CPV and oscillations in quarks physics

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December 3, 2019

Outline

Overview

1. Oscillations : $B_s \leftrightarrow \bar{B}_s$, $B \leftrightarrow \bar{B}$, $K^0 \leftrightarrow \bar{K}^0$, $D^0 \leftrightarrow \bar{D}^0$, $n \leftrightarrow \bar{n}$, ν.
2. CPV: 'Matter $\neq$ antimatter'.
3. Baryogenesis . Macro: matter $>>$ antimatter . Micro: matter $\simeq$ antimatter.
4. Exp. CPV in K, B and B_s .... D (2019!).
5. Baryons?. charm, top?. PMNS (leptons?). Higgs?. Strong CPV...
6. SM CPV : CKM (observed). 'Charged' currents.
7. CPV to measure CKM angles and phase . Unitarity triangle.
8. Other related phenomena: FCNC, PV, CV, TRV, CPT, etc.
9. Lab for hadronic corrections.
10. Calculations. OK for B, B_s and K (but $\Delta I = 1/2$). Problems for D.

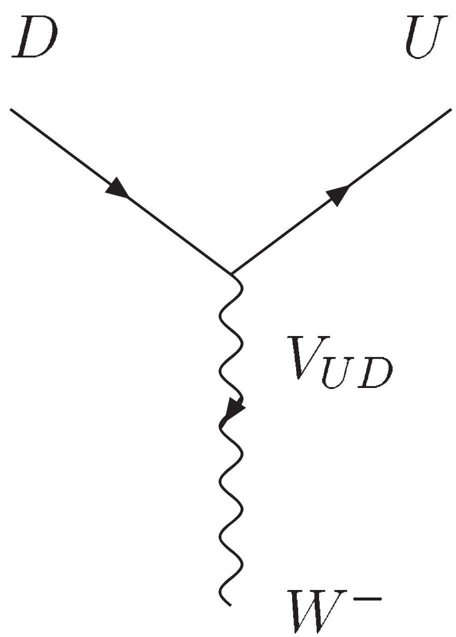
Oscillations/CPV/FCNC and 'New' Physics. Historical.

1. c quark. GIM mechanism, universality, FCNC. Predict m_c.
2. CKM. From CPV in K
3. Top quark. Large mass hints from $B^0 - \bar{B}^0$
4. Third family. To have CPV (CKM).
5. Direct CPV in kaons.
6. Oscillations/CPV in B, B_s and D.
7. Very sensitive to new Physics. $\Lambda \sim 10^3$ TeV. Kill Extended Technicolor!: $\Lambda_{\mathrm{ETC}} > 600$ TeV!. From Δm_K, ϵ_K
8. No Superweak. From dCPV in K
9. 'Null' tests.

1. 1964 J. Cronin (Nobel 1980). 'Indirect' CPV.
2. CPC; $K_1 \to 2\pi$ ($CP(2\pi) = 1$) and $K_2 \to 3\pi$ ($CP(3\pi) = -1$).
3. But $K_1 \to 3\pi$ or $K_2 \to 2\pi$ means CPV.
4. 1967 CPV was observed in semileptonic decays $K_L^0 \to \pi^{\pm} l^{\mp} \nu_l$
5. 1967 CPV: Sakharov conditions to baryogenesis. New Physics!
6. 1970 (1964) GIM mechanism.
7. 1973 Kobayashi-Maskawa (CKM): CPV 1 phase SM. 3 families. Nobel 2008.

Flavor Physics in SM: Flavor P., Oscillations, CPV and so on.

$$D' = \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{\mathrm{CKM}} D = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} D$$



$$\begin{aligned} & d \to u \\ & s \to u \\ & c \to s,\ d \\ & b \to c,\ u \\ & t \to b,\ s,\ d \end{aligned}$$

Cabibbo-Kobayashi-Maskawa.

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - A^2\lambda^5(\rho + i\eta) & 1 - \frac{\lambda^2}{2} - A^2\lambda^6(\rho + i\eta) & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 - A\lambda^4(\rho + i\eta) & 1 \end{pmatrix} + \mathcal{O}(\lambda$$

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}| + |V_{us}|}}, \; s_{23} = A\lambda^2, \; s_{13}\mathrm{e}^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta)$$

$$\lambda = 0.22537(61), \; A = 0.814^{+0.023}_{-0.024}, \; \bar\rho = 0.117(21), \; \bar\eta = 0.353(13)$$

$$\sin 2\beta = \sin 2\phi_1 = 0.682(19), \; \gamma = \delta = \phi_3 = 68.0^{+8.0}_{-8.5}, \; \alpha = \phi_2 = 85.4^{+3.9}_{-3.8}$$

$$J = \mathrm{Im}[V_{us}V_{cd}V_{cs}^*V_{ub}^*] = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta = A^2\lambda^6\eta$$

