Review of charm physics: a theory perspective

Thomas Mannel

Theoretische Physik 1, Universität Siegen, 57068 Siegen, Germany

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1 Introduction: why charm?

Charm physics has attracted significant and renewed attention due to new observations. On one hand, there has been convincing evidence of D-$\overline{D}$ mixing, paving the road to interesting weak interaction effects and maybe even to some new physics, on the other hand, a large number of narrow states is observed in the mass region of the J/ψ, which hints at some interesting effects in strong interaction physics of charmonia-like systems.

In this micro-review I will focus only on the electroweak and "new physics" aspects of charm physics; the spectroscopy of the new states cannot (yet?) be analyzed from fundamental QCD, and hence it is difficult at present to arrive at some conclusion concerning the QCD part of the standard model from these spectroscopic data.

From the flavour point of view the charm quark offers several unique possibilities. The flavour structure of the standard model, encoded in the fermion masses and in the CKM and PMNS mixing matrices, is quite peculiar. Strange and bottom physics test this flavour structure in a very similar way, since both are "down-type" quarks. Charm physics offers a possibility to test the flavour physics of the "up-type" quarks which has to be investigated as well in order to have a full test of the flavour structure.

One important observation in flavour physics is the strong suppression of flavour-changing neutral currents (FCNC's), which is implemented in the standard model by the Glashow-Iliopoulos-Maiani (GIM) mechanism [1]. GIM ensures that tree-level FCNC's are absent, implying also that FCNC's induced by loop diagrams yield finite results. In case of degenerate quark masses the standard model would have an additional flavour symmetry, which would protect it from any FCNC, even at loop level. This flavour symmetry is broken by the mass differences of the up-type quarks and of the down type quarks, and hence all FCNC's in the standard model are proportional to $(m_{u_i}^2 - m_{u_j}^2)$ or $(m_{d_i}^2 - m_{d_j}^2)$.

Thus, for the bottom and the strange quarks we have as an estimate, including a loop factor

$$\text{GIM-Suppression} \propto \text{CKM Factor} \, \frac{1}{16\pi^2} \frac{m_t^2 - m_u^2}{M_W^2} \tag{1}$$

indicating that the GIM mechanism is weakened by the large top mass. For this reason FCNC effects can appear at an observable level for strange and bottom quarks; in particular, the observation of B-$\overline{B}$ mixing in 1987 by ARGUS here at DESY [2] was the first hint at a large top mass, since for a lighter top quark these oscillations could not have been observed.

However, for charm the role of the up- and down-type quarks is interchanged. The corresponding GIM factor becomes

$$\text{GIM-Suppression} \propto \text{CKM Factor} \, \frac{1}{16\pi^2} \frac{m_b^2 - m_d^2}{M_W^2} \tag{2}$$

resulting in a heavy suppression factor $\sim m_b^2/M_W^2$. Thus the SM contributions to up-type FCNC's like $c \to u$, $t \to c$ etc are in general tiny.

In turn, this opens an interesting new window to new physics, since the standard model "pollution" in these processes is small and the relative strength of a possible new physics contribution will thus be enhanced

$$\left(\frac{\text{New Physics Signal}}{\text{Standard Model noise}}\right)_{\text{up-type}} > \left(\frac{\text{New Physics Signal}}{\text{Standard Model noise}}\right)_{\text{down-type}}$$

assuming that a new physics contribution does not exhibit a GIM-like structure.

The only alternative possibility to investigate up-type flavour physics is by processes involving the top quark. However, due to the large mass and its lifetime, which is small compared to typical times for the formation of a hadron from quark constituents, the physics of the top quark is completely different. In particular, there is no formation of top hadrons such that e.g. T-$\overline{T}$ oscillations will not be possible. Hence the charm quark offers the unique possibility to study up-type quark flavour physics.

2 "Bread and butter" charm physics

A large portion of charm flavour physics is related to standard processes involving the $\Delta C = \pm 1$ effective interaction. As in all quark flavour physics, the problem consists of calculating the hadronic matrix elements of operators formulated in terms of quarks and gluons. Since the charm quark mass is only about 1.2 GeV, it is a borderline case for the application of heavy quark expansions, since $\Lambda_{\text{QCD}}/m_c \sim 0.3 - 0.4$.

