

New Physics from rare decays of charm

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Abundance of charm data in the current and future low energy flavor experiments makes it possible to study rare decays of D -mesons with ever increased precision. I discuss theoretical implications of derived constraints on New Physics models from these transitions. I argue that those constraints could be competitive with results of direct searches for New Physics particles (including Dark Matter) at the Large Hadron Collider.

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1. Introduction

Large quantities of charmed mesons and baryons produced in high energy physics experiments make studies of New Physics (NP) in charm transitions a natural and vibrant avenue for research. Similarly to searches for NP in beauty decays [1], strategies for exposition of traces of possible New Physics particles in charm transitions involve three main directions: (1) studies of processes that are not allowed in the Standard Model (SM), (2) studies of processes that are not allowed in the Standard Model at tree level, and (3) studies of the processes that are allowed in the Standard Model [2]. In this talk I will concentrate on the second option.

Flavor-changing neutral currents (FCNC) have been a prime vehicle of low energy NP studies in quark and lepton transitions for a long time. This is so primarily due to the fact that elementary currents of that type are not allowed in the Standard Model. It is however possible to generate such currents by quantum fluctuations, i.e. by considering electroweak interactions at one loop level. Due to the left-handed nature of charged weak interactions in the SM, such currents would be induced with the coefficients that are proportional to the masses (squared) of quarks running in those loops. It is this fact that makes studies of NP in charm and beauty transitions very different: in B -physics, a huge mass of the intermediate top quark assures that experimentally well-studied $\Delta b = 1$ and $\Delta b = 2$ transitions are saturated by the SM contributions. Further, the induced SM effective operators are local, which enormously simplifies theoretical calculations of rare and $B^0 - \bar{B}^0$ mixing transitions – and therefore a proper interpretation of experimental data.

On the contrary, in charm, it is both relatively small mass of the intermediate bottom quark and tiny values of corresponding Cabibbo-Kobayashi-Maskawa (CKM) matrix elements make the short-distance SM amplitudes very small. This also assures that long-distance QCD effects dominate the SM predictions of most FCNC $\Delta c = 1$ and $\Delta c = 2$ transitions. What makes charm transitions interesting is the fact that while $D^0 - \bar{D}^0$ mixing parameters have been constrained [3, 4], rare decays of the $D^0 \rightarrow \ell^+ \ell^-$ type have never been observed. This fact makes them a prime target for New Physics searches in low energy experiments.

It is important to point out that decays of charmed states can probe a variety of beyond the Standard Model scenarios, with both heavy ($m_{NP} \gg m_D$) and light ($m_{NP} \ll m_D$) New Physics particles.

2. Heavy New Physics: mixing and rare decays

In general, rare decays of D mesons are mediated by quark-level FCNC transitions $c \rightarrow u \ell \ell$ and $c \rightarrow u \gamma^*$ (followed by $\gamma^* \rightarrow \ell \ell$). Both these decays and $D^0 - \bar{D}^0$ mixing only proceed at one loop in the SM, and, due to the structure of the CKM matrix, in both of these transitions Glashow-Iliopoulos-Maiani (GIM) mechanism is very effective.

In this talk I will concentrate on the simplest of rare leptonic decays, $D^0 \rightarrow \ell^+ \ell^-$. This transition has a very small SM contribution, so it could serve as a very clean probe of amplitudes induced by NP particles. Other rare decays (such as $D \rightarrow \rho \gamma$, etc.) could receive rather significant SM contributions, which are rather difficult to compute. For more information on those decays please see [5, 6, 7, 8]. There exist several experimental constraints on $D^0 \rightarrow \ell_1^+ \ell_2^-$ transitions,

resulting in the upper limits on flavor-diagonal and off-diagonal branching fractions [3, 9, 10, 11],

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) &< 7.6 \times 10^{-9}, \quad \mathcal{B}(D^0 \rightarrow e^+ e^-) < 7.9 \times 10^{-8}, \quad \text{and} \\ \mathcal{B}(D^0 \rightarrow \mu^\pm e^\mp) &< 1.3 \times 10^{-8}. \end{aligned} \quad (2.1)$$

