CP Violation in Non-leptonic Charmed Meson Decays

Pietro Santorelli

Dipartimento di Fisica
Università degli Studi di Napoli Federico II

Physics of Heavy Quarks and Hadrons
Dubna, 18 July 2013

Recent Experimental results on Direct CPV in D Decays

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

$$\Delta a_{\mathrm{CP}} = (-0.82 \pm 0.21 \pm 0.11)\% \qquad (\text{LHCb}\,(2012)),$$

Recent Experimental results on Direct CPV in D Decays

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

$$\begin{aligned}
\Delta a_{\rm CP} &= (-0.82 \pm 0.21 \pm 0.11)\% && \text{(LHCb (2012))},\\
&= (-0.62 \pm 0.21 \pm 0.10)\% && \text{(CDF (2012))},\\
&= (-0.87 \pm 0.41 \pm 0.06)\% && \text{(Belle (2012))},\\
&= (+0.24 \pm 0.62 \pm 0.26)\% && \text{(BaBaR (2008))},\\
&= (-0.34 \pm 0.15 \pm 0.10)\% && \text{(LHCb (2013))},\\
&= (+0.49 \pm 0.30 \pm 0.14)\% && \text{(LHCb (2013))}.
\end{aligned}$$

Recent Experimental results on Direct CPV in D Decays

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

$$\begin{aligned}
\Delta a_{\rm CP} &= (-0.82 \pm 0.21 \pm 0.11)\% && (\text{LHCb}\,(2012)),\\
&= (-0.62 \pm 0.21 \pm 0.10)\% && (\text{CDF}\,(2012)),\\
&= (-0.87 \pm 0.41 \pm 0.06)\% && (\text{Belle}\,(2012)),\\
&= (+0.24 \pm 0.62 \pm 0.26)\% && (\text{BaBaR}\,(2008)),\\
&= (-0.34 \pm 0.15 \pm 0.10)\% && (\text{LHCb}\,(2013)),\\
&= (+0.49 \pm 0.30 \pm 0.14)\% && (\text{LHCb}\,(2013)).
\end{aligned}$$

A naive weighted average

$$\Delta a_{\rm CP} = (-0.33 \pm 0.12)\%$$

Plan of the talk

Plan of the talk

1. The description of the CP Violation

Plan of the talk

1. The description of the CP Violation
2. The non-leptonic decays of D mesons

Plan of the talk

1. The description of the CP Violation
2. The non-leptonic decays of D mesons
3. A Simple Model

Plan of the talk

1. The description of the CP Violation
2. The non-leptonic decays of D mesons
3. A Simple Model
4. Are the experimental data compatible with the Standard Model?

Plan of the talk

1. The description of the CP Violation
2. The non-leptonic decays of D mesons
3. A Simple Model
4. Are the experimental data compatible with the Standard Model?
5. Conclusions

Standard Model and CP Violation

In the SM CP Violation can emerge in the interaction involving charged currents.

$$\overline{\psi}_1 \gamma_\mu \psi_2 \xrightarrow{\text{CP}} -\overline{\psi}_2 \gamma^\mu \psi_1$$
$$\overline{\psi}_1 \gamma_\mu \gamma_5 \psi_2 \xrightarrow{\text{CP}} -\overline{\psi}_2 \gamma^\mu \gamma_5 \psi_1$$
$$W_\mu \xrightarrow{\text{CP}} -W^{\dagger\mu}$$

Standard Model and CP Violation

In the SM CP Violation can emerge in the interaction involving charged currents.

$$\overline{\psi}_1 \gamma_\mu \psi_2 \xrightarrow{\text{CP}} -\overline{\psi}_2 \gamma^\mu \psi_1$$

$$\overline{\psi}_1 \gamma_\mu \gamma_5 \psi_2 \xrightarrow{\text{CP}} -\overline{\psi}_2 \gamma^\mu \gamma_5 \psi_1$$

$$W_\mu \xrightarrow{\text{CP}} -W^{\dagger\mu}$$

$$\mathscr{L} = gV_{12}\, \overline{\psi}_1 \gamma_\mu (1-\gamma_5) \psi_2 W^\mu + gV_{12}^*\, \overline{\psi}_2 \gamma_\mu (1-\gamma_5) \psi_1 W^{\dagger\mu}$$

Standard Model and CP Violation

In the SM CP Violation can emerge in the interaction involving charged currents.

$$\overline{\psi}_1 \gamma_\mu \psi_2 \xrightarrow{\text{CP}} -\overline{\psi}_2 \gamma^\mu \psi_1$$
$$\overline{\psi}_1 \gamma_\mu \gamma_5 \psi_2 \xrightarrow{\text{CP}} -\overline{\psi}_2 \gamma^\mu \gamma_5 \psi_1$$
$$W_\mu \xrightarrow{\text{CP}} -W^{\dagger\mu}$$

$$\mathscr{L} = gV_{12}\, \overline{\psi}_1 \gamma_\mu (1-\gamma_5) \psi_2 W^\mu + gV_{12}^*\, \overline{\psi}_2 \gamma_\mu (1-\gamma_5) \psi_1 W^{\dagger\mu}$$
$$\Downarrow \qquad\qquad \Downarrow$$
$$\mathscr{L}^{\text{CP}} = gV_{12}\, \overline{\psi}_2 \gamma^\mu (1-\gamma_5) \psi_1 W^\dagger_\mu + gV_{12}^*\, \overline{\psi}_1 \gamma^\mu (1-\gamma_5) \psi_2 W_\mu$$

Standard Model and CP Violation

In the SM CP Violation can emerge in the interaction involving charged currents.

$$\overline{\psi}_1 \gamma_\mu \psi_2 \xrightarrow{\text{CP}} -\overline{\psi}_2 \gamma^\mu \psi_1$$
$$\overline{\psi}_1 \gamma_\mu \gamma_5 \psi_2 \xrightarrow{\text{CP}} -\overline{\psi}_2 \gamma^\mu \gamma_5 \psi_1$$
$$W_\mu \xrightarrow{\text{CP}} -W^{\dagger\mu}$$

$$\mathscr{L} = gV_{12}\, \overline{\psi}_1 \gamma_\mu (1-\gamma_5) \psi_2 W^\mu + gV_{12}^*\, \overline{\psi}_2 \gamma_\mu (1-\gamma_5) \psi_1 W^{\dagger\mu}$$
$$\Downarrow \qquad\qquad \Downarrow$$
$$\mathscr{L}^{\text{CP}} = gV_{12}\, \overline{\psi}_2 \gamma^\mu (1-\gamma_5) \psi_1 W^\dagger_\mu + gV_{12}^*\, \overline{\psi}_1 \gamma^\mu (1-\gamma_5) \psi_2 W_\mu$$

Neutral Flavoured Mesons

A generic flavoured neutral meson M^0 (K^0, D^0, B_d^0 and B_s^0) with non-zero eigenvalue of flavor F and its antiparticle $\bar{M}^0$ are defined by

$$F\left|M^0\right\rangle = +\left|M^0\right\rangle \qquad F\left|\bar{M}^0\right\rangle = -\left|\bar{M}^0\right\rangle$$

Neutral Flavoured Mesons

A generic flavoured neutral meson M^0 (K^0, D^0, B_d^0 and B_s^0) with non-zero eigenvalue of flavor F and its antiparticle $\bar{M}^0$ are defined by

$$F\left|M^0\right\rangle = +\left|M^0\right\rangle \qquad F\left|\bar{M}^0\right\rangle = -\left|\bar{M}^0\right\rangle$$

Moreover,

$$CP\left|M^0\right\rangle = \left|\bar{M}^0\right\rangle \qquad CP\left|\bar{M}^0\right\rangle = \left|M^0\right\rangle$$

Neutral Flavoured Mesons

A generic flavoured neutral meson M^0 (K^0, D^0, B_d^0 and B_s^0) with non-zero eigenvalue of flavor F and its antiparticle $\bar{M}^0$ are defined by

$$F\left|M^0\right\rangle = +\left|M^0\right\rangle \qquad F\left|\bar{M}^0\right\rangle = -\left|\bar{M}^0\right\rangle$$

Moreover,

$$CP\left|M^0\right\rangle = \left|\bar{M}^0\right\rangle \qquad CP\left|\bar{M}^0\right\rangle = \left|M^0\right\rangle$$

Weak interactions don't conserve flavour quantum numbers and so M^0 and $\bar{M}^0$ cannot be physical states.

Neutral Flavoured Mesons

A generic flavoured neutral meson M^0 (K^0, D^0, B_d^0 and B_s^0) with non-zero eigenvalue of flavor F and its antiparticle $\bar{M}^0$ are defined by

$$F\left|M^0\right\rangle = +\left|M^0\right\rangle \qquad F\left|\bar{M}^0\right\rangle = -\left|\bar{M}^0\right\rangle$$

Moreover,

$$CP\left|M^0\right\rangle = \left|\bar{M}^0\right\rangle \qquad CP\left|\bar{M}^0\right\rangle = \left|M^0\right\rangle$$

Weak interactions don't conserve flavour quantum numbers and so M^0 and $\bar{M}^0$ cannot be physical states.
But, if CP is conserved, the physical states are

$$M_\pm = \frac{1}{\sqrt{2}}\left[\left|M^0\right\rangle \pm \left|\bar{M}^0\right\rangle\right] \qquad CP|M_\pm\rangle = \pm|M_\pm\rangle$$

Neutral Flavoured Mesons:Time Evolution

The exact time evolution of $\bar{M}^0$ and M^0 is prohibitively complicated: M^0 and $\bar{M}^0$ couple together and can decay into other states.

Starting from initial states which are linear combinations of $\bar{M}^0$ and M^0, we can study the time evolution of the coefficients by considering the weak interactions as perturbation to the strong ones. At the second order in the weak interactions and in the subspace $M^0 - \bar{M}^0$, the effective hamiltonian can be written as

$$\imath\hbar \frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle$$

Neutral Flavoured Mesons:Time Evolution

The exact time evolution of $\bar{M}^0$ and M^0 is prohibitively complicated: M^0 and $\bar{M}^0$ couple together and can decay into other states.
Starting from initial states which are linear combinations of $\bar{M}^0$ and M^0, we can study the time evolution of the coefficients by considering the weak interactions as perturbation to the strong ones. At the second order in the weak interactions and in the subspace $M^0 - \bar{M}^0$, the effective hamiltonian can be written as

$$\imath\hbar \frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle \qquad \boldsymbol{H} = \boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}$$

Neutral Flavoured Mesons:Time Evolution

The exact time evolution of $\bar{M}^0$ and M^0 is prohibitively complicated: M^0 and $\bar{M}^0$ couple together and can decay into other states.