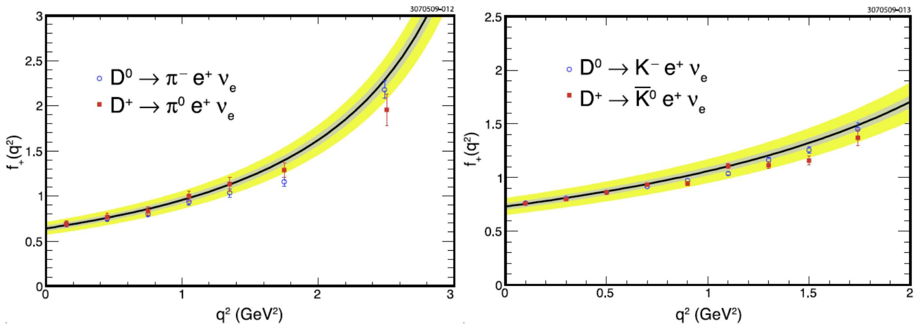

Figure 1: Data and theory predictions for exclusive semileptonic D decays [5].

Semileptonic decays are easier to treat and, in particular for exclusive decays, precises data has been taken e.g. at CLEO-c and the B facotries. The non-perturbative methods that may be used to calculate the necessary form factors are either lattice calculation [3] or (finite mass)

QCD sum rules. As an example, we show the results of a QCD sum rule estiamate [4]. Once the non-perturbative input is fixed, the data may be used for an independent extraction of V_{cd} and V_{cs}.

The extraction of the CKM elements proceeds through the measurement of the exclusive decays $D \to \pi \ell \bar{\nu}_\ell$ and $D \to K \ell \bar{\nu}_\ell$. The differential rate in the limit of vanishing final state masses reads

$$\frac{d\Gamma(D \to \pi \ell \nu)}{dq^2} = \frac{G_F^2 |V_{cd}|^2}{24\pi^3} p_\pi^3 |f_+(q^2)|^2 \tag{3}$$

which is expressed in terms of the form factor f_+.

Fig. 1 shows the data for the form factor f_+ for the decays $D \to \pi \ell \bar{\nu}_\ell$ and $D \to K \ell \bar{\nu}_\ell$. in comparison with the theoretical prediction. Based on a QCD sum rule claculation one may extract a value for V_{cd}; we obtain $V_{cd} = 0.225 \pm 0.005 \pm 0.003^{+0.016}_{-0.012}$[4]. Note that this value is competitive with the value based on neutrino-antineutrino interactions [6].

Charmed hadrons have a large number of noneptonic decays due to the sizable mass of the charm quark. However, these decays are even more difficult to compute as the corresponding B decays, heavy mass expansion methods will not work as well here. While two body decays may be treated by the standard factorization assumption, the three and even four body decays are of interest for CP violation studies.

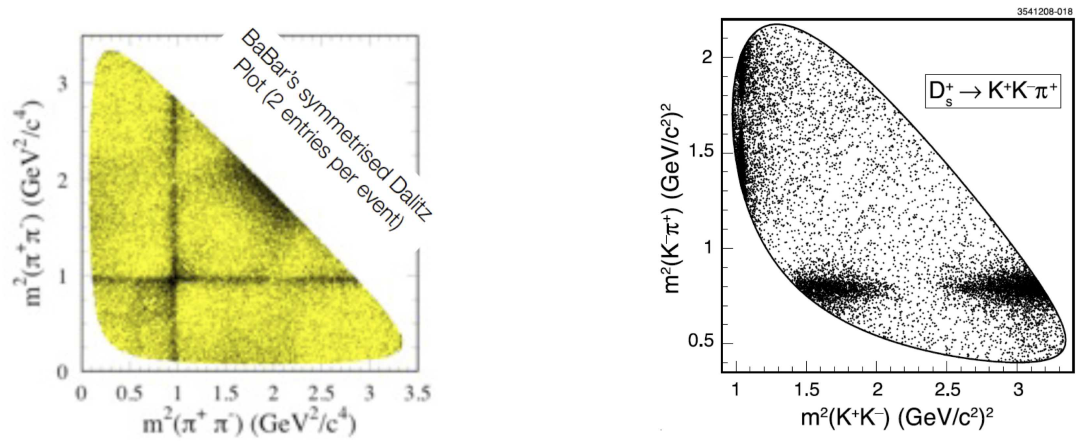

Figure 2: Dalitz distributions for three-body decays of the D meson.

Fig. 2 shows data for multiparticle final states from BaBar [7] and CLEO-c [8] for the decay $D_s \to \pi\pi\pi$ and $D_s \to KK\pi$ as examples for the quality of the present data. The resonance structures due the ρ, K^* and ϕ resonances are clearly visible; however a quantitative description of the Dalitz distrbutions is still difficult. However, as we shall see below, one may still define intresting observables with respect to CP violation studies.

