# CPV and oscillations in quarks physics

C. Ramirez [1]

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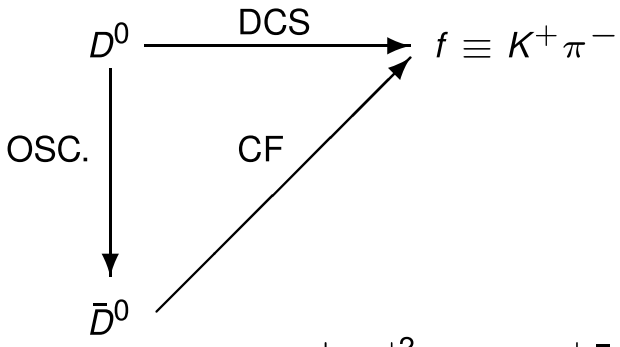
# Oscillations and CPV in charm physics

1. CPV in up-quarks sector ($u,\ c,\ t$). 2019 discovered . SM (CKM) tests?.
2. For CF/DCS: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, etc.
   CPV, in the SM very small , $10^{-8}$ (Delepine 1212.6281).
   'Null test' : CPV $\Rightarrow$ New Physics!, even QCD corrections.
3. In SCS: $D^0 \to K^-K^+,\ \pi^+\pi^-$. 2019 discovered . dCPV ($\sim 10^{-3}$).
4. Semileptonic. CPV in oscillations.
5. Entangled/Cascade CPV/CPTV/TRV so on
6. New Physics?. CPV large in LR theories (even $10^{-2}$!).

# Time evolut. $D^0 \leftrightarrow \bar{D}^0 \to f$.

$$\text{CF}: A_{K^-\pi^+} = A(D^0 \to K^-\pi^+ \equiv f) = \bar{A}_{K^+\pi^-} = A(\bar{D}^0 \to \bar{f}).\ \text{`Right'sign}$$

$$\text{DCS}: A_{K^+\pi^-} = A(D^0 \to \bar{f}) = \bar{A}_{K^-\pi^+} = A(\bar{D}^0 \to f).\text{`Wrong'sign.}\ -z = y + ix,\ \tau = \Gamma\, t$$




$$r_{\bar{f}}(t) = \frac{\Gamma(D^0 \to \bar{f})}{\Gamma(D^0 \to f)}(t) = R_D^+ + \sqrt{R_D^+}\, y'^+_{\bar{f}}\, \tau + \frac{R^+_{M\bar{f}}}{2}\tau^2$$

$$\bar{r}_f(t) = \frac{\Gamma(\bar{D}^0 \to f)}{\Gamma(\bar{D}^0 \to \bar{f})}(t) = R_D^- + \sqrt{R_D^-}\, y'^-_{f}\, \tau + \frac{R^-_{Mf}}{2}\tau^2$$

$$R_D^+ = \left|\frac{A_{\bar{f}}}{A_f}\right|^2,\ R_D^- = \left|\frac{\bar{A}_f}{\bar{A}_{\bar{f}}}\right|^2,\ d_f = \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|^2.\ e_f = \left|\frac{q}{p}\right|\sqrt{d_f}$$

$$y'^+_{\bar{f}} = \sqrt{R_D^+}\,\text{Re}\,(z\lambda_{\bar{f}\theta}),\ y'^-_{f} = \sqrt{R_D^-}\,\text{Re}\,(z\bar{\lambda}_{f\theta}),\ R^+_{M\bar{f}} = \frac{R^+_{\bar{f}}}{2}\left[(1+|\lambda_{\bar{f}\theta}|^2)y^2 - (1-|\lambda_{\bar{f}\theta}|^2)x^2\right]$$

$$\lambda_f = \frac{1}{\bar{\lambda}_f} = -|\lambda_f|e^{-i\phi_f},\ \bar{\lambda}_{\bar{f}} = \frac{1}{\lambda_{\bar{f}}} = -|\bar{\lambda}_{\bar{f}}|e^{-i\bar{\phi}_{\bar{f}}};\ |\lambda_f| = e_f\sqrt{R_D^-},\ |\bar{\lambda}_{\bar{f}}| = \frac{\sqrt{R_D^+}}{e_f}$$

