CP Violation and Heavy Hadrons

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Abstract

I review several topics involving CP violation with heavy hadrons. In particular, I discuss (i) Hyperons: CP violation in the decay $\Lambda^0 \rightarrow p\pi^-$, (ii) Charm: indirect CP violation in the $D^0$ system, both within and beyond the SM, and (iii) Beauty: indirect CP violation in the neutral $B$-meson system beyond the SM.

1 Introduction

CP violation is one of the most intriguing mysteries in particle physics. To date, it has been unambiguously observed only in $K^0 - \bar{K^0}$ mixing. According to the standard model (SM), CP violation is due to a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. However, since this one parameter is included to “explain” only one experimental measurement, we can hardly claim to understand the origin of CP violation. If we want to go further, we will need to see CP violation outside of the kaon system.

Still, even if CP violation is observed elsewhere, we will want to know the answers to a number of questions:

- Can this new CP violation be explained by the phase of the CKM matrix? In other words, we need to know the SM predictions for CP violation outside the kaon system.

- If not, what new physics could be responsible? I.e., we need to know the beyond-the-SM predictions for CP violation.

- Can we identify the new physics? That is, can we distinguish among the various new physics possibilities?

In this talk, I will discuss several possibilities for the observation of CP violation outside the kaon system. However, I should stress that the subject of CP violation with heavy hadrons is vast. Thus, in light of time constraints, I will restrict my discussion to 3 topics, which have been inspired by the title of this conference:

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1. Hyperons: CP violation in $\Lambda^0 \to p\pi^-$,

2. Charm: Indirect CP violation with neutral $D$ mesons, both within and beyond the SM,

3. Beauty: Indirect CP violation with neutral $B$ mesons beyond the SM.

There are numerous subjects which I don’t have the time to discuss. These include: the electric dipole moment of the neutron, triple products, direct CP violation with $D$ mesons (both within and beyond the SM), charmed baryons, direct CP violation in the $B$ system (within and beyond the SM), indirect CP violation in the neutral $B$ system within the SM, $B$ baryons, etc.

## 2 Hyperons

Consider the decay $\Lambda^0 \to p\pi^-$. This is a complex system – the final state can be in an $s$-wave (parity-violating amplitude) or $p$-wave (parity-conserving), and can have isospin $I = 1/2$ or $3/2$. The most general Lorentz-invariant amplitude for this decay can be written

$$M = G_F m_u^2 \bar{u}_p (A - B\gamma_5) u_\Lambda .$$

We define $\hat{\sigma}$ to be the polarization of the $\Lambda$, $\vec{q}$ to be the momentum of the proton, and

$$s \equiv A ,$$

$$p \equiv \left( \frac{|\vec{q}|}{E_p + M_p} \right) B .$$

The differential cross section for this process is a complicated function of $s$, $p$, and the spins of the $\Lambda$ and the $p$. However, if the proton polarization is not measured, it can be written

$$\frac{d\Gamma}{d\Omega} \sim 1 + \alpha \hat{q} \cdot \hat{\sigma} ,$$

where

$$\alpha = 2 \frac{\text{Re} s^* p}{|s|^2 + |p|^2} .$$

Now compare $\Lambda^0 \to p\pi^-$ with $\Sigma^0 \to \bar{p}\pi^+$. If CP is a good symmetry, $\alpha = -\bar{\alpha}$. Therefore we define the CP-violating asymmetry

$$A \equiv \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} .$$

(If the proton polarization is measured, there are additional CP-violating asymmetries.) We would like to calculate the prediction for this quantity in the SM. To this end, we separate $s$ and $p$ into $I = 1/2$ and $3/2$ pieces:

$$s = -\sqrt{\frac{2}{3}} s_1 e^{i(\delta_1 + \phi_1)} + \sqrt{\frac{1}{3}} s_3 e^{i(\delta_3 + \phi_3)} ,$$

$$p = -\sqrt{\frac{2}{3}} p_1 e^{i(\delta_1 + \phi_1)} + \sqrt{\frac{1}{3}} p_3 e^{i(\delta_3 + \phi_3)} ,$$

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where the $\delta$’s are the strong phases and the $\phi$’s are the weak (CKM) phases. The key point is that all these quantities, apart from the weak phases, have been measured experimentally \cite{1, 2}. Plugging in the measured values, we obtain

\[
A(\Lambda^0) = 0.13 \sin(\phi_1^p - \phi_1^s) + 0.001 \sin(\phi_1^p - \phi_3^s) - 0.0024 \sin(\phi_3^p - \phi_1^s).
\]

(9)

To finish the job, we now need to calculate the weak phases for the various spin and isospin amplitudes.