$$= 3.1(2)\cdot 10^{-5}, \; \text{CPVJarlskog invariant}$$

CKM, experimental information

Quantity	Exper. value ($Q(\Delta Q)$)	$Q/\Delta Q$	exp. source
$\lvert V_{ud}\rvert$	0.97417(21)	4428	nuclear $0^+ \to 0^+$ β decays
$\lvert V_{us}\rvert$	0.2248(6)	282	semileptonic K_{l_3} decays
$\lvert V_{ub}\rvert$	$3.72(19) \cdot 10^{-3}$	20	exclusive B decays
$\lvert V_{ub}\rvert$	$4.49(16)^{+16}_{-18} \cdot 10^{-3}$	19	inclusive B decays
$\lvert V_{cd}\rvert$	0.220(5)	28	$(\nu/\bar{\nu})N \to \mu^{\mp}(c/\bar{c})X$
$\lvert V_{cs}\rvert$	0.995(16)	62	semileptonic D decay
$\lvert V_{cb}\rvert$	$40.5(15) \cdot 10^{-3}$	32	semileptonic B decay
$\lvert V_{td}\rvert$	0.0082(6)	14	Δm_B
$\lvert V_{ts}\rvert$	0.0400(27)	15	Δm_{B_s}
$\lvert V_{tb}\rvert$	1.009(31)	32	$t \to Wb$, unitarity CKM3
$\lvert V_{td}/V_{ts}\rvert$	0.211(1)(11)	20	Δm_{B_q}
γ	$\left(73.2^{+6.3}_{-7.0}\right)^{\circ}$	10	$B^{\pm} \to DK^{\pm}$
$\sin 2\beta,\ \beta$	$0.691(17),\ 21.5^{+8}_{-7}$	41	$B^0 \to \psi K^0$
α	$\left(87.6^{+3.5}_{-3.3}\right)^{\circ}$	25	$B \to \pi\pi$

Table: Direct measured CKM quatities, 2016

Time evolution

Wigner-Weisskopf. effe. Hamiltonian. Two meson P^0-$\overline{P}^0$. Flavor basis

$$H = M - \frac{i}{2}\Gamma = \begin{pmatrix} H_{11} & p^2 \\ q^2 & H_{22} \end{pmatrix},$$

M and Γ hermitian, H is not: P^0 and $\overline{P}^0$ unstable. Eigenvalue eq.

$$H|P_i> \equiv \mu_i|P_i>, \text{ with } i = H,\ L$$

The eigenvalues/vectors. PDG-Gershon, Nir

$$\begin{aligned} \mu_{H,\ L} &= \frac{1}{2}\left[t_r \pm \Delta\mu\right] = \mathrm{Re}(\mu) + i\mathrm{Im}(\mu) = m_{H,\ L} - \frac{i}{2}\Gamma_{H,\ L}, \\ N_H|M_H> &= p\sqrt{1+\theta}\,|M^0> - q\sqrt{1-\theta}\,|\bar{M}^0> \\ N_L|M_L> &= p\sqrt{1-\theta}\,|M^0> + q\sqrt{1+\theta}\,|\bar{M}^0> \end{aligned}$$

with $t_r = \mathrm{Tr}(H) = H_{11} + H_{22}$, $d = \det(H)$, $\Delta\mu = \sqrt{t_r^2 - 4d} = \mu_H - \mu_L$.

with $\theta\Delta\mu \equiv H_{11} - H_{22}$ and $N_{L,\ H} = |p|^2|1 \mp \theta| + |q|^2|1 \pm \theta|$.

$$(\Delta\mu)^2 \equiv t_r^2 - 4d = (H_{11} - H_{22})^2 + 4p^2q^2 = (\theta\Delta\mu)^2 + 4p^2q^2 = \frac{4p^2q^2}{1-\theta^2}$$

with $\Delta\mu = -2pq/\sqrt{1-\theta^2} = \Gamma(x - iy) \equiv \Gamma z$. Defining $2\Gamma = \Gamma_H + \Gamma_L$

$$\Delta m \equiv m_H - m_L = \mathrm{Re}(\Delta\mu) \equiv \Gamma x,\ \Delta\Gamma \equiv \Gamma_H - \Gamma_L = -2\mathrm{Im}(\Delta\mu) \equiv 2\Gamma y,$$

They are not orthogonal if CPT, CP or T is violated

$$N_L N_H < M_H|M_L >= |p|^2\sqrt{(1-\theta)(1+\theta^*)} - |q|^2\sqrt{(1+\theta)(1-\theta^*)}$$

The time evolved states are

$$
\begin{aligned}
|M^0(t)> &= (g_+(t) + \theta g_-(t))\,|M^0> - \frac{q}{p}\sqrt{1-\theta^2}\; g_-(t)|\bar{M}^0> \\
|\bar{M}^0(t)> &= -\frac{p}{q}\sqrt{1-\theta^2} g_-(t)|M^0> + (g_+(t) - \theta g_-(t))\,|\bar{M}^0>
\end{aligned}
$$

where

$$
\begin{aligned}
g_\pm(t) &\equiv \frac{1}{2}\left(e^{-i\mu_H t} \pm e^{-i\mu_L t}\right) = \mathrm{e}^{-i\mu t}\begin{cases} \cos \Delta\mu t/2 \\ i \sin \Delta\mu t/2 \end{cases} \\
|g_\pm|^2 &= \frac{1}{2}\mathrm{e}^{-\tau}\left[\cosh y\tau \pm \cos x\tau\right],\;\; g_-^* g_+ = -\frac{1}{2}\mathrm{e}^{-\tau}\left[\sinh y\tau - i \sin x\tau\right]
\end{aligned}
$$

with $\mu = (\mu_H + \mu_L)/2 = m - i\Gamma/2$, $A_f \equiv |< f|M^0 >$, $\bar{A}_f \equiv < f|\bar{M}^0 >$.
Time dependent amplitudes

$$A_f(t) = A_f[g_+(t) - \lambda_{f\theta} g_-(t)],\ \bar{A}_f(t) = \bar{A}_f[g_+(t) - \bar{\lambda}_{f\theta} g_-(t)]$$

