole range above $x_s > 0$, this will have changed by that time! In the hypothetical, yet generic scenario exhibited in Fig. 2, $x_s$ values in the window between $\sim 10$ and $\sim 17$ would require NP.

The SM parameters might get measured with an accuracy approaching what can realistically ever be achieved, namely $\delta m \approx 3$ GeV, $\delta [V(cb)] = 1\%$, $\delta [V(ub)] \approx 2\%$ and $\delta [V(td)] = 10\%$. In order to attain such levels of precision one will have to measure the photon spectrum in $B \to \gamma + X$, and analyse inclusive as well as exclusive semileptonic decays separately for $B^- \to K^- e^-$ and $B^- \to K^- \mu^-$ mesons (for $|V_{ub}|$), or measure $BR(K \to \pi^+ \pi^- \nu \bar{\nu})$ and/or $\Delta m(B_s)$ vs. $\Delta m(B_d)$ with $\sim 20$% accuracy (for $|V_{td}|$).

With some luck, $f_B$ might get determined through $B \to \pi \nu$ decays. Even without that gift the KM triangle might already be overconstrained before meaningful CP studies are undertaken in B decays. Without loss of generality one can normalize the baseline to unity. Together with $|V_{ub}|/|V_{cb}|$ and $|V_{td}|/|V_{cb}|$ the lengths of the three sides are known thus defining the triangle from which one reads off the value of the angle $\beta$. Employing Eqs. (8) one can then determine the value for $B_s f_B^2$ required to reproduce $|\epsilon_K|/\Delta m(B_s)$. Inserting the value thus inferred for $B_s f_B^2$ together with that for $|V_{td}|$ and $m_t$ into the SM expression for $\Delta m(B_d)$, one can finally check whether the observed magnitude for $\Delta m(B_d)$ is reproduced.

Now to the hoped-for heroic deeds. The CP asymmetry in $B_d \to \psi K_S$ yields (within SM) the quantity $\sin 2\beta$ unequivocally. If $|V_{td}|$ and/or $f_B$ are known independently, then a difference in the value of $\sin 2\beta$ as measured in $B_d/B_d \to \psi K_S$ and as inferred from the KM triangle establishes the intervention of NP. Otherwise the normalized triangle is defined through its baseline of unit length, the side $|V(ub)/AV(cb)|$ and the angle $\beta$, i.e. purely through measurements in the B system.

From the observed CP asymmetry in $B_d/B_d \to \pi^+ \pi^-$ one deduces the angle $\alpha$. If this measured value of $\alpha$ differs significantly from the value that is inferred from the KM triangle, NP has finally been found in an unequivocal way.

In principle one can measure the third angle $\gamma$ in two different ways, namely

- through a difference in $\Gamma(B^- \to D^0/D^0K^+)$ vs. $\Gamma(B^- \to D^+D^-K^+)$; it represents direct CP violation and is proportional to $\sin 2\gamma$ [17,18];
- through a difference in $B_s \to K_S \rho^0$ vs. $B_s \to K_S \rho^0$; it involves $B_s - B_s$ oscillations and depends on $\sin 2\gamma$.

While the first of these two methods definitely has some promise and relevance since it can be undertaken at a symmetric B factory, the second one has not too much of it, I believe. The CP asymmetries in $B_d \to \psi K_S$ and $B_d \to \pi^+ \pi^-$ will be measured sooner and with greater accuracy than in $B_s \to K_S \rho^0$, and $\gamma$ will be known as $\gamma = 180^\circ - \alpha - \beta$ within SM! The real motivation in determining $\gamma$ independently is to search for a manifestation of NP. Yet this is a more promising undertaking in a mode that commands a higher branching ratio, a more striking signature and a cleaner interpretation: the modes $B_s \to \psi \phi$ and $B_s \to \phi \eta$ fit the bill [19], in particular since SM predicts a very small CP asymmetry for it ($\lesssim 2\%$). Comparing $B_s \to \psi \phi$ with $B_s \to \phi \eta$ thus represents a practically zero background search for NP!

As I will stress later on, it will be mandatory to measure the angles $\alpha$ and $\beta$ as precisely as possible – for the ultimate analysis. Yet at intermediate stages one can perform a very valuable and promising research program even if one has to restrict oneself to the HERA-B “menu”, namely a study of three reactions: (i) $B_d/B_d \to \psi K_S$, (ii) $B_s - B_s$ oscillations, and (iii) $B_s \to \phi \phi$, $\phi \eta$. To sketch what can be achieved through such a menu I assume that $|V(ub)|$, $|V(ub)|$ and $m_t$ have been determined with good accuracy. If $|V_{td}|$ has been extracted from $BR(K \to \pi^+ \pi^- \nu \bar{\nu})$ by that time, the KM triangle will have been defined. One reads off the value predicted for the angle $\beta$ and using Eqs. (8) one infers the

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4 Final state interactions in general and “Penguin” effects in particular could modify the relation between $\alpha$ and the CP asymmetry, in that case $B_d \to \pi^+ \pi^-$ might well exhibit also direct CP violation that could in principle be observed at CESR.

