On the "ΔA_{CP} saga"

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About the Title

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The question arose because LHCb collaboration, at the end of 2011, measured LHCb Coll. PRL 108, 11602 (2012)

$$\Delta A_{\rm CP} = a_{CP}(K^+K^-) - a_{\rm CP}(\pi^+\pi^-)$$

$$\Delta A_{\rm CP} = (-0.82 \pm 0.21 \pm 0.11)\%$$

$$\Delta A_{\rm CP} \approx -1\%$$

Is this value compatible with the Standard Model?
Is this a signal of New Physics?

ΔA_{CP} Measurements and HFAG world average

- CDF arXiv:1207.2158 [hep-ex] $\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$
- Belle arXiv:1212.1975 [hep-ex] $\Delta A_{CP} = (-0.87 \pm 0.41 \pm 0.06)\%$
- LHCb LHCb-CONF-2013-003 $\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$
- LHCb arXiv:1405.2797 [hep-ex] $\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$

Including also Babar and Belle individual measurements HFAG (in May 2014) obtained (J. Brod @ FPCP 2014)

$$\Delta A_{CP} = (-0.253 \pm 0.104)\%$$

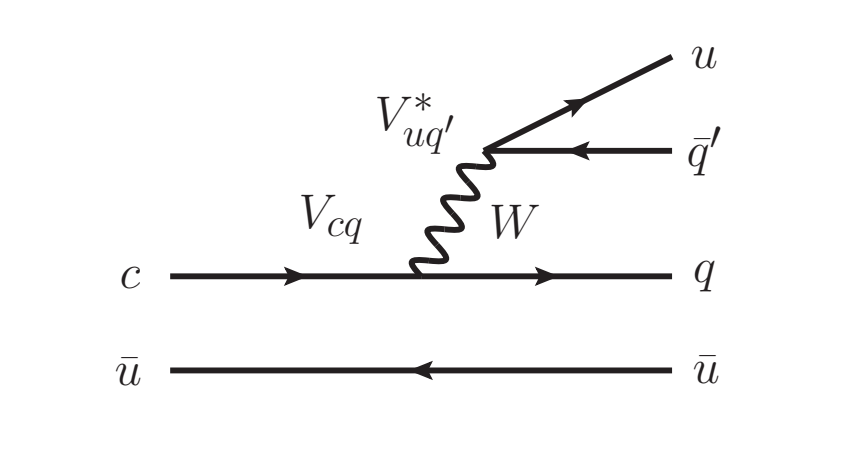
Last HFAG (11 June 2014) uses only latest LHCb results
(by putting together the individual measurements):

$$\Delta A_{CP} = (-0.21 \pm 0.19)\%$$

Outline

- Non-leptonic Decays of D Mesons
- CP Violation and ΔA_{CP}
- A Model for Cabibbo Suppressed Decays
- Conclusions

Hadronic two-body Decays of D Meson



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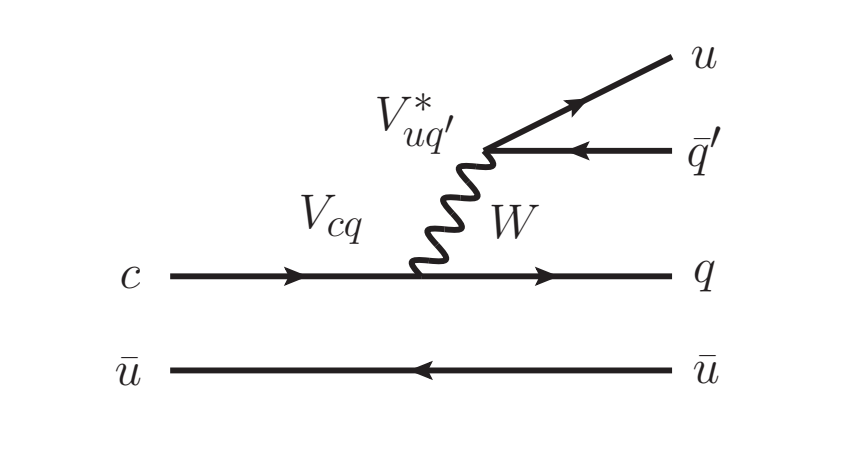

