CP Violation in nonleptonic two-body decays of D Mesons

Pietro Santorelli

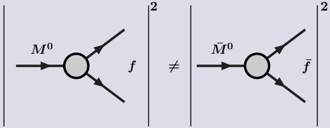
Dipartimento di Fisica
Università di Napoli Federico II
&
INFN − Sezione di Napoli

CHARM 2016
Bologna, Italia
5 ÷ 9 September 2016

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

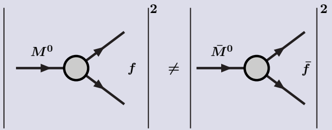
$$|\mathscr{A}(M^0 \to f)| \neq |\mathscr{A}(\bar{M}^0 \to \bar{f})|$$



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

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



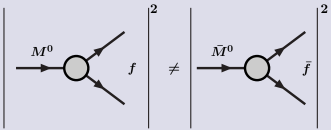
A nonzero direct CP asymmetry is present only when the decay amplitude is

$$\mathscr{A} = A_1\, e^{\imath\delta_1} + A_2\, e^{\imath\delta_2}$$

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

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



A nonzero direct CP asymmetry is present only when the decay amplitude is

$$\mathscr{A} = A_1\, e^{\imath\delta_1} + A_2\, e^{\imath\delta_2}$$

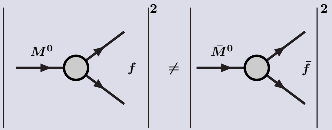
the CP conjugate amplitude is

$$\bar{\mathscr{A}} = A_1^*\, e^{\imath\delta_1} + A_2^*\, e^{\imath\delta_2}$$

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

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



A nonzero direct CP asymmetry is present only when the decay amplitude is

$$\mathscr{A} = A_1\, e^{\imath\delta_1} + A_2\, e^{\imath\delta_2}$$

the CP conjugate amplitude is

$$\bar{\mathscr{A}} = A_1^*\, e^{\imath\delta_1} + A_2^*\, e^{\imath\delta_2}$$

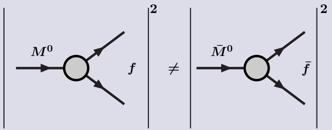
and the CP asymmetry is:

$$a_{\rm CP}^{dir} = \frac{|\mathscr{A}|^2 - |\bar{\mathscr{A}}|^2}{|\mathscr{A}|^2 + |\bar{\mathscr{A}}|^2} = \frac{2\,\Im(A_1^*\,A_2)\,\sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2\,\Re(A_1^*\,A_2)\,\cos(\delta_1 - \delta_2)}$$

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

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



A nonzero direct CP asymmetry is present only when the decay amplitude is

$$\mathscr{A} = A_1\, e^{\imath\delta_1} + A_2\, e^{\imath\delta_2}$$

the CP conjugate amplitude is

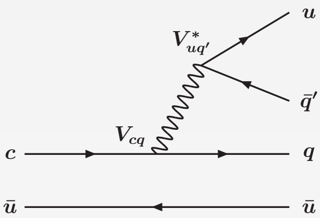
$$\bar{\mathscr{A}} = A_1^*\, e^{\imath\delta_1} + A_2^*\, e^{\imath\delta_2}$$

and the CP asymmetry is:

$$a_{\mathrm{CP}}^{dir} = \frac{|\mathscr{A}|^2 - |\bar{\mathscr{A}}|^2}{|\mathscr{A}|^2 + |\bar{\mathscr{A}}|^2} = \frac{2\,\Im(A_1^*\,A_2)\,\sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2\,\Re(A_1^*\,A_2)\,\cos(\delta_1 - \delta_2)} \approx 2\,\Im\left(\frac{A_2}{A_1}\right)\sin(\delta_1 - \delta_2)$$

Hadronic two-body Decays of D Meson (1)

In the Standard Model flavour changing transitions are induced by exchange of W bosons:



- CKM hierarchy leads to two-generation dominance

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - \imath\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-\imath\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

	UT_{fit}
λ	0.22534 ± 0.00065
A	0.821 ± 0.012
ρ	0.136 ± 0.024
η	0.361 ± 0.014

UTFit Collaboration

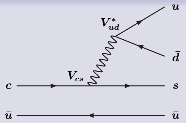
Hadronic two-body Decays of D Meson (2)

Due to the CKM hierarchy we can classify decay processes into three classes

Cabibbo Favoured (CF)

$|V_{cs}V_{ud}^*| \approx \lambda^0$ as,

for example, $D^0 \to K^- \pi^+$

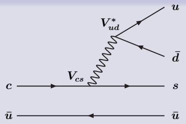


Hadronic two-body Decays of D Meson (2)

Due to the CKM hierarchy we can classify decay processes into three classes

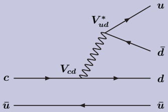
Cabibbo Favoured (CF)

$|V_{cs} V_{ud}^*| \approx \lambda^0$ as,
for example, $D^0 \to K^- \pi^+$



Singly Cabibbo Suppressed (SCS)

$|V_{cd} V_{ud}^*| \approx \lambda$
($D^0 \to \pi^+ \pi^-$)



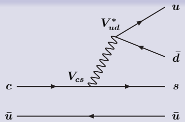
Hadronic two-body Decays of D Meson (2)

Due to the CKM hierarchy we can classify decay processes into three classes

Cabibbo Favoured (CF)

$|V_{cs}V_{ud}^{*}| \approx \lambda^{0}$ as,

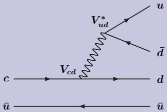
for example, $D^0 \to K^- \pi^+$



Singly Cabibbo Suppressed (SCS)

$|V_{cd}V_{ud}^{*}| \approx \lambda$

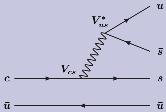
($D^0 \to \pi^+ \pi^-$)