Starting from initial states which are linear combinations of $\bar{M}^0$ and M^0, we can study the time evolution of the coefficients by considering the weak interactions as perturbation to the strong ones. At the second order in the weak interactions and in the subspace $M^0 - \bar{M}^0$, the effective hamiltonian can be written as

$$\imath\hbar \frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle \qquad \boldsymbol{H} = \boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma} \qquad \begin{array}{c} \boldsymbol{M} = \boldsymbol{M}^\dagger \\ \boldsymbol{\Gamma} = \boldsymbol{\Gamma}^\dagger \end{array}$$

Neutral Flavoured Mesons:Time Evolution

The exact time evolution of $\bar{M}^0$ and M^0 is prohibitively complicated: M^0 and $\bar{M}^0$ couple together and can decay into other states.
Starting from initial states which are linear combinations of $\bar{M}^0$ and M^0, we can study the time evolution of the coefficients by considering the weak interactions as perturbation to the strong ones. At the second order in the weak interactions and in the subspace $M^0 - \bar{M}^0$, the effective hamiltonian can be written as

$$\imath\hbar \frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle \qquad \boldsymbol{H} = \boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma} \qquad \begin{array}{c} \boldsymbol{M} = \boldsymbol{M}^\dagger \\ \boldsymbol{\Gamma} = \boldsymbol{\Gamma}^\dagger \end{array}$$

Note that

$$\frac{d}{dt}\langle\psi|\,\psi\rangle = -\frac{1}{\hbar}\langle\psi|\,\boldsymbol{\Gamma}\,|\psi\rangle$$

Neutral Flavoured Mesons:Time Evolution

The exact time evolution of $\bar{M}^0$ and M^0 is prohibitively complicated: M^0 and $\bar{M}^0$ couple together and can decay into other states.
Starting from initial states which are linear combinations of $\bar{M}^0$ and M^0, we can study the time evolution of the coefficients by considering the weak interactions as perturbation to the strong ones. At the second order in the weak interactions and in the subspace $M^0 - \bar{M}^0$, the effective hamiltonian can be written as

$$\imath \hbar \frac{d}{dt} |\psi\rangle = \boldsymbol{H} |\psi\rangle \qquad \boldsymbol{H} = \boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma} \qquad \begin{array}{c} \boldsymbol{M} = \boldsymbol{M}^\dagger \\ \boldsymbol{\Gamma} = \boldsymbol{\Gamma}^\dagger \end{array}$$

Note that

$$\frac{d}{dt} \langle \psi | \psi \rangle = -\frac{1}{\hbar} \langle \psi | \boldsymbol{\Gamma} | \psi \rangle$$

Moreover,

$$\boldsymbol{H} = H_{strong} + H_{e.m.} + H_{weak}$$

Neutral Flavoured Mesons:Time Evolution

The exact time evolution of $\bar{M}^0$ and M^0 is prohibitively complicated: M^0 and $\bar{M}^0$ couple together and can decay into other states.

Starting from initial states which are linear combinations of $\bar{M}^0$ and M^0, we can study the time evolution of the coefficients by considering the weak interactions as perturbation to the strong ones. At the second order in the weak interactions and in the subspace $M^0 - \bar{M}^0$, the effective hamiltonian can be written as

$$\imath\hbar \frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle \qquad \boldsymbol{H} = \boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma} \qquad \boldsymbol{M} = \boldsymbol{M}^\dagger \quad \boldsymbol{\Gamma} = \boldsymbol{\Gamma}^\dagger$$

Note that

$$\frac{d}{dt}\langle\psi|\,\psi\rangle = -\frac{1}{\hbar}\langle\psi|\,\boldsymbol{\Gamma}\,|\psi\rangle$$

Moreover,

$$\boldsymbol{H} = H_{strong} + H_{e.m.} + H_{weak} = H_{\Delta F=0} + H_{\Delta F=1}$$

Neutral Flavoured Mesons:Time Evolution (1)

A generic state $|\psi\rangle = a(t)\left|M^0\right\rangle + b(t)\left|\bar{M}^0\right\rangle$ satisfy the equation

$$\imath\hbar \frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle$$

Neutral Flavoured Mesons:Time Evolution (1)

A generic state $|\psi\rangle = a(t)\left|M^0\right\rangle + b(t)\left|\bar{M}^0\right\rangle$ satisfy the equation

$$\imath\hbar\frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle$$

$\rightarrow$

$$\imath\hbar\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

Neutral Flavoured Mesons:Time Evolution (1)

A generic state $|\psi\rangle = a(t)\left|M^0\right\rangle + b(t)\left|\bar{M}^0\right\rangle$ satisfy the equation

$$\imath\hbar\frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle \quad \Rightarrow \quad \imath\hbar\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

where

$$\left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right) = \begin{pmatrix} M_{11} - (\imath/2)\Gamma_{11} & M_{12} - (\imath/2)\Gamma_{12} \\ M_{21} - (\imath/2)\Gamma_{21} & M_{22} - (\imath/2)\Gamma_{22} \end{pmatrix}$$

Neutral Flavoured Mesons:Time Evolution (1)

A generic state $|\psi\rangle = a(t)\left|M^0\right\rangle + b(t)\left|\bar{M}^0\right\rangle$ satisfy the equation

$$\imath\hbar\frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle$$

→

$$\imath\hbar\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

where

$$\left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right) = \begin{pmatrix} M_{11} - (\imath/2)\Gamma_{11} & M_{12} - (\imath/2)\Gamma_{12} \\ M_{21} - (\imath/2)\Gamma_{21} & M_{22} - (\imath/2)\Gamma_{22} \end{pmatrix}$$

with

Mass matrix elements

$$M_{11} = M_{11}^* = m_0 + \left\langle M^0\right| H_w \left|M^0\right\rangle + \sum_n \mathscr{P}\frac{|\langle n| H_w \left|M^0\right\rangle|^2}{m_0 - E_n}$$

$$M_{22} = M_{22}^* = m_0 + \left\langle \bar{M}^0\right| H_w \left|\bar{M}^0\right\rangle + \sum_n \mathscr{P}\frac{|\langle n| H_w \left|\bar{M}^0\right\rangle|^2}{m_0 - E_n}$$

$$M_{12} = M_{21}^* = \underbrace{\left\langle M^0\right| H_w \left|\bar{M}^0\right\rangle}_{=0} + \sum_n \mathscr{P}\frac{\left\langle M^0\right| H_w |n\rangle\langle n| H_w \left|\bar{M}^0\right\rangle}{m_0 - E_n}$$

Neutral Flavoured Mesons:Time Evolution (1)

A generic state $|\psi\rangle = a(t)\left|M^0\right\rangle + b(t)\left|\bar{M}^0\right\rangle$ satisfy the equation

$$\imath\hbar\frac{d}{dt}|\psi\rangle = \boldsymbol{H}|\psi\rangle \quad \Rightarrow \quad \imath\hbar\frac{d}{dt}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right)\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

where

$$\left(\boldsymbol{M} - \frac{\imath}{2}\boldsymbol{\Gamma}\right) = \begin{pmatrix} M_{11} - (\imath/2)\Gamma_{11} & M_{12} - (\imath/2)\Gamma_{12} \\ M_{21} - (\imath/2)\Gamma_{21} & M_{22} - (\imath/2)\Gamma_{22} \end{pmatrix}$$

with

Mass matrix elements

$$M_{11} = M_{11}^* = m_0 + \left\langle M^0\right| H_w \left|M^0\right\rangle + \sum_n \mathscr{P}\frac{|\langle n| H_w \left|M^0\right\rangle|^2}{m_0 - E_n}$$

$$M_{22} = M_{22}^* = m_0 + \left\langle \bar{M}^0\right| H_w \left|\bar{M}^0\right\rangle + \sum_n \mathscr{P}\frac{|\langle n| H_w \left|\bar{M}^0\right\rangle|^2}{m_0 - E_n}$$

$$M_{12} = M_{21}^* = \underbrace{\left\langle M^0\right| H_w \left|\bar{M}^0\right\rangle}_{=0} + \sum_n \mathscr{P}\frac{\left\langle M^0\right| H_w |n\rangle \langle n| H_w \left|\bar{M}^0\right\rangle}{m_0 - E_n}$$

Decay matrix elements

$$\Gamma_{11} = \Gamma_{11}^* = 2\pi\sum_n \delta(m_0 - E_n)|\langle n| H_w \left|M^0\right\rangle|^2$$

$$\Gamma_{22} = \Gamma_{22}^* = 2\pi\sum_n \delta(m_0 - E_n)|\langle n| H_w \left|\bar{M}^0\right\rangle|^2$$

$$\Gamma_{12} = \Gamma_{21}^* = 2\pi\sum_n \delta(m_0 - E_n) \times \left\langle M^0\right| H_w |n\rangle \langle n| H_w \left|\bar{M}^0\right\rangle$$

Neutral Flavoured Mesons:Time Evolution(2)

CPT symmetry

$$M_{11} = M_{22}$$
$$\Gamma_{11} = \Gamma_{22}$$

Neutral Flavoured Mesons:Time Evolution(2)

CPT symmetry

$$M_{11} = M_{22}$$
$$\Gamma_{11} = \Gamma_{22}$$

Neutral Flavoured Mesons:Time Evolution(2)

CPT symmetry

$$M_{11} = M_{22}$$
$$\Gamma_{11} = \Gamma_{22}$$

→

$$\left|M_a\right\rangle = p\left|M^0\right\rangle + q\left|\bar{M}^0\right\rangle$$
$$\left|M_b\right\rangle = p\left|M^0\right\rangle - q\left|\bar{M}^0\right\rangle$$

Neutral Flavoured Mesons:Time Evolution(2)

CPT symmetry

$$\begin{aligned} M_{11} &= M_{22} \\ \Gamma_{11} &= \Gamma_{22} \end{aligned}$$

$$\begin{aligned} |M_a\rangle &= p\left|M^0\right\rangle + q\left|\bar{M}^0\right\rangle \\ |M_b\rangle &= p\left|M^0\right\rangle - q\left|\bar{M}^0\right\rangle \end{aligned}$$

$$\frac{q}{p} = \pm\sqrt{\frac{H_{21}}{H_{12}}} = \pm\sqrt{\frac{M_{12}^* - (\imath/2)\Gamma_{12}^*}{M_{12} - (\imath/2)\Gamma_{12}}}$$

Neutral Flavoured Mesons:Time Evolution(2)

CPT symmetry

$$\begin{aligned} M_{11} &= M_{22} \\ \Gamma_{11} &= \Gamma_{22} \end{aligned}$$

$\Rightarrow$

$$\begin{aligned} |M_a\rangle &= p\left|M^0\right\rangle + q\left|\bar{M}^0\right\rangle \\ |M_b\rangle &= p\left|M^0\right\rangle - q\left|\bar{M}^0\right\rangle \end{aligned}$$

$$\frac{q}{p} = \pm\sqrt{\frac{H_{21}}{H_{12}}} = \pm\sqrt{\frac{M_{12}^* - (\imath/2)\Gamma_{12}^*}{M_{12} - (\imath/2)\Gamma_{12}}}$$

$$|M_{a,b}(t)\rangle = e^{-\imath\lambda_{a,b}t}\,|M_{a,b}(0)\rangle = e^{-\imath m_{a,b}t}e^{-\Gamma_{a,b}t/2}\,|M_{a,b}(0)\rangle$$

Neutral Flavoured Mesons:Time Evolution(2)

CPT symmetry

$$M_{11} = M_{22}$$
$$\Gamma_{11} = \Gamma_{22}$$

$\Rightarrow$

$$|M_a\rangle = p\left|M^0\right\rangle + q\left|\bar{M}^0\right\rangle$$
$$|M_b\rangle = p\left|M^0\right\rangle - q\left|\bar{M}^0\right\rangle$$

$$\frac{q}{p} = \pm\sqrt{\frac{H_{21}}{H_{12}}} = \pm\sqrt{\frac{M_{12}^* - (\imath/2)\Gamma_{12}^*}{M_{12} - (\imath/2)\Gamma_{12}}}$$

$$|M_{a,b}(t)\rangle = e^{-\imath\lambda_{a,b}t}|M_{a,b}(0)\rangle = e^{-\imath m_{a,b}t}e^{-\Gamma_{a,b}t/2}|M_{a,b}(0)\rangle$$

$$\lambda_a \equiv m_a - (\imath/2)\Gamma_a = H_{11} + \frac{q}{p}H_{12} = H_{11} + \sqrt{H_{12}H_{21}}$$
$$\lambda_b \equiv m_b - (\imath/2)\Gamma_b = H_{11} - \frac{q}{p}H_{12} = H_{11} - \sqrt{H_{12}H_{21}}$$