$\lambda_{f\theta} \equiv \lambda_f \sqrt{1-\theta^2} - \theta$, $\lambda_f = 1/\bar{\lambda}_f = q\bar{A}_f/pA_f$. $\Gamma_f(t) \equiv |A_f(t)|^2$

$$\frac{2\Gamma_f(t)\mathrm{e}^{\tau}}{(1+|\lambda_{f\theta}|^2)\,|A_f|^2} = \cosh(y\tau) + C_{f\theta}\cos(x\tau) + D_{f\theta}\sinh(y\tau) - S_{f\theta}\sin(x\tau)$$

$$\int_0^{\infty} \mathrm{d}\tau \frac{2\Gamma_f(t)\mathrm{e}^{\tau}}{\Gamma\,|A_f|^2} = \frac{1+|\lambda_{f\theta}|^2 + 2y\mathrm{Re}\lambda_{f\theta}}{1-y^2} + \frac{1-|\lambda_{f\theta}|^2 - 2x\mathrm{Im}\lambda_{f\theta}}{1+x^2}$$

with $\tau = \Gamma t$. two damped coupled pendulums. Pulsations with $\omega_P = \Delta m = \Gamma x,\ Q \simeq x$

Theory $\leftrightarrow$ experiment

$M_{12},\ \Gamma_{12} \leftrightarrow \Delta m,\ \Delta\Gamma,\ |p/q|$

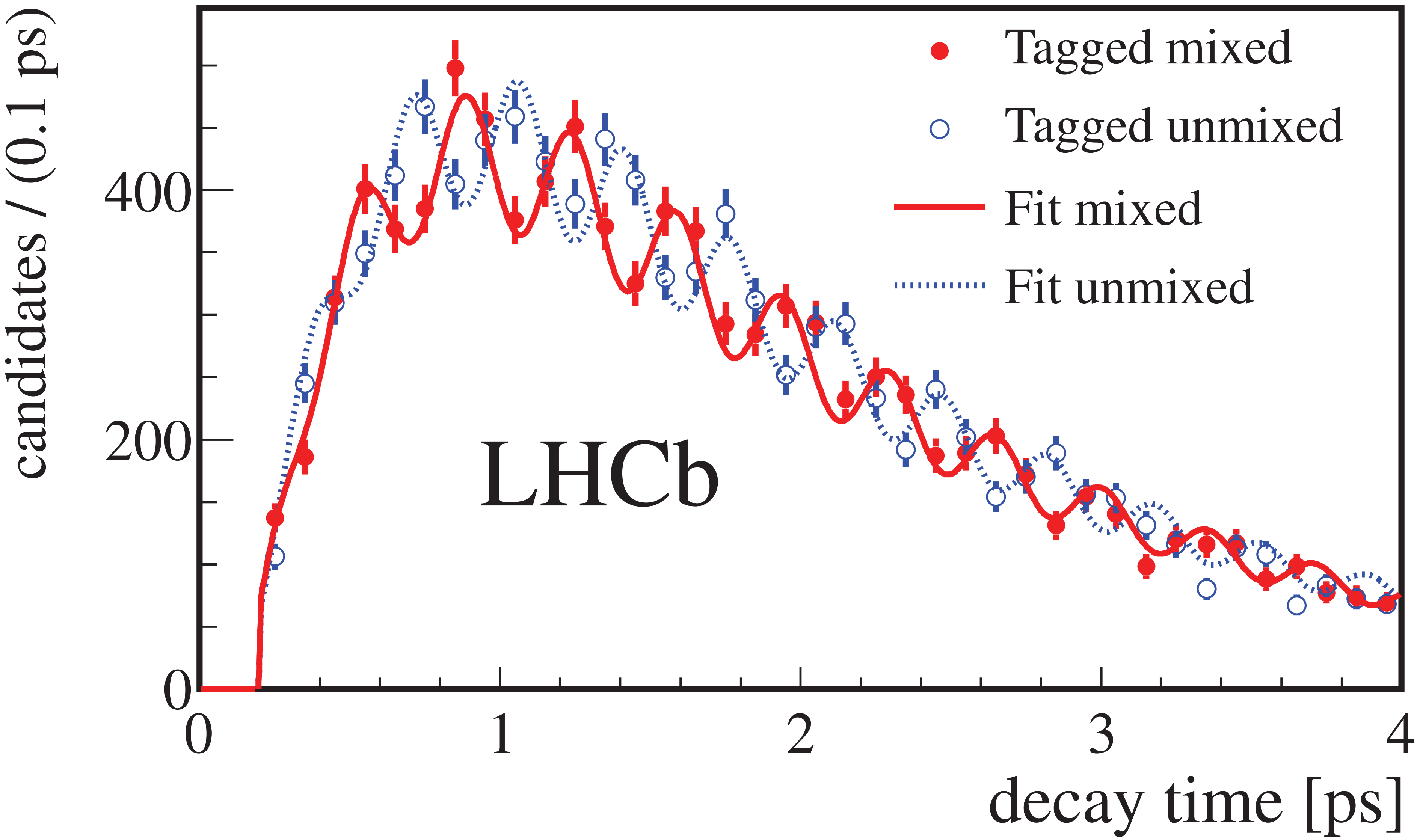
$$(pq)^2 = |M_{12}|^2\left(1-|a|^2-2i|a|\cos\theta\right) = \left(\frac{\Delta m}{2}+i\frac{\Delta\Gamma}{4}\right)^2,\ a=\frac{\Gamma}{2M}\equiv|a|e^{i\theta}$$

