Annihilation, Rescattering, and CP Asymmetries in $B$ Meson Decays

Boris Blok and Michael Gronau
Department of Physics
Technion – Israel Institute of Technology, Haifa 32000, Israel

and

Jonathan L. Rosner
Enrico Fermi Institute and Department of Physics
University of Chicago, Chicago, IL 60637

ABSTRACT

A number of $B$ meson decays may proceed only through participation of the spectator quark, whether through amplitudes proportional to $f_B/m_B$ or via rescattering from other less-suppressed amplitudes. An expected hierarchy of amplitudes in the absence of rescattering will be violated by rescattering corrections. Such violations could point the way toward channels in which final-state interactions could be important. Cases in which final state phases can lead to large CP asymmetries are pointed out.

PACS codes: 12.15.Hh, 12.15.Ji, 13.25.Hw, 14.40.Nd

\footnote{To be submitted to Phys. Rev. Lett.}
The decays of $B$ mesons have the potential for exhibiting CP violation under a variety of conditions \[1\]. Decays to CP eigenstates like $J/\psi K_S$ and $\pi^+\pi^-$ are expected to display an appreciable time-dependent rate asymmetry between $B^0$ and $\bar{B}^0$, whose interpretation in terms of pure CKM phases relies on the assumption of the dominance of a single weak phase \[2\]. Decays to non-CP eigenstates also can exhibit rate asymmetries in the presence of at least two contributing amplitudes whose weak and strong phases both differ from one another. However, the strong phases cannot be evaluated reliably \textit{a priori}. Instead, one must rely on constructions based on amplitude triangles or quadrangles \[3\], in which one can separate out weak from strong phases by comparing rates for processes with those for their charge-conjugates.

In the present note we propose a test for large final-state interactions which, while it does not yield precisely quantitative information on final-state phases, can indicate in which channels such phases are likely to be large. These channels are then prospects for searches for CP violation in rate asymmetries. We will only discuss direct CP asymmetries between instantaneous decays of $B$ mesons of opposite flavors, disregarding (in the case of neutral $B$ mesons) time-dependent $B - \bar{B}$ mixing effects. Such asymmetries, which require flavor-tagging, are obtained by time-integrated measurements and can be carried out also in a symmetric $e^+e^-$ collider operating at the $\Upsilon(4S)$.

We consider processes $B \to PP$, where $P$ is a pseudoscalar meson. Similar results hold when one or both pseudoscalars are replaced by vector mesons $V$. There are many processes in which the spectator quark necessarily plays a role in the decay, whether through exchange ($E$) or annihilation ($A$) with the $b$ quark or via rescattering. In the case of exchange or annihilation, the decay amplitude is expected to contain a power of $f_B/m_B$, where $f_B \simeq 200$ MeV is the $B$ meson decay constant. Such an amplitude is expected to be suppressed by a factor of roughly $\lambda^2$ \[4\], where $\lambda = 0.22$ is a parameter introduced by Wolfenstein \[5\] to classify the hierarchy of elements in the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

Processes in which the $b$ quark decay contributes to final states without the intervention of the spectator quark are expected to dominate $B \to PP$ decays. These processes consist of tree amplitudes which are color-favored ($T$) or color-suppressed ($C$) and penguin ($P$) amplitudes. (The notation is that of \[4\].) In many cases such amplitudes can contribute through rescattering to the processes involving the participation of the spectator quark \[6\]. Our purpose is to enumerate and classify these situations.

In Table I we list all the $B \to PP$ processes for which $T$, $C$, or $P$ amplitudes cannot contribute except via rescattering. Also shown are the powers of $\lambda$ in the amplitudes (which are the same whether the amplitudes arise from exchange or annihilation or via rescattering from $T$ or $C$). Any process of order $\lambda^n$ should effectively appear of order $\lambda^n (f_B/m_B) \simeq O(\lambda^{n+2})$ if rescattering is not important, whereas rescattering could in principle enhance this amplitude beyond this level to a maximum of $O(\lambda^n)$.

