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

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

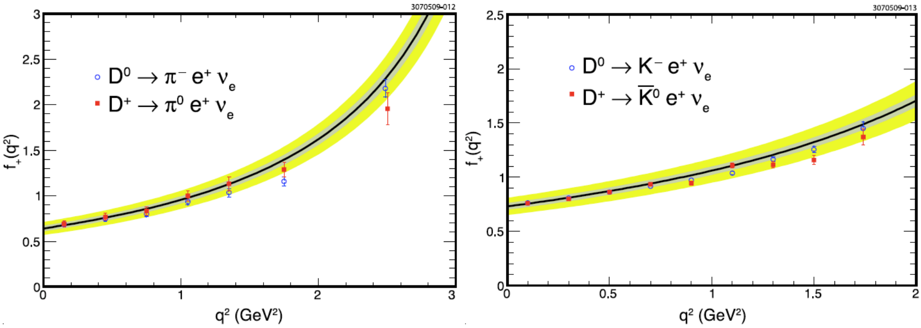
Charm: Novel access to flavour dynamics

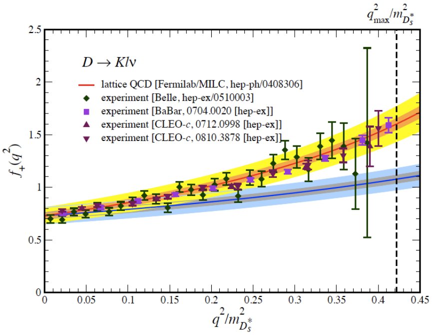
Bread and Butter Processes

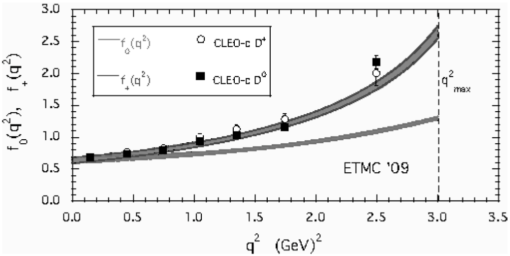
- (Semi-)leptonics: $c \longrightarrow s\ell\bar{\nu}_\ell$ and $c \longrightarrow d\ell\bar{\nu}_\ell$
- Non-leptonics: $c \longrightarrow s\bar{q}q'$ and $c \longrightarrow d\bar{q}q'$
- Access to CKM matrix elements
- Non-leptonic multiparticle decays: CP violation

Charm Semi-Leptonics

- Dedicated Charm Experiment: CLEO-c:







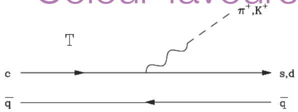
- From factor calculations: lattice and QCD SR
- Direct determinations of V_{cs} and V_{cd}

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

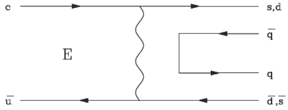
(Khodjamirian et al.)