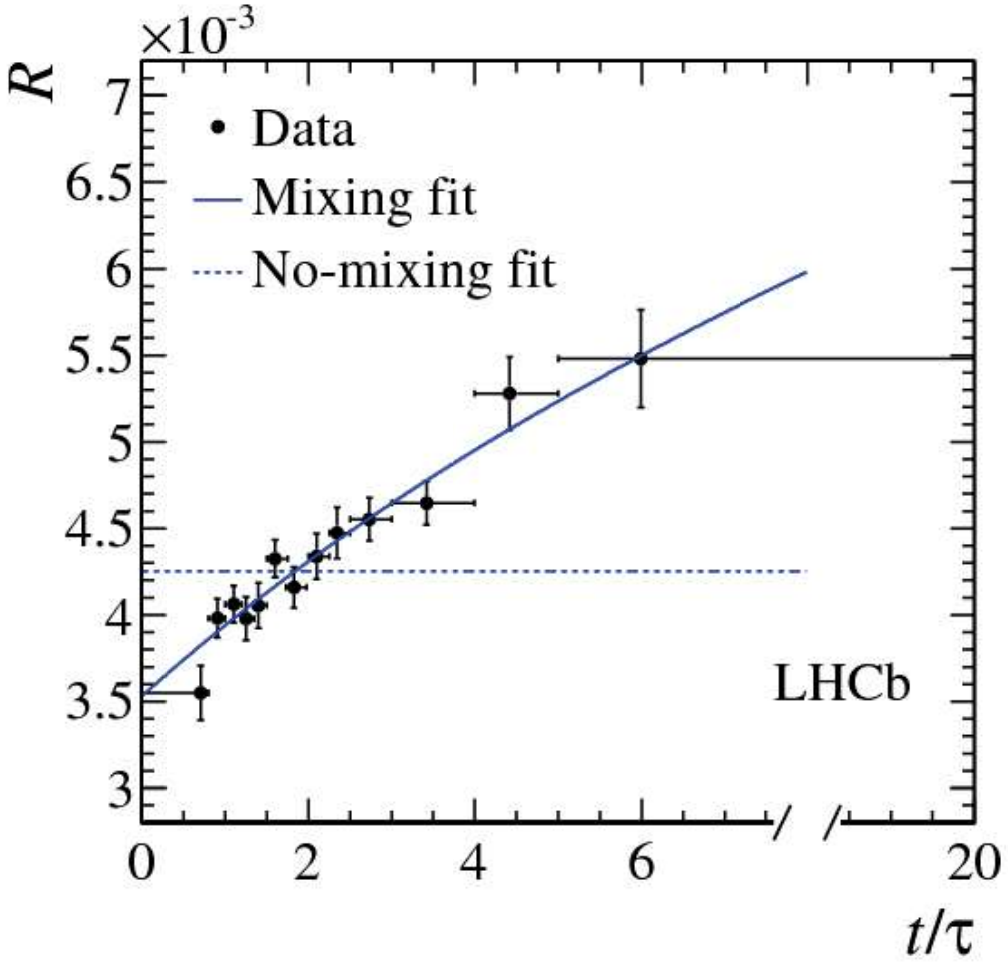
For CP self-conjugate states ($\bar{f} = f$). Thus $R_D^+ = R_D^- = 1$ and

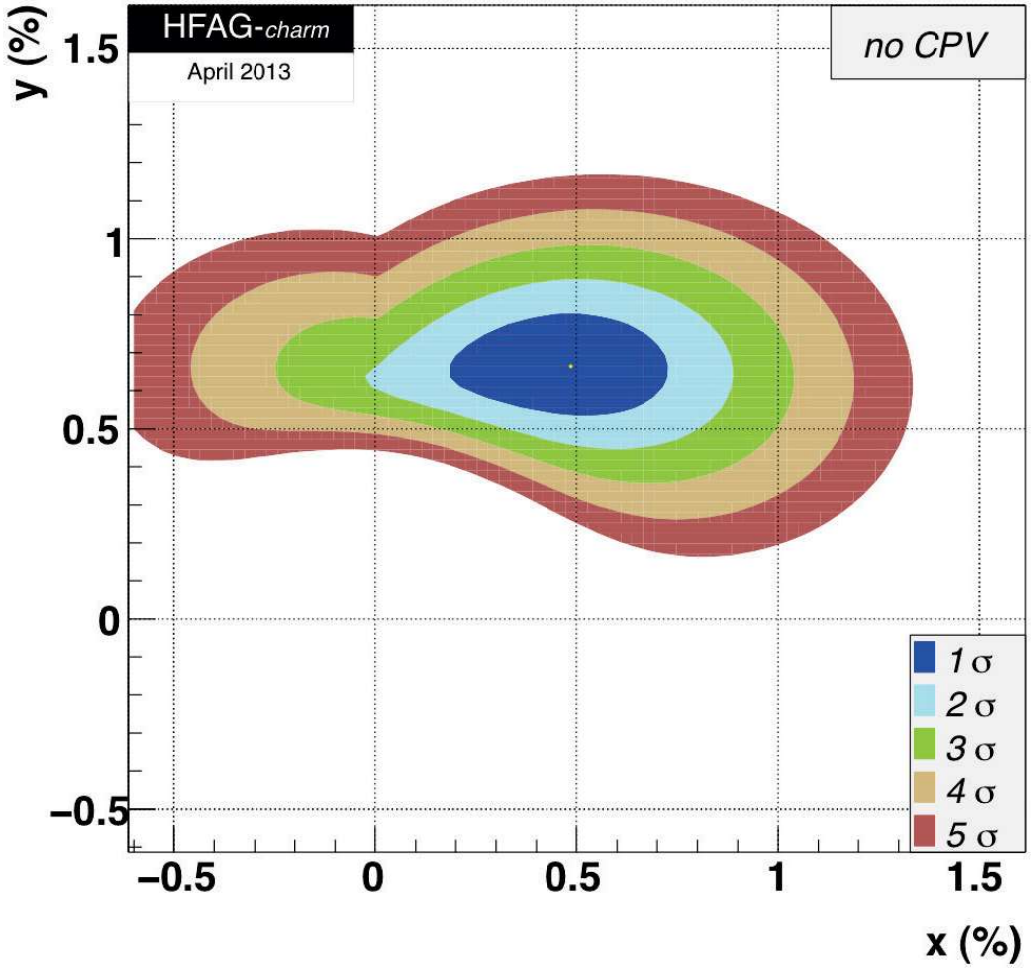
$$\lambda_{\bar{f}} = \lambda_f = \bar{\lambda}_{\bar{f}}^{-1} = \bar{\lambda}_f^{-1} = -e_f\, e^{i\phi_f},\ \bar{\phi}_{\bar{f}} = -\phi_f$$