The most promising decays have amplitudes of order $f_B\lambda^2/m_B$. It would be interesting to search for the modes in Table I to see if they show evidence for the expected suppression due to the factor $f_B/m_B$. If they are enhanced, there is some chance that the rescattering amplitude can generate a final-state phase large enough to give rise to
an observable CP-violating rate asymmetry in the decay. In the following discussion we will describe a possible mechanism for such enhancement.

Recently some progress was made in understanding the role of final state interactions in $B$ decays [5, 6, 7, 8, 9, 11, 10]. In Ref. [3] it was argued that, contrary to simple intuition [12], soft final state interactions do not disappear in the large $m_B$ limit and may be significant in hadronic $B$ decays. In Ref. [10] sizable rescattering effects via inelastic charge-exchange,

$$\pi^+ D^- \to \pi^0 \bar{D}^0, \quad (1)$$

were calculated in $B^0 \to \pi^0 \bar{D}^0$. Let us summarize the results of this analysis, which will then be applied to our case.

The processes $B^0 \to \pi^+ D^-$ and $B^0 \to \pi^0 \bar{D}^0$ are conventionally given by “color-allowed” and “color-suppressed” amplitudes, $\hat{T} \propto a_1$ and $\hat{C} \propto a_2$, respectively, which are determined experimentally, $a_2/a_1 \approx 0.2$ [13]. When calculated in the naïve factorization approximation [14], $\hat{T}$ and $\hat{C}$ are related to isospin-related processes, $I = 0$, 2, respectively. The existence of large phases can be tested experimentally by measuring the rates of $B^0 \to \pi^0 \bar{D}^0$ and $B^0 \to \pi^0 \bar{D}^0$ due to rescattering effects from $B^0 \to \pi^+ \pi^- \to \pi^0 \pi^0$. The calculation leading to Eq. (2) involves quite a few assumptions, and can therefore mainly serve for illustrative purposes [15]. Smaller rescattering effects were calculated in Ref. [11] for processes of the type $B \to PV$.

To sum up, the results of the analysis of Ref. [10] suggest that in the two cases of $B^0 \to \pi^0 \bar{D}^0$ and $B^0 \to \pi^0 \bar{D}^0$, the rescattering amplitudes into the final states may carry large phases, and are likely to be smaller by a factor of about $\lambda$ than the decay amplitudes to the intermediate $\pi^+ D^-$ and $\pi^+ \pi^-$ states, respectively. The existence of large phases can be tested experimentally by measuring the rates of $B^0 \to \pi^0 \bar{D}^0$ and $B^0 \to \pi^0 \bar{D}^0$ of isospin-related processes. Since the final states are mixtures of two isospin states ($I = 1/2$, 3/2 and $I = 0$, 2, respectively), the amplitudes of these processes obey two triangle relations with the amplitudes of two other pairs of processes, $B^0 \to \pi^+ D^-$, $B^+ \to \pi^+ \bar{D}^0$ and $B^0 \to \pi^+ \pi^-$, $B^+ \to \pi^+ \pi^0$, respectively. Recattering effects into these final states are expected to be smaller than in the color-suppressed processes. Thus, the smaller sides of the two triangles, associated with the $B^0 \to \pi^0 \bar{D}^0$ and $B^0 \to \pi^0 \pi^0$ amplitudes, will form sizable angles with each of the other two sides. In the case of the $B \to \pi \pi$ isospin triangle, one would have to isolate the contribution from a penguin amplitude which carries a different weak phase [16]. So far, the two large sides
of the $B \to \pi \bar{D}$ triangle have been measured, while an upper limit exists on $B^0 \to \pi^0 \bar{D}^0$. This sets a mild upper bound on the corresponding phase \[17\].

A similar situation is expected to hold in the processes on the left-hand-side of Table 1. In addition to the direct $E$ and $A$ amplitudes, which are suppressed by $f_B/m_B$, these processes obtain contributions of rescattering from intermediate states given in the right-hand-side of the Table. Also specified are the types $(T, C, P)$ of decay amplitudes into the intermediate states and the corresponding Regge trajectories $(K^*, K^{**}, \rho, a_2)$ exchanged between the intermediate and final states.

