Review of Charm Physics
A Theory Perspective

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Disclaimer

I will not talk about the “new states” X,Y,Z ....

- ... although this is currently a “hot topic”,
- ... but it concerns mainly our (non)-understanding of low-energy QCD,
- ... thus it has its own relevance with respect to QCD
- Emphasis is laid on Charm-Flavour Aspects,
- ... including a possible shot at “new physics” from precision flavour physics
Contents

1. Introduction
2. Bread and Butter of Charm
3. Charm Mixing
4. CP in Charm, New Physics
5. Rare Decays
Introduction: Looking up ...

- Flavour Physics of charm: Compared to $B$ and $K$: The roles of up and down quarks are interchanged
- Complementarity to top quark (flavour) physics
- Up-type Flavour tests are mandatory for a full test of our understanding of Flavour Physics
Charm is unique ...

- FCNC’s are suppressed in the SM by GIM
- For bottom and strange:
  \[
  \text{GIM} \propto \frac{1}{16\pi^2} \frac{m_t^2 - m_u^2}{M_W^2}
  \]
  GIM is weakened by the large Top mass
- For charm (and top):
  \[
  \text{GIM} \propto \frac{1}{16\pi^2} \frac{m_b^2 - m_d^2}{M_W^2}
  \]
  GIM is MUCH more efficient
Up-type FCNC's have a very small SM “pollution”

Relative Strength of New Physics (NP) in Up vs. Down-Type FCNC’s might be different

Cleaner (but not neccessary larger) signals of new physics:

\[
\left( \frac{\text{NP Signal}}{\text{SM noise}} \right)_{\text{up-type}} > \left( \frac{\text{NP Signal}}{\text{SM noise}} \right)_{\text{down-type}}
\]

Top plays a special role

- No Top Hadrons
- Flavour Phenomenology less rich
- Strong interactions perturbative

Charm: Novel access to flavour dynamics
Bread and Butter Processes

- (Semi-)leptonics: \( c \rightarrow s\ell \bar{\nu}_\ell \) and \( c \rightarrow d\ell \bar{\nu}_\ell \)
- Non-leptonics: \( c \rightarrow s\bar{q}q' \) and \( c \rightarrow d\bar{q}q' \)
- Access to CKM matrix elements
- Non-leptonic multiparticle decays: CP violation
Charm Semi-Leptonics

Dedicated Charm Experiment: CLEO-c:

- $D^0 \to \pi^- e^+ \nu_e$
- $D^+ \to \pi^0 e^+ \nu_e$
- $D^0 \to K^- e^+ \nu_e$
- $D^+ \to \bar{K}^0 e^+ \nu_e$
- From factor calculations: lattice and QCD SR
- Direct determinations of $V_{cs}$ and $V_{cd}$

$$V_{cd} = 0.225 \pm 0.005 \pm 0.003^{+0.016}_{-0.012}$$

(Khodjamirian et al.)

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Charm Non-Leptononics: Two Body Decays

T = Colour-favoured Tree

C = Colour-suppressed tree

E = Exchange

A = Annihilation

The QC
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$K^-\pi^+$</td>
<td>3.891±0.077</td>
<td>$T + E$</td>
</tr>
<tr>
<td></td>
<td>$\overline{K}^0\pi^0$</td>
<td>2.380±0.092</td>
<td>$(C - E)/\sqrt{2}$</td>
</tr>
<tr>
<td></td>
<td>$\overline{K}^0\eta$</td>
<td>0.962±0.060</td>
<td>$\frac{C}{\sqrt{2}}\sin(\theta_\eta + \phi_1) - \frac{\sqrt{3}E}{\sqrt{2}}\cos(\theta_\eta + 2\phi_1)$</td>
</tr>
<tr>
<td></td>
<td>$\overline{K}^0\eta'$</td>
<td>1.900±0.108</td>
<td>$-\frac{C}{\sqrt{2}}\cos(\theta_\eta + \phi_1) - \frac{\sqrt{3}E}{\sqrt{2}}\sin(\theta_\eta + 2\phi_1)$</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$\overline{K}^0\pi^+$</td>
<td>3.074±0.097</td>
<td>$C + T$</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$\overline{K}^0K^+$</td>
<td>2.98±0.17</td>
<td>$C + A$</td>
</tr>
<tr>
<td></td>
<td>$\pi^+\eta$</td>
<td>1.84±0.15</td>
<td>$T\cos(\theta_\eta + \phi_1) - \sqrt{2}A\sin(\theta_\eta + \phi_1)$</td>
</tr>
<tr>
<td></td>
<td>$\pi^+\eta'$</td>
<td>3.95±0.34</td>
<td>$T\sin(\theta_\eta + \phi_1) + \sqrt{2}A\cos(\theta_\eta + \phi_1)$</td>
</tr>
</tbody>
</table>

