Searching for New Physics with Charm

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I provide a comprehensive review of indirect searches for New Physics with charmed mesons. I discuss current theoretical and experimental challenges and successes in understanding decays and mixings of those mesons. I argue that in many New Physics scenarios strong constraints, that surpass those from other search techniques, could be placed on the allowed model parameter space using the existent data from studies of charm transitions. This has direct implications for direct searches of physics beyond the Standard Model at the LHC.

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1. Introduction

Processes involving charm quarks provide a unique place to search for indirect effects of New Physics (NP). They furnish a rather unique access to processes in the up-quark sector, which is not yet available in the decays of top quarks: neutral mesons containing charm quark are the only mesons in that sector that can have flavor oscillations.

A distinctive feature of charmed quark systems is that they involve a "not-so-heavy" charm quark. That means that all charmed hadrons' masses, $\mathcal{O}(2\text{ GeV})$, are placed in the middle of the region where non-perturbative hadronic physics is operative. While this fact does not markedly affect theoretical description of leptonic and semileptonic decays of charmed hadrons, it poses significant challenges in the analyses of their hadronic transitions. There is a great deal of optimism, however, that abundant experimental data would provide some hints on the structure of charm hadronic decays. In addition, recent advances in lattice Quantum Chromodynamics (QCD) and other non-perturbative techniques provide us with hope that those problems will eventually be overcome. One can place types of searches for New Physics in the charm quark sector into three distinct categories,

1. Searches in the processes that are *allowed* in the Standard Model.

   In light of what was said above, it might be difficult to identify New Physics contributions to charm-initiated processes that are allowed in the Standard Model (SM). Yet, it is still possible. Searches of that type include testing relations among SM-allowed processes that are known to hold only in the SM, but not necessarily in models beyond the Standard Model. A usual example, which has traditionally been employed in B-physics, is testing Cabbibo-Kobayashi-Maskawa (CKM) triangle relations. Another example is to look for processes where QCD seem to be under theoretical control, such as leptonic decays of D-mesons, $D_q \to \ell\bar{\nu}$.

2. Searches in the processes that are *forbidden* in the Standard Model *at tree level*.

   Processes that involve flavor-changing neutral current (FCNC) interactions that change charm quantum number by one or two units do not occur in the Standard Model at tree level, as terms that mediate such interactions are absent from the SM Lagrangian. However, they can happen in the Standard Model at one loop level, which makes them rather rare. Processes like that can receive New Physics contributions from both tree-level interactions mediated by new interactions, as well from one-loop corrections with NP particles. Processes of that type include $D^0 - \overline{D}^0$ mixing, or inclusive and exclusive transitions mediated by $c \to u\gamma$ or $c \to u\ell\bar{\ell}$. Lastly, searches for CP-violation in charm decays could be included here as well.

3. Searches in the processes that are *forbidden* in the Standard Model.

   There are a set of processes that, while allowed by space-time symmetries, are forbidden in the Standard Model. Processes of that type are so rare that searches for their signatures require incredibly high statistics experiments. Their observation, however, would constitute a high-impact discovery, as it would unambiguously point towards physics beyond the Standard Model. Examples include searches for lepton- and baryon-number-violating transitions such as $D^0 \to n\bar{\nu}$ or $D^0 \to \bar{p}e^+$, etc.

In what follows we shall review theoretical status of searches for New Physics in charm decays.

2. Processes allowed in the Standard Model

2.1 Leptonic decays of D^+ and D_s mesons

Due to their overall simplicity, charm leptonic decays could serve as nice laboratories to study New Physics, as the Standard Model "background" depends on a single non-perturbative parameter, the decay constant f_{D_q},

$$\langle 0|\bar{q}\gamma^\mu\gamma_5 c|D_q\rangle = if_{D_q}p_D^\mu. \tag{2.1}$$

In the quark model, f_{D_q} parameterizes the amplitude of probability for the heavy and light quarks to "find each other" in a meson. Thus, in the SM, the leptonic decay width can be written as

$$\Gamma(D_q \to \ell\nu) = \frac{G_F^2}{8\pi}f_{D_q}^2 m_\ell^2 M_{D_q}\left(1-\frac{m_\ell^2}{M_{D_q}^2}\right)^2 |V_{cq}|^2 \quad, \tag{2.2}$$

where $q=d,s$ for D^+ or D_s states respectively, M_{D_q} is the D_q mass, m_ℓ is the mass of the final state lepton, and $|V_{cq}|$ is the *CKM* matrix element associated with the $c \to q$ transition. Due to helicity suppression the rate goes as m_ℓ^2, which plays a role in NP searches as many NP models could have a different parametric dependence on m_ℓ^2 (or not at all). Thus, provided an accurate calculation of the SM contribution (and, in particular, f_{D_q}) is available, one can place rather tight constraints on some models of New Physics.

Experiment	Mode	$\mathscr{B}(x10^3)$	f_{D_s} (MeV)
CLEO-c	$\mu^+\nu_\mu$	$5.94\pm0.66\pm0.31$	$264\pm15\pm7$
CLEO-c	$\tau^+\nu_\tau$	$80.0\pm13.0\pm4.0$	$310\pm25\pm8$
CLEO-c	$\tau^+\nu_\tau$	$61.7\pm7.1\pm3.6$	$275\pm10\pm5$
CLEO-c	combined		$274\pm10\pm5$
Belle	$\mu^+\nu_\mu$	$6.44\pm0.76\pm0.52$	$279\pm16\pm12$
Average			275 ± 10
Theory			f_{D_s} (MeV)
HPQCD			241 ± 3
FNAL			$249\pm3\pm16$

Table 1: Experimental/theoretical results for D_s decay constant before 2009 (see [1] for more details).