Theoretically, both in case of $D^0 - \bar{D}^0$ mixing and $c \rightarrow u \ell^+ \ell^-$ transitions, all possible NP contributions can be summarized in terms of effective Hamiltonians. For the rare decays

$$\mathcal{H}_{NP}^{\text{rare}} = \sum_{i=1}^{10} \frac{\tilde{C}_i(\mu)}{\Lambda^2} \tilde{Q}_i, \quad (2.2)$$

where \tilde{C}_i are the Wilson coefficients, and the \tilde{Q}_i are the effective operators. Here Λ represents a scale of possible New Physics interactions that generate \tilde{Q}_i 's. There are only ten of those operators with canonical dimension six,

$$\begin{aligned} \tilde{Q}_1 &= (\bar{\ell}_L \gamma_\mu \ell_L) (\bar{u}_L \gamma^\mu c_L), & \tilde{Q}_4 &= (\bar{\ell}_R \ell_L) (\bar{u}_R c_L), \\ \tilde{Q}_2 &= (\bar{\ell}_L \gamma_\mu \ell_L) (\bar{u}_R \gamma^\mu c_R), & \tilde{Q}_5 &= (\bar{\ell}_R \sigma_{\mu\nu} \ell_L) (\bar{u}_R \sigma^{\mu\nu} c_L), \\ \tilde{Q}_3 &= (\bar{\ell}_L \ell_R) (\bar{u}_R c_L), \end{aligned} \quad (2.3)$$

with five additional operators $\tilde{Q}_6, \dots, \tilde{Q}_{10}$ that can be obtained from operators in Eq. (2.3) by interchanging $L \leftrightarrow R$, e.g. $\tilde{Q}_6 = (\bar{\ell}_R \gamma_\mu \ell_R) (\bar{u}_R \gamma^\mu c_R)$, $\tilde{Q}_7 = (\alpha/4) (\bar{\ell}_R \gamma_\mu \ell_R) (\bar{u}_L \gamma^\mu c_L)$, etc.

The Hamiltonian of Eq. (2.2) is quite generic, so it also contains the SM contribution usually denoted by the operators $Q_9 = (\alpha/4) (\tilde{Q}_1 + \tilde{Q}_7)$ and $Q_{10} = (\alpha/4) (\tilde{Q}_7 - \tilde{Q}_1)$ (together with a substitution $\Lambda \rightarrow \sqrt{G_F^{-1}}$). It is worth noting that matrix elements of several operators or their linear combinations vanish in the calculation of $\mathcal{B}(D^0 \rightarrow \ell^+ \ell^-)$: $\langle \ell^+ \ell^- | \tilde{Q}_5 | D^0 \rangle = \langle \ell^+ \ell^- | \tilde{Q}_{10} | D^0 \rangle = 0$ (identically), $\langle \ell^+ \ell^- | Q_9 | D^0 \rangle \equiv (\alpha/4) \langle \ell^+ \ell^- | (\tilde{Q}_1 + \tilde{Q}_7) | D^0 \rangle = 0$ (vector current conservation), etc. The most general $D^0 \rightarrow \ell^+ \ell^-$ decay amplitude can be written as

$$\mathcal{M}(D^0 \rightarrow \ell^+ \ell^-) = \bar{u}(p_-, s_-) [A + \gamma_5 B] v(p_+, s_+), \quad (2.4)$$

Any NP contribution described by the operators of Eq. (2.3) gives for the amplitudes A and B ,

$$\begin{aligned} |A| &= \frac{f_D M_D^2}{4\Lambda^2 m_c} [\tilde{C}_{3-8} + \tilde{C}_{4-9}], \\ |B| &= \frac{f_D}{4\Lambda^2} \left[2m_\ell (\tilde{C}_{1-2} + \tilde{C}_{6-7}) + \frac{M_D^2}{m_c} (\tilde{C}_{4-3} + \tilde{C}_{9-8}) \right], \end{aligned} \quad (2.5)$$

with $\tilde{C}_{i-k} \equiv \tilde{C}_i - \tilde{C}_k$. The amplitude of Eq. (2.4) results in the branching fractions for the lepton flavor-diagonal and off-diagonal decays,

