Abstract

I review the signals for New Physics in CP-violating measurements in $B$ and $\Lambda_b$ decays. I also discuss ways of identifying this New Physics, should such a signal be found.

For the past decade or so, there has been an enormous amount of effort, both theoretical and experimental, devoted to the study of $b$ physics. The main goal, as always, is to find physics beyond the standard model (SM). In this review, I will address two questions:

1. What are signals of New Physics?
2. If such a signal is found, can we identify the New Physics?

I will focus principally, but not exclusively, on measurements which can be made at hadron colliders. Also, I will concentrate on measurements of CP violation.

In order to detect New Physics, we must observe a deviation from the SM prediction for some process. However, all such predictions have some theoretical input, and the uncertainty on this input limits our ability to deduce the presence of New Physics. In my discussion below, I will rate the various signals of New Physics using the ever-popular “star system” [1] to indicate the size of the theoretical uncertainty:

- $\star\star\star \implies$ theoretical uncertainty $\lesssim 1\%$,
- $\star\star \implies$ theoretical uncertainty $\lesssim 5\%$,
- $\star \implies$ theoretical uncertainty $\lesssim 25\%$.

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I begin the discussion by reviewing the predictions of the SM, along with the size of the theoretical uncertainty. Note that the following list of predictions is long, but not comprehensive. Any deviation from the SM prediction indicates the presence of New Physics.

- $A_{CP}^{\text{dir}}(B \to \Psi K) = 0$. The decay $B \to \Psi K$ (charged or neutral) has effectively only one weak decay amplitude. In addition to the tree amplitude, there may be a penguin contribution, but (i) it is expected to be small, and (ii) its weak phase is essentially the same as that of the tree. The direct CP asymmetry is therefore predicted to vanish in the SM.  

- $A_{CP}^{\text{mix}}(B_d^0(t) \to \Psi K_s) = A_{CP}^{\text{mix}}(B_d^0(t) \to \phi K_s)$. The decay $B_d^0 \to \phi K_s$ is pure $b \to s$ penguin, which is dominated by an internal $t$-quark (CKM matrix elements $V_{tb}V_{ts}$). In the Wolfenstein parametrization of the CKM matrix [2], $V_{tb}V_{ts}$ has only a small $[O(\lambda^2)]$ imaginary piece, so that the penguin decay amplitude is approximately real, as is the amplitude for $B_d^0 \to \Psi K_s$. Both CP asymmetries therefore measure $\sin 2\beta$ in the SM. Any deviation from this result indicates the presence of New Physics in the $b \to s$ penguin amplitude [3].

- $A_{CP}(B_0^0(t) \to D^* \rho)$ measures $2\beta + \gamma$. The angular analysis of this decay mode allows one to extract the quantity $2\beta + \gamma$ [4]. This may well be the second function of CP phases, after $\sin 2\beta$, to be measured at $B$-factories.

- $A_{CP}^{\text{mix}}(B_s^0(t) \to \Psi \phi) \simeq 0$. In the SM, this CP asymmetry probes $\arg(V_{tb}V_{cs}V_{tb}V_{ts}^*)$. As mentioned above, $V_{ts}$ has a small $[O(\lambda^2)]$ imaginary piece in the Wolfenstein parametrization, so a nonzero asymmetry is expected at the several percent level. If a larger asymmetry is measured, this probably indicates New Physics in $B_s^0 - \bar{B}_s^0$ mixing.

- $A_{CP}(B^\pm \to D K^\mp) = A_{CP}^{\text{mix}}(B_s^0(t) \to D_s^\pm K^\mp)$. In the SM, both of these CP asymmetries probe the weak phase $\gamma$ [5, 6]. Any discrepancy in the values of $\gamma$ obtained in these methods points to the presence of New Physics in $B_s^0 - \bar{B}_s^0$ mixing.

- Inclusive $A_{CP}^{\text{dir}}(b \to s \gamma) = 0$. In order to have a direct CP asymmetry, one requires two decay amplitudes with different weak and strong phases. For the decay $b \to s \gamma$, rescattering effects must be significant for this to occur. However, in the SM, such effects are tiny [7], so that the direct asymmetry effectively vanishes.