Accurate calculations of non-perturbative QCD parameters are very challenging, for which lattice QCD represents an appealing approach. In the past a big stumbling block in the lattice studies of QCD has been the inclusion of dynamical quark effects, i.e. "unquenching" lattice QCD. In the recent years, technical developments such as highly improved actions of QCD and the availability of "2+1flavor" MILC configurations with 3 flavors of improved staggered quarks have lead to results with much higher accuracy and allowed for consistent estimate of both statistical and systematic errors involved in the simulations. Two groups have reported charm decay constant

calculations with three dynamical quark flavors, the Fermilab/MILC Lattice collaboration [2] and the HPQCD collaboration [3]. Their results, along with experimental measurements from CLEO-c and Belle, are presented in Table 1. As can be easily seen, there is a 3.6σ discrepancy between HPQCD-predicted and experimentally extracted values of f_{D_s}, which could in principle be due to New Physics interactions. This is because f_{D_s} was extracted from experimental data assuming only SM interactions. Note that theoretical predictions and experimental extractions for f_{D^+} are consistent with each other, the discrepancy is only observed in the D_s system.

The possibility of New Physics being responsible for this discrepancy has been studied in [4] and subsequently by many authors (see [5] for a recent summary). In principle, leptonic decays could be sensitive probes of NP interactions mediated by charged particles. Models with an extended Higgs sector, which include new charged scalar states, or models with broken left-right symmetry, which include massive vector $W_R^\pm$ states, are examples of such interactions. To account for New Physics, one can make a substitution [5]

$$G_F V_{cs}^* m_\ell \to G_F V_{cs}^* m_\ell + G_A^\ell m_\ell + G_P^\ell \frac{m_{D_s}^2}{m_c + m_s} \tag{2.3}$$

in Eq. (2.2) for the D_s. Here G_A^ℓ and G_P^ℓ parameterize new couplings and masses of NP interactions.

Indeed, NP contribution to the $c \to q\ell\nu$ interaction would affect other processes, such as leptonic $D^+ \to \ell\nu$ and semileptonic $D \to M\ell\bar{\nu}$ decays. It is quite hard to satisfy all constraints from those processes simultaneously [5] in many popular models of New Physics. Besides, new experimental results from CLEOc [6] lead to a new experimental average reported by the Heavy Flavor Averaging Group (HFAG) [7],

$$f_{D_s} = 256.9 \pm 6.8 \text{ MeV}, \tag{2.4}$$

and new lattice QCD predictions (for various numbers of sea-quark flavors n_f) reported at the Lattice-2009 conference by the Fermilab/MILC collaboration and by the European Twisted-Mass Collaboration (ETMC) [8]

$$\begin{aligned} f_{D_s} &= 260 \pm 10 \text{ MeV} \ \ [n_f = 2+1] \ \ \text{(FNAL/MILC)}, \\ f_{D_s} &= 244 \pm 8 \text{ MeV} \ \ \ [n_f = 2] \ \ \ \ \ \ \text{(ETMC)} \end{aligned} \tag{2.5}$$

cast a serious doubt that this discrepancy is caused by New Physics.

There are excellent prospects for further insights into the "f_{D_s}-problem." Besides new lattice evaluations of this quantity by the same and other collaborations (for instance, with possible improvements on new MILC ensembles with $n_f = 2+1+1$, i.e. including charm sea quarks), new measurements with a percent accuracy will be available from the BES-III collaboration in a few years [9]. This, together with continuous improvement of BaBar and Belle results, should provide a resolution of the "f_{D_s}-problem."

2.2 CKM triangle relations in charm

Another way to search for New Physics in the SM-allowed processes is to test relations that only hold in the SM, but not necessarily in general. An example of such relation is a CKM "charm unitarity triangle" relation.

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0 \tag{2.6}$$

Relations like Eq. (2.6) hold in the SM due to a single phase of the CKM matrix driving CP-violation in the SM, which is not always so in general BSM models. Moreover, processes that are used to extract CKM parameters in Eq. (2.6) can be affected by New Physics, which might lead to difference in the shape of the triangle extracted from different transitions.

In fact, there are several unitarity triangles that involve charm inputs [10]. Since all CP-violating effects in the flavor sector of the SM are related to the single phase of the CKM matrix, all of the CKM unitarity triangles, including the one in Eq. (2.6), have the same area, $A = J/2$, where J is the Jarlskog invariant. This fact could provide a non-trivial check of the Standard Model, if measurements of all sides of these triangles are performed with sufficient accuracy and then compared to areas of other CKM unitarity triangles.

Unfortunately, the "charm triangle" is rather "squashed", with one side being much shorter then the other two. In terms of the Wolfenstein parameter $\lambda = 0.22$, the relation in Eq. (2.6) has one side $\mathcal{O}(\lambda^5)$ with the other two being $\mathcal{O}(\lambda)$. This triangle relation is however quite interesting because all measurements needed to extract the CKM matrix elements in Eq. (2.6) come from the tree-level processes. Thus, its area should be a measure of CP-violation in the SM, which can be compared to the area of the more familiar "B-physics triangle",

$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0 \tag{2.7}$$

which receives input from loop-dominated processes like B-mixing and whose area squared is $A_c^2 = (2.32 \pm 0.31) \times 10^{-10}$. Compared to this, the area of the "charm unitarity triangle" in Eq. (2.6) is $A_c^2 = (-1.34 \pm 5.46) \times 10^{-6}$ (obtained using inputs from [11]), which is clearly not precise enough for meaningful comparison.