$|V_{cs}V_{us}^{*}| \approx \lambda$

($D^0 \to K^+ K^-$,

$D^0 \to K^0 \bar{K}^0$)

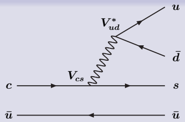


Hadronic two-body Decays of D Meson (2)

Due to the CKM hierarchy we can classify decay processes into three classes

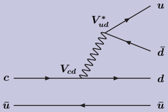
Cabibbo Favoured (CF)

$|V_{cs} V_{ud}^{*}| \approx \lambda^{0}$ as,
for example, $D^0 \to K^- \pi^+$

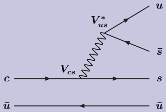


Singly Cabibbo Suppressed (SCS)

$|V_{cd} V_{ud}^{*}| \approx \lambda$
($D^0 \to \pi^+ \pi^-$)

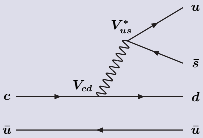


$|V_{cs} V_{us}^{*}| \approx \lambda$
($D^0 \to K^+ K^-$,
$D^0 \to K^0 \bar{K}^0$)



Double Cabibbo Suppressed (DCS)

$|V_{cd} V_{us}^{*}| \approx \lambda^{2}$
($D^0 \to K^+ \pi^-$)



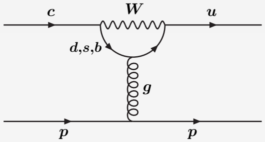
Weak Effective Hamiltonian: The SCS case

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

Weak Effective Hamiltonian: The SCS case

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

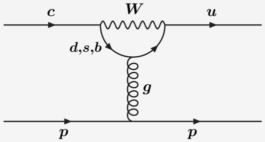
The QCD penguins operators



Weak Effective Hamiltonian: The SCS case

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

The QCD penguins operators

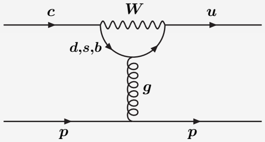


$$\begin{aligned}
O_3 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\alpha}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\beta}\right]\\
O_4 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\beta}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\alpha}\right]\\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

Weak Effective Hamiltonian: The SCS case

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

The QCD penguins operators



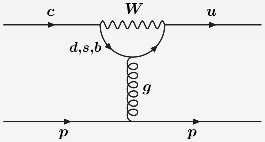
$$\begin{aligned}
O_3 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\alpha}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\beta}\right]\\
O_4 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\beta}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\alpha}\right]\\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

$$H_{\mathrm{W}}^{\mathrm{SCS}} = \frac{G_F}{\sqrt{2}} V_{ud}\, V_{cd}^{*}\left[C_1(\mu)O_1^d(\mu) + C_2(\mu)O_2^d(\mu)\right] \qquad (q = q' = d)$$

Weak Effective Hamiltonian: The SCS case

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

The QCD penguins operators



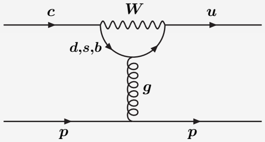
$$
\begin{aligned}
O_3 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\alpha}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\beta}\right]\\
O_4 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\beta}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\alpha}\right]\\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

$$
\begin{aligned}
H_{\mathrm{W}}^{\mathrm{SCS}} &= \frac{G_F}{\sqrt{2}} V_{ud}\, V_{cd}^{*}\left[C_1(\mu)O_1^{d}(\mu) + C_2(\mu)O_2^{d}(\mu)\right] && (q = q' = d)\\
&+ \frac{G_F}{\sqrt{2}} V_{us}\, V_{cs}^{*}\left[C_1(\mu)O_1^{s}(\mu) + C_2(\mu)O_2^{s}(\mu)\right] && (q = q' = s)
\end{aligned}
$$

Weak Effective Hamiltonian: The SCS case

$$O_2^{q,q'} = [\bar{q}^\alpha \gamma^\mu (1-\gamma_5) c_\alpha][\bar{u}^\beta \gamma_\mu (1-\gamma_5) q'_\beta] \qquad O_1^{q,q'} = [\bar{q}^\alpha \gamma^\mu (1-\gamma_5) c_\beta][\bar{u}^\beta \gamma_\mu (1-\gamma_5) q'_\alpha]$$

The QCD penguins operators



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

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

CP Asymmetries: The SCS case

The amplitudes are made of two parts. For the D^0, for example, we have:

$$\mathscr{A}^{SCS} = \frac{1}{2}(V_{cs}^* V_{us} - V_{cd}^* V_{ud}) A^{(1,2)}\ e^{\imath\delta} - \frac{1}{2} V_{cb}^* V_{ub} A^{(P)}\ e^{\imath\delta'}$$

and so the direct CP asymmetry is given by

$$a_{CP}^{dir} \approx \eta A^2 \lambda^4 \sin(\delta - \delta') \left[\frac{A^{(P)}}{A^{(1,2)}} \right] \approx (6 \times 10^{-4})\ \sin(\delta - \delta') \left[\frac{A^{(P)}}{A^{(1,2)}} \right]$$

- Strong phase difference could be large due to the resonances
- Penguin amplitude of the order of tree amplitude

$$a_{CP}^{dir} \approx 10^{-4} \div 10^{-3}$$

CP Asymmetries: The SCS case

The amplitudes are made of two parts. For the D^0, for example, we have:

$$\mathscr{A}^{SCS} = \frac{1}{2}(V_{cs}^* V_{us} - V_{cd}^* V_{ud}) A^{(1,2)}\ e^{\imath\delta} - \frac{1}{2} V_{cb}^* V_{ub} A^{(P)}\ e^{\imath\delta'}$$

and so the direct CP asymmetry is given by

$$a_{CP}^{dir} \approx \eta A^2 \lambda^4 \sin(\delta - \delta') \left[\frac{A^{(P)}}{A^{(1,2)}}\right] \approx (6 \times 10^{-4})\ \sin(\delta - \delta') \left[\frac{A^{(P)}}{A^{(1,2)}}\right]$$