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^*-i\Gamma_{12}^*/2}{M_{12}-i\Gamma_{12}/2} = \frac{M_{12}^*}{M_{12}}\frac{1-ia^*}{1-ia} \equiv \left|\frac{q}{p}\right|^2 e^{2i\phi} = \sqrt{\frac{1+|a|^2-2|a|\sin\theta}{1+|a|^2+2|a|\sin\theta}}e^{2i\phi}$$

$$(\Delta m)^2-\left(\frac{\Delta\Gamma}{2}\right)^2 = 4|M_{12}|^2|(1-a^2),\ \Delta m\Delta\Gamma = 8|M_{12}|^2 a\cos\theta$$

$$1-\left|\frac{q}{p}\right|^4 = \frac{4a\sin\theta}{1+a^2-2a\sin\theta},\ \tan\left(2(\phi+\theta_M)\right) = -\frac{a^2\sin^2(2\theta)}{1+a^2\cos 2\theta}$$

B_s oscillations. 1304.4741, fig. 2



Oscillation parameters

Quantity	Exp.	SM	Quantity	Exp.	SM
τ_{B_s} [ps]	1.497(15)	-	τ_B [ps]	1.519(7)	-
Δm_{B_s} [ps^{-1}]	17.768(24)	17.30(26)	Δm_B [ps^{-1}]	0.5055(20)	0.543(9
$\Delta\Gamma_{B_s}$ [ps^{-1}]	0.083(6)	0.088(20)	$\Delta\Gamma_B$ [ns^{-1}]	-11(14)	2.8(5)
x_{B_s}	26.74(22)		x_B	0.774(6)	
y_{B_s}	0.088(14)		y_B	$\pm$0.015(18)	
τ_D [ps]	0.4101(15)		τ_{K_S} [ps]	89.54(4)	-
x_D [%]	$0.55^{+0.12}_{-0.13}$		τ_{K_L} [ns]	51.16(21)	-
y_D [%]	0.83(13)		Δm_K [ns^{-1}]	5.293(9)	-
Δm_D [ns^{-1}]	13.4		$\Delta\Gamma_K$ [ns^{-1}]	-11.144(6)	-
$\Delta\Gamma_D$ [ns^{-1}]	40.5		$x_{K_{L/S}}$	270.8/0.47	

Table: Oscillation parameters. The ‘quality’ factor is $Q \simeq x$.
$\Delta m_K = 3.506(6)\ \mu$eV$=6.24 \cdot 10^{-42}$ Kg. (nanotech. $1.7 \cdot 10^{-27}$ Kg$=m_p$).
$\Delta m_K / m_K \simeq 7 \cdot 10^{-15}$

CPV, theory

1. weak phases: $\phi \to -\phi$ CP transformation
2. $|q/p| \neq 1$: CPV oscillations.
3. $|A_f/\bar{A}_{\bar{f}}| \neq 1$ direct CPV
4. $\arg\lambda_f \neq 0,\ \pi$ CPV interference: oscillations and decay.

Oscillations and CPV in charm physics

1. CPV in up-quarks sector $(u,\ c,\ t)$. 2019 discovered . SM (CKM) tests?.
2. In SCS: $D^0 \to K^- K^+,\ \pi^+\pi^-$. 2019 discovered . dCPV ($\sim 10^{-3}$).
3. 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': Observe CPV $\Rightarrow$ New Physics!, even QCD corrections.
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. $D^0 \to f$. $D^0 \leftrightarrow \bar{D}^0$

$$\mathrm{CF}: A_{K^-\pi^+} = A(D^0 \to K^-\pi^+ \equiv f) = \bar{A}_{K^+\pi^-} = A(\bar{D}^0 \to \bar{f})$$
$$\mathrm{DCS}: A_{K^+\pi^-} = A(D^0 \to \bar{f}) = \bar{A}_{K^-\pi^+} = A(\bar{D}^0 \to f)$$