In addition, relations like $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$ could be tested. It could provide an interesting cross-check on the value of V_{cb} extracted in B-decays, if sufficient accuracy on the experimental measurement of V_{cd} and V_{cs} is achieved. It is however unlikely that the required accuracy will be achieved in the near future (for new work in this direction see [12]).

3. Processes forbidden in the Standard Model at tree level

Processes forbidden in the SM at tree level involve FCNC, which can manifest themselves in rare decays and meson-anti-meson mixing. The phenomenon of meson-anti-meson mixing occurs in the presence of operators that change quark flavor by two units [1]. While those operators can be generated in the Standard Model at one loop, they can also be generated in its many possible extensions. With the potential window to discern large NP effects in the charm sector as well as the anticipated improved accuracy for future mixing measurements, the motivation for a comprehensive up-to-date theoretical analysis of New Physics contributions to D meson mixing is compelling.

3.1 New Physics in $D^0 - \overline{D^0}$ mixing

The presence of $\Delta C = 2$ operators produce off-diagonal terms in the meson-anti-meson mass matrix, so that the basis of flavor eigenstates no longer coincides with the basis of mass eigenstates. Those two bases, however, are related by a linear transformation,

$$|D_{\frac{1}{2}}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \tag{3.1}$$

where the complex parameters p and q are obtained from diagonalizing the $D^0 - \overline{D}^0$ mass matrix. Neglecting CP-violation leads to $p = q = 1/\sqrt{2}$. The mass and width splittings between mass eigenstates are

$$x_D = \frac{m_1 - m_2}{\Gamma_D}, \qquad y_D = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}, \tag{3.2}$$

where Γ_D is the average width of the two neutral D meson mass eigenstates. Because of the absence of superheavy down-type quarks destroying Glashow-Iliopoulos-Maiani (GIM) cancellation, it is expected that x_D and y_D should be rather small in the Standard Model. The quantities which are actually measured in experimental determinations of the mass and width differences, are $y_D^{(CP)}$ (measured in time-dependent $D \to KK, \pi\pi$ analyses), x_D', and y_D' (measured in $D \to K\pi$ and similar transitions), are defined as

$$
\begin{aligned}
y_D^{(CP)} &= y_D \cos\phi - x_D \sin\phi \left(\frac{A_m}{2} - A_{prod} \right) , \\
x_D' &= x_D \cos\delta_{K\pi} + y_D \sin\delta_{K\pi} , \\
y_D' &= y_D \cos\delta_{K\pi} - x_D \sin\delta_{K\pi} ,
\end{aligned}
\tag{3.3}
$$

where $A_{prod} = \left(N_{D^0} - N_{\overline{D}^0} \right) / \left(N_{D^0} + N_{\overline{D}^0} \right)$ is the so-called production asymmetry of D^0 and $\overline{D}^0$ (giving the relative weight of D^0 and $\overline{D}^0$ in the sample) and $\delta_{K\pi}$ is the strong phase difference between the Cabibbo favored and double Cabibbo suppressed amplitudes [13], which can be measured in $D \to K\pi$ transitions. A fit to the current database of experimental analyses by the Heavy Flavor Averaging Group (HFAG) gives [14, 7]

$$
\begin{aligned}
x_D &= 0.0100^{+0.0024}_{-0.0026} , \qquad y_D = 0.0076^{+0.0017}_{-0.0018} , \\
1 - |q/p| &= 0.06 \pm 0.14, \quad \phi = -0.05 \pm 0.09,
\end{aligned}
\tag{3.4}
$$

where ϕ is a CP-violating phase. It is important to note that the size of the signal allows to conclude that the former "smoking gun" signal for New Physics in $D^0 - \overline{D}^0$ mixing, $x \gg y$ no longer applies. Also, CP-violating is charm is clearly small. The question that arises now is how to use available data to probe for physics beyond the Standard Model.

Theoretical predictions for x_D and y_D obtained in the framework of the Standard Model are quite complicated. I will not be discussing those here, instead referring the interested reader to recent reviews [1]. It might be advantageous to note that there are two approaches to describe $D^0 - \overline{D}^0$ mixing, neither of which give very reliable results because m_c is in some sense intermediate between heavy and light.

Let me introduce a scale $\Lambda \sim 1$ GeV to be a scale characteristic of the strong interactions. The "inclusive" approach [15, 16] is based on the operator product expansion (OPE) in the formal limit $m_c \gg \Lambda$, where x_D and y_D can be expanded in terms of matrix elements of local operators. The use of the OPE relies on local quark-hadron duality, and on Λ/m_c being small enough to allow a truncation of the series after the first few terms. This, however, is not realized in $D^0 - \overline{D}^0$ mixing, as the leading term in $1/m_c$ is suppressed by four and six powers of the strange quark mass for x_D and y_D respectively. The parametrically-suppressed higher order terms in $1/m_c$ can have less powers of m_s, thus being more important numerically [16]. This results in reshuffling of the OPE series, making it a triple expansion in $1/m_c$, m_s, and α_s. The (numerically) leading term

contains over twenty matrix elements of dimension-12, eight-quark operators, which are difficult to compute reliably. A naive power counting then yields $x_D, y_D < 10^{-3}$. The "exclusive" approach [17] more realistically assumes $m_c \simeq \Lambda$ and sums over intermediate hadronic states. Since there are cancellations between states within a given $SU(3)$ multiplet, one needs to know the contribution of each state with high precision. However, D meson is not light enough to have only a few open decay channels. In the absence of sufficiently precise data one is forced to use some assumptions. Large effects in y_D appear for decays close to D threshold, where an analytic expansion in $SU(3)_F$ violation is no longer possible. Thus, even though theoretical calculations of x_D and y_D are quite uncertain, the values $x_D \sim y_D \sim 1\%$ are natural in the Standard Model [18].