- Strong phase difference could be large due to the resonances
- Penguin amplitude of the order of tree amplitude

$$a_{CP}^{dir} \approx 10^{-4} \div 10^{-3}$$

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

$$\begin{aligned} \Delta A_{\mathrm{CP}} &= (-0.82 \pm 0.21 \pm 0.11)\% && (\text{LHCb}\,(2012)) \\ &= (-0.62 \pm 0.21 \pm 0.10)\% && (\text{CDF}\,(2012)) \\ &= (-0.87 \pm 0.41 \pm 0.06)\% && (\text{Belle}\,(2012)) \end{aligned}$$

CP Asymmetries: The SCS case

The amplitudes are made of two parts. For the D^0, for example, we have:

$$\mathscr{A}^{SCS} = \frac{1}{2}(V_{cs}^* V_{us} - V_{cd}^* V_{ud}) A^{(1,2)}\, e^{\imath\delta} - \frac{1}{2} V_{cb}^* V_{ub} A^{(P)}\, e^{\imath\delta'}$$

and so the direct CP asymmetry is given by

$$a_{CP}^{dir} \approx \eta A^2 \lambda^4 \sin(\delta - \delta') \left[\frac{A^{(P)}}{A^{(1,2)}}\right] \approx (6 \times 10^{-4}) \sin(\delta - \delta') \left[\frac{A^{(P)}}{A^{(1,2)}}\right]$$

- Strong phase difference could be large due to the resonances
- Penguin amplitude of the order of tree amplitude

$$a_{CP}^{dir} \approx 10^{-4} \div 10^{-3}$$

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

$$\begin{aligned}
\Delta A_{\rm CP} &= (-0.82 \pm 0.21 \pm 0.11)\% && (\text{LHCb}\,(2012)) \\
&= (-0.62 \pm 0.21 \pm 0.10)\% && (\text{CDF}\,(2012)) \\
&= (-0.87 \pm 0.41 \pm 0.06)\% && (\text{Belle}\,(2012))
\end{aligned}$$

$$\Delta A_{\rm CP} = -(0.16 \pm 0.19)\%$$

HFAG (July 2016)

Amplitude calculations

The main point is the evaluation of the amplitudes:

$$A(D \to f) = \langle f|\, H_{\rm W}\, |D\rangle = \frac{G_F}{\sqrt{2}} VV^* C_j(\mu) \boxed{\langle f|\, O_j(\mu)\, |D\rangle}$$

Amplitude calculations

The main point is the evaluation of the amplitudes:

$$A(D \to f) = \langle f|\, H_{\mathrm{w}}\, |D\rangle = \frac{G_F}{\sqrt{2}} VV^* C_j(\mu) \boxed{\langle f|\, O_j(\mu)\, |D\rangle}$$

- The Wilson coefficients $C_i(\mu)$ summarize the physics contributions from scales higher than μ and due to asymptotic freedom of QCD they can be calculated in perturbation theory as long as μ is not too small.

Amplitude calculations

The main point is the evaluation of the amplitudes:

$$A(D \to f) = \langle f | H_{\rm w} | D \rangle = \frac{G_F}{\sqrt{2}} V V^* C_j(\mu) \boxed{\langle f | O_j(\mu) | D \rangle}$$

- The Wilson coefficients $C_i(\mu)$ summarize the physics contributions from scales higher than μ and due to asymptotic freedom of QCD they can be calculated in perturbation theory as long as μ is not too small.
- The hadronic matrix elements are dominated by non-perturbative QCD: they summarize the physics contributions to the amplitude from scales lower than μ
  - HQET is expected to do not work well, due to the large Λ_{QCD}/m_c corrections
  - $\chi-$perturbation theory cannot work due to the large m_c mass
  - from first principles: Lattice QCD (in the not so near future)

see also talks by A. Lenz, A. El-Khadra, G. Martinelli

Amplitude calculations

The main point is the evaluation of the amplitudes:

$$A(D \to f) = \langle f | H_{\rm W} | D \rangle = \frac{G_F}{\sqrt{2}} VV^* C_j(\mu) \boxed{\langle f | O_j(\mu) | D \rangle}$$

- The Wilson coefficients $C_i(\mu)$ summarize the physics contributions from scales higher than μ and due to asymptotic freedom of QCD they can be calculated in perturbation theory as long as μ is not too small.
- The hadronic matrix elements are dominated by non-perturbative QCD: they summarize the physics contributions to the amplitude from scales lower than μ
  - HQET is expected to do not work well, due to the large Λ_{QCD}/m_c corrections
  - $\chi-$perturbation theory cannot work due to the large m_c mass
  - from first principles: Lattice QCD (in the not so near future)

see also talks by A. Lenz, A. El-Khadra, G. Martinelli

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

Amplitude calculations: the $SU(3)_F$ approach

The idea to study charmed particles by assuming $SU(3)_F$ flavour symmetry is very old

Altarelli, Cabibbo, and Maiani (1975)
Kingsley, Treiman, Wilczek, and Zee (1975)
Einhorn and Quigg (1975)
Voloshin, Zakharov, and Okun (1975)
Cabibbo and Maiani (1978)
Quigg (1980)

and quite simple (in principle):

$$(\bar{s}c)(\bar{u}s) \sim \mathbf{3} \otimes \overline{\mathbf{3}} \otimes \mathbf{3} \sim \mathbf{3} \oplus \mathbf{3}' \oplus \overline{\mathbf{6}} \oplus \mathbf{15}$$

Due to the fact that

$$(D^0, D^+, D_s) \sim \overline{\mathbf{3}} \qquad\qquad PP \sim (\mathbf{8} \otimes \mathbf{8})_S = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{27}$$

$$\langle PP | \mathscr{H} | D \rangle \sim \langle \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{27} | \left(\mathbf{3} \oplus \overline{\mathbf{6}} \oplus \mathbf{15}\right) | \overline{\mathbf{3}} \rangle$$