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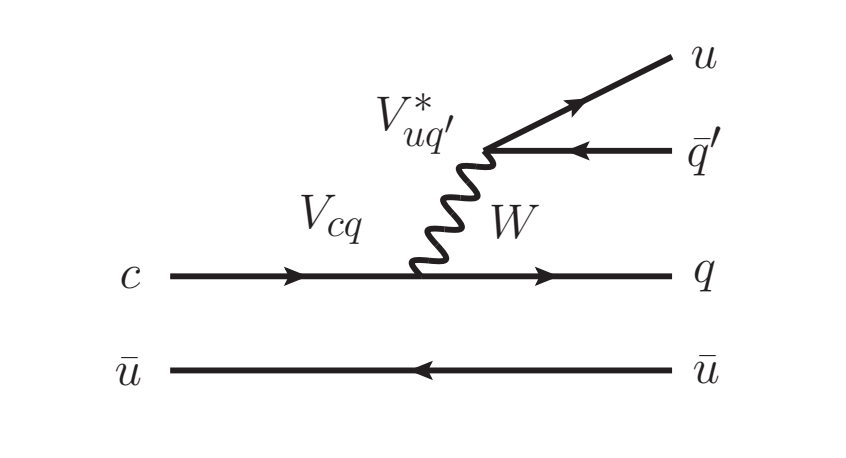

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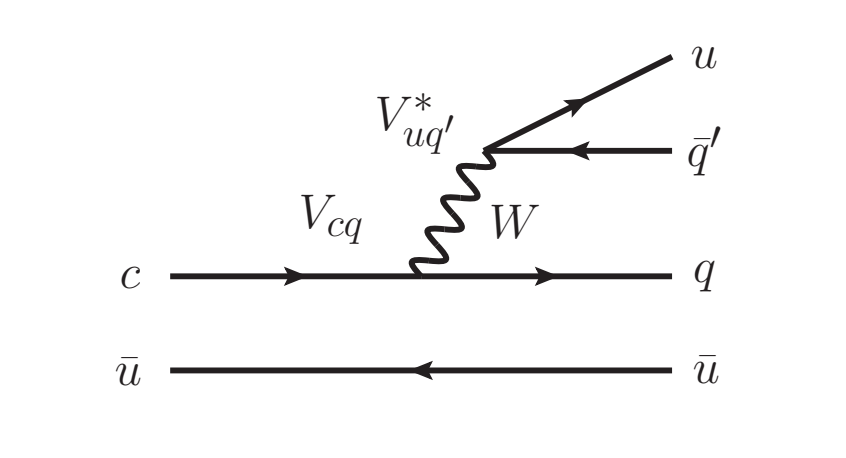

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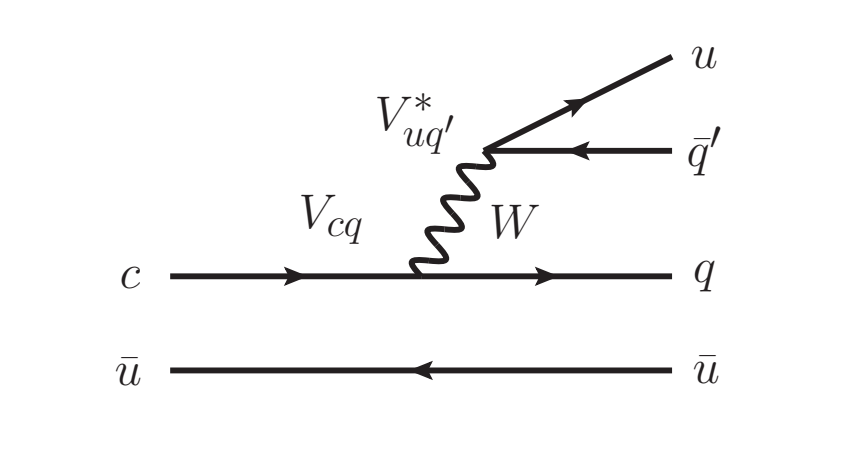