It then appears that experimental results of Eq. (3.4) are consistent with the SM predictions. Yet, those predictions are quite uncertain to be subtracted from the experimental data to precisely constrain possible NP contributions. In this situation the following approach can be taken. One can neglect the SM contribution altogether and assume that NP saturates the experimental result. This way, however, only an upper bound on the NP parameters can be placed. A subtlety of this method is related to the fact that the SM and NP contributions can have either the same or opposite signs. While the sign of the SM contribution cannot be calculated reliably due to hadronic uncertainties, x_D computed within a given NP model can be determined. This stems from the fact that NP contributions are generated by heavy degrees of freedom making short-distance OPE reliable. This means that only the part of parameter space of NP models that generate x_D of the same sign as observed experimentally can be reliably constrained.

Any NP degree of freedom will generally be associated with a generic heavy mass scale M, at which the NP interaction will be most naturally described. At the scale m_c of the charm mass, this description will have been modified by the effects of QCD, which should be taken into account. In order to see how NP might affect the mixing amplitude, it is instructive to consider off-diagonal terms in the neutral D mass matrix,

$$\left(M - \frac{i}{2}\Gamma\right)_{12} = \frac{1}{2M_D}\langle \overline{D}^0|\mathscr{H}_w^{\Delta C=-2}|D^0\rangle + \frac{1}{2M_D}\sum_n \frac{\langle \overline{D}^0|\mathscr{H}_w^{\Delta C=-1}|n\rangle \langle n|\mathscr{H}_w^{\Delta C=-1}|D^0\rangle}{M_D - E_n + i\varepsilon} \quad (3.5)$$

where the first term contains $\mathscr{H}_w^{\Delta C=-2}$, which is an effective $|\Delta C| = 2$ hamiltonian, represented by a set of operators that are local at the $\mu \simeq m_D$ scale. Note that a b-quark also gives a (negligible) contribution to this term. This term only affects x_D, but not y_D.

The second term in Eq. (3.5) is given by a double insertion of the effective $|\Delta C| = 1$ Hamiltonian $\mathscr{H}_w^{\Delta C=-1}$. This term is believed to give dominant contribution to $D^0 - \overline{D}^0$ mixing in the Standard Model, affecting both x and y. It is also generally believed that NP cannot give any sizable contribution to this term, since $\mathscr{H}_w^{\Delta C=-1}$ Hamiltonian also mediates non-leptonic D-decays, which should then also be affected by this NP contribution. To see why this is not so, consider a non-leptonic D^0 decay amplitude, $A[D^0 \to n]$, which includes a small NP contribution, $A[D^0 \to n] = A_n^{(SM)} + A_n^{(NP)}$. Here, $A_n^{(NP)}$ is assumed to be smaller than the current experimental uncertainties on those decay rates. This ensures that NP effects cannot be seen in the current experimental analyses of non-leptonic D-decays. Then, y_D is

$$y_D \simeq \sum_n \frac{\rho_n}{\Gamma_D} A_n^{(SM)} A_n^{(SM)} + 2\sum_n \frac{\rho_n}{\Gamma_D} A_n^{(NP)} A_n^{(SM)} \quad . \quad (3.6)$$

The first term of Eq. (schematic) represents the SM contribution to y_D. The SM contribution to y_D is known to vanish in the limit of exact flavor $SU(3)$. Moreover, the first order correction is also absent, so the SM contribution arises only as a *second* order effect [18]. This means that in the flavor $SU(3)$ limit the lifetime difference y_D is dominated by the second term in Eq. (3.6), i.e. New Physics contributions, even if their contibutions are tiny in the individual decay amplitudes [19]! A realistic calculation reveals that NP contribution to y_D can be as large as several percent in R-parity-violating SUSY models [20] or as small as $\sim 10^{-10}$ in the models with interactions mediated by charged Higgs particles [19].

As mentioned above, heavy BSM degrees of freedom cannot be produced in charm meson decays, but can nevertheless affect effective $|\Delta C| = 2$ Hamiltonian by changing Wilson coefficients and/or introducing new operator structures. By integrating out those new degrees of freedom associated with new interactions at a high scale M, we are left with an effective hamiltonian written in the form of a series of operators of increasing dimension. It turns out that a model-independent study of NP $|\Delta C| = 2$ contributions is possible, as any NP model will only modify Wilson coefficients of those operators [21, 22],

$$\mathscr{H}_{NP}^{|\Delta C|=2} = \frac{1}{M^2} \left[\sum_{i=1}^{8} C_i(\mu)\, Q_i \right], \tag{3.7}$$

where C_i are dimensionless Wilson coefficients, and the Q_i are the effective operators:

$$
\begin{aligned}
Q_1 &= (\overline{u}_L^\alpha \gamma_\mu c_L^\alpha)\,(\overline{u}_L^\beta \gamma^\mu c_L^\beta)\,, & Q_5 &= (\overline{u}_R^\alpha c_L^\beta)\,(\overline{u}_L^\beta c_R^\alpha)\,, \\
Q_2 &= (\overline{u}_R^\alpha c_L^\alpha)\,(\overline{u}_R^\beta c_L^\beta)\,, & Q_6 &= (\overline{u}_R^\alpha \gamma_\mu c_R^\alpha)\,(\overline{u}_R^\beta \gamma^\mu c_R^\beta)\,, \\
Q_3 &= (\overline{u}_R^\alpha c_L^\beta)\,(\overline{u}_R^\beta c_L^\alpha)\,, & Q_7 &= (\overline{u}_L^\alpha c_R^\alpha)\,(\overline{u}_L^\beta c_R^\beta)\,, \\
Q_4 &= (\overline{u}_R^\alpha c_L^\alpha)\,(\overline{u}_L^\beta c_R^\beta)\,, & Q_8 &= (\overline{u}_L^\alpha c_R^\beta)\,(\overline{u}_L^\beta c_R^\alpha)\,,
\end{aligned}
\tag{3.8}
$$