# $D^0 \leftrightarrow \bar{D}^0$. Oscillations, mixing, etc. (2013) HFLAV-19

$$x \equiv \frac{\Delta m_d}{\Gamma_D} = 0.43(10)\ \%,\ y \equiv \frac{\Delta\Gamma_D}{2\Gamma_D} = 0.63(6)\ \%,\ \left|\frac{q}{p}\right| = 0.999(14),\ \phi \equiv \text{“arg } (q/p)\text{”} = -\left(12.9^{99}_{87}\right)^\circ$$

$D^0 \to K^0_S\pi^+\pi^-$. HFLAV, 1909.12524, p. 286.



# CPV Observables. $D^0 \to K\pi,\ KK,\ \pi\pi$

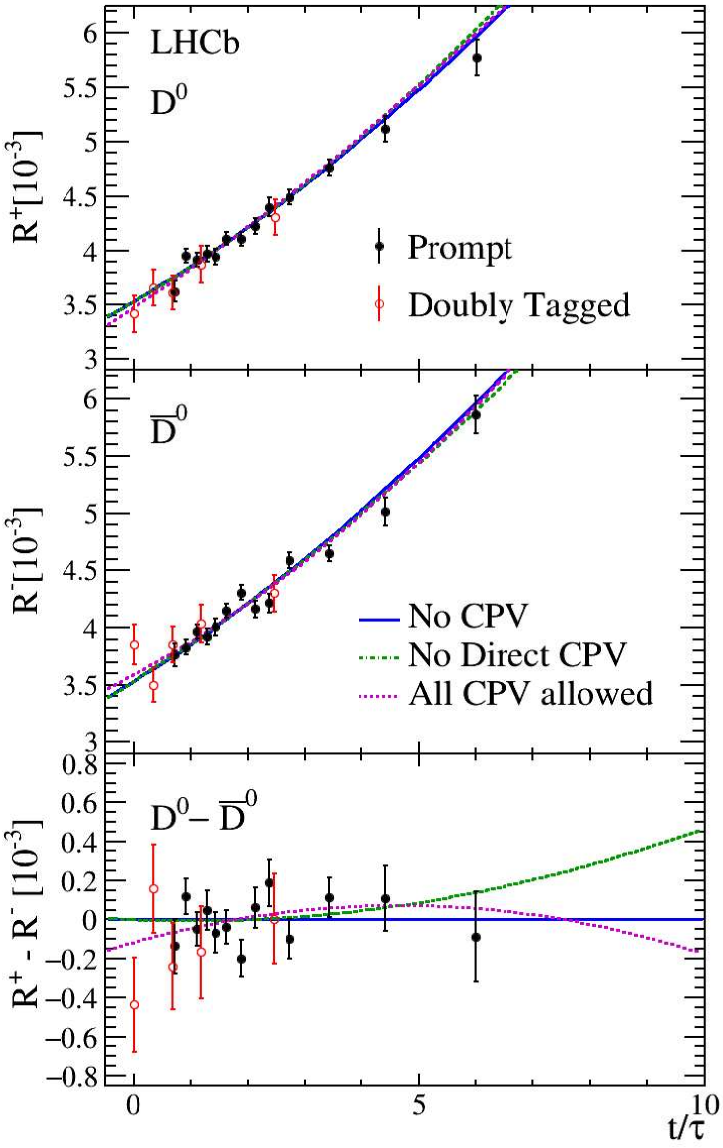
CPV observables:

