CP violation in charm

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Introduction

Murphy's law:

Modern charm physics experiments acquire ample statistics; many decay rates are quite large.

THUS:

It is very difficult to provide model-independent theoretical description of charmed quark systems.

Now, this does not apply to CP-violation in charm: both measurements and predictions are hard…

CP-violation preliminary

- In any quantum field theory CP-symmetry can be broken

1. Explicitly through dimension-4 operators ("hard")

   Example: Standard Model (CKM): $\bar{\psi}_i \psi_k \overset{CP}{\Rightarrow} \bar{\psi}_k \psi_i, \ \varphi \overset{CP}{\Rightarrow} \varphi$

   $$\mathcal{L}_{Yuk} = \zeta_{ik} \bar{\psi}_i \psi_k \varphi + H.c. \overset{CP}{\not\Rightarrow} \mathcal{L}_{Yuk}$$

2. Explicitly through dimension <4 operators ("soft")

   Example: SUSY

3. Spontaneously (CP is a symmetry of the Lagrangian, but not of the ground state)

   Example: multi-Higgs models, left-right models

- These mechanisms can be probed in charm transitions

CP-violation in charmed mesons

- Possible sources of CP violation in charm transitions:

  - CPV in Δc = 1 decay amplitudes ("direct" CPV)

$$A\left(D \to f\right) \equiv A_f = \left|A_1\right| e^{i\delta_1} e^{i\phi_1} + \left|A_2\right| e^{i\delta_2} e^{i\phi_2}, \quad \Delta\delta \neq 0, \Delta\phi \neq 0$$

  - CPV in $D^0 - \overline{D^0}$ mixing matrix (Δc = 2) $\left[M - i\frac{\Gamma}{2}\right]_{ij} = \begin{pmatrix} A & p^2 \\ q^2 & A \end{pmatrix}$

$$R_m^2 = \left|\frac{p}{q}\right|^2 = \frac{2M_{12} - i\Gamma_{12}}{2M_{12}^* - i\Gamma_{12}^*} \neq 1$$

  - CPV in the interference of decays with and without mixing

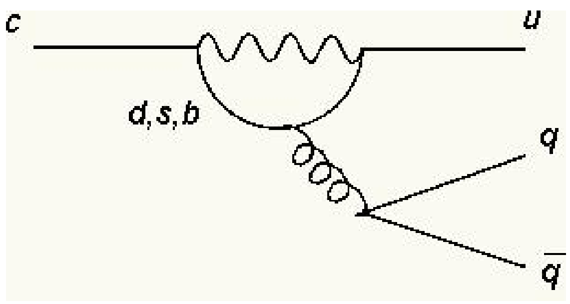
$$\lambda_f = \frac{q}{p}\frac{\overline{A_f}}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A_f}}{A_f}\right|$$

- One can separate various sources of CPV by customizing observables

Comment

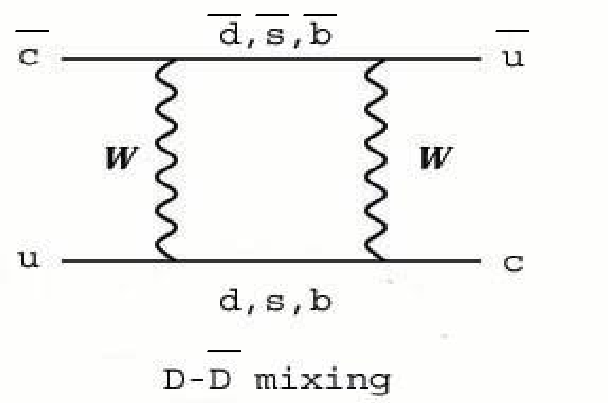
- Generic expectation is that CP-violating observables in the SM are small

$\Delta c = 1$ amplitudes



Penguin amplitude

$\Delta c = 2$ amplitudes



- The Unitarity Triangle for charm:

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

$$\sim \lambda \qquad \sim \lambda \qquad \sim \lambda^5$$

With b-quark contribution neglected: only 2 generations contribute
$\Rightarrow$ **real 2x2 Cabibbo matrix**

Any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$
Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

How to observe CP-violation?

- There exists a variety of CP-violating observables

1. "Static" observables, such as electric dipole moment
2. "Dynamical" observables:
   a. Transitions that are forbidden in the absence of CP-violation

   $$CP\left[\text{initial state}\right] \neq CP\left[\text{final state}\right]$$

   b. Mismatch of transition probabilities of CP-conjugated processes

   $$\Gamma\left(D \to f\right) \neq \Gamma\left(\overline{D} \to \overline{f}\right)$$

   c. Various asymmetries in decay distributions, etc.

