Rare charm decays

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Abstract. Rare charm decays offer possibility to search for signals beyond SMin the up-quark sector. CP conserving and CP violating contributions within the SMand beyond are reviewed for inclusive $c \to u\gamma$ and $c \to ul^+l^-$ and exclusive $D \to V\gamma$, $D \to P(V)l^+l^-$and $D \to l^+l^-$ decays.

1. Introduction

For many years flavor changing neutral current (FCNC) processes were considered as an important tool in searches of new physics. Many experimental results for K and B physics, as well as a number theoretical approaches, enable to study down-quark sector very precisely. Accordingly, new physics (NP) was expected to be observed first in the down-quark sector. The up-quark sector was not considered to be easily accessible for search of new physics, due to difficulties in the treatment of charm meson dynamics. In D decays long distance contributions dominate over short distance effects. The main task is how to separate information on short distance dynamics, within Standard Model (SM) or in its extensions. This is a longstanding problem in rare charm decays. In addition, in FCNC charm processes the GIM mechanism results in the interplay of CKM parameters and masses of down-like quarks leading to a strong amplitudes suppression. In the last few years additional motivation for charm physics appeared after LHCb collaboration found unexpectedly large CP violating asymmetry in charm decays [1, 2, 3].That triggered many studies and additional checks of the observed anomaly. Although discrepancy has decreased after new measurements [3, 4], new studies of rare charm decays appeared in the meantime questioning possibilities to search for CP violating signals in rare charm decays.

This review is organized as follows:In Sec. 2 SM contributions to $c \to u\gamma$ and $c \to ul^+l^-$ decay modes and exclusive decay channels are reviewed. In Sec. 3 NP contribution in inclusive and exclusive decay channels is discussed. Sec. 4 contains discussion on CP violation in rare charm decays. Last section contains a summary.

2. SM and contributions in rare charm inclusive and exclusive decay modes

The most common way to approach these processes is to use effective low-energy Lagrangian and the operator product expansion. Within SM short distance contributions in $c \to u\gamma$ and $c \to ul^+l^-$ transitions are described by:

$$\mathcal{L}_{eff}^{SD} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} C_i Q_i, \tag{1}$$

The operators are then:

$$
\begin{aligned}
Q_7 &= \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma_{\mu\nu} (1+\gamma_5) c, \\
Q_9 &= \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{l} \gamma^\mu l, \\
Q_{10} &= \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{l} \gamma^\mu \gamma_5 l. \qquad (2)
\end{aligned}
$$

In (1) C_i denote, as usual, effective Wilson coefficients (they are determined at the scale $\mu = m_c$), $F_{\mu\nu}$ is the electromagnetic field strenght and $q_L = \frac{1}{2}(1-\gamma_5)q$. In the case of $c \to u\gamma$ decay only C_7 contributes, while in the case of $c \to ul^+l^-$ all three Wilson coefficents are present. At the one-loop level contributions coming from penguin diagrams are strongly GIM suppressed giving a branching ratio $\sim 10^{-18}$ [5, 6, 7, 8, 9]. The QCD corrections enhance this rate to $BR(c \to u\gamma)_{SM} = 2.5 \times 10^{-8}$ [10, 11]. Within SM the short distance contribution coming from $Q_{7,9}$ leads to the branching ratio [8, 12, 13, 14]

$$BR(D \to X_u e^+ e^-)^{SD}_{SM} \simeq 3.7 \times 10^{-9}. \qquad (3)$$

However, this short distance contribution is overshadowed by long distance contributions, which are result of the nonleptonic D decays [8, 12]. The branching ratio for the inclusive decay is:

$$BR(D \to X_u e^+ e^-)^{LD}_{SM} \sim \mathcal{O}(10^{-6}). \qquad (4)$$

The amplitude for the $D \to V\gamma$ decay can be most generally written as:

$$
\begin{aligned}
\mathcal{A}[D(p) \to V(p'\epsilon'\gamma(q,\epsilon)] &= -iA_{CP} \epsilon_{\mu\nu\alpha\beta} q^\mu \epsilon^{*\nu} p^\alpha \epsilon^{*\prime,\beta} \\
&+ A_{PV}[(\epsilon^{*\prime,\beta} \cdot q)(\epsilon^{*\nu} \cdot q) - (p \cdot q)(\epsilon^{*\nu}\ \epsilon^{*\nu})]\,. \qquad (5)
\end{aligned}
$$

