

New physics in $\Delta\Gamma_d$

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We analyze the possibility of having new physics effects in the decay rate difference, $\Delta\Gamma_d$, of neutral B_d mesons. Three different sources of enhancement are considered, CKM unitarity violations, beyond standard model effects in the tree-level dimension six operators $(\bar{d}p)(\bar{p}'b)$ with $p, p' = u, c$; and large enhancements of the almost unconstrained operators $(\bar{d}b)(\bar{\tau}\tau)$. We find that deviations of several hundred per cent from the standard model prediction of $\Delta\Gamma_d$ are not excluded by current experimental data.

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1. Introduction

There is a longstanding discrepancy between experimental results for the like-sign dimuon asymmetry measured by the D0 Collaboration [1]-[4] and the corresponding standard model predictions [5]-[9]. In [10] an interesting connection between the dimuon asymmetry and the decay rate difference of neutral B_d mesons was suggested: the measured enhancement of the dimuon asymmetry could also be explained by an enhanced decay rate difference of the neutral B_d mesons. Moreover, $\Delta\Gamma_d$, is currently only weakly constrained by direct measurements. This was the motivation for the study in [11] where indirect experimental constraints on possible new physics enhancements of $\Delta\Gamma_d$ were studied; we present here the main findings of [11].

2. Neutral B mixing

Due to electroweak interactions the neutral states B_d and \bar{B}_d oscillate into each other, the time evolution of this system is given by solving the Schrödinger-like equation

$$i\frac{d}{dt}\begin{pmatrix} |B_d\rangle \\ |\bar{B}_d\rangle \end{pmatrix} = \Sigma^d \begin{pmatrix} |B_d\rangle \\ |\bar{B}_d\rangle \end{pmatrix} \quad \text{where} \quad \Sigma^d = M_d - \frac{i}{2}\Gamma_d = \begin{pmatrix} M_{11}^d - \frac{i\Gamma_{11}^d}{2} & M_{12}^d - \frac{i\Gamma_{12}^d}{2} \\ M_{12}^{d*} - \frac{i\Gamma_{12}^{d*}}{2} & M_{11}^d - \frac{i\Gamma_{11}^d}{2} \end{pmatrix}. \quad (2.1)$$

Diagonalizing Σ^d gives the physical eigenstates $\{|B_H\rangle, |B_L\rangle\}$ with the masses M_H^d, M_L^d and the decay rates Γ_H^d, Γ_L^d . To provide a mathematical description of the mixing process it is useful to define the observables $\Delta M_d = M_H^d - M_L^d$ and $\Delta\Gamma_d = \Gamma_H^d - \Gamma_L^d$. Theoretically ΔM_d and $\Delta\Gamma_d$ can be calculated from the components of Σ^d according to the formulas

$$\Delta M_d \approx 2|M_{12}^d| \quad \text{and} \quad \Delta\Gamma_d \approx 2|\Gamma_{12}^d|\cos(\phi_d) \quad \text{where} \quad \phi_d = \arg\left(-\frac{M_{12}^d}{\Gamma_{12}^d}\right). \quad (2.2)$$

Only ΔM_d and $\Delta\Gamma_d$ are directly accessible in experiment, the phase ϕ_d can be calculated from the measurement of the semileptonic asymmetry

$$a_{sl}^d = \left|\frac{\Gamma_{12}^d}{M_{12}^d}\right| \sin(\phi_d). \quad (2.3)$$

By combining data from Belle, BABAR, D0, DELPHI and LHCb the following direct experimental bound for $\Delta\Gamma_d$ is available

$$\frac{\Delta\Gamma_d^{HFAG}}{\Gamma_d} = (0.1 \pm 1.0)\% [12] \quad (2.4)$$

which can be compared to the standard model prediction

$$\frac{\Delta\Gamma_d^{SM}}{\Gamma_d} = (0.42 \pm 0.08)\% [5].$$

3. Sources of enhancement for $\Delta\Gamma_d$

3.1 CKM unitarity violations

Let $\lambda_q^d = V_{qd}^* V_{qb}$, from the unitarity of the 3×3 CKM matrix the following condition is satisfied $\lambda_u^d + \lambda_c^d + \lambda_t^d = 0$. However in different extensions of the standard model the previous equality is broken according to $\lambda_u^d + \lambda_c^d + \lambda_t^d = \delta_{CKM}^d$; for instance in 4th family studies $\delta_{CKM}^d \approx 10^{-2}$ leading to a potential enhancement factor on $\Delta\Gamma_d$ of 300%.