5 It is at least amusing to note that this asymmetry would vanish for $\gamma = 90^\circ$ whereas the previous one would be maximal.
required size of $B_B f_B^2$. Then one is in a position to perform four sensitive tests of SM: (α) Using $m_t$ and the inferred value of $B_B f_B^2$, one can check whether the observed value of $\Delta m(B_s)$ is reproduced. (β) Compare $\sin 2\beta$ as deduced from the KM triangle with the CP asymmetry actually observed in $B_s \rightarrow \psi K_S$. (γ) Search for $B_s \rightarrow \bar{B}_s$ oscillations. As mentioned in the preceding section, at that time $x_s$ will be predicted to fall into one or two relatively narrow windows. (δ) Any observation of a CP asymmetry in $B_s \rightarrow \psi K_S$ establishes the intervention of NP.

If on the other hand $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ has not been observed (yet) with sufficient reliability, then one has to use the observed CP asymmetry in $B_s \rightarrow \psi K_S$ as the final defining element in the KM triangle; three tests then remain: (α) Is $\Delta m(B_s)$ reproduced with the value for $B_B f_B^2$ as deduced from $\beta$? (β) Probe $B_s \rightarrow \bar{B}_s$ oscillations. (γ) Search for a CP asymmetry in $B_s \rightarrow \phi K$.

Finally I would like to comment on how production asymmetries, if present, can be employed with great profit. As we have heard from Berger, differences in the production of $B$ and $\bar{B}$ mesons in $pP$ collisions are expected to occur at a level of maybe up to 10%, but only in the extremely forward (or backward) region. Surprises, of course, could happen, i.e. larger production asymmetries could occur in wider parts of phase space, and I would rate them as mere sins against orthodoxy rather than outright heresies. As such one should - in the spirit of “peccate fortiter” - make use of them once they occur, irrespective of what they mean for the pure doctrine; for they would remove the need for an independent flavour tag. Consider a beam of $N + \bar{N}$ neutral $B$ mesons; its decay into a CP eigenstate like $\psi K_S$ as a function of proper time $t$ is given by

$$\text{rate} \left( B^{\text{new}} \rightarrow \psi K_S; t \right) \propto e^{-\Gamma t} \left( 1 + \frac{N - \bar{N}}{N + \bar{N}} \sin 2\beta \sin \Delta m t \right).$$ (10)

If there is a production asymmetry $-N \neq \bar{N}$ - then CP violation becomes observable without an independent flavour tag. Furthermore the quantity $(N - \bar{N})/(N + \bar{N})$ can be tracked independently through decays into CP non-eigenstates:

$$\text{rate} \left( B^{\text{new}} \rightarrow \psi K^\mp \pi^\pm; t \right) \propto e^{-\Gamma t} \left( 1 + \frac{N - \bar{N}}{N + \bar{N}} \cos \Delta m t \right).$$ (11a)

$$\text{rate} \left( B^{\text{new}} \rightarrow \psi K^\mp \pi^\pm; t \right) \propto e^{-\Gamma t} \left( 1 - \frac{N - \bar{N}}{N + \bar{N}} \cos \Delta m t \right).$$ (11b)

That way one can check also for a detector bias.

6. LHC – the ultimate measurements

I am going to argue now that the LHC will satisfy essential needs in a complete program of beauty physics - even if all prior enterprises have succeeded as well as promised by their proponents. This judgement is based on three reasons, of which the last one is truly major:

1. $x_s > 20$ is quite possible (below I will cite some relevant examples); this range seems to be well beyond the reach of any pre-LHC enterprise.

2. Detailed measurements of $b \rightarrow s \ell^+ \ell^-$, $d \ell^+ \ell^-$ transitions will require statistics that can be accumulated only at the LHC.

3. As far as CP violation is concerned there are three possible outcomes for a dedicated program:

A) No CP violation is observed in $B$ decays! To be more specific: it is found that CP asymmetries in relevant $B$ decays are at most a few percent. Since there exist three families, $B^0 - \bar{B}^0$ oscillations proceed speedily and based on what we already know of the KM parameters, I regard this scenario as the least likely outcome. Yet in that case we would have established that the KM mechanism is not behind $K_L \rightarrow \pi \pi$, that it is not even a significant factor there! It would force us to abandon the SM paradigm of CP violation and to attribute the observed CP violation in $K_L$ decays to the intervention of as yet unidentified NP, with two immediate consequences: (i) It would lead to the formulation of a baffling theoretical puzzle, namely “Why is there no significant KM source for CP violation?”. (ii) On the experimental side it would lend topical urgency to searches for different manifestations of CP violation in light-quark systems, such as the electric dipole moments of neutrons or electrons, the transverse muon polarization in $K_{\mu 3}$ decays, $BR(K_L \rightarrow \pi^0 \ell^+ \ell^-)$ etc.