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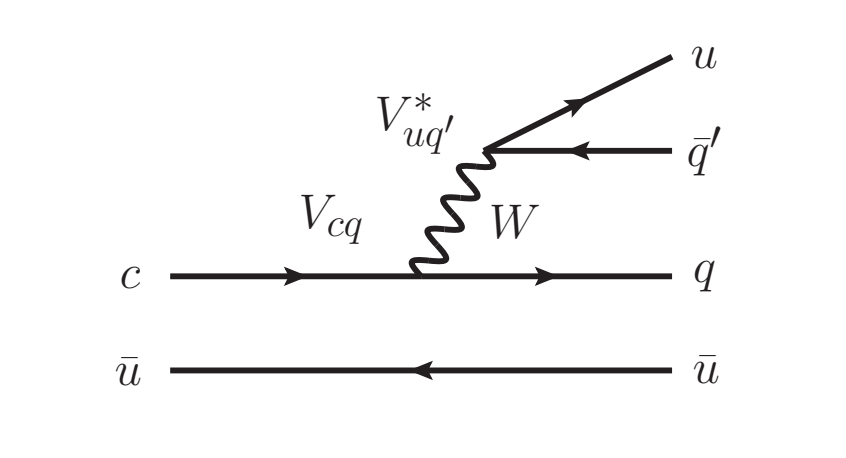

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DCS Double Cabibbo Suppressed: $|V_{cd}V^*_{us}| \approx \lambda^2$ ($D^0 \to K^+\pi^-$)

Weak Effective Hamiltonian

The effective field theory formalism allows to separate the short and long distances and it is easy to include perturbative QCD corrections.

$$
\begin{aligned}
H_{\rm W}^{\rm SCS} &= \frac{G_F}{\sqrt{2}} V_{ud} V_{cd}^* \left[C_1 O_1^d + C_2 O_2^d\right] + \frac{G_F}{\sqrt{2}} V_{us} V_{cs}^* \left[C_1 O_1^s + C_2 O_2^s\right] \\
&- \frac{G_F}{\sqrt{2}} V_{ub} V_{cb}^* \sum_{i=3}^{6} C_i O_i + h.c.
\end{aligned}
$$

Current-Current Operators

$$
\begin{aligned}
O_2 &= \left[\bar{q}^\alpha \gamma^\mu (1-\gamma_5) c_\alpha\right]\left[\bar{u}^\beta \gamma_\mu (1-\gamma_5) q'_\beta\right] \\
O_1 &= \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\beta\right]\left[\bar{q}^\beta \gamma_\mu (1-\gamma_5) q'_\alpha\right]
\end{aligned}
$$

$q = q' \in \{d, s\}$ *for SCS*

Penguin Operators

$$
\begin{aligned}
O_3 &= \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\alpha\right] \sum_{p=u,d,s} \left[\bar{p}^\beta \gamma_\mu (1-\gamma_5) p_\beta\right] \\
O_4 &= \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\beta\right] \sum_{p=u,d,s} \left[\bar{p}^\beta \gamma_\mu (1-\gamma_5) p_\alpha\right] \\
O_5 &= \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\alpha\right] \sum_{p=u,d,s} \left[\bar{p}^\beta \gamma_\mu (1+\gamma_5) p_\beta\right] \\
O_6 &= \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\beta\right] \sum_{p=u,d,s} \left[\bar{p}^\beta \gamma^\mu (1+\gamma_5) p_\alpha\right]
\end{aligned}
$$

Hadronic Matrix Elements

We have to evaluate

$$\langle f| H_{\mathrm{w}} |D\rangle = \frac{G_F}{\sqrt{2}} VV^* C_j \langle f| O_j |D\rangle + \ldots$$

- The Wilson coefficients can be computed perturbatively

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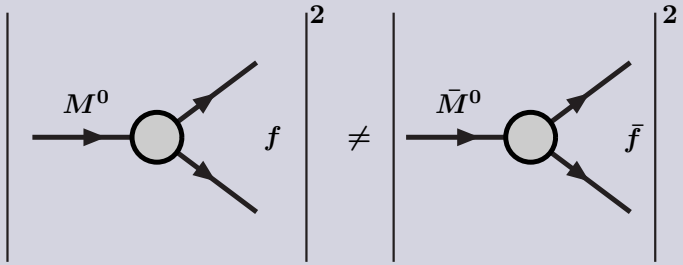
- Models of calculations can be useful to estimate order of magnitudes
  - Factorization & Final state Interactions
  - Flavour symmetries ($SU(3)_F$, Isospin, U-spin, etc.)