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow \ell^+ \ell^-) &= \frac{M_D}{8\pi\Gamma_D} \sqrt{1 - \frac{4m_\ell^2}{M_D^2}} \left[\left(1 - \frac{4m_\ell^2}{M_D^2}\right) |A|^2 + |B|^2 \right], \\ \mathcal{B}(D^0 \rightarrow \mu^+ e^-) &= \frac{M_D}{8\pi\Gamma_D} \left(1 - \frac{m_\mu^2}{M_D^2}\right)^2 [|A|^2 + |B|^2]. \end{aligned} \quad (2.6)$$

I neglected the electron mass in the latter expression. Note that constraints on lepton flavor violating interactions, similar to the ones obtained from $\mathcal{B}(D^0 \rightarrow \mu^+ e^-)$ in Eq. (2.6), can also be obtained from two-body charmed quarkonium decays [12].

According to Eq. (2.5), the Standard Model contribution that appears due to Q_9 , vanishes in the $m_\ell \rightarrow 0$ limit. Any NP model that contribute to $D^0 \rightarrow \ell^+ \ell^-$ can be constrained from the bounds on the Wilson coefficients in Eq. (2.5). It is important to point out that because of this helicity suppression, studies of $D^0 \rightarrow e^+ e^-$ (and therefore analyses of lepton universality in those decays) are very complicated experimentally.

Model	$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-)$
Standard Model (LD)	$\sim \text{several} \times 10^{-13}$
$Q = +2/3$ Vectorlike Singlet	4.3×10^{-11}
$Q = -1/3$ Vectorlike Singlet	$1 \times 10^{-11} (m_S/500 \text{ GeV})^2$
$Q = -1/3$ Fourth Family	$1 \times 10^{-11} (m_S/500 \text{ GeV})^2$
Z' Standard Model (LD)	$2.4 \times 10^{-12} / (M_{Z'}(\text{TeV}))^2$
Family Symmetry	0.7×10^{-18} (Case A)
RPV-SUSY	$4.8 \times 10^{-9} (300 \text{ GeV}/m_{\tilde{d}_k})^2$
Experiment	$\leq 7.6 \times 10^{-9}$

Table 1: Predictions for $D^0 \rightarrow \mu^+ \mu^-$ branching fraction from correlations of rare decays and $D^0 - \bar{D}^0$ mixing for $x_D \sim 1\%$ (from [13]). Notice that experimental constraints are beginning to probe charm sector of R-parity violating SUSY models.

In studying NP contributions to rare decays in charm, it might be advantageous to study *correlations* of various processes, for instance $D^0 - \bar{D}^0$ mixing and rare decays [13]. In general, one cannot predict the rare decay rate by knowing just the mixing rate, even if both x_D and $\mathcal{B}(D^0 \rightarrow \ell^+ \ell^-)$ are dominated by a single operator contribution. It is, however, possible to do so for a restricted subset of NP models [13]. The results are presented in Table 1.

3. Light New Physics: rare charm decays into final states with missing energy

The high-intensity $e^+ e^-$ flavor factories could provide a perfect opportunity to search for rare processes that require high purity of the final states. In particular, searches for D -decays to the final states that contain neutrinos, such as $D \rightarrow \pi(\rho) \nu \bar{\nu}$, are possible at those machines due to the fact that pairs of D -mesons are produced in a charge-correlated state. Thus, there is an opportunity to tag the decaying heavy meson “on the other side,” which provides the charge or CP-identification [14] of the decaying “signal” D meson. This way, a variety of processes that are experimentally seen as transitions with “missing energy” are possible.