As an example, consider $B^0 \to K^+ D_s^-$. The amplitude of this process contains two terms: the direct $\bar{E}$ amplitude and the contributions of rescattering from $\pi^+ D^-$ and from $\pi^0 \bar{D}^0$ states, which are described in terms of $K^*, K^{**}$ Regge exchange. The decay amplitudes into $\pi^+ D^-$ ($T$) dominates over the decay amplitude into $\pi^0 \bar{D}^0$ ($C/\sqrt{2}$). In the chiral limit (in which the mass of the $s$ quark vanishes, $m_s \to 0$), $K^*$ exchange is equivalent to $\rho$ exchange. Chiral corrections and the $K^{**}$ trajectory are expected to increase the amplitude. The contribution to $B^0 \to K^+ D_s^-$, via the rescattering process $\pi^+ D^- \to K^+ D_s^-$ is approximately equal to the contribution to $B^0 \to \pi^0 \bar{D}^0$ via the rescattering process (1). Thus, assuming the results of Ref. [10], we find that the amplitude of $B^0 \to K^+ D_s^-$ obtains two terms: a direct amplitude $\bar{E}$ which is real and of order $\lambda^4$, and a contribution from rescattering via $\pi^+ D^-$, which is of order $\lambda^3$ and which carries a large final state phase. Thus, $A(B^0 \to K^+ D_s^-)$ is expected to be enhanced by a factor $1/\lambda$ compared to the naive $f_B/m_B$ suppression and to obtain a sizable final-state interaction phase. The enhancement can be tested by measuring the rate of this process.

Similar effects exist in all the other processes in Table 1. For instance, the amplitude of $B^+ \to K^0 D^+$ consists of a real direct term of order $\lambda^5$, and an amplitude due to rescattering from $\pi^0 D^+_s$ which is of order $\lambda^4$ and has a large strong phase.

We conclude that rescattering from intermediate states leads to amplitudes suppressed by $\lambda$ rather than by $f_B/m_B$. The presence of large final state phases in these amplitudes does not guarantee large CP asymmetries. For this one requires that two different weak phases contribute to a process. In $B^0 \to K^+ D_s^-$, $\bar{T}$ ($\bar{C}$) and $\bar{E}$ involve the same weak phase $\text{Arg}(V_{cb}^* V_{ud})$, and no CP asymmetry is expected between the rate of this process and its charge-conjugate. A similar situation holds in $B^+ \to K^0 D^+$.

In order to search for cases in which CP asymmetries can be expected as a consequence of two different weak phases, we limit our attention to processes in Table 1, in which the contribution to an amplitude from rescattering involves a penguin ($P$) term. The weak phase of this amplitude may differ from the phase of the direct $E$ or $A$ amplitude. There are four such classes of processes.

In the first class, $B_s \to D^+ D^-$ and $B_s \to D^0 \bar{D}^0$, all amplitudes involve the same CKM phase, $\text{Arg}(V_{cb}^* V_{cs}) = \text{Arg}(V_{ub}^* V_{ts})$ (mod $\pi$), and one expects no CP asymmetry.

In the second and third class, involving $B^0 \to D^0 \bar{D}^0$ or $D_s^+ D_s^-$ and $B^0 \to K^+ K^-$, respectively, the direct amplitude and the penguin contribution to rescattering involve different weak phases, $\text{Arg}(V_{cb}^* V_{cd}) \neq \text{Arg}(V_{ub}^* V_{td})$, $\text{Arg}(V_{ub}^* V_{ud}) \neq \text{Arg}(V_{ib}^* V_{td})$. (We neglect the effect of $u$ and $c$ quarks in $b \to d$ penguin amplitudes \[13\]). The asymmetries in the processes belonging to these two classes are proportional to the sines of the corre-
sponding weak phase differences, namely to \(\sin \beta\) and \(\sin \alpha\), respectively, where \(\alpha\) and \(\beta\) are two angles of the CKM unitarity triangle \([1]\). Since the penguin amplitude is sub-dominant in the decays to intermediate states, the rescattering effects in the asymmetries are suppressed by