$$T = 3.003 \pm 0.023$$

$$C = (2.565 \pm 0.030) \exp [i(-152.11 \pm 0.57)^\circ]$$

$$E = (1.372 \pm 0.036) \exp [i(123.62 \pm 1.25)^\circ]$$

$$A = (0.452 \pm 0.058) \exp [i(19^{+15}_{-14})^\circ]$$
Charm Nonleptonics: Dalitz Analyses

- Relevant for CP violation studies
Transitions between $D^0$ and $\bar{D}^0$:

Two Mass Eigenstates in the neutral $D$ System

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \quad |p|^2 + |q|^2 = 1$$

Mixing Parameters

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

Opens a window to new physics

Opens the road to time-dependent CP violation
**Standard Model: At the quark level:**

\[
\begin{align*}
|\mathbf{x}| & \sim \mathcal{O}(10^{-3} \ldots -2), \\
|\mathbf{y}| & \sim \mathcal{O}(10^{-3} \ldots -2)
\end{align*}
\]

**Pollution by long distance effects**

\[
\begin{align*}
\bar{u} & \rightarrow s \rightarrow c \rightarrow \bar{u} \\
\bar{c} & \rightarrow u \rightarrow s \rightarrow \bar{c}
\end{align*}
\]

- Non-perturbative contributions

*Makes it difficult to precisely predict SM expectations*
Exclusive calculations $D \rightarrow [K\pi/\pi\pi/\pi\rho/\ldots] \rightarrow \bar{D}$

Inclusive calculation:
OPE in terms of inverse Powers of the charm mass

(Falk, Grossman, Ligeti, Nir, Petrov)
(Uraltsev, Georgi, Simmons, Ricciati, Ohl)
There are data!!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No CPV</th>
<th>No direct CPV</th>
<th>CPV-allowed</th>
<th>CPV-allowed 95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$ (%)</td>
<td>$0.61^{+0.19}_{-0.20}$</td>
<td>$0.59 \pm 0.20$</td>
<td>$0.59 \pm 0.20$</td>
<td>[0.19, 0.97]</td>
</tr>
<tr>
<td>$y$ (%)</td>
<td>$0.79 \pm 0.13$</td>
<td>$0.81 \pm 0.13$</td>
<td>$0.80 \pm 0.13$</td>
<td>[0.54, 1.05]</td>
</tr>
</tbody>
</table>
Mixing seems established, but no single 5σ measurement!
Interpretation of Charm Mixing

- **Difficult**, due to long distance contributions
- A scenario $|x| > 1\%$ and $|x| \gg |y|$ could be interpreted as a manifestation of NP
- ... but seems to be ruled out already
- Observations can be due to SM dynamics
- ... yet may still contain a large NP contribution
- A precise SM prediction requires a theoretical breakthrough
- Knowing $x$ and $y$ is also of practical importance with respect to CP violation
In the SM:

- Couplings to the third family are small
- SM Charm Physics is “two family physics”
- only small pollution from the third family
- CP violating effects are tiny
- Weak phase in CS decays: $V_{cs} = 1\ldots + i\lambda^4$

- No weak phases in CA and DCS modes
$D^0 - \bar{D}^0$ Oscillations open an additional window to CP

$$A_{CP}(t) = [x \sin \phi_{CP} + y \epsilon_{CP} \cos \phi_{CP}] \left( \frac{t}{\tau} \right)$$