Authors of [15] have reinvestigated long distance dynamics. Using QCD sum rules result for the tensor form factors ($T^\rho \simeq T^\omega \simeq 0.7 \pm 0.2$) they found that parity conserving (violating)amplitudes are $(A^{\rho,\omega}_{PC,PV})^{SD} \simeq 0.6(2) \times 10^{-9}/m_D |C_7(m_c)/0.4 \cdot 10^{-2}|$ where superscripts ρ, ω denote appropriate vector meson state V. For the determination of short distance contribution one has to know matrix element of the Q_7 operator. In the calculations of it the tensor form-factors are present [15]. The long distance contribution was estimated by knowing that the relation $BR(D^0 \to K^{*0}\gamma)/BR(D^0 \to K^{*0}\rho^0) = BR(D^0 \to \phi\gamma)/BR(D^0 \to \phi\rho^0)$ is a consequence of vector meson dominance [15] $|(A^V_{PC,PV})^{LD}| = [32\pi/2m_D^3(1-\frac{m_V^2}{m_D^2})^{-3}\Gamma(D \to V\gamma)]^{1/2}$, what gives, for $V = \phi$, $|(A^\phi_{PC,PV})^{LD}| = 5.9(4) \times 10^{-8}/m_D$. These estimations are close to the previously determined ones in [5, 6].

The SM short distance contributions to $D^0 \to \gamma\gamma$ and $D^0 \to \mu^+\mu^-$ can be determined using effective Lagrangian (1), while in both decay modes the dominant contribution comes from long distance effects [12, 9]. Recently $D^0 \to \gamma\gamma$ and $D^0 \to l^+l^-$ were reconsidered in [13]. The branching ratio coming from long and short distance contributions are $BR^{SM}_{LD}(D^0 \to \gamma\gamma) \simeq (1-3) \times 10^{-8}$, $BR^{2-loops}_{SD}(D^0 \to \gamma\gamma) \simeq (3.6-8.1) \times 10^{-12}$. In $D^0 \to l^+l^-$ decay also SM long distance contribution dominates over short distance on. Authors of [13] considered contributions coming from $\gamma\gamma$ intermediate states due to long distance dynamics in $D^0 \to \gamma\gamma$ arriving at the value $BR(D^0 \to \mu^+\mu^-) \sim (2.7-8.0) \times 10^{-13}$. Recently LHCb improved bound on the branching ratio $BR(D^0 \to \mu^+\mu^-) \leq 6.2 \times 10^{-9}$ [17].

Among all exclusive decay modes containing lepton pair in the final state, the simplest one for experimental searches are $D^+ \to \pi^+\ell^+\ell^-$ and $D_s^+ \to K^+\ell^+\ell^-$. Close to the ϕ resonant peak

Decay mode	Branching ratio	Reference
$D \to \rho(\omega)\gamma$	0.6×10^{-5}	Isidori & Kamenik 2012
$D \to K^+K^-\gamma$	$1.35 \times 10^{-5}\ (\phi)$	Isidori & Kamenik 2012
$D \to X_u l^+ l^-$	$\mathcal{O}(10^{-6})$	Paul et al, 2011
$D^+ \to \pi^+ l^+ l^-$	2×10^{-6}	Fajfer et al, 2007
$D_s^+ \to K^+ l^+ l^-$	6×10^{-6}	Fajfer et al, 2007
$D \to \pi^+ K^- l^+ l^-$	$\mathcal{O}(10^{-5})$	Cappiello et al, 2013
$D \to \pi^+ \pi^- l^+ l^-$	$\mathcal{O}(10^{-6})$	Cappiello et al, 2013
$D \to K^+ K^- l^+ l^-$	$\mathcal{O}(10^{-7})$	Cappiello et al, 2013
$D \to \pi^- K^+ l^+ l^-$	$\mathcal{O}(10^{-8})$	Cappiello et al, 2013
$D \to \gamma\gamma$	$(1-3) \times 10^{-8}$	Paul et al, 2010
$D \to \mu^+\mu^-$	$(7-8) \times 10^{-13}$	Paul et al, 2010