3.2 Current-current standard model operators

In this section we consider the possibility of having new physics effects in tree level standard model operators and its consistency with recent experimental observations, a similar study and its implications over the CKM phase γ has been discussed in [13].

We are concerned with the following effective Hamiltonian

$$\mathcal{H}_{eff}^{current, |\Delta B|=1} = \frac{4G_F}{\sqrt{2}} \sum_{p,p'=u,c} V_{pd}^* V_{p'b} \sum_{i=1,2} C_i^{pp'}(\mu) Q_i^{pp'} + h.c. \quad (3.1)$$

with

$$\begin{aligned} Q_1^{pp'} &= (\bar{d}^\alpha p^\beta)_{V-A} (\bar{p}'^\beta b^\alpha)_{V-A}, \\ Q_2^{pp'} &= (\bar{d}^\alpha p^\alpha)_{V-A} (\bar{p}'^\beta b^\beta)_{V-A}. \end{aligned} \quad (3.2)$$

New physics effects will produce shifts over the standard model Wilson coefficients according to

$$C_{1,2}^{pp'} = C_{1,2}^{SM} + \Delta C_{1,2}^{pp'}. \quad (3.3)$$

To constrain the values of $\Delta C_{1,2}^{pp'}$ we consider different observables depending on the up type quark structure indicated by the labels pp' in Eqns. (3.1) and (3.2). The most important bounds arise from the operators related with the transitions $b \rightarrow u\bar{u}d$, $b \rightarrow c\bar{u}d$ and $b \rightarrow c\bar{c}d$ with Wilson coefficients C^{uu} , C^{uc} and C^{cc} respectively. The decays $B \rightarrow \pi\pi$, $B \rightarrow \pi\rho$ and $B \rightarrow \rho\rho$ provide limits for ΔC^{uu} . To calculate the bounds on ΔC^{uc} the relevant processes are $B \rightarrow D\pi$ and $B \rightarrow Dh$ with $h = \pi, \eta$ and ω . Regarding that the decay width of the B_d meson is dominated by the transition $b \rightarrow c\bar{u}d$ an extra constraint for ΔC^{uc} can be imposed from the decay rate itself. The shift ΔC^{cc} is bounded by the process $B \rightarrow X_d\gamma$, the observable $\sin(2\beta)$ and the semileptonic asymmetry a_{sl}^d defined in Eqn. (2.3). We visualize graphically the parameter space available for new physics by plotting the real and imaginary parts of $\Delta C_{1,2}^{qq'}$, as an example we present the results for ΔC_2^{cc} in the left panel of Fig. (1).

Finally the effects of $\Delta C_{1,2}^{qq'}$ over $\Delta\Gamma_d$ can be estimated by using Eqns. (2.2) and (3.3) together with the expression