Neglecting the $\mathbf{3} \propto V_{cb}^* V_{ub}$ we have

B. Grinstein and R.F. Lebed PRD 53 (1996) 6344
I. Hinchliffe and T.A. Kaeding, PRD 54 (1996) 914

$$\mathscr{H} = \frac{V_{cd}^* V_{us}}{\sqrt{2}} H_0^6 + \frac{(V_{cd}^* V_{ud} - V_{cs}^* V_{us})}{2} H_{1/2}^6 - \frac{V_{cs}^* V_{ud}}{\sqrt{2}} H_1^6 - \frac{(V_{cd}^* V_{ud} - 3 V_{cs}^* V_{us})}{2\sqrt{6}} H_{1/2}^{15} + \frac{(V_{cd}^* V_{us} + V_{cs}^* V_{ud})}{\sqrt{2}} H_1^{15} + \frac{V_{cd}^* V_{ud}}{\sqrt{3}} H_{3/2}^{15}$$

see also talk by A.Paul

Using Wigner-Eckart theorem we have

$$\langle \mathbf{8} | \, | \mathbf{15} | \, | \overline{\mathbf{3}} \rangle \qquad \langle \mathbf{27} | \, | \mathbf{15} | \, | \overline{\mathbf{3}} \rangle \qquad \langle \mathbf{8} | \, | \overline{\mathbf{6}} | \, | \overline{\mathbf{3}} \rangle$$

What about Experimental data and $SU(3)_F$ Symmetry?

In the limit of SU(3) flavour symmetry

$$A(D^0 \to K^+ K^-) = -A(D^0 \to \pi^+ \pi^-) \quad \Rightarrow$$

What about Experimental data and $SU(3)_F$ Symmetry?

In the limit of SU(3) flavour symmetry

$$A(D^0 \to K^+ K^-) = -A(D^0 \to \pi^+ \pi^-) \quad \Rightarrow \quad a_{CP}^{dir}(K^+ K^-) = -a_{CP}^{dir}(\pi^+ \pi^-)$$

What about Experimental data and $SU(3)_F$ Symmetry?

In the limit of SU(3) flavour symmetry

$$A(D^0 \to K^+ K^-) = -A(D^0 \to \pi^+ \pi^-) \quad \Rightarrow \quad a_{CP}^{dir}(K^+ K^-) = -a_{CP}^{dir}(\pi^+ \pi^-)$$

$$\begin{aligned} Br(D^0 \to \pi^+ \pi^-) &= (1.421 \pm 0.025) \times 10^{-3} \\ Br(D^0 \to K^+ K^-) &= (4.01 \pm 0.07) \times 10^{-3} \end{aligned}$$

PDG (2014)

$$\begin{aligned} a_{CP}^{dir}(\pi^+ \pi^-) &= (+0.00 \pm 0.15)\% \\ a_{CP}^{dir}(K^+ K^-) &= (-0.16 \pm 0.12)\% \end{aligned}$$

HFAG (July 2016)

What about Experimental data and $SU(3)_F$ Symmetry?

In the limit of SU(3) flavour symmetry

$$A(D^0 \to K^+K^-) = -A(D^0 \to \pi^+\pi^-) \quad \Rightarrow \quad a_{CP}^{dir}(K^+K^-) = -a_{CP}^{dir}(\pi^+\pi^-)$$

$$\begin{aligned} Br(D^0 \to \pi^+\pi^-) &= (1.421 \pm 0.025) \times 10^{-3} \\ Br(D^0 \to K^+K^-) &= (4.01 \pm 0.07) \times 10^{-3} \end{aligned}$$

PDG (2014)

$$\begin{aligned} a_{CP}^{dir}(\pi^+\pi^-) &= (+0.00 \pm 0.15)\% \\ a_{CP}^{dir}(K^+K^-) &= (-0.16 \pm 0.12)\% \end{aligned}$$

HFAG (July 2016)

Regarding D^+, $SU(3)_F$ predicts

$$\tan\theta_C \underbrace{A(D^+ \to \bar{K}^0\pi^+)}_{\text{CF}} = \sqrt{2}\,\underbrace{A(D^+ \to \pi^0\pi^+)}_{\text{SCS}}$$

$$\frac{Br(D^+ \to \pi^0\pi^+)}{Br(D^+ \to K_S\pi^+)} = \tan^2(\theta_C)\frac{PhS(D^+ \to \pi^0\pi^+)}{PhS(D^+ \to \bar{K}^0\pi^+)} = 0.057\,(0.077 \pm 0.004)$$

What about Experimental data and $SU(3)_F$ Symmetry?

In the limit of SU(3) flavour symmetry

$$A(D^0 \to K^+ K^-) = -A(D^0 \to \pi^+ \pi^-) \quad \Rightarrow \quad a_{CP}^{dir}(K^+ K^-) = -a_{CP}^{dir}(\pi^+ \pi^-)$$

$$\begin{aligned} Br(D^0 \to \pi^+\pi^-) &= (1.421 \pm 0.025) \times 10^{-3} \\ Br(D^0 \to K^+K^-) &= (4.01 \pm 0.07) \times 10^{-3} \end{aligned}$$

PDG (2014)

$$\begin{aligned} a_{CP}^{dir}(\pi^+ \pi^-) &= (+0.00 \pm 0.15)\% \\ a_{CP}^{dir}(K^+ K^-) &= (-0.16 \pm 0.12)\% \end{aligned}$$

HFAG (July 2016)

Regarding D^+, $SU(3)_F$ predicts

$$\tan\theta_C \underbrace{A(D^+ \to \bar{K}^0\pi^+)}_{\text{CF}} = \sqrt{2}\, \underbrace{A(D^+ \to \pi^0\pi^+)}_{\text{SCS}}$$

$$\frac{Br(D^+ \to \pi^0\pi^+)}{Br(D^+ \to K_S\pi^+)} = \tan^2(\theta_C)\frac{PhS(D^+ \to \pi^0\pi^+)}{PhS(D^+ \to \bar{K}^0\pi^+)} = 0.057\,(0.077 \pm 0.004)$$