B) Large CP asymmetries are found - but they are not (quite) consistent with the KM predictions! This scenario - which I regard as the most likely outcome - will represent indirect, but unequivocal evidence for the intervention of NP in $B$ transitions. Taken together with measurements of $m_{top}$, $\Delta m(B_s)$, $BR(b \rightarrow s\gamma)$, $BR(b \rightarrow s\ell^+\ell^-)$ and hopefully $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $BR(b \rightarrow d\gamma)$ it would provide a test even with some definite clues about the nature of the NP involved. It would also allow us to check to which degree the KM mechanism contributes to $K_L \rightarrow \pi \pi$.

C) Large CP asymmetries are found without evidence for NP - even when extrapolating down to $K_L$ decays! Also such a scenario would provide us with the seeds for more profound knowledge, since it addresses one of the most central mysteries of the Standard Model, namely the generation of fermion masses. After a comprehensive analysis of $B$ decays the KM matrix will be known. Keep in mind that the KM matrix which arises due to a non-trivial diagonalization of the up-type and the down-type quark mass matrices, contains unique information over and above the six quark mass eigenvalues. Some attempts have been undertaken to construct the KM matrix in terms of the six quark masses.
by conjecturing a simple form of the quark mass matrices at a high (SUSY) GUT scale and then evolve it down to the hadronic scales probed in heavy flavour decays. Comprehensive studies of this kind have recently been given in Refs. [20,21]; I summarize their results for $m_{\text{top}} = 180\text{GeV}$ in a way that is convenient for my discussion (see Table 2). I have assumed $[B_s f^+_u(B_s)]/[B_d f^+_u(B_d)] = 1.1$ to translate $V(ts)/V(td)$ into $x_s/x_d$. The symbols A-E and I-III refer to different classes of mass matrices analysed in Refs. [20] and [21]. The details are not important here, and I anticipate considerable theoretical evolution to take place over the next few years; but I want to use these numbers to illustrate important benchmarks for the ultimate measurements:

- One better be able to probe $B_s$-$\bar{B}_s$ oscillations up to $x_s \sim 40$ or even beyond.
- Both $\sin 2\beta$ and $\sin 2\alpha$ have to be measured – that is non-negotiable!
- While one aims for a 20–30% accuracy for the first and second round measurements, the goal has to be to finally achieve a 5% precision or better to exploit the discovery guarantee to the fullest and to distinguish between the different scenarios.

- In addition one has to strive to perform as precise measurements as possible for $B \rightarrow \gamma \rho$, $\gamma \omega$ vs. $B \rightarrow \gamma K^*$, $B \rightarrow \ell^+ \ell^- \pi^+/\rho^0/\omega$ vs. $B \rightarrow \ell^+ \ell^- K/K^*$ (including the $\ell^+$ vs. $\ell^-$ spectra), $B \rightarrow \mu^+ \mu^-$, $(\tau^+ \tau^-)$ etc.

It is obvious that only the LHC has the “statistical” muscle to accumulate the necessary sample sizes. The challenge is: can the LHC develop the required “systematic” brain!

### 7. Outlook

A long and arduous, if not outright tortuous journey lies ahead of us. What should keep us going is the realization that the insights that will be gained from a comprehensive and detailed program of beauty physics

- are of fundamental importance,
- cannot be obtained any other way, and
- cannot become obsolete.

Finally I can explain why Mont St. Michel represents such a fitting allegory for the research program we have been discussing here. Some buildings, like the church or “La Merveille”, are more spectacular than others, but it is the whole ensemble that makes Le Mont – like beauty physics – so unique and irresistible, and it is only because of the whole (data) base and foundation that the spire crowning the rock can point – to the New Standard Model!

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### References


### Table 2

<table>
<thead>
<tr>
<th>KM parameters as predicted in Refs. [20,21]</th>
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<tbody>
<tr>
<td>A</td>
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<tr>
<td>$</td>
</tr>
<tr>
<td>$x_s/x_d$</td>
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<tr>
<td>$\sin 2\beta$</td>
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<tr>
<td>$\sin 2\alpha$</td>
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<td>$\sin \gamma$</td>
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It takes, of course, the trained eye of a theorist to discern the simple pattern underlying these values for the KM parameters.