\[
\frac{P'}{T'} \sim \left| \frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}} \right| \frac{\alpha_s(m_b)}{12\pi} \ln\left(\frac{m_t^2}{m_b^2}\right) \sim \lambda \to \lambda^2 ,
\]

and by

\[
\frac{P}{T} \sim \left| \frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}} \right| \frac{\alpha_s(m_b)}{12\pi} \ln\left(\frac{m_t^2}{m_b^2}\right) \sim \lambda \to \lambda^2 ,
\]

respectively. Consequently, CP asymmetries are estimated at the level of 10% in \(B^0 \to D^0 \bar{D}^0\) or \(D^+ D^-\) and in \(B^0 \to K^+ K^-\). The largest asymmetries are expected in \(B_s \to \pi^+ \pi^-\) and \(B_s \to \pi^0 \pi^0\). In these rather rare processes, the direct amplitudes are of order \(\lambda^0\) and carry a weak phase \(\text{Arg}(V_{ub}^* V_{ts})\). The penguin amplitude \(P'\) dominates \(B_s\) decays to the \(K K\) intermediate states. Its weak phase is \(\text{Arg}(V_{ub}^* V_{ts})\), and its magnitude can be estimated by

\[
P' \sim |V_{tb}^* V_{ts}|(\alpha_s(m_b)/12\pi) \ln(m_t^2/m_b^2) \sim \lambda^4 .
\]

The rescattering amplitudes into the charged and neutral \(\pi \pi\) states are smaller by a factor \(\lambda\) and carry large final state phases. Thus, the magnitudes of the two interfering amplitudes differ by no more than one power of \(\lambda\), their weak phase-difference is \(\gamma\) and their strong phase difference is likely to be large. One therefore expects in \(B_s \to \pi^+ \pi^-\) and in \(B_s \to \pi^0 \pi^0\) large asymmetries, possibly of a few tens of percent, which are proportional to \(\sin \gamma\).

Let us note that similar rescattering effects inducing CP asymmetries are expected also in processes which do not require participation of the spectator quark. One such example, in which large asymmetries are expected, is \(B^0 \to K^0 \bar{K}^0\). In this case, the direct amplitude is pure penguin \([2]\) and has a magnitude

\[
P \sim |V_{tb}^* V_{td}|(\alpha_s(m_b)/12\pi) \ln(m_t^2/m_b^2) \sim \lambda^4 \to \lambda^5 .
\]

The \(K^0 \bar{K}^0\) final state can be also obtained by decay to and rescattering from a \(\pi^+ \pi^-\) state. The amplitude of \(B^0 \to \pi^+ \pi^-\) is given by \(T \sim V_{ub}^* V_{ud} \sim \lambda^3 \to \lambda^4\); the rescattering amplitude into \(K^0 \bar{K}^0\) is smaller by a factor \(\lambda\) and carries a large strong phase. Hence, the two amplitudes are of comparable magnitudes and may have quite different strong phases. The resulting asymmetry which is proportional to \(\sin \alpha\) can be sizable. A similar result was obtained in Ref. \([13]\), in which the rescattering amplitude via the \(\pi^+ \pi^-\) state was represented by the soft part of the \(u\) quark contribution to the penguin amplitude \(P\).

A remark is in order about the magnitude of the factor \(f_B/m_B \simeq \lambda^2\) which we have assumed to characterize suppressed amplitudes. Such a suppression of exchange and annihilation amplitudes of \(B\) decays to two pseudoscalars is obtained when assuming factorization and simple form factors \([20]\). This picture is clearly an oversimplification. As we have shown, it is quite possible that these amplitudes may be suppressed only by \(\lambda\)
due to rescattering effects. A similar suppression, of order $2\pi f_B/m_B \simeq \lambda$, characterizes the inclusive annihilation amplitude $[21]$. The extra $2\pi$ factor has a simple explanation. The non-suppressed amplitudes involve beta-decay type transitions in which one quark decays three, whereas the suppressed amplitudes involve exchange or annihilation of an initial heavy quark and an initial spectator antiquark into a two-quark final state. The factor of $2\pi$ takes account of the presence of one less quark in the final state.