Regarding D^0 decays, $SU(3)_F$ predicts

$$\frac{Br(D^0 \to K^+\pi^-)}{Br(D^0 \to K^-\pi^+)} = \tan^4(\theta_C) = 0.0029\,(0.00356 \pm 0.00008)$$

$$A(D^0 \to K^0\overline{K}^0) = 0\,(Br(D^0 \to K_S K_S) = (0.18 \pm 0.04) \times 10^{-3})$$

PDG (2014)

$SU(3)_F$: D into PP channels

An Analysis with the inclusion of linear $SU(3)_F$ Breaking

- The $Br(D \to PP)$ are seventeen;
- The Wigner-Eckart Theorem gives five (complex) Reduced Matrix Elements (including **3**)

$SU(3)_F$: D into PP channels

An Analysis with the inclusion of linear $SU(3)_F$ Breaking

- The $Br(D \to PP)$ are seventeen;
- The Wigner-Eckart Theorem gives five (complex) Reduced Matrix Elements (including **3**)

$\boxed{\textbf{SU(3) SYMMETRY BREAKING CORRECTIONS SHOULD BE INCLUDED}}$

$SU(3)_F$: D into PP channels

An Analysis with the inclusion of linear $SU(3)_F$ Breaking

- The $Br(D \to PP)$ are seventeen;
- The Wigner-Eckart Theorem gives five (complex) Reduced Matrix Elements (including **3**)

SU(3) SYMMETRY BREAKING CORRECTIONS SHOULD BE INCLUDED

- The $SU(3)_F$ first order breaking RME are fifteen
- Not all the RME are independent and so, considering the independent ones, we reduce them to thirteen (25 real parameters)

$SU(3)_F$: D into PP channels

An Analysis with the inclusion of linear $SU(3)_F$ Breaking

- The $Br(D \to PP)$ are seventeen;
- The Wigner-Eckart Theorem gives five (complex) Reduced Matrix Elements (including **3**)

SU(3) SYMMETRY BREAKING CORRECTIONS SHOULD BE INCLUDED

- The $SU(3)_F$ first order breaking RME are fifteen
- Not all the RME are independent and so, considering the independent ones, we reduce them to thirteen (25 real parameters)
- The experimental data on Branching ratios (excluding η and η') are sixteen !

A BRUTE FORCE ANALYSIS CANNOT BE DONE

Grinstein and Lebed (1996), Hinchliffe and Kaeding (1996), Grossman and Robinson (2013), Hiller, Jung and Schacht (2013)

$SU(3)_F$: D into PP channels

An Analysis with the inclusion of linear $SU(3)_F$ Breaking

- The $Br(D \to PP)$ are seventeen;
- The Wigner-Eckart Theorem gives five (complex) Reduced Matrix Elements (including **3**)

SU(3) SYMMETRY BREAKING CORRECTIONS SHOULD BE INCLUDED

- The $SU(3)_F$ first order breaking RME are fifteen
- Not all the RME are independent and so, considering the independent ones, we reduce them to thirteen (25 real parameters)
- The experimental data on Branching ratios (excluding η and η') are sixteen !

A BRUTE FORCE ANALYSIS CANNOT BE DONE

Grinstein and Lebed (1996), Hinchliffe and Kaeding (1996), Grossman and Robinson (2013), Hiller, Jung and Schacht (2013)

- They include in the fit the $a_{CP}^{dir}(f)$ (25 data, 25 parameters)
- The agreement with the data is good (No, assumptions)
- Very large enhancement of Penguin contributions, **3**, for large Δa_{CP}

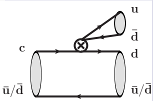
G. Hiller, M. Jung and S. Schacht, PRD 87 (2013) 014024

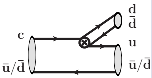
$SU(3)_F$ & topological amplitudes in D into PP

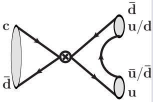
L.-L. Chau (1983), L.-L. Chau, H.-Y. Cheng (1986) and (1987)

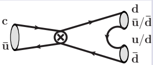
S. Müller, U. Nierste, and S. Schacht, PRD 92 (2015) 014004

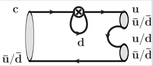
- $A(D \to PP)$, in the $SU(3)_F$ limit, are written in terms of Topological Amplitudes;

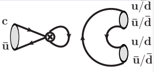










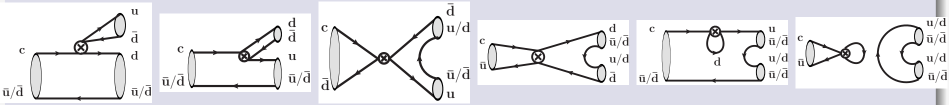


$SU(3)_F$ & topological amplitudes in D into PP

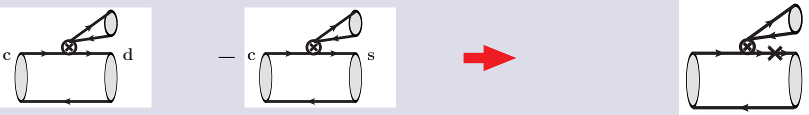
L.-L. Chau (1983), L.-L. Chau, H.-Y. Cheng (1986) and (1987)

S. Müller, U. Nierste, and S. Schacht, PRD 92 (2015) 014004

- $A(D \to PP)$, in the $SU(3)_F$ limit, are written in terms of Topological Amplitudes;



- First order $SU(3)_F$ violations are included in terms of Topological Amplitudes