- Depending on the initial and final states, these observables can be affected by all three sources of CP-violation

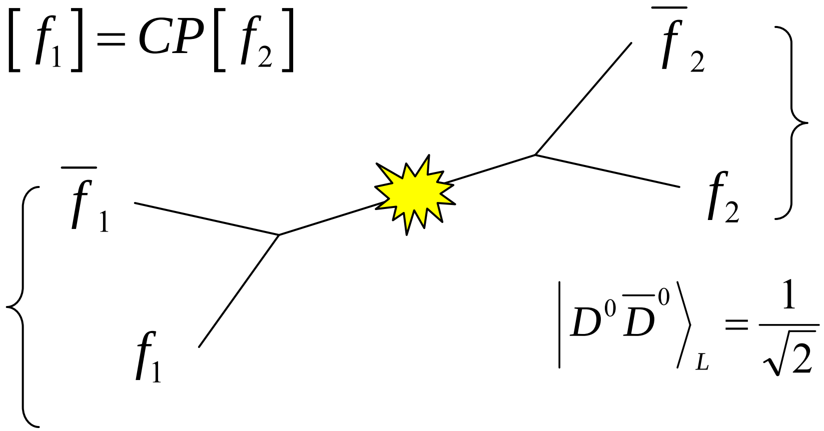
a. Transitions forbidden w/out CP-violation

τ-charm factory (BES/CLEO-c)

Recall that CP of the states in $D^0\overline{D^0} \to (F_1)(F_2)$ are anti-correlated at ψ(3770):

- a simple signal of CP violation: $\psi(3770) \to D^0\overline{D^0} \to (CP\pm)(CP\pm)$

$$CP[f_1] = CP[f_2]$$



CP eigenstate f_2

CP eigenstate f_1

$$\left|D^0\overline{D}^0\right\rangle_L = \frac{1}{\sqrt{2}}\left[\left|D^0(k_1)\overline{D}^0(k_2)\right\rangle + (-1)^L\left|D^0(k_2)\overline{D}^0(k_1)\right\rangle\right]$$

$$\Gamma_{F_1F_2} = \frac{\Gamma_{F_1}\Gamma_{F_2}}{2R_m^2}\left[\left(2+x^2+y^2\right)\left|\lambda_{F_1}-\lambda_{F_2}\right|^2 + \left(x^2+y^2\right)\left|1-\lambda_{F_1}\lambda_{F_2}\right|^2\right]$$

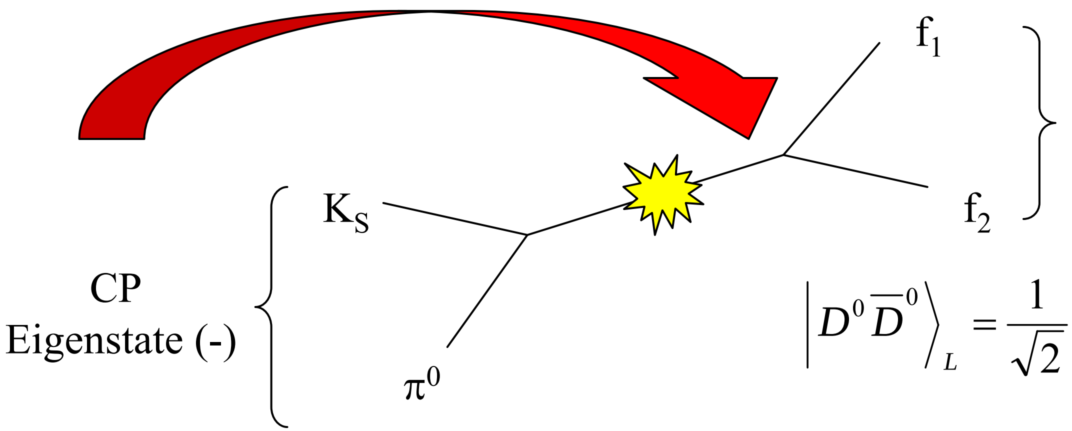
$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

- CP-violation in the **rate** → of the *second order* in CP-violating parameters.
- Cleanest measurement of CP-violation!