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

with

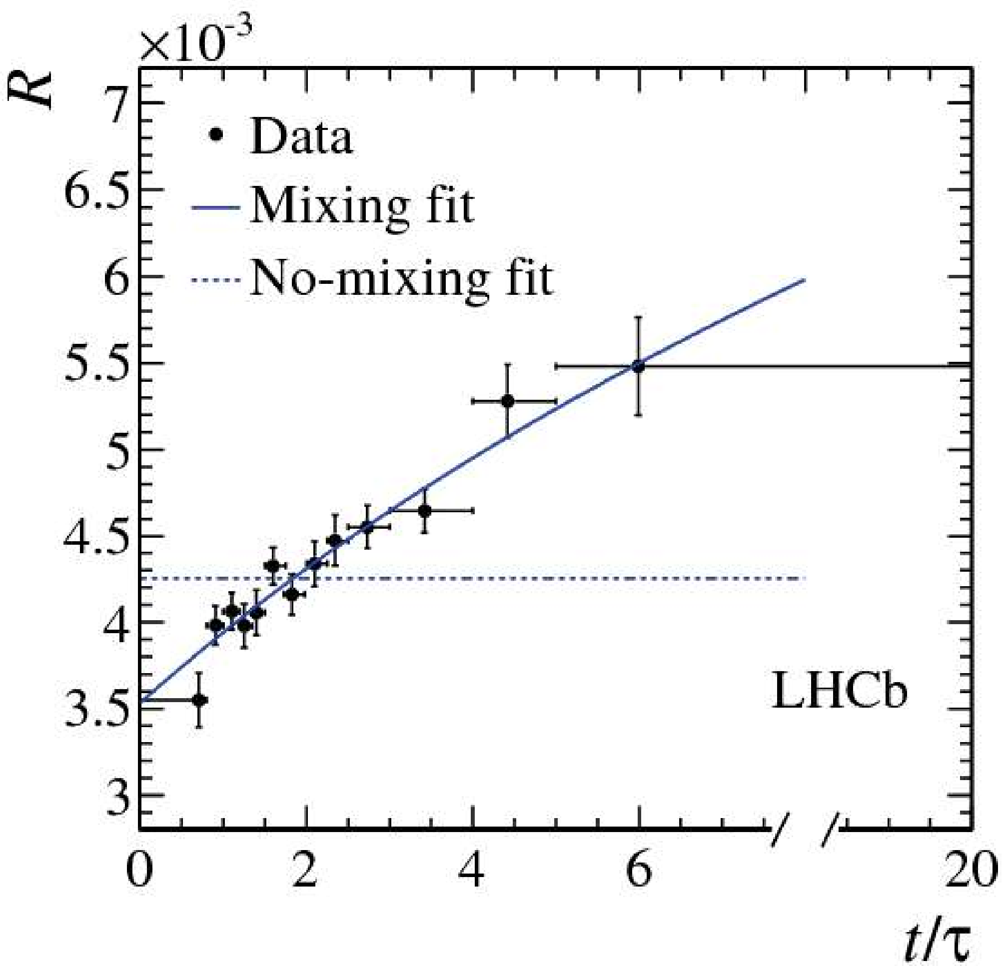
$$R^+_{\bar{f}} = \left|\frac{A_{\bar{f}}}{A_f}\right|^2,\ y'^+_{\bar{f}} = \sqrt{R^+_{\bar{f}}}\left[y\mathrm{Re}\lambda_{\bar{f}\theta} - x\mathrm{Im}\lambda_{\bar{f}\theta}\right],\ R^+_{M\bar{f}} = \frac{R^+_{\bar{f}}}{2}\left[(1+|\lambda_{\bar{f}\theta}|^2)y^2 - (1-|\lambda_{\bar{f}\theta}|^2)x^2\right]$$
$$R^-_f = \left|\frac{\bar{A}_f}{\bar{A}_{\bar{f}}}\right|^2,\ y'^-_f = \sqrt{R^-_f}\left[y\mathrm{Re}\,\bar{\lambda}_{f\theta} - x\mathrm{Im}\bar{\lambda}_{f\theta}\right]$$
$$\lambda_f = \frac{1}{\bar{\lambda}_f} = -|\lambda_f|e^{-i\phi_f},\ \bar{\lambda}_{\bar{f}} = \frac{1}{\lambda_{\bar{f}}} = -|\bar{\lambda}_{\bar{f}}|e^{-i\bar{\phi}_{\bar{f}}};\ |\lambda_f| = \left|\frac{q}{p}\right|\sqrt{d_f R^-_f},\ |\bar{\lambda}_{\bar{f}}| = \left|\frac{p}{q}\right|\sqrt{\frac{R^+_{\bar{f}}}{d_f}},\ d_f = \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|^2$$

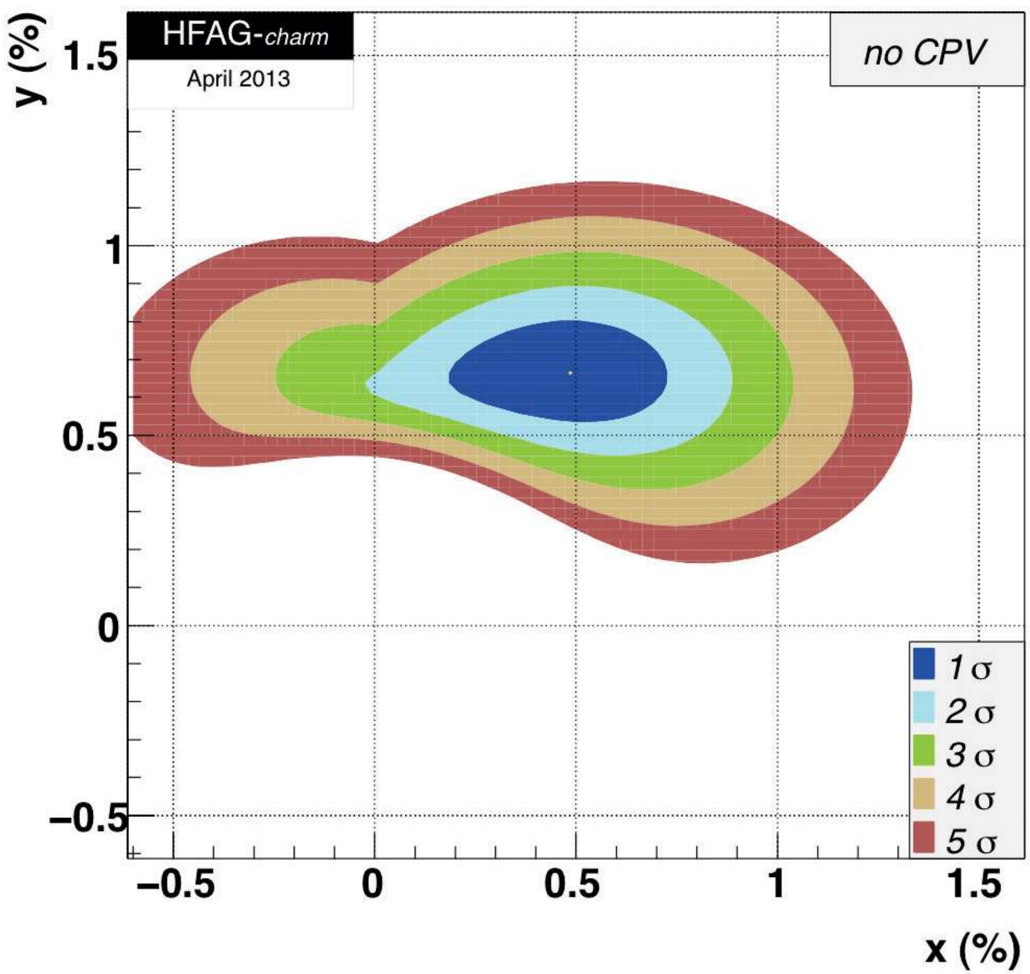
For CP self-conjugate states, $\bar{f} = f$. Thus $R^+_{\bar{f}} = R^-_f = 1$ and