CP Violation in the Decays: The Direct CPV

This occurs when the decay amplitudes for CP conjugate processes into final states f and $\bar{f}$ are different in modulus

$$|\mathscr{A}(M^0 \to f)| \neq |\mathscr{A}(\bar{M}^0 \to \bar{f})|$$

in our case $f = \bar{f}$



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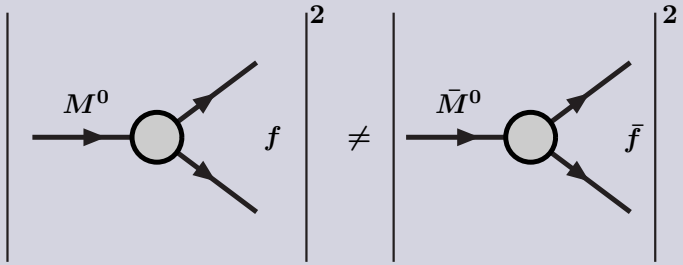

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$$\mathscr{A} = T\, e^{\imath \delta_T} + P\, e^{\imath \delta_P}$$

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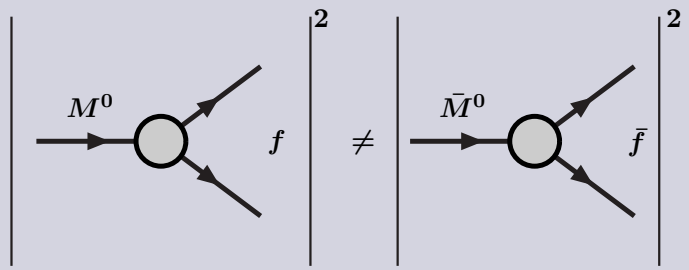

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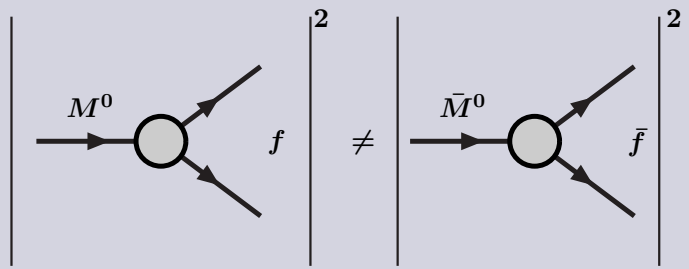

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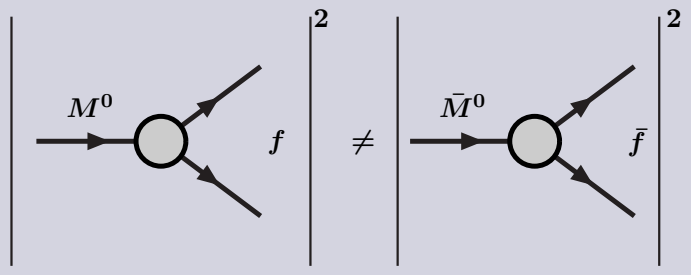

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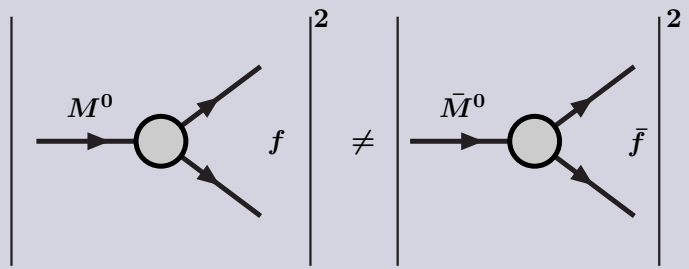

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Obviously, New Physics could be responsible of a $|P/T|$ enhancement

see, for example, talk by Buras

SU(3) Symmetry and SCS D Decays

In the limit of SU(3) flavour symmetry

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May 2014 LHCb arXiv:1405.2797[hep-ex]