In order for there to be CP violation at all, there must be at least two amplitudes with different CKM phases which contribute to the decay process. If not, all the $\phi$’s are equal, and the asymmetry vanishes. For the decay $\Lambda^0 \to p\pi^-$, there are, in fact, several such amplitudes. The tree contributions have CKM phase $V_{ud}^*V_{us}$, while the penguin contributions have a phase $V_{cd}^*V_{cs}$, or $V_{td}^*V_{ts}$, depending on the internal quark in the loop. (Using the unitarity of the CKM matrix, the $V_{cd}^*V_{cs}$ piece can be eliminated in favour of $V_{ud}^*V_{us}$ and $V_{td}^*V_{ts}$.) At the quark level, one uses the effective Hamiltonian \cite{3}

\[
H_W^{SM} = \frac{G_F}{\sqrt{2}} V_{ud}^*V_{us} \sum_i c_i(\mu)Q_i(\mu) + h.c.,
\]

(10)

where the $c_i(\mu)$ are the Wilson coefficients and the $Q_i(\mu)$ are the 4-quark operators. Using the renormalization group, the $c_i$’s can be calculated; in the Wolfenstein parametrization the CP-violating phase is

\[
\text{Im} \left( \frac{V_{td}^*V_{ts}}{V_{ud}^*V_{us}} \right) = A^2 \lambda^4 \eta \leq 0.001.
\]

(11)

So far, so good. However, the quarks now have to be put into hadrons. That is, we have to calculate the hadronic matrix elements

\[
\langle p\pi | H_W^{SM} | \Lambda^0 \rangle = \text{Re} M'_l + \text{Im} M'_l,
\]

(12)

where

\[
\phi'_l \approx \frac{\text{Im} M'_l}{\text{Re} M'_l}.
\]

(13)

Unfortunately, we don’t know how to calculate these hadronic matrix elements, and it is here that a large uncertainty enters the SM prediction. The best we can do is to use the vacuum saturation approximation, which we know is unreliable, since it cannot reproduce the $\Delta I = 1/2$ rule. In this case we find \cite{4, 5}

\[
A(\Lambda^0) \approx -(1 - 5) \times 10^{-5}.
\]

(14)

(The E871 experiment \cite{6} expects to reach a sensitivity of about $10^{-4}$ on $A(\Lambda^0) + A(\Xi^-)$, where $\Xi^-$ corresponds to the process $\Xi^- \to \Lambda^0\pi^-$. The SM prediction for $A(\Xi^-)$ is $-(1 - 10) \times 10^{-5}$ \cite{6}, so an asymmetry might just barely be measurable.) The main point here is that, due to hadronic uncertainties, the SM prediction for this asymmetry is very imprecise – we really only know its order of magnitude.
How does the prediction for this asymmetry change in the presence of physics beyond the SM? New physics can affect the asymmetry only if there are new decay amplitudes. One way to analyze this is to use an effective lagrangian involving all possible 4-quark operators, and calculate their contributions to $A(\Lambda^0)$ including constraints from $\epsilon$ and $\epsilon'/\epsilon$ [10]. If the scale of new physics is less than 8 TeV, one finds that certain operators can give an asymmetry $A(\Lambda^0) \sim 10^{-4}$. On the other hand, in most models of new physics the new operators are not all independent, so the effective lagrangian analysis may not tell the whole story. For example, in the Weinberg model, one finds $A(\Lambda^0) \sim -2.5 \times 10^{-5}$, and the “isoconjugate” left-right symmetric model gives $A(\Lambda^0) \sim -1.1 \times 10^{-5}$ [2, 8, 11]. In other words, despite the effective-lagrangian analysis, in specific models it seems difficult to obtain larger asymmetries than in the SM.