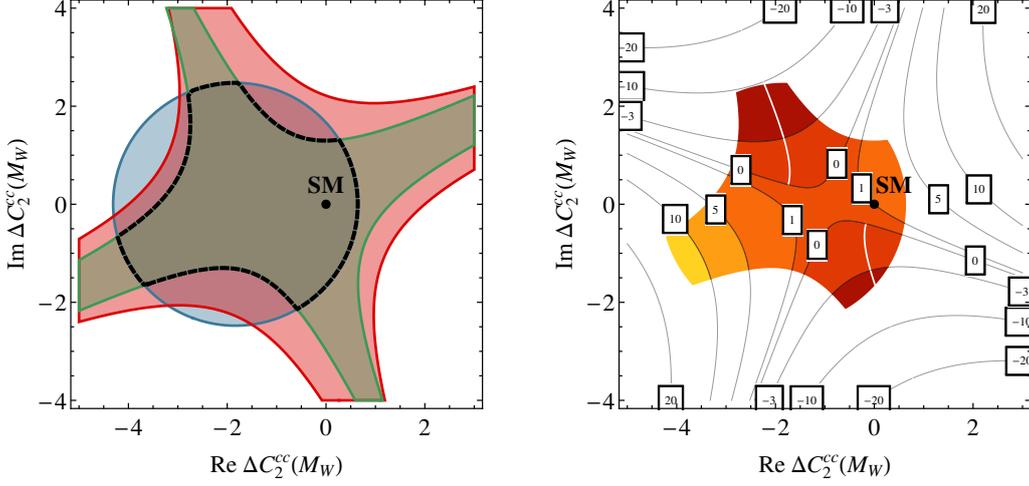


Figure 1: Left panel: Allowed parameter space in the $\text{Re } \Delta C_2^{cc}$ - $\text{Im } \Delta C_2^{cc}$ plane. The constraints shown correspond to $B \rightarrow X_d \gamma$ (Blue), α_{sl}^d (Green) and $\sin(2\beta)$ (Red). The region contained within the dashed black line represent the combined constraints from the different observables. Right panel: contours of $\Delta\Gamma_d/\Delta\Gamma_d^{SM}$ along with the combined constraints.

$$\begin{aligned} \Gamma_{12}^d &= \frac{1}{2M_{B_d}} \langle \bar{B}_d | \text{Im} \left(i \int d^4 x \hat{T} \left[\mathcal{H}_{eff}^{current, \Delta B=1}(x) \mathcal{H}_{eff}^{current, \Delta B=1}(0) \right] \right) | B_d \rangle \\ &= - \left(\lambda_c^2 \Gamma_{12}^{cc,d}(C_1^{cc}, C_2^{cc}) + 2\lambda_c \lambda_u \Gamma_{12}^{uc,d}(C_1^{uc}, C_2^{uc}) + \lambda_u^2 \Gamma_{12}^{uu,d}(C_1^{uu}, C_2^{uu}) \right). \end{aligned} \quad (3.4)$$

The enhancement factors can be read by plotting the contour lines for $\Delta\Gamma_d/\Delta\Gamma_d^{SM}$, we provide an example of this strategy in the right panel of Fig. (1). Our calculations show that there is room for new physics in $C_{1,2}^{uu}$ and $C_{1,2}^{uc}$ leading to enhancement factors of 1.6 in both cases. The most interesting result arises from C_2^{cc} where an enhancement factor of 14 is allowed by current experimental results. All the bounds were calculated at 90% C.L..

3.3 Operators $(\bar{d}b)(\bar{\tau}\tau)$

In the third part of our analysis we consider the effective operators $(\bar{d}b)(\bar{\tau}\tau)$, they are well suppressed within the standard model, however they are not quite constrained by the experimental data available nowadays; the approach followed in this section is analogous to the study performed for B_s mesons in [14]. Here we take into account the following effective Hamiltonian

$$\mathcal{H}_{eff}^{b \rightarrow d \tau^+ \tau^-} = -\frac{4G_F}{\sqrt{2}} \lambda_t^d \sum_{i,j} C_{i,j}(\mu) Q_{i,j} \quad (3.5)$$

and study the scalar, vector and tensor Dirac structures of $(\bar{d}b)(\bar{\tau}\tau)$

$$\begin{aligned}
Q_{S,AB} &= (\bar{d}P_A b) (\bar{\tau}P_B \tau), \\
Q_{V,AB} &= (\bar{d}\gamma^\mu P_A b) (\bar{\tau}\gamma_\mu P_B \tau), \\
Q_{T,A} &= (\bar{d}\sigma^{\mu\nu} P_A b) (\bar{\tau}\sigma_{\mu\nu} P_A \tau)
\end{aligned} \tag{3.6}$$

with Wilson coefficients $C_{S,AB}$, $C_{V,AB}$ and $C_{T,A}$ respectively. Following the notation of [14]: $A, B = R, L$ and $P_{R,L} = (1 \pm \gamma_5)/2$.