$$
\begin{aligned}
A^f(t) &= \frac{|A_f(t)|^2 - |\bar{A}_{\bar{f}}(t)|^2}{|A_f(t)|^2 + |\bar{A}_{\bar{f}}(t)|^2},\ A_D^f = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2},\ A_D^{R_f} \equiv \frac{R_f^+ - R_f^-}{R_f^+ + R_f^-} \\
A_{\rm CP}^{\bar{f}} &= \frac{\Gamma_{\bar{f}} - \bar{\Gamma}_f}{\Gamma_{\bar{f}} + \bar{\Gamma}_f} = \frac{(1 + A_D^f)\left(R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^+}\, y'^+_{\bar{f}}\right) - (1 - A_D^f)\left(R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^-}\, y'^-_{\bar{f}}\right)}{(1 + A_D^f)\left(R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^+}\, y'^+_{\bar{f}}\right) + (1 - A_D^f)\left(R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^-}\, y'^-_{\bar{f}}\right)} \\
A_\Gamma^{\bar{f}} &\equiv \frac{\widehat{\Gamma}_{\bar{f}} - \widehat{\bar{\Gamma}}_f}{\widehat{\Gamma}_{\bar{f}} + \widehat{\bar{\Gamma}}_f} = \frac{y'^-_f / \sqrt{R_f^-} - y'^+_{\bar{f}} / \sqrt{R_{\bar{f}}^+}}{2 + 3(y'^+_{\bar{f}} / \sqrt{R_{\bar{f}}^+} + y'^-_f / \sqrt{R_f^-}) + 4 y'^+_{\bar{f}} y'^-_f / \sqrt{R_{\bar{f}}^+ R_f^-}}
\end{aligned}
\tag{5}
$$

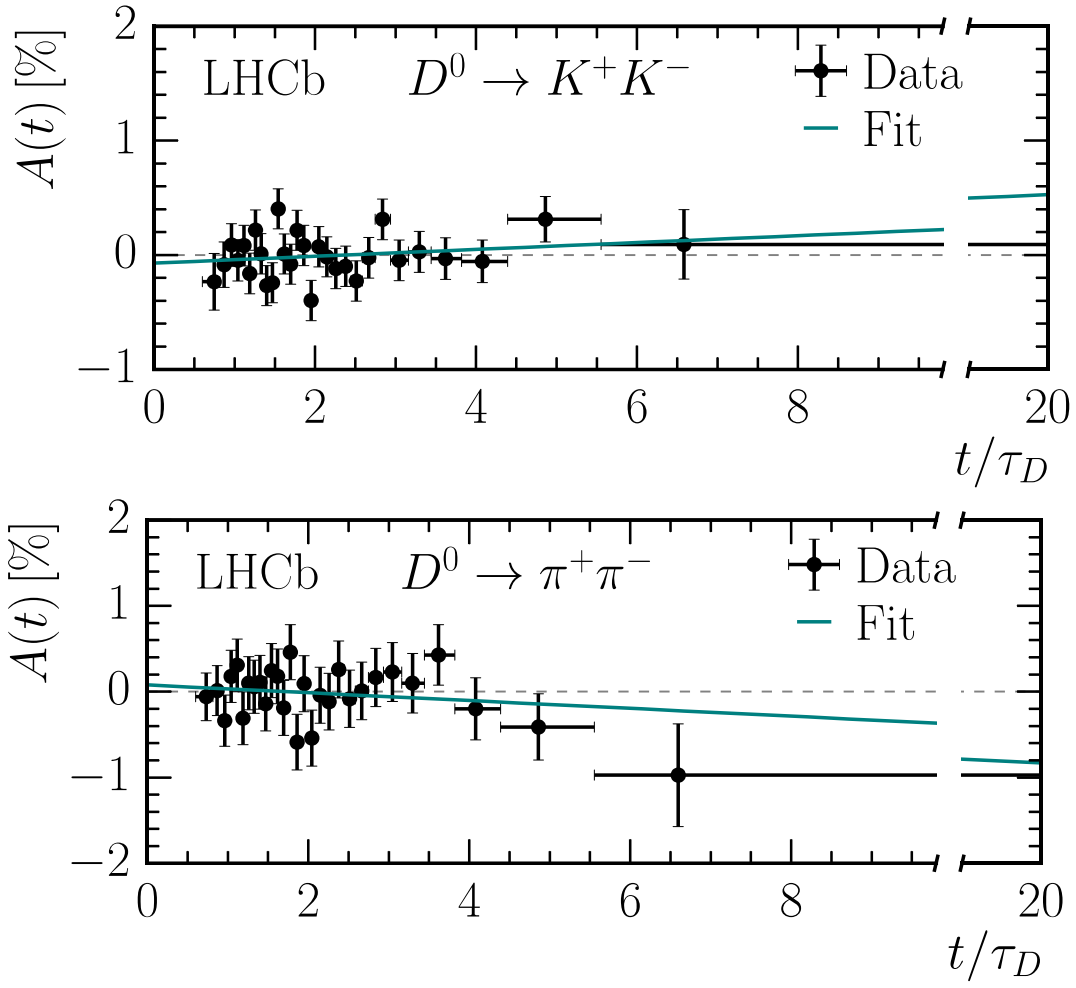
With the effective width/lifetime and the integrated ratio