Neutral Flavoured Mesons:Time Evolution(2)

CPT symmetry

$$M_{11} = M_{22}$$
$$\Gamma_{11} = \Gamma_{22}$$

$$|M_a\rangle = p|M^0\rangle + q|\bar{M}^0\rangle$$
$$|M_b\rangle = p|M^0\rangle - q|\bar{M}^0\rangle$$

$$\frac{q}{p} = \pm\sqrt{\frac{H_{21}}{H_{12}}} = \pm\sqrt{\frac{M_{12}^* - (\imath/2)\Gamma_{12}^*}{M_{12} - (\imath/2)\Gamma_{12}}}$$

$$|M_{a,b}(t)\rangle = e^{-\imath\lambda_{a,b}t}|M_{a,b}(0)\rangle = e^{-\imath m_{a,b}t}e^{-\Gamma_{a,b}t/2}|M_{a,b}(0)\rangle$$

$$\lambda_a \equiv m_a - (\imath/2)\Gamma_a = H_{11} + \frac{q}{p}H_{12} = H_{11} + \sqrt{H_{12}H_{21}}$$
$$\lambda_b \equiv m_b - (\imath/2)\Gamma_b = H_{11} - \frac{q}{p}H_{12} = H_{11} - \sqrt{H_{12}H_{21}}$$
$$m_{a,b} = M_{11} \pm \Re\sqrt{H_{12}H_{21}}$$

Neutral Flavoured Mesons:Time Evolution(2)

CPT symmetry

$$M_{11} = M_{22}$$
$$\Gamma_{11} = \Gamma_{22}$$

$\Rightarrow$

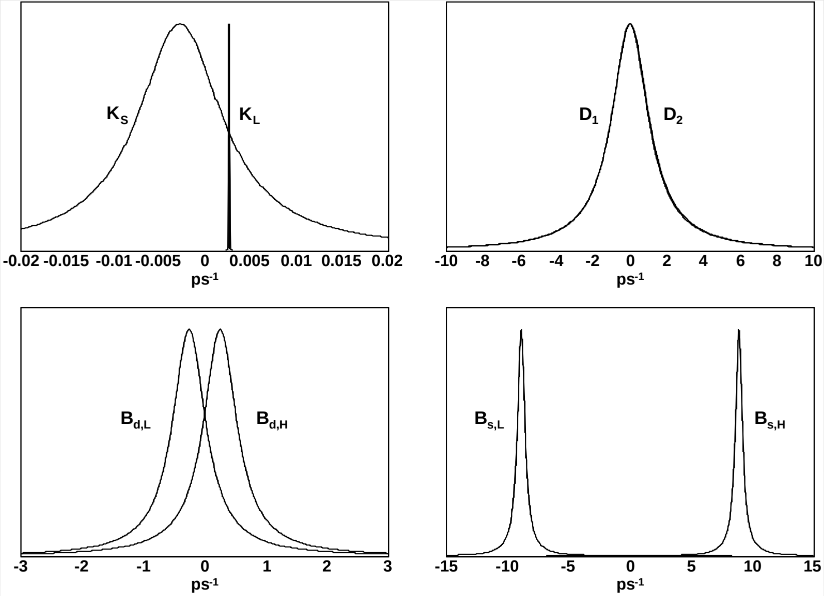
$$|M_a\rangle = p|M^0\rangle + q|\bar{M}^0\rangle$$
$$|M_b\rangle = p|M^0\rangle - q|\bar{M}^0\rangle$$

$$\frac{q}{p} = \pm\sqrt{\frac{H_{21}}{H_{12}}} = \pm\sqrt{\frac{M_{12}^* - (\imath/2)\Gamma_{12}^*}{M_{12} - (\imath/2)\Gamma_{12}}}$$

$$|M_{a,b}(t)\rangle = e^{-\imath\lambda_{a,b}t}|M_{a,b}(0)\rangle = e^{-\imath m_{a,b}t}e^{-\Gamma_{a,b}t/2}|M_{a,b}(0)\rangle$$

$$\lambda_a \equiv m_a - (\imath/2)\Gamma_a = H_{11} + \frac{q}{p}H_{12} = H_{11} + \sqrt{H_{12}H_{21}}$$
$$\lambda_b \equiv m_b - (\imath/2)\Gamma_b = H_{11} - \frac{q}{p}H_{12} = H_{11} - \sqrt{H_{12}H_{21}}$$
$$m_{a,b} = M_{11} \pm \Re\sqrt{H_{12}H_{21}}$$
$$\Gamma_{a,b} = \Gamma_{11} \mp 2\Im\sqrt{H_{12}H_{21}}$$

Widths and Mass Differences



M.Gersabeck, arXiv:1207.2195 [hep-ex]

Neutral Flavoured Mesons:Time Evolution(3)

It is very simple to evaluate the time evolution of the flavour eigenstates:

$$\begin{aligned} \left|M^0(t)\right\rangle &= f_+(t)\left|M^0\right\rangle + \frac{q}{p} f_-(t)\left|\bar{M}^0\right\rangle \\ \left|\bar{M}^0(t)\right\rangle &= f_+(t)\left|\bar{M}^0\right\rangle + \frac{p}{q} f_-(t)\left|M^0\right\rangle \end{aligned}$$

Neutral Flavoured Mesons:Time Evolution(3)

It is very simple to evaluate the time evolution of the flavour eigenstates:

$$\begin{aligned} \left|M^0(t)\right\rangle &= f_+(t)\left|M^0\right\rangle + \frac{q}{p} f_-(t)\left|\bar{M}^0\right\rangle \\ \left|\bar{M}^0(t)\right\rangle &= f_+(t)\left|\bar{M}^0\right\rangle + \frac{p}{q} f_-(t)\left|M^0\right\rangle \end{aligned}$$

where

$$f_\pm(t) = \frac{1}{2} e^{-\imath m_a t} e^{-\Gamma_a t/2}\left[1 \pm e^{-\imath \Delta m t} e^{-\Delta\Gamma t/2}\right]$$

Neutral Flavoured Mesons:Time Evolution(3)

It is very simple to evaluate the time evolution of the flavour eigenstates:

$$\begin{aligned} \left|M^0(t)\right\rangle &= f_+(t)\left|M^0\right\rangle + \frac{q}{p} f_-(t)\left|\bar{M}^0\right\rangle \\ \left|\bar{M}^0(t)\right\rangle &= f_+(t)\left|\bar{M}^0\right\rangle + \frac{p}{q} f_-(t)\left|M^0\right\rangle \end{aligned}$$

where

$$f_\pm(t) = \frac{1}{2} e^{-\imath m_a t} e^{-\Gamma_a t/2} \left[1 \pm e^{-\imath \Delta m t} e^{-\Delta\Gamma t/2}\right]$$

Probability to find at time t the same flavour eigenstate which it had at time $t = 0$

$$P[M^0(t) \to M^0] = P[\bar{M}^0(t) \to \bar{M}^0] = |f_+(t)|^2$$

Neutral Flavoured Mesons:Time Evolution(3)

It is very simple to evaluate the time evolution of the flavour eigenstates:

$$\begin{aligned} \left|M^0(t)\right\rangle &= f_+(t)\left|M^0\right\rangle + \frac{q}{p} f_-(t)\left|\bar{M}^0\right\rangle \\ \left|\bar{M}^0(t)\right\rangle &= f_+(t)\left|\bar{M}^0\right\rangle + \frac{p}{q} f_-(t)\left|M^0\right\rangle \end{aligned}$$

where

$$f_\pm(t) = \frac{1}{2} e^{-\imath m_a t} e^{-\Gamma_a t/2}\left[1 \pm e^{-\imath \Delta m t} e^{-\Delta\Gamma t/2}\right]$$

Probability to find at time t the same flavour eigenstate which it had at time $t = 0$

$$P[M^0(t) \to M^0] = P[\bar{M}^0(t) \to \bar{M}^0] = |f_+(t)|^2$$

Probability that an initial M^0 becomes $\bar{M}^0$ and *viceversa*

$$\begin{aligned} P[M^0(t) \to \bar{M}^0] &= \left|\frac{q}{p}\right|^2 |f_-(t)|^2 \\ P[\bar{M}^0(t) \to M^0] &= \left|\frac{p}{q}\right|^2 |f_-(t)|^2 \end{aligned}$$

Mixing Parameters

$$P[M^0(t) \to M^0] = \frac{1}{2} e^{-\Gamma t} (\cosh(y\Gamma t) + \cos(x\Gamma t))$$

$$P[M^0(t) \to \bar{M}^0] = \frac{1}{2} \left|\frac{q}{p}\right|^2 e^{-\Gamma t} (\cosh(y\Gamma t) - \cos(x\Gamma t))$$

Mixing Parameters

$$P[M^0(t) \to M^0] = \frac{1}{2} e^{-\Gamma t} (\cosh(y\Gamma t) + \cos(x\Gamma t))$$

$$P[M^0(t) \to \bar{M}^0] = \frac{1}{2} \left|\frac{q}{p}\right|^2 e^{-\Gamma t} (\cosh(y\Gamma t) - \cos(x\Gamma t))$$

$$x \equiv \frac{m_b - m_a}{\Gamma} = \frac{\Delta m}{\Gamma}$$

$$y \equiv \frac{\Gamma_b - \Gamma_a}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

$$\Gamma \equiv \frac{\Gamma_b + \Gamma_a}{2}$$

Mixing Parameters

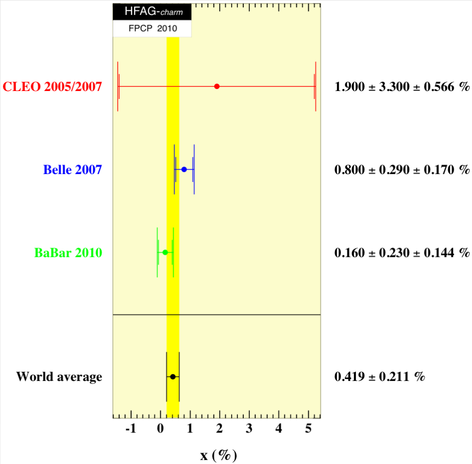
$$P[M^0(t) \to M^0] = \frac{1}{2} e^{-\Gamma t} (\cosh(y\Gamma t) + \cos(x\Gamma t))$$

$$P[M^0(t) \to \bar{M}^0] = \frac{1}{2} \left|\frac{q}{p}\right|^2 e^{-\Gamma t} (\cosh(y\Gamma t) - \cos(x\Gamma t))$$

$$x \equiv \frac{m_b - m_a}{\Gamma} = \frac{\Delta m}{\Gamma}$$

$$y \equiv \frac{\Gamma_b - \Gamma_a}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

$$\Gamma \equiv \frac{\Gamma_b + \Gamma_a}{2}$$



Mixing Parameters

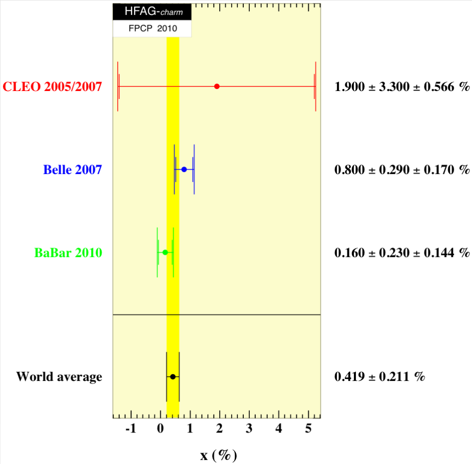
$$P[M^0(t) \to M^0] = \frac{1}{2} e^{-\Gamma t} (\cosh(y\Gamma t) + \cos(x\Gamma t))$$