What if f_1 or f_2 is not a CP-eigenstate

τ-charm factory (BES/CLEO-c)

- If CP violation is neglected: mass eigenstates = CP eigenstates
- CP eigenstates do NOT evolve with time, so can be used for "tagging"



$$D_{CP(+)} \to f_1 f_2$$

$$\left|D^0\overline{D}^0\right\rangle_L = \frac{1}{\sqrt{2}}\left[\left|D^0(k_1)\overline{D}^0(k_2)\right\rangle + (-1)^L\left|D^0(k_2)\overline{D}^0(k_1)\right\rangle\right]$$

- τ-charm factories have good CP-tagging capabilities

  CP anti-correlated $\psi(3770)$: $CP(tag)\,(-1)^L = \overbrace{[CP(K_S)\,CP(\pi^0)]}^{(-)}\,(-1) = +1$

  CP correlated $\psi(4140)$

Can measure (y cos φ): $B^l_\pm = \dfrac{\Gamma\left(D_{CP\pm} \to X l \nu\right)}{\Gamma_{tot}}$

$$y\cos\phi = \frac{1}{4}\left(\frac{B^l_+}{B^l_-} - \frac{B^l_-}{B^l_+}\right)$$

D. Atwood, A.A.P., hep-ph/0207165
D. Asner, W. Sun, hep-ph/0507238

b. Mismatch of transition probabilities

- At least two components of the transition amplitude are required

Look at charged D's: $A\left(D^+ \to f\right) \equiv A_f = |A_1| e^{i\delta_1} e^{i\phi_1} + |A_2| e^{i\delta_2} e^{i\phi_2}$

Then, a charge asymmetry will provide a CP-violating observable

$$a_f = \frac{\Gamma\left(D^+ \to f\right) - \Gamma\left(D^- \to \overline{f}\right)}{\Gamma\left(D^+ \to f\right) + \Gamma\left(D^- \to \overline{f}\right)} = \frac{2\,\mathrm{Im}\,A_1 A_2^* \sin\left(\delta_1 - \delta_2\right)}{|A_1|^2 + |A_2|^2 + 2\,\mathrm{Re}\,A_1 A_2^* \cos\left(\delta_1 - \delta_2\right)}$$

...or, introducing $r_f = |A_2/A_1|$: $a_f = 2 r_f \sin\phi \sin\delta$

Prediction sensitive to details of hadronic model

- Same formalism applies if one of the amplitudes is generated by New Physics

→ need $r_f \sim 1$ % for O(1%) charge asymmetry

b. Mismatch of transition probabilities - II

➢ This can be generalized for neutral D-mesons too:

$$a_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \quad \text{and} \quad a_{\overline{f}} = \frac{\Gamma(D \to \overline{f}) - \Gamma(\overline{D} \to f)}{\Gamma(D \to \overline{f}) + \Gamma(\overline{D} \to f)}$$

➢ Each of those asymmetries can be expanded as

$$a_f = a_f^d + a_f^m + a_f^i$$

direct, mixing, interference

$$a_f^d = 2r_f \sin\phi_f \sin\delta_f$$

$$a_f^m = -R_f \frac{y'_f}{2}\left(R_m - R_m^{-1}\right)\cos\phi$$

$$a_f^i = R_f \frac{x'_f}{2}\left(R_m + R_m^{-1}\right)\sin\phi$$

1. similar formulas available for $\overline{f}$
2. for CP-eigenstates: $f=\overline{f}$ and $y_f' \to y$

Those observables are of the <u>first</u> order in CPV parameters, but require tagging

What to expect?

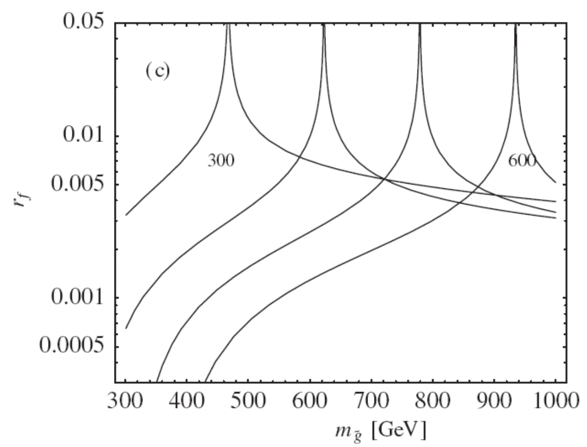
- Standard Model asymmetries (in 10^{-3}):

Final state	$\pi^+\eta$	$\pi^+\eta'$	$K^+\overline{K^0}$	$\pi^+\rho^0$	$\pi^0\rho^+$	$K^{*+}\overline{K^0}$	$K^+\overline{K^{*0}}$
a_f, $\cos\delta > 0$	-1.5±0.4	0.04±0.01	1.0±0.3	-2.3±0.6	2.9±0.8	-0.9±0.3	2.8±0.8
a_f, $\cos\delta < 0$	-0.7±0.4	0.02±0.01	0.5±0.3	-1.2±0.6	1.5±0.8	-0.5±0.3	1.4±0.7