$$
\begin{aligned}
\widehat{\Gamma}_{\bar{f}} &\equiv \frac{1}{<\tau_{\bar{f}}>} = \Gamma \frac{1 + y'^+_{\bar{f}} / \sqrt{R_{\bar{f}}^+}}{1 + 2 y'^+_{\bar{f}} / \sqrt{R_{\bar{f}}^+}} \sim \Gamma \left(1 - \frac{y'^+_{\bar{f}}}{\sqrt{R_{\bar{f}}^+}}\right) \\
R_{\bar{f}} &\equiv \frac{\Gamma_{\bar{f}}}{\Gamma_f(0)} = R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^+}\, y'^+_{\bar{f}} + R_{M\bar{f}}^+
\end{aligned}
$$

# CPVint, CF/DCS ($D^0 \to K\pi$), SCS ($D^0 \to \pi\pi$, $KK$).




LHCb 1611.06143 CF/DCS




LHCb 1702.0649 SCS

# CPVint in $D^0$, $\bar{D}^0$

| parameter | value | parameter | value | Parameter | value |
|---|---|---|---|---|---|
| $R_f^+$ $[10^{-3}]$ | 3.454(45) | $R_f^-$ | 3.454(45) | $A_D[10^{-3}]$ | 0.00(6) |
| $y_f'^+$ $[10^{-3}]$ | 5.01(74) | $y_f'^-$ | 5.54(74) | $y_f'^+ - y_f'^-$ $[10^{-3}]$ | 0.53(105) |
| $x_f'^{+2}$ $[10^{-5}]$ | 6.1(37) | $x_f'^{-2}$ | 1.6(39) | $x_f'^{+2} - x_f'^{-2}$ $[10^{-5}]$ | 4.5(54) |
| $R_{\bar{f}}$ $[10^{-3}]$ | 3.454(31) | | | | |
| $y_{\bar{f}}'^+$ $[10^{-3}]$ | 5.01(56) | $y_{\bar{f}}'^-$ | 5.54(56) | $y_{\bar{f}}'^+ - y_{\bar{f}}'^-$ $[10^{-3}]$ | -0.53(79) |
| $x_{\bar{f}}'^{+2}$ $[10^{-5}]$ | 6.1(31) | $x_{\bar{f}}'^{-2}$ | 1.6(31) | $x_{\bar{f}}'^{+2} - x_{\bar{f}}'^{-2}$ $[10^{-5}]$ | 4.5(44) |
| $R_{\bar{f}}$ $[10^{-3}]$ | 3.454(31) | $y_{\bar{f}}'$ $[10^{-3}]$ | 5.28(52) | $x_{\bar{f}}'^2$ $[10^{-5}]$ | 3.9(27) |
| $A_{CP}^{K\pi}$ $[10^{-3}]$ | 3(3)(6) | $A_{CP}^{KK}$ $[10^{-3}]$ | 0.4(12)(10) | $A_{CP}^{\pi\pi}$ $[10^{-3}]$ | 0.7(14)(11) |
| $A_\Gamma^{K\pi}$ $[10^{-3}]$ | 0.16(10) | $A_\Gamma^{KK}$ $[10^{-3}]$ | -0.44(23)(6) | $A_\Gamma^{\pi\pi}$ $[10^{-3}]$ | 0.25(43)(7) |
| $y_{CP}$ $[10^{-3}]$ | 7.15(111) | $\Delta A_{CP}$ $[10^{-3}]$ | -1.54(29) | $R_M$ $[10^{-3}]$ | 0.13(27) |

Table: CF/DCS CP parameters fits from 1712.03220 p. 7 (1611.06143 see p.11 table 3 and p. 10 fig. 3). HFAG-16 p. 303). First table: allowing full CPV. Second one: assuming direct CPC and CPC for the third one. 1911.01114 for $A_\Gamma^h h$. Integrated and effective CPV measurements, from 1704.00041 and 1702.06490. $\Delta A_{CP}$, 1903.08726.