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

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

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





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

1. Allowed semileptonic decays $D^0 \to K^- l^+ \nu \equiv f\ (A_f)$, $\bar{D}^0 \to K^+ l^- \bar{\nu}\ (\bar{A}_{\bar{f}})$
2. Forbidden $(\Delta C = \Delta Q)$ $A_{\bar{f}} = \bar{A}_f = 0$
3. ‘wrong’ sign/appearance

$$\Gamma(D_0 \to \bar{f})(t) = \left|\frac{q}{p} g_-(t) \bar{A}_{\bar{f}}\right|^2 \simeq |\bar{A}_{\bar{f}}|\, \mathrm{e}^{-\tau} \frac{R_M^+}{2} \tau^2$$

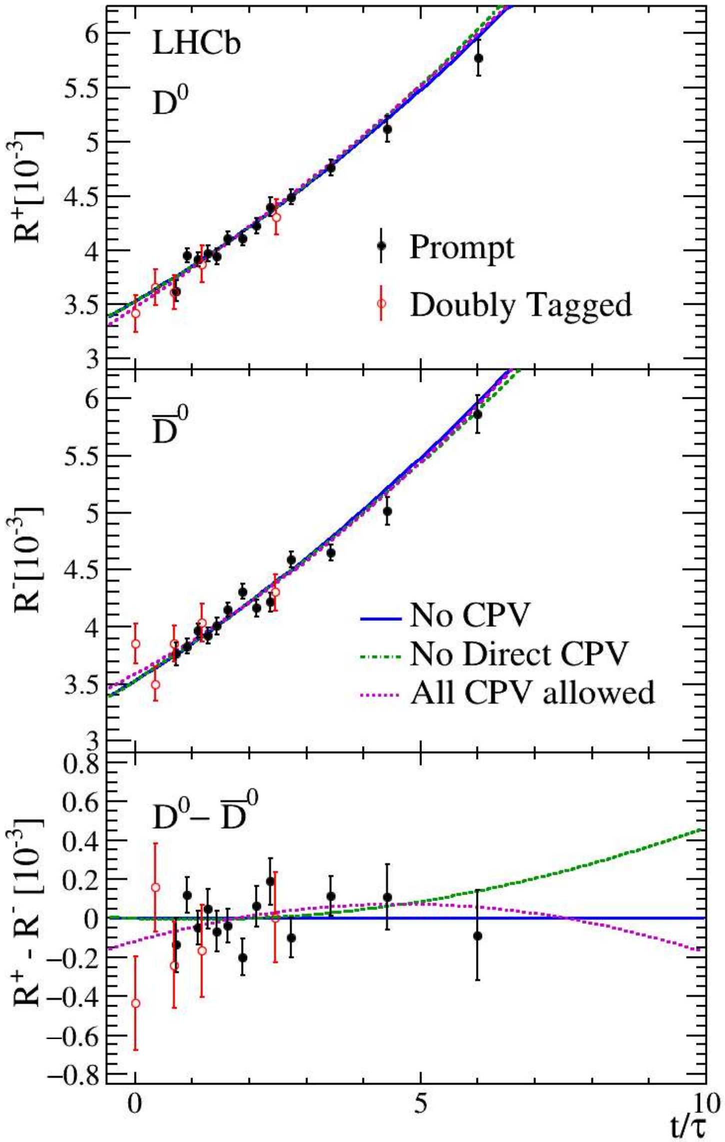
$$\Gamma(\bar{D}_0 \to f)(t) = \left|\frac{p}{q} g_-(t) A_f\right|^2 \simeq |A_f|\, \mathrm{e}^{-\tau} \frac{R_M^-}{2} \tau^2$$