We comment briefly on expected branching ratios for the interesting processes. One must distinguish between those processes in which the magnitude of rescattering is expected to be merely detectable and those in which it can lead to a measurable CP-violating decay rate asymmetry. For example, the amplitude for $B^0 \to K^+ D_s^-$ is expected to be of order $\lambda$ times that for the observed process $B^0 \to \pi^+ D^-$ which feeds it via rescattering. Since the branching ratio for the latter process is about 0.3%, observation of a rate for $B^0 \to K^+ D_s^-$ high enough to imply rescattering effects, namely with a branching ratio of about $10^{-4}$, is within the reach of present or modestly upgraded $B$ meson experiments.

The use of the anticipated large final state phases to observe a CP-violating asymmetry is somewhat more demanding, but within the capabilities of several planned high-intensity sources of $B$ mesons. The decays $B^0 \to D^0 \bar{D}^0$ and $B^0 \to D_s^+ D_s^-$ are expected to be fed by rescattering from both tree and penguin contributions in $B^0 \to D^+ D^-$. One expects the branching ratio for the latter process to be about $\lambda^2$ that for the observed process $B^0 \to D^- D_s^+$, or about $(1/20)(0.8\%)$. Rescattering will probably cost another factor of $\lambda^2$ in rate, leading to a branching ratio $B(B^0 \to D^0 \bar{D}^0) \simeq 2 \times 10^{-5}$. As we have estimated, a rate asymmetry of order 10% could arise between this process and its charge-conjugate. The situation in $B^0 \to K^+ K^-$, where an asymmetry at a similar level is expected, is somewhat less favorable. This process is fed by rescattering from $B^0 \to \pi^+ \pi^-$, the rate of which is likely to be about $10^{-5}$ [22], so $B(B^0 \to K^+ K^-)$ should be somewhat below $10^{-6}$. Finally, rates at a similar level are expected for $B_s \to \pi^+ \pi^-$ and $B_s \to \pi^0 \pi^0$, which are fed by rescattering from $B_s \to K^+ K^- (K^0 \bar{K}^0)$ whose branching ratios is probably about $10^{-5}$, similar to that of $B^0 \to K^+ \pi^- [22]$. As we noted, the asymmetry in $B_s \to \pi \pi$ may be very large due to the interference between the amplitudes $E'$ and the rescattering amplitude from $P'$ which differ by no more than one power of $\lambda$.

In summary, while it is very difficult to study quantitatively final state interactions at the $B$ mass, our analysis indicates that in $B$ decays which require the participation of the spectator quark, rescattering effects are likely to enhance decay rates by an order of magnitude relative to naive expectations. Such enhancement may indicate large final state phases, which would lead in certain cases to sizable CP asymmetries.

We thank J. Alexander, J. Bartelt, G. C. Moneti, D. Wyler, and D-X. Zhang for discussions and the CERN Theory Group for a congenial atmosphere in which part of this collaboration was carried out. This work was supported in part by the United States- Israel Binational Science Foundation under Research Grant Agreement 94-00253/2, by the Israel Science Foundation, and by the United States Department of Energy under Contract No. DE FG02-90ER40560.
References

[1] For discussions with references to earlier literature see, e.g., I. I. Bigi and A. I. Sanda, Nucl. Phys. B281, 41 (1987); I. Dunietz, Ann. Phys. (N.Y.) 184, 350 (1988); Y. Nir and H. R. Quinn, Ann. Rev. Nucl. Part. Sci. 42, 211 (1992); B. Winstein and L. Wolfenstein, Rev. Mod. Phys. 65, 1113 (1993).

[2] M. Gronau, Phys. Rev. Lett. 63, 1451 (1989); D. London and R. D. Peccei, Phys. Lett. B 223, 257 (1989); B. Grinstein, Phys. Lett. B 229, 280 (1989).