# CPV Observables. CP self-conjugate ($\bar{f} = f$).

$$A_\Gamma^f = \frac{\tau(\bar{D}^0 \to f) - \tau(D^0 \to f)}{\tau(\bar{D}^0 \to f) + \tau(D^0 \to f)} = \frac{1}{2}(y'^-_f - y'^+_{\bar{f}}) \simeq \frac{1}{2}\left(|\lambda_f| - |\lambda_f|^{-1}\right) yc_f - \frac{1}{2}\left(|\lambda_f| + |\lambda_f|^{-1}\right) xs_f$$
$$\simeq \frac{1}{2}\left(e_f - \frac{1}{e_f}\right) yc_f - \frac{1}{2}\left(e_f + \frac{1}{e_f}\right) xs_f$$

$$y_{\rm CP} \equiv \frac{\widehat{\Gamma}_f + \widehat{\bar{\Gamma}}_f}{2\Gamma} - 1 = -\frac{1}{2}\left(y'^+_f + y'^-_f\right) = -\frac{1}{2}\left[y(|\lambda_f| + 1/|\lambda_f|)c_f - x(|\lambda_f| - 1/|\lambda_f|)s_f\right]$$
$$\simeq \frac{1}{2}\left(e_f + \frac{1}{e_f}\right) yc_f - \frac{1}{2}\left(e_f - \frac{1}{e_f}\right) xs_f = 7.15(111)\cdot 10^{-3}$$

For CP self-conjugate states, $\bar{f} = f$. Thus $R^+_{\bar{f}} = R^-_f = 1$ and

$$\lambda_{\bar{f}} = \lambda_f = \bar{\lambda}^{-1}_{\bar{f}} = \bar{\lambda}^{-1}_f = -\sqrt{d_f}\left|\frac{q}{p}\right| e^{i\phi_f} = -e_f e^{i\phi_f},\ \bar{\phi}_{\bar{f}} = -\phi_f$$

$$d_{KK} = 1 - 8.8\cdot 10^{-4},\ d_{\pi\pi} = 1 - 1.28\cdot 10^{-3}\ \text{Theo.} \tag{6}$$

# CPV in oscillations. $D^0 \to K^- l^+ \nu$, Semileptonic

1. Difficult to calculate $|q/p|$. Non perturbative QCD. The main contribution, $\epsilon_D = |q/p| - 1 \sim (m_b/v)^2 \sim 3 \cdot 10^{-4}$. Exp. $\epsilon_D = 1(14) \cdot 10^{-3}$.
2. Allowed semileptonic decays $D^0 \to K^- l^+ \nu \equiv f$ $(A_f)$, $\bar{D}^0 \to K^+ l^- \bar{\nu}$ $(\bar{A}_{\bar{f}})$
3. Forbidden $(\Delta C = \Delta Q)$ $A_{\bar{f}} = \bar{A}_f = 0$. in SM.
4. 'wrong' sign/appearance

$$\begin{aligned} \Gamma(D^0 \to \bar{f})(t) &= \left| \frac{q}{p} g_-(t) \bar{A}_{\bar{f}} \right|^2 \simeq |\bar{A}_{\bar{f}}| \, \mathrm{e}^{-\tau} \frac{R_M^+}{2} \tau^2 \\ \Gamma(\bar{D}^0 \to f)(t) &= \left| \frac{p}{q} g_-(t) A_f \right|^2 \simeq |A_f| \, \mathrm{e}^{-\tau} \frac{R_M^-}{2} \tau^2 \end{aligned}$$

5. Any difference: CPV 'in oscillations'

$$A_{\mathrm{SL}} = \frac{|A_{\bar{f}}(t)|^2 - |\bar{A}_f(t)|^2}{|A_{\bar{f}}(t)|^2 + |\bar{A}_f(t)|^2} = \frac{\left| q^2 \bar{A}_{\bar{f}} / p^2 A_f \right|^2 - 1}{\left| q^2 \bar{A}_{\bar{f}} / p^2 A_f \right|^2 + 1} \simeq \frac{|q/p|^4 - 1}{|q/p|^4 + 1} \equiv A_M = 0.6(6)(8) \ \% \ [BesIII 1810.03127, p.5]$$