F. Buccella et al, Phys. Lett. B302, 319, 1993

- New Physics (in new tree-level interaction and new loop effects):

Model	r_f
Extra quarks in vector-like rep	$< 10^{-3}$
RPV SUSY	$< 1.5\times10^{-4}$
Two-Higgs doublet	$< 4\times10^{-4}$



Y. Grossman, A. Kagan, Y. Nir, Phys Rev D 75, 036008, 2007

Experimental constraints

➢ HFAG provides the following averages from BaBar, Belle, CDF, E687, E791, FOCUS, CLEO collaborations

Decay mode	CP asymmetry
$D^0 \to K^+K^-$	$+0.0136 \pm 0.012$
$D^0 \to K_S^0 K_S^0$	-0.23 ± 0.19
$D^0 \to \pi^+\pi^-$	$+0.0127 \pm 0.0125$
$D^0 \to \pi^0\pi^0$	$+0.001 \pm 0.048$
$D^0 \to \pi^+\pi^-\pi^0$	$+0.01 \pm 0.09$
$D^0 \to K_S^0\pi^0$	$+0.001 \pm 0.013$
$D^0 \to K^-\pi^+\pi^0$	-0.031 ± 0.086
$D^0 \to K^+\pi^-\pi^0$	-0.001 ± 0.052
$D^0 \to K_S^0\pi^+\pi^-$	-0.009 ± 0.042
$D^0 \to K^+\pi^-\pi^+\pi^-$	-0.018 ± 0.044
$D^0 \to K^+K^-\pi^+\pi^-$	-0.082 ± 0.073

Decay mode	CP asymmetry
$D^+ \to K_S^0\pi^+$	-0.016 ± 0.017
$D^+ \to K_S^0 K^+$	$+0.071 \pm 0.062$
$D^+ \to K^+K^-\pi^+$	$+0.007 \pm 0.008$
$D^+ \to \pi^+\pi^-\pi^+$	-0.017 ± 0.042
$D^+ \to K_S^0 K^+\pi^+\pi^-$	-0.042 ± 0.068

Most measurements are at the percent sensitivity

Time-dependent observables

Time dependent $D^0(t) \to K^+K^-$ (lifetime difference analysis):
separate datasets for D⁰ and $\overline{D^0}$

$$\Delta Y_{KK} = \frac{\Gamma'\left(D^0 \to K^+K^-\right) - \Gamma'\left(\overline{D^0} \to K^+K^-\right)}{\Gamma'\left(D^0 \to K^+K^-\right) + \Gamma'\left(\overline{D^0} \to K^+K^-\right)} = \frac{A_m}{2} y \cos\phi - x \sin\phi$$

S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir, A.A. Petrov, Phys. Lett. B486, 418 (2000)

$$\Delta Y_{KK} = a^m_{KK} + a^i_{KK}$$

← universal for all final states

This analysis requires

1. time-dependent studies
2. initial flavor tagging ("the D* trick")

BaBar [2003]: $\Delta Y=(-0.8\pm0.6\pm0.2)\times10^{-2}$
Belle [2003]: $\Delta Y=(+0.20\pm0.63\pm0.30)\times10^{-2}$

World average: $\Delta Y=(-0.35\pm0.47)\times10^{-2}$

Y. Grossman, A. Kagan, Y. Nir, Phys Rev D 75, 036008, 2007

Untagged observables

Look for CPV signals that are

1. first order in CPV
2. do not require flavor tagging

Consider the final states that can be reached by both $\overline{D^0}$ and D^0, but are not CP eigenstates ($\pi\rho$, KK^*, $K\pi$, $K\rho$, …)

$$A_{CP}^{U}\left(f,t\right)=\frac{\Sigma_f-\Sigma_{\overline{f}}}{\Sigma_f+\Sigma_{\overline{f}}}$$

where

$$\Sigma_f=\Gamma\left(D^0\to f\right)[t]+\Gamma\left(\overline{D^0}\to f\right)[t]$$

A.A.P., PRD69, 111901(R), 2004
hep-ph/0403030

CP violation: untagged asymmetries

Expect time-dependent asymmetry…

$$A_{CP}^{U}(f,t) = \frac{1}{D(t)} e^{-\Gamma t}\left[A + B(\Gamma t) + C(\Gamma t)^2\right]$$