To get bounds on the Wilson Coefficients we use direct and indirect constraints. Direct bounds arise from particle transitions where the chain $b \rightarrow d\tau^+\tau^-$ appears at tree level; indirect estimations are derived from processes where the terms given in Eqns. (3.6) arise as a consequence of operator mixing, loop level corrections or both. The direct category includes the processes $B_d \rightarrow \tau^+\tau^-$, $B \rightarrow X_d\tau^+\tau^-$ and $B^+ \rightarrow \pi^+\tau^+\tau^-$. In the first case the following experimental bound is available $Br(B_d \rightarrow \tau^+\tau^-) < 4.1 \times 10^{-3}$ [15]. In the second and third cases currently there are not experimental measurements for the branching ratios. However we can estimate an upper limit for these observables by considering the space available for new B_d decays, i.e. those that have not been measured yet. To fulfill this task we compare the ratio $\left(\frac{\tau_{B_d}}{\tau_{B_d}} - 1\right)_{SM}$ against $\left(\frac{\tau_{B_d}}{\tau_{B_d}} - 1\right)_{exp}$ and ignore new physics effects in the B_s sector; our result is $Br(B_d \rightarrow X_{new}) \leq 1.5\%$. From $B_d \rightarrow \tau^+\tau^-$ we get chirality independent bounds for C_S and C_V , whereas from $B \rightarrow X_d\tau^+\tau^-$ and $B^+ \rightarrow \pi^+\tau^+\tau^-$ we get constraints for all the Dirac structures shown in Eqns. (3.6). Indirect bounds are calculated from the branching ratios of the processes $B_d \rightarrow X_d\gamma$ and $B^+ \rightarrow \pi^+\mu^+\mu^-$. In the case of $B_d \rightarrow X_d\gamma$ the tensor element in Eqns. (3.6) mixes with the operator mediating the transition $b \rightarrow d\gamma$. For the process $B^+ \rightarrow \pi^+\mu^+\mu^-$ there are contributions from mixing between the vector and tensor components of Eqns. (3.6) and the operators responsible for the chains $b \rightarrow d\gamma$ and $b \rightarrow dl^+l^-$.

To quantify the effects of our $(\bar{d}b)(\bar{\tau}\tau)$ operators over $\Delta\Gamma_d$ we first parametrize the new physics contributions in Γ_{12}^d through the factor $\tilde{\Delta}_d$

$$\Gamma_{12}^d = \Gamma_{12}^{d,SM} \tilde{\Delta}_d. \tag{3.7}$$

The relationship between $\tilde{\Delta}_d$ and the Wilson coefficients of the operators in Eqns. (3.6) is established by the following inequalities

$$\begin{aligned}
|\tilde{\Delta}_d|_{S,AB} &< 1 + (0.41_{-0.08}^{+0.13})|C_{S,AB}(m_b)|^2 \\
|\tilde{\Delta}_d|_{V,AB} &< 1 + (0.42_{-0.08}^{+0.13})|C_{V,AB}(m_b)|^2 \\
|\tilde{\Delta}_d|_{T,A} &< 1 + (0.42_{-0.08}^{+0.13})|C_{T,A}(m_b)|^2
\end{aligned} \tag{3.8}$$

here we are assuming single operator dominance; i.e. we are analyzing the effect of only one operator from Eqns. (3.6) at a time by switching on the corresponding Wilson coefficient and setting the others to zero. The subindex of $|\tilde{\Delta}_d|$ in Eqns. (3.8) indicates the operator under study.

We finally arrive to the following enhancement factors at 90% *C.L.*

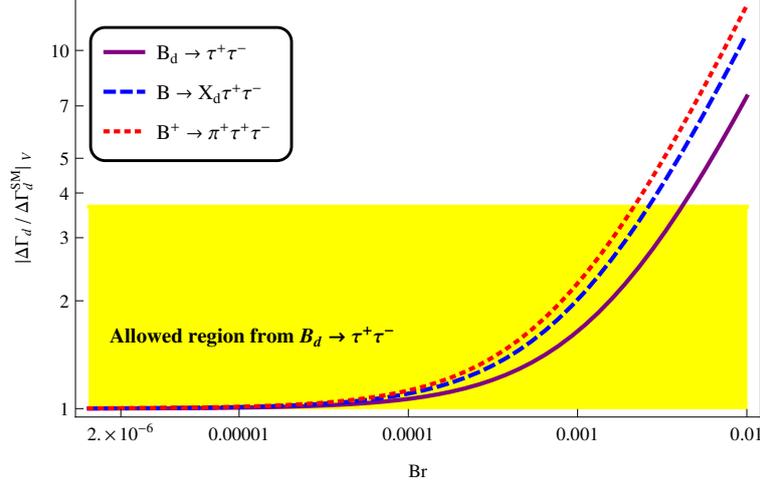


Figure 2: Bounds on the enhancement factor for $\Delta\Gamma_d$ as a function of the improvement on the experimental limits over the branching ratios for the processes $B_d \rightarrow \tau^+\tau^-$ (purple), $B_d \rightarrow X_d\tau^+\tau^-$ (blue) and $B_d \rightarrow \pi^+\tau^+\tau^-$ (red). Only the effect induced by the vectorial version of the $(\bar{d}b)(\bar{\tau}\tau)$ operators is shown at 90% C. L..