where α and β are color indices. In total, there are eight possible operator structures that exhaust the list of possible independent contributions to $|\Delta C| = 2$ transitions. Note that earlier Ref. [21] used a slightly different set of operators than [22], which can be related to each other by a linear transformation. Taking operator mixing into account, a set of constraints on the Wilson coefficients of Eq. (3.7) can be placed,

$$
\begin{aligned}
|C_1| &\le 5.7 \times 10^{-7} \left[\tfrac{M}{1\,\text{TeV}} \right]^2, \\
|C_2| &\le 1.6 \times 10^{-7} \left[\tfrac{M}{1\,\text{TeV}} \right]^2, \qquad\qquad
& |C_4| &\le 5.6 \times 10^{-8} \left[\tfrac{M}{1\,\text{TeV}} \right]^2, \\
|C_3| &\le 5.8 \times 10^{-7} \left[\tfrac{M}{1\,\text{TeV}} \right]^2, \qquad\qquad
& |C_5| &\le 1.6 \times 10^{-7} \left[\tfrac{M}{1\,\text{TeV}} \right]^2.
\end{aligned}
\tag{3.9}
$$

The constraints on $C_6 - C_8$ are identical to those on $C_1 - C_3$ [22]. Note that Eq. (3.9) implies that New Physics particles, for some unknown reason, has highly suppressed couplings to charmed quarks. Alternatively, the tight constraints of Eq. (3.9) probes NP at the very high scales: $M \ge (4-10) \times 10^3$ TeV for tree-level NP-mediated charm mixing and $M \ge (1-3) \times 10^2$ TeV for loop-dominated mixing via New Physics particles.

A contribution to $D^0 - \overline{D}^0$ mixing from a particular NP model can be obtained by calculating matching conditions for the Wilson coefficients C_i at the scale M, running their values down to

Model	Approximate Constraint
Fourth Generation	$\|V_{ub'}V_{cb'}\| \cdot m_{b'} < 0.5$ (GeV)
$Q = -1/3$ Singlet Quark	$s_2 \cdot m_S < 0.27$ (GeV)
$Q = +2/3$ Singlet Quark	$\|\lambda_{uc}\| < 2.4 \cdot 10^{-4}$
Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark
	Box: Parameter space can reach observed x_D
Generic Z'	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
Family Symmetries	$m_1/f > 1.2 \cdot 10^3$ TeV (with $m_1/m_2 = 0.5$)
Left-Right Symmetric	No constraint
Alternate Left-Right Symmetric	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV)
	$(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
Vector Leptoquark Bosons	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
Flavor Conserving Two-Higgs-Doublet	No constraint
Flavor Changing Neutral Higgs	$m_H/C > 2.4 \cdot 10^3$ TeV
FC Neutral Higgs (Cheng-Sher)	$m_H/\|\Delta_{uc}\| > 600$ GeV
Scalar Leptoquark Bosons	See entry for RPV SUSY
Higgsless	$M > 100$ TeV
Universal Extra Dimensions	No constraint
Split Fermion	$M/\|\Delta y\| > (6 \cdot 10^2$ GeV$)$
Warped Geometries	$M_1 > 3.5$ TeV
MSSM	$\|(\delta_{12}^u)_{LR,RL}\| < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
	$\|(\delta_{12}^u)_{LL,RR}\| < .25$ for $\tilde{m} \sim 1$ TeV
SUSY Alignment	$\tilde{m} > 2$ TeV
Supersymmetry with RPV	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde{d}_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
Split Supersymmetry	No constraint

Table 2: Approximate constraints on NP models from D^0 mixing (from [21]).

μ and computing the relevant matrix elements of four-quark operators. This program has been executed in Ref. [21] for 21 well-motivated NP models, which will be actively studied at LHC. The results are presented in Table 2. As can be seen, out of 21 models considered, only four received no useful constraints from $D^0 - \overline{D}^0$ mixing. More informative exclusion plots can be found in that paper [21] as well. It is interesting to note that some models *require* large signals in the charm system if mixing and FCNCs in the strange and beauty systems are to be small (as in, for example, the SUSY alignment model [23, 24, 25]).

3.2 New Physics in rare decays of charmed mesons

I will call *rare* those decays of D mesons that are mediated by quark-level FCNC transitions $c \to u\gamma$ (rare radiative) and $c \to u\ell\ell$ (rare leptonic and semileptonic). These decays only proceed at one loop in the SM, so just like in $D^0 - \overline{D}^0$ mixing GIM mechanism is very effective. Here I will concentrate on the simplest rare leptonic decays $D^0 \to \ell^+\ell^-$. These transitions have a very

small SM contribution, so they could be very clean probes of NP amplitudes. Other transitions rare decays (such as $D \to \rho\gamma$, etc.) could receive rather significant SM contributions, which are quite difficult to compute. For more information on those decays please see Refs. [26].