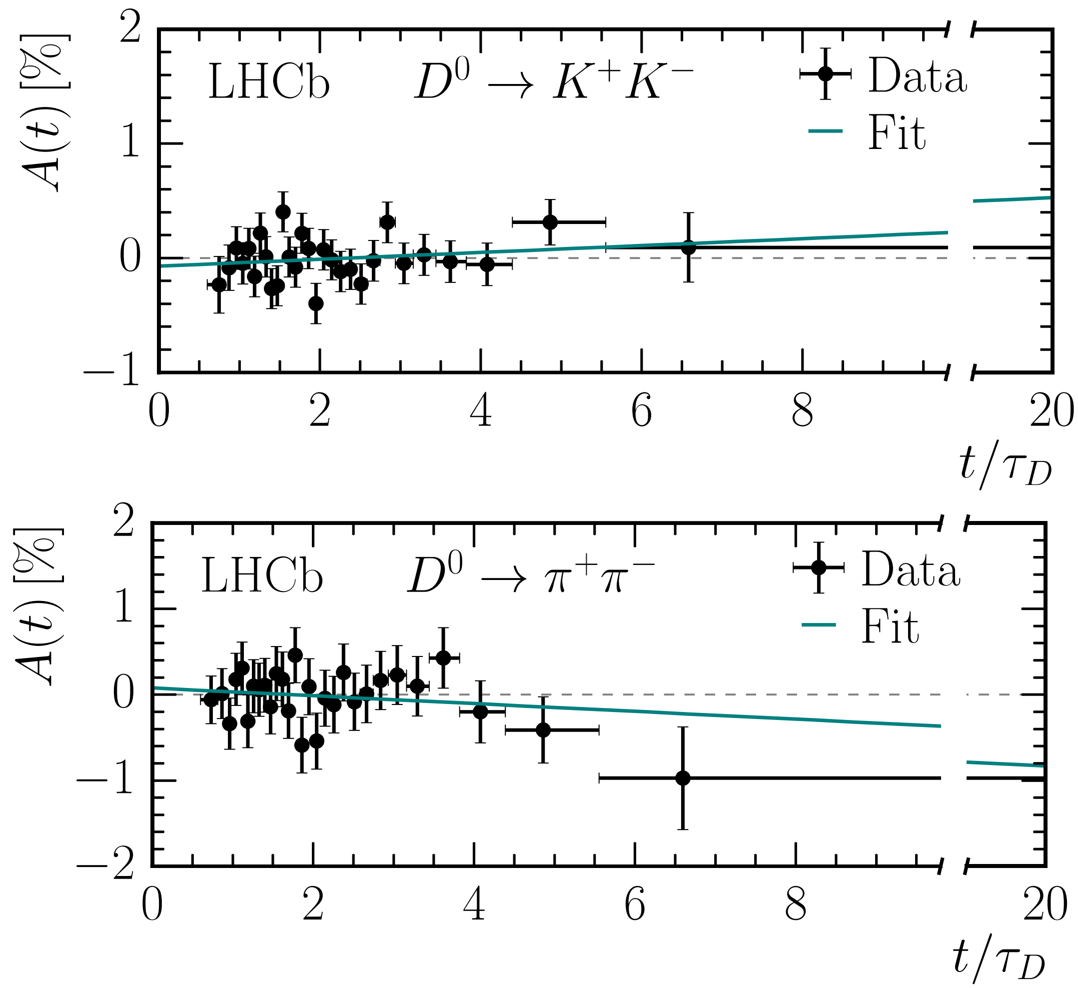
4. Any difference: CPV ‘in oscillations’

$$A_{\mathrm{SL}} = \frac{|A_{\bar{f}}(t)|^2 - |\bar{A}_f(t)|^2}{|A_{\bar{f}}(t)|^2 + |\bar{A}_f(t)|^2} = \frac{\left|q^2 \bar{A}_{\bar{f}}/p^2 A_f\right|^2 - 1}{\left|q^2 \bar{A}_{\bar{f}}/p^2 A_f\right|^2 + 1} \simeq \frac{|q/p|^4 - 1}{|q/p|^4 + 1} \equiv A_M$$

5. if no direct CPV is present $|A_f| = |\bar{A}_{\bar{f}}|$.
6. $R_M^+ \simeq R_M^- = R_M = (x^2 + y^2)/2 = 0.013(27)\ \%$

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





LHCb 1611.06143 CF/DCS

LHCb 1702.0649 SCS

CPV 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_f $[10^{-3}]$	3.454(31)				
$y_f'^{+}$ $[10^{-3}]$	5.01(56)	$y_f'^{-}$	5.54(56)	$y_f'^{+} - y_f'^{-}$ $[10^{-3}]$	-0.53(79)
$x_f'^{+2}$ $[10^{-5}]$	6.1(31)	$x_f'^{-2}$	1.6(31)	$x_f'^{+2} - x_f'^{-2}$ $[10^{-5}]$	4.5(44)
R_f $[10^{-3}]$	3.454(31)	y_f' $[10^{-3}]$	5.28(52)	$x_f'^{2}$ $[10^{-5}]$	3.9(27)
$A_{\mathrm{CP}}^{K\pi}$ $[10^{-3}]$	3(3)(6)	A_{CP}^{KK} $[10^{-3}]$	0.4(12)(10)	$A_{\mathrm{CP}}^{\pi\pi}$ $[10^{-3}]$	0.7(14)(11)
$A_{\Gamma}^{K\pi}$ $[10^{-3}]$	0.16(10)	A_{Γ}^{KK} $[10^{-3}]$	-0.44(23)(6)	$A_{\Gamma}^{\pi\pi}$ $[10^{-3}]$	0.25(43)(7)
y_{CP} $[10^{-3}]$	7.15(111)	ΔA_{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. ΔA_{CP}, 1903.08726.