Standard Model predicts extremely small branching ratios for D -decay processes with neutrinos in the final state, i.e. $\mathcal{B}(D^0 \rightarrow \nu \bar{\nu}) \simeq 1 \times 10^{-30}$, and $\mathcal{B}(D^0 \rightarrow \nu \bar{\nu} \gamma) \simeq 3 \times 10^{-14}$ [15]. Thus, any detection of decays of D states into channels with missing energy in the current round of experiments indicate presence of new physics. It is important to note that these NP models could

be substantially different from the models described in previous sections: experimentally, it is impossible to say if the missing energy \cancel{E} signature was generated by a neutrino or by some other extremely weakly-interacting particle.

Recently, a variety of models with light, $\sim \mathcal{O}(MeV)$ dark matter (DM) particles have been proposed to explain the null results of experiments designed for indirect searches for dark matter (see, e.g. [16, 17]). Such models predict couplings between quarks and DM particles that can be described using effective field theory (EFT) methods [18]. These models can be tested at e^+e^- flavor factories by studying D (or B) mesons decaying into a pair of light dark matter particles or a pair of DM particles and a photon. The latter process might become important for models with fermion dark matter states as it eliminates helicity suppression of the final state [15]. It is conceivable that searches for light DM in heavy meson decays could even be more sensitive than direct detection and other experiments, as DM couplings to heavy quarks could be enhanced, as happens in some models of DM, such as Higgs portal [16].

Branching ratios for the heavy meson states decaying into $\chi_s\bar{\chi}_s$ and $\chi_s\bar{\chi}_s\gamma$, where χ_s is a DM particle of spin s can be computed in EFT framework. Since it is production of a scalar χ_0 state states that is not helicity-suppressed, I only present the constraints on the models with scalar DM particles here. Discussion of other cases of $s = 1/2$ and $s = 1$ can be found in [15]. A generic effective Hamiltonian for scalar DM interactions has a simple form,

$$\mathcal{H}_{eff} = 2 \sum_i \frac{C_i}{\Lambda^2} O_i, \quad (3.1)$$

where Λ is the scale associated with the particle(s) mediating interactions between the SM and DM fields, and C_i are the Wilson coefficients. The effective operators O_i are

$$\begin{aligned} O_1 &= m_c(\bar{u}_R c_L)(\chi_0^* \chi_0), & O_3 &= (\bar{u}_L \gamma^\mu c_L)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0), \\ O_2 &= m_c(\bar{u}_L c_R)(\chi_0^* \chi_0), & O_4 &= (\bar{u}_R \gamma^\mu c_R)(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0), \end{aligned} \quad (3.2)$$

where $\overleftrightarrow{\partial} = (\vec{\partial} - \overleftarrow{\partial})/2$ and the DM *anti-particle* $\bar{\chi}_0$ may or may not coincide with χ_0 . The decay branching ratio for the two-body decay $D^0 \rightarrow \chi_0\chi_0$ is

$$\mathcal{B}(D^0 \rightarrow \chi_0\chi_0) = \frac{(C_1 - C_2)^2}{4\pi M_D \Gamma_{D^0}} \left[\frac{f_D M_D^2 m_c}{\Lambda^2 (m_c + m_q)} \right]^2 \sqrt{1 - 4x_\chi^2} \quad (3.3)$$

where $x_\chi = m_\chi/M_{D^0}$ is a rescaled DM mass. Clearly, this rate is not helicity-suppressed, so it could be quite a sensitive tool to determine DM properties at e^+e^- flavor factories.