Table 1. Branching ratios for charm meson decays. The second column contains the SM theoretical predictions in which long- distance contribution is dominant. The last column contains the most recent references.

the long distance amplitude for $D^+ \to \pi^+\mu^+\mu^-$ decay is, to a good approximation, determined by non-factorizable contributions of four-quark operators in $\mathcal{H}^s$. The width of ϕ resonance is very narrow ($\Gamma_\phi/m_\phi \approx 4 \times 10^{-3}$) and well separated from other vector resonances in the $\bar{q}q$ spectrum of $D \to P\ell^+\ell^-$. Relying on vector meson dominance hypothesis the q^2-dependence of the decay spectrum close to the resonant peak follows the Breit-Wigner shape [12, 22, 21]

$$\mathcal{A}^{\phi}_{\rm LD}\left[D \to \pi\phi \to \pi\ell^-\ell^+\right] = \frac{iG_F}{\sqrt{2}}\lambda_s \frac{8\pi\alpha}{3}\, a_\phi e^{i\delta_\phi}\, \frac{m_\phi \Gamma_\phi}{q^2 - m_\phi^2 + i m_\phi \Gamma_\phi}\, \bar{u}(k_-)\,\gamma_\mu p^\mu\, v(k_+)\,. \qquad (6)$$

The result for branching ratios for $D \to \pi\ell^-\ell^+$ are given in Table 1. A very nice study of LHCb [18] gave for the first time non-resonant branching fractions $BR(D^+ \to \pi^+\mu^+\mu^-) \leq 7.3(8.3) \times 10^{-8}$.

The detailed analysis of the semileptonic four body $D \to h\,hl^+l^-$ decays was done in the work of Ref. [23]. The dominant long-distance contributions (bremsstrahlung and hadronic effects) are calculated and total branching ratios and the (m_{ll}^2, m_{hh}^2) Dalitz plots are presented. Branching ratios for these decay modes are also presented in Table 1.

3. New physics searches in rare charm decays

The long distance contribution dominates for two or three order of magnitude over the short distance contribution in the above discussed decays. In inclusive $D \to X_u\gamma$ or exclusive $D \to V\gamma$ decays only huge increase of C_7^{eff} Wilson coefficient would lead to observable effects in the branching ratio. However, such contributions within particular model of new physics are strongly constrained by other low-energy phenomenological constraints. One of the most popular extension of the SM is MSSM. Following discussion in [21] the model with non-universal soft-breaking terms, knowing that gluino (according to LHC bounds) cannot be lighter than 1.3 TeV, would give $Br(c \to u\gamma)_{gluino} \sim 5 \times 10^{-8}$. Rather high mass of gluino would also give rise to SM $BR(c \to ul^+l^-)$ by about factor 2. As noticed in [14, 21, 22] other SM extensions might give larger increase of both inclusive branching ratios. However, even if the short distance contribution is enlarged by NP, long distance effects screen it in the branching ratios for all exclusive rare charm decays.