To sum up: the SM predictions for CP violation in hyperon decays have large uncertainties. In the presence of new physics, the CP-violating asymmetries may be larger than in the SM, but the calculations are both uncertain and model-dependent. It may be possible to observe such asymmetries experimentally, but (i) even if they are observed, it may not be clear whether or not new physics is involved, and (ii) even if new physics is involved, it will be very difficult to identify it. All in all, this is a very messy system.

3 Charm

In order to get indirect CP violation in neutral D-meson decays, one needs a final state $f$ to which both $D^0$ and $\bar{D}^0$ can decay. Then the interference of the two amplitudes $D^0 \rightarrow f$ and $D^0 \rightarrow \bar{D}^0 \rightarrow f$ can lead to CP violation. Obviously, for this to occur, one needs $D^0-\bar{D}^0$ mixing.

In the SM, the short-distance contributions to $D^0-\bar{D}^0$ mixing are due to box diagrams with internal $d$, $s$ and $b$ quarks. The calculation of these yields [12]

$$x_D \equiv \frac{\Delta M_D}{\Gamma_D} \sim 10^{-6}. \quad (15)$$

However, since all particles in the loops are light compared to the weak scale, the short-distance calculation is unreliable – long-distance effects can be important. Two estimates of these long-distance contributions have been done. Using intermediate dispersive contributions, one finds $x_D \lesssim 6 \times 10^{-5}$ [13], and heavy quark effective theory gives $x_D \sim 6 \times 10^{-6}$ [14]. The upshot is that $D^0-\bar{D}^0$ mixing is tiny in the SM: the $D$ meson will almost always decay before mixing. Thus, the SM predicts essentially no indirect CP violation in the neutral $D$-meson system.

On the other hand, the present experimental limit on $D^0-\bar{D}^0$ mixing, coming from $D^0 \rightarrow K^+\pi^-$, is well above the SM prediction [15]:

$$x_D^{\text{expt}} < 0.083. \quad (16)$$

So there is plenty of room for new physics to contribute to such mixing. And in fact, there are many models of new physics which do just that:
1. Fourth Generation [16]: Box diagrams with internal $b'$ quarks contribute to $D^0$-$\overline{D^0}$ mixing.

2. Z-mediated FCNC’s [17]: If the $u$- and $c$-quarks mix with a left-handed singlet up-type quark, flavour-changing neutral currents (FCNC’s) of the $Z$ are induced. These FCNC’s lead to $D^0$-$\overline{D^0}$ mixing at tree level.

3. Multi-Higgs-Doublet Models: If one imposes natural flavour conservation (NFC), then there are new contributions to the mixing through box diagrams with internal charged-Higgses and $b$ quarks [18]. These are important for large values of $\tan \beta$. If NFC is not imposed, there will be flavour-changing couplings of the neutral Higgses, leading to tree-level contributions to $D^0$-$\overline{D^0}$ mixing [19].

4. Supersymmetry with Quark-Squark Alignment [20]: In this class of non-minimal SUSY models, box diagrams with internal gluinos and $u$- and $c$-squarks contribute to $D^0$-$\overline{D^0}$ mixing.

5. Light Scalar Leptoquarks [21]: Here the contributions to the mixing come from box diagrams with internal leptons and leptoquarks.

In all cases, for certain choices of the new-physics parameters, these models can yield values of $x_D$ up to the experimental limit. (In fact, if the mixing is as large as the limit of Eq. (16), the analysis leading to this limit may be invalidated [22].) Also, in all cases new phases are introduced into $D^0$-$\overline{D^0}$ mixing.