6. if no direct CPV is present $|A_f| = |\bar{A}_{\bar{f}}|$. $R_M^+ \simeq R_M^- = R_M = (x^2 + y^2)/2 = 1.3(27) \cdot 10^{-4}$ PDG, Belle 0802.2952

# Direct CPV discovery.

1. SM prediction, $A_D^f$. f.e. Li 1903.10638 p. 5 in

$$\begin{aligned} A(D^0 \to K^+K^-) &= \lambda_s T^{KK} + \lambda_b P^{KK} = \lambda_s T^{KK}\left(1 + r_s R^{KK}\right) \\ A(D^0 \to \pi^+\pi^+) &= \lambda_d T^{\pi\pi} + \lambda_b P^{\pi\pi} = \lambda_d T^{\pi\pi}\left(1 + r_d R^{\pi\pi}\right) \end{aligned}$$

with $\lambda_i = V_{ui}V_{ci}^*,\ i = d,\ s,\ b$. UT: $\sum \lambda_i = 0$.
$r_i = \lambda_b/\lambda_i$, $r_s = 6.74 \cdot 10^{-4} e^{-i\gamma}$ and $r_d = -7.03 \cdot 10^{-4} e^{-i\gamma}$
$R^{KK} = P^{KK}/T^{KK} = 0.45 e^{131^0 i}$ and $R^{\pi\pi} = P^{\pi\pi}/T^{\pi\pi} = 0.66 e^{134^0 i}$. dCPV

$$\begin{aligned} A_D^{KK} &= -2r_s \sin\gamma \mathrm{Im} R^{KK} = -0.73 \cdot 10^{-3} \simeq 0.4(12)(10) \cdot 10^{-3},\ (\mathrm{exp.}) \\ A_D^{\pi\pi} &= -2r_d \sin\gamma \mathrm{Im} R^{\pi\pi} = 0.64 \cdot 10^{-3} \simeq 0.7(14)(11) \cdot 10^{-3},\ (\mathrm{exp.}) \end{aligned}$$

2. Exp. LHCb 1903.08726. $5.3\sigma$ effect. Theo./exp. agreement.

$$\Delta A_{\mathrm{CP}}^{\mathrm{dir.}} = A_D^{K^+K^-} - A_D^{\pi^+\pi^-} = -1.56(29) \cdot 10^{-3}\ (\mathrm{LHCb}) \simeq -1.4 \cdot 10^{-3}\ (\mathrm{SM}$$

# Direct CPV.

| Mode | BR[%] | $A_{CP}$ [%] | Mode | BR[%] | $A_{CP}$ [%] |
|---|---|---|---|---|---|
| CF: $D^0 \to K^-\pi^+$ | 3.95(5) | 0.1(7) | $D^0 \to K_L\pi^0$ | 1.0(7) | |
| $D^+ \to K^0_S\pi^+$ | 1.47(7) | -0.41(9) | $D^+ \to K^0_L\pi^+$ | 1.46(5) | - |
| $D^0 \to \bar{K}^0_S\eta$ | $4.79(30)\cdot 10^{-3}$ | - | $D^0 \to \bar{K}^0_S\eta'$ | $9.4(5)\cdot 10^{-3}$ | - |
| $D^0 \to \bar{K}^0_S\pi^0$ | 1.19(4) | - | $D^+_s \to K^+\bar{K}^0$ | 2.95(14) | - |
| $D^+_s \to K^+K^0_S$ | 1.49(6) | - | $D^+_s \to K^+K^-\pi^+$ | 5.39(21) | - |
| $D^+_s \to K^+K^0_S\pi^0$ | 1.52(22) | - | $D^+_s \to 2\pi^+\pi^0$ | 1.09(5) | - |
| $D^+_s \to \pi^+\eta$ | $3.53(21)\cdot 10^{-3}$ | - | $D^+_s \to \pi^+\eta'$ | $4.67(29)\cdot 10^{-3}$ | - |
| $D^\pm \to K^\mp\pi^\pm\pi^\pm$ | 9.22(17) | -0.16(15)(9) | $D^\pm \to K^0_S\pi^\pm\pi^0$ | 7.24(21) | 0.3(9)(3) |
| $D^0 \to K^-\pi^+\pi^0$ | 13.9(5) | | $D^0 \to K^0_s\pi^+\pi^-$ | 2.82(19) | |
| DCS: $D^0 \to K^+\pi^-$ | $1.38(3)\cdot 10^{-4}$ | 0.0(16) | | - | - |
| $D^+ \to K^+\pi^0$ | $1.83(26)\cdot 10^{-4}$ | -3.5(107)(99) | $D^+ \to K^+\pi^-\pi^+$ | $5.27(23)\cdot 10^{-4}$ | |
| $D^+ \to K^+\eta$ | $1.08(17)\cdot 10^{-4}$ | - | $D^+ \to K^+\eta'$ | $1.76(22)\cdot 10^{-4}$ | - |
| $D^+_s \to K^+\pi^0$ | $6.3(21)\cdot 10^{-4}$ | - | $D^+_s \to K^+\eta$ | $1.76(35)\cdot 10^{-3}$ | - |
| $D^+_s \to K^+\eta'$ | $1.8(6)\cdot 10^{-3}$ | - | $D^+_s \to K^0_S\pi^+$ | $1.21(6)\cdot 10^{-3}$ | - |
| $D^+_s \to K^+\pi^+\pi^-$ | $6.5(4)\cdot 10^{-3}$ | - | $D^+_s \to K^0\pi^+\pi^0$ | 1.00(18) | - |
| SCS: $D^0 \to \pi^-\pi^+$ | 0.140(3) | -0.20(19)(10) | $D^+ \to \pi^+\pi^0$ | 0.119(6) | 2.9(29)(3) |
| $D^0 \to K^-K^+$ | 0.398(7) | -0.06(15)(10) | $A_{CP}(K^+K^- - \pi^+\pi^-)$ | – | -0.154(29) |
| $D^0 \to K^-K^+\pi^+\pi^-$ | 0.243(12) | -8.2(56)(47) | $D^\pm \to \pi^+\pi^-\pi^\pm$ | 0.318(18) | 1.7(42) |
| $D^0 \to K^0_s 2\pi^0$ | 9.1(11) | | $D^\pm \to K^+K^-\pi^\pm$ | 0.95(3) | 0.39(61) |