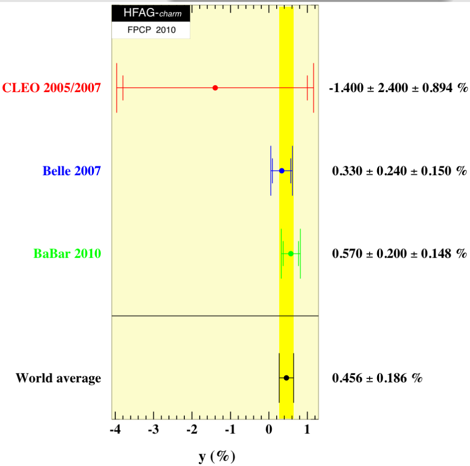
$$P[M^0(t) \to \bar{M}^0] = \frac{1}{2} \left|\frac{q}{p}\right|^2 e^{-\Gamma t} (\cosh(y\Gamma t) - \cos(x\Gamma t))$$

$$x \equiv \frac{m_b - m_a}{\Gamma} = \frac{\Delta m}{\Gamma}$$

$$y \equiv \frac{\Gamma_b - \Gamma_a}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

$$\Gamma \equiv \frac{\Gamma_b + \Gamma_a}{2}$$





Neutral Flavoured Mesons: Types of CP Violation

CP Violation in the Mixing

This occurs when the physical states do not coincide with CP eigenstates,

$$|q| \neq |p|$$

Neutral Flavoured Mesons: Types of CP Violation

CP Violation in the Mixing

This occurs when the physical states do not coincide with CP eigenstates,

$$|q| \neq |p|$$

For example if

$M^0 \to f \not\leftarrow \bar{M}^0$ *or* $M^0 \not\to f \leftarrow \bar{M}^0$

Neutral Flavoured Mesons: Types of CP Violation

CP Violation in the Mixing

This occurs when the physical states do not coincide with CP eigenstates,

$$|q| \neq |p|$$

For example if

$$M^0 \to f \not\leftarrow \bar{M}^0 \quad or \quad M^0 \not\to f \leftarrow \bar{M}^0$$

As in the case of semileptonic decay modes

$$M^0 \to \ell^+ X \not\leftarrow \bar{M}^0 \quad and \quad M^0 \not\to \ell^- X \leftarrow \bar{M}^0$$

Neutral Flavoured Mesons: Types of CP Violation

CP Violation in the Mixing

This occurs when the physical states do not coincide with CP eigenstates,

$$|q| \neq |p|$$

For example if

$$M^0 \to f \not\leftarrow \bar{M}^0 \quad or \quad M^0 \not\to f \leftarrow \bar{M}^0$$

As in the case of semileptonic decay modes

$$M^0 \to \ell^+ X \not\leftarrow \bar{M}^0 \quad and \quad M^0 \not\to \ell^- X \leftarrow \bar{M}^0$$

$$\frac{\Gamma(M^0(t) \to \ell^- X) - \Gamma(\bar{M}^0(t) \to \ell^+ X)}{\Gamma(M^0(t) \to \ell^- X) + \Gamma(\bar{M}^0(t) \to \ell^+ X)} = \frac{1 - |p/q|^4}{1 + |p/q|^4}$$

Neutral Flavoured Mesons: Types of CP Violation

CP Violation in the Mixing

This occurs when the physical states do not coincide with CP eigenstates,

$$|q| \neq |p|$$

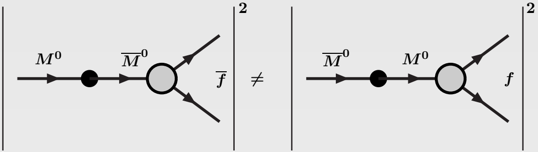
For example if

$$M^0 \to f \not\leftarrow \bar{M}^0 \quad \text{or} \quad M^0 \not\to f \leftarrow \bar{M}^0$$

As in the case of semileptonic decay modes

$$M^0 \to \ell^+ X \not\leftarrow \bar{M}^0 \quad \text{and} \quad M^0 \not\to \ell^- X \leftarrow \bar{M}^0$$

$$\frac{\Gamma(M^0(t) \to \ell^- X) - \Gamma(\bar{M}^0(t) \to \ell^+ X)}{\Gamma(M^0(t) \to \ell^- X) + \Gamma(\bar{M}^0(t) \to \ell^+ X)} = \frac{1 - |p/q|^4}{1 + |p/q|^4}$$



Neutral Flavoured Mesons: Types of CP Violation

CP Violation in the Mixing

This occurs when the physical states do not coincide with CP eigenstates,

$$|q| \neq |p|$$

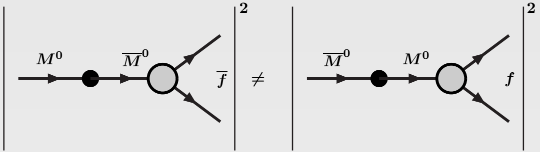
For example if

$M^0 \to f \not\leftarrow \bar{M}^0$ or $M^0 \not\to f \leftarrow \bar{M}^0$

As in the case of semileptonic decay modes

$M^0 \to \ell^+ X \not\leftarrow \bar{M}^0$ and $M^0 \not\to \ell^- X \leftarrow \bar{M}^0$

$$\frac{\Gamma(M^0(t) \to \ell^- X) - \Gamma(\bar{M}^0(t) \to \ell^+ X)}{\Gamma(M^0(t) \to \ell^- X) + \Gamma(\bar{M}^0(t) \to \ell^+ X)} = \frac{1 - |p/q|^4}{1 + |p/q|^4}$$



This kind of CPV is of the indirect type

Neutral Flavoured Mesons: Types of CP Violation(1)

CP Violation in the Decays (Direct)

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

$$|A(i \to f)| \neq |A(\overline{i} \to \overline{f})|$$

Neutral Flavoured Mesons: Types of CP Violation(1)

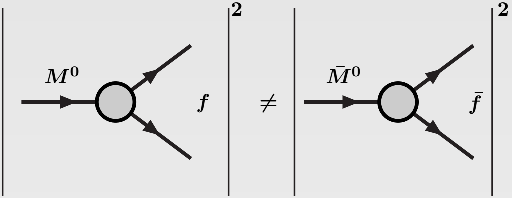
CP Violation in the Decays (Direct)

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

$$|A(i \to f)| \neq |A(\overline{i} \to \overline{f})|$$

In this case $\Delta m \approx \Delta\Gamma \approx 0$ and

$$a_{\mathrm{CP}}^{\mathrm{dir}} = \frac{\Gamma(M^0 \to f) - \Gamma(\bar{M}^0 \to \overline{f})}{\Gamma(M^0 \to f) + \Gamma(\bar{M}^0 \to \overline{f})}$$



Neutral Flavoured Mesons: Types of CP Violation(1)

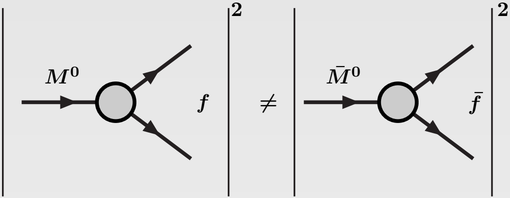
CP Violation in the Decays (Direct)

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

$$|A(i \to f)| \neq |A(\bar{i} \to \bar{f})|$$

In this case $\Delta m \approx \Delta\Gamma \approx 0$ and

$$a_{\mathrm{CP}}^{\mathrm{dir}} = \frac{\Gamma(M^0 \to f) - \Gamma(\bar{M}^0 \to \bar{f})}{\Gamma(M^0 \to f) + \Gamma(\bar{M}^0 \to \bar{f})}$$



This kind of CPV is the only one is also possible for charged particles, which are forbidden to mix by charge conservation.

Neutral Flavoured Mesons: Types of CP Violation(2)

CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

Neutral Flavoured Mesons: Types of CP Violation(2)

CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \rightarrow f \leftarrow \bar{M}^0$$

Neutral Flavoured Mesons: Types of CP Violation(2)

CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \to f \leftarrow \bar{M}^0$$

- This is the case of $CPf = \pm f$: $D^0 \to KK, \pi\pi \leftarrow \bar{D}^0$

Neutral Flavoured Mesons: Types of CP Violation(2)

CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \to f \leftarrow \bar{M}^0$$

- This is the case of $CPf = \pm f$: $D^0 \to KK, \pi\pi \leftarrow \bar{D}^0$
- but not only: for example $D^0(\overline{D}^0) \to K^- \pi^+$

Neutral Flavoured Mesons: Types of CP Violation(2)

CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \to f \leftarrow \bar{M}^0$$

- This is the case of $CPf = \pm f$: $D^0 \to KK, \pi\pi \leftarrow \bar{D}^0$
- but not only: for example $D^0(\overline{D}^0) \to K^-\pi^+$

$$A(M^0 \to f) + A(M^0 \to \bar{M}^0) A(\bar{M}^0 \to f)$$

Neutral Flavoured Mesons: Types of CP Violation(2)

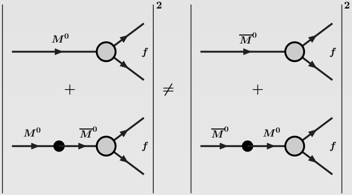
CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \to f \leftarrow \bar{M}^0$$

- This is the case of $CPf = \pm f$: $D^0 \to KK, \pi\pi \leftarrow \bar{D}^0$
- but not only: for example $D^0(\overline{D}^0) \to K^-\pi^+$

$$A(M^0 \to f) + A(M^0 \to \bar{M}^0) A(\bar{M}^0 \to f)$$



Neutral Flavoured Mesons: Types of CP Violation(2)

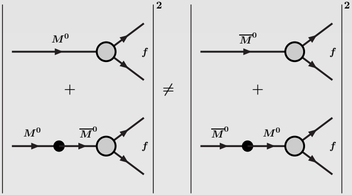
CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \to f \leftarrow \bar{M}^0$$

- This is the case of $CPf = \pm f$: $D^0 \to KK, \pi\pi \leftarrow \bar{D}^0$
- but not only: for example $D^0(\overline{D}^0) \to K^-\pi^+$

$$A(M^0 \to f) + A(M^0 \to \bar{M}^0)A(\bar{M}^0 \to f)$$



Useful definition

$$\lambda_f = \frac{\langle \bar{M}^0 | \, M_a \rangle}{\langle M^0 | \, M_a \rangle} \frac{A(\bar{M}^0 \to f)}{A(M^0 \to f)} = \frac{q}{p} \frac{\bar{A}_f}{A_f}$$

Neutral Flavoured Mesons: Types of CP Violation(2)

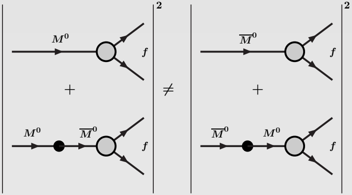
CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \to f \leftarrow \bar{M}^0$$

- This is the case of $CPf = \pm f$: $D^0 \to KK, \pi\pi \leftarrow \bar{D}^0$
- but not only: for example $D^0(\overline{D}^0) \to K^-\pi^+$

$$A(M^0 \to f) + A(M^0 \to \bar{M}^0)A(\bar{M}^0 \to f)$$



Useful definition

$$\lambda_f = \frac{\langle \bar{M}^0 | M_a \rangle}{\langle M^0 | M_a \rangle} \frac{A(\bar{M}^0 \to f)}{A(M^0 \to f)} = \frac{q}{p} \frac{\bar{A}_f}{A_f}$$