- $\phi_{CP}$: Weak Phase in $D^0 - \bar{D}^0$ mixing
- $\epsilon_{CP}$: Corresponds to the $\epsilon$ parameter for the Kaons
- In the SM: $x, y \sim 1\%$ and $\sin \phi_{CP}, \epsilon_{CP} \leq 10^{-3}$

\[ A_{CP}(t) \sim 10^{-5} \text{ in the SM} \]

This is an experimental challenge

Good news for LHCb:

$D^0(t) \rightarrow K_S\phi, K^+K^-, \pi^+\pi^-, K^+\pi^-$
CP in Charm as Indication of New Physics

- Baryon Asymmetry: CP violation beyond CKM
- CP Asymmetries are linear in the NP amplitude
- Tiny SM Effects $\rightarrow$ Very small SM background:
  $$A_{\text{CP}}(t) \sim 10^{-3} \text{ in some NP models}$$
- Large CP sensitivity in final state distributions
Ultimate tool for CP Studies:

- Local Asymmetries will be larger than integrated ones
- Can rely on relative instead of absolute normalization
- Can give us more information on the nature of the NP

(Bigi, Hanhart, Meissner, Gardener, TM, ...)

\[
D_s^+ \rightarrow K^+K^-\pi^+
\]
Current Status of Charm CP

- Belle(2005)
- Belle(2005)
- Belle(2007)
- Belle(2007)
- BaBar(2008)
- BaBar(2008)
- BaBar(2008)
- BaBar(2008)
- Belle(2008)
- Belle(2008)
- Belle(2008)
- Belle(2008)
- BaBar(2008)
- BaBar(2008)
- BaBar(2010)

Decays:
- \( D^0 \rightarrow K^+\pi^-\pi^0 \)
- \( D^0 \rightarrow K^+\pi^+\pi^- \)
- \( D^0 \rightarrow \pi^+\pi^- \)
- \( D^0 \rightarrow K^+K^- \)
- \( D^0 \rightarrow \pi^+\pi^- \)
- \( D^0 \rightarrow K^+K^- \)
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- \( D^0 \rightarrow K^+K^- \)
- \( D^0 \rightarrow \pi^+\pi^- \)
- \( D^0 \rightarrow K^+K^- \)
- \( D^0 \rightarrow \pi^+\pi^- \)

\( A_{CP} \times 10^{-2} \)
**Rare Decays**

- $c \to u + \gamma$ transitions
  - $D_{(s)} \to \gamma + K^*/\rho/\omega/\phi$
  - ... SM short distance contribution: $\text{BR} \sim \text{few} \times 10^{-8}$
  - ... dominated by long distance contributions:
    - $\text{BR}(D^0 \to K^*\gamma) \sim 10^{-5} - 10^{-4}$
    - $\text{BR}(D^0 \to \rho\gamma) \sim 10^{-6} - 10^{-5}$
  - NP appears as local “Penguin” operators
  - Can a convincing NP case be constructed in these decays?

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**c → u + ℓ⁺ℓ⁻ transitions**

- $D_{(s)} \rightarrow ℓ⁺ℓ⁻ + K^*/ρ/ω/ϕ$
- ... also dominated by long distance contributions:
  $\text{BR}(D^0 \rightarrow π/ρ + ℓ⁺ℓ⁻) \sim 10^{-6}$

- **Analysis of the lepton spectra can help**
- **Likewise: Can a convincing NP case be constructed in these decays?**
  - $D^0 \rightarrow μ⁺μ⁻$: A channel for LHCb!
    - In the SM: $\text{BR}(D^0 \rightarrow μ⁺μ⁻) \sim 10^{-12}$
  - $D^0 \rightarrow γγ$: Not a channel for LHCb!
    - LD Contributions, interplay with $D^0 \rightarrow μ⁺μ⁻$
  - “Forbidden” Modes: $D^0 \rightarrow e⁺μ⁻$ etc...
Conclusions

- Charm offers a unique possibility to test Flavour in the up sector
- Complementarity with Top Quark Physics
- Evidence for $D$-$\overline{D}$ Oscillations opens new roads
- SM background in charm is much smaller than in bottom or strange
- CP violation studies in final state distributions offer high sensitivity

Charm Studies are mandatory to complete our test of flavour