… and time-integrated asymmetry

$$A_{CP}^{U}(f,t) = \frac{1}{D}\left[A + B + 2C\right]$$

… whose coefficients are computed to be

$$A = \left|A_f\right|^2 \left[\left(1 - \left|\overline{A}_{\overline{f}}\right|^2 / \left|A_f\right|^2\right) + R\left(1 - \left|A_{\overline{f}}\right|^2 / \left|\overline{A}_f\right|^2\right)\right],$$

$$B = -2y\sqrt{R}\left[\sin\phi \sin\delta\left(\left|\overline{A}_f\right|^2 + \left|A_{\overline{f}}\right|^2\right) - \cos\phi\cos\delta\left(\left|\overline{A}_f\right|^2 - \left|A_{\overline{f}}\right|^2\right)\right],$$

$$C = \frac{x^2}{2} A.$$

$$\frac{A\left(D^0 \to f\right)}{A\left(\overline{D^0} \to f\right)} = \sqrt{R} e^{i\delta}$$

This is true for any final state f

CP violation: untagged asymmetries ($K^+\pi^-$)

For a particular final state $K\pi$, the time-integrated asymmetry is simple

$$A_{CP}^{U}\left(K^+\pi^-\right) = -y\sin\delta\sin\phi\sqrt{R}$$

This asymmetry is

1. non-zero due to large SU(3) breaking
2. contains no model-dependent hadronic parameters (R and δ are experimental observables)
3. could be as large as 0.04% for NP

Note: larger by O(100) for SCS decays ($\pi\rho$, ...) where R ~ 1

A.A.P., PRD69, 111901(R), 2004
hep-ph/0403030

CP-violation in charmed baryons

- Other observables can be constructed for baryons, e.g.

$$A(\Lambda_c \to N\pi) = \overline{u}_N(p,s)\left[A_S + A_P\gamma_5\right]u_{\Lambda_c}(p_\Lambda, s_\Lambda)$$

These amplitudes can be related to "asymmetry parameter" $\alpha_{\Lambda_c} = \frac{2\,\mathrm{Re}\left(A_S^* A_P\right)}{\left|A_S\right|^2 + \left|A_P\right|^2}$

… which can be extracted from $\frac{dW}{d\cos\vartheta} = \frac{1}{2}\left(1 + P\alpha_{\Lambda_c}\cos\vartheta\right)$

Same is true for $\overline{\Lambda}_c$-decay

If CP is conserved $\alpha_{\Lambda_c} \overset{CP}{\Rightarrow} -\overline{\alpha}_{\Lambda_c}$, thus CP-violating observable is

$$A_f = \frac{\alpha_{\Lambda_c} + \overline{\alpha}_{\Lambda_c}}{\alpha_{\Lambda_c} - \overline{\alpha}_{\Lambda_c}}$$

FOCUS[2006]: $A_{\Lambda\pi}$=-0.07±0.19±0.24

Conclusions

- Charm provides great opportunities for New Physics studies
  - large available statistics
  - small Standard Model background
- Different observables should be used to disentangle CP-violating contributions to $\Delta c=1$ and $\Delta c=2$ amplitudes
  - time-dependent and time-independent charge asymmetries
  - CP-tagged measurements
- Observation of CP-violation in the current round of experiments provide "smoking gun" signals for New Physics
  - new observables should be considered
    - untagged CP-asymmetries
    - triple-product correlators in D -> VV decays
    - CP-asymmetries in baryon decays

Additional slides

"Static" observables for CP-violation

I. Intrinsic particle properties

✓ electric dipole moments:

$$\vec{d} = \int d^3x \; \vec{x}\rho(\vec{x})$$

should be (anti-)alligned with spin $\vec{s}$!

Experimental limits:

Particle	Exp Limit, e cm	Theory (SM), e cm
neutron	$\|d_n\| < 6.3 \times 10^{-26}$	$\|d_n\| \sim 10^{-32}$
electron	$\|d_e\| < 4 \times 10^{-27}$	$\|d_e\| \sim 10^{-37}$
muon	$\|d_\mu\| < 7 \times 10^{-19}$	$\|d_\mu\| \sim 10^{-35}$

$$\vec{d} \xrightarrow{\mathcal{T}} \vec{d} \quad || \quad \vec{s} \xrightarrow{\mathcal{T}} -\vec{s}$$

however

$$\vec{d} \xrightarrow{\mathcal{P}} -\vec{d} \quad || \quad \vec{s} \xrightarrow{\mathcal{P}} \vec{s}$$

thus, if $\vec{d} \neq 0 \Rightarrow \mathcal{T}$ or $\mathcal{CP}$ is broken

Low energy strong interaction effects might complicate predictions!