CP Symmetry implies

$$\lambda_f = \frac{1}{\lambda_f} \Rightarrow \lambda_f = 1$$

Neutral Flavoured Mesons: Types of CP Violation(2)

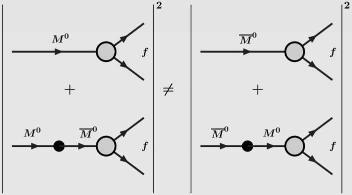
CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \to f \leftarrow \bar{M}^0$$

- This is the case of $CPf = \pm f$: $D^0 \to KK, \pi\pi \leftarrow \bar{D}^0$
- but not only: for example $D^0(\overline{D}^0) \to K^-\pi^+$

$$A(M^0 \to f) + A(M^0 \to \bar{M}^0) A(\bar{M}^0 \to f)$$



Useful definition

$$\lambda_f = \frac{\langle \bar{M}^0 | M_a \rangle}{\langle M^0 | M_a \rangle} \frac{A(\bar{M}^0 \to f)}{A(M^0 \to f)} = \frac{q}{p} \frac{\bar{A}_f}{A_f}$$

CP Symmetry implies

$$\lambda_f = \frac{1}{\lambda_f} \Rightarrow \lambda_f = 1$$

Neutral Flavoured Mesons: Types of CP Violation(2)

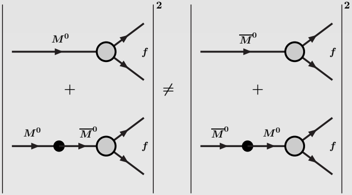
CPV in the interference of mixing and decays

This occurs when both, M^0 and $\bar{M}^0$, decay into the same final state

$$M^0 \to f \leftarrow \bar{M}^0$$

- This is the case of $CPf = \pm f$: $D^0 \to KK, \pi\pi \leftarrow \bar{D}^0$
- but not only: for example $D^0(\overline{D}^0) \to K^-\pi^+$

$$A(M^0 \to f) + A(M^0 \to \bar{M}^0) A(\bar{M}^0 \to f)$$



Useful definition

$$\lambda_f = \frac{\langle \bar{M}^0 | M_a \rangle}{\langle M^0 | M_a \rangle} \frac{A(\bar{M}^0 \to f)}{A(M^0 \to f)} = \frac{q}{p} \frac{\bar{A}_f}{A_f}$$

CP Symmetry implies

$$\lambda_f = \frac{1}{\lambda_f} \Rightarrow \lambda_f = 1$$

- $|\lambda_f| \neq 1$ CPV in mixing or decay
- $\Im(\lambda_f) \neq 0$ CPV in interf. mixing and decay

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

$$a_{CP}(h^+h^-,t) = \frac{\Gamma(D^0(t)\to h^+h^-) - \Gamma(\bar{D}^0(t)\to h^+h^-)}{\Gamma(D^0(t)\to h^+h^-) + \Gamma(\bar{D}^0(t)\to h^+h^-)} \overset{x\sim y\ll 1}{\approx} \frac{\Gamma(D^0\to h^+h^-) - \Gamma(\bar{D}^0\to h^+h^-)}{\Gamma(D^0\to h^+h^-) + \Gamma(\bar{D}^0\to h^+h^-)} + \frac{t}{\tau_D} a_{\rm CP}^{\rm ind}$$

$$= a_{\rm CP}^{\rm dir}(h^+h^-) + \frac{t}{\tau_D} a_{\rm CP}^{\rm ind}$$

where t is the proper decay time. The integrated asymmetry

$$a_{CP}(h^+h^-) \approx a_{\rm CP}^{\rm dir}(h^+h^-) + a_{\rm CP}^{\rm ind}\int dt\,\frac{t}{\tau_D}D(t)$$

$$= a_{\rm CP}^{\rm dir}(h^+h^-) + a_{\rm CP}^{\rm ind}\frac{\langle t\rangle}{\tau_D}$$

where $D(t)$ is the observed distribution of proper decay time

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

$$
\begin{aligned}
a_{CP}(h^+h^-,t) &= \frac{\Gamma(D^0(t)\to h^+h^-)-\Gamma(\bar{D}^0(t)\to h^+h^-)}{\Gamma(D^0(t)\to h^+h^-)+\Gamma(\bar{D}^0(t)\to h^+h^-)} \overset{x\sim y\ll 1}{\approx} \\
&\quad \frac{\Gamma(D^0\to h^+h^-)-\Gamma(\bar{D}^0\to h^+h^-)}{\Gamma(D^0\to h^+h^-)+\Gamma(\bar{D}^0\to h^+h^-)} + \frac{t}{\tau_D}a_{\mathrm{CP}}^{\mathrm{ind}} \\
&= a_{\mathrm{CP}}^{\mathrm{dir}}(h^+h^-) + \frac{t}{\tau_D}a_{\mathrm{CP}}^{\mathrm{ind}}
\end{aligned}
$$

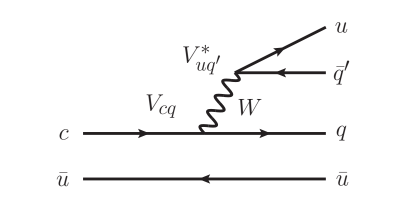
where t is the proper decay time. The integrated asymmetry

$$
\begin{aligned}
a_{CP}(h^+h^-) &\approx a_{\mathrm{CP}}^{\mathrm{dir}}(h^+h^-) + a_{\mathrm{CP}}^{\mathrm{ind}}\int dt\,\frac{t}{\tau_D}D(t) \\
&= a_{\mathrm{CP}}^{\mathrm{dir}}(h^+h^-) + a_{\mathrm{CP}}^{\mathrm{ind}}\frac{\langle t\rangle}{\tau_D}
\end{aligned}
$$

where $D(t)$ is the observed distribution of proper decay time

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

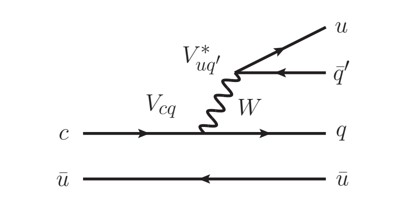
Hadronic two-body Decays of D Meson



- CKM hierarchy leads to two-generation dominance ($\lambda \simeq 0.23$)

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

Hadronic two-body Decays of D Meson

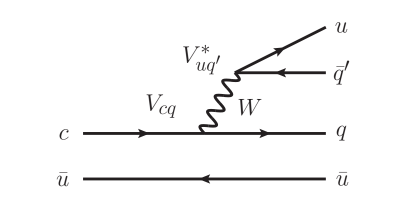


- CKM hierarchy leads to two-generation dominance ($\lambda \simeq 0.23$)

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

- We classify the decay processes into three classes

Hadronic two-body Decays of D Meson

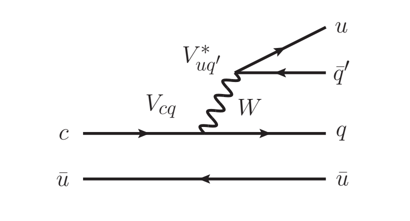


- CKM hierarchy leads to two-generation dominance ($\lambda \simeq 0.23$)

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

- We classify the decay processes into three classes
  - Cabibbo Favoured (CF): $|V_{cs} V^*_{ud}| \approx 1$ as, for example, $D^0 \to K^- \pi^+$

Hadronic two-body Decays of D Meson

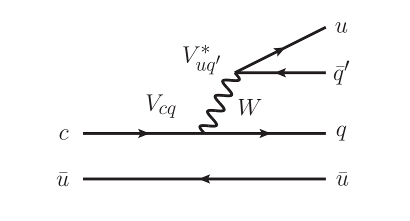


- CKM hierarchy leads to two-generation dominance ($\lambda \simeq 0.23$)

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

- We classify the decay processes into three classes
  - Cabibbo Favoured (CF): $|V_{cs} V^*_{ud}| \approx 1$ 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

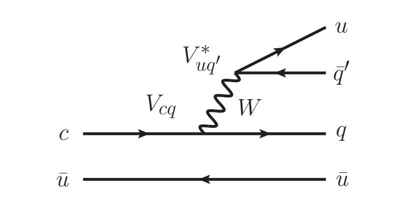


- CKM hierarchy leads to two-generation dominance ($\lambda \simeq 0.23$)

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

- We classify the decay processes into three classes
  - Cabibbo Favoured (CF): $|V_{cs}V^*_{ud}| \approx 1$ 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



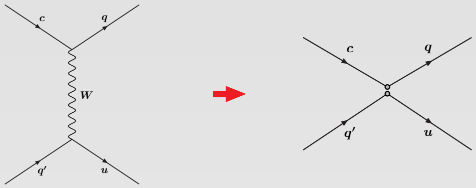
- CKM hierarchy leads to two-generation dominance ($\lambda \simeq 0.23$)

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

- We classify the decay processes into three classes
  - Cabibbo Favoured (CF): $|V_{cs} V^*_{ud}| \approx 1$ 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): $|V_{cd} V^*_{us}| \approx \lambda^2$ ($D^0 \to K^+ \pi^-$)

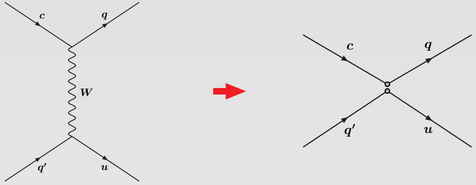
Weak Effective Hamiltonian

The Effective Field Theory approach allows to build an effective hamiltonian in which short and long distance contributions are separate.



Weak Effective Hamiltonian

The Effective Field Theory approach allows to build an effective hamiltonian in which short and long distance contributions are separate.

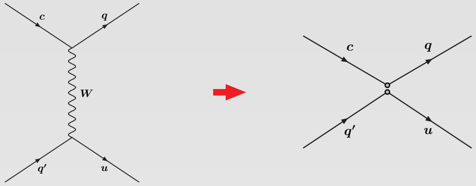


We have the tree operators
$q, q' \in \{d, s\}$

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

Weak Effective Hamiltonian

The Effective Field Theory approach allows to build an effective hamiltonian in which short and long distance contributions are separate.

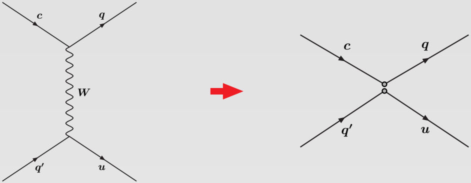


We have the tree operators
$q, q' \in \{d, s\}$

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

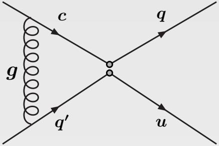
Weak Effective Hamiltonian

The Effective Field Theory approach allows to build an effective hamiltonian in which short and long distance contributions are separate.



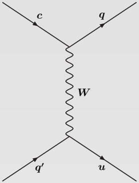
We have the tree operators
$q, q' \in \{d, s\}$

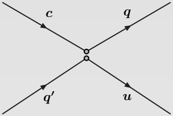
$$
\begin{aligned}
O_2 &= \left[\bar{q}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\alpha}\right]\left[\bar{u}^{\beta}\gamma_{\mu}(1-\gamma_5)q'_{\beta}\right] \\
O_1 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\beta}\right]\left[\bar{q}^{\beta}\gamma_{\mu}(1-\gamma_5)q'_{\alpha}\right]
\end{aligned}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



Weak Effective Hamiltonian

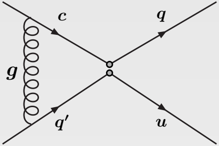
The Effective Field Theory approach allows to build an effective hamiltonian in which short and long distance contributions are separate.