The authors of [19] have analyzed warped extra dimensional models contributions to chromomagnetic dipole operator. They explained why the calculation of the coefficient of the lowest

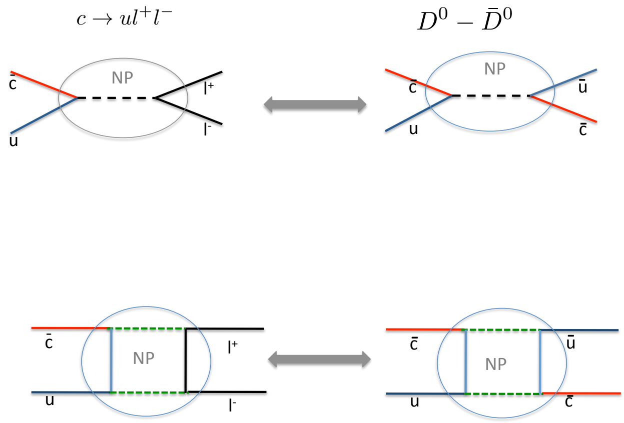

Figure 1. NP contributions to $c \to ul^+l^-$ and $D^0 - \bar{D}^0$ at tree and loop level.

dimension (5D) operator has to be finite. They found that branching ratio for the inclusive decay is $BR(D^0 \to X_u\gamma) \simeq 1 \times 10^{-8}$.

If one considers contributions of a new scalar or pseudoscalar particle mediating decay $c \to u\ell^+\ell^-$, then the same particle would contribute to $D^0 - \bar{D}^0$ oscillations and the physical observable from this process immediatelly strongly constrain couplings of this operator. The same holds for the flavor changing Z or new Z' boson. If new physics is generated at the loop level in $c \to u\ell^+\ell^-$ then it contributes to $D^0 - \bar{D}^0$ at the loop level too, as presented in Fig. 1. A number of NP models have been explored in literature [14, 22, 21, 26]. Even in the cases when relatively large couplings are allowed in the certain model, the effects are screened by long distance dynamics. The branching ratios for the inclusive $D \to X_u l^+l^-$ and $D \to P/Vl^+l^-$ decays, when calculated within existing theoretical approaches cannot receive any measurable impact of NP. The only relevant question is, can we find such observables that the short distance dynamics is uncovered. The differential branching ratio might get rather small enhancement at high lepton invariant mass [21, 26]. The new physics detection in these decay modes was also discussed. It was found that two angular asymmetries, namely the T-odd di-plane asymmetry and the forward-backward di-lepton asymmetry offer direct tests of new physics due to tiny SM backgrounds [14].

The effects of the extra heavy up vector-like quark on the decay spectrum of $D^+ \to \pi^+l^+l^-$ and $D_s^+ \to K^+l^+l^-$ decays were also considered in Ref. [22, 21]. It was found that there is a tiny increase of the differential decay rate in the region of large di-lepton mass. The R-parity violating supersymmetric model can also modify short distance dynamics in $c \to ul^+l^-$decays. The relevant parameters were constrained using current upper bound on the $D^+ \to \pi^+l^+l^-$ decay rate. Present bounds still allow small modification of the SM differential decay rate distribution [21].

The authors of [20] analyzed effects of models with a warped extra dimension on rare charm decays. New degrees of freedom in these models are bounded above a few TeV. In rare charm decays they can leave an order of magnitude signatures larger than what the SM can generate, due to contributions to C_9 and C_{10} Wilson coefficients. These kind of flavor structure can have large effects in rare charm decays, sometimes orders of magnitude larger than what the SM can generate. It is interesting that these models do not give any significant effects in beauty and strange hadron processes. This can be achieved even without giving the up-quark sector a special dynamical advantage. The effects are on tree level effects and can be larger than the loop-level enhancement found in the Little Higgs models [14].