3 Charm mixing

A special case for a FCNC is the $\Delta C = \pm 2$ interaction leading to the mixing of D^0 and $\overline{D}^0$. Thus in general, the charm eigenstates D^0 and $\overline{D}^0$ are not the same as the mass eigenstates due to this interaction. Rather, the two mass eigenstates $D_{1/2}$ are superpositions of the two according to

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \quad \text{with} \quad |p|^2 + |q|^2 = 1 \tag{4}$$

In general, the two mass eigenstates have different mass eigenvalues as well as a different width. The mixing parameters are defined as

$$x = \frac{m_1 - m_2}{\Gamma} \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \quad \text{with} \quad \Gamma = \frac{1}{2}(\Gamma_1 + \Gamma_2) \tag{5}$$

In the standard model, the $\Delta C = \pm 2$ interaction is mediated at the quark level by the box diagrams shown in Fig. 3. However, only the b-quark contribution becomes an effectively local interaction, while the d and the s contributions contain long distance pieces. Unfortunately, unlike in the case of B-$\bar{B}$ oscillations, the purely short distance piece is suppressed by the small CKM factor $(V_{cb}V_{ub}^*)^2$ while the long distance parts are proportional to $(V_{cs}V_{us}^*)^2$ and $(V_{cd}V_{ud}^*)^2$ and hence do not suffer from a strong CKM suppression. However, as has been pointed out in eq.(2), there is still a factor m_s^2/M_W^2 aside from the CKM factors, and hence we expect in general only small D^0-$\overline{D}^0$ mixing.

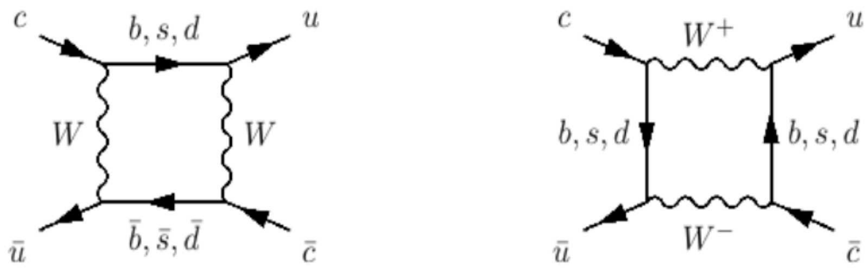

Figure 3: Quark level diagrams for D^0-$\overline{D}^0$ mixing

The long distance effects originating from the intermediate s and d quarks correspond in the hadronic world to common decay channels of the D and the $\overline{D}$; an example is shown in Fig. 4

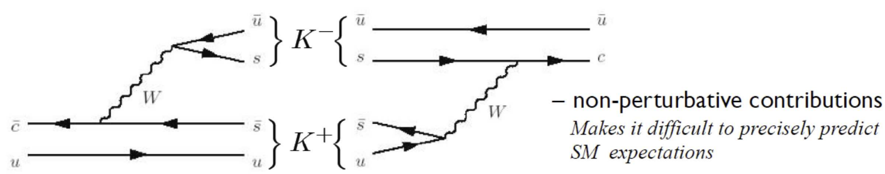

Figure 4: Example for a long distance contribution to D^0-$\overline{D}^0$ mixing

The long distance contributions are diffcult to estimate, and hence there is a substantial theoretical uncertainty in the calculation of x and y in the standard model. The typical results cover a range of $|x| \sim \mathcal{O}(10^{-3\ldots-2})$, $|y| \sim \mathcal{O}(10^{-3\ldots-2})$ [9]. The basis of these calculations are either an exclusive ansatz by summing over the possible common decay modes $D \to [K\pi/\pi\pi/\pi\rho/\ldots] \to \overline{D}$

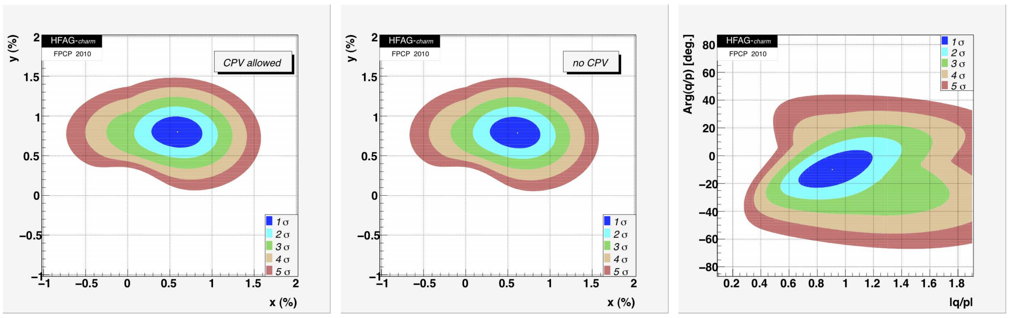

Figure 5: HFAG average for x and y

or by employing an operator product expansion which yields a series in inverse powers of the charm mass.