[3] M. Gronau and D. Wyler, Phys. Lett. B 265, 172 (1991); I. Dunietz, Phys. Lett. B 270, 75 (1991); M. Gronau, J. L. Rosner, and D. London, Phys. Rev. Lett. 73, 21 (1994); O. F. Hernández, D. London, M. Gronau, and J. L. Rosner, Phys. Lett. B 333, 500 (1994); M. Gronau, O. F. Hernández, D. London, and J. L. Rosner, Phys. Rev. D 50, 4529 (1994); N. G. Deshpande and X.-G. He, Phys. Rev. Lett. 74, 26, 4099(E) (1995); 75, 1703, 3064 (1995); 76, 360 (1996); M. Gronau and J. L. Rosner, Phys. Rev. D 53, 2516 (1996); M. Gronau and J. L. Rosner, Phys. Rev. Lett. 76, 1200 (1996); A. S. Dighe, M. Gronau, and J. L. Rosner, Phys. Rev. D 54, 3309 (1996); A. S. Dighe and J. L. Rosner, Phys. Rev. D 54, 4677 (1996).

[4] M. Gronau, O. F. Hernández, D. London, and J. L. Rosner, Phys. Rev. D 52, 6356, 6374 (1995), and references therein.

[5] L. Wolfenstein, Phys. Rev. Lett. 51, 1945 (1983).

[6] Similar effects in $D$ decays were studied, for instance, in J. F. Donoghue, Phys. Rev. D 33, 1516 (1986), and in M. Bauer, B. Stech and M. Wirbel, Zeit. Phys. C 34, 103 (1987).

[7] N. G. Deshpande and C. O. Dib, Phys. Lett. B 319, 313 (1993).

[8] H. Zheng, Phys. Lett. B 356, 107 (1995).

[9] J. F. Donoghue, E. Golowich, A. A. Petrov and J. M. Soares, Phys. Rev. Lett. 77, 2178 (1996).

[10] B. Blok and I. Halperin, Phys. Lett. B 385, 324 (1996).

[11] G. Nardulli and T. N. Pham, Phys. Lett. B 391, 165 (1997).

[12] J. D. Bjorken, Nucl. Phys. B (Proc. Suppl.) 11, 325 (1989).

[13] M. S. Alam et al. (CLEO Collaboration), Phys. Rev. D 50, 43 (1994).

[14] Bauer, Stech and Wirbel, Ref. 6.
In the calculation of Ref. [10] the phases of the two rescattered amplitudes $A(B^0 \rightarrow \pi^+D^- \rightarrow \pi^0D^0)$ and $A(B^0 \rightarrow \pi^+\pi^- \rightarrow \pi^0\pi^0)$ are the sums of two large unrelated phases which involve large theoretical uncertainties. In both cases the magnitude of $M'/M_{dir}$ is approximately one.

[16] M. Gronau and D. London, Phys. Rev. Lett. 65, 3381 (1990).

[17] H. Yamamoto, Harvard University Report No. HUTP-94/A006, 1994 (unpublished).

[18] A. J. Buras and R. Fleischer, Phys. Lett. B 341, 379 (1995).

[19] J. M. Gérard and W. S. Hou, Phys. Lett. B 253, 478 (1991).

[20] A. N. Kamal and T. N. Pham, Phys. Rev. D 50, 395 (1994); Z-z. Xing, Phys. Rev. D 53, 2847 (1996); D. Du, L-b. Guo and D-X. Zhang, BIHEP-96-38, TECHNION-PH-96-25.

[21] See, for instance, M. B. Voloshin, N. G. Uraltsev, V. A. Khoze, and M. A. Shifman, Yad. Fiz. 46, 181 (1987) [Sov. J. Nucl. Phys. 46, 112 (1987)].

[22] D. M. Asner et al. (CLEO Collaboration), Phys. Rev. D 53, 1039 (1996).
Table 1: $B \to PP$ amplitudes involving only suppressed graphs.