- Exclusive $A_{CP}^{\text{mix}}(b \to s \gamma) = 0$. The photon emitted in the decay $b \to s \gamma$ is predominantly left-handed, while that emitted in the CP-conjugate decay is...
right-handed. Thus, one does not have the same final state for $B_d$ and $\bar{B}_d$ decays, so that the indirect CP asymmetry for exclusive states is expected to vanish [8]. Of course, this is true only to the extent that the photon helicity is purely left-handed or right-handed. In fact, there are corrections of $O(2m_s/m_b) \simeq 5\%$, so that this is the size of the asymmetry expected in the SM. Anything larger indicates New Physics. **

- There are many techniques for getting CKM phase information using flavour $SU(3)$ symmetry [9]. Generally, these are $1\star$ methods, since $SU(3)$-breaking effects are typically of order $f_K/f_\pi \sim 25\%$. In order to detect New Physics using such methods, the effects must therefore be larger than this theoretical uncertainty.

- One exception is a method involving $B_{d,s}^0 \to K^{(*)}\bar{K}^{(*)}$ decays, which can be used to obtain the CP phase $\alpha$ [10]. In this case, one extracts $\alpha$ using a double ratio in which the $SU(3)$-breaking effects largely cancel, thus reducing the theoretical uncertainty considerably. **

- Suppose that $A_{CP}^{mix}(B_s^0(t) \to \Psi\phi)$ is actually measured, and the CKM phase $\chi (\sim 2 - 5\%)$ extracted. Within the 3-generation SM, one expects [11]

$$\sin \chi = \left| \frac{V_{us}}{V_{ud}} \right|^2 \frac{\sin \beta \sin(\gamma - \chi)}{\sin(\beta + \gamma)} . \quad (1)$$

Any violation of this relation implies the presence of New Physics. ***

- One can look for an inconsistency between the unitarity triangle as constructed from measurements of the angles and that constructed from measurements of the sides. However, this method is limited by the large theoretical uncertainties in the extraction of the sides. *

- One can look for an inconsistency between measurements of the angles and exclusive hadronic rates. For example, indirect constraints on $\gamma$ imply that $\gamma < 90^\circ$, while early studies of $B \to \pi K$ decays seemed to indicate that $\gamma > 90^\circ$ [12]. Of course, the hadronic uncertainties are very large in such methods, so it is difficult to conclude that New Physics is present. *

As stated earlier, the above is only a partial list of possible signals of New Physics. Because of space limitations, I cannot give more than a cursory description of each. However, below I discuss in more detail two additional observables which are perhaps less well-known.

Suppose a New-Physics amplitude contributes to (charged or neutral) $B \to \Psi K$ decays. How would we detect it? As mentioned above, the obvious answer is to measure the direct CP asymmetry. However,

$$A_{CP}^{dir}(B \to \Psi K) \sim A_{SM} A_{NP} \sin \phi \sin \Delta , \quad (2)$$
where $\phi$ and $\Delta$ are the relative weak and strong phases, respectively. Unfortunately, from this expression one sees that if $\Delta = 0$, the direct CP asymmetry will vanish, and the New Physics will remain hidden.

The situation can be improved by considering instead the decay $B \to \Psi K^*$ [13]. The time-dependent decay rate can be written in the helicity basis as

$$
\Gamma(B_d^0(t) \to \Psi K^*) \sim \sum_{\lambda\sigma} \left[ \Lambda_{\lambda\sigma} + \Sigma_{\lambda\sigma} \cos \Delta m t - \rho_{\lambda\sigma} \sin \Delta m t \right] g_{\lambda} g_{\sigma},
$$

where $\lambda, \sigma = 0, \parallel, \perp$. The important observable here is $\Lambda_{\perp i}$, which can be written schematically as

$$
\Lambda_{\perp i} \sim (A_{SM}^i A_{NP}^i - A_{SM}^i A_{NP}^i) \sin \phi \cos(\Delta_{\perp i}) , \quad i = 0, \parallel .
$$

Note the appearance of the $\cos(\Delta_{\perp i})$ factor. It is this term which appears (and not $\sin(\Delta_{\perp i})$ term) due to the interference of CP-even and CP-odd helicities. The key point is that even if the strong phases are zero, $\Delta_{\perp i} = 0$, $\Lambda_{\perp i}$ will not vanish. Thus, this observable is complementary to $A_{dir}^{CP}(B \to \Psi K)$, and it will be important to measure both of these quantities to test for the presence of New Physics. Note also that the theoretical uncertainty is tiny, so that $\Lambda_{\perp i}$ is a $3 \star$ observable.