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HFAG June 2014

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Large SU(3) Violation

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$$H_w = H_{\Delta U=1} + H_{\Delta U=0} = \underbrace{\sin\theta_C \cos\theta_C}_{\sim\lambda} \tilde{H}_{\Delta U=1} + \underbrace{V_{ub}\, V_{cb}^*}_{\sim\lambda^3 \cdot \lambda^2} \tilde{H}_{\Delta U=0}$$

A Simple Model to Evaluate SCS D Decays

- We assume that $SU(3)_F$ breaking effects are due to FSI
- We evaluate *bare* amplitudes using $SU(3)_F$ symmetry (less model dependent than factorization)

Buccella, Lusignoli, Pugliese, P.S., Phys. Rev. D88 (2013), 074011

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$$\begin{aligned} H_{\Delta U=1} &= \frac{G_F}{2\sqrt{2}} (V_{us}\, V_{cs}^* - V_{ud}\, V_{cd}^*)[C_1(O_1^s - O_1^d) + C_2(O_2^s - O_2^d)] \\ &\simeq \frac{G_F}{\sqrt{2}} \sin\theta_C \cos\theta_C [C_1(O_1^s - O_1^d) + C_2(O_2^s - O_2^d)]. \end{aligned}$$

A Simple Model to Evaluate SCS D Decays (1)

There are only two independent combinations of S-wave states having U=1

$$H_{\Delta U=1}\left|D^0\right\rangle = a\left|v_1\right\rangle + b\left|v_2\right\rangle$$

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\end{aligned}$$

$$A(D^0 \to K^+K^-) = \left\langle K^+K^-\right| H_{\Delta U=1}\left|D^0\right\rangle = a\left\langle K^+K^-\right|\, v_1\rangle + b\left\langle K^+K^-\right|\, v_2\rangle$$

$$A(D^0 \to \pi^+\pi^-) = \left\langle \pi^+\pi^-\right| H_{\Delta U=1}\left|D^0\right\rangle = a\left\langle \pi^+\pi^-\right|\, v_1\rangle + b\left\langle \pi^+\pi^-\right|\, v_2\rangle$$

A Simple Model to Evaluate SCS D Decays (2)

More interestingly the two independent combinations of S-wave states having U=1 can be written in terms of two representations of $SU(3)$

$$
\begin{aligned}
|8, U=1\rangle = \frac{\sqrt{3}}{2\sqrt{5}} \quad & \Big\{ \quad |K^+K^- > + |K^-K^+ > - |\pi^+\pi^- > - |\pi^-\pi^+ > \\
& - \quad \Big[|\pi^0\pi^0 > - |\eta_8\eta_8 > - \frac{1}{\sqrt{3}} (|\pi^0\eta_8 > + |\eta_8\pi^0 >) \Big] \Big\}, \\
|27, U=1\rangle = \frac{1}{\sqrt{10}} \quad & \Big\{ \quad |K^+K^- > + |K^-K^+ > - |\pi^+\pi^- > - |\pi^-\pi^+ > \\
& + \quad \frac{3}{2} \Big[|\pi^0\pi^0 > - |\eta_8\eta_8 > - \frac{1}{\sqrt{3}} (|\pi^0\eta_8 > + |\eta_8\pi^0 >) \Big] \Big\}.
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$$|27, U=1\rangle = \frac{1}{\sqrt{10}} \left\{ |K^+K^- > + |K^-K^+ > - |\pi^+\pi^- > - |\pi^-\pi^+ > + \frac{3}{2} \left[|\pi^0\pi^0 > - |\eta_8\eta_8 > - \frac{1}{\sqrt{3}}(|\pi^0\eta_8 > + |\eta_8\pi^0 >) \right] \right\}.$$

$$\langle 8, U=1 | H_{\Delta U=1} | D^0 \rangle \propto T - \frac{2}{3} C$$

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$$\Rightarrow$$

$$A(D^0 \to K^+K^-) = \alpha \left(T - \frac{2}{3}C \right) + \beta (T + C)$$

$$A(D^0 \to \pi^+\pi^-) = \gamma \left(T - \frac{2}{3}C \right) + \delta (T + C)$$