Charm mixing has attracted a lot of attention recently due to some experimental evidence. Fig. 5 shows the HFAG average [10] of the various data, ruling out the no-mixing case at a level of 5 σ. The most recent analyses yield $x = (0.59 \pm 0.20)\%$, $y = (0.80 \pm 0.13)\%$, $|p/q| = 0.91^{+0.19}_{-0.16}$ and $\arg(p/q) = -0.175^{+0.162}_{-0.152}$ rad, and hence there is evidence for D-$\overline{D}$ mixing. However, up to now there is no single 5 σ measurement.

From the theoretical side, the interpretation of these results is difficult due to long distance effects. A scenario where $|x| > 1\%$ and $|x| \gg |y|$ could be interpreted as a manifestion of new physics, however, this seems to be ruled out by the present data, which lie well within the standard-model expectations. However, due to the substantial hadronic uncertainties it may still contain a large new-physics contribution; a precise prediction within the standard model clearly requires a theoretical breakthrough in our ability to calculate hadronic matrix elements.

Although it is difficult to obtain a theory prediction for x and y, it is still of practical importance to know the values of these parameters, since the mixing opens the road to the possibility of time dependent CP asymmetries.

4 CP violation and new physics

Due to the small CKM angles between the first and third as well as between the second and the third family charm physics is mainly "two family" physics. Hence, in the standard model, the "pollution" of the third family is small and thus also all CP violating effects are small: There are no weak phases (and hence no CP violation) neither in Cabibbo allowed nor in doubly Cabibbo suppressed decays, and in singly Cabibbo suppressed decays the weak phase is of the order λ^4 where $\lambda \sim 0.2$ is the Wolfenstein parameter.

A direct CP violation usually occurs through an interference of two amplitudes with different CP phases. In the standard model this is the interference of a tree and a penguin diagram as shown in Fig. 6. It is well known that the resulting CP asymmetries are proportional to the strong phase difference of the two amplitudes and hence a quantitative estimate normally suffers from hadronic uncertainties.

However, due to the presence of D-$\overline{D}$ mixing the time evolution generates a phase difference $\sim \Delta m_D\, t$ where $\Delta m_D \propto x$ is the mass difference in the neutral D system. With respect to the

CP asymmetry, this phase difference acts like a strong phase and hence D-$\overline{D}$ oscillations offer a new window to measure CP asymmetries.

The time dependent CP asymmetry due to the small values of x and y may be written as

$$\mathcal{A}_{\rm CP}(t) = [x \sin\phi_{\rm CP} + y\,\epsilon_{\rm CP} \cos\phi_{\rm CP}] \left(\frac{t}{\tau}\right) \tag{6}$$

where $\phi_{\rm CP}$ is the weak phase of the D-$\overline{D}$ mixing amplitude, and $\epsilon_{\rm CP}$ corresponds to the parameter ϵ know from the kaon system and τ is the average lifetime. In the standard model we have $x, y \sim 1\%$ and $\phi_{\rm CP}, \epsilon_{\rm CP} \sim 10^{-3}$ and hence $\mathcal{A}_{\rm CP,SM}(t \sim \tau) = 10^{-5}$. Clearly such a small CP asymmetry is an exprimental challenge; in turn, if a sizable effect would turn up it would immediately imply the presence of new physics. In any case, channels like $D^0(t) \to K_s\phi, K^+K^-, \pi^+\pi^-, K^+\pi^-$ are interesting places to look for a CP asymmetry.

The ultimate tool for CP violation studies is to use the phase space distributions of multi-particle final states [11]. In general, local asymmetries can be expected to be larger than integrated ones, and one can also rely on relative normalizations instead of absolute ones. Furthermore, a phase space distribution may also give some hint on the nature of a possible new physics effect. The sensitivity and definitions of appropriate observables is currently under study.

Fig. 7 shows the current status of CP violation in charm decays [12] . There is no indication of an effect, however, we may expect that the uncertainties will reduce significantly in the near future.

5 FCNC decays

Rare FCNC decays are mediated by quark transitons of the form $c \to u + \gamma$ or $c \to u + \ell^+ + \ell^-$. At the quark level, these decays are supressed by the GIM mechanism, but there are also large long distance contributions, which are hard to calculate and which are several orders of magnitude larger than the short distance pieces.