Charm Non-Leptonics: Two Body Decays

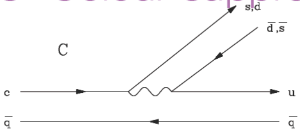
T=Colour-favoured Tree



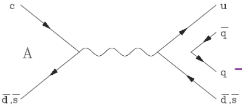
E=Exchange



C=Colour-suppressed tree



A=Annihilation

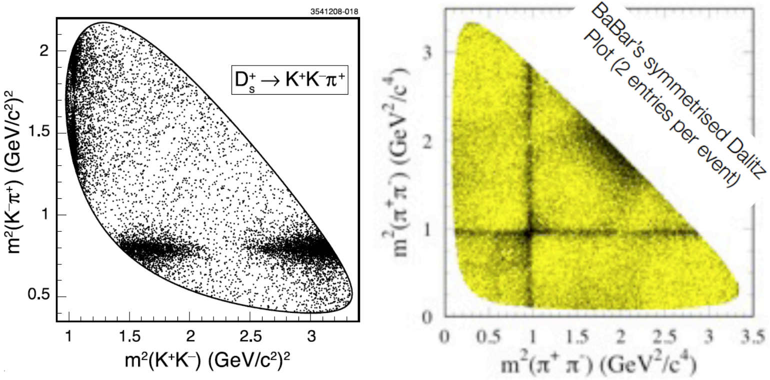


The
QC

Meson	Decay mode	$\mathcal{B}$ [10] (%)	Rep.
D^0	$K^-\pi^+$	3.891±0.077	$T+E$
	$\overline{K}^0\pi^0$	2.380±0.092	$(C-E)/\sqrt{2}$
	$\overline{K}^0\eta$	0.962±0.060	$\frac{C}{\sqrt{2}}\sin(\theta_\eta+\phi_1)-\frac{\sqrt{3}E}{\sqrt{2}}\cos(\theta_\eta+2\phi_1)$
	$\overline{K}^0\eta'$	1.900±0.108	$-\frac{C}{\sqrt{2}}\cos(\theta_\eta+\phi_1)-\frac{\sqrt{3}E}{\sqrt{2}}\sin(\theta_\eta+2\phi_1)$
D^+	$\overline{K}^0\pi^+$	3.074±0.097	$C+T$
D_s^+	$\overline{K}^0K^+$	2.98±0.17	$C+A$
	$\pi^+\eta$	1.84±0.15	$T\cos(\theta_\eta+\phi_1)-\sqrt{2}A\sin(\theta_\eta+\phi_1)$
	$\pi^+\eta'$	3.95±0.34	$T\sin(\theta_\eta+\phi_1)+\sqrt{2}A\cos(\theta_\eta+\phi_1)$

$$\begin{aligned}
T &= 3.003 \pm 0.023 \\
C &= (2.565 \pm 0.030)\ \exp\left[i(-152.11 \pm 0.57)^\circ\right] \\
E &= (1.372 \pm 0.036)\ \exp\left[i(123.62 \pm 1.25)^\circ\right] \\
A &= (0.452 \pm 0.058)\ \exp\left[i(19^{+15}_{-14})^\circ\right]
\end{aligned}$$

Charm Nonleptonics: Dalitz Analyses



- Relevant for CP violation studies

Charm Mixing

- Transitions between D^0 and $\overline{D}^0$:
  Two Mass Eigenstates in the neutral D System

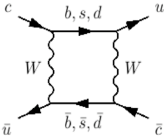
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \qquad |p|^2 + |q|^2 = 1$$

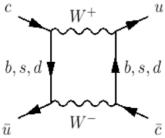
- Mixing Parameters

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

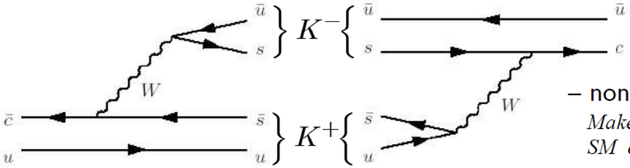
- Opens a window to new physics
- Opens the road to time-dependent CP violation

- Standard Model: At the quark level:





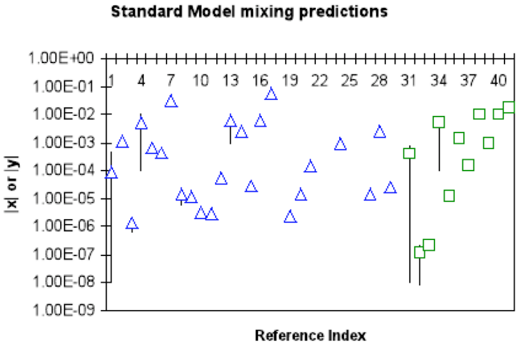
- Pollution by long distance effects



– non-perturbative contributions

Makes it difficult to precisely predict SM expectations

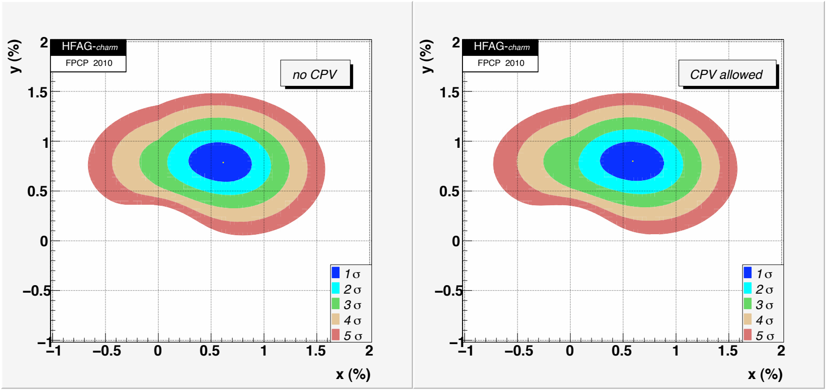
In the SM: $|x| \sim \mathcal{O}(10^{-3 \dots -2})$, $|y| \sim \mathcal{O}(10^{-3 \dots -2})$



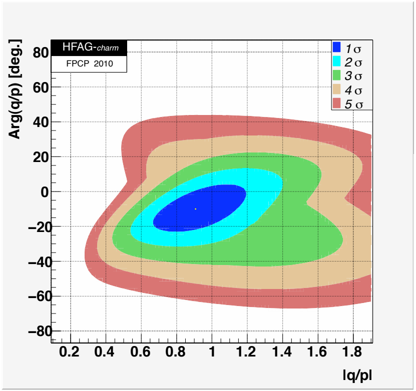
(Petrov)

- Exclusive calculations $D \to [K\pi/\pi\pi/\pi\rho/\ldots] \to \overline{D}$
  (Falk, Grossman, Ligeti, Nir, Petrov)
- Inclusive calculation:
  OPE in terms of inverse Powers of the charm mass
  (Uraltsev, Georgi, Simmons. Ricciati, Ohl)

There are data !!