$$\begin{aligned}
 |\tilde{\Delta}_d|_{S,AB} &\leq 1.6 \\
 |\tilde{\Delta}_d|_{V,AB} &\leq 3.7 \\
 |\tilde{\Delta}_d|_{T,R} &\leq 1.2.
 \end{aligned}
 \tag{3.9}$$

Stronger bounds for $|\tilde{\Delta}_d|$ can be established if upper limits for the branching ratios of the processes $B_d \rightarrow \tau^+\tau^-$, $B \rightarrow X_d\tau^+\tau^-$ and $B^+ \rightarrow \pi^+\tau^+\tau^-$ are reduced experimentally; this effect is shown explicitly in Fig. (2) for the vector structure of the $(\bar{d}b)(\bar{\tau}\tau)$ operators.

4. Like sign dimuon asymmetry

Experimentally the D0 collaboration has measured the raw like sign dimuon charge asymmetry $A = A_{CP} + A_{bkg}$ [1]-[4], after removing the backgrounds A_{bkg} the remaining component A_{CP} is the result of CP violation arising from neutral B meson interactions. Before 2013 it was assumed that A_{CP} was caused only by CP violation in mixing between the B_d and \bar{B}_d states leading to

$$A_{CP} \propto A_{sl}^d = C_d a_{sl}^d + C_s a_{sl}^s. \tag{4.1}$$

The terms $a_{sl}^{d,s}$ are the semileptonic asymmetries and $C_{d,s}$ are proportionality constants depending on the production fractions, oscillation parameters and decay widths of $B_{d,s}$. Based on this interpretation D0 reported in 2011 a measurement for A_{sl}^d that was in disagreement with the standard model prediction by 3.9σ [3].

Recently the contribution of CP violation in interference between decays with and without mixing was included in the analysis of A_{CP} . According to [10] this implies the replacement of Eqn. (4.1) by

$$A_{CP} \propto A_{sl}^d + C_{\Gamma_d} \frac{\Delta\Gamma_d}{\Gamma_d} + C_{\Gamma_s} \frac{\Delta\Gamma_s}{\Gamma_s}, \quad (4.2)$$

here $\frac{\Delta\Gamma_s}{\Gamma_s}$ is highly suppressed by the constant C_{Γ_s} in comparison with the contribution due to $\frac{\Delta\Gamma_d}{\Gamma_d}$.

In principle Eqn. (4.2) may suggest that the tension between theory and experiment for A_{CP} could be eliminated if $\Delta\Gamma_d$ gets enhanced through non standard model physics. However a more detailed study reveals that Eqn. (4.2) is the first approximation towards the inclusion of CP violation in interference; instead of having a complete dependence on $\Delta\Gamma_d$ it is expected that the relevant contribution to the interference depends on the components Γ_{12}^{cc} and Γ_{12}^{uc} , see Eqn. (3.4), in a more convoluted way than the one given in $\Delta\Gamma_d$ [16]; this possibility is currently under further investigation [17].

5. Conclusions

We have explored the possibility of having new physics effects on $\Delta\Gamma_d$ within the Heavy Quark Expansion. Firstly we found that by breaking the unitarity of the CKM matrix by 10^{-2} we can have a deviation of 300% with respect to the standard model expectation on $\Delta\Gamma_d$. Our analysis of dimension six tree level standard model effective operators shows interesting deviations over $\Delta\Gamma_d^{SM}$, the most remarkable example is given by $(\bar{d}c)(\bar{c}b)$ where an enhancement factor of 14 is allowed by current experimental data. Finally in the case of the effective operators $(\bar{d}b)(\bar{c}\tau)$ we have found that $\Delta\Gamma_d$ can be nearly 4 times bigger than in the standard model. We mentioned that as a first approximation there is a relationship between $\Delta\Gamma_d$ and the dimuon asymmetry A_{CP} measured by D0, describing briefly possible corrections that could be useful in reducing the gap between theory and experiment for A_{CP} . Thus we strongly motivate some further experimental studies of $\Delta\Gamma_d$.

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