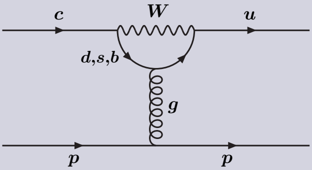




We have the tree operators
$q, q' \in \{d, s\}$

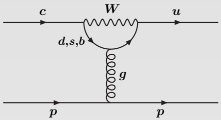
$$O_2 = \left[\bar{q}^\alpha \gamma^\mu (1-\gamma_5) c_\alpha\right]\left[\bar{u}^\beta \gamma_\mu (1-\gamma_5) q'_\beta\right]$$
$$O_1 = \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\beta\right]\left[\bar{q}^\beta \gamma_\mu (1-\gamma_5) q'_\alpha\right]$$





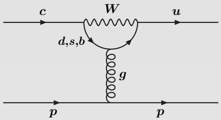
Weak Effective Hamiltonian (1)

The QCD penguins operators



Weak Effective Hamiltonian (1)

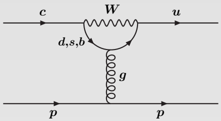
The QCD penguins operators



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

Weak Effective Hamiltonian (1)

The QCD penguins operators



$$O_3 = \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\alpha\right] \sum_{p=u,d,s} \left[\bar{p}^\beta \gamma_\mu (1-\gamma_5) p_\beta\right]$$

$$O_4 = \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\beta\right] \sum_{p=u,d,s} \left[\bar{p}^\beta \gamma_\mu (1-\gamma_5) p_\alpha\right]$$

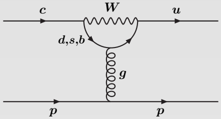
$$O_5 = \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\alpha\right] \sum_{p=u,d,s} \left[\bar{p}^\beta \gamma_\mu (1+\gamma_5) p_\beta\right]$$

$$O_6 = \left[\bar{u}^\alpha \gamma^\mu (1-\gamma_5) c_\beta\right] \sum_{p=u,d,s} \left[\bar{p}^\beta \gamma^\mu (1+\gamma_5) p_\alpha\right]$$

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

Weak Effective Hamiltonian (1)

The QCD penguins operators

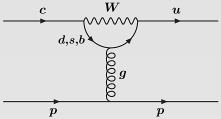


$$
\begin{aligned}
O_3 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\alpha}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\beta}\right]\\
O_4 &= \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\beta}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\alpha}\right]\\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

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

Weak Effective Hamiltonian (1)

The QCD penguins operators



$$O_3 = \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\alpha}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\beta}\right]$$

$$O_4 = \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\beta}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma_{\mu}(1-\gamma_5)p_{\alpha}\right]$$

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

$$O_6 = \left[\bar{u}^{\alpha}\gamma^{\mu}(1-\gamma_5)c_{\beta}\right]\sum_{p=u,d,s}\left[\bar{p}^{\beta}\gamma^{\mu}(1+\gamma_5)p_{\alpha}\right]$$

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

Hadronic Matrix Elements

We have to evaluate

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

Hadronic Matrix Elements

We have to evaluate

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

- The Wilson coefficient can be evaluated perturbatively

Hadronic Matrix Elements

We have to evaluate

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

- The Wilson coefficient can be evaluated perturbatively
- The hadronic matrix elements are dominated by non-perturbative QCD
  - from first principle: Lattice QCD (in the not so near future)
  - QCD factorization is expected don't work well, due to the large Λ_{QCD}/m_c corrections

Hadronic Matrix Elements

We have to evaluate

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

- The Wilson coefficient can be evaluated perturbatively
- The hadronic matrix elements are dominated by non-perturbative QCD
  - from first principle: Lattice QCD (in the not so near future)
  - QCD factorization is expected don't work well, due to the large Λ_{QCD}/m_c corrections
- Models of calculations can be useful to estimates order of magnitudes
  - Factorization & Final state Interactions
  - Flavour symmetries ($SU(3)_F$, isospin, U-spin, etc.)

Factorization: A Simple Model to Evaluate Matrix Elements

The idea (due to Feynman) is

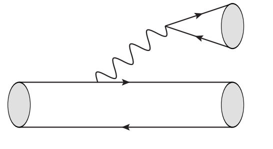
$$\langle M_1\, M_2 |\, J^\mu J'_\mu \,| D\rangle \approx \langle M_1 |\, J^\mu \,| D\rangle \langle M_2 |\, J'_\mu \,| 0\rangle$$

Factorization: A Simple Model to Evaluate Matrix Elements

The idea (due to Feynman) is

$$\langle M_1\, M_2 |\, J^\mu\, J'_\mu\, | D \rangle \approx \langle M_1 |\, J^\mu\, | D \rangle \, \langle M_2 |\, J'_\mu\, | 0 \rangle$$

Color allowed external W emission tree amplitude: T $\rightarrow$

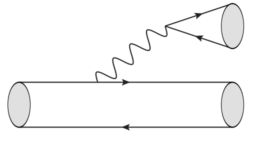


Factorization: A Simple Model to Evaluate Matrix Elements

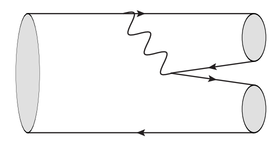
The idea (due to Feynman) is

$$\langle M_1\, M_2 |\, J^\mu J'_\mu \,| D\rangle \approx \langle M_1 |\, J^\mu \,| D\rangle \langle M_2 |\, J'_\mu \,| 0\rangle$$

Color allowed external W emission tree amplitude: T $\rightarrow$



Color suppressed internal W emission tree amplitude: C $\rightarrow$

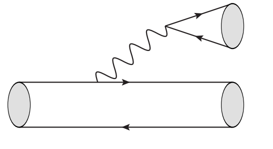


Factorization: A Simple Model to Evaluate Matrix Elements

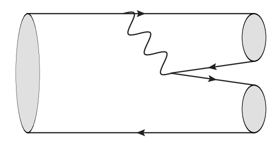
The idea (due to Feynman) is

$$\langle M_1\, M_2 |\, J^{\mu}\, J'_{\mu}\, | D\rangle \approx \langle M_1 |\, J^{\mu}\, | D\rangle \, \langle M_2 |\, J'_{\mu}\, | 0\rangle$$

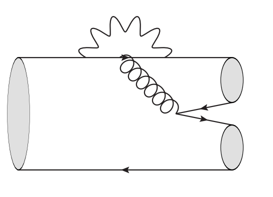
Color allowed external W emission tree amplitude: T $\rightarrow$



Color suppressed internal W emission tree amplitude: C $\rightarrow$



QCD Penguin amplitude: P $\rightarrow$



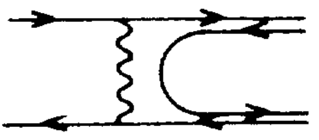
Factorization: Simple Model to Evaluate Matrix Elements (1)

$$\langle M_1\, M_2 |\, J^\mu J'_\mu \,| D\rangle \approx \ldots + \langle 0 |\, J^\mu \,| D\rangle \, \langle M_1\, M_2 |\, J'_\mu \,| 0\rangle$$

Factorization: Simple Model to Evaluate Matrix Elements (1)

$$\langle M_1\, M_2 |\, J^{\mu}\, J'_{\mu}\, | D\rangle \approx ... + \langle 0 |\, J^{\mu}\, | D\rangle \, \langle M_1\, M_2 |\, J'_{\mu}\, | 0\rangle$$

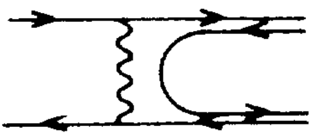
W−Exchange amplitude



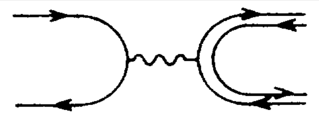
Factorization: Simple Model to Evaluate Matrix Elements (1)

$$\langle M_1\, M_2 |\, J^{\mu}\, J'_{\mu}\, | D \rangle \approx \ldots + \langle 0 |\, J^{\mu}\, | D \rangle \, \langle M_1\, M_2 |\, J'_{\mu}\, | 0 \rangle$$

W−Exchange amplitude



Annihilation amplitude



Factorization: Decay Constants and Form Factors

$$\langle P_i(p)|\, A^\mu\, |0\rangle = -i\, f_{P_i}\, p^\mu$$

$$\langle V_i(p,\lambda)|\, V^\mu\, |0\rangle = m_i\, f_{V_i}\, \varepsilon^{*\mu}(\lambda)$$

Factorization: Decay Constants and Form Factors

$$\langle P_i(p)| A^\mu |0\rangle = -i\, f_{P_i}\, p^\mu$$

$$\langle V_i(p,\lambda)| V^\mu |0\rangle = m_i\, f_{V_i}\, \varepsilon^{*\mu}(\lambda)$$

$$\langle P_i(p_i)| V^\mu |P_j(p_j)\rangle = \left(p_i^\mu + p_j^\mu - \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\right) f_+(q^2) + \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\, f_0(q^2)$$

Factorization: Decay Constants and Form Factors

$$\begin{aligned}
\langle P_i(p)|\, A^\mu \,|0\rangle &= -i\, f_{P_i}\, p^\mu \\
\langle V_i(p,\lambda)|\, V^\mu \,|0\rangle &= m_i\, f_{V_i}\, \varepsilon^{*\mu}(\lambda) \\
\langle P_i(p_i)|\, V^\mu \,|P_j(p_j)\rangle &= \left(p_i^\mu + p_j^\mu - \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\right) f_+(q^2) + \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\, f_0(q^2) \\
\langle V_i(p_i)|\, A^\mu \,|P_j(p_j)\rangle &= i\,(m_j + m_i)\, A_1(q^2) \left(\varepsilon^{*\mu} - \frac{\varepsilon^* \cdot q}{q^2}\, q^\mu\right) - \\
&\quad -i\, A_2(q^2)\, \frac{\varepsilon^* \cdot q}{m_j + m_i} \left(p_i^\mu + p_j^\mu - \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\right) + \\
&\quad +i\, 2\, m_i\, A_0(q^2)\, \frac{\varepsilon^* \cdot q}{q^2}\, q^\mu
\end{aligned}$$

Factorization: Decay Constants and Form Factors

$$
\begin{aligned}
\langle P_i(p)|\,A^\mu\,|0\rangle &= -i\, f_{P_i}\, p^\mu \\
\langle V_i(p,\lambda)|\,V^\mu\,|0\rangle &= m_i\, f_{V_i}\, \varepsilon^{*\mu}(\lambda) \\
\langle P_i(p_i)|\,V^\mu\,|P_j(p_j)\rangle &= \left(p_i^\mu + p_j^\mu - \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\right) f_+(q^2) + \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\, f_0(q^2) \\
\langle V_i(p_i)|\,A^\mu\,|P_j(p_j)\rangle &= i\,(m_j + m_i)\, A_1(q^2)\left(\varepsilon^{*\mu} - \frac{\varepsilon^*\cdot q}{q^2}\, q^\mu\right) - \\
&\quad -i\, A_2(q^2)\, \frac{\varepsilon^*\cdot q}{m_j + m_i}\left(p_i^\mu + p_j^\mu - \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\right) + \\
&\quad +i\, 2\, m_i\, A_0(q^2)\, \frac{\varepsilon^*\cdot q}{q^2}\, q^\mu \\
\langle V_i(p_i)|\,V^\mu\,|P_j(p_j)\rangle &= 2\, V(q^2)\, \frac{\varepsilon^\mu{}_{\nu\rho\sigma}\, p_j^\nu\, p_i^\rho\, \varepsilon^{*\sigma}}{m_j + m_i}
\end{aligned}
$$