Applying the formalism described above, distribution of the photon energy and decay width of the radiative transition $D^0 \rightarrow \chi_0\chi_0\gamma$ can be computed,

$$\frac{d\Gamma}{dE_\gamma}(D^0 \rightarrow \chi_0\chi_0\gamma) = \frac{f_D^2 \alpha C_3 C_4}{3\Lambda^4} \left(\frac{F_D}{4\pi} \right)^2 \frac{2M_D^2 E_\gamma (M_D(1 - 4x_\chi^2) - 2E_\gamma)^{3/2}}{\sqrt{M_D - 2E_\gamma}} \quad (3.4)$$

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow \chi_0\chi_0\gamma) &= \frac{f_D^2 \alpha C_3 C_4 M_D^5}{6\Lambda^4 \Gamma_{D^0}} \left(\frac{F_D}{4\pi} \right)^2 \\ &\times \left(\frac{1}{6} \sqrt{1 - 4x_\chi^2} (1 - 16x_\chi^2 - 12x_\chi^4) - 12x_\chi^4 \log \frac{2x_\chi}{1 + \sqrt{1 - 4x_\chi^2}} \right), \end{aligned} \quad (3.5)$$

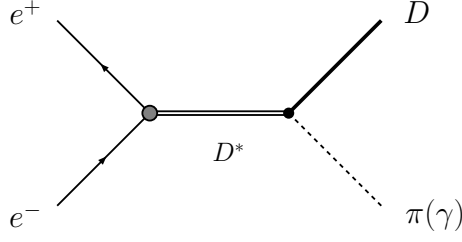


Figure 1: Probing the $c\bar{u} \rightarrow e^+e^-$ vertex with the $D^*(2007)^0$ resonance production in e^+e^- collisions.

We observe that Eqs. (3.4) and (3.5) do not depend on $C_{1,2}$. This can be most easily seen from the fact that $D \rightarrow \gamma$ form factors of scalar and pseudoscalar currents are zero. This implies that studies of both $D^0 \rightarrow \mathcal{E}$ and $D^0 \rightarrow \gamma \mathcal{E}$ processes probe complementary operators in the effective Hamiltonian of Eq. (3.1). Similar conclusions follow for the decays of beauty-flavored mesons into the final states with missing energy, where energy scales (DM heavy mediator masses) of order 10 TeV are probed by currently available data [15].

4. Probing rare charm transitions in production experiments

As was mentioned in Section 3, studies of lepton universality in $D^0 \rightarrow \ell^+\ell^-$ decays could be complicated due to helicity suppression of this decay, which makes the branching ratio of $D^0 \rightarrow e^+e^-$ tiny. This feature persists in many models of NP. An interesting alternative to $D^0 \rightarrow e^+e^-$ process that is *not* helicity-suppressed is a related decay $D^*(2007)^0 \rightarrow e^+e^-$. While also probing the FCNC $c\bar{u} \rightarrow \ell^+\ell^-$ transition, this decay is sensitive to the contributions of operators that $D^0 \rightarrow \ell^+\ell^-$ cannot be sensitive to. Unfortunately, a direct study of the $D^* \rightarrow e^+e^-$ decay is practically impossible, since the D^* decays strongly or electromagnetically.

Nevertheless, it might be possible to probe the $D^* \rightarrow e^+e^-$ transition experimentally [19]. Assuming time-reversal invariance, it would be equivalent to measure the corresponding *production* process $e^+e^- \rightarrow D^*$, as shown in Fig. 1. In order to do so, a run of an e^+e^- collider, such as BEPCII or VEPP-2000, at the center-of-mass energy corresponding to the mass of the D^* meson, $\sqrt{s} \approx 2007$ MeV, should be performed. If produced, the D^{*0} resonance will decay via strong ($D^{*0} \rightarrow D^0\pi^0$) or electromagnetic ($D^{*0} \rightarrow D^0\gamma$) interactions with branching fractions of $(61.9 \pm 2.9)\%$ and $(38.1 \pm 2.9)\%$ respectively.¹ A single charmed particle in the final state at this \sqrt{s} could serve as an excellent tag for such process, with other sources of production of a single D meson being negligibly small [19]. A thorough study of both short-distance and long-distance contributions to $e^+e^- \rightarrow D^*$ in the Standard Model and in NP models has been performed. This process, albeit very rare, has clear advantages with respect to the $D \rightarrow e^+e^-$ decay: the helicity suppression is absent, and a richer set of effective operators can be probed. Employing the most recent values of the Wilson coefficients for $c \rightarrow u$ transition [20], it was shown that, contrary to other rare decays of charmed mesons, long-distance SM contributions are under theoretical control and contribute at the same order of magnitude as the short-distance ones. Similar opportunities exist for B -decays as well [19, 21].