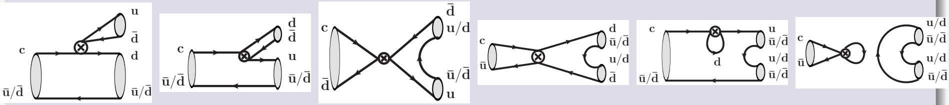


$SU(3)_F$ & topological amplitudes in D into PP

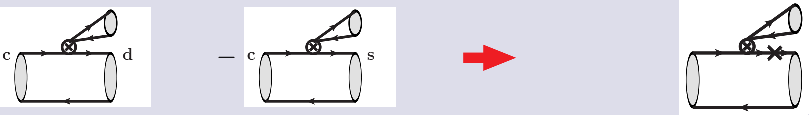
L.-L. Chau (1983), L.-L. Chau, H.-Y. Cheng (1986) and (1987)

S. Müller, U. Nierste, and S. Schacht, PRD 92 (2015) 014004

- $A(D \to PP)$, in the $SU(3)_F$ limit, are written in terms of Topological Amplitudes;



- First order $SU(3)_F$ violations are included in terms of Topological Amplitudes



- Redundancies as in the case of RME
- $1/N_c$ counting rules: $(T, A) \approx$ *Factorization* $+ \delta_{T,A}$, where $\delta_{T,A} \sim 1/N_c^2$
- $SU(3)_F$-breaking corrections $< 50\%$, corrections $1/N_c^2 < 15\%$ of the factorized ones: $\boxed{\chi^2 = 0}$ (# parameters $\geqslant$ # data)

$SU(3)_F$ & topological amplitudes in D into PP(2)

What about direct CP asymmetries?

- Penguins and Penguins annihilations are not constrained by Branching ratios

IT IS NOT POSSIBLE TO PREDICT CP ASYMMETRIES

$SU(3)_F$ & topological amplitudes in D into PP(2)

What about direct CP asymmetries?

- Penguins and Penguins annihilations are not constrained by Branching ratios

IT IS NOT POSSIBLE TO PREDICT CP ASYMMETRIES

- But one can build combinations of CP asymmetries containing only those topological amplitudes obtained by the fit: sum rules of CP asymmetries
  - $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ and $D^0 \to \pi^0\pi^0$;
  - $D^+ \to \bar{K}^0 K^+$, $D_s^+ \to K^0\pi^+$ and $D_s^+ \to K^+\pi^0$.

S. Müller, U. Nierste, and S. Schacht, PRL 115 (2015) 251802

- $a_{\mathrm{CP}}^{dir}(D^0 \to K_S K_S)$ receives contribution from E(obtained in their previous paper) and PA diagrams. A perturbative estimation of PA allows to give

$$a_{\mathrm{CP}}^{dir}(D^0 \to K_S K_S) \leqslant 1.1\%$$

U. Nierste, and S. Schacht, PRD 92 (2015) 054036

A pure topological amplitudes analysis in D into PP (SCS)

R. Dhir, C. S. Kim, and S. Oh, Int. J. Mod. Phys. A30 (2015) 1550104

- Fit the topological amplitudes to all the $D \to PP$ SCS channels (including final state with $\eta^{(\prime)}$) and measured CP asymmetries
- All possible topological amplitudes
- The $SU(3)_F$ breaking effects are included (a parameter for any different type of final state, $\Delta_{\pi\pi}$, $\Delta_{K\pi}$, $\Delta_{\pi\eta}$, Δ_{KK} and $\Delta_{K\eta}$)

Results

- 23 exp. data and 22 parameters: $\chi^2/d.o.f \sim 10$ (essentially due to the CP asymmetries)
- They predict

Mode	$a_{\mathrm{CP}}^{\mathrm{dir}}$	**Exp. (HFAG, July 2016)**
$D^0 \to \pi^+\pi^-$	$+3.3 \times 10^{-4}$	$(-0.0 \pm 1.5) \times 10^{-3}$
$D^0 \to K^+K^-$	-7.3×10^{-4}	$(-1.6 \pm 1.2) \times 10^{-3}$
$D^0 \to K_S K_S$	-5.8×10^{-4}	$(-46 \pm 54) \times 10^{-3}$
$D^0 \to \pi^0\eta$	-4.7×10^{-4}	–
$D^0 \to \pi^0\eta'$	-3.3×10^{-4}	–

Improved Factorization & FSI (1)

A. Biswas, N. Sinha, and G. Abbas, PRD 92 (2015), 014032

- Improved factorization (T, C)

$$a_1(\mu) = C_1(\mu) + C_2(\mu)\left(\frac{1}{N_c} + \alpha(\mu)\chi_1 e^{i\phi_1}\right) \qquad \mu = \sqrt{\Lambda m_D(1-r_2^2)} \qquad r_2^2 = m_{P_2}^2/m_D^2$$

$$a_2(\mu) = C_2(\mu) + C_1(\mu)\left(\frac{1}{N_c} + \alpha(\mu)\chi_2 e^{i\phi_2}\right)$$

- W-emission (E) and W-annihilation (A) contributions are considered ($C_i(\mu)$ at $\mu = \sqrt{\Lambda m_D(1-r_1^2)(1-r_2^2)}$)
- Form factors from experimental data(semileptonic decays) and Lattice results; q^2-dependence by "z-expansion"
- Resonant FSI are considered by K-matrix approach (for $I=0$ $f_0(1710)$, $I=1$ $a_0(1450)$ and $I=1/2$ $K_0^*(1950)$)
- 13 parameters, 28 experimental data (BRs)

Improved Factorization & FSI (2)