The key point here is that, if we see large $D^0$-$\overline{D^0}$ mixing, this is a clear signal of new physics. If such a mixing is observed, it is possible that we may also find indirect CP violation. In order to do so, we need a final state $f$ to which both $D^0$ and $\overline{D^0}$ can decay. One possibility is to look at doubly-Cabbibo-suppressed (DCS) $D^0$ decays, for example into the final state $\pi^- K^+$. The decay $D^0(t) \to \pi^- K^+$ interferes, through mixing, with the Cabibbo-allowed (CA) decay $\overline{D^0}(t) \to \pi^- K^+$. ($D^0(t)$ and $\overline{D^0}(t)$ are the time-evolved states which at $t = 0$ were $D^0$ and $\overline{D^0}$, respectively.) CP violation will be indicated (with a caveat, to be discussed below) by an asymmetry $a_{CP}^{DCS}$ in the rates for these two processes. This CP asymmetry measures the relative phase of the two amplitudes:

$$a_{CP}^{DCS} = \frac{\text{Im} \left[ \frac{(D^0 \to \pi^- K^+) (\overline{D^0} \to \pi^+ K^-)}{(D^0 \to \overline{D^0}) (\overline{D^0} \to \pi^- K^+)} \right]}{\phi_M V_{cs} V_{ud} e^{i\delta_{CA}}}$$

$$= - \frac{V_{cd} V_{us} e^{i\delta_{DCS}}}{\phi_M V_{cs} V_{ud}} \sin(\phi_M + \delta_{CA} - \delta_{DCS})$$

where $\phi_M$ is the (weak) phase of $D^0$-$\overline{D^0}$ mixing, the $\delta$’s are strong phases, and I have used the Wolfenstein parametrization, in which the CKM matrix elements involving the first two generations are essentially real. There are two points which should be noted here. First, the asymmetry is small [O$(\lambda^2)$]. This is because the two interfering decay amplitudes are not of comparable size. Second, this asymmetry depends on the unknown
strong phases – in fact, even if $\phi_M = 0$, the asymmetry would still be nonzero. (Obviously, this would not be a signal of CP violation, but is an example of how the strong phases can “fake” CP violation.)

Fortunately, it is possible to disentangle the weak and strong phases by also looking at the CP-conjugate asymmetry $\bar{a}_{CP}^{DCS}$, i.e. comparing the rates for $\bar{D}^0(t) \to \pi^+K^-$ and $D^0(t) \to \pi^+K^-:

$$
\bar{a}_{CP}^{DCS} = -\frac{|V_{cd}V_{us}|}{V_{cs}V_{ud}} \sin(-\phi_M + \delta_{CA} - \delta_{DCS}).
$$

By using both asymmetries, one can determine $\phi_M$ and $\delta_{CA} - \delta_{DCS}$, up to discrete ambiguities.

On the other hand, one can avoid all dependence on strong phases, and get a larger asymmetry, by choosing a singly-Cabibbo-suppressed (SCS) decay such as $D^- \to \pi^+\pi^-$. In this case,

$$
a_{CP}^{SCS} = \text{Im} \left[ \frac{(D^0 \to \pi^+\pi^-)}{(D^0 \to D^0) (\bar{D}^0 \to \pi^+\pi^-)} \right]
= \text{Im} \left[ \frac{V_{cd}V_{us}^* e^{i\delta_{SCS}}}{\phi_M V_{ud}^* e^{i\delta_{SCS}}} \right]
= -\sin(\phi_M).
$$

Since the two decay amplitudes are the same size, the asymmetry can be quite large, considerably larger, in fact, than was the case for doubly-Cabbibo-suppressed $D^0$ decays. Furthermore, since a CP-eigenstate final state is used, there is no strong phase dependence in the asymmetry.

Finally, the number of $D$’s needed to measure a CP-asymmetry is proportional to $1/(BR(D \to f)a_{CP}^2)$. Because of this, it is easier to look for CP violation using singly-Cabibbo-suppressed $D$ decays – although the branching ratio is smaller, the asymmetry is considerably larger. On the other hand, doubly-Cabibbo-suppressed $D^0$ decays are more useful in the search for $D^0$-$\bar{D}^0$ mixing.

### 4 Beauty

The $B$ system is the most promising place to look for CP violation outside of the kaon system. The SM predicts large CP-violating asymmetries in certain decays of neutral $B$ mesons. I will not give more than a cursory review of the SM predictions for indirect CP violation in the $B$ system, as this subject is covered in more detail elsewhere in these proceedings [23].