4. Rare D decays and direct CP violation

Since the end of 2011 the direct CP violating asymmetry in charm decays has been subject of many studies. The experimental results of LHC-b [1, 2, 3, 4] indicated unexpected large CP violatin in the difference of CP violating asymmetries for $D \to \pi^+\pi^-(K^+K^-)$. In 2014 an update of LHCb collaboration result HFAG [3] produced the world average CP asymmetry, $\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-) = (-0.253 \pm 0.104)\%$. Still the size of CP violating asymmetry in $D \to \pi^+\pi^-(K^+K^-)$ is still being questioned. However, all these measurement and studies stimulated a number of new analyses of possible CP violating effects in rare charm decays. The CP violating symmetry is introduced as:

$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}. \tag{7}$$

The authors [15] investigated CP violating observables in $D \to V\gamma \to \; P^+P^-\gamma$ decays. If CP violation is due to NP effects [15, 16], then it is most likely a result of the chromomagnetic operator Q_8 contribution [19]. In the case of rare D decays CP violation results from mixing of Q_8 into Q_7 under QCD renormalization.

$$\mathrm{Im}[C_7^{NP}(m_c)]| \simeq \mathrm{Im}[C_8^{NP}(m_c)]| \simeq 0.02 \times 10^{-2}. \tag{8}$$

The imaginary part of C_7^{SM} is two orders of magnitude smaller. The NP contribution is comparable in size with the real part of SM $|C_7^{SM-eff}(m_c)| = (0.5 \pm 0.1) \times 10^{-2}$. This means that if the phase of long distance contribution can be neglected and relative strong phase is maximal, the CP asymmetry can reach $\mathcal{O}(1\%)$ level. The current world average of CP violating asymmetry in ΔA_{CP}, following work of [15] leads to CP asymmetry in $D \to K^+K^-\gamma$ of the order 1%.

In rare decays $D \to P\ell^+\ell^-$ the CP violating effects might arise due to the interference of resonant part of the long distance contribution and the new physics affected short distance contribution. The appropriate observables, the differential direct CP asymmetry and partial decay width CP asymmetry are introduced in a model independent way [25]. If supersymmetric and Z'-enhanced scenarios are assumed and if the size of Wilson coefficients C_9 and C_{10} is compatible with the observed CP asymmetry in nonleptonic charm decays and flavor constraints, it was found in [23] that new physics effects in $D^0 \to h_1h_2l^+l^-$ might reach the $\sim 1\%$ level. In Table 2 predictions for size of CP violating asymmetries in rare charm decays are presented.

It is interesting that the direct CP-violating asymmetry in neutral D-meson decays leads to stronger model parameter constraints than the current experimental bound on the neutron electric dipole moment for certain class of NP models, as noticed in [28].

5. Summary

The SM contribution to rare charm decays are rather well known. For all decay modes amplitudes are fully dominated by long distance dynamics. Branching ratios itself cannot reveal information on the size of short distance contribution. One has to construct and measure additional observables, as differential rate, forward-backward asymmetries, T-odd asymmetries. New physics might be hidden only in short distance contribution and therefore measurement

Decay mode	size	Reference
$D \to \rho(\omega)\gamma$	$\leq 3\%$	Zwicky et al, 2012
$D \to K^+K^-\gamma$	$\leq 0.7\%$	Isidori & Kamenik 2012
$D \to X_u l^+ l^-$	$\leq 3\%$	Paul et al, 2012
$D^+ \to \pi^+\mu^+\mu^-$	$\leq 1\%$	Fajfer & Košnik, 2013
$D^+ \to hh\mu^+\mu^-$	$\leq 1\%$	Cappiello et al, 2013

Table 2. CP violating asymmetries for charm rare decays, size and the original reference.The four last decay modes have the CP asymmetry in the vicinity ϕ resonance.

of these new observables might help in distinguishing new physics contributions from Standard Model ones. Interesting signals of NP might arise in $D \to \rho(\omega)\gamma$ and $D \to K^+K^-\gamma$, as well as in decays with the leptonic pair in the final state $D \to X_u l^+ l^-$, $D^+ \to \pi^+\mu^+\mu^-$, $D^+ \to hh\mu^+\mu^-$. Search for CP violating signals in rare charm decays became important with the experimental hint for a presence of new CP violating source in nonleptonic charm decays. The study of rare charm decays were revived and number of studies of CP violation in rare charm decays were done. If the CP violation in D nonleptonic decay will remain on the present level, then one expects that in all rare charm decays that CP violating asymmetries might be of of the order 1%.

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