A. Biswas, N. Sinha, and G. Abbas, PRD 92 (2015), 014032

Modes	Fit result (10^{-3})	Experimental Value (10^{-3})
$D^0 \to \pi^+\pi^-$	1.44 ± 0.027	1.402 ± 0.026
$D^0 \to \pi^0\pi^0$	1.14 ± 0.56	0.8209 ± 0.035
$D^0 \to K^+K^-$	4.06 ± 0.77	3.96 ± 0.08
$D^0 \to K^0\bar{K}^0$	0.342 ± 0.052	0.34 ± 0.08
$D^0 \to \pi^0\eta$	1.47 ± 0.90	0.68 ± 0.07
$D^0 \to \pi^0\eta'$	2.17 ± 0.65	0.90 ± 0.14
$D^0 \to \eta\eta$	1.27 ± 0.27	1.67 ± 0.20
$D^0 \to \eta\eta'$	0.953 ± 0.183	1.05 ± 0.26
$D^+ \to \pi^+\pi^0$	0.889 ± 0.451	1.19 ± 0.06
$D^+ \to K^+\bar{K}^0$	3.75 ± 0.63	5.66 ± 0.32
$D^+ \to \pi^+\eta$	4.72 ± 0.21	3.53 ± 0.21
$D^+ \to \pi^+\eta'$	6.76 ± 2.19	4.67 ± 0.29
$D_s^+ \to \pi^+K^0$	1.96 ± 0.90	2.42 ± 0.12
$D_s^+ \to \pi^0K^+$	0.817 ± 0.464	0.63 ± 0.21
$D_s^+ \to K^+\eta$	1.50 ± 0.75	1.76 ± 0.35
$D_s^+ \to K^+\eta'$	0.707 ± 0.049	1.8 ± 0.6

$$\chi^2 = \sum_i \frac{(Br_i^{th} - Br_i^{exp})^2}{\sigma^2_{Br_i^{th}} + \sigma^2_{Br_i^{exp}}}$$

$SU(3)_F$ & FSI (1)

F. Buccella, M. Lusignoli, A. Pugliese and P.S., PRD 88 (2013) 074011
F. Buccella, E. Franco, M. Lusignoli, A. Paul, A. Pugliese, P.S., L. Silvestrini, in preparation

D^0 SCS & U-spin Symmetry

⋆ D^0 is U-spin singlet

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

⋆ Two RME (we choose them reals and call T' and C')

⋆ $SU(3)_F$ violation from FSI

D^0 CF and DCS and all D^+, D_s decays

⋆ Three RME (T, C, D): $\langle \mathbf{8} | | \mathbf{15} | | \bar{\mathbf{3}} \rangle$ $\langle \mathbf{27} | | \mathbf{15} | | \bar{\mathbf{3}} \rangle$ $\langle \mathbf{8} | | \bar{\mathbf{6}} | | \bar{\mathbf{3}} \rangle$

⋆ A parameter (K) takes into account the non conservation of the current $\bar{s}\gamma_\mu(1-\gamma_5)q$ with an opposite sign in the CF and in the DCS.

$SU(3)_F$ & FSI (1)

F. Buccella, M. Lusignoli, A. Pugliese and P.S., PRD 88 (2013) 074011
F. Buccella, E. Franco, M. Lusignoli, A. Paul, A. Pugliese, P.S., L. Silvestrini, in preparation

D^0 SCS & U-spin Symmetry

⋆ D^0 is U-spin singlet

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

⋆ Two RME (we choose them reals and call T' and C')

⋆ $SU(3)_F$ violation from FSI

D^0 CF and DCS and all D^+, D_s decays

⋆ Three RME (T, C, D): $\langle \mathbf{8} | |\mathbf{15}| | \bar{\mathbf{3}} \rangle$ $\langle \mathbf{27} | |\mathbf{15}| | \bar{\mathbf{3}} \rangle$ $\langle \mathbf{8} | |\bar{\mathbf{6}}| | \bar{\mathbf{3}} \rangle$

⋆ A parameter (K) takes into account the non conservation of the current $\bar{s}\gamma_\mu(1-\gamma_5)q$ with an opposite sign in the CF and in the DCS.

Final State Interactions

We describe the FSI as the effect of resonances in the scattering of the final particles.
In other words, strong phases are generated by the resonances responsible for rescattering of final states.
Assuming no exotic resonances belonging to the 27 representation, the possible resonances have SU(3)$_F$ and isospin quantum numbers ($\mathbf{8}, I=1$), ($\mathbf{8}, I=1/2$), ($\mathbf{8}, I=0$) and ($\mathbf{1}, I=0$). Moreover, the two states with $I=0$ can be mixed, yielding two resonances:

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

$SU(3)_F$ & FSI (1)

F. Buccella, M. Lusignoli, A. Pugliese and P.S., PRD 88 (2013) 074011
F. Buccella, E. Franco, M. Lusignoli, A. Paul, A. Pugliese, P.S., L. Silvestrini, in preparation

D^0 SCS & U-spin Symmetry

⋆ D^0 is U-spin singlet

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

⋆ Two RME (we choose them reals and call T' and C')

⋆ $SU(3)_F$ violation from FSI

D^0 CF and DCS and all D^+, D_s decays

⋆ Three RME (T, C, D): $\langle \mathbf{8} | |\mathbf{15}| | \bar{\mathbf{3}} \rangle$ $\langle \mathbf{27} | |\mathbf{15}| | \bar{\mathbf{3}} \rangle$ $\langle \mathbf{8} | |\bar{\mathbf{6}}| | \bar{\mathbf{3}} \rangle$

⋆ A parameter (K) takes into account the non conservation of the current $\bar{s}\gamma_\mu(1-\gamma_5)q$ with an opposite sign in the CF and in the DCS.