The phase information of the CKM matrix can be displayed elegantly using the so-called unitarity triangle (Fig. 1). The 3 internal angles, $\alpha$, $\beta$ and $\gamma$, can be probed through indirect CP violation in the $B$ system. As in the charm system, such CP violation occurs through the interference of the two amplitudes $B^0 \to f$ and $B^0 \to \bar{B}^0 \to f$, where $f$ is a final state to which both $B^0$ and $\bar{B}^0$ can decay. The angles $\alpha$, $\beta$ and $\gamma$ can be measured through CP violation in the decays $\bar{B}_d \to \pi^+\pi^-$, $\bar{B}_d \to \Psi K_s$ and $\bar{B}_s \to D_s^\pm K^\mp$, respectively. These angles are already somewhat constrained by present
experimental data: within the SM, one has $-0.90 \leq \sin 2\alpha \leq 1.0$, $0.32 \leq \sin 2\beta \leq 0.94$, and $0.34 \leq \sin^2 \gamma \leq 1.0$.

Through a measurement of these CP asymmetries, the presence of new physics can be detected. This can be done in 3 ways:

1. The relation $\alpha + \beta + \gamma = \pi$ is violated.

2. Although $\alpha + \beta + \gamma = \pi$, one finds values for the CP phases which are outside of the SM predictions.

3. The CP angles measured are consistent with the SM predictions, and add up to 180°, but are inconsistent with the measurements of the sides of the unitarity triangle.

In any of these cases, we will want to identify the type of new physics which is responsible.

As in the $D$ system, new physics enters principally through $B^0-\bar{B}^0$ mixing, since there are no models of new physics which contribute significantly to $B$ decays. The key question concerns the phase of the new contributions. If the phase of the new-physics contribution is the same as that of the SM, then the CP asymmetries will be unchanged from the SM predictions. However, since the $V_{td}/\lambda V_{cb}$ side of the unitarity triangle is extracted from the measured value of $B^0-\bar{B}^0$ mixing, it will differ from its SM value. Thus, the new physics will be detected via item (3) above – the angles and the sides of the triangle will be inconsistent with one another. On the other hand, if the phase of the new-physics contribution is different from that in the SM, the CP asymmetries will themselves be changed, and the new physics can be detected via any of items (1)-(3).

There are a number of models of new physics which can contribute to $B^0-\bar{B}^0$ mixing:

1. Fourth Generation: Box diagrams with internal $t'$ quarks contribute to $B^0-\bar{B}^0$ mixing. There are new phases.
2. Z-mediated FCNC’s: The mixing of the ordinary down-type quarks with a left-handed singlet down-type quark induces flavour-changing couplings of the Z. These FCNC’s lead to $B^0 - \overline{B^0}$ mixing at tree level, with new phases.

3. Multi-Higgs-Doublet Models with NFC: There are new contributions to the mixing through box diagrams with internal charged-Higgses and t quarks. The phase is the same as in the SM.

4. Multi-Higgs-Doublet Models without NFC: If NFC is not imposed, there will be flavour-changing couplings of the neutral Higgses, leading to tree-level contributions to $B^0 - \overline{B^0}$ mixing. There can be new phases.

5. Minimal Supersymmetry: There are numerous new contributions to $B^0 - \overline{B^0}$ mixing, through box diagrams with internal ordinary and supersymmetric particles. In minimal SUSY, all contributions have the same phase as the SM.

6. Non-minimal Supersymmetry: In non-minimal SUSY models, the new box diagrams can have different phases than in the SM. In general, such models have a very large number of parameters, so that there is little predictivity.

Now, suppose that we find evidence for physics beyond the SM through the measurements of CP asymmetries. How can we distinguish among the various possibilities for new physics? Some progress can be made via a simple observation. Any new physics which affects $B^0 - \overline{B^0}$ mixing, which is a flavour-changing process, will also affect rare flavour-changing “penguin” decays such as $b \to sX$ or $b \to dX$. For some models, or regions of new-physics parameter space, the effects can be quite large. In this case, the measurements of the branching ratios for penguin decays can so constrain the parameters of the new physics as to render its effects in $B^0 - \overline{B^0}$ mixing, and hence the CP asymmetries, unimportant. It is an experimental question whether or not measurements of the rates for such penguin decays can be made before the CP asymmetries are measured. Regardless, it is clear that measurements of CP asymmetries and penguin decays will give complementary information.