Final State Interactions in SCS D Decays

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The possible resonances have SU(3) and isospin quantum numbers $(8, I = 1)$, $(8, I = 0)$ and $(1, I = 0)$. Moreover, the two states with $I = 0$ can be mixed, yielding two resonances:

$$
\begin{aligned}
|f_0> &= \sin\phi \ |8, I = 0> + \cos\phi \ |1, I = 0> \\
|f_0'> &= -\cos\phi \ |8, I = 0> + \sin\phi \ |1, I = 0>
\end{aligned}
$$

The mixing angle ϕ and the strong phases δ_0, δ_0' and δ_1 are our model parameters, together with the two independent weak decay amplitudes

Final State Interactions in SCS D Decays (1)

$$
\begin{aligned}
A(D^0 \to \pi^+\pi^-) &= \left(T - \frac{2}{3}C\right)\left\{-\frac{3}{10}\left(e^{\imath\delta_0} + e^{\imath\delta_0'}\right) + \left(-\frac{3}{10}\cos(2\phi) + \frac{3}{4\sqrt{10}}\sin(2\phi)\right)\left(e^{\imath\delta_0'} - e^{\imath\delta_0}\right)\right\} \\
&- \left(T + C\right)\frac{2}{5}, \\
A(D^0 \to K^+K^-) &= \left(T - \frac{2}{3}C\right)\left\{\frac{3}{20}\left(e^{\imath\delta_0} + e^{\imath\delta_0'}\right) + \left(\frac{3}{20}\cos(2\phi) + \frac{3}{4\sqrt{10}}\sin(2\phi)\right)\left(e^{\imath\delta_0'} - e^{\imath\delta_0}\right)\right. \\
&\qquad \left. + \frac{3}{10}e^{\imath\delta_1}\right\} \\
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$$

SU(3) limit

$$\sin\phi = 1 \qquad \delta_0 = \delta_1$$

$$\langle 1, I = 0 | H_{\Delta U=1} | D^0 \rangle = 0 \Rightarrow \cancel{\delta_0'}$$

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Parameters

$$
\begin{aligned}
C/T &= -0.53 \\
\phi &= 22^\circ \\
\delta_0 &= 148^\circ \\
\delta_0' &= 53^\circ \\
\delta_1 &= 83^\circ
\end{aligned}
$$

Results

$$
\begin{aligned}
\frac{\Gamma(D^0 \to K_S K_S)}{\Gamma(D^0 \to K^+K^-)} &= 0.0429\ (0.043 \pm 0.010) \\
\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^+K^-)} &= 0.354\ (0.354 \pm 0.010) \\
\frac{\Gamma(D^0 \to \pi^0\pi^0)}{\Gamma(D^0 \to K^+K^-)} &= 0.202\ (0.202 \pm 0.013) \\
\left|\frac{A_2(D^0 \to \pi^+\pi^-)}{A_0(D^0 \to \pi^+\pi^-)}\right| &= 0.40\ (0.41 \pm 0.01)
\end{aligned}
$$

Direct CPV in SCS D Decays (1)

The second amplitude P is provided by

$$\langle f | H_{\Delta U=0} | D^0 \rangle$$

where

$$H_{\Delta U=0} = -\frac{G_F}{\sqrt{2}} V_{ub} V_{cb}^* \left\{ \underbrace{\sum_{i=3}^{6} C_i O_i}_{\text{Penguins}} + \underbrace{\frac{1}{2}\left[C_1(O_1^s + O_1^d) + C_2(O_2^s + O_2^d)\right]}_{\text{Tree (T}', \text{C}') \text{ Penguin Contraction}} \right\}$$

Note that

$$|T'/T| = |C'/C| = \left| \frac{V_{ub} V_{cb}^*}{\sin\theta_C \cos\theta_C} \right| \simeq 10^{-4}$$

Direct CPV in SCS D Decays (2)

$$\mathscr{A}(K^+K^-) \simeq T f_T(\delta_i, \phi, C/T) + P\, f_P(\delta_i, \phi)$$