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

CPV observables:

$$A^f(t) = \frac{|A_f(t)|^2 - |\bar{A}_{\bar{f}}(t)|^2}{|A_f(t)|^2 + |\bar{A}_{\bar{f}}(t)|^2},\ A_D^f = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2},\ A_D^{R_f} \equiv \frac{R_f^+ - R_f^-}{R_f^+ + R_f^-}$$

$$A_{\rm CP}^{\bar{f}} = \frac{\Gamma_{\bar{f}} - \bar{\Gamma}_f}{\Gamma_{\bar{f}} + \bar{\Gamma}_f} = \frac{(1 + A_D^f)\left(R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^+}\, y'^+_{\bar{f}}\right) - (1 - A_D^f)\left(R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^-}\, y'^-_{\bar{f}}\right)}{(1 + A_D^f)\left(R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^+}\, y'^+_{\bar{f}}\right) + (1 - A_D^f)\left(R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^-}\, y'^-_{\bar{f}}\right)}$$

$$A_\Gamma^{\bar{f}} \equiv \frac{\widehat{\Gamma}_{\bar{f}} - \widehat{\bar{\Gamma}}_f}{\widehat{\Gamma}_{\bar{f}} + \widehat{\bar{\Gamma}}_f} = \frac{y'^-_f / \sqrt{R_f^-} - y'^+_{\bar{f}} / \sqrt{R_{\bar{f}}^+}}{2 + 3(y'^+_{\bar{f}} / \sqrt{R_{\bar{f}}^+} + y'^-_f / \sqrt{R_f^-}) + 4 y'^+_{\bar{f}} y'^-_f / \sqrt{R_{\bar{f}}^+ R_f^-}} \tag{2}$$

With the effective width/lifetime and the integrated ratio

$$\widehat{\Gamma}_{\bar{f}} \equiv \frac{1}{< \tau_{\bar{f}} >} = \Gamma \frac{1 + y'^+_{\bar{f}} / \sqrt{R_{\bar{f}}^+}}{1 + 2y'^+_{\bar{f}} / \sqrt{R_{\bar{f}}^+}} \sim \Gamma \left(1 - \frac{y'^+_{\bar{f}}}{\sqrt{R_{\bar{f}}^+}}\right)$$

$$R_{\bar{f}} \equiv \frac{\Gamma_{\bar{f}}}{\Gamma_f(0)} = R_{\bar{f}}^+ + \sqrt{R_{\bar{f}}^+}\, y'^+_{\bar{f}} + R_{M\bar{f}}^+$$

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

$$\simeq \frac{1}{2}\left(\left|\frac{q\sqrt{d_f}}{p}\right| - \left|\frac{p}{q\sqrt{d_f}}\right|\right) y \cos\phi_f - \frac{1}{2}\left(\left|\frac{q\sqrt{d_f}}{p}\right| + \left|\frac{p}{q\sqrt{d_f}}\right|\right) x \sin\phi_f$$

$$y_{\mathrm{CP}} \equiv \frac{\widehat{\Gamma}_f + \widehat{\bar{\Gamma}}_f}{2\Gamma} - 1 = -\frac{1}{2}\left(y'^+_f + y'^-_f\right) = -\frac{1}{2}\left[y(|\lambda_f| + 1/|\lambda_f|)\cos\phi_f - x(|\lambda_f| - 1/|\lambda_f|)\sin\phi_f\right]$$

$$\simeq \frac{1}{2}\left(\left|\frac{q\sqrt{d_f}}{p}\right| + \left|\frac{p}{q\sqrt{d_f}}\right|\right) y \cos\phi_f - \frac{1}{2}\left(\left|\frac{q\sqrt{d_f}}{p}\right| - \left|\frac{p}{q\sqrt{d_f}}\right|\right) x \sin\phi_f = 7.15(111)\cdot 10^{-3}$$

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

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

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

Direct CPV discovery.

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

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

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

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

2. Exp. LHCb 1903.08726. 5.3σ 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)	
$D^+ \to K_S^0 \pi^+$	1.47(7)	-0.41(9)	$D^+ \to K_L^0 \pi^+$	1.46(5)	-
$D^0 \to \bar{K}_S^0 \eta$	$4.79(30) \cdot 10^{-3}$	-	$D^0 \to \bar{K}_S^0 \eta'$	$9.4(5) \cdot 10^{-3}$	-
$D^0 \to \bar{K}_S^0 \pi^0$	1.19(4)	-	$D_s^+ \to K^+ \bar{K}^0$	2.95(14)	-
$D_s^+ \to K^+ K_S^0$	1.49(6)	-	$D_s^+ \to K^+ K^- \pi^+$	5.39(21)	-
$D_s^+ \to K^+ K_S^0 \pi^0$	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)	$D^\pm \to K_S^0 \pi^\pm \pi^0$	7.24(21)	0.3(9)(3)
$D^0 \to K^- \pi^+ \pi^0$	13.9(5)		$D^0 \to K_s^0 \pi^+ \pi^-$	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)	$D^+ \to K^+ \pi^- \pi^+$	$5.27(23) \cdot 10^{-4}$	
$D^+ \to K^+ \eta$	$1.08(17) \cdot 10^{-4}$	-	$D^+ \to K^+ \eta'$	$1.76(22) \cdot 10^{-4}$	-
$D_s^+ \to K^+ \pi^0$	$6.3(21) \cdot 10^{-4}$	-	$D_s^+ \to K^+ \eta$	$1.76(35) \cdot 10^{-3}$	-
$D_s^+ \to K^+ \eta'$	$1.8(6) \cdot 10^{-3}$	-	$D_s^+ \to K_S^0 \pi^+$	$1.21(6) \cdot 10^{-3}$	-
$D_s^+ \to K^+ \pi^+ \pi^-$	$6.5(4) \cdot 10^{-3}$	-	$D_s^+ \to K^0 \pi^+ \pi^0$	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)
$D^0 \to K_s^0 2\pi^0$	9.1(11)		$D^\pm \to K^+ K^- \pi^\pm$	0.95(3)	0.39(61)