As an example, consider a model with Z-mediated FCNC’s. The flavour-changing $Zbd$ and $Zbs$ couplings, which can affect both $B^0 - \overline{B^0}$ mixing and B decays, are parametrized by $U_{db}$ and $U_{sb}$, respectively. The present experimental bound on $BR(B \to \mu^+\mu^- X)$ constrains these couplings to be

$$|U_{qb}| < 1.7 \times 10^{-3}. \quad (20)$$

For maximal values of these parameters, $B^0_d - \overline{B^0_d}$ mixing may be dominated by Z-mediated FCNC’s; its contribution to $B^0_s - \overline{B^0_s}$ mixing can $\lesssim 15\%$. In both cases, the CP asymmetries can be affected.

However, Z-mediated FCNC’s also contribute to penguin decays. For example, there is a tree-level contribution to the decay $b \to q\ell^+\ell^-$. In the SM, $BR(B \to X_s \mu^+\mu^-)$ and $BR(B \to X_d \mu^+\mu^-)$ are

$$BR(B \to X_s \mu^+\mu^-) = (5.7 \pm 1.3) \times 10^{-6},$$

$$BR(B \to X_d \mu^+\mu^-) = (3.3 \pm 2.8) \times 10^{-7}. \quad (21)$$
For maximal values of the $U_{qb}$ couplings, we find

$$BR(B \to X \mu^+\mu^-) = 5 \times 10^{-5},$$  \hspace{1cm} (22)$$

which is 1-2 orders of magnitude above the SM prediction. (Of course, this is a bit of a cheat, since $BR(B \to \mu^+\mu^- X)$ was used to constrain the $U_{qb}$.)

Consider the decay $B^0_q \to l^+l^-$. For values of the decay constants $f_{B_s} = 232$ MeV and $f_{B_d} = 200$ MeV, The SM predicts

$$BR(B^0_s \to \mu^+\mu^-) = (3.5 \pm 1.0) \times 10^{-9},$$
$$BR(B^0_d \to \mu^+\mu^-) = (1.5 \pm 1.4) \times 10^{-10}. \hspace{1cm} (23)$$

On the other hand, with $Z$-mediated FCNC’s one finds

$$BR(B^0_s \to \mu^+\mu^-)|_{Z-FCNC} < 5.8 \times 10^{-8},$$
$$BR(B^0_d \to \mu^+\mu^-)|_{Z-FCNC} < 4.2 \times 10^{-8}. \hspace{1cm} (24)$$

Thus, for maximal values of the $U_{qb}$, the predicted rates for $B^0_s \to l^+l^-$ and $B^0_d \to l^+l^-$ are respectively about 20 and 300-400 times larger than those expected in the SM.

As a further example, consider electroweak penguin decays (EWP’s), which are mainly mediated by $Z$ exchange, rather than gluon exchange. An example of such a decay, which involves the transition $b \to s$, is $B^0_s \to \phi \pi^0$. Here the virtual $Z$ essentially turns into the $\pi^0$ – because of isospin, a gluon could not do this. $Z$-mediated FCNC’s will of course contribute to such decays. For this particular decay, we find

$$|\frac{A_{Z-FCNC}}{A_{SM}}| < 5.5. \hspace{1cm} (25)$$

An example of an electroweak penguin decay involving a $b \to d$ transition is $B^+ \to \phi \pi^+$. Here,

$$|\frac{A_{Z-FCNC}}{A_{SM}}| < 22.9. \hspace{1cm} (26)$$

Obviously, the effects of $Z$-mediated FCNC’s on such decays are enormous. The branching ratios for pure electroweak penguin decays can be increased by as much as a factor of $\sim 25$ $(b \to s)$ or $\sim 500$ $(b \to d)$! These are clearly “smoking gun” signals of new physics.