Experimentally, at present, there are only the upper limits [11, 27, 28, 29] on $D^0 \to \ell^+\ell^-$ decays,

$$\mathscr{B}_{D^0 \to \mu^+\mu^-} \leq 1.3 \times 10^{-6}, \quad \mathscr{B}_{D^0 \to e^+e^-} \leq 1.2 \times 10^{-6}, \text{ and } \mathscr{B}_{D^0 \to \mu^\pm e^\mp} \leq 8.1 \times 10^{-7}. \quad (3.10)$$

Theoretically, just like in the case of mixing discussed above, all possible NP contributions to $c \to u\ell^+\ell^-$ can also be summarized in an effective hamiltonian,

$$\mathscr{H}_{NP}^{rare} = \sum_{i=1}^{10} \widetilde{C}_i(\mu) \, \widetilde{Q}_i, \quad (3.11)$$

where $\widetilde{C}_i$ are again Wilson coefficients, and the $\widetilde{Q}_i$ are the effective operators. In this case, however, there are ten of them,

$$\begin{aligned}
\widetilde{Q}_1 &= (\bar{\ell}_L \gamma_\mu \ell_L)(\bar{u}_L \gamma^\mu c_L), & \widetilde{Q}_4 &= (\bar{\ell}_R \ell_L)(\bar{u}_R c_L), \\
\widetilde{Q}_2 &= (\bar{\ell}_L \gamma_\mu \ell_L)(\bar{u}_R \gamma^\mu c_R), & \widetilde{Q}_5 &= (\bar{\ell}_R \sigma_{\mu\nu} \ell_L)(\bar{u}_R \sigma^{\mu\nu} c_L), \\
\widetilde{Q}_3 &= (\bar{\ell}_L \ell_R)(\bar{u}_R c_L),
\end{aligned} \quad (3.12)$$

with five additional operators $\widetilde{Q}_6, \ldots, \widetilde{Q}_{10}$ that can be obtained from operators in Eq. (3.12) by the substitutions $L \to R$ and $R \to L$. It is worth noting that only eight operators contribute to $D^0 \to \ell^+\ell^-$, as $\langle \ell^+\ell^- | \widetilde{Q}_5 | D^0 \rangle = \langle \ell^+\ell^- | \widetilde{Q}_{10} | D^0 \rangle = 0$. The most general $D^0 \to \ell^+\ell^-$ decay amplitude can be written as

$$\mathscr{M} = \bar{u}(\mathbf{p}_-, s_-)[A + B\gamma_5] v(\mathbf{p}_+, s_+), \quad (3.13)$$

which result in the branching fractions

$$\begin{aligned}
\mathscr{B}_{D^0 \to \ell^+\ell^-} &= \frac{M_D}{8\pi\Gamma_D} \sqrt{1 - \frac{4m_\ell^2}{M_D^2}} \left[\left(1 - \frac{4m_\ell^2}{M_D^2}\right)|A|^2 + |B|^2 \right], \\
\mathscr{B}_{D^0 \to \mu^+ e^-} &= \frac{M_D}{8\pi\Gamma_D} \left(1 - \frac{m_\mu^2}{M_D^2}\right)^2 \left[|A|^2 + |B|^2\right].
\end{aligned} \quad (3.14)$$

I neglected the electron mass in the latter expression. Any NP contribution described by the operators of Eq. (3.12) gives for the amplitudes A and B,

$$\begin{aligned}
|A| &= G\frac{f_D M_D^2}{4m_c} \left[\widetilde{C}_{3-8} + \widetilde{C}_{4-9} \right], \\
|B| &= G\frac{f_D}{4} \left[2m_\ell \left(\widetilde{C}_{1-2} + \widetilde{C}_{6-7} \right) + \frac{M_D^2}{m_c} \left(\widetilde{C}_{4-3} + \widetilde{C}_{9-8} \right) \right],
\end{aligned} \quad (3.15)$$

with $\widetilde{C}_{i-k} \equiv \widetilde{C}_i - \widetilde{C}_k$. Any NP model that contribute to $D^0 \to \ell^+\ell^-$ can be constrained from the constraints on the Wilson coefficients in Eq. (3.15).

Model	$\mathscr{B}(D^0 \to \mu^+\mu^-)$
Experiment	$\leq 1.3 \times 10^{-6}$
Standard Model (LD)	$\sim$ several $\times 10^{-13}$
$Q = +2/3$ Vectorlike Singlet	4.3×10^{-11}
$Q = -1/3$ Vectorlike Singlet	1×10^{-11} $(m_S/500\ \text{GeV})^2$
$Q = -1/3$ Fourth Family	1×10^{-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	4.8×10^{-9} $(300\ \text{GeV}/m_{\tilde{d}_k})^2$

Table 3: Predictions for $D^0 \to \mu^+\mu^-$ branching fraction for $x_D \sim 1\%$ (from [30])

It is, however, possible to go further. In particular, it might be advantageous to study *correlations* of New Physics contributions to various processes, for instance $D^0 - \overline{D}^0$ mixing and rare decays [30]. In general, one cannot predict the rare decay rate by knowing just the mixing rate, even if both x_D and $\mathscr{B}_{D^0 \to \ell^+\ell^-}$ are dominated by a given NP contribution. It is, however, possible for a restricted subset of NP models [30]. The results are presented in Table 3. Note that similar correlated studies can be done with other systems, for instance correlating results in K, B and D mixing [31].