Parameter	No CPV	No direct CPV	CPV-allowed	CPV-allowed 95% C.L.
x (%)	$0.61\,^{+0.19}_{-0.20}$	0.59 ± 0.20	0.59 ± 0.20	$[0.19,\ 0.97]$
y (%)	0.79 ± 0.13	0.81 ± 0.13	0.80 ± 0.13	$[0.54,\ 1.05]$



EPS 2009

$x = (0.976 \pm 0.249)\%$

$y = (0.833 \pm 0.160)\%$

$|q/p| = 0.866 \pm 0.160$

$\varphi = -0.148 \pm 0.126$ rad

FPCP 2010

$x = (0.59 \pm 0.20)\%$

$y = (0.80 \pm 0.13)\%$

$|q/p| = 0.91^{+0.19}_{-0.16}$

$\varphi = -10^{+9.3}_{-8.7}$ deg

($\varphi = -0.175^{+0.162}_{-0.152}$ rad)

- Mixing seems established,
  but no single 5σ measurement!

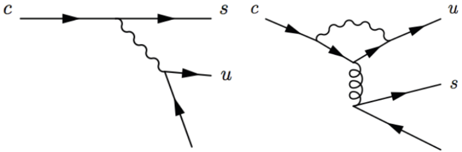
Interpretation of Charm Mixing

- 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 our 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

CP in Charm

In the SM:

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



(a) *Tree diagram.* (b) *Penguin diagram.*

- No weak phases in CA and DCS modes

- $D^0 - \overline{D}^0$ Oscillations open an additional window to CP

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

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

$$\boxed{\mathcal{A}_{\rm CP}(t) \sim 10^{-5} \text{ in the SM}}$$

- This is an experimental challenge
- Good news for LHCb:
  $D^0(t) \to K_s\phi, K^+K^-, \pi^+\pi^-, K^+\pi^-$

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 $\to$ Very small SM background:

$$\mathcal{A}_{\rm CP}(t) \sim 10^{-5} \text{ in some NP models}$$

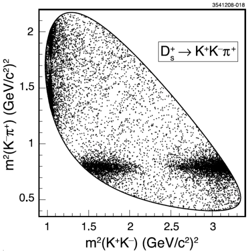
- Large CP sensitivity in final state distributions

CP Studies in Final State Distribution

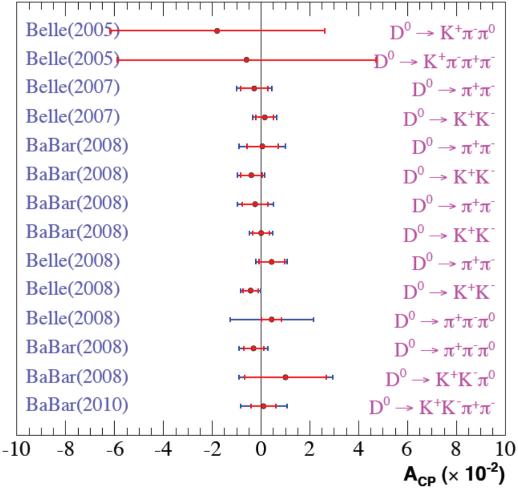
Ultimate tool for CP Studies:

- 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, ...)



Current Status of Charm CP



Rare Decays

$c \to u + \gamma$ transitions

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

$c \to u + \ell^+\ell^-$ transitions

- $D_{(s)} \to \ell^+\ell^- + K^*/\rho/\omega/\phi$
- ... also dominated by long distance contributions:
  $\mathrm{BR}(D^0 \to \pi/\rho + \ell^+\ell^-) \sim 10^{-6}$
- Analysis of the lepton spectra can help
- Likewise: Can a convincing NP case be constructed in these decays?
- $D^0 \to \mu^+\mu^-$: A channel for LHCb!
  In the SM: $\mathrm{BR}(D^0 \to \mu^+\mu^-) \sim 10^{-12}$
- $D^0 \to \gamma\gamma$: Not a channel for LHCb!
  LD Contributions, interplay with $D^0 \to \mu^+\mu^-$
- "Forbidden" Modes: $D^0 \to e^+\mu^-$ 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 stange
- CP violation studies in final state distributions offer high sensitivity

Charm Studies are mandatory to complete our test of flavour