The $c \to u + \gamma$ transitions at the quark level correspond to the decays $D_{(s)} \to \gamma + K^*/\rho/\omega/\phi$. The short distance piece mediated by the electromagnetic penguin diagram analgous to the one

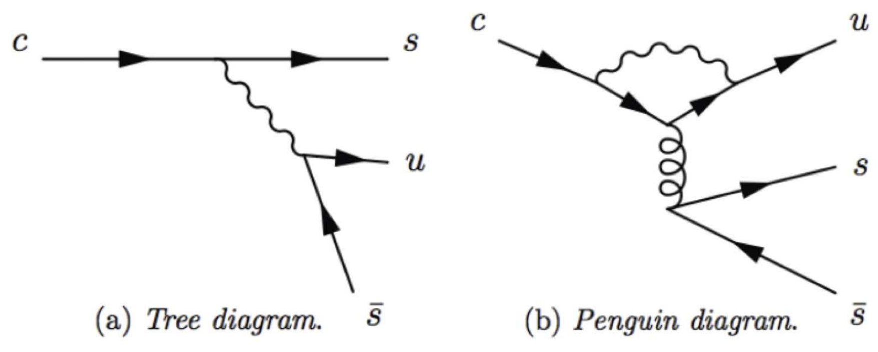

Figure 6: Tree and penguin diagrams for charm

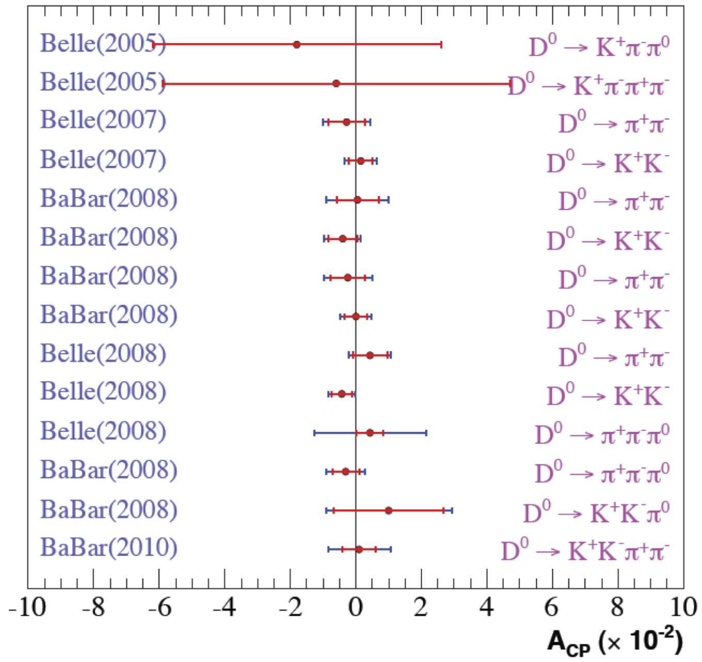

Figure 7: Current status of Charm CP measurements.

shown in Fig. 6 (b) yields a very small contribution of the order of BR $\sim$ few $\times 10^{-8}$ reflecting the GIM suppression. However, an estimate of the long distance contribution yields much larger branching ratios of the order $\text{BR}(D^0 \to K^*\gamma) \sim 10^{-5} - 10^{-4}$ and $\text{BR}(D^0 \to \rho\gamma) \sim 10^{-6} - 10^{-5}$ with a substantial uncertainty.

Any "new physics" in this case would appear through a local, penguin-like contribution of similar structure as the short distance operators. Unless this has an enormous coefficient that overwhelms even the long-distance contribution, this will be hard to identify. Again a theoretical breakthrough would be needed in the calculation of hadronic matrix elements before a convincing case for new physics in theses decays can be constructed.

The situation is not much different for the $c \to u + \ell^+ + \ell^-$ case. The decays $D_{(s)} \to \ell^+\ell^- + K^*/\rho/\omega/\phi$ are also dominated by long distance contributions, e.g. $\text{BR}(D^0 \to \pi/\rho + \ell^+\ell^-) \sim 10^{-6}$ which is again three orders of magnitude larger than the short distance piece. However, the additional information contained in the lepton mass- and energy spectra my help to construct a new physics case.

Finally, purely leptonic FCNC modes may be good candidates for a search at LHC, while the mode $D^0 \to \gamma\gamma$ will be a challenge at any hadron machine. However, from the theoretical side, the mode $D^0 \to \gamma\gamma$ also has long distance contributions which are not well under control, which in turn pollute some of the interesting modes such as $D^0 \to \mu^+\mu^-$. Standard model estimates yield a small braching ratio, $\text{BR}(D^0 \to \mu^+\mu^-) \sim 10^{-12}$.

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