Factorization: Decay Constants and Form Factors

$$\begin{aligned}
\langle P_i(p)|\, A^\mu \,|0\rangle &= -i\, f_{P_i}\, p^\mu \\
\langle V_i(p,\lambda)|\, V^\mu \,|0\rangle &= m_i\, f_{V_i}\, \varepsilon^{*\mu}(\lambda) \\
\langle P_i(p_i)|\, V^\mu \,|P_j(p_j)\rangle &= \left(p_i^\mu + p_j^\mu - \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\right) f_+(q^2) + \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\, f_0(q^2) \\
\langle V_i(p_i)|\, A^\mu \,|P_j(p_j)\rangle &= i\,(m_j + m_i)\, A_1(q^2) \left(\varepsilon^{*\mu} - \frac{\varepsilon^* \cdot q}{q^2}\, q^\mu\right) - \\
&\quad -i\, A_2(q^2)\, \frac{\varepsilon^* \cdot q}{m_j + m_i} \left(p_i^\mu + p_j^\mu - \frac{m_j^2 - m_i^2}{q^2}\, q^\mu\right) + \\
&\quad + i\, 2\, m_i\, A_0(q^2)\, \frac{\varepsilon^* \cdot q}{q^2}\, q^\mu \\
\langle V_i(p_i)|\, V^\mu \,|P_j(p_j)\rangle &= 2\, V(q^2)\, \frac{\varepsilon^\mu{}_{\nu\rho\sigma}\, p_j^\nu\, p_i^\rho\, \varepsilon^{*\sigma}}{m_j + m_i}
\end{aligned}$$

$$\begin{aligned}
f_+(0) &= f_0(0) \\
A_0(0) &= \frac{m_i + m_j}{2\, m_i} A_1(0) + \frac{m_i - m_j}{2\, m_i} A_2(0)
\end{aligned}$$

Factorization: The $D^0 \to \pi^-\pi^+$ Amplitude

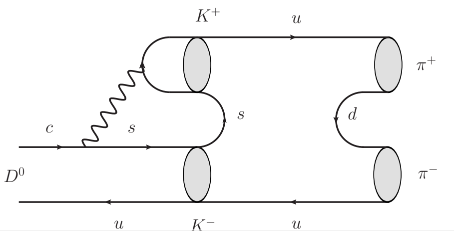
$$
\begin{aligned}
\mathscr{A}_W(D^0 \to \pi^-\pi^+) \quad &= \\
-\frac{G_F}{\sqrt{2}} V_{ud} V_{cd}^* \quad &\times \quad \left[(C_2 + \xi\, C_1) \left\langle \pi^- \middle| \bar{d}\gamma_\mu c \middle| D^0 \right\rangle \left\langle \pi^+ \middle| \bar{u}\gamma^\mu \gamma_5 d \middle| 0 \right\rangle \right] \\
+\frac{G_F}{\sqrt{2}} V_{ub} V_{cb}^* \quad &\times \quad \Big[(C_4 + \xi\, C_3) \left\langle \pi^- \middle| \bar{d}\gamma_\mu c \middle| D^0 \right\rangle \left\langle \pi^+ \middle| \bar{u}\gamma^\mu \gamma_5 d \middle| 0 \right\rangle \\
&\quad -2\,(C_6 + \xi\, C_5) \left\langle \pi^-\pi^+ \middle| \bar{u} u \middle| 0 \right\rangle \left\langle 0 \middle| \bar{u}\gamma_5 c \middle| D^0 \right\rangle \\
&\quad +2\,(C_6 + \xi\, C_5) \left\langle \pi^- \middle| \bar{d} c \middle| D^0 \right\rangle \left\langle \pi^+ \middle| \bar{u}\gamma_5 d \middle| 0 \right\rangle \Big]
\end{aligned}
$$

$$
\begin{aligned}
\left\langle 0 \middle| \bar{u}\gamma_5 c \middle| D^0 \right\rangle \quad &= \quad -\imath \frac{f_D\, m_D^2}{m_u + m_c} \\
\left\langle \pi^+ \middle| \bar{u}\gamma_5 d \middle| 0 \right\rangle \quad &= \quad \frac{f_\pi\, m_\pi^2}{m_u + m_d}
\end{aligned}
$$

$$
\xi = \frac{1}{N_c} \to 0
$$

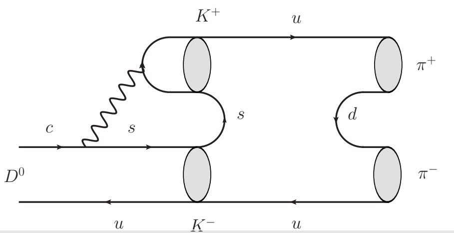
Final State Interaction Effects

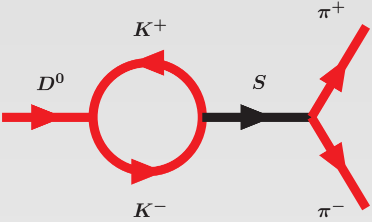
These long-distance effects are dominated by resonances with the correct quantum numbers and masses very near the one of charmed mesons.



Final State Interaction Effects

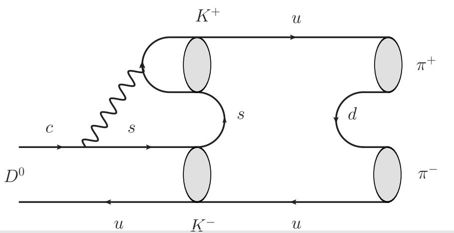
These long-distance effects are dominated by resonances with the correct quantum numbers and masses very near the one of charmed mesons.

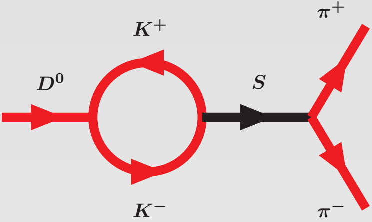




Final State Interaction Effects

These long-distance effects are dominated by resonances with the correct quantum numbers and masses very near the one of charmed mesons.





for the PP final state a scalar octet, S_c with $J^P = 0^+$

$$g_{888}\, d_{abc}\, P_a\, P_b\, S_c$$

for a PV final state 0^- $\tilde{P}$ resonance

$$f_{abc}\,(\partial_\mu\, \tilde{P}_a)\, V_b^\mu\, P_c$$

$$\sin\delta_8\, \exp(i\delta_8) = \frac{\Gamma(\tilde{P})}{2\,(m_{\tilde{P}} - m_D) - i\,\Gamma(\tilde{P})}$$

Results

This kind of approach gives:

- a quite good agreement with the experimental data (at that time) on the branching ratios;
- Direct CP violation effects of the order of 10^{-3}.

In particular

$$\Delta a_{\rm CP} = a_{\rm CP}^{\rm dir}(K^+K^-) - a_{\rm CP}^{\rm dir}(\pi^+\pi^-) \simeq 0.11 \times 10^{-3}$$

Buccella, Lusignoli, Miele, Pugliese, P.S., Phys. Rev. D51 (1995) 3478

Now the question is:

Is a CP violation as large as the first experimental results a sign of new physics or not?

Singly Cabibbo Suppressed D Decays

In the limit of SU(3) flavour symmetry

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

Singly Cabibbo Suppressed D Decays

In the limit of SU(3) flavour symmetry

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

Singly Cabibbo Suppressed D Decays

In the limit of SU(3) flavour symmetry

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

Thus $Br(D^0 \to \pi^+\pi^-)$ should be larger than $Br(D^0 \to K^+K^-)$ (Phase space differences)

Experimentally

$$\begin{aligned} Br(D^0 \to \pi^+\pi^-) &= (1.401 \pm 0.027) \times 10^{-3} \\ Br(D^0 \to K^+K^-) &= (3.96 \pm 0.08) \times 10^{-3} \end{aligned}$$

Singly Cabibbo Suppressed D Decays

In the limit of SU(3) flavour symmetry

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

Thus $Br(D^0 \to \pi^+\pi^-)$ should be larger than $Br(D^0 \to K^+K^-)$ (Phase space differences)

Experimentally

$$\begin{aligned} Br(D^0 \to \pi^+\pi^-) &= (1.401 \pm 0.027) \times 10^{-3} \\ Br(D^0 \to K^+K^-) &= (3.96 \pm 0.08) \times 10^{-3} \end{aligned}$$

Combining data from Babar, Belle and LHCb Franco, Mishima and Silvestrini (JHEP 1205 (2012) 140) found

$$\begin{aligned} a_{CP}^{dir}(\pi^+ \pi^-) &= (0.45 \pm 0.26)\% \\ a_{CP}^{dir}(K^+ K^-) &= (-0.21 \pm 0.24)\% \end{aligned}$$

Singly Cabibbo Suppressed D Decays

In the limit of SU(3) flavour symmetry

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

Thus $Br(D^0 \to \pi^+\pi^-)$ should be larger than $Br(D^0 \to K^+K^-)$ (Phase space differences)

Experimentally

$$\begin{aligned} Br(D^0 \to \pi^+\pi^-) &= (1.401 \pm 0.027) \times 10^{-3} \\ Br(D^0 \to K^+K^-) &= (3.96 \pm 0.08) \times 10^{-3} \end{aligned}$$

Combining data from Babar, Belle and LHCb Franco, Mishima and Silvestrini (JHEP 1205 (2012) 140) found

$$\begin{aligned} a_{CP}^{dir}(\pi^+ \pi^-) &= (0.45 \pm 0.26)\% \\ a_{CP}^{dir}(K^+ K^-) &= (-0.21 \pm 0.24)\% \end{aligned}$$

Large SU(3) Violation

A Simple Model to Evaluate SCS D Decays

- We assume that $SU(3)_{\rm F}$ breaking effects are due to FSI

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 dependence than in factorization)

Buccella, Lusignoli, Pugliese, P.S., arXiv:1305.7343 [hep-ph]

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 dependence than in factorization)

Buccella, Lusignoli, Pugliese, P.S., arXiv:1305.7343 [hep-ph]

- The D^0 is a U-spin singlet

A Simple Model to Evaluate SCS D Decays

- We assume that $SU(3)_{\mathrm{F}}$ breaking effects are due to FSI
- We evaluate *bare* amplitudes using $SU(3)_{\mathrm{F}}$ symmetry (less model dependence than in factorization)

Buccella, Lusignoli, Pugliese, P.S., arXiv:1305.7343 [hep-ph]

- The D^0 is a U-spin singlet
- The effective Hamiltonian

$$H_w = H_{\Delta U=1} + H_{\Delta U=0} =$$

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 dependence than in factorization)

Buccella, Lusignoli, Pugliese, P.S., arXiv:1305.7343 [hep-ph]

- The D^0 is a U-spin singlet
- The effective Hamiltonian

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

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 dependence than in factorization)

Buccella, Lusignoli, Pugliese, P.S., arXiv:1305.7343 [hep-ph]

- The D^0 is a U-spin singlet
- The effective Hamiltonian

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

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

A Simple Model to Evaluate Cabibbo Suppressed D Decays

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

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

A Simple Model to Evaluate Cabibbo Suppressed D Decays

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

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

where

$$\begin{aligned} |v_1\rangle &= \frac{1}{2}\Big\{|K^+K^- > +|K^-K^+ > -|\pi^+\pi^- > -|\pi^-\pi^+ > \Big\} \\ |v_2\rangle &= \frac{\sqrt{3}}{2\sqrt{2}}\Big\{|\pi^0\pi^0 > -|\eta_8\eta_8 > -\frac{1}{\sqrt{3}}\left(|\pi^0\eta_8 > +|\eta_8\pi^0 >\right)\Big\} \end{aligned}$$

A Simple Model to Evaluate Cabibbo Suppressed D Decays

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

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

where

$$\begin{aligned}
\left|v_1\right\rangle &= \frac{1}{2}\Big\{|K^+K^- > + |K^-K^+ > - |\pi^+\pi^- > - |\pi^-\pi^+ > \Big\} \\
\left|v_2\right\rangle &= \frac{\sqrt{3}}{2\sqrt{2}}\Big\{|\pi^0\pi^0 > - |\eta_8\eta_8 > - \frac{1}{\sqrt{3}}\left(|\pi^0\eta_8 > + |\eta_8\pi^0 >\right)\Big\}
\end{aligned}$$

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

A Simple Model to Evaluate Cabibbo Suppressed D Decays

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

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

where

$$|v_1\rangle = \frac{1}{2}\left\{|K^+ K^- > +|K^- K^+ > -|\pi^+ \pi^- > -|\pi^- \pi^+ > \right\}$$

$$|v_2\rangle = \frac{\sqrt{3}}{2\sqrt{2}}\left\{|\pi^0 \pi^0 > -|\eta_8 \eta_8 > -\frac{1}{\sqrt{3}}\left(|\pi^0 \eta_8 > +|\eta_8 \pi^0 >\right)\right\}$$

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

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

A Simple Model to Evaluate SCS D Decays (1)

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

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

A Simple Model to Evaluate SCS D Decays (1)

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

$$|8, U=1\rangle = \frac{\sqrt{3}}{2\sqrt{5}} \left\{ |K^+K^- > + |K^-K^+ > - |\pi^+\pi^- > - |\pi^-\pi^+ > - \left[|\pi^0\pi^0 > - |\eta_8\eta_8 > - \frac{1}{\sqrt{3}}(|\pi^0\eta_8 > + |\eta_8\pi^0 >) \right] \right\},$$

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

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

$$\langle 27, U=1 | H_{\Delta U=1} | D^0 \rangle \propto T + C$$

A Simple Model to Evaluate SCS D Decays (1)

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

$$|8, U=1\rangle = \frac{\sqrt{3}}{2\sqrt{5}} \Big\{ |K^+K^- > + |K^-K^+ > - |\pi^+\pi^- > - |\pi^-\pi^+ > - \Big[|\pi^0\pi^0 > - |\eta_8\eta_8 > - \frac{1}{\sqrt{3}}(|\pi^0\eta_8 > + |\eta_8\pi^0 >) \Big] \Big\},$$

$$|27, U=1\rangle = \frac{1}{\sqrt{10}} \Big\{ |K^+K^- > + |K^-K^+ > - |\pi^+\pi^- > - |\pi^-\pi^+ > + \frac{3}{2} \Big[|\pi^0\pi^0 > - |\eta_8\eta_8 > - \frac{1}{\sqrt{3}}(|\pi^0\eta_8 > + |\eta_8\pi^0 >) \Big] \Big\}.$$

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

$$\langle 27, U=1 | H_{\Delta U=1} | D^0 \rangle \propto T + C$$

$\Rightarrow$

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

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

Final State Interactions in SCS D Decays

The necessary SU(3) breaking is determined by the final state interactions, described as the effect of resonances in the scattering of the final particles.

Final State Interactions in SCS D Decays

The necessary SU(3) breaking is determined by the final state interactions, described 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.

Final State Interactions in SCS D Decays

The necessary SU(3) breaking is determined by the final state interactions, described 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) 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)

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

Final State Interactions in SCS D Decays (1)

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

SU(3) limit

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

$$\langle 1, I = 0 | H_{\Delta U=1} | D^0 \rangle = 0 \Rightarrow \not\delta_0'$$

Final State Interactions in SCS D Decays (1)

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

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

SU(3) limit

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

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

Parameters

$$C/T = -0.53$$
$$\phi = 22^\circ$$
$$\delta_0 = 148^\circ$$
$$\delta_0' = 53^\circ$$
$$\delta_1 = 83^\circ$$

Results

$$\frac{\Gamma(D^0 \to K_S K_S)}{\Gamma(D^0 \to K^+K^-)} = 0.0429\ (0.043 \pm 0.010)$$

$$\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^+K^-)} = 0.354\ (0.354 \pm 0.010)$$

$$\frac{\Gamma(D^0 \to \pi^0\pi^0)}{\Gamma(D^0 \to K^+K^-)} = 0.202\ (0.202 \pm 0.013)$$

Direct CPV in SCS D Decays

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

$$\mathscr{A} = A\, e^{\imath\delta_A} + B\, e^{\imath\delta_B}$$

Direct CPV in SCS D Decays

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

$$\mathscr{A} = A\, e^{\imath\delta_A} + B\, e^{\imath\delta_B}$$

the CP conjugate amplitude is

$$\bar{\mathscr{A}} = A^*\, e^{\imath\delta_A} + B^*\, e^{\imath\delta_B}$$

Direct CPV in SCS D Decays

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

$$\mathscr{A} = A\, e^{\imath\delta_A} + B\, e^{\imath\delta_B}$$

the CP conjugate amplitude is

$$\bar{\mathscr{A}} = A^*\, e^{\imath\delta_A} + B^*\, e^{\imath\delta_B}$$

and the CP asymmetry is:

$$a_{\rm CP}^{\rm dir} = \frac{|\mathscr{A}|^2 - |\bar{\mathscr{A}}|^2}{|\mathscr{A}|^2 + |\bar{\mathscr{A}}|^2}$$

Direct CPV in SCS D Decays

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

$$\mathscr{A} = A\, e^{\imath\delta_A} + B\, e^{\imath\delta_B}$$

the CP conjugate amplitude is

$$\bar{\mathscr{A}} = A^*\, e^{\imath\delta_A} + B^*\, e^{\imath\delta_B}$$

and the CP asymmetry is:

$$a_{\rm CP}^{\rm dir} = \frac{|\mathscr{A}|^2 - |\bar{\mathscr{A}}|^2}{|\mathscr{A}|^2 + |\bar{\mathscr{A}}|^2} = \frac{2\,\Im(A^*\,B)\,\sin(\delta_A - \delta_B)}{|A|^2 + |B|^2 + 2\,\Re(A^*\,B)\,\cos(\delta_A - \delta_B)}$$

Direct CPV in SCS D Decays

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

$$\mathscr{A} = A\, e^{\imath\delta_A} + B\, e^{\imath\delta_B}$$

the CP conjugate amplitude is

$$\bar{\mathscr{A}} = A^*\, e^{\imath\delta_A} + B^*\, e^{\imath\delta_B}$$

and the CP asymmetry is:

$$a_{\rm CP}^{\rm dir} = \frac{|\mathscr{A}|^2 - |\bar{\mathscr{A}}|^2}{|\mathscr{A}|^2 + |\bar{\mathscr{A}}|^2} = \frac{2\,\Im(A^*\,B)\,\sin(\delta_A - \delta_B)}{|A|^2 + |B|^2 + 2\,\Re(A^*\,B)\,\cos(\delta_A - \delta_B)}$$

What about the amplitude B?

Direct CPV in SCS D Decays (1)

The amplitude B is provided by

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

where

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

But

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

Direct CPV in SCS D Decays (1)

The amplitude B is provided by

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

where

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

But

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

Large CPV can be due only to the Penguin terms

Direct CPV in SCS D Decays (2)

Neglecting the contribution of the terms containing T' and C'

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

Direct CPV in SCS D Decays (2)

Neglecting the contribution of the terms containing T' and C'

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

and so

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

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

Direct CPV in SCS D Decays (2)

Neglecting the contribution of the terms containing T' and C'

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

and so

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

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

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

Direct CPV in SCS D Decays (2)

Neglecting the contribution of the terms containing T' and C'

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

and so

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

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

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

$$\Delta a_{\rm CP} = 3.03\, 10^{-3}\ \kappa$$

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 an accurate description of decay branching ratios

The experimental situation regarding the CP violating asymmetries is at present rather confused, but we think anyhow of interest to have shown that large asymmetries can be obtained, considering the uncertainties of long distance contributions and even without invoking New Physics.

Bibliography: New Physics

1. Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D **75** (2007) 036008 [hep-ph/0609178];
2. G. Isidori, J. F. Kamenik, Z. Ligeti and G. Perez, Phys. Lett. B **711** (2012) 46 [arXiv:1111.4987 [hep-ph]];
3. K. Wang and G. Zhu, Phys. Lett. B **709** (2012) 362 [arXiv:1111.5196 [hep-ph]];
4. G. Hiller, Y. Hochberg and Y. Nir, Phys. Rev. D **85** (2012) 116008 [arXiv:1204.1046 [hep-ph]];
5. G. F. Giudice, G. Isidori and P. Paradisi, JHEP **1204** (2012) 060 [arXiv:1201.6204 [hep-ph]];
6. W. Altmannshofer, R. Primulando, C. -T. Yu and F. Yu, JHEP **1204** (2012) 049 [arXiv:1202.2866 [hep-ph]];
7. C. -H. Chen, C. -Q. Geng and W. Wang, Phys. Rev. D **85** (2012) 077702 [arXiv:1202.3300 [hep-ph]];
8. O. Gedalia, J. F. Kamenik, Z. Ligeti and G. Perez, Phys. Lett. B **714** (2012) 55 [arXiv:1202.5038 [hep-ph]];
9. T. Mannel and N. Uraltsev, JHEP **1303** (2013) 064 [arXiv:1205.0233 [hep-ph]];
10. B. Keren-Zur, P. Lodone, M. Nardecchia, D. Pappadopulo, R. Rattazzi and L. Vecchi, Nucl. Phys. B **867** (2013) 429 [arXiv:1205.5803 [hep-ph]];
11. R. Barbieri, D. Buttazzo, F. Sala and D. M. Straub, JHEP **1210** (2012) 040 [arXiv:1206.1327 [hep-ph]];
12. A. D. Dolgov, S. I. Godunov, A. N. Rozanov and M. I. Vysotsky, JETP Lett. **96** (2012) 290 [arXiv:1206.6652 [hep-ph]];
13. C. Delaunay, J. F. Kamenik, G. Perez and L. Randall, JHEP **1301** (2013) 027 [arXiv:1207.0474 [hep-ph]].

Bibliography: Standard Model

1. M. Golden and B. Grinstein, Phys. Lett. B **222** (1989) 501,
2. D. Pirtskhalava and P. Uttayarat, Phys. Lett. B **712** (2012) 81 [arXiv:1112.5451 [hep-ph]];
3. B. Bhattacharya, M. Gronau and J. L. Rosner, Phys. Rev. D **85** (2012) 054014 [arXiv:1201.2351 [hep-ph]];
4. T. Feldmann, S. Nandi and A. Soni, JHEP **1206** (2012) 007 [arXiv:1202.3795 [hep-ph]];
5. J. Brod, Y. Grossman, A. L. Kagan and J. Zupan, JHEP **1210** (2012) 161 [arXiv:1203.6659 [hep-ph]].
6. E. Franco, S. Mishima and L. Silvestrini, JHEP **1205** (2012) 140 [arXiv:1203.3131 [hep-ph]].