4. "Smoking gun" signals: CP-violation in charm

Another possible manifestation of new physics interactions in the charm system is associated with the observation of (large) CP-violation [1, 32]. This is due to the fact that all quarks that build up the hadronic states in weak decays of charm mesons belong to the first two generations. Since 2×2 Cabibbo quark mixing matrix is real, no CP-violation is possible in the dominant tree-level diagrams which describe the decay amplitudes. CP-violating amplitudes can be introduced in the Standard Model by including penguin or box operators induced by virtual b-quarks. However, their contributions are strongly suppressed by the small combination of CKM matrix elements $V_{cb}V_{ub}^*$. It is thus widely believed that the observation of (large) CP violation in charm decays or mixing would be an unambiguous sign for New Physics. The SM "background" here is quite small, giving CP-violating asymmetries of the order of 10^{-3}.

No CP-violation has been observed in charm transitions yet. However, available experimental constraints of Eq. (3.4) can provide some tests of CP-violating NP models. For example, a set of constraints on the imaginary parts of Wilson coefficients of Eq. (3.7) can be placed,

$$
\begin{aligned}
&\text{Im}\,[C_1] \leq 1.1 \times 10^{-7} \left[\frac{M}{1\ \text{TeV}}\right]^2, \\
&\text{Im}\,[C_2] \leq 2.9 \times 10^{-8} \left[\frac{M}{1\ \text{TeV}}\right]^2, \qquad
\begin{aligned}
&\text{Im}\,[C_4] \leq 1.1 \times 10^{-8} \left[\frac{M}{1\ \text{TeV}}\right]^2, \\
&\text{Im}\,[C_5] \leq 3.0 \times 10^{-8} \left[\frac{M}{1\ \text{TeV}}\right]^2.
\end{aligned} \\
&\text{Im}\,[C_3] \leq 1.1 \times 10^{-7} \left[\frac{M}{1\ \text{TeV}}\right]^2,
\end{aligned}
\tag{4.1}
$$

Just like the constraints of Eq. (3.9), they give a sense of how NP particle couple to the Standard Model.

Other tests can also be performed. For instance, neglecting direct CP-violation in the decay amplitudes, one can write a "theory-independent" relation among $D^0 - \overline{D}^0$ mixing amplitudes [33,

34],

$$\frac{x}{y} = \frac{1 - |q/p|}{\tan \phi} \tag{4.2}$$

Current experimental results $x/y \approx 0.8 \pm 0.3$ imply that amount of CP-violation in the $D^0 - \overline{D}^0$ mixing matrix is comparable to CP-violation in the interference of decays and mixing amplitudes. An extensive study of exclusive decays should be performed [35], which could also shed some light on how large CP-violation in charm decay amplitudes could be. Finally, new observables, such as CP-violating "untagged" decay asymmetries [36] should be studied in hadronic decays [37] of charmed mesons.

5. Conclusions

With first results from the LHC experiments coming out this year, we are eagerly awaiting discoveries of new particles and interactions at the TeV scale. Their proper *identification* is an important task that will require inputs from collider, low-energy and astrophysical experiments. Constraints on indirect effects of New Physics at flavor factories will help to distinguish among models possibly observed at the LHC. I reviewed recent progress in theoretical understanding of NP constraints in charm transitions, which were chiefly driven by recent experimental observation of $D^0 - \overline{D}^0$ mixing as well as experimental studies of other charm meson transitions. With many LHC-favorite models already receiving interesting constraints from charm physics, new experimental results, especially in the studies of CP-violation, will be be indispensable for physics of the LHC era.

Acknowledgments

References

[1] M. Artuso, B. Meadows and A. A. Petrov, Ann. Rev. Nucl. Part. Sci. **58**, 249 (2008). A. A. Petrov, *In the Proceedings of Flavor Physics and CP Violation (FPCP 2003), Paris, France, 3-6 Jun 2003, pp MEC05* [arXiv:hep-ph/0311371]. S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. **26N7**, 1 (2003); G. Burdman and I. Shipsey, Ann. Rev. Nucl. Part. Sci. **53**, 431 (2003); X. Q. Li, X. Liu and Z. T. Wei, Front. Phys. China **4**, 49 (2009).

[2] C. Aubin *et al.*, Phys. Rev. Lett. **95**, 122002 (2005) [arXiv:hep-lat/0506030].

[3] E. Follana, C. T. H. Davies, G. P. Lepage and J. Shigemitsu [HPQCD Collaboration and UKQCD Collaboration], Phys. Rev. Lett. **100**, 062002 (2008) [arXiv:0706.1726 [hep-lat]].

[4] B. A. Dobrescu and A. S. Kronfeld, Phys. Rev. Lett. **100**, 241802 (2008) [arXiv:0803.0512 [hep-ph]];
A. G. Akeroyd and C. H. Chen, Phys. Rev. D **75**, 075004 (2007) [arXiv:hep-ph/0701078];
A. G. Akeroyd, Prog. Theor. Phys. **111**, 295 (2004) [arXiv:hep-ph/0308260]; A. Kundu and S. Nandi, Phys. Rev. D **78**, 015009 (2008) [arXiv:0803.1898 [hep-ph]]; I. Dorsner, S. Fajfer, J. F. Kamenik and N. Kosnik, Phys. Lett. B **682**, 67 (2009) [arXiv:0906.5585 [hep-ph]].

[5] A. S. Kronfeld, arXiv:0912.0543 [hep-ph].

[6] J. P. Alexander *et al.* [CLEO Collaboration], Phys. Rev. D **79**, 052001 (2009) [arXiv:0901.1216 [hep-ex]]; P. U. E. Onyisi *et al.* [CLEO Collaboration], Phys. Rev. D **79**, 052002 (2009) [arXiv:0901.1147 [hep-ex]]; P. Naik *et al.* [The CLEO Collaboration], Phys. Rev. D **80**, 112004 (2009) [arXiv:0910.3602 [hep-ex]].