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$$a_{CP}(K^+K^-) \simeq \frac{2\, T\, \Im(P)\, \Im(f_T\, f_P^*)}{T^2\, |f_T|^2} + \ldots \quad = \quad +1.5\, \frac{\Im(P)}{T}$$

$$a_{CP}(\pi^+\pi^-) \quad = \quad -3.4\, \frac{\Im(P)}{T}$$

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$$\frac{\Im(P)}{T} = \frac{|V_{ub}\,V_{cb}|}{\sin\theta_C\cos\theta_C}\sin\gamma\;\frac{< K^+K^-|\,\sum_{i=3}^{6}\,C_i Q_i + \frac{1}{2}[C_1\{Q_1^s + Q_1^d\} + C_2\{Q_2^s + Q_2^d\}]\,|D^0 >}{< K^+K^-|\,C_1(Q_1^s - Q_1^d) + C_2(Q_2^s - Q_2^d)\,|D^0 >} = 6.3\,10^{-4}\;\frac{\hat{P}}{\hat{T}}$$

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$$\Delta A_{\rm CP} = 3.03\; 10^{-3}\; \frac{\hat{P}}{\hat{T}}$$

With

$$\left| \frac{\hat{P}}{\hat{T}} \right| \approx 1$$

we obtain the central value of the world average result

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Conclusions

We analyzed the Singly-Cabibbo-Suppressed decays of the neutral D mesons in the framework of a model that ascribes all of the large SU(3) violations to final state interactions.

The values of the strong phases are in principle suitable to predict consistent CP violations in the decay amplitudes.

We were able to give a good description of decay branching ratios

The experimental situation regarding the CP violating asymmetries seems to be rather clear: there is no significant CP violation in the SCS decays at the level of 10^{-3}.

Nevertheless, we think interesting to have shown that large asymmetries can be obtained, considering the uncertainties of long distance contributions, even without invoking New Physics.

Backup Slides

HFAG World Averages

Year	Experiment	CP Asymmetry in the decay mode D0 to π+π-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2014	LHCb	R. Aaij et al. (LHCb Collab.), arXiv:1405.2797 (2014).	-0.0020 ± 0.0019 ± 0.0010
2012	BELLE	B.R. Ko et al. (BELLE Collab.), arXiv:1212.1975 (2012).	+0.0055 ± 0.0036 ± 0.0009
2012	CDF	T. Aaltonen et al. (CDF Collab.), Phys. Rev. D 85, 012009 (2012).	+0.0022 ± 0.0024 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
.	.	COMBOS average	+0.0005 ± 0.0015

Year	Experiment	CP Asymmetry in the decay mode D0 to K+K-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2014	LHCb	R. Aaij et al. (LHCb Collab.), arXiv:1405.2797 (2014).	-0.0006 ± 0.0015 ± 0.0010
2012	BELLE	B.R Ko et al. (BELLE Collab.), arXiv: 1212.1975 (2012).	-0.0032 ± 0.0021 ± 0.0009
2012	CDF	T. Aaltonen et al. (CDF Collab.), Phys. Rev. D 85, 012009 (2012).	-0.0024 ± 0.0022 ± 0.0009
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	+0.0000 ± 0.0034 ± 0.0013
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.000 ± 0.022 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	-0.001 ± 0.022 ± 0.015
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.010 ± 0.049 ± 0.012
1994	E687	P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).	+0.024 ± 0.084
.	.	COMBOS average	-0.0016 ± 0.0012

$H_{\Delta U=0}$

In this case, there are three independent symmetric states of two pseudoscalar mesons:

$$\frac{1}{2}\left\{|K^+K^->+|K^-K^+>+|\pi^+\pi^->+|\pi^-\pi^+>\right\};$$
$$\frac{1}{4}\left\{3\,|\pi^0\pi^0>+|\eta_8\eta_8>+\sqrt{3}\,(|\pi^0\eta_8>+|\eta_8\pi^0>)\right\};$$
$$\frac{1}{\sqrt{3}}\left\{\frac{1}{4}|\pi^0\pi^0>+\frac{3}{4}|\eta_8\eta_8>-\frac{\sqrt{3}}{4}(|\pi^0\eta_8>+|\eta_8\pi^0>)+|K^0\bar{K}^0>+|\bar{K}^0K^0>\right\}$$

that give rise to three amplitudes transforming as 27, 8 and 1 under SU(3) (for the $Q_{1(2)}$ part) and to two amplitudes transforming as 8 and 1 (for the penguin part)