| CKM Factor | Order in $\lambda$ | Process | Suppressed amplitude | Rescatters from: |
|------------|--------------------|---------|----------------------|------------------|
| $V_{cb}V_{ud}$ | $\lambda^2$ | $B^0 \to K^+ D_s^-$ | $E$ | $\pi^+ D^-$ |
| | | | | $\tilde{T}$ |
| | | | | $K^*, K^{**}$ |
| | | | | $\pi^0 \tilde{D}^0$ |
| | | | | $\tilde{C}/\sqrt{2}$ |
| | | | | $K^*, K^{**}$ |
| $V_{cb}V_{cs}$ | $\lambda^2$ | $B_s \to D^+ D^-$ | $\tilde{E}$ | $D_s^+ D_s^-$ |
| | | | | $T + \tilde{P}$ |
| | | | | $K^*, K^{**}$ |
| | | | | $D_s^+ D_s^-$ |
| | | | | $\tilde{T} + \tilde{P}$ |
| | | | | $K^*, K^{**}$ |
| $V_{cb}V_{us}$ | $\lambda^3$ | $B_s \to \pi^+ D^-$ | $\lambda \tilde{E}$ | $K^+ D_s^-$ |
| | | | | $\lambda \tilde{T}$ |
| | | | | $K^*, K^{**}$ |
| | | | | $-\lambda \tilde{E}/\sqrt{2}$ |
| | | | | $K^+ D_s^-$ |
| | | | | $\lambda \tilde{T}$ |
| | | | | $K^*, K^{**}$ |
| $V_{cb}V_{cd}$ | $\lambda^3$ | $B^0 \to D^0 D^0$ | $-E'$ | $D^+ D^-$ |
| | | | | $T' + P'$ |
| | | | | $\rho, a_2$ |
| | | | | $D^+ D^-$ |
| | | | | $\tilde{T}' + \tilde{P}'$ |
| | | | | $K^*, K^{**}$ |
| | | | | $\pi^0 \pi^0$ |
| | | | | $(P - C)/\sqrt{2}$ |
| | | | | $K^*, K^{**}$ |
| $V_{ub}V_{ud}$ | $\lambda^3$ | $B^0 \to K^+ K^-$ | $-E$ | $\pi^+ \pi^-$ |
| | | | | $-T + P$ |
| | | | | $K^*, K^{**}$ |
| | | | | $\pi^0 \pi^0$ |
| | | | | $(P - C)/\sqrt{2}$ |
| | | | | $K^*, K^{**}$ |
| | | | | $K^0 \bar{K}^0$ |
| | | | | $\rho, a_2$ |
| $V_{ub}V_{cs}$ | $\lambda^3$ | $B^+ \to K^0 D^+$ | $A$ | $\pi^0 D_s^+$ |
| | | | | $-T/\sqrt{2}$ |
| | | | | $K^*, K^{**}$ |
| | | | | $K^+ D^0$ |
| | | | | $-\tilde{C}$ |
| | | | | $\rho, a_2$ |
| | | | | $K^*, K^{**}$ |
| | | | | $K^+ D_s^+$ |
| | | | | $-\tilde{T}$ |
| | | | | $K^*, K^{**}$ |
| $V_{ub}V_{us}$ | $\lambda^4$ | $B_s \to \pi^+ \pi^-$ | $-E'$ | $K^+ K^-$ |
| | | | | $-(T' + P')$ |
| | | | | $K^*, K^{**}$ |
| | | | | $K^0 \bar{K}^0$ |
| | | | | $P'$ |
| | | | | $K^*, K^{**}$ |
| | | | | $K^0 \bar{K}^0$ |
| | | | | $P'$ |
| | | | | $K^*, K^{**}$ |
| $V_{ub}V_{cd}$ | $\lambda^4$ | $B^+ \to K^0 D_s^+$ | $-\lambda \tilde{A}$ | $\pi^+ D^0$ |
| | | | | $\lambda \tilde{C}$ |
| | | | | $K^*, K^{**}$ |
| | | | | $\pi^0 D^+$ |
| | | | | $\lambda \tilde{T}/\sqrt{2}$ |
| | | | | $K^*, K^{**}$ |
| | | | | $K^0 \bar{K}^0$ |
| | | | | $P'$ |
| | | | | $K^*, K^{**}$ |
| | | | | $K^0 \bar{K}^0$ |
| | | | | $P'$ |
| | | | | $K^*, K^{**}$ |
| | | | | $\pi^0 D^0$ |
| | | | | $\lambda \tilde{C}/\sqrt{2}$ |
| | | | | $K^*, K^{**}$ |

$^a$Penguin annihilation (also of this order) ignored