Final State Interactions

We describe the FSI as the effect of resonances in the scattering of the final particles.
In other words, strong phases are generated by the resonances responsible for rescattering of final states.
Assuming no exotic resonances belonging to the 27 representation, the possible resonances have SU(3)$_F$ and isospin quantum numbers ($\mathbf{8}, I=1$), ($\mathbf{8}, I=1/2$), ($\mathbf{8}, I=0$) and ($\mathbf{1}, I=0$). 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', δ_1 and $\delta_{1/2}$ are our model parameters together with the amplitudes T, T', C, C', D, and K. Moreover, we assume that

$$T' = T(1+\varepsilon) \text{ and } C' = C(1-\varepsilon)$$

The phases for the decay modes of D_s^+ is expected to be different from those coming in the D^0 and D^+:

$$\delta_1' = \delta_1(1-\varepsilon_\delta) \text{ and } \delta'_{\frac{1}{2}} = \delta_{\frac{1}{2}}(1-\varepsilon_\delta)$$

Comparison with data

F. Buccella, E. Franco, M. Lusignoli, A. Paul, A. Pugliese, P.S., L. Silvestrini, in preparation

Channel	**Fit** ($\times 10^{-3}$)	**Exp.** ($\times 10^{-3}$)
CF		
$\mathrm{BR}(D^+ \to \pi^+ K_S)$	15.72 ± 0.41	15.3 ± 0.6
$\mathrm{BR}(D^+ \to \pi^+ K_L)$	14.34 ± 0.37	14.6 ± 0.5
$\mathrm{BR}(D^0 \to \pi^+ K^-)$	39.31 ± 0.40	39.3 ± 0.4
$\mathrm{BR}(D^0 \to \pi^0 K_S)$	11.9 ± 0.33	12.0 ± 0.4
$\mathrm{BR}(D^0 \to \pi^0 K_L)$	9.39 ± 0.27	10.0 ± 0.7
$\mathrm{BR}(D_s^+ \to K^+ K_S)$	15.0 ± 0.5	15.0 ± 0.5
SCS		
$\mathrm{BR}(D^0 \to \pi^+ \pi^-)$	1.42 ± 0.03	1.421 ± 0.025
$\mathrm{BR}(D^0 \to \pi^0 \pi^0)$	0.83 ± 0.04	0.826 ± 0.035
$\mathrm{BR}(D^+ \to \pi^+ \pi^0)$	1.22 ± 0.06	1.24 ± 0.06
$\mathrm{BR}(D^0 \to K^+ K^-)$	4.02 ± 0.06	4.01 ± 0.07
$\mathrm{BR}(D^0 \to K_S K_S)$	0.17 ± 0.04	0.18 ± 0.04
$\mathrm{BR}(D^+ \to K^+ K_S)$	2.89 ± 0.12	2.95 ± 0.15
$\mathrm{BR}(D_s^+ \to \pi^0 K^+)$	1.03 ± 0.04	0.63 ± 0.21
$\mathrm{BR}(D_s^+ \to \pi^+ K_S)$	1.24 ± 0.06	1.22 ± 0.06
DCS		
$\mathrm{BR}(D^+ \to \pi^0 K^+)$	0.155 ± 0.005	0.189 ± 0.025
$\mathrm{BR}(D^0 \to \pi^- K^+)$	0.140 ± 0.003	0.1399 ± 0.0027

$$\chi^2/NdF \approx 8/(16-11) = 1.6$$

Channel	Fit ($\times 10^{-3}$)	Exp. ($\times 10^{-3}$)
CF		
$\mathrm{BR}(D^0 \to K_S \eta)$	3.56 ± 0.1	4.85 ± 0.3
$\mathrm{BR}(D_s^+ \to \pi^+ \eta)$	34.1 ± 1.5	17.0 ± 0.9
SCS		
$\mathrm{BR}(D^0 \to \eta \eta)$	0.96 ± 0.1	1.70 ± 0.20
$\mathrm{BR}(D^+ \to \pi^+ \eta)$	2.84 ± 0.22	3.66 ± 0.22
$\mathrm{BR}(D^0 \to \pi^0 \eta)$	0.70 ± 0.04	0.69 ± 0.07
$\mathrm{BR}(D_s^+ \to K^+ \eta)$	1.14 ± 0.07	1.77 ± 0.35
DCS		
$\mathrm{BR}(D^+ \to K^+ \eta)$	0.047 ± 0.002	0.112 ± 0.018

$$\frac{a_{CP}^{\mathrm{dir}}(\pi^+\pi^-)}{a_{CP}^{\mathrm{dir}}(K^+K^-)} \approx -2$$

Conclusions

- The $D \to PP$ is an interesting laboratory to study CP Violation
- The $SU(3)_F$ flavour symmetry is a powerful guide to study these processes, but it is not exhaustive if you want to predict CPV asymmetries
- Many approaches has been used (with $SU(3)_F$) but a lot of work should be done.

Backup Slides

$D \to PV$ and $SU(3)_F$

L. L. Chau and H. Y. Cheng, PRD 36, 137 (1987)
F. Buccella, M. Lusignoli, G. Miele, A. Pugliese, and P. S., PRD 51, 3478 (1995)
B. Bhattacharya and J. L. Rosner, PRD 79, 034016 (2009)
H. Y. Cheng and C.W. Chiang, PRD 81, 074021 (2010)
Z. T. Zou, C. Li, and C. D. Liu, Chin. Phys. C 37, 093101 (2013)
Q. Qin, H.-n. Li, C.-D. Liu, and F.-S. Yu, PRD 89, 054006 (2014).
H.-Y. Cheng, C.-W. Chiang, and A.-L. Kuo, PRD 93 (2016), 114010

- $D \to PV$ modes by using Topological Diagram approach
- $SU(3)_F$ symmetry reduces the number of amplitudes to four: T, C, E, A
- Depending on the spectator quark is in the V or in the P we have $\mathscr{A}_V$ and $\mathscr{A}_P$, respectively
- Amplitudes: T_P, T_V, C_P, C_V, E_P, E_V, A_P, A_V and so 15 free real parameters
- Measured CF Branching ratios: sixteen
- Many solutions but the favoured one reproduces the Br for SCS and DCS decay modes

"Exact flavor SU(3)-symmetric approach is still sufficiently adequate to provide an overall explanation for the current data"

see also talk by B. Loiseau