Furthermore, this holds equally for $B_d^0(t) \to \Psi K^*$ and for $B^\pm \to \Psi K^\pm$. That is, one can simply add all charged and neutral $B$ decays together – no tagging or time-dependent measurements are needed to obtain $\Lambda_{\perp i}$, making it a particularly interesting quantity from an experimental point of view.

All of the methods mentioned above deal with $B$ mesons. However, there are also useful tests for New Physics using $B$ baryons. In particular, one can look at $T$-violating triple-product correlations in charmless $\Lambda_b$ decays [14].

Triple-product (TP) correlations take the form $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where each $v_i$ is a spin or momentum. TP correlations are odd under $T$, which implies, by the CPT theorem, that they are also odd under $CP$. By measuring a nonzero value of

$$
A_T \equiv \frac{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) - \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) + \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)},
$$

one obtains a signal for a nonzero TP correlation. However, there is a complication: strong phases can produce a nonzero value of $A_T$, even if there is no $CP$ violation (i.e. if the weak phases are zero). In order to be sure that one is truly probing $T$ and $CP$ violation, the value of $A_T$ must be compared with that of $\bar{A}_T$, which is the $T$-odd asymmetry measured in the $CP$-conjugate decay process.

Consider the decays $\Lambda_b \to F_1 P$ and $F_1 V$, where $F_1$ is a fermion ($p, \Lambda, ...$), $P$ is a pseudoscalar ($K^-, \eta, ...$), and $V$ is a vector ($K^{*-}, \phi, ...$). For $\Lambda_b \to F_1 P$, there is only one possible triple product: $\vec{p}_{F_1} \cdot (\vec{s}_{F_1} \times \vec{s}_{\Lambda_b})$. On the other hand, in $\Lambda_b \to F_1 V$ decays, one has 3 spins and 1 independent momentum. This implies that there are 4 possible TP’s. In all cases, we would like to know the expectations for the sizes of these TP’s in the SM.
One can analyze $\Lambda_b$ decays using factorization [14]:

$$A(\Lambda_b \to F_1 P/V) = \sum_{\mathcal{O}, \mathcal{O}'} \langle P/V|\mathcal{O}|0\rangle \langle F_1|\mathcal{O}'|\Lambda_b\rangle .$$

(6)

For $\Lambda_b \to F_1 P$ one can then write

$$\mathcal{M}_P = if_P \bar{p}_P^\mu \langle F_1|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b\rangle X_P + if_P \bar{p}_P^\mu \langle F_1|\bar{u}\gamma_\mu(1+\gamma_5)b|\Lambda_b\rangle Y_P ,$$

(7)

where $X_P$ and $Y_P$ are functions of CKM matrix elements, Wilson coefficients and masses. Similarly, for $\Lambda_b \to F_1 V$, one has

$$\mathcal{M}_V = m_V g_V \varepsilon_V^\mu \langle F_1|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b\rangle X_V + m_V g_V \varepsilon_V^\mu \langle F_1|\bar{u}\gamma_\mu(1+\gamma_5)b|\Lambda_b\rangle Y_V .$$

(8)

Like any CP-violating signal, in order to have a nonzero triple-product correlation, one needs two interfering amplitudes. Thus, from the above expressions, one sees that both $X_P$ and $Y_P$ must be nonzero to have TP’s in $\Lambda_b \to F_1 P$ ($\Lambda_b \to F_1 V$).

Now, it is easy to see that both $X_P$ and $X_V$ are nonzero in the SM. After all, all operators in effective Hamiltonian involve a left-handed $b$. The real question is: are $Y_P$ and/or $Y_V$ nonzero in the SM? The answer is that, for particular $F_1 P$ final states, one can “grow” a right-handed current due to the Fierzing of certain SM operators. Furthermore, the $Y_P$ in such cases can be sizeable. However, for $F_1 V$ final states, this doesn’t work – the matrix elements of the above operators vanish for a final-state $V$. Therefore $Y_V \approx 0$ in SM. The end result is that [14]

- $A_T^{pK} = -18\%$.

- The triple products for all other decays are expected to be small, at most $O(1\%)$. These include the final states $pK^*$, $\Lambda\eta$, $\Lambda\eta'$, $\Lambda\phi$.

The bottom line is that many triple-product correlations in $\Lambda_b$ decays are expected to be tiny in the SM. This suggests that this is a good place to look for New Physics.

I now turn to the issue of identifying the New Physics. Should a New-Physics signal be found, precise identification will have to wait for direct production at high-energy colliders. However, it is still possible to get a fairly good idea of the type of New Physics just by studying $B/\Lambda_b$ processes.

New Physics can affect $B^0-\bar{B}^0$ mixing and/or $B/\Lambda_b$ decays. One expects that penguin decays will be most affected, but there could be New-Physics contributions to tree-level processes. It is therefore useful to classify the New Physics as affecting either the $b \to s$ FCNC or the $b \to d$ FCNC.

With this in mind, there are two complementary approaches to identifying the New Physics:
1. One can consider various New-Physics models [15]. For each model, one examines the predicted effects on CP violation and rare $B/\Lambda_b$ decays. By comparing the pattern of effects with what is observed, one can see if the model is a viable candidate.

2. One can analyze effects using a model-independent (effective lagrangian) approach. The determination of which New-Physics operators are or are not present will help in ruling out candidate models of New Physics.

Below I give examples of each of these approaches.

I begin with a discussion of two specific models of New Physics, and examine their predictions for CP violation in the $B$ system. The first model involves $Z$-mediated FCNC’s: if the $d$, $s$ and $b$-quarks mix with a vector-singlet down-type quark, flavour-changing $Z$ couplings are generated [16]. In particular, one can have $Zbd$ and $Zbs$ FCNC couplings, denoted $U_{db}$ and $U_{sb}$. These may be complex, and can contribute to both $B^0 - \bar{B}^0$ mixing and $B/\Lambda_b$ decays.

The constraints on $U_{db}$ and $U_{sb}$ come principally from the following measurements: $BR(B \to X\mu^+\mu^-) < 5 \times 10^{-5}$ (UA1) [17] and $BR(B \to X_s e^+e^-) \leq 1.01 \times 10^{-5}$ (BELLE) [18]. One finds [19]

$$|U_{db}| \leq 0.002 \quad , \quad |U_{sb}| \leq 7.6 \times 10^{-4}. \quad (9)$$

With these constraints, $Z$-mediated FCNC’s will not significantly affect $b \to s$ FCNC’s. However, there can be important effects in $b \to d$ FCNC processes [15]: $Z$-mediated FCNC’s can have

- significant effects on $B^0_d - \bar{B}^0_d$ mixing, with or without new phases,
- little effect on gluonic $b \to d$ penguin processes, such as $B^0_d \to K^0 \bar{K}^0$,
- huge effects on $b \to d\ell^+\ell^-$, $B^0_d \to \ell^+\ell^-$ and $b \to d$ electroweak-penguin decays, such as $B^+ \to \phi\pi^+$.

Thus, should this pattern of New-Physics effects be observed, it would suggest the presence of $Z$-mediated FCNC’s.

Another model of New Physics which has been much discussed is supersymmetry (SUSY). In SUSY models with minimal flavour violation, all contributions to $B^0 - \bar{B}^0$ mixing and penguin decays are proportional to the same combination of CKM matrix elements as found in the SM. As a consequence, there are no new effects in CP-violating observables, and the extracted values of $\alpha$, $\beta$, $\gamma$ will be the true (SM) values. The unitarity triangle (UT) as constructed from measurements of the angles will therefore be the SM UT. On the other hand, there are SUSY contributions to $K^0 - \bar{K}^0$, $B^0_d - \bar{B}^0_d$ and $B^0_s - \bar{B}^0_s$ mixing, so that the measurements of the sides of the unitarity triangle are not the true SM values. The UT as constructed from the sides
will therefore *not* be the SM UT. Thus, one can detect this type of New Physics by observing a discrepancy between the two unitarity triangles.

In such minimal SUSY models, the contributions to meson mixing can be distinguished by a single parameter $f$. Depending on the value of $f$, the profile of the unitarity triangle will change [20]:

$$f_{A_d} \sqrt{B_{A_d}} = 230 \pm 40 \text{ MeV}, \quad B_K = 0.87 \pm 0.19$$

(Here the allowed regions correspond to $f = 0$ [SM, solid line], $f = 0.25$ [long dashed line], and $f = 0.5$ [short dashed line].) The size of these regions is due principally to the large theoretical errors of $\sim 20\%$.

In order to detect this type of New Physics, one must distinguish the UT of the SM ($f = 0$) from one with a nonzero value of $f$. From the above figure, it is obvious that this will be very difficult to do. Therefore, unless we can substantially reduce the theoretical uncertainties, it will be almost impossible to see the effects of minimal SUSY models in the $B$ system. On the other hand, if one finds New-Physics effects in CP-violating observables (e.g. $A_{\text{mix}}^{CP}(B_d^0(t) \rightarrow \Psi K_s) \neq A_{\text{mix}}^{CP}(B_d^0(t) \rightarrow \phi K_s)$), then these models can be ruled out.

I now turn to model-independent methods for identifying the New Physics. Consider first the decay $B \rightarrow \Psi K$. One can perform an isospin decomposition of this decay: since $B$ and $K$ are isodoublets, and $\Psi$ an isosinglet, the weak hamiltonian has an $I = 0$ and $I = 1$ piece, with

$$\langle \Psi K^+ | H_{\text{eff}}^{I=0} | B^+ \rangle = \langle \Psi K^0 | H_{\text{eff}}^{I=0} | B_d^0 \rangle, \quad (10)$$
\[ \langle \Psi K^+ | \mathcal{H}^{l=1}_{\text{eff}} | B^+ \rangle = -\langle \Psi K^0 | \mathcal{H}^{l=1}_{\text{eff}} | B^0_d \rangle . \]  

(11)

Now, we know that any direct CP asymmetry in this decay is a signal of New Physics. But what kind of New Physics is it? We can obtain some information as follows [21]: define

\[ A_{CP}^+ \equiv A_{CP}^{\text{dir}} \text{ in } B^+ \rightarrow \Psi K^+ , \quad A_{CP}^0 \equiv A_{CP}^{\text{dir}} \text{ in } \overline{B}_d \rightarrow \Psi \overline{K} \]  

(12)

and

\[ S \equiv \frac{1}{2} \left[ A_{CP}^0 + A_{CP}^+ \right] , \quad D \equiv \frac{1}{2} \left[ A_{CP}^0 - A_{CP}^+ \right] . \]  

(13)

Note that \( S \neq 0 \) and \( D \neq 0 \) are both signals of New Physics. However, there is a difference between them: \( S \) is due to isospin 0 effects, while \( D \) is due to isospin 1 effects. Their measurement gives us model-independent information about the underlying New Physics.

Finally, I return to triple products in \( \Lambda_b \) decays. Above, we saw that the triple-product asymmetries in \( \Lambda_b \rightarrow pK^{*-} \) are expected to be very small. Suppose now that we measure a large triple product. What New Physics could be responsible?

From Eq. (8), we see that we need operators which contribute to the matrix element \( \langle p|\bar{u}\gamma_\mu(1 + \gamma_5)b|\Lambda_b \rangle \). It is straightforward to write these down. They are [22]:

\[ \bar{s}(1 + \gamma_5)b \bar{u}(1 - \gamma_5)u , \quad \bar{s}\gamma_\mu(1 + \gamma_5)b \bar{u}\gamma_\mu(1 + \gamma_5)u . \]  

(14)

The point here is that a significant triple-product signal in \( \Lambda_b \rightarrow pK^{*-} \) would (i) tell us that New Physics is present, and (ii) indicate which New-Physics operators can contribute. Thus, triple-product asymmetries in \( \Lambda_b \) decays can serve as a diagnostic tool for New Physics.

This same procedure can be applied to other decays such as \( \Lambda_b \rightarrow \Lambda\eta, \Lambda_b \rightarrow \Lambda\phi \), etc. In this way, we can get a more complete picture of which New-Physics operators are or are not present [22].

To sum up: there are many, many signals of New Physics in \( B/\Lambda_b \) processes. In addition, there are many ways of determining which types of New Physics might be responsible for these signals. It is quite likely that we will have a fairly good idea of what kind of New Physics is present in these decays.

Let’s hope that Nature is kind, and we actually see some evidence of New Physics!
References