[7] Heavy Flavor Averaging Group (HFAG), http://www.slac.stanford.edu/xorg/hfag/charm/

[8] R. van der Water, talk at Lattice 2009; B. Blossier *et al.*, JHEP **0907**, 043 (2009) [arXiv:0904.0954 [hep-lat]].

[9] D. M. Asner *et al.*, arXiv:0809.1869 [hep-ex].

[10] I. I. Y. Bigi and A. I. Sanda, arXiv:hep-ph/9909479.

[11] Particle Data Group, 'Review of Particle Physics', Phys. Lett. B **667**, 1 (2008).

[12] R. D. Ball *et al.* [The NNPDF Collaboration], Nucl. Phys. B **823**, 195 (2009) [arXiv:0906.1958 [hep-ph]].

[13] S. Bergmann, *et. al*, Phys. Lett. B **486**, 418 (2000); A. F. Falk, Y. Nir and A. A. Petrov, JHEP **9912**, 019 (1999).

[14] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 211802 (2007); M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007); K. Abe *et al.* [BELLE Collaboration], Phys. Rev. Lett. **99**, 131803 (2007).

[15] A. Datta, D. Kumbhakar, Z. Phys. C**27**, 515 (1985); A. A. Petrov, Phys. Rev. D**56**, 1685 (1997); E. Golowich and A. A. Petrov, Phys. Lett. B **625**, 53 (2005).

[16] H. Georgi, Phys. Lett. B297, 353 (1992); T. Ohl, G. Ricciardi and E. Simmons, Nucl. Phys. B403, 605 (1993); I. Bigi and N. Uraltsev, Nucl. Phys. B **592**, 92 (2001).

[17] J. Donoghue, E. Golowich, B. Holstein and J. Trampetic, Phys. Rev. D33, 179 (1986); L. Wolfenstein, Phys. Lett. B164, 170 (1985); P. Colangelo, G. Nardulli and N. Paver, Phys. Lett. B242, 71 (1990); T.A. Kaeding, Phys. Lett. B357, 151 (1995); E. Golowich and A. A. Petrov, Phys. Lett. B **427**, 172 (1998); A. A. Anselm and Y. I. Azimov, Phys. Lett. B **85**, 72 (1979).

[18] 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).

[19] E. Golowich, S. Pakvasa and A. A. Petrov, Phys. Rev. Lett. **98**, 181801 (2007).

[20] A. A. Petrov and G. K. Yeghiyan, Phys. Rev. D **77**, 034018 (2008).

[21] E. Golowich, J. Hewett, S. Pakvasa and A. A. Petrov, Phys. Rev. D **76**, 095009 (2007).

[22] O. Gedalia, Y. Grossman, Y. Nir and G. Perez, Phys. Rev. D **80**, 055024 (2009) [arXiv:0906.1879 [hep-ph]].

[23] Y. Nir and N. Seiberg, Phys. Lett. B **309**, 337 (1993).

[24] M. Ciuchini et al., Phys. Lett. B **655**, 162 (2007).

[25] W. Altmannshofer, A. J. Buras and P. Paradisi, arXiv:1001.3835 [hep-ph].

[26] G. Burdman, E. Golowich, J. Hewett and S. Pakvasa, Phys. Rev. D **66**, 014009 (2002); G. Burdman, E. Golowich, J. L. Hewett and S. Pakvasa, Phys. Rev. D **52**, 6383 (1995) [arXiv:hep-ph/9502329]; S. Fajfer and S. Prelovsek, Phys. Rev. D **73**, 054026 (2006) [arXiv:hep-ph/0511048]. S. Fajfer, S. Prelovsek and P. Singer, Eur. Phys. J. C **6**, 471 (1999) [arXiv:hep-ph/9801279]; S. Fajfer, S. Prelovsek and P. Singer, Phys. Rev. D **58**, 094038 (1998) [arXiv:hep-ph/9805461]; I. I. Y. Bigi, F. Gabbiani and A. Masiero, Z. Phys. C **48**, 633 (1990).

[27] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **93**, 191801 (2004) [arXiv:hep-ex/0408023].

[28] I. Abt *et al.* [HERA-B Collaboration], Phys. Lett. B **596**, 173 (2004) [arXiv:hep-ex/0405059].

[29] D. E. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **68**, 091101 (2003) [arXiv:hep-ex/0308059].

[30] E. Golowich, J. Hewett, S. Pakvasa and A. A. Petrov, Phys. Rev. D **79**, 114030 (2009).

[31] K. Blum, Y. Grossman, Y. Nir and G. Perez, Phys. Rev. Lett. **102**, 211802 (2009).

[32] I. I. Bigi, arXiv:0902.3048 [hep-ph]; A. A. Petrov, *In the Proceedings of International Workshop on Charm Physics (Charm 2007), Ithaca, New York, 5-8 Aug 2007, pp 11* [arXiv:0711.1564 [hep-ph]].

[33] Y. Grossman, Y. Nir and G. Perez, Phys. Rev. Lett. **103**, 071602 (2009) [arXiv:0904.0305 [hep-ph]].

[34] A. L. Kagan and M. D. Sokoloff, Phys. Rev. D **80**, 076008 (2009) [arXiv:0907.3917 [hep-ph]].

[35] Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D **75**, 036008 (2007) [arXiv:hep-ph/0609178].

[36] A. A. Petrov, Phys. Rev. D **69**, 111901 (2004) [arXiv:hep-ph/0403030].

[37] A. Ryd and A. A. Petrov, "Hadronic D and D_s Meson Decays," arXiv:0910.1265 [hep-ph].