Another example of new physics which can significantly affect both $B^0$-$\bar{B}^0$ mixing and penguin decays is a fourth generation. Since the CKM matrix in this case is $4 \times 4$, the parameter space is quite complicated. However, suppose that $V_{td} \sim 0$, $V_{ut} = 0.005$, $V_{tb} = V_{t'b} \approx 1/\sqrt{2}$, and $m_{\ell'} = 480$ GeV. Then $B^0_d - \bar{B}^0_d$ mixing is dominated by the box diagram with internal $t'$ quarks. The phase of the mixing is then $arg(V_{t'd}V_{t'b}^*)^2$, which may be quite different from the SM. This will lead to CP asymmetries which may differ substantially from the SM.

However, for this same choice of parameters, all penguin decays involving the $b$-$d$ FCNC will also be dominated by the fourth generation. Comparing the predictions for $b \to d$ penguin decays in this model with those of the SM, we find

$$BR(b \to d\gamma)|_{4-gen} \approx \frac{1}{4}BR(b \to d\gamma)|_{SM}, \hspace{1cm} (27)$$
\[ BR(b \to dq \bar{q})|_{4-gen} \approx \frac{1}{5} BR(b \to dq \bar{q})|_{SM}, \]

\[ BR(B^0_d \to l^+l^-)|_{4-gen} = 8 \ BR(B^0_d \to l^+l^-)|_{SM}, \]

\[ BR(b \to d)_{EWP}|_{4-gen} = 8 \ BR(b \to d)_{EWP}|_{SM}. \]

There are errors on the SM predictions, so the first two are only marginal signals of new physics. However, the last two would be quite convincing signals of physics beyond the SM.

Note that not all models of new physics which can affect \( B^0-\overline{B^0} \) mixing, and hence the CP asymmetries, have clear signals in penguin decays. However, some of them do, so that measurements of CP asymmetries and rare penguin decays will give complementary information. Both will be necessary if we hope to identify the new physics.

5 Conclusions

To recap: in order to test the SM explanation of CP violation, it will be necessary to observe it outside of the kaon system. There are numerous possibilities for this. In this talk I have concentrated on three of them, involving hyperons, neutral \( D \) mesons, and neutral \( B \) mesons. In all cases, should CP violation be observed, we will want to know the answers to three questions. Specifically, (i) can it be explained by the SM, (ii) if not, what types of new physics can be responsible, and (iii) can we distinguish among different models of new physics?

- CP Violation in Hyperon Decays: Such CP violation requires the interference of tree and penguin diagrams, just like \( \epsilon'/\epsilon \). There are numerous processes and several CP-violating observables. Within the SM, the asymmetries are small, of order \( 10^{-5} \). However, the calculations have large theoretical uncertainties. In certain models of physics beyond the SM, there may be enhancements in the CP asymmetries, but these predictions also have large errors. In short, while it would be nice to observe CP violation in hyperon decays, it will be very difficult to determine if it is consistent with the SM, or if new physics is necessary.

- Indirect CP Violation in \( D^0 \) Decays: Any such CP-violating asymmetries require there to be \( D^0-\overline{D^0} \) mixing. In the SM, this mixing is negligible, so that there is no indirect CP violation. Going beyond the SM, there are many models which can accomodate a mixing as large as the current experimental limit. Note that the observation of such mixing would already be a clear signal of new physics. If the mixing is sizeable, it may be possible to also measure CP-violating asymmetries. The most promising processes involve singly-Cabibbo-suppressed \( D \) decays.

- Indirect CP Violation in \( B^0 \) Decays: The SM predicts large asymmetries in the neutral \( B \) system. It is possible to extract CKM phase information with no hadronic uncertainty. By measuring the angles and sides of the unitarity triangle, it is possible to test the SM explanation of CP violation. There are several ways in which new physics can manifest itself:
1. The relation $\alpha + \beta + \gamma = \pi$ is violated.
2. Although $\alpha + \beta + \gamma = \pi$, one finds values for the CP phases which are outside of the SM predictions.
3. The CP angles measured are consistent with the SM predictions, and add up to $180^\circ$, but are inconsistent with the measurements of the sides of the unitarity triangle.

In any of these cases, there are several models of physics beyond the SM which could be involved. It may be possible to distinguish among the different candidate models by looking at rare penguin decays. The measurements of the CP asymmetries and such rare decays will give complementary information.

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