¹Note that the charged mode $D^{*0} \rightarrow D^+\pi^-$ is forbidden by the lack of the available phase space.

5. Conclusions and outlook

The absence of any hints of new particles from direct searches at the LHC experiments makes careful studies of their possible quantum effects an important tool in our arsenal of methods for probing physics beyond the Standard Model. Abundance of charm data in the current and future low energy flavor experiments makes it possible to study New Physics in rare decays of D -mesons with ever increased precision. The obtained constraints from a variety of methods described in this talk could be competitive with results of continuing direct searches for New Physics particles at the Large Hadron Collider.

References

- [1] Y. Nir, CERN-2015-001, pp.123-156 [arXiv:1605.00433 [hep-ph]].
- [2] S. Fajfer, arXiv:1509.01997 [hep-ph]; A. A. Petrov, PoS BEAUTY **2009**, 024 (2009), M. Artuso, B. Meadows and A. A. Petrov, Ann. Rev. Nucl. Part. Sci. **58**, 249 (2008)
- [3] Y. Amhis *et al.* [Heavy Flavor Averaging Group (HFAG) Collaboration], arXiv:1412.7515 [hep-ex].
- [4] A. F. Falk, Y. Grossman, Z. Ligeti and A. A. Petrov, Phys. Rev. D **65**, 054034 (2002); A. F. Falk, *et al* Phys. Rev. D **69**, 114021 (2004); I. I. Y. Bigi and N. G. Uraltsev, Nucl. Phys. B **592**, 92 (2001)
- [5] S. de Boer and G. Hiller, Phys. Rev. D **93**, no. 7, 074001 (2016)
- [6] S. Fajfer, N. Kosnik and S. Prelovsek, Phys. Rev. D **76**, 074010 (2007)
- [7] S. Fajfer and N. Kosnik, Eur. Phys. J. C **75**, no. 12, 567 (2015)
- [8] A. Paul, I. I. Bigi and S. Recksiegel, Phys. Rev. D **83**, 114006 (2011)
- [9] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. B **725**, 15 (2013)
- [10] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. B **754**, 167 (2016)
- [11] M. Petric *et al.* [Belle Collaboration], Phys. Rev. D **81**, 091102 (2010)
- [12] D. E. Hazard and A. A. Petrov, arXiv:1607.00815 [hep-ph].
- [13] E. Golowich, J. Hewett, S. Pakvasa and A. A. Petrov, Phys. Rev. D **79**, 114030 (2009); E. Golowich, J. Hewett, S. Pakvasa and A. A. Petrov, Phys. Rev. D **76**, 095009 (2007)
- [14] D. Atwood and A. A. Petrov, Phys. Rev. D **71**, 054032 (2005)
- [15] A. Badin and A. A. Petrov, Phys. Rev. D **82**, 034005 (2010); Y. G. Aditya, K. J. Healey and A. A. Petrov, Phys. Lett. B **710**, 118 (2012)
- [16] M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B **662**, 53 (2008)
- [17] J. L. Feng and J. Kumar, Phys. Rev. Lett. **101**, 231301 (2008)
- [18] A. A. Petrov and A. E. Blechman, “Effective Field Theories,” ISBN: 978-981-4434-92-8, World Scientific Publishing, 2016.
- [19] A. Khodjamirian, T. Mannel and A. A. Petrov, JHEP **1511**, 142 (2015)
- [20] S. de Boer, B. Muller and D. Seidel, JHEP **1608**, 091 (2016)
- [21] B. Grinstein and J. M. Camalich, Phys. Rev. Lett. **116**, no. 14, 141801 (2016)