# Triple product: $D^0 \to K^+K^-\pi^+\pi^-$

$$
\begin{aligned}
A_L(l) &= \delta = \frac{\Gamma(K_L^0 \to \pi^- l^+ \nu_l) - \Gamma(K_L^0 \to \pi^+ l^- \bar{\nu}_l)}{\Gamma(K_L^0 \to \pi^- l^+ \nu_l) + \Gamma(K_L^0 \to \pi^+ l^- \bar{\nu}_l)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = \frac{2\mathrm{Re}\epsilon}{1 + |\epsilon|^2} \\
\eta_{+-\gamma} &\equiv \frac{A(K_L^0 \to \pi^+\pi^-\gamma)}{A(K_S^0 \to \pi^+\pi^-\gamma)} = 2.35(7) \cdot 10^{-3} \cdot \mathrm{e}^{44(4)^\circ i} \ \text{IndirectCPV} \\
A(K_L \to \pi^+\pi^- e^+ e^-) &= \frac{N(\sin(2\phi) > 0) - N(\sin(2\phi) < 0)}{N(\sin(2\phi) > 0) + N(\sin(2\phi) < 0)} = 13.7(15)\% \\
A(K_S \to \pi^+\pi^- e^+ e^-) &= \frac{N(\sin(2\phi) > 0) - N(\sin(2\phi) < 0)}{N(\sin(2\phi) > 0) + N(\sin(2\phi) < 0)} = -0.4(8)\%
\end{aligned}
$$

where $\phi$ is the angle between $\pi^+\pi^-$ and $e^- e^+$ planes.

$$
\begin{aligned}
C_T(D^0) &= \mathbf{p}_{K+} \cdot \left(\mathbf{p}_{\pi+} \times \mathbf{p}_{\pi-}\right), \ \bar{C}_T(\bar{D}^0) = \mathbf{p}_{K-} \cdot \left(\mathbf{p}_{\pi-} \times \mathbf{p}_{\pi+}\right) \\
A_T(D^0) &= \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \ \bar{A}_T(D^0) = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)} \\
a_{\mathrm{CP}}^{\mathrm{T-odd}} &= \frac{1}{2}\left(A_T - \bar{A}_T\right) \\
A_T &= -7.18(41)(13)\%, \ \bar{A}_T = -7.55(41)(12), \ a_{\mathrm{CP}}^{\mathrm{T-odd}} = 0.35(21). \ \mathit{HFLAV} - 18, \ \mathit{p}.308
\end{aligned} \tag{7}
$$

# Conclusions

1. By now SM-CKM ok, except Baryogenesis.
2. CPV (and PV, CV) a powerful tool for search New Physics
3. still sectors unexplored: U-quarks CPV?, baryons?, leptons ($\tau$-physics, neutrinos), $W$, $Z$ and higgs?, scattering, etc.
4. 'Null' tests: $K \to \pi 2\nu$, $